K_S lifetime and QM test with interferometry @ KLOE

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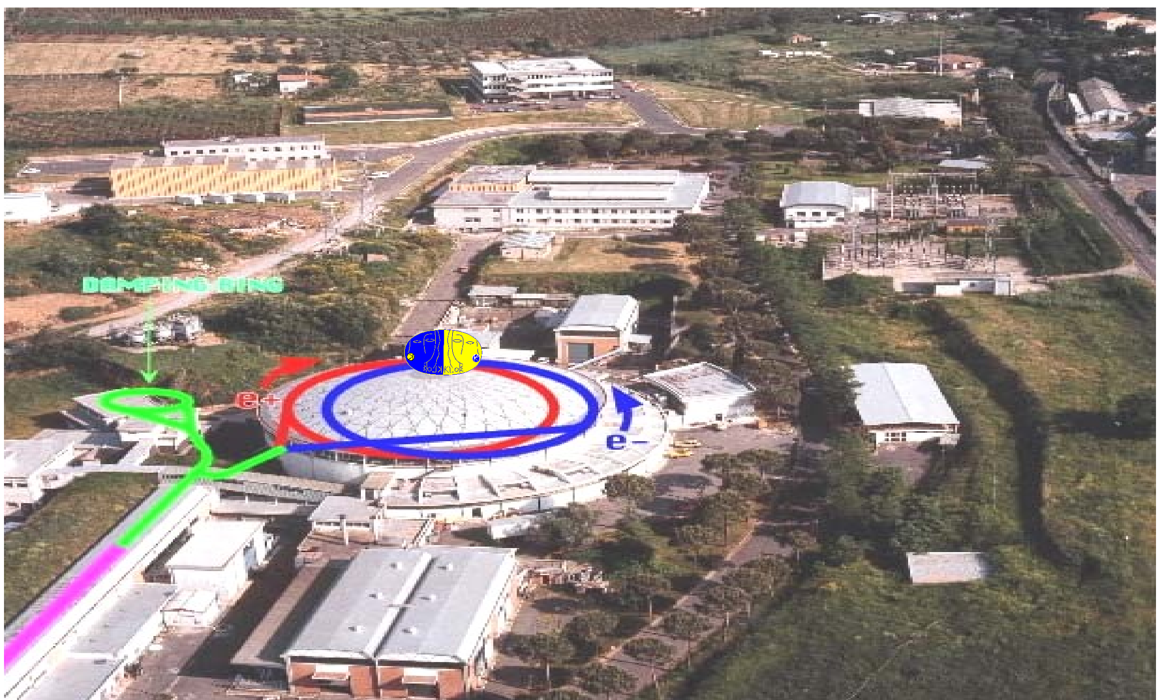
for the KLOE collaboration

The Daϕne e^+e^- collider

- Collisions at c.m. energy around the ϕ mass: $\sqrt{s} \sim 1019.4$ MeV
- Beam crossing angle $\alpha_{CRS} \sim \pi - 0.025$ rad
- ϕ momentum in lab. syst. $p_\phi \sim 13$ MeV/c
- Cross section for ϕ production @ peak: $\sigma_\phi \sim 3\ \mu b$
- End of Kloe data taking (2006) luminosity : $L_{PEAK} \sim 1.4 \times 10^{32}\ cm^{-2}\ s^{-1}$



Main ϕ decay mode	BR, %
K^+K^-	49.1
K_SK_L	34.0
$\rho\pi,\ \pi^+\pi^-\pi^0$	15.4
$\eta\gamma$	1.3

The KLOE detector

Beam pipe (spherical, 10 cm ∅, 0.5 mm thick)

Drift chamber (∅=4 m, L=3.3 m)

90% He + 10% IsoB, X_0=900m, ~2600 s.w.

$\sigma(p_t)/p_t \sim 0.4\%$; $\sigma_{hit} \sim 150\ \mu m$ (xy),

~ 2 mm (z) ; $\sigma_{vertex} \sim 1$ mm

Electromagnetic calorimeter

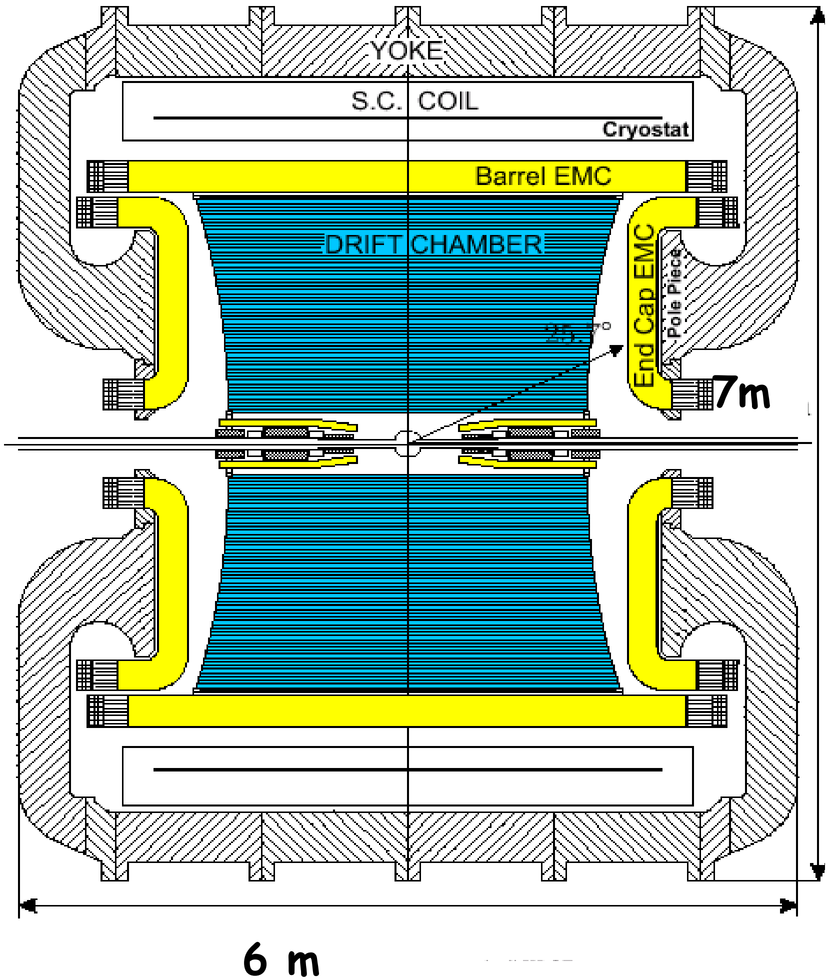
Lead/scintillating fibers 4880 PMT's

$\sigma_E = 5.7\% / \sqrt{E(GeV)}$

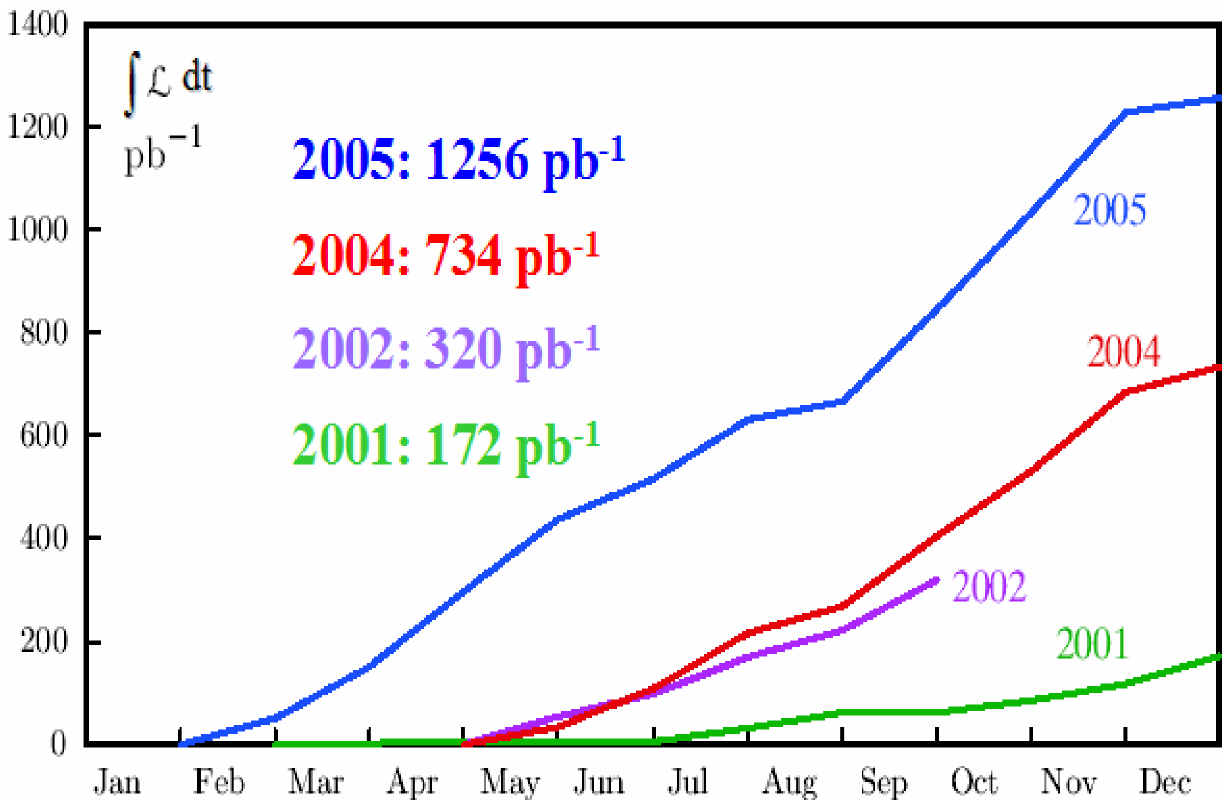
$\sigma_t = 54\ ps / \sqrt{E(GeV)} \oplus 100\ ps$

$\sigma_L(\gamma\gamma) \sim 1.5$ cm (π^0 from $K_L \rightarrow \pi^+\pi^-\pi^0$)

Superconducting coil B = 0.52 T



KLOE data taking



KLOE data taking ended on march 2006

$\int L dt \sim 2.5\ fb^{-1} \sim 2.5 \times 10^{9}\ K_S K_L$ pairs

Neutral kaons @ KLOE

- KLOE provides **monochromatic** (p=110 MeV/c) and **pure** beam of kaons from ϕ decay ($J^{PC} = 1^{--}$)

$$K_S \longleftarrow \phi \longrightarrow K_L \qquad \sim 10^6 \text{ events / pb}^{-1}$$

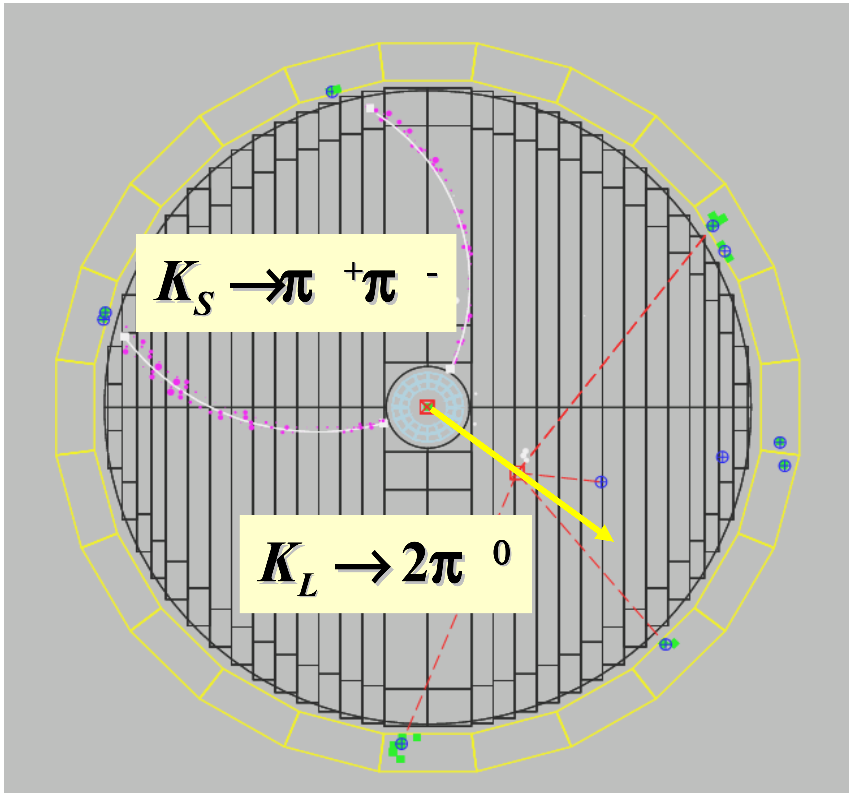
where observation of K_S (K_L) tags presence of K_L (K_S)

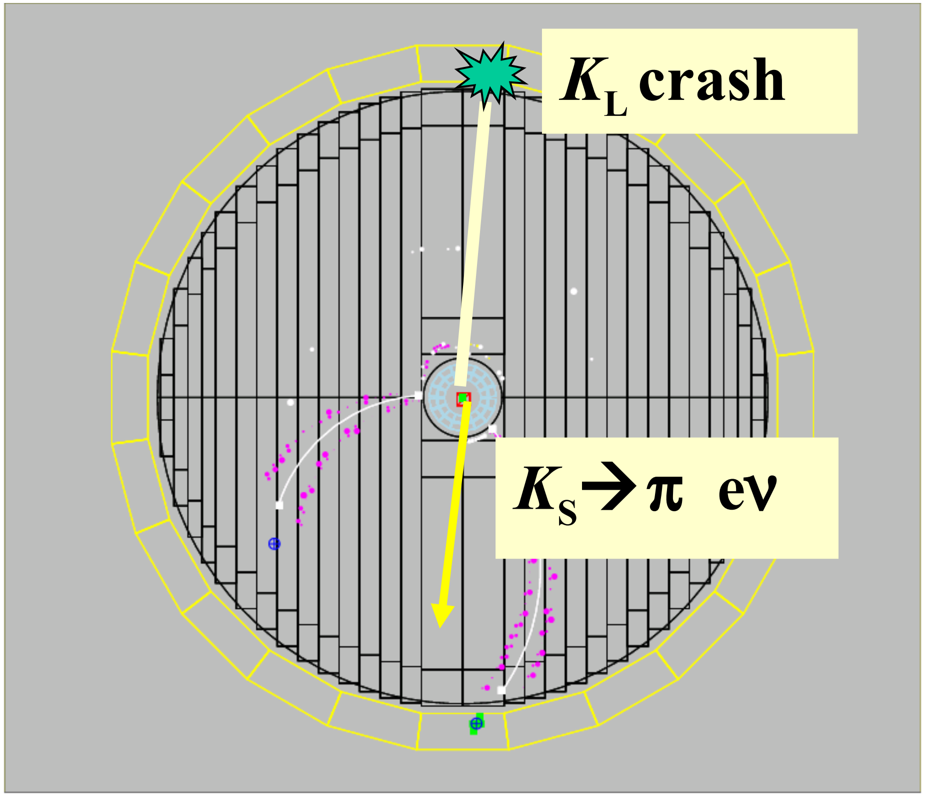
- This allows:

- precise measurements (absolute BR's, lifetimes)

- interference measurements with K_SK_L system

Tagging





K_L tagged by $K_S \to \pi^+\pi^-$

Efficiency ~ 70% (geometrical)

K_L momentum resolution ~ 1 MeV

K_L angular resolution ~ 1°

K_S tagged by K_L interaction in EmC

Efficiency ~ 30%

K_S momentum resolution ~ 1 MeV

K_S angular resolution ~ 1°

Neutral kaon

Interferometry

Quantum Mechanics coherence test

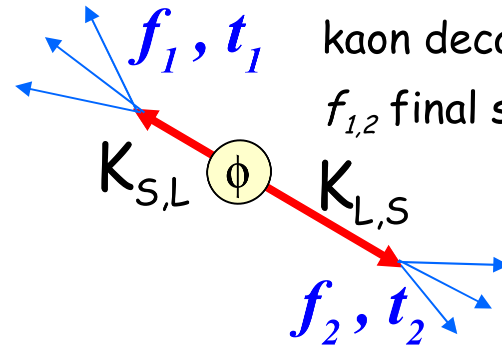
- The $K^0\bar{K}^0$ state from ϕ ($J^{PC}=1^{--}$) decay is required to be :

$t_{1,2}$ proper time

kaon decay into

$f_{1,2}$ final state.

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



Time evolution obeys a Shrodinger-like eq. with $H=M-i/2\Gamma$. In QM we have

$$I(f_1,t_1;f_2,t_2) \sim |a_{1S}a_{2L}|^2 + |a_{1L}a_{2S}|^2 - 2(1-\zeta_{SL})\Re\{(a_{1S}a_{2L})^*(a_{1L}a_{2S})\}$$

where
$$a_{1S(L)} = \langle f_1 | T | K_{S(L)}(t_1) \rangle$$
$$a_{2S(L)} = \langle f_2 | T | K_{S(L)}(t_2) \rangle$$

decoherence parameter

- Value $\zeta \neq 0$ indicates deviation from QM.

Simple QM → $f_1=f_2=\pi^+\pi^-$ the event distribution as function of $\Delta t=|t_2-t_1|$ gives:

$$I(\Delta t) \sim e^{-\Gamma_L \Delta t} + e^{-\Gamma_S \Delta t} - 2(1-\zeta_{SL}) e^{-(\Gamma_L+\Gamma_S)\Delta t/2} \cos(\Delta m \Delta t)$$

initial symmetry requires → no events at the same time ($\Delta t=0$).

- Fit function : $I(\Delta t) \sim e^{-\Gamma_L \Delta t} + e^{-\Gamma_S \Delta t} - 2(1-\zeta_{SL}) e^{-(\Gamma_L+\Gamma_S)\Delta t/2} \cos(\Delta m \Delta t)$

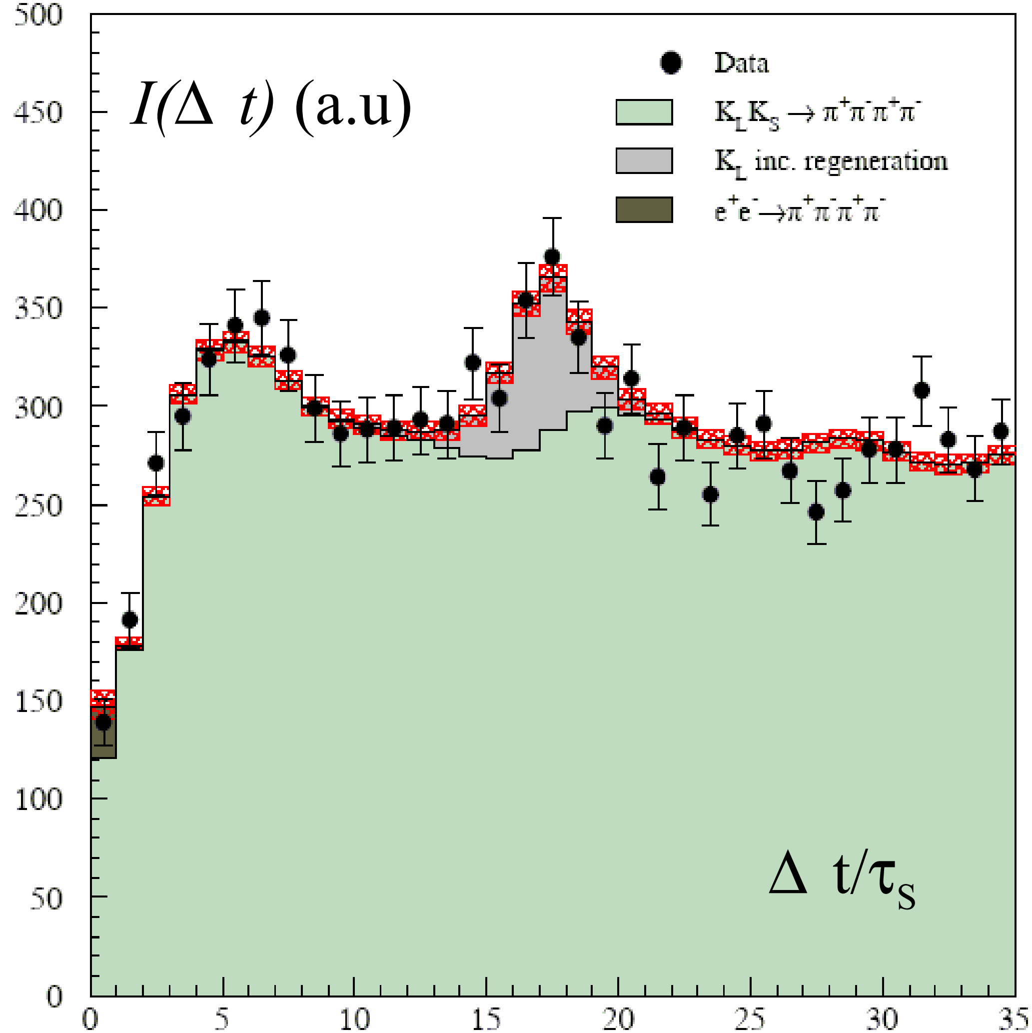
Γ_S, Γ_L, Δm fixed from PDG ;

- After including resolution, efficiency, BKG from coherent and incoherent regeneration on beam pipe, non-resonant $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$ process, 380 pb^{-1} analyzed data gives :

$$\zeta_{SL} = (1.8 \pm 4.0_{stat} \pm 0.7_{syst}) \times 10^{-2}$$

$$\zeta_{0\bar{0}} = (1.0 \pm 2.1_{stat} \pm 0.4_{syst}) \times 10^{-6}$$

KLOE PLB 642(2006) 315



- Analyzed data: L=1.5 fb^{-1} (2004-05 data) gives :

$\rightarrow$ high sensitivity to ζ_{00}

Improvement x 2 wrt published result

KLOE final

$$\zeta_{SL} = (0.3 \pm 1.8_{stat} \pm 0.6_{syst}) \times 10^{-2}$$

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

[Journal of Physics: Conf.Series 171 (2009) 012008]

CPLEAR

$$p\bar{p} \rightarrow \underbrace{K^0 K^0, \bar{K}^0 \bar{K}^0}_{\text{S-like}}, \underbrace{K^0 \bar{K}^0}_{\text{S-unlike}}$$

KK produced in a $J^{PC} = 1^{--}$ state (BR=0.7%)

From measured asymmetry $A=(P_{unlike}-P_{like})/(\ +\ )$ Bertlmann et al. obtains [**PRD60 (1999) 114032**] :

$$\zeta_{SL} = 0.13 \pm 0.16 \qquad \zeta_{0\bar{0}} = 0.4 \pm 0.7$$

BELLE

$$\Upsilon(4S) \rightarrow \underbrace{B^0 B^0, \bar{B}^0 \bar{B}^0}_{\text{SF}}, \underbrace{B^0 \bar{B}^0}_{\text{OF}}$$

From $A = (P_{OF}-P_{SF}) / (\ +\ )$

Belle obtains [**PRL99(2007)131802**] :

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

Decoherence and ~~CPT~~ due to QG effects

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].

at most one expects: $|\omega^2| = O\left(\frac{E^2/M_{PLANCK}}{\Delta\Gamma}\right) \sim 10^{-5} \rightarrow |\omega| \sim 10^{-3}$

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

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

- Analysed data: 1 fb^{-1} (2005 data)

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

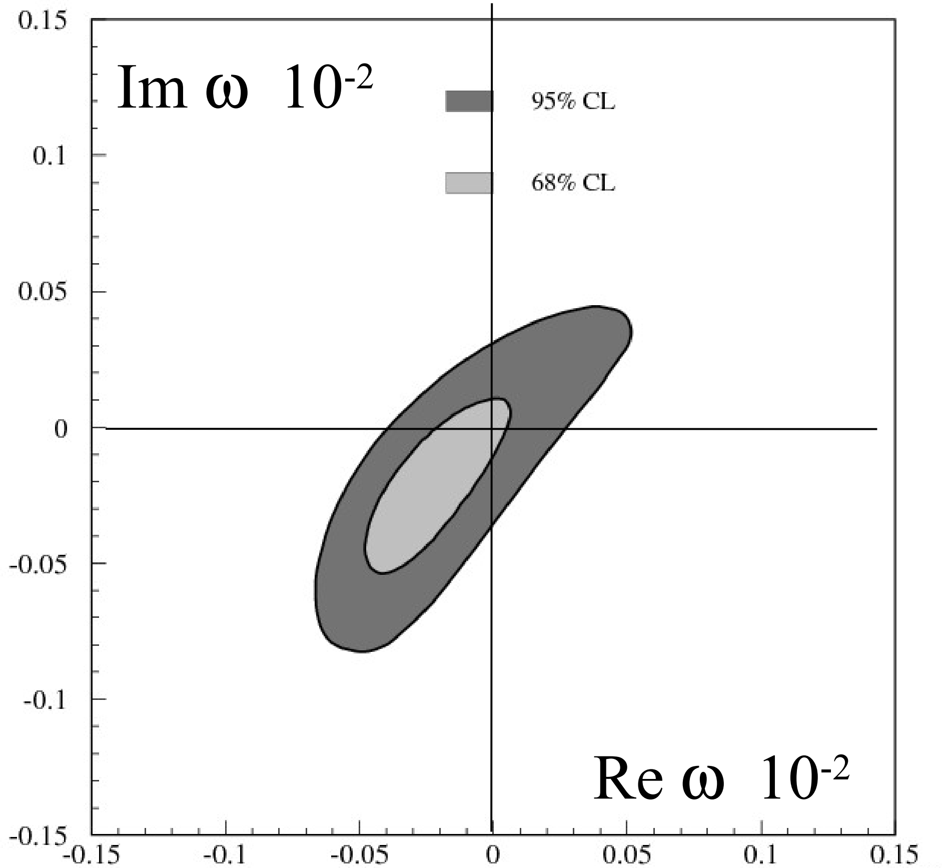
KLOE final :

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

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

$$|\omega|<1.0\times 10^{-3}\ @\ 95\%\,CL$$

[Journal of Physics: Conf.Series 171 (2009) 012008]



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

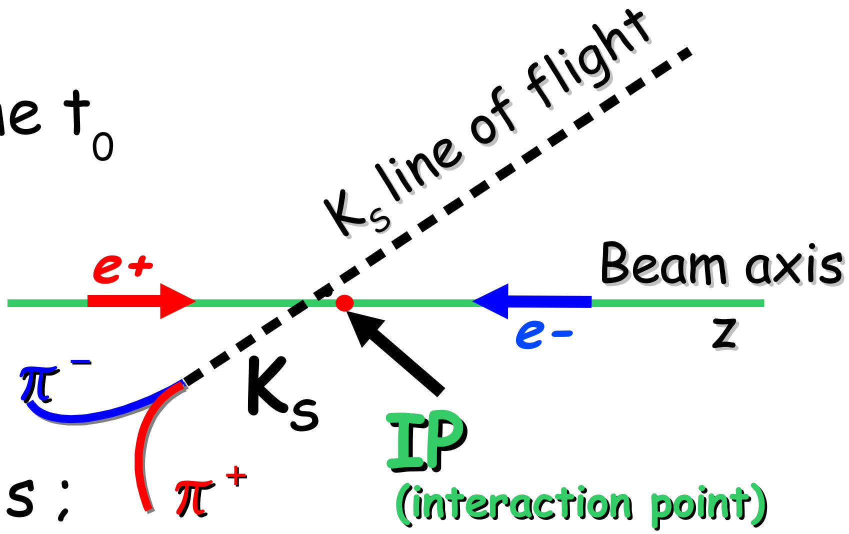
$$-0.0084\le\Re\,\omega\le 0.0100\quad \text{at}\ \ 95\%\ \text{C.L.}$$

Ks lifetime

Analysis

Introduction

- 730 pb^{-1} (2004 Data) ;
- Lifetime from fit to proper time t_0 distribution of $K_S \rightarrow \pi^+ \pi^-$ decay ;
- ϕ position event by event



Selection

- require good tracking fit for π's ;
- $|M_{\pi+\pi-} - M_K| < 2$ MeV ($\sim 2\sigma$) ;
- Acceptance cuts to improve vtx resolution ;
- After all cuts → ~25 million decay events

Redundant determination of k_S momentum :

i) from pion tracks : $p_S(\pi\pi)$;

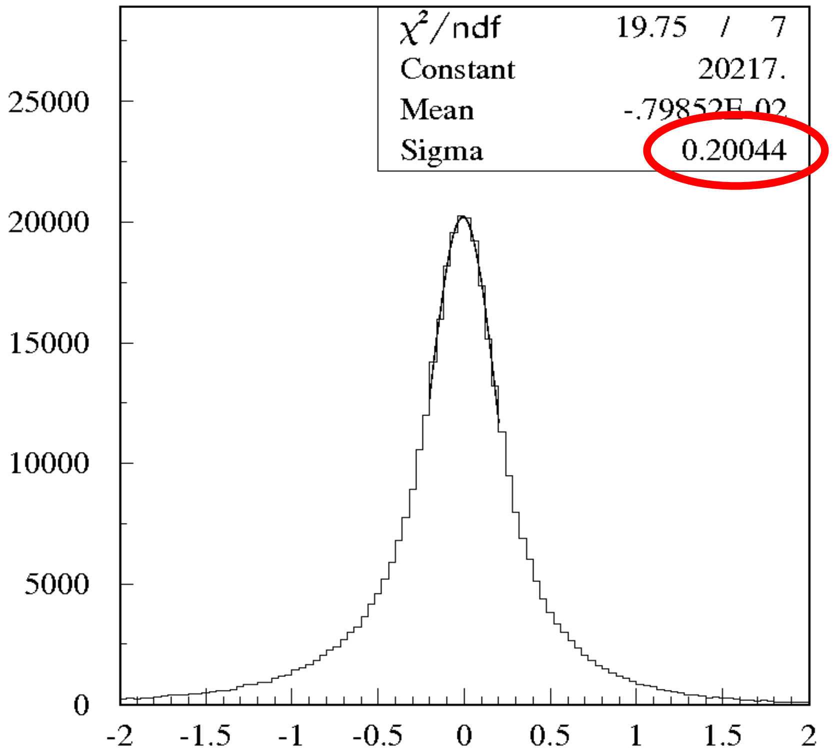
ii) by using informations from line of flight and $\sqrt{s}$: p_S(boost)

Data-MC comparison

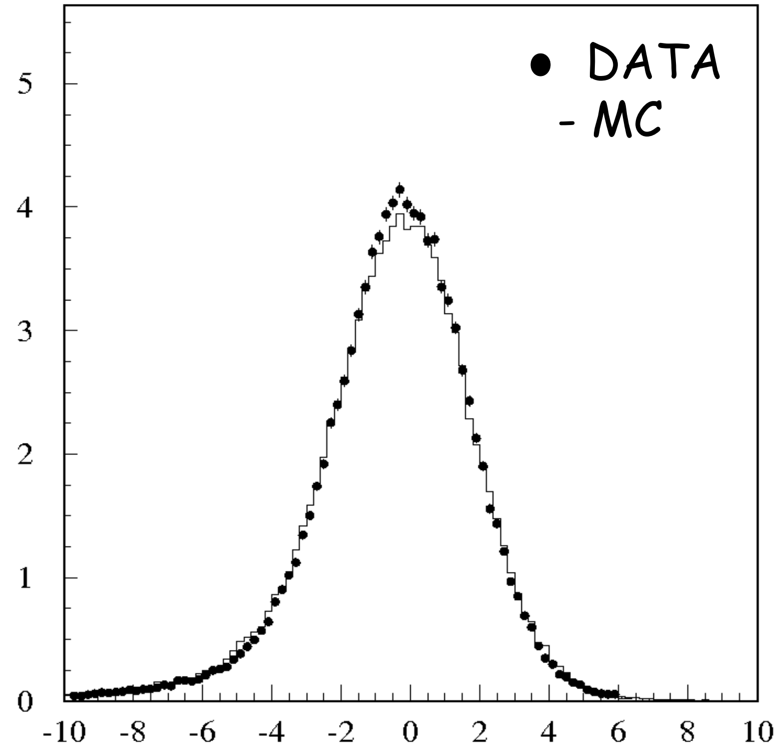
z_{IP} resolution

(typical collision region ~ 3 cm)

K_S momentum



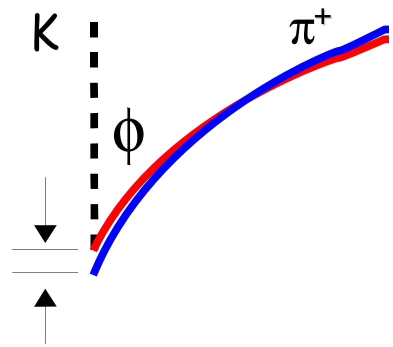
$z_{IP} - z_{IP}^{MC}$ (cm)



$p_S(\pi\pi) - p_S(\text{boost})$

VTX position calibration

- VTX position calibration correlated with momentum calibration

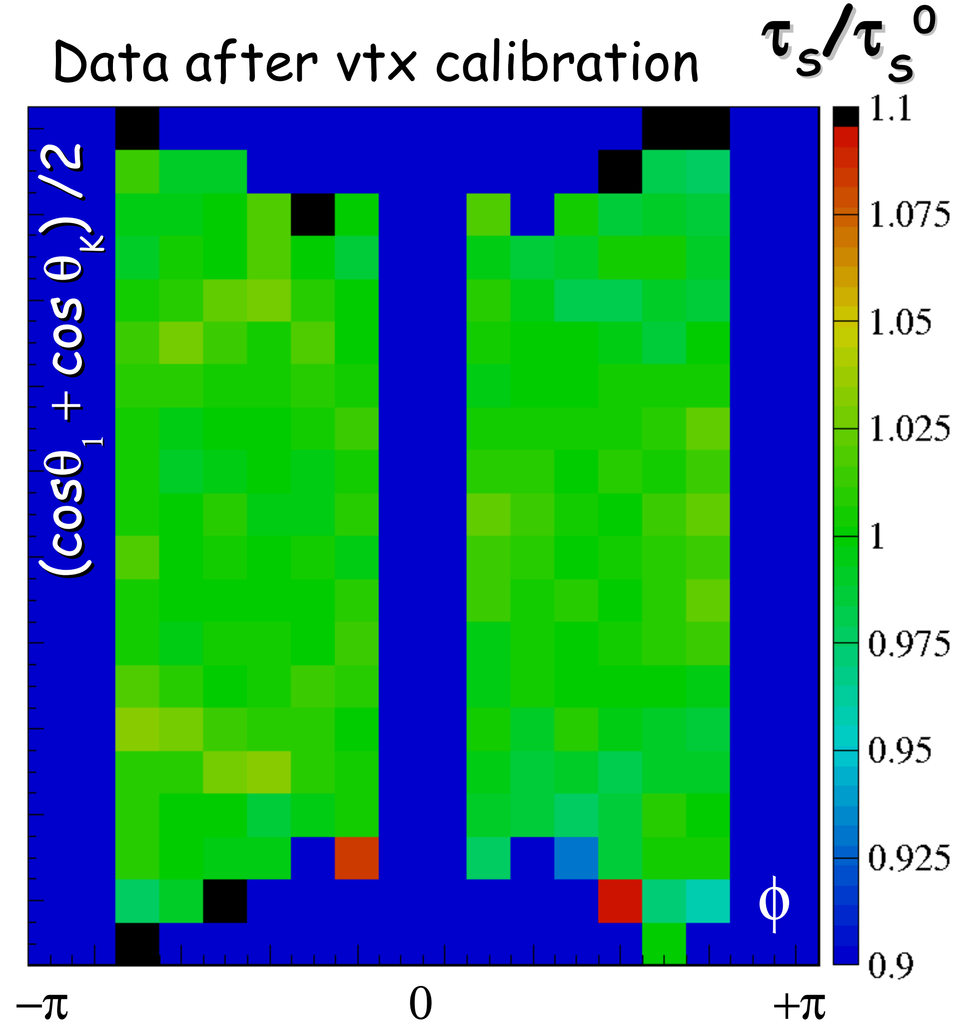


$dl = a\, dp$

- Bias **dl** depends on ϕ ;
- Calibrated using

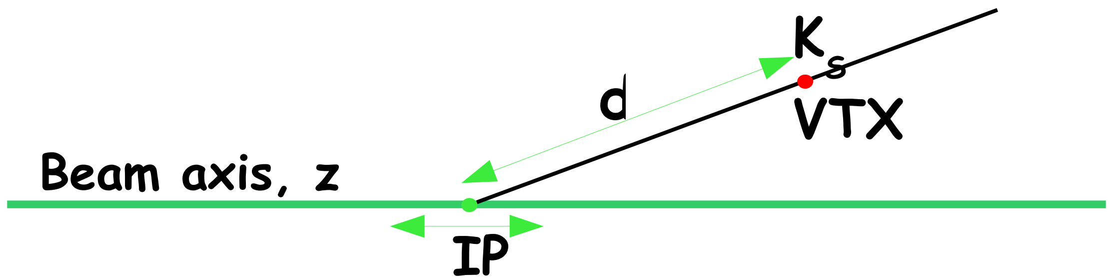
$$dp = p_{S\ 2\pi} - p_{S\ boost}$$

from Monte Carlo

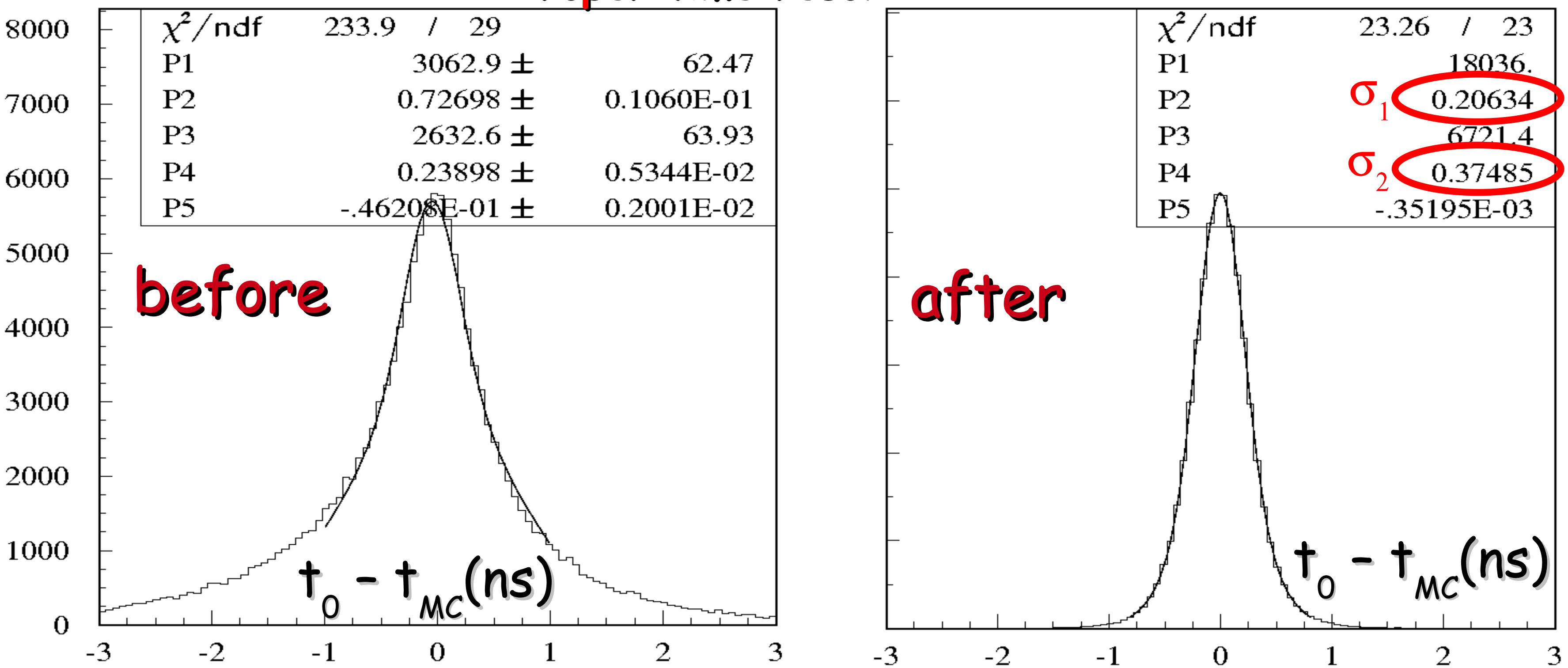


Time resolution

Improve time resolution with a geometrical fit: K_s direction fixed, free parameters are IP position and decay distance, *d*

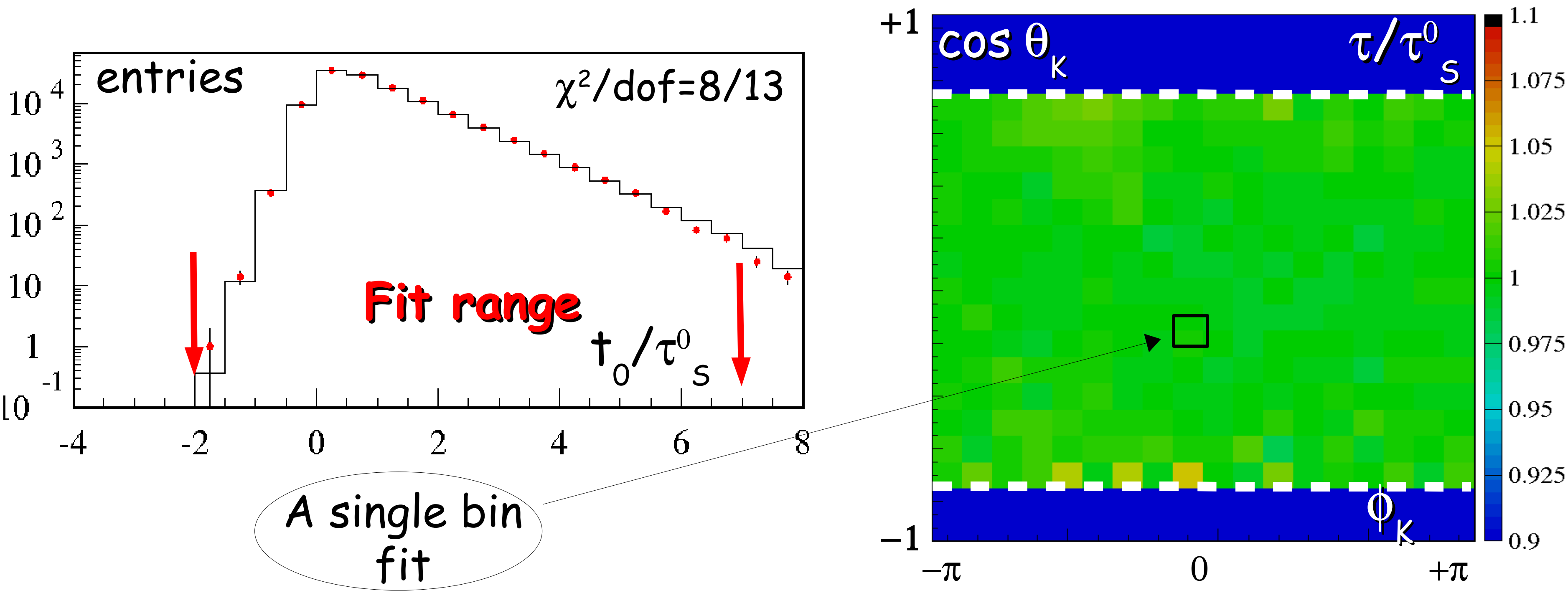


Proper time resolution on MC



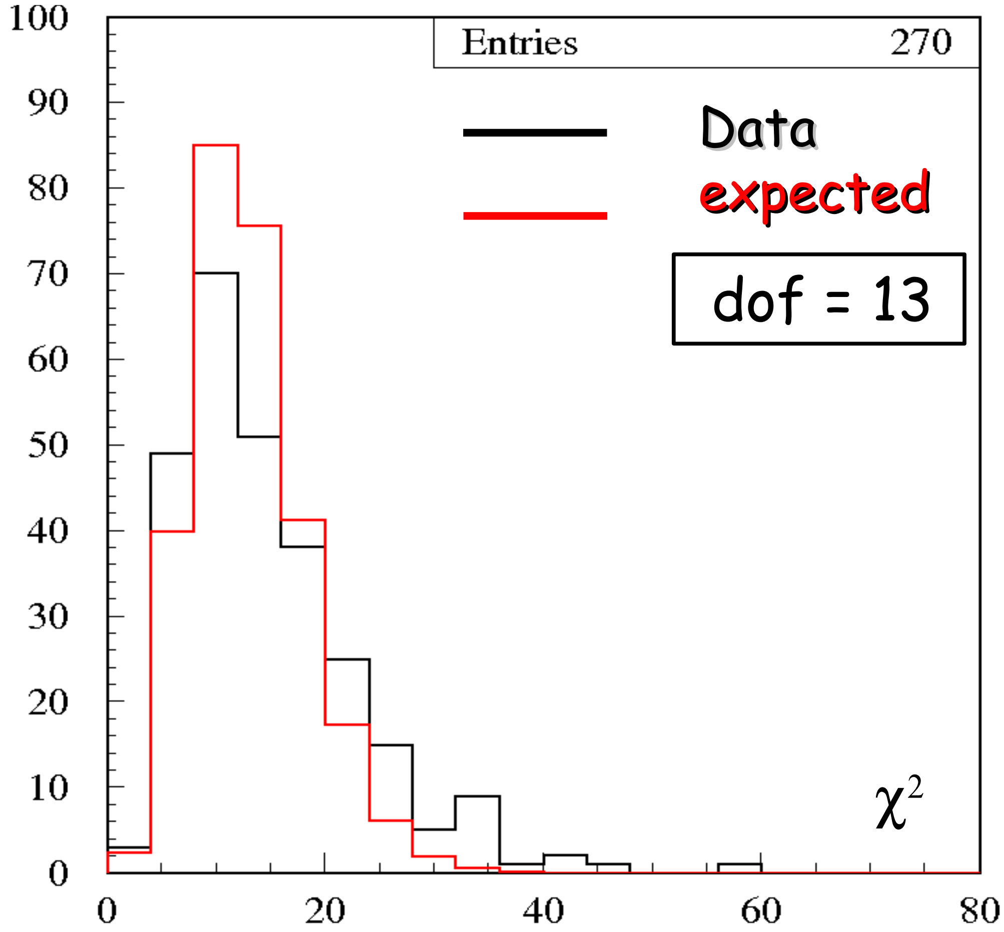
Proper time Fit

- Results as function of K_s direction (different resolutions) ;
- Fit range: 18 bins from -2 to +7 τ^0_s ;
- Resolution described by two gaussians ;
- 5 parameter fit : τ_s + 4 parameters describing resolution



Lifetime obtained from a weighted average on 270 independent fits

Goodness of Fit



- The distribution of χ^2 from each fit to data is compared with the expected distribution.

- Few bins at the border of the FV have bad probability → variation of the result by 6×10^{-4} (included in the systematic error)

Result and systematics

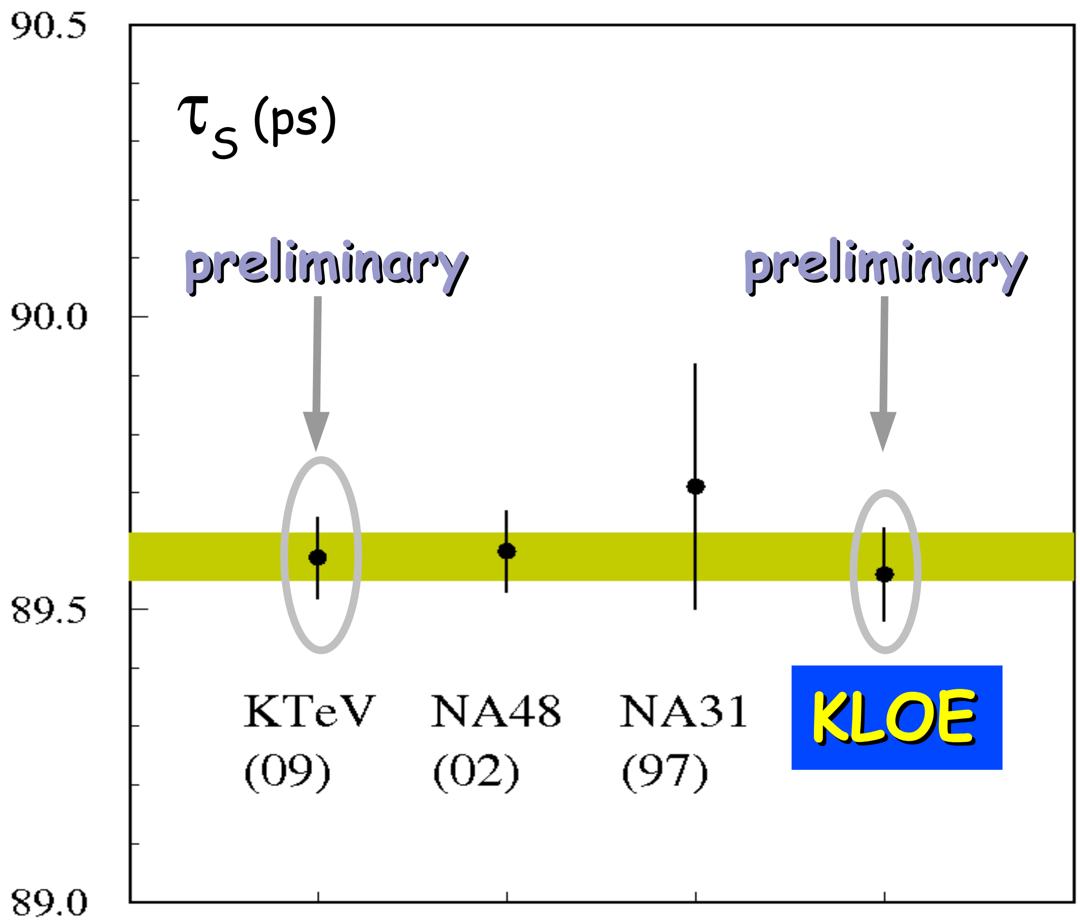
Systematic errors

Source	fractional value x10^4
- selection cuts :	3.3
- cos θ_K FV cut	5.7
- Kaon mass :	0.4
- fit range :	5.0

$$\tau_{Ks} = (\, 89.56 \pm 0.03_{stat} \pm 0.07_{syst}) \text{ ps}$$

preliminary

Updated results on K_s lifetime



New world average → τ_S = **89.59 ± 0.04** (ps) (4.6×10^{-4})

(PDG08 = 5.6×10^{-4})

Conclusion

- Many KLOE measurements have been refined and finalized with full statistics ;

- KLOE performed the best QM test with interferometry ;

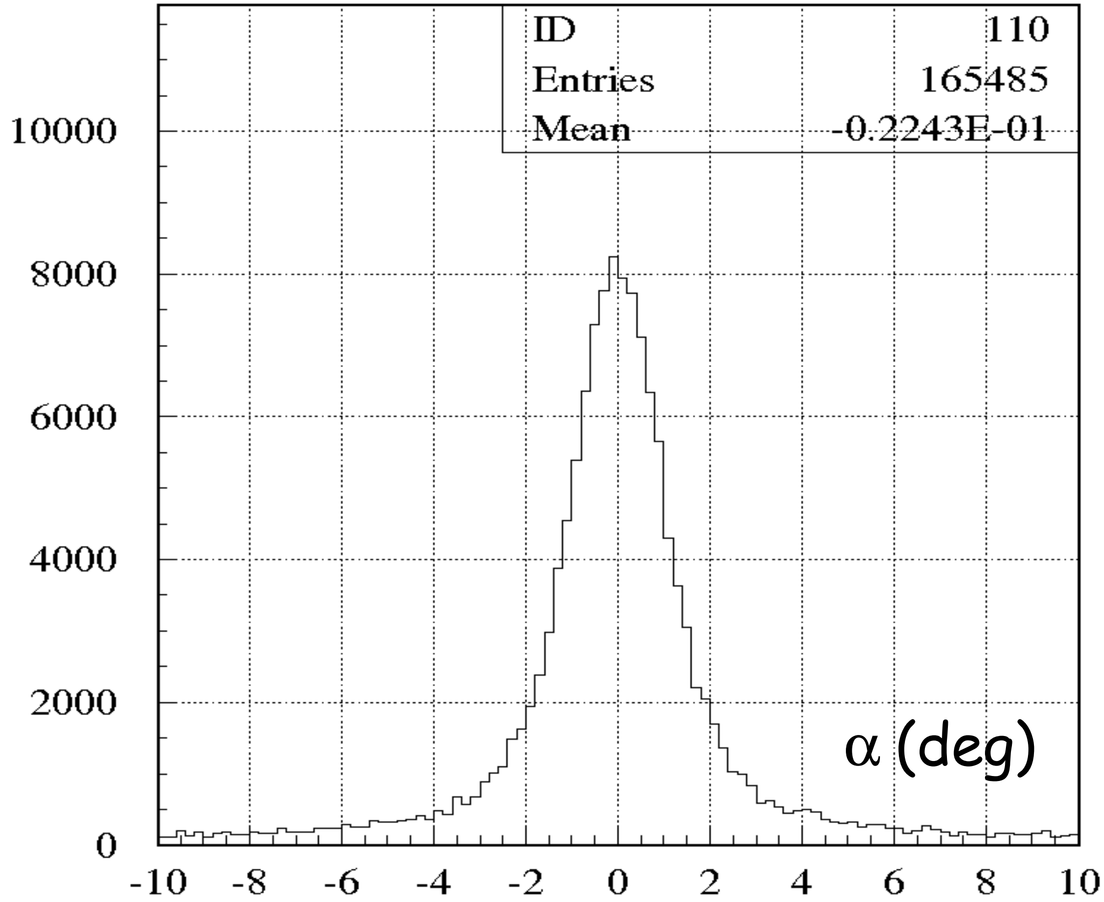
- New preliminary result on Ks lifetime: good agreement with recent measurements ;

- Neutral kaon interferometry, CPT symmetry and QM tests are one of the main issues of the KLOE-2 physics program (see Gauzzi talk). Limits on the parameters for these specific issues can be improved by a factor of ten.

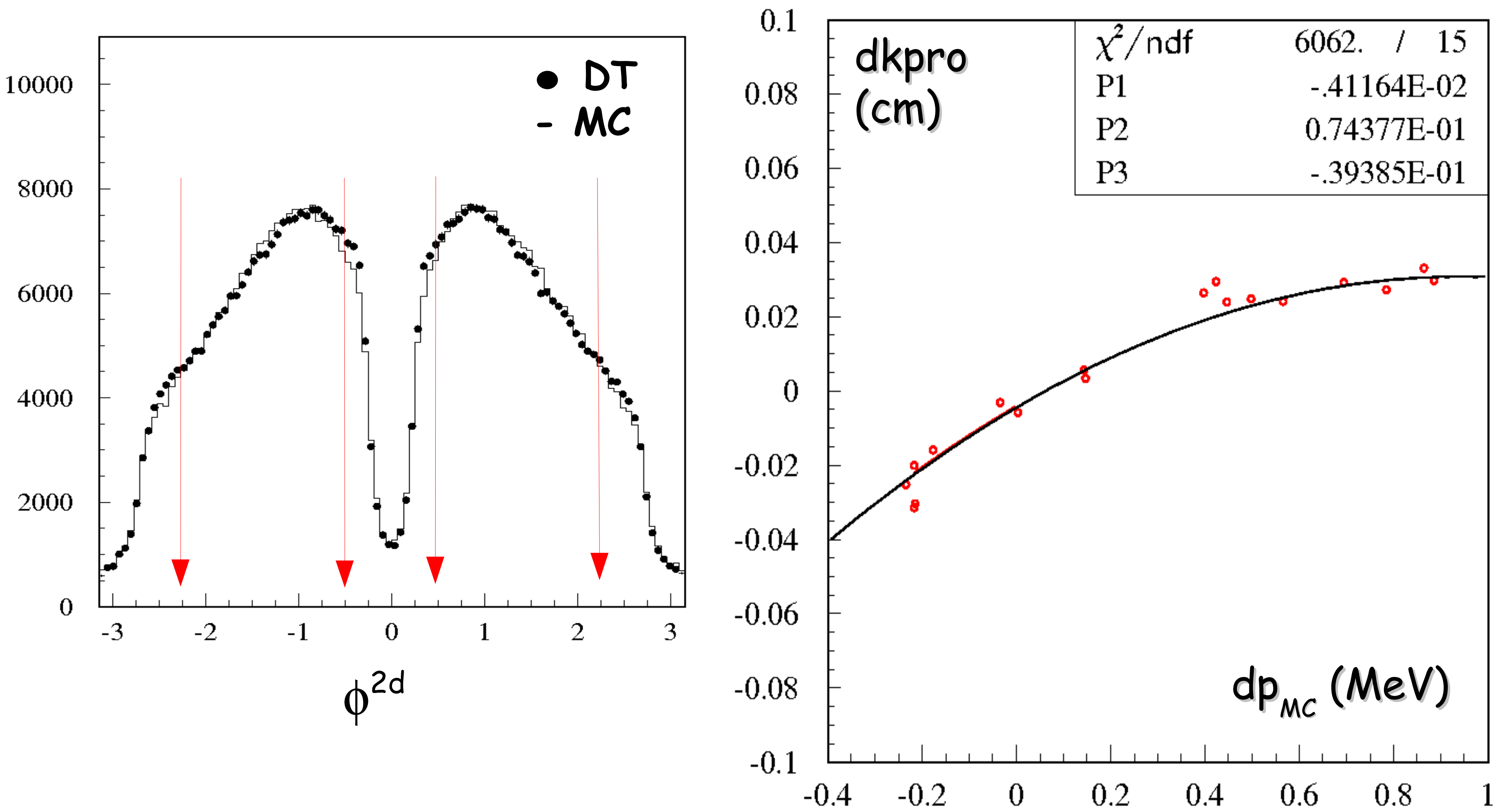
SPARES

Test from KL-crash (Data)

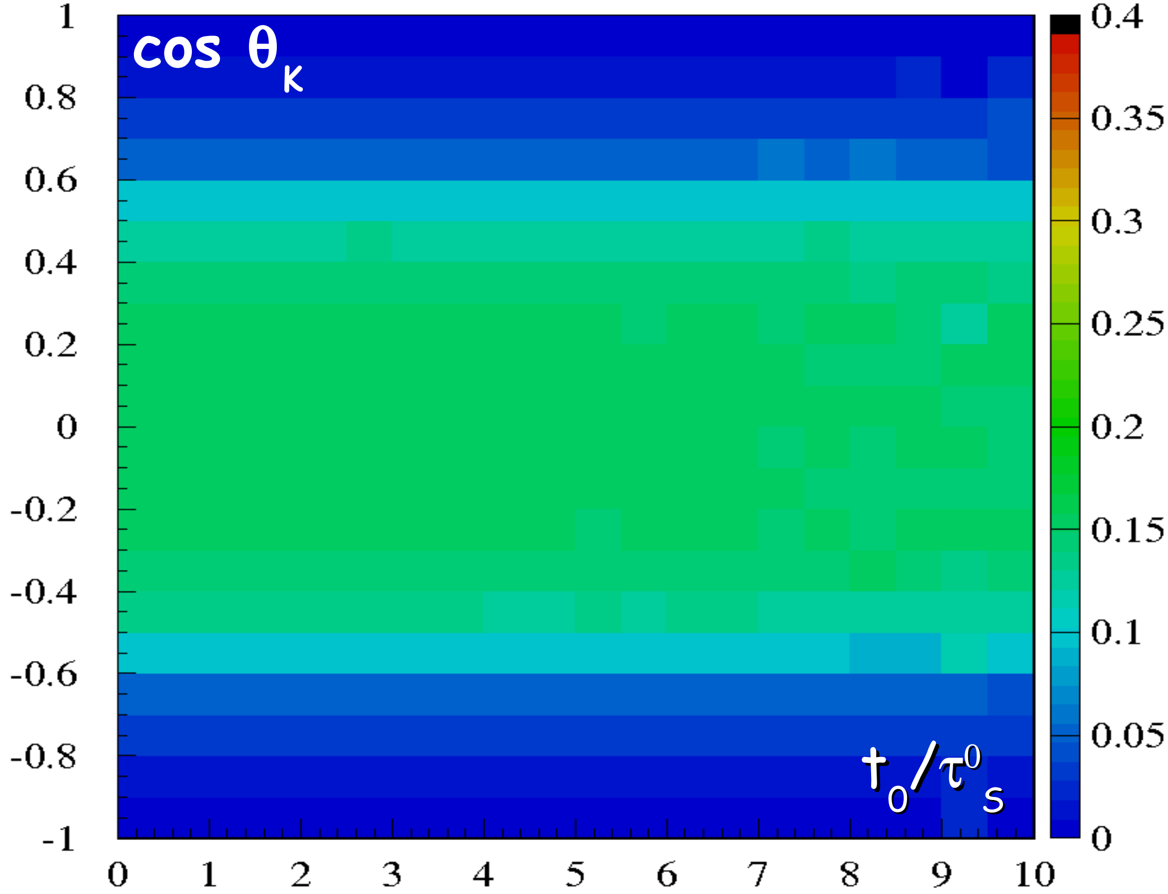
By using KL-crash **position** and **time** we perform a test for K_S direction as derived from pions (α= angular deviation)



Vertex calibration



Efficiency



cos θ_K
t_0/τ^0_S
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0 1 2 3 4 5 6 7 8 9 10
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0

KLOE-2

Mode	Test of	Param.	Present best published measurement	KLOE-2 $L=50\ fb^{-1}$
$\pi^+\pi^-$ $\pi^+\pi^-$	QM	ζ_{00}	$(1.0 \pm 2.1) \times 10^{-6}$	$\pm 0.1 \times 10^{-6}$
$\pi^+\pi^-$ $\pi^+\pi^-$	QM	ζ_{SL}	$(1.8 \pm 4.1) \times 10^{-2}$	$\pm 0.2 \times 10^{-2}$
$\pi^+\pi^-$ $\pi^+\pi^-$	CPT & QM	α	$(-0.5 \pm 2.8) \times 10^{-17}$ GeV	$\pm 2 \times 10^{-17}$ GeV
$\pi^+\pi^-$ $\pi^+\pi^-$	CPT & QM	β	$(2.5 \pm 2.3) \times 10^{-19}$ GeV	$\pm 0.1 \times 10^{-19}$ GeV
$\pi^+\pi^-$ $\pi^+\pi^-$	CPT & QM	γ	$(1.1 \pm 2.5) \times 10^{-21}$ GeV	$\pm 0.2 \times 10^{-21}$ GeV compl. pos. hyp. $\pm 0.1 \times 10^{-21}$ GeV
$\pi^+\pi^-$ $\pi^+\pi^-$	CPT & EPR corr.	$Re(\omega)$	$(1.1 \pm 7.0) \times 10^{-4}$	$\pm 2 \times 10^{-5}$
$\pi^+\pi^-$ $\pi^+\pi^-$	CPT & EPR corr.	$Im(\omega)$	$(3.4 \pm 4.9) \times 10^{-4}$	$\pm 2 \times 10^{-5}$
$K_{S,L} \rightarrow \pi e \nu$	CPT & Lorentz	Δa_0	[$(0.4 \pm 1.8) \times 10^{-17}$ GeV]	$\pm 2 \times 10^{-18}$ GeV
$\pi^+\pi^-$ $\pi^+\pi^-$	CPT & Lorentz	Δa_Z	[$(2.4 \pm 9.7) \times 10^{-18}$ GeV]	$\pm 7 \times 10^{-19}$ GeV
$\pi^+\pi^-$ $\pi e \nu$	CPT & Lorentz	$\Delta a_{X,Y}$	[$<10^{-21}$ GeV]	$\pm 4 \times 10^{-19}$ GeV

[....] = preliminary