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Tests of discrete symmetries in the kaon system

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Abstract. The status of ongoing experiments with kaons is reported, with a focus on the prospects for discrete symmetries tests.

1. Introduction
The first observation of a charged kaon dates back to an experiment performed with cosmic rays in the French Alps by Leprince-Ringuet and L’héritier [1] during the II World War, while the first evidence of a neutral kaon, i.e. the decay of a neutral particle into two charged particles, came few years later, in 1947, with the observation by Rochester and Butler of the decay of a neutral particle into two charged particles, the famous V-particles [2].

The discovery of K mesons and their properties had an important influence on the development of particle physics and its theoretical understanding culminated with the formulation of the Standard Model, and also provided beautiful tests of the basic principles of Quantum Mechanics. For instance the study of the properties of kaon decays led to the introduction of the strangeness quantum number by Gell-Mann and Nishijima, and to the explanation of the regeneration phenomena as one of the most beautiful manifestation of the superposition principle of Quantum Mechanics by Pais and Piccioni.

The kaon system is also one of the most suited physical system for the study of the fundamental discrete symmetries of Nature, exhibiting parity non-conservation, the $\tau - \theta$ anomaly phenomenon [3], a CP violation effect in the $K^0 - \bar{K}^0$ mixing, and also time reversal violation, and direct CP violation.

After more than 70 years from their first observation, kaons are still the subject of an intense experimental scrutiny, especially concerning discrete symmetries. The present paper reports the status of the ongoing experiments in the field, updating previous reports [4, 5]; for general and historical reviews the reader is referred to several excellent papers and books in the literature [6].

2. Rare kaon decays
2.1. The golden mode: $K \to \pi \nu \bar{\nu}$
Precise measurements in the Flavor sector can probe extremely high energy scales, in a complementary way with respect to the LHC high energy frontier. In fact, the present LHC searches at high transverse momenta exclude wide regions of the parameter space for New Physics (NP), thus increasing the importance of the study of rare processes sensitive to very high energy. In this respect the improved measurements of the branching ratios of the two golden...
modes $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ will constitute one of the top highlights of flavour physics in the next years. $K^+ \to \pi^+\nu\bar{\nu}$ is CP conserving while $K_L \to \pi^0\nu\bar{\nu}$ is governed by CP violation. Both decays are very rare being FCNC processes and with the highest CKM suppression. These decays are theoretically very clean in SM, and the calculation of their branching ratios within the SM includes next-to-leading order (NLO) QCD corrections to the top quark contributions, NNLO QCD corrections to the charm contribution, and NLO electroweak corrections to both top and charm contributions. Moreover, extensive calculations of isospin breaking effects and non-perturbative effects have been performed. The most recent evaluations are

$$BR(K_L \to \pi^0\nu\bar{\nu}) = (3.4 \pm 0.6) \times 10^{-11}$$  \hspace{1cm} (1)$$

$$BR(K^+ \to \pi^+\nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$$  \hspace{1cm} (2)$$

obtained using the parametric expressions for the branching ratios of these two decays in terms of the CKM parameter inputs [7].

In some models of NP large enhancement with respect to the above SM predictions are possible. In this sense the $K \to \pi\nu\bar{\nu}$ modes play a key role in seeking NP beyond the SM. This is clear from Fig.1, which reproduces the BR values predicted by the SM and by some models of NP [8]. Apart from establishing a direct signal of NP, the correlation of the BR of the two modes can be exploited to probe the flavour structure of NP theories and, therefore, to distinguish among different classes of NP scenarios. The exclusion region given by the Grossman-Nir consistency condition [9], and limiting the BR ratio of the two decay modes in the correlation plane is also reported in Fig.1.

![Figure 1](image.png)

**Figure 1.** Correlation between the branching ratios of the charged and neutral $K \to \pi\nu\bar{\nu}$ decays showing the predictions of SM and some NP models [8].

Experimentally the charged decay mode has been observed by E959 and E787 experiments at BNL. The result $BR(K^+ \to \pi^+\nu\bar{\nu}) = (1.73 \pm 1.15) \times 10^{-10}$ is based on 7 events [10] and is compatible with the SM prediction. The CP-violating neutral $K_L \to \pi^0\nu\bar{\nu}$ decay has not been observed yet. An upper limit on the BR was set by the E391a collaboration at KEK [11]: $BR(K_L \to \pi^0\nu\bar{\nu}) < 260 \times 10^{-10}$ (90% C.L.).
2.2. NA62 experiment at CERN
The main goal of the NA62 experiment at CERN [12] is to collect about 100 K$^+ \to \pi^+\nu\bar{\nu}$ events with a signal-over-background ratio $S/B \sim 5$ by the end of 2018.

Its scheme is typical of a fixed-target experiment, with a proton beam from SPS hitting a target and producing an intense unseparated beam of charged hadrons selected in momentum at 75 GeV/c. The experimental method relies on exploiting a decay-in-flight technique, a long decay region with an extended detector and the event-by-event measurement of kaon momenta. Positive charged kaons are used in order to get, at the same proton energy and flux, higher kaon fluxes and lower pion background.

The NA62 analysis strategy is based on the accurate kinematic reconstruction of all the particles detected in the event to disentangle the signal from the huge amount of background processes, a precise timing to associate correctly the $\pi^+$ with the parent $K^+$, a system of efficient vetoes to reject events with $\gamma$'s and $\mu$'s in the final state, effective particle identification systems to identify $K^+$ among other particles of the intense hadron beam and to distinguish $\pi^+$ from $\mu^+$ and $e^+$ in the final states (see Fig.2).

![Figure 2. Drawing of the NA62 apparatus at SPS, CERN.](image)

The trigger system and the beam line commissioning up to nominal intensity have been completed in 2015, together with a low intensity run with a minimum bias trigger for detector quality studies. The latter show good performance of the apparatus, in line with the expectations. After the completion of the detector commissioning, the Physics run started in 2016 and is currently ongoing. Possible extension of the run starting from year 2021 with the aim of a broader Physics program is under discussion and will partly depend on the outcome of the present run.

2.3. KOTO experiment at J-PARC
The KOTO experiment [13] at the high-intensity proton accelerator facility J-PARC (Japan Proton Accelerator Research Complex) aims to observe for the first time the rare decay $K_L \to \pi^0\nu\bar{\nu}$, which is experimentally very challenging because both initial state and final decay products are completely neutral.

A decay volume for $K_L$ is surrounded by particle detectors. The signature of a $K_L \to \pi^0\nu\bar{\nu}$ decay is two photons from a $\pi^0$ decay and no other visible particles in the final state. An electromagnetic calorimeter is placed downstream of the decay volume to detect the two photons. All the $K_L$ decay modes except $K_L \to \pi^0\nu\bar{\nu}$ and $K_L \to \gamma\gamma$ have at least two charged particles, or two or more extra photons in the final state. These decays can be rejected by detecting additional particles with the surrounding detectors. The $K_L \to \gamma\gamma$ decays can be rejected by requiring a finite transverse momentum for the two photon system. In the case of $K_L \to \pi^0\nu\bar{\nu}$
decay, the two photon system has a finite transverse momentum due to the missing momentum of the two undetected neutrinos. The decay vertex is calculated and the $K_L \to \pi^0 \nu \bar{\nu}$ decay reconstructed from two photons in the calorimeter, with the assumption that the two photons come from a $\pi^0$ decay on the line of flight.

The KOTO detector consists mainly of the CsI crystal calorimeter, the charged-particle veto counters (CV) in front of it, and the main-barrel photon veto counters (MB) surrounding the decay volume in the vacuum vessel (see Fig.3).

![Figure 3. Sketch of the KOTO detector at J-PARC [13].](image)

The analysis of the first 100 hours of the physics run in 2013 [13], after determining all the selection criteria and estimating background levels, showed one observed event in the signal region, as shown in Fig.4, while $0.34 \pm 0.16$ background events were expected. This result corresponds to an upper limit of $5.1 \times 10^{-8}$ for the branching fraction of the $K_L \to \pi^0 \nu \bar{\nu}$ decay at the 90% confidence level (C.L.), still higher than the previous limit set by the E391a experiment.

After several detector upgrades, e.g. the replacement of the vacuum pipe with a thinner one and the installation of new scintillator counters to improve the rejection of the $K_L \to \pi^+ \pi^- \pi^0$ background; the installation of a beam profile monitor for improving the rejection of neutrons, and of an In-beam charged veto chamber to cope with higher beam intensities, in years 2015 and 2016 the KOTO experiment continued to collect data, and improved results are expected in the near future.

2.4. Searches for rare kaon decays at LHCb
The LHCb experiment recently proved to be competitive in the searches for rare kaon decays at LHC at least for the cleanest decay channels with a closed kinematics, a controllable background, and in the proximity of the interaction region like the $K_S \to \mu^+ \mu^-$ decay. This is a Flavour Changing Neutral Current (FCNC) transition that has not yet been observed, and is suppressed in the SM, with an expected branching fraction [14] $\text{BR}(K_S \to \mu^+ \mu^-) = (5.0 \pm 1.5) \times 10^{-12}$. NP effects might enhance this value.

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$. A search for the decay $K_L \to \mu^+ \mu^-$ has been performed using a data sample of 1.0 fb$^{-1}$ of pp collisions at $\sqrt{s} = 7$ TeV collected by the LHCb experiment at LHC. The observed number of candidates is consistent with no signal hypothesis, corresponding to an upper limit of $\text{BR}(K_S \to \mu^+ \mu^-) < 11(9) \times 10^{-8}$ at 95 (90)% confidence level [15]. An analysis using 2 fb$^{-1}$ of data further improves this limit and provides the following preliminary result: $\text{BR}(K_S \to \mu^+ \mu^-) < 6.9(5.8) \times 10^{-9}$ at 95 (90)% CL [16].
Figure 4. Reconstructed $\pi^0$ transverse momentum ($P_T$) versus decay vertex position ($Z_{vtx}$) of the events with all the analysis cuts imposed. The region surrounded with a thick solid line is the signal region. The black dots represent the data, and the contour indicates the distribution of the $K_L \to \pi^0 \nu \bar{\nu}$ decay from MC [13].

The LHCb trigger system has been partially modified to overcome one of the main limitation for these studies, and it will undergo a major upgrade in the next future, facilitating not only the study of $K_S \to \mu^+ \mu^-$ but also of other rare kaon decays as $K_S \to e^+ e^- \mu^+ \mu^-$, $K_S \to e^+ e^- e^+ e^-$, and $K_S \to \pi^0 \mu^+ \mu^- $.

3. Testing CPT symmetry with entangled neutral kaons

3.1. Direct test of CPT symmetry in transitions

CPT symmetry at present appears to be the only discrete symmetry of Quantum Mechanics respected in Nature. This result has a very solid theoretical foundation in the well known CPT theorem [17, 18, 19, 20], ensuring exact CPT invariance for any quantum field theory formulated on flat space-time assuming (1) Lorentz invariance, (2) Locality, and (3) Unitarity (i.e. conservation of probability).

A violation of the CPT symmetry would have a dramatic impact on our present theoretical picture and would definitely constitute an unambiguous signal of a New Physics framework, thus strongly motivating both experimental searches and theoretical studies on this subject.

CPT invariance has been confirmed by all present experimental tests, particularly in the neutral kaon system where strong limits have been set to a variety of possible CPT violation effects which might arose in a quantum gravity scenario [21, 22, 23, 24, 25, 26, 27]. The best limits on the $\delta$ parameter expressing CPT violation in the $K^0\bar{K}^0$ mixing matrix, i.e. in the standard Weisskopf-Wigner approach [28] are obtained in the CPLEAR experiment for $\Re \delta$ [29], and using the Bell-Steinberger relation for $\Im \delta$ [30, 31], yielding a stringent limit on the difference of mass terms for $K^0$ and $\bar{K}^0$: $|m_{K^0} - m_{\bar{K}^0}| < 4 \times 10^{-19}$ GeV at 95% c.l. [21].

The $CPT$ violating probe has been, however limited to a difference of masses (and other intrinsic properties) for a particle and its anti-particle, i.e. to diagonal mass terms. In many physical phenomena the perturbing effect does not appear at first order in perturbation theory: it would be sufficient that the perturbation breaks a symmetry of the non-perturbed states. This vanishing effect at first order for the diagonal elements, like e.g. the case of the electric dipole moment for $T$ violation, is not present for transitions (non-diagonal elements) [32].
In the following a recently proposed CPT test for transitions in the neutral kaon system will be discussed in some detail [33], where the exchange of in and out states (and CP conjugation), required for a direct and genuine CPT test, is performed exploiting the entanglement of the kaon pair produced at a φ-factory. This methodology has been proposed for a direct test of the T symmetry in the same context [34], similarly to the one adopted for the performed test in the B meson system at B-factories [35, 36, 37, 38, 32, 39]. The decay is not an essential ingredient for a non-vanishing effect and it is only used for filtering the appropriate initial and final states of the neutral kaon transition [40]. Explicitly, in the standard Weisskopf-Wigner approach to this system, the CPT-violating effects can be connected to the $\delta$ parameter, a genuine CPT-violating effect independent of $\Delta \Gamma = \Gamma_{S} - \Gamma_{L}$, with $\Gamma_{S}$ and $\Gamma_{L}$ the widths of the physical states.

In order to implement this test, the Einstein-Podolsky-Rosen (EPR) entanglement of neutral mesons produced at a φ-factory must be exploited. In fact in this case the initial state of the kaon pair produced in $\phi \rightarrow K^{0}\bar{K}^{0}$ decay can be rewritten in terms of any pair of orthogonal states $|K_{+}\rangle$ and $|K_{-}\rangle$:

$$|i\rangle = \frac{1}{\sqrt{2}}\{|K^{0}\rangle|\bar{K}^{0}\rangle - |\bar{K}^{0}\rangle|K^{0}\rangle\} = \frac{1}{\sqrt{2}}\{|K_{+}\rangle|K_{-}\rangle - |K_{-}\rangle|K_{+}\rangle\}. \quad (3)$$

Here one can consider the states $|K_{+}\rangle$, $|K_{-}\rangle$ defined as follows: $|K_{+}\rangle$ is the state filtered by the decay into $\pi\pi$ ($\pi^{+}\pi^{-}$ or $\pi^{0}\pi^{0}$), a pure CP = +1 state; analogously $|K_{-}\rangle$ is the state filtered by the decay into $3\pi^{0}$, a pure CP = −1 state. Their orthogonal states correspond to the states which cannot decay into $\pi\pi$ or $3\pi^{0}$, defined, respectively, as

$$|\bar{K}_{-}\rangle \propto |K_{L}\rangle - \eta_{\pi\pi}|K_{S}\rangle$$
$$|\bar{K}_{+}\rangle \propto |K_{S}\rangle - \eta_{3\pi^{0}}|K_{L}\rangle,$$  \quad (4)

with $\eta_{\pi\pi} = \langle \pi\pi |T|K_{L}\rangle/\langle \pi\pi |T|K_{S}\rangle$ and $\eta_{3\pi^{0}} = \langle 3\pi^{0} |T|K_{S}\rangle/\langle 3\pi^{0} |T|K_{L}\rangle$. With these definitions of states, it can be shown that the condition of orthogonality $K_{-}\rightarrow K_{+}$ = 0, (i.e. $|K_{+}\rangle \equiv |\bar{K}_{-}\rangle$ and $|K_{-}\rangle \equiv |\bar{K}_{+}\rangle$) corresponds to assume negligible direct CP (or CPT) violation contributions, assumption quite well satisfied for neutral kaons [33]. The validity of the $\Delta S = \Delta Q$ rule is also assumed, so that the two flavor orthogonal eigenstates $|K^{0}\rangle$ and $|\bar{K}^{0}\rangle$ are identified by the charge of the lepton in semileptonic decays, i.e. a $|K^{0}\rangle$ can decay into $\pi^{-}\ell^{+}\nu$ and not into $\pi^{+}\ell^{-}\bar{\nu}$, and vice-versa for a $|\bar{K}^{0}\rangle$.

Thus, exploiting the perfect anticorrelation of the states implied by Eq. (3), it is possible to have a “flavor-tag” or a “CP-tag”, i.e. to infer the flavor (K$^{0}$ or $\bar{K}^{0}$) or the CP ($K_{+}$ or $K_{-}$) state of the still alive kaon by observing a specific flavor decay ($\pi^{+}\ell^{-}\nu$ or $\pi^{-}\ell^{+}\bar{\nu}$) or CP decay ($\pi\pi$ or $\pi^{0}\pi^{0}\pi^{0}$) of the other (and first decaying) kaon in the pair.

In this way one can experimentally access – for instance – the transition $K^{0} \rightarrow K_{+}$, taken as reference, and the $K_{+} \rightarrow K^{0}$, $K^{0} \rightarrow K_{+}$ and $K_{+} \rightarrow K^{0}$ transitions, i.e. the $T$, CP and CPT conjugated transitions, respectively. Specifically for the CPT symmetry test, one can directly compare the probabilities for the reference transition and the CPT conjugated one through the following ratios of probabilities:

$$R_{1,\text{CPT}}(\Delta t) = \frac{P[K_{+}(0) \rightarrow K^{0}(\Delta t)]}{P[K^{0}(0) \rightarrow K_{+}(\Delta t)]}$$
$$R_{2,\text{CPT}}(\Delta t) = \frac{P[K^{0}(0) \rightarrow K_{-}(\Delta t)]}{P[K_{-}(0) \rightarrow K^{0}(\Delta t)]}$$
$$R_{3,\text{CPT}}(\Delta t) = \frac{P[\bar{K}_{+}(0) \rightarrow K^{0}(\Delta t)]}{P[\bar{K}^{0}(0) \rightarrow K_{+}(\Delta t)]}$$
$$R_{4,\text{CPT}}(\Delta t) = \frac{P[\bar{K}^{0}(0) \rightarrow K_{-}(\Delta t)]}{P[K_{-}(0) \rightarrow K^{0}(\Delta t)]}. \quad (5)$$

\footnote{It is important to underline that both these assumptions can be relaxed for some specific observables, as discussed below.}
The measurement of any deviation from the prediction $R_{i,CPT}(\Delta t) = 1$ imposed by CPT invariance is a signal of CPT violation. It is worth noting that for $\Delta t = 0$:

$$R_{1,CPT}(0) = R_{2,CPT}(0) = R_{3,CPT}(0) = R_{4,CPT}(0) = 1,$$

i.e. the CPT-violating effect is built in the time evolution of the system, and it is absent at $\Delta t = 0$, within our approximations.

For $\Delta t \gg \tau_S$, assuming the presence of CPT violation only in the mass matrix ($\delta \neq 0$) and nothing else, one gets:

$$R_{2,CPT}(\Delta t \gg \tau_S) \simeq 1 - 4\Re \delta$$

$$R_{4,CPT}(\Delta t \gg \tau_S) \simeq 1 + 4\Re \delta,$$

i.e. the CPT-violating effect built in the time evolution reaches a “plateau” regime and dominates in this limit. It is a genuine effect because $\Re \delta$ does not depend on $\Delta \Gamma$ as an essential ingredient [32, 40].

At a $\phi$-factory one can define two observable ratios:

$$R_{2,CPT}^{\exp}(\Delta t) = \frac{I(\ell^-, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^-; \Delta t)}$$

$$R_{4,CPT}^{\exp}(\Delta t) = \frac{I(\ell^+, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^+; \Delta t)},$$

where $I(f_1, f_2; \Delta t)$ are the double decay rates into decay products $f_1$ and $f_2$ as a function of the difference of kaon decay times $\Delta t$ [34, 42], with $f_1$ occurring before $f_2$ decay for $\Delta t > 0$, and vice versa for $\Delta t < 0$.

They are related to the $R_{i,CPT}(\Delta t)$ ratios defined in eqs (5) as follows, for $\Delta t \geq 0$:

$$R_{2,CPT}^{\exp}(\Delta t) = R_{2,CPT}(\Delta t) \times D_{CPT}$$

$$R_{4,CPT}^{\exp}(\Delta t) = R_{4,CPT}(\Delta t) \times D_{CPT},$$

whereas for $\Delta t < 0$ one has:

$$R_{2,CPT}^{\exp}(\Delta t) = R_{1,CPT}(|\Delta t|) \times D_{CPT}$$

$$R_{4,CPT}^{\exp}(\Delta t) = R_{3,CPT}(|\Delta t|) \times D_{CPT},$$

with

$$D_{CPT} = \frac{|\langle \pi\pi| T[K_+] \rangle|^2}{|\langle \pi\pi| T[K_-] \rangle|^2} = \frac{\text{BR}(K_L \to 3\pi^0) \Gamma_L}{\text{BR}(K_S \to \pi\pi) \Gamma_S},$$

where the last r.h.s. equality holds with a high degree of accuracy, at least $O(10^{-7})$. The value of $D_{CPT}$ can be therefore directly evaluated from branching ratios and lifetimes.

The explicit expressions of ratios (9) and (10) (neglecting higher order terms in small parameters and for not too large negative $\Delta t$) are:

$$R_{2,CPT}^{\exp}(\Delta t) = \frac{P[K^0(0) \to K_-(\Delta t)]}{P[K^0(0) \to K^0(\Delta t)]} \times D_{CPT}$$

$$\simeq \left| 1 - 2\delta \right|^2 \left| 1 + 2\delta e^{-i(\lambda_S - \lambda_L)\Delta t} \right|^2 \times D_{CPT},$$

(14)
\[ R_{2,CPT}^{\text{exp}}(\Delta t) = \frac{P[K^0(0) \rightarrow K_-(\Delta t)]}{P[K_-(0) \rightarrow K^0(\Delta t)]} \times D_{CPT} \]
\[ \simeq |1 + 2\delta|^2 |1 - 2\delta e^{-i(\lambda_S - \lambda_L)\Delta t}|^2 \times D_{CPT} . \] (15)

The expected behavior of the observables \( R_{2,CPT}^{\text{exp}}(\Delta t) \) and \( R_{4,CPT}^{\text{exp}}(\Delta t) \) as a function of \( \Delta t \), and without the approximations of eqs.(14) and (15), is shown in figure 5, where – for visualization purposes – the probabilities involved have been evaluated fixing the CPT violating parameters \( \Re \delta \) and \( \Im \delta \) to a value different from zero, and equal to their present uncertainties [21], i.e. \( \Re \delta = 3.3 \times 10^{-4} \) and \( \Im \delta = 1.6 \times 10^{-5} \). In figure 6 a zoom of the \( \Delta t > 0 \) region, where the “plateau” regimes (7) and (8) dominate, is shown. Experimentally, this is the most interesting and statistically most populated region, where the best sensitivity to CPT violation effects can be reached by the KLOE-2 experiment [33, 34, 41].

The presence of direct CP violation contributions in the decay amplitudes, even though in principle could mimic CPT violation effects, turns out to be totally irrelevant for the plateau.

**Figure 5.** The ratios \( R_{2,CPT}^{\text{exp}}(\Delta t) \) and \( R_{4,CPT}^{\text{exp}}(\Delta t) \) as a function of \( \Delta t \). For visualization purposes the CPT violating parameters have been fixed to the values \( \Re \delta = 3.3 \times 10^{-4} \) and \( \Im \delta = 1.6 \times 10^{-5} \).
Figure 6. A zoom of the plots shown in Fig.1 in the region $0 \leq \Delta t \leq 20\tau_S$.

The region $\Delta t \gg \tau_S$ (see detailed description in Ref. [33]). The effect of a possible violation of the $\Delta S = \Delta Q$ rule is also not affecting the CPT test in the same region with the double ratio defined as:

$$\frac{R_{2,CPT}^{\text{exp}}(\Delta t \gg \tau_S)}{R_{4,CPT}^{\text{exp}}(\Delta t \gg \tau_S)} = 1 - 8\Re\delta - 8\Re x_-$$.  

(16)

with $x_-$ describing CPT violation in the $\Delta S \neq \Delta Q$ semileptonic decay amplitudes. Therefore the double ratio (16) constitutes one of the most robust observables for the proposed CPT test. It is independent of $D_{CPT}$, and in the limit $\Delta t \gg \tau_S$ it exhibits a pure and genuine CPT violating effect, even without the assumptions of the validity of the $\Delta S = \Delta Q$ rule and of negligible contaminations from direct CP violation.

3.2. The KLOE-2 experiment at DAΦNE

KLOE-2 represents the continuation of the KLOE experiment with a new physics program mainly focused on the study of K short and $\eta$ decays as well as on kaon interferometry and tests of discrete symmetries [41, 42]. The new data taking campaign aims to collect more than 5 fb$^{-1}$
of integrated luminosity at the upgraded DAΦNE, which is implementing an innovative collision scheme based on a crab-waist configuration [43, 44]. An improved KLOE detector [45] will allow in particular to perform CPT symmetry and quantum coherence tests using entangled neutral kaons with an unprecedented precision. Improvements of about one order of magnitude in almost all present limits on CPT violation and decoherence parameters are expected [41, 42, 23, 24]. The KLOE-2 data taking campaign started in November 2014, collected 3 fb$^{-1}$ of integrated luminosity at the end of 2016, and the goal of 5 fb$^{-1}$ is expected to be reached in the next 1-1.5 years.

KLOE-2 data are being analysed [46] to get a precise measurement of the two observable ratios $R_{2,CPT}^{\exp}(\Delta t)$ and $R_{4,CPT}^{\exp}(\Delta t)$. By considering a large $\Delta t$ interval in the statistically most populated region, e.g. $0 \leq \Delta t \leq 300 \tau_S$, a statistical sensitivity on the double ratio (16) of $(3.0 \times 10^{-3})$ can be obtained for $L = 5 \text{ fb}^{-1}$ [33].

4. Conclusions

Rare K decays constitute a unique probe of possible Physics beyond the SM, complementary to LHC. The two golden modes $K^+ \to \pi^+ \nu \bar{\nu}$ and $K_L \to \pi^0 \nu \bar{\nu}$ are addressed by the new generation of kaon experiments at hadron machines (NA62 and KOTO), both operational and presently collecting data. The first phase of the NA62 data taking campaign will be completed by the end of 2018.

The LHCb experiment turned out to be suited for the search of some rare $K_S$ decays, and new results and improvements are expected after the detector upgrade.

A novel CPT test has been studied in the neutral kaon system based on the direct comparison of a transition probability with its CPT reverse transition. The proposed measurement is fully robust and might shed light on possible CPT violation mechanisms.

CPT symmetry and quantum mechanics tests with entangled neutral kaon pairs will be one of the key issues at KLOE-2. The newly proposed CPT test in transitions is being implemented, and new results are expected soon.

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