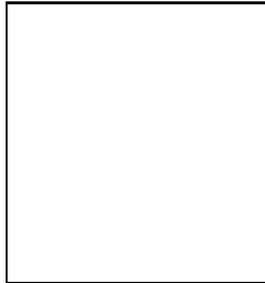


Recent results from KLOE

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In this report I will present the recent results on K mesons from the KLOE experiment at the DAFNE e^+e^- collider working at the center of mass energy $\sim 1\text{GeV} \sim m_\phi$. They include V_{us} determinations, the test on the unitarity of the first row of the CKM matrix and the related experimental measurements. Tests of lepton universality from leptonic and semileptonic decays will be also discussed. Then I will present tests of quantum coherence, CPT and Lorentz symmetry performed by studying the time evolution of the neutral kaon system.

1 The KLOE experiment

The KLOE detector operates at DAFNE, an e^+e^- collider working at the center of mass energy $W \sim m_\phi \sim 1.02\text{ GeV}$. The ϕ mesons are produced essentially at rest and decay to $K_S K_L$ ($K^+ K^-$) $\sim 34\%$ ($\sim 49\%$) of the times. The K mesons are produced in a pure $J^{PC} = 1^{--}$ coherent quantum state, so that observation of a K_S (K^+) in an event signals (tags) the presence of a K_L (K^-) and vice-versa: highly pure, almost monochromatic, back-to-back K_S (K^+) and K_L (K^-) beams can be obtained. Moreover K_S and K_L are distinguishable on the basis of their decay length: $\lambda_S \sim 0.6\text{ cm}$ and $\lambda_L \sim 340\text{ cm}$.

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The KLOE detector consists essentially of a drift chamber (DC), surrounded by an electromagnetic calorimeter (EMC). The DC¹ is a cylinder of 4 m diameter and 3.3 m in length which constitutes a large fiducial volume for K_L decays ($\sim 1/2$ of λ_L). The momentum resolution for tracks at large polar angle is $\sigma_p/p \leq 0.4\%$. The EMC² is a lead-scintillating fiber calorimeter consisting of a barrel and two endcaps, which cover 98% of the solid angle. The energy resolution is $\sigma_E/E \sim 5.7\%/\sqrt{E(\text{GeV})}$. The intrinsic time resolution is $\sigma_T = 54\text{ps}/\sqrt{E(\text{GeV})} \oplus 50\text{ps}$. A superconducting coil surrounding the barrel provides a 0.52 T magnetic field.

The present report is based on a first data sample of $\sim 500 \text{ pb}^{-1}$, except for quantum coherence, CPT and Lorentz symmetry tests; at present KLOE has about 2.2 fb^{-1} on disk.

2 V_{us} determination

In the Standard Model, the coupling of the W boson to the weak charged current is written as

$$\frac{g}{\sqrt{2}} W_\alpha^+ (\bar{\mathbf{U}}_L \mathbf{V}_{\text{CKM}} \gamma^\alpha \mathbf{D}_L + \bar{e}_L \gamma^\alpha \nu_{eL} + \bar{\mu}_L \gamma^\alpha \nu_{\mu L} + \bar{\tau}_L \gamma^\alpha \nu_{\tau L}) + \text{h.c.}, \quad (1)$$

where $\mathbf{U}^T = (u, c, t)$, $\mathbf{D}^T = (d, s, b)$ and L is for lefthanded. In the coupling above there is only one coupling constant for leptons and quarks. Quarks are mixed by the Cabibbo-Kobayashi-Maskawa matrix, \mathbf{V}_{CKM} , which must be unitary.

The most precise check on the unitarity of the \mathbf{V}_{CKM} matrix is provided by measurements of $|V_{us}|$ and $|V_{ud}|$, the contribution of V_{ub} being at the level of 10^{-5} . $|V_{us}|$ may be extracted by the measurements of the semileptonic decay rates, fully inclusive of radiation, which are given by:

$$\Gamma(K_{\ell 3}(\gamma)) = \frac{C_K^2 G_F^2 M_K^5}{192\pi^3} S_{\text{EW}} |V_{us}|^2 |f_+(0)|^2 I_{K\ell} \left(1 + \delta_K^{\text{SU}(2)} + \delta_{K\ell}^{\text{EM}}\right)^2. \quad (2)$$

In the above expression, the index K denotes $K^0 \rightarrow \pi^\pm$ and $K^\pm \rightarrow \pi^0$ transitions, for which $C_K^2 = 1$ and $1/2$, respectively. M_K is the appropriate kaon mass, S_{EW} is the universal short-distance electroweak correction³ and $\ell = e, \mu$. Following a common convention, $f_+(0) \equiv f_+^{K^0\pi^-}(0)$. The mode dependence is contained in the δ terms: the long-distance electromagnetic (EM) corrections, which depend on the meson charges and lepton masses and the SU(2)-breaking corrections, which depend on the kaon species⁴. $I_{K\ell}$ is the integral of the dimensionless Dalitz-plot density over the physical region for non radiative decays and includes $|\tilde{f}_{+,0}(t)|^2$, the reduced form factor, defined below.

$|V_{us}|$ can be also extracted from $K \rightarrow \mu\nu$ decays using the relation

$$\frac{\Gamma(K_{\mu 2}(\gamma))}{\Gamma(\pi_{\mu 2}(\gamma))} = \frac{|V_{us}|^2}{|V_{ud}|^2} \frac{f_K^2}{f_\pi^2} \frac{m_K \left(1 - m_\mu^2/m_K^2\right)^2}{m_\pi \left(1 - m_\mu^2/m_\pi^2\right)^2} \times (0.9930 \pm 0.0035), \quad (3)$$

where f_π and f_K are the pion- and kaon-decay constants and the uncertainty in the numerical factor is dominantly from structure-dependent radiative corrections. This ratio can be combined with direct measurements of $|V_{ud}|$ to obtain $|V_{us}|$.

The measurement of V_{us} from leptonic and semileptonic kaon decays allows both the test the unitarity of the CKM matrix and the leptonic quark universality. Moreover the universality of electron and muon interactions can be tested by measuring the ratio $\Gamma(K \rightarrow \pi\mu\nu)/\Gamma(K \rightarrow \pi e\nu)$ and the comparison between the measurement of V_{us} from leptonic decays and that from semileptonic decays allows to put bounds on new physics.

The experimental inputs to eq. 2 and 3 are the semileptonic and leptonic decay rates, fully inclusive of radiation, *i.e.* branching ratios (BR) and lifetimes, and the reduced form factors $\tilde{f}_+(t)$ and $\tilde{f}_0(t)$, whose behaviour as a function of t , the 4-momentum transfer squared $(P_K - p_\pi)^2$,

is obtained from the decay pion spectra. Details on the measurements and the treatment of correlations can be found in ref. ⁵. In this report I will present the recent measurement of the $K_{\mu 3}$ form factors, the charged kaon life time, the $\text{BR}(K_{13}^{\pm})$ and the $\text{BR}(K^+ \rightarrow \pi^+\pi^0)$

3 $K_{\mu 3}$ from factors

The largest uncertainty in calculating $|V_{us}|$ from the decays rates is due to the difficulties in computing the matrix element $\langle \pi | J_{\alpha}^{had} | K \rangle$ which has the form:

$$\langle \pi | J_{\alpha}^{had} | K \rangle = f_+(0) \times ((P + p)_{\alpha} f_+(t) + (P - p)_{\alpha} (f_0(t) - f_+(t) \Delta_{K\pi}/t)) \quad (4)$$

where $P(p)$ is the $K(\pi)$ momentum, $t = (P - p)^2$ and $\Delta_{K\pi} = M_K^2 - m_{\pi}^2$. The above equation defines the vector and scalar form factors (FF) $f_+(t) = f_+(0) \tilde{f}_+(t)$ and $f_0(t) = f_+(0) \tilde{f}_0(t)$, which take into account the non point-like structure of the pions and kaons. The term $f_+(0)$ has been factored out, since the FFs must have the same value at $t = 0$. If the FFs are expanded in powers of t up to t^2 as $\tilde{f}_{+,0}(t) = 1 + \lambda'_{+,0} \frac{t}{m^2} + \frac{1}{2} \lambda''_{+,0} \left(\frac{t}{m^2}\right)^2$, four parameters (λ'_+ , λ''_+ , λ'_0 and λ''_0) need to be determined from the decay pion spectrum in order to be able to compute the phase-space integral. However, this parametrization of the form factors is problematic, because the values for the λ s obtained from fits to the experimental decay spectrum are strongly correlated ⁶. It is therefore necessary to obtain a form for $\tilde{f}_0(t)$ and $\tilde{f}_+(t)$ with at least t and t^2 terms but with only one parameter. The Callan-Treiman relation ⁷ fixes the value of scalar FF at $t = \Delta_{K\pi}$ (the so-called Callan-Treiman point) to the ratio of the pseudoscalar decay constants f_K/f_{π} . $\tilde{f}_0(\Delta_{K\pi}) = \frac{f_K}{f_{\pi}} \frac{1}{f_+(\Delta_{K\pi})} + \Delta_{CT}$, where Δ_{CT} , SU(2)-breaking correction ⁸, is of $\mathcal{O}(10^{-3})$. A recent dispersive parametrization for the scalar form factor ⁹, $\tilde{f}_0(t) = \exp\left[\frac{t}{\Delta_{K\pi}}(\ln C - G(t))\right]$, allows the constraint given by the Callan-Treiman relation to be exploited, such that $C = \tilde{f}_0(\Delta_{K\pi})$ and $\tilde{f}_0(0) = 1$. $G(t)$ is derived from $K\pi$ scattering data. As suggested in ref. ⁹, a good approximation to the dispersive parametrization is $\tilde{f}_0(t) = 1 + \lambda_0 \frac{t}{m^2} + \frac{\lambda_0^2 + p_2}{2} \left(\frac{t}{m^2}\right)^2 + \frac{\lambda_0^3 + 3p_2\lambda_0 + p_3}{6} \left(\frac{t}{m^2}\right)^3$ with p_2 and p_3 given in ref. ⁹. Also for the vector FF we make use of a dispersive parameterization ¹⁰, twice subtracted at $t = 0$, $\tilde{f}_+(t) = \exp\left[\frac{t}{m_{\pi}^2}(\Lambda_+ + H(t))\right]$, where $H(t)$ is obtained from $K\pi$ scattering data and Λ_+ has to be determined from the fit to experimental data. At KLOE energies clean and efficient

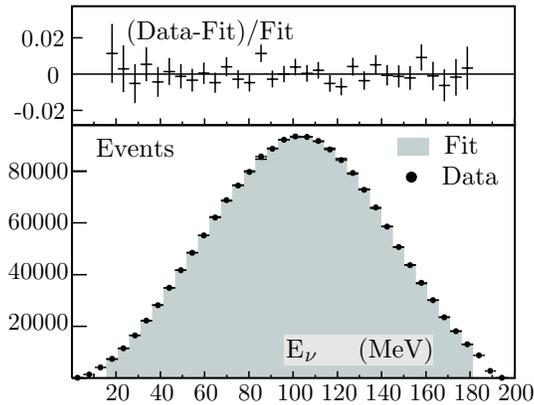


Figure 1: Residuals of the fit (top plots) and E_{ν} distribution for data events superimposed on the fit result (bottom plot)

π/μ separation, required to measure the t spectrum, is difficult. The FF parameters have

been therefore obtained from fits to the distribution of the neutrino energy E_ν after integration over the pion energy. About 1.8 Million of $K_{\mu 3}$ are selected by means of kinematic cuts, time of flight (TOF) measurements and calorimetric information. Details on the analysis can be found in ref. ¹¹. Using the dispersive parameterizations for the vector and scalar FF's and combining the $K_{\mu 3}$ and $K_{e 3}$ data, we find $\lambda_+ = (25.7 \pm 0.4 \pm 0.4 \pm 0.2_{\text{param}}) \times 10^{-3}$ and $\lambda_0 = (14.0 \pm 1.6 \pm 1.3 \pm 0.2_{\text{param}}) \times 10^{-3}$ with $\chi^2/\text{dof} = 2.6/3$ and a correlation coefficient of -0.26 . The result of the fit on $K_{\mu 3}$ data is shown in figure 1. Preliminary results based on $1fb^{-1}$ have been also obtained and averaged with that presented above: $\lambda_+ = (26.0 \pm 0.5_{\text{stat+syst}}) \times 10^{-3}$ and $\lambda_0 = (15.1 \pm 1.4_{\text{stat+syst}}) \times 10^{-3}$

4 $\tau(K^\pm)$, $\text{BR}(K_{l3}^\pm)$ and $\text{BR}(K^+ \rightarrow \pi^+\pi^0)$

We have combined the recent published measurements of the semileptonic BRs and the charged kaon lifetime to use them in the evaluation of $|V_{us}|$.

At KLOE, two methods are used to reconstruct the proper decay time distribution for charged kaons. The first is to obtain the decay time from the kaon path length in the DC, accounting for the continuous change in the kaon velocity due to ionization energy losses. A fit to the proper-time distribution in the interval from 15–35 ns ($1.6\tau_\pm$) gives the result $\tau_\pm = 12.364 \pm 0.031_{\text{stat}} \pm 0.031_{\text{syst}}$ ns. Alternately, the decay time can be obtained from the precise measurement of the arrival times of the photons from $K^+ \rightarrow \pi^+\pi^0$ decays. In this case, a fit to the proper-time distribution in the interval from 13–42 ns ($2.3\tau_\pm$) gives the result $\tau_\pm = 12.337 \pm 0.030_{\text{stat}} \pm 0.020_{\text{syst}}$ ns. Taking into account the statistical correlation between these two measurements ($\rho = 0.307$), we obtain the average value $\tau_\pm = 12.347 \pm 0.030$ ns, see ¹².

To measure $\text{BR}(K_{e3}^\pm)$ and $\text{BR}(K_{\mu 3}^\pm)$, we use both $K \rightarrow \mu\nu$ and $K \rightarrow \pi\pi^0$ decays as tags. We measure the semileptonic BRs separately for K^+ and K^- . Therefore, $\text{BR}(K_{e3})$ and $\text{BR}(K_{\mu 3})$ are each determined from four independent measurements (K^+ and K^- decays; $\mu\nu$ and $\pi\pi^0$ tags). Two-body decays are removed by kinematics and the photons from the π^0 are reconstructed to reconstruct the K^\pm decay point. From the TOF and momentum measurement for the lepton tracks, we obtain the m_l^2 distribution shown in figure 2. Further details are given in ¹³. Using the

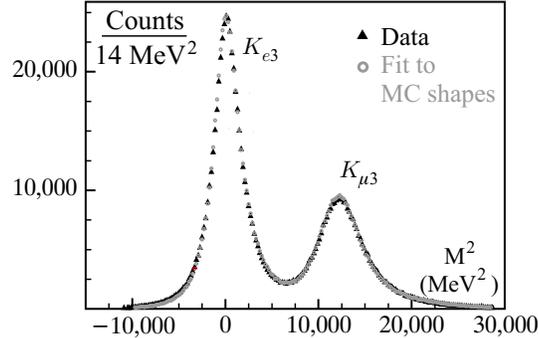


Figure 2: Distribution of m_l^2 , from TOF information, for K_{l3}^\pm events.

above result for τ_\pm to estimate the fiducial volume acceptance, we obtain $\text{BR}(K_{e3}) = 0.04972 \pm 0.00053$ and $\text{BR}(K_{\mu 3}) = 0.03273 \pm 0.00039$, which we use in our evaluation of $|V_{us}|$.

We have also obtained a preliminary result on the $\text{BR}(K^+ \rightarrow \pi^+\pi^0)$, which is crucial to perform the fit of all K^\pm BRs and for the $|V_{us}|$ determination of several experiments (NA48, ISTRAP, E865) in the normalization of the BRs (K_{l3}^\pm). About 800000 $K^+ \rightarrow \pi^+\pi^0$ have been select with kinematic cuts. Our preliminary result, $\text{BR}(K^+ \rightarrow \pi^+\pi^0) = (20.658 \pm 0.065 \pm 0.090)\%$, is lower than the PDG value ¹⁴ of about 1.3%. Further details can be found in ref. ¹⁵.

5 $|f_+(0)V_{us}|$ and lepton universality

Using the $\text{BR}(K_{l3}^{0,\pm})$, $\tau(K_L)$, $\tau(K^\pm)$ and the FFs from the KLOE results and $\tau(K_S)$ from the PDG¹⁴, the values of $|f_+(0)V_{us}|$ has been evaluated for K_{Le3} , $K_{L\mu3}$, K_{Se3} , K_{e3}^\pm and $K_{\mu3}^\pm$ decay modes. The inputs from theory, according to eq. 2, are the SU(2)-breaking correction evaluated with ChPT to $\mathcal{O}(p^4)$, as described in¹⁶, the long distance EM corrections to the full inclusive decay rate evaluated with ChPT to $\mathcal{O}(e^2p^2)$ ¹⁶ using low-energy constants from ref.¹⁷.

The average on the five different determination obtained taking into account all correlations is: $|f_+(0)V_{us}| = 0.2157 \pm 0.0006$ with $\chi^2/\text{dof} = 7.0/4$.

Comparison of the values of $|f_+(0)V_{us}|$ for K_{e3} and $K_{\mu3}$ modes provides a test of lepton universality. We calculate the following quantity

$$r_{\mu e} \equiv \frac{|f_+(0)V_{us}|_{\mu3, \text{exp}}^2}{|f_+(0)V_{us}|_{e3, \text{exp}}^2} = \frac{\Gamma_{\mu3}}{\Gamma_{e3}} \frac{I_{e3}(1 + \delta_{Ke})^2}{I_{\mu3}(1 + \delta_{K\mu})^2}, \quad (5)$$

where $\delta_{K\ell}$ stands for $\delta_K^{\text{SU}(2)} + \delta_{K\ell}^{\text{EM}}$. In the SM $r_{\mu e} = 1$. Averaging between charged and neutral modes, we find $r_{\mu e} = 1.000 \pm 0.008$. The sensitivity of this result is competitive with that obtained for $\pi \rightarrow l\nu$ and $\tau \rightarrow l\nu$ decays^{18,19} whose accuracy is $\sim 0.4\%$.

6 Test of CKM unitarity

To get the value of $|V_{us}|$ we have used the recent determination of $f_+(0) = 0.9644 \pm 0.0049$ from RBC and UKQCD Collaborations obtained from a lattice calculation with 2 + 1 flavors of dynamical domain-wall fermions²². Using their value for $f_+(0)$, our K_{l3} results give $|V_{us}| = 0.2237 \pm 0.0013$. Additional information is provided by the determination of the ratio $|V_{us}/V_{ud}|$, using eq. 3. From our measurements of $\text{BR}(K_{\mu2})$ and τ_\pm , $\Gamma(\pi_{\mu2})$ from ref.¹⁴ and the recent lattice determination of f_K/f_π from the HPQCD/UKQCD collaboration, $f_K/f_\pi = 1.189 \pm 0.007$ ²¹, we obtain $|V_{us}/V_{ud}|^2 = 0.0541 \pm 0.0007$. We perform a fit to the above ratio and our result $|V_{us}|^2 = 0.05002 \pm 0.00057$ together with the result $|V_{ud}|^2 = 0.9490 \pm 0.0005$ from superallowed β -decays²⁰. We find $1 - |V_{us}|^2 - |V_{ud}|^2 = 0.0004 \pm 0.0007$ ($\sim 0.6\sigma$) and confirm the unitarity of the CKM quark mixing matrix as applied to the first row. The result of the fit is shown in figure 3.

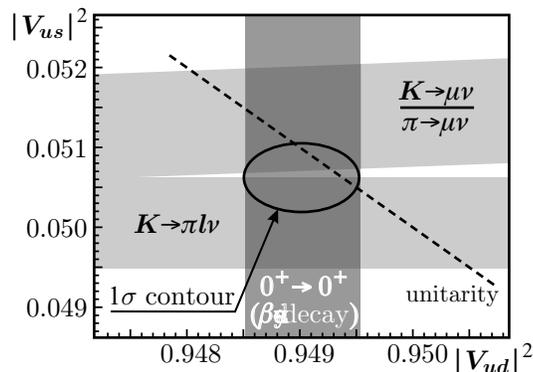


Figure 3: KLOE results for $|V_{us}|^2$, $|V_{us}/V_{ud}|^2$ and $|V_{ud}|^2$ from β -decay measurements, shown as 2σ wide grey bands. The ellipse is the 1σ contour from the fit. The unitarity constraint is illustrated by the dashed line.

7 Bounds on new physics from K_{l2} decays

The comparison between the values for $|V_{us}|$ obtained from helicity-suppressed $K_{\ell2}$ decays and helicity-allowed $K_{\ell3}$ decays allows to put bounds on new physics. We study the quantity $R_{\ell23} =$

$\left| \frac{V_{us}(K_{\mu 2})}{V_{us}(K_{\ell 3})} \times \frac{V_{ud}(0^+ \rightarrow 0^+)}{V_{ud}(\pi_{\mu 2})} \right|$, which is unity in the SM, but would be affected only in $V_{us}(K_{\mu 2})$ by the presence of non-vanishing scalar or right-handed currents. A scalar current due to a charged Higgs exchange is expected to lower the value of $R_{\ell 23}$, which becomes (see ²³): $R_{\ell 23} = \left| 1 - \frac{m_{K^+}^2}{m_{H^+}^2} \left(1 - \frac{m_{\pi^+}^2}{m_{K^+}^2} \right) \frac{\tan^2 \beta}{1 + \epsilon_0 \tan \beta} \right|$ with $\tan \beta$ the ratio of the two Higgs vacuum expectation values in the MSSM and $\epsilon_0 \approx 0.01$ ²⁴. Using our result on $K_{\mu 2}$ and $K_{\ell 3}$ decays, the lattice determinations of $f_+(0)$ and f_K/f_π and the value of $|V_{ud}|$ discussed above, we obtain $R_{\ell 23} = 1.008 \pm 0.008$. Fig. 4 shows the region in the $\{m_{H^+}, \tan \beta\}$ plane excluded at 95% CL by our result for $R_{\ell 23}$.

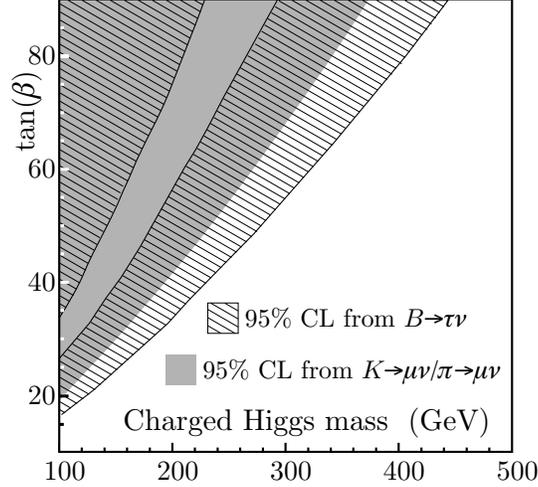


Figure 4: Region in the m_{H^+} - $\tan \beta$ plane excluded by our result for $R_{\ell 23}$; the region excluded by measurements of $\text{BR}(B \rightarrow \tau \nu)$ is also shown.

The ratio $R_K = \frac{\text{BR}(K_{e 2})}{\text{BR}(K_{\mu 2})}$ is extremely well known in the SM, being almost free on hadronic uncertainties. Since the electron channel is helicity suppressed R_K is sensitive to contributions from physics beyond the SM. Deviations up to few percent on R_K are expected in minimal supersymmetric extensions of the SM and should be dominated by lepton-flavour violating contributions with tauonic neutrinos emitted ²⁵. KLOE has selected about 8000 $K_{e 2}$ events on 1.7 pb^{-1} by performing a direct search without the tag of the other kaon. Background from $K_{\mu 2}$ has been reduced by means of kinematic cuts and calorimeter particle identification. Our preliminary result, $R_K = (2.55 \pm 0.05 \pm 0.5) \times 10^{-5}$, allows to put bounds on the charged Higgs mass and $\tan \beta$ for different slepton mass matrix off-diagonal elements $\Delta_{1,3}$. An accuracy of $\sim 1\%$ is expected increasing the data sample analyzed, the control sample and Monte Carlo statistics.

8 Test of quantum coherence, CPT and Lorentz symmetry with the neutral kaons

Test of quantum mechanics (QM) can be performed by studying the time evolution of the quantum correlated $K_S K_L$ system, in particular studying the interference pattern of the decay $K_L K_S \rightarrow \pi^+ \pi^- \pi^+ \pi^-$. The distribution of the difference decay times is given by:

$$I(|\Delta t|) \propto e^{-|\Delta t| \Gamma_L} + e^{-|\Delta t| \Gamma_S} - 2 \cos(\Delta m |\Delta t|) e^{-\frac{\Gamma_S + \Gamma_L}{2} |\Delta t|} \quad (6)$$

One of the most direct ways to search for deviations from QM is to introduce a decoherence parameter ζ ²⁶, *i.e.* multiplying by a factor $(1 - \zeta)$ the interference term in the last equation. The definition of ζ depends on the basis chosen for the initial state ²⁷ $|i\rangle \propto |K_S(+\vec{p})\rangle |K_L(-\vec{p})\rangle - |K_L(+\vec{p})\rangle |K_S(-\vec{p})\rangle$ or $|i\rangle \propto |K^0(+\vec{p})\rangle |\bar{K}^0(-\vec{p})\rangle - |\bar{K}^0(+\vec{p})\rangle |K^0(-\vec{p})\rangle$.

The case $\zeta = 1$ (*i.e.* total decoherence) corresponds to the spontaneous factorization of states (known as Furry’s hypothesis²⁸). Selecting a pure sample of $K_L K_S \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ and fitting eq. 6 to data, KLOE has obtained the following preliminary result based on $1fb^{-1}$: $\zeta_{SL} = 0.009 \pm 0.022_{\text{stat}}$ and $\zeta_{00} = (0.03 \pm 0.12_{\text{stat}}) \times 10^{-5}$ consistent with QM predictions.

In a quantum gravity framework, space-time fluctuations at the Planck scale ($\sim 10^{-33}$ cm), might induce a pure state to evolve into a mixed one²⁹. This decoherence, in turn, necessarily implies *CPT* violation³⁰. In this context the *CPT* operator may be “ill-defined” and *CPT* violation effects might also induce a breakdown of the correlation in the initial state^{31,32} which can be parametrized in general as: $|i\rangle \propto |K_S(+\vec{p})\rangle|K_L(-\vec{p})\rangle - |K_L(+\vec{p})\rangle|K_S(-\vec{p})\rangle + \omega (|K_S(+\vec{p})\rangle|K_S(-\vec{p})\rangle - |K_L(+\vec{p})\rangle|K_L(-\vec{p})\rangle)$ where ω is a complex parameter describing *CPT* violation. Its order of magnitude might be at most $|\omega| \sim \sqrt{(M_K^2/M_{\text{Planck}})/\Delta\Gamma} \sim 10^{-3}$, with $\Delta\Gamma = \Gamma_S - \Gamma_L$. KLOE has improved its limit on the ω parameter using about $1fb^{-1}$. The preliminary results, obtained by fitting the $I(\Delta t; \pi^+ \pi^- \pi^+ \pi^-)$ distribution, are $\text{Re}\omega = (-2.5_{-2.3}^{+3.1}) \times 10^{-4}$ and $\text{Im}\omega = (-2.2_{-3.1}^{+3.4}) \times 10^{-4}$, consistent with quantum coherence and *CPT* symmetry. The accuracy reaches the interesting region of the Planck’s scale.

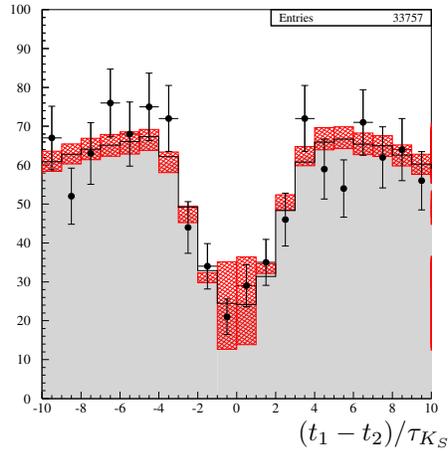


Figure 5: Fit of the difference $t_1 - t_2$ of the decay times of $K_S \rightarrow \pi^+ \pi^-$ and $K_L \rightarrow \pi^+ \pi^-$, where t_1 is the time of the kaon having $\cos\theta > 0$, in the range $0 < t_{\text{sid}} < 4h$. The black points are the experimental data, the histogram is the fit results and the hatched area is the uncertainty arising from the efficiency, the resolution and the background evaluation

Another possibility for *CPT* violation is based on spontaneous breaking of Lorentz symmetry in the context of the Standard Model Extension (SME)^{33,34}. In the SME *CPT* violation manifests to lowest order only in the δ parameter, describing *CPT* violation in the time evolution, which exhibits a dependence on the kaon 4-momentum:

$$\delta(p, \theta, t_{\text{sid}}) = \frac{1}{2\pi} \int_0^{2\pi} \delta(\vec{p}, t_{\text{sid}}) d\phi = \frac{i \sin\phi_{SW} e^{i\phi_{SW}} \gamma}{\Delta m} \quad (7)$$

$$(\Delta a_0 + \beta \Delta a_Z \cos\chi \cos\theta + \beta \Delta a_Y \sin\chi \cos\theta \sin\Omega t_{\text{sid}} + \beta \Delta a_X \sin\chi \cos\theta \cos\Omega t_{\text{sid}})$$

after integration on ϕ , where θ and ϕ are the conventional polar and azimuthal angles defined in the laboratory frame around the z axis. Δa_μ are four *CPT* and Lorentz symmetry violating coefficients for the two valence quarks, β is the kaon velocity, $\gamma = 1/\sqrt{1-\beta^2}$, ϕ_{SW} is the superweak angle, χ is the angle between the z laboratory axis and the Earth’s rotation axis and Ω is Earth’s sidereal frequency. The sidereal time (t_{sid}) dependence arises from the rotation

of the Earth. KLOE has measured the $\Delta a_{X,Y,Z}$ parameters by using the channel $K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ and performing an analysis on the polar angle θ and the sidereal time t_{sid} . Fitting the distribution of the decay times difference $I(t_1 - t_2; \pi^+ \pi^- (\cos \theta_1 > 0) \pi^+ \pi^- (\cos \theta_2 < 0); t_{sid})$ we obtain the preliminary results based on $1fb^{-1}$: $\Delta a_X = (-6.3 \pm 6.0) \times 10^{-18}$ GeV, $\Delta a_Y = (-2.8 \pm 5.9) \times 10^{-18}$ GeV and $\Delta a_Z = (-2.4 \pm 9.7) \times 10^{-18}$ GeV. The result of the fit is shown in fig. 5. A limit on the Δa_0 parameter has been obtained through the difference on the K_S and K_L semileptonic charge asymmetry integrated on t_{sid} and on a symmetrical polar angle region. Our preliminary result is $\Delta a_0 = (0.4 \pm 1.8) \times 10^{-17}$ GeV

References

1. M. Adinolfi *et al.* (KLOE Collaboration), *Nucl. Instrum. Methods* **A488** (2002) 51
2. M. Adinolfi *et al.* (KLOE Collaboration), *Nucl. Instrum. Methods* **A482** (2002) 364
3. A. Sirlin *Nucl. Phys.* **B196** (1982) 83.
4. V. Cirigliano *et al.*, *Eur Phys. J* **23** (2002) 121.
5. F. Ambrosino *et al.* (KLOE Collaboration), *J. High Energy Phys.* **04** (2008) 059
6. P. Franzini, Opening remarks, PoS(KAON)002 (2007).
7. C.G. Callan, S.B. Treiman, *Phys. Rev. Lett.* **16** (1966) 153.
8. J. Gasser, H. Leutwyler, *Nucl. Phys.* **B250** (1985) 465.
9. V. Bernard, M. Oertel, E. Passemar and J. Stern, *Phys. Lett.* **B638** (2006) 480.
10. V. Bernard, M. Oertel, E. Passmar and J. Stern, private communication. They compute a dispersion relation for $\ln f_+$ twice subtracted at $t = 0$, using $K\pi$ p -wave scattering data, as done in Ref.9.
11. F. Ambrosino, *et al.* (KLOE Collaboration), *J. High Energy Phys.* **12** (2007) 105
12. F. Ambrosino, *et al.* (KLOE Collaboration), *J. High Energy Phys.* **01** (2008) 073.
13. F. Ambrosino *et al.* (KLOE Collaboration), *J. High Energy Phys.* **02** (2008) 098
14. W.-M. Yao. *et al.* (Particle Data Group), *J. Phys.* **G33** (2006) 1 and 2007 web updates.
15. F. Ambrosino, *et al.* (KLOE Collaboration), [arXiv:0804.4577](https://arxiv.org/abs/0804.4577)
16. V. Cirigliano *et al.* *Eur Phys. J* **23** (2002) 121
17. S. Descotes-Genon and B. Moussallam, *Eur Phys. J* **C42** (2005) 403
18. M.J. Ramsey-Musolf, S. Su and S. Turlin, *Phys. Rev.* **C76** (2007) 095017.
19. M. Davier, A. Höcker and Z. Zhang, *Rev. Mod. Phys* **78** (2006) 1043.
20. I.S. Towner and J.C. Hardy, [arXiv:0710.3181](https://arxiv.org/abs/0710.3181).
21. E. Follana *et al.*, (HPQCD/UKQCD Collaboration), [arXiv:0706.1726](https://arxiv.org/abs/0706.1726)
22. P.A. Boyle *et al.*, (RBC/UKQCD Collaboration), [arXiv:0710.5136](https://arxiv.org/abs/0710.5136)
23. G. Isidori and P. Paradisi, *Phys. Lett.* **B639** (2006) 499
24. G. Isidori and A. Retico, *J. High Energy Phys.* **11** (2001) 001
25. A. Masiero, P. Paradisi, R. Petronzio, *Phys. Rev.* **D74** (2006) 011701
26. P. H. Eberhard, “Tests of Quantum Mechanics at a ϕ factory” in *The second DaΦne handbook*, ed. L. Maiani, G. Pancheri, N. Paver, Vol.I
27. R. A. Bertlmann *et al.*, *Phys. Rev.* **D60** (1999) 114032
28. W. H. Furry, *Phys. Rev.* **D49** (1936) 393
29. S. Hawking, *Commun. Math. Phys.* **87** (1982) 395
30. R. Wald, *Phys. Rev.* **D21** (1980) 2742
31. J. Bernabeu, N. Mavromatos, J. Papavassiliou, *Phys. Rev. Lett.* **92** (2004) 131601
32. J. Bernabeu, N. Mavromatos, J. Papavassiliou, A. Waldron-Lauda, *Nucl. Phys.* **B744** (2006) 180
33. V. A. Kostelecky, *Phys. Rev.* **61** (1999) 016002
34. V. A. Kostelecky, *Phys. Rev.* **64** (2001) 076001