Kaon interferometry at KLOE: status and perspectives

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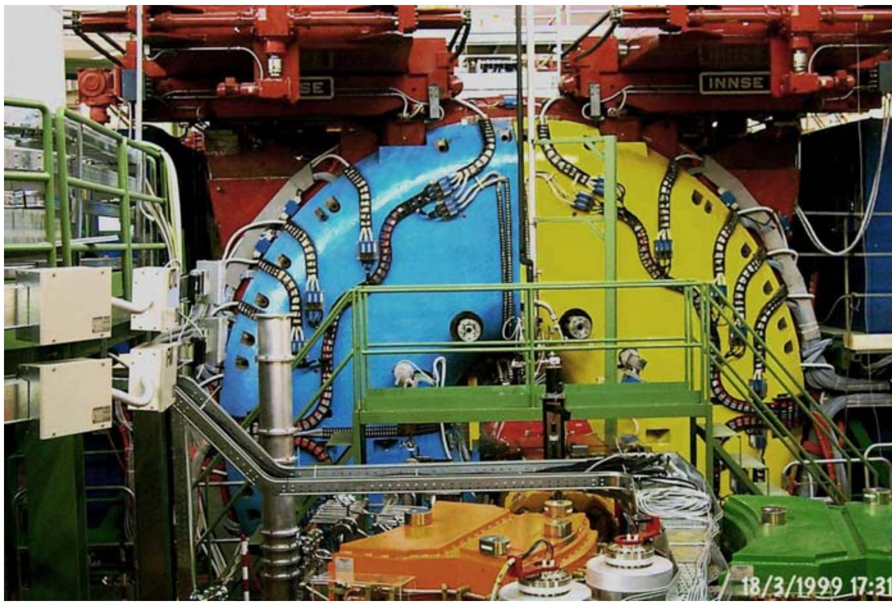
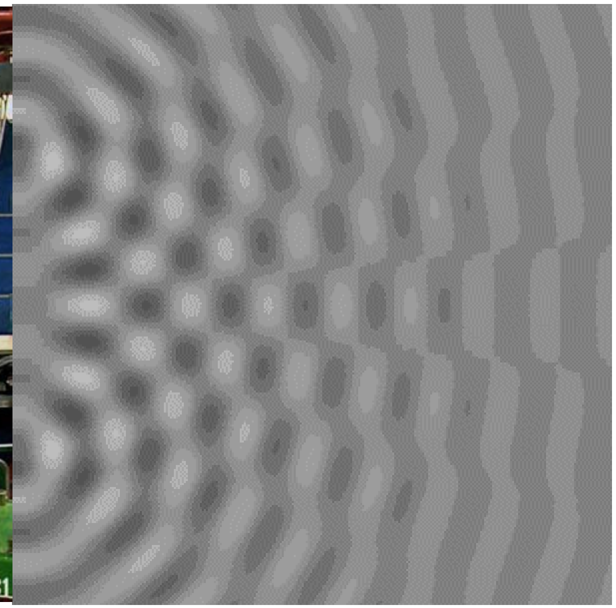


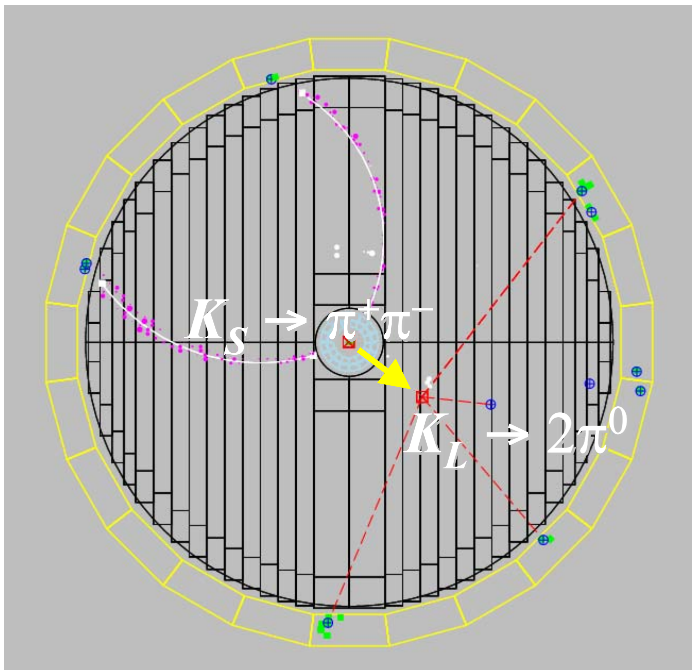


Workshop on e^+e^- in the 1-2 GeV range: Physics and Accelerator Prospects
10-13 September 2003 - Alghero, Italy

Neutral kaons at a ϕ-factory

- $e^+e^- \to \phi$ $\sigma_\phi \sim 3\ \mu b$
  $W = m_\phi = 1019.4$ MeV

- $BR(\phi \to K^+K^-) = 49.2\%$
- $BR(\phi \to K^0\bar{K}^0) = 33.8\%$
- $BR(\phi \to \pi^+\pi^-\pi^0) = 15.5\%$
- $BR(\phi \to \eta\gamma) = 1.3\%$



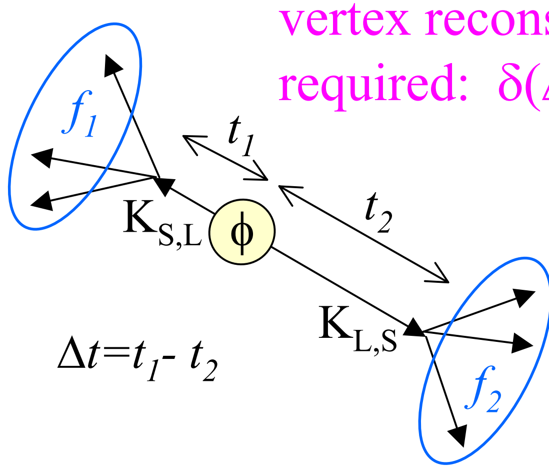
$\sim 10^6$ neutral kaon pairs per pb^{-1} produced in an antisymmetric quantum state $J^{PC} = 1^{--}$:

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

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

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

For interferometry a good K decay vertex reconstruction capability is required: $\delta(\Delta t) \leq 1\ \tau_S$



Kaon interferometry: what can be measured

Double differential time distribution:

$$I(f_1,t_1;f_2,t_2)=C_{12}\left\{|\eta_1|^2 e^{-\Gamma_L t_1-\Gamma_S t_2}+|\eta_2|^2 e^{-\Gamma_S t_1-\Gamma_L t_2}-2|\eta_1||\eta_2|e^{-(\Gamma_S+\Gamma_L)(t_1+t_2)/2}\cos[\Delta m(t_1-t_2)+\phi_2-\phi_1]\right\}$$

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

$$\eta_i=|\eta_i|e^{i\phi_i}=\langle f_i|K_L\rangle/\langle f_i|K_S\rangle \qquad C_{12}=\frac{N^2}{2}\left|\langle f_1|K_S\rangle\langle f_2|K_S\rangle\right|^2$$

$f_i = \pi^+\pi^-,\ \pi^0\pi^0,\ \pi l\nu,\ \pi^+\pi^-\pi^0,\ 3\pi^0,\ \pi^+\pi^-\gamma$ ..etc

characteristic interference term at a ϕ-factory => interferometry

Integrating in (t_1+t_2) we get the time difference ($\Delta t=t_1-t_2$) distribution (1-dim plot):

$$I(f_1,f_2;\Delta t\ge 0)=\frac{C_{12}}{\Gamma_S+\Gamma_L}\left[|\eta_1|^2 e^{-\Gamma_L\Delta t}+|\eta_2|^2 e^{-\Gamma_S\Delta t}-2|\eta_1||\eta_2|e^{-(\Gamma_S+\Gamma_L)\Delta t/2}\cos(\Delta m\Delta t+\phi_2-\phi_1)\right]$$

for $\Delta t<0 \quad \Delta t\rightarrow|\Delta t|$ and $1\leftrightarrow 2$

From these distributions for various final states f_i we can measure the following quantities:

$$\Gamma_S\ ,\ \Gamma_L\ ,\Delta m\ ,\ |\eta_i|\ ,\ \arg(\eta_i)=\phi_i$$

Kaon interferometry: main observables

mode	measured quantity	parameters
$\phi \to K_S K_L \to \pi^+\pi^- \; \pi^+\pi^-$	$I(\pi^+\pi^-, \pi^+\pi^-; \Delta t)$	$\Delta m \quad (\Gamma_S \quad \Gamma_L)$
$\phi \to K_S K_L \to \pi^+\pi^- \; \pi^0\pi^0$	$A(\Delta t) = \dfrac{I(\pi^+\pi^-, \pi^0\pi^0; \Delta t > 0) - I(\pi^+\pi^-, \pi^0\pi^0; \Delta t < 0)}{I(\pi^+\pi^-, \pi^0\pi^0; \Delta t > 0) + I(\pi^+\pi^-, \pi^0\pi^0; \Delta t < 0)}$	$\Re\left(\dfrac{\varepsilon'}{\varepsilon}\right) \quad \Im\left(\dfrac{\varepsilon'}{\varepsilon}\right)$
$\phi \to K_S K_L \to \pi \ell \nu \; \pi \ell \nu$	$A_{CPT}(\Delta t) = \dfrac{I(\pi^- e^+ \nu, \pi^+ e^- \bar{\nu}; \Delta t > 0) - I(\pi^- e^+ \nu, \pi^+ e^- \bar{\nu}; \Delta t < 0)}{I(\pi^- e^+ \nu, \pi^+ e^- \bar{\nu}; \Delta t > 0) + I(\pi^- e^+ \nu, \pi^+ e^- \bar{\nu}; \Delta t < 0)}$	$\Re\delta_K - \Re\left(\dfrac{d^*}{a}\right)$ $\Im\delta_K + \Im\left(\dfrac{c^*}{a}\right)$
$\phi \to K_S K_L \to \pi\pi \; \pi \ell \nu$	$A(\Delta t) = \dfrac{I(\pi^- e^+ \nu, \pi^+\pi^-; \Delta t) - I(\pi^+ e^- \bar{\nu}, \pi^+\pi^-; \Delta t)}{I(\pi^- e^+ \nu, \pi^+\pi^-; \Delta t) + I(\pi^+ e^- \bar{\nu}, \pi^+\pi^-; \Delta t)}$	$A_L = 2\left(\Re\varepsilon_K - \Re\delta_K + \Re\, b/a + \Re\, d^*/a\right)$ $\phi_{\pi\pi}$

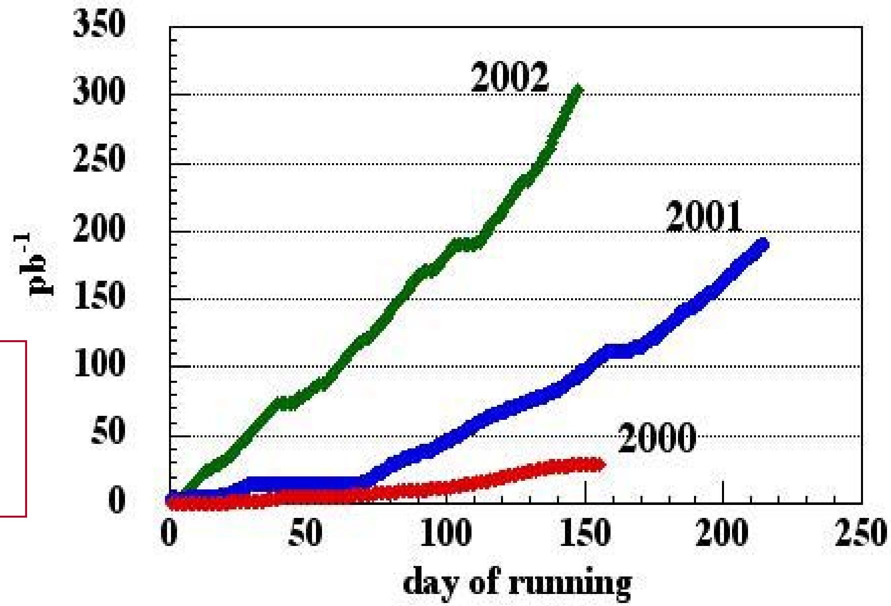
KLOE data taking history

Year	$\int Ldt$	pb^{-1}/day		
		average	peak	
2000	25 pb^{-1}	**0.1**	**0.4**	First published results
2001	170 pb^{-1}	**0.7**	**1.8**	Luminosity improved but high background Further analyses published
2002	280 pb^{-1}	**2.0**	**4.5**	Higher luminosity and background reduced Analysis in progress

in 2002

$$L_{peak} = 7.8\times10^{31}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

An upgrade of the machine has been done.
An increase in luminosity (> ×2)
is expected in the next data taking.

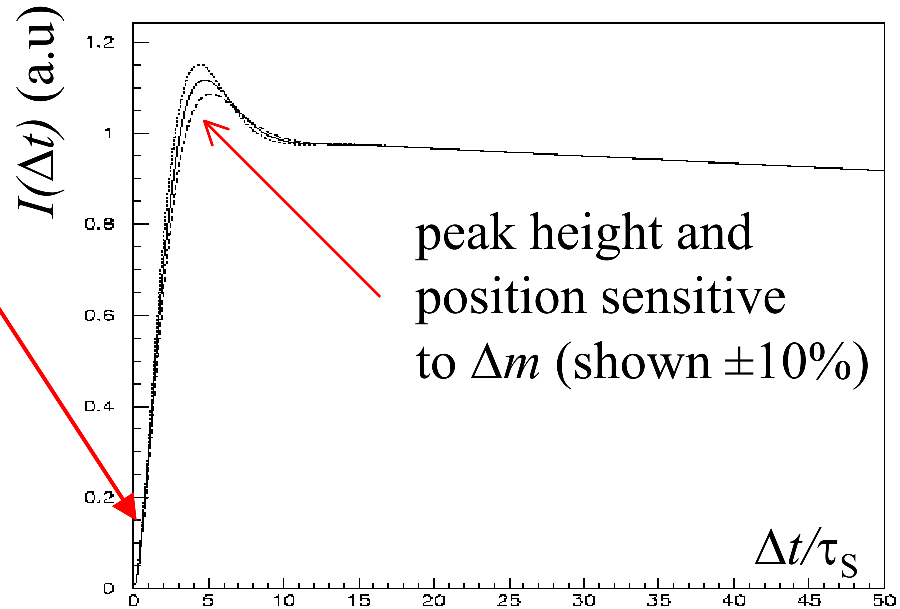


$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \, \pi^+\pi^-$

- Same final state for both kaons: $f_1 = f_2 = \pi^+\pi^-$ ($\pi^0\pi^0$ or $\pi l \nu -$ same charge leptons)

$$I\left(\pi^+\pi^-, \pi^+\pi^-; |\Delta t|\right) \propto e^{-\Gamma_L |\Delta t|} + e^{-\Gamma_S |\Delta t|} - 2e^{-(\Gamma_S + \Gamma_L)|\Delta t|/2} \cos\left(\Delta m |\Delta t|\right)$$

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



- no $\eta_{\pi\pi}$ dependence (only in the scale factor)
- fitting the Δt measured distribution Δm can be evaluated

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

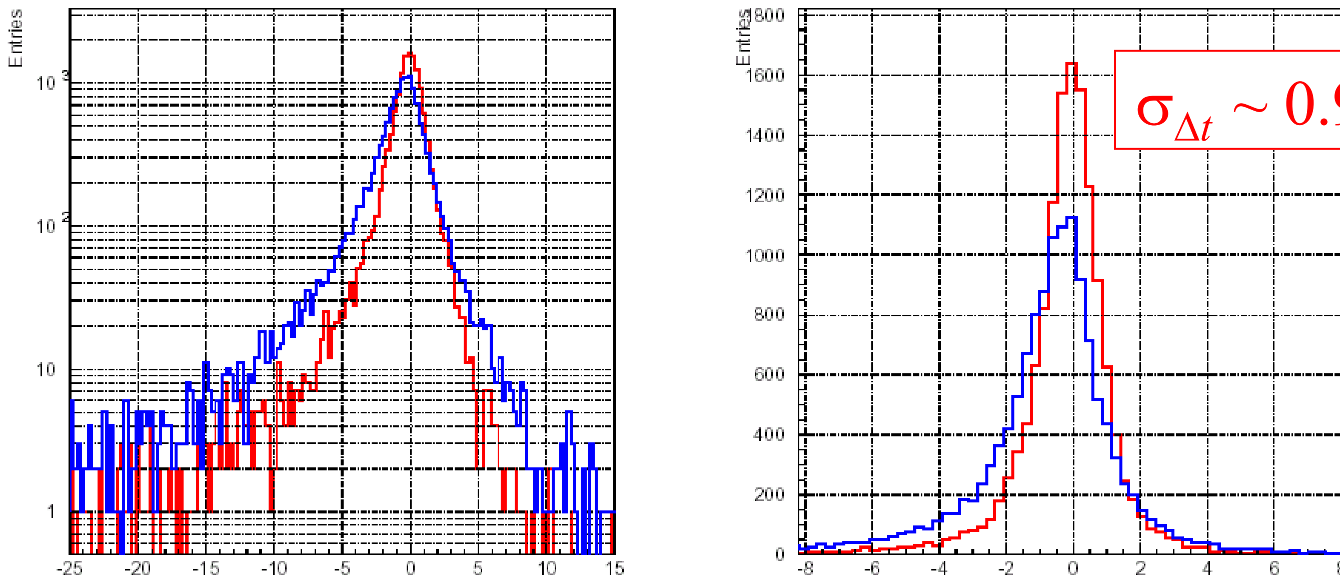
A kinematic fit is performed to improve the vertex and Δt resolution:

MC results : before fit

after fit

log scale

linear scale



$\sigma_{\Delta t} \sim 0.9\ \tau_S$

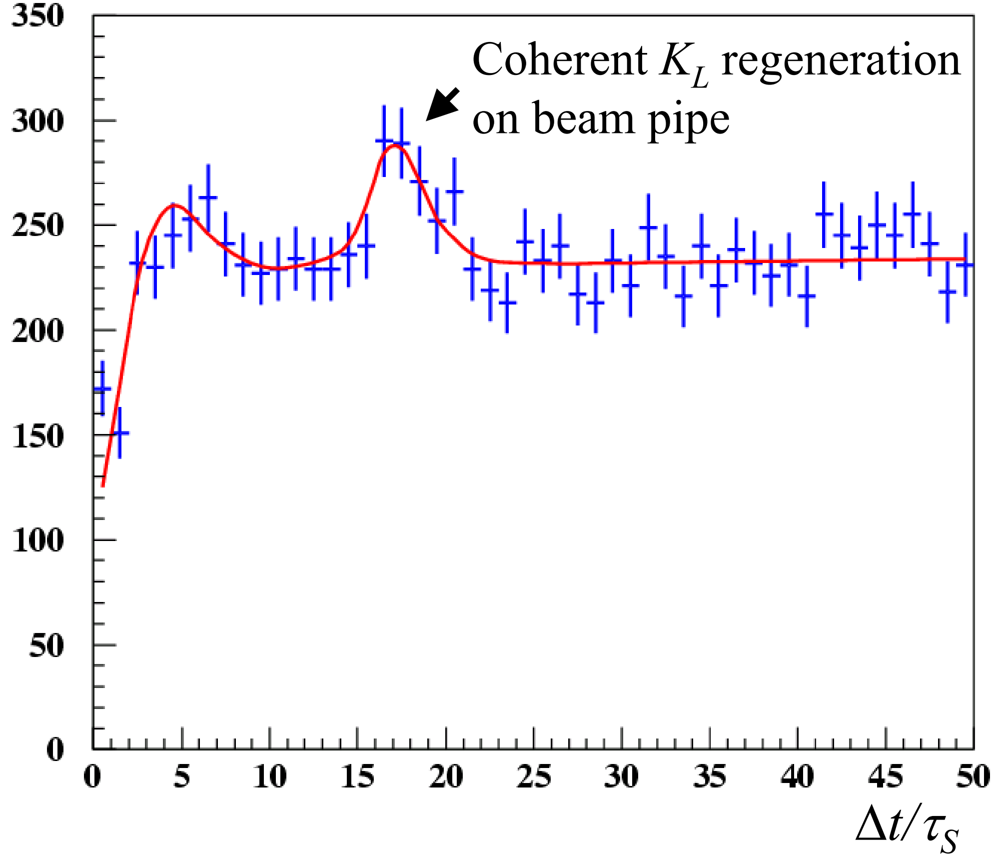
$\left|\Delta t\right|_{rec} - \left|\Delta t\right|_{true}$ in τ_S units

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

Fit including Δt resolution and efficiency effects + regeneration:
Γ_S, Γ_L fixed from PDG

KLOE preliminary
340 pb^{-1} (2001 + 2002 data)

$\mathbf{\Delta m = (5.64 \pm 0.37) \times 10^{-11}\, \hbar\, s^{-1}}$
PDG '02: $(5.301 \pm 0.016) \times 10^{-11}\, \hbar\, s^{-1}$



At a new ϕ-factory with 500 fb^{-1} :
$\delta\Delta m \sim 0.009 \times 10^{-11}\, \hbar\, s^{-1}$

$\phi \to K_S K_L \to \pi^+\pi^-\ \pi^+\pi^-$: measurement of decoherence

$$I(\pi^+\pi^-,\pi^+\pi^-;|\Delta t|) \propto e^{-\Gamma_L|\Delta t|} + e^{-\Gamma_S|\Delta t|} - 2\cdot(1-\zeta)\cdot e^{-(\Gamma_S+\Gamma_L)|\Delta t|/2}\cos(\Delta m|\Delta t|)$$

interference term modified introducing a decoherence parameter ζ:

$\zeta=0$ → "orthodox" QM

$\zeta=1$ → Furry's hypothesis (spontaneous factorization) [W.Furry, P.R.49 (1936) 393]

decoherence ζ depends on the basis in which is written the initial state (QM not!):

$$K_S K_L - K_L K_S \qquad \text{or} \qquad K^0 \overline{K}^0 - \overline{K}^0 K^0 \quad \ldots\ldots$$

For a generic basis $\{K_\alpha, K_\beta\}$ we can write:

$$I(f_1,t_1;f_2,t_2) = \tfrac{1}{2}\left[\left|\langle f_1|K_\alpha(t_1)\rangle\langle f_2|K_\beta(t_2)\rangle\right|^2 + \left|\langle f_1|K_\beta(t_1)\rangle\langle f_2|K_\alpha(t_2)\rangle\right|^2 - 2\cdot(1-\zeta_{K_\alpha,K_\beta})\cdot\Re\left(\langle f_1|K_\beta(t_1)\rangle\langle f_2|K_\alpha(t_2)\rangle\langle f_1|K_\alpha(t_1)\rangle^*\langle f_2|K_\beta(t_2)\rangle^*\right)\right]$$

R.A. Bertlmann et al., Phys. Rev. D60 (1999) 114032 using CPLEAR data obtain:

$$\zeta_{K_S,K_L} = 0.13 \pm 0.16$$

$$\zeta_{K^0,\overline{K}^0} = 0.4 \pm 0.7$$

KLOE VERY PRELIMINARY (340 pb^{-1}):

$$\zeta_{K_S K_L} = 0.12 \pm 0.08$$

$$\zeta_{K^0\overline{K}^0} = (0.8 \pm 0.5) \times 10^{-5}$$

Background due to $\phi \to (f_0+a_0)\gamma \to K^0\overline{K}^0\gamma$

$$\phi \to (f_0 + a_0)\gamma \to K^0\overline{K}^0\gamma$$

the kaon pair is in a C-even state:

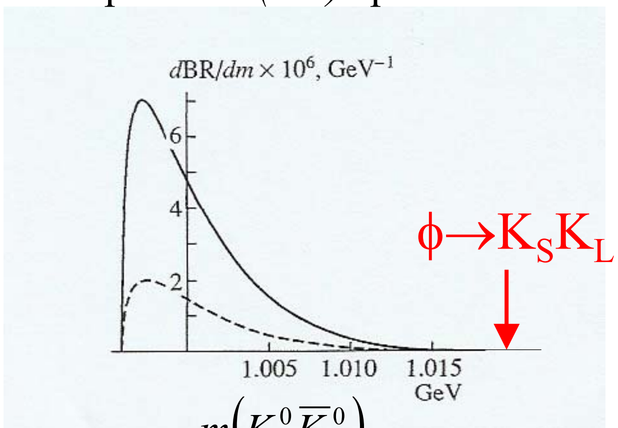
$$|i\rangle = \frac{1}{\sqrt{2}}\left\{K^0\overline{K}^0 + \overline{K}^0K^0\right\} \cong \frac{1}{\sqrt{2}}\left\{K_SK_S - K_LK_L\right\}$$

Recent evaluations of $\phi \to (f_0 + a_0)\gamma \to K^0\overline{K}^0\gamma$ report a BR in the range $(1 \div 4) \times 10^{-8}$

[1] J.A. Oller, Nucl.Phys. A714 (2003) 161 ; [2] N.N. Achasov, V.V. Gubin, Phys. Rev D64 (2001) 094016 ; Phys.Atom.Nucl. 65 (2002) 1939]

The most recent one based on KLOE results on $\phi\to\pi^0\pi^0\gamma$ and $\phi\to\eta\pi^0\gamma$.

expected *m(KK)* spectrum



$m\left(K^0\overline{K}^0\right)$

The impact of this background on the interferometry measurements is negligible at KLOE

...and also at a new 500 fb^{-1} ϕ-factory

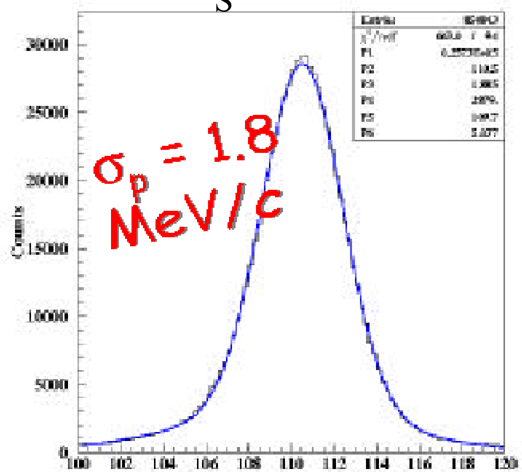
Background due to $\phi \rightarrow (f_0+a_0)\gamma \rightarrow K^0\overline{K}^0\gamma$

This background can be largely reduced exploiting:

1. different spatial behaviour of decay distributions
2. detection of the radiated photon with $E\gamma \sim 20$ MeV
3. measurement of at least one kaon momentum (e.g. in ε'/ε measurements)

A 3-σ cut on P_K will select $m(K^0\overline{K}^0) > 1017$ MeV

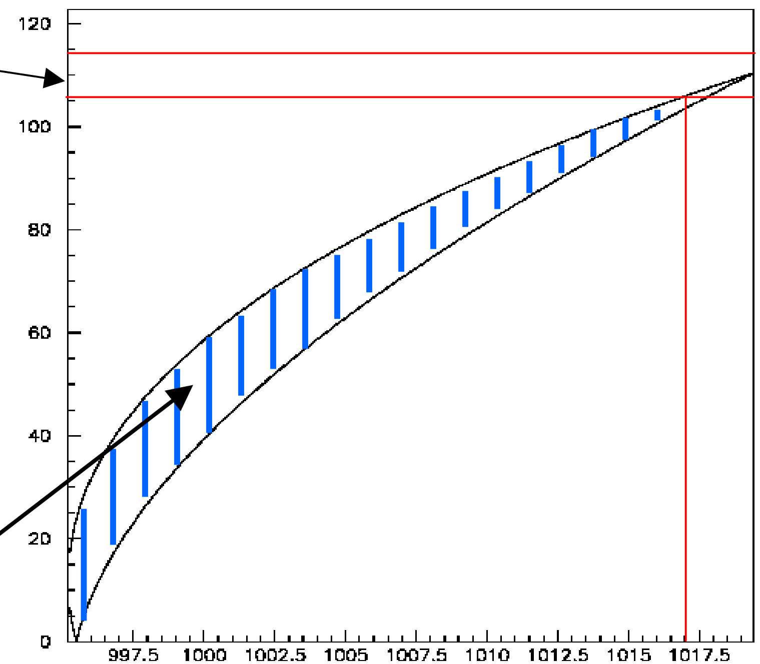
$K_S \rightarrow \pi^+\pi^-$



P_K (MeV/c)

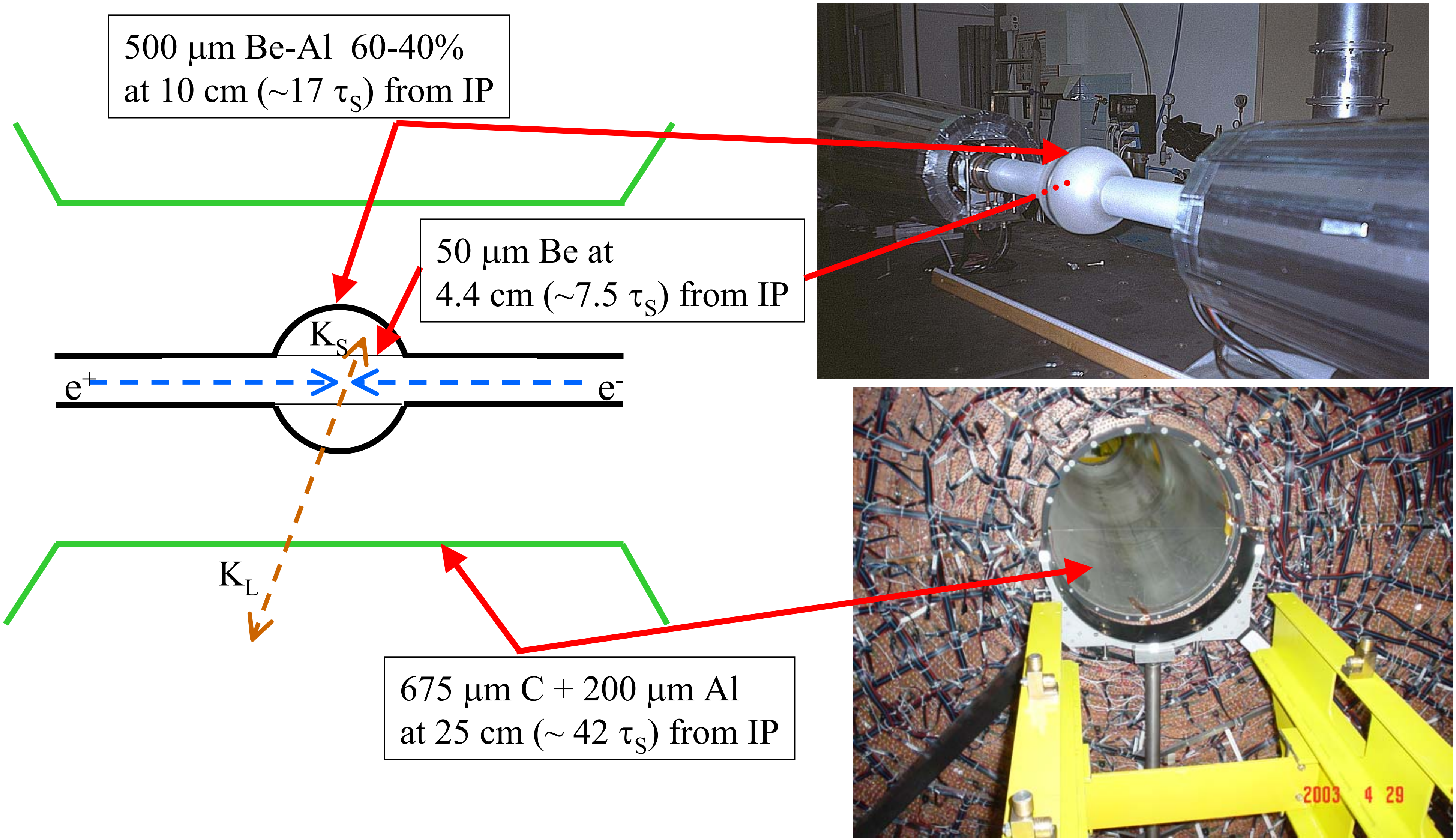
Kaon momentum is kinematically limited inside this band

P_K (MeV/c)

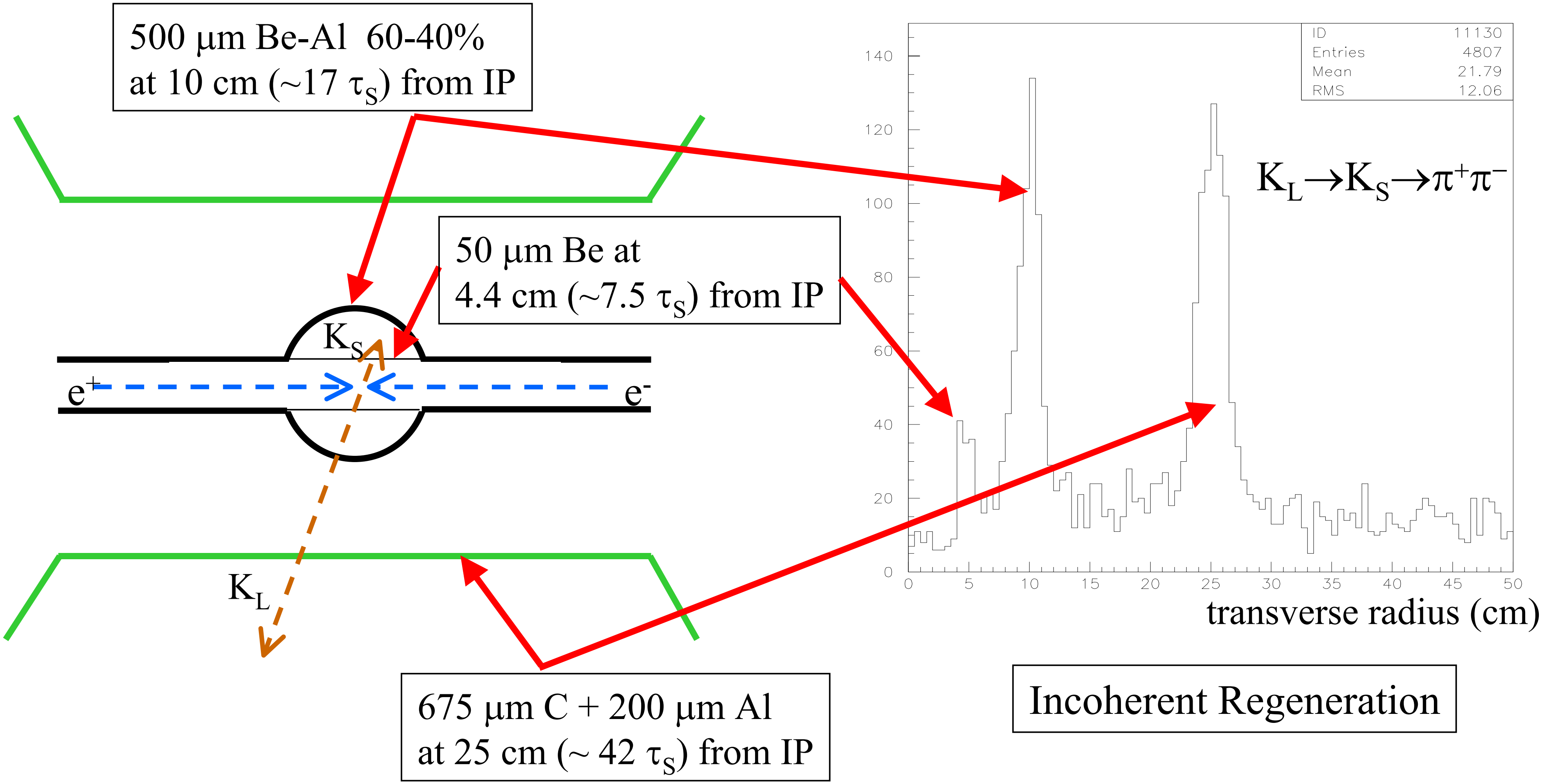


$m(K^0\overline{K}^0)$ (MeV)

Regenerators



Regenerators

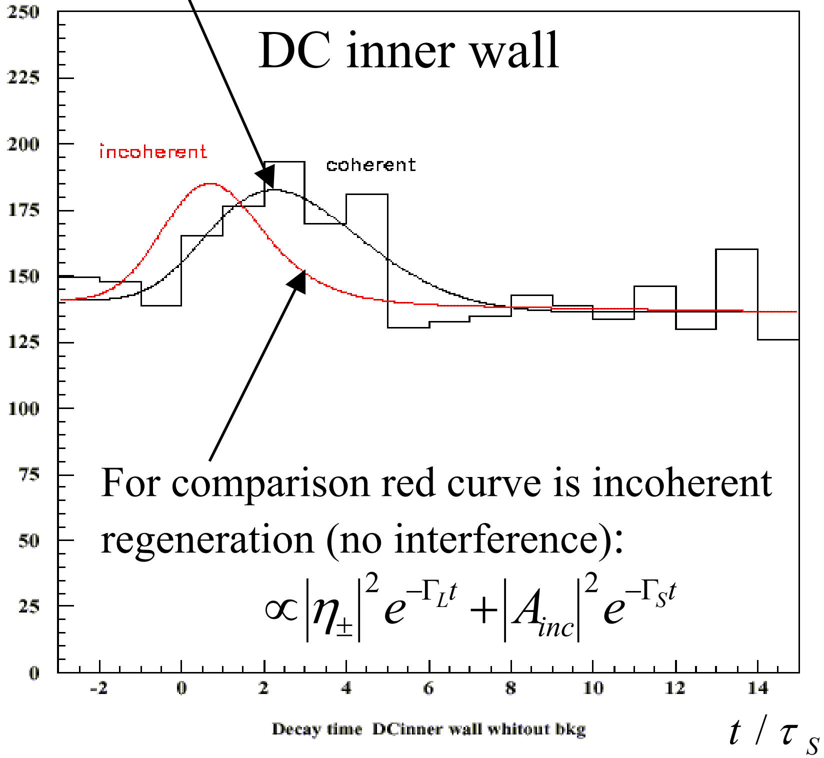


Coherent regeneration

Coherent regeneration can occur only in the strictly forward direction:

$$|K_L\rangle \rightarrow |K_L\rangle + \rho_{coh}|K_S\rangle \qquad \rho_{coh} = |\rho_{coh}|e^{i\phi_{coh}}$$ is the regeneration parameter

$$I(\pi^+\pi^-,t) = |\langle\pi^+\pi^-|K_S\rangle|^2 \left[|\eta_\pm|^2 e^{-\Gamma_L t} + |\rho_{coh}|^2 e^{-\Gamma_S t} + 2|\eta_\pm||\rho_{coh}|e^{-(\Gamma_S+\Gamma_L)t/2}\cos(\Delta m t + \phi_{coh} - \phi_\pm)\right]$$



For comparison red curve is incoherent regeneration (no interference):

$$\propto |\eta_\pm|^2 e^{-\Gamma_L t} + |A_{inc}|^2 e^{-\Gamma_S t}$$

This interference term is important for thin regenerators, i.e. when $|\rho_{coh}| \sim |\eta_\pm|$ as for the beam pipe and inner DC wall

- incoherent regeneration subtracted
- fit including *t* resolution effects
- preliminary KLOE results (340 pb^{-1}) (DC inner wall):

$$|\rho_{coh}| = (16.6 \pm 6.6)\times 10^{-4}$$

$$\phi_{coh} = -1.19 \pm 0.27 \text{ rad}$$

Near future

- KLOE is refining analysis tools for interferometry
- need at least 10 × more data to begin interferometry program
- Examples of estimated uncertainty @10 fb^{-1} are:

on	$\Re\left(\frac{\varepsilon'}{\varepsilon}\right)$	$\Re\delta - \Re\left(\frac{d^*}{a}\right)$	$\sim 5\times10^{-4}$
on	$\Im\left(\frac{\varepsilon'}{\varepsilon}\right)$	$\Im\delta + \Im\left(\frac{c^*}{a}\right)$	$\sim 20\times\left(5\times10^{-4}\right)$

- Measurements of ***Im*** parts are less precise (w.r.t. ***Re***) mainly because of
  - less statistics (interference term lasts $\sim 2\tau_S$)
  - decay vertex resolution effects

Future

At a new ϕ-factory providing an integrated luminosity of ~ 500 fb^{-1}:

• Knowledge of Δm, Γ_S, Γ_L improved

• Measurement of the ***Im*** of CP and CPT parameters at a precision level comparable with present one on ***Re*** might be feasible

• Interferometry with rarer final state should be feasible (or improved)

• Several proposed QM tests at a ϕ-factory - almost all requiring very high statistics - could be possible