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Search for CPT violation and decoherence effects in the neutral kaon system

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and the KLOE collaboration [1]

Abstract. The neutral kaon system offers a unique possibility to perform fundamental tests of CPT invariance, as well as of the basic principles of quantum mechanics. The most recent limits on several kinds of possible CPT violation and decoherence mechanisms, which in some cases might be justified in a quantum gravity framework, are reviewed, including the latest results obtained by the KLOE experiment at the DAΦNE e^+e^- collider. No deviation from the expectations of quantum mechanics and CPT symmetry is observed, while the precision of the measurements, in some cases, reaches the interesting Planck scale region.

1. Introduction

The three discrete symmetries of quantum mechanics, C (charge conjugation), P (parity), and T (time reversal) are known to be violated in nature, both singly and in pairs. Only the combination of the three - CPT (in any order) - appears to be an exact symmetry of nature. An intuitive justification of this [1] can be based on the fact that our space-time is four dimensional, and that for an even dimensional space, from well known geometrical arguments, reflection of all axes is equivalent to a rotation. For instance, in the case of a plane, i.e. a two dimensional space, both coordinate axes change sign under total reflection, and exactly the same happens for a 180° rotation around the origin. Therefore one would be tempted to assume PT reflection as equivalent to a rotation in four dimensional space-time. However it can be easily verified that the time coordinate is not exactly equivalent to a space coordinate, due to the pseudo-euclidean nature of our four dimensional space-time; to restore the equivalence it can be shown that it is necessary to add C conjugation to the PT operation. Therefore the CPT operation, and not simply PT, appears to be equivalent to the reflection of all four axes in our space-time.

[1] The KLOE collaboration: F. Ambrosino, A. Antonelli, M. Antonelli, F. Archilli, P. Beltrame, G. Bencivenni, S. Bertolucci, C. Bini, C. Bloise, S. Bocchetta, F. Bossi, P. Branchini, G. Capon, D. Capriotti, T. Capussela, F. Ceradini, P. Ciambrone, E. De Lucia, A. De Santis, P. De Simone, G. De Zorzi, A. Denig, A. Di Domenico, C. Di Donato, B. Di Micco, M. Dreucci, G. Felici, S. Fiore, P. Franzini, C. Gatti, P. Gauzzi, S. Giovannella, E. Graziani, V. Kulikov, G. Lanfranchi, J. Lee-Franzini, M. Martini, P. Massarotti, S. Meola, S. Miscetti, M. Moulson, S. Müller, F. Murtas, M. Napolitano, F. Nguyen, M. Palutan, E. Pasqualucci, A. Passeri, V. Patera, P. Santangelo, B. Sciascia, A. Sibidanov, T. Spadaro, M. Testa, L. Tortora, P. Valente, G. Venanzoni, R. Versaci.

A rigorous proof of the CPT theorem can be found in Refs. [2–5] (see also Refs. [6–8] for some recent developments). This theorem ensures that exact CPT invariance holds for any quantum field theory formulated on flat space-time assuming (1) Lorentz invariance, (2) Locality, and (3) Unitarity (i.e. conservation of probability). Testing the validity of CPT invariance therefore probes the most fundamental assumptions of our present understanding of particles and their interactions.

The neutral kaon doublet is one of the most intriguing systems in nature. During its time evolution a neutral kaon oscillates between its particle and antiparticle states with a beat frequency $\Delta m \approx 5.3\times10^9$ s^{-1} , where Δm is the small mass difference between the exponentially decaying states $\mathrm{K_L}$ and $\mathrm{K_S}$. The fortunate coincidence that Δm is about half the decay width of $\mathrm{K_S}$ makes it possible to observe a variety of intricate interference phenomena in the time evolution and decay of neutral kaons. In turn, such observations enable us to test quantum mechanics, the interplay of different conservation laws and the validity of various symmetry principles. In particular the extreme sensitivity of the neutral kaon system to a variety of CPT-violating effects makes it one of the best candidates for an accurate experimental test of this symmetry. As a figure of merit, the fractional mass difference $(m_{\mathrm{K}^0} - m_{\bar{\mathrm{K}}^0})/m_{\mathrm{K}^0}$ can be considered: it can be measured at the level of $\mathcal{O}(10^{-18})$ for neutral kaons, while, for comparison, a limit of $\mathcal{O}(10^{-14})$ can be reached on the corresponding quantity for the $\mathrm{B}^0 - \bar{\mathrm{B}}^0$ system, and only of $\mathcal{O}(10^{-8})$ for proton-antiproton [9]. Interferometric methods applied to neutral kaon pairs at a ϕ-factory add new possibilities for this kind of tests [10].

2. The neutral kaon system

The time evolution of a neutral kaon that is initially a generic superposition of K^0 and $\bar{\mathrm{K}}^0$,

$$|\mathrm{K}(0)\rangle = a(0)|\mathrm{K}^0\rangle + b(0)|\bar{\mathrm{K}}^0\rangle \ , \tag{1}$$

can be described by the state vector

$$|\mathrm{K}(t)\rangle = a(t)|\mathrm{K}^0\rangle + b(t)|\bar{\mathrm{K}}^0\rangle + \sum_j c_j(t)|f_j\rangle \ , \tag{2}$$

where t is the time in the kaon rest frame, f_j's with $\{j = 1, 2, ...\}$ represent all possible decay final states, and $a(t)$, $b(t)$, and $c_j(t)$ are time dependent functions. In the Wigner-Weisskopf approximation [11], which is valid for times larger than the typical strong interaction formation time, the functions $a(t)$ and $b(t)$, describing the time evolution of the state in the $\{\mathrm{K}^0, \bar{\mathrm{K}}^0\}$ sub-space, obey the Schrödinger-like equation

$$i\frac{\partial}{\partial t}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = \mathbf{H}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} \ , \tag{3}$$

where the effective Hamiltonian $\mathbf{H}$ is a 2×2 complex, not Hermitian, and time independent matrix. It can be decomposed in terms of its hermitian and anti-hermitian parts

$$\begin{aligned} \mathbf{H} &= \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} = \\ &= \mathbf{M} - \frac{i}{2}\mathbf{\Gamma} = \begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix} \ , \end{aligned} \tag{4}$$

where $\mathbf{M}$ and $\mathbf{\Gamma}$ are two hermitian matrices with positive eigenvalues, usually called *mass* and *decay* matrices, and indices 1 and 2 stand for K^0 and $\bar{\mathrm{K}}^0$, respectively.

The matrix $\mathbf{H}$ is characterized by eight independent real parameters; seven of them are observables, while an overall phase is arbitrary and unphysical, and can be fixed by convention.

The conservation of discrete symmetries constrains the matrix elements of $\mathbf{H}$, and the following phase-invariant conditions hold[2]:

$$H_{11} = H_{22} \quad \text{for } CPT \text{ conservation,} \tag{5}$$
$$|H_{12}| = |H_{21}| \quad \text{for } T \text{ conservation,} \tag{6}$$
$$H_{11} = H_{22} \text{ and } |H_{12}| = |H_{21}| \quad \text{for } CP \text{ conservation.} \tag{7}$$

The eigenvalues of $\mathbf{H}$ are

$$\begin{aligned} \lambda_S &= m_S - i\Gamma_S/2 \\ \lambda_L &= m_L - i\Gamma_L/2 \ , \end{aligned} \tag{8}$$

where $m_{S,L}$ and $\Gamma_{S,L}$ are the masses and widths of the physical states, respectively. It is also useful to define the differences

$$\begin{aligned} \Delta m &= m_L - m_S > 0 \\ \Delta\Gamma &= \Gamma_S - \Gamma_L > 0 \end{aligned} \tag{9}$$

and the so called *superweak* phase

$$\tan\phi_{SW} = \frac{2\Delta m}{\Delta\Gamma} \ . \tag{10}$$

The physical states that diagonalize $\mathbf{H}$ are the short- and long-lived states with lifetimes $\tau_S = \Gamma_S^{-1}$ and $\tau_L = \Gamma_L^{-1}$, respectively; they evolve in time as pure exponentials

$$\begin{aligned} |\mathrm{K_S}(t)\rangle &= e^{-i\lambda_S t}|\mathrm{K_S}\rangle \\ |\mathrm{K_L}(t)\rangle &= e^{-i\lambda_L t}|\mathrm{K_L}\rangle \ , \end{aligned} \tag{11}$$

and are usually written as:

$$\begin{aligned} |\mathrm{K_S}\rangle &= \frac{1}{\sqrt{2(1+|\epsilon_S|^2)}}\{(1+\epsilon_S)|\mathrm{K}^0\rangle + (1-\epsilon_S)|\bar{\mathrm{K}}^0\rangle\} \\ |\mathrm{K_L}\rangle &= \frac{1}{\sqrt{2(1+|\epsilon_L|^2)}}\{(1+\epsilon_L)|\mathrm{K}^0\rangle - (1-\epsilon_L)|\bar{\mathrm{K}}^0\rangle\} \ , \end{aligned} \tag{12}$$

where $\epsilon_{S,L}$ are two small complex parameters describing the CP impurity in the physical states; one can equivalently define the parameters

$$\epsilon \equiv (\epsilon_S + \epsilon_L)/2 \ , \qquad \delta \equiv (\epsilon_S - \epsilon_L)/2 \ . \tag{13}$$

Ignoring negligible quadratic terms, they can be expressed in terms of the elements of $\mathbf{H}$ as:

$$\epsilon = \frac{H_{12} - H_{21}}{2(\lambda_S - \lambda_L)} = \frac{-i\Im M_{12} - \frac{1}{2}\Im\Gamma_{12}}{\Delta m + i\,(\Delta\Gamma)/2} \tag{14}$$

$$\delta = \frac{H_{11} - H_{22}}{2(\lambda_S - \lambda_L)} = \frac{\frac{1}{2}\left(M_{22} - M_{11} - \frac{i}{2}\,(\Gamma_{22} - \Gamma_{11})\right)}{\Delta m + i\,(\Delta\Gamma)/2} \ . \tag{15}$$

It is convenient to adopt a phase convention such that $\Im\Gamma_{12} = 0$, fixing the phase of ϵ to ϕ_{SW}, i.e. $\epsilon = |\epsilon|e^{i\phi_{SW}}$ (e.g. see Refs. [15,18]). Then it is easy to show that

- $\delta \neq 0$ implies CPT violation;
- $\epsilon \neq 0$ implies T violation;
- $\epsilon \neq 0$ or $\delta \neq 0$ implies CP violation.

[2] For general reviews on discrete symmetries in the neutral kaon system see Refs. [12–17].

2.1. CPT violation in semileptonic decays

The semileptonic decay amplitudes can be parametrized as follows [12]:

$$\begin{aligned} \langle \pi^- l^+ \nu | T | \mathrm{K}^0 \rangle &= a + b \;, \qquad \langle \pi^+ l^- \bar{\nu} | T | \bar{\mathrm{K}}^0 \rangle = a^* - b^* \\ \langle \pi^+ l^- \bar{\nu} | T | \mathrm{K}^0 \rangle &= c + d \;, \qquad \langle \pi^- l^+ \nu | T | \bar{\mathrm{K}}^0 \rangle = c^* - d^* \end{aligned} \tag{16}$$

where a, b, c, d are complex quantities; CPT invariance implies $b = d = 0$, $\Delta S = \Delta Q$ rule implies $c = d = 0$, T invariance implies $\Im a = \Im b = \Im c = \Im d = 0$, while CP invariance implies $\Im a = \Re b = \Im c = \Re d = 0$. Then three measurable parameters can be defined:

$$y = -b/a \;, \qquad x_+ = c^*/a \;, \qquad x_- = -d^*/a \;; \tag{17}$$

x_+ (x_-) describes the violation of the $\Delta S = \Delta Q$ rule in CPT conserving (violating) decay amplitudes, while y parametrizes CPT violation for $\Delta S = \Delta Q$ transitions. Then the semileptonic charge asymmetries for K_S and K_L states can be expressed as

$$\begin{aligned} A_{S,L} &= \frac{\Gamma(\mathrm{K_{S,L}} \to \pi^- l^+ \nu) - \Gamma(\mathrm{K_{S,L}} \to \pi^+ l^- \bar{\nu})}{\Gamma(\mathrm{K_{S,L}} \to \pi^- l^+ \nu) + \Gamma(\mathrm{K_{S,L}} \to \pi^+ l^- \bar{\nu})} \\ &= 2\Re\epsilon \pm 2\Re\delta - 2\Re y \pm 2\Re x_- \;. \end{aligned} \tag{18}$$

Any difference between A_S and A_L signals a violation of the CPT symmetry:

$$A_S - A_L = 4(\Re\delta + \Re x_-) \;. \tag{19}$$

2.2. CPT violation in two pion decays

In the case of $\mathrm{K} \to \pi^+\pi^-, \pi^0\pi^0$ decays, the decay amplitudes can be decomposed in terms of definite isospin $I = 0, 2$ of the final state:

$$\begin{aligned} \langle \pi\pi; I | T | \mathrm{K}^0 \rangle &= (A_I + B_I) e^{i\delta_I} \\ \langle \pi\pi; I | T | \bar{\mathrm{K}}^0 \rangle &= (A_I^* - B_I^*) e^{i\delta_I} \;. \end{aligned} \tag{20}$$

Here A_I (B_I) describe the CPT-conserving (CPT-violating) part of $\pi\pi$ decay amplitudes; δ_I is the $\pi\pi$ strong interaction phase shift for channel of total isospin I. The following observable decay amplitude ratios can be defined:

$$\begin{aligned} \eta_{+-} &\equiv |\eta_{+-}| e^{i\phi_{+-}} \equiv \frac{\langle \pi^+\pi^- | T | \mathrm{K_L} \rangle}{\langle \pi^+\pi^- | T | \mathrm{K_S} \rangle} = \epsilon_L + i\frac{\Im A_0}{\Re A_0} + \frac{\Re B_0}{\Re A_0} + \epsilon' \\ \eta_{00} &\equiv |\eta_{00}| e^{i\phi_{00}} \equiv \frac{\langle \pi^0\pi^0 | T | \mathrm{K_L} \rangle}{\langle \pi^0\pi^0 | T | \mathrm{K_S} \rangle} = \epsilon_L + i\frac{\Im A_0}{\Re A_0} + \frac{\Re B_0}{\Re A_0} - 2\epsilon' \end{aligned} \tag{21}$$

where

$$\epsilon' = \frac{1}{\sqrt{2}} e^{i(\delta_2 - \delta_0)} \frac{\Re A_2}{\Re A_0} \left[i \left(\frac{\Im A_2}{\Re A_2} - \frac{\Im A_0}{\Re A_0} \right) + \left(\frac{\Re B_2}{\Re A_2} - \frac{\Re B_0}{\Re A_0} \right) \right] \;; \tag{22}$$

$\epsilon' \neq 0$ signals direct CP violation (see Refs. [12, 19–21]). It can be shown that

$$\begin{aligned} \phi_{00} - \phi_{+-} &\simeq \frac{3}{\sqrt{2}|\eta_{+-}|} \frac{\Re A_2}{\Re A_0} \left(\frac{\Re B_2}{\Re A_2} - \frac{\Re B_0}{\Re A_0} \right) \approx -3\Im\left(\frac{\epsilon'}{\epsilon}\right) \;, \\ \phi_{+-} - \phi_{SW} &\simeq \frac{-1}{\sqrt{2}|\eta_{+-}|} \left(\frac{M_{11} - M_{22}}{2\Delta m} + \frac{\Re B_0}{\Re A_0} \right) \;. \end{aligned} \tag{23}$$

Therefore any phase difference between the η_{+-} and η_{00} parameters is a signal of CPT violation in the $\pi\pi$ decay, while a difference between ϕ_{+-} and ϕ_{SW} is a signal of CPT violation in the mixing and/or decay.

The following quantity, obtained combining semileptonic and two pion decays parameters,

$$\Re\left(\frac{2}{3}\eta_{+-} + \frac{1}{3}\eta_{00}\right) - \frac{A_L}{2} = \Re\left(y + x_- + \frac{\Re B_0}{\Re A_0}\right) \tag{24}$$

signals CPT violation if different from zero.

3. Experiments

In the CPLEAR experiment [18], a high flux of antiprotons is stopped in a gaseous hydrogen target. From the antiproton annihilation process, the following rare reactions with a branching fraction of about 0.4% are selected to obtain K^0 or $\bar{\mathrm{K}}^0$ beams:

$$\begin{aligned} (\mathrm{p\bar{p}})_{\text{at rest}} &\rightarrow \mathrm{K}^0 + \mathrm{K}^- + \pi^+ \\ (\mathrm{p\bar{p}})_{\text{at rest}} &\rightarrow \bar{\mathrm{K}}^0 + \mathrm{K}^+ + \pi^- \ . \end{aligned} \tag{25}$$

The annihilation channel with a branching ratio of 0.07%

$$(\mathrm{p\bar{p}})_{\text{at rest}} \rightarrow \mathrm{K}^0 + \bar{\mathrm{K}}^0 \tag{26}$$

is instead selected to obtain correlated $\mathrm{K}^0\bar{\mathrm{K}}^0$ pairs.

The whole detector is embedded in a solenoidal magnet that provides a homogeneous longitudinal field of 0.44 T. The charged particles are measured by a series of cylindrical tracking detectors, followed by a particle identification detector (PID) for charged kaon identification, and electron/pion separation. The outermost detector is a 6 radiation lengths calorimeter used to detect photons from π^0 decays.

The CPLEAR detector was fully operational between 1992 and 1996, collecting a total of 1.1×10^{13} antiproton interactions.

In the KTeV experiment [22] at Fermilab, two neutral kaon beams are formed from the secondary particles produced by 800 GeV/c protons colliding on a beryllium oxide target using a system of collimators, absorbers and sweeping magnets. The neutral kaon decays are detected in 110 - 158 m range from the production target. One of the beams passes through an active regenerator, made of scintillator, which produces a coherent mixture of $\mathrm{K_S}$ and $\mathrm{K_L}$ states. The regenerator alternates between the two neutral beams in order to reduce systematic differences between $\mathrm{K_L}$ and $\mathrm{K_S}$ decays.

The charged decay products are detected in a drift chamber spectrometer. The spectrometer is equipped with two chambers before and two after an analyzing magnet. Each chamber measures charged particle tracks in horizontal and vertical views. The neutral decay products are measured in a calorimeter composed by an array of 3100 Cesium Iodine (CsI) crystals, located after the spectrometer. A nearly hermetic photon veto system (up to 100 mrad) rejects background events for the $\pi^0\pi^0$ mode coming from interactions in the regenerator, semileptonic and $\mathrm{K_L} \rightarrow \pi^0\pi^0\pi^0$ decays.

The KTeV results presented here refers to data collected in the periods 1996-1997 and 1999.

DAΦNE, the Frascati ϕ-factory [23], is an e^+e^- collider working at a center of mass energy of $\sqrt{s} \sim 1020$ MeV, corresponding to the peak of the ϕ resonance. The ϕ-meson production cross section is $\sim 3\mu$b, and its decay into $\mathrm{K}^0\bar{\mathrm{K}}^0$ has a branching fraction of 34%. The neutral kaon pair is produced in a coherent quantum state with the ϕ-meson quantum numbers $J^{PC} = 1^{--}$:

$$|i\rangle = \frac{1}{\sqrt{2}}\{|\mathrm{K}^0\rangle|\bar{\mathrm{K}}^0\rangle - |\bar{\mathrm{K}}^0\rangle|\mathrm{K}^0\rangle\} = \frac{N}{\sqrt{2}}\{|\mathrm{K_S}\rangle|\mathrm{K_L}\rangle - |\mathrm{K_L}\rangle|\mathrm{K_S}\rangle\} \ , \tag{27}$$

where $N = \sqrt{(1+|\epsilon_S|^2)(1+|\epsilon_L|^2)}/(1-\epsilon_S\epsilon_L) \simeq 1$ is a normalization factor.

The detection of a kaon at large (small) times *tags* a K_S (K_L) in the opposite direction. This is a unique feature at a ϕ-factory, not possible at fixed target experiments, that can be exploited to select pure $K_{S,L}$ beams.

The KLOE detector consists mainly of a large volume drift chamber [24] surrounded by an electromagnetic calorimeter [25], both inside a superconducting coil providing an axial 0.52 T magnetic field. At KLOE a K_S is tagged by identifying the interaction of the K_L in the calorimeter (K_L-crash), while a K_L is tagged by detecting a $K_S \to \pi^+\pi^-$ decay near the interaction point (IP). KLOE completed the data taking in March 2006 with a total integrated luminosity of ~ 2.5 fb^{-1}, corresponding to $\sim 7.5 \times 10^9$ ϕ-mesons produced.

4. "Standard" CPT symmetry tests

In this section the best experimental limits on the previously mentioned CPT-violating parameters (*standard* tests) are reviewed.

The CPLEAR collaboration measured the following time-dependent decay rate asymmetry:

$$A_\delta(\tau) = \frac{\bar{R}_+(\tau) - \alpha R_-(\tau)}{\bar{R}_+(\tau) + \alpha R_-(\tau)} + \frac{\bar{R}_-(\tau) - \alpha R_+(\tau)}{\bar{R}_-(\tau) + \alpha R_+(\tau)} \tag{28}$$

where

$$\begin{aligned} R_+(\tau) &= R\left[\mathrm{K^0}_{t=0} \to (\pi^- e^+ \nu)_{t=\tau}\right] \ , \ R_-(\tau) = R\left[\mathrm{K^0}_{t=0} \to (\pi^+ e^- \bar{\nu})_{t=\tau}\right] \\ \bar{R}_+(\tau) &= R\left[\bar{\mathrm{K}}^0_{t=0} \to (\pi^- e^+ \nu)_{t=\tau}\right] \ , \ \bar{R}_-(\tau) = R\left[\bar{\mathrm{K}}^0_{t=0} \to (\pi^+ e^- \bar{\nu})_{t=\tau}\right] \ , \end{aligned} \tag{29}$$

and $\alpha = (1 + 4\Re\epsilon_L)$. In the limit of large times one has $A_\delta(\tau \gg \tau_S) = 8\Re\delta$, yielding the best measurement of $\Re\delta$ [26]:

$$\Re\delta = (0.30 \pm 0.33_{\mathrm{stat}} \pm 0.06_{\mathrm{syst}}) \times 10^{-3} \ . \tag{30}$$

The KTeV collaboration exploited the coherent regeneration phenomenon, occurring when a kaon beam traverses a slab of material, which modifies a pure K_L beam into a coherent superposition of K_L and K_S, i.e. $|K_L\rangle \to |K_L\rangle + \rho|K_S\rangle$, where ρ is the *regeneration* (complex) parameter. The fit of the measured $\pi^+\pi^-$ (and $\pi^0\pi^0$) decay intensity downstream the regenerator with the function

$$\begin{aligned} R_{+-(00)}(t) \ \propto \ & |\rho|^2 e^{-\Gamma_S t} + |\eta_{+-(00)}|^2 e^{-\Gamma_L t} \\ & +2|\rho||\eta_{+-(00)}| e^{-(\Gamma_S+\Gamma_L)t/2} \cos\left[\Delta m t + \phi(\rho) - \phi_{+-(00)}\right] \ , \end{aligned} \tag{31}$$

yields the best CPT tests using eqs. (23) [22] :

$$\begin{aligned} \phi_{00} - \phi_{+-} &= (0.39 \pm 0.22_{\mathrm{stat}} \pm 0.45_{\mathrm{syst}})^\circ \\ \phi_{+-} - \phi_{SW} &= (0.61 \pm 0.62_{\mathrm{stat}} \pm 1.01_{\mathrm{syst}})^\circ \ , \end{aligned} \tag{32}$$

consistent with no CPT violation[3]. KTeV also measured the asymmetry A_L given in eq. (18) [27]

$$A_L = (3322 \pm 58_{\mathrm{stat}} \pm 47_{\mathrm{syst}}) \times 10^{-6} \ . \tag{34}$$

[3] These results are slightly improved in a preliminary KTeV analysis [28]:

$$\begin{aligned} \phi_{00} - \phi_{+-} &= (0.30 \pm 0.35)^\circ \\ \phi_\epsilon - \phi_{SW} &= (0.40 \pm 0.56)^\circ \ , \end{aligned} \tag{33}$$

where $\phi_\epsilon \simeq (\phi_{00} + 2\phi_{+-})/3$.

This result can be used in combination with two pion decay measurements to test CPT symmetry as in eq. (24) [27]:

$$\Re\left(y + x_- + \frac{\Re B_0}{\Re A_0}\right) = \Re\left(\frac{2}{3}\eta_{+-} + \frac{1}{3}\eta_{00}\right) - \frac{A_L}{2} = (-3 \pm 35) \times 10^{-6} . \tag{35}$$

The first measurement of the K_S semileptonic charge asymmetry has been performed by the KLOE collaboration analysing a part of the collected data (380 pb^{-1}) [29]:

$$A_S = (1.5 \pm 9.6_{\text{stat}} \pm 2.9_{\text{syst}}) \times 10^{-3} \tag{36}$$

The uncertainty on A_S can be reduced at the level of $\approx 3 \times 10^{-3}$ with the analysis of the full data sample.

Using the values of A_L, $\Re\delta$, and $\Re\epsilon$ from other experiments the real part of the CPT violating parameters y and x_- (see eqs. (17)) can be evaluated [29]:

$$\begin{aligned} \Re x_- &= \frac{A_S - A_L}{4} - \Re\delta = (-0.8 \pm 2.5) \times 10^{-3} \\ \Re y &= \Re\epsilon - \frac{A_S + A_L}{4} = (0.4 \pm 2.5) \times 10^{-3} . \end{aligned} \tag{37}$$

The unitarity relation, originally derived by Bell and Steinberger [30]:

$$\begin{aligned} &\left(\frac{\Gamma_S + \Gamma_L}{\Gamma_S - \Gamma_L} + i \tan\phi_{SW}\right)\left[\frac{\Re\epsilon}{1 + |\epsilon|^2} - i\Im\delta\right] = \\ &= \frac{1}{\Gamma_S - \Gamma_L}\sum_f \mathcal{A}^*(\mathrm{K_S} \to f)\mathcal{A}(\mathrm{K_L} \to f) \equiv \sum_f \alpha_f , \end{aligned} \tag{38}$$

where the sum runs over all accessible final states f appearing in the decay amplitudes $\mathcal{A}(\mathrm{K_{S,L}} \to f)$, can be used to bound $\Im\delta$ (and other parameters), after having provided all the α_i parameters, Γ_S, Γ_L, and ϕ_{SW} as inputs. Using KLOE measurements, values from Particle Data Group (PDG) [9], and a combined fit of KLOE and CPLEAR data, the following result is obtained [9, 31](see also Ref. [32]):

$$\Re\epsilon = (161.2 \pm 0.6) \times 10^{-5} , \qquad \Im\delta = (-0.6 \pm 1.9) \times 10^{-5} , \tag{39}$$

which provides the best limit on $\Im\delta$, the main limiting factor of this result being the uncertainty on the phase ϕ_{+-} entering in the parameter $\alpha_{\pi^+\pi^-}$. The complete information of the fit gives also the following results [9, 31]:

$$\Re\delta = (2.5 \pm 2.3) \times 10^{-4} , \qquad \Re x_- = (-4.2 \pm 1.7) \times 10^{-3} . \tag{40}$$

The limits on $\Im(\delta)$ and $\Re(\delta)$ can be used, through eq.(15), to constrain the mass and width difference between $\mathrm{K^0}$ and $\mathrm{\bar{K}^0}$. In the limit $\Gamma_{11} = \Gamma_{22}$, i.e. neglecting CPT-violating effects in the decay amplitudes, the best bound on the neutral kaon mass difference is obtained:

$$|m_{\mathrm{K^0}} - m_{\mathrm{\bar{K}^0}}| < 5.1 \times 10^{-19} \text{ GeV} \quad \text{at 95 \% CL} .$$

A preliminary update of this analysis including the latest results on ϕ_{+-} and ϕ_{00} by the KTeV collaboration [28] yields slightly improved results [33]:

$$\Re\epsilon = (161.2 \pm 0.6) \times 10^{-5} , \qquad \Im\delta = (-0.1 \pm 1.4) \times 10^{-5} \tag{41}$$

$$|m_{\mathrm{K^0}} - m_{\mathrm{\bar{K}^0}}| < 4.0 \times 10^{-19} \text{ GeV} \quad \text{at 95 \% CL} . \tag{42}$$

5. Decoherence and CPT violation

The quantum interference between the two kaons initially in the entangled state in eq. (27) and decaying in the CP violating channel $\phi \to K_S K_L \to \pi^+\pi^-\pi^+\pi^-$, has been observed for the first time by the KLOE collaboration [34] analyzing a data sample corresponding to $L \simeq 380$ pb^{-1}. Here the final results obtained in the analysis of a different and larger data sample, corresponding to $L \simeq 1.5$ fb^{-1}, are presented for the first time[4]. The measured Δt distribution, with Δt the absolute value of the time difference of the two $\pi^+\pi^-$ decays, can be fitted with the distribution:

$$I(\pi^+\pi^-,\pi^+\pi^-;\Delta t) \propto e^{-\Gamma_L \Delta t} + e^{-\Gamma_S \Delta t} - 2(1-\zeta_{SL}) e^{-\frac{(\Gamma_S+\Gamma_L)}{2}\Delta t} \cos(\Delta m \Delta t) \ , \quad (43)$$

where the quantum mechanical expression in the $\{K_S, K_L\}$ basis has been modified with the introduction of a decoherence parameter ζ_{SL}, and a factor $(1-\zeta_{SL})$ multiplying the interference term. Analogously, a $\zeta_{0\bar{0}}$ parameter can be defined in the $\{K^0, \bar{K}^0\}$ basis [35]. After having included resolution and detection efficiency effects, having taken into account the background due to coherent and incoherent K_S-regeneration on the beam pipe wall, the small contamination of non-resonant $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ events, and keeping fixed in the fit Δm, Γ_S and Γ_L to the PDG values, the fit is performed on the Δt distribution, as shown in Fig.1.

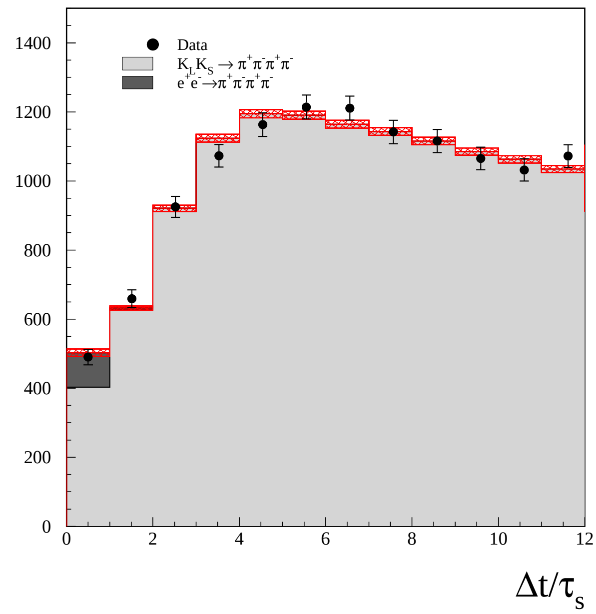

Figure 1. Fit of the measured $I(\pi^+\pi^-,\pi^+\pi^-;\Delta t)$ distribution. The black points with errors are data and the solid histogram is the fit result. The uncertainty arising from the efficiency correction is shown as the hatched area.

The following results are obtained:

$$\begin{aligned} \zeta_{SL} &= (0.3 \pm 1.8_{\rm stat} \pm 0.6_{\rm syst}) \times 10^{-2} \\ \zeta_{0\bar{0}} &= (1.4 \pm 9.5_{\rm stat} \pm 3.8_{\rm syst}) \times 10^{-7} \ , \end{aligned} \quad (44)$$

compatible with the prediction of quantum mechanics, i.e. $\zeta_{SL} = \zeta_{0\bar{0}} = 0$, and no decoherence effect. In particular the result on $\zeta_{0\bar{0}}$ has a very high accuracy, $\mathcal{O}(10^{-6})$, due to the CP

[4] The KLOE results presented in this section on the ζ_{SL}, $\zeta_{0\bar{0}}$, γ, $\Re(\omega)$, and $\Im(\omega)$ parameters can be considered to supersede the previous ones [34], as in the new analysis the systematic uncertainties due to regeneration processes are more accurately evaluated.

suppression present in the specific decay channel; it improves of five orders of magnitude the previous limit obtained by Bertlmann and co-workers [35] in a re-analysis of CPLEAR data [36]. This result can also be compared to a similar one recently obtained in the B meson system [37], where an accuracy of $\mathcal{O}(10^{-2})$ has been reached.

The decoherence mechanism can be made more specific in the case it is induced by quantum gravity effects (for a general review see Ref. [38]). In fact one of the main open problem in quantum gravity is related to what is commonly known as the black hole *information-loss paradox*. In 1976 Hawking showed [39] that the formation and evaporation of black holes, as described in the semiclassical approximation, appear to transform pure states near the event horizon of black holes into mixed states. This corresponds to a loss of information about the initial state, in striking conflict with quantum mechanics and its unitarity description. At a microscopic level, in a quantum gravity picture, space-time might be subjected to inherent non-trivial quantum metric and topology fluctuations at the Planck scale ($\sim 10^{-33}$ cm), called generically *space-time foam*, with associated microscopic event horizons. This space-time structure might induce a pure state to evolve into a mixed one, i.e. decoherence of apparently isolated matter systems [40]. This decoherence, in turn, necessarily implies, by means of a theorem [41], CPT violation, in the sense that the quantum mechanical operator generating CPT transformations cannot be consistently defined.

The information-loss paradox generated a lively debate during the last decades with no generally accepted solution. Even the recent proposed solutions in favor of no-loss and preservation of information do not completely solve the problem, some aspects of which still remaining a puzzle (see for instance Refs. [42–44]). It seems therefore extremely interesting to put experimental limits at the level of the Planck scale region on possible decoherence effects.

The above mentioned decoherence mechanism inspired the formulation of a phenomenological model [45] in which a single kaon is described by a density matrix ρ that obeys a modified Liouville-von Neumann equation:

$$\frac{d\rho}{dt} = -i\mathbf{H}\rho + i\rho\mathbf{H}^{\dagger} + L(\rho;\alpha,\beta,\gamma) \tag{45}$$

where the extra term $L(\rho;\alpha,\beta,\gamma)$ would induce decoherence in the system, and depends on three real parameters, α, β and γ, which violate CPT symmetry and quantum mechanics (they satisfy the inequalities $\alpha,\ \gamma > 0$ and $\alpha\gamma > \beta^2$ - see Refs. [45, 46]). They have mass dimension and are guessed to be at most of $\mathcal{O}(m_K^2/M_{Planck}) \sim 2 \times 10^{-20}$ GeV, where $M_{Planck} = 1\sqrt{G_N} = 1.22 \times 10^{19}$ GeV is the Planck mass.

The CPLEAR collaboration, studying the time behaviour of single neutral kaon decays to $\pi^+\pi^-$ and $\pi e\nu$ final states, obtained the following results [47]:

$$\begin{aligned} \alpha &= (-0.5 \pm 2.8) \times 10^{-17}\,\text{GeV} \\ \beta &= (2.5 \pm 2.3) \times 10^{-19}\,\text{GeV} \\ \gamma &= (1.1 \pm 2.5) \times 10^{-21}\,\text{GeV}\ . \end{aligned} \tag{46}$$

The KLOE collaboration, studying the same $I(\pi^+\pi^-,\pi^+\pi^-;\Delta t)$ distribution as in the ζ parameters analysis, in the simplifying hypothesis of complete positivity[5] [48], i.e. $\alpha = \gamma$ and $\beta = 0$, obtained the following result:

$$\gamma = \left(0.7 \pm 1.2_{\text{stat}} \pm 0.3_{\text{syst}}\right) \times 10^{-21}\,\text{GeV}\ , \tag{47}$$

[5] This hypothesis, reducing the number of free parameters, makes the fit of the experimental distribution easier, even though it is not strictly necessary from the analysis point of view.

All results are compatible with no CPT violation, while the sensitivity approaches (and in the case of the γ parameter reaches) the interesting level of $\mathcal{O}(10^{-20}\,\text{GeV})$.

As discussed above, in a quantum gravity framework inducing decoherence, the CPT operator is *ill-defined*. This consideration might have intriguing consequences in correlated neutral kaon states, where the resulting loss of particle-antiparticle identity could induce a breakdown of the correlation of state (27) imposed by Bose statistics [38, 49–51]. As a result the initial state (27) can be parametrized in general as:

$$|i\rangle = \frac{1}{\sqrt{2}}\left[|\mathrm{K}^0\rangle|\bar{\mathrm{K}}^0\rangle - |\bar{\mathrm{K}}^0\rangle|\mathrm{K}^0\rangle + \omega\left(|\mathrm{K}^0\rangle|\bar{\mathrm{K}}^0\rangle + |\bar{\mathrm{K}}^0\rangle|\mathrm{K}^0\rangle\right)\right] , \tag{48}$$

where ω is a complex parameter describing a completely novel CPT violation phenomenon, not included in previous analyses. Its order of magnitude could be at most

$$|\omega| \sim \left[(m_K^2/M_{\text{Planck}})/\Delta\Gamma\right]^{1/2} \sim 10^{-3}$$

with $\Delta\Gamma = \Gamma_S - \Gamma_L$. An analysis performed by the KLOE collaboration on the same $I(\pi^+\pi^-, \pi^+\pi^-; \Delta t)$ distribution as before, including in the fit the modified initial state eq.(48), yields a measurement of the complex parameter ω

$$\begin{aligned} \Re(\omega) &= \left(-1.6^{+3.0}_{-2.1}{}_{\text{stat}} \pm 0.4_{\text{syst}}\right) \times 10^{-4} \\ \Im(\omega) &= \left(-1.7^{+3.3}_{-3.0}{}_{\text{stat}} \pm 1.2_{\text{syst}}\right) \times 10^{-4} , \end{aligned} \tag{49}$$

with an accuracy already in the range of the interesting Planck scale region. The contour plot of Im ω versus Re ω at the 68% and 95% of confidence level is shown in fig. 2. The upper limit

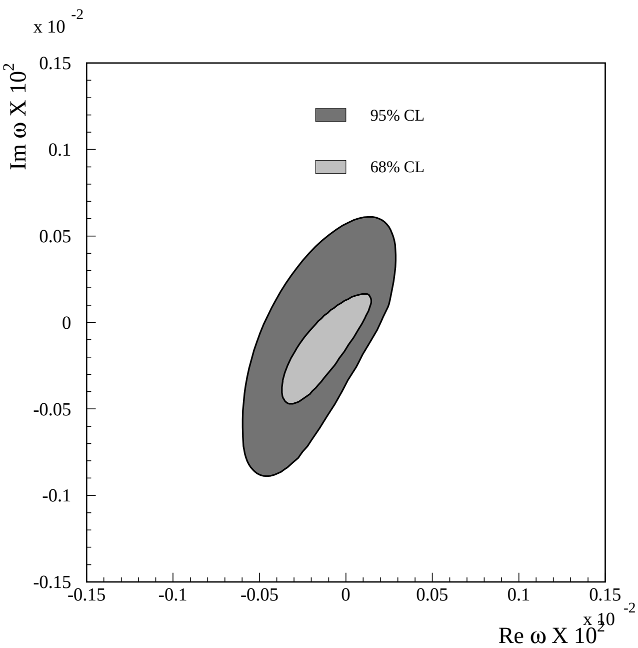

Figure 2. Contour plot of Im ω versus Re ω at the 68% and 95% of confidence level.

is $|\omega| \leq 1.0 \times 10^{-3}$ at 95 % CL. For comparison, in the B meson system the following bound is obtained from a re-analysis of data [52]: $-0.0084 \leq \Re(\omega) \leq 0.0100$ at 95 % CL .

6. CPT violation and Lorentz symmetry breaking

CPT invariance holds for any realistic Lorentz-invariant quantum field theory. However a very general theoretical possibility for CPT violation is based on spontaneous breaking of Lorentz symmetry, which appears to be compatible with the basic tenets of quantum field theory and retains the property of gauge invariance and renormalizability (Standard Model Extensions - SME). In SME for neutral kaons, CPT violation manifests to lowest order only in the parameter δ (e.g. B_I, y and x_- vanish at first order), and exhibits a dependence on the 4-momentum of the kaon:

$$\delta \approx i \sin\phi_{SW} e^{i\phi_{SW}} \gamma_K (\Delta a_0 - \vec{\beta_K} \cdot \Delta\vec{a})/\Delta m \tag{50}$$

where γ_K and $\vec{\beta_K}$ are the kaon boost factor and velocity in the observer frame, and Δa_μ are four CPT- and Lorentz-violating coefficients for the two valence quarks in the kaon.

Following Ref. [54], the time dependence arising from the rotation of the Earth can be explicitly displayed in eq.(50) by choosing a three-dimensional basis $(\hat{X}, \hat{Y}, \hat{Z})$ in a non-rotating frame, with the $\hat{Z}$ axis along the Earth's rotation axis, and a basis $(\hat{x}, \hat{y}, \hat{z})$ for the rotating (laboratory) frame. The CPT violating parameter δ may then be expressed as:

$$\begin{aligned} \delta &= \frac{1}{2\pi}\int_0^{2\pi} \delta(\vec{p}, t_{sid}) d\phi \\ &= \frac{i \sin\phi_{SW} e^{i\phi_{SW}}}{\Delta m} \gamma_K \{\Delta a_0 + \beta_K \Delta a_Z \cos\theta \cos\chi \\ &\quad + \beta_K (\Delta a_Y \sin\chi \cos\theta \sin\Omega t_{sid} + \Delta a_X \sin\chi \cos\theta \cos\Omega t_{sid})\} , \end{aligned} \tag{51}$$

where t_{sid} is the sidereal time, Ω is the Earth's sidereal frequency, $\cos\chi = \hat{z} \cdot \hat{Z}$, θ and ϕ are the conventional polar and azimuthal angles defined in the laboratory frame about the $\hat{z}$ axis, and an integration on the azimuthal angle ϕ has been performed, assuming a symmetric decay distribution in this variable[6]. The sensitivity to the four Δa_μ parameters can be very different for fixed target and collider experiments, showing complementary features [54].

At KLOE the Δa_0 parameter can be measured through the difference $A_S - A_L$, by performing the measurement of each asymmetry with a symmetric integration over the polar angle θ, thus averaging to zero any possible contribution from the terms proportional to $\cos\theta$ in eq.(51):

$$A_S - A_L \simeq \left[\frac{4\Re\left(i \sin\phi_{SW} e^{i\phi_{SW}}\right) \gamma_K}{\Delta m} \right] \Delta a_0 \ . \tag{52}$$

In this way a first preliminary evaluation of the Δa_0 parameter can be obtained by KLOE [10,56]:

$$\Delta a_0 = (0.4 \pm 1.8) \times 10^{-17} \text{ GeV} \ . \tag{53}$$

With the analysis of the full KLOE data sample ($L = 2.5$ fb^{-1}) a precision of $\sigma(\Delta a_0) \sim 7 \times 10^{-18}$ GeV could be reached.

At KLOE the $\Delta a_{X,Y,Z}$ parameters can be evaluated performing a sidereal time dependent analysis of the asymmetry:

$$A(\Delta t) = \frac{I(\pi^+\pi^-(+), \pi^+\pi^-(-); \Delta t > 0) - I(\pi^+\pi^-(+), \pi^+\pi^-(-); \Delta t < 0)}{I(\pi^+\pi^-(+), \pi^+\pi^-(-); \Delta t > 0) + I(\pi^+\pi^-(+), \pi^+\pi^-(-); \Delta t < 0)} \ , \tag{54}$$

[6] Although not necessary, this assumption is taken here in order to simplify formulas.

where the two identical final states are distinguished by their emission in the forward ($\cos\theta > 0$) or backward ($\cos\theta < 0$) hemispheres (denoted by the symbols + and −, respectively), and Δt is the time difference between (+) and (−) $\pi^+\pi^-$ decays. A preliminary analysis based on a data sample corresponding to a L $\sim$ 1fb^{-1} yields the following results [10, 56, 57]:

$$\begin{aligned} \Delta a_X &= (-6.3 \pm 6.0) \times 10^{-18} \text{ GeV} \\ \Delta a_Y &= (2.8 \pm 5.9) \times 10^{-18} \text{ GeV} \\ \Delta a_Z &= (2.4 \pm 9.7) \times 10^{-18} \text{ GeV} . \end{aligned} \quad (55)$$

A preliminary measurement performed by the KTeV collaboration [58] based on the search of sidereal time variation of the phase ϕ_{+-} constrains Δa_X and Δa_Y to less than 9.2×10^{-22} GeV at 90% C.L. These results can also be compared to similar ones recently obtained in the B meson system [59], where an accuracy on the Δa_μ^B parameters of $\mathcal{O}(10^{-13}\text{GeV})$ has been reached.

7. Future plans

A proposal [60–62] has been presented for a physics program to be carried out with an upgraded KLOE detector, KLOE-2, at an upgraded DAΦNE machine, which has been assumed to deliver an integrated luminosity up to $20 \div 50$ fb^{-1}. The major upgrade of the KLOE detector would consist in the addition of an inner tracker for the improvement of decay vertex resolution, therefore improving the resolution on Δt, and consequently the sensitivity on several parameters based on kaon interferometry measurements.

The KLOE-2 program concerning neutral kaon interferometry is summarized in table 1, where the KLOE-2 statistical sensitivities on the main parameters which can be extracted from kaon decay time distributions $I(f_1, f_2; \Delta t)$ (with different choices of final states f_1 and f_2) are listed in the hypothesis of an integrated luminosity $L = 50$ fb^{-1}, and compared to the best present measurements. Improvements of about one order of magnitude in almost all present limits on CPT violation and decoherence parameters are expected.

Recently an experimental test of the new collision scheme proposed by Raimondi [63] to increase the luminosity has been successfully carried out at DAΦNE [62]. The KLOE-2 plan can be divided in two phases: in the first one (officially approved) KLOE restarts taking data with a minimal upgrade at the end of 2009, with the aim of collecting an integrated luminosity $L \sim 5$ fb^{-1}, while in the second phase the major upgrade of the detector, including the inner tracker, is made with the aim of collecting an integrated luminosity $L \geq 20$ fb^{-1}, and performing the full interferometry program described above.

8. Conclusions

The neutral kaon system constitutes an excellent laboratory for the study of the CPT symmetry and the basic principles of quantum mechanics. Several parameters related to possible CPT violations, including decoherence and Lorentz symmetry breaking effects, have been measured, in some cases with a precision reaching the interesting Planck scale region. Simple quantum coherence tests have been also performed. All results are consistent with no violation of the CPT symmetry and/or quantum mechanics.

A ϕ-factory represents a unique opportunity to push forward these studies. It is also an ideal place to investigate the entanglement and correlation properties of the produced $K^0\bar{K}^0$ pairs. The KLOE physics program is going to be continued (KLOE-2), and improvements are expected in almost all present limits.

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Table 1. KLOE-2 statistical sensitivities on several parameters.

f_1	f_2	Param.	Best measurement	KLOE-2 (50 fb^{-1})
$K_S \to \pi e \nu$		A_S	$(1.5 \pm 11) \times 10^{-3}$ [29]	$\pm 1 \times 10^{-3}$
$\pi^+\pi^-$	$\pi l \nu$	A_L	$(3322 \pm 58 \pm 47) \times 10^{-6}$ [22]	$\pm 25 \times 10^{-6}$
$\pi^+\pi^-$	$\pi^0\pi^0$	$\Re\frac{\epsilon'}{\epsilon}$	$(1.65 \pm 0.26) \times 10^{-3}$ [9]	$\pm 0.2 \times 10^{-3}$
$\pi^+\pi^-$	$\pi^0\pi^0$	$\Im\frac{\epsilon'}{\epsilon}$	$(-1.2 \pm 2.3) \times 10^{-3}$ [9]	$\pm 3 \times 10^{-3}$
$\pi^+ l^- \bar{\nu}$	$\pi^- l^+ \nu$	$(\Re\delta + \Re x_-)$	$\Re\delta = (0.25 \pm 0.23) \times 10^{-3}$ [9]	$\pm 0.2 \times 10^{-3}$
			$\Re x_- = (-4.2 \pm 1.7) \times 10^{-3}$ [9]	
$\pi^+ l^- \bar{\nu}$	$\pi^- l^+ \nu$	$(\Im\delta + \Im x_+)$	$\Im\delta = (-0.6 \pm 1.9) \times 10^{-5}$ [9]	$\pm 3 \times 10^{-3}$
			$\Im x_+ = (0.2 \pm 2.2) \times 10^{-3}$ [9]	
$\pi^+\pi^-$	$\pi^+\pi^-$	Δm	$5.288 \pm 0.043 \times 10^9 s^{-1}$ [22]	$\pm 0.03 \times 10^9 s^{-1}$
$\pi^+\pi^-$	$\pi^+\pi^-$	ζ_{SL}	$(1.8 \pm 4.1) \times 10^{-2}$ [34]	$\pm 0.2 \times 10^{-2}$
			[$(0.3 \pm 1.9) \times 10^{-2}$ this paper]	
$\pi^+\pi^-$	$\pi^+\pi^-$	$\zeta_{0\bar{0}}$	$(1.0 \pm 2.1) \times 10^{-6}$ [34]	$\pm 0.1 \times 10^{-6}$
			[$(0.1 \pm 1.0) \times 10^{-6}$ this paper]	
$\pi^+\pi^-$	$\pi^+\pi^-$	α	$(-0.5 \pm 2.8) \times 10^{-17}$ GeV [47]	$\pm 2 \times 10^{-17}$ GeV
$\pi^+\pi^-$	$\pi^+\pi^-$	β	$(2.5 \pm 2.3) \times 10^{-19}$ GeV [47]	$\pm 0.1 \times 10^{-19}$ GeV
$\pi^+\pi^-$	$\pi^+\pi^-$	γ	$(1.1 \pm 2.5) \times 10^{-21}$ GeV [47]	$\pm 0.2 \times 10^{-21}$ GeV
				(compl. pos. hyp.)
			$(1.3^{+2.8}_{-2.4} \pm 0.4) \times 10^{-21}$ GeV [34]	$\pm 0.1 \times 10^{-21}$ GeV
			[$(0.7 \pm 1.2) \times 10^{-21}$ GeV this paper]	
$\pi^+\pi^-$	$\pi^+\pi^-$	$\Re\omega$	$(1.1^{+8.7}_{-5.3} \pm 0.9) \times 10^{-4}$ [34]	$\pm 2 \times 10^{-5}$
			[$(-1.6^{+3.0}_{-2.1} \pm 0.4) \times 10^{-4}$ this paper]	
$\pi^+\pi^-$	$\pi^+\pi^-$	$\Im\omega$	$(3.4^{+4.8}_{-5.0} \pm 0.6) \times 10^{-4}$ [34]	$\pm 2 \times 10^{-5}$
			[$(-1.7^{+3.3}_{-3.0} \pm 1.2) \times 10^{-4}$ this paper]	
$K_{S,L} \to \pi e \nu$		Δa_0	(prelim.: $(0.4 \pm 1.8) \times 10^{-17}$ GeV [56])	$\pm 1 \times 10^{-18}$ GeV
$\pi^+\pi^-$	$\pi^+\pi^-$	Δa_Z	(prelim.: $(2.4 \pm 9.7) \times 10^{-18}$ GeV [57])	$\pm 1 \times 10^{-18}$ GeV
$\pi^+\pi^-$	$\pi^+\pi^-$	Δa_X, Δa_Y	(prelim.: $< 9.2 \times 10^{-22}$ GeV [58])	$\pm 8 \times 10^{-19}$ GeV

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