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Recent results on CP and CPT tests at KLOE/KLOE-2

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Abstract

Neutral kaon pairs produced in ϕ decays offer a unique possibility to perform fundamental tests of discrete symmetries. Among the most recent results obtained by the KLOE experiment at DAΦNE, the Frascati ϕ-factory, there is the new best limit on the branching ratio of the CP-violating decay $\mathrm{K_S} \to 3\pi^0$, BR $< 2.6 \times 10^{-8}$ at 90% C.L.. The search for possible violations of the CPT symmetry and Lorentz invariance in the context of the Standard-Model Extension (SME) is also described; the new analysis approach fully exploits quantum interferometry in $\phi \to K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$ decays. Finally the status and perspectives of the new data taking campaign with the KLOE-2 experiment at the upgraded DAΦNE machine are briefly reviewed.

Keywords:
CP violation, CPT violation, neutral kaons, ϕ-factory

1. Status of DAΦNE and KLOE/KLOE-2

DAΦNE, the Frascati ϕ-factory 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 $\mathrm{K^0\bar{K}^0}$ has a branching fraction of 34%, yielding $\sim 10^6$ $\mathrm{K^0\bar{K}^0}$ pairs per pb^{-1} of integrated luminosity.

The KLOE experiment at DAΦNE completed its first data taking campaign in March 2006 with a total integrated luminosity of ~ 2.5 fb^{-1}, corresponding to a production of $\sim 7.5 \times 10^9$ ϕ-mesons and $\sim 2.5 \times 10^9$ $\mathrm{K^0\bar{K}^0}$ pairs.

The KLOE detector is a 4π detector setup, which is able to measure both charged and neutral particles. It consists of a large volume drift chamber [1], which provides excellent momentum and vertex reconstruction for charged particles, and a barrel shaped electromagnetic calorimeter with two end-caps [2], made from lead and scintillating fibers, which surrounds the drift chamber. The energy deposits of charged and neutral particles in the calorimeter are measured with very good time resolution, which allows for the identification of charged particles based on their time of flight. Drift chamber and calorimeter are enclosed in a superconducting solenoid, providing an axial 0.52 T magnetic field.

After a successful experimental test [3], DAΦNE has been upgraded implementing an innovative collision scheme based on a *crab-waist* configuration, providing an improvement in the peak luminosity of a factor ~ 3.

The KLOE-2 experiment [4] aims to continue and extend the physics program of its predecessor by collecting $O(10\ \mathrm{fb}^{-1})$ of data at the upgraded DAΦNE with an improved KLOE detector. The KLOE-2 physics program has been described in detail in Ref. [4] and among the main issues includes neutral kaon interferometry and tests of discrete symmetries and quantum mechanics. The upgrade of the KLOE detector would consist of in addition (i) an inner tracker based on cylindrical GEM technology for the improvement of tracking and decay vertex resolution close to the interaction point (IP), (ii) a $e^\pm$ tagging system for the $\gamma\gamma$ physics, and (iii)

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two calorimeters in the final focusing region to improve acceptance and efficiency for photons coming from the IP and neutral kaon decays inside the detector volume.

The KLOE solenoid constitutes a strong perturbation on the machine optics, modifying the DAΦNE working conditions with respect to the test experiment described in Ref.[3]. The commissioning phase of the upgraded machine is in progress and is expected to be concluded by the end of year 2012. In the meanwhile the KLOE detector upgrades are being completed and their installation is foreseen for the beginning of year 2013.

2. Neutral K mesons at KLOE

In the K^0-$\bar{K}^0$ system the physical states $|K_S\rangle$, $|K_L\rangle$, i.e. the states with definite masses $m_{S,L}$ and lifetimes $\tau_{S,L}$ which evolve as a function of the kaon proper time t as pure exponentials

$$\begin{aligned} |K_S(t)\rangle &= e^{-i\lambda_S t}|K_S\rangle \\ |K_L(t)\rangle &= e^{-i\lambda_L t}|K_L\rangle \,. \end{aligned} \quad (1)$$

with $\lambda_{S,L} = m_{S,L} - i\Gamma_{S,L}/2$, and $\Gamma_{S,L} = (\tau_{S,L})^{-1}$, can be expressed in terms of the CP eigenstates

$$\begin{aligned} |K_1\rangle &= \frac{1}{\sqrt{2}}\left[|K^0\rangle + |\bar{K}^0\rangle\right] \qquad \text{CP=+1} \\ |K_2\rangle &= \frac{1}{\sqrt{2}}\left[|K^0\rangle - |\bar{K}^0\rangle\right] \qquad \text{CP=-1} \end{aligned} \quad (2)$$

as:

$$|K_S\rangle = \frac{1}{\sqrt{(1+|\epsilon_S|^2)}}\left[|K_1\rangle + \epsilon_S|K_2\rangle\right] \quad (3)$$

$$|K_L\rangle = \frac{1}{\sqrt{(1+|\epsilon_L|^2)}}\left[|K_2\rangle + \epsilon_L|K_1\rangle\right] \,, \quad (4)$$

with ϵ_S and ϵ_L two small complex parameters describing the CP impurity in the physical states. One can equivalently define $\epsilon \equiv (\epsilon_S + \epsilon_L)/2$, and $\delta \equiv (\epsilon_S - \epsilon_L)/2$; adopting a suitable phase convention (e.g. the Wu-Yang phase convention [5]) $\epsilon \neq 0$ implies T violation, $\delta \neq 0$ implies CPT violation, while $\delta \neq 0$ or $\epsilon \neq 0$ implies CP violation.

At a ϕ-factory neutral kaons are produced in pairs in a coherent quantum state with the ϕ-meson quantum numbers $J^{PC} = 1^{--}$:

$$\begin{aligned} |i\rangle &= \frac{1}{\sqrt{2}}\{|K^0\rangle|\bar{K}^0\rangle - |\bar{K}^0\rangle|K^0\rangle\} \\ &= \frac{\mathcal{N}}{\sqrt{2}}\{|K_S\rangle|K_L\rangle - |K_L\rangle|K_S\rangle\} \,, \end{aligned} \quad (5)$$

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

The observable quantity is the double differential decay rate of the state $|i\rangle$ into decay products f_1 and f_2 at proper times t_1 and t_2, respectively. After integration on $(t_1 + t_2)$ at fixed time difference $\Delta t = t_1 - t_2$, the decay intensity can be written as follows [6]:

$$\begin{aligned} I(f_1, f_2; \Delta t \geq 0) = C_{12}\{&|\eta_1|^2 e^{-\Gamma_L \Delta t} + |\eta_2|^2 e^{-\Gamma_S \Delta t} \\ &-2|\eta_1||\eta_2| e^{-\frac{(\Gamma_S+\Gamma_L)}{2}\Delta t}\cos[\Delta m \Delta t + \phi_2 - \phi_1]\} \,. \end{aligned} \quad (6)$$

This expression is valid for $\Delta t \geq 0$, while for $\Delta t < 0$ the substitutions $\Delta t \rightarrow |\Delta t|$ and $1 \leftrightarrow 2$ have to be applied, and with $\Delta m = m_L - m_S$,

$$\eta_i \equiv |\eta_i|e^{i\phi_i} = \frac{\langle f_i|T|K_L\rangle}{\langle f_i|T|K_S\rangle} \,, \quad (7)$$

$$C_{12} = \frac{|\mathcal{N}|^2}{2(\Gamma_S + \Gamma_L)}|\langle f_1|T|K_S\rangle\langle f_2|T|K_S\rangle|^2 \,. \quad (8)$$

Due to the huge difference in the lifetimes of the physical states ($\tau_L \gg \tau_S$), for $t_1 \gg t_2, \tau_S$ (or $t_2 \gg t_1, \tau_S$) the decay intensity in eq.(6) behaves like the initial state were an incoherent mixture of states $|K_S\rangle|K_L\rangle$ and $|K_L\rangle|K_S\rangle$. Hence the detection of a kaon at large times *tags* a K_S 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 beams.

3. Search for CP violation in K_S decay

The decay $K_S \rightarrow 3\pi^0$ violates CP invariance. The parameter η_{000}, defined as the ratio of K_S to K_L decay amplitudes, can be written as:

$$\eta_{000} = \frac{\langle 3\pi^0|T|K_S\rangle}{\langle 3\pi^0|T|K_L\rangle} = \epsilon_S + \epsilon'_{000} \,, \quad (9)$$

where ϵ_S quantifies the K_S CP impurity and ϵ'_{000} is due to a direct CP-violating term. Since we expect $\epsilon'_{000} \ll \epsilon_S$ (at lowest order in Chiral Perturbation Theory one has [7, 8]: $\epsilon'_{000} = -2\epsilon'$, with ϵ' the direct CP violation parameter in $\pi\pi$ decays), it follows that $\eta_{000} \sim \epsilon_S$, and therefore in the Standard Model one has (assuming CPT invariance, i.e. $\epsilon_S = \epsilon$) BR($K_S \rightarrow 3\pi^0$) $\sim 1.9 \times 10^{-9}$ to an accuracy of a few %, making the direct observation of this decay quite a challenge.

The best upper limit on BR($K_S \rightarrow 3\pi^0$) comes from the analysis of 450 pb^{-1} data collected by the KLOE experiment in years 2001-2002 [9]: BR($K_S \rightarrow 3\pi^0$) $< 1.2 \times 10^{-7}$ at 90% C.L. Here we report the result of a new improved analysis using 1.7 fb^{-1} of data collected by KLOE in years 2004-2005.

The K_S mesons are identified with high efficiency ($\sim$ 34%) via detection of K_L mesons which cross the drift chamber without decaying and then interact with the electromagnetic calorimeter. The K_S 4-momentum is then determined using the measured position of the K_L meson and the known momentum of the ϕ meson, which is estimated as an average of the momentum distribution measured using large angle Bhabha scattering events. The search for the $K_S \to 3\pi^0 \to 6\gamma$ decay is then carried out by selecting events with six photons with momenta reconstructed using time and energy measured by the electromagnetic calorimeter. Background originates mainly from the $K_S \to 2\pi^0$ events with two spurious clusters from fragmentation of the electromagnetic showers (so called splitting) or accidental activity, or from false K_L identification for $\phi \to K_S K_L \to \pi^+\pi^-, 3\pi^0$ events. In the latter case charged pions from K_S decays interact in the DAΦNE low-β insertion quadrupoles, ultimately simulating the K_L interaction in the calorimeter, while K_L decays close to the IP producing six photons. To suppress this kind of background we first reject events with charged particles coming from the vicinity of the interaction region. Moreover, we cut also on the reconstructed velocity and energy of the tagging K_L meson [10]. In the next stage of the analysis we perform a kinematic fit with 11 constraints: energy and momentum conservation, the kaon mass and the velocity of the six photons. Cutting on the χ^2 of the fit considerably reduces the background from bad quality reconstructed events with a very good signal efficiency. In order to reject events with split and accidental clusters we look at the correlation between two χ^2-like discriminating variables $\chi^2_{2\pi}$ and $\chi^2_{3\pi}$, see Fig.1 (top); $\chi^2_{2\pi}$ is calculated by an algorithm selecting four out of six clusters best satisfying the kinematic constraints of the two body decay, therefore it verifies the $K_S \to 2\pi^0 \to 4\gamma$ hypothesis. The pairing of clusters is based on the requirement $m_{\gamma\gamma} = m_{\pi^0}$ and on the opening angle of the reconstructed pions trajectories in the K_S center of mass frame. Moreover, we check the consistency of the energy and momentum conservation in the $\phi \to K_S K_L$, $K_S \to 2\pi^0$ decay hypothesis; $\chi^2_{3\pi}$ instead verifies the signal hypothesis by looking at the reconstructed masses of three pions. For every choice of cluster pairs we calculate the quadratic sum of the residuals between the nominal π^0 mass and the invariant masses of three photon pairs. In order to improve the quality of the photon selection using $\chi^2_{2\pi}$, we cut on the variable $\Delta E = (m_\phi/2 - \sum E_{\gamma_i})/\sigma_E$ where γ_i stands for the ith photon from four chosen in the $\chi^2_{2\pi}$ estimator and σ_E is the appropriate resolution. For $K_S \to 2\pi^0$ decays plus two background clusters, we expect $\Delta E \sim 0$, while for $K_S \to 3\pi^0$ $\Delta E \sim m_{\pi^0}/\sigma_E$. At the end of the analysis we cut also on the minimal distance between photon clusters to refine rejection of events with splitted clusters, as shown in Fig.1 (bottom). From 1.7 fb^{-1}

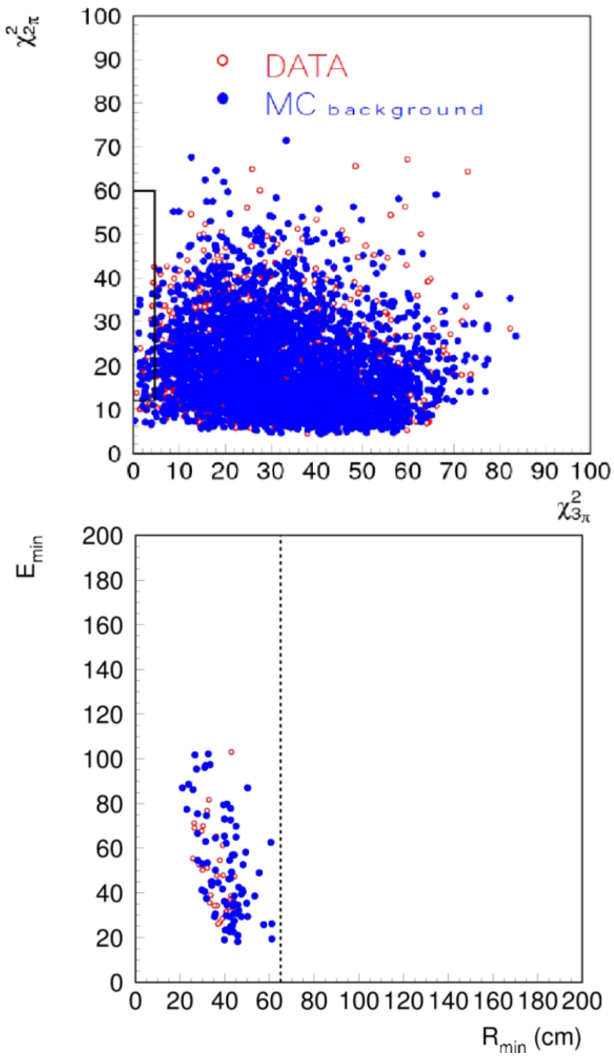

Figure 1: Top: distribution of $\chi^2_{3\pi}$ vs $\chi^2_{2\pi}$ for data and MC background; the signal box definition is shown. Bottom: distribution of the minimal energy of the cluster versus minimal distance ($R_{\rm min}$) between clusters in the event for data and MC background; the dashed line corresponds to the $R_{\rm min}$ cut used.

of data we count $n_s = 0$ candidates with $n_{bkg} = 0$ background events expected from Monte Carlo with an effective statistics of two times that of the data. Hence, we have obtained as KLOE final upper limit:

$$\mathrm{BR}(K_S \to 3\pi^0) < 2.6 \times 10^{-8} \quad \text{at 90\% C.L.,} \qquad (10)$$

which is almost five times lower than the latest published result [9]. This limit can be directly translated into a limit on $|\eta_{000}|$:

$$|\eta_{000}| = \sqrt{\frac{\tau_L}{\tau_S}\frac{\mathrm{BR}(\mathrm{K_S}\to 3\pi^0)}{\mathrm{BR}(\mathrm{K_L}\to 3\pi^0)}} < 0.0088 \quad \text{at } 90\% \text{ C.L.} \,. \tag{11}$$

4. CPT and Lorentz symmetry test using neutral kaon interferometry

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, as developed by Kostelecký [11, 12, 13], 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 mixing parameter δ, (e.g. vanish at first order in the decay amplitudes), and exhibits a dependence on the 4-momentum of the kaon:

$$\delta \approx i \sin\phi_{SW} e^{i\phi_{SW}} \gamma_K (\Delta a_0 - \vec{\beta_K}\cdot\Delta\vec{a})/\Delta m \tag{12}$$

where γ_K and $\vec{\beta_K}$ are the kaon boost factor and velocity in the observer frame, $\phi_{SW} = \arctan(2\Delta m/\Delta\Gamma)$ is the so called *superweak* phase, and Δa_μ are four CPT- and Lorentz-violating coefficients for the two valence quarks in the kaon.

Following Ref. [12], the time dependence arising from the rotation of the Earth can be explicitly displayed in eq.(12) 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 (see Fig.2). The CPT violating parameter δ may then be expressed as:

$$\begin{aligned} \delta(\vec{p},t_{sid}) = \frac{i\sin\phi_{SW}e^{i\phi_{SW}}}{\Delta m}\gamma_K\{&\Delta a_0 \\ &+\beta_K\Delta a_Z\cos\theta\cos\chi \\ &-\beta_K\Delta a_Z\sin\theta\cos\phi\sin\chi \\ &-\beta_K\Delta a_X\sin\theta\sin\phi\sin\Omega t_{sid} \\ &+\beta_K\Delta a_X\cos\theta\sin\chi\cos\Omega t_{sid} \\ &+\beta_K\Delta a_X\sin\theta\cos\phi\cos\chi\cos\Omega t_{sid} \\ &+\beta_K\Delta a_Y\cos\theta\sin\chi\sin\Omega t_{sid} \\ &+\beta_K\Delta a_Y\sin\theta\cos\phi\cos\chi\sin\Omega t_{sid} \\ &+\beta_K\Delta a_Y\sin\theta\sin\phi\cos\Omega t_{sid}\} \end{aligned} \tag{13}$$

where $\vec{p}$ is the kaon momentum, 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 of the kaon momentum defined in the laboratory frame about the $\hat{z}$ axis. The sensitivity to the four Δa_μ parameters can be very different for fixed target and collider experiments, showing complementary features [12]. At a fixed target experiment usually the kaon momentum direction is fixed, while $|\vec{p}|$ might vary within a certain interval. On the contrary, at a ϕ-factory kaons are emitted in all directions with the characteristic *p-wave* angular distribution $dN/d\Omega \propto \sin^2\theta$, while $|\vec{p}|$ is almost fixed[1].

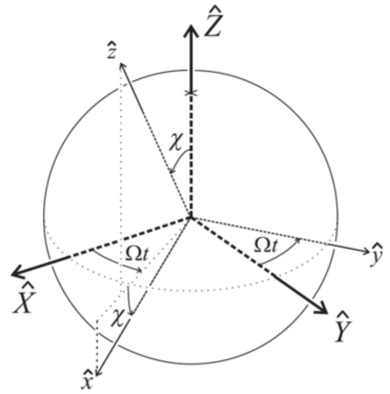

Figure 2: Basis $(\hat{x},\hat{y},\hat{z})$ for the rotating frame, and basis $(\hat{X},\hat{Y},\hat{Z})$ for the fixed non-rotating frame. The laboratory frame precesses around the Earth's rotation axis $\hat{Z}$ at the sidereal frequency Ω. The angle between $\hat{Z}$ and the positron beam direction $\hat{z}$ defined in the laboratory frame of KLOE is $\chi \simeq 113°$.

At KLOE the analysis strategy to measure the four Δa_μ parameters is based on exploiting the neutral kaon interferometry. In particular when $f_1 = f_2 = \pi^+\pi^-$ the corresponding η_i parameters can be slightly different for the two kaons due to the momentum dependence of the CPT violation effects as come from eq.(13):

$$\begin{aligned} \eta_1 &= \epsilon_L + \epsilon' = \epsilon - \delta(\vec{p_1},t_{sid}) + \epsilon' \\ \eta_2 &= \epsilon_L + \epsilon' = \epsilon - \delta(\vec{p_2},t_{sid}) + \epsilon' \,, \end{aligned} \tag{14}$$

with $\vec{p_2} = \vec{p_\phi} - \vec{p_1}$. The distribution $I(f_1, f_2; \Delta t)$ is extremely sensitive to any deviation from unity of the ratio η_1/η_2 in the interference region (i.e. $\Delta t \approx 0$). Therefore a suitable analysis of the decays $\phi \to \mathrm{K_S K_L} \to \pi^+\pi^-, \pi^+\pi^-$ as a function of sidereal time and kaon momenta can provide a measurement of the four parameters Δa_μ.

In the analysis strategy adopted by KLOE the event selection chain is fully symmetric for the two kaon decay vertices in order to minimize any possible systematic effect induced by asymmetric selection criteria. The background contamination in the sample is of the order

[1] At DAΦNE $|\vec{p}|$ is not fixed because of a small ϕ meson momentum $\vec{p_\phi}$ in the laboratory frame ($|\vec{p_\phi}| \simeq 13$ MeV/c).

of 1.7% and is mainly due to the kaon regeneration on the beam pipe. The signal has a very clean topology, two decay vertices reconstructed from two pairs of tracks, and a global fit using the closed kinematics of the event in the signal hypothesis improves the resolution on the reconstructed time difference Δt, as shown in Fig.3.

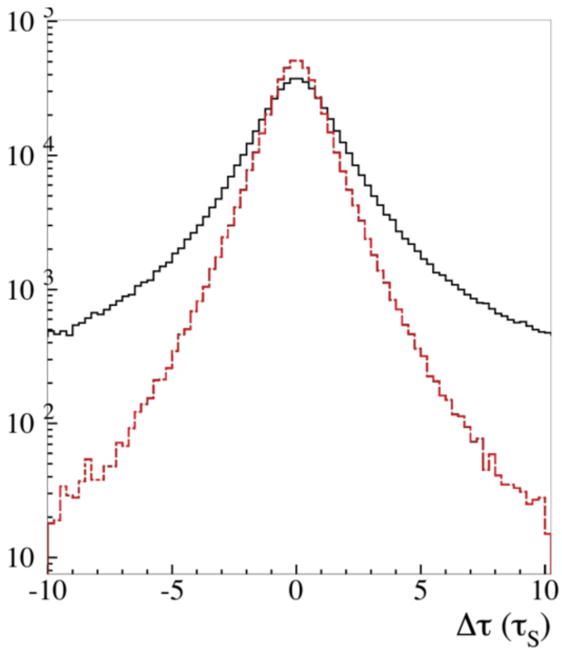

Figure 3: Resolution on the time difference Δt as obtained by the MC simulation. The solid histogram represents the distribution of the variable $\Delta\tau = \Delta t_{rec} - \Delta t_{true}$, the dashed one is obtained after the global fit. Only the events passing the global fit are shown.

The two kaons are distinguished by their emission in the forward ($\cos\theta > 0$) or backward ($\cos\theta < 0$) hemispheres, as sketched in Fig.4. The data sample is divided in two subsets in which the kaons going in the forward direction ($\cos\theta > 0$) are emitted in a quadrant along ($\cos\phi > 0$) or opposite ($\cos\phi < 0$) to the ϕ momentum $\vec{p_\phi}$, thus having a higher (or lower) value of γ_K than the companion kaons emitted in the backward direction (see Fig.4). Moreover the data are divided into four bins of sidereal time. In this way fitting simultaneously the corresponding eight $I(\pi^+\pi^-, \pi^+\pi^-; \Delta t)$ distributions one is able to observe possible modulation effects induced by the CPT-violating parameter δ in eq.(13) as a function of sidereal time and kaon momentum.

It is worth noting that the presence of the small momentum $\vec{p_\phi}$ makes $\gamma_{K,1} \neq \gamma_{K,2}$ on an event-by-event basis, which is a necessary condition in order to have the $I(\pi^+\pi^-, \pi^+\pi^-; \Delta t)$ distribution sensitive to the CPT violation effects induced by the Δa_0 parameter.

The expected sensitivity on the Δa_μ parameters, using

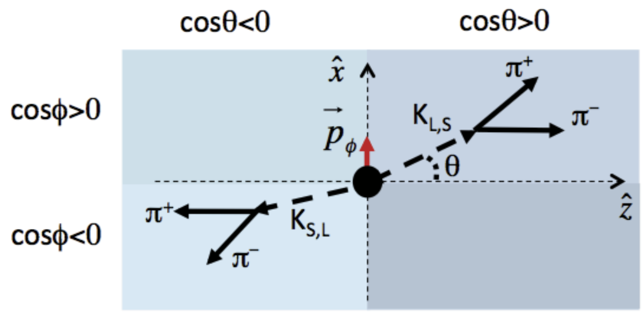

Figure 4: Sketch of the quadrant subdivisions as seen in a top view of the KLOE detector; $\vec{p_\phi}$ is directed along the $\hat{x}$ axis.

this method and with the full KLOE statistics, has been evaluated with the MC simulation including data control samples for corrections data/MC. It turns out to be $\sim 1 \times 10^{-17}$ GeV for Δa_0 and in the range $(2 \div 4) \times 10^{-18}$ GeV for $\Delta a_{X,Y,Z}$.

At KLOE, while the analysis of the full data sample is being completed, a preliminary result has been obtained using a slightly different reconstruction procedure and only about half of the total available statistics ($\sim 1\ \mathrm{fb}^{-1}$). In this preliminary analysis a full integration over the azimuthal angle has been performed without any distinction between the ($\cos\phi > 0$) and ($\cos\phi < 0$) quadrants, washing out the sensitivity to possible effects due to Δa_0. The results are [14, 15]:

$$\begin{aligned}
\Delta a_X &= (-6.3 \pm 6.0) \times 10^{-18}\ \mathrm{GeV} \\
\Delta a_Y &= (2.8 \pm 5.9) \times 10^{-18}\ \mathrm{GeV} \\
\Delta a_Z &= (2.4 \pm 9.7) \times 10^{-18}\ \mathrm{GeV}\ .
\end{aligned} \tag{15}$$

They can be compared to similar results obtained in the B meson system [16], where an accuracy on the Δa_μ^B parameters of $O(10^{-13}\mathrm{GeV})$ has been reached.

5. Perspectives and conclusions

The neutral kaon system constitutes an excellent laboratory for the study of the discrete symmetries, and a ϕ-factory represents a unique opportunity to push forward these studies. At KLOE several tests of CP and CPT symmetries have been performed [17, 14, 15]. This physics program is going to be continued and extended with the KLOE-2 project [4] improving the precision in the measurement of several parameters; new kind of time-reversal T tests might also be feasible [18].

In the meanwhile the analysis of the full KLOE data set is being completed. A new best upper limit on the branching ratio of the CP-violating decay $K_S \to 3\pi^0$

has been measured. At KLOE-2 this analysis will benefit of the presence of new low θ calorimeters, and it might be possible to have a first observation of the decay with an integrated luminosity of $O(10\ \text{fb}^{-1})$. A new refined method has been implemented to perform a test of the CPT and Lorentz symmetries using neutral kaon interferometry. At KLOE-2 it will benefit of the new inner tracker detector improving the Δt resolution, and of the new collision scheme with a doubled $\vec{p}_\phi$ momentum (increasing the sensitivity on the Δa_0 parameter).

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