

Overview of KLOE results on kaon physics and KLOE-2 perspectives

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Abstract. Kaon physics program of KLOE is being continued at the upgraded KLOE-2 system, therefore an overview of KLOE results in this field is shortly presented together with prospects for KLOE-2.

1 Introduction

The National Laboratory in Frascati (LNF-INFN, Italy) hosts the e^+e^- collider known as ϕ -factory DAΦNE [1–3]. The collider was designed to operate at the peak of ϕ resonance ($\sqrt{s} = m_\phi \approx 1019 \text{ MeV}$) producing ϕ mesons almost at rest ($\beta_\phi \approx 0.015$) since electrons and positrons collide with small transverse momenta. A ϕ meson decays mostly into kaon pairs (49% into K^+K^- and 34% into $K_S K_L$), which makes a ϕ -factory the natural place for kaon physics studies. From 2001 to 2006 KLOE has collected 2.5 fb^{-1} of integrated luminosity [4]. The detector consists of a cylindrical drift chamber [5] and an electromagnetic calorimeter [6] surrounded by a superconducting coil which produces an axial magnetic field parallel to the beam axis.

At KLOE, reconstruction of the K_S decay close to interaction region (clean selection of $K_S \rightarrow \pi^+\pi^-$, BR=69%) allows to tag a K_L presence which makes KLOE an excellent place for K_L decay measurements. Additionally a detection of the K_L hit in the calorimeter module tags the presence of the K_S , which makes KLOE a unique place to study pure K_S beams e.g. the measurement of $BR(K_S \rightarrow \pi^0\pi^0\pi^0)$. A study of both kaons decays in single event is also possible. Since both of them are produced in a pure quantum state ($J^{PC} = 1^{--}$), it is possible to study e.g. quantum interference effects.

At KLOE, the physics program was related to the good accuracy of reconstruction of K_L decays in large fiducial volume, while at KLOE-2 an increased interest will be focused on the physics close to the interaction point as rare K_S decays, $K_S - K_L$ interference, multi-lepton events, as well as η , η' and K^\pm decays. More details about whole KLOE-2 physics program can be found in Ref. [7]. The main modification of KLOE system from the point of view of kaon physics is installation of a light-material Inner Tracker detector based on the Cylindrical GEM technology to improve charged vertex reconstruction and to increase the acceptance for low transverse momentum tracks [8–11].

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Parameter	Measurement	Ref.
BR(K_{e3}) = 0.4008(15) BR($K_{\mu3}$) = 0.2699(14)	based on 13×10^6 K_L decays tagged by $K_S \rightarrow \pi^+\pi^-$ fit the time dependence over	[12]
$\tau_L=50.92(30)$ ns	0.4 τ_L of 8.5×10^6 $K_L \rightarrow 3\pi^0$ decays tagged by $K_S \rightarrow \pi^+\pi^-$	[13]
$\lambda'_+ = (25.5 \pm 1.8) \times 10^{-3}$ $\lambda''_+ = (1.4 \pm 0.8) \times 10^{-3}$	based on 2×10^6 $K_{L,e3}$ decays tagged by $K_S \rightarrow \pi^+\pi^-$ from tagged K_S beam	[14]
BR($K_S \rightarrow \pi e \nu$) = $7.046(91) \times 10^{-4}$	1.2×10^8 events (20% of full data sample)	[14]
$\lambda'_+ = (25.6 \pm 1.5_{stat} \pm 0.9_{syst}) \times 10^{-3}$ $\lambda''_+ = (1.5 \pm 0.7_{stat} \pm 0.4_{syst}) \times 10^{-3}$ $\lambda_0 = (15.4 \pm 1.8_{stat} \pm 1.3_{syst}) \times 10^{-3}$	based on 1.8×10^6 $K_{L,\mu3}$ decays tagged by $K_S \rightarrow \pi^+\pi^-$ and from combined with with $K_{L,e3}$ data	[15]

Table 1. Summary of KLOE results from neutral kaons useful for V_{us} measurement.

2 CKM matrix

The measurement of the CKM mixing matrix element V_{us} and information about lepton universality is provided at KLOE by precise measurements of semileptonic kaon decay rates. The ratio $\Gamma(K \rightarrow \mu\nu)/\Gamma(\pi \rightarrow \mu\nu)$ from the leptonic kaon decays is an independent measurement of $|V_{us}|^2 / |V_{ud}|^2$, which, together with the result of $|V_{ud}|$ from the superallowed $0^+ \rightarrow 0^+$ nuclear β transitions and V_{ub} from semileptonic B decays provide the most precise test of the CKM matrix unitarity using relation $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$. At the present level of accuracy $|V_{ub}|^2$ can be neglected. This allows the universality of lepton and quark weak couplings to be tested.

The kaon semileptonic decay rate is given by:

$$\Gamma(K_{l3}) = \frac{C_K^2 G_F^2 M_K^5}{192\pi^3} S_{EW} |V_{us}|^2 |f_+(0)|^2 I_{K,l}(\lambda) (1 + 2\Delta_K^{SU(2)} + 2\Delta_{K,l}^{EM}) \quad (1)$$

where $K = K^0, K^\pm$, $l = e, \mu$ and C_K is the Clebsch-Gordan coefficient, equal to 1/2 and 1 for K^\pm and K^0 , respectively. The experimental input is the decay width $\Gamma(K_{l3})$ obtained from the kaon lifetime and the semileptonic BRs, inclusive of radiation, while the theoretical inputs are: the form factor $f_+(0) \equiv f_+^{K^0\pi^-}(0)$ evaluated at zero momentum transfer, the long-distance electromagnetic corrections $\Delta_{K,l}^{EM}$, the universal short-distance electroweak correction $S_{EW} = 1.0232$ and the SU(2)-breaking $\Delta_K^{SU(2)}$. One or more slope parameters λ , measured from the decay spectra, are used to describe the form factor dependence on the momentum transfer which enters in the phase space integral $I_{K,l}(\lambda)$. KLOE has measured all relevant inputs for charged and neutral kaons: BR's, lifetimes (K_L, K^\pm), form factors.

The inputs for $|V_{us}|$ from the neutral kaons measurements at KLOE are gathered in table 1. The world average error on V_{us} $f_+(0)$ value determination is 0.19% [16], while taking into account KLOE results only it is 0.28% [17]. Combining these results together with the 5 fb^{-1} data foreseen at KLOE-2, we can improve the accuracy on the measurement of the K_L lifetime and $K_{S,e3}$ branching ratio. Statistical uncertainties on BRs and lifetimes have been obtained scaling present KLOE statistics to 5 fb^{-1} total integrated luminosity, while systematic errors have been estimated conservatively. The expected accuracies are presented in table 2.

Mode	$V_{us} f_+(0)$	% err	World average [16]				KLOE-2 prospects with 5 fb^{-1}				
			BR	τ	Δ	I	% err	BR	τ	Δ	I
K_{Le3}	0.2163(6)	0.26	0.09	0.20	0.11	0.05	0.20	0.09	0.13	0.11	0.06
$K_{L\mu3}$	0.2166(6)	0.28	0.15	0.18	0.11	0.06	0.24	0.15	0.13	0.11	0.08
K_{Se3}	0.2155(13)	0.61	0.60	0.02	0.11	0.05	0.32	0.30	0.03	0.11	0.06
K_{e3}^\pm	0.2172(8)	0.36	0.27	0.06	0.23	0.05	0.48	0.25	0.05	0.40	0.06
$K_{\mu3}^\pm$	0.2170(11)	0.51	0.45	0.06	0.23	0.06	0.48	0.27	0.05	0.39	0.08
Average	0.2165(4)	0.19					0.14				

Table 2. Comparison of world average value of $V_{us} f_+(0)$ [16] with KLOE-2 prospects [7].

The present fractional experimental uncertainty on $V_{us} f_+(0)$ equal to 0.19% can be reduced to 0.14%, using KLOE and KLOE-2 statistics and combining with world average. This result together with more precise measurements of $f_+(0)$ and V_{ud} would allow to obtain precision at the level of a 10^{-4} in the test on the unitarity relation.

3 Charge asymmetry of K_S

The charge asymmetry for semileptonic decays of neutral kaons can be defined with K_S and K_L semileptonic decay widths as follows:

$$A_{S,L} = \frac{\Gamma(K_{S,L} \rightarrow \pi^- e^+ \nu) - \Gamma(K_{S,L} \rightarrow \pi^+ e^- \bar{\nu})}{\Gamma(K_{S,L} \rightarrow \pi^- e^+ \nu) + \Gamma(K_{S,L} \rightarrow \pi^+ e^- \bar{\nu})} \quad (2)$$

$$= 2 [Re(\epsilon_{S,L}) - Re(y) \pm Re(x_{\pm})]$$

to the first order in parameters ϵ_S, ϵ_L which can be expressed in terms of the CP and CPT violation parameters ϵ_K and δ_K :

$$\epsilon_{L/S} = \epsilon_K \mp \delta_K. \quad (3)$$

The semileptonic kaon decays ($K \rightarrow \pi e \nu$) can be described with the following decay amplitudes:

$$\begin{aligned} \langle \pi^- e^+ \nu | H_{weak} | K^0 \rangle &= \mathcal{A}_+, \\ \langle \pi^+ e^- \bar{\nu} | H_{weak} | \bar{K}^0 \rangle &= \bar{\mathcal{A}}_-, \\ \langle \pi^+ e^- \bar{\nu} | H_{weak} | K^0 \rangle &= \mathcal{A}_-, \\ \langle \pi^- e^+ \nu | H_{weak} | \bar{K}^0 \rangle &= \bar{\mathcal{A}}_+, \end{aligned} \quad (4)$$

where H_{weak} stands for weak Hamiltonian. One introduces the following useful notation:

$$x = \frac{\bar{\mathcal{A}}_+}{\mathcal{A}_+}, \quad \bar{x} = \left(\frac{\mathcal{A}_-}{\bar{\mathcal{A}}_-} \right)^*, \quad y = \frac{\bar{\mathcal{A}}_-^* - \mathcal{A}_+}{\bar{\mathcal{A}}_-^* + \mathcal{A}_+}, \quad (5)$$

$$x_{\pm} = \frac{x \pm \bar{x}^*}{2} = \frac{1}{2} \left[\frac{\bar{\mathcal{A}}_+}{\mathcal{A}_+} \pm \left(\frac{\mathcal{A}_-}{\bar{\mathcal{A}}_-} \right)^* \right].$$

Sum and difference of the A_S and A_L allow to search for the CPT symmetry violation, either in the decay amplitudes through the parameter y or in the mass matrix through the parameter δ_K :

$$\begin{aligned} A_S + A_L &= 4Re(\epsilon) - 4Re(y), \\ A_S - A_L &= 4Re(\delta_K) + 4Re(x_{\pm}). \end{aligned} \quad (6)$$

The charge asymmetry was measured by the KTeV experiment for long-lived kaon [18] and by the KLOE - for the short-lived one [14]:

$$\begin{aligned} A_L &= (3.322 \pm 0.058_{stat} \pm 0.047_{syst}) \times 10^{-3}, \\ A_S &= (1.5 \pm 9.6_{stat} \pm 2.9_{syst}) \times 10^{-3}. \end{aligned} \quad (7)$$

These results allow for the most precise tests of the CPT symmetry in semileptonic decays of neutral kaons, although the accuracy on A_L is more than two orders of magnitude better than on the A_S . Additionally, the total error on A_S is dominated by the available statistics.

Presently the KLOE data set of 1.7 fb^{-1} is being reanalysed aiming at the determination of the semileptonic asymmetry for K_S . As the analyzed data sample is 4 times larger, an twofold reduction of the statistical error is expected. Moreover, the KLOE-2 experiment arises prospects of measuring A_S with a statistical uncertainty at the level of 3×10^{-3} .

4 Rare K_S decays

The mechanisms of the CP violation can be investigated by searches of the CP-prohibited rare decays $K_S \rightarrow 3\pi^0$. The channel $K_S \rightarrow 3\pi^0$ is a pure CP-violating process whereas $K_S \rightarrow \pi^+\pi^-\pi^0$ violates CP for I=1 or 3 in the final state. This CP violation is usually expressed in terms of the following amplitude ratios:

$$\begin{aligned} \eta_{+-0} &= \frac{\langle \pi^+\pi^-\pi^0 | H | K_S \rangle}{\langle \pi^+\pi^-\pi^0 | H | K_L \rangle} = \epsilon_K + \epsilon'_{+-0}, \\ \eta_{000} &= \frac{\langle \pi^0\pi^0\pi^0 | H | K_S \rangle}{\langle \pi^0\pi^0\pi^0 | H | K_L \rangle} = \epsilon_K + \epsilon'_{000}, \end{aligned} \quad (8)$$

where ϵ'_{+-0} and ϵ'_{000} describe CP violation in decay.

The KLOE experiment set the most precise upper limit on $\text{BR}(K_S \rightarrow 3\pi^0)$ using 1.7 fb^{-1} data-set [19]:

$$\text{BR}(K_S \rightarrow 3\pi^0) < 2.6 \times 10^{-8}, \quad (9)$$

based on a kinematic fit, testing of signal and background hypotheses and kinematical differences between $K_S \rightarrow 2\pi^0$ and $K_S \rightarrow 3\pi^0$. This result allows for constraining $|\epsilon'_{000}| \leq 0.0088$ at 90% CL. The sensitivity on $\text{BR}(K_S \rightarrow 3\pi^0)$ can be improved to 10^{-8} with 5 fb^{-1} data-set to be collected by the KLOE-2 experiment.

Presently, the direct search of $K_S \rightarrow \pi^+\pi^-\pi^0$ is being performed on the same KLOE data set. The best value of the branching ratio for this process is an average of three indirect measurements with uncertainty at the level of 30% [20], while the ongoing analysis of KLOE data shows a possibility to obtain the relative uncertainty below 20% in a direct measurement.

5 Quantum Mechanics and CPT symmetry tests

Neutral kaons produced from decay of ϕ meson are in an entangled states. If both kaons decay into identical final states, e.g. $\pi^+\pi^-$ the decay rate of the system is proportional to:

$$I(\pi^+\pi^-, \pi^+\pi^-, \Delta t) \propto e^{-\Gamma_L \Delta t} + e^{-\Gamma_S \Delta t} - 2e^{-\frac{\Gamma_L + \Gamma_S}{2} \Delta t} \cos(\Delta m \Delta t), \quad (10)$$

where Δm is the mass difference between K_L and K_S , Δt is the difference of decay times of two kaons. Presence of the interference term $2e^{-\frac{\Gamma_L + \Gamma_S}{2} \Delta t} \cos(\Delta m \Delta t)$ implies that the kaons cannot decay at the

same time, and it is an example of correlation of the type pointed out for the first time by Einstein, Podolsky and Rosen [21].

Both, T and CPT symmetry tests at KLOE-2 require identification of $K_S \rightarrow \pi\pi$, $K_L \rightarrow \pi^\pm \ell^\mp \nu$ and $K_S \rightarrow \pi^\pm \ell^\mp \nu$, $K_L \rightarrow 3\pi^0$ events. Reconstruction of $K_L \rightarrow 3\pi^0 \rightarrow 6\gamma$ decay has to be performed based on the calorimeter measurement only. The new reconstruction method is similar to Global Positioning System (GPS). For each cluster a sphere centered at its position is created. This sphere with unknown radius represents possible origin points of γ . The point of $K_L \rightarrow 3\pi^0 \rightarrow 6\gamma$ is identified as intersection of 6 such spheres (a common origin point of all photons).

5.1 Decoherence

It is physically possible that the coherent state of two kaons emerging from the phi decay can factorize and loose coherence [22]. The amount of deviation from prediction of quantum mechanics can be parametrized as the decoherence parameter ζ suppressing the interference in the following way:

$$I(\pi^+\pi^-, \pi^+\pi^-, \Delta t) \propto e^{-\Gamma_L \Delta t} + e^{-\Gamma_S \Delta t} - 2(1 - \zeta_{SL})e^{-\frac{\Gamma_L + \Gamma_S}{2} \Delta t} \cos(\Delta m \Delta t). \quad (11)$$

The usual quantum mechanics case corresponds to $\zeta = 0$, while $\zeta = 1$ implies the total decoherence. In general ζ depends on the basis in which the initial state is expressed. KLOE measured the decoherence parameter based on $\approx 1.5 \text{ fb}^{-1}$ data sample [23]. The experimental points of signal events $\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^-\pi^+\pi^-$ were fitted with Eq. 11 modified with parameters expressing decoherence. The fit was performed taking into account resolution and detection efficiency, the background from coherent and incoherent K_S regeneration on the beam pipe wall, and the small contamination from the non-resonant $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$ channel. The obtained results show no deviation from quantum mechanics within the accuracy [23]:

$$\begin{aligned} \zeta_{SL} &= (0.3 \pm 1.8_{stat} \pm 0.6_{syst}) \cdot 10^{-2}, \\ \zeta_{00} &= (1.4 \pm 9.5_{stat} \pm 3.8_{syst}) \cdot 10^{-7}. \end{aligned} \quad (12)$$

Increased statistics at KLOE-2 together with the usage of the inner tracker would allow to reach factor four of improvement in sensitivity.

5.2 CPT and Lorentz invariance test

In the framework of the Standard Model Extension (SME) [24–26], the δ_K parameter depends on the kaon four-momentum in the following way:

$$\delta_K \approx i \sin\phi_{SW} e^{i\phi_{SW}} \gamma_K (\Delta a_0 - \vec{\beta}_K \cdot \Delta \vec{a}) / \Delta m, \quad (13)$$

where γ_K and $\vec{\beta}_K$ are the boost factor and velocity of the kaon in the observer rest frame, respectively, $\phi_{SW} = \arctan(2\Delta m / \Delta \Gamma)$ is the superweak phase with Δm and $\Delta \Gamma$ the differences of mass and width between K_S and K_L , respectively, and Δa_μ are four CPT and Lorentz violating coefficients. The experimental observable at fixed time difference $\Delta \tau = \tau_1 - \tau_2$ is therefore the following [22]:

$$I_{f_1, f_2}(\Delta \tau) \propto e^{-\Gamma |\Delta \tau|} \left[|\eta_1|^2 e^{\frac{1}{2} \Delta \Gamma \Delta \tau} + |\eta_2|^2 e^{\frac{1}{2} \Delta \Gamma \Delta \tau} - 2 \text{Re}(\eta_1 \eta_2^* e^{-i \Delta m \Delta \tau}) \right] \quad (14)$$

where $\eta_j = \langle f_j | T | K_L \rangle / \langle f_j | T | K_S \rangle \approx \epsilon_K - \delta_K(\vec{p}_j, t_s)$, f_1 and f_2 denote kaon final states, $\Gamma = \Gamma_S + \Gamma_L$. In the reported measurement $f_1 = f_2 = \pi^+\pi^-$ and due to the fully destructive quantum interference at $\Delta \tau = 0$ the distribution (14) is sensitive to the η_1 / η_2 ratio. This analysis is based on looking for a possible dependence of $I_{f_1, f_2}(\Delta \tau)$ on a sidereal time.

The data sample of 1.7 fb^{-1} total integrated luminosity was analyzed to select $\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ events selected using the invariant mass of pairs of particles, two-body kinematics and missing momentum and energy. The total contamination from background events was established from the Monte Carlo simulation and amounts to 1.5% coming mostly from kaons regenerated without momentum deflection. Selected events were transformed to the sidereal frame and K mesons were labeled accordingly to their momentum direction (forward, backward) with respect to the momentum of the ϕ meson. The two data samples are further divided into four 6 h long sidereal time periods, so finally the fit of distribution (14) is performed to eight data subsets. It results with the first measurement of all four parameters in the kaon sector and at present the most precise measurement of these parameters in the quark sector of SME [27]:

$$\begin{aligned} \Delta a_0 &= (-6.0 \pm 7.7_{stat} \pm 3.1_{syst}) \times 10^{-18} \text{ GeV}, \\ \Delta a_x &= (0.9 \pm 1.5_{stat} \pm 0.6_{syst}) \times 10^{-18} \text{ GeV}, \\ \Delta a_y &= (-2.0 \pm 1.5_{stat} \pm 0.5_{syst}) \times 10^{-18} \text{ GeV}, \\ \Delta a_z &= (3.1 \pm 1.7_{stat} \pm 0.5_{syst}) \times 10^{-18} \text{ GeV}. \end{aligned}$$

The ongoing data-taking campaign of KLOE-2 at upgraded DAΦNE collider will improve statistical uncertainties due to higher luminosity of the collider and at the same time systematic uncertainties due to the installation of the Inner Tracker detector [8, 10, 11]. The Inner Tracker will improve resolution on the vertex position and acceptance for tracks with low transverse momentum. Expected accuracies on Δa_0 , $\Delta a_{x,y}$ and Δa_z are $(5.2, 1.3 \text{ and } 2.2) \times 10^{-18}$, respectively.

5.3 CPT and T symmetry test in transition

A direct test of the T symmetry is possible at the KLOE-2 detector with neutral kaons [28]. These states can be defined as states with definite flavour of CP:

$$\begin{aligned} \mathcal{S} |K^0\rangle &= +1 |K^0\rangle, \\ \mathcal{S} |\bar{K}^0\rangle &= -1 |\bar{K}^0\rangle, \end{aligned} \tag{15}$$

$$\begin{aligned} |K_+\rangle &= \frac{1}{\sqrt{2}} [|K^0\rangle + |\bar{K}^0\rangle] \text{ with CP} = +1, \\ |K_-\rangle &= \frac{1}{\sqrt{2}} [|K^0\rangle - |\bar{K}^0\rangle] \text{ with CP} = -1, \end{aligned} \tag{16}$$

and identified through observation of their decay products. At the moment of decay of the first kaon the state of the second, still-living kaon is immediately known (due to quantum entanglement). Identification of its state at the moment of decay after time Δt allows to observe a transition between the strangeness and CP-definite states. For each of the possible transitions a time-dependent ratio of probabilities can be defined as an observable of the T symmetry test. Two of those ratios can be measured at KLOE-2:

$$R_2(\Delta t) = \frac{P[K^0(0) \rightarrow K_-(\Delta t)]}{P[K_-(0) \rightarrow K^0(\Delta t)]} \sim \frac{I(\ell^-, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^+; \Delta t)}, \tag{17}$$

$$R_4(\Delta t) = \frac{P[\bar{K}^0(0) \rightarrow K_-(\Delta t)]}{P[K_-(0) \rightarrow \bar{K}^0(\Delta t)]} \sim \frac{I(\ell^+, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^-; \Delta t)}. \tag{18}$$

with a sensitivity at the level of 10^{-3} . Asymptotically, their deviation from unity should be proportional to real part of δ_K which is a T violating parameter of the neutral kaon system [28].

Constructing time-dependent ratios sensitive to CPT violation is also possible [29]:

$$R_{2,CPT}(\Delta t) = \frac{P[K^0(0) \rightarrow K_-(\Delta t)]}{P[K_-(0) \rightarrow K^0(\Delta t)]}, \quad (19)$$

$$R_{4,CPT}(\Delta t) = \frac{P[\bar{K}^0(0) \rightarrow K_-(\Delta t)]}{P[K_-(0) \rightarrow \bar{K}^0(\Delta t)]}. \quad (20)$$

leading to a double ratio as CPT violation observable in the $\Delta t \gg \tau_S$ limit is equal to $1 - 8\Re\delta_K - 8\Re x_-$. Again, possible deviation from unity would inform about CPT noninvariance [29]. So far, this parameter was not measured, but it is one of the KLOE-2 milestones.

6 Summary

In the recent years a long list of physics results from neutral kaon was provided by the KLOE experiment: measurement of V_{us} , study of CP and CPT discrete symmetries, search for decoherence of entangled kaons. Presently the KLOE-2 detector is collecting new data sample for broader and more precise results.

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References

- [1] A. Gallo *et al.*, Conf. Proc. C060626 (2006) 604, SLAC-PUB-12093.
- [2] M. Zobov *et al.*, Phys. Rev. Lett. **104**, 174801 (2010).
- [3] C. Milardi *et al.*, JINST **7**, 2012,T03002.
- [4] F. Bossi, E. De Lucia, J. Lee-Franzini, S. Miscetti, M. Palutan and KLOE Collaboration, Rivista del Nuovo Cimento Vol.31 (2008) N.10
- [5] M. Adinolfi, *et al.*, Nucl. Instrum. Meth. A **461** (2001) 25-28
- [6] M. Adinolfi *et al.*, Nucl. Instrum. Meth. A **482** (2002) 364
- [7] G. Amelino-Camelia *et al.* (KLOE-2 Collaboration), Eur. Phys. J. C **68** (2010) 619-681
- [8] M. Alfonsi *et al.*, Nucl. Instr. & Meth. A **617** (2010) 151
- [9] A. Balla *et al.*, Nucl. Instrum. Meth. A **845** (2017) 266
- [10] KLOE-2 Collaboration, F. Archilli *et al.*, LNF-10/3(P) INFN-LNF, arXiv:1002.2572
- [11] A. Balla *et al.*, Nucl. Instr. & Meth. A **604** (2009) 23
- [12] KLOE Collaboration, F. Ambrosino *et al.*, Phys. Lett. B **632** (2006) 76
- [13] F. Ambrosino *et al.* [KLOE Collaboration], Phys. Lett. B **626** (2005) 15

- [14] KLOE Collaboration, Phys. Lett. B **636** (2006), p. 173-182
- [15] F. Ambrosino *et al.* [KLOE Collaboration], JHEP **0712** (2007) 105
- [16] M. Moulson, arXiv:1411.5252 [hep-ex].
- [17] F. Ambrosino *et al.* [KLOE Collaboration], JHEP **0804** (2008) 059
- [18] KTeV Collaboration, Phys. Rev. Lett. **88** (2002), p. 181601-181606
- [19] D. Babusci *et al.* [KLOE Collaboration], Phys. Lett. B **723** (2013) 54
- [20] C. Patrignani *et al.* [Particle Data Group], Chin. Phys. C **40** (2016) no.10, 100001.
- [21] A. Einstein, B. Podolsky, N. Rosen, Physical Review **47** (1935) 777.
- [22] *Handbook on neutral kaon interferometry at a Phi-factory*, editor: A. Di Domenico, Frascati Physics Series **43** (2007)
- [23] A. Di Domenico *et al.* [KLOE Collaboration], J. Phys. Conf. Ser. **171** (2009) 012008
- [24] V. A. Kostelecký, Phys. Rev. Lett. **80** (1998) 1818
- [25] V. A. Kostelecký, Phys. Rev. D **61** (1999) 016002
- [26] V. A. Kostelecký, Phys. Rev. D **64** (2001) 076001
- [27] D. Babusci *et al.* [KLOE-2 Collaboration], Phys. Lett. B **730** (2014) 89
- [28] J. Bernabeu, A. Di Domenico and P. Villanueva-Perez, Nucl. Phys. B **868** (2013) 102
- [29] J. Bernabeu, A. Di Domenico and P. Villanueva-Perez, JHEP **1510** (2015) 139