Testing fundamental physical principles with entangled neutral K mesons

Antonio Di Domenico

Dipartimento di Fisica, Sapienza Università di Roma

and INFN sezione di Roma, Italy

Workshop on

Questioning Fundamental Physical Principles 2014

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Fundamental tests possible with entangled neutral kaons

a) **Test of Quantum coherence**
Bertlmann, Grimus, Hiesmayr PR D60 (1999) 114032
KLOE coll. PLB 642(2006) 315, FP40 (2010) 852
CPLEAR PLB 422 (1999) 339

b) **Test of CPT symmetry + Quantum coherence**
Bernabeu, Mavromatos et al. PRL 92 (2004) 131601, NPB744 (2006) 180 [J.Ellis et al. NPB241, 381; PRD 53, 3846]
KLOE coll. PLB 642(2006) 315, FP40 (2010) 852 [CPLEAR PLB 364 (1995) 239]

c) **Test of Lorentz and CPT symmetry**
Kostelecky PRD61 (1999) 016002, PRD64 (2001) 076001
KLOE coll. PLB 730 (2014) 89

d) **Direct Test of T (time-reversal) symmetry**
Bernabeu, A.D.D. et al. NPB 868 (2013) 102

e) **Bell's inequality test**
Hiesmayr, A.D.D. et al. EPJC (2012) 72:1856

f) **Kaonic quantum eraser (Bohr's complementarity)**
Bramon, Garbarino, Hiesmayr PRL (2004) 020405

g) **Test of collapse models**
Donadi, Bassi, Curceanu, A.D.D., Hiesmayr et al.
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T, CP and CPT violation parameters for neutral kaons

$$|\Psi\rangle = a(t)|K^0\rangle + b(t)|\overline{K}^0\rangle \qquad i\frac{\partial}{\partial t}|\Psi\rangle = \mathbf{H}|\Psi\rangle \qquad \mathbf{H} = \mathbf{M} - \frac{i}{2}\Gamma = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{pmatrix}$$

$$|K_{S,L}\rangle = \frac{1}{\sqrt{2\left(1+|\varepsilon_{S,L}|^2\right)}}\left[\left(1+\varepsilon_{S,L}\right)|K^0\rangle \pm \left(1-\varepsilon_{S,L}\right)|\overline{K}^0\rangle\right]$$

$$\lambda_S = m_S - \frac{i}{2}\Gamma_S \quad , \quad \lambda_L = m_L - \frac{i}{2}\Gamma_L$$

$$|K_{S,L}(t)\rangle = e^{-i\lambda_{S,L} t}|K_{S,L}(0)\rangle$$

T, CP and CPT violation parameters:

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

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

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

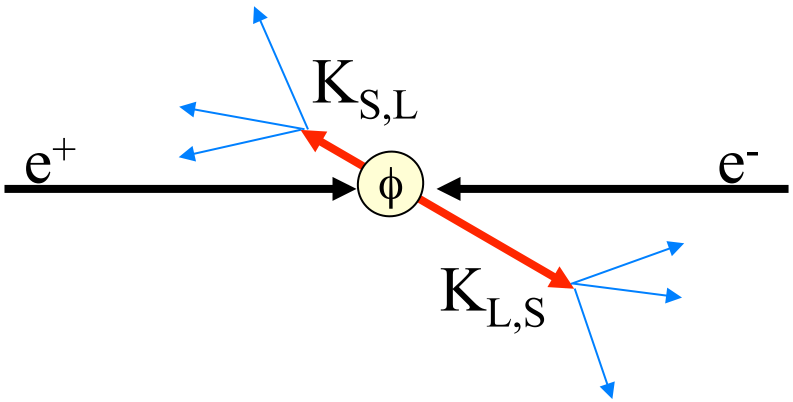
$|\varepsilon| \cong 2.232 \times 10^{-3}$

CPT violation: $|\delta| <\sim 10^{-4}$ $\quad \Rightarrow \left|m_{K^0} - m_{\overline{K}^0}\right| / m_K < 10^{-18}$

Neutral kaons at a ϕ-factory

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

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



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

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

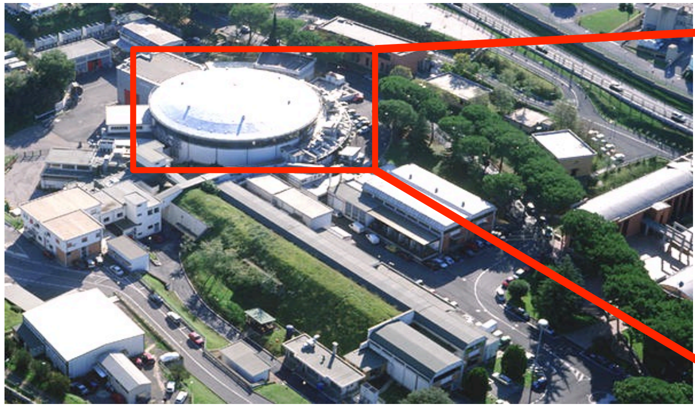
$$N = \sqrt{\left(1+|\varepsilon_S|^2\right)\left(1+|\varepsilon_L|^2\right)} \Big/ \left(1-\varepsilon_S\varepsilon_L\right) \cong 1$$

$p_K = 110$ MeV/c

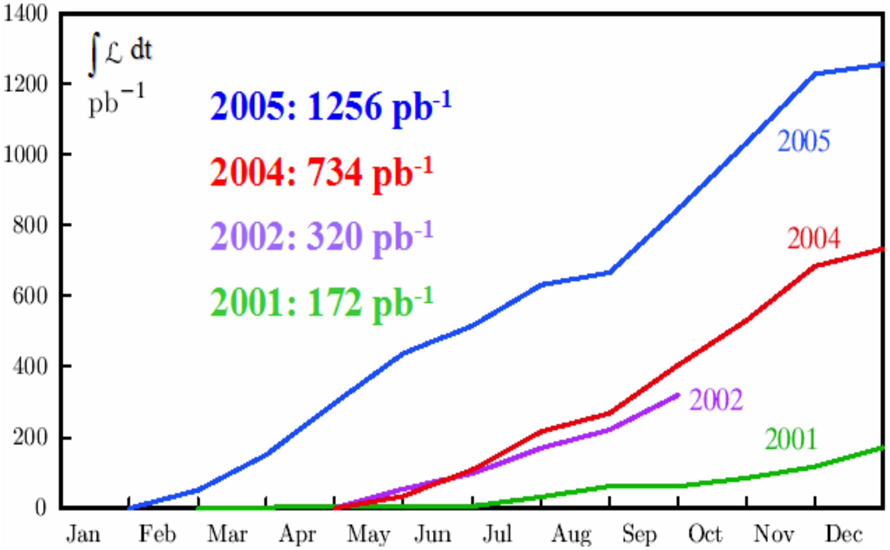
$\lambda_S = 6$ mm $\qquad \lambda_L = 3.5$ m

The KLOE detector at the Frascati φ-factory DAΦNE

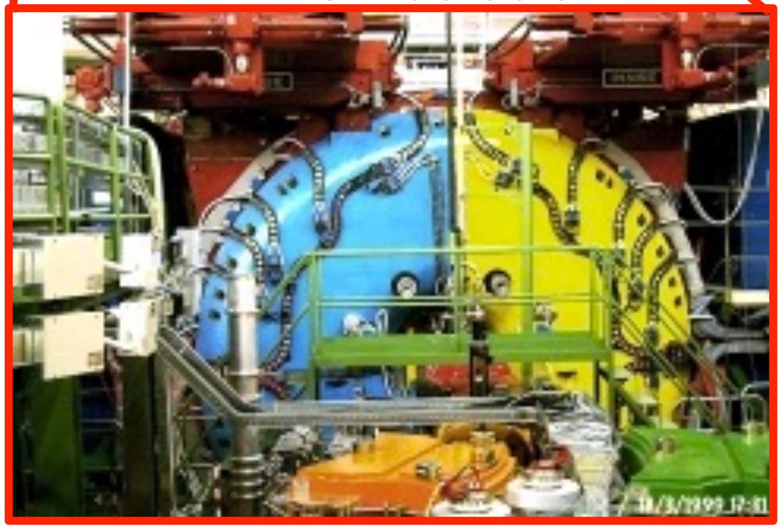
DAFNE collider



Integrated luminosity (KLOE)



KLOE detector



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

(2001 - 05) $\rightarrow \sim 2.5 \times 10^9\ K_S K_L$ pairs

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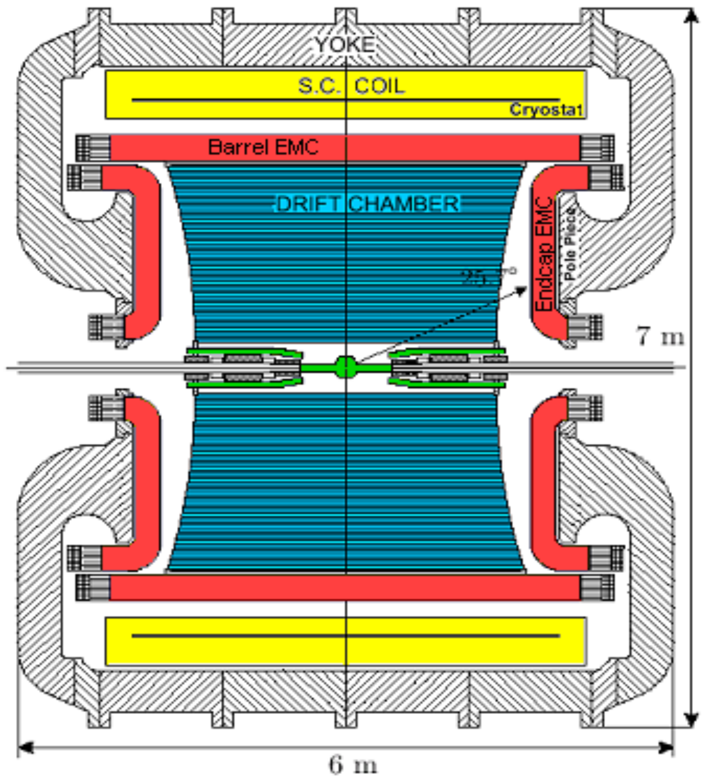

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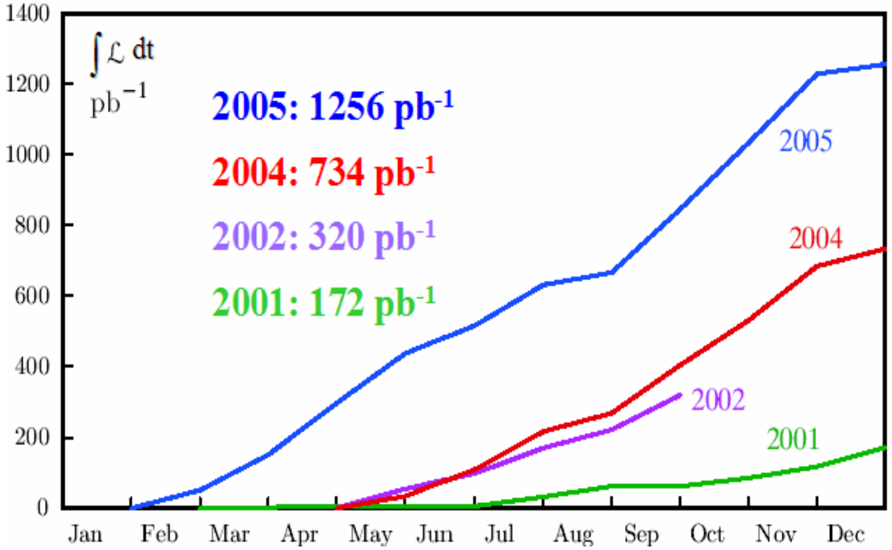

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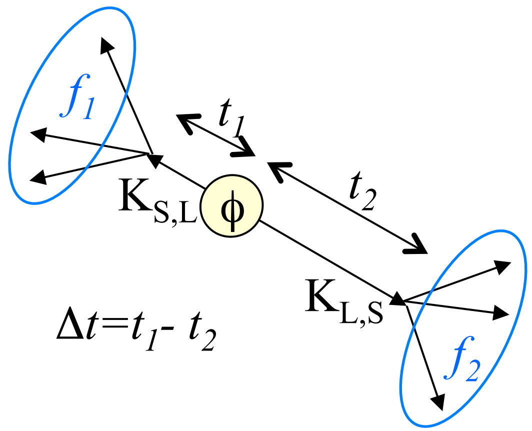
Lead/scintillating fiber calorimeter
drift chamber
4 m diameter × 3.3 m length
helium based gas mixture

Neutral kaon interferometry



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

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:

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

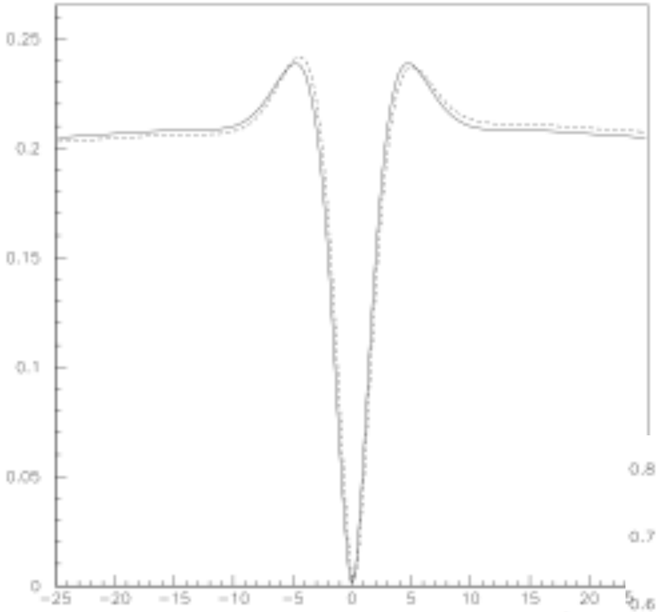
$$C_{12} = \frac{|N|^2}{2}\left|\langle f_1|T|K_S\rangle\langle f_2|T|K_S\rangle\right|^2$$

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

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



$\Delta t/\tau_S$

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

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

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

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

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

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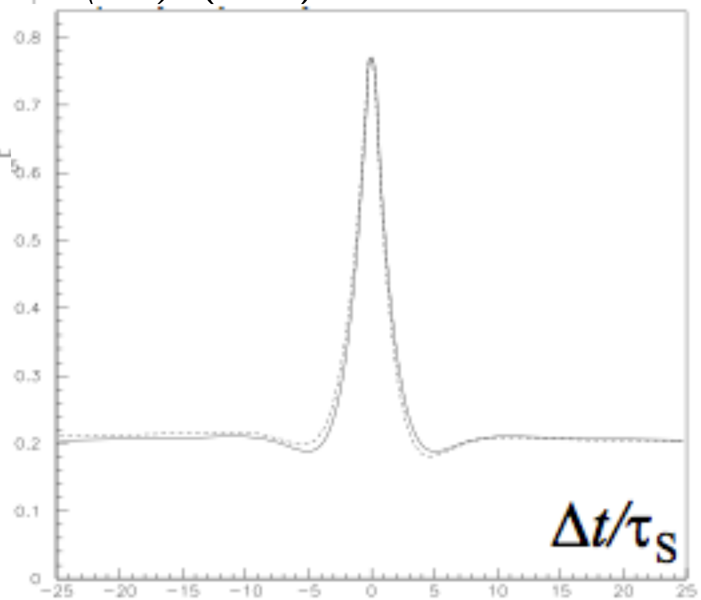

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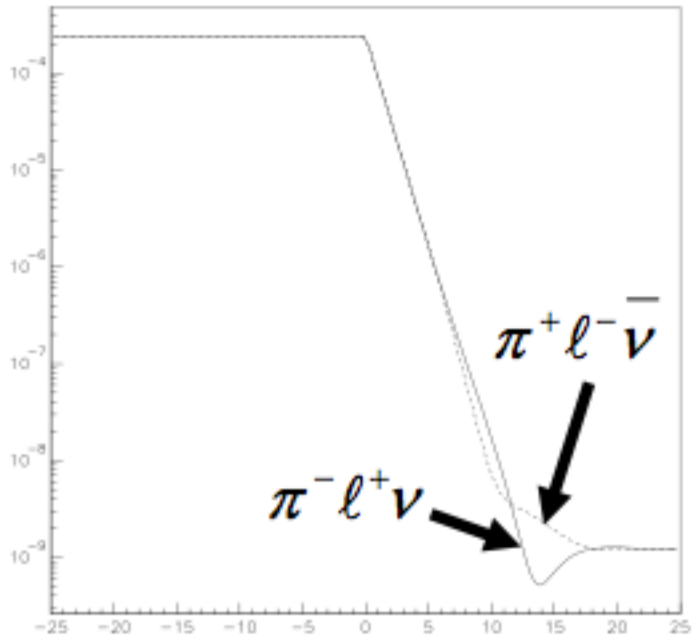


$\Delta t/\tau_S$

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

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

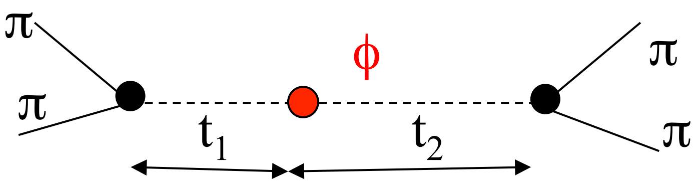
$$\phi_{\pi\pi}$$

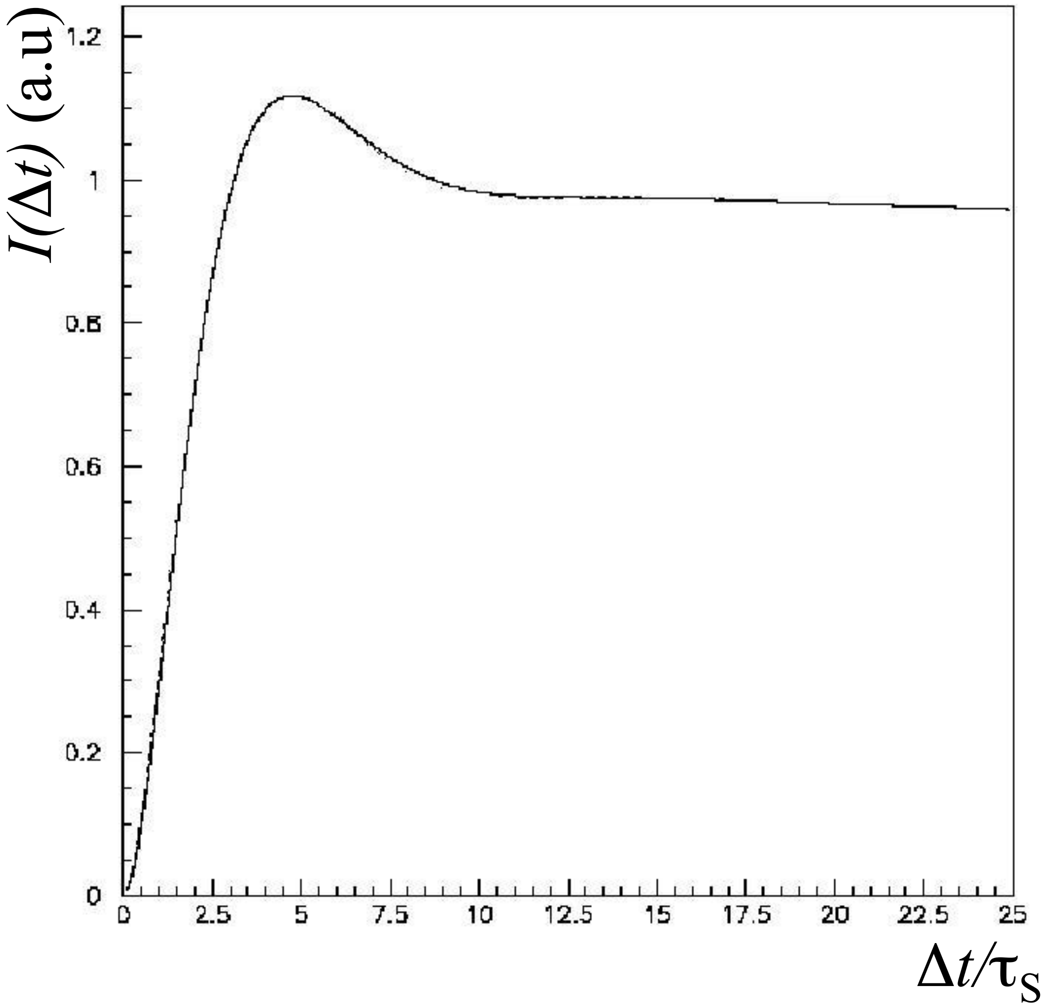
$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$

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

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

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





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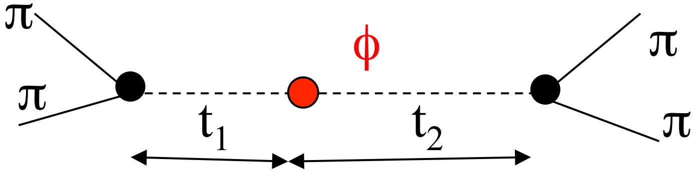
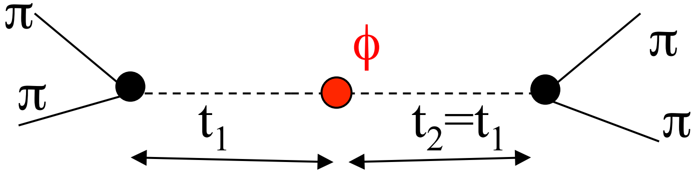
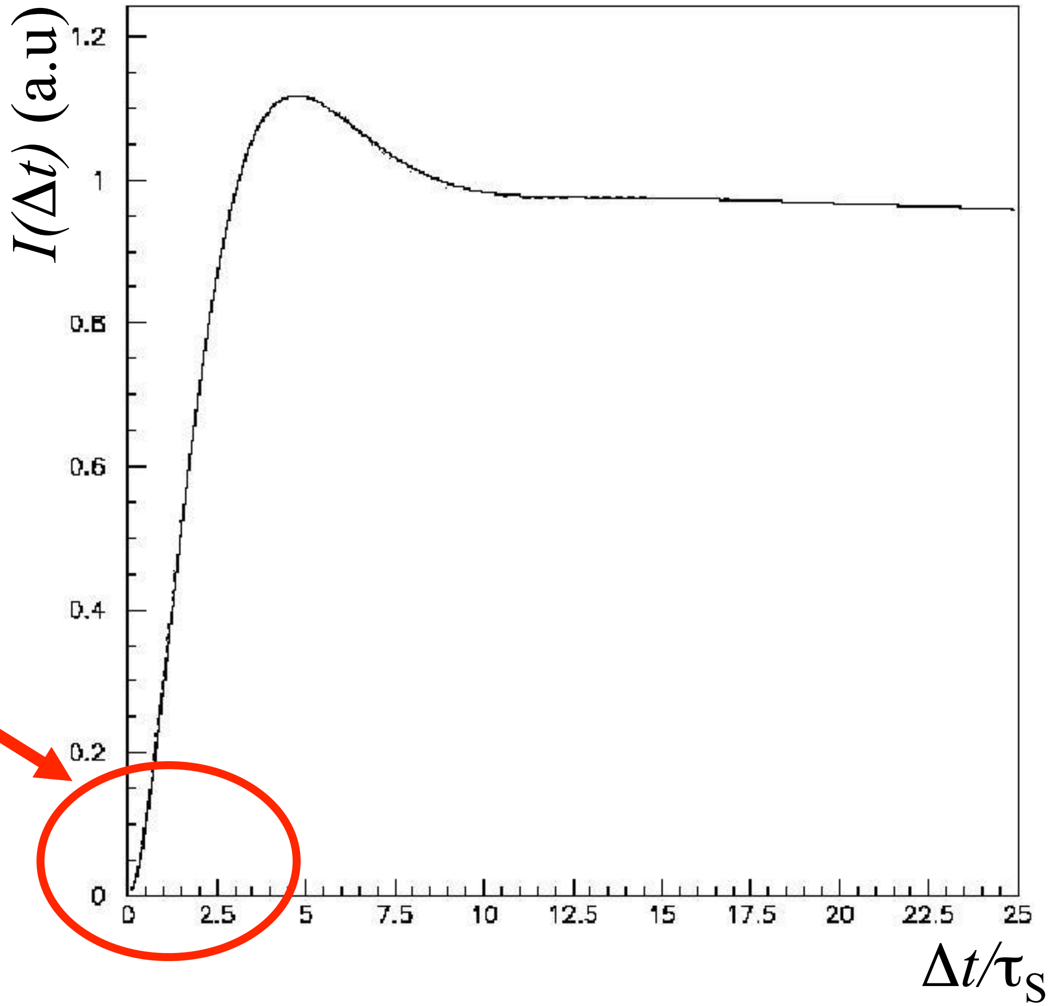


EPR correlation:

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





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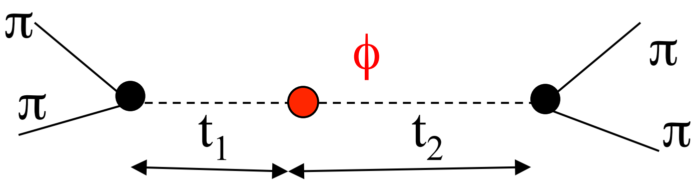

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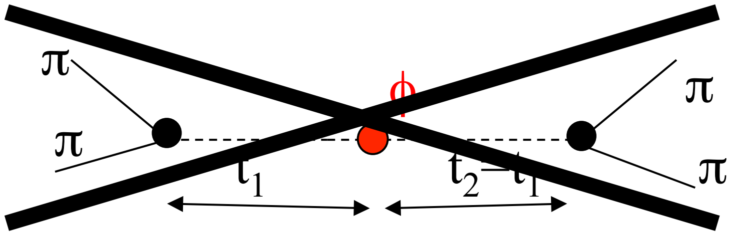

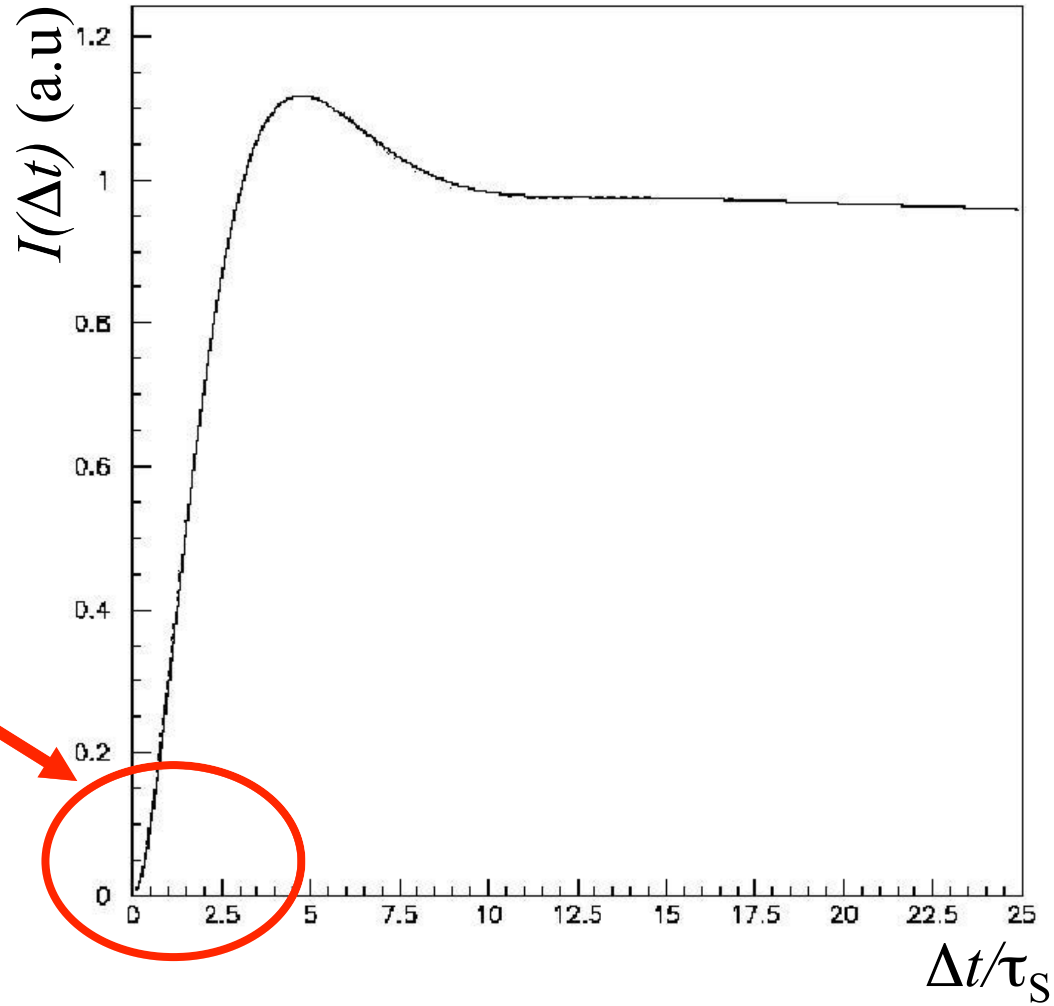

test of quantum coherence
(or search for decoherence effects)

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

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

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

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

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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)

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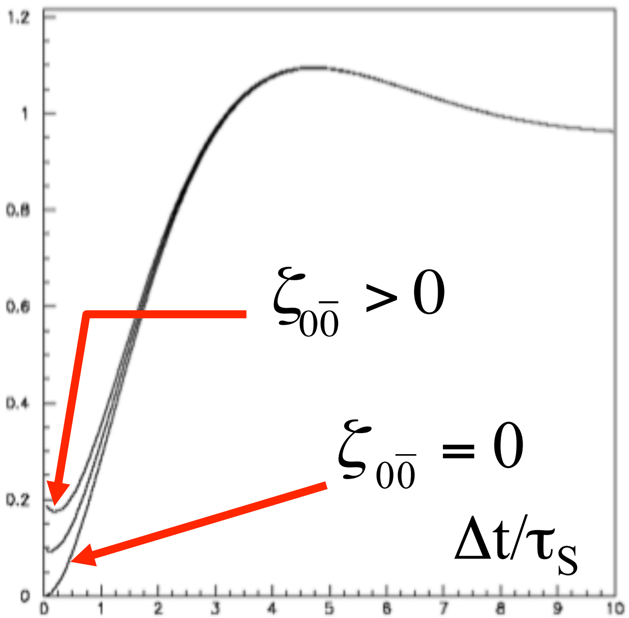
I(Δt) (a.u.)



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- 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

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

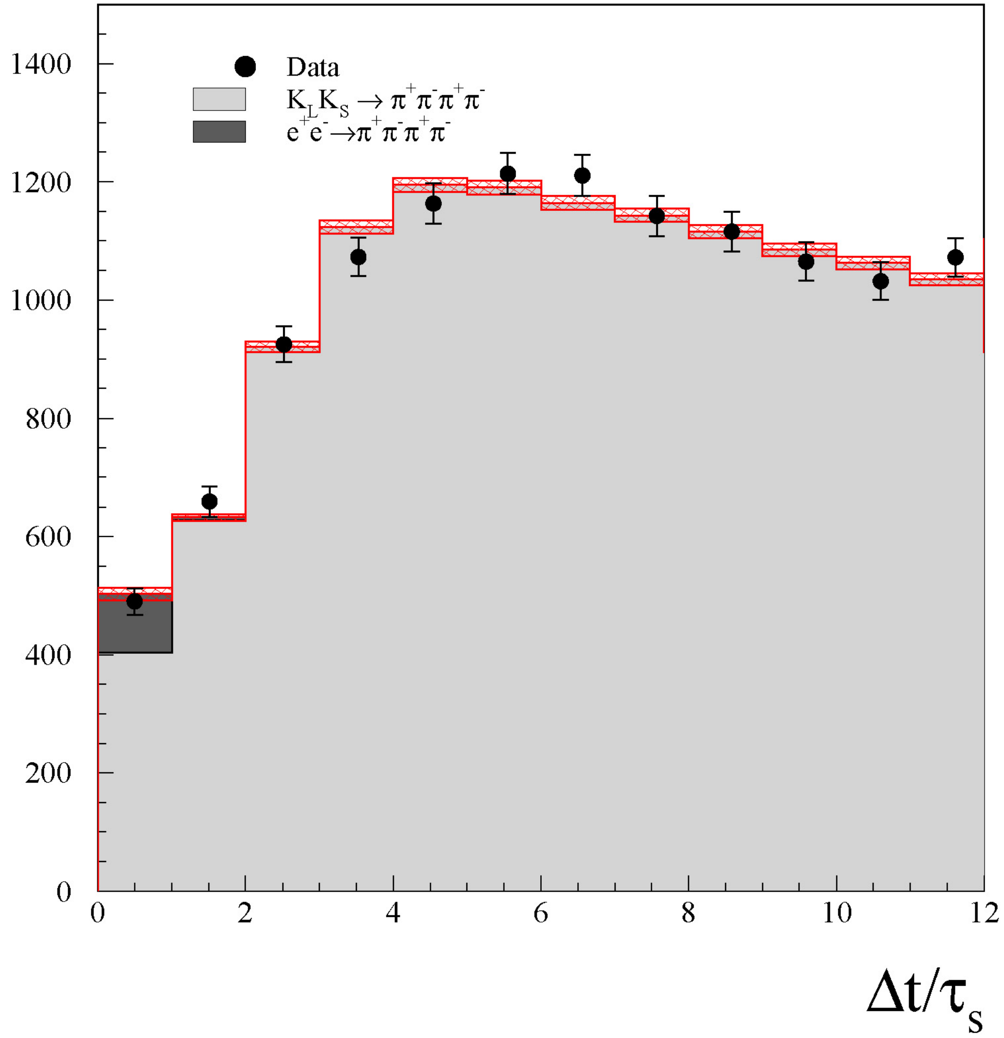
Observable suppressed by CP violation: $|\eta_{+-}|^2 \sim |\varepsilon|^2 \sim 10^{-6}$
=> terms $\zeta_{00}/|\eta_{+-}|^2$ => high sensitivity to ζ_{00}

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

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

In the B-meson system, BELLE coll. (PRL 99 (2007) 131802) obtains:

$$\zeta^{B}_{0\bar{0}} = 0.029 \pm 0.057$$



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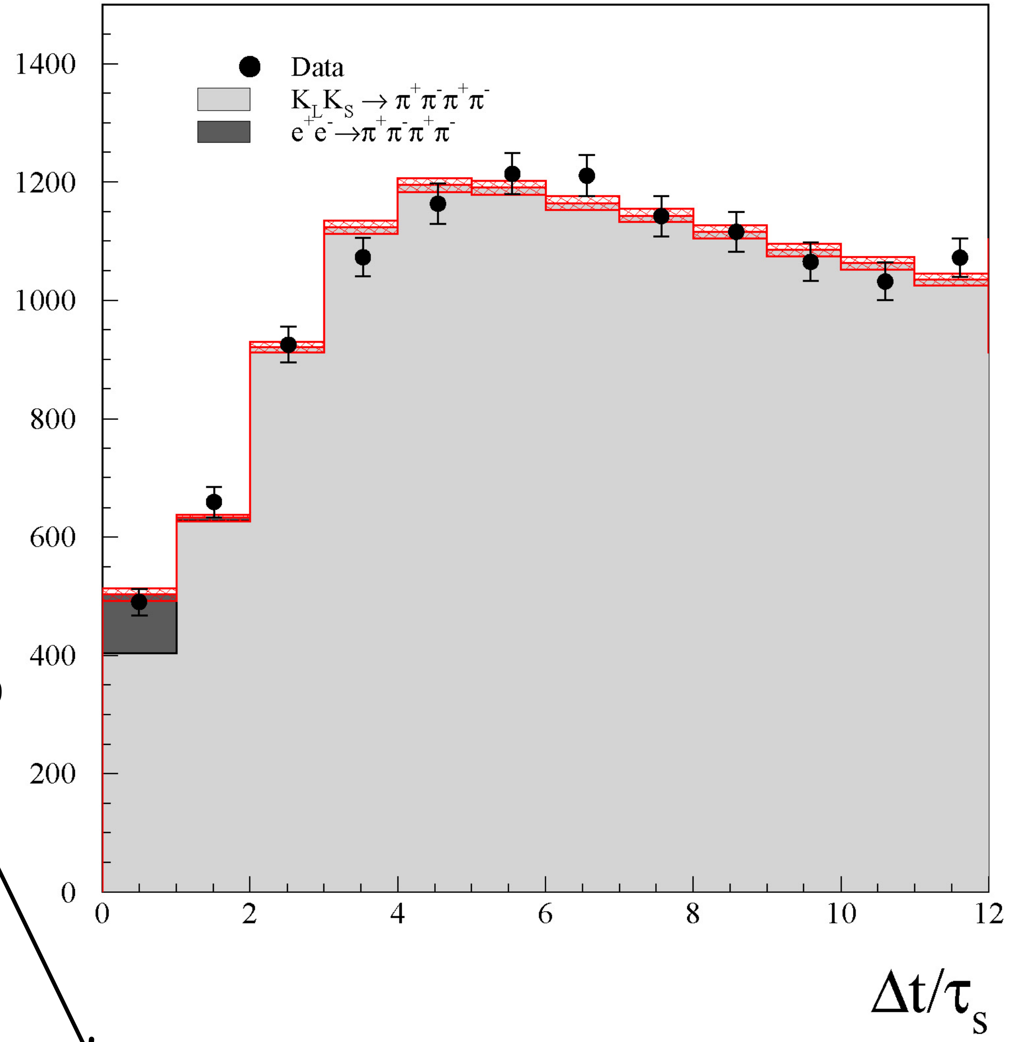


Best precision achievable in an entangled system

Search for decoherence and CPT violation effects

Decoherence and CPT violation

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

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

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 and CPT violation

Study of time evolution of **single kaons** decaying in π+π− 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

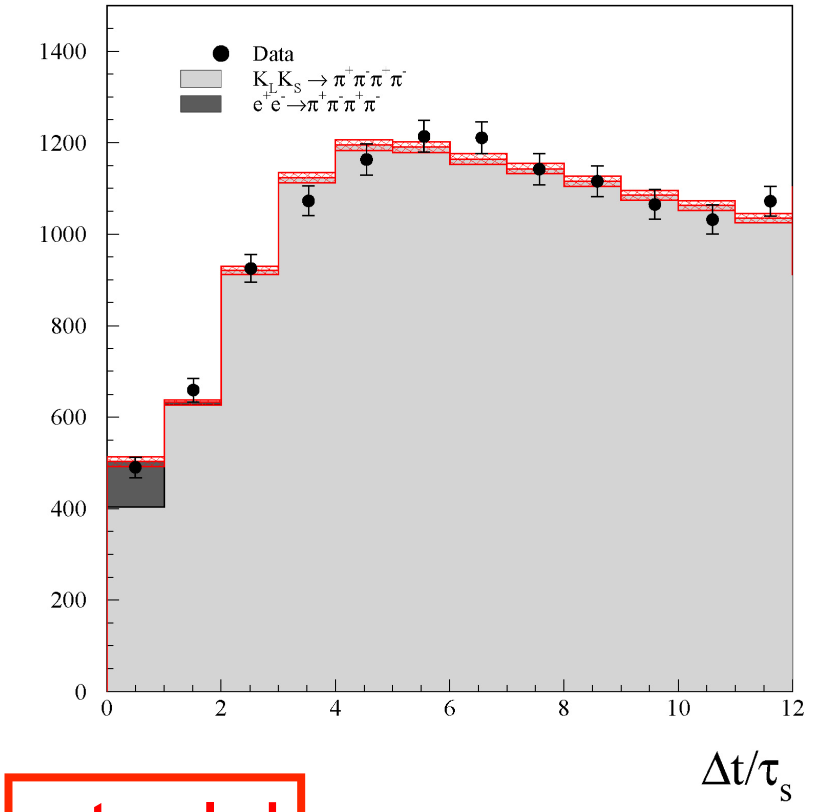
In the complete positivity hypothesis
$\alpha = \gamma$, $\beta = 0$
=> only one independent parameter: γ

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

KLOE result L=1.5 fb^{-1}

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

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



entangled kaons

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

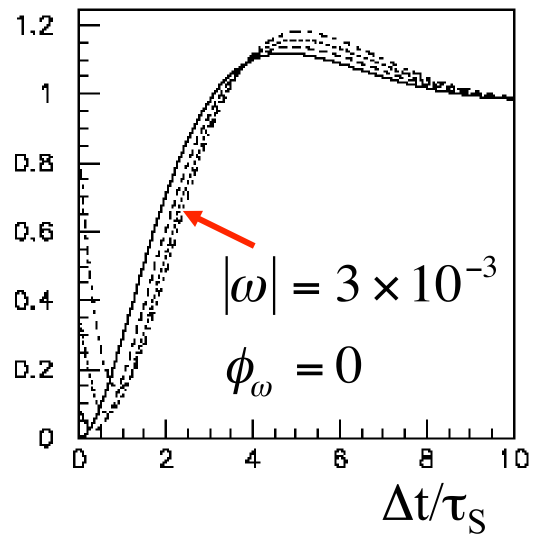
In presence of decoherence and CPT violation induced by quantum gravity (CPT operator "ill-defined") the definition of the particle-antiparticle states could be modified. This in turn could induce a breakdown of the correlations imposed by Bose statistics (EPR correlations) to the kaon state:

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

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

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

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



at most one expects:

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

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 (α,β,γ,ω) could be simultaneously disentangled.

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

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

- Analysed data: 1.5 fb^{-1}

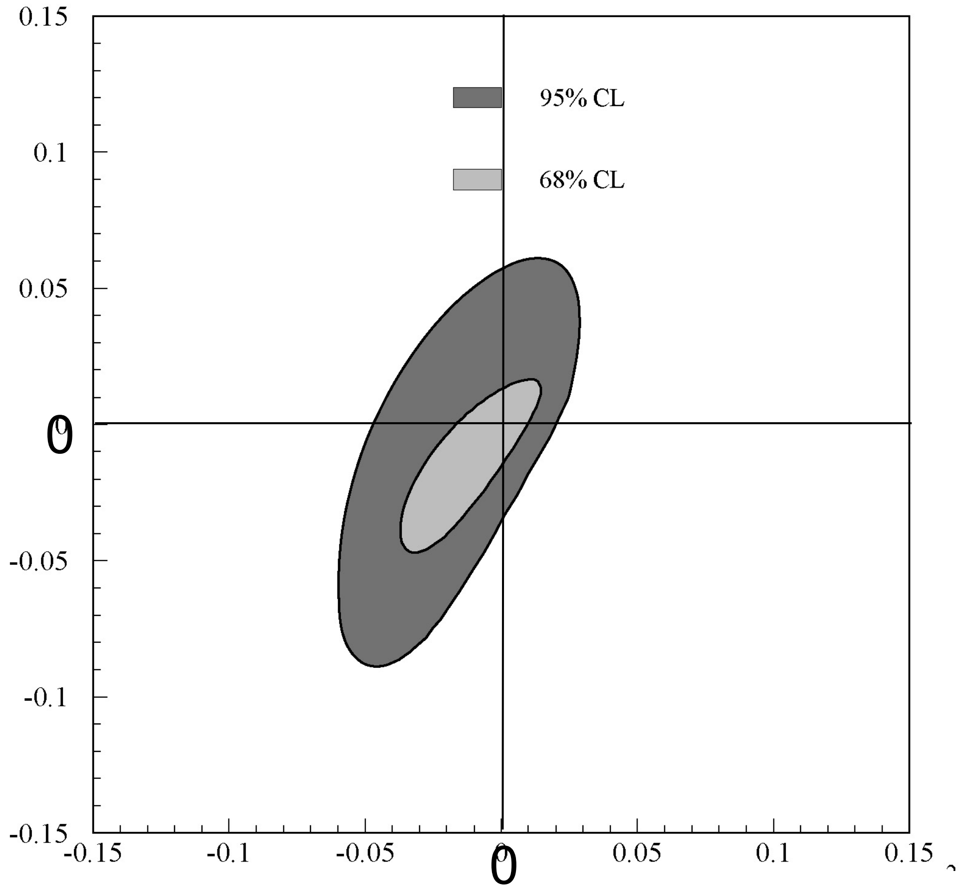
KLOE result: PLB 642(2006) 315
Found. Phys. 40 (2010) 852

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

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

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

Im ω x10^{-2}



Re ω x10^{-2}

In the B system [Alvarez, Bernabeu, Nebot JHEP 0611, 087]:

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

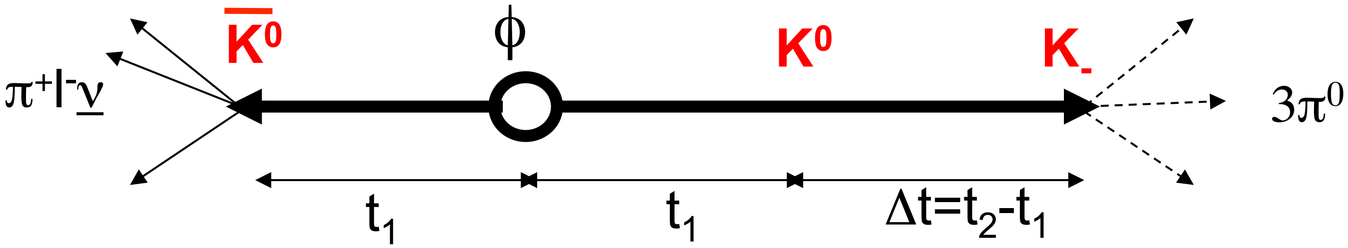
Direct test of time reversal symmetry

Direct test of Time Reversal symmetry with neutral kaons

- EPR correlations at a ϕ-factory (or B-factory) can be exploited to study other transitions involving also "CP states" K_+ and K_- (K_1, K_2)

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

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



Direct test of Time Reversal symmetry with neutral kaons

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

- decay as filtering measurement
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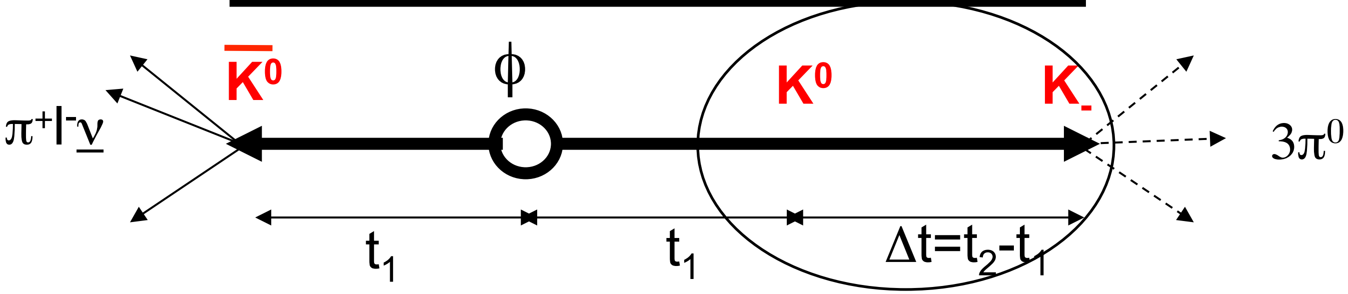

$$K^0 \rightarrow K_-$$

reference process

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$$
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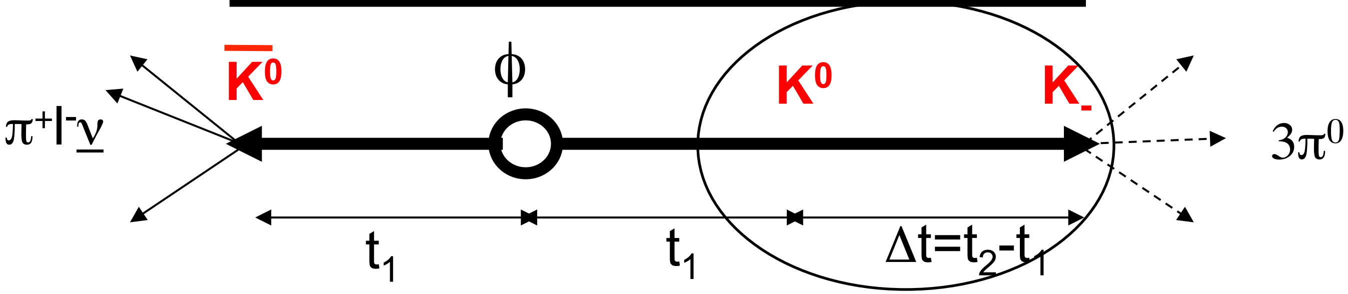
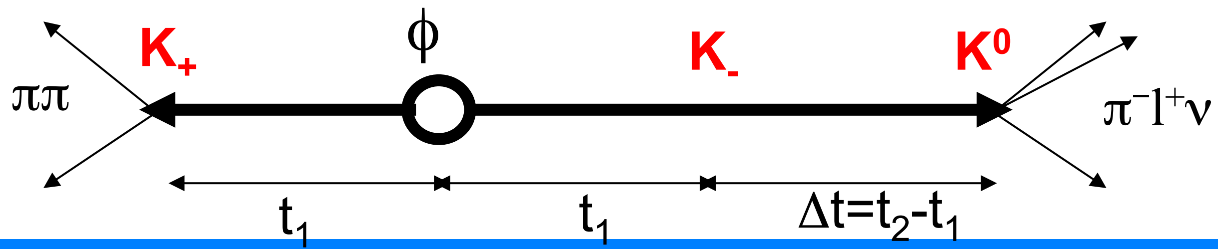


$$K^0 \rightarrow K_-$$ reference process



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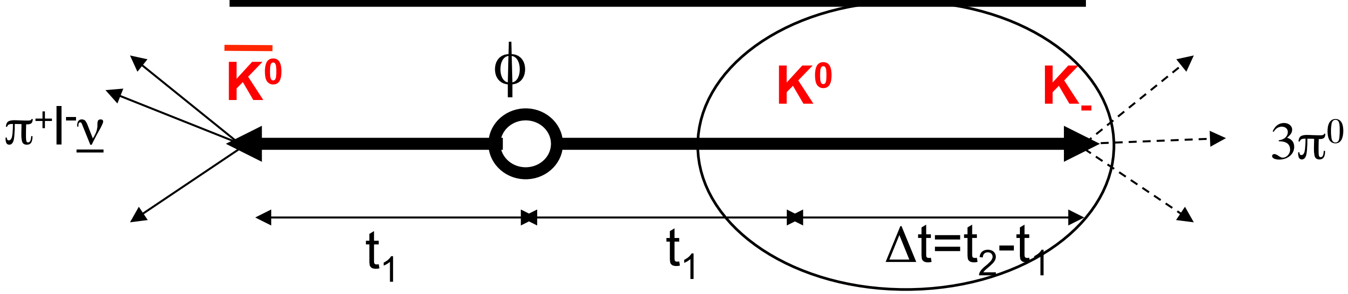
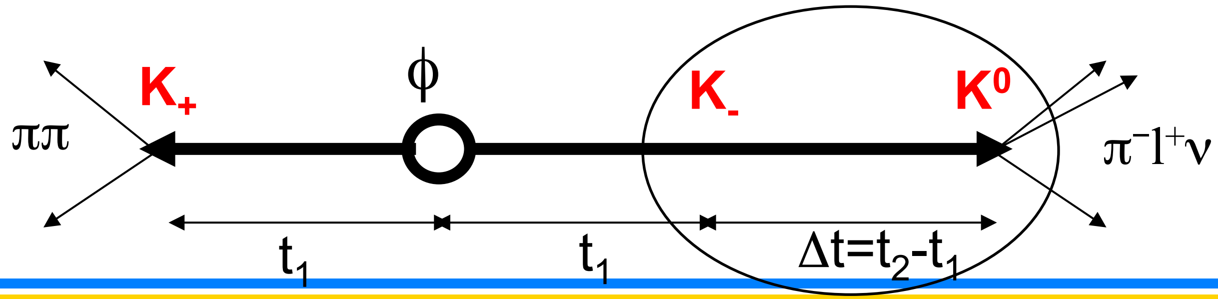


$K^0 \rightarrow K_-$ reference process

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



Direct test of Time Reversal symmetry with neutral kaons

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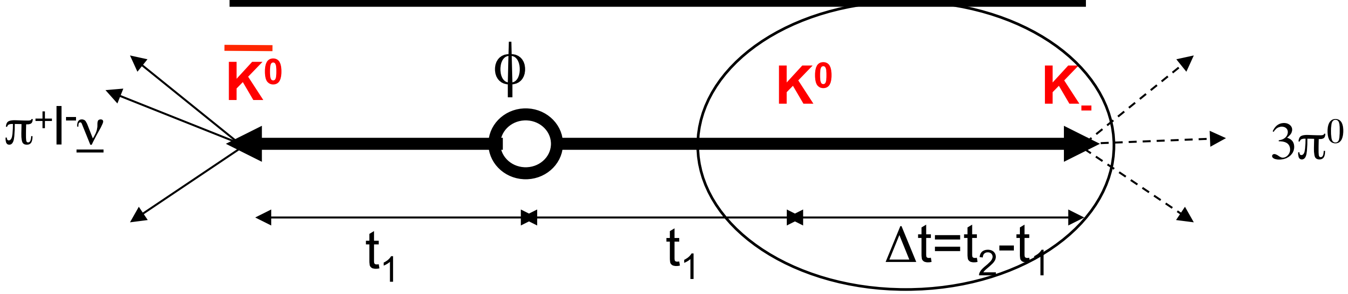
$$= \frac{1}{\sqrt{2}}\left[|K_+(\vec{p})\rangle|K_-(-\vec{p})\rangle - |K_-(\vec{p})\rangle|K_+(-\vec{p})\rangle\right]$$

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

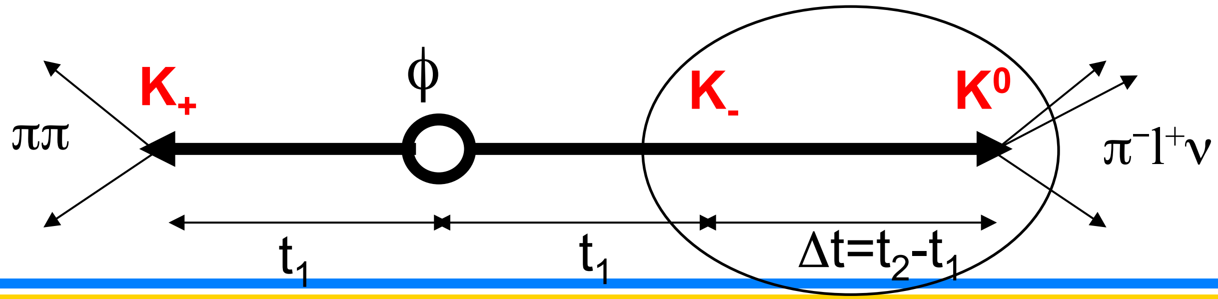


$K^0 \to K_-$ reference process

Note: CP-conjugated process

$\bar{K}^0 \to K_-$

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



Direct test of Time Reversal symmetry with neutral kaons

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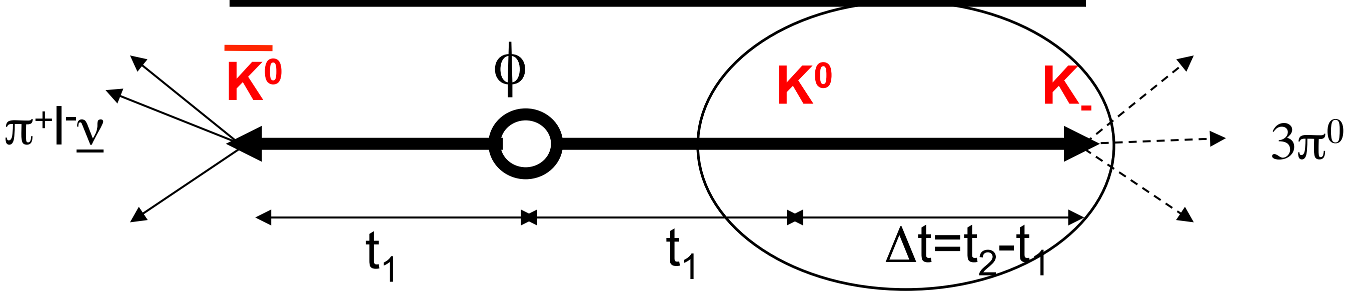
$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0(\vec{p})\rangle|\overline{K}^0(-\vec{p})\rangle - |\overline{K}^0(\vec{p})\rangle|K^0(-\vec{p})\rangle\right]$$
$$= \frac{1}{\sqrt{2}}\left[|K_+(\vec{p})\rangle|K_-(-\vec{p})\rangle - |K_-(\vec{p})\rangle|K_+(-\vec{p})\rangle\right]$$

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



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

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

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

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

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

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:

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

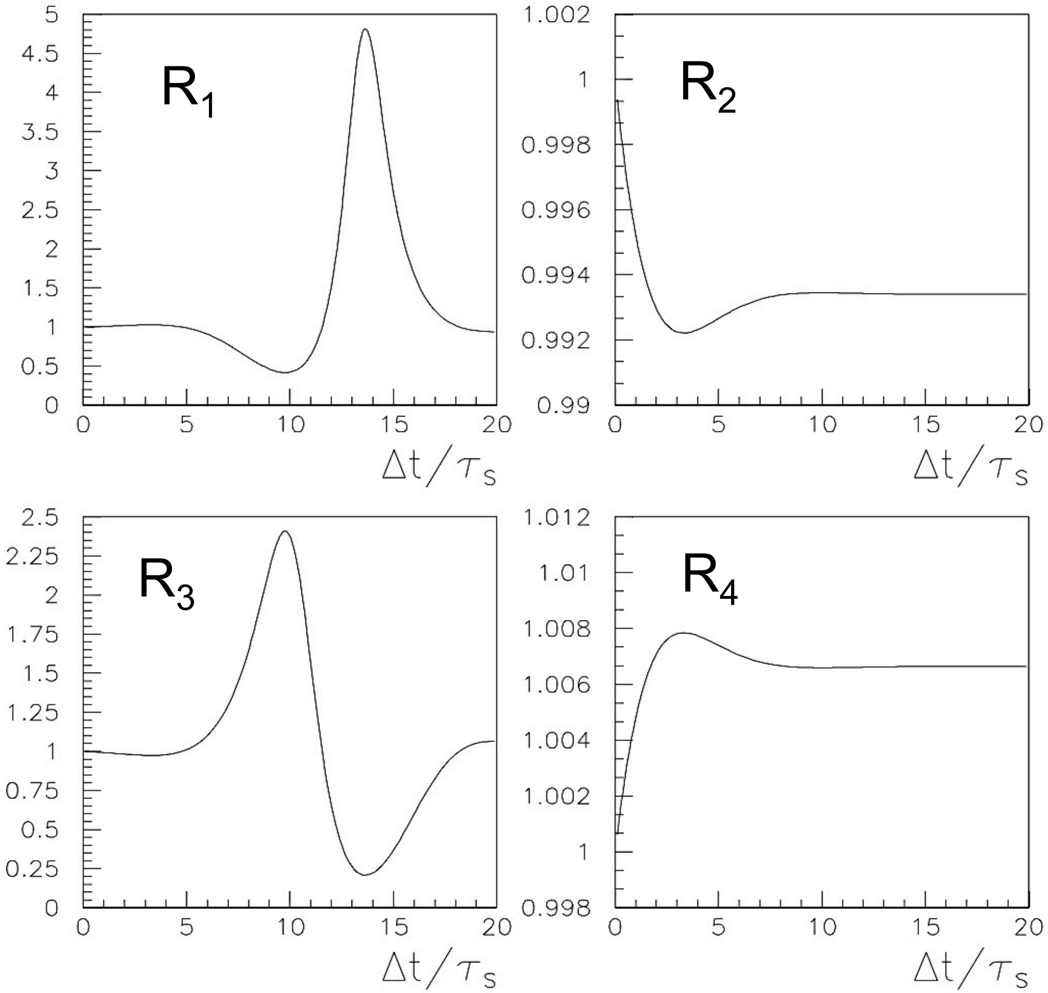
Any deviation from R_i=1 constitutes a violation of T-symmetry

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

Test feasible at KLOE-2 with L=*O*(10 fb^{-1})

Direct test of Time Reversal symmetry with neutral kaons

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

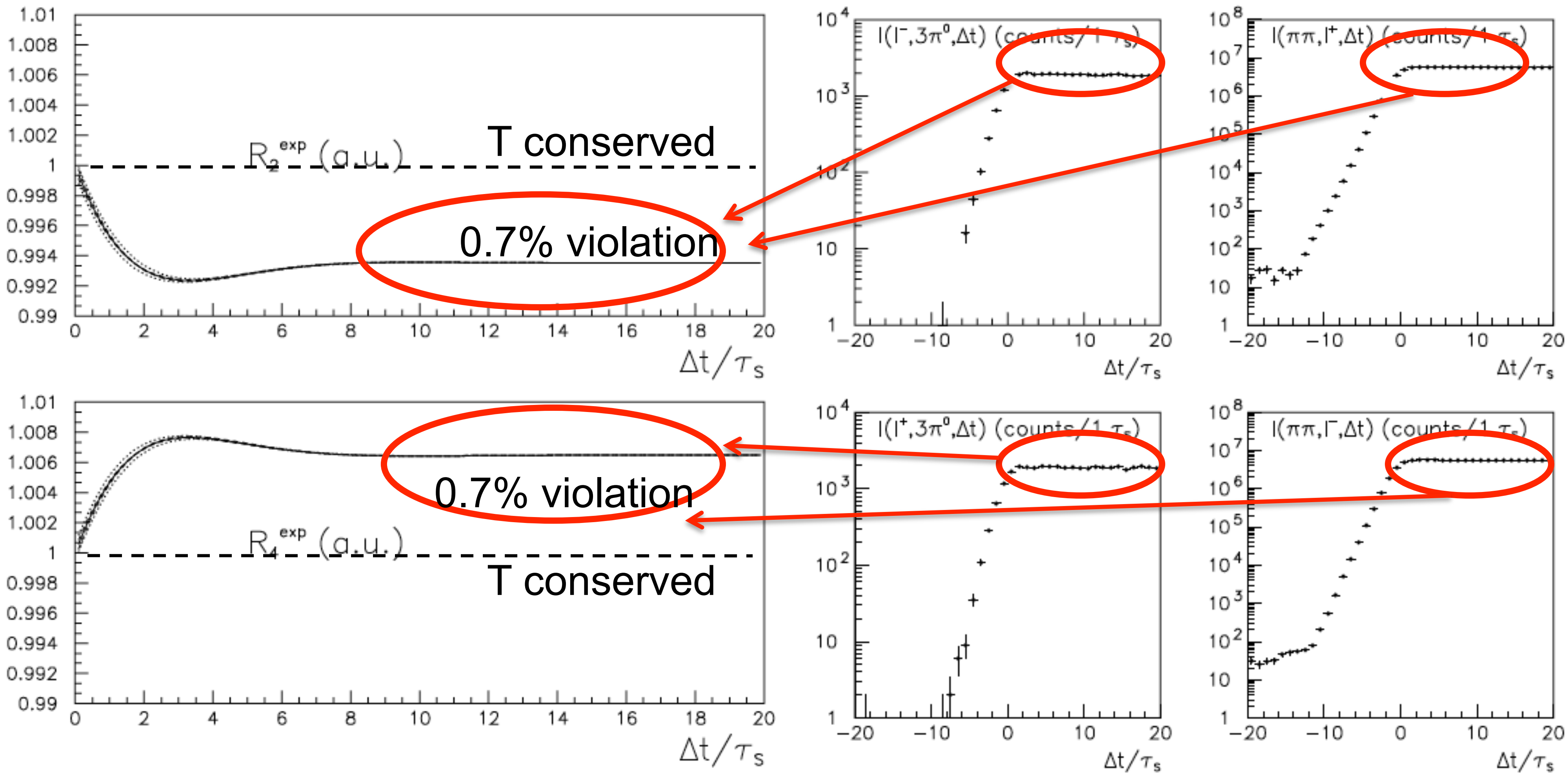


$R_i(\Delta t=0)=1$

$R_2(\Delta t>>\tau_S)=1-4\mathrm{Re}(\varepsilon)$
$R_4(\Delta t>>\tau_S)=1+4\mathrm{Re}(\varepsilon)$

Direct test of Time Reversal symmetry with neutral kaons

toy MC with L=10 fb^{-1}



$R_2(\Delta t >> \tau_S) = 1-4Re(\varepsilon) \sim 0.993$

$R_4(\Delta t >> \tau_S) = 1+4Re(\varepsilon) \sim 1.007$

Direct test of CPT symmetry with neutral kaons

CPT symmetry test

Reference		CPT-conjugate	
Transition	Decay products	Transition	Decay products
$K^0 \to K_+$	$(\ell^-, \pi\pi)$	$K_+ \to \bar{K}^0$	$(3\pi^0, \ell^-)$
$K^0 \to K_-$	$(\ell^-, 3\pi^0)$	$K_- \to \bar{K}^0$	$(\pi\pi, \ell^-)$
$\bar{K}^0 \to K_+$	$(\ell^+, \pi\pi)$	$K_+ \to K^0$	$(3\pi^0, \ell^+)$
$\bar{K}^0 \to K_-$	$(\ell^+, 3\pi^0)$	$K_- \to K^0$	$(\pi\pi, \ell^+)$

One can define the following ratios of probabilities:

$$
\begin{aligned}
R_{1,\mathcal{CPT}}(\Delta t) &= P\left[K^0(0) \to K_+(\Delta t)\right] / P\left[K_+(0) \to \bar{K}^0(\Delta t)\right] \\
R_{2,\mathcal{CPT}}(\Delta t) &= P\left[K^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to \bar{K}^0(\Delta t)\right] \\
R_{3,\mathcal{CPT}}(\Delta t) &= P\left[\bar{K}^0(0) \to K_+(\Delta t)\right] / P\left[K_+(0) \to K^0(\Delta t)\right] \\
R_{4,\mathcal{CPT}}(\Delta t) &= P\left[\bar{K}^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to K^0(\Delta t)\right]
\end{aligned}
$$

Any deviation from $R_{i,CPT}=1$ constitutes a violation of CPT-symmetry

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

Significant test at KLOE-2 with L=*O*(10 fb^{-1}), feasibility study ongoing

Future perspectives

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 an 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**)

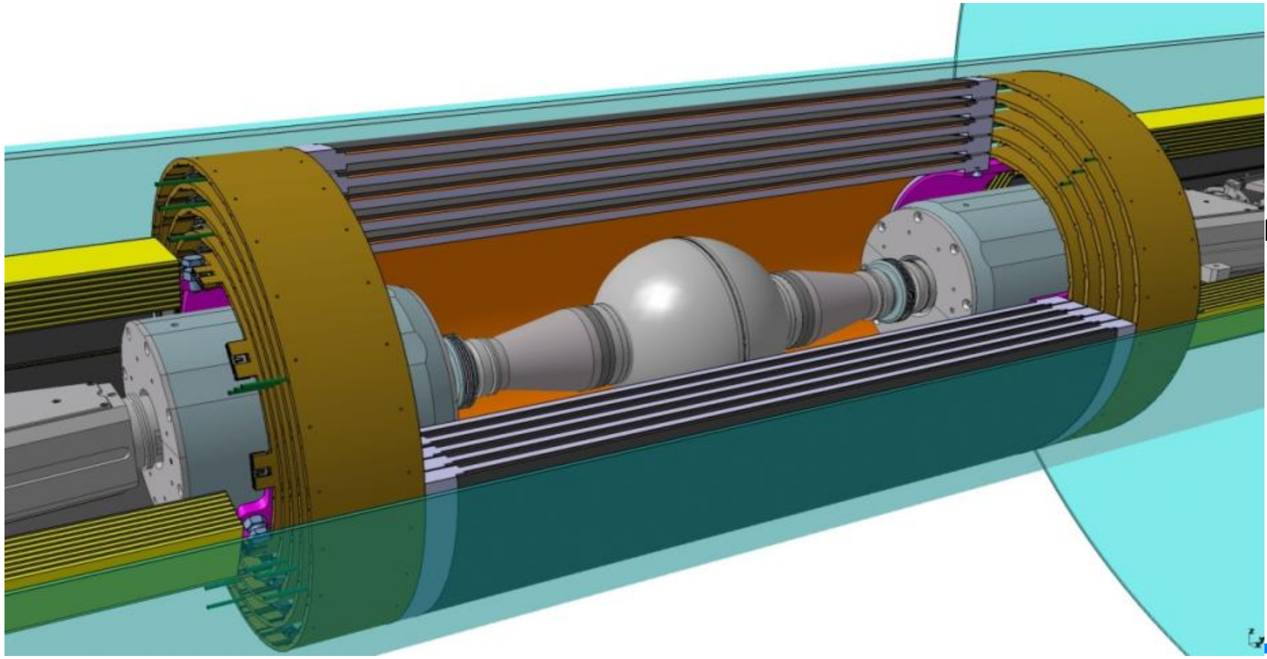
- Neutral kaon interferometry, CPT symmetry & QM tests
- Kaon physics, CKM, LFV, rare K_S decays
- η,η' physics
- Light scalars, $\gamma\gamma$ physics
- Hadron cross section at low energy, a_μ
- Dark forces: search for light U boson

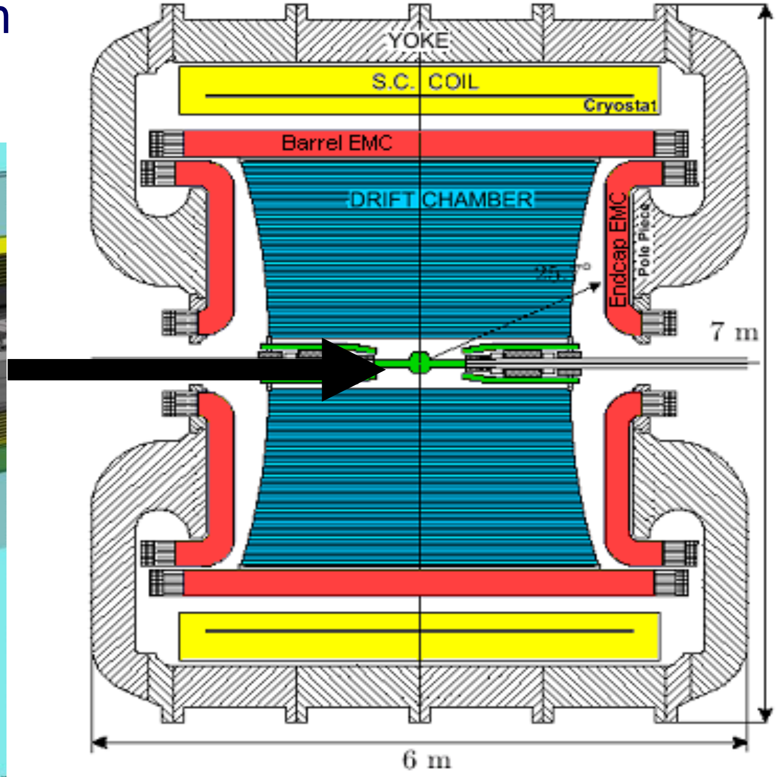
Detector upgrade:

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

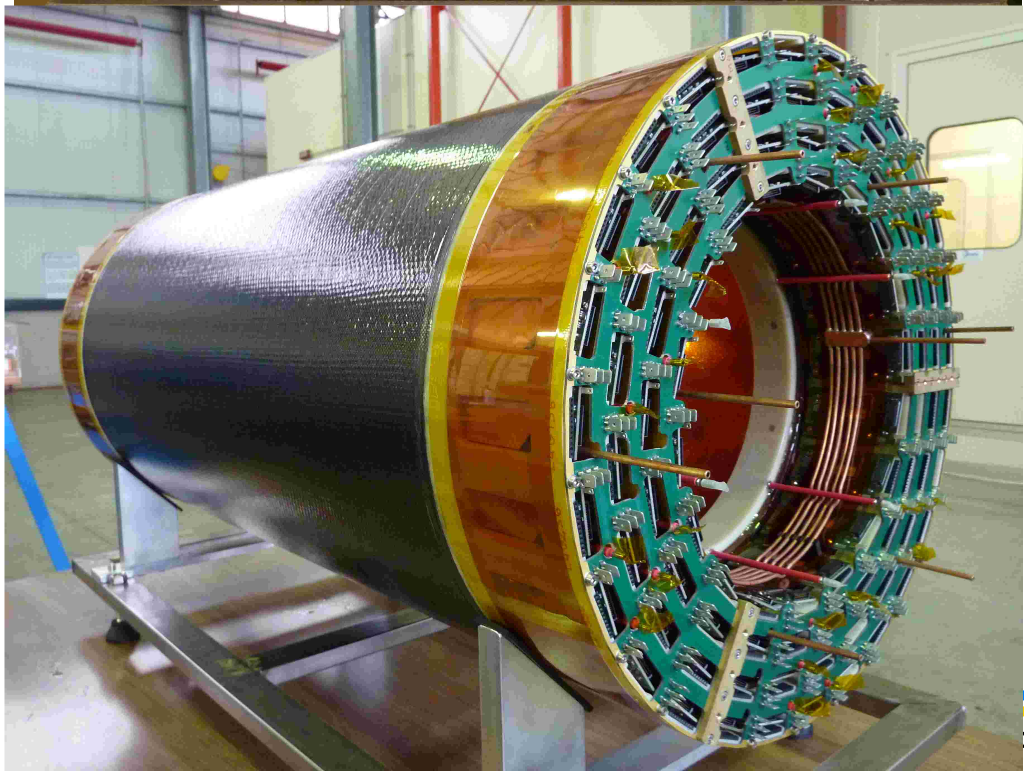
Inner tracker at KLOE-2

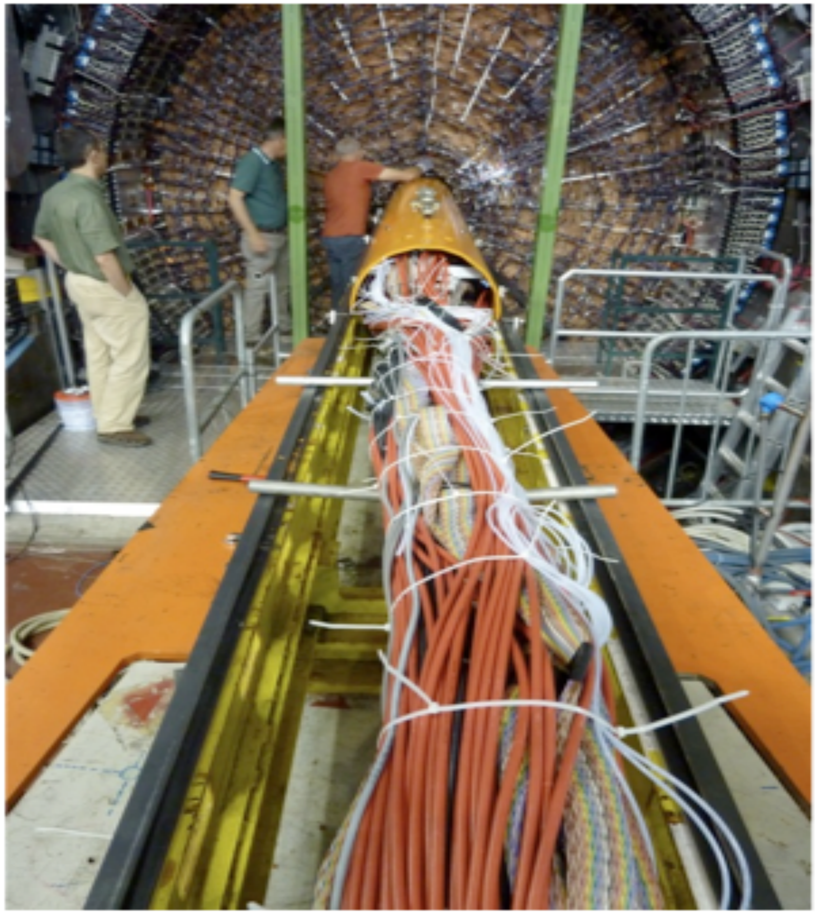
- 4 independent tracking layers for a fine vertex reconstruction of K_S and η
- 200 µm $\sigma_{r\phi}$ and 500 µm σ_z spatial resolutions with XV readout
- 700 mm active length
- from 150 to 250 mm radii
- 1.8% X_0 total radiation length in the active region
- Realized with **Cylindrical-GEM** detectors





Inner tracker at KLOE

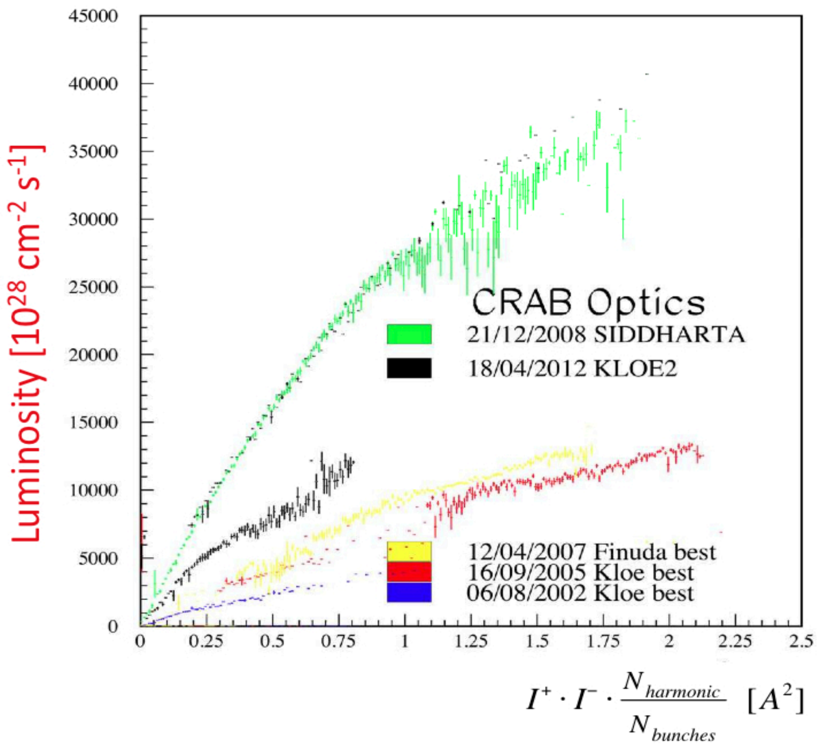


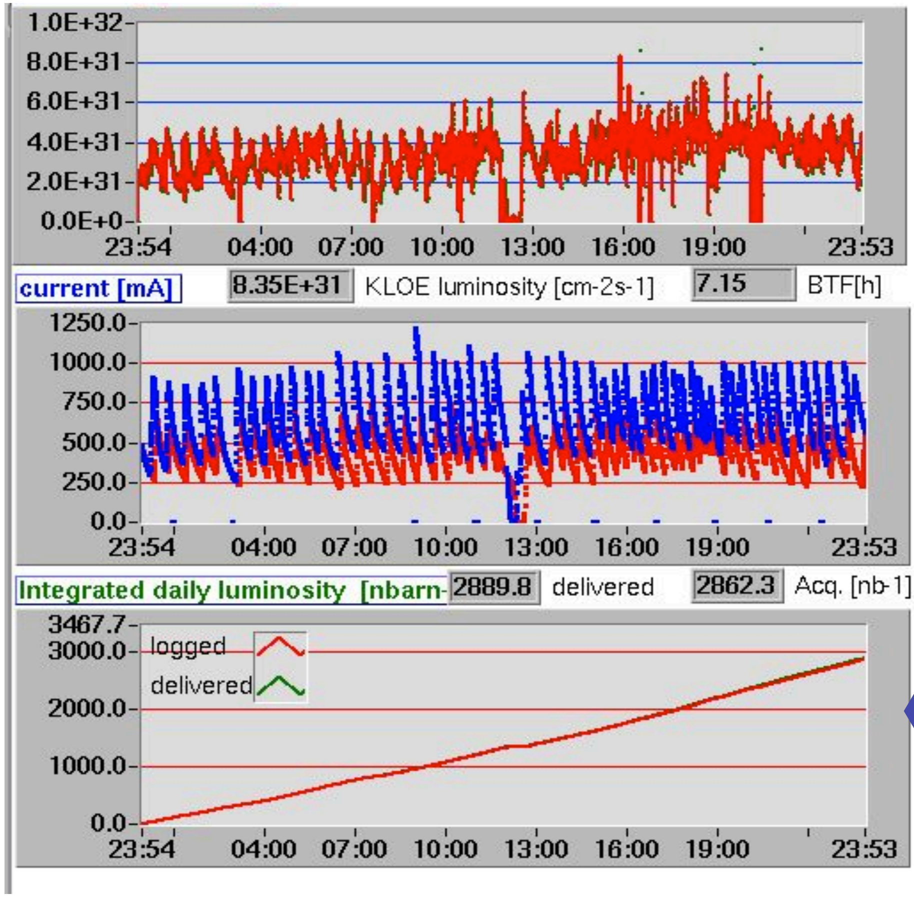


- -Construction and installation inside KLOE completed (July 2013)
- - Commissioning in progress

DAΦNE luminosity upgrade

- **DAΦNE upgrade (2008): new interaction scheme; large beam crossing angle + crabbed waist sextupoles**





- **Installation of the new DAΦNE IR + KLOE-2 upgrades completed in July 2013**

- Feb. 2014: one week after restarting collisions
- Crab sextupoles off
- Uptime ~ 100%

Prospects for KLOE-2

Param.	Present best published measurement	KLOE-2 (IT) $L=5\ fb^{-1}$	KLOE-2 (IT) $L=10\ fb^{-1}$
ζ_{00}	$(0.1 \pm 1.0) \times 10^{-6}$	$\pm 0.26 \times 10^{-6}$	$\pm 0.18 \times 10^{-6}$
ζ_{SL}	$(0.3 \pm 1.9) \times 10^{-2}$	$\pm 0.49 \times 10^{-2}$	$\pm 0.35 \times 10^{-2}$
α	$(-0.5 \pm 2.8) \times 10^{-17}$ GeV	$\pm 5.0 \times 10^{-17}$ GeV	$\pm 3.5 \times 10^{-17}$ 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
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
$Re(\omega)$	$(-1.6 \pm 2.6) \times 10^{-4}$	$\pm 0.70 \times 10^{-4}$	$\pm 0.49 \times 10^{-4}$
$Im(\omega)$	$(-1.7 \pm 3.4) \times 10^{-4}$	$\pm 0.86 \times 10^{-4}$	$\pm 0.61 \times 10^{-4}$
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
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
Δa_X	$(3.3 \pm 2.2) \times 10^{-18}$ GeV	$\pm 0.76 \times 10^{-18}$ GeV	$\pm 0.54 \times 10^{-18}$ GeV
Δa_Y	$(-0.7 \pm 2.0) \times 10^{-18}$ GeV	$\pm 0.76 \times 10^{-18}$ GeV	$\pm 0.54 \times 10^{-18}$ GeV

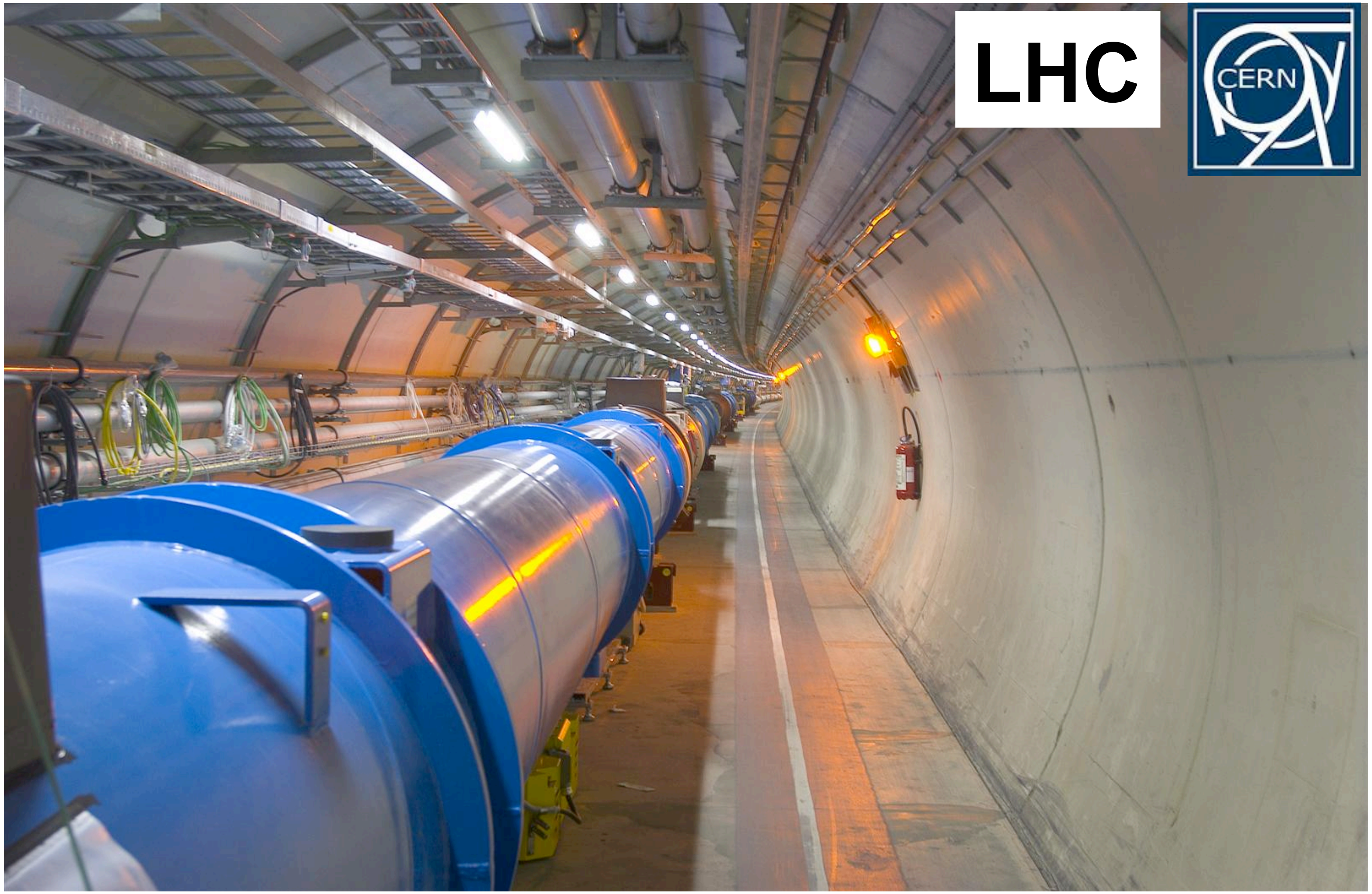
$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$ elsewhere??

Is it possible to perform these tests of Quantum Mechanics and CPT symmetry with entangled neutral kaons elsewhere than a ϕ-factory?

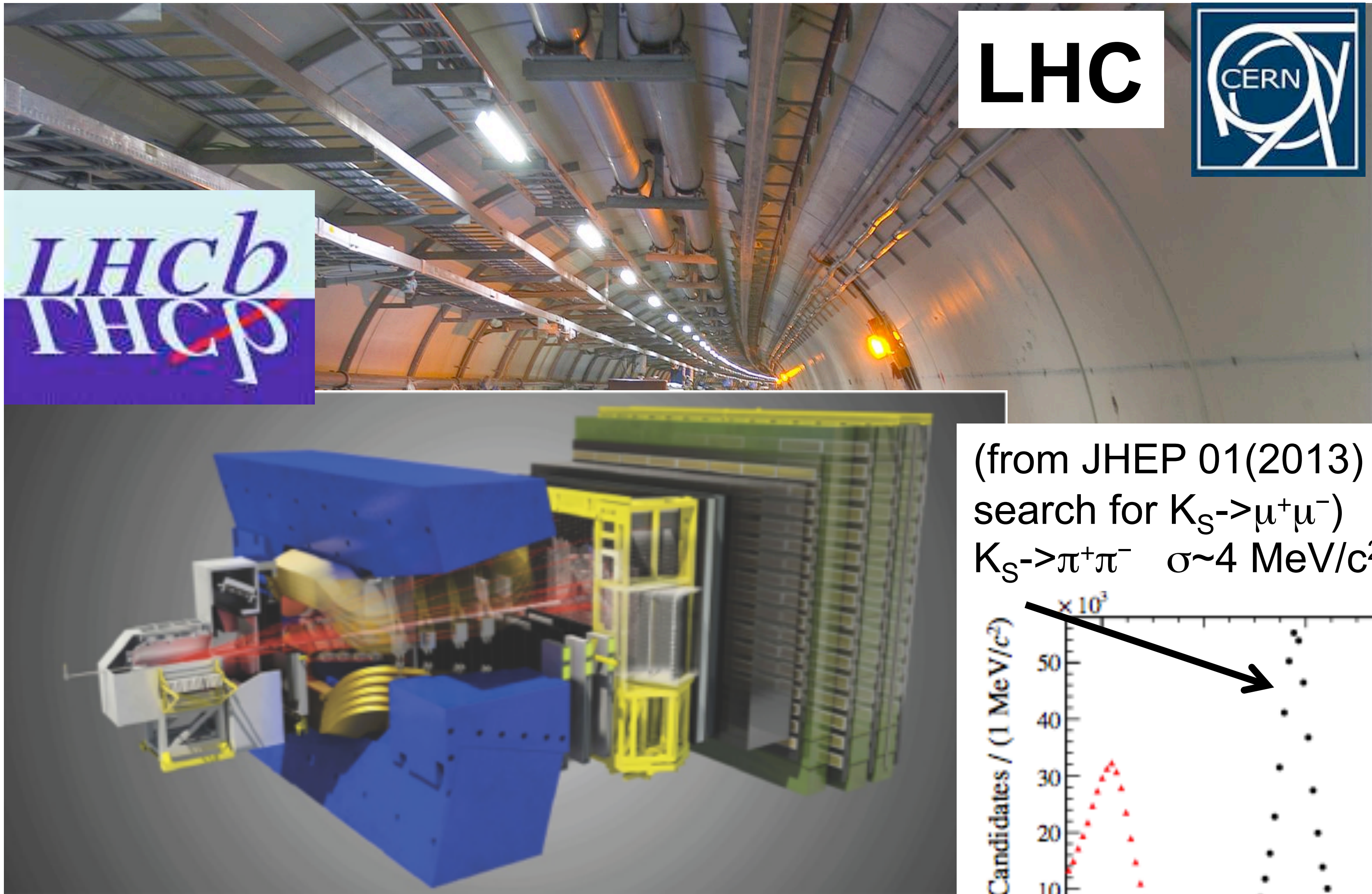
As we have seen the process $\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$ is very rich in Physics and plays a key role in this respect.

From the experimental point of view the main advantage of this process is the “closed” kinematics which makes it “easily” observable – in principle – also in a “hadron machine” environment.

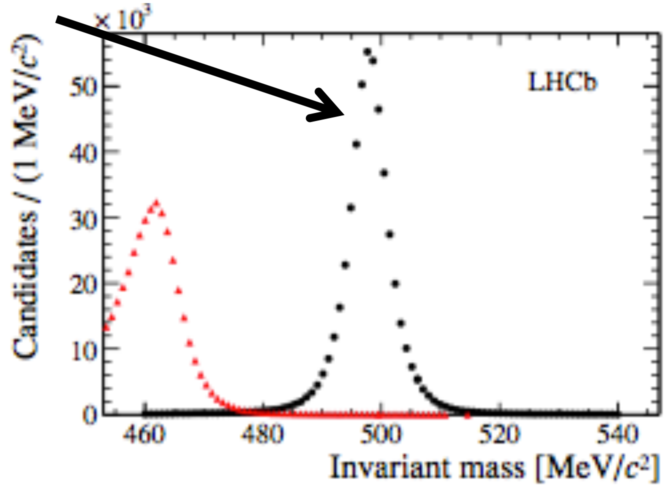
$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$ at LHC??



$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$ at LHC??



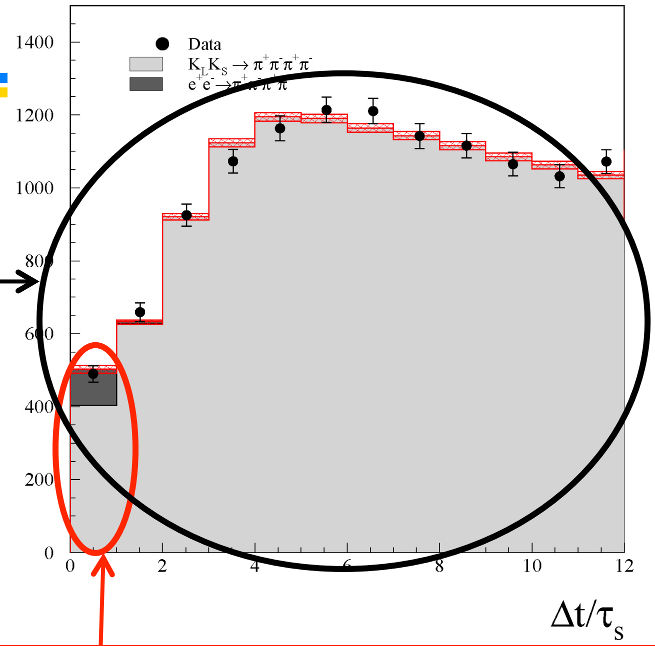
(from JHEP 01(2013) 090
search for $K_S \rightarrow \mu^+\mu^-$)
$K_S \rightarrow \pi^+\pi^-$ σ~4 MeV/c^2



=> feasibility study, A.D.D. + T. Ruf (CERN), ongoing

$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$ at LHCb: statistics

at KLOE
λ_S~6 mm (P=110 MeV/c)
L=1.5 fb-1
$4.4\text{x}10^9$ ϕ's



At LHCb:
~0.2 < λ_S~ 0.8 m (~3 < P < ~20 GeV/c)
σ(pp->ϕX)~1800 μb -> $1.8\text{x}10^{12}$ ϕ's /fb^{-1}
(in LHCb acceptance PLB 703(2011) 267)

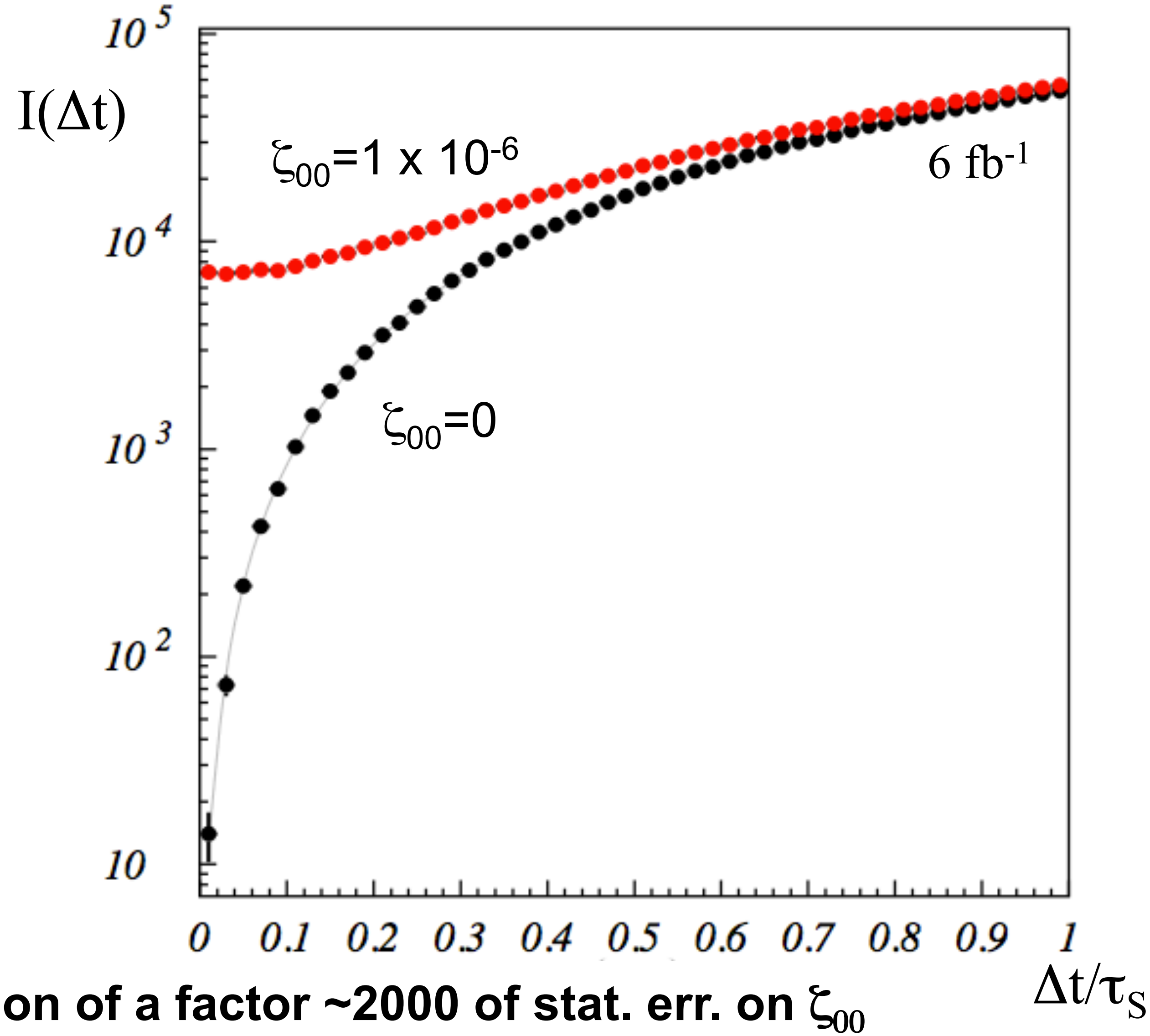
NOT including the efficiency one expects:
N(ϕ-> $K_S K_L$->$\pi^+\pi^-\pi^+\pi^-$) = $1.5\text{x}10^5$ evts/fb^{-1} in 0-1 τ_S range

x 6 fb^{-1} ~ $9.0\text{x}10^5$ evts

$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$ at LHCb: toy MC simulation

FIT in 0 -1 τ_S range
N events = 10^6 (~6fb^{-1})

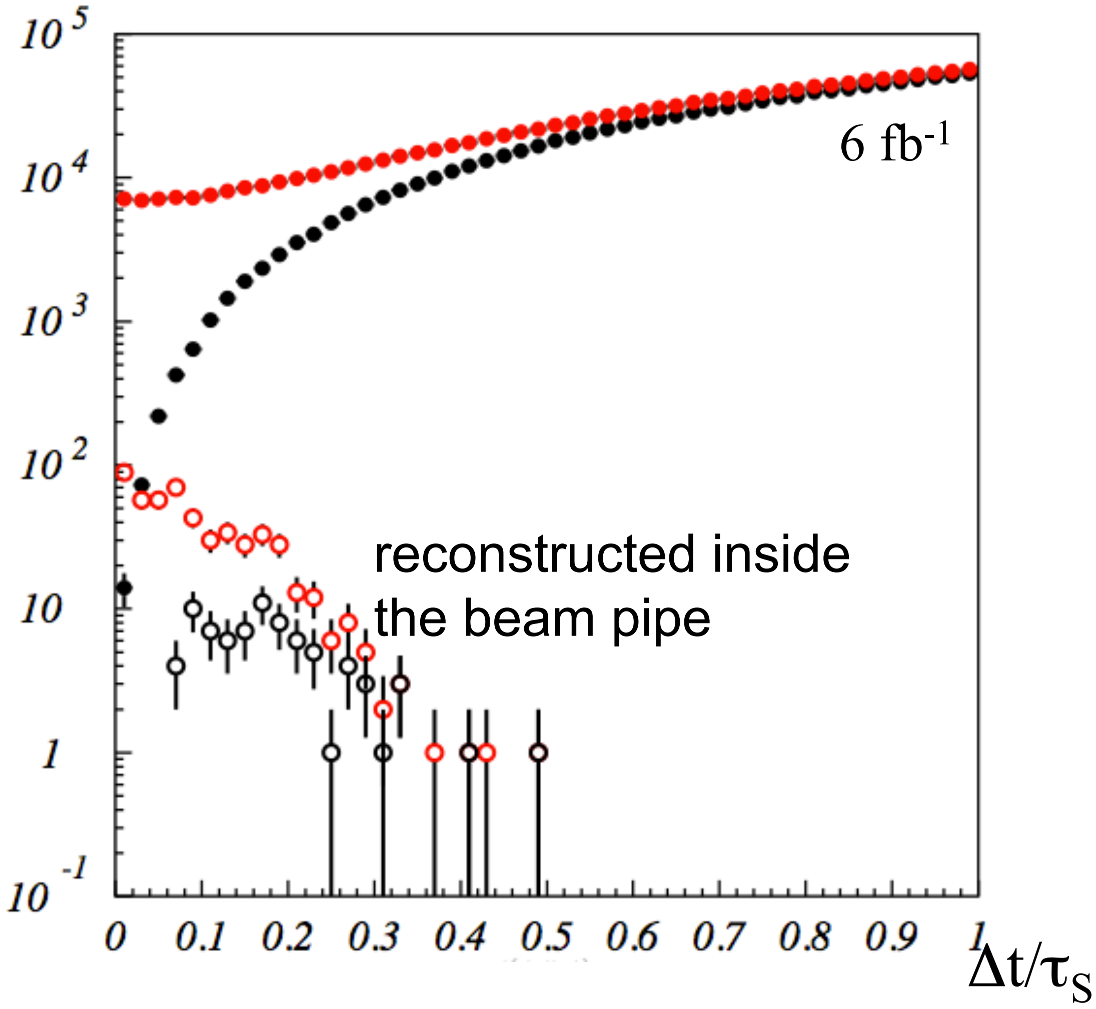
	$\sigma(\zeta_{00})$
KLOE 1.5 fb^{-1}	$\pm 1.0 \times 10^{-6}$
LHCb 6 fb^{-1}	$\pm 0.4 \times 10^{-9}$



in principle reduction of a factor ~2000 of stat. err. on ζ_{00}

$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$ at LHCb: toy MC simulation

-In order to avoid K_S regeneration on the beam pipe, both kaon vertices are required to be reconstructed inside the beam pipe: r< 5 mm



- Δt resolution effects are totally negligible
- only $0 < \Delta t < 0.3\ \tau_S$ range can be reconstructed (both kaons decaying at short times), which is the most relevant for CPT and QM tests!!
- large background to be rejected/subtracted
- trigger efficiency to be increased

Prospects for KLOE-2 and LHCb

PRELIMINARY

Param.	Present best published measurement	KLOE-2 (IT) $L=5\ fb^{-1}$	KLOE-2 (IT) $L=10\ fb^{-1}$	LHCb $L=6\ fb^{-1}$
ζ_{00}	$(0.1 \pm 1.0) \times 10^{-6}$	$\pm 0.26 \times 10^{-6}$	$\pm 0.18 \times 10^{-6}$	$\pm 0.04 \times 10^{-6}$
ζ_{SL}	$(0.3 \pm 1.9) \times 10^{-2}$	$\pm 0.49 \times 10^{-2}$	$\pm 0.35 \times 10^{-2}$	$\pm 0.11 \times 10^{-2}$
α	$(-0.5 \pm 2.8) \times 10^{-17}$ GeV	$\pm 5.0 \times 10^{-17}$ GeV	$\pm 3.5 \times 10^{-17}$ GeV	
β	$(2.5 \pm 2.3) \times 10^{-19}$ GeV	$\pm 0.50 \times 10^{-19}$ GeV	$\pm 0.35 \times 10^{-19}$ 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	compl. pos. hyp. $\pm 0.07 \times 10^{-21}$ GeV
$Re(\omega)$	$(-1.6 \pm 2.6) \times 10^{-4}$	$\pm 0.70 \times 10^{-4}$	$\pm 0.49 \times 10^{-4}$	$\pm 0.70 \times 10^{-4}$
$Im(\omega)$	$(-1.7 \pm 3.4) \times 10^{-4}$	$\pm 0.86 \times 10^{-4}$	$\pm 0.61 \times 10^{-4}$	$\pm 1.1 \times 10^{-4}$
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	
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	
Δa_X	$(3.3 \pm 2.2) \times 10^{-18}$ GeV	$\pm 0.76 \times 10^{-18}$ GeV	$\pm 0.54 \times 10^{-18}$ GeV	
Δa_Y	$(-0.7 \pm 2.0) \times 10^{-18}$ GeV	$\pm 0.76 \times 10^{-18}$ GeV	$\pm 0.54 \times 10^{-18}$ GeV	

Conclusions

- The entangled neutral kaon system at a ϕ-factory is an excellent laboratory for studies of fundamental physical principles, e.g. the study of discrete symmetries and of the basic principles of Quantum Mechanics;
- Several parameters related to possible decoherence and/or CPT violation (CPT violation and Lorentz symmetry breaking) have been recently measured at KLOE, in same cases with a precision reaching the interesting Planck's scale region;
- All results are consistent with no symmetry violation and no decoherence

- Neutral kaon interferometry, CPT symmetry and QM tests are one of the main issues of the **KLOE-2** physics program. (EPJC 68 (2010) 619-681)
- The precision of several tests could be improved by about one order of magnitude.

- **LHCb** might further improve these limits.
  The main advantages are: (i) copious ϕ production rate
  (ii) excellent reconstruction capabilities in the interesting $\Delta t \sim 0$ region
  (iii) accurate Δt reconstruction → negligible Δt resolution
- The main challenging issues are: (iv) background rejection and subtraction
  (v) trigger efficiency; ➔ feasibility study ongoing.