CPT and QM tests using kaon interferometry

A. Di Domenico
Dipartimento di Fisica, Università di Roma "La Sapienza",
and I.N.F.N. Sezione di Roma,
P.le A. Moro, 2, I-00185 Rome, Italy
e-mail: antonio.didomenico@roma1.infn.it

The neutral kaon system offers a unique possibility to perform fundamental tests of CPT invariance, as well as of the basic principles of quantum mechanics. The most recent and significant limits on CPT violation are reviewed, including the ones related to possible decoherence mechanisms or Lorentz symmetry breaking, which might be induced by quantum gravity. The experimental results show no deviations from the expectations of quantum mechanics and CPT symmetry, while the accuracy in some cases reaches the interesting Planck's scale region. Finally, perspectives on this kind of experimental studies at the upgraded DAΦNE e^+e^- collider at Frascati are briefly discussed.

I. INTRODUCTION

The three discrete symmetries of quantum mechanics, C (charge conjugation), P (parity), and T (time reversal) are known to be violated in nature, both singly and in pairs. Only the combination of the three - CPT (in any order) - appears to be an exact symmetry of nature.

A rigorous proof of the CPT theorem can be found in Refs. [1–4] (see also Refs. [5–7] for some recent developments); it ensures that exact CPT invariance holds for any quantum field theory assuming (1) Lorentz invariance, (2) Locality, and (3) Unitarity (i.e. conservation of probability). Testing the validity of CPT invariance therefore probes the most fundamental assumptions of our present understanding of particles and their interactions.

The neutral kaon doublet is one of the most intriguing systems in nature. During its time evolution a neutral kaon oscillates between its particle and antiparticle states with a beat frequency $\Delta m \approx 5.3 \times 10^9$ s^{-1} , where Δm is the small mass difference between the exponentially decaying states $\mathrm{K_L}$ and $\mathrm{K_S}$. The fortunate coincidence that Δm is about half the decay width of $\mathrm{K_S}$ makes possible to observe a variety of intricate interference phenomena in the production and decay of neutral kaons. In turn, such observations enable us to test quantum mechanics, the interplay of different conservation laws and the validity of various symmetry principles. In particular the extreme sensitivity of the neutral kaon system to a variety of CPT-violating effects makes it one of the best candidates for an accurate experimental test of this symmetry [9]. As a figure of merit, the fractional mass difference $\left(m_{\mathrm{K}^0} - m_{\bar{\mathrm{K}}^0}\right)/m_{\mathrm{K}^0}$ can be considered: it can be measured at the level of $\mathcal{O}(10^{-18})$ for neutral kaons, while, for comparison, a limit of $\mathcal{O}(10^{-14})$ can be reached on the corresponding quantity for the $\mathrm{B}^0 - \bar{\mathrm{B}}^0$ system, and only of $\mathcal{O}(10^{-8})$ for proton-antiproton [8].

II. CPT TEST FROM UNITARITY

One of the most precise and significant test of the CPT symmetry comes from the unitarity relation, originally derived by Bell and Steinberger [10]:

$$\left(\frac{\Gamma_S + \Gamma_L}{\Gamma_S - \Gamma_L} + i \tan\phi_{SW}\right)\left[\frac{\Re\epsilon}{1+|\epsilon|^2} - i\Im\delta\right] = \frac{1}{\Gamma_S - \Gamma_L}\sum_f A^*(K_S \to f)A(K_L \to f) \equiv \sum_f \alpha_f \ , \quad (1)$$

where ϵ and δ are the usual complex parameters describing CP and CPT violation in the $\mathrm{K}^0-\bar{\mathrm{K}}^0$ mixing, respectively; Γ_S and Γ_L are the widths of the physical states $\mathrm{K_S}$ and $\mathrm{K_L}$; ϕ_{SW} is the superweak phase; $A(K_i \to f)$ is the decay amplitude of the state K_i into final state f, and the sum runs over all possible final states. The above relationship can be used to bound the parameter $\Im\delta$, after having provided all the α_i parameters, Γ_S, Γ_L, and ϕ_{SW} as inputs. Using several measurements from the KLOE experiment [11], values from Particle Data Group (PDG), and a combined fit of KLOE and CPLEAR data, the following result is obtained [8]:

$$\Re\epsilon = (161.2 \pm 0.6) \times 10^{-5}$$
$$\Im\delta = (-0.6 \pm 1.9) \times 10^{-5} \ , \quad (2)$$

which is the best limit on $\Im\delta$, the main limiting factor of this result being the uncertainty on the phase ϕ_{+-} entering in the parameter $\alpha_{\pi^+\pi^-}$.

The limits on $\Im(\delta)$ and $\Re(\delta)$ [12] can be used to constrain the mass and width difference between K^0 and $\bar{\mathrm{K}}^0$. In the limit $\Gamma_{\mathrm{K}^0} = \Gamma_{\bar{\mathrm{K}}^0} = 0$, i.e. neglecting CPT-violating effects in the decay amplitudes, the best bound on the neutral kaon mass difference is obtained:

$$|m_{\mathrm{K}^0} - m_{\bar{\mathrm{K}}^0}| < 5.1 \times 10^{-19}\ \mathrm{GeV} \quad \text{at } 95\ \%\ \mathrm{CL}\ .$$

A preliminary update including the latest results on ϕ_{+-} by the KTeV collaboration [13] yields slightly improved results [14]:

$$\Re\epsilon = (161.2 \pm 0.6) \times 10^{-5}$$
$$\Im\delta = (-0.1 \pm 1.4) \times 10^{-5}$$
$$|m_{\mathrm{K}^0} - m_{\bar{\mathrm{K}}^0}| < 4.0 \times 10^{-19}\ \mathrm{GeV} \quad \text{at 95 \% CL} .$$

III. CPT AND QM TESTS

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 production cross section is $\sim 3\mu$b, and its decay into $K^0\bar{K}^0$ has a branching fraction of 34%. The neutral kaon pair is produced in a coherent quantum state with quantum numbers $J^{PC} = 1^{--}$:

$$|i\rangle = \frac{1}{\sqrt{2}}\{|K^0\rangle|\bar{K}^0\rangle - |\bar{K}^0\rangle|K^0\rangle\}$$
$$= \frac{N}{\sqrt{2}}\{|K_S\rangle|K_L\rangle - |K_L\rangle|K_S\rangle\} \qquad (3)$$

where $N = \sqrt{(1+|\epsilon_S|^2)(1+|\epsilon_L|^2)}/(1-\epsilon_S\epsilon_L) \simeq 1$ is a normalization factor, and $\epsilon_{S,L} = \epsilon \pm \delta$.

The detection of a kaon at large (small) times *tags* a K_S (K_L) in the opposite direction.

The KLOE detector consists mainly of a large volume drift chamber[15] surrounded by an electromagnetic calorimeter[16]. A superconducting coil provides a 0.52 T solenoidal magnetic field.
At KLOE a K_S is tagged by identifying the interaction of the K_L in the calorimeter (K_L-crash), while a K_L is tagged by detecting a $K_S \to \pi^+\pi^-$ decay near the interaction point (IP).

KLOE completed the data taking in March 2006 with a total integrated luminosity L ~ 2.5 fb^{-1}, corresponding to $\sim 7.5 \times 10^{-9}$ ϕ-mesons produced.

The quantum interference between the two kaons initially in the *entangled* state in eq.(3) and decaying in the CP violating channel $\phi \to \mathrm{K_S K_L} \to \pi^+\pi^-\pi^+\pi^-$, has been observed for the first time by the KLOE collaboration [17]. The measured Δt distribution, with Δt the absolute value of the time difference of the two $\pi^+\pi^-$ decays, can be fitted with the distribution:

$$I(\pi^+\pi^-, \pi^+\pi^-; \Delta t) \propto e^{-\Gamma_L \Delta t} + e^{-\Gamma_S \Delta t}$$
$$-2(1-\zeta_{SL}) e^{-\frac{(\Gamma_S+\Gamma_L)}{2}\Delta t} \cos(\Delta m \Delta t) \ , \qquad (4)$$

where the quantum mechanical expression 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 $\{\mathrm{K}^0, \bar{\mathrm{K}}^0\}$ basis [18]. After having included resolution and detection efficiency effects, having taken into account the background due to coherent and incoherent $\mathrm{K_S}$-regeneration on the beam pipe wall, the small contamination of non-resonant $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ events, and keeping fixed in the fit Δm, Γ_S and Γ_L to the PDG values, the fit is performed on the Δt distribution. The analysis of a data sample corresponding to L ~ 380 pb^{-1} yields the following results [17]:

$$\zeta_{SL} = 0.018 \pm 0.040_{\mathrm{stat}} \pm 0.007_{\mathrm{syst}}$$
$$\zeta_{0\bar{0}} = (1.0 \pm 2.1_{\mathrm{stat}} \pm 0.4_{\mathrm{syst}}) \times 10^{-6} \ , \qquad (5)$$

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 accuracy, $\mathcal{O}(10^{-6})$, due to the CP suppression present in the specific decay channel; it improves of five orders of magnitude the previous limit obtained by Bertlmann and co-workers [18] in a re-analysis of CPLEAR data [19]. This result can also be compared to a similar one recently obtained in the B meson system [20], where an accuracy of $\mathcal{O}(10^{-2})$ has been reached.

At a microscopic level, in a quantum gravity picture, space-time might be subjected to inherent non-trivial quantum metric and topology fluctuations at the Planck scale ($\sim 10^{-33}$ cm), called generically *space-time foam*, with associated microscopic event horizons. This space-time structure, might induce a pure state to evolve into a mixed one, i.e. decoherence of apparently isolated matter systems [21]. This decoherence, in turn, necessarily implies, by means of a theorem [22], CPT violation, in the sense that the quantum mechanical operator generating CPT transformations cannot be consistently defined.

A model for decoherence can be formulated [23] in which a single kaon is described by a density matrix ρ that obeys a modified Liouville-von Neunmann equation:

$$\frac{d\rho}{dt} = -i\mathbf{H}\rho + i\rho\mathbf{H}^\dagger + L(\rho; \alpha, \beta, \gamma) \qquad (6)$$

where $\mathbf{H}$ is the neutral kaon effective Hamiltonian, and the extra term $L(\rho;\alpha,\beta,\gamma)$ would induce decoherence in the system, and depends on three real parameters, α, β and γ, which violate CPT symmetry and quantum mechanics (they satisfy the inequalities $\alpha,\ \gamma > 0$ and $\alpha\gamma > \beta^2$ - see Refs. [23, 24]). They have mass dimension and are guessed to be at most of $\mathcal{O}(m_K^2/M_{Planck}) \sim 2 \times 10^{-20}$ GeV, where $M_{Planck} = 1\sqrt{G_N} = 1.22 \times 10^{19}$ GeV is the Planck mass.

The CPLEAR collaboration, studying the time behaviour of single neutral kaon decays to $\pi^+\pi^-$ and $\pi e \nu$ final states, obtained the following results [25]:

$$\alpha = (-0.5 \pm 2.8) \times 10^{-17}\ \mathrm{GeV}$$
$$\beta = (2.5 \pm 2.3) \times 10^{-19}\ \mathrm{GeV}$$
$$\gamma = (1.1 \pm 2.5) \times 10^{-21}\ \mathrm{GeV} \ . \qquad (7)$$

The KLOE collaboration, studying the same $I(\pi^+\pi^-,\pi^+\pi^-;\Delta t)$ distribution as in the ζ parameters analysis, in the simplifying hypothesis of complete positivity[38] [26], i.e. $\alpha=\gamma$ and $\beta=0$, obtained the following result [17]:

$$\gamma = \left(1.3^{+2.8}_{-2.4}{}_{\rm stat} \pm 0.4_{\rm syst}\right) \times 10^{-21}\,\mathrm{GeV}\ , \quad (8)$$

All results are compatible with no CPT violation, while the sensitivity approaches the interesting level of $\mathcal{O}(10^{-20}\,\mathrm{GeV})$.

As discussed above, in a quantum gravity framework inducing decoherence, the CPT operator is *ill-defined*. This consideration might have intriguing consequences in correlated neutral kaon states, where the resulting loss of particle-antiparticle identity could induce a breakdown of the correlation of state (3) imposed by Bose statistics [27, 28]. As a result the initial state (3) can be parametrized in general as:

$$\begin{aligned}|i\rangle &= \frac{1}{\sqrt{2}}[|K^0\rangle|\bar{K}^0\rangle - |\bar{K}^0\rangle|K^0\rangle \\ &\quad +\omega\left(|K^0\rangle|\bar{K}^0\rangle + |\bar{K}^0\rangle|K^0\rangle\right)]\ , \quad (9)\end{aligned}$$

where ω is a complex parameter describing a completely novel CPT violation phenomenon, not included in previous analyses. Its order of magnitude could be at most

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

with $\Delta\Gamma=\Gamma_S-\Gamma_L$. A similar analysis performed by the KLOE collaboration on the same $I(\pi^+\pi^-,\pi^+\pi^-;\Delta t)$ distribution as before, including in the fit the modified initial state eq.(9), yields the first measurement of the complex parameter ω [17]:

$$\begin{aligned}\Re(\omega) &= \left(1.1^{+8.7}_{-5.3}{}_{\rm stat} \pm 0.9_{\rm syst}\right) \times 10^{-4} \\ \Im(\omega) &= \left(3.4^{+4.8}_{-5.0}{}_{\rm stat} \pm 0.6_{\rm syst}\right) \times 10^{-4}\ , \quad (10)\end{aligned}$$

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

A preliminary analysis of a KLOE data sample corresponding to L ~ 1 fb^{-1} yields the following updated results [33]:

$$\begin{aligned}\zeta_{SL} &= 0.009 \pm 0.022_{\rm stat} \\ \zeta_{0\bar{0}} &= (0.03 \pm 1.2_{\rm stat}) \times 10^{-6} \\ \gamma &= \left(0.8^{+1.5}_{-1.3}{}_{\rm stat}\right) \times 10^{-21}\,\mathrm{GeV} \\ \Re(\omega) &= \left(-2.5^{+3.1}_{-2.3}{}_{\rm stat}\right) \times 10^{-4} \\ \Im(\omega) &= \left(-2.2^{+3.4}_{-3.1}{}_{\rm stat}\right) \times 10^{-4}\ ,\end{aligned}$$

while the analysis of the full KLOE data sample is being completed.

IV. CPT VIOLATION AND LORENTZ SYMMETRY BREAKING

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 [29–31], 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 parameter δ, and exhibits a dependence on the 4-momentum of the kaon:

$$\delta \approx i\sin\phi_{SW} e^{i\phi_{SW}} \gamma_K(\Delta a_0 - \vec{\beta_K}\cdot\Delta\vec{a})/\Delta m \quad (11)$$

where γ_K and $\vec{\beta_K}$ are the kaon boost factor and velocity in the observer frame, and Δa_μ are four CPT- and Lorentz-violating coefficients for the two valence quarks in the kaon.

Following Ref. [30], the time dependence arising from the rotation of the Earth can be explicitly displayed in eq. (11) 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. The CPT violating parameter δ may then be expressed as:

$$\begin{aligned}\delta &= \frac{1}{2\pi}\int_0^{2\pi}\delta(\vec{p},t_{sid})d\phi \\ &= \frac{i\sin\phi_{SW}e^{i\phi_{SW}}}{\Delta m}\gamma_K\{\Delta a_0 \\ &\quad +\beta_K\Delta a_Z\cos\theta\cos\chi \\ &\quad +\beta_K(\Delta a_Y\sin\chi\cos\theta\sin\Omega t_{sid} \\ &\quad +\Delta a_X\sin\chi\cos\theta\cos\Omega t_{sid})\}\ , \quad (12)\end{aligned}$$

where 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 defined in the laboratory frame about the $\hat{z}$ axis, and an integration on the azimuthal angle ϕ has been performed, assuming a symmetric decay distribution in this variable[39]. The sensitivity to the four Δa_μ parameters can be very different for fixed target and collider experiments, showing complementary features [30].

At KLOE the Δa_0 parameter can be evaluated through the difference of the semileptonic charge asymmetries:

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

by performing the measurement of each asymmetry with a symmetric integration over the polar angle θ, thus averaging to zero any possible contribution from the terms proportional to $\cos\theta$ in eq.(12):

$$A_S - A_L \simeq \left[\frac{4\Re\left(i\sin\phi_{SW}e^{i\phi_{SW}}\right)\gamma_K}{\Delta m}\right]\Delta a_0\ . \quad (13)$$

In this way a first preliminary evaluation of the Δa_0 parameter can be obtained by KLOE [9, 32]:

$$\Delta a_0 = (0.4 \pm 1.8) \times 10^{-17} \text{ GeV} . \qquad (14)$$

With the analysis of the full KLOE data sample ($L = 2.5$ fb^{-1}) an accuracy $\sigma(\Delta a_0) \sim 7 \times 10^{-18}$ GeV could be reached.

At KLOE the $\Delta a_{X,Y,Z}$ parameters can be evaluated performing a sidereal time dependent analysis of the asymmetry:

$$A(\Delta t) = \frac{N^+ - N^-}{N^+ + N^-} ,$$

with

$$N^+ = I\left(\pi^+\pi^-(+), \pi^+\pi^-(-); \Delta t > 0\right)$$
$$N^- = I\left(\pi^+\pi^-(+), \pi^+\pi^-(-); \Delta t < 0\right) ,$$

where the two identical final states are distinguished by their emission in the forward ($\cos\theta > 0$) or backward ($\cos\theta < 0$) hemispheres (denoted by the symbols $+$ and $-$, respectively), and Δt is the time difference between $(+)$ and $(-)$ $\pi^+\pi^-$ decays. A preliminary analysis based on a data sample corresponding to a L $\sim$ 1fb^{-1} yields the following results [9, 32, 33]:

$$\Delta a_X = (-6.3 \pm 6.0) \times 10^{-18} \text{ GeV}$$
$$\Delta a_Y = (2.8 \pm 5.9) \times 10^{-18} \text{ GeV}$$
$$\Delta a_Z = (2.4 \pm 9.7) \times 10^{-18} \text{ GeV} . \qquad (15)$$

A preliminary measurement performed by the KTeV collaboration [34] based on the search of sidereal time variation of the phase ϕ_{+-} constrains Δa_X and Δa_Y to less than 9.2×10^{-22} GeV at 90% C.L. These results can also be compared to similar ones recently obtained in the B meson system [35], where an accuracy on the Δa_μ^B parameters of $\mathcal{O}(10^{-13}\text{GeV})$ has been reached.

V. FUTURE PLANS

A proposal [36, 37] has been presented for a physics program to be carried out with an upgraded KLOE detector, KLOE-2, at an upgraded DAΦNE machine, which is expected to deliver an integrated luminosity up to $20 \div 50$ fb^{-1}. The major upgrade of the KLOE detector would consist in the addition of an inner tracker for the improvement of decay vertex resolution, therefore improving the sensitivity on several parameters based on kaon interferometry measurements. The KLOE-2 program concerning neutral kaon interferometry is summarized in table I, where the KLOE-2 statistical sensitivities on the main parameters that can be extracted from kaon decay time distributions $I(f_1, f_2; \Delta t)$ (with different choices of final states f_1 and f_2) are listed in the hypothesis of an integrated luminosity $L = 50$ fb^{-1}, and compared to the best presently published measurements.

VI. CONCLUSIONS

The neutral kaon system constitutes an excellent laboratory for the study of the CPT symmetry and the basic principles of quantum mechanics. Several parameters related to possible CPT violations, including decoherence and Lorentz symmetry breaking effects, have been measured, in some cases with a precision reaching the interesting Planck's scale region. Simple quantum coherence tests have been also performed. All results are consistent with no violation of the CPT symmetry and/or quantum mechanics.

A ϕ-factory represents a unique opportunity to push forward these studies. It is also an ideal place to investigate the entanglement and correlation properties of the produced $K^0\bar{K}^0$ pairs. A proposal for continuing the KLOE physics program (KLOE-2) at an improved DAΦNE machine, able to deliver an integrated luminosity up to $20 \div 50$ fb^{-1}, has been recently presented. Improvements by about one order of magnitude in almost all present limits are expected.

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TABLE I: KLOE-2 statistical sensitivities on several parameters.

f_1	f_2	**Parameter**	**Best published meas.**	**KLOE-2 (50 fb^{-1})**
$K_S \to \pi e \nu$		A_S	$(1.5 \pm 11) \times 10^{-3}$	$\pm 1 \times 10^{-3}$
$\pi^+\pi^-$	$\pi l \nu$	A_L	$(3322 \pm 58 \pm 47) \times 10^{-6}$	$\pm 25 \times 10^{-6}$
$\pi^+\pi^-$	$\pi^0\pi^0$	$\Re\frac{\epsilon'}{\epsilon}$	$(1.65 \pm 0.26) \times 10^{-3}$ (PDG fit)	$\pm 0.2 \times 10^{-3}$
$\pi^+\pi^-$	$\pi^0\pi^0$	$\Im\frac{\epsilon'}{\epsilon}$	$(-1.2 \pm 2.3) \times 10^{-3}$ (PDG fit)	$\pm 3 \times 10^{-3}$
$\pi^+ l^- \bar{\nu}$	$\pi^- l^+ \nu$	$(\Re\delta + \Re x_-)$	$\Re\delta = (0.25 \pm 0.23) \times 10^{-3}$ (PDG) $\Re x_- = (-4.2 \pm 1.7) \times 10^{-3}$ (PDG)	$\pm 0.2 \times 10^{-3}$
$\pi^+ l^- \bar{\nu}$	$\pi^- l^+ \nu$	$(\Im\delta + \Im x_+)$	$\Im\delta = (-0.6 \pm 1.9) \times 10^{-5}$ (PDG) $\Im x_+ = (0.2 \pm 2.2) \times 10^{-3}$ (PDG)	$\pm 3 \times 10^{-3}$
$\pi^+\pi^-$	$\pi^+\pi^-$	Δm	$5.288 \pm 0.043 \times 10^9 s^{-1}$	$\pm 0.03 \times 10^9 s^{-1}$
$\pi^+\pi^-$	$\pi^+\pi^-$	ζ_{SL}	$(1.8 \pm 4.1) \times 10^{-2}$	$\pm 0.2 \times 10^{-2}$
$\pi^+\pi^-$	$\pi^+\pi^-$	$\zeta_{0\bar{0}}$	$(1.0 \pm 2.1) \times 10^{-6}$	$\pm 0.1 \times 10^{-6}$
$\pi^+\pi^-$	$\pi^+\pi^-$	α	$(-0.5 \pm 2.8) \times 10^{-17}$ GeV	$\pm 2 \times 10^{-17}$ GeV
$\pi^+\pi^-$	$\pi^+\pi^-$	β	$(2.5 \pm 2.3) \times 10^{-19}$ GeV	$\pm 0.1 \times 10^{-19}$ GeV
$\pi^+\pi^-$	$\pi^+\pi^-$	γ	$(1.1 \pm 2.5) \times 10^{-21}$ GeV	$\pm 0.2 \times 10^{-21}$ GeV (compl. pos. hyp.) $\pm 0.1 \times 10^{-21}$ GeV
$\pi^+\pi^-$	$\pi^+\pi^-$	$\Re\omega$	$(1.1^{+8.7}_{-5.3} \pm 0.9) \times 10^{-4}$	$\pm 2 \times 10^{-5}$
$\pi^+\pi^-$	$\pi^+\pi^-$	$\Im\omega$	$(3.4^{+4.8}_{-5.0} \pm 0.6) \times 10^{-4}$	$\pm 2 \times 10^{-5}$
$K_{S,L} \to \pi e \nu$		Δa_0	(prelim.: $(0.4 \pm 1.8) \times 10^{-17}$ GeV)	$\pm 1 \times 10^{-18}$ GeV
$\pi^+\pi^-$	$\pi^+\pi^-$	Δa_Z	(prelim.: $(2.4 \pm 9.7) \times 10^{-18}$ GeV)	$\pm 1 \times 10^{-18}$ GeV
$\pi^+\pi^-$	$\pi^+\pi^-$	Δa_X, Δa_Y	(prelim.: $< 9.2 \times 10^{-22}$ GeV)	$\pm 8 \times 10^{-19}$ GeV

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