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Physics Letters B 632 (2006) 215–218
PHYSICS LETTERS B
www.elsevier.com/locate/physletb

Constraints on the new particle in $\Sigma^+ \to p\mu^+\mu^-$

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Received 22 September 2005; received in revised form 18 October 2005; accepted 20 October 2005

Available online 2 November 2005

Editor: T. Yanagida

Abstract

The HyperCP Collaboration has presented the branching ratio of $\Sigma^+ \to p\mu^+\mu^-$ to be $(8.6^{+6.6}_{-5.4} \pm 5.5) \times 10^{-8}$ and suggested a new boson P^0 with a mass of 214.3 ± 0.5 MeV to induce the flavor changing transition of $s \to d\mu^+\mu^-$. We demonstrate that to explain the data, the new particle cannot be a scalar but pseudoscalar based on the direct constraints from $K^+ \to \pi^+\mu^+\mu^-$ and $K_L \to \mu^+\mu^-$, respectively. Moreover, we determine that the decay width of the pseudoscalar should be in the range of 10^{-7} MeV with the lifetime of 10^{-14} s.

PACS: 11.30.Er; 13.25.Hw

According to the report of the HyperCP Collaboration [1], the observation of three events for the decay $\Sigma^+ \to p\mu^+\mu^-$ reveals the possibilities of new physics, as the branching ratio $\mathrm{Br}(\Sigma^+ \to p\mu^+\mu^-) = (8.6^{+6.6}_{-5.4} \pm 5.5) \times 10^{-8}$ is claimed to be larger than the prediction within the Standard Model [1–3]. The analysis in Ref. [1] has found an unexpectedly narrow dimuon distribution, which cannot be explained by the form factors used to deform the phase space due to their mildly momentum dependences [2,3]. The plausible explanation can be the threshold effect which is induced as $m_{\mu^+\mu^-} = (p_{\mu^+} + p_{\mu^-})$ is approaching to the pole of some unknown intermediate boson, suggesting a two-body $\Sigma^+ \to pP^0$, $P^0 \to \mu^+\mu^-$ decay shown in Fig. 1a, with the P^0 mass being $m_{P^0} = 214.3 \pm 0.5$ MeV [1] and the branching ratio [1]

$$\mathrm{Br}\big(\Sigma^+ \to pP^0, P^0 \to \mu^+\mu^-\big) = \big(3.1^{+2.4}_{-1.9} \pm 1.5\big) \times 10^{-8}. \tag{1}$$

If the effect is true, the flavor-changing neutral current (FCNC) of the $s \to d$ transition is discovered at tree level. Clearly, the most important task is to check the reality of the experiment. Note that the observed events are only three and the physical properties of this unknown particle remain ambiguous. Nevertheless, the investigations can proceed via the decays of $K^+ \to \pi^+\mu^+\mu^-$ and $K_L \to \mu^+\mu^-$ since they share the same effective four-fermion interaction at quark level as shown in Fig. 1. In this Letter, we will explore the constraints on the new particle suggested by the HyperCP Collaboration by relating the three decay modes.

We start with the general effective four-fermion interaction for $s \to d\mu^+\mu^-$ in Fig. 1 by including all possible scalar-type currents, given by

$$\mathcal{L}_{\rm NP} = \frac{\lambda_{ij}}{q^2 - m_{P^0}^2 + i m_{P^0}\Gamma_{P^0}} \bar{d}\Gamma_i s \bar{u}\Gamma_j v + \text{H.C.}, \tag{2}$$

where $q = p_{\mu^+} + p_{\mu^-}$, Γ_{P^0} is the decay width, u (v) denotes the μ^- (μ^+) spinor and λ_{ij} are the combined coupling constants with $i, j = S$ and P for $\Gamma_{i,j} = 1$ and γ_5, representing scalar and pseudoscalar currents, respectively. We stress the necessity of the decay width Γ_{P^0} in Eq. (2) for the threshold enhancement around the pole near $m_{\mu^+\mu^-} = 214.3$ MeV. In Eq. (2), there are four kinds of couplings through $S \otimes S$, $P \otimes P$, $S \otimes P$ and $P \otimes S$ currents. Note that the latter two are parity-odd terms with the physical states being the mixtures of scalar and pseudoscalar [4]. Moreover, the last one could also violate CP symmetry through the longitudinal muon polarization in $K_L \to \mu^+\mu^-$ [4]. However, we shall not consider CP violation in the present Letter.

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doi:10.1016/j.physletb.2005.10.056

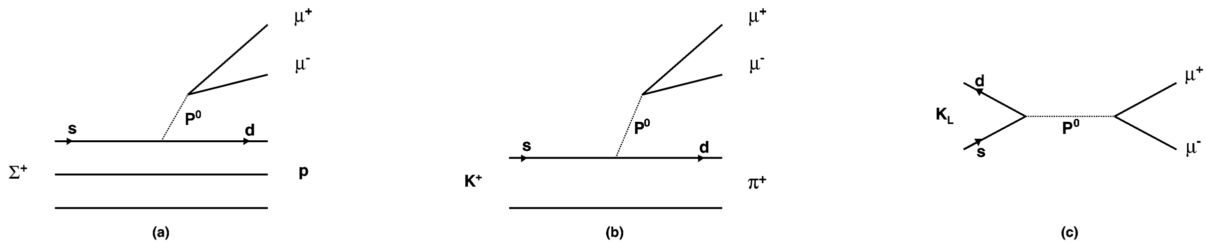

Fig. 1. Diagrams for (a) $\Sigma^+ \to pP^0$, $P^0 \to \mu^+\mu^-$, (b) $K^+ \to \pi^+ P^0$, $P^0 \to \mu^+\mu^-$ and (c) $K_L \to P^0$, $P^0 \to \mu^+\mu^-$.

We now apply $\mathcal{L}_{\rm NP}$ in Eq. (2) to the decay of $\Sigma^+ \to pP^0$, $P^0 \to \mu^+\mu^-$. The amplitude is found to be

$$\mathcal{A}_{\Sigma^+} \equiv \mathcal{A}\big(\Sigma^+ \to pP^0, P^0 \to \mu^+\mu^-\big) = \frac{\lambda_{ij}}{q^2 - m_{P^0}^2 + i m_{P^0}\Gamma_{P^0}} \langle p|\bar{d}\Gamma_i s|\Sigma^+\rangle \bar{u}\Gamma_j v\,. \tag{3}$$

To evaluate the amplitude, we parametrize

$$\langle p|\bar{d}s|\Sigma^+\rangle = f_S \bar{u}_p u_\Sigma, \qquad \langle p|\bar{d}\gamma_5 s|\Sigma^+\rangle = g_P \bar{u}_p \gamma_5 u_\Sigma, \tag{4}$$

where the form factors are given by [5]

$$f_S = f_1\big(q^2\big)\frac{m_\Sigma - m_p}{m_s - m_d}, \qquad g_P = g_1\big(q^2\big)\frac{m_\Sigma + m_p}{m_s + m_d}, \tag{5}$$

with [5,6]

$$f_1\big(q^2\big) = \frac{f_1(0)}{\big(1 - \frac{q^2}{m_V^2}\big)^2}, \qquad g_1\big(q^2\big) = \frac{g_1(0)}{\big(1 - \frac{q^2}{m_A^2}\big)^2},$$
$$f_1(0) = -1.0, \quad g_1(0) = 0.35,$$
$$m_V = 0.97 \text{ GeV}, \quad m_A = 1.25 \text{ GeV}. \tag{6}$$

It is noted that the momentum dependences are expressed as the double-pole expansions.

To test possibilities of new physics from $\Sigma^+ \to pP^0$, $P^0 \to \mu^+\mu^-$, we study the decays of $K^+ \to \pi^+\mu^+\mu^-$ and $K_L \to \mu^+\mu^-$ due to $\mathcal{L}_{\rm NP}$ in Eq. (2). The amplitudes of $K^+ \to \pi^+ P^0$, $P^0 \to \mu^+\mu^-$ and $K_L \to P^0$, $P^0 \to \mu^+\mu^-$ are given by

$$\mathcal{A}_{K^+} = \frac{\lambda_{ij}}{q^2 - m_{P^0}^2 + i m_{P^0}\Gamma_{P^0}} \langle \pi^+|\bar{d}\Gamma_i s|K^+\rangle \bar{u}\Gamma_j v,$$
$$\mathcal{A}_{K_L} = \frac{\lambda_{ij}}{q^2 - m_{P^0}^2 + i m_{P^0}\Gamma_{P^0}} \times \big[\langle 0|\bar{d}\Gamma_i s|K_L\rangle + \langle 0|\bar{s}\Gamma_i d|K_L\rangle\big]\bar{u}\Gamma_j v, \tag{7}$$

respectively. Here, we have defined $\mathcal{A}_{K^+} \equiv \mathcal{A}(K^+ \to \pi^+ P^0$, $P^0 \to \mu^+\mu^-)$ and $\mathcal{A}_{K_L} \equiv \mathcal{A}(K_L \to P^0, P^0 \to \mu^+\mu^-)$. It is noted that there are no contributions from $\langle \pi^+|\bar{d}\gamma_5 s|K^+\rangle$ and $\langle 0|\bar{d}s|K_L\rangle + \langle 0|\bar{s}d|K_L\rangle$ due to the parity conservation in strong interaction. Therefore, $K^+ \to \pi^+\mu^+\mu^-$ can only be used to constrain the couplings of $S \otimes S$ (P), while $K_L \to \mu^+\mu^-$ to those of $P \otimes S$ (P). The matrix elements in Eq. (7) by means of equation of motion are found to be

$$\langle \pi^+|\bar{d}s|K^+\rangle = \frac{m_K^2 - m_\pi^2}{m_s - m_d} f_+,$$
$$\langle 0|\bar{d}\gamma_5 s|K_L\rangle + \langle 0|\bar{s}\gamma_5 d|K_L\rangle = i\sqrt{2} f_K \frac{m_K^2}{m_s + m_d}, \tag{8}$$

where $f_+ \simeq 1$ and $f_K = 160$ MeV [7].

To proceed, we first concentrate on $S \otimes S$ (P) couplings. The experimental measurement for the decay of $K^+ \to \pi^+\mu^+\mu^-$ is [7]

$$\text{Br}(K^+ \to \pi^+\mu^+\mu^-) = (8.1 \pm 1.4) \times 10^{-8}. \tag{9}$$

It has been demonstrated that the dominate contribution for the decay is from the one-photon exchange in the Standard Model, which can be referred, such as in Ref. [8]. Since the partial branching ratio of the three-body decay is proportional to $|\mathcal{A}|^2/m^3 \cdot \tau$, where $|\mathcal{A}|^2$ is the squared amplitude and m (τ) is the mass (lifetime) of the mother particle. For the $S \otimes S$ (P) currents, from Eqs. (3)–(7) we have

$$|\mathcal{A}_{K^+}|^2/|\mathcal{A}_{\Sigma^+}|^2 \simeq 0.25, \tag{10}$$

$(1/m_K^3)/(1/m_\Sigma^3) \simeq 14$ and $\tau_{K^+}/\tau_{\Sigma^+} = 1.5 \times 10^2$. After integrating the phase space, we find that

$$\frac{\text{Br}(K^+ \to \pi^+ P^0, P^0 \to \mu^+\mu^-)}{\text{Br}(\Sigma^+ \to pP^0, P^0 \to \mu^+\mu^-)} \sim \text{O}\big(10^2\big) \ \big(\text{O}\big(10^3\big)\big) \tag{11}$$

for the $S \otimes S$ (P) currents. Note that the estimation of the ratio in Eq. (11) is independent of the property of the new particle. When $\text{Br}(\Sigma^+ \to pP^0, P^0 \to \mu^+\mu^-)$ is in the range of $\text{O}(10^{-8})$, in any case, $\text{Br}(K^+ \to \pi^+ P^0, P^0 \to \mu^+\mu^-)$ should be of $\text{O}(10^{-6}\text{–}10^{-5})$ if the interaction is $S \otimes S$ (P), which is clearly out of the limitation in Eq. (9). As a result, the tree level flavor-changing $s \to d\mu^+\mu^-$ transition resulting from the new physics of $S \otimes S$ (P) currents is unambiguously ruled out based on the data of $K^+ \to \pi^+\mu^+\mu^-$.

We now turn to the new physics from $P \otimes P$ and $P \otimes S$ currents. Currently, the experimental measurement on $K_L \to \mu^+\mu^-$ is [7]

$$\text{Br}(K_L \to \mu^+\mu^-) = (6.87 \pm 0.12) \times 10^{-9}, \tag{12}$$

which is almost saturated by the absorptive (imaginary) part, dominated by the measured mode of $K_L \to \gamma\gamma$ with $\text{Br}(K_L \to \gamma\gamma) = (5.56 \pm 0.06) \times 10^{-4}$ [7], i.e., $\text{Br}_{\rm abs}(K_L \to \mu^+\mu^-) = (6.66 \pm 0.07) \times 10^{-9}$. However, there is still a possibility of the cancellation among the short-distance amplitude and the real part of the long-distance part [9,10]. Nevertheless, it is believed that the new physics contribution to the decay branching ratio cannot excess of $\text{O}(10^{-9})$ [9]. To be conservative, we shall use

$$\text{Br}_{K_L} \equiv \text{Br}\big(K_L \to P^0, P^0 \to \mu^+\mu^-\big) \leqslant 10^{-9} \tag{13}$$

as our working assumption to constrain the new physics.

Beginning with a rough estimate, if we assume that $\Gamma_{P^0} \simeq 1$ MeV, we find that the ratio of Br_{K_L} and $\text{Br}_{\Sigma^+} \equiv \text{Br}(\Sigma^+ \to$