Latest discrete symmetries and Quantum Mechanics studies with KLOE-2

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Abstract. The KLOE-2 experiment at the INFN Laboratori Nazionali di Frascati (LNF) is currently taking data at the upgraded e^+e^- DAFNE collider, representing the continuation of KLOE with a new physics program including kaon interferometry and test of discrete symmetries among the main topics. In fact entangled neutral kaon pairs produced at DAFNE are a unique tool to probe discrete symmetries and/or QM basic principles at the utmost precision. The status of the latest ongoing analyses on KLOE data using the most refined analyses tools will be presented and discussed including prospects for KLOE-2: (i) search for decoherence and CPT violation effects in the $\phi \to K_S K_L \to \pi^+\pi^-\pi^+\pi^-$ decay, (ii) test of CP and CPT symmetries in K_S semileptonic decays, (iii) test of Time reversal and CPT in transitions in $\phi \to K_S K_L \to \pi e \nu, 3\pi^0 (2\pi^0)$ decays, (iv) study of the $K_S \to \pi^+\pi^-\pi^0$ decay.

1. The KLOE experiment

DAΦNE is a e^+e^- collider localized in Frascati near Rome. Energy of the beams is adjusted to operate at the peak of ϕ meson resonance ($\sqrt{s} = m_\phi \approx 1019$ MeV). Due to a small transverse momenta of colliding beams, the created ϕ mesons are almost at rest ($\beta_\phi \approx 0.015$). The main decay channels of ϕ meson are pairs of neutral or charged kaons, with branching ratios of 34% and 49%, respectively. Due to conservation of quantum numbers in ϕ meson decay, the created K meson pairs are entangled, which allows one to obtain a pure beams of kaons (so called tagging technique) or perform a measurement based on quantum interferometry.

   The above mentioned studies are performed on data collected by the KLOE detector, which surrounds e^+ and e^- beams interaction point. The cylindrically shaped KLOE detector consists of two main parts: a drift chamber and, surrounding it, a electromagnetic calorimeter, both inserted in a 0.52 T magnetic field. The detector collected in total about 2.5 fb^{-1} of data in two runs in the year 2001-2002 and 2004-2005, with loose trigger conditions which allows to a broad physics program.

2. The Quantum Decoherence and CP, CPT and Lorentz Symmetries

The quantum interference between the two kaons initially in the entangled state and decaying into CP-violating channel $\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^-\pi^+\pi^-$ is described by the following decay intensity distribution:

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

where Δt is the absolute value of the time differences of the two $\pi^+\pi^-$ decays. In the above expression the parameter ζ_{SL} is introduced to account for possible decoherence effect. Analogously, a $\zeta_{0\bar{0}}$ parameter can be used if Eq. 1 is expressed in the $\{K^0, \bar{K}^0\}$ basis. The decoherence parameter influence on $I(\pi^+\pi^-, \pi^+\pi^-; \Delta t)$ distribution is shown on Figure 1 (left). The most sensitive part of the spectra lies in the region of Δt close to 0. Using the standard quantum mechanics description, no decoherence should be observed ($\zeta = 0$), while the total decoherence corresponds to $\zeta = 1$, where kaons are no longer entangled. A analysis of a KLOE data sample corresponding to $L \approx 1.5$ fb[1]
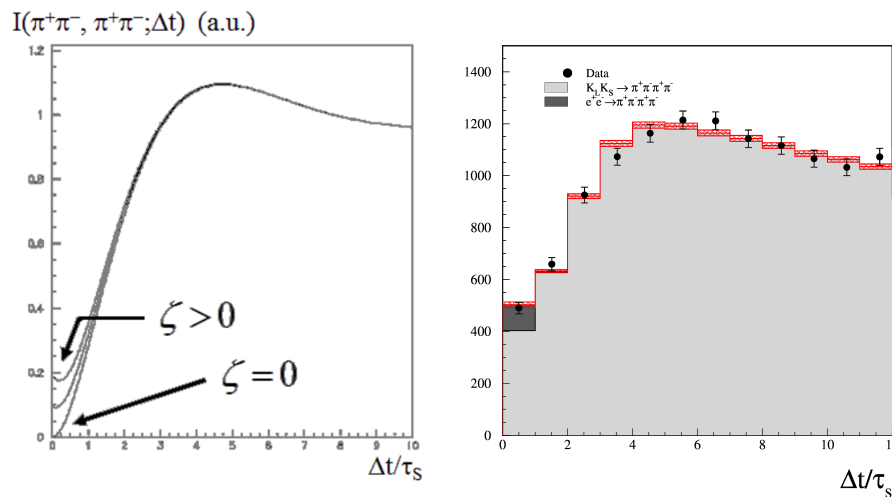

Figure 1. The $I(\pi^+\pi^-, \pi^+\pi^-; \Delta t)$ distribution with different values of the decoherence parameter $\zeta = \{0, 2\cdot 10^{-6}, 4\cdot 10^{-6}\}$ (left) compared with experimental one (right), where Monte Carlo simulation is fitted into data points. Figures are taken from [1, 2].

is based on the selection of two separate charged vertices, each formed by two opposite-curvature tracks inside the drift chamber, with an invariant mass and total momentum compatible with the two neutral kaon decays. The experimental points were fitted with Eq. 1 and taking into account detection resolution and efficiency as well as the background contribution from coherent and incoherent K_S regeneration on the beam-pipe wall and contamination from $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$ channel. The result of the fit to the data is shown on Figure 1 (right) and is equal to [2]:

$$\zeta_{SL} = (0.3 \pm 1.8_{stat} \pm 0.6_{syst}) \cdot 10^{-2}, \quad (2)$$

$$\zeta_{0\bar{0}} = (1.4 \pm 9.5_{stat} \pm 3.8_{syst}) \cdot 10^{-7}, \quad (3)$$
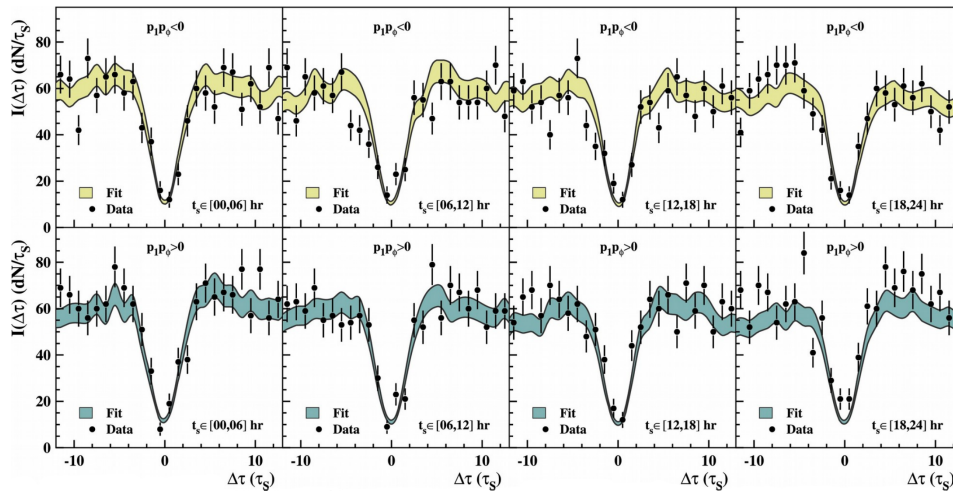
Figure 2. Results of the fit (color bands) to the double decay intensity distributions for data (black points) divided into 4 bins of sidereal time and two angular bins. Figure is adapted from [5]

showing no deviation from the quantum mechanics predictions. The bin width is optimized for the Δt resolution, which is approximately $1\tau_S$. This will be improved at KLOE-2 with the insertion of the Inner Tracker detector that allows to obtain better resolution on vertex reconstruction.

In addition, by using kaon interferometry with both kaons decaying in $\pi^+\pi^-$ pairs, the existence of CPT-violating and Lorentz-invariance violating effects predicted by the Standard Model Extension (SME) model was tested [3, 4]. Possible violation of the Lorentz invariance entails a dependence of the CPT-violating parameter δ on the sidereal time:

$$\delta \approx i \sin\phi_{SW} e^{i\phi_{SW}} \gamma_K (\Delta a_0 - \vec{\beta_K} \cdot \Delta\vec{a})/\Delta m, \tag{4}$$

where ϕ_{SW} stands for the superweak phase, γ_K and $\vec{\beta_K}$ are the kaon boost factor and velocity in the observer frame and a_μ are the four CPT- and Lorentz-violating coefficients. Figure 2 presents the KLOE-2 results on the kaon decay-time difference ratios, in units of the K_S lifetime τ_S for different orientations and sidereal times. The obtained results on Δa_μ parameters are consistent with no evidence of the CPT-violating effect and by reaching the sensitivity at the level $O(10^{-18})$ GeV are presently the most precise measurement in the quark sector of the SME.

Another component of KLOE-2 program concerning test of CPT symmetry violation is a test using asymmetries of the semileptonic decays:

$$A_{S,L} = \frac{\Gamma(K_{S,L} \to \pi^- e^+ \nu) - \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})}{\Gamma(K_{S,L} \to \pi^- e^+ \nu) + \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})} \tag{5}$$

$$= 2\left[Re\,(\epsilon_K) \pm Re\,(\delta_K) - Re\,(y) \pm Re\,(x_-)\right], \tag{6}$$

where ϵ_K and δ_K stand for CP and CPT violation in the mass matrix, respectively, while y parametrizes CPT violation assuming $\Delta S = \Delta Q$ rule and x_- is a small term that accounts for $\Delta S = \Delta Q$ rule violation. The difference:

$$A_S - A_L = 4[Re\,(\delta_K) - Re\,(x_-)] \tag{7}$$

is sensitive only to CPT violation effect originating from the mass matrix, while x_- value is experimentally limited to -0.002 ± 0.006 [8]. However, accuracy on A_L determination ($\sigma(A_L) = 0.7 \times 10^{-4}$ [10]) is more than two orders of magnitude bigger than this of the A_S and the uncertainty on A_S ($\sigma(A_S) = 0.01$ [9]) is dominated by the data sample statistics. Therefore, further studies of $K_S \to \pi e \nu$ decay using sample four times bigger in statistics than the previous KLOE analysis can improve the precision of CPT test. More than 10^5 of $K_S \to \pi e \nu$ decays were reconstructed (see Figure 3, left) and will be used to determine the charge asymmetry and branching ratio for K_S semileptonic decays.

Another two-kaon observable sensitive to the real part of CPT symmetry violation term is defined by using ratios of probabilities of transitions constructed for $K_L \to 3\pi^0$ decay accompanied by $K_S \to \pi e \nu$ and its CPT-conjugated partner $K_L K_S \to \pi e \nu\, \pi^+ \pi^-$ [6]:

$$R_{2,4}(\Delta t) = \frac{I(K_{e \mp 3}, 3\pi^0; \Delta t)}{I(\pi\pi, K_{e \mp 3}; \Delta t)} \frac{BR(K_L \to 3\pi^0)}{BR(K_S \to \pi\pi)} \frac{\Gamma_L}{\Gamma_S}. \tag{8}$$

In particular in asymptotic regime the discrepancy of $R_2(\Delta t)$ and $R_4(\Delta t)$ ratio from unity is related to the CPT symmetry violating parameter δ as:

$$R_{2,4}(\Delta t) \sim 1 \mp Re(\delta),\ \text{for } \Delta t >> \tau_S. \tag{9}$$

In order to measure the double decay rates introduced in Eq. 8 the reconstruction of a pair of kaon decays separated by a time interval Δt, in asymptotic plateau region of $\Delta t >> \tau_S$ should be $O(1\tau_S)$ which translates to decay point spatial resolution $O(1cm)$. The preliminary spectrum for $\phi \to K_S K_L \to \pi^\pm l^\mp \nu 3\pi^0$ as a function of Δt is shown on right panel on Figure 3.

KLOE-2 has recently established an upper limit for the CP-violating rare decays $K_S \to 3\pi^0$ branching fraction $Br(K_S \to 3\pi^0) < 2.6 \times 10^{-8}$ and the amplitude ratio $\eta_{000} = A(K_S \to 3\pi^0)/A(K_L \to 3\pi^0) < 0.0088$ (90% c.l) [7]. The group is also looking for the $K_S \to \pi^+ \pi^- \pi^0$ decay. An analysis based on $L = 1.7$ fb^{-1} will be the first measurement to date that makes use of the direct detection of this decay channel.

3. Summary

The neutral kaon system is an excellent laboratory for the study of CPT symmetry and the basic principles of Quantum Mechanics. The entangled pairs of $K_S K_L$ mesons allows to measure several parameters related to decoherence, the CP, CPT and Lorentz invariance. Using enhanced luminosity of DAΦNE and with new detectors, KLOE-2 is in the middle

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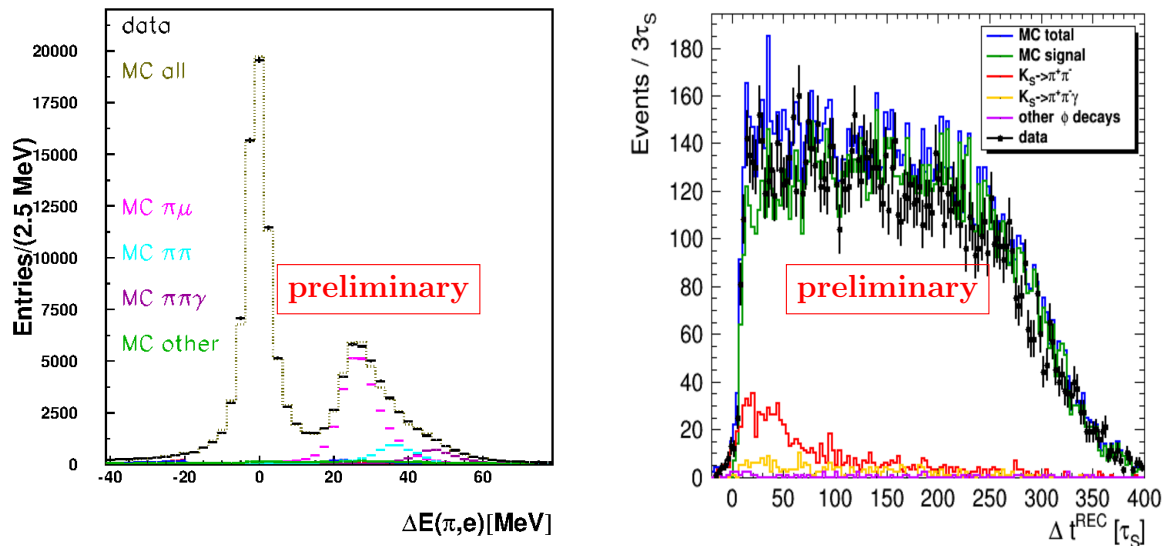IOP Publishing

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Figure 3. Left: distribution of $\Delta E(\pi, e) = E_{miss} - p_{miss}$ for all selected events after normalization procedure. Due to a non-registered neutrino in the decay, the $\Delta E(\pi, e)$ for $K_S \to \pi e \nu$ events takes value to zero. Right: spectrum of selected events in $\phi \to K_S K_L \to \pi^\pm l^\mp \nu 3\pi^0$ decay as a function of time interval Δt.

of data taking and is aiming to acquire more than 5 fb^{-1} of data. Significant progress is going to be made in all results concerning tests of CPT, CP and quantum mechanics.

Acknowledgments

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