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LATEST RESULTS ON KAON PHYSICS AT KLOE-2

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on behalf of KLOE-2 Collaboration

Abstract

The most recent results obtained by the KLOE-2 collaboration with entangled neutral kaons produced at DAΦNE are briefly reviewed: (i) an improved search for decoherence and $\mathscr{CPT}$ violation effects in the process $\phi \to \mathrm{K_S K_L} \to \pi^+\pi^-\pi^+\pi^-$, constraining with the utmost precision several phenomenological models; (ii) the first direct test of the $\mathscr{T}$ and $\mathscr{CPT}$ symmetries in neutral kaon transitions between flavor and $\mathscr{CP}$ eigenstates, by studying the processes $\phi \to \mathrm{K_S K_L} \to \pi^+\pi^- \pi e\nu$, $\phi \to \mathrm{K_S K_L} \to \pi e\nu\, 3\pi^0$; (iii) a new measurement of the $\mathrm{K_S} \to \pi e\nu$ branching fraction, that in combination with the previous KLOE result improves the total precision by almost a factor of two, and allows a new derivation of $f_+(0)|V_{us}|$.

KLOE AND DAΦNE

DAΦNE, the Frascati ϕ-factory [1], 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 production cross section is ~3 μb, and the $\phi \to \mathrm{K^0\bar{K}^0}$ decay has a branching fraction of 34%. The neutral kaon pair is produced into a fully anti-symmetric entangled state with quantum numbers $J^{\mathscr{PC}} = 1^{--}$:

$$|i\rangle = \frac{1}{\sqrt{2}}\{|\mathrm{K^0}\rangle|\mathrm{\bar{K}^0}\rangle - |\mathrm{\bar{K}^0}\rangle|\mathrm{K^0}\rangle\} = \frac{\mathscr{N}}{\sqrt{2}}\{|\mathrm{K_S}\rangle|\mathrm{K_L}\rangle - |\mathrm{K_L}\rangle|\mathrm{K_S}\rangle\} \quad (1)$$

with $\mathscr{N} = \sqrt{(1+|\epsilon_S|^2)(1+|\epsilon_L|^2)/(1-\epsilon_S\epsilon_L)} \simeq 1$ a normalization factor, and $\epsilon_{S,L}$ the small $\mathscr{CP}$ impurities in the mixing of the physical states $\mathrm{K_{S,L}}$ with definite widths $\Gamma_{S,L}$ and masses $m_{S,L}$.

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, is an observable quantity at a ϕ-factory. After integration on (t_1+t_2) at fixed time difference $\Delta t = t_2 - t_1 \geq 0$, the decay intensity can be written as follows [2]:

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

with $\Delta m = m_L - m_S$, $\eta_i \equiv |\eta_i|e^{i\phi_i} = \frac{\langle f_i|T|\mathrm{K_L}\rangle}{\langle f_i|T|\mathrm{K_S}\rangle}$, and $C_{12} = \frac{|\mathscr{N}|^2}{2(\Gamma_S+\Gamma_L)}|\langle f_1|T|\mathrm{K_S}\rangle\langle f_2|T|\mathrm{K_S}\rangle|^2$.

The detection of a kaon at large times t_2 satisfying the condition $e^{-(\Gamma_S-\Gamma_L)\Delta t}/|\eta_2| \ll 1$ *post-tags* a $\mathrm{K_S}$ state 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 very pure $\mathrm{K_S}$ beams [3].

The KLOE experiment operated at DAΦNE with a detector mainly consisting of a large volume drift chamber [4] surrounded by an electromagnetic calorimeter [5], both immersed in a 0.52 T uniform magnetic field provided by a superconducting coil. KLOE completed its data taking campaign in 2006 collecting an integrated luminosity of 2.5 fb^{-1}. A second data taking campaign was carried out in years 2014-2018 by the KLOE-2 experiment [6], the successor of KLOE, at an upgraded DAΦNE collider [7, 8], collecting an integrated luminosity of 5.5 fb^{-1}. In total KLOE and KLOE-2 collected 8 fb^{-1} of data, corresponding to $\sim 2.4\times10^{10}$ ϕ-mesons and $\sim 8\times10^{9}$ $\mathrm{K_S K_L}$ pairs produced. All the results presented in this paper have been obtained using the KLOE data sample.

SEARCH FOR DECOHERENCE AND $\mathscr{CPT}$ VIOLATION EFFECTS

The quantum interference between the decays of the entangled kaons in state (1) is studied in the $\mathscr{CP}$-violating process $\phi \to \mathrm{K_S K_L} \to \pi^+\pi^-\pi^+\pi^-$, which exhibits the characteristic Einstein–Podolsky–Rosen correlations that prevent both kaons to decay into $\pi^+\pi^-$ at the same time. The measured Δt distribution can be fitted with the distribution:

$$I(\pi^+\pi^-,\pi^+\pi^-;\Delta t) \propto e^{-\Gamma_L\Delta t} + e^{-\Gamma_S\Delta t} -2(1-\zeta_{SL})e^{-\frac{(\Gamma_S+\Gamma_L)}{2}|\Delta t|}\cos(\Delta m\Delta t) , \quad (3)$$

where the quantum mechanical expression (2) in the $\{\mathrm{K_S},\mathrm{K_L}\}$ 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 $\{\mathrm{K^0},\mathrm{\bar{K}^0}\}$ basis [9]. Δt resolution and detection efficiency effects, as well as background contributions due to $\mathrm{K_S}$-regeneration on the beam pipe wall, and the non-resonant $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ process, are all taken into account in the fit. Figure 1 shows as an example the result in the case of the ζ_{SL} decoherence model. The analysis of a data sample corresponding to L ~ 1.7 fb^{-1} yields the following results [10]:

$$\begin{aligned} \zeta_{SL} &= (0.1 \pm 1.6_{stat} \pm 0.7_{syst}) \times 10^{-2} \\ \zeta_{0\bar{0}} &= (-0.5 \pm 8.0_{stat} \pm 3.7_{syst}) \times 10^{-7} , \end{aligned} \quad (4)$$

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 high precision, $\mathscr{O}(10^{-6})$, due to the $\mathscr{CP}$ suppression present in the specific decay channel; it is an improvement of five orders of magnitude over the limit obtained by a re-analysis of CPLEAR data [9, 11]. This

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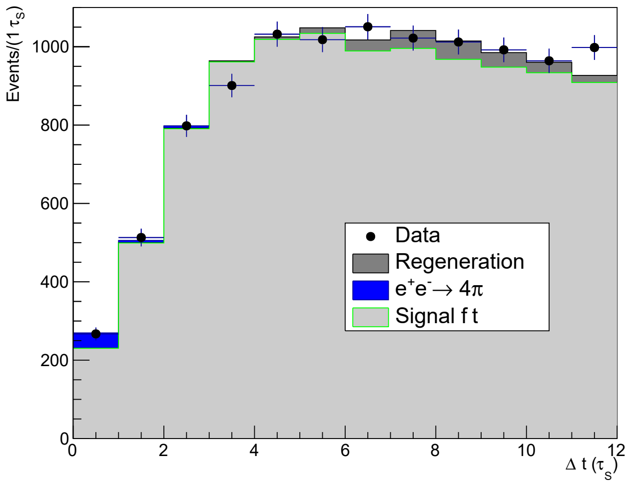

Figure 1: Data and fit distribution for the $\zeta_{\rm SL}$ decoherence model with background contributions displayed.

result can also be compared to a similar test in the B meson system [12], where an accuracy of $\mathcal{O}(10^{-2})$ is reached.

Decoherence effects may appear in a quantum gravity scenario in connections with $\mathcal{CPT}$ violation, being the quantum mechanical operator generating $\mathcal{CPT}$ transformations *ill-defined*. In this case a model for decoherence can be formulated [13, 14] in which neutral kaons are described by a density matrix ρ that obeys a modified Liouville-von Neumann equation. In this context γ is one of the relevant parameters describing decoherence and $\mathcal{CPT}$ violation. It has mass units and in a quantum gravity scenario it is presumed to be at most of $\mathcal{O}(m_K^2/M_{\rm Planck}) \sim 2 \times 10^{-20}$ GeV. Fitting the same $I(\pi^+\pi^-, \pi^+\pi^-; \Delta t)$ distribution as in the ζ parameters analysis, the following result is obtained [10]:

$$\gamma = \left(1.3 \pm 9.4_{\rm stat} \pm 4.2_{\rm syst}\right) \times 10^{-22}\ \text{GeV}, \quad (5)$$

compatible with no decoherence and $\mathcal{CPT}$ violation, improving the previous result by CPLEAR [15], while the sensitivity reaches the interesting Planck's region.

As discussed above, in a quantum gravity framework inducing decoherence, the $\mathcal{CPT}$ operator is ill-defined. This consideration has intriguing consequences in entangled neutral kaon states, where the resulting loss of particle-antiparticle identity could induce a breakdown of the correlation in state (1) imposed by Bose statistics [16]. As a result the initial state (1) can be parametrized in general as:

$$\begin{aligned}|i\rangle &= \frac{1}{\sqrt{2}}[|\mathrm{K}^0\rangle|\bar{\mathrm{K}}^0\rangle - |\bar{\mathrm{K}}^0\rangle|\mathrm{K}^0\rangle \\ &\quad +\omega\left(|\mathrm{K}^0\rangle|\bar{\mathrm{K}}^0\rangle + |\bar{\mathrm{K}}^0\rangle|\mathrm{K}^0\rangle\right)], \quad (6)\end{aligned}$$

where ω is a complex parameter describing a novel $\mathcal{CPT}$ violation phenomenon, and in this scenario its order of magnitude is expected to be at most:

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

with $\Delta\Gamma = \Gamma_S - \Gamma_L$. The study performed on the Δt distribution of the $\phi \to \mathrm{K_S K_L} \to \pi^+\pi^-\pi^+\pi^-$ process including in the fit the modified initial state Eq. (6), yields the most precise measurement of the complex parameter ω [10]:

$$\begin{aligned}\Re(\omega) &= \left(-2.3^{+1.9}_{-1.5\,\rm stat} \pm 0.6_{\rm syst}\right) \times 10^{-4} \\ \Im(\omega) &= \left(-4.1^{+2.8}_{-2.6\,\rm stat} \pm 0.9_{\rm syst}\right) \times 10^{-4}, \quad (7)\end{aligned}$$

with an accuracy that already reaches the interesting Planck scale region.

Results (4), (5), and (7) represent a sizeable improvement with respect to previous measurements [9, 11, 15, 17]. They are consistent with no deviation from quantum mechanics and $\mathcal{CPT}$ symmetry, while for some parameters the precision reaches the interesting level at which – in the most optimistic scenarios – quantum gravity effects might show up. They provide the most stringent limits up to date on the considered models.

DIRECT $\mathcal{T}$, $\mathcal{CP}$, $\mathcal{CPT}$ TESTS

In order to realize direct tests of $\mathcal{T}$, $\mathcal{CP}$, $\mathcal{CPT}$ symmetries in neutral kaon transition processes, it is necessary to compare the probability of a reference transition with its symmetry conjugate. The exchange of *in* and *out* states required for a genuine test involving an anti-unitary transformation implied by time-reversal $\mathcal{T}$, can be implemented exploiting the entanglement of $\mathrm{K}^0\bar{\mathrm{K}}^0$ pairs [18, 19], as briefly described in the following.

The initial kaon pair produced in $\phi \to \mathrm{K}^0\bar{\mathrm{K}}^0$ decays can be rewritten in terms of any pair of orthogonal states:

$$\begin{aligned}|i\rangle &= \frac{1}{\sqrt{2}}\{|\mathrm{K}^0\rangle|\bar{\mathrm{K}}^0\rangle - |\bar{\mathrm{K}}^0\rangle|\mathrm{K}^0\rangle\} \\ &= \frac{1}{\sqrt{2}}\{|\mathrm{K}_+\rangle|\mathrm{K}_-\rangle - |\mathrm{K}_-\rangle|\mathrm{K}_+\rangle\}. \quad (8)\end{aligned}$$

Here the states $|\mathrm{K}_-\rangle$, $|\mathrm{K}_+\rangle$ are defined as the states which cannot decay into pure $\mathcal{CP} = \pm 1$ final states, $\pi\pi$ or $3\pi^0$, respectively [18, 19]. The condition of orthogonality $\langle \mathrm{K}_-|\mathrm{K}_+\rangle = 0$, corresponds to assume negligible direct $\mathcal{CP}$ and/or $\mathcal{CPT}$ violation contributions in the decay, while the $\Delta S = \Delta Q$ rule is also assumed, so that the two flavor orthogonal eigenstates $|\mathrm{K}^0\rangle$ and $|\bar{\mathrm{K}}^0\rangle$ are identified by the charge of the lepton in semileptonic decays. Thus, exploiting the perfect anticorrelation of the states implied by Eq. (8), it is possible to have a "flavor-tag"or a "$\mathcal{CP}$-tag", i.e. to infer the flavor (K^0 or $\bar{\mathrm{K}}^0$) or the $\mathcal{CP}$ (K_+ or K_-) state of the still alive kaon by observing a specific flavor decay ($\pi^+\ell^-\nu$ or $\pi^-\ell^+\bar{\nu}$, in short ℓ^+ or ℓ^-) or $\mathcal{CP}$ decay ($\pi\pi$ or $3\pi^0$) of the other (and first decaying) kaon in the pair. Then the decay of the surviving kaon into a semileptonic (ℓ^+ or ℓ^-), $\pi\pi$ or $3\pi^0$ final state, filter the kaon final state as a flavor or $\mathcal{CP}$ state.

In this way one can identify a reference transition (e.g. $\mathrm{K}^0 \to \mathrm{K}_-$) and its symmetry conjugate (e.g. the $\mathcal{CPT}$-conjugated $\mathrm{K}_- \to \bar{\mathrm{K}}^0$), and directly compare them through the corresponding ratios of probabilities. The observable

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ratios for the various symmetry tests can be defined as follows [20]:

$$\begin{aligned}
R_{2,\mathcal{T}} &\equiv \frac{I(\ell^-, 3\pi^0; \Delta t \gg \tau_S)}{I(\pi\pi, \ell^+; \Delta t \gg \tau_S)} \cdot \frac{1}{D_{\mathcal{CPT}}} \\
&= 1 - 4\Re\epsilon + 4\Re x_+ + 4\Re y\,, && (9)\\
R_{4,\mathcal{T}} &\equiv \frac{I(\ell^+, 3\pi^0; \Delta t \gg \tau_S)}{I(\pi\pi, \ell^-; \Delta t \gg \tau_S)} \cdot \frac{1}{D_{\mathcal{CPT}}} \\
&= 1 + 4\Re\epsilon + 4\Re x_+ - 4\Re y\,, && (10)\\
R_{2,\mathcal{CP}} &\equiv \frac{I(\ell^-, 3\pi^0; \Delta t \gg \tau_S)}{I(\ell^+, 3\pi^0; \Delta t \gg \tau_S)} \\
&= 1 - 4\Re\epsilon_S - 4\Re x_- + 4\Re y\,, && (11)\\
R_{4,\mathcal{CP}} &\equiv \frac{I(\pi\pi, \ell^+; \Delta t \gg \tau_S)}{I(\pi\pi, \ell^-; \Delta t \gg \tau_S)} \\
&= 1 + 4\Re\epsilon_L - 4\Re x_- - 4\Re y\,, && (12)\\
R_{2,\mathcal{CPT}} &\equiv \frac{I(\ell^-, 3\pi^0; \Delta t \gg \tau_S)}{I(\pi\pi, \ell^-; \Delta t \gg \tau_S)} \cdot \frac{1}{D_{\mathcal{CPT}}} \\
&= 1 - 4\Re\delta + 4\Re x_+ - 4\Re x_-\,, && (13)\\
R_{4,\mathcal{CPT}} &\equiv \frac{I(\ell^+, 3\pi^0; \Delta t \gg \tau_S)}{I(\pi\pi, \ell^+; \Delta t \gg \tau_S)} \cdot \frac{1}{D_{\mathcal{CPT}}} \\
&= 1 + 4\Re\delta + 4\Re x_+ + 4\Re x_-\,. && (14)
\end{aligned}$$

where $I(f_1, f_2; \Delta t \gg \tau_S)$ is the double decay rate (2) in the asymptotic region $\Delta t \gg \tau_S$ [2, 18, 19], with f_1 occurring before f_2 decay and $\Delta t > 0$. The constant factor $D_{\mathcal{CPT}}$ is defined as:

$$D_{\mathcal{CPT}} = \frac{\left|\langle 3\pi^0 | T | \mathrm{K}_- \rangle\right|^2}{\left|\langle \pi^+\pi^- | T | \mathrm{K}_+ \rangle\right|^2} = \frac{\mathrm{BR}\left(\mathrm{K_L} \to 3\pi^0\right)}{\mathrm{BR}\left(\mathrm{K_S} \to \pi^+\pi^-\right)} \frac{\Gamma_L}{\Gamma_S}\,,$$

and can be determined from measurable branching fractions and lifetimes of $\mathrm{K_{S,L}}$ states [19, 20]. For $\Delta t = 0$ one has by construction no symmetry violation, within our assumptions. The measurement of any deviation from the prediction $R_{i,s} = 1$ (with $s = \mathcal{T}, \mathcal{CP}$, or $\mathcal{CPT}$, and $i = 2, 4$) imposed by the symmetry invariance is a direct signal of the symmetry violation built in the time evolution of the system. The following double ratios independent of the factor $D_{\mathcal{CPT}}$ can also be defined:

$$\begin{aligned}
DR_{\mathcal{T},\mathcal{CP}} &\equiv \frac{R_{2,\mathcal{T}}}{R_{4,\mathcal{T}}} \equiv \frac{R_{2,\mathcal{CP}}}{R_{4,\mathcal{CP}}} = 1 - 8\Re\epsilon + 8\Re y\,, && (15)\\
DR_{\mathcal{CPT}} &\equiv \frac{R_{2,\mathcal{CPT}}}{R_{4,\mathcal{CPT}}} = 1 - 8\Re\delta - 8\Re x_-\,. && (16)
\end{aligned}$$

The r.h.s. of Eqs.(9)-(16) is evaluated to first order in small parameters; ϵ and δ are the usual $\mathcal{T}$ and $\mathcal{CPT}$ violation parameters in the neutral kaon mixing, respectively, and $\epsilon_{S,L} = \epsilon \pm \delta$ the $\mathcal{CP}$ impurities in the physical states $\mathrm{K_S}$ and $\mathrm{K_L}$; the small parameter y describes a possible $\mathcal{CPT}$ violation in the $\Delta S = \Delta Q$ semileptonic decay amplitudes, while x_+ and x_- describe $\Delta S \neq \Delta Q$ semileptonic decay amplitudes with $\mathcal{CPT}$ invariance and $\mathcal{CPT}$ violation, respectively. Therefore the r.h.s. of Eqs.(9)-(16) shows the effect of symmetry violations only in the effective Hamiltonian description of the neutral kaon system according to the Weisskopf-Wigner approximation, without the presence of other possible sources of symmetry violations. The small spurious effects due to the release of our assumptions are also shown, including possible $\Delta S = \Delta Q$ rule violations ($x_+, x_- \neq 0$) and/or direct $\mathcal{CPT}$ violation effects ($y \neq 0$). It is worth noting that the direct $\mathcal{CP}$ ϵ' effects are fully negligible in the asymptotic region $\Delta t \gg \tau_S$ [18, 19].

The KLOE-2 collaboration recently completed the analysis of a data sample corresponding to an integrated luminosity $L = 1.7\ \mathrm{fb}^{-1}$ collected at the DAΦNE ϕ-factory, and measured all eight observables defined in Eqs.(9)-(16). The Δt distributions of the $\phi \to \mathrm{K_S K_L} \to \pi^+\pi^-\ \pi e\nu$ and $\phi \to \mathrm{K_S K_L} \to \pi e\nu\ 3\pi^0$ processes are studied in the asymptotic region $\Delta t \gg \tau_S$. A time of flight technique is used to identify semileptonic decays for both $\mathrm{K_S}$ and $\mathrm{K_L}$. $\mathrm{K_L} \to 3\pi^0$ decays are identified reconstructing the decay position and time using a trilateration method applied to the best candidate set of six reconstructed photons from π^0 decays. Residual background for the $\phi \to \mathrm{K_S K_L} \to \pi e\nu\ 3\pi^0$ channel is evaluated with the aid of Monte Carlo (MC) simulation and subtracted. Signal selection efficiencies are evaluated from MC and corrected with data using independent control samples. The Δt distributions of observables ratios (9)-(16) are then constructed and fitted with a constant.

The final results obtained for the eight observable ratios (9)-(16) are summarized in Fig.2, and compared with the expected values from $\mathcal{CPT}$ invariance and $\mathcal{T}$ violation extrapolated from observed $\mathcal{CP}$ violation in the $\mathrm{K^0} - \bar{\mathrm{K}}^0$ mixing [21].

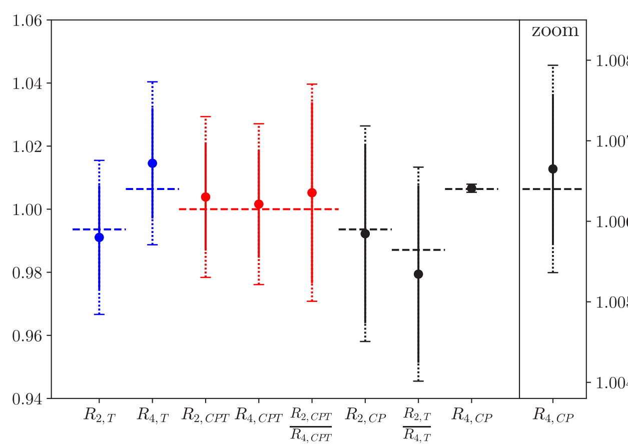

Figure 2: Comparison of the measured symmetry-violation-sensitive single and double ratios (9)-(16) and their expected values (horizontal dashed lines). Solid error bars denote statistical uncertainties and dotted error bars represent total uncertainties (including systematic uncertainties and the error on the $D_{\mathcal{CPT}}$ factor in case of single $\mathcal{T}$ and $\mathcal{CPT}$-violation sensitive ratios). The right-hand-side panel magnifies the region of the $\mathcal{CP}$-violation-sensitive ratio $R_{4,\mathcal{CP}}$.

For the $\mathcal{T}$ and $\mathcal{CPT}$ single ratios a total error of 2.5 % is reached, while for the double ratios (15) and (16) the total error is increased to 3.5 %, with the advantage of in principle a doubled sensitivity to violation effects, and of

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independence from the $D_{\mathcal{CPT}}$ factor. The measurement of the single ratio $R_{4,\mathcal{CP}}$ benefits of highly allowed decay rates for the involved channels, reaching an error of 0.13 %.

The double ratio $DR_{\mathcal{CPT}}$ is our best observable for testing $\mathcal{CPT}$, free from approximations and model independent, while $DR_{\mathcal{T},\mathcal{CP}}$ assumes no direct $\mathcal{CPT}$ violation and is even under $\mathcal{CPT}$, therefore it does not disentangle $\mathcal{T}$ and $\mathcal{CP}$ violation effects, contrary to the genuine $\mathcal{T}$ and $\mathcal{CP}$ single ratios.

No result on $\mathcal{T}$ and $\mathcal{CPT}$ observables shows evidence of symmetry violation. We observe $\mathcal{CP}$ violation in transitions in the single ratio $R_{4,\mathcal{CP}}$ with a significance of 5.2σ, in agreement with the known $\mathcal{CP}$ violation in the $K^0-\bar{K}^0$ mixing [21] using a different observable.

NEW MEASUREMENT OF $\mathcal{B}(K_S \to \pi e \nu)$

The branching fraction for semileptonic decays of charged and neutral kaons together with the lifetime measurements are used to determine the $|V_{us}|$ element of the Cabibbo–Kobayashi–Maskawa quark mixing matrix. The relation among the matrix elements of the first row, $|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=1$, provides the most stringent test of the unitarity of the quark mixing matrix.

Different factors contribute to the uncertainty in determining $|V_{us}|$ from kaon decays, discussed in Refs. [22–25] and among the six semileptonic decays the contribution of the lifetime uncertainty is smallest for the K_S meson. Nevertheless, given the lack of pure high-intensity K_S meson beams compared with $K^\pm$ and K_L mesons, the measurements of K_S semileptonic decays from the KLOE [26,27] and NA48 [28] experiments provide the least precise determination of $|V_{us}|$.

A data sample corresponding to an integrated luminosity of $L = 1.63\ \text{fb}^{-1}$ collected by KLOE was analyzed by the KLOE-2 collaboration. K_S states are tagged by identifying the interaction of their entangled partners in the calorimeter (K_L-crash). The $K_S \to \pi e \nu$ signal selection exploits a boosted decision tree (BDT) classifier built with kinematic variables measured with DC only together with time-of-flight measurements from EMC. The signal yield is provided by the fit to the reconstructed electron mass distribution shown in Fig.3, and is then normalised to $K_S \to \pi^+\pi^-$ decays in the same data set. $K_L \to \pi e \nu$ data control samples are used to evaluate signal selection efficiencies. Finally the branching fraction is derived [29]:

$$\mathcal{B}(K_S \to \pi e \nu) = (7.211 \pm 0.046_{\text{stat}} \pm 0.052_{\text{syst}}) \times 10^{-4}.$$

The previous result from KLOE [26], based on an independent data sample corresponding to $0.41\ \text{fb}^{-1}$ of integrated luminosity, is $\mathcal{B}(K_S \to \pi e \nu) = (7.046 \pm 0.076_{\text{stat}} \pm 0.049_{\text{syst}}) \times 10^{-4}$. The combination of the two results, accounting for correlations between the two measurements, gives

$$\mathcal{B}(K_S \to \pi e \nu) = (7.153 \pm 0.037_{\text{stat}} \pm 0.043_{\text{syst}}) \times 10^{-4},$$

reducing the overall uncertainty on the branching fraction at the 0.8% level. The value of $|V_{us}|$ is related to the K_S semileptonic branching fraction by the equation

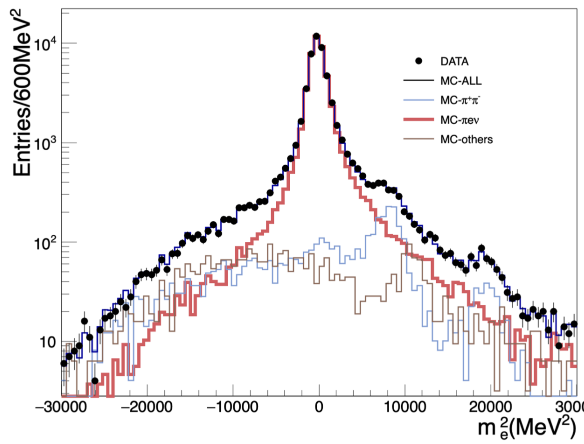

Figure 3: The m_e^2 distribution for data, MC signal and background compared with the fit result.

$$\mathcal{B}(K_S \to \pi \ell \nu) = \frac{G^2(f_+(0)|V_{us}|)^2}{192\pi^3}\tau_S m_K^5 I_K^\ell S_{\text{EW}}(1+\delta_{\text{EM}}^{K\ell}),$$

where I_K^ℓ is the phase-space integral, which depends on measured semileptonic form factors, S_{EW} is the short-distance electro-weak correction, $\delta_{\text{EM}}^{K\ell}$ is the mode-dependent long-distance radiative correction, and $f_+(0)$ is the form factor at zero momentum transfer for the $\ell\nu$ system. Using the values $S_{\text{EW}} = 1.0232 \pm 0.0003$ [30], $I_K^e = 0.15470 \pm 0.00015$ and $\delta_{\text{EM}}^{Ke} = (1.16 \pm 0.03)\ 10^{-2}$ from Ref. [25], and the world average values for the K_S mass and lifetime [21] we derive

$$f_+(0)|V_{us}| = 0.2170 \pm 0.0009,$$

with a sizable reduction of the uncertainty with respect to the previous derivation, from 0.6% to 0.4%.

CONCLUSION

Recent analyses by the KLOE-2 collaboration on entangled neutral kaons yielded improved precision tests of Quantum Mechanics and $\mathcal{CPT}$ symmetry, the first direct tests of $\mathcal{T}$ and $\mathcal{CPT}$ symmetries in neutral kaon transitions, and a new measurement of the $K_S \to \pi e \nu$ branching fraction.

The analysis of the total $8\ \text{fb}^{-1}$ of data collected by KLOE and KLOE-2 is in progress and will constitute a unique opportunity to push forward a rich Physics program including these kind of studies on discrete symmetries, and on the properties of the entanglement of neutral kaons.

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