Frascati Physics Series Vol. XXXVI (2004), pp.
DAΦNE 2004: Physics at meson factories – Frascati, June 7-11 , 2004
Short Talk in Plenary Session

RECENT PROGRESS ON THE RARE DECAY $K_L \to \pi^0\mu^+\mu^-$

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1 Introduction

Studies of direct CP-violation are important to test the Standard Model, and possibly to discover New Physics effects. Here, we consider the following rare K_L modes, with CP-violating and CP-conserving contributions

	Direct-CPV	Indirect-CPV	CPC
$K_L \to \pi^0\nu\bar{\nu}$	$\sim 100\%$	$\sim 0\%$	$\sim 0\%$
$K_L \to \pi^0 e^+e^-$	$\sim 40\%$	$\sim 60\%$	$\sim 0\%$
$K_L \to \pi^0\mu^+\mu^-$	$\sim 30\%$	$\sim 35\%$	$\sim 35\%$

While the theoretical complexity increases, recent experimental results now permit reliable estimates for ICPV and CPC, making the $\ell^+\ell^-$ modes competitive with the $\nu\bar{\nu}$ one.

The CPC contribution proceeds through two photons, which can be in a scalar 0^{++} or tensor 2^{++} state. The former is helicity suppressed, hence contribute only for $\mu^+\mu^-$, while the later, much smaller, is the dominant one [1] for e^+e^-. Our work was to estimate the 0^{++} CPC contribution [2].

2 CP–conserving contribution

At leading order in Chiral Perturbation Theory, the process proceeds through a charged meson $(\pi; K)$ loop followed by a photon loop, see fig.1a. Provided one can parametrize the vertex $M\left(K_L \to \pi^0 P^+ P^-\right) = G_8 m_K^2 a(z)$, with $z = \left(p_{P^+} + p_{P^-}\right)^2 / m_K^2$ the invariant mass and $a(z)$ some function, the differential rate can be factorized

$$\Gamma_{\ell^+\ell^-} = \frac{G_8^2 m_K^5 \alpha^4}{512\pi^7} \int_{4r_\ell^2}^{(1-r_\pi)^2} dz\ |a(z)|^2 \lambda_\pi^{1/2} \left| \mathcal{J}\left(\frac{r_\pi^2}{z}, \frac{r_\ell^2}{z}\right)\right|^2 \frac{r_\ell^2}{z} \left(1 - \frac{4r_\ell^2}{z}\right)^{3/2}$$

where $\lambda_\pi = \lambda\left(1, r_\pi^2, z\right)$ is the standard two-body kinematical function for $\pi^0 (PP)_{0^{++}}$ in a $L = 0$ wave, r_ℓ^2/z is the helicity suppression factor and $\left(1 - 4r_\ell^2/z\right)^{3/2}$ stands for the lepton pair in a $L = 1$ wave. The two-loop function $\mathcal{J}$ describes the transitions $(PP)_{0^{++}} \to \ell^+\ell^-$ and is exactly the one occurring in $K_S \to (PP)_{0^{++}} \to \gamma\gamma \to \ell^+\ell^-$ [2, 3].

To proceed, we took the ratio $R_{\gamma\gamma} = \Gamma_{\ell^+\ell^-}/\Gamma_{\gamma\gamma}$, with $\Gamma_{\gamma\gamma}$ the $K_L \to \pi^0\gamma\gamma$ rate computed with the same $a(z)$ parametrization of the vertex $K_L \to \pi^0 P^+ P^-$ [4]. The crucial point is that for a large range of parametrization, $R_{\gamma\gamma}$ is stable. This means that both modes react similarly to modulations in the distribution of momentum entering the scalar subprocess. Given this observation, we infer the branching ratio of $\ell^+\ell^-$ from the experimental result for $\gamma\gamma$. In doing so, some higher order chiral corrections are included in our result. Taking $B\left(K_L \to \pi^0\gamma\gamma\right)^{\exp} = (1.42 \pm 0.13) \times 10^{-6}$ as the average of the KTeV and NA48 measurements [5], we find $B\left(K_L \to \pi^0\mu^+\mu^-\right)_{CPC}^{0^{++}} = (5.2 \pm 1.6) \times 10^{-12}$, with a conservative error estimate of 30%.

Finally, the differential rate is in fig.1b, and it shows that an appropriate kinematical cut can reduce the relative contamination of the CPC contribution to below 10%.

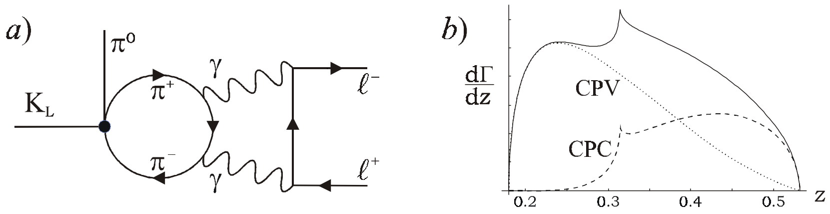

Figure 1: *a) Typical CPC pion loop contribution, b) Differential rate.*

3 Phenomenological Analysis

The final parametrizations are ($\kappa = 10^4 \,\mathrm{Im}\,\lambda_t = 1.36 \pm 0.12$)

$$B\left(K_L \to \pi^0 e^+ e^-\right) \approx \left(2.4\kappa^2 \pm 6.2\,|a_S|\,\kappa + 15.7\,|a_S|^2\right) \times 10^{-12}$$

$$B\left(K_L \to \pi^0 \mu^+ \mu^-\right) \approx \left(1.0\kappa^2 \pm 1.6\,|a_S|\,\kappa + 3.7\,|a_S|^2 + 5.2\right) \times 10^{-12}$$

The κ^2 terms are DCPV, the ICPV parameter a_S is the counterterm dominating $K_S \to \pi^0 \ell^+ \ell^-$, recently measured by NA48/1 [6] $|a_S^{\exp}| = 1.2 \pm 0.2$. The interference between DCPV and ICPV has been argued to lead to positive sign [1, 7]. In the same notation, $B\left(K_L \to \pi^0 \nu\bar{\nu}\right) \approx \left(16\kappa^2\right) \times 10^{-12}$, see [8].

It is important to note that the muon mode DCPV term receives an additional helicity-suppressed axial-vector FCNC contribution, somewhat compensating the overall phase-space suppression. Due to this fact, the two modes have different sensitivities to the underlying weak physics, and the plot of the muon mode against the electron one for various $\mathrm{Im}\,\lambda_t$ is not a trivial straight line (see fig.2). This plot is then well-suited to study possible impacts of New Physics. Taking as an example the model of Buras et al. [9], we get the theoretical predictions for positive interference:

	S.M. $\left(\times 10^{-11}\right)$	EEWP $\left(\times 10^{-11}\right)$	Experiment [10]
$K_L \to \pi^0 \nu\bar{\nu}$	3.0 ± 0.6	31 ± 10	$< 5.9 \times 10^{-7}$
$K_L \to \pi^0 e^+ e^-$	$3.7^{+1.1}_{-0.9}$	9.0 ± 1.6	$< 2.8 \times 10^{-10}$
$K_L \to \pi^0 \mu^+ \mu^-$	1.5 ± 0.3	4.3 ± 0.7	$< 3.8 \times 10^{-10}$

In conclusion, the set of decays $K_L \to \pi^0 \nu\bar{\nu}$, $\pi^0 e^+ e^-$ and $\pi^0 \mu^+ \mu^-$ is now under theoretical control, and provides for a stringent test of the Standard

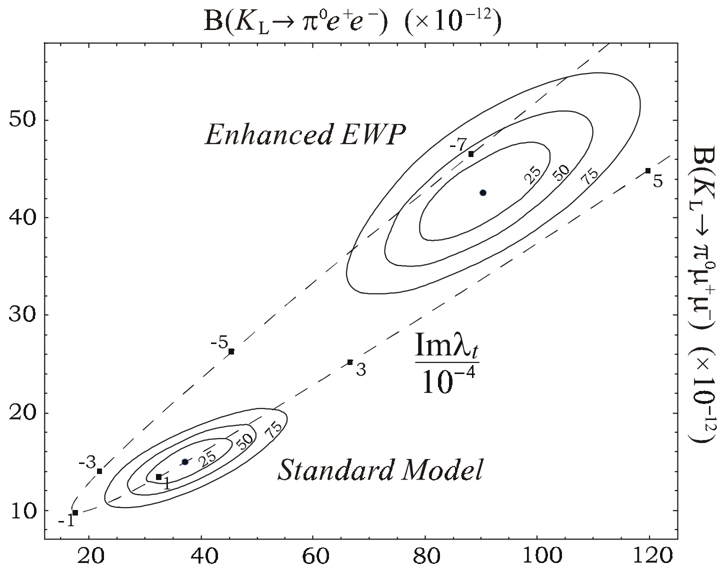

Figure 2: *SM and EEWP* [9] *theoretical predictions.*

Model. In addition, if a signal of New Physics is found, the observed pattern of branching ratios will give information on its nature. Experimentally, it is then clear that the $K_L \to \pi^0\mu^+\mu^-$ mode should be seriously considered. Also, additional measurements of $K_S \to \pi^0\ell^+\ell^-$ would be certainly very desirable since the main uncertainty on the theoretical prediction for the CPV parts, and thus the spreading of the confidence regions in Fig.2, comes from a_S.

4 Acknowledgements

This work has been supported by IHP-RTN, EC contract No. HPRN-CT-2002-00311 (EURIDICE).

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