Tests of quantum mechanics and discrete symmetries in entangled neutral K (B, D) meson systems

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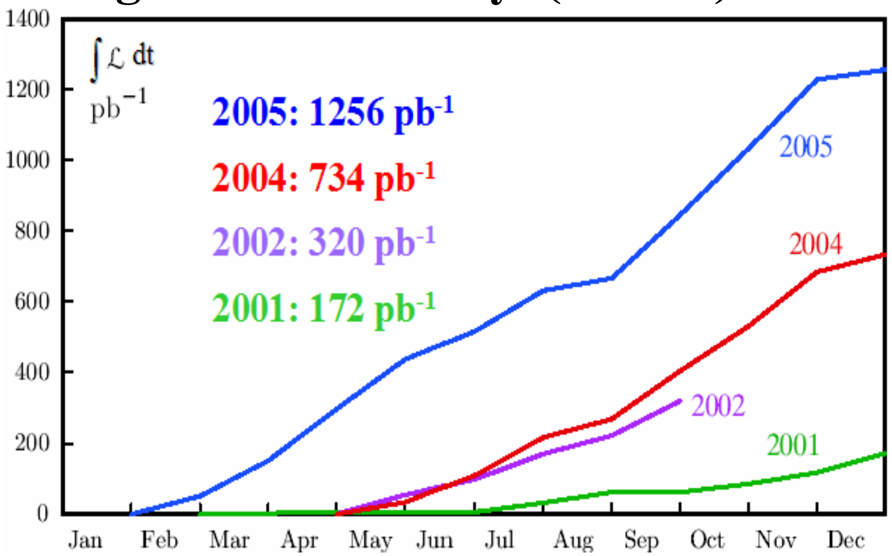
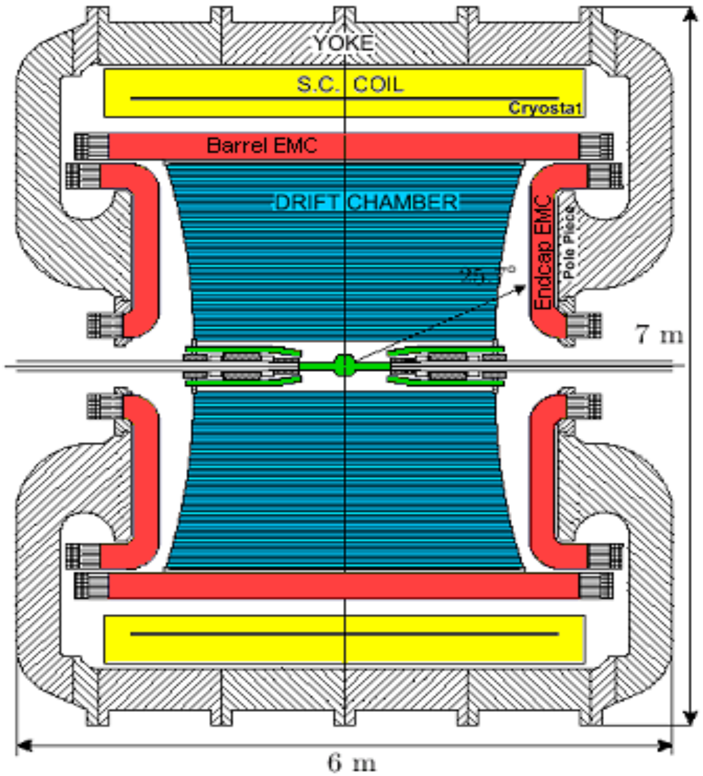
Status of DAΦNE and KLOE/KLOE-2

The KLOE detector at the Frascati ϕ-factory DAΦNE

Integrated luminosity (KLOE)





Lead/scintillating fiber calorimeter

drift chamber

4 m diameter × 3.3 m length

helium based gas mixture

Total KLOE $\int \mathcal{L}\, dt \sim 2.5\ fb^{-1}$

(2001 - 05)

$\rightarrow \sim 2.5 \times 10^9\ K_S K_L$ pairs

KLOE-2 at upgraded DAΦNE

DAΦNE upgraded in luminosity:

- new scheme of the interaction region (crabbed waist scheme) at DAΦNE (proposal by P. Raimondi)
- increase L by a factor x 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**)

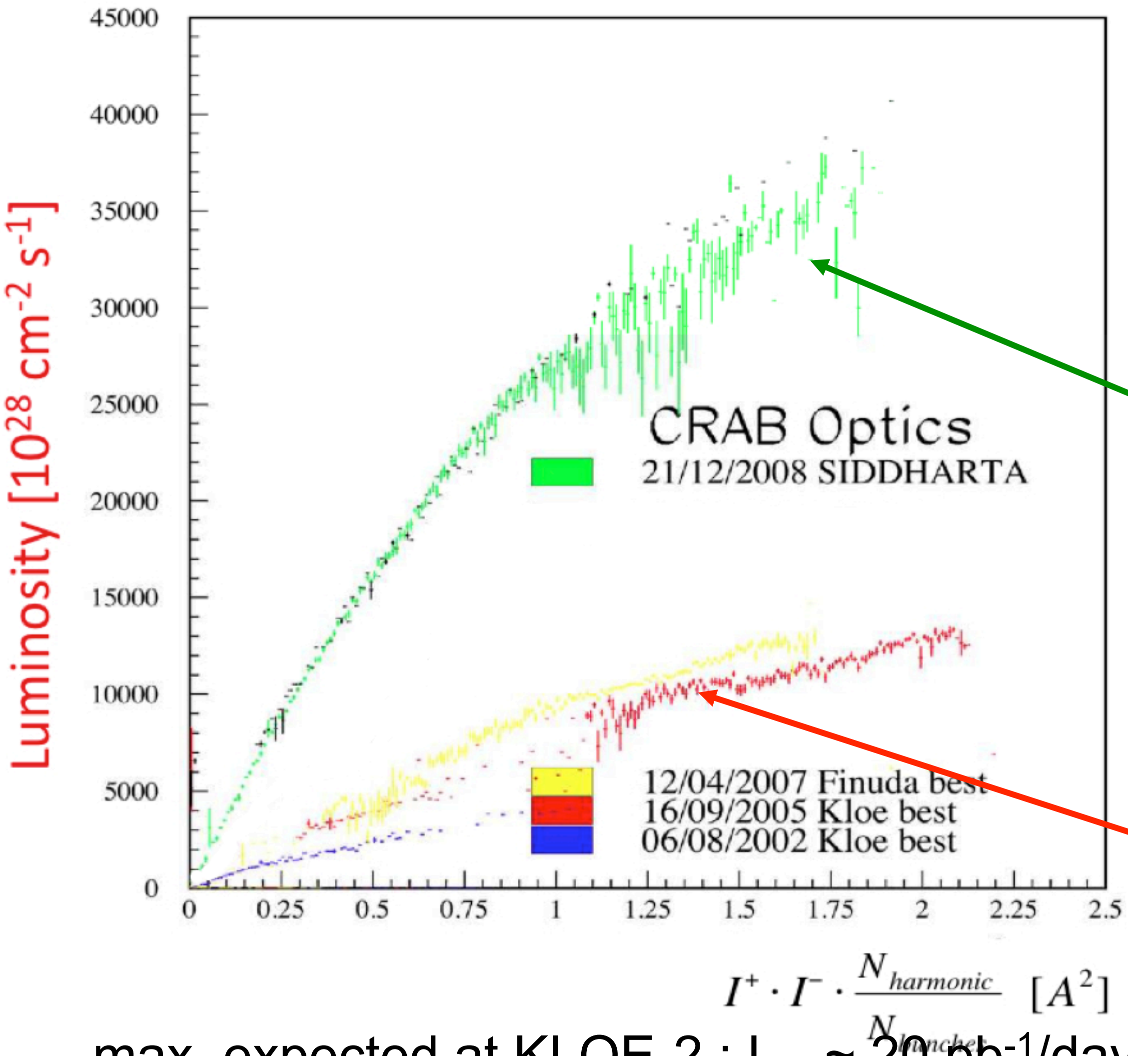
- Neutral kaon interferometry, CPT symmetry & QM tests
- Kaon physics, CKM, LFV, rare K_S decays
- η,η' physics
- Light scalars, $\gamma\gamma$ physics
- Hadron cross section at low energy, a_μ
- Dark forces: search for light U boson

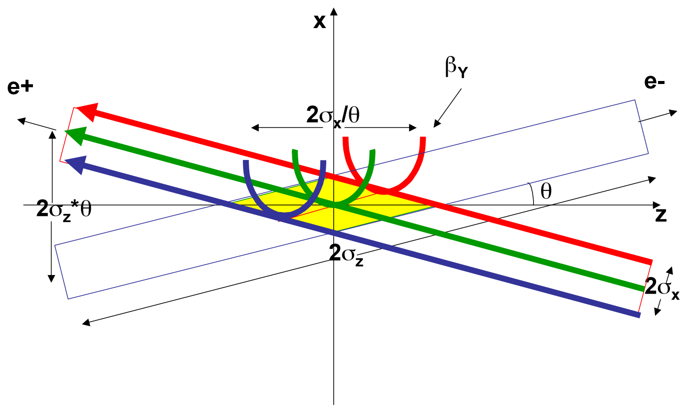
Detector upgrade:

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

DAΦNE luminosity upgrade

Crabbed waist scheme at DAΦNE





Crabbed waist is realized with a sextupole in phase with the IP in X and at $\pi/2$ in Y

NEW COLLISION SCHEME:
Large Piwinski angle
Crab-Waist compensation SXTs

Old collision scheme

max. expected at KLOE-2 : L_{int} ~ 20 pb^{-1}/day x 200 dd/year = 4 fb^{-1} /year

DAΦNE luminosity upgrade

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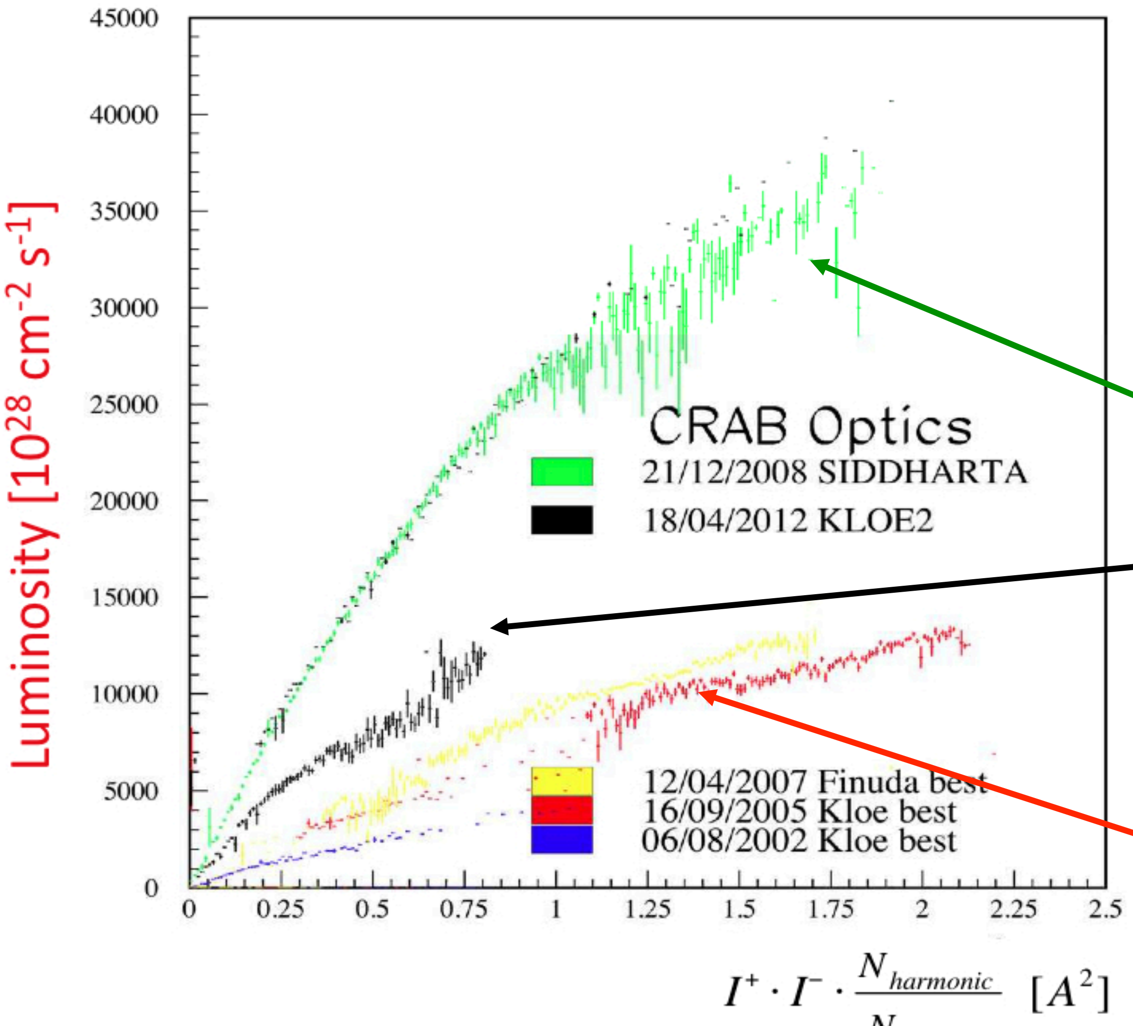

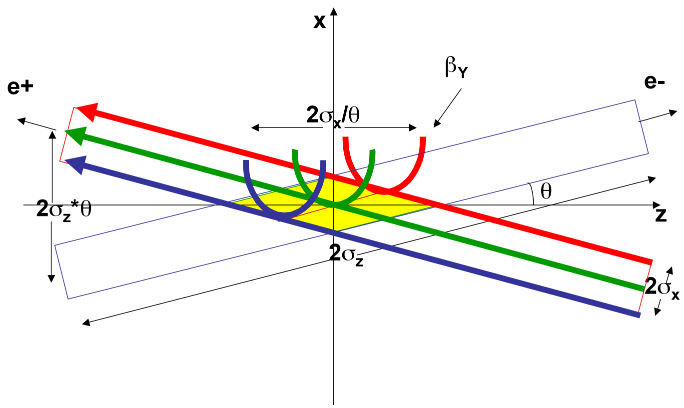

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Present commissioning phase
New coll. scheme + KLOE det.

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DAΦNE luminosity upgrade

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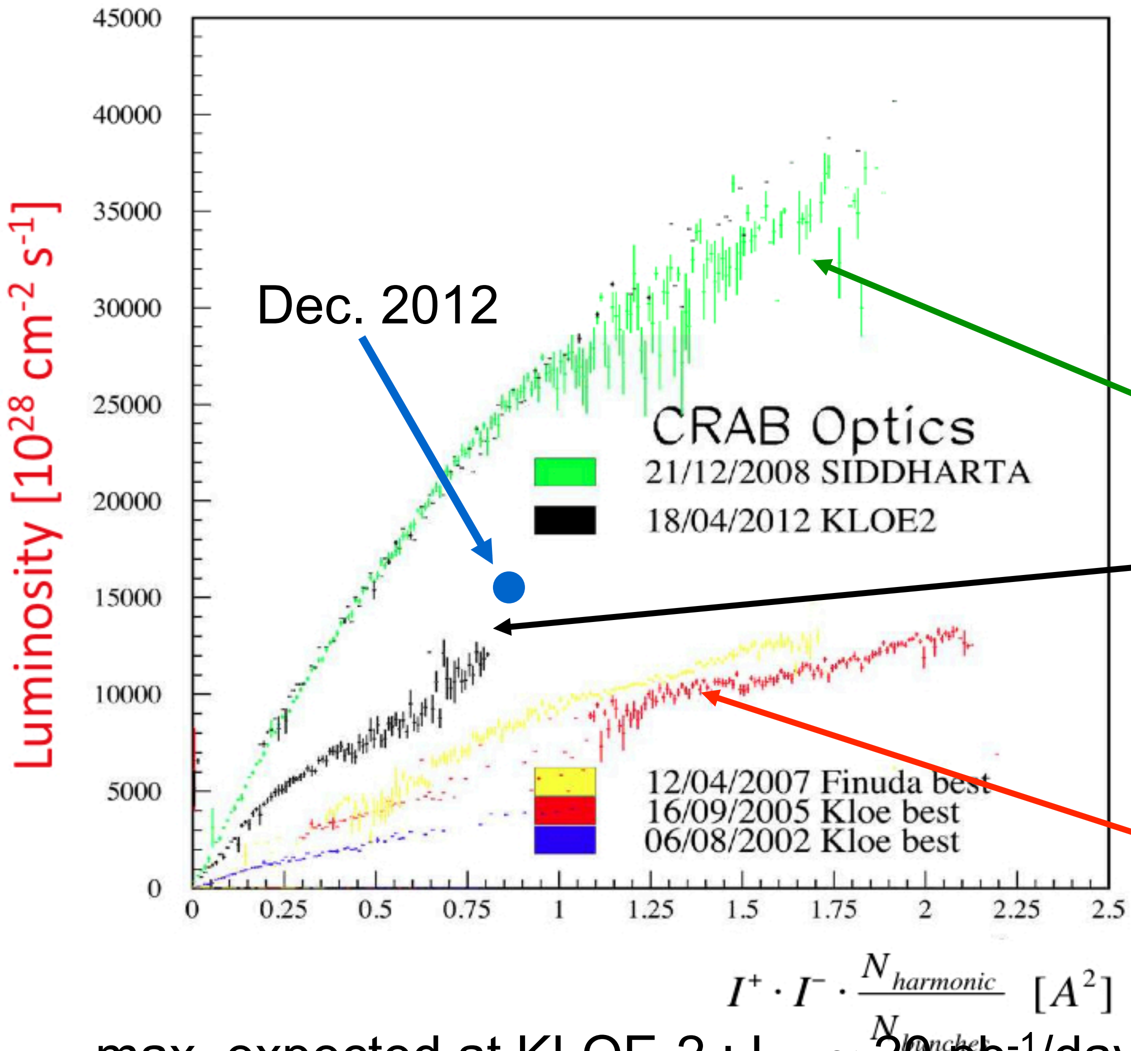

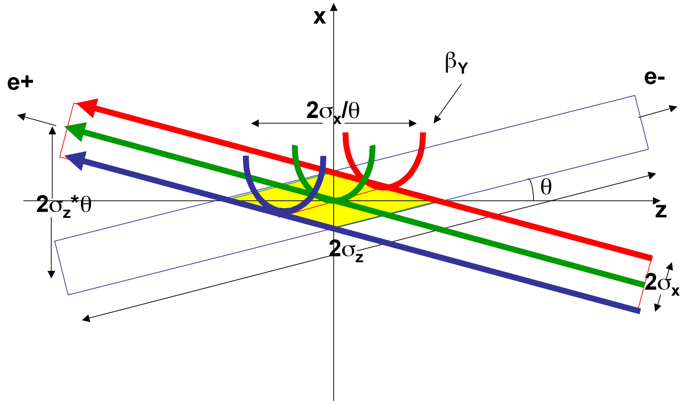

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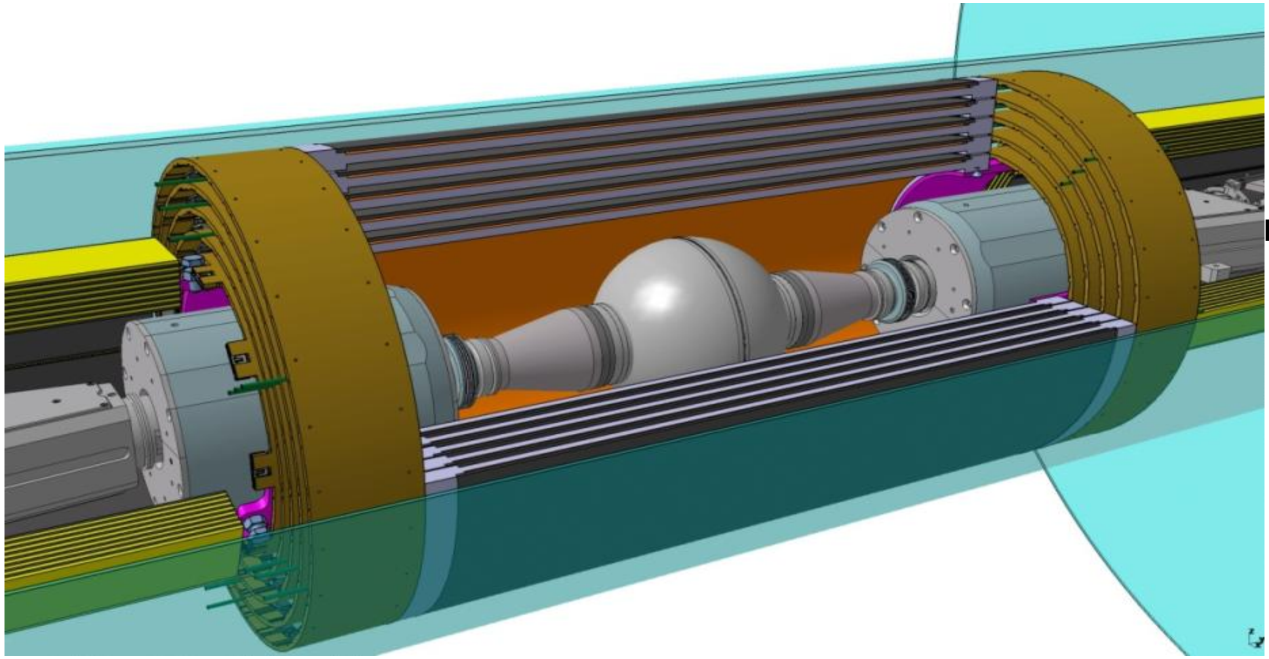
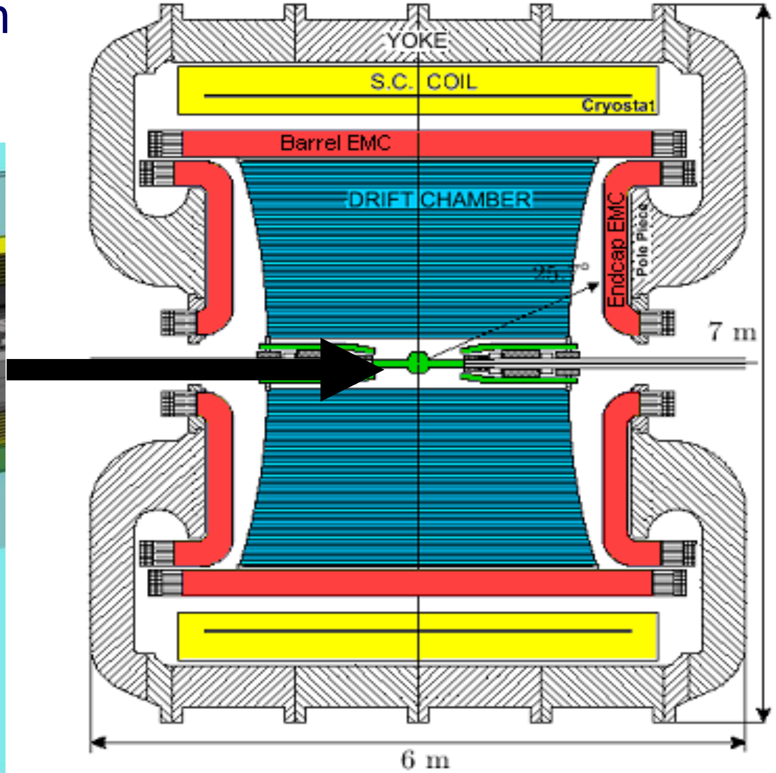
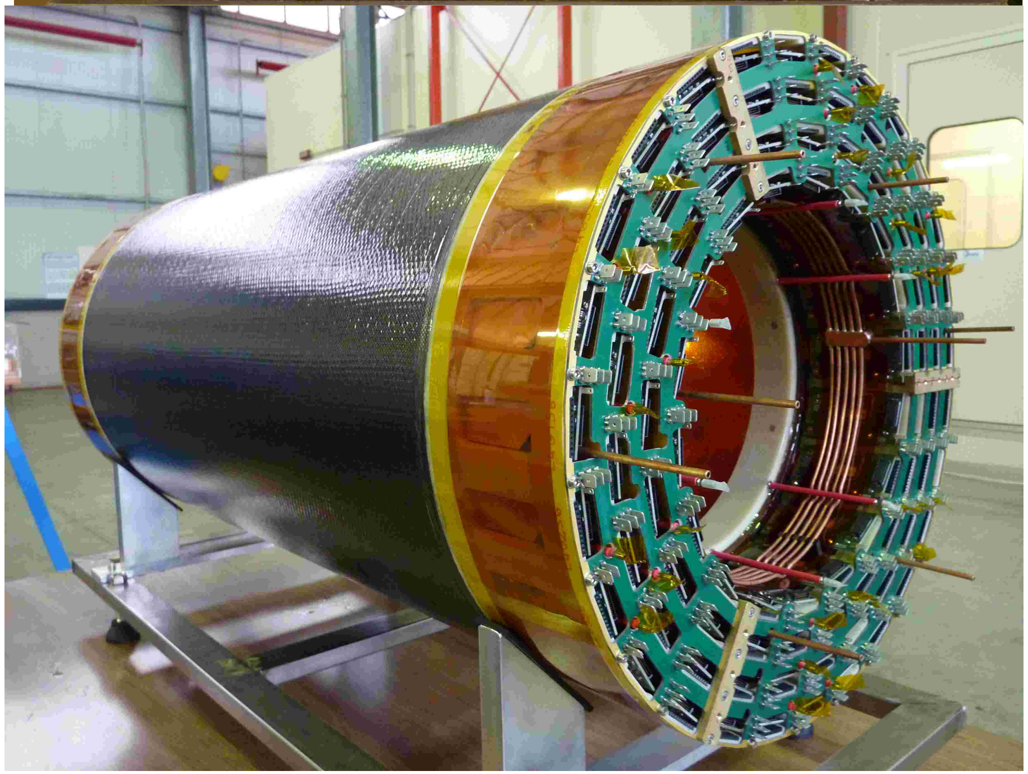
Inner tracker at KLOE-2

- 4 independent tracking layers for a fine vertex reconstruction of K_S and η
- 200 μm $\sigma_{r\phi}$ and 500 μm σ_z spatial resolutions with XV readout
- 700 mm active length
- from 150 to 250 mm radii
- 1.8% X_0 total radiation length in the active region
- Realized with **Cylindrical-GEM** detectors





Inner tracker at KLOE



- Construction completed
- Installation inside KLOE (by summer 2013)
- Commissioning (autumn 2013)

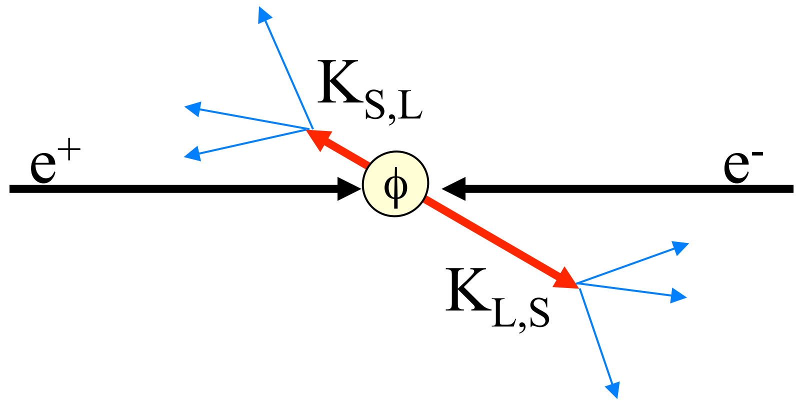
Entangled neutral kaons at a ϕ-factory

K

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

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

$p_K = 110$ MeV/c
$\lambda_S = 6$ mm $\lambda_L = 3.5$ m



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

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

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

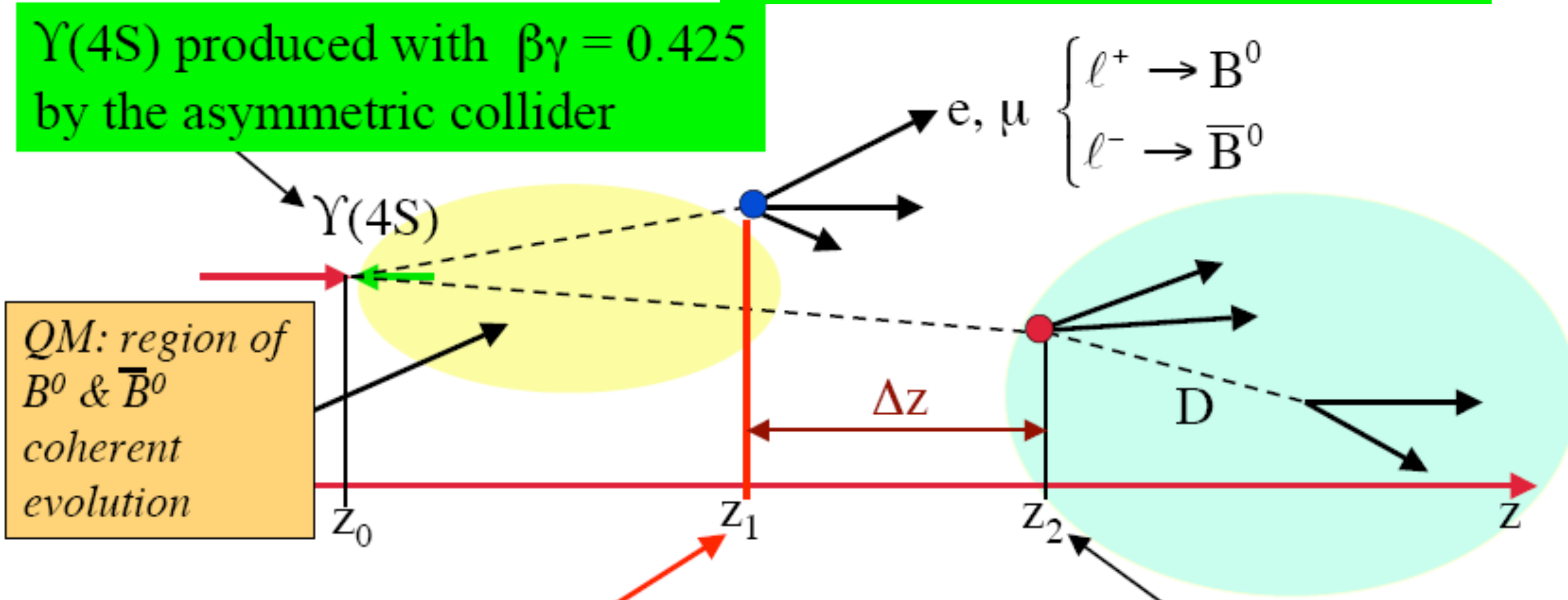
List of KLOE discrete symmetries and QM tests with K^0 K

Mode	Test of	Param.	KLOE measurement
$K_L \to \pi^+\pi^-$	CP	BR	$(1.963 \pm 0.012 \pm 0.017) \times 10^{-3}$
$K_S \to 3\pi^0$	CP	BR	$< 2.6 \times 10^{-8}$
$K_S \to \pi e \nu$	CP	A_S	$(1.5 \pm 11) \times 10^{-3}$
$K_S \to \pi e \nu$	CPT	$\mathrm{Re}(x_-)$	$(-0.8 \pm 2.5) \times 10^{-3}$
$K_S \to \pi e \nu$	CPT	$\mathrm{Re}(y)$	$(0.4 \pm 2.5) \times 10^{-3}$
using unitarity (Bell-Steinberger rel.)	T CPT	$\mathrm{Re}(\varepsilon)$ $\mathrm{Im}(\delta)$	$(159.6 \pm 1.3) \times 10^{-5}$ $(0.4 \pm 2.1) \times 10^{-5}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	α	$(-10 \pm 37) \times 10^{-17}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	β	$(1.8 \pm 3.6) \times 10^{-19}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	γ	$(0.4 \pm 4.6) \times 10^{-21}$ GeV compl. pos. hyp. $(0.7 \pm 1.2) \times 10^{-21}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	$\mathrm{Re}(\omega)$	$(-1.6 \pm 2.6) \times 10^{-4}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	$\mathrm{Im}(\omega)$	$(-1.7 \pm 3.4) \times 10^{-4}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & Lorentz	Δa_0	$(0.4 \pm 1.8) \times 10^{-17}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & Lorentz	Δa_Z	$(2.4 \pm 9.7) \times 10^{-18}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & Lorentz	Δa_X	$(-6.3 \pm 6.0) \times 10^{-18}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & Lorentz	Δa_Y	$(2.8 \pm 5.9) \times 10^{-18}$ GeV

Entangled B meson pairs

B

$$|i\rangle = \frac{1}{\sqrt{2}}\left[|B^0(\vec{p})\rangle|\bar{B}^0(-\vec{p})\rangle - |\bar{B}^0(\vec{p})\rangle|B^0(-\vec{p})\rangle\right]$$



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

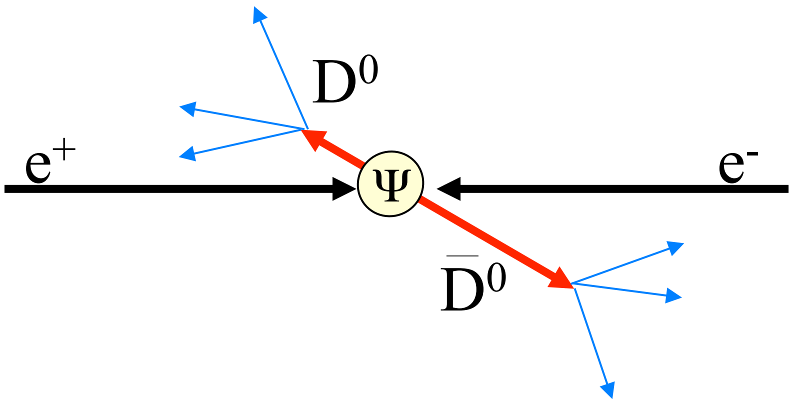
$$\Delta t \approx \Delta z / c\beta\gamma$$

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

Entangled neutral D mesons at a τ-charm factory

D

Production of the vector meson $\Psi(3770)$ in e^+e^- annihilations:



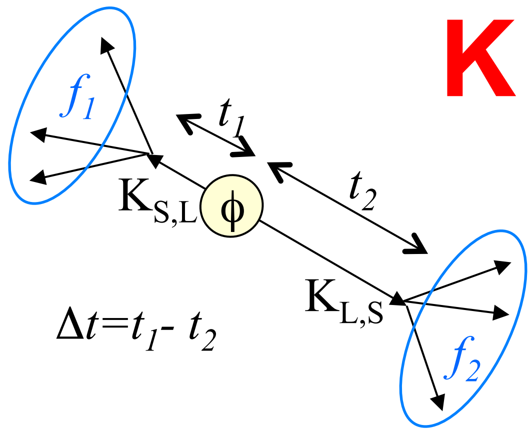
$e^+e^- \rightarrow \Psi(3770) \rightarrow D^0\overline{D}^0$

$$|i\rangle = \frac{1}{\sqrt{2}}\left[\left|D^0(\vec{p})\right\rangle\left|\overline{D}^0(-\vec{p})\right\rangle - \left|\overline{D}^0(\vec{p})\right\rangle\left|D^0(-\vec{p})\right\rangle\right]$$

assume symmetric machine

Neutral kaon interferometry

K



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

Double differential time distribution:

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

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

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

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

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

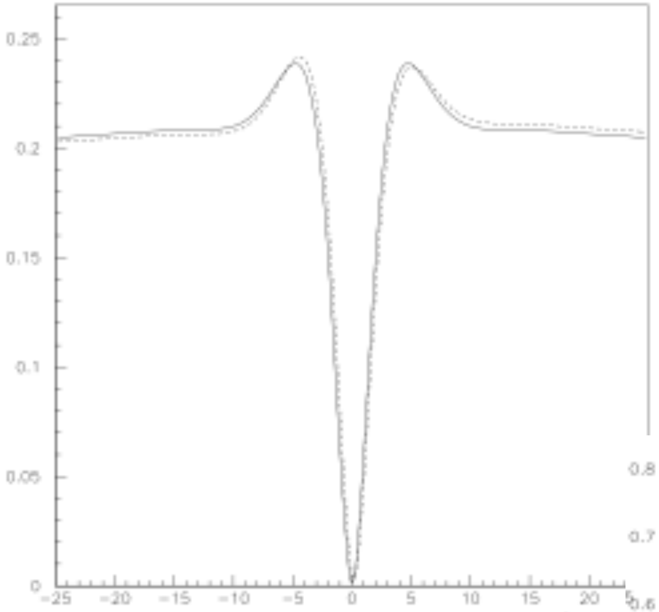
characteristic interference term at a ϕ-factory => interferometry

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)



$\Delta t/\tau_S$

$\phi \to K_S K_L \to \pi^+\pi^- \; \pi^0\pi^0$

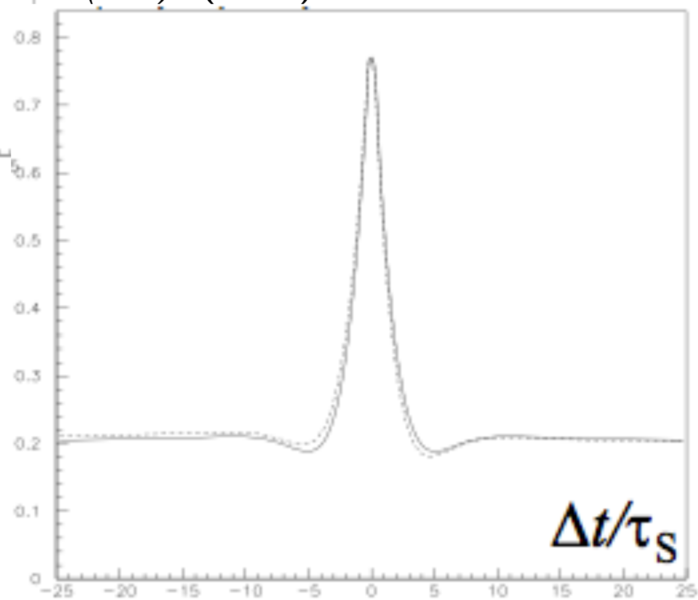
$$\Re\left(\frac{\varepsilon'}{\varepsilon}\right) \quad \Im\left(\frac{\varepsilon'}{\varepsilon}\right)$$

$$\Re\delta + \Re x_-$$

$$\Im\delta + \Im x_+$$

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

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



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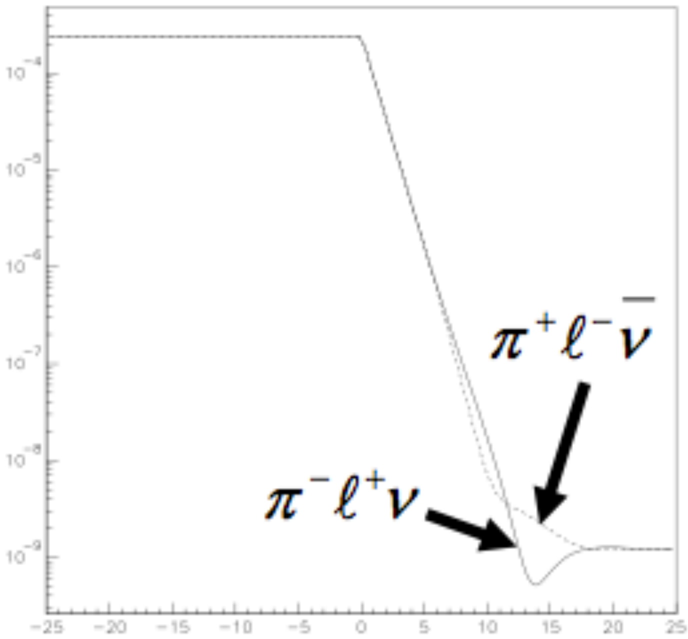


$\Delta t/\tau_S$

$\phi \to K_S K_L \to \pi\pi \;\; \pi\ell\nu$

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

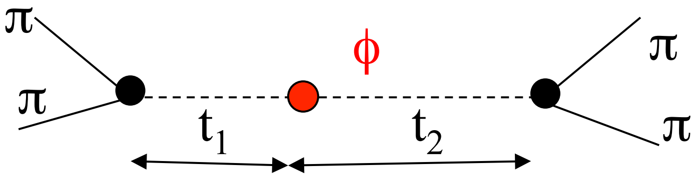
$$\phi_{\pi\pi}$$

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

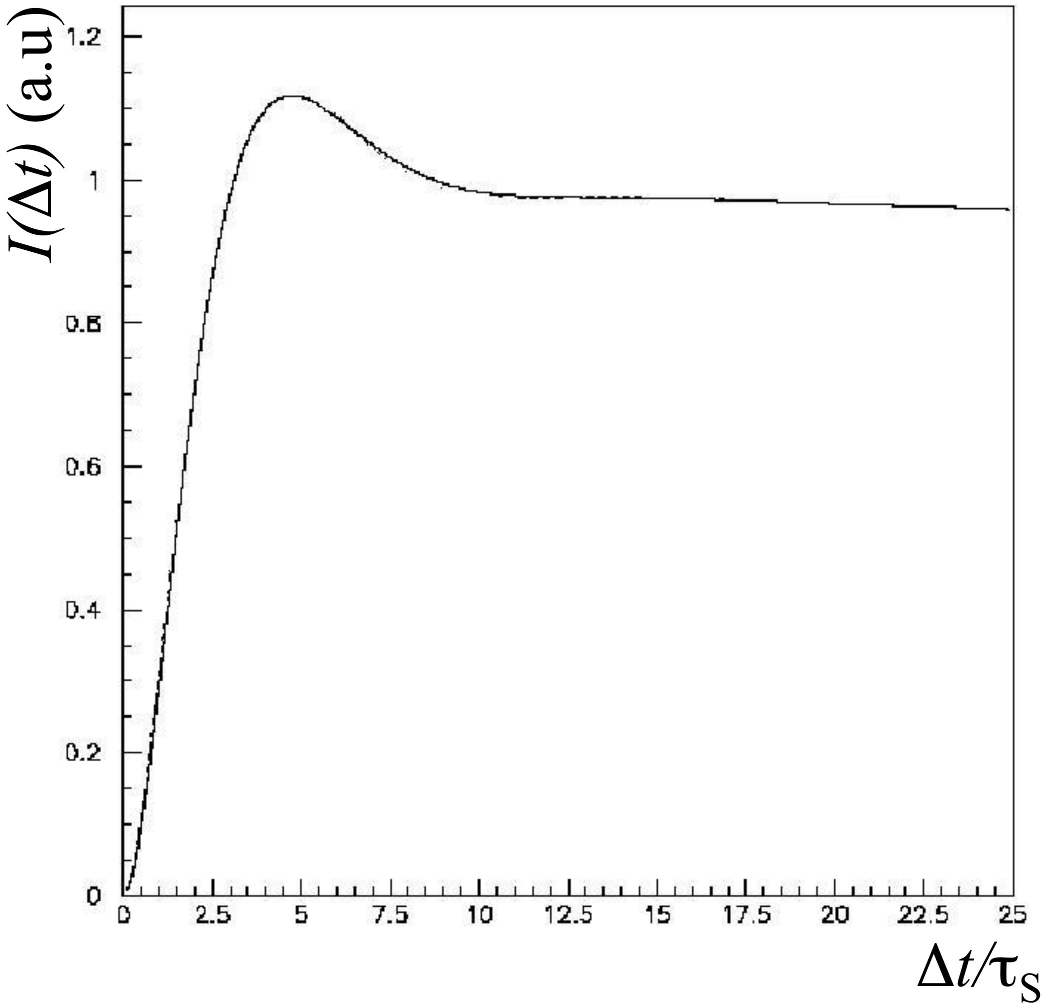
K

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

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



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



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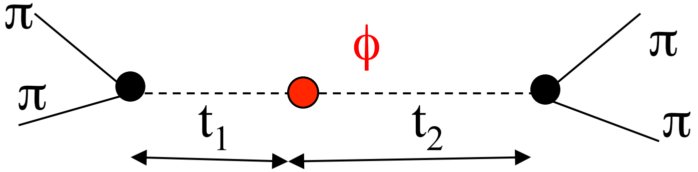
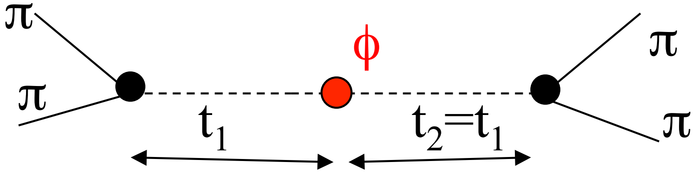


EPR correlation:

no simultaneous decays (Δt=0) in the same final state due to the destructive quantum interference



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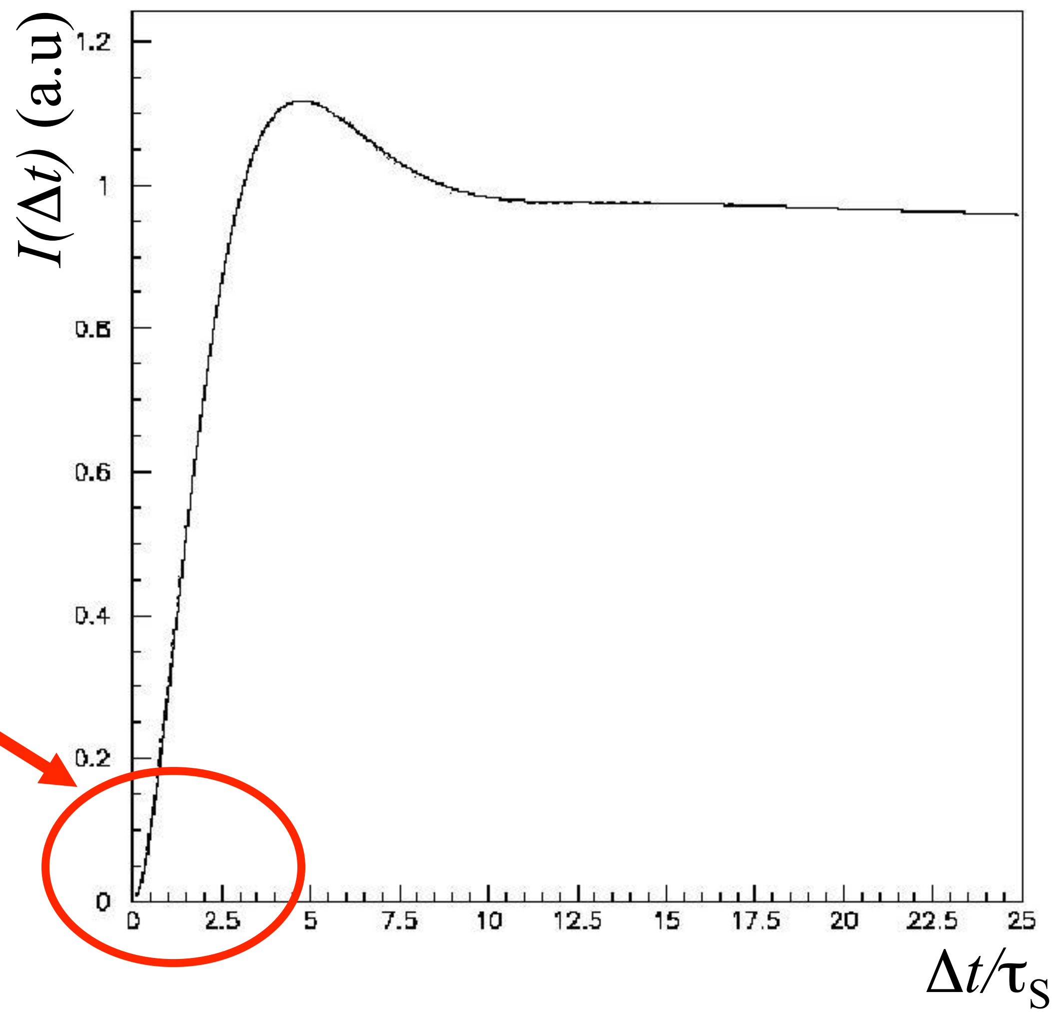

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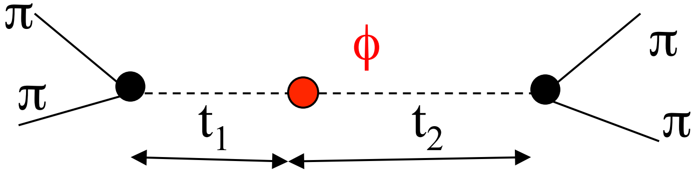

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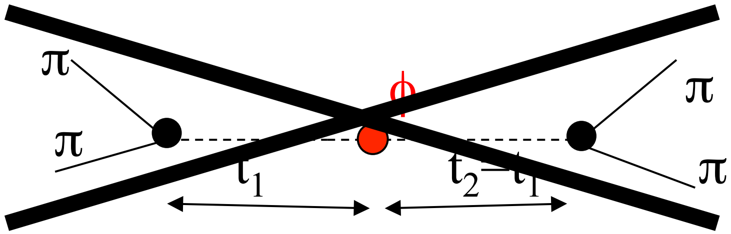

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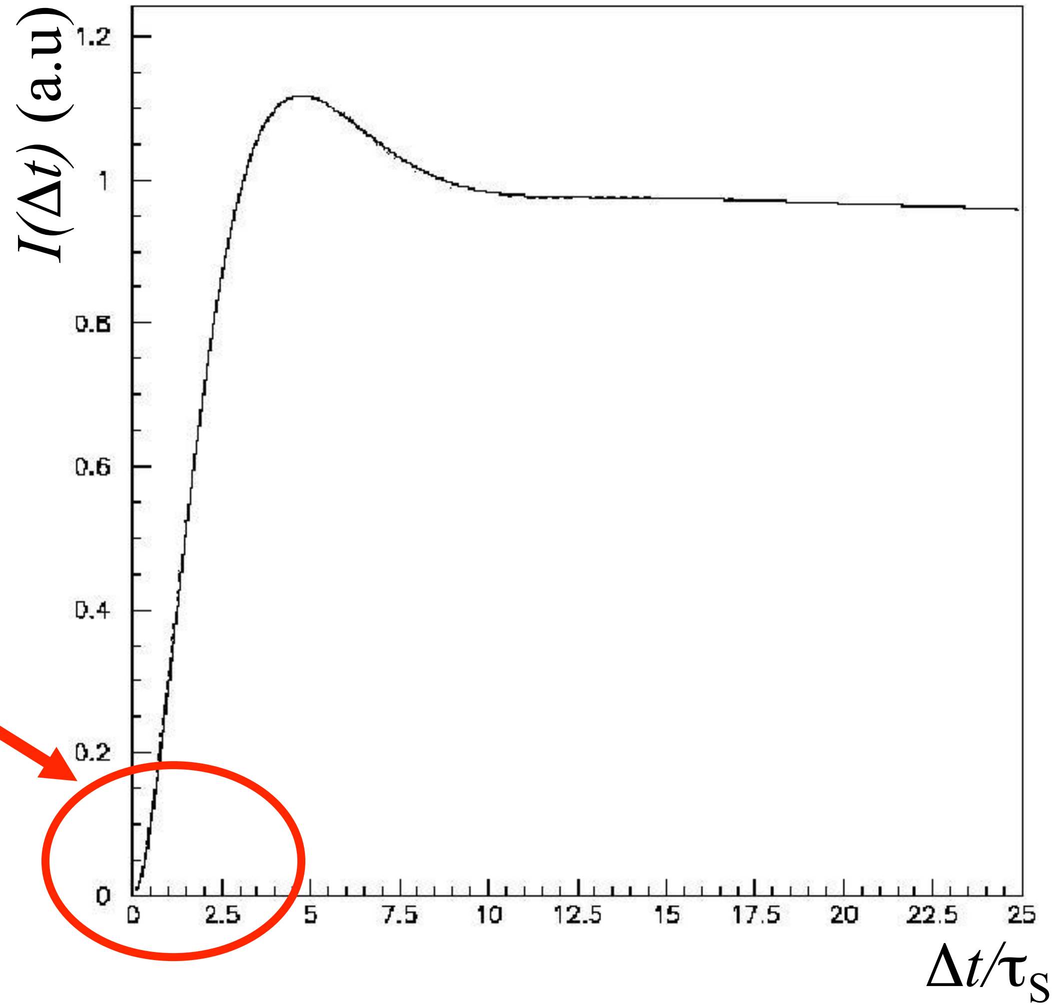

K

test of quantum coherence
(or search for decoherence and CPT violation effects)

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

K

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

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

$$-2\Re\left(\langle\pi^+\pi^-,\pi^+\pi^-|K^0\overline{K}^0(\Delta t)\rangle\langle\pi^+\pi^-,\pi^+\pi^-|\overline{K}^0K^0(\Delta t)\rangle^*\right)\Big]$$

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

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

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

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

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Decoherence parameter:

$\zeta_{0\bar{0}} = 0 \quad \to \quad$ QM

$\zeta_{0\bar{0}} = 1 \quad \to \quad$ 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

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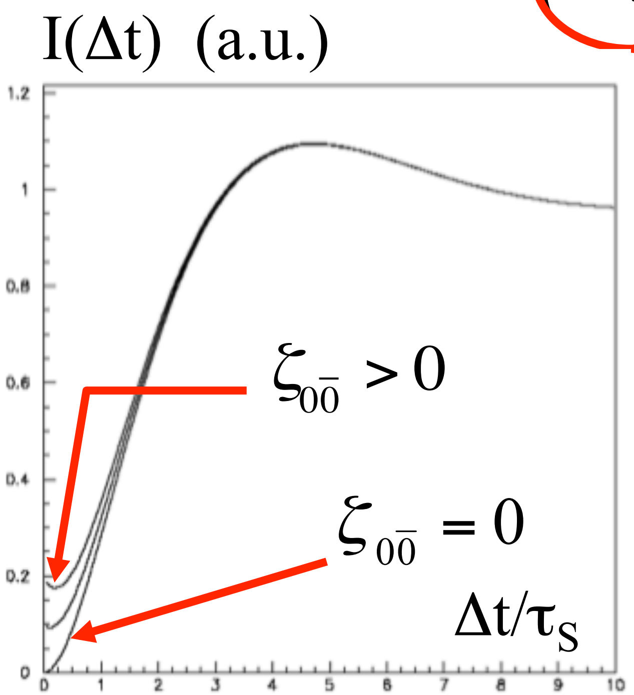
$$-\left(1-\zeta_{0\bar{0}}\right)\cdot 2\Re\left(\langle\pi^+\pi^-,\pi^+\pi^-|K^0\overline{K}^0(\Delta t)\rangle\langle\pi^+\pi^-,\pi^+\pi^-|\overline{K}^0K^0(\Delta t)\rangle^*\right)\Big]$$



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K

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

KLOE result: PLB 642(2006) 315 Found. Phys. 40 (2010) 852

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

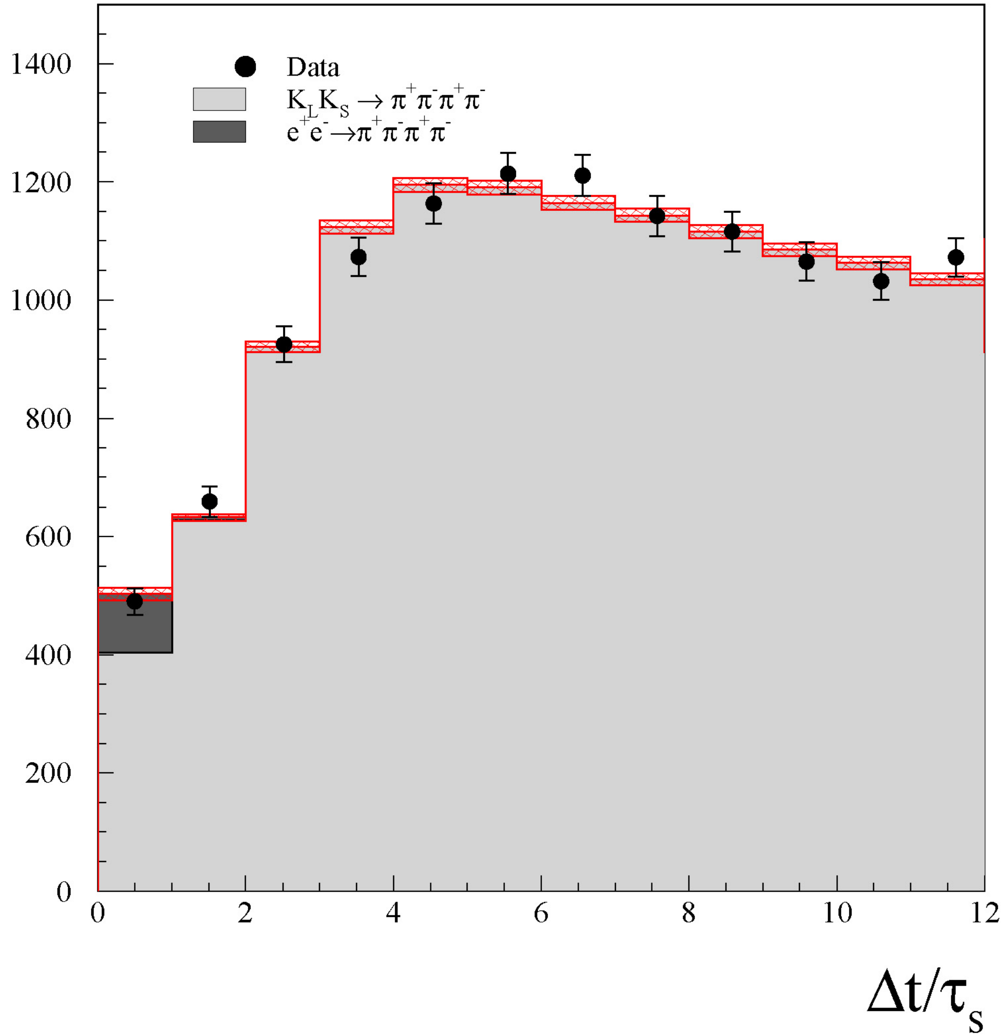
Observable suppressed by CP violation: $|\eta_{+-}|^2 \sim |\varepsilon|^2 \sim 10^{-6}$

=> terms $\zeta_{00}/|\eta_{+-}|^2$

=> high sensitivity to ζ_{00}

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

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



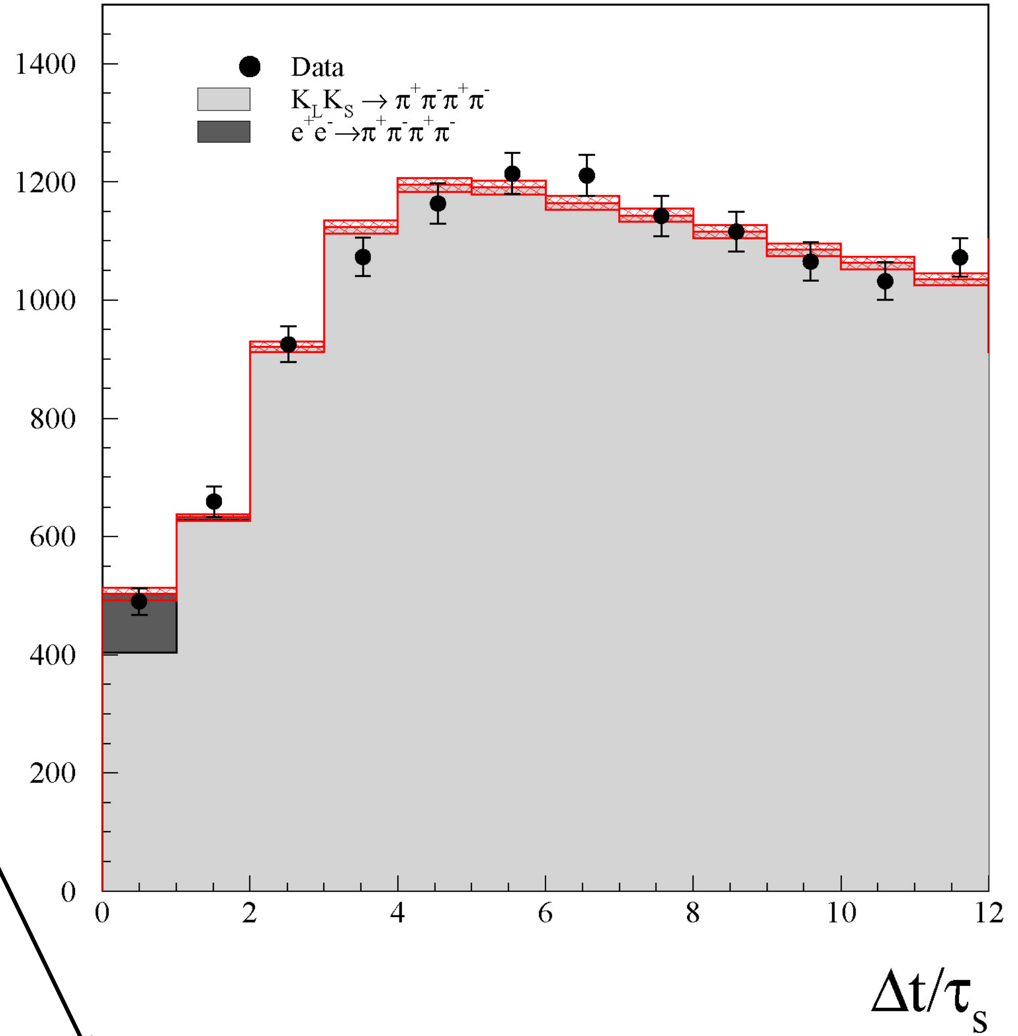
$\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$: test of quantum coherence

K

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

KLOE result: PLB 642(2006) 315
Found. Phys. 40 (2010) 852

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



Observable suppressed by CP violation: $|\eta_{+-}|^2 \sim |\varepsilon|^2 \sim 10^{-6}$
=> terms $\zeta_{00}/|\eta_{+-}|^2$
=> 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

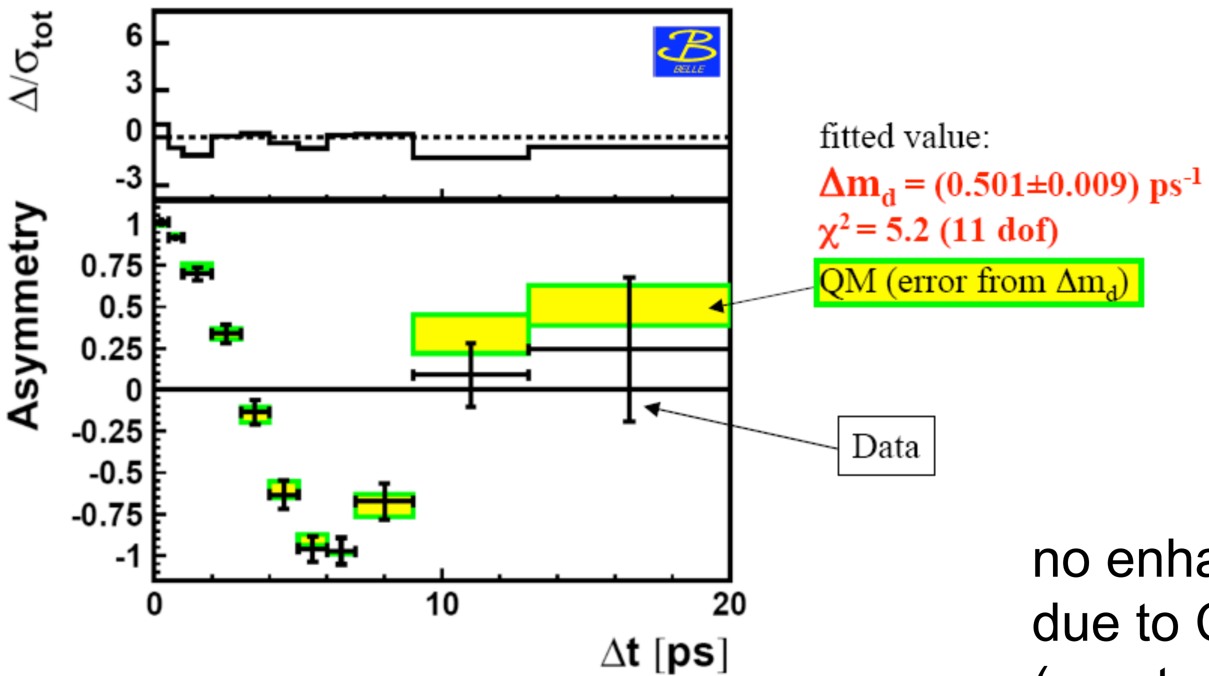
Test of quantum coherence in neutral B mesons

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

$$A(\Delta t)=\frac{I(\ell^{\pm},\ell^{\mp};\Delta t)-I(\ell^{\pm},\ell^{\pm};\Delta t)}{I(\ell^{\pm},\ell^{\mp};\Delta t)+I(\ell^{\pm},\ell^{\pm};\Delta t)}=\cos(\Delta m\Delta t)\Rightarrow(1-\zeta_{0\bar{0}})\cos(\Delta m\Delta t)+\zeta_{0\bar{0}}(....)$$

QM prediction

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



L~150 fb^{-1}

BELLE PRL 99 131802 (2007)

$$\boxed{\zeta_{0\bar{0}}=0.029\pm0.057}$$

no enhanced sensitivity due to CP violation here (η not very small)

$$\left|\frac{\langle f|T|B_H\rangle}{\langle f|T|B_L\rangle}\right|=\left|\frac{1-\lambda_f}{1+\lambda_f}\right|$$

Test of quantum coherence in neutral D mesons

D

Δt **integrated** rates: opposite sign di-lepton and same sign di-lepton ($\Delta C=\Delta Q$ rule and CPT invariance assumed)

$$\boxed{\frac{1-R}{1+R} = Q \quad \Rightarrow \quad (1-\zeta_{SL})Q}$$

QM prediction

$$Q = \frac{1-y^2}{1+x^2} \approx 1 \qquad\qquad R = \frac{2\sqrt{I(\ell^+,\ell^+)\cdot I(\ell^-,\ell^-)}}{I(\ell^+,\ell^-)+I(\ell^-,\ell^+)}$$

bounds on ζ at the level of $10^{-2} - 10^{-3}$ can be set with $O(10^{10})$ $D^0\underline{D}^0$ pairs measuring integrated opposite/same sign di-lepton rates

Decoherence and CPT violation

K

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

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

extra term inducing decoherence:
pure state => mixed state

<u>Possible decoherence due quantum gravity effects:</u>

Black hole information loss paradox => 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 <u>space-time foam</u>) could give rise to decoherence effects, which would necessarily entail a violation of CPT [2].

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

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

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

At most: $\alpha,\beta,\gamma = O\left(\frac{M_K^{\,2}}{M_{PLANCK}}\right) \approx 2\times10^{-20}$ 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]

$\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$: decoherence & CPTV by QG

K

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

CPLEAR **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

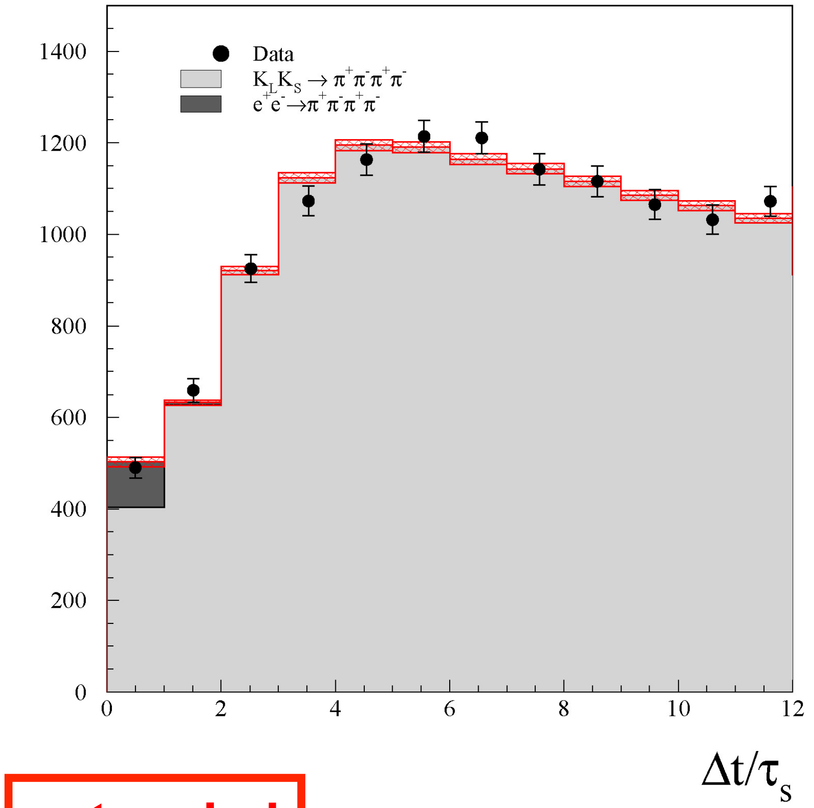
In the complete positivity hypothesis
$\alpha = \gamma$, $\beta = 0$
=> only one independent parameter: γ

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

KLOE result L=1.5 fb^{-1}

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

PLB 642(2006) 315
Found. Phys. 40 (2010) 852



entangled kaons

$\phi \to K_S K_L \to \pi^+\pi^- \, \pi^+\pi^-$: 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].

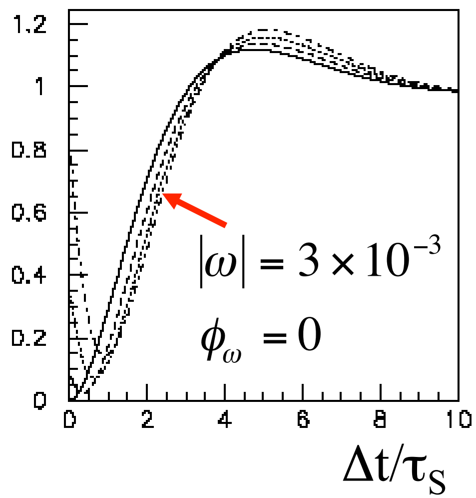
$$|i\rangle \propto \left(|K^0\rangle|\bar{K}^0\rangle - |\bar{K}^0\rangle|K^0\rangle\right) + \omega\left(|K^0\rangle|\bar{K}^0\rangle + |\bar{K}^0\rangle|K^0\rangle\right)$$

$$\propto \left(|K_S\rangle|K_L\rangle - |K_L\rangle|K_S\rangle\right) + \omega\left(|K_S\rangle|K_S\rangle - |K_L\rangle|K_L\rangle\right)$$

at most one expects:

$$\boxed{|\omega|^2 = O\left(\frac{E^2/M_{PLANCK}}{\Delta\Gamma}\right) \approx 10^{-5} \Rightarrow |\omega| \sim 10^{-3}}$$

$I(\pi^+\pi^-, \pi^+\pi^-; \Delta t)$ (a.u.)



In some microscopic models of space-time foam arising from non-critical string theory:

[Bernabeu, Mavromatos, Sarkar PRD 74 (2006) 045014]

$$|\omega| \sim 10^{-4} \div 10^{-5}$$

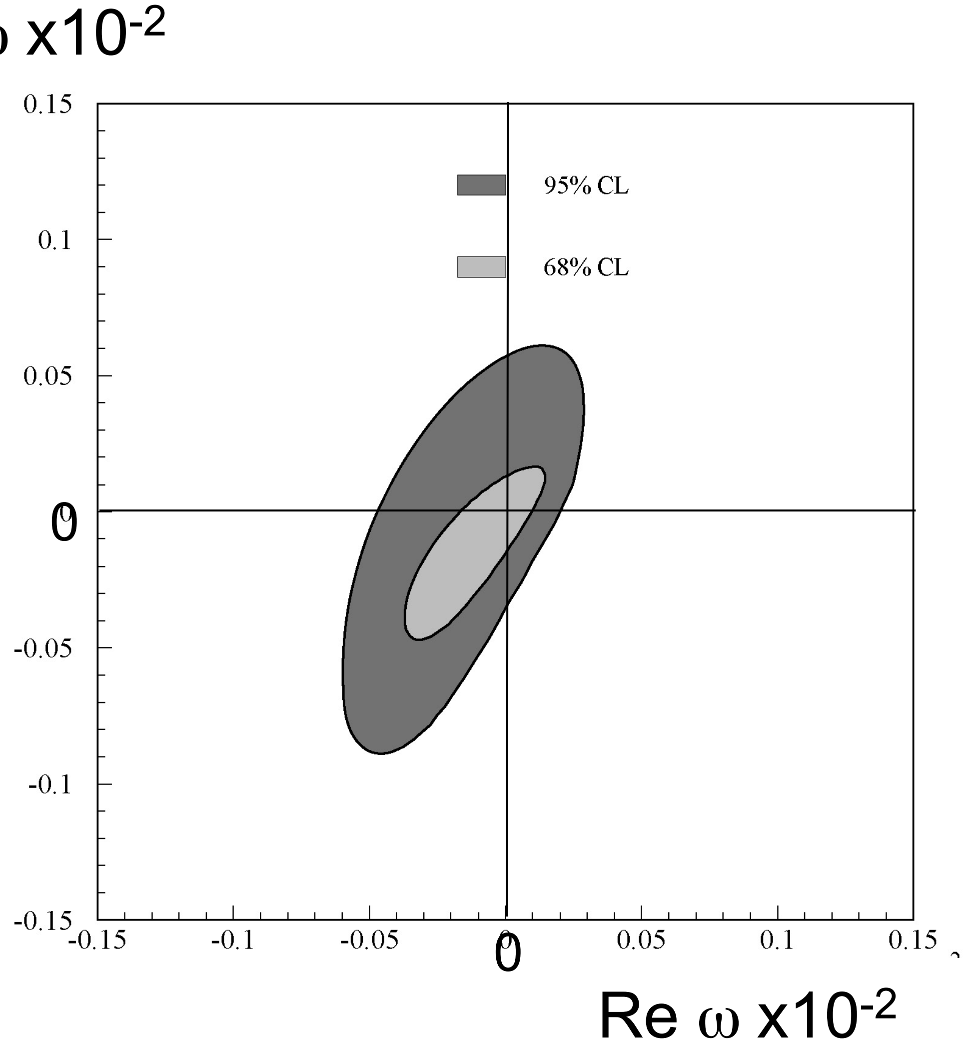
The maximum sensitivity to ω is expected for $f_1 = f_2 = \pi^+\pi^-$

All CPTV effects induced by QG ($\alpha, \beta, \gamma, \omega$) could be simultaneously disentangled.

$\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$: 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
Found. Phys. 40 (2010) 852

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

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

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

CPT violation in entangled B states

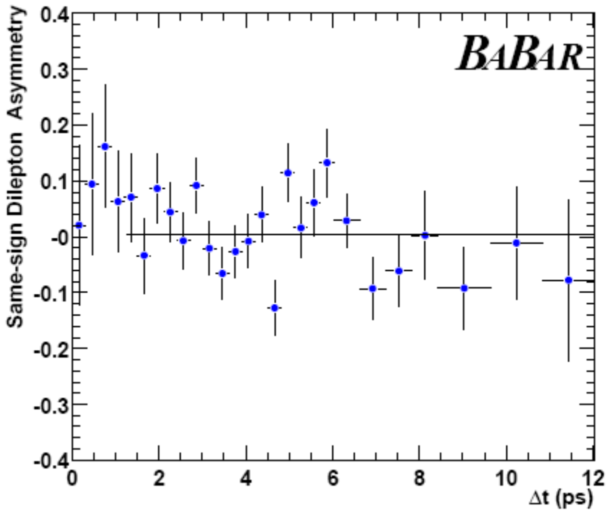
B

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

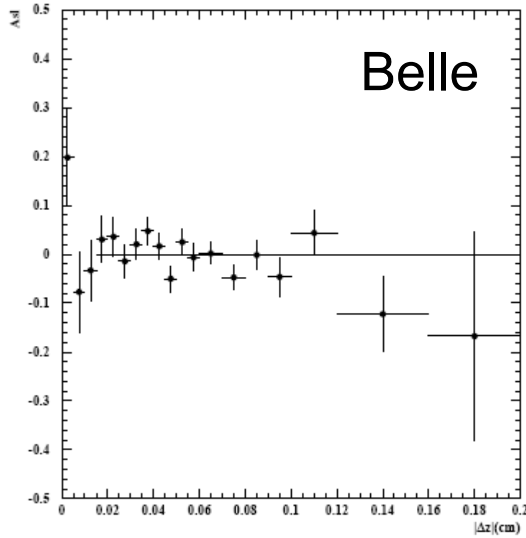
$$A_{sl}(\Delta t) = \frac{I(\ell^+,\ell^+;\Delta t) - I(\ell^-,\ell^-;\Delta t)}{I(\ell^+,\ell^+;\Delta t) + I(\ell^-,\ell^-;\Delta t)}$$

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

L~20 fb^{-1}



(a) Babar, $\Delta t = \frac{"\Delta t(ps)"}{1.53ps}\Gamma^{-1}$



L~90 fb^{-1}

(b) Belle, $\Delta t = \frac{|\Delta z|}{0.0186cm}\Gamma^{-1}$

Alvarez, Bernabeu, Nebot JHEP 0611, 087:

$$\boxed{-0.0084 \leq \Re\omega \leq 0.0100 \quad \text{at } 95\% \text{ C.L.}}$$

CPT and Lorentz invariance test

CPT and Lorentz invariance violation (SME)

K

Kostelecky et al. developed a phenomenological effective model providing a framework for CPT and Lorentz violations, based on spontaneous breaking of CPT and Lorentz symmetry, which might happen in quantum gravity (e.g. in some models of string theory)

Standard Model Extension (SME) [Kostelecky PRD61, 016002, PRD64, 076001]

CPT violation in neutral kaons according to SME:

- CPTV only in mixing, not in decay, at first order (i.e. $B_I = y = x_- = 0$)
- δ cannot be a constant (momentum dependence)

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

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

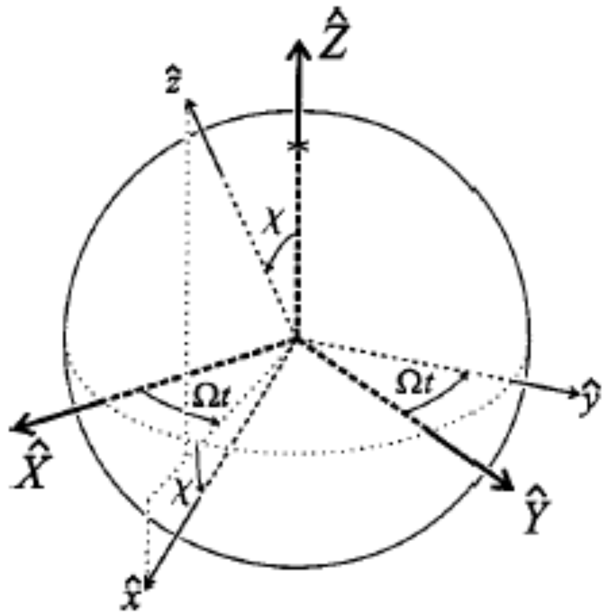
where Δa_μ are four parameters associated to SME lagrangian terms and related to CPT and Lorentz violation.

CPT and Lorentz invariance violation (SME)

K

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

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:



(in general z lab. axis is non-normal to Earth's surface)

$$\delta(\vec{p},t) = \frac{i\sin\phi_{SW}e^{i\phi_{SW}}}{\Delta m}\gamma_K\Big\{\underline{\Delta a_0}$$
$$+\beta_K\underline{\Delta a_Z}\left(\cos\theta\cos\chi - \sin\theta\sin\phi\sin\chi\right)$$
$$+\beta_K\left[-\underline{\Delta a_X}\sin\theta\sin\phi + \underline{\Delta a_Y}\left(\cos\theta\sin\chi + \sin\theta\cos\phi\cos\chi\right)\right]\sin\Omega t$$
$$+\beta_K\left[+\underline{\Delta a_Y}\sin\theta\sin\phi + \underline{\Delta a_X}\left(\cos\theta\sin\chi + \sin\theta\cos\phi\cos\chi\right)\right]\cos\Omega t\Big\}$$

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

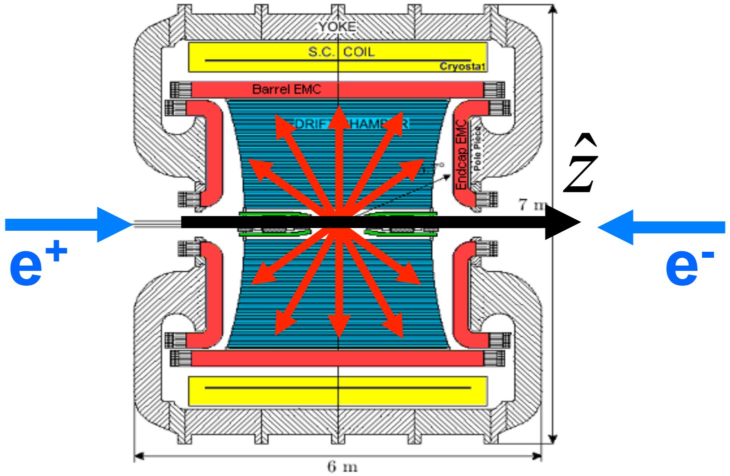
CPT and Lorentz invariance violation (SME)

K

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

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:

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



$$\delta(\vec{p},t) = \frac{i\sin\phi_{SW} e^{i\phi_{SW}}}{\Delta m}\gamma_K \Big\{ \underline{\Delta a_0}$$
$$+\beta_K \underline{\Delta a_Z} (\cos\theta\cos\chi - \sin\theta\sin\phi\sin\chi)$$
$$+\beta_K \left[-\underline{\Delta a_X} \sin\theta\sin\phi + \underline{\Delta a_Y} (\cos\theta\sin\chi + \sin\theta\cos\phi\cos\chi) \right] \sin\Omega t$$
$$+\beta_K \left[+\underline{\Delta a_Y} \sin\theta\sin\phi + \underline{\Delta a_X} (\cos\theta\sin\chi + \sin\theta\cos\phi\cos\chi) \right] \cos\Omega t \Big\}$$

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

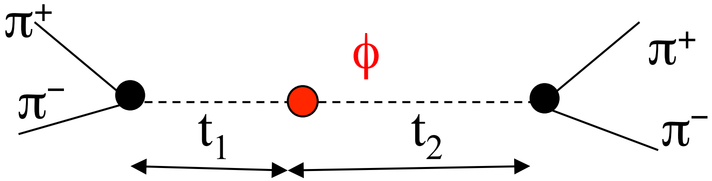
Exploiting neutral kaon interferometry

K

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

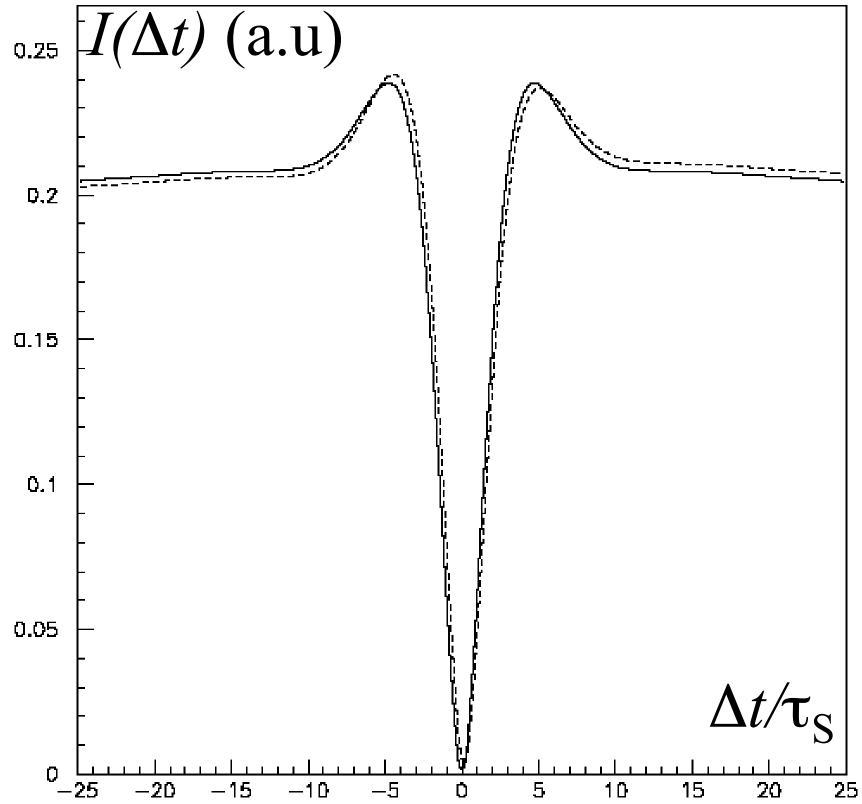
$$\eta_i = |\eta_i| e^{i\phi_i} = \langle f_i|T|K_L\rangle / \langle f_i|T|K_S\rangle$$

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



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

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

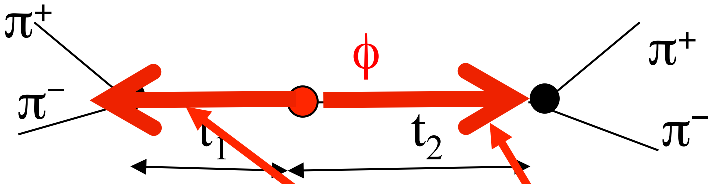


Exploiting neutral kaon interferometry

K

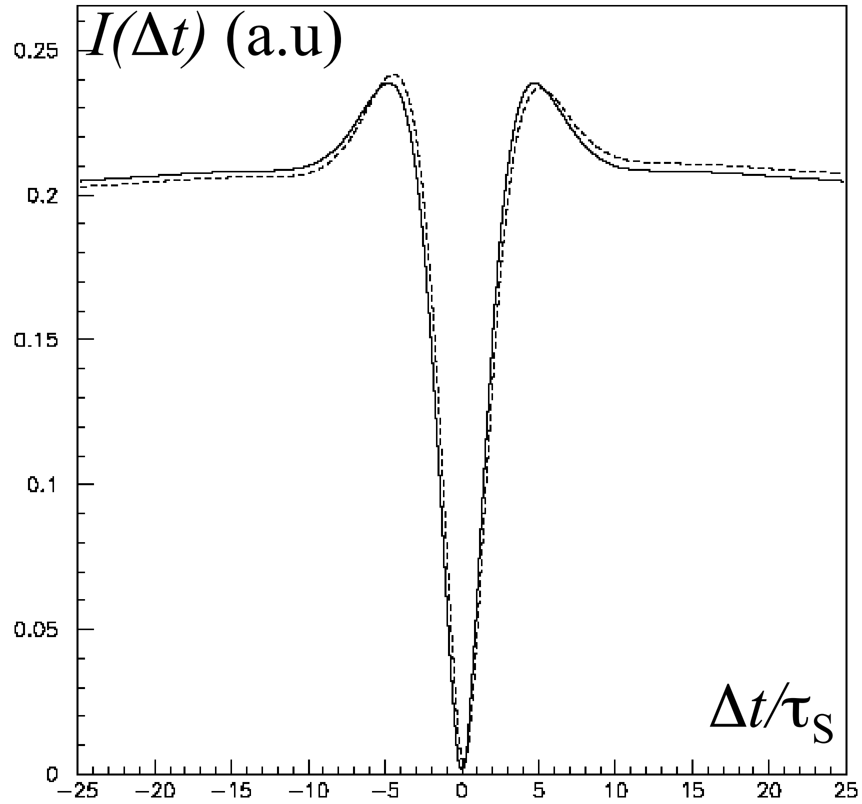
$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle|\overline{K}^0\rangle - |\overline{K}^0\rangle|K^0\rangle\right] \qquad \eta_i = |\eta_i|e^{i\phi_i} = \langle f_i|T|K_L\rangle / \langle f_i|T|K_S\rangle$$

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



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

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

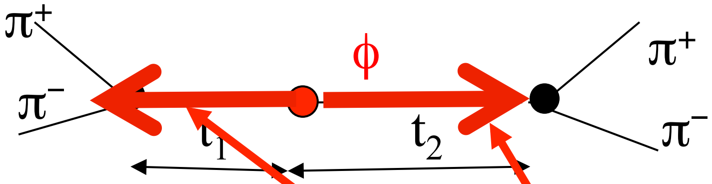


Exploiting neutral kaon interferometry

K

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

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

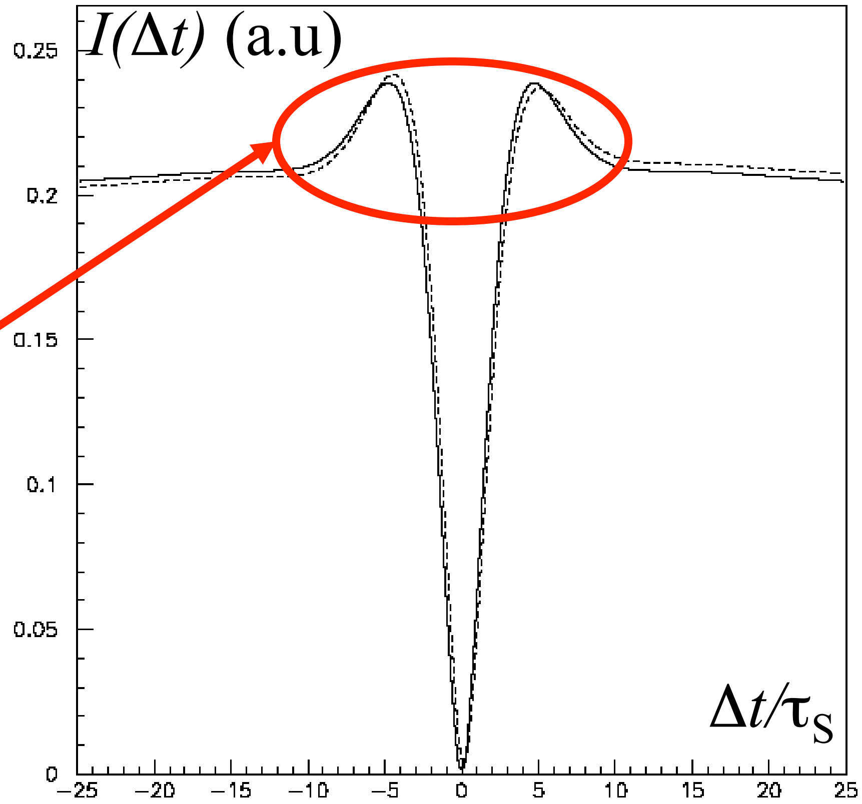


$$\eta_{+-}^{(1)} = \varepsilon\left(1 - \delta(+\vec{p},t)/\varepsilon\right)$$

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

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

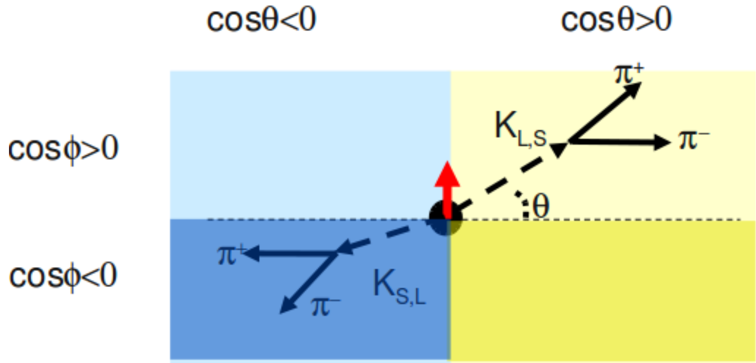
$\Re(\Delta\delta/\varepsilon) \approx 0$ because $\Delta\delta \perp \varepsilon$
from the asymmetry at **large** Δt



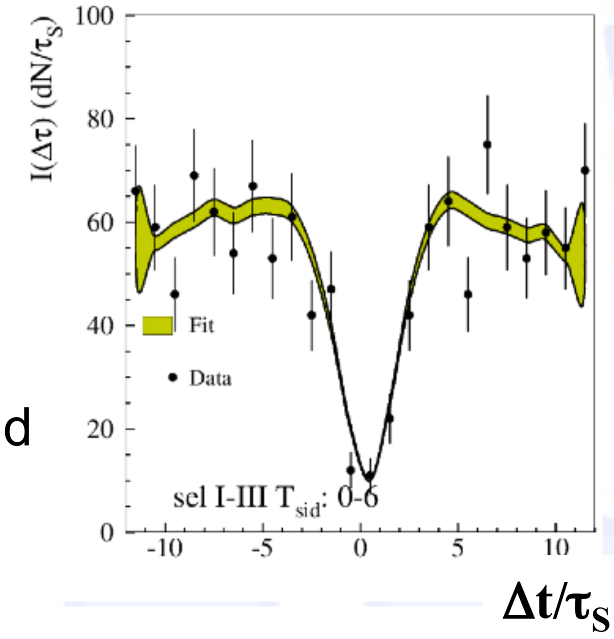
Measurement of Δa_μ at KLOE

K

The analysis is performed in
4 bins of sidereal time
x 2 bins for the ϕ quadrant of the forward kaon
x 30 bins of Δt = 240 bins



Example:
1 bin sidereal time (0-4 hours)
for quadrant ($\cos\theta>0$ $\cos\phi>0$).
Data: black points
Fit result: green band (stat. err. only)



with L=1.7 fb^{-1} KLOE final result **(2013)**

$$\Delta a_0 = \left(-6.0 \pm 7.7_{STAT} \pm 3.1_{SYST}\right) \times 10^{-18} \text{ GeV}$$

$$\Delta a_X = \left(0.9 \pm 1.5_{STAT} \pm 0.6_{SYST}\right) \times 10^{-18} \text{ GeV}$$

$$\Delta a_Y = \left(-2.0 \pm 1.5_{STAT} \pm 0.5_{SYST}\right) \times 10^{-18} \text{ GeV}$$

$$\Delta a_Z = \left(-3.1 \pm 1.7_{STAT} \pm 0.6_{SYST}\right) \times 10^{-18} \text{ GeV}$$

An improvement in the precision of a factor ~ 3
wrt old KLOE preliminary results.

CPT and Lorentz invariance violation (SME)

B

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

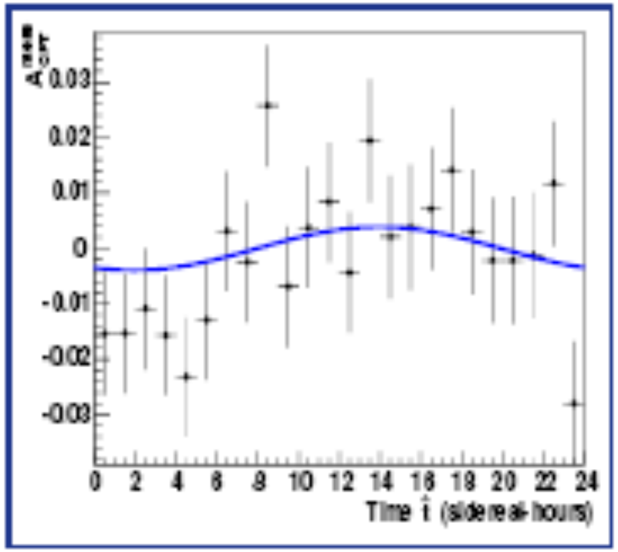
boosted B's at B-factory (almost fixed direction)
=> cannot distinguish between Δa_0^B and Δa_Z^B

searching for a dependence of the form

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

A_{CPT}
dilepton
asymmetry

L~232 fb^{-1}



Babar

[PRL 100 (2008) 131802]

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

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

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

i.e. ~O(10^{-13} GeV)

CPT and Lorentz invariance violation (SME)

D

$$\xi = \frac{\gamma_D \left(\Delta a_0^D - \vec{\beta}_D \cdot \Delta \vec{a}^D \right)}{\Delta \lambda}$$

boosted D's from photoproduction at fixed target experiment
=> cannot distinguish between Δa_0^D and Δa_Z^D

D*->Dπ
D in right-sign hadronc decays

$$A_{CPT}(t) = \frac{I\left(D^0 \to K^-\pi^+(t)\right) - I\left(\overline{D}^0 \to K^+\pi^-(t)\right)}{I\left(D^0 \to K^-\pi^+(t)\right) + I\left(\overline{D}^0 \to K^+\pi^-(t)\right)}$$

FOCUS at FNAL **[PLB 556 (2003) 7]**

$$f(x,y,\delta)\left[\Delta a_0^D + 0.6 \Delta a_Z^D\right] \cong (1.0 \pm 1.1) \times 10^{-16} \ \text{GeV}$$

$$f(x,y,\delta) \Delta a_X^D \cong (-1.6 \pm 2.0) \times 10^{-16} \ \text{GeV}$$

$$f(x,y,\delta) \Delta a_Y^D \cong (-1.6 \pm 2.0) \times 10^{-16} \ \text{GeV}$$

i.e. ~O(10^{-12} GeV)

$$f(x,y,\delta) = xy/3 + 0.06(x\cos\delta + y\sin\delta)$$

Prospects for KLOE-2

Prospects for KLOE-2 at upgraded DAΦNE

K

Param.	Present best published measurement	KLOE-2 L=5 fb^{-1}	KLOE-2 L=10 fb^{-1}	KLOE-2 L=20 fb^{-1}
$K_S \rightarrow 3\pi^0$	$<2.6 \times 10^{-8}$	$<1.3 \times 10^{-8}$	$<0.6 \times 10^{-8}$	$<3\times 10^{-9}$ - seen
A_S	$(1.5 \pm 11) \times 10^{-3}$	$\pm 2.7 \times 10^{-3}$	$\pm 1.9 \times 10^{-3}$	$\pm 1.4 \times 10^{-3}$
A_L	$(332.2 \pm 5.8 \pm 4.7) \times 10^{-5}$	$\pm 8.9 \times 10^{-5}$	$\pm 6.3 \times 10^{-5}$	$\pm 4.5 \times 10^{-5}$
$\mathrm{Re}(\varepsilon'/\varepsilon)$	$(1.53 \pm 0.26) \times 10^{-3}$	$\pm 0.72 \times 10^{-3}$	$\pm 0.51 \times 10^{-3}$	$\pm 0.36 \times 10^{-3}$
$\mathrm{Im}(\varepsilon'/\varepsilon)$	$(-1.72 \pm 2.02) \times 10^{-3}$	$\pm 9.4 \times 10^{-3}$	$\pm 6.7 \times 10^{-3}$	$\pm 4.7 \times 10^{-3}$
$\mathrm{Re}(\delta)+\mathrm{Re}(x_-)$	$\mathrm{Re}(\delta) = (0.24 \pm 0.23) \times 10^{-3}$ (*) $\mathrm{Re}(x_-) = (-4.1 \pm 1.7) \times 10^{-3}$ (*)	$\pm 0.7 \times 10^{-3}$	$\pm 0.5 \times 10^{-3}$	$\pm 0.4 \times 10^{-3}$
$\mathrm{Im}(\delta)+\mathrm{Im}(x_+)$	$\mathrm{Im}(\delta) = (-0.7 \pm 1.4) \times 10^{-5}$ (*) $\mathrm{Im}(x_+) = (0.2 \pm 2.2) \times 10^{-3}$ (*)	$\pm 9 \times 10^{-3}$	$\pm 7 \times 10^{-3}$	$\pm 5 \times 10^{-3}$
Δm	$(5.2797 \pm 0.0195) \times 10^{9}\ \mathrm{s}^{-1}$	$\pm 0.096 \times 10^{9}\ \mathrm{s}^{-1}$	$\pm 0.068 \times 10^{9}\ \mathrm{s}^{-1}$	$\pm 0.048 \times 10^{9}\ \mathrm{s}^{-1}$

(*) = analysis using Bell-Steinberger relation

Prospects for KLOE-2 at upgraded DAΦNE

K

Para m.	Present best published measurement	KLOE-2 (IT) L=5 fb^{-1}	KLOE-2 (IT) L=10 fb^{-1}	KLOE-2 (IT) L=20 fb^{-1}
ζ_{00}	$(0.1 \pm 1.0) \times 10^{-6}$	$\pm 0.26 \times 10^{-6}$	$\pm 0.18 \times 10^{-6}$	$\pm 0.13 \times 10^{-6}$
ζ_{SL}	$(0.3 \pm 1.9) \times 10^{-2}$	$\pm 0.49 \times 10^{-2}$	$\pm 0.35 \times 10^{-2}$	$\pm 0.25 \times 10^{-2}$
α	$(-0.5 \pm 2.8) \times 10^{-17}$ GeV	$\pm 5.0 \times 10^{-17}$ GeV	$\pm 3.5 \times 10^{-17}$ GeV	$\pm 2.5 \times 10^{-17}$ GeV
β	$(2.5 \pm 2.3) \times 10^{-19}$ GeV	$\pm 0.50 \times 10^{-19}$ GeV	$\pm 0.35 \times 10^{-19}$ GeV	$\pm 0.25 \times 10^{-19}$ GeV
γ	$(1.1 \pm 2.5) \times 10^{-21}$ GeV compl. pos. hyp. $(0.7 \pm 1.2) \times 10^{-21}$ GeV	$\pm 0.75 \times 10^{-21}$ GeV compl. pos. hyp. $\pm 0.33 \times 10^{-21}$ GeV	$\pm 0.53 \times 10^{-21}$ GeV compl. pos. hyp. $\pm 0.23 \times 10^{-21}$ GeV	$\pm 0.38 \times 10^{-21}$ GeV compl. pos. hyp. $\pm 0.16 \times 10^{-21}$ GeV
Re(ω)	$(-1.6 \pm 2.6) \times 10^{-4}$	$\pm 0.70 \times 10^{-4}$	$\pm 0.49 \times 10^{-4}$	$\pm 0.35 \times 10^{-4}$
Im(ω)	$(-1.7 \pm 3.4) \times 10^{-4}$	$\pm 0.86 \times 10^{-4}$	$\pm 0.61 \times 10^{-4}$	$\pm 0.43 \times 10^{-4}$
Δa_0	[$(-6.2 \pm 8.8) \times 10^{-18}$ GeV]	$\pm 4.8 \times 10^{-18}$ GeV	$\pm 3.4 \times 10^{-18}$ GeV	$\pm 2.4 \times 10^{-18}$ GeV
Δa_Z	[$(-0.7 \pm 1.0) \times 10^{-18}$ GeV]	$\pm 0.6 \times 10^{-18}$ GeV	$\pm 0.4 \times 10^{-18}$ GeV	$\pm 0.3 \times 10^{-18}$ GeV
$\Delta a_{X,Y}$	[$<10^{-21}$ GeV]	$\pm 0.76 \times 10^{-18}$ GeV	$\pm 0.54 \times 10^{-18}$ GeV	$\pm 0.38 \times 10^{-18}$ GeV

[….] = preliminary

Direct test of T symmetry

Direct test of Time Reversal symmetry with neutral kaons K

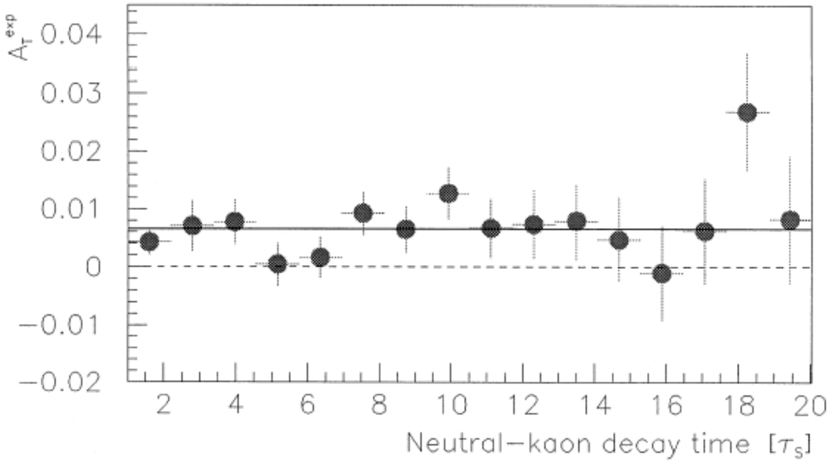
- A direct evidence for T violation would mean an experiment that, considered by itself, clearly shows T violation INDEPENDENT and unconnected to the results for CP violation and CPT invariance

- Only one evidence of T violation: Kabir asymmetry, comparing a process with its T-conjugated one, i.e. $K^0 \to \bar{K}^0$ vs $\bar{K}^0 \to K^0$ performed by the CPLEAR experiment

$$A_T = \frac{P(\overline{K}^0 \to K^0) - P(K^0 \to \overline{K}^0)}{P(\overline{K}^0 \to K^0) + P(K^0 \to \overline{K}^0)}$$

$\langle \mathbf{A_T} \rangle$ **= (6.6 ± 1.3) · 10^{-3}**

PLB444(1998)43



- Remark: $K^0 \to \bar{K}^0$ is a CPT-even transition, so $CP \equiv T$ in this case ! <u>we cannot distinguish between CP or T tests (not independent)</u>

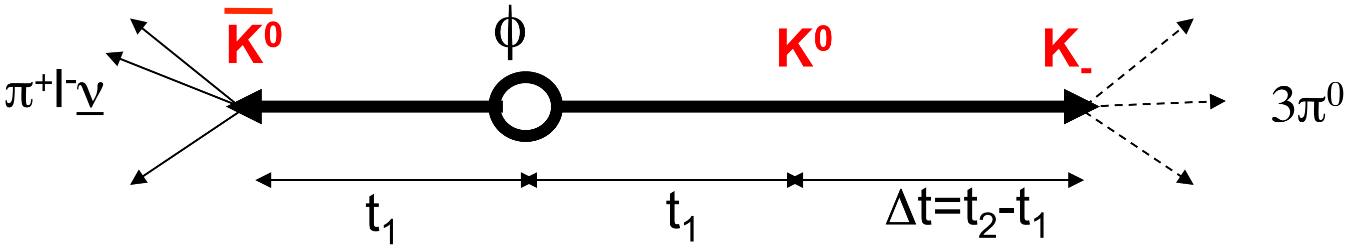
Entanglement in neutral meson pairs

K

- EPR correlations at a ϕ-factory (or B-factory) can be exploited to study other transitions involving also "CP states" K_+ and K_-

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

- decay as filtering measurement
- entanglement -> preparation of state



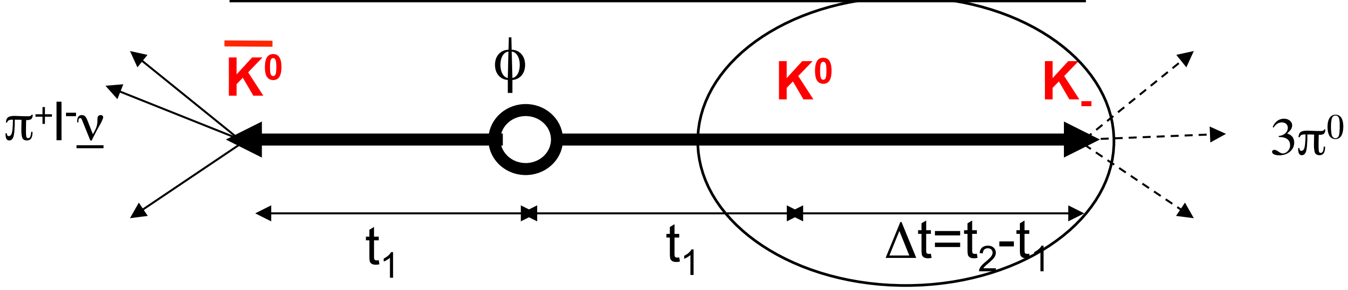
Entanglement in neutral meson pairs

K

- EPR correlations at a ϕ-factory (or B-factory) can be exploited to study other transitions involving also "CP states" K_+ and K_-

$$|i\rangle = \frac{1}{\sqrt{2}}\left[\left|K^0(\vec{p})\right\rangle\left|\bar{K}^0(-\vec{p})\right\rangle - \left|\bar{K}^0(\vec{p})\right\rangle\left|K^0(-\vec{p})\right\rangle\right]$$
$$= \frac{1}{\sqrt{2}}\left[\left|K_+(\vec{p})\right\rangle\left|K_-(-\vec{p})\right\rangle - \left|K_-(\vec{p})\right\rangle\left|K_+(-\vec{p})\right\rangle\right]$$

- decay as filtering measurement
- entanglement -> preparation of state



$K^0 \rightarrow K_-$ reference process

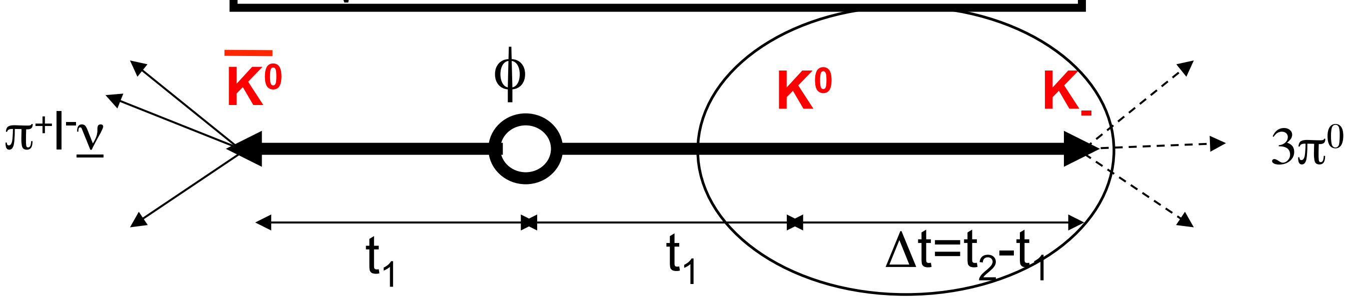
Entanglement in neutral meson pairs

K

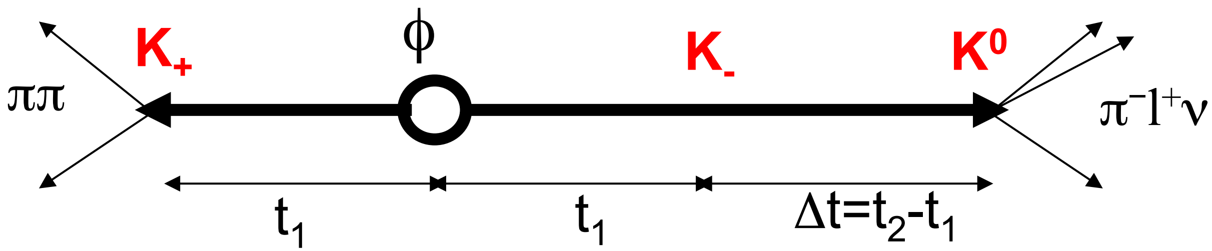
- EPR correlations at a ϕ-factory (or B-factory) can be exploited to study other transitions involving also "CP states" K_+ and K_-

$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0(\vec{p})\rangle|\bar{K}^0(-\vec{p})\rangle - |\bar{K}^0(\vec{p})\rangle|K^0(-\vec{p})\rangle\right]$$
$$= \frac{1}{\sqrt{2}}\left[|K_+(\vec{p})\rangle|K_-(-\vec{p})\rangle - |K_-(\vec{p})\rangle|K_+(-\vec{p})\rangle\right]$$

- decay as filtering measurement
- entanglement -> preparation of state



$$K^0 \rightarrow K_-$$ reference process

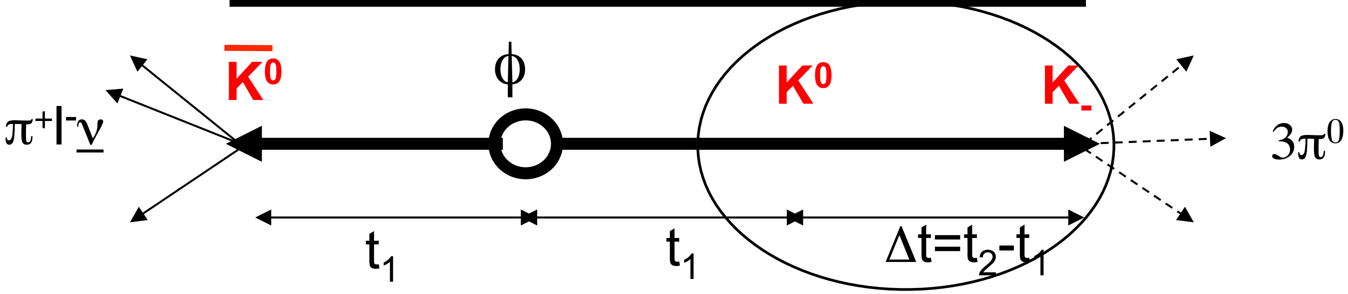


Entanglement in neutral meson pairs

- EPR correlations at a ϕ-factory (or B-factory) can be exploited to study other transitions involving also "CP states" K_+ and K_-

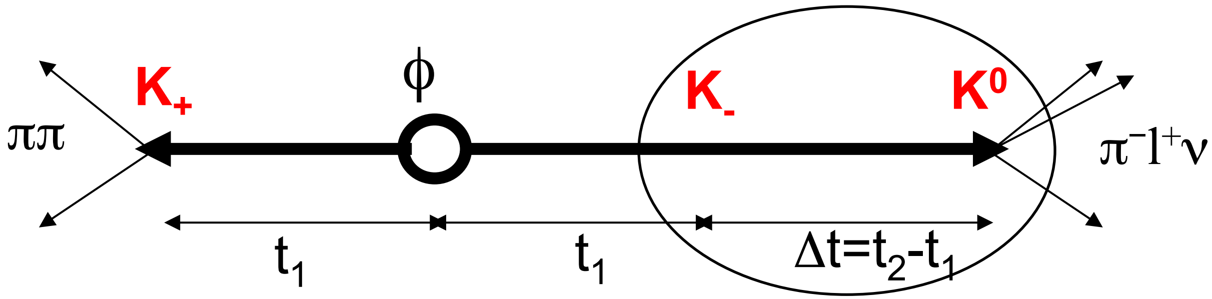
$$|i\rangle = \frac{1}{\sqrt{2}}\left[\left|K^0(\vec{p})\right\rangle\left|\bar{K}^0(-\vec{p})\right\rangle - \left|\bar{K}^0(\vec{p})\right\rangle\left|K^0(-\vec{p})\right\rangle\right]$$
$$= \frac{1}{\sqrt{2}}\left[\left|K_+(\vec{p})\right\rangle\left|K_-(-\vec{p})\right\rangle - \left|K_-(\vec{p})\right\rangle\left|K_+(-\vec{p})\right\rangle\right]$$

- decay as filtering measurement
- entanglement -> preparation of state



$K^0 \rightarrow K_-$ reference process

$K_- \rightarrow K^0$ T-conjugated process

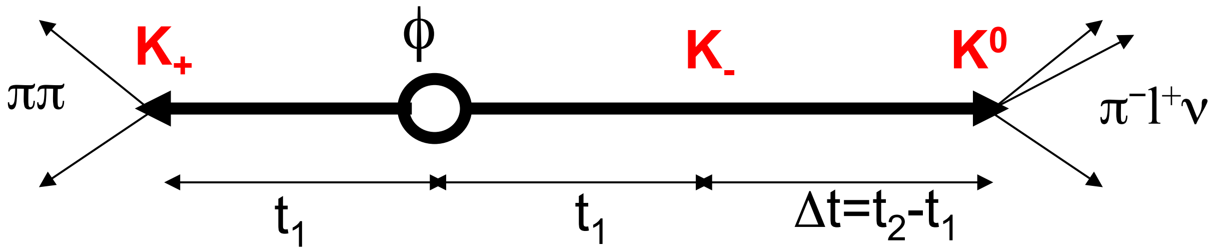


Entanglement in neutral meson pairs

- EPR correlations at a ϕ-factory (or B-factory) can be exploited to study other transitions involving also "CP states" K_+ and K_-

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

e.g.



$$I(\pi\pi, l^+; \Delta t) = C(\pi\pi, l^+) \times P[K_-(0) \to K^0(\Delta t)]$$

In general with $f_{\underline{X}}$ decayng before f_Y, i.e. $\Delta t>0$:

$$I(f_{\bar{X}}, f_Y; \Delta t) = C(f_{\bar{X}}, f_Y) \times P\left[\mathrm{K_X}(0) \to \mathrm{K_Y}(\Delta t)\right]$$

with
$$C(f_{\bar{X}}, f_Y) = \frac{1}{2(\Gamma_S + \Gamma_L)}\left|\langle f_{\bar{X}}|T|\bar{\mathrm{K}}_\mathrm{X}\rangle\langle f_Y|T|\mathrm{K_Y}\rangle\right|^2$$

Direct test of Time Reversal symmetry with neutral kaons K

T symmetry test

Reference		T-conjugate	
Transition	Final state	Transition	Final state
$\bar{K}^0 \to K_-$	$(\ell^+, \pi^0\pi^0\pi^0)$	$K_- \to \bar{K}^0$	$(\pi^0\pi^0\pi^0, \ell^-)$
$K_+ \to K^0$	$(\pi^0\pi^0\pi^0, \ell^+)$	$K^0 \to K_+$	$(\ell^-, \pi\pi)$
$\bar{K}^0 \to K_+$	$(\ell^+, \pi\pi)$	$K_+ \to \bar{K}^0$	$(\pi^0\pi^0\pi^0, \ell^-)$
$K_- \to K^0$	$(\pi\pi, \ell^+)$	$K^0 \to K_-$	$(\ell^-, \pi\pi)$

One can define the following ratios of probabilities:

$$\begin{aligned}
R_1(\Delta t) &= P\left[K^0(0) \to K_+(\Delta t)\right] / P\left[K_+(0) \to K^0(\Delta t)\right] \\
R_2(\Delta t) &= P\left[K^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to K^0(\Delta t)\right] \\
R_3(\Delta t) &= P\left[\bar{K}^0(0) \to K_+(\Delta t)\right] / P\left[K_+(0) \to \bar{K}^0(\Delta t)\right] \\
R_4(\Delta t) &= P\left[\bar{K}^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to \bar{K}^0(\Delta t)\right] .
\end{aligned}$$

Any deviation from R_i=1 constitutes a violation of T-symmetry

J. Bernabeu, A.D.D., P. Villanueva: NPB 868 (2013) 102

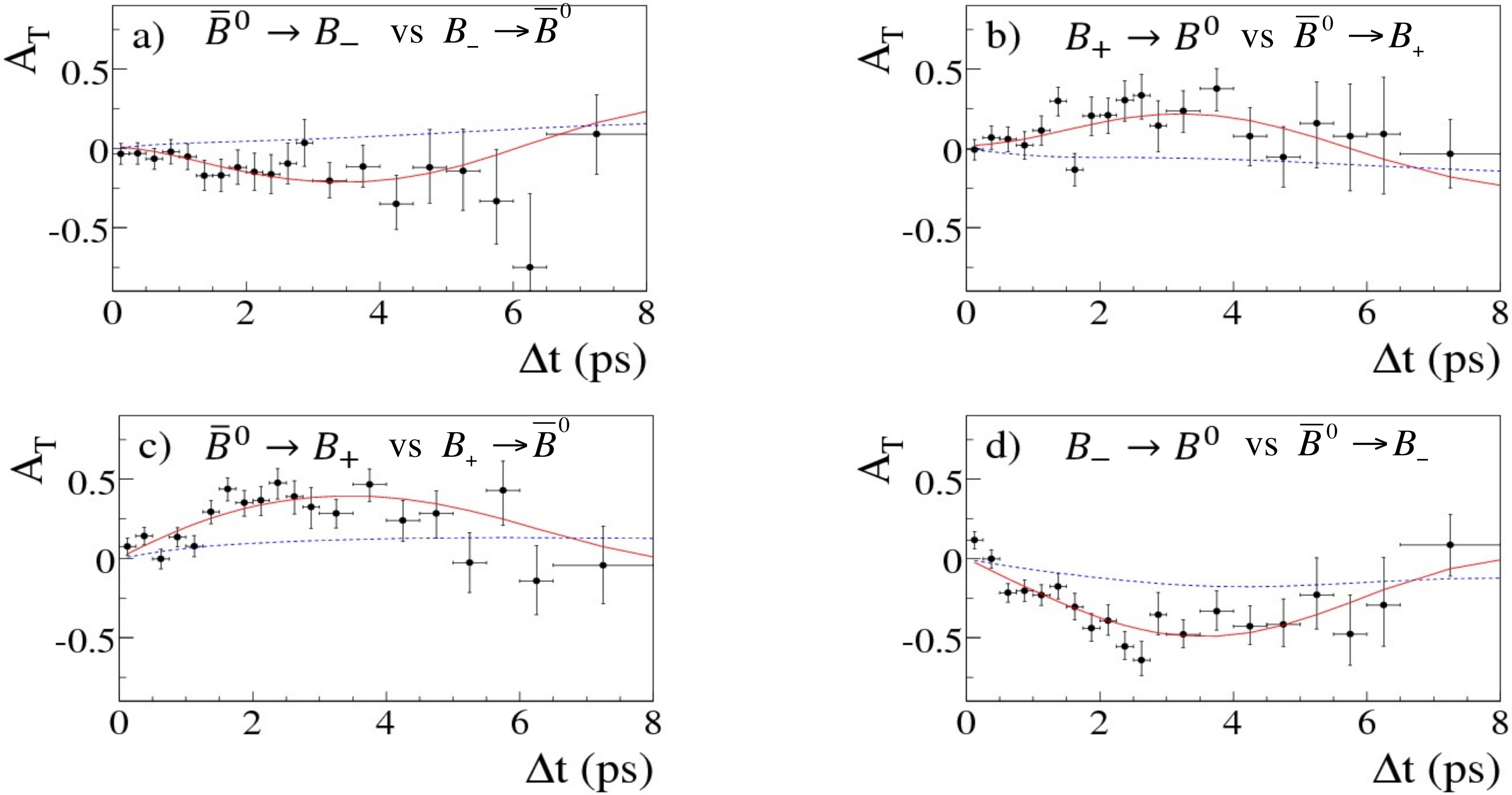
T test could be feasible at KLOE-2 with L=O(10 fb^{-1}) but challenging

Direct test of Time Reversal symmetry in neutral B mesons **B**

$$
\begin{aligned}
\Delta S_T^+ &= -1.37 \pm 0.14 \pm 0.06 \\
\Delta S_T^- &= 1.17 \pm 0.18 \pm 0.11 \\
\Delta C_T^+ &= 0.10 \pm 0.16 \pm 0.08 \\
\Delta C_T^- &= 0.04 \pm 0.16 \pm 0.08
\end{aligned}
$$

Direct T violation observed at BABAR in the B's with significance of 14 σ

Babar coll. PRL 109 (2012) 211801



Direct test of symmetries with neutral kaons

K

Conjugate= reference

already in the table with conjugate as reference

Two identical conjugates for one reference

Reference	T-conjugate	CP-conjugate	CPT-conjugate
$K^0 \to K^0$	$K^0 \to K^0$	$\bar{K}^0 \to \bar{K}^0$	$\bar{K}^0 \to \bar{K}^0$
$K^0 \to \bar{K}^0$	$\bar{K}^0 \to K^0$	$\bar{K}^0 \to K^0$	$K^0 \to \bar{K}^0$
$K^0 \to K_+$	$K_+ \to K^0$	$\bar{K}^0 \to K_+$	$K_+ \to \bar{K}^0$
$K^0 \to K_-$	$K_- \to K^0$	$\bar{K}^0 \to K_-$	$K_- \to \bar{K}^0$
$\bar{K}^0 \to K^0$	$K^0 \to \bar{K}^0$	$K^0 \to \bar{K}^0$	$\bar{K}^0 \to K^0$
$\bar{K}^0 \to \bar{K}^0$	$\bar{K}^0 \to \bar{K}^0$	$K^0 \to K^0$	$K^0 \to K^0$
$\bar{K}^0 \to K_+$	$K_+ \to \bar{K}^0$	$K^0 \to K_+$	$K_+ \to K^0$
$\bar{K}^0 \to K_-$	$K_- \to \bar{K}^0$	$K^0 \to K_-$	$K_- \to K^0$
$K_+ \to K^0$	$K^0 \to K_+$	$K_+ \to \bar{K}^0$	$\bar{K}^0 \to K_+$
$K_+ \to \bar{K}^0$	$\bar{K}^0 \to K_+$	$K_+ \to K^0$	$K^0 \to K_+$
$K_+ \to K_+$	$K_+ \to K_+$	$K_+ \to K_+$	$K_+ \to K_+$
$K_+ \to K_-$	$K_- \to K_+$	$K_+ \to K_-$	$K_- \to K_+$
$K_- \to K^0$	$K^0 \to K_-$	$K_- \to \bar{K}^0$	$\bar{K}^0 \to K_-$
$K_- \to \bar{K}^0$	$\bar{K}^0 \to K_-$	$K_- \to K^0$	$K^0 \to K_-$
$K_- \to K_+$	$K_+ \to K_-$	$K_- \to K_+$	$K_+ \to K_-$
$K_- \to K_-$	$K_- \to K_-$	$K_- \to K_-$	$K_- \to K_-$

Alternative formulation of Bell's inequality for kaons

K

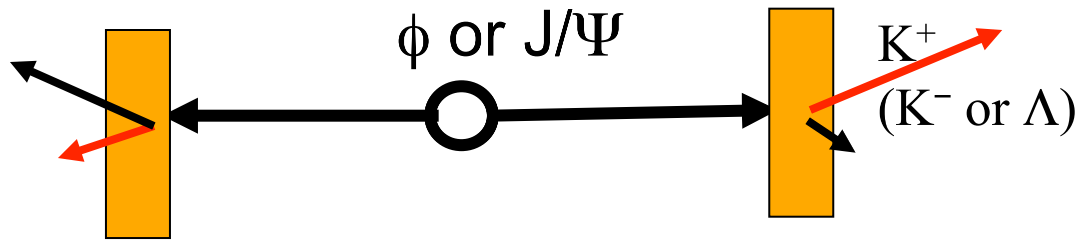
$$\boxed{|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0(\vec{p})\rangle|\bar{K}^0(-\vec{p})\rangle - |\bar{K}^0(\vec{p})\rangle|K^0(-\vec{p})\rangle\right]}$$

CHSH-Bell inequality:

Hiesmayr, A.D.D., et al. EPJC (2012) 72:1856

$$\min_{\text{all } \rho_{\text{sep}}} S(n,m,n',m')[\rho_{\text{sep}}] \le S(n,m,n',m')[\rho]$$
$$\le \max_{\text{all } \rho_{\text{sep}}} S(n,m,n',m')[\rho_{\text{sep}}] \quad (3)$$

where the extremum is taken over all separable states.



At a τ-charm running at J/Ψ(1s): BR(J/Ψ-> $K_S K_L$)~1.5 x 10^{-4} => O(10^8) KK pairs

Advantage: more boosted kaons wrt ϕ:
λ_S~ 8 cm => K_S reaches the beam pipe wall !!

Conclusions

- **Entangled neutral meson systems** are unique and excellent laboratories for the study of basic principles of quantum mechanics and discrete symmetries.
- Several parameters related to possible (i) decoherence and CPT violation, (ii) CPT violation and Lorentz symmetry breaking have been recently measured at **KLOE** for **K** mesons and at **Belle** and **Babar** for **B** mesons (and also in **D** 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 QM and 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 are possible at Super B-factories
- At a high luminosity **symmetric τ-charm factory** improvements are possible – to some extent - also with time-integrated observables