

Title: Experimental tests of CPT symmetry

Date: Oct 25, 2012 02:00 PM

URL: <http://pirsa.org/12100120>

Abstract: The three discrete symmetries of Quantum Mechanics, charge conjugation, parity, and time reversal, are all violated, singly or in pairs. CPT is the only combination of these symmetries which appears to be conserved in Nature. Even though this result is in agreement with the well known CPT theorem, that holds for standard quantum field theories, CPT violation in some cases might be expected and justified in the framework of a quantum theory of gravity. Here the last and more refined experimental searches for CPT violation effects will be reported with a special focus on the tests performed on neutral meson systems and the interplay between CPT symmetry and the basic principles of Quantum Mechanics. No deviation from the expectations of CPT symmetry and quantum mechanics is observed, while the precision of the measurements, in some cases, reaches the interesting Planck scale region. Finally, prospects for this kind of experimental studies will be presented.

CPT: introduction

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

CPT theorem (Luders, Jost, Pauli, Bell 1955 -1957):

Exact CPT invariance holds for any quantum field theory which assumes:

(1) Lorentz invariance (2) Locality (3) Unitarity (i.e. conservation of probability).

Testing the validity of the CPT symmetry probes the most fundamental assumptions of our present understanding of particles and their interactions.

Extension of CPT theorem to a theory of quantum gravity far from obvious (e.g. CPT violation appears in some models with space-time foam backgrounds).

No predictive theory incorporating CPT violation => only phenomenological models to be constrained by experiments.

CPT: introduction

Consequences of CPT symmetry: equality of masses, lifetimes, $|q|$ and $|\mu|$ of a particle and its anti-particle.

Neutral meson systems are the most intriguing systems in nature; they offer unique possibilities to test CPT invariance;

e.g. taking as figure of merit the fractional difference between the masses of a particle and its anti-particle:

neutral K system

$$\left| m_{K^0} - m_{\bar{K}^0} \right| / m_K < 10^{-18}$$

neutral B system

$$\left| m_{B^0} - m_{\bar{B}^0} \right| / m_B < 10^{-14}$$

proton- anti-proton

$$\left| m_p - m_{\bar{p}} \right| / m_p < 10^{-8}$$

CPT: introduction

Consequences of CPT symmetry: equality of masses, lifetimes, $|q|$ and $|\mu|$ of a particle and its anti-particle.

Neutral meson systems are the most intriguing systems in nature; they offer unique possibilities to test CPT invariance;

e.g. taking as figure of merit the fractional difference between the masses of a particle and its anti-particle:

$$\text{neutral K system} \quad |m_{K^0} - m_{\bar{K}^0}| / m_K < 10^{-18}$$
$$\text{neutral B system} \quad |m_{B^0} - m_{\bar{B}^0}| / m_B < 10^{-14}$$
$$\text{proton- anti-proton} \quad |m_p - m_{\bar{p}}| / m_p < 10^{-8}$$

CPT: introduction

Consequences of CPT symmetry: equality of masses, lifetimes, $|q|$ and $|\mu|$ of a particle and its anti-particle.

Neutral meson systems are the most intriguing systems in nature; they offer unique possibilities to test CPT invariance;

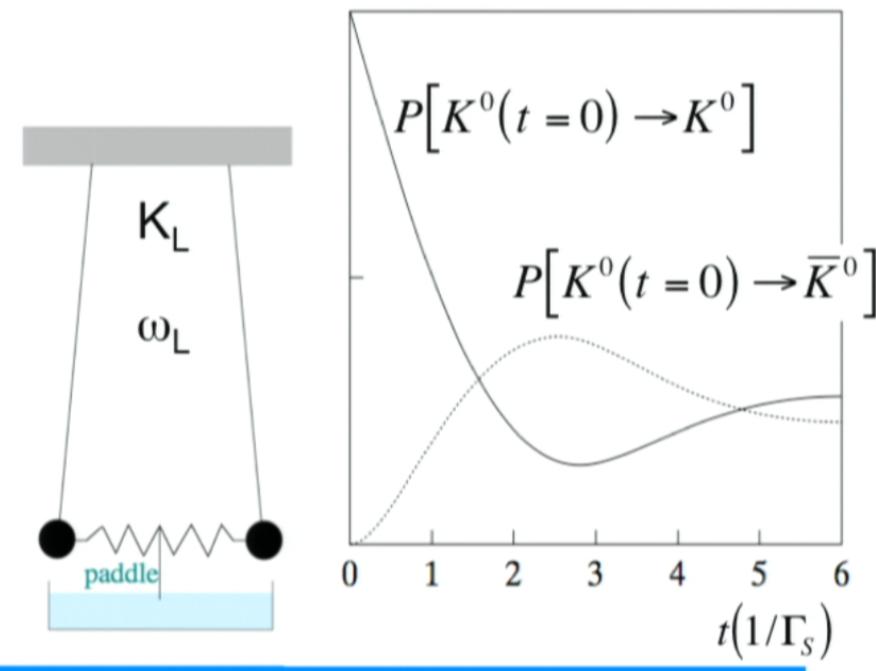
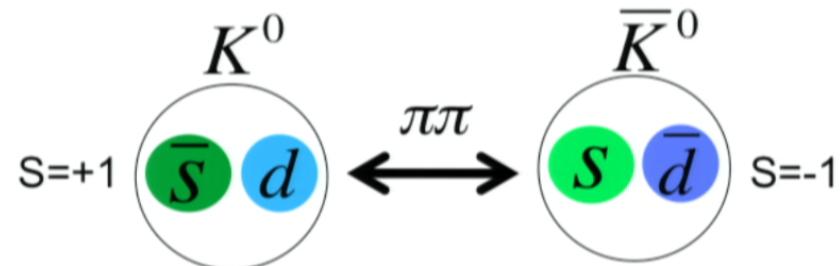
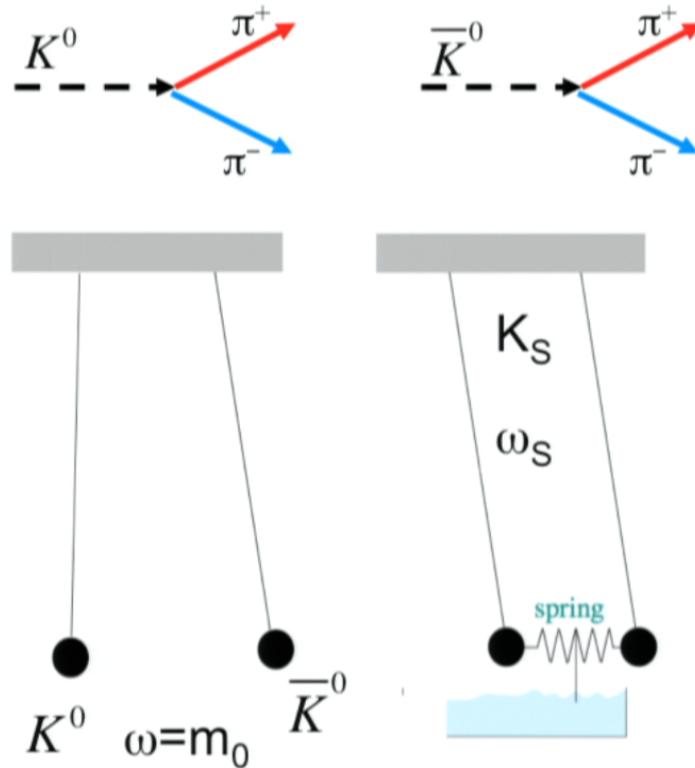
e.g. taking as figure of merit the fractional difference between the masses of a particle and its anti-particle:

neutral K system	$ m_{K^0} - m_{\bar{K}^0} / m_K < 10^{-18}$	K
neutral B system	$ m_{B^0} - m_{\bar{B}^0} / m_B < 10^{-14}$	B
proton- anti-proton	$ m_p - m_{\bar{p}} / m_p < 10^{-8}$	

The neutral kaon: a two-level quantum system

K

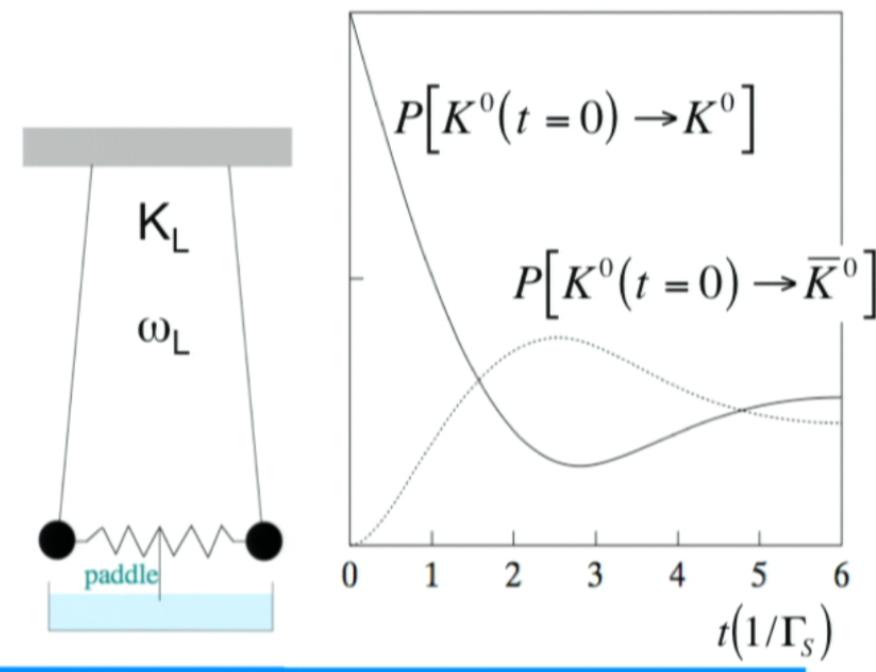
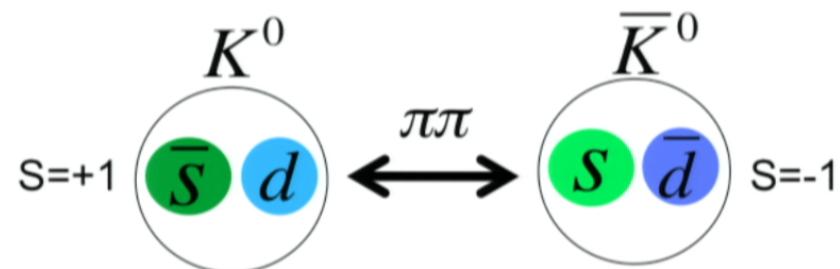
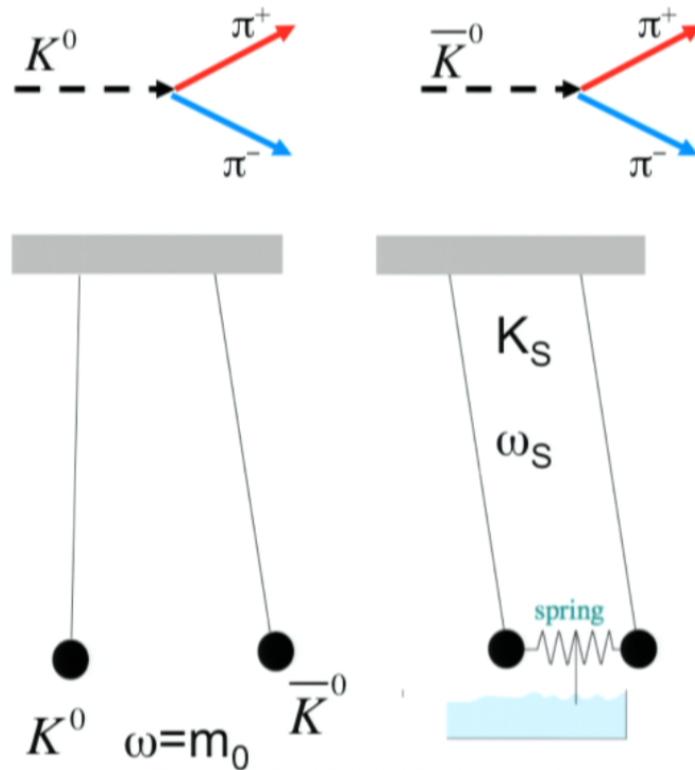
K^0 and \bar{K}^0 can decay to common final states due to weak interactions:
strangeness oscillations



The neutral kaon: a two-level quantum system

K

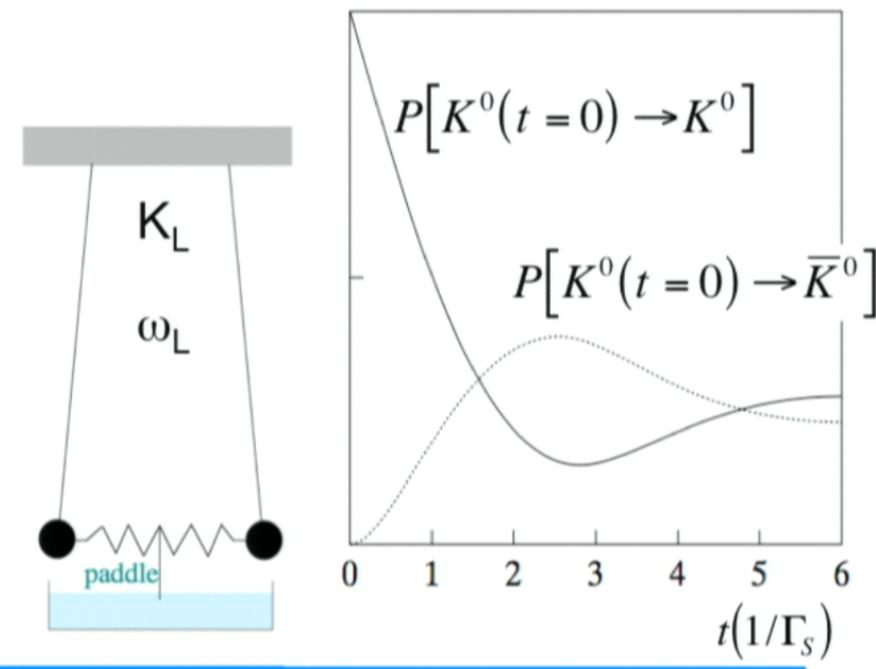
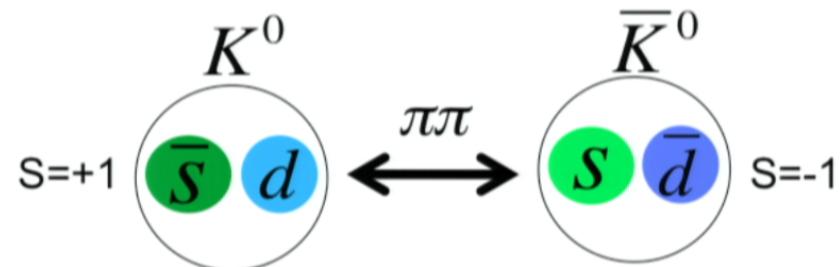
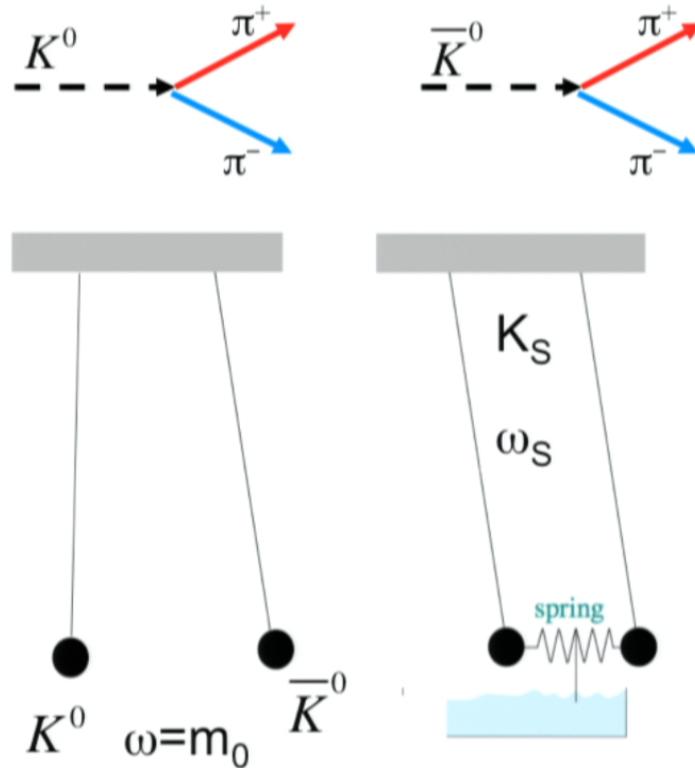
K^0 and \bar{K}^0 can decay to common final states due to weak interactions:
strangeness oscillations



The neutral kaon: a two-level quantum system

K

K^0 and \bar{K}^0 can decay to common final states due to weak interactions:
strangeness oscillations



K

The neutral kaon system: introduction

The time evolution of a two-component state vector Ψ in the $\{K^0, \bar{K}^0\}$ space is given by (Wigner-Weisskopf approximation):

$$i \frac{\partial}{\partial t} \Psi(t) = \mathbf{H} \Psi(t)$$

\mathbf{H} is the effective hamiltonian (non-hermitian), decomposed into a Hermitian part (mass matrix \mathbf{M}) and an anti-Hermitian part ($i/2$ decay matrix Γ) :

$$\mathbf{H} = \mathbf{M} - \frac{i}{2} \Gamma = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{pmatrix}$$

Diagonalizing the effective Hamiltonian:

eigenvalues	eigenstates
$\lambda_{S,L} = m_{S,L} - \frac{i}{2} \Gamma_{S,L}$ $ K_{S,L}(t)\rangle = e^{-i\lambda_{S,L}t} K_{S,L}(0)\rangle$ $\tau_S \sim 90 \text{ ps} \quad \tau_L \sim 51 \text{ ns}$ $\langle K_S K_L \rangle \cong \varepsilon_S^* + \varepsilon_L \neq 0$	$ K_{S,L}\rangle = \frac{1}{\sqrt{2(1+ \varepsilon_{S,L})}} \left[(1+\varepsilon_{S,L}) K^0\rangle \pm (1-\varepsilon_{S,L}) \bar{K}^0\rangle \right]$ $= \frac{1}{\sqrt{(1+ \varepsilon_{S,L})}} \left[K_{1,2}\rangle + \varepsilon_{S,L} K_{2,1}\rangle \right]$ $K_{1,2}\rangle$ are CP=±1 states small CP impurity ~2×10^{-3}

K

The neutral kaon system: introduction

The time evolution of a two-component state vector Ψ in the $\{K^0, \bar{K}^0\}$ space is given by (Wigner-Weisskopf approximation):

$$i \frac{\partial}{\partial t} \Psi(t) = \mathbf{H} \Psi(t)$$

\mathbf{H} is the effective hamiltonian (non-hermitian), decomposed into a Hermitian part (mass matrix \mathbf{M}) and an anti-Hermitian part ($i/2$ decay matrix Γ) :

$$\mathbf{H} = \mathbf{M} - \frac{i}{2} \Gamma = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{pmatrix}$$

Diagonalizing the effective Hamiltonian:

eigenvalues	eigenstates
$\lambda_{S,L} = m_{S,L} - \frac{i}{2} \Gamma_{S,L}$ $ K_{S,L}(t)\rangle = e^{-i\lambda_{S,L}t} K_{S,L}(0)\rangle$ $\tau_S \sim 90 \text{ ps} \quad \tau_L \sim 51 \text{ ns}$ $\langle K_S K_L \rangle \cong \varepsilon_S^* + \varepsilon_L \neq 0$	$ K_{S,L}\rangle = \frac{1}{\sqrt{2(1+ \varepsilon_{S,L})}} \left[(1+\varepsilon_{S,L}) K^0\rangle \pm (1-\varepsilon_{S,L}) \bar{K}^0\rangle \right]$ $= \frac{1}{\sqrt{(1+ \varepsilon_{S,L})}} \left[K_{1,2}\rangle + \varepsilon_{S,L} K_{2,1}\rangle \right]$ $K_{1,2}\rangle$ are CP=±1 states <small>small CP impurity ~2×10^{-3}</small>

K

The neutral kaon system: introduction

The time evolution of a two-component state vector Ψ in the $\{K^0, \bar{K}^0\}$ space is given by (Wigner-Weisskopf approximation):

$$i \frac{\partial}{\partial t} \Psi(t) = \mathbf{H} \Psi(t)$$

\mathbf{H} is the effective hamiltonian (non-hermitian), decomposed into a Hermitian part (mass matrix \mathbf{M}) and an anti-Hermitian part ($i/2$ decay matrix Γ) :

$$\mathbf{H} = \mathbf{M} - \frac{i}{2} \Gamma = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{pmatrix}$$

Diagonalizing the effective Hamiltonian:

eigenvalues	eigenstates
$\lambda_{S,L} = m_{S,L} - \frac{i}{2} \Gamma_{S,L}$ $ K_{S,L}(t)\rangle = e^{-i\lambda_{S,L}t} K_{S,L}(0)\rangle$ $\tau_S \sim 90 \text{ ps} \quad \tau_L \sim 51 \text{ ns}$ $\langle K_S K_L \rangle \cong \varepsilon_S^* + \varepsilon_L \neq 0$	$ K_{S,L}\rangle = \frac{1}{\sqrt{2(1+ \varepsilon_{S,L})}} [(1+\varepsilon_{S,L}) K^0\rangle \pm (1-\varepsilon_{S,L}) \bar{K}^0\rangle]$ $= \frac{1}{\sqrt{(1+ \varepsilon_{S,L})}} [K_{1,2}\rangle + \varepsilon_{S,L} K_{2,1}\rangle]$ $K_{1,2}\rangle$ are CP=±1 states <small>small CP impurity ~2×10^{-3}</small>

CPT violation: “standard” picture

CPT violation in the mixing:

$$\varepsilon_{S,L} = \varepsilon \pm \delta$$

$$\varepsilon = \frac{H_{12} - H_{21}}{2(\lambda_S - \lambda_L)} = \frac{-i\Im m_{12} - \Im \Gamma_{12}/2}{\Delta m + i\Delta\Gamma/2}$$

$$\delta = \frac{H_{11} - H_{22}}{2(\lambda_S - \lambda_L)} = \frac{1}{2} \frac{(m_{22} - m_{11}) - (i/2)(\Gamma_{22} - \Gamma_{11})}{\Delta m + i\Delta\Gamma/2}$$

$$m_{11} \equiv m_{K^0}, \quad m_{22} \equiv m_{\bar{K}^0}$$

$$\Gamma_{11} \equiv \Gamma_{K^0}, \quad \Gamma_{22} \equiv \Gamma_{\bar{K}^0}$$

$$\Delta m = m_L - m_S, \quad \Delta\Gamma = \Gamma_S - \Gamma_L$$

$$\Delta m = 3.5 \times 10^{-15} \text{ GeV}$$

$$\Delta\Gamma \approx \Gamma_S \approx 2\Delta m = 7 \times 10^{-15} \text{ GeV}$$

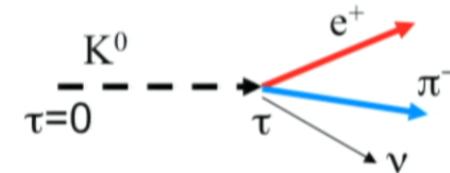
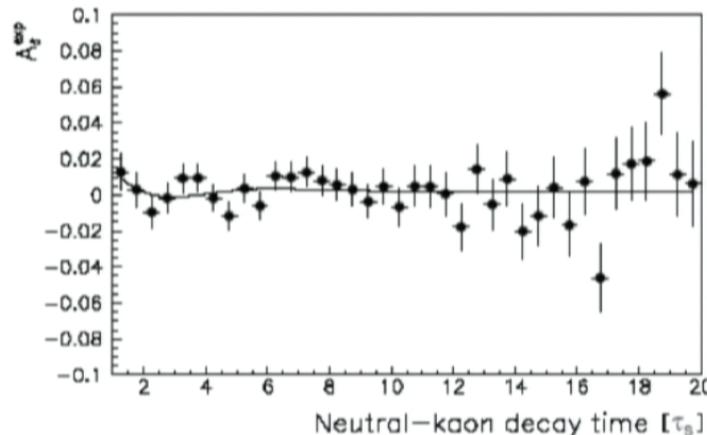
- $\delta \neq 0$ implies CPT violation
 - $\varepsilon \neq 0$ implies T violation
 - $\varepsilon \neq 0$ or $\delta \neq 0$ implies CP violation
- (with a phase convention $\Im \Gamma_{12} = 0$)

1) “Standard” tests of CPT symmetry

CPT test: “standard” picture – $\text{Re}(\delta)$

K

Test of **CPT** in the time evolution of neutral kaons using the semileptonic asymmetry (CPLEAR experiment - CERN)



$$\left\{ \begin{array}{l} A_\delta(\tau) = \frac{\bar{R}_+(\tau) - \alpha R_-(\tau)}{\bar{R}_+(\tau) + \alpha R_-(\tau)} + \frac{\bar{R}_-(\tau) - \alpha R_+(\tau)}{\bar{R}_-(\tau) + \alpha R_+(\tau)} \\ R_{+(-)}(\tau) = R \left(K^0_{t=0} \rightarrow (e^{+(-)} \pi^{-(+)} \nu)_{t=\tau} \right) \\ \bar{R}_{-(+)}(\tau) = R \left(\bar{K}^0_{t=0} \rightarrow (e^{-(+)} \pi^{+(-)} \nu)_{t=\tau} \right) \\ \alpha = 1 + 4 \Re \varepsilon_L \end{array} \right.$$

$$A_\delta(\tau \gg \tau_S) = 8 \Re \delta$$

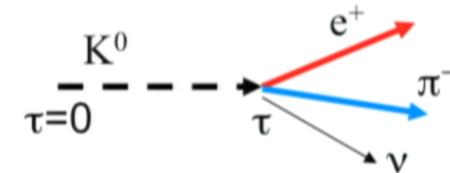
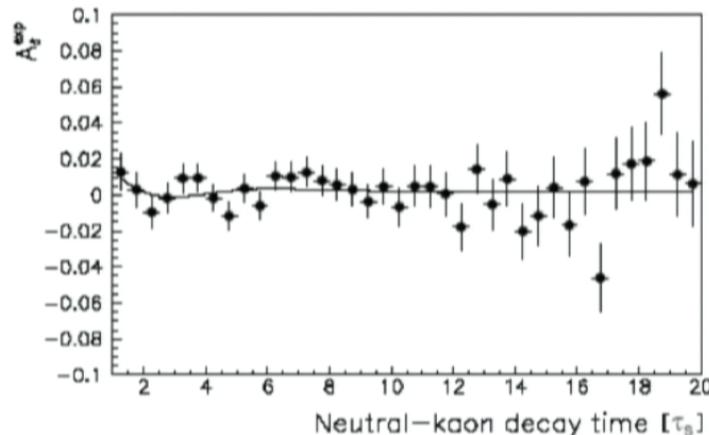
$$\Re \delta = (0.30 \pm 0.33 \pm 0.06) \times 10^{-3}$$

PLB444 (1998) 52

CPT test: “standard” picture – $\text{Re}(\delta)$

K

Test of **CPT** in the time evolution of neutral kaons using the semileptonic asymmetry (CPLEAR experiment - CERN)



$$\left\{ \begin{array}{l} A_\delta(\tau) = \frac{\bar{R}_+(\tau) - \alpha R_-(\tau)}{\bar{R}_+(\tau) + \alpha R_-(\tau)} + \frac{\bar{R}_-(\tau) - \alpha R_+(\tau)}{\bar{R}_-(\tau) + \alpha R_+(\tau)} \\ R_{+(-)}(\tau) = R \left(K^0_{t=0} \rightarrow (e^{+(-)} \pi^{-(+)} \nu)_{t=\tau} \right) \\ \bar{R}_{-(+)}(\tau) = R \left(\bar{K}^0_{t=0} \rightarrow (e^{-(+)} \pi^{+(-)} \nu)_{t=\tau} \right) \\ \alpha = 1 + 4 \Re \varepsilon_L \end{array} \right.$$

$$A_\delta(\tau \gg \tau_S) = 8 \Re \delta$$

$$\Re \delta = (0.30 \pm 0.33 \pm 0.06) \times 10^{-3}$$

PLB444 (1998) 52

CPT test: the Bell-Steinberger relation

K

Unitarity constraint:

$$|K\rangle = a_S |K_S\rangle + a_L |K_L\rangle$$

$$\left(-\frac{d}{dt} \|K(t)\|^2 \right)_{t=0} = \sum_f |a_S \langle f | T | K_S \rangle + a_L \langle f | T | K_L \rangle|^2$$

$$\left(\frac{\Gamma_S + \Gamma_L}{\Gamma_S - \Gamma_L} + i \tan \phi_{SW} \right) \left(\frac{\Re \varepsilon}{1 + |\varepsilon|^2} - i \Im \delta \right) = \frac{1}{\Gamma_S - \Gamma_L} \sum_f \langle f | T | K_S \rangle^* \langle f | T | K_L \rangle$$

CPT test: the Bell-Steinberger relation

K

Unitarity constraint:

$$|K\rangle = a_S |K_S\rangle + a_L |K_L\rangle$$

$$\left(-\frac{d}{dt} \|K(t)\|^2 \right)_{t=0} = \sum_f |a_S \langle f | T | K_S \rangle + a_L \langle f | T | K_L \rangle|^2$$

$$\left(\frac{\Gamma_S + \Gamma_L}{\Gamma_S - \Gamma_L} + i \tan \phi_{SW} \right) \left(\frac{\Re \varepsilon}{1 + |\varepsilon|^2} - i \Im \delta \right) = \frac{1}{\Gamma_S - \Gamma_L} \sum_f \langle f | T | K_S \rangle^* \langle f | T | K_L \rangle$$

All measurable quantities:
branching ratios of main kaon decays, $\eta_i = \langle f_i | T | K_L \rangle / \langle f_i | T | K_S \rangle$
 $\tau_S, \tau_L, \phi_{SW} = \arctan(2\Delta m / \Delta \Gamma)$
(from KLOE, CPLEAR, KTeV, NA48 experiments)

CPT test: the Bell-Steinberger relation

K

Unitarity constraint:

$$|K\rangle = a_S |K_S\rangle + a_L |K_L\rangle$$

$$\left(-\frac{d}{dt} \|K(t)\|^2 \right)_{t=0} = \sum_f |a_S \langle f | T | K_S \rangle + a_L \langle f | T | K_L \rangle|^2$$

$$\left(\frac{\Gamma_S + \Gamma_L}{\Gamma_S - \Gamma_L} + i \tan \phi_{SW} \right) \left(\frac{\Re \varepsilon}{1 + |\varepsilon|^2} - i \Im \delta \right) = \frac{1}{\Gamma_S - \Gamma_L} \sum_f \langle f | T | K_S \rangle^* \langle f | T | K_L \rangle$$

Recent KTeV result:

$$\text{Im } \delta = (-1.5 \pm 1.6) \times 10^{-5}$$

All measurable quantities:
branching ratios of main kaon
decays, $\eta_i = \langle f_i | T | K_L \rangle / \langle f_i | T | K_S \rangle$
 $\tau_S, \tau_L, \phi_{SW} = \arctan(2\Delta m / \Delta \Gamma)$
(from KLOE, CPLEAR, KTeV,
NA48 experiments)

PRD 83, 092001 (2011)

CPT test: the Bell-Steinberger relation

K

Unitarity constraint:

$$|K\rangle = a_S |K_S\rangle + a_L |K_L\rangle$$

$$\left(-\frac{d}{dt} \|K(t)\|^2 \right)_{t=0} = \sum_f |a_S \langle f | T | K_S \rangle + a_L \langle f | T | K_L \rangle|^2$$

$$\left(\frac{\Gamma_S + \Gamma_L}{\Gamma_S - \Gamma_L} + i \tan \phi_{SW} \right) \left(\frac{\Re \varepsilon}{1 + |\varepsilon|^2} - i \Im \delta \right) = \frac{1}{\Gamma_S - \Gamma_L} \sum_f \langle f | T | K_S \rangle^* \langle f | T | K_L \rangle$$

All measurable quantities:
 branching ratios of main kaon decays, $\eta_i = \langle f_i | T | K_L \rangle / \langle f_i | T | K_S \rangle$
 $\tau_S, \tau_L, \phi_{SW} = \arctan(2\Delta m / \Delta \Gamma)$
 (from KLOE, CPLEAR, KTeV, NA48 experiments)

Recent KTeV result:

$$\text{Im } \delta = (-1.5 \pm 1.6) \times 10^{-5}$$

PRD 83, 092001 (2011)

CPT test: the “standard” picture

K

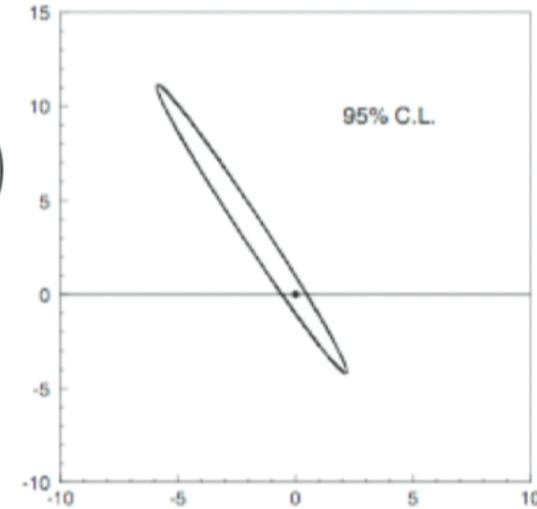
$$\delta = \frac{1}{2} \frac{(m_{\bar{K}^0} - m_{K^0}) - (i/2)(\Gamma_{\bar{K}^0} - \Gamma_{K^0})}{\Delta m + i\Delta\Gamma/2}$$

$$\begin{aligned} & (\Gamma_{K^0} - \Gamma_{\bar{K}^0}) \\ & (10^{-18} \text{ GeV}) \end{aligned}$$

Combining $\text{Re}\delta$ and $\text{Im}\delta$ results

$$\text{Re } \delta = (0.30 \pm 0.33) \times 10^{-3}$$

$$\text{Im } \delta = (-1.5 \pm 1.6) \times 10^{-5}$$



Assuming $(\Gamma_{\bar{K}^0} - \Gamma_{K^0}) = 0$, i.e. no CPT viol. in decay:

$$(m_{K^0} - m_{\bar{K}^0}) (10^{-18} \text{ GeV})$$

$$|m_{\bar{K}^0} - m_{K^0}| < 4.8 \times 10^{-19} \text{ GeV} \quad \text{at 95% c.l.}$$

CPT test: the “standard” picture

K

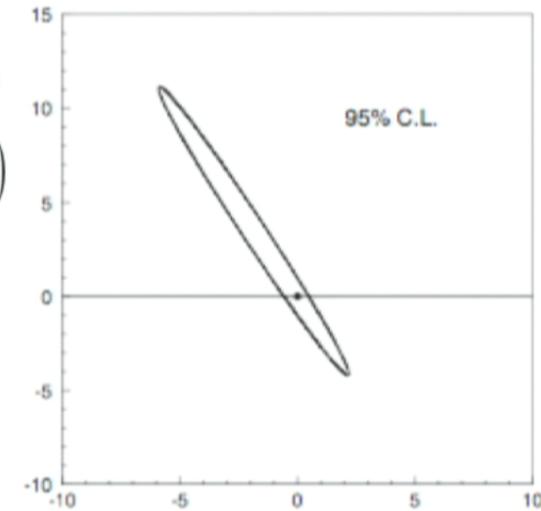
$$\delta = \frac{1}{2} \frac{(m_{\bar{K}^0} - m_{K^0}) - (i/2)(\Gamma_{\bar{K}^0} - \Gamma_{K^0})}{\Delta m + i\Delta\Gamma/2}$$

$$\begin{aligned} & (\Gamma_{K^0} - \Gamma_{\bar{K}^0}) \\ & (10^{-18} \text{ GeV}) \end{aligned}$$

Combining $\text{Re}\delta$ and $\text{Im}\delta$ results

$$\text{Re } \delta = (0.30 \pm 0.33) \times 10^{-3}$$

$$\text{Im } \delta = (-1.5 \pm 1.6) \times 10^{-5}$$



Assuming $(\Gamma_{\bar{K}^0} - \Gamma_{K^0}) = 0$, i.e. no CPT viol. in decay:

$$(m_{K^0} - m_{\bar{K}^0}) (10^{-18} \text{ GeV})$$

$$|m_{\bar{K}^0} - m_{K^0}| < 4.8 \times 10^{-19} \text{ GeV} \quad \text{at 95% c.l.}$$

CPT test: the “standard” picture

B

From the study of the time evolution of neutral B mesons with opposite flavor (and also other) decays

$$A_{CPT} = \frac{P(B^0 \rightarrow B^0) - P(\bar{B}^0 \rightarrow \bar{B}^0)}{P(B^0 \rightarrow B^0) + P(\bar{B}^0 \rightarrow \bar{B}^0)}$$

PDG av.

BABAR PRL 96, 251802 (2006)
BELLE PRD85, 071105(R) (2012)

$$\text{Re } z = (1.9 \pm 3.7 \pm 3.3) \times 10^{-2}$$

$$\text{Im } z = (-0.8 \pm 0.4) \times 10^{-2}$$

Assuming $(\Gamma_{B^0} - \Gamma_{\bar{B}^0}) = 0$, i.e. no CPT viol. in decay:

$$|m_{B^0} - m_{\bar{B}^0}| < \sim 5 \times 10^{-14} \text{ GeV} \quad \text{at 95% c.l.}$$

K

Neutral kaons at a ϕ -factory

Production of the vector meson ϕ in e^+e^- annihilations:

- $e^+e^- \rightarrow \phi \quad \sigma_\phi \sim 3 \text{ } \mu\text{b}$

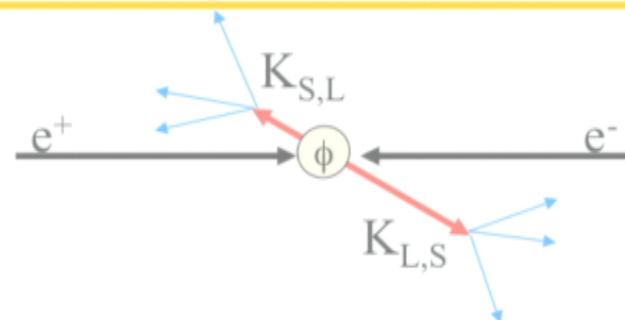
$$W = m_\phi = 1019.4 \text{ MeV}$$

- $\text{BR}(\phi \rightarrow K^0\bar{K}^0) \sim 34\%$

- $\sim 10^6$ neutral kaon pairs per pb^{-1} produced in an antisymmetric quantum state with $J^{PC} = 1^-$:

$$\mathbf{p}_K = 110 \text{ MeV/c}$$

$$\lambda_S = 6 \text{ mm} \quad \lambda_L = 3.5 \text{ m}$$



$$\begin{aligned} |t\rangle &= \frac{1}{\sqrt{2}} [|K^0(p)\rangle |K^0(-\vec{p})\rangle - |\bar{K}^0(\vec{p})\rangle |K^0(-\vec{p})\rangle] \\ &= \frac{N}{\sqrt{2}} [|K_S(\vec{p})\rangle |K_L(-\vec{p})\rangle - |K_L(\vec{p})\rangle |K_S(-\vec{p})\rangle] \end{aligned}$$

$$N = \sqrt{\left(1 + |\varepsilon_S|^2\right)\left(1 + |\varepsilon_L|^2\right)} / \left(1 - \varepsilon_S \varepsilon_L\right) \approx 1$$

(KK are not perfectly back-to back in the lab because ϕ has a small momentum $p(\phi) \sim 13 \text{ MeV}$)

The detection of a kaon at large (small) times tags a K_S (K_L)
⇒ possibility to select a pure K_S beam (unique at a ϕ -factory, not possible at fixed target experiments)

K

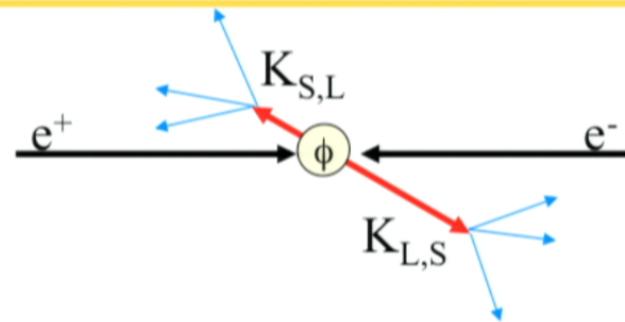
Neutral kaons at a ϕ -factory

Production of the vector meson ϕ in e^+e^- annihilations:

- $e^+e^- \rightarrow \phi \quad \sigma_\phi \sim 3 \text{ } \mu\text{b}$
 $W = m_\phi = 1019.4 \text{ MeV}$
- $\text{BR}(\phi \rightarrow K^0\bar{K}^0) \sim 34\%$
- $\sim 10^6$ neutral kaon pairs per pb^{-1} produced in an antisymmetric quantum state with $J^{PC} = 1^-$:

$$p_K = 110 \text{ MeV/c}$$

$$\lambda_S = 6 \text{ mm} \quad \lambda_L = 3.5 \text{ m}$$



$$\begin{aligned}|i\rangle &= \frac{1}{\sqrt{2}} \left[|K^0(\vec{p})\rangle |\bar{K}^0(-\vec{p})\rangle - |\bar{K}^0(\vec{p})\rangle |K^0(-\vec{p})\rangle \right] \\ &= \frac{N}{\sqrt{2}} \left[|K_S(\vec{p})\rangle |K_L(-\vec{p})\rangle - |K_L(\vec{p})\rangle |K_S(-\vec{p})\rangle \right]\end{aligned}$$

$$N = \sqrt{\left(1 + |\varepsilon_S|^2\right)\left(1 + |\varepsilon_L|^2\right)} / \left(1 - \varepsilon_S \varepsilon_L\right) \cong 1$$

(KK are not perfectly back-to back in the lab because ϕ has a small momentum $p(\phi) \sim 13 \text{ MeV}$)

The detection of a kaon at large (small) times tags a K_S (K_L)
⇒ possibility to select a pure K_S beam (unique at a ϕ -factory, not possible at fixed target experiments)

K

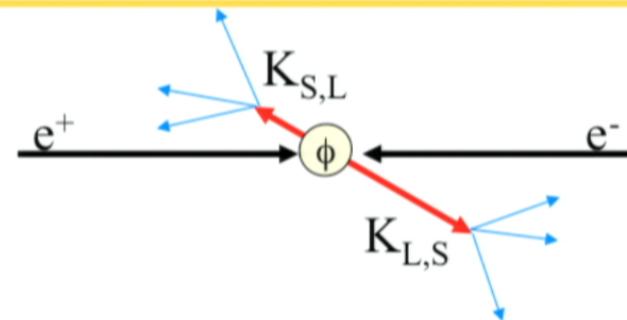
Neutral kaons at a ϕ -factory

Production of the vector meson ϕ in e^+e^- annihilations:

- $e^+e^- \rightarrow \phi \quad \sigma_\phi \sim 3 \text{ } \mu\text{b}$
 $W = m_\phi = 1019.4 \text{ MeV}$
- $\text{BR}(\phi \rightarrow K^0\bar{K}^0) \sim 34\%$
- $\sim 10^6$ neutral kaon pairs per pb^{-1} produced in an antisymmetric quantum state with $J^{PC} = 1^-$:

$$p_K = 110 \text{ MeV/c}$$

$$\lambda_S = 6 \text{ mm} \quad \lambda_L = 3.5 \text{ m}$$



$$\begin{aligned}|i\rangle &= \frac{1}{\sqrt{2}} \left[|K^0(\vec{p})\rangle |\bar{K}^0(-\vec{p})\rangle - |\bar{K}^0(\vec{p})\rangle |K^0(-\vec{p})\rangle \right] \\&= \frac{N}{\sqrt{2}} \left[|K_S(\vec{p})\rangle |K_L(-\vec{p})\rangle - |K_L(\vec{p})\rangle |K_S(-\vec{p})\rangle \right]\end{aligned}$$

$$N = \sqrt{\left(1 + |\varepsilon_S|^2\right)\left(1 + |\varepsilon_L|^2\right)} / \left(1 - \varepsilon_S \varepsilon_L\right) \cong 1$$

(KK are not perfectly back-to back in the lab because ϕ has a small momentum $p(\phi) \sim 13 \text{ MeV}$)

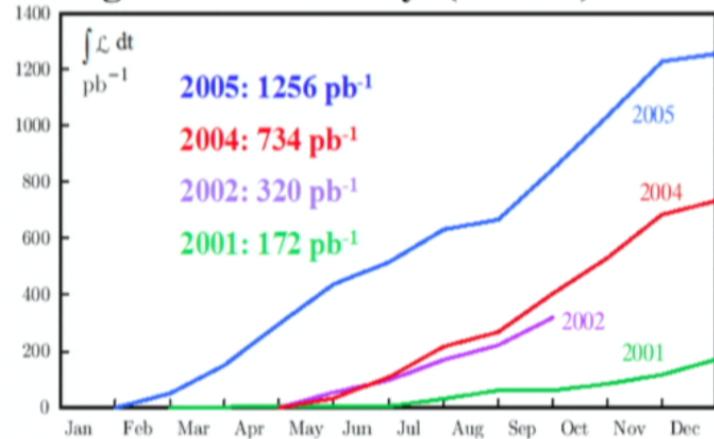
The detection of a kaon at large (small) times tags a K_S (K_L)
⇒ possibility to select a pure K_S beam (**unique** at a ϕ -factory, not possible at fixed target experiments)

The KLOE detector at the Frascati ϕ -factory DAΦNE K

DAFNE
collider



Integrated luminosity (KLOE)



KLOE detector



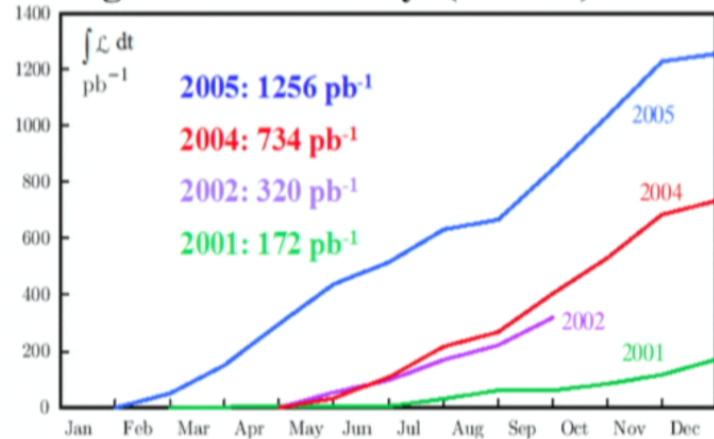
Total KLOE $\int \mathcal{L} dt \sim 2.5 \text{ fb}^{-1}$
(2001 - 05) $\rightarrow \sim 2.5 \times 10^9 K_S K_L$ pairs

The KLOE detector at the Frascati ϕ -factory DAΦNE K

DAFNE
collider



Integrated luminosity (KLOE)



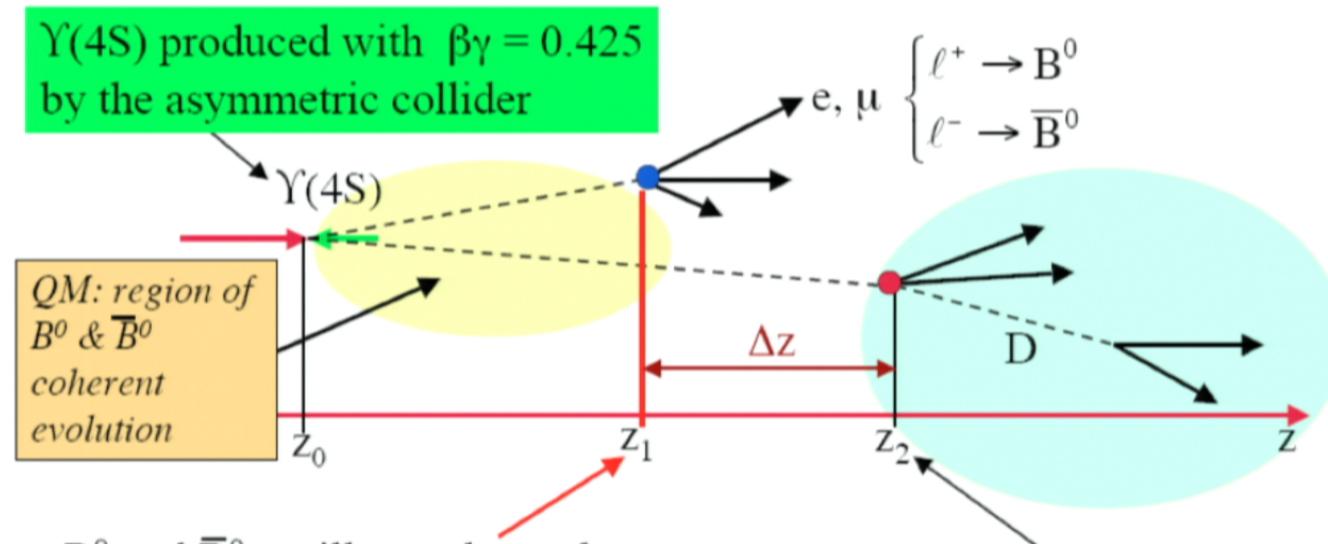
KLOE detector



Total KLOE $\int \mathcal{L} dt \sim 2.5$ fb⁻¹
(2001 - 05) $\rightarrow \sim 2.5 \times 10^9$ K_SK_L pairs

Correlated B meson pairs

B



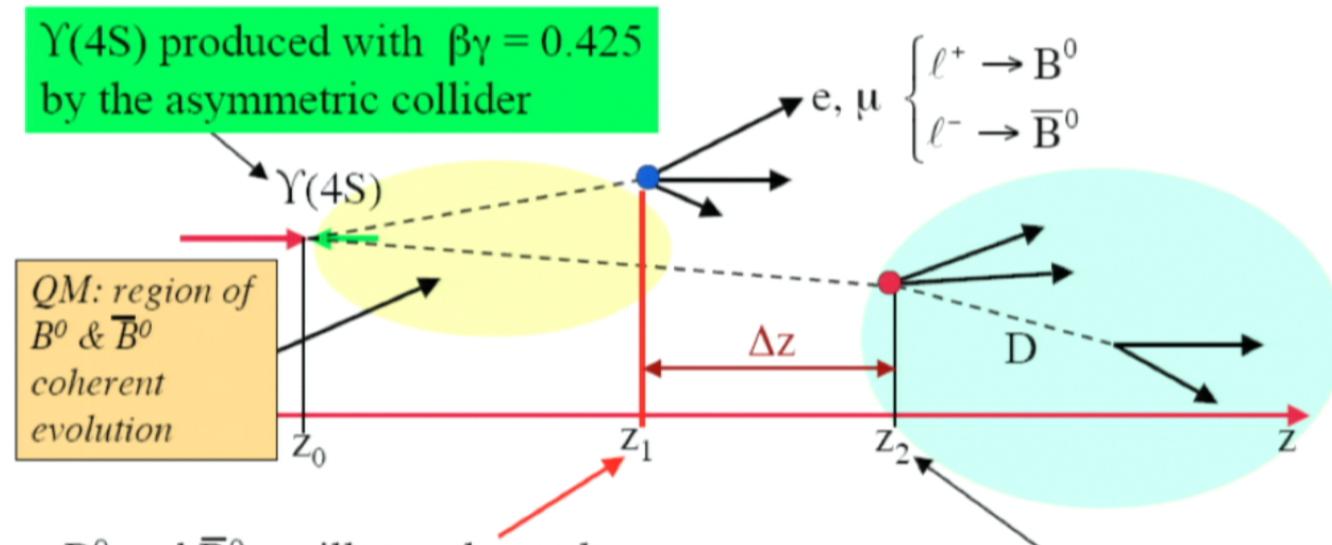
B^0 and \bar{B}^0 oscillate coherently.
When the **first** decays, the other is
known to be of the opposite
flavour, at the same proper time

Than the other B^0 oscillates
freely before decaying
after a time given by
$$\Delta t \approx \Delta z / c \beta \gamma$$

N.B. : production vertex position z_0 not very well known : only Δz is available !

Correlated B meson pairs

B



B^0 and \bar{B}^0 oscillate coherently.
When the first decays, the other is
known to be of the opposite
flavour, at the same proper time

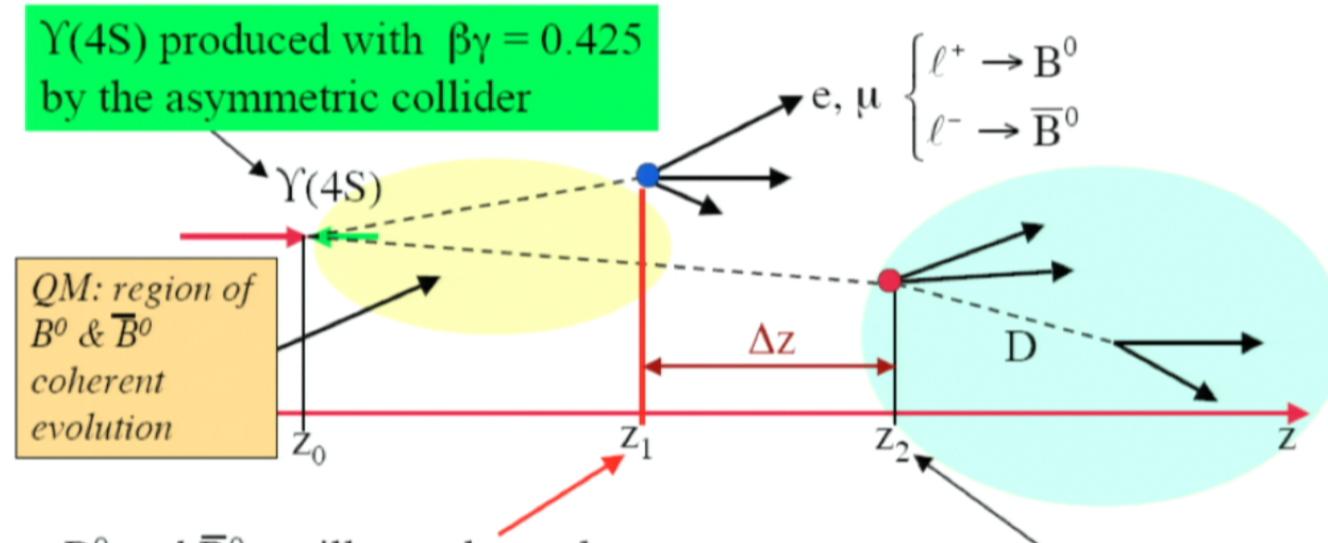
Than the other B^0 oscillates
freely before decaying
after a time Δt

$$\Delta t \approx \Delta z$$

N.B. : production vertex position z_0 not very well known : only



Correlated B meson pairs



B^0 and \bar{B}^0 oscillate coherently.
When the **first** decays, the other is
known to be of the opposite
flavour, at the same proper time

Than the other B^0 oscillates
freely before decaying
after a time given by
$$\Delta t \approx \Delta z / c \beta \gamma$$

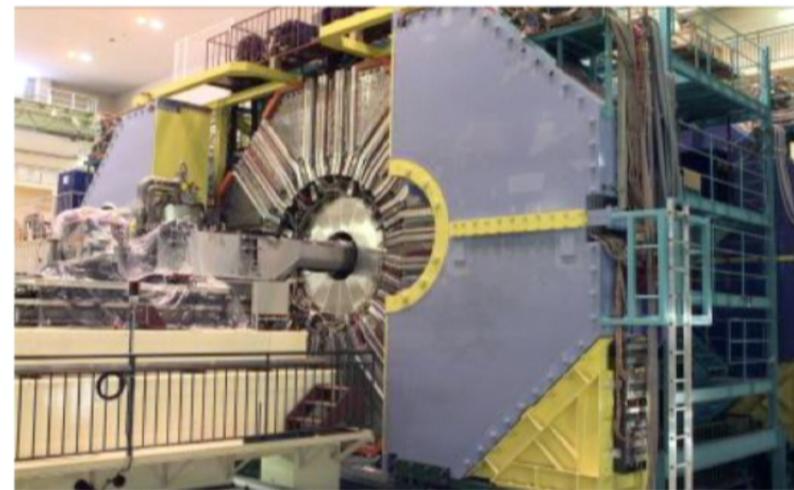
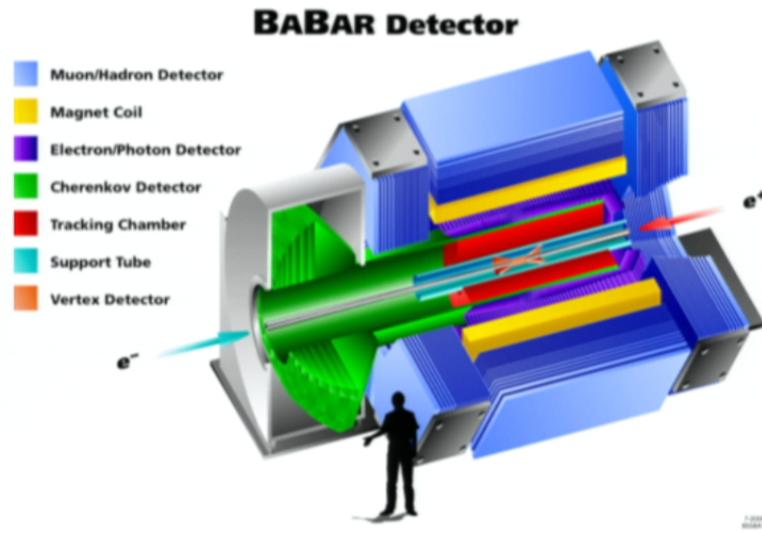
N.B. : production vertex position z_0 not very well known : only Δz is available !

B-factories

B

BABAR @ PEP-II
collected $L=557 \text{ fb}^{-1}$

BELLE @ KEKB
collected $L=1040 \text{ fb}^{-1}$



Neutral kaon interferometry

K

$$|i\rangle = \frac{N}{\sqrt{2}} [|K_s(\vec{p})\rangle |K_L(-\vec{p})\rangle - |K_L(\vec{p})\rangle |K_s(-\vec{p})\rangle]$$

Double differential time distribution:

$$I(f_1, t_1; f_2, t_2) = C_{12} \left\{ |\eta_1|^2 e^{-\Gamma_L t_1 - \Gamma_S t_2} + |\eta_2|^2 e^{-\Gamma_S t_1 - \Gamma_L t_2} \right.$$

$$\left. - 2|\eta_1||\eta_2| e^{-(\Gamma_S + \Gamma_L)(t_1 + t_2)/2} \cos[\Delta m(t_2 - t_1) + \phi_1 - \phi_2] \right\}$$

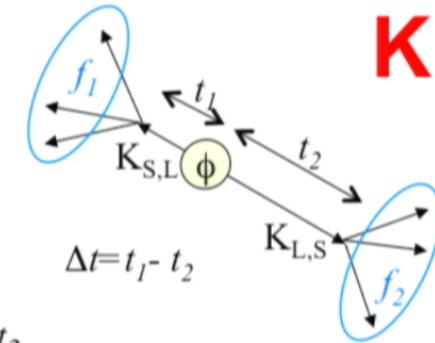
where $t_1(t_2)$ is the proper time of one (the other) kaon decay into f_1 (f_2) final state and:

$$\eta_i = |\eta_i| e^{i\phi_i} = \langle f_i | T | K_L \rangle / \langle f_i | T | K_S \rangle$$

$$C_{12} = \frac{|N|^2}{2} \left| \langle f_1 | T | K_S \rangle \langle f_2 | T | K_S \rangle \right|^2$$

**characteristic interference term
at a ϕ -factory => interferometry**

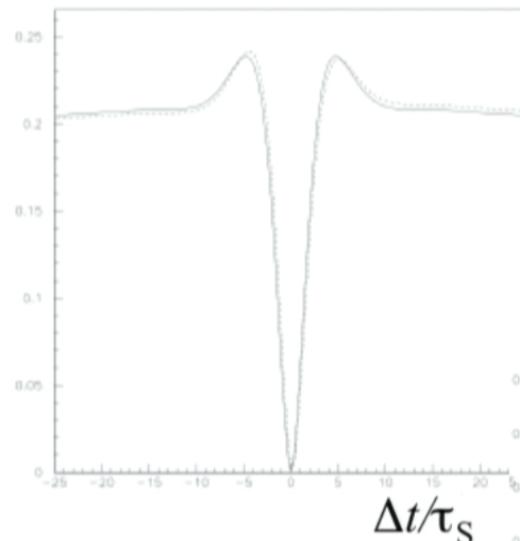
From these distributions for various final states f_i one can measure the following quantities: Γ_S , Γ_L , Δm , $|\eta_i|$, $\phi_i \equiv \arg(\eta_i)$



Neutral kaon interferometry: main observables

K

$I(\Delta t)$ (a.u)

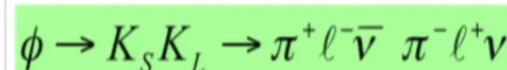


$\phi \rightarrow K_S K_L \rightarrow \pi^+ \ell^- \bar{\nu} \pi^- \ell^+ \nu$

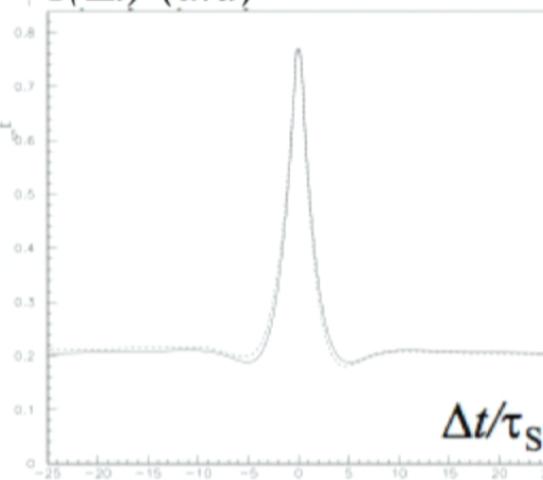
$$\Re\left(\frac{\varepsilon'}{\varepsilon}\right) \quad \Im\left(\frac{\varepsilon'}{\varepsilon}\right)$$

$\Re\delta + \Re x_-$

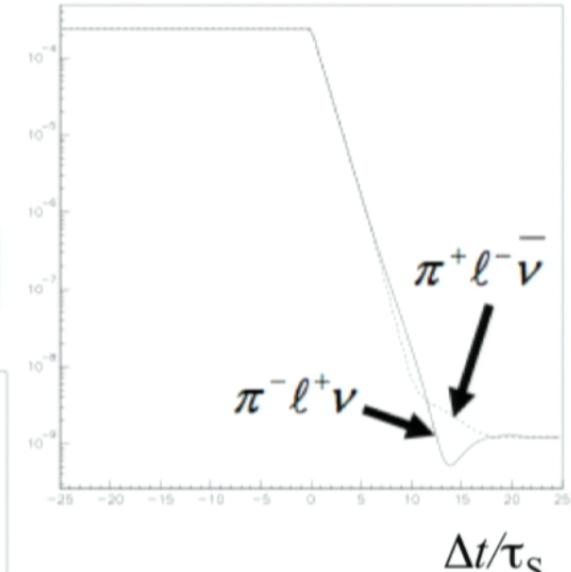
$\Im\delta + \Im x_+$



$I(\Delta t)$ (a.u)



$I(\Delta t)$ (a.u)



$\phi \rightarrow K_S K_L \rightarrow \pi\pi \pi\ell\nu$

$$A_L = 2\Re\varepsilon - \Re\delta - \Re y - \Re x_-$$

$$\phi_{\pi\pi}$$

A. Di Domenico

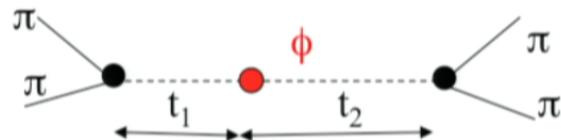
Experimental search for quantum gravity: the hard facts – October 22 – 25, 2012 – Waterloo, ON, Canada

$$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \quad \pi^+ \pi^-$$

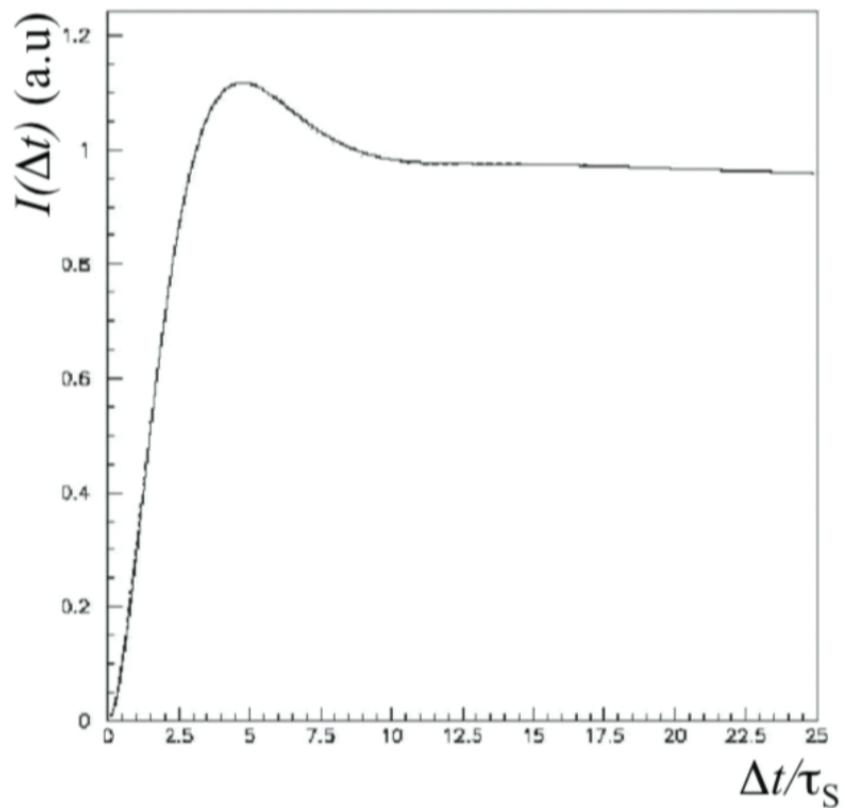
K

$$|i\rangle = \frac{1}{\sqrt{2}} \left[|K^0\rangle |\bar{K}^0\rangle - |\bar{K}^0\rangle |K^0\rangle \right]$$

$$\Delta t = |t_1 - t_2|$$



Same final state for both kaons: $f_1 = f_2 = \pi^+ \pi^-$



$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$: test of quantum coherence

K

$$|i\rangle = \frac{1}{\sqrt{2}} \left[|K^0\rangle |\bar{K}^0\rangle - |\bar{K}^0\rangle |K^0\rangle \right]$$

$$\begin{aligned} I(\pi^+ \pi^-, \pi^+ \pi^-; \Delta t) = & \frac{N}{2} \left[\left| \langle \pi^+ \pi^-, \pi^+ \pi^- | K^0 \bar{K}^0(\Delta t) \rangle \right|^2 + \left| \langle \pi^+ \pi^-, \pi^+ \pi^- | \bar{K}^0 K^0(\Delta t) \rangle \right|^2 \right. \\ & \left. - 2 \Re \left(\langle \pi^+ \pi^-, \pi^+ \pi^- | K^0 \bar{K}^0(\Delta t) \rangle \langle \pi^+ \pi^-, \pi^+ \pi^- | \bar{K}^0 K^0(\Delta t) \rangle^* \right) \right] \end{aligned}$$

$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$: test of quantum coherence

K

$$|i\rangle = \frac{1}{\sqrt{2}} \left[|K^0\rangle |\bar{K}^0\rangle - |\bar{K}^0\rangle |K^0\rangle \right]$$

$$\begin{aligned} I(\pi^+ \pi^-, \pi^+ \pi^-; \Delta t) = & \frac{N}{2} \left[\left| \langle \pi^+ \pi^-, \pi^+ \pi^- | K^0 \bar{K}^0(\Delta t) \rangle \right|^2 + \left| \langle \pi^+ \pi^-, \pi^+ \pi^- | \bar{K}^0 K^0(\Delta t) \rangle \right|^2 \right. \\ & \left. - (1 - \zeta_{00}) \cdot 2 \Re \left(\langle \pi^+ \pi^-, \pi^+ \pi^- | K^0 \bar{K}^0(\Delta t) \rangle \langle \pi^+ \pi^-, \pi^+ \pi^- | \bar{K}^0 K^0(\Delta t) \rangle^* \right) \right] \end{aligned}$$

$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$: test of quantum coherence

K

$$|i\rangle = \frac{1}{\sqrt{2}} \left[|K^0\rangle |\bar{K}^0\rangle - |\bar{K}^0\rangle |K^0\rangle \right]$$

$$I(\pi^+ \pi^-, \pi^+ \pi^-; \Delta t) = \frac{N}{2} \left[\left| \langle \pi^+ \pi^-, \pi^+ \pi^- | K^0 \bar{K}^0(\Delta t) \rangle \right|^2 + \left| \langle \pi^+ \pi^-, \pi^+ \pi^- | \bar{K}^0 K^0(\Delta t) \rangle \right|^2 \right]$$

$$-(1 - \zeta_{00}) \cdot 2 \Re \left(\langle \pi^+ \pi^-, \pi^+ \pi^- | K^0 \bar{K}^0(\Delta t) \rangle \langle \pi^+ \pi^-, \pi^+ \pi^- | \bar{K}^0 K^0(\Delta t) \rangle^* \right)$$

Decoherence parameter:

$$\zeta_{00} = 0 \quad \rightarrow \quad \text{QM}$$

$$\zeta_{00} = 1 \quad \rightarrow \quad \text{total decoherence}$$

(also known as Furry's hypothesis
or spontaneous factorization)
[W.Furry, PR 49 (1936) 393]

Bertlmann, Grimus, Hiesmayr PR D60 (1999) 114032

Bertlmann, Durstberger, Hiesmayr PRA 68 012111 (2003)

$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$: test of quantum coherence

K

$$|i\rangle = \frac{1}{\sqrt{2}} \left[|K^0\rangle |\bar{K}^0\rangle - |\bar{K}^0\rangle |K^0\rangle \right]$$

$$I(\pi^+ \pi^-, \pi^+ \pi^-; \Delta t) = \frac{N}{2} \left[\left| \langle \pi^+ \pi^-, \pi^+ \pi^- | K^0 \bar{K}^0(\Delta t) \rangle \right|^2 + \left| \langle \pi^+ \pi^-, \pi^+ \pi^- | \bar{K}^0 K^0(\Delta t) \rangle \right|^2 \right]$$

$$-(1 - \zeta_{00}) \cdot 2 \Re \left(\langle \pi^+ \pi^-, \pi^+ \pi^- | K^0 \bar{K}^0(\Delta t) \rangle \langle \pi^+ \pi^-, \pi^+ \pi^- | \bar{K}^0 K^0(\Delta t) \rangle^* \right)$$

Decoherence parameter:

$$\zeta_{00} = 0 \rightarrow \text{QM}$$

$$\zeta_{00} = 1 \rightarrow \text{total decoherence}$$

(also known as Furry's hypothesis
or spontaneous factorization)
[W.Furry, PR 49 (1936) 393]

Bertlmann, Grimus, Hiesmayr PR D60 (1999) 114032

Bertlmann, Durstberger, Hiesmayr PRA 68 012111 (2003)

$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$: test of quantum coherence

K

$$|i\rangle = \frac{1}{\sqrt{2}} \left[|K^0\rangle |\bar{K}^0\rangle - |\bar{K}^0\rangle |K^0\rangle \right]$$

$$I(\pi^+ \pi^-, \pi^+ \pi^-; \Delta t) = \frac{N}{2} \left[\left| \langle \pi^+ \pi^-, \pi^+ \pi^- | K^0 \bar{K}^0(\Delta t) \rangle \right|^2 + \left| \langle \pi^+ \pi^-, \pi^+ \pi^- | \bar{K}^0 K^0(\Delta t) \rangle \right|^2 \right]$$

$$-(1 - \zeta_{00}) \cdot 2 \Re \left(\langle \pi^+ \pi^-, \pi^+ \pi^- | K^0 \bar{K}^0(\Delta t) \rangle \langle \pi^+ \pi^-, \pi^+ \pi^- | \bar{K}^0 K^0(\Delta t) \rangle^* \right)$$

Decoherence parameter:

$$\zeta_{00} = 0 \rightarrow \text{QM}$$

$$\zeta_{00} = 1 \rightarrow \text{total decoherence}$$

(also known as Furry's hypothesis
or spontaneous factorization)
[W.Furry, PR 49 (1936) 393]

Bertlmann, Grimus, Hiesmayr PR D60 (1999) 114032

Bertlmann, Durstberger, Hiesmayr PRA 68 012111 (2003)

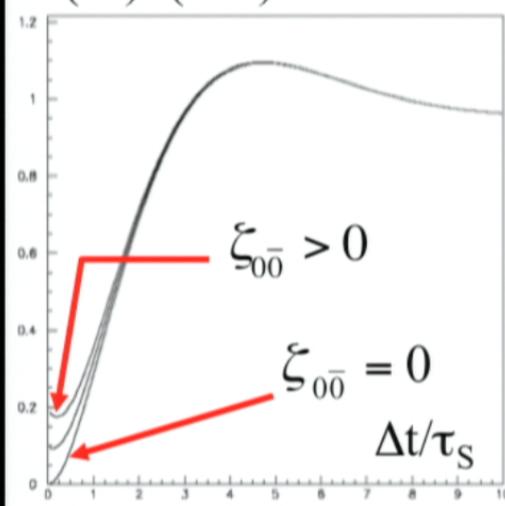
$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$: test of quantum coherence

K

$$|i\rangle = \frac{1}{\sqrt{2}} \left[|K^0\rangle |\bar{K}^0\rangle - |\bar{K}^0\rangle |K^0\rangle \right]$$

$$I(\pi^+ \pi^-, \pi^+ \pi^-; \Delta t) = \frac{N}{2} \left[\left| \langle \pi^+ \pi^-, \pi^+ \pi^- | K^0 \bar{K}^0(\Delta t) \rangle \right|^2 + \left| \langle \pi^+ \pi^-, \pi^+ \pi^- | \bar{K}^0 K^0(\Delta t) \rangle \right|^2 \right]$$

$$I(\Delta t) \text{ (a.u.)} - (1 - \zeta_{00}) \cdot 2 \Re \left(\langle \pi^+ \pi^-, \pi^+ \pi^- | K^0 \bar{K}^0(\Delta t) \rangle \langle \pi^+ \pi^-, \pi^+ \pi^- | \bar{K}^0 K^0(\Delta t) \rangle^* \right)$$



Decoherence parameter:

$$\zeta_{00} = 0 \rightarrow \text{QM}$$

$$\zeta_{00} = 1 \rightarrow \text{total decoherence}$$

(also known as Furry's hypothesis
or spontaneous factorization)
[W.Furry, PR 49 (1936) 393]

Bertlmann, Grimus, Hiesmayr PR D60 (1999) 114032

Bertlmann, Durstberger, Hiesmayr PRA 68 012111 (2003)

$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$: test of quantum coherence

K

- Analysed data: $L=1.5 \text{ fb}^{-1}$
- Fit including Δt resolution and efficiency effects + regeneration

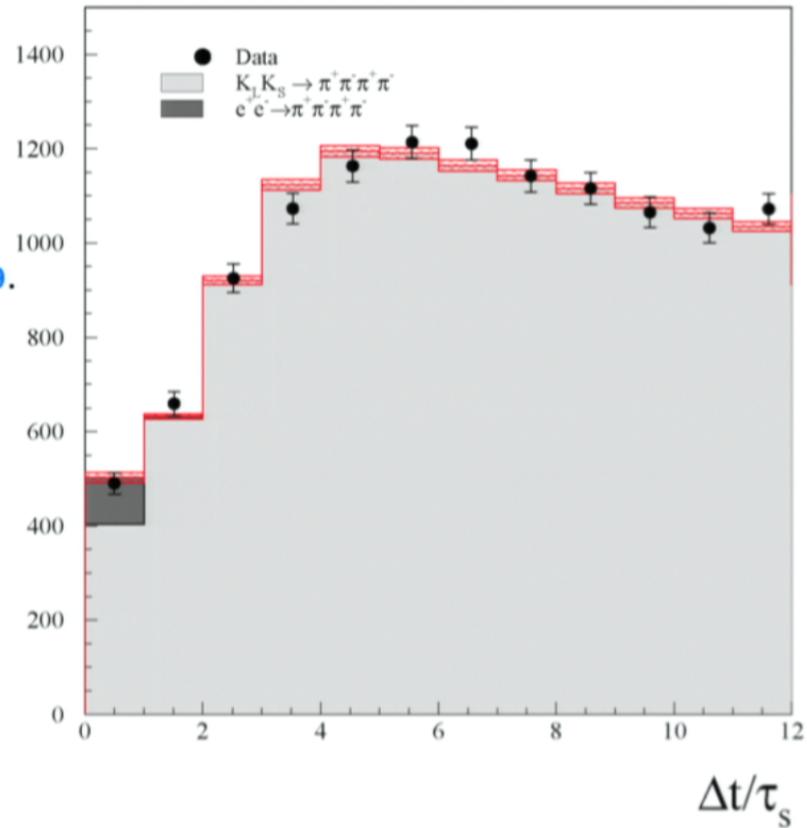
KLOE result: PLB 642(2006) 315
J.Phys.Conf.Ser.171:012008,2009.

$$\zeta_{0\bar{0}} = (1.4 \pm 9.5_{\text{STAT}} \pm 3.8_{\text{SYST}}) \times 10^{-7}$$

Observable suppressed by CP violation: $|\eta_{+-}|^2 \sim |\varepsilon|^2 \sim 10^{-6}$
 \Rightarrow terms $\zeta_{00}/|\eta_{+-}|^2$
 \Rightarrow high sensitivity to ζ_{00}

From CPLEAR data, Bertlmann et al.
(PR D60 (1999) 114032) obtain:

$$\zeta_{0\bar{0}} = 0.4 \pm 0.7$$



$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$: test of quantum coherence

K

- Analysed data: $L=1.5 \text{ fb}^{-1}$
- Fit including Δt resolution and efficiency effects + regeneration

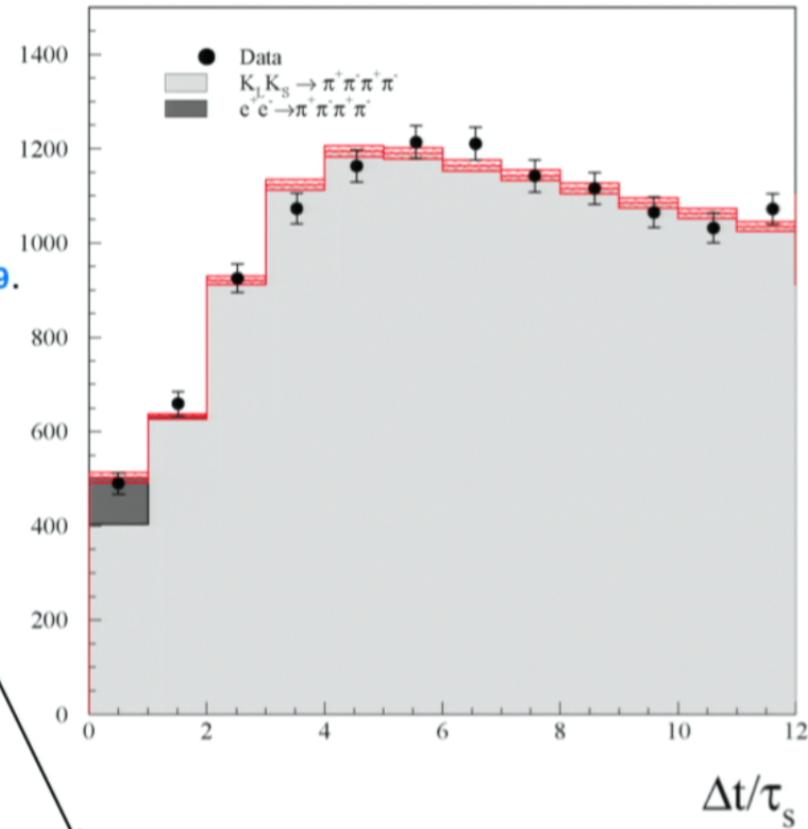
KLOE result: PLB 642(2006) 315
J.Phys.Conf.Ser.171:012008,2009.

$$\zeta_{0\bar{0}} = (1.4 \pm 9.5_{\text{STAT}} \pm 3.8_{\text{SYST}}) \times 10^{-7}$$

Observable suppressed by CP violation: $|\eta_{+-}|^2 \sim |\varepsilon|^2 \sim 10^{-6}$
 \Rightarrow terms $\zeta_{00}/|\eta_{+-}|^2$
 \Rightarrow high sensitivity to ζ_{00}

From CPLEAR data, Bertlmann et al.
(PR D60 (1999) 114032) obtain:

$$\zeta_{0\bar{0}} = 0.4 \pm 0.7$$



Best precision achievable in an entangled system

$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$: test of quantum coherence

K

The decoherence parameter ζ depends on the basis in which the spontaneous factorization mechanism is specified:

$$\zeta = 0 \text{ (QM)}$$

$$\zeta = 1 \text{ (total decoherence)}$$

$K_S K_L$
basis

$$|i\rangle = \frac{1}{\sqrt{2}} [|K_S\rangle |K_L\rangle - |K_L\rangle |K_S\rangle]$$

$$\Rightarrow |K_S\rangle |K_L\rangle \text{ or } |K_L\rangle |K_S\rangle$$

$$|\eta_{+-}| = \left| \frac{\langle \pi^+ \pi^- | T | K_L \rangle}{\langle \pi^+ \pi^- | T | K_S \rangle} \right| \sim 10^{-3}$$

I $\propto \langle \pi^+ \pi^-, \pi^+ \pi^- | T | i \rangle^2$
suppressed by CP violation

$$I \propto \langle \pi^+ \pi^- | T | K_S \rangle \langle \pi^+ \pi^- | T | K_L \rangle^2$$

suppressed by CP violation

$K^0 \bar{K}^0$
basis

$$|i\rangle = \frac{1}{\sqrt{2}} [|K^0\rangle |\bar{K}^0\rangle - |\bar{K}^0\rangle |K^0\rangle]$$

$$\Rightarrow |K^0\rangle |\bar{K}^0\rangle \text{ or } |\bar{K}^0\rangle |K^0\rangle$$

$$\left| \frac{\langle \pi^+ \pi^- | T | K^0 \rangle}{\langle \pi^+ \pi^- | T | \bar{K}^0 \rangle} \right| \sim 1$$

I $\propto \langle \pi^+ \pi^-, \pi^+ \pi^- | T | i \rangle^2$
suppressed by CP violation

$$I \propto \langle \pi^+ \pi^- | T | K^0 \rangle \langle \pi^+ \pi^- | T | \bar{K}^0 \rangle^2$$

not suppressed by CP violation

=> intuitive explanation of the high sensitivity to $\zeta_{0\bar{0}}$

$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$: test of quantum coherence

K

The decoherence parameter ζ depends on the basis in which the spontaneous factorization mechanism is specified:

$$\zeta = 0 \text{ (QM)}$$

$$\zeta = 1 \text{ (total decoherence)}$$

$K_S K_L$
basis

$$|i\rangle = \frac{1}{\sqrt{2}} [|K_S\rangle |K_L\rangle - |K_L\rangle |K_S\rangle]$$

$$\Rightarrow |K_S\rangle |K_L\rangle \text{ or } |K_L\rangle |K_S\rangle$$

$$|\eta_{+-}| = \left| \frac{\langle \pi^+ \pi^- | T | K_L \rangle}{\langle \pi^+ \pi^- | T | K_S \rangle} \right| \sim 10^{-3}$$

I $\propto \langle \pi^+ \pi^-, \pi^+ \pi^- | T | i \rangle^2$
suppressed by CP violation

$$I \propto \langle \pi^+ \pi^- | T | K_S \rangle \langle \pi^+ \pi^- | T | K_L \rangle^2$$

suppressed by CP violation

$K^0 \bar{K}^0$
basis

$$|i\rangle = \frac{1}{\sqrt{2}} [|K^0\rangle |\bar{K}^0\rangle - |\bar{K}^0\rangle |K^0\rangle]$$

$$\Rightarrow |K^0\rangle |\bar{K}^0\rangle \text{ or } |\bar{K}^0\rangle |K^0\rangle$$

$$\left| \frac{\langle \pi^+ \pi^- | T | K^0 \rangle}{\langle \pi^+ \pi^- | T | \bar{K}^0 \rangle} \right| \sim 1$$

I $\propto \langle \pi^+ \pi^-, \pi^+ \pi^- | T | i \rangle^2$
suppressed by CP violation

$$I \propto \langle \pi^+ \pi^- | T | K^0 \rangle \langle \pi^+ \pi^- | T | \bar{K}^0 \rangle^2$$

not suppressed by CP violation

=> intuitive explanation of the high sensitivity to $\zeta_{0\bar{0}}$

$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$: test of quantum coherence

K

The decoherence parameter ζ depends on the basis in which the spontaneous factorization mechanism is specified:

$$\zeta = 0 \text{ (QM)}$$

$$\zeta = 1 \text{ (total decoherence)}$$

$K_S K_L$
basis

$$|i\rangle = \frac{1}{\sqrt{2}} [|K_S\rangle |K_L\rangle - |K_L\rangle |K_S\rangle]$$

$$\Rightarrow |K_S\rangle |K_L\rangle \text{ or } |K_L\rangle |K_S\rangle$$

$$|\eta_{+-}| = \left| \frac{\langle \pi^+ \pi^- | T | K_L \rangle}{\langle \pi^+ \pi^- | T | K_S \rangle} \right| \sim 10^{-3}$$

I $\propto \langle \pi^+ \pi^-, \pi^+ \pi^- | T | i \rangle^2$
suppressed by CP violation

$$I \propto \langle \pi^+ \pi^- | T | K_S \rangle \langle \pi^+ \pi^- | T | K_L \rangle^2$$

suppressed by CP violation

$K^0 \bar{K}^0$
basis

$$|i\rangle = \frac{1}{\sqrt{2}} [|K^0\rangle |\bar{K}^0\rangle - |\bar{K}^0\rangle |K^0\rangle]$$

$$\Rightarrow |K^0\rangle |\bar{K}^0\rangle \text{ or } |\bar{K}^0\rangle |K^0\rangle$$

$$\left| \frac{\langle \pi^+ \pi^- | T | K^0 \rangle}{\langle \pi^+ \pi^- | T | \bar{K}^0 \rangle} \right| \sim 1$$

I $\propto \langle \pi^+ \pi^-, \pi^+ \pi^- | T | i \rangle^2$
suppressed by CP violation

$$I \propto \langle \pi^+ \pi^- | T | K^0 \rangle \langle \pi^+ \pi^- | T | \bar{K}^0 \rangle^2$$

not suppressed by CP violation

=> intuitive explanation of the high sensitivity to $\zeta_{0\bar{0}}$

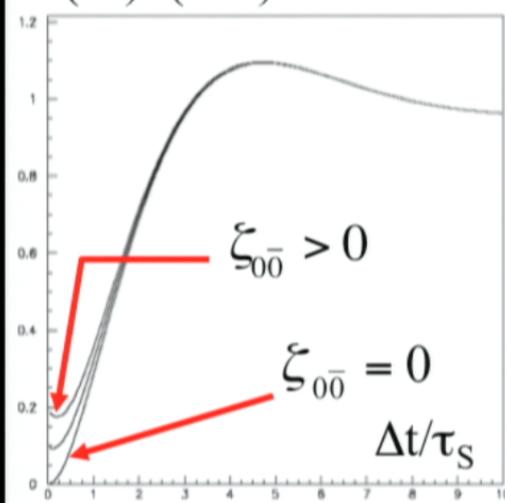
$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$: test of quantum coherence

K

$$|i\rangle = \frac{1}{\sqrt{2}} \left[|K^0\rangle |\bar{K}^0\rangle - |\bar{K}^0\rangle |K^0\rangle \right]$$

$$I(\pi^+ \pi^-, \pi^+ \pi^-; \Delta t) = \frac{N}{2} \left[\left| \langle \pi^+ \pi^-, \pi^+ \pi^- | K^0 \bar{K}^0(\Delta t) \rangle \right|^2 + \left| \langle \pi^+ \pi^-, \pi^+ \pi^- | \bar{K}^0 K^0(\Delta t) \rangle \right|^2 \right]$$

$$I(\Delta t) \text{ (a.u.)} - (1 - \zeta_{00}) \cdot 2 \Re \left(\langle \pi^+ \pi^-, \pi^+ \pi^- | K^0 \bar{K}^0(\Delta t) \rangle \langle \pi^+ \pi^-, \pi^+ \pi^- | \bar{K}^0 K^0(\Delta t) \rangle^* \right)$$



Decoherence parameter:

$$\zeta_{00} = 0 \rightarrow \text{QM}$$

$$\zeta_{00} = 1 \rightarrow \text{total decoherence}$$

(also known as Furry's hypothesis
or spontaneous factorization)
[W.Furry, PR 49 (1936) 393]

Bertlmann, Grimus, Hiesmayr PR D60 (1999) 114032

Bertlmann, Durstberger, Hiesmayr PRA 68 012111 (2003)

Test of quantum coherence in neutral B mesons

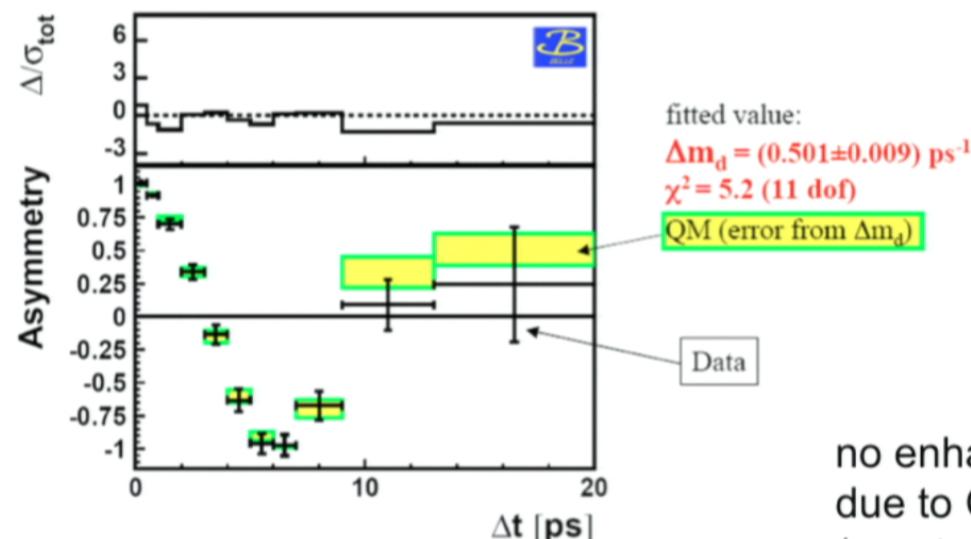
B

Δt dependent rates: opposite sign di-lepton vs same sign di-lepton

$$A(\Delta t) = \frac{I(\ell^\pm, \ell^\mp; \Delta t) - I(\ell^\pm, \ell^\pm; \Delta t)}{I(\ell^\pm, \ell^\mp; \Delta t) + I(\ell^\pm, \ell^\pm; \Delta t)} = \cos(\Delta m \Delta t)$$

QM prediction

After correcting for Δt resolution and selection efficiency by a deconvolution procedure:



$L \sim 150 \text{ fb}^{-1}$

BELLE PRL 99 131802 (2007)

$$\xi_{00} = 0.029 \pm 0.057$$

no enhanced sensitivity
due to CP violation here
(η not very small) $\left| \frac{\langle f_{CP} | T | B_H \rangle}{\langle f_{CP} | T | B_L \rangle} \right| \sim O(1)$

Test of quantum coherence in neutral B mesons

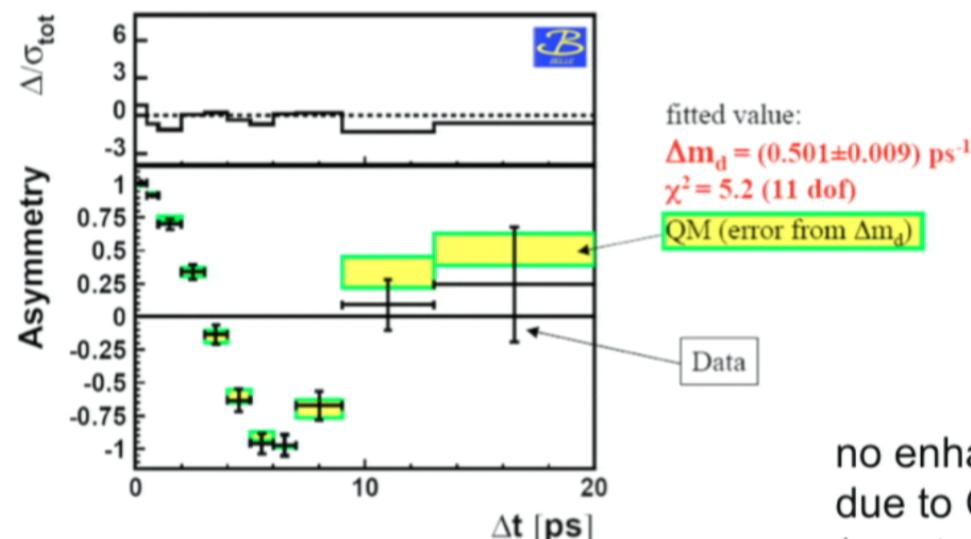
B

Δt dependent rates: opposite sign di-lepton vs same sign di-lepton

$$A(\Delta t) = \frac{I(\ell^\pm, \ell^\mp; \Delta t) - I(\ell^\pm, \ell^\pm; \Delta t)}{I(\ell^\pm, \ell^\mp; \Delta t) + I(\ell^\pm, \ell^\pm; \Delta t)} = \cos(\Delta m \Delta t)$$

QM prediction

After correcting for Δt resolution and selection efficiency by a deconvolution procedure:



$L \sim 150 \text{ fb}^{-1}$

BELLE PRL 99 131802 (2007)

$$\xi_{00} = 0.029 \pm 0.057$$

no enhanced sensitivity
due to CP violation here
 $(\eta \text{ not very small})$

$$\left| \frac{\langle f_{CP} | T | B_H \rangle}{\langle f_{CP} | T | B_L \rangle} \right| \sim O(1)$$

Test of quantum coherence in neutral B mesons

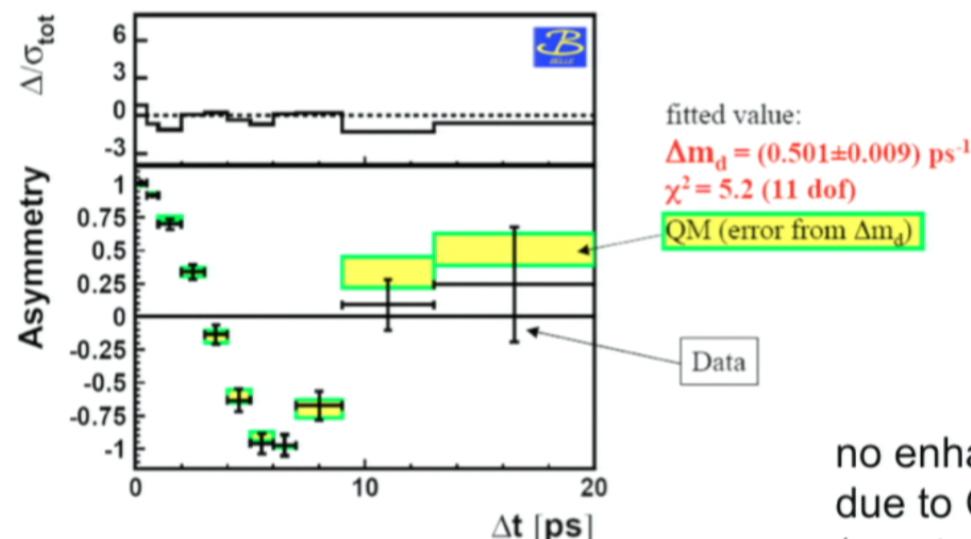
B

Δt dependent rates: opposite sign di-lepton vs same sign di-lepton

$$A(\Delta t) = \frac{I(\ell^\pm, \ell^\mp; \Delta t) - I(\ell^\pm, \ell^\pm; \Delta t)}{I(\ell^\pm, \ell^\mp; \Delta t) + I(\ell^\pm, \ell^\pm; \Delta t)} = \cos(\Delta m \Delta t)$$

QM prediction

After correcting for Δt resolution and selection efficiency by a deconvolution procedure:



$L \sim 150 \text{ fb}^{-1}$

BELLE PRL 99 131802 (2007)

$$\xi_{00} = 0.029 \pm 0.057$$

no enhanced sensitivity
due to CP violation here
 $(\eta \text{ not very small})$

$$\left| \frac{\langle f_{CP} | T | B_H \rangle}{\langle f_{CP} | T | B_L \rangle} \right| \sim O(1)$$

Test of quantum coherence in neutral B mesons

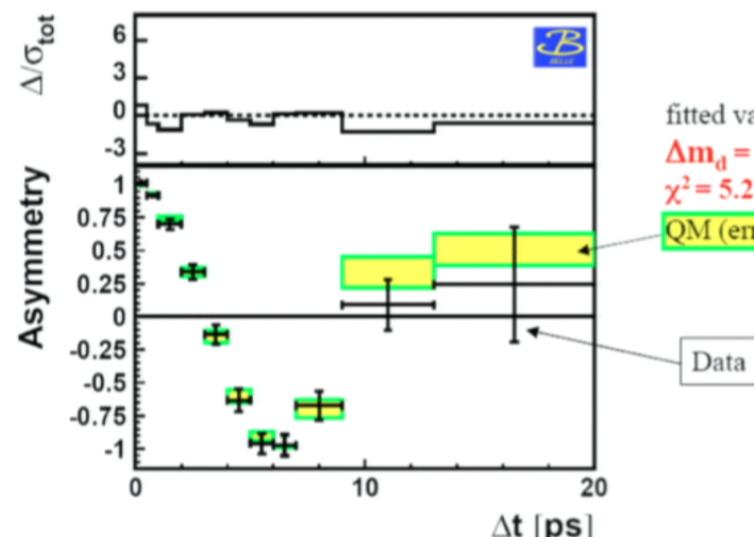
B

Δt dependent rates: opposite sign di-lepton vs same sign di-lepton

$$A(\Delta t) = \frac{I(\ell^\pm, \ell^\mp; \Delta t) - I(\ell^\pm, \ell^\pm; \Delta t)}{I(\ell^\pm, \ell^\mp; \Delta t) + I(\ell^\pm, \ell^\pm; \Delta t)} = \cos(\Delta m \Delta t)$$

QM prediction

After correcting for Δt resolution and selection efficiency by a deconvolution procedure:



fitted value:
 $\Delta m_d = (0.501 \pm 0.009) \text{ ps}^{-1}$
 $\chi^2 = 5.2 \text{ (11 dof)}$

$L \sim 150 \text{ fb}^{-1}$

BELLE PRL 99 131802 (2007)

$$\xi_{00} = 0.029 \pm 0.057$$

no enhanced sensitivity
due to CP violation here
(η not very small) $\left| \frac{\langle f_{CP} | T | B_H \rangle}{\langle f_{CP} | T | B_L \rangle} \right| \sim O(1)$

Decoherence and CPT violation

Modified Liouville – von Neumann equation for the density matrix of the kaon system:

$$\dot{\rho}(t) = \underbrace{-iH\rho + i\rho H^+}_{QM} + L(\rho)$$

extra term inducing decoherence:
 pure state \Rightarrow mixed state

Possible decoherence due quantum gravity effects:

Black hole information loss paradox \Rightarrow Possible decoherence near a black hole.

Hawking [1] suggested that at a microscopic level, in a quantum gravity picture, non-trivial space-time fluctuations (generically space-time foam) could give rise to decoherence effects, which would necessarily entail a violation of CPT [2].

J. Ellis et al.[3-6] \Rightarrow model of decoherence for neutral kaons \Rightarrow 3 new CPTV param. α, β, γ :

$$L(\rho) = L(\rho; \alpha, \beta, \gamma)$$

$$\alpha, \gamma > 0 , \quad \alpha\gamma > \beta^2$$

At most: $\alpha, \beta, \gamma = O\left(\frac{M_K^2}{M_{PLANCK}}\right) \approx 2 \times 10^{-20} \text{ GeV}$

[1] Hawking, Comm.Math.Phys.87 (1982) 395; [2] Wald, PR D21 (1980) 2742;[3] Ellis et. al, NP B241 (1984) 381; PRD53 (1996)3846 [4] Huet, Peskin, NP B434 (1995) 3; [5] Benatti, Floreanini, NPB511 (1998) 550 [6] Bernabeu, Ellis, Mavromatos, Nanopoulos, Papavassiliou: Handbook on kaon interferometry [hep-ph/0607322]

Decoherence and CPT violation

Modified Liouville – von Neumann equation for the density matrix of the kaon system:

$$\dot{\rho}(t) = \underbrace{-iH\rho + i\rho H^+}_{QM} + L(\rho)$$

extra term inducing decoherence:
 pure state \Rightarrow mixed state

Possible decoherence due quantum gravity effects:

Black hole information loss paradox \Rightarrow Possible decoherence near a black hole.

Hawking [1] suggested that at a microscopic level, in a quantum gravity picture, non-trivial space-time fluctuations (generically space-time foam) could give rise to decoherence effects, which would necessarily entail a violation of CPT [2].

J. Ellis et al.[3-6] \Rightarrow model of decoherence for neutral kaons \Rightarrow 3 new CPTV param. α, β, γ :

$$L(\rho) = L(\rho; \alpha, \beta, \gamma)$$

$$\alpha, \gamma > 0 , \quad \alpha\gamma > \beta^2$$

At most: $\alpha, \beta, \gamma = O\left(\frac{M_K^2}{M_{PLANCK}}\right) \approx 2 \times 10^{-20} \text{ GeV}$

[1] Hawking, Comm.Math.Phys.87 (1982) 395; [2] Wald, PR D21 (1980) 2742;[3] Ellis et. al, NP B241 (1984) 381; PRD53 (1996)3846 [4] Huet, Peskin, NP B434 (1995) 3; [5] Benatti, Floreanini, NPB511 (1998) 550 [6] Bernabeu, Ellis, Mavromatos, Nanopoulos, Papavassiliou: Handbook on kaon interferometry [hep-ph/0607322]

$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$: decoherence & CPTV

K

Study of time evolution of **single kaons**
decaying in $\pi^+ \pi^-$ and semileptonic final state

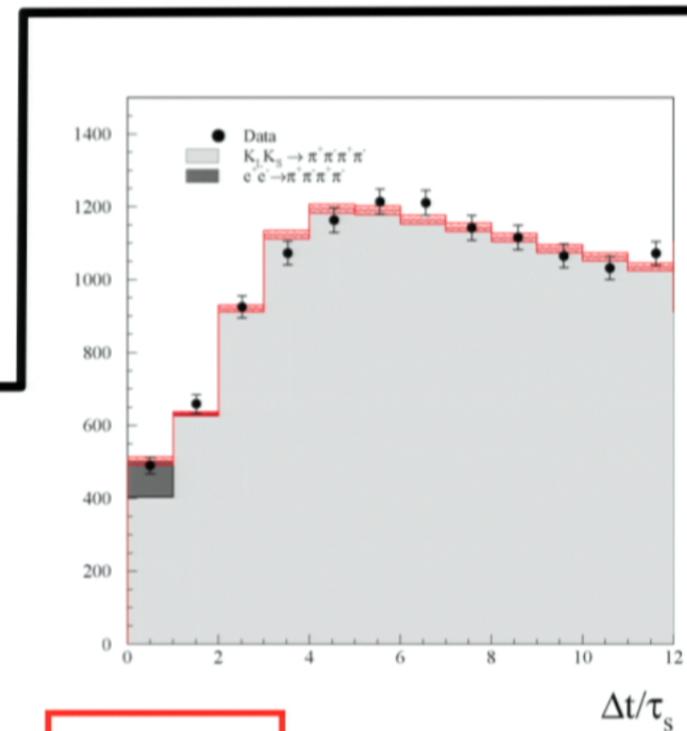
CLEAR PLB 364, 239 (1999)

$$\alpha = (-0.5 \pm 2.8) \times 10^{-17} \text{ GeV}$$

$$\beta = (2.5 \pm 2.3) \times 10^{-19} \text{ GeV}$$

$$\gamma = (1.1 \pm 2.5) \times 10^{-21} \text{ GeV}$$

single
kaons



In the complete positivity hypothesis

$$\alpha = \gamma, \quad \beta = 0$$

=> only one independent parameter: γ

The fit with $I(\pi^+ \pi^-, \pi^+ \pi^-; \Delta t, \gamma)$ gives:

KLOE result $L=1.5 \text{ fb}^{-1}$

$$\gamma = (0.7 \pm 1.2_{\text{STAT}} \pm 0.3_{\text{SYST}}) \times 10^{-21} \text{ GeV}$$

entangled
kaons

PLB 642(2006) 315
J.Phys.Conf.Ser.171:012008,2009.

$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$: decoherence & CPTV

K

Study of time evolution of **single kaons**
decaying in $\pi^+ \pi^-$ and semileptonic final state

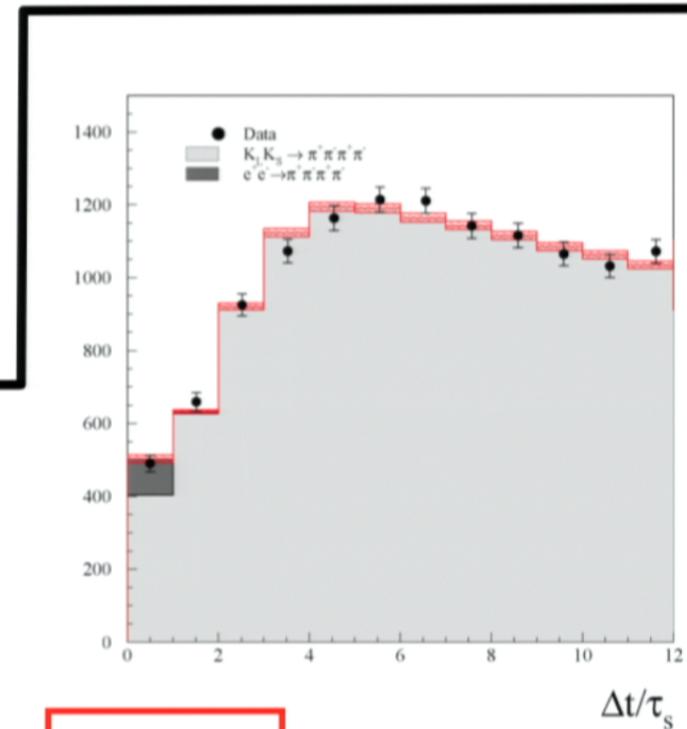
CLEAR PLB 364, 239 (1999)

$$\alpha = (-0.5 \pm 2.8) \times 10^{-17} \text{ GeV}$$

$$\beta = (2.5 \pm 2.3) \times 10^{-19} \text{ GeV}$$

$$\gamma = (1.1 \pm 2.5) \times 10^{-21} \text{ GeV}$$

single
kaons



In the complete positivity hypothesis

$$\alpha = \gamma, \quad \beta = 0$$

=> only one independent parameter: γ

The fit with $I(\pi^+ \pi^-, \pi^+ \pi^-; \Delta t, \gamma)$ gives:

KLOE result $L=1.5 \text{ fb}^{-1}$

$$\gamma = (0.7 \pm 1.2_{\text{STAT}} \pm 0.3_{\text{SYST}}) \times 10^{-21} \text{ GeV}$$

entangled
kaons

PLB 642(2006) 315
J.Phys.Conf.Ser.171:012008,2009.

$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$: CPT violation in entangled K states K

In presence of decoherence and CPT violation induced by quantum gravity (CPT operator “ill-defined”) the definition of the particle-antiparticle states could be modified. This in turn could induce a breakdown of the correlations imposed by Bose statistics (EPR correlations) to the kaon state:

[Bernabeu, et al. PRL 92 (2004) 131601, NPB744 (2006) 180].

$$\begin{aligned}|i\rangle &\propto \left(|K^0\rangle|\bar{K}^0\rangle - |K^0\rangle|\bar{K}^0\rangle \right) + \omega \left(|K^0\rangle|\bar{K}^0\rangle + |K^0\rangle|\bar{K}^0\rangle \right) \\ &\propto \left(|K_S\rangle|K_L\rangle - |K_L\rangle|K_S\rangle \right) + \omega \left(|K_S\rangle|K_S\rangle - |K_L\rangle|K_L\rangle \right)\end{aligned}$$

$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$: CPT violation in entangled K states **K**

In presence of decoherence and CPT violation induced by quantum gravity (CPT operator “ill-defined”) the definition of the particle-antiparticle states could be modified. This in turn could induce a breakdown of the correlations imposed by Bose statistics (EPR correlations) to the kaon state:

[Bernabeu, et al. PRL 92 (2004) 131601, NPB744 (2006) 180].

$$\begin{aligned}|i\rangle &\propto \left(|K^0\rangle|\bar{K}^0\rangle - |K^0\rangle|\bar{K}^0\rangle \right) + \omega \left(|K^0\rangle|\bar{K}^0\rangle + |K^0\rangle|\bar{K}^0\rangle \right) \\ &\propto \left(|K_S\rangle|K_L\rangle - |K_L\rangle|K_S\rangle \right) + \omega \left(|K_S\rangle|K_S\rangle - |K_L\rangle|K_L\rangle \right)\end{aligned}$$

$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$: CPT violation in entangled K states **K**

Fit of $I(\pi^+ \pi^-, \pi^+ \pi^-; \Delta t, \omega)$:

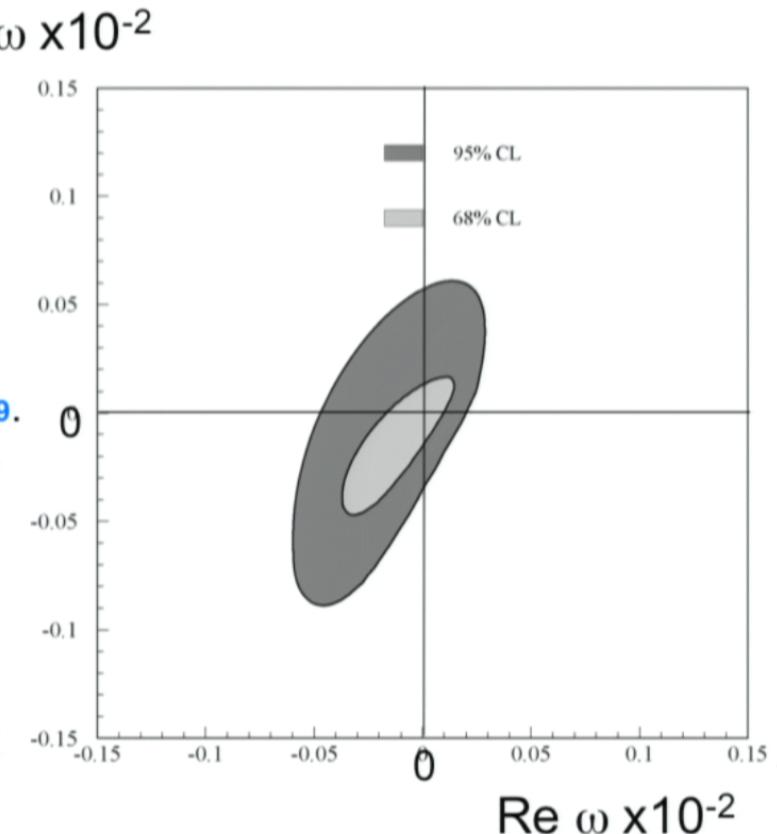
- Analysed data: 1.5 fb^{-1}

KLOE result: PLB 642(2006) 315
J.Phys.Conf.Ser.171:012008,2009.

$$\Re \omega = (-1.6_{-2.1}^{+3.0} \text{STAT} \pm 0.4_{\text{SYST}}) \times 10^{-4}$$

$$\Im \omega = (-1.7_{-3.0}^{+3.3} \text{STAT} \pm 1.2_{\text{SYST}}) \times 10^{-4}$$

$$|\omega| < 1.0 \times 10^{-3} \text{ at } 95\% \text{ C.L.}$$



CPT violation in entangled B states

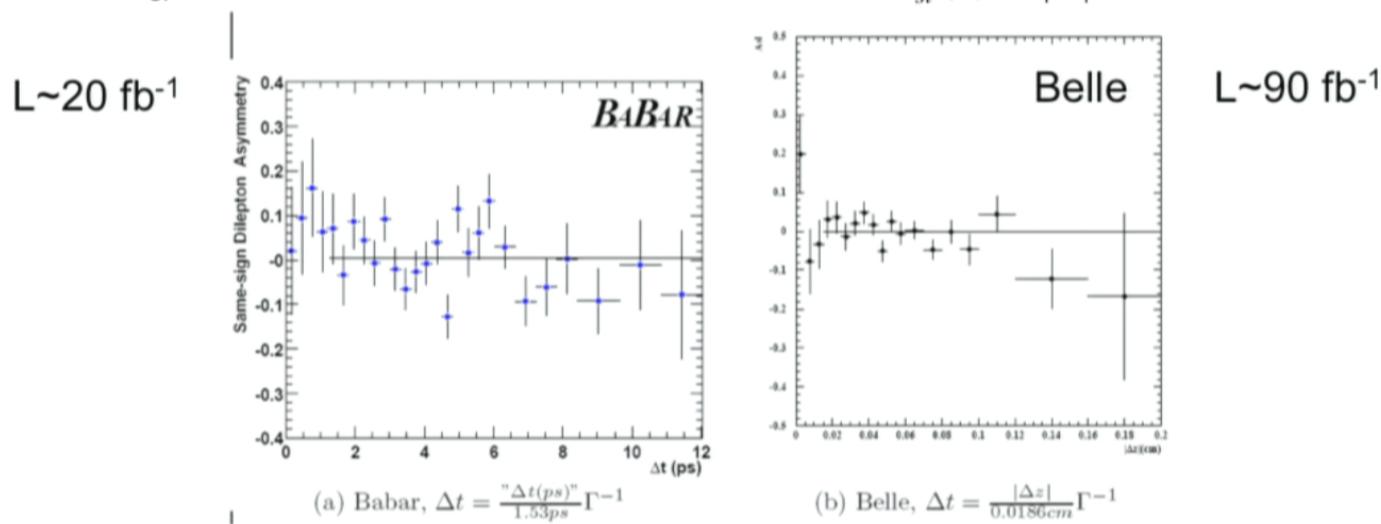
B

Observable asymmetry of Δt dependent rates: same sign di-lepton

$$A_{sl}(\Delta t) = \frac{I(\ell^+, \ell^+; \Delta t) - I(\ell^-, \ell^-; \Delta t)}{I(\ell^+, \ell^+; \Delta t) + I(\ell^-, \ell^-; \Delta t)}$$

- For $\omega=0$ equal sign di-lepton time asymmetry A_{sl} is exactly time independent
- For $\omega \neq 0$ A_{sl} acquires a time dependence

$$A_{sl}(0) \propto |\omega|^2$$



Alvarez, Bernabeu, Nebot JHEP 0611, 087:

$-0.0084 \leq \Re \omega \leq 0.0100$ at 95% C.L.

CPT violation in entangled B states

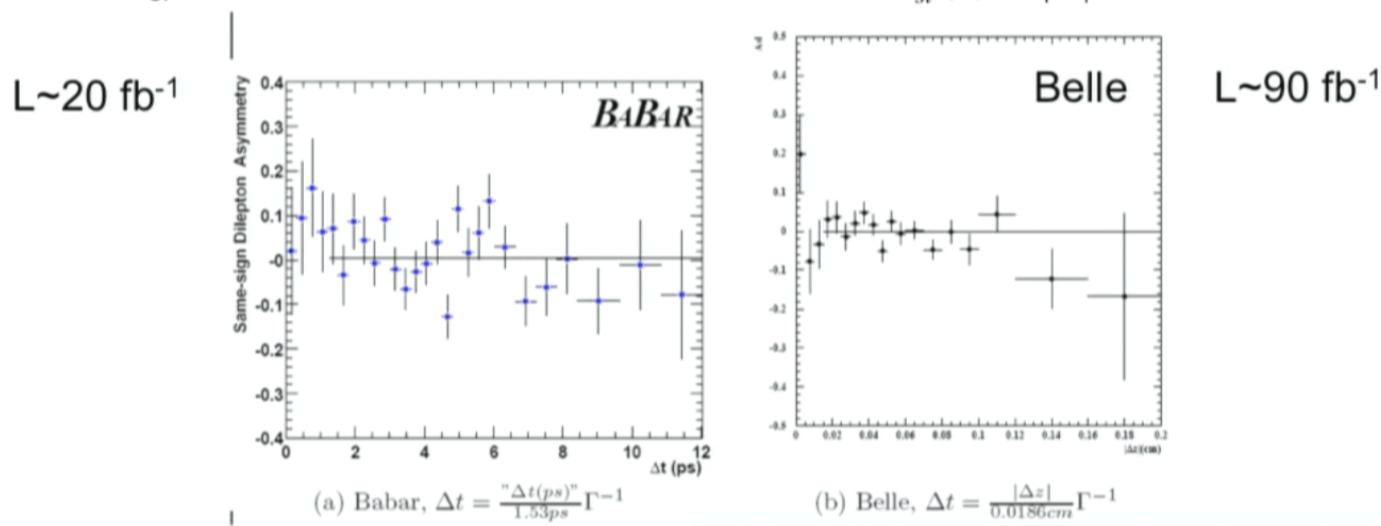
B

Observable asymmetry of Δt dependent rates: same sign di-lepton

$$A_{sl}(\Delta t) = \frac{I(\ell^+, \ell^+; \Delta t) - I(\ell^-, \ell^-; \Delta t)}{I(\ell^+, \ell^+; \Delta t) + I(\ell^-, \ell^-; \Delta t)}$$

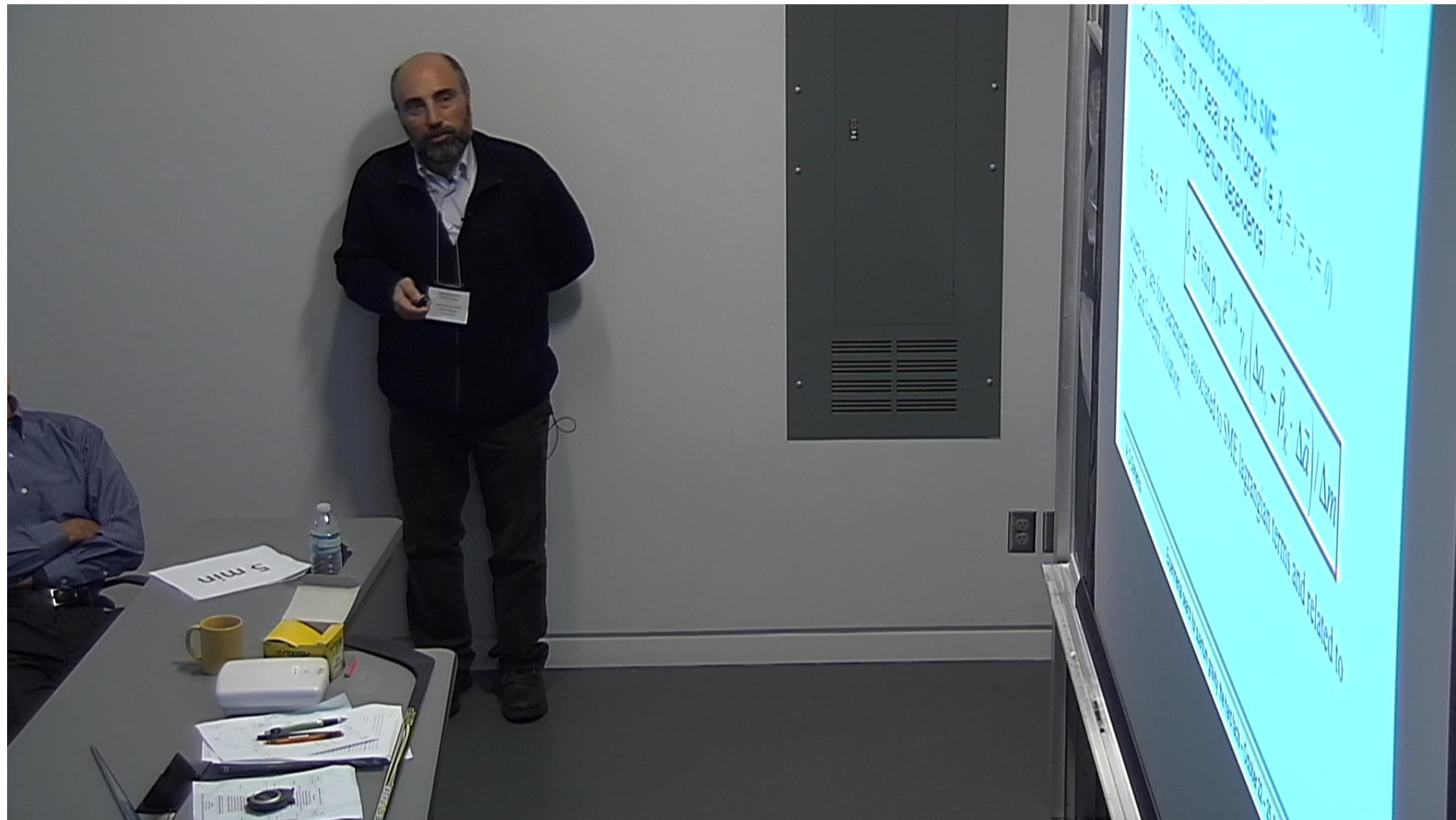
- For $\omega=0$ equal sign di-lepton time asymmetry A_{sl} is exactly time independent
- For $\omega \neq 0$ A_{sl} acquires a time dependence

$$A_{sl}(0) \propto |\omega|^2$$



Alvarez, Bernabeu, Nebot JHEP 0611, 087:

$-0.0084 \leq \Re \omega \leq 0.0100$ at 95% C.L.



CPT and Lorentz invariance violation (SME)

K

$$\delta = i \sin \phi_{SW} e^{i\phi_{SW}} \gamma_K (\Delta a_0 - \vec{\beta}_K \cdot \Delta \vec{a}) / \Delta m$$

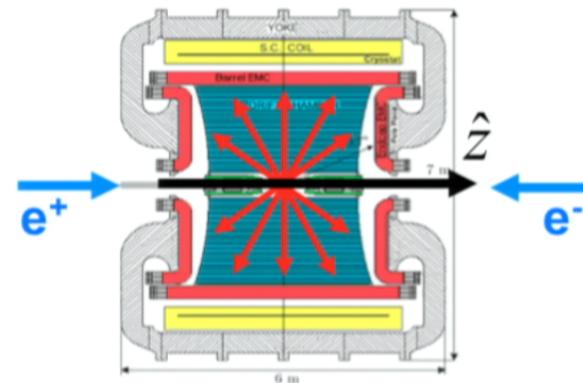
δ depends on sidereal time t since laboratory frame rotates with Earth.

For a ϕ -factory there is an additional dependence on the polar and azimuthal angle θ, ϕ of the kaon momentum in the laboratory frame:

$$\begin{aligned} \delta(\vec{p}, t) = & \frac{i \sin \phi_{SW} e^{i\phi_{SW}}}{\Delta m} \gamma_K \left\{ \Delta a_0 \right. \\ & + \beta_K \underline{\Delta a_z} (\cos \theta \cos \chi - \sin \theta \sin \phi \sin \chi) \\ & + \beta_K \left[-\underline{\Delta a_x} \sin \theta \sin \phi + \underline{\Delta a_y} (\cos \theta \sin \chi + \sin \theta \cos \phi \cos \chi) \right] \sin \Omega t \\ & \left. + \beta_K \left[+\underline{\Delta a_y} \sin \theta \sin \phi + \underline{\Delta a_x} (\cos \theta \sin \chi + \sin \theta \cos \phi \cos \chi) \right] \cos \Omega t \right\} \end{aligned}$$

Ω : Earth's sidereal frequency χ : angle between the z lab. axis and the Earth's rotation axis

At DAΦNE K mesons are produced with angular distribution $dN/d\Omega \propto \sin^2 \theta$

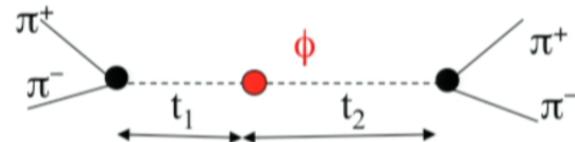


Exploiting neutral kaon interferometry

K

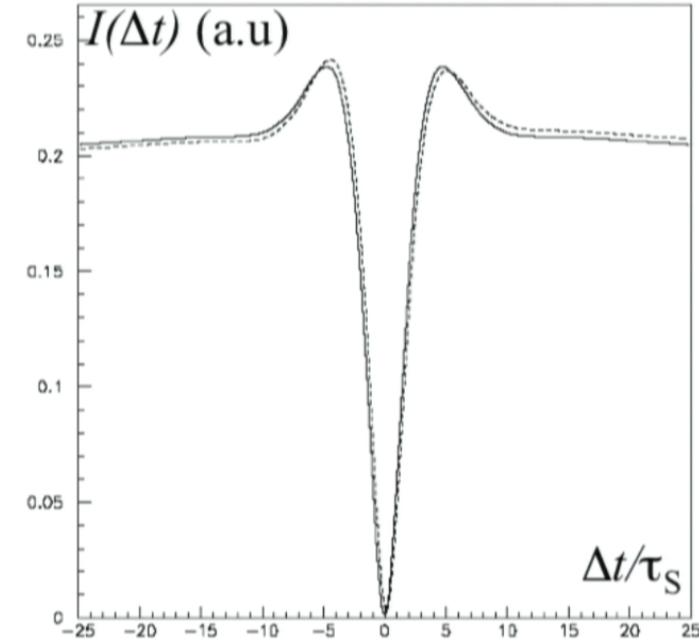
$$|i\rangle = \frac{1}{\sqrt{2}} [|K^0\rangle |\bar{K}^0\rangle - |\bar{K}^0\rangle |K^0\rangle] \quad \eta_i = |\eta_i| e^{i\phi_i} = \langle f_i | T | K_L \rangle / \langle f_i | T | K_S \rangle$$

$$I(f_1, f_2; \Delta t) \propto \left\{ |\eta_1|^2 e^{-\Gamma_L \Delta t} + |\eta_2|^2 e^{-\Gamma_S \Delta t} - 2|\eta_1||\eta_2| e^{-(\Gamma_S + \Gamma_L)\Delta t/2} \cos(\Delta m \Delta t + \phi_2 - \phi_1) \right\}$$



$$\eta_{+-}^{(1)} = \varepsilon (1 - \delta(+\vec{p}, t) / \varepsilon)$$

$$\eta_{+-}^{(2)} = \varepsilon (1 - \delta(-\vec{p}, t) / \varepsilon)$$

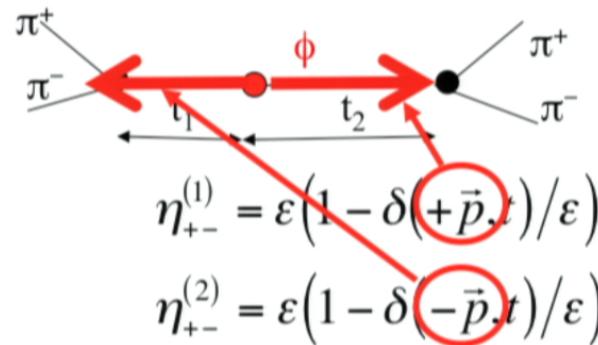


Exploiting neutral kaon interferometry

K

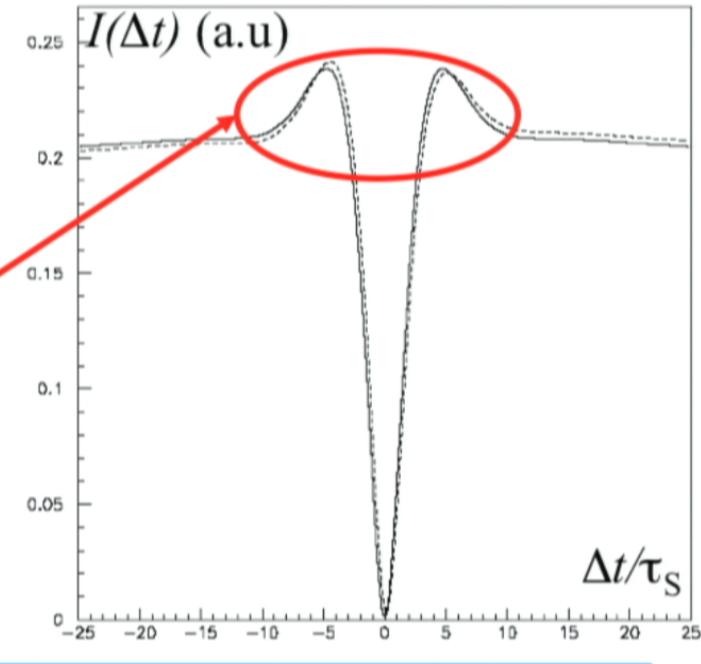
$$|i\rangle = \frac{1}{\sqrt{2}} [|K^0\rangle |\bar{K}^0\rangle - |\bar{K}^0\rangle |K^0\rangle] \quad \eta_i = |\eta_i| e^{i\phi_i} = \langle f_i | T | K_L \rangle / \langle f_i | T | K_S \rangle$$

$$I(f_1, f_2; \Delta t) \propto \left\{ |\eta_1|^2 e^{-\Gamma_L \Delta t} + |\eta_2|^2 e^{-\Gamma_S \Delta t} - 2|\eta_1||\eta_2| e^{-(\Gamma_S + \Gamma_L)\Delta t/2} \cos(\Delta m \Delta t + \phi_2 - \phi_1) \right\}$$



$\Im(\Delta\delta/\epsilon)$
from the asymmetry at small Δt

$\Re(\Delta\delta/\epsilon) \approx 0$ because $\Delta\delta \perp \epsilon$
from the asymmetry at large Δt



Measurement of $\Delta a_{x,y,z}$ at KLOE

K

$\Delta a_{x,y,z}$ from $\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$
 (analysis vs polar angle θ and sidereal time t ;
 integration in azimuthal angle ϕ)

$I[\pi^+ \pi^- (\cos \theta > 0), \pi^+ \pi^- (\cos \theta < 0); \Delta t]$
 • at $\Delta t \sim \tau_s$ sensitive to $\text{Im}(\delta/\varepsilon)$

With $L=1 \text{ fb}^{-1}$ (preliminary): $\chi^2/\text{dof}=131/117$

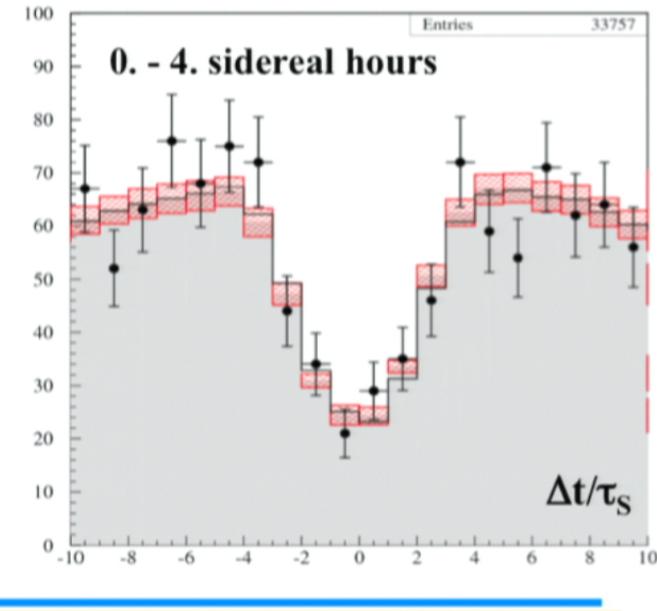
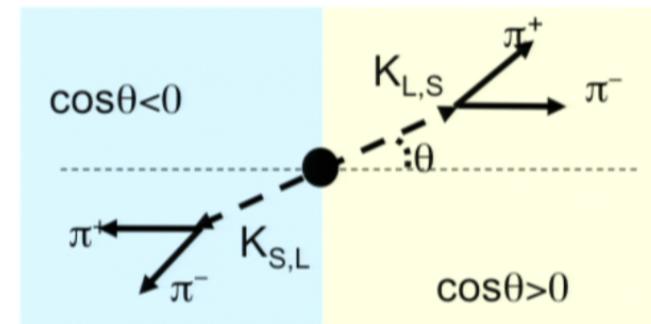
$$\Delta a_X = (-6.3 \pm 6.0) \times 10^{-18} \text{ GeV}$$

$$\Delta a_Y = (2.8 \pm 5.9) \times 10^{-18} \text{ GeV}$$

$$\Delta a_Z = (2.4 \pm 9.7) \times 10^{-18} \text{ GeV}$$

KTeV : $\Delta a_X, \Delta a_Y < 9.2 \times 10^{-22} \text{ GeV}$ @ 90% CL

BABAR $\Delta a_{x,y}^B, (\Delta a_0^B - 0.30 \Delta a_Z^B) \sim O(10^{-13} \text{ GeV})$



A. Di Domenico

Experimental search for quantum gravity: the hard facts – October 22 – 25, 2012 – Waterloo, ON, Canada

CPT and Lorentz invariance violation (SME)

B

$$z = \frac{\gamma_K \left(\Delta a_0^B - \vec{\beta}_K \cdot \Delta \vec{a}^B \right)}{\Delta m - i \Delta \Gamma / 2}$$

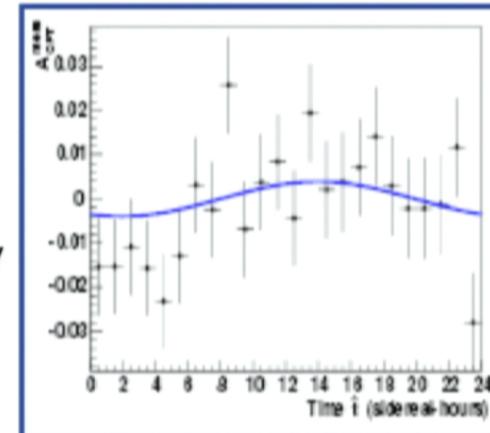
boosted B's at B-factory (almost fixed direction)
 => cannot distinguish between Δa_0^B and Δa_z^B

searching for a dependence of the form

$$z = z_0 + z_1 \cos(\Omega t + \phi)$$

A_{CPT}
 dilepton
 asymmetry

$L \sim 232 \text{ fb}^{-1}$



Babar

[PRL 100 (2008) 131802]

$$\Delta a_0^B - 0.30 \Delta a_z^B \cong (-3.0 \pm 2.4)(\Delta m / \Delta \Gamma) \times 10^{-15} \text{ GeV}$$

$$\Delta a_X^B \cong (-22 \pm 7)(\Delta m / \Delta \Gamma) \times 10^{-15} \text{ GeV}$$

i.e. $\sim O(10^{-13} \text{ GeV})$

$$\Delta a_Y^B \cong (-14^{+10}_{-13})(\Delta m / \Delta \Gamma) \times 10^{-15} \text{ GeV}$$

A. Di Domenico

Experimental search for quantum gravity: the hard facts – October 22 – 25, 2012 – Waterloo, ON, Canada

KLOE-2 at upgraded DAΦNE

K

DAΦNE upgraded in luminosity:

- new scheme of the interaction region (crabbed waist scheme) at DAΦNE (proposal by P. Raimondi)
- increase L by a factor $\times 3$ demonstrated by a successful experimental test

KLOE-2 experiment:

- extend the KLOE physics program at DAΦNE upgraded in luminosity
- Collect $O(10)$ fb^{-1} of integrated luminosity in the next 2-3 years

Physics program (see EPJC 68 (2010) 619-681)

- Neutral kaon interferometry, CPT symmetry & QM tests
- Kaon physics, CKM, LFV, rare K_S decays
- η, η' physics
- Light scalars, $\gamma\gamma$ physics
- Hadron cross section at low energy, muon anomaly

Detector upgrade:

- $\gamma\gamma$ tagging system:
- inner tracker:
- small angle and quad calorimeters:
- FEE maintenance and upgrade
- Computing and networking update
- etc.. (Trigger, software, ...)

Prospect for Super B-factories

B

Test of	Param.	Present best measurement	Super B-factory $L \sim 50 \text{ ab}^{-1}$ (stat. only)
CPT	$\text{Re } z$	$(1.9 \pm 4.9) \times 10^{-2}$	$\pm 0.4 \times 10^{-2}$
CPT	$\text{Im } z$	$(-8 \pm 4) \times 10^{-3}$	$\pm 0.4 \times 10^{-3}$
QM	ζ_{00}	$(2.9 \pm 5.7) \times 10^{-2}$	$\pm 3.6 \times 10^{-3}$
QM	ζ_{SL}	$(0.4 \pm 1.7) \times 10^{-2}$	$\pm 1 \times 10^{-3}$
CPT & QM	α, β, γ		
CPT & EPR corr.	$\text{Re}(\omega)$	<0.01	$\pm 4 \times 10^{-4}$
CPT & EPR corr.	$\text{Im}(\omega)$		
CPT & Lorentz	$\Delta a_0 - 0.3 \Delta a_Z$	$(-3.0 \pm 2.4) \times \Delta m / \Delta \Gamma$ $\times 10^{-15} \text{ GeV}$	$\pm 1.5 \times \Delta m / \Delta \Gamma$ $\times 10^{-16} \text{ GeV}$
CPT & Lorentz	Δa_X	$(-22 \pm 7) \times \Delta m / \Delta \Gamma$ $\times 10^{-15} \text{ GeV}$	$\pm 4.4 \times \Delta m / \Delta \Gamma$ $\times 10^{-16} \text{ GeV}$
CPT & Lorentz	Δa_Y	$(-14 \pm 12) \times \Delta m / \Delta \Gamma$ $\times 10^{-15} \text{ GeV}$	$\pm 7.6 \times \Delta m / \Delta \Gamma$ $\times 10^{-16} \text{ GeV}$

Conclusions

- Neutral meson systems are unique and excellent laboratories for the study of discrete symmetries (e.g. recent first direct T viol. observed), and in particular CPT symmetry.
 - Several parameters related to possible
 - CPT violation (within QM)
 - Decoherence and CPT violation
 - CPT violation and Lorentz symmetry breakinghave been recently measured at **KLOE** for **K** mesons and at **Belle** and **Babar** for **B** mesons, with very high precision, especially for kaons. In some cases the precision reaches the interesting Planck's scale region.
 - All results are consistent with no CPT violation.
 - CPT symmetry and QM tests are one of the main issues of the **KLOE-2** physics program; a significant improvement in the precision is expected.
 - **Improvements in CPT tests are expected at Super B-factories**
-