CPT and Lorentz symmetry tests with entangled neutral kaons at KLOE and KLOE-2

Michał Silarski
Jagiellonian University

on behalf of the KLOE/KLOE-2 collaborations

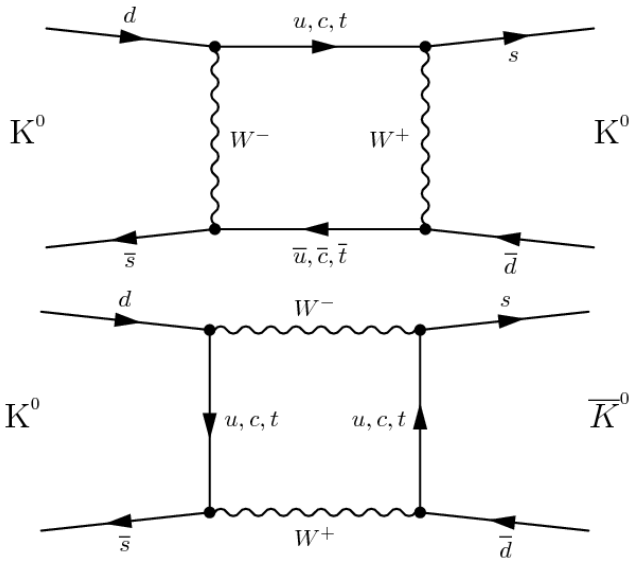
- Kaon interferometry at the Φ-factory
- DAΦNE and KLOE
- CPT and Lorentz symmetry tests
- Summary and outlook

BEACH2014, Birmingham, 26 July 2014

Introduction

- Time evolution of the $K^0 \leftrightarrow \overline{K^0}$ system in the rest frame:

$$i\frac{\partial}{\partial t}\begin{pmatrix}|K^0>\\|\overline{K^0}>\end{pmatrix} = \mathbf{H}\begin{pmatrix}|K^0>\\|\overline{K^0}>\end{pmatrix} = \left[\boldsymbol{M} - \frac{i}{2}\boldsymbol{\Gamma}\right]\begin{pmatrix}|K^0>\\|\overline{K^0}>\end{pmatrix}$$



$$\boldsymbol{\Gamma} = \begin{pmatrix}\Gamma_{11} & \Gamma_{12}\\ \Gamma^*_{12} & \Gamma_{22}\end{pmatrix} \qquad \boldsymbol{M} = \begin{pmatrix}M_{11} & M_{12}\\ M^*_{12} & M_{22}\end{pmatrix}$$

- The eigenstates of **H**:

$$|K_S> = \frac{1}{\sqrt{1+|\varepsilon_S|^2}}\left(|K_1> + \varepsilon_S|K_2>\right) \quad (\tau = 0.9\cdot10^{-10}\ \text{s};\ c\tau = 2.68\ \text{cm})$$

$$|K_L> = \frac{1}{\sqrt{1+|\varepsilon_L|^2}}\left(|K_2> + \varepsilon_L|K_1>\right) \quad (\tau = 5.1\cdot10^{-8}\ \text{s};\ c\tau = 155\ \text{cm})$$

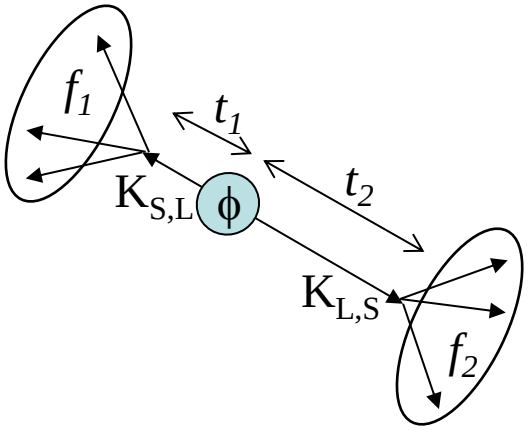
$\boldsymbol{\varepsilon_S \neq \varepsilon_L \Rightarrow}$ **CPTV**

Kaon interferometry at the Φ-factory

- ϕ decays provide entangled kaons pairs:

$$|\phi>=\frac{1}{\sqrt{2}}\left(|K^0>|\overline{K^0}>-|\overline{K^0}>|K^0>\right)=N(|K_S(\vec{p})>|K_L(\vec{p})>-|K_S(-\vec{p})>|K_L(\vec{p})>)$$

$$N=\frac{\sqrt{(1+|\varepsilon_S|^2)(1+|\varepsilon_L|^2)}}{(1-\varepsilon_S\varepsilon_L)}$$



- The intensity of kaon decays into final states f_1 and f_2 at proper times t_1 and t_2:

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

$$\eta_i=\frac{\langle f_i|T|K_L\rangle}{\langle f_i|T|K_S\rangle}$$

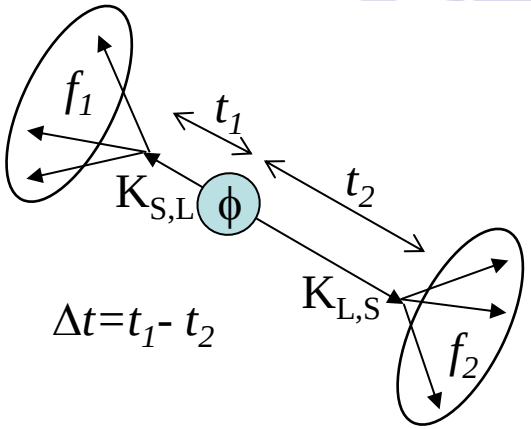
$$C_{12}=\frac{N^2}{2}|\langle f_1|T|K_S\rangle\langle f_2|T|K_s\rangle|^2$$

- **Complete destructive quantum interference prevents the two kaons from decaying into the same final state at the same time**

Kaon interferometry at the Φ-factory

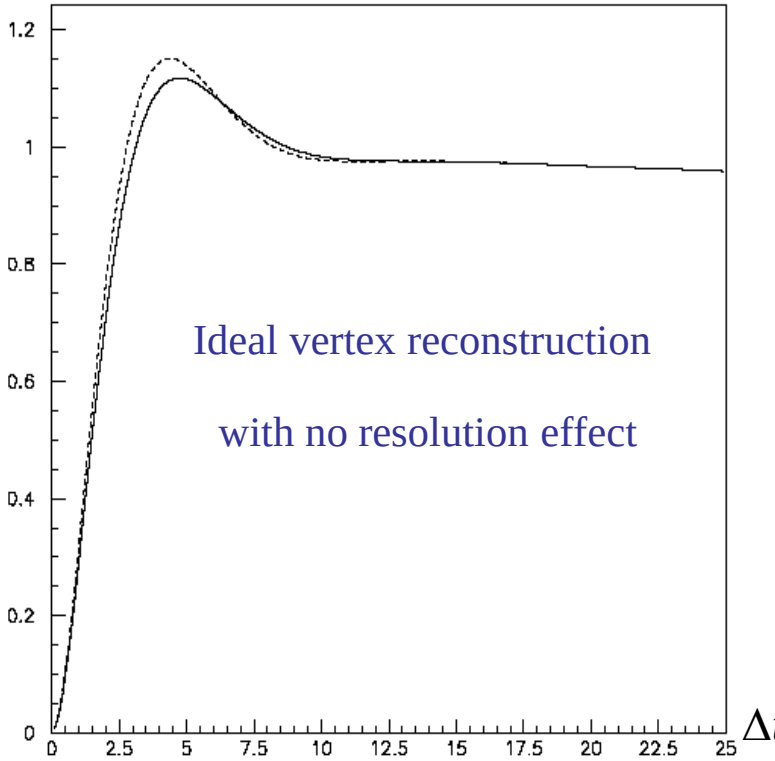
- Interference patterns for different kaon decays provide studies of different symmetries:

$$\phi \longrightarrow K_S K_L \longrightarrow \pi^+\pi^-\pi^0\pi^0 \Longrightarrow \frac{\varepsilon'}{\varepsilon} \text{ (CPV)}$$
$$\phi \longrightarrow K_S K_L \longrightarrow \pi^\pm l^\pm \nu\, \pi^0\pi^0\pi^0, \pi\pi \Longrightarrow \text{T violation}$$
$$\phi \longrightarrow K_S K_L \longrightarrow \pi^- l^+ \nu\, \pi^+ l^- \bar{\nu} \Longrightarrow \text{CPT and } \Delta S = \Delta Q \text{ rule}$$
$$\phi \longrightarrow K_S K_L \longrightarrow \pi^\pm l^\mp \nu\pi\pi \Longrightarrow \text{CPT and } \Delta S = \Delta Q \text{ rule}$$



$$\boldsymbol{\phi \longrightarrow K_S K_L \longrightarrow \pi^+\pi^-\pi^+\pi^-}$$
$$\Longrightarrow \textbf{CPT, Lorentz Symmetry,}$$
Quantum Mechanics and Quantum Gravity

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



Kaon interferometry: $\Phi \to K_S K_L \to \pi^+\pi^-\pi^+\pi^-$

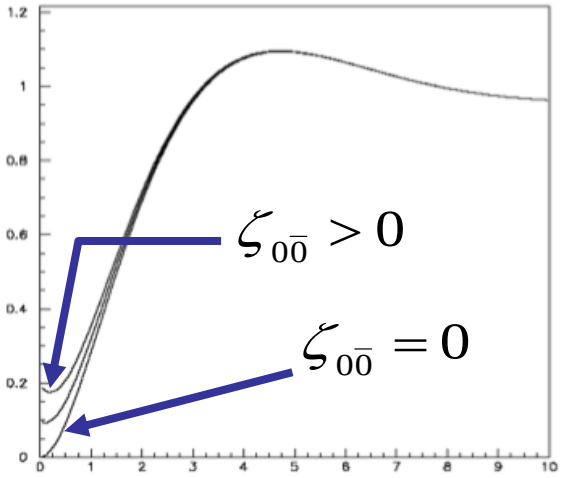
$$I\left(\pi^+\pi^-,\pi^+\pi^-;|\Delta t|\right) \propto e^{-\Gamma_L|\Delta t|} + e^{-\Gamma_S|\Delta t|} - 2(1-\zeta_{SL})e^{-(\Gamma_S+\Gamma_L)|\Delta t|/2}\cos\left(\Delta m|\Delta t|\right)$$

Modified interference term introducing a decoherence parameter ζ.

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

$\zeta_{SL} = 1 \quad \to \quad$ total decoherence

[W.Furry, PR 49 (1936) 393]

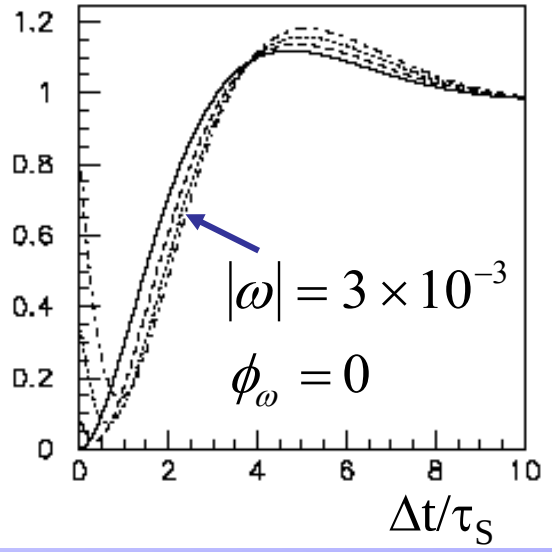


$I(\pi^+\pi^-, \pi^+\pi^-;\Delta t)$ (a.u.)

Quantum Gravity could also imply at Planck scale modified particle/antiparticle states:

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

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

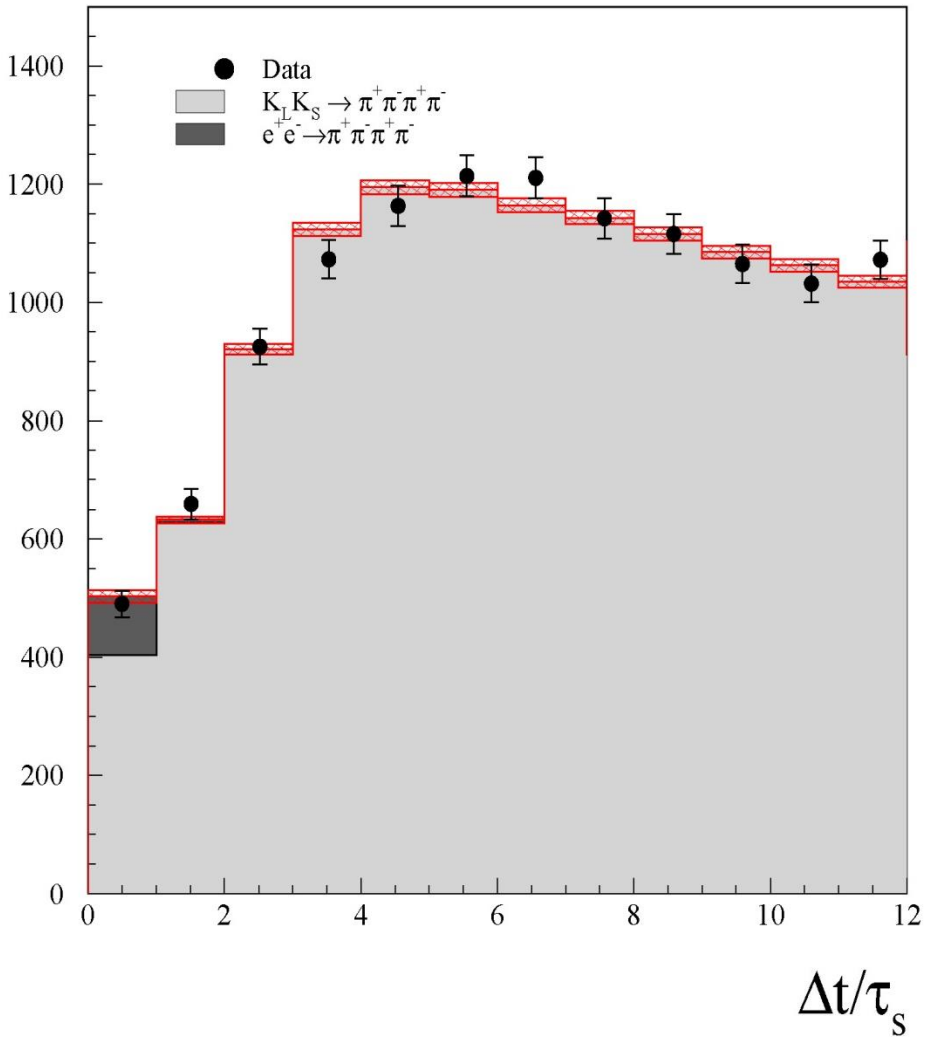


Kaon interferometry: $\Phi \to K_S K_L \to \pi^+\pi^-\pi^+\pi^-$

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

$$\zeta_{SL} = \left(0.3 \pm 1.8_{\mathrm{STAT}} \pm 0.6_{\mathrm{SYST}}\right) \times 10^{-3}$$
$$\zeta_{00} = \left(1.4 \pm 9.5_{\mathrm{STAT}} \pm 3.8_{\mathrm{SYST}}\right) \times 10^{-7}$$

$$\Re\omega = \left(-1.6^{+3.0}_{-2.1\,STAT} \pm 0.4_{SYST}\right) \times 10^{-4}$$
$$\Im\omega = \left(-1.7^{+3.3}_{-3.0\,STAT} \pm 1.2_{SYST}\right) \times 10^{-4}$$
$$|\omega| < 1.0 \times 10^{-3} \quad \text{at} \quad 95\%\ \text{C.L.}$$



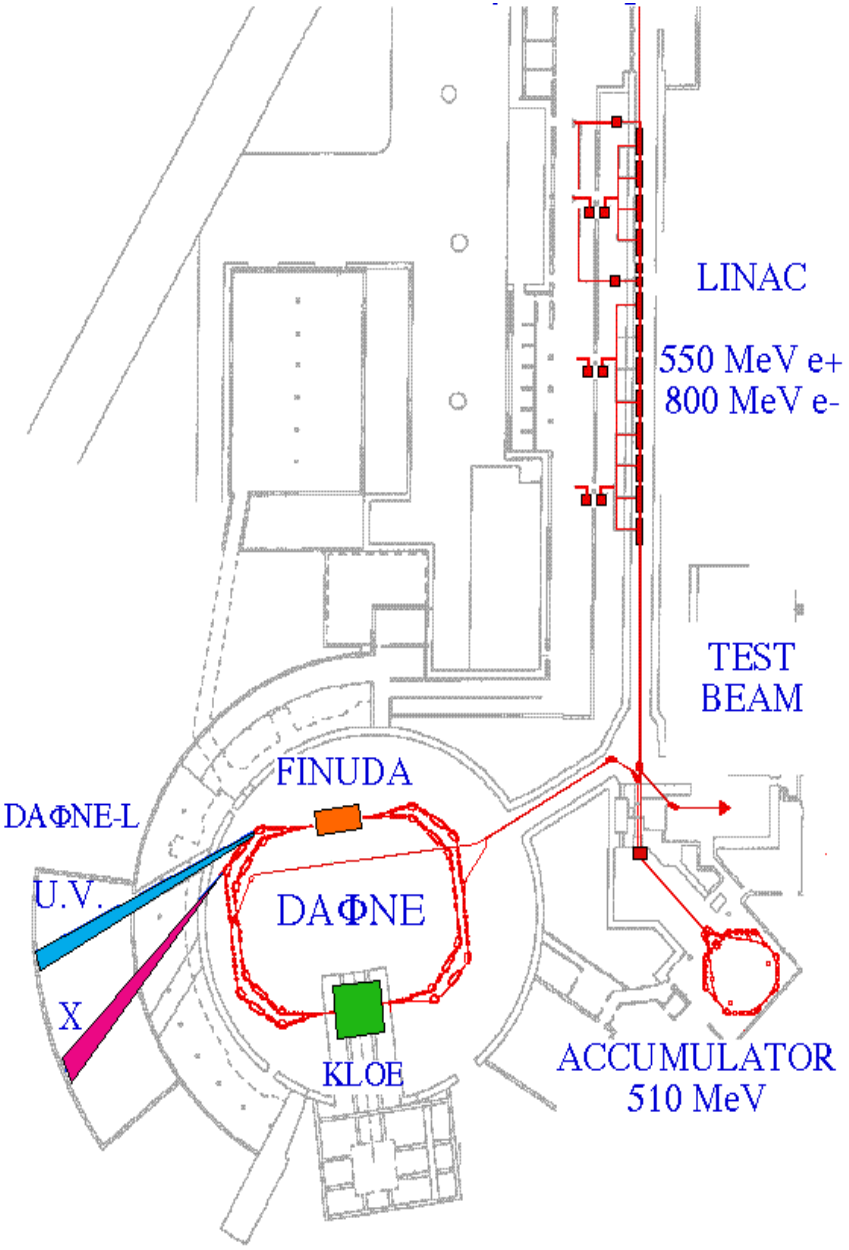
PLB 642(2006) 315
J.Phys.Conf.Ser.171(2009) 012008

The DAΦNE Φ-factory

- e^+e^- collider @ $\sqrt{s} = M_\varphi = 1019.4$ MeV
- LAB momentum $p_\varphi \sim 15$ MeV/c
- $\sigma_{peak} \sim 3$ μb
- Separate e^+e^- rings to reduce beam-beam interaction
- Beams crossing angle: 15 mrad
- Peak luminosity 1.5×10^{32} $cm^{-2}s^{-1}$

KLOE run:

- Daily performance: 7-8 pb^{-1}
- Best month $\int L\,dt \sim 200$ pb^{-1}
- Total KLOE:
  $\int L\,dt \sim 2500$ pb^{-1} at φ mass peak
  + 250 pb^{-1} off peak (@ 1 GeV)



KLOE (K LOng Experiment)

Large cylindrical drift chamber

- Uniform tracking and vertexing in all volume
- Helium based gas mixture (90% He – 10% $IsoC_4H_{10}$)
- Stereo wire geometry

$\sigma_p/p = 0.4\ \%$

$\sigma_{xy} = 150\ \mu m$; $\sigma_z = 2\ mm$

$\sigma_{vtx} \sim 3\ mm$

$\sigma(M_{\pi\pi}) \sim 1\ MeV$

Lead/scintillating-fiber calorimeter

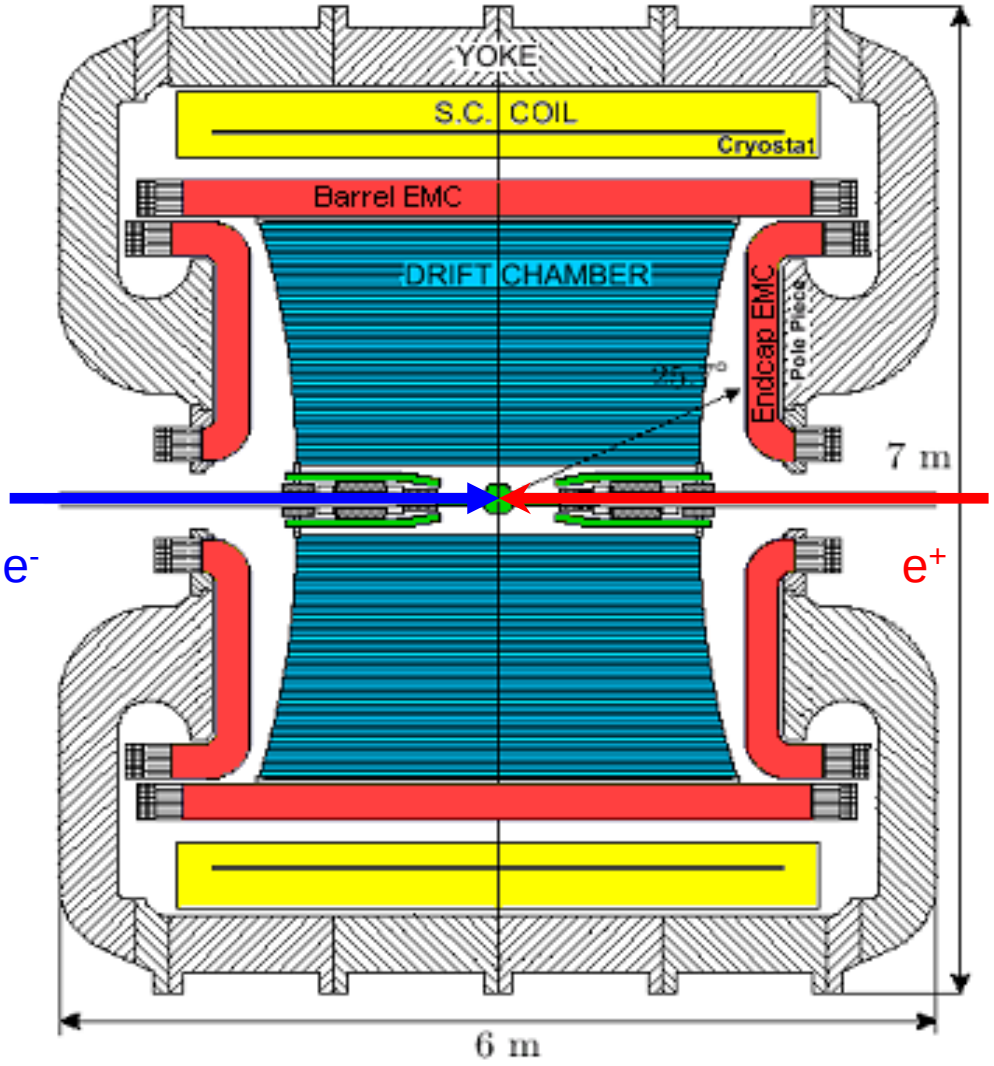
- Hermetical coverage
- High efficiency for low energy photons

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

$\sigma_t = 57\ ps / \sqrt{E(GeV)} \oplus 100\ ps$

$\sigma_{vtx}(\gamma\gamma) \sim 1.5\ cm$

Superconducting coil
B = 0.52 T



CPT and Lorentz symmetry tests

- For two identical final states time can only be ordered according to kaon momentum in a given/assigned direction

$$I(\pi^+\pi^-,\pi^+\pi^-,\Delta\tau) \propto |\eta_1|^2 e^{\Gamma_L|\Delta\tau|} + |\eta_2|^2 e^{-\Gamma_S|\Delta\tau|} - 2|\eta_1||\eta_2| e^{\frac{-(\Gamma_S+\Gamma_L)}{2}|\Delta\tau|}\cos(\Delta m|\Delta\tau|)$$

$$\eta_1 = \varepsilon - \delta(\vec{p}_{K_1}) \qquad \eta_2 = \varepsilon - \delta(\vec{p}_{K_2})$$

- δ is the CPT violation parameter in the Kaon system.
- According to the SME (Kostelecky) and anti-CPT theorem, CPT violation should appear together with Lorentz Invariance breaking (Greenberg)⇒ direction dependent modulation of δ:

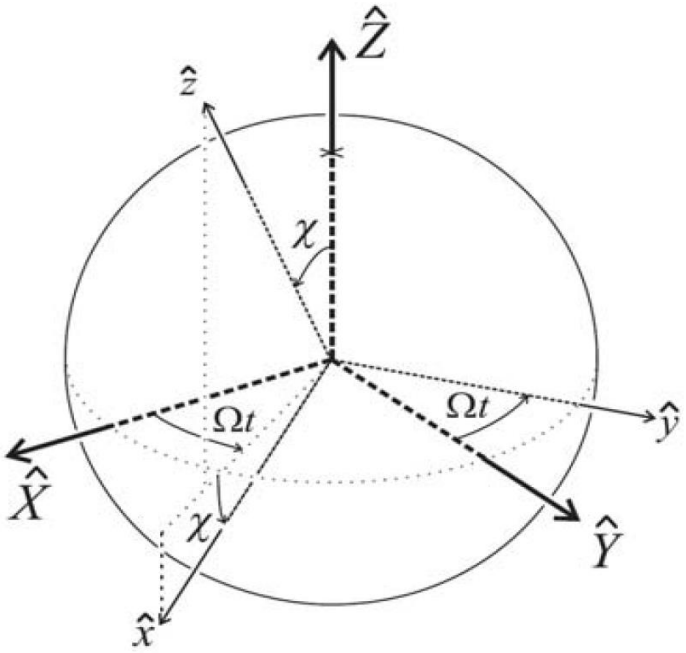
$$\delta \simeq i \sin\phi_{SW} e^{i\phi_{SW}} \gamma_K (\Delta a_0 - \vec{\beta}_K \Delta\vec{a})/\Delta m$$

V. A. Kostelecký Phys. Rev. D 64, 076001
O. W. Greenberg Phys. Rev. Lett. 89, 231602

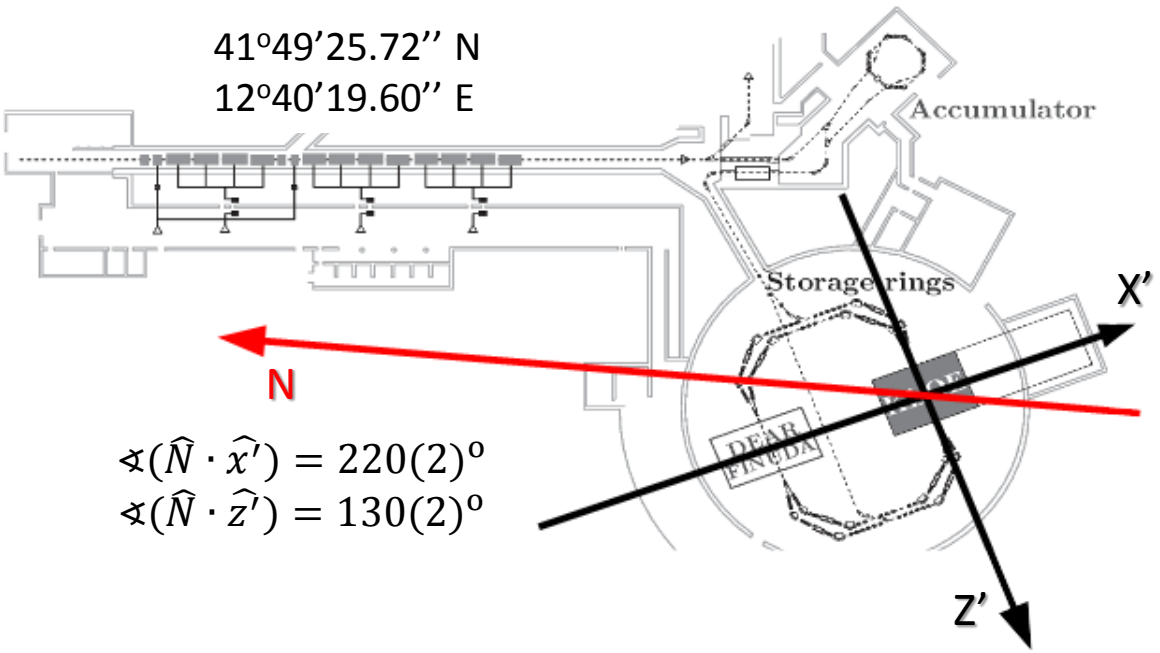
- Ordering kaon according to their momenta it is possible to have the two η coefficients containing two different δ CPT violating parameter.

CPT and Lorentz symmetry tests

- Choice of the reference frame: the $\hat{Z}$ axis along the Earth's rotation axis (accounting for the sidereal time dependence due to the Earth rotation)



41°49'25.72'' N
12°40'19.60'' E



$\sphericalangle(\hat{N} \cdot \hat{x'}) = 220(2)^{\circ}$
$\sphericalangle(\hat{N} \cdot \hat{z'}) = 130(2)^{\circ}$

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

Sidereal time

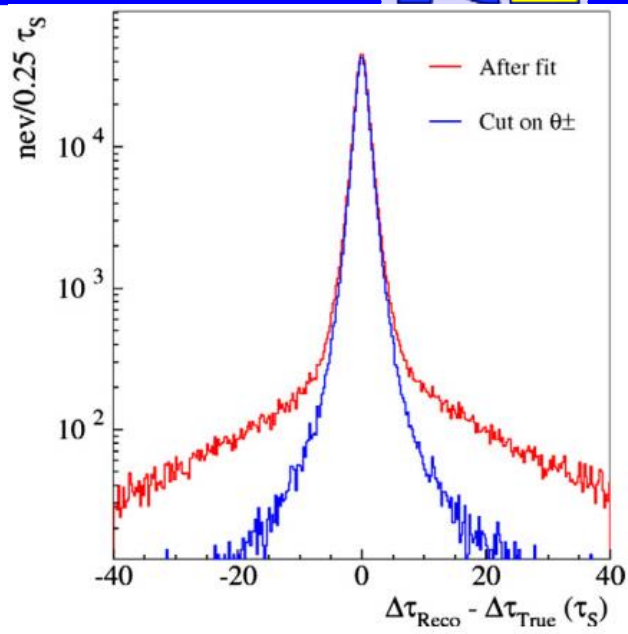
CPT and Lorentz symmetry tests

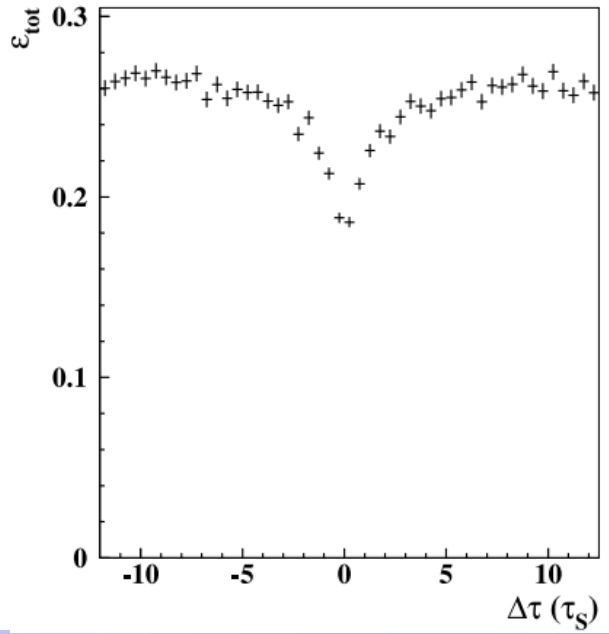
- **Measurement of the $\phi \to K_S K_L \to \pi^+\pi^-\ \pi^+\ \pi^-$**

- Events preselection requiring 2 reconstructed vertices with two tracks and:
  - $|M_{rec} - m_K| < 5$ MeV/c^2 (assuming pion hypothesis for both tracks)
  - $\sqrt{E^2{}_{miss} + \vec{p}^{\,2}{}_{miss}} < 10$ MeV
  - -50 MeV^2/c^4 < $M^2{}_{miss}$ < 10 MeV^2/c^4
  - $\left| p^*{}_{1,2} - p^*{}_0 \right| < 10$ MeV/c $\left(p^*{}_0 = \sqrt{\frac{s}{4} - m^2{}_K} \right)$

- A global kinematic fit applied to improve the kaon decay length reconstruction
- Cut on the pion opening angle $\cos\vartheta < -0.975$ (events with deteriorated time resolution)
- Vertices inside the beam pipe (reduction of the K_S regeneration background) $\Rightarrow \Delta\tau \in [-12\tau_s; -12\tau_s]$

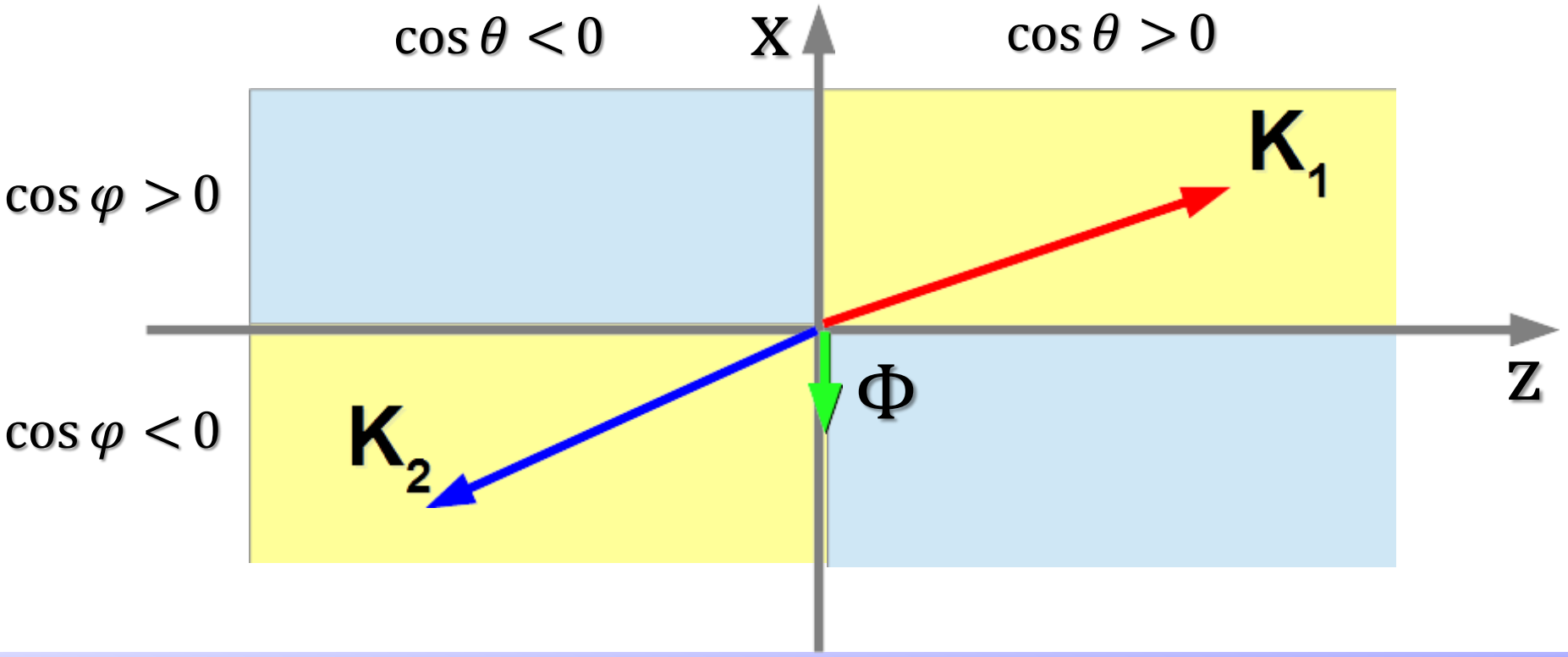
- The residual background contamination: regeneration (2%) and $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$(0.5%)



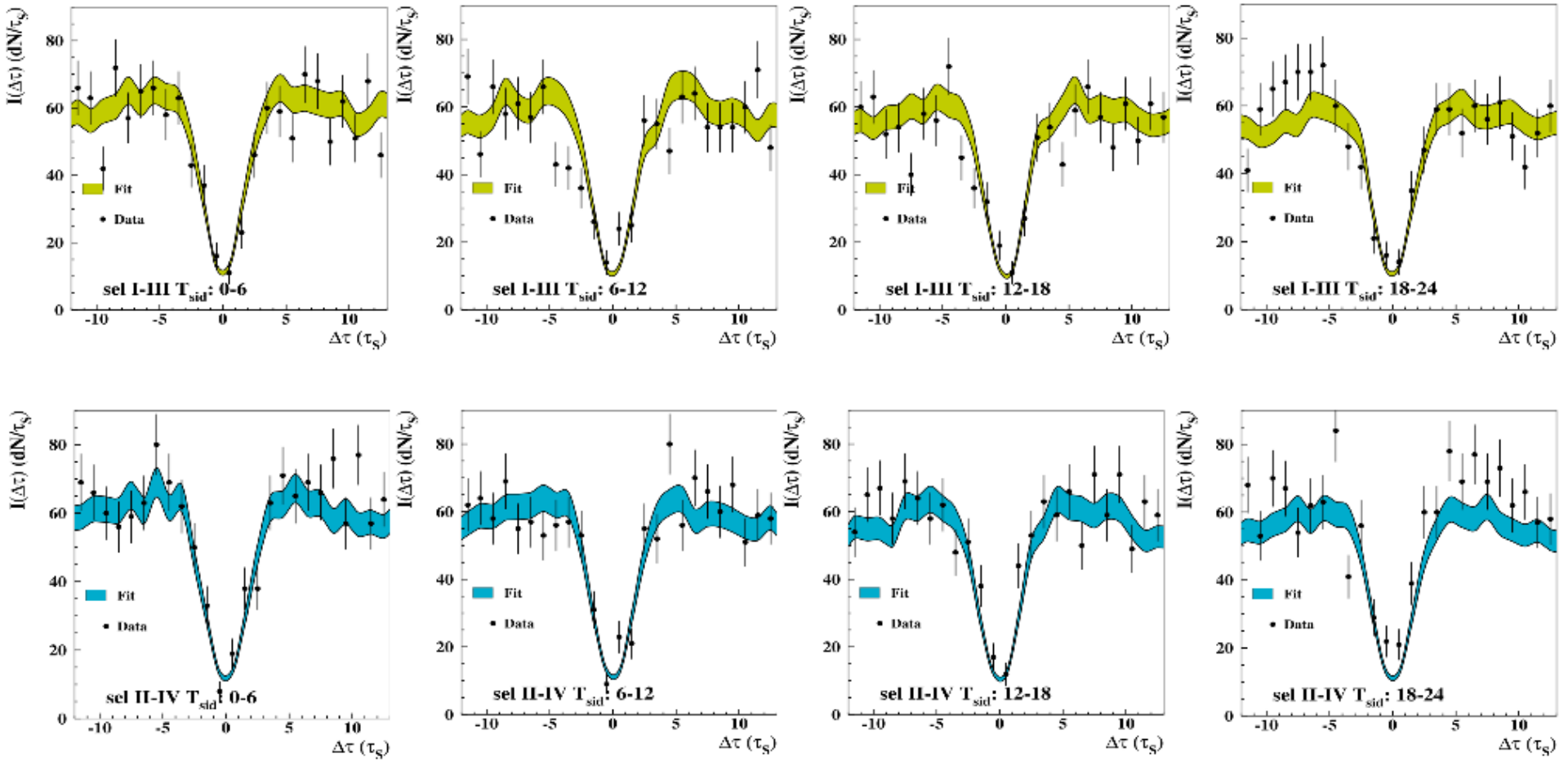


CPT and Lorentz symmetry tests

- Kaons were ordered according to their *z* momenta component
- Data sample analyzed for different intervals of sidereal time and kaon emission angle:
  $4_{\text{sidereal}} \times 2_{\text{angular}} = 8$ I(Δτ) distributions
- Simultaneous fit to all distributions taking into account the 4π background subtraction and data/MC efficiency correction for regeneration



CPT and Lorentz symmetry tests



192 Data points fit simultaneously with 5 free parameters; χ^2_{Fit}/ndof = 211/187 (P=10%)

Final results

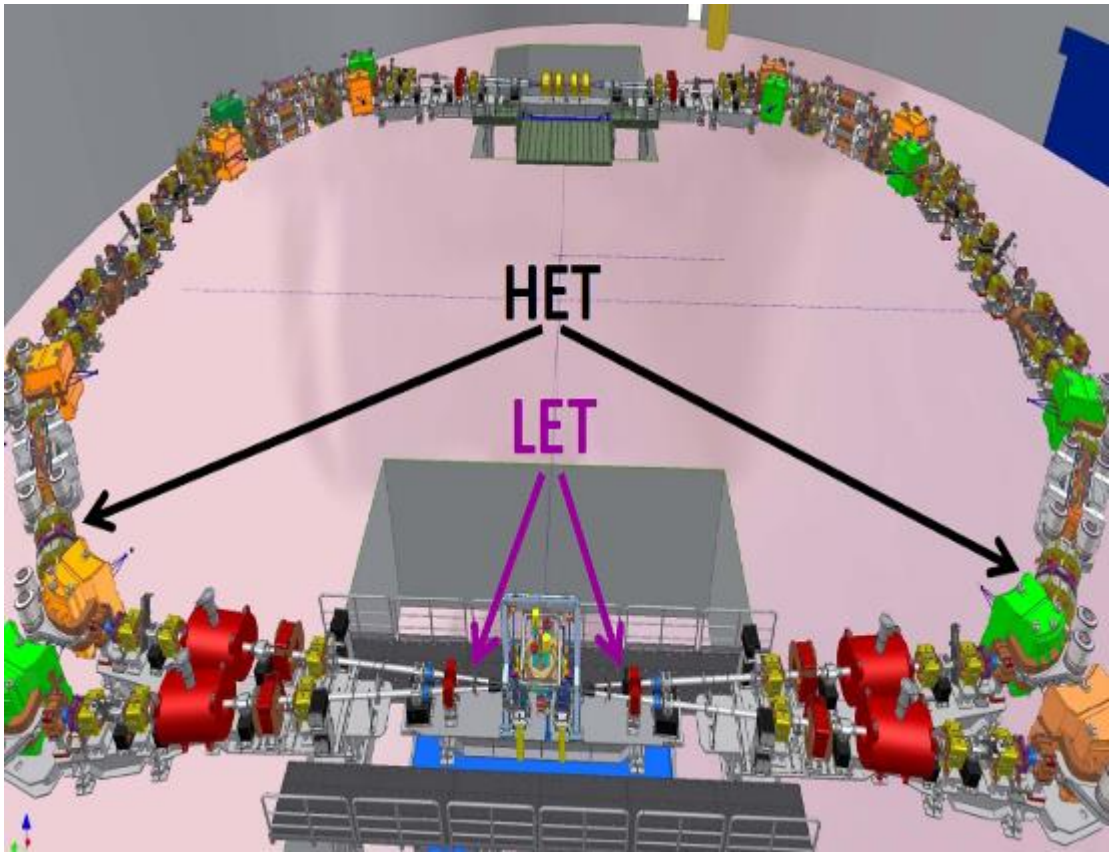
$$\Delta a_0 = (-6.0 \pm 7.7_{stat} \pm 3.1_{sys}) \, 10^{-18} \text{ GeV}$$
$$\Delta a_x = (0.9 \pm 1.5_{stat} \pm 0.6_{sys}) \, 10^{-18} \text{ GeV}$$
$$\Delta a_y = (-2.0 \pm 1.5_{stat} \pm 0.5_{sys}) \, 10^{-18} \text{ GeV}$$
$$\Delta a_z = (3.1 \pm 1.7_{stat} \pm 0.6_{sys}) \, 10^{-18} \text{ GeV}$$

- Summary of systematic uncertainties:

Parameter	Cuts stability [10^{-18} GeV]	Fit range [10^{-18} GeV]	Bkg. subtr. [10^{-18} GeV]	KLOE ref. Frame [10^{-18} GeV]	TOTAL [10^{-18} GeV]
Δa_0	1.1	2.4	1.3	1.0	3.1
Δa_x	0.3	0.3	0.4	0.2	0.6
Δa_y	0.2	0.3	0.2	0.2	0.5
Δa_z	0.2	0.2	0.4	0.4	0.6

KLOE upgrades: γγ taggers

Measurement of leptons momenta in $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-X$



LET: E_e ~ 160-230 MeV

- Inside KLOE detector
- LYSO+SiPM
- σ_E<10% for E>150 MeV

HET: E_e > 400 MeV

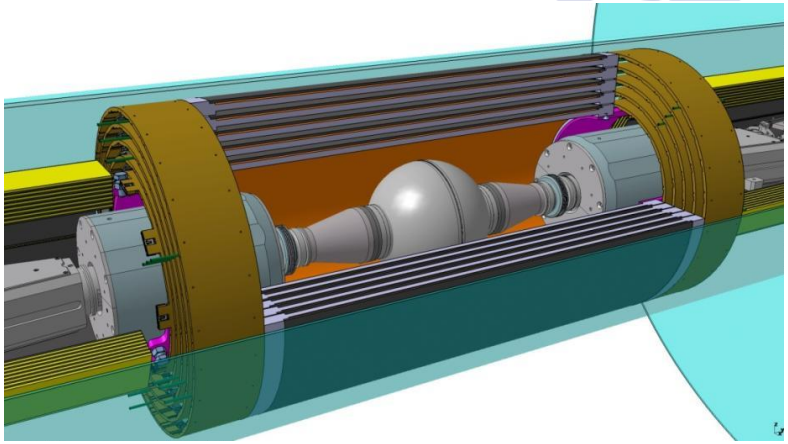
- 11 m from IP
- Scintillator hodoscopes
- σ_E ~ 2.5 MeV
- σ_T ~ 200 ps

γγ taggers are installed and ready for the first KLOE-2 run

KLOE upgrades: IR detectors

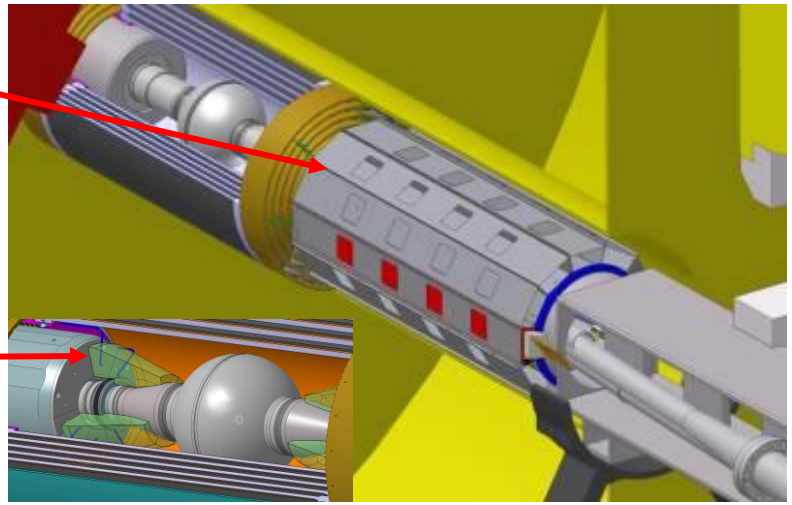
INNER TRACKER

- 4 layers of cylindrical triple GEM
- Better vertex reconstruction near IP
- Larger acceptance for low p_t tracks



QCALT

- W + scintillator tiles + SiPM/WLS
- Low-beta quadrupoles: coverage for K_L decays



CCALT

- LYSO + SiPM
- Increase acceptance for γ's from IP ($21^o \rightarrow 8^o$)

IT: NIMA 628 (2011),194
QCALT: NIMA 617 (2010),105
CCALT: NPB 197 (2009), 215

Summary and outlook

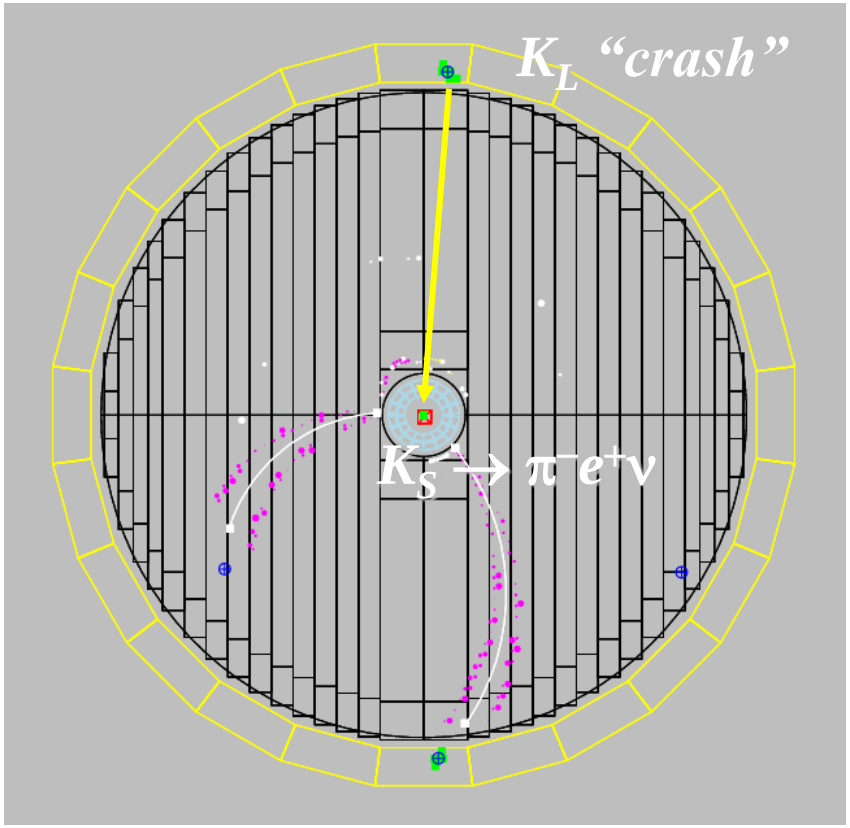
- The φ-factory provides entangled kaon pairs which can be used to probe fundamental symmetries and search for physics beyond the Standard Model
- KLOE has performed the test of CPT and Lorentz invariance with sensitivity at the level of 10^{-18} GeV
- Further improvements expected (up to one order of magnitude) for KLOE-2 physics run (larger sample + improved performances)
- KLOE upgrades: installed, commissioning almost completed
- DAΦNE beams optimization: in progress

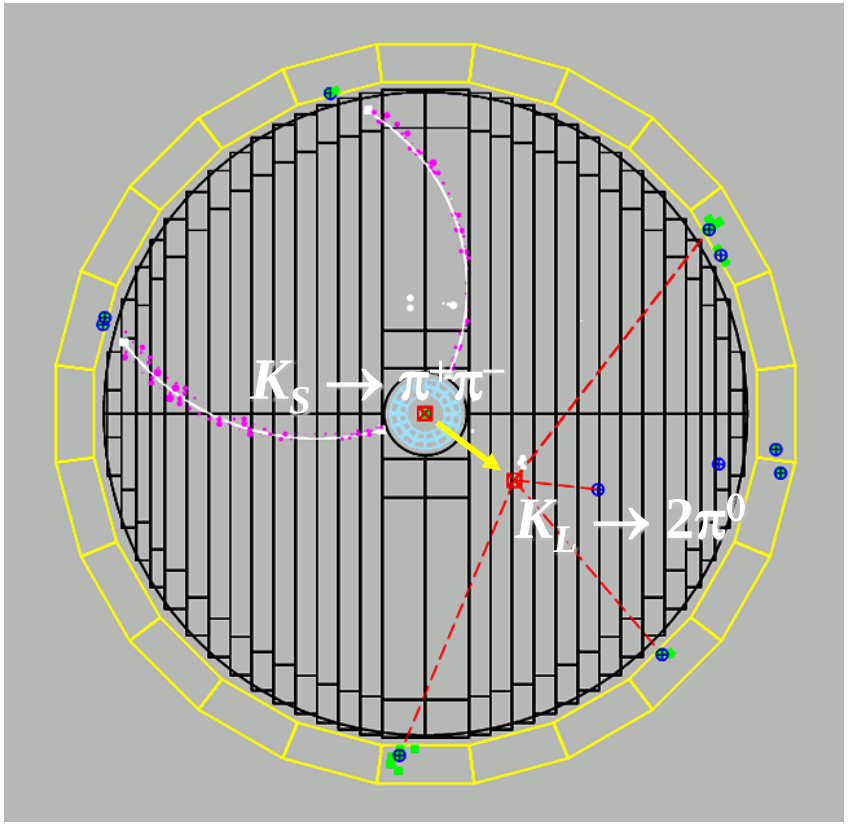
THANK YOU
FOR ATTENTION

SPARES

K_S and K_L tagging

A Φ-factory offers the possibility to select pure kaon beams:



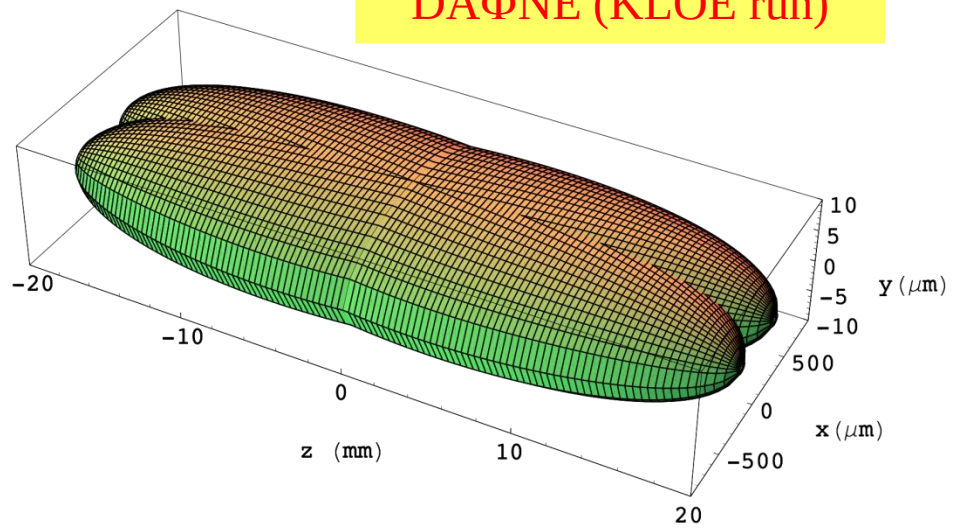


K_S tagged by K_L interaction in EmC
Efficiency ~ 30%
K_S angular resolution: ~ 1° (0.3° in φ)
K_S momentum resolution: ~ 2 MeV

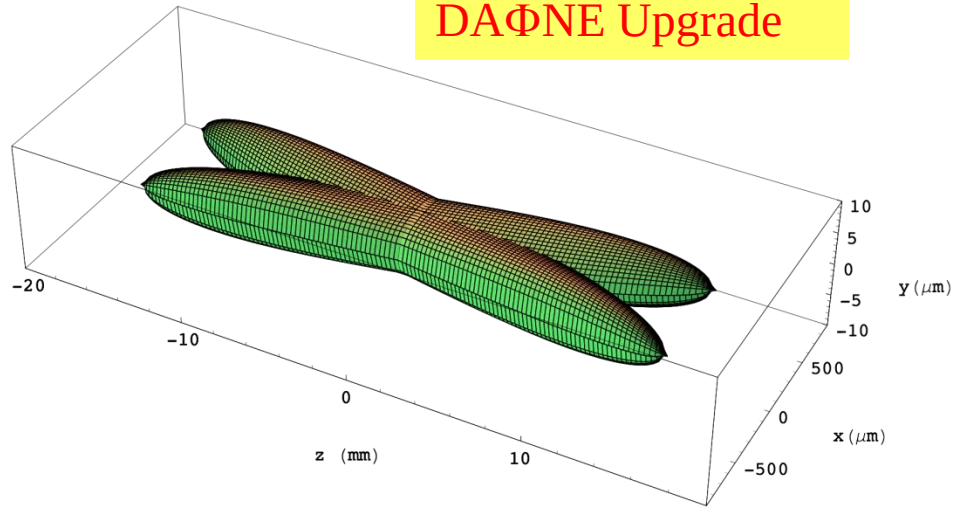
K_L tagged by $K_S \to \pi^+\pi^-$ vertex at IP
Efficiency ~ 70%
K_L angular resolution: ~ 1°
K_L momentum resolution: ~ 2 MeV

DAΦNE upgrade

DAΦNE (KLOE run)



DAΦNE Upgrade

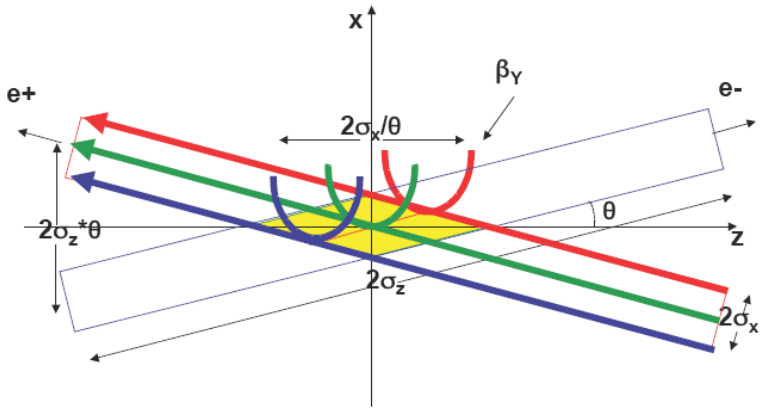


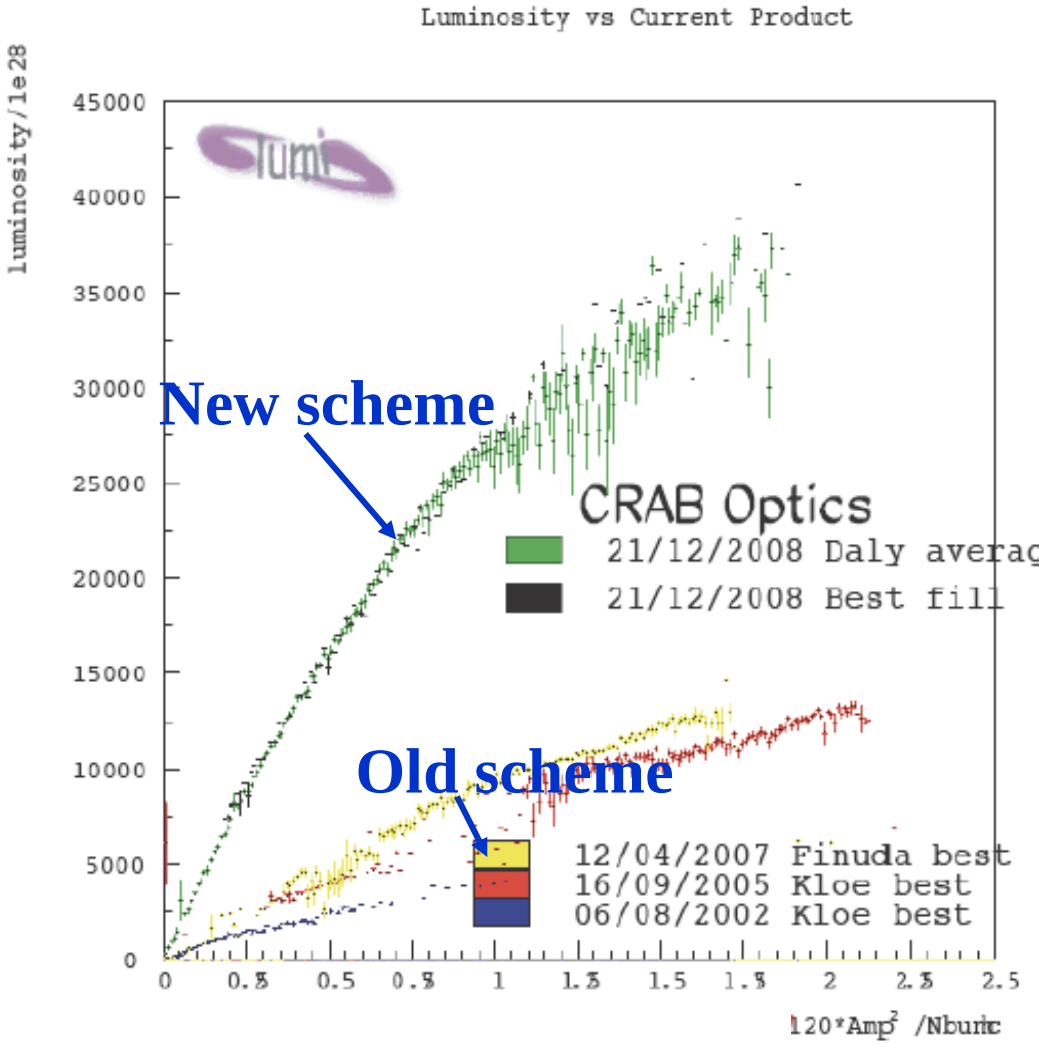
	DAΦNE (KLOE run)	DAΦNE Upgrade
I_{bunch} (mA)	13	13
N_{bunch}	110	110
β_y^* (cm)	1.7	0.65
β_x^* (cm)	170	20
σ_y^* (μm)	7	2.6
σ_x^* (μm)	700	200
σ_z (mm)	25	20
θ_{cross} (mrad) (half)	12.5	25
$\Phi_{Piwinski}$	0.45	2.5
L ($cm^{-2}s^{-1}$)	1.5×10^{32}	$>5 \times 10^{32}$

DAΦNE upgrade

New interaction scheme implemented: large beam crossing angle + sextupoles for crabbed waist optics

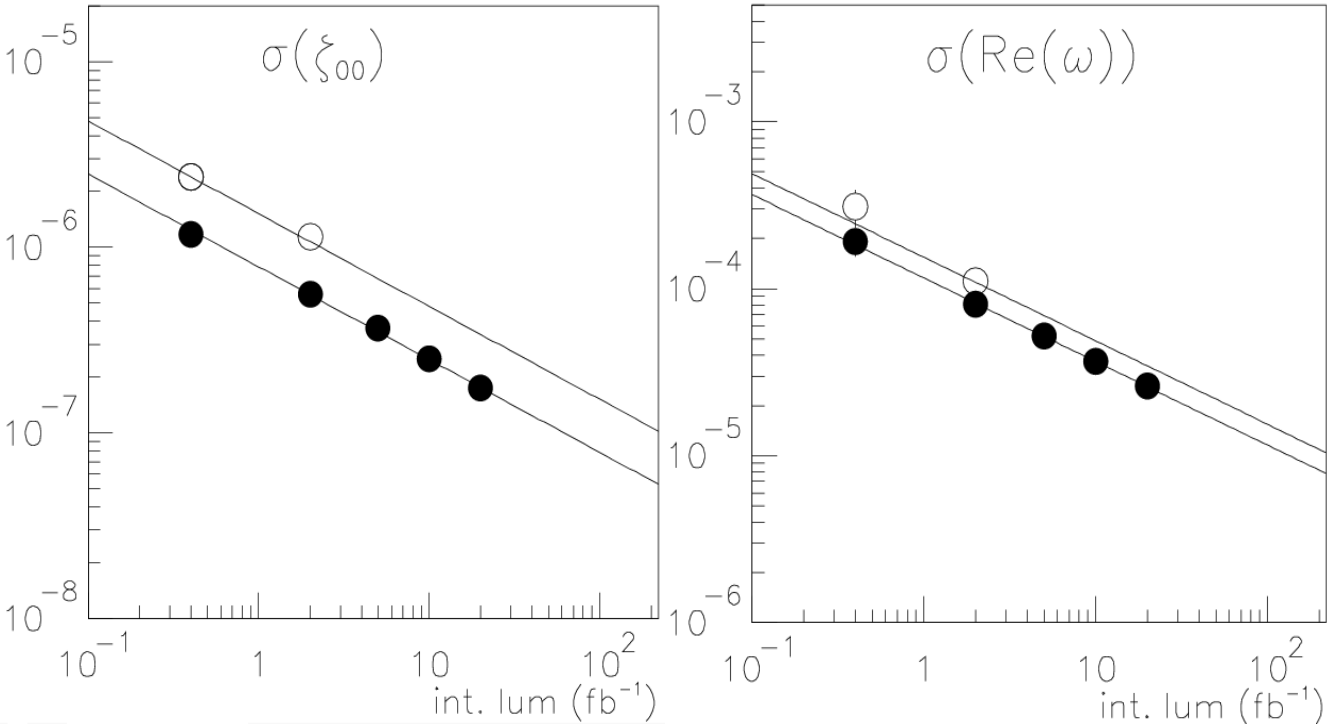
- $L_{new} \sim 3 \times L_{old}$
- $\int L dt = 1\ pb^{-1}/hour$





$$I(\pi^+\pi^-,\pi^+\pi^-,\Delta\tau\,) \propto e^{-(\Gamma_S+\Gamma_L)|\Delta\tau|}\left[|\eta_1|^2 e^{\frac{-\Delta\Gamma}{2}\Delta\tau} + |\eta_2|^2 e^{\frac{-\Delta\Gamma}{2}\Delta\tau} - 2\Re e\left(\eta_1\eta_2{}^* e^{-i\Delta m\Delta\tau}\right)\right]$$

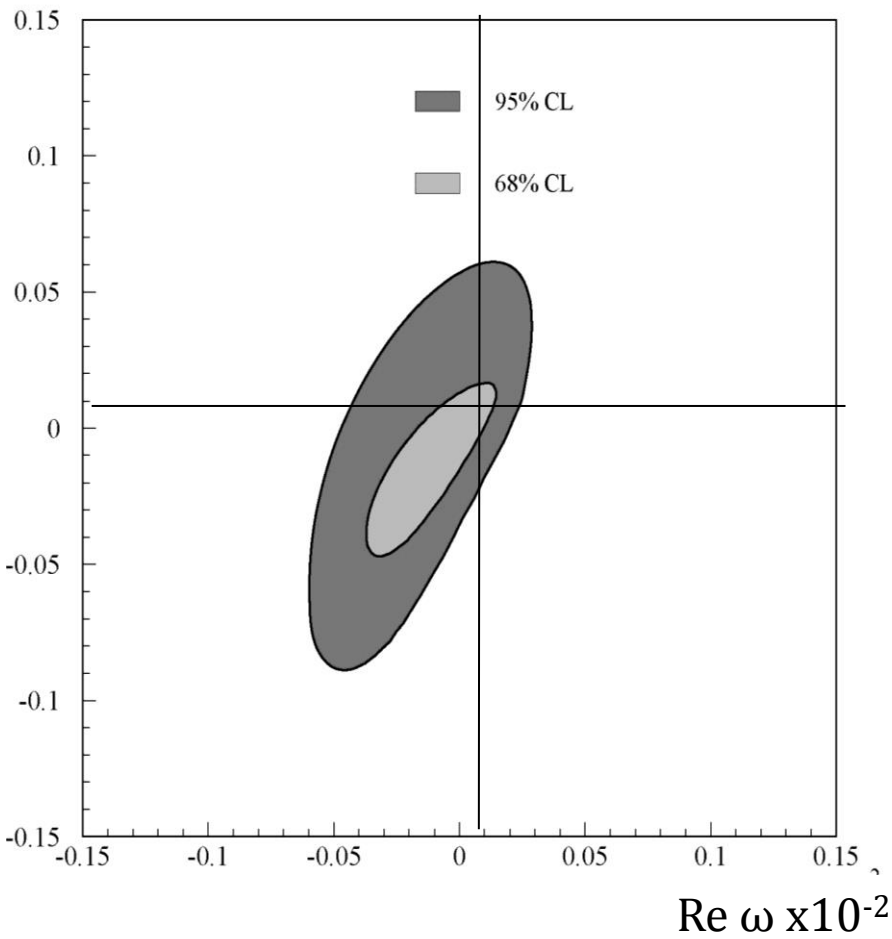
- ○ sensitivity with the present KLOE resolution ($\sigma(\Delta t) \approx \tau_S$)
- ● sensitivity with improved resolution ($\sigma(\Delta t) \approx 0.3\ \tau_S$ expected)



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

PRESENT KLOE

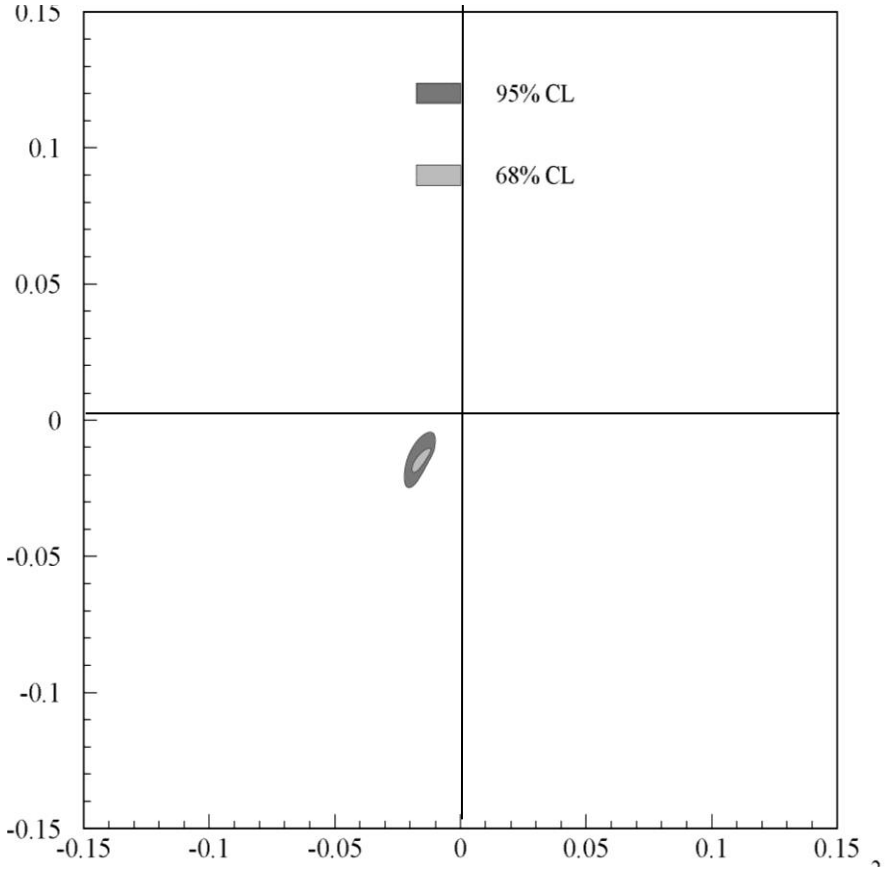
Im ω x10^{-2}



Re ω x10^{-2}

ACHIEVABLE AT KLOE-2

Im ω x10^{-2}



Re ω x10^{-2}