Kaon Physics with KLOE/KLOE-2

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on behalf of the KLOE-2 collaboration

International Symposium Lepton and Hadron Physics at Meson - Factories
Messina, 13-15 October 2013

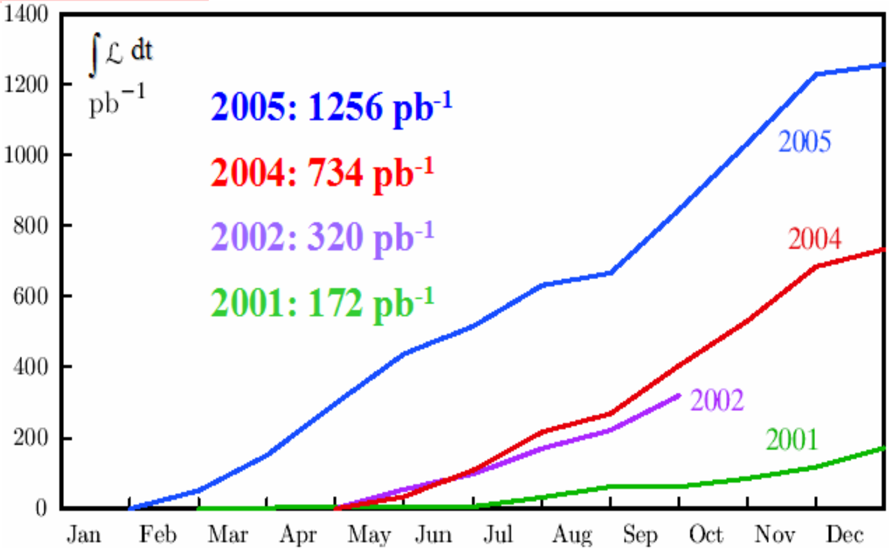
DAΦNE: the Frascati ϕ-factory

KLOE run (2001-2005):
Daily performance: $\int L\,dt$ 7-8 pb^{-1}
Peak L ~ $1.5\ 10^{32}$ $cm^{-2}s^{-1}$
Total KLOE $\int L\,dt$ ~ 2.4 fb^{-1} at ϕ mass peak + 250 pb^{-1} off peak (@ 1 GeV)

BR's for Φ decays	
K^+K^-	49.1%
K_SK_L	**34.1%**
$\rho\pi + \pi^+\pi^-\pi^0$	15.5%
$\eta\gamma$	1.31%

→ ~2.5×10^9 K_SK_L pairs
→ ~3.6×10^9 K^+K^- pairs
→ ~10^8 η' s

- e^+e^- collider @ $\sqrt{s} = M_\phi = 1019.4$ MeV
- LAB momentum p_ϕ ~ 13 MeV/c
- σ_{peak} ~ 3 μb
- Separate e^+e^- rings to reduce beam-beam interaction
- Beams crossing angle: 12.5 mrad



KLOE results in kaon physics

- ➢ **KLOE has measured all relevant parameters for charged and neutral kaons: BR's, lifetimes, form factors**
- ➢ **SM test in the flavor sector** through precise measurements of V_{us} and $R_K = \Gamma(K \to e\nu) / \Gamma(K \to \mu\nu)$
- ➢ **CPT and quantum mechanics tests** with the analysis of the QM interference of neutral kaons, K_s semileptonic decays, unitary (Bell-Steinberger relation)
- ➢ **Recent results and ongoing analysis**

✓ K_S regeneration

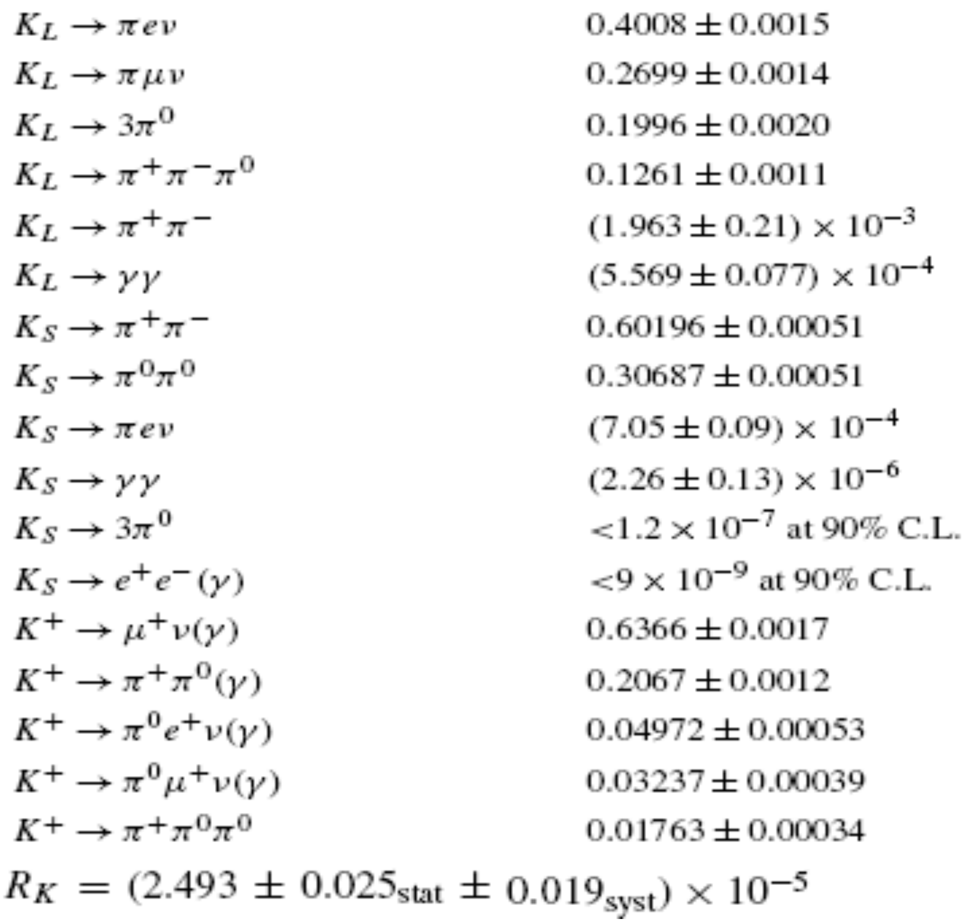
✓ K_S semilep asym.

✓ ……….

✓ $K^+ \to \pi^+\pi^+\pi^-$

✓ $K_S \to \pi^0\pi^0\pi^0$

✓ $K_SK_L \to \pi^+\pi^-\pi^+\pi^-$ (test of CPT and Lorentz symmetry)



$K_L \to \pi e \nu$	0.4008 ± 0.0015
$K_L \to \pi \mu \nu$	0.2699 ± 0.0014
$K_L \to 3\pi^0$	0.1996 ± 0.0020
$K_L \to \pi^+\pi^-\pi^0$	0.1261 ± 0.0011
$K_L \to \pi^+\pi^-$	$(1.963 \pm 0.21) \times 10^{-3}$
$K_L \to \gamma\gamma$	$(5.569 \pm 0.077) \times 10^{-4}$
$K_S \to \pi^+\pi^-$	0.60196 ± 0.00051
$K_S \to \pi^0\pi^0$	0.30687 ± 0.00051
$K_S \to \pi e \nu$	$(7.05 \pm 0.09) \times 10^{-4}$
$K_S \to \gamma\gamma$	$(2.26 \pm 0.13) \times 10^{-6}$
$K_S \to 3\pi^0$	$<1.2 \times 10^{-7}$ at 90% C.L.
$K_S \to e^+e^-(\gamma)$	$<9 \times 10^{-9}$ at 90% C.L.
$K^+ \to \mu^+\nu(\gamma)$	0.6366 ± 0.0017
$K^+ \to \pi^+\pi^0(\gamma)$	0.2067 ± 0.0012
$K^+ \to \pi^0 e^+ \nu(\gamma)$	0.04972 ± 0.00053
$K^+ \to \pi^0 \mu^+ \nu(\gamma)$	0.03237 ± 0.00039
$K^+ \to \pi^+\pi^0\pi^0$	0.01763 ± 0.00034

$$R_K = (2.493 \pm 0.025_{\mathrm{stat}} \pm 0.019_{\mathrm{syst}}) \times 10^{-5}$$

$\tau_L = 50.92 \pm 0.17_{\mathrm{stat}} \pm 0.25_{\mathrm{syst}}$ [ns]

$\tau_{+/-} = 12.347 \pm 0.030$ [ns]

$|V_{us}| = 0.2253 \pm 0.0007$ JHEP04(2008)059

$\tau_S = 89.562 \pm 0.029_{\mathrm{stat}} \pm 0.043_{\mathrm{syst}}$ [ps] EPJC71,1604

$K_S \to 3\pi^0$ $< 2.6 \times 10^{-8}$ at 90% C.L. PLB723,54

Measurement of BR($K^+ \rightarrow \pi^+\pi^-\pi^+(\gamma)$)

Measurement of absolute BR($K^+\to\pi^+\pi^-\pi^+(\gamma)$)

- *this measurement completes the KLOE program of precise and fully inclusive of FSR $K^\pm$ dominant BR's*
- *this BR enters in the CUSP analysis to extract the $\pi\pi$ phase shift done by NA48,* **PLB 633 (2006)**
- *needed to perform a global fit to $K^\pm$ BR's*

lifetime and absolute BRs by KLOE

(dBR/d$\tau^\pm$ and correlations available)

$K^+\to\mu\nu$	**0.6366(18)**	**0.3%**	*PLB 632(2006)*
$K^+\to\pi^+\pi^0$	**0.2065(9)**	**0.5%**	*PLB 666(2008)*
$K^\pm\to\pi^0 e^\pm\nu$	**0.0497(5)**	**1.0%**	*JHEP 02(2008)*
$K^\pm\to\pi^0\mu^\pm\nu$	**0.0324(4)**	**1.2%**	*JHEP 02(2008)*
$K^\pm\to\pi^\pm\pi^0\pi^0$	**0.0176(3)**	**1.7%**	*PLB 597(2004)*
$\tau^\pm$	**12.347(30) ns**	**0.24%**	*JHEP 01 (2008)*

PLB 666 (2008)

BR($K^\pm\to\pi^\pm\pi^+\pi^-$)= 0.0568(22)

from $(1-\Sigma\mathrm{BR}_{\mathrm{KLOE}})$

Flavianet fit '010 BR($K\to\pi^+\pi^-\pi^+$) = (5.73 ± 0.16)% $\Delta\mathrm{BR}/\mathrm{BR} = 2.7\mathrm{x}10^{-2}$

EPJC 69 (2010) 399

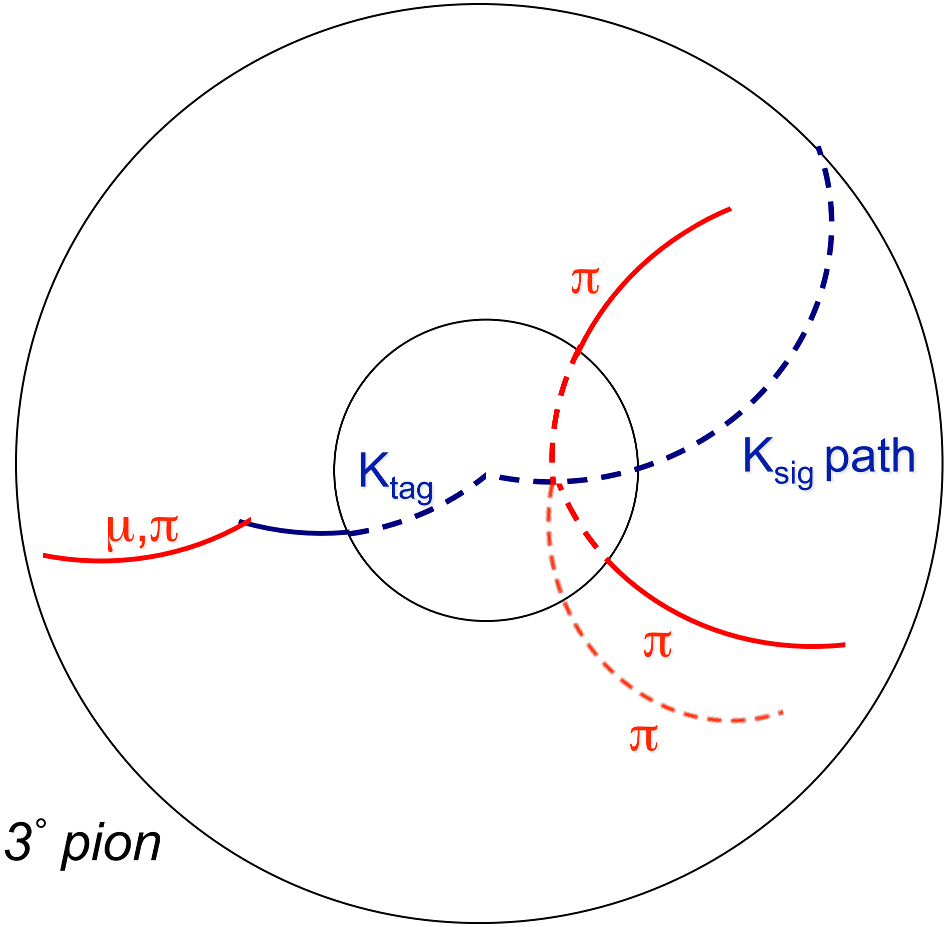
available measurement dates back to 72' (no informations on radiation cut-off)

CHIANG (2330 evts) BR($K\to\pi^+\pi^-\pi^+$) = (5.56 ± 0.20)% $\Delta\mathrm{BR}/\mathrm{BR} = 3.6\mathrm{x}10^{-2}$

PRD 6 (1972) 1254

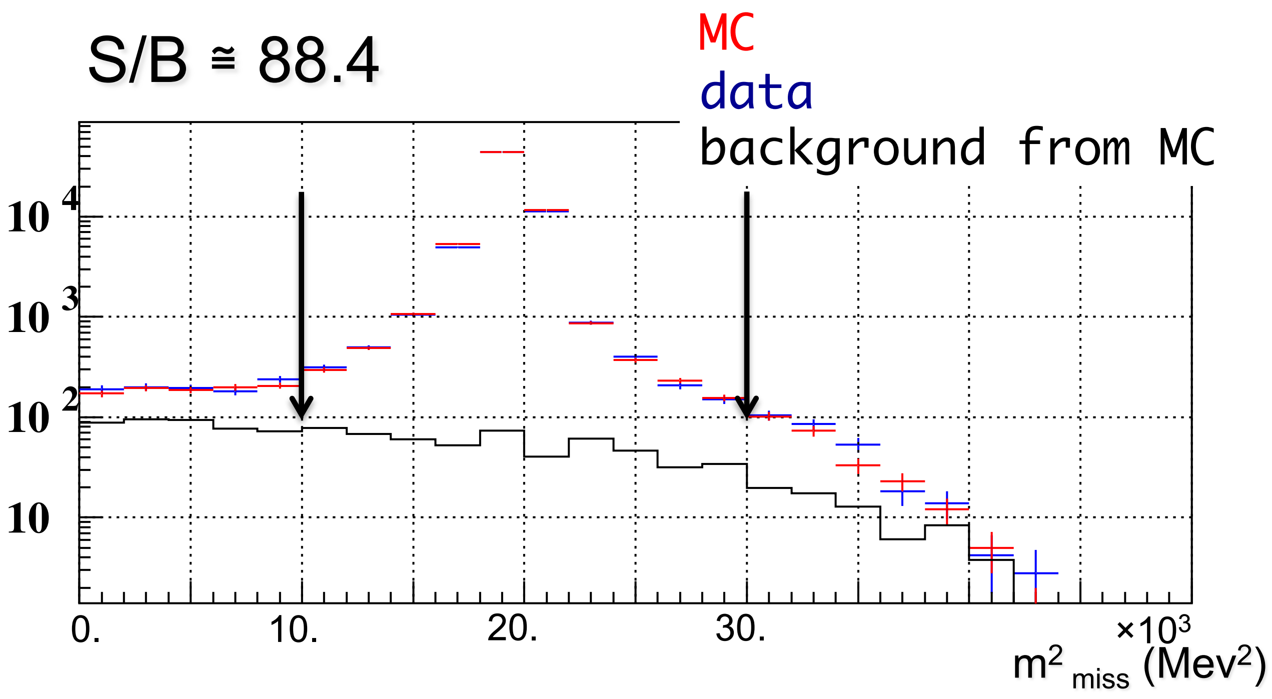
BR($K^+ \rightarrow \pi^+\pi^-\pi^+(\gamma)$): analysis strategy

- triggering $\mu^-\nu$ tag on one side
- the expected path of the signal K is given by the tag K track backward extrapolated to the I.P.
- in the signal hemisphere we require two reconstructed tracks making a vertex along the K path *before the inner wall of the DC* (R^{DC}_{inner} = 25 cm, $\alpha_{GEO} \cong$ 26 %)
- signal ➔ *missing mass spectrum of the 3° pion*
- *selection efficiency* measured on MC, and corrected using data&MC control samples



BR($K^+ \rightarrow \pi^+\pi^-\pi^+(\gamma)$): analysis strategy

- tracks backward extrapolated with Distance of Closest Approach to tagged K track, DCA < 3. cm
- Distance of Closest Approach between two selected tracks, DCA$_{tt}$ < 3. cm
- track momentum in K rest frame, p*(m_π) < 190. MeV/c to remove 2 bodies decays
- ρ_{xy} < 24. cm
- NO charge requirements
- opening angle between the two selected tracks ➔ $|\cos(\theta_{12})|<0.90$



- *fit of the missing mass spectrum using the MC signal and background shapes*

N(K^+ -> 3π)	χ^2/ndf	$\mathcal{P}(\chi^2$/ndf)
45054 ± 212	47.6/45	.36

BR($K^+ \to \pi^+\pi^-\pi^+(\gamma)$): result

$$BR(K^+ -> \pi^+\pi^-\pi^+) = \frac{N_{K->3\pi}}{N_{tag}} \times \frac{1}{\varepsilon_{sel} C_{TB} C_f C_{crv}}$$

sel. eff. ($K^+ -> \pi^- X$ control sample)

tag bias correction (MC)

machine bck filter correction and cosmic veto correction

tag $K^- -> \mu^- \bar{\nu}$

using 174 pb^{-1} of the KLOE data sample

KLOE preliminary

$BR(K^+ -> \pi^+\pi^-\pi^+(\gamma)) = (0.05526 \pm 0.00035_{stat} \pm 0.00036_{syst})$, $\Delta BR/BR = 9.2 \times 10^{-3}$

CHIANG (2330 evts) BR($K \to \pi^+\pi^-\pi^+$) = (5.56 ± 0.20)% $\Delta BR/BR = 3.6 \times 10^{-2}$
PRD 6 (1972) 1254

KLOE (1-ΣBR) '08 BR($K \to \pi^+\pi^-\pi^+$) = (5.68 ± 0.22)% $\Delta BR/BR = 3.8 \times 10^{-2}$
PLB 666 (2008)

Flavianet fit '010 BR($K \to \pi^+\pi^-\pi^+$) = (5.73 ± 0.16)% $\Delta BR/BR = 2.7 \times 10^{-2}$
EPJC 69 (2010) 399

Search for CP violation in K_S decay

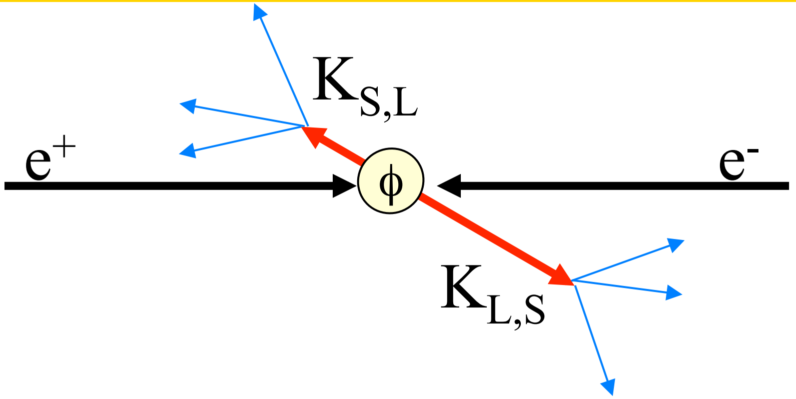
Neutral kaons at a ϕ-factory

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
- $BR(\phi \to K^0\overline{K}^0) \sim 34\%$
- $\sim 10^6$ 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



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

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

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

$K_S \to \pi^0\pi^0\pi^0$: a pure CP violating decay

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

$$|K_S\rangle = \frac{1}{\sqrt{(1+|\varepsilon_S|)}}\left[|K_1\rangle + \varepsilon_S|K_2\rangle\right] \qquad |K_L\rangle = \frac{1}{\sqrt{(1+|\varepsilon_L|)}}\left[|K_2\rangle + \varepsilon_L|K_1\rangle\right]$$

$$\boxed{\varepsilon_S = \varepsilon + \delta} \qquad \boxed{\varepsilon_L = \varepsilon - \delta}$$

(δ: CPT viol.)

$3\pi^0$ is a pure CP=-1 state; observation of $K_S \to 3\pi^0$ is an unambiguous sign of CP violation in mixing and/or in decay.

$$\eta_{000} = \frac{\langle \pi^0\pi^0\pi^0|T|K_S\rangle}{\langle \pi^0\pi^0\pi^0|T|K_L\rangle} = \varepsilon_S + \varepsilon'_{000}$$

$$|\eta_{000}| = \sqrt{\frac{\tau_L}{\tau_S}\frac{BR(K_S \to 3\pi^0)}{BR(K_L \to 3\pi^0)}}$$

to lowest order in χPT [PRD21,178 (1980)]:

$$\varepsilon'_{000} = -2\varepsilon'$$

Standard Model prediction:

$BR(K_S \to 3\pi^0) = 1.9 \cdot 10^{-9}$

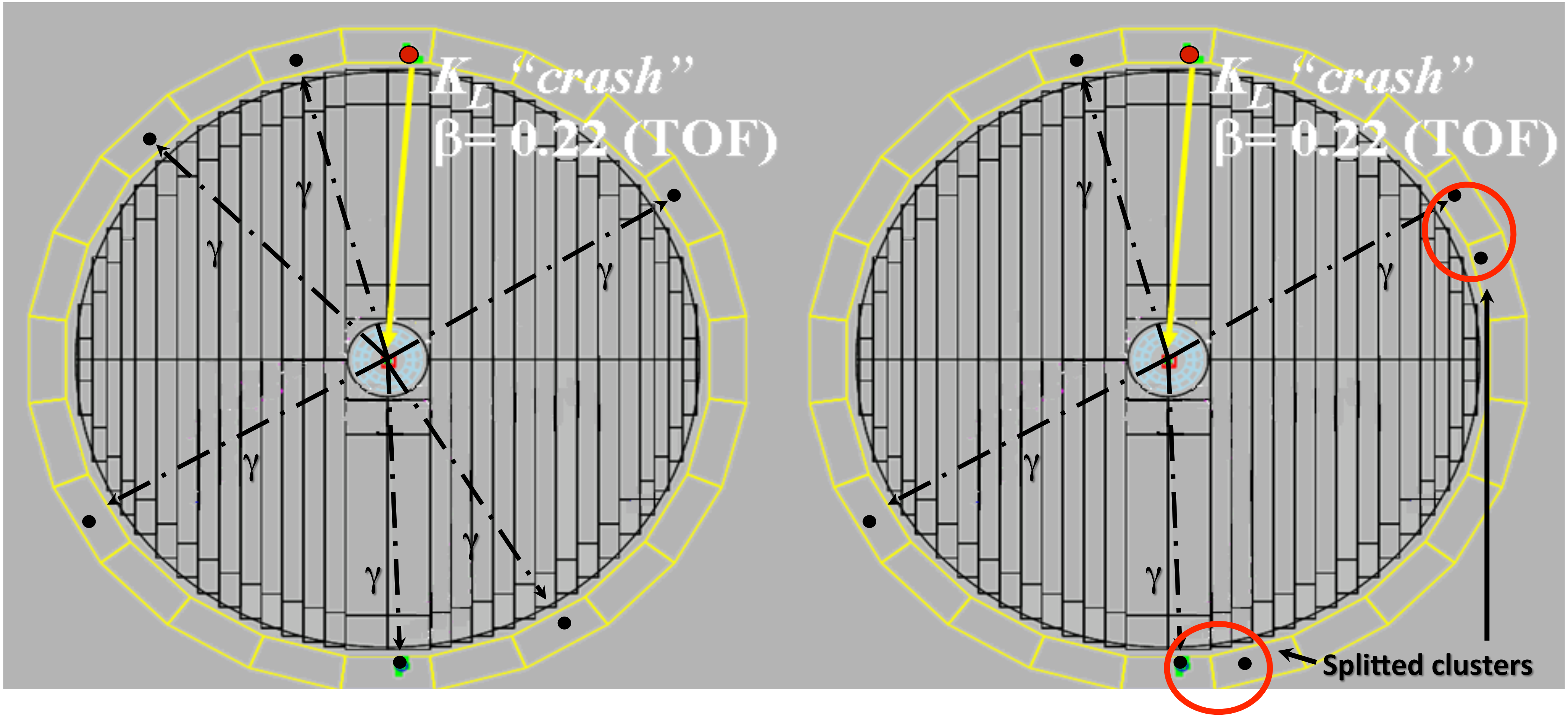
SND 1999: $BR(K_S \to 3\pi^0) < 1.4 \cdot 10^{-5}$

NA48 2004: $BR(K_S \to 3\pi^0) < 7.4 \cdot 10^{-7}$

KLOE 2005: $BR(K_S \to 3\pi^0) < 1.2 \cdot 10^{-7}$

$K_S \to \pi^0\pi^0\pi^0$: analysis strategy

SIGNAL **BACKGROUND**



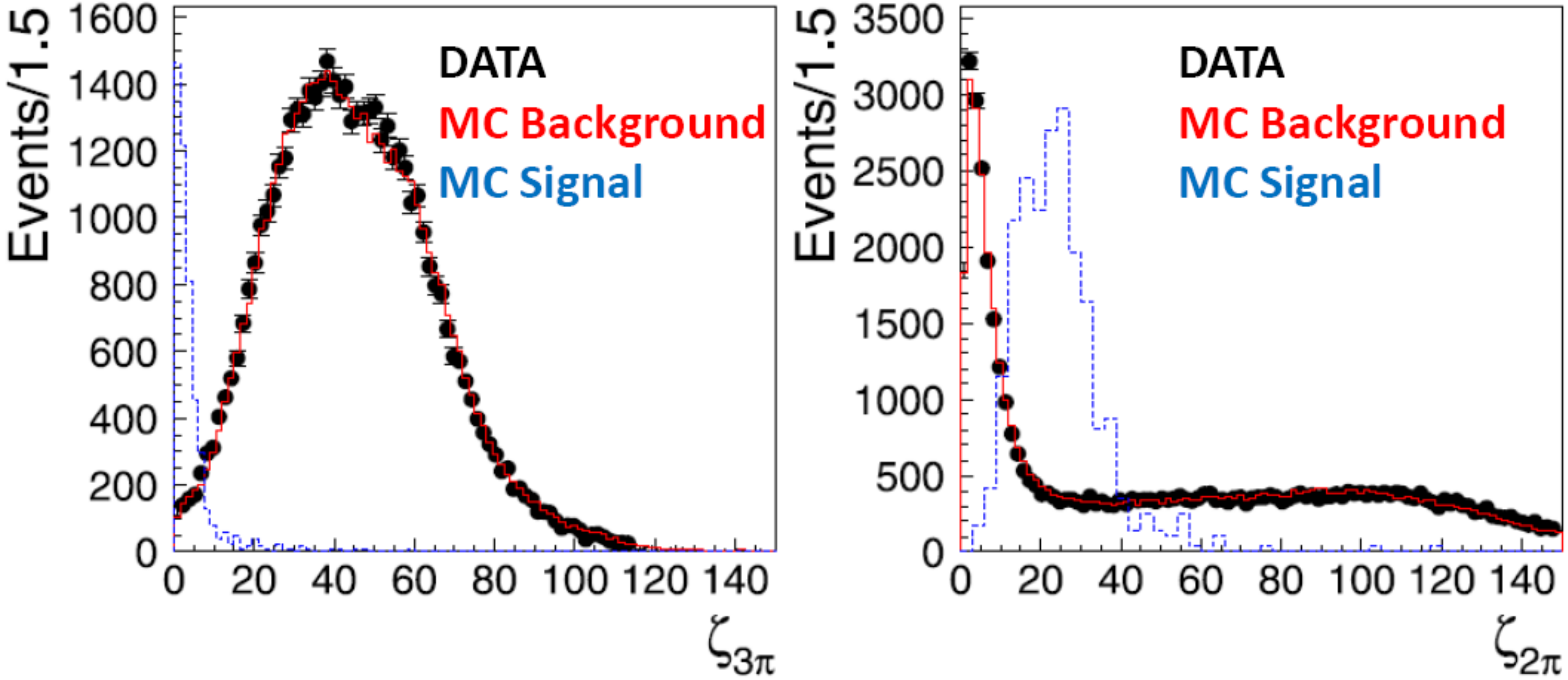
$K_S \to 3\pi^0 \to 6\gamma$

$K_S \to 2\pi^0$ + accidental/splitted clusters

$K_L \to 3\pi^0$, $K_S \to \pi^+ \pi^-$ („fake K_L-crash")

$K_S \rightarrow \pi^0\pi^0\pi^0$: analysis strategy

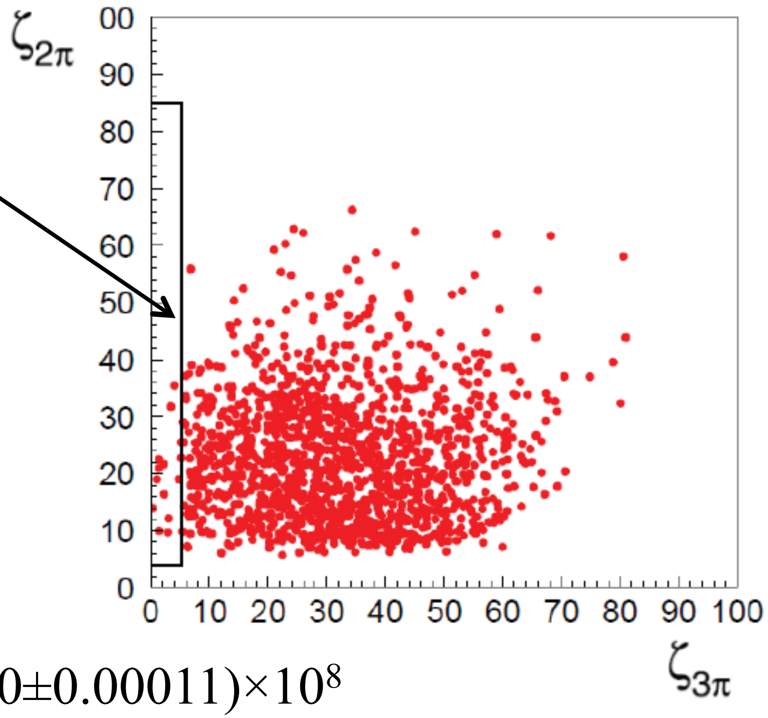
- The previous KLOE analysis has been updated:
  - improving clustering procedure to reduce split clusters
  - hardening the $\beta^*(K_L)$ cut for tagging the Ks decays
  - 1.7 fb^{-1} KLOE entire data set (~1.7×10^9 K_SK_L pairs)
- 6 prompt γ's required
- Reject background with χ^2-like variables ($\zeta_{2\pi}$, $\zeta_{3\pi}$) in the $3\pi^0$ and $2\pi^0$ hypothesis ($2\pi^0$ hyp.: selecting 4 γ consistent with E,p conservation)

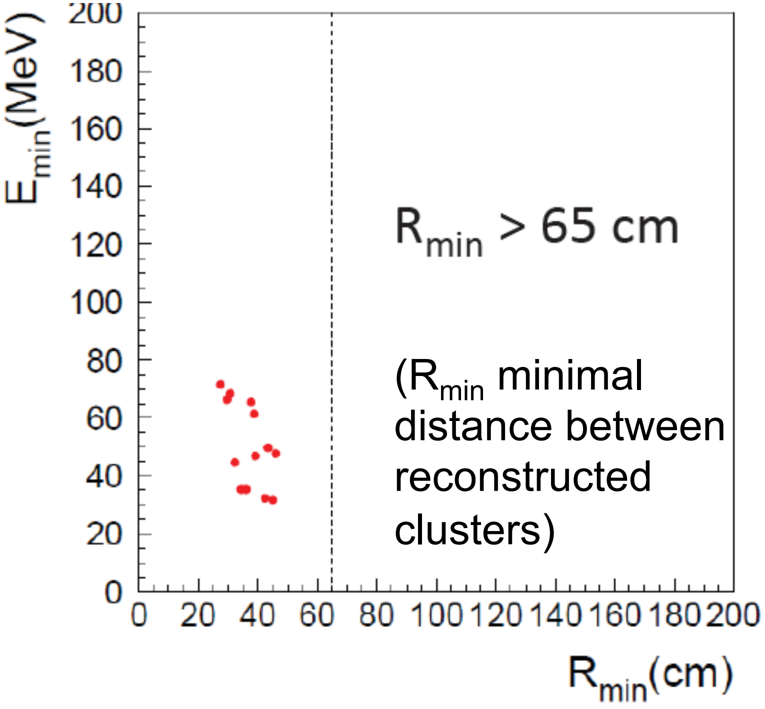


$K_S \to \pi^0\pi^0\pi^0$: result

- N_{obs} =0 evts. in data ; N_{MC}=0 evts. in MC ; N_{SM}=0.12 evts expected in SM

- signal box
- $R_{min} > 65$ cm
- $\varepsilon_{3\pi} = 0.23(1)$





$R_{min} > 65$ cm

(R_{min} minimal distance between reconstructed clusters)

- $N_{3\pi^0} \leq 2.33/\varepsilon_{3\pi^0}$ at 90% C.L.
- Normalized to $N_{2\pi^0}/\varepsilon_{2\pi^0}=(1.14130\pm0.00011)\times10^8$

FINAL KLOE RESULT

$BR(K_S \to 3\pi^0) < 2.6 \times 10^{-8}$ @ 90% CL

$|\eta_{000}| < 0.0088$ @ 90% CL

PLB 723 (2013) 54   x5 improvement on U.L. and x2 on |η| wrt KLOE(2005)

This result points to the feasibility of the first observation at KLOE-2 (BR_{SM}~1.9×10^{-9})

CPT and Lorentz invariance test with entangled neutral kaons

CPT and Lorentz invariance violation (SME)

- CPT theorem (Luders, Jost, Pauli, Bell 1955 -1957):

Exact CPT invariance holds for any quantum field theory which assumes:
(1) Lorentz invariance (2) Locality (3) Unitarity (i.e. conservation of probability).

- “Anti-CPT theorem” (Greenberger 2002):

Any unitary, local, point-particle quantum field theory that violates CPT invariance necessarily violates Lorentz invariance.

- 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:

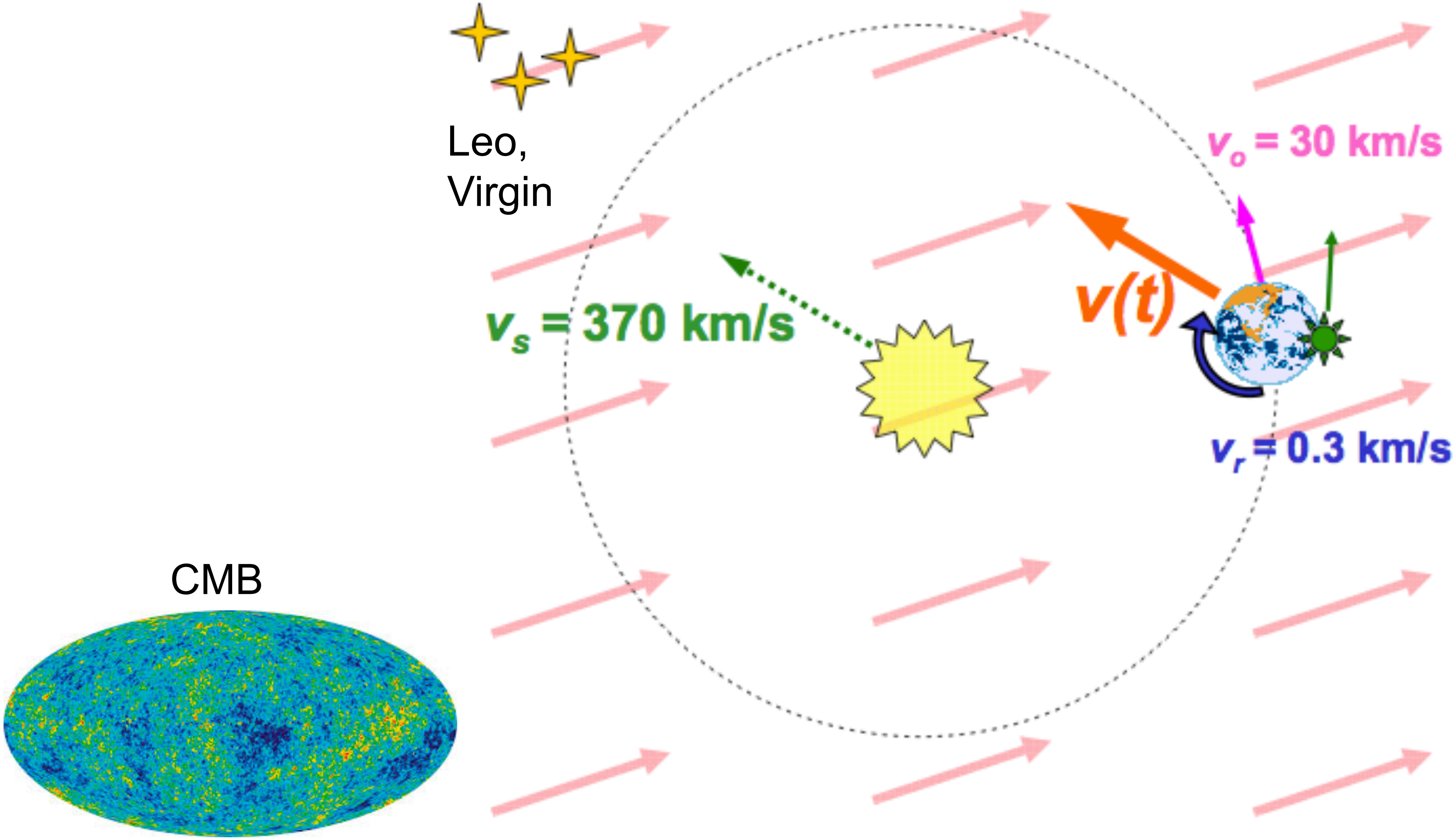
- At first order CPTV appears only in mixing parameter δ (no direct CPTV in decay)
- δ cannot be a constant (momentum dependence)

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

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

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

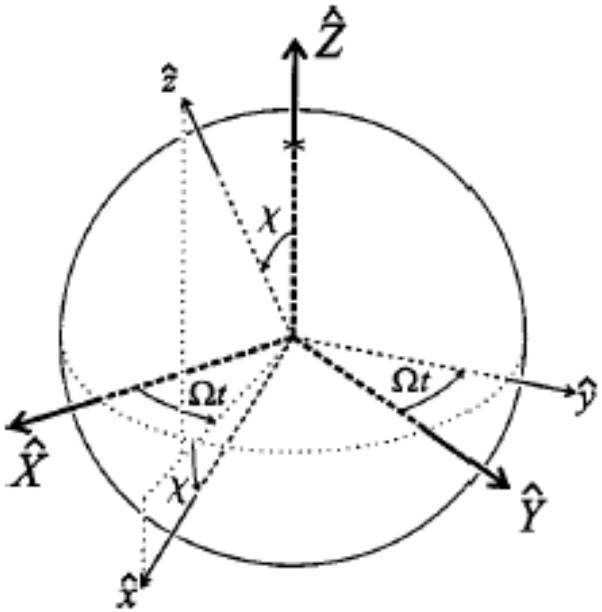
The Earth as a moving laboratory



Search for CPT and Lorentz invariance violation (SME)

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

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)

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

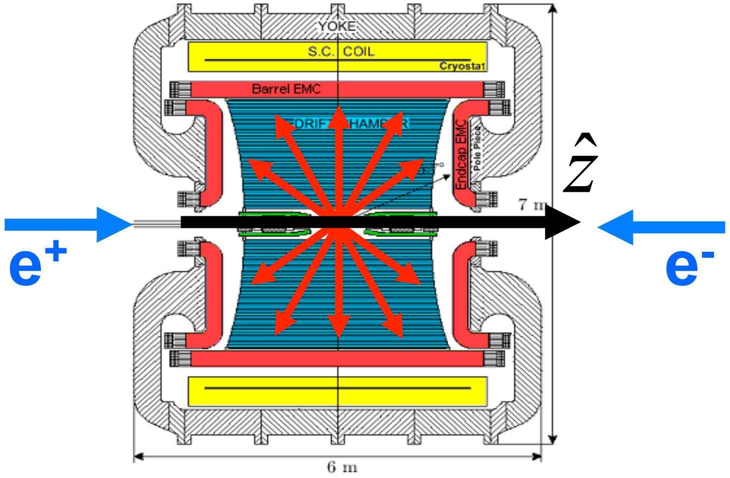
Ω: Earth’s sidereal frequency   χ : angle between the z lab. axis and the Earth’s rotation axis

Search for CPT and Lorentz invariance violation (SME)

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

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/dΩ ∝ $\sin^2\theta$



$$\delta(\vec{p},t) = \frac{i\sin\phi_{SW} e^{i\phi_{SW}}}{\Delta m}\gamma_K \Big\{ \underline{\Delta a_0}$$

$$+\beta_K \underline{\Delta a_Z}\left(\cos\theta\cos\chi - \sin\theta\sin\phi\sin\chi\right)$$

$$+\beta_K\left[-\underline{\Delta a_X}\sin\theta\sin\phi + \underline{\Delta a_Y}\left(\cos\theta\sin\chi + \sin\theta\cos\phi\cos\chi\right)\right]\sin\Omega t$$

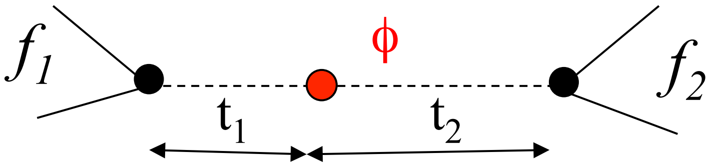
$$+\beta_K\left[+\underline{\Delta a_Y}\sin\theta\sin\phi + \underline{\Delta a_X}\left(\cos\theta\sin\chi + \sin\theta\cos\phi\cos\chi\right)\right]\cos\Omega t\Big\}$$

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

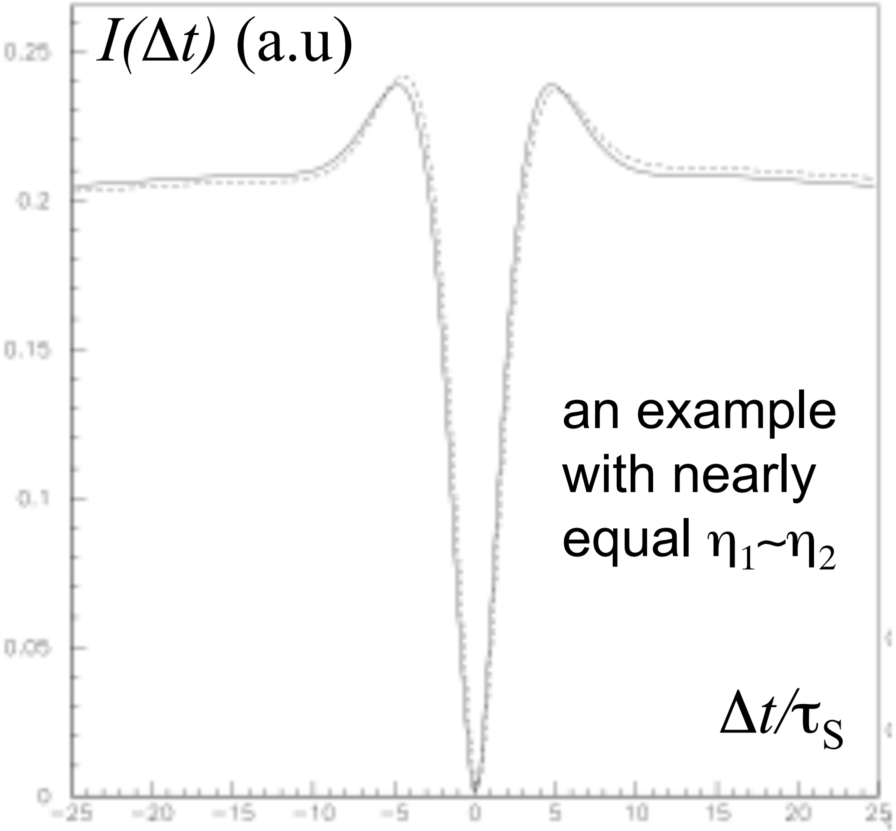
Search for CPTV and LV: exploiting EPR correlations

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

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



$\Delta t = t_1 - t_2$



an example with nearly equal $\eta_1 \sim \eta_2$

Search for CPTV and LV: exploiting EPR correlations

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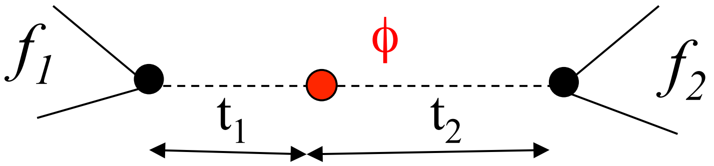
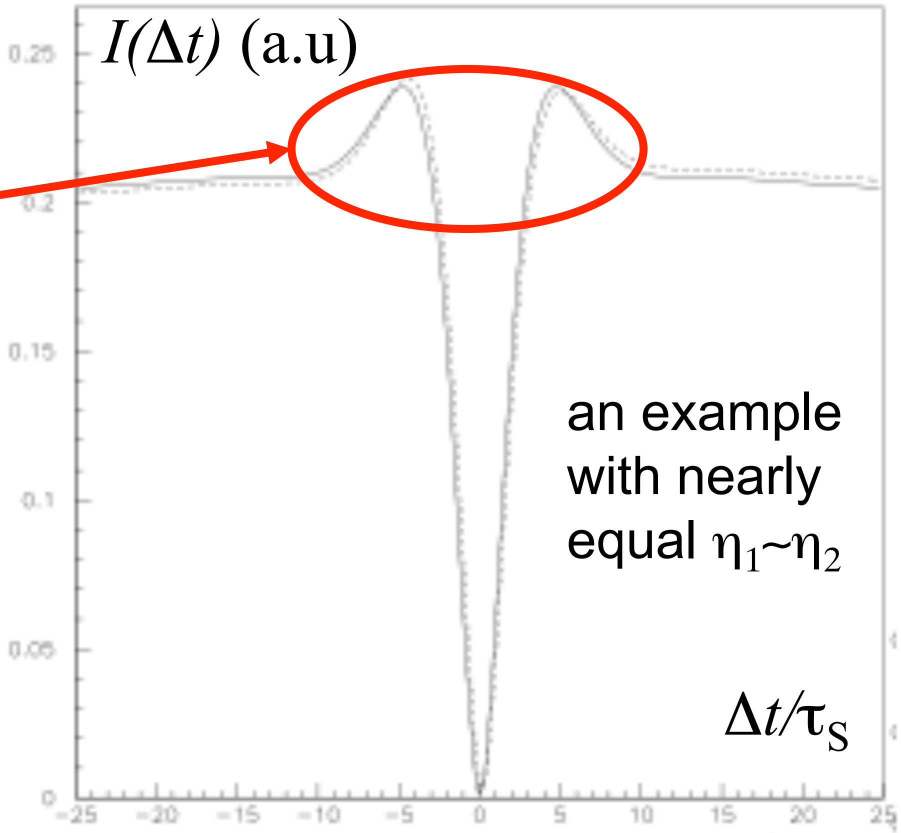


$\Delta t = t_1 - t_2$

η_2/η_1
from the asymmetry at **small** Δt



an example with nearly equal $\eta_1 \sim \eta_2$

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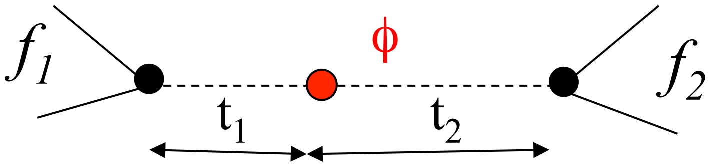
$$\eta_i = |\eta_i| e^{i\phi_i} = \langle f_i|T|K_L\rangle / \langle f_i|T|K_S\rangle$$

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

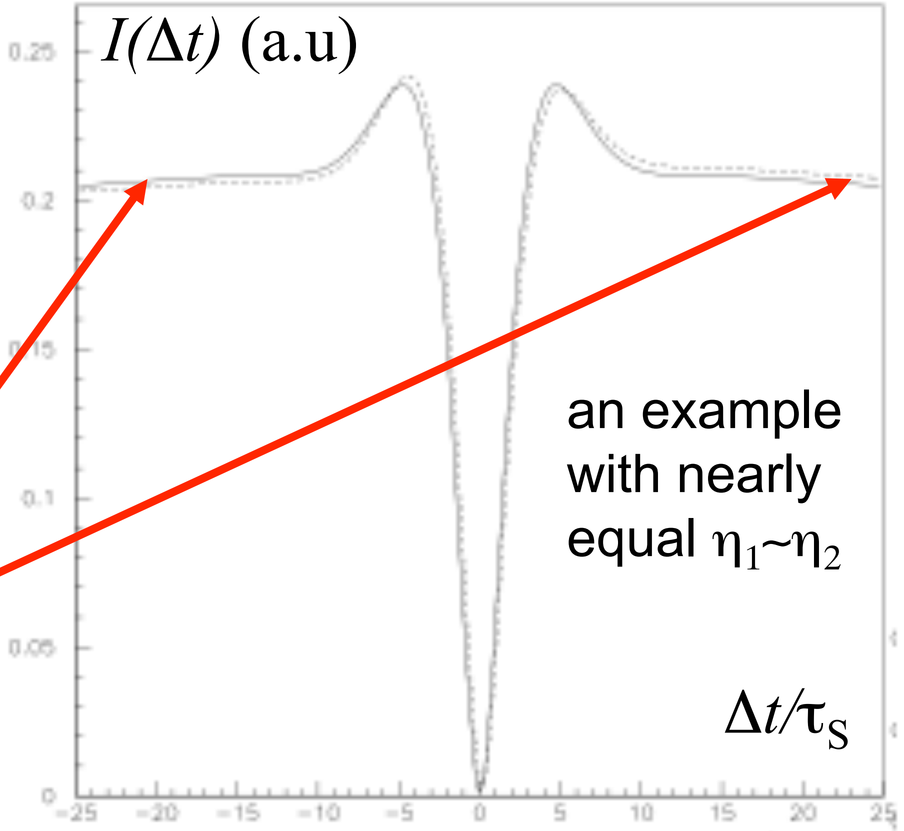


$\Delta t = t_1 - t_2$

η_2/η_1
from the asymmetry at **small** Δt

$|\eta_2/\eta_1|^2$

from the asymmetry at **large** Δt

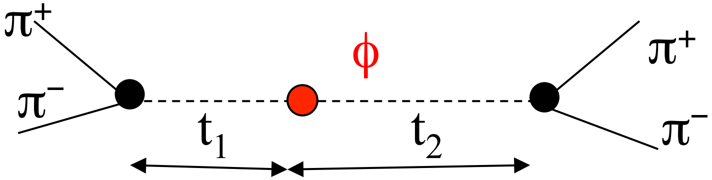


an example with nearly equal $\eta_1 \sim \eta_2$

Search for CPTV and LV: exploiting EPR correlations

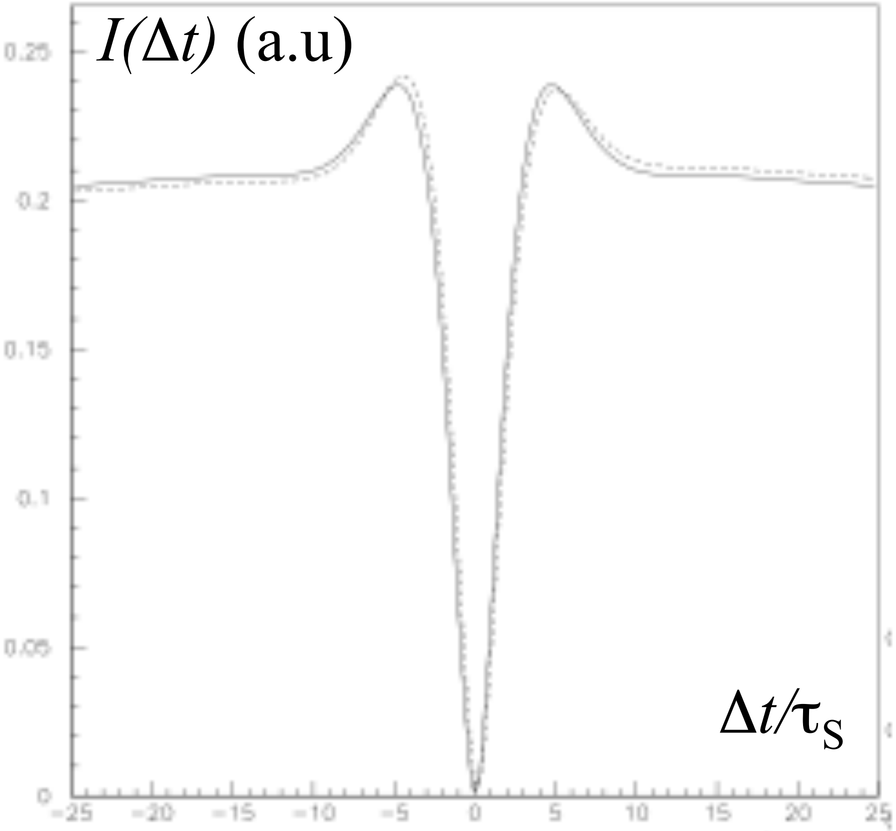
$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle|\bar{K}^0\rangle - |\bar{K}^0\rangle|K^0\rangle\right] \qquad \eta_i = |\eta_i|e^{i\phi_i} = \langle f_i|T|K_L\rangle / \langle f_i|T|K_S\rangle$$

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



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

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



Search for CPTV and LV: exploiting EPR correlations

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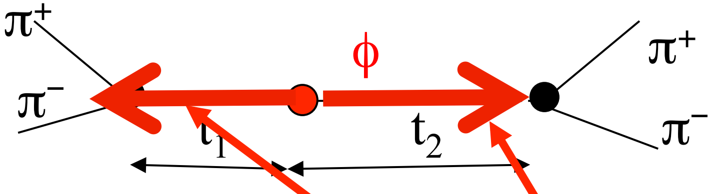

$$\eta^{(1)}_{+-} = \varepsilon\left(1 - \delta(+\vec{p},t)/\varepsilon\right)$$

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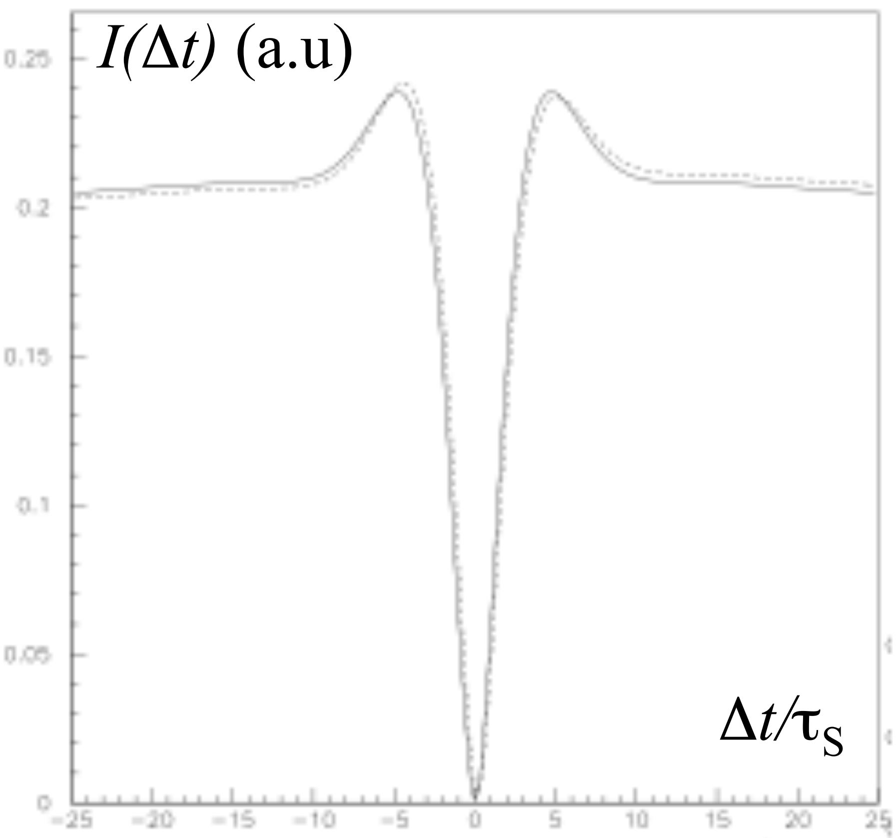

Search for CPTV and LV: exploiting EPR correlations

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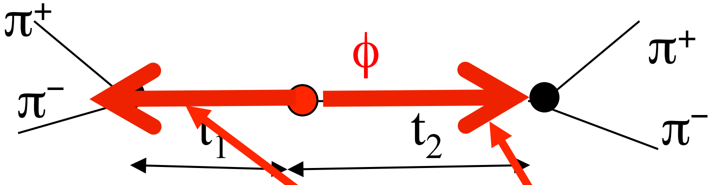
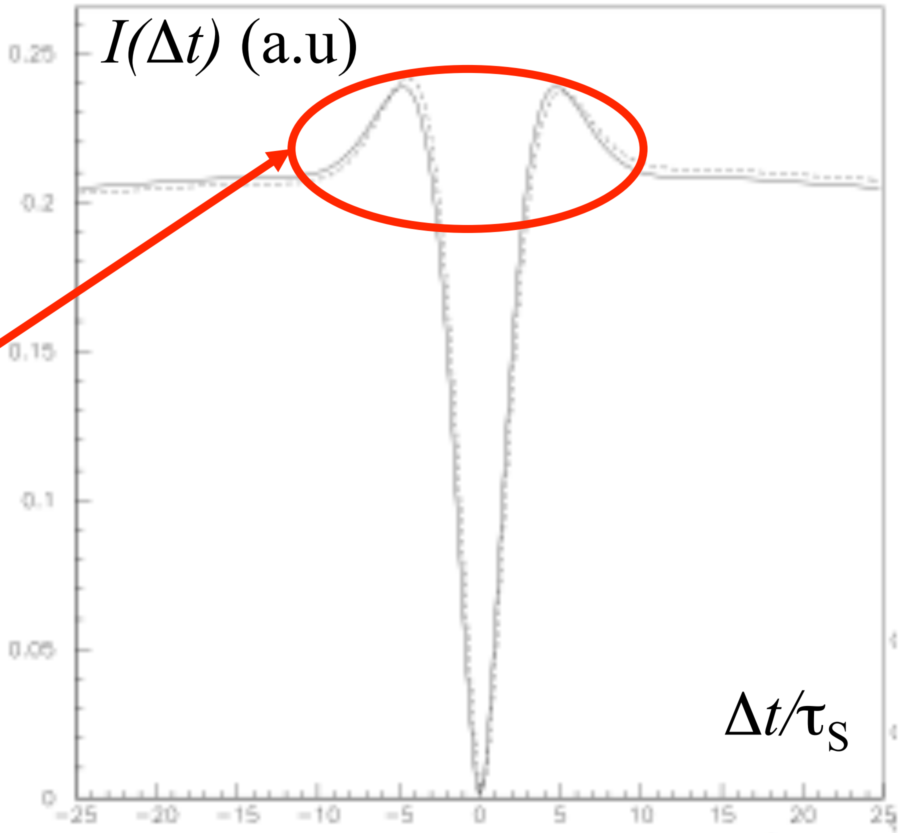


$$\eta^{(1)}_{+-} = \varepsilon\left(1 - \delta(+\vec{p},t)/\varepsilon\right)$$

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

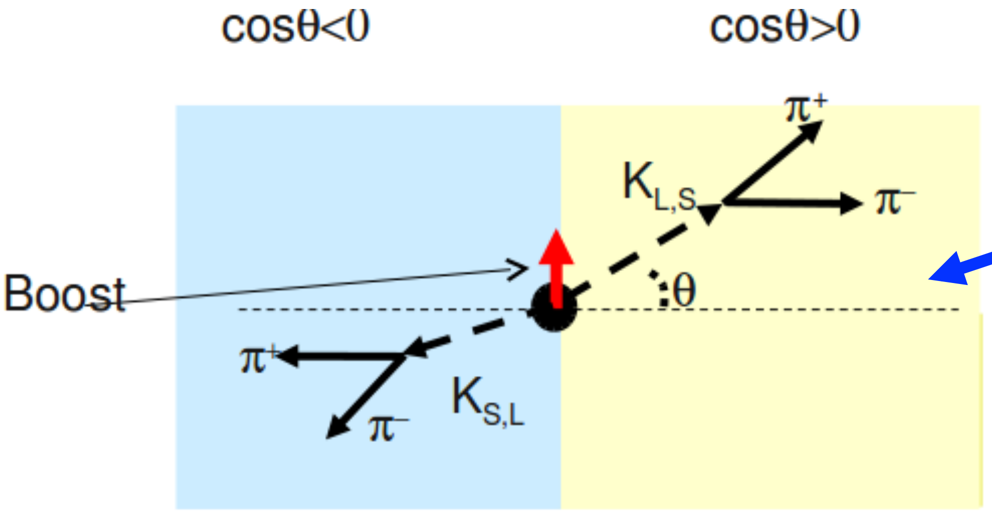
$\Im(\delta/\varepsilon)$
from the asymmetry at **small** Δt

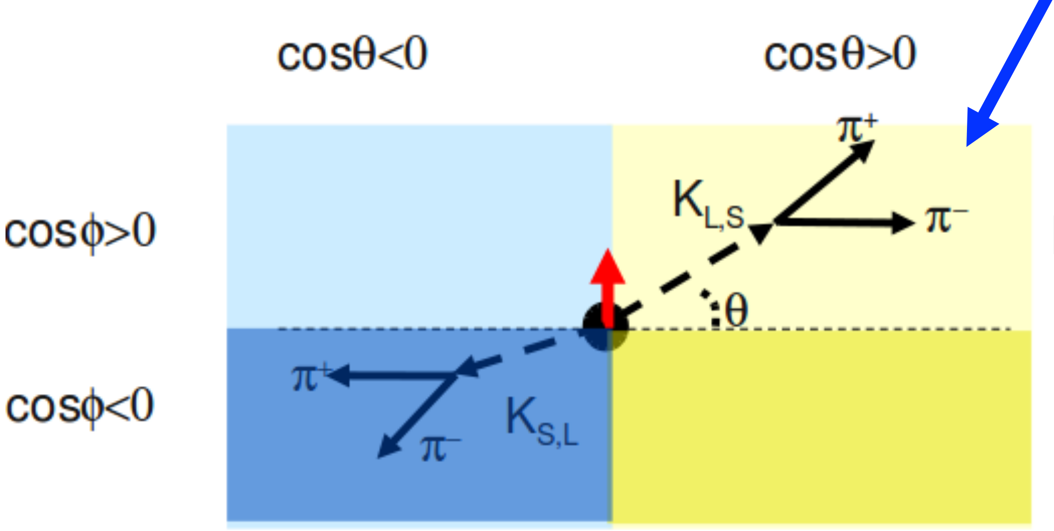
$\Re(\delta/\varepsilon) \approx 0$ because $\delta \perp \varepsilon$
from the asymmetry at **large** Δt



Search for CPTV and LV: analysis strategy

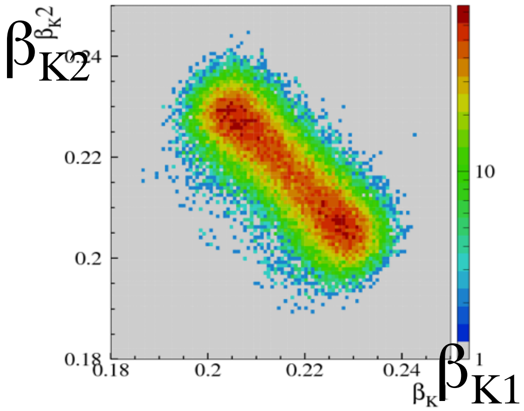
$$\boxed{\delta = i\sin\phi_{SW} e^{i\phi_{SW}}\gamma_K\left(\Delta a_0 - \vec{\beta}_K\cdot\Delta\vec{a}\right)/\Delta m}$$



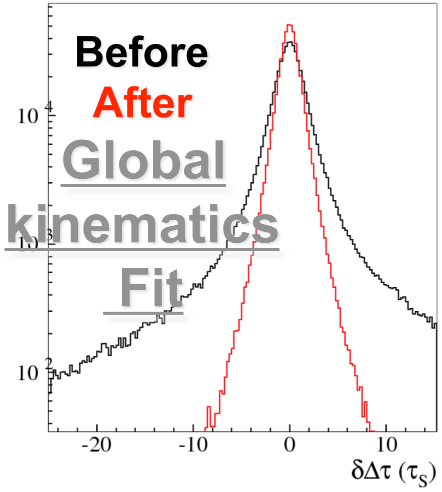


Possible effects due to Δa_0 are washed out in the simple forward – backward analysis (integration in ϕ).

The quadrant analysis (ϕ momentum ➔ kaons with different γ factors: $\gamma_{K1} \neq \gamma_{K2}$) recovers sensitivity to Δa_0



Δt resolution



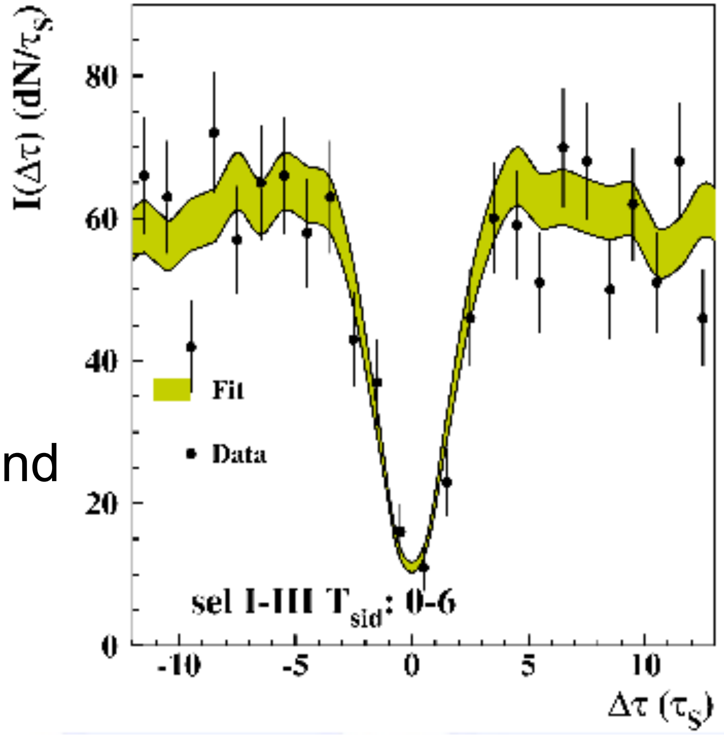
Search for CPTV and LV: results

Data divided in
4 sidereal time bins
x 2 angular bins

Simultaneous fit of the Δt distributions to extract Δa_μ parameters

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

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



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

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

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

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

$\chi^2 = 211/184$ (P=8%)
Fit error includes:
-Data/MC eff. correction (~2%)
(Kμ_3 control sample)
- single bin MC efficiency (~5%)

Search for CPTV and LV: results

Data divided in
4 sidereal time bins
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Simultaneous fit of the Δt distributions to extract Δa_μ parameters

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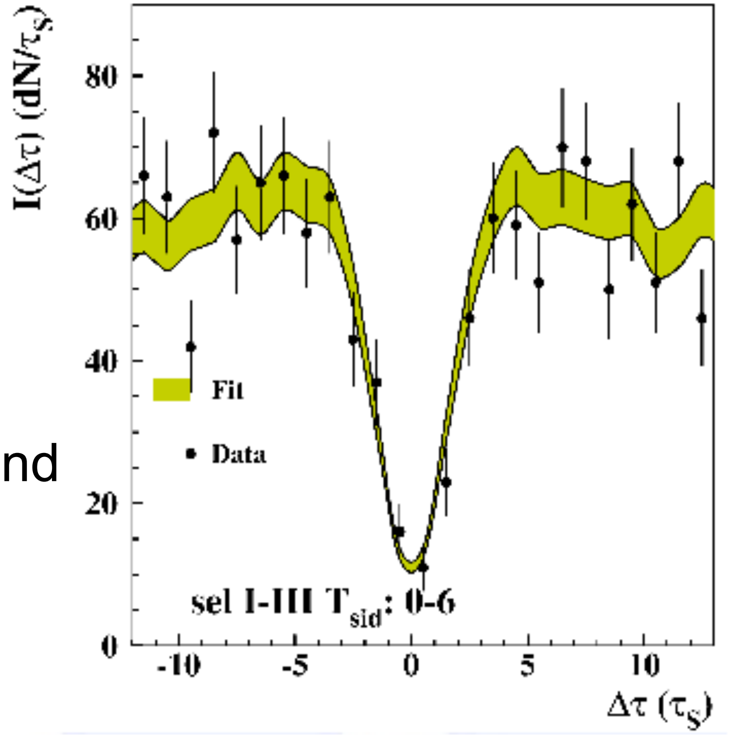

$$\Delta a_0 = \left(-6.0 \pm 7.7_{STAT} \pm 3.1_{SYST}\right) \times 10^{-18} \ \text{GeV}$$

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Par	Cut stability	Fit Range	Bkg. subtr	KLOE ref. frame	**Total**
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**

Perspectives and Conclusions

Prospects for KLOE-2 at upgraded DAΦNE

Param.	Present best published measurement	KLOE-2 L=5 fb^{-1}	KLOE-2 L=10 fb^{-1}	KLOE-2 L=20 fb^{-1}
$BR(K_S \to 3\pi^0)$	$< 2.6 \times 10^{-8}$	$< 0.9 \times 10^{-8}$	$< 4 \times 10^{-9}$	$< 2 \times 10^{-9}$ - 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	$(332.2 \pm 5.8 \pm 4.7) \times 10^{-5}$	$\pm 8.9 \times 10^{-5}$	$\pm 6.3 \times 10^{-5}$	$\pm 4.5 \times 10^{-5}$
$Re(\varepsilon'/\varepsilon)$	$(1.92 \pm 0.21) \times 10^{-3}$	$\pm 0.72 \times 10^{-3}$	$\pm 0.51 \times 10^{-3}$	$\pm 0.36 \times 10^{-3}$
$Im(\varepsilon'/\varepsilon)$	$(-1.72 \pm 2.02) \times 10^{-3}$	$\pm 9.4 \times 10^{-3}$	$\pm 6.7 \times 10^{-3}$	$\pm 4.7 \times 10^{-3}$
$Re(\delta)+Re(x_-)$	$Re(\delta) = (0.29 \pm 0.27) \times 10^{-3}$ $Re(x_-) = (-0.8 \pm 2.5) \times 10^{-3}$	$\pm 0.7 \times 10^{-3}$	$\pm 0.5 \times 10^{-3}$	$\pm 0.4 \times 10^{-3}$
$Im(\delta)+Im(x_+)$	$Im(\delta) = (-0.6 \pm 1.9) \times 10^{-5}$ (*) $Im(x_+) = (0.2 \pm 2.2) \times 10^{-3}$ (**)	$\pm 9 \times 10^{-3}$	$\pm 7 \times 10^{-3}$	$\pm 5 \times 10^{-3}$
Δm	$(5.2797 \pm 0.0195) \times 10^{9}\ s^{-1}$	$\pm 0.096 \times 10^{9}\ s^{-1}$	$\pm 0.068 \times 10^{9}\ s^{-1}$	$\pm 0.048 \times 10^{9}\ s^{-1}$

(*) = using Bell-Steinberger rel. (**) = KLOE-CPLEAR combined fit

Prospects for KLOE-2 at upgraded DAΦNE

Param.	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	$(-6.0 \pm 8.3) \times 10^{-18}$ GeV	$\pm 2.4 \times 10^{-18}$ GeV	$\pm 1.7 \times 10^{-18}$ GeV	$\pm 1.2 \times 10^{-18}$ GeV
Δa_Z	$(-3.1 \pm 1.8) \times 10^{-18}$ GeV	$\pm 5.2 \times 10^{-19}$ GeV	$\pm 3.7 \times 10^{-19}$ GeV	$\pm 2.6 \times 10^{-19}$ GeV
$\Delta a_{X,Y}$	[$<10^{-21}$ GeV]	$\pm 4.7 \times 10^{-19}$ GeV	$\pm 3.3 \times 10^{-19}$ GeV	$\pm 2.3 \times 10^{-19}$ GeV

[….] = preliminary (IT) = with Inner Tracker

Conclusions

- DAΦNE commissioning in progress
- KLOE detector fully operational
- KLOE-2 upgrades installed (see Bossi's talk)
- An improvement of about one order of magnitude in the precision of several CP/CPT symmetry and QM tests is expected at KLOE-2 (EPJC 68 (2010) 619-681)
- T symmetry test with entangled kaons feasible with O(10fb^{-1}) (NPB868 (2013)102)
- The analysis of the full KLOE data set is being completed:
- New upper limit for BR($K_S \to 3\pi^0$). At KLOE-2 this analysis will benefit of the presence of low θ calorimeters QCALT- CCALT. With O(10fb^{-1}) it might be possible to have a first observation of the decay
- New limits on CPT and Lorentz violation parameters Δa_μ. At KLOE-2 this analysis will benefit of the new inner tracker detector improving Δt resolution, and of the new interaction region scheme with a doubled φ momentum (increasing the sensitivity to Δa_0).
- New preliminary result on BR($K^+ \to \pi^+\pi^-\pi^+ (\gamma)$). Improvement possible with the analysis of the full KLOE data sample.

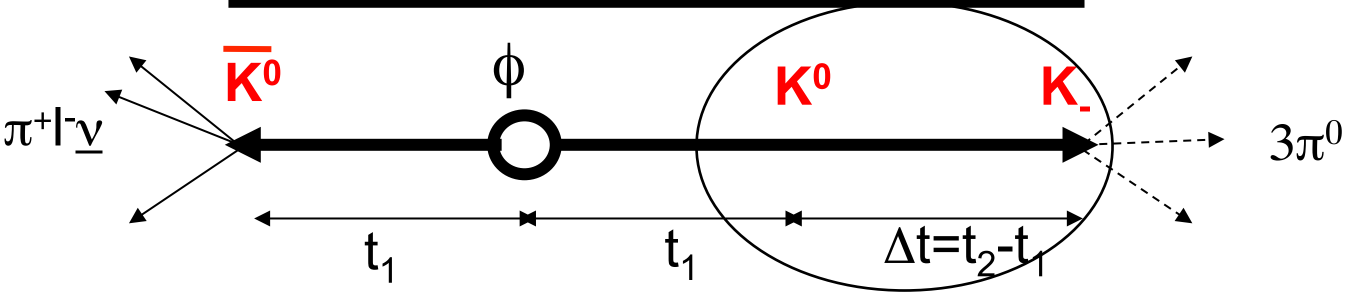
spare slides

Entanglement in neutral meson pairs

- Entangled states in QM: the INDIVIDUAL STATE of each neutral meson is NOT DEFINED BEFORE the observation of the decay of its orthogonal partner.
- transitions involving also “CP states” K_+ ($\pi\pi$ decay) and K_- ($3\pi^0$ decay)

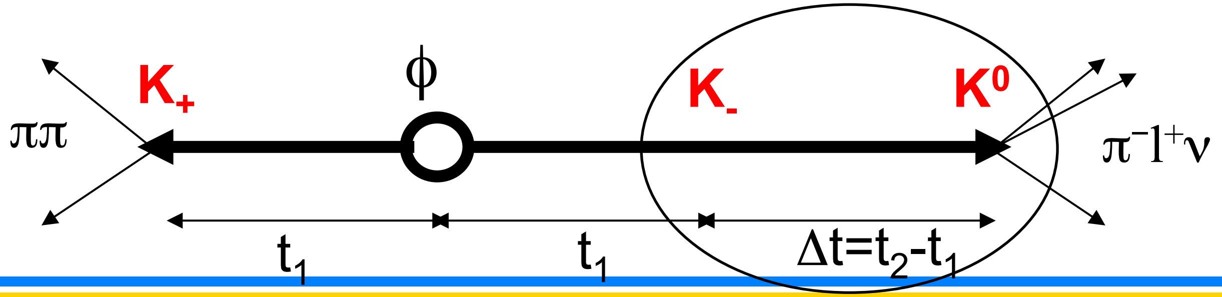
$$\boxed{\begin{aligned}|i\rangle &= \frac{1}{\sqrt{2}}\left[|K^0(\vec{p})\rangle|\bar{K}^0(-\vec{p})\rangle - |\bar{K}^0(\vec{p})\rangle|K^0(-\vec{p})\rangle\right] \\ &= \frac{1}{\sqrt{2}}\left[|K_+(\vec{p})\rangle|K_-(-\vec{p})\rangle - |K_-(\vec{p})\rangle|K_+(-\vec{p})\rangle\right]\end{aligned}}$$

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



$K^0 \rightarrow K_-$ reference process

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



Direct test of Time Reversal symmetry with neutral kaons

T symmetry test

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

One can define the following ratios of probabilities:

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

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}) (but quite challenging !!)