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Different nature of ρ and a_1

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Within the very same framework using lowest-order chiral interactions and optionally s-channel resonances it is shown that the ρ meson can be understood as a preformed (quark-antiquark) state — with only a small admixture of a π-π state — whereas the a_1 meson can be understood as a ρ-π state without the need for a preformed state.

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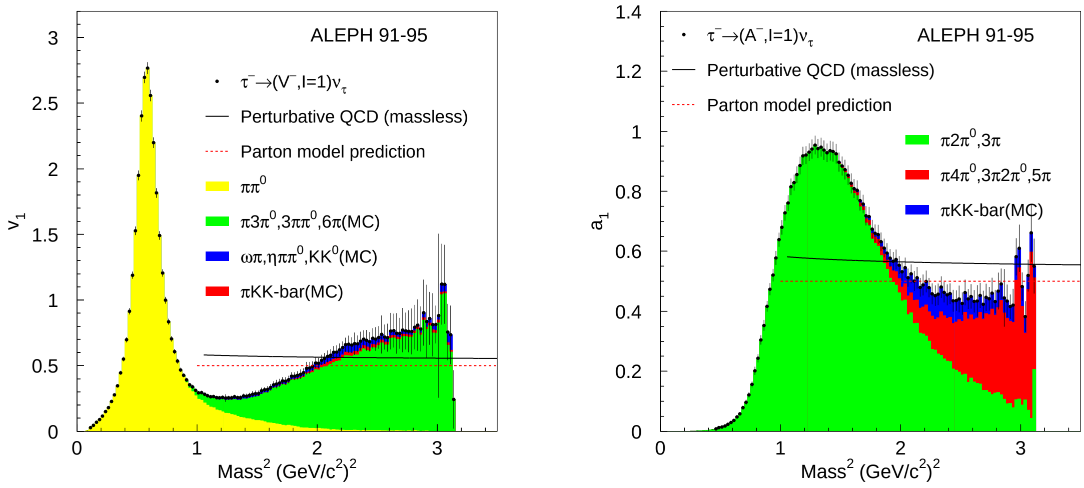

Figure 1: Spectral information of the vector (*left*) and axial-vector (*right*) current. Figures taken from [1].

1. Introduction

The isovector–vector and the isovector–axial-vector current,

$$\vec{j}_\mu^{\,V} = \bar{q}\,\vec{\tau}\gamma_\mu\, q \quad \text{and} \quad \vec{j}_\mu^{\,A} = \bar{q}\,\vec{\tau}\gamma_\mu\gamma_5\, q\,, \tag{1.1}$$

respectively, are related by a chiral transformation.[1] These currents can be called chiral partners on the fundamental level. In a world where chiral symmetry was not broken, the corresponding current-current correlators would show the same spectral information. In the real world chiral symmetry is spontaneously broken. A prominent peak — the ρ meson — shows up in the vector spectrum (measured in e^+e^- collisions and τ decays). On the other hand, in the axial-vector spectrum a broad bump appears — the a_1 meson (also accessible in τ decays). Both experimental informations are displayed in Fig. 1. It is tempting to call ρ and a_1 chiral partners on the hadronic level.

In the following strong indications are brought forward that these "chiral partners" do not only differ in mass but even in their nature [2]: The ρ meson appears dominantly as a quark-antiquark state with small modifications from an attractive pion-pion interaction [3]. The a_1 meson, on the other hand, can be understood as a meson-molecule state [4, 5, 6, 7] mainly formed by the attractive interaction between pion and ρ meson. A key issue here is that the meson-meson interactions are fixed by chiral symmetry breaking. It will be demonstrated that one can understand the vector and the axial-vector spectrum very well within this interpretation. It will also be shown that the opposite cases, namely ρ as a pion-pion molecule or a_1 as a quark-antiquark state lead to less satisfying results.

We are aiming at an understanding of the respective low-energy part of the spectra depicted in Fig. 1. Both show a resonant structure: In the vector spectrum (left panel) there is a peak at

[1]Here $\vec{\tau}$ denotes the isospin matrices.

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about 770 MeV called the ρ meson. In the axial-vector spectrum (right panel) there is a broad bump at about 1250 MeV called the a_1 meson. Actually both low-energy parts are governed by a (quasi-)two-particle final state — $\pi\pi$ for the vector and $\rho\pi$ for the axial-vector channel. The latter can be deduced from a Dalitz plot analysis of the three-pion final state [6].

The general strategy is the following: The two-particle state is subject to final-state interactions (rescattering). We want to figure out whether this final-state interaction is sufficient to create the respective resonant structure seen in Fig. 1 or whether one needs in addition a preformed resonance, i.e. an elementary hadronic state which microscopically should be regarded as a quark-antiquark state. This intrinsic structure is, however, not resolved at the hadronic level.

We study two scenarios: For the first scenario we only include the final-state interactions which we describe via a Bethe-Salpeter equation. The kernel is taken from the lowest-order chiral interaction. It is important to note that the strength of this final-state interaction is fixed by chiral symmetry breaking and is therefore parameter free. In the second scenario we include in addition a preformed resonance. If we got a reasonable description of the data from the first scenario, we would conclude that the resonance in the considered channel is a dynamically generated state, a meson-meson molecule. Otherwise, we would conclude that the resonance has a non-negligible or even dominant quark-antiquark contribution which can be quantified in the second scenario.

2. Nature of resonances: The ρ meson

Instead of the two-pion spectrum of Fig. 1, left panel, we study the electromagnetic form factor of the pion in the time-like region [3]: Due to isospin symmetry this contains the same information [1]. The relevant processes are depicted in Fig. 2. The lowest-order chiral interaction of the two-pion system is given by the non-linear sigma model [8]. We have two parameters at our disposal: the renormalization points (a) for the loop of the transition from the virtual photon to pions (top left panel in Fig. 2) and (b) for the loop appearing in the Bethe-Salpeter equation (middle panel in Fig. 2). These renormalization points are not (completely) free, however: First of all, both have to be in a reasonable range (see below). Second, the renormalization point for the loop in the Bethe-Salpeter equation can be fixed by the requirement of approximate crossing symmetry [4] (see also Ref. [9] for a different line of reasoning which yields the same result).

The result of the first scenario (only final-state interaction) is shown in Fig. 3, left panel. The full line labeled "low μ" is obtained for both renormalization points set to the pion mass. Obviously, one fails to describe the data. If the renormalization points are increased, it is possible to create a peak structure. The dotted line labeled "high μ" is obtained for both renormalization points set to 1.1 TeV. Finally, one gets the dashed line labeled "two μs" by setting the first renormalization point (photon-to-pion transition) to 10 TeV and the second one to 1.1 TeV. Thus, from a purely technical point of view the approach allows for a description of the data (dashed line). From the physical point of view, however, it must be stressed that only the full line corresponds to a reasonable calculation, since the renormalization points should lie in a reasonable range and not orders of magnitude away from typical hadronic scales. We conclude that with a physically reasonable choice of parameters one cannot explain the pion form factor within a scenario which includes only pion-pion rescattering. One needs in addition an elementary resonance as we will show next. A similar conclusion has been drawn in Ref. [12] studying the pion-pion scattering phase shifts.

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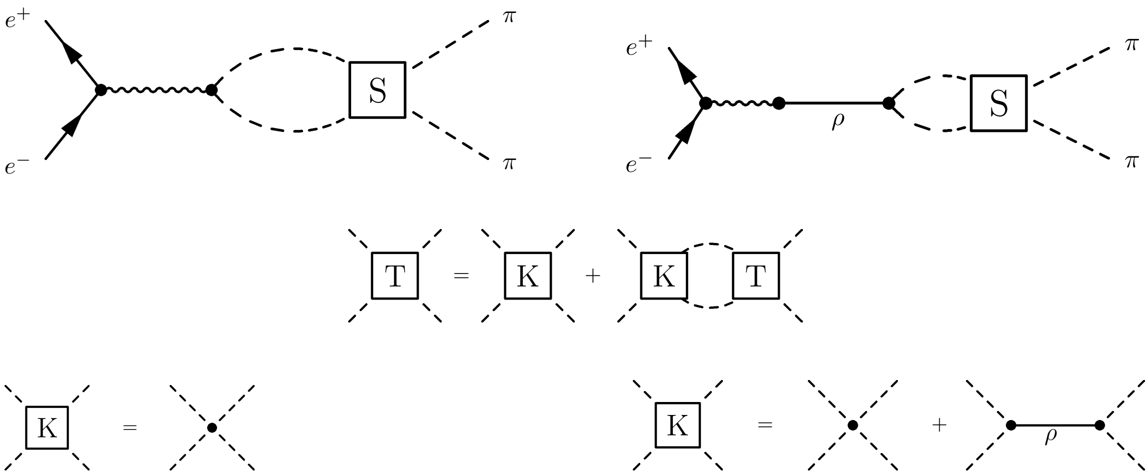

Figure 2: Description of the electromagnetic form factor of the pion within the two scenarios. The processes from which the form factor is extracted are depicted in the top panels. For the first scenario (only final-state rescattering) only the top left diagram enters. For the second scenario both diagrams in the top line are considered. The boxes labeled with S denote the S-matrix of pion-pion scattering. It is obtained from the T-matrix which in turn results from the solution of a Bethe-Salpeter equation (middle panel). The kernel K of the Bethe-Salpeter equation for the first/second scenario is shown in the bottom left/right panel. In the first scenario this kernel is fixed by the lowest-order chiral interaction. It is a point interaction as depicted in the lower panels. In addition, for the second scenario the preformed resonance appears in the kernel. For further details see main text and Ref. [3].

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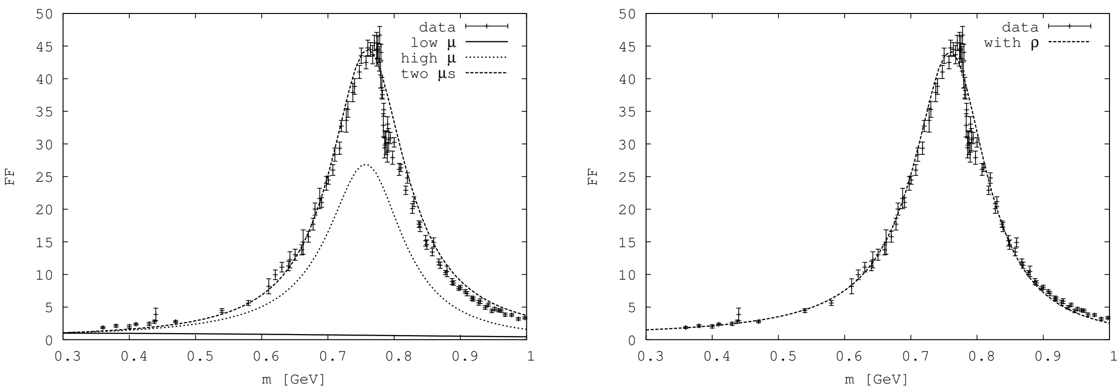

Figure 3: *Left:* The pion form factor in the first scenario (only rescattering of pions). The physically reasonable calculation is shown by the full line. The other calculations are technically possible, but physically unreasonable, since they correspond to renormalization points in the TeV range. See main text and Ref. [3] for details. *Right:* The pion form factor in the second scenario where an elementary resonance is included in addition. Data taken from Refs. [10, 11].

We now turn to the second scenario where an elementary resonance is included in addition to the pure rescattering studied in the first scenario. The form factor is now obtained from the sum of diagrams shown in the top line of Fig. 2. The Bethe-Salpeter equation is formally unchanged, Fig. 2, middle, but the kernel is now given by the sum of the point interaction obtained from the non-linear sigma model and the elementary resonance, cf. Fig. 2, bottom left. As additional parameters one has now the mass of the elementary resonance and its couplings to the photon and to two pions. Actually, changes in the renormalization points can be compensated by changes in these resonance parameters. Therefore, one has effectively three free parameters. As shown in Fig. 3, right panel, one gets an excellent description of the pion form factor [3]. In particular, there is no two-peak structure in the theory curve since the pion contact interaction alone is not very strong, as already shown by the full line in Fig. 3, left. We conclude that the ρ meson is dominantly a preformed (i.e. quark-antiquark) state with a small two-pion admixture and not a pion-pion molecule.

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3. Nature of resonances: The a_1 meson

The analysis of the a_1 meson exactly resembles the one presented for the ρ meson, but the result will be just the opposite: We will show in the following that the a_1 meson can be understood as a π-ρ molecule.

The relevant processes for the description of the decay $\tau \to \nu_\tau + 3\pi$ are schematically depicted in Fig. 4. The lowest-order chiral interaction of the ρ-π system is given by the Weinberg-Tomozawa interaction [13, 14, 4].

Results of the calculations for both scenarios are compared to data in Fig. 5. In the first scenario the a_1 meson emerges as a dynamically generated state from final-state interactions of vector and pseudoscalar mesons. That axial-vector mesons can be created in this way has been suggested in Ref. [4] and later in Ref. [5]. In these works a coupled-channel treatment of π-ρ and K-K^* has been presented. We follow this approach, but note in passing that the strangeness channel is not very important for the a_1 meson [6]. For the first scenario we take the parameter-free scattering amplitude from Ref. [4]. Then we are left with only one free parameter, the renormalization point μ_2 of the entrance loop from the W-boson to hadrons (cf. Fig. 4, top left). We recall that this parameter should be in a reasonable range. By only tuning μ_2 we get a decent description of the data as shown in Fig. 5, left panel. This means that we can essentially describe the position, height and width of the a_1 bump with one parameter which is in the GeV range (and not in the TeV range as for the case of the ρ meson).

In the second scenario where we include in addition an elementary resonance we typically generate a double peak structure (dotted line in Fig. 5, right panel). This is not surprising since we know from the first scenario that the final-state interaction between ρ and π is strong enough to create a resonance dynamically. An additional elementary resonance can only be hidden, if its coupling to the ρ-π system is weak (which essentially brings back the first scenario) or if its mass is fine-tuned such that it appears at the position of the dynamically generated resonance. The latter possibility is shown as the full line in Fig. 5, right panel. While this is technically possible we regard it as rather unnatural that a quark-antiquark and a meson-meson state appear at the very same position. Therefore, the natural explanation of the τ-decay data shown in Fig. 5 is that the a_1

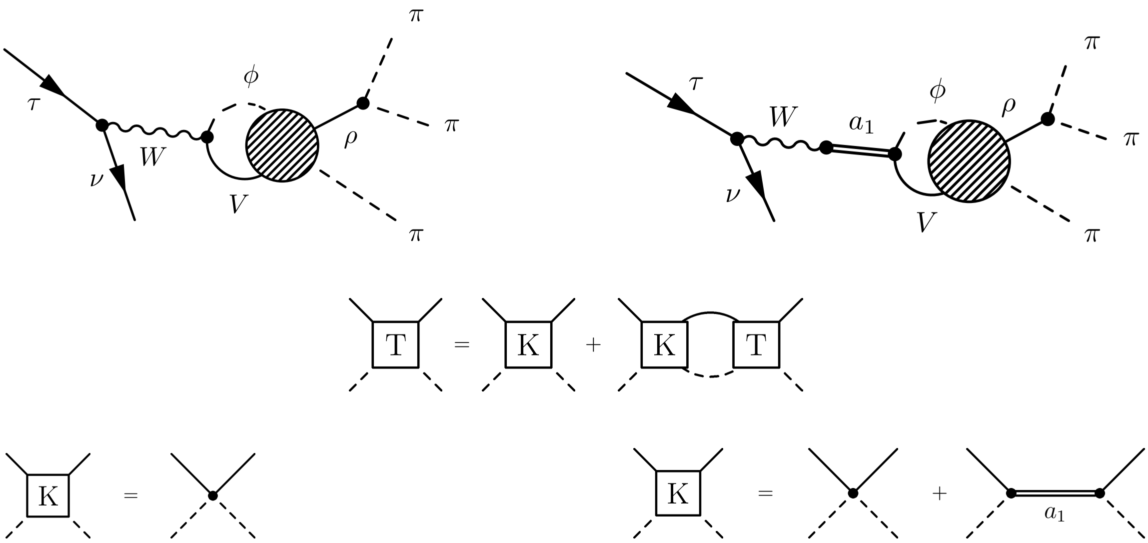

Figure 4: Description of the process $\tau \to \nu_\tau + 3\pi$ within the two scenarios. The diagrams which correspond to the considered process are depicted in the top panels. For the first scenario (only final-state rescattering) only the top left diagram enters. For the second scenario both diagrams in the top line are considered. The shaded circles denote the S-matrix of the scattering of vector mesons (V, full lines) on Goldstone bosons (ϕ, dashed lines) taking into account three flavors. The S-matrix is obtained from the T-matrix which in turn results from the solution of a Bethe-Salpeter equation (middle panel). The kernel K of the Bethe-Salpeter equation for the first/second scenario is shown in the bottom left/right panel. In the first scenario this kernel is fixed by the lowest-order chiral interaction. It is a point interaction as depicted in the lower panels. In addition, for the second scenario the preformed resonance appears in the kernel. For further details see main text and Ref. [6].

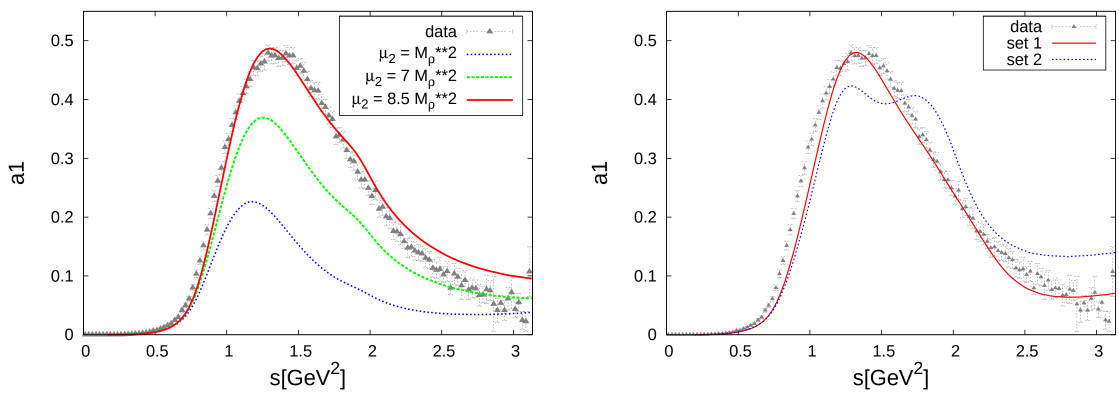

Figure 5: The axial-vector spectral information in the three-pion final state described by the first (*left*) and the second (*right*) scenario. See main text and Ref. [6] for details. Data taken from Ref. [1].

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meson is a dynamically generated state, i.e. a meson-meson molecule [6, 7] as suggested in Refs. [4, 5].

To summarize we have shown strong indications that the ρ and a_1, the “chiral partners” at the level of hadrons, are not only different in mass, but actually different in nature: The ρ meson is dominantly a quark-antiquark state whereas the a_1 is dominantly a meson-meson state (mostly ρ-π).

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References

[1] S. Schael *et al.* [ALEPH Collaboration], “Branching ratios and spectral functions of tau decays: Final ALEPH measurements and physics implications,” Phys. Rept. **421**, 191 (2005) [arXiv:hep-ex/0506072].

[2] S. Leupold and M. Wagner, “Chiral Partners in a Chirally Broken World,” Int. J. Mod. Phys. A **24**, 229 (2009) [arXiv:0807.2389 [nucl-th]].

[3] S. Leupold, “Information on the structure of the rho meson from the pion form-factor,” arXiv:0907.0100 [hep-ph].

[4] M. F. M. Lutz and E. E. Kolomeitsev, “On meson resonances and chiral symmetry,” Nucl. Phys. A **730**, 392 (2004) [arXiv:nucl-th/0307039].

[5] L. Roca, E. Oset and J. Singh, “Low lying axial-vector mesons as dynamically generated resonances,” Phys. Rev. D **72**, 014002 (2005) [arXiv:hep-ph/0503273].

[6] M. Wagner and S. Leupold, “Information on the structure of the a1 from tau decay,” Phys. Rev. D **78**, 053001 (2008) [arXiv:0801.0814 [hep-ph]].

[7] M. Wagner and S. Leupold, “Tau decay and the structure of the a1,” Phys. Lett. B **670**, 22 (2008) [arXiv:0708.2223 [hep-ph]].

[8] J. Gasser and H. Leutwyler, “Chiral Perturbation Theory To One Loop,” Annals Phys. **158**, 142 (1984).

[9] T. Hyodo, D. Jido and A. Hosaka, “Origin of the resonances in the chiral unitary approach,” Phys. Rev. C **78**, 025203 (2008) [arXiv:0803.2550 [nucl-th]].

[10] L. M. Barkov *et al.*, “Electromagnetic Pion Form-Factor In The Timelike Region,” Nucl. Phys. B **256**, 365 (1985).

[11] R. R. Akhmetshin *et al.* [CMD-2 Collaboration], “Reanalysis of Hadronic Cross Section Measurements at CMD-2,” Phys. Lett. B **578**, 285 (2004) [arXiv:hep-ex/0308008].

[12] J. A. Oller and E. Oset, “N/D Description of Two Meson Amplitudes and Chiral Symmetry,” Phys. Rev. D **60**, 074023 (1999) [arXiv:hep-ph/9809337].

[13] S. Weinberg, “Pion scattering lengths,” Phys. Rev. Lett. **17**, 616 (1966).

[14] Y. Tomozawa, “Axial vector coupling renormalization and the meson baryon scattering lengths,” Nuovo Cim. **46A**, 707 (1966).