T and CPT symmetries

Phenomenology of neutral kaon

T violation

Direct measurement of T violation in CPLEAR

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Tests of CPT

What do we learn from 2π sector

Direct measurement of CPT invariance

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$K0\ \overline{K0}$ mass and width differences

T and CPT symmetries

CP violation has been observed since 1964 in K sector. It is very important to understand if it is accompanied by T violation such as to conserve CPT .

CPT symmetry is a very fundamental symmetry: within the framework of local field theory , of Lorentz invariance and of the usual spin satistics requirement, any order of the triple product CPT represents an exact symmetry

J.S.Bell Proc Royal Soc A231(1955) 479
G..Luders Ann Phys. 2 (1957) 1
R.Jost Helv. Phys. Acta 30(1957) 409

CPT implies equality of mass and lifetime for particle and antiparticle

$$\frac{M_{e^+} - M_{e^-}}{M_e} < 4\times10^{-8} \qquad \frac{M_{\bar{p}} - M_p}{M_p} < 3\times10^{-9} \qquad \frac{M_{\bar{n}} - M_n}{M_n} < 2\times10^{-4}$$

$$\frac{\tau_{\mu^+} - \tau_{\mu^-}}{\tau_\mu} < 2\times10^{-4} \qquad \frac{\tau_{\pi^+} - \tau_{\pi^-}}{\tau_\pi} < 2\times10^{-3} \qquad \frac{\tau_{K^+} - \tau_{K^-}}{\tau_K} < 2\times10^{-4}$$

☞The neutral kaon system, where we have observed CP violation, is a sensitive place to look for departure of CPT symmetry .

☞This search should be done as open-mind as possible, i.e. not making a priori assumptions
In the past , often looked for mass difference ("indirect" CPT violation) assuming width equality (no direct CPT violation)

☞CPLEAR has for the first time accurately measured the real part of the CPT mixing parameter Re(δ) , allowing to give bounds on *both* K^0 $\bar{K}^0$ mass and width difference.

Phenomenology of K^0 $\overline{K}^0$ system

Time evolution of the state

$$i\frac{\partial}{\partial\tau}\begin{pmatrix}K^0(\tau)\\ \overline{K}^0(\tau)\end{pmatrix} = \Lambda\begin{pmatrix}K^0(\tau)\\ \overline{K}^0(\tau)\end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix}K^0(\tau)\\ \overline{K}^0(\tau)\end{pmatrix}$$

$$M_{ij} = m_0\delta_{ij} + \sum_f \frac{\langle i|H|f\rangle\langle f|H|j\rangle}{m_0 - E_f} \qquad \Gamma_{ij} = \sum_f \langle i|H|f\rangle\langle f|H|j\rangle\ \delta(m_0 - E_f)$$

$$\boxed{\begin{array}{l} \text{CPT invariance} \Rightarrow \Lambda_{11} = \Lambda_{22} \\ \text{T invariance} \Rightarrow |\Lambda_{12}| = |\Lambda_{21}| \\ \text{CP invariance} \equiv \text{Both T and CPT invariances} \end{array}}$$

$$\boxed{\varepsilon_T = \frac{2i\Delta m}{2\Delta m + i\Delta\Gamma}\cdot\frac{|\Lambda_{12}|^2 - |\Lambda_{21}|^2}{\Delta m\Delta\Gamma}}$$

which has the phase: $\arg(\varepsilon_T) = \text{atan}\frac{2\Delta m}{\Delta\Gamma} \equiv \varphi_{SW} \quad \sim 45°$

$$\boxed{\delta = \frac{\Lambda_{22} - \Lambda_{11}}{2\Delta m + i\Delta\Gamma} = \frac{M_{22} - M_{11}}{2\Delta m + i\Delta\Gamma} - \frac{i}{2}\ \frac{\Gamma_{22} - \Gamma_{11}}{2\Delta m + i\Delta\Gamma}}$$

$$\delta = \delta_\perp + \delta_{//}$$

ε_T # 0 means T violation $\qquad$ δ#0 means CPT violation

K_L and K_S (states of defined life time) are the eigenvectors of the Λ with eigenvalues

$$m_S - \frac{i}{2}\Gamma_S \qquad \Delta m = m_L - m_S$$

$$m_L - \frac{i}{2}\Gamma_L \qquad \Delta\Gamma = \Gamma_S - \Gamma_L$$

If initial strangeness (e,g, by strong interactions) is defined:

$$K^0(\tau)\rangle = \frac{1}{2}\cdot\left[(1-2\delta)|K^0\rangle + (1-2\varepsilon_T)e^{-i\varphi_\Gamma}|\bar{K}^0\rangle\right]e^{-i\lambda_S\tau}$$

$$+\frac{1}{2}\cdot\left[(1+2\delta)|K^0\rangle - (1-2\varepsilon_T)e^{-i\varphi_\Gamma}|\bar{K}^0\rangle\right]e^{-i\lambda_L\tau}$$

$$|\bar{K}^0(\tau)\rangle = \frac{1}{2}\cdot\left[(1+2\delta)|\bar{K}^0\rangle + (1+2\varepsilon_T)e^{i\varphi_\Gamma}|K^0\rangle\right]e^{-i\lambda_S\tau}$$

$$+\frac{1}{2}\cdot\left[(1-2\delta)|\bar{K}^0\rangle - (1+2\varepsilon_T)e^{i\varphi_\Gamma}|K^0\rangle\right]e^{-i\lambda_L\tau}$$

T violation and tests of CPT with neutral Kaons

A direct test of T violation in the neutral kaon system can be performed from the asymmetry of two T conjugate rates A_T

$$A_T(\tau) = \frac{R(\bar{K}^0_{\tau=0} \to K^0(\tau)) - R(K^0_{\tau=0} \to \bar{K}^0(\tau))}{R(\bar{K}^0_{\tau=0} \to K^0(\tau)) + R(K^0_{\tau=0} \to \bar{K}^0(\tau))}$$
$$= 4\Re(\varepsilon_T)$$

-originally proposed by Kabir (1970)
-real test of micro-reversibility with exchange of initial and final states.

This requires tagging of strangeness both at production and decay time

initial tagging : CPLEAR method using strong interactions

decay tagging: uses semi-leptonic decay and assume that

$K^0 \to \pi^- e^+ \nu \qquad K^0 \neq \pi^+ e^- \nu$ ($\Delta S=\Delta Q$ rule)

$$A_l(\tau) = \frac{R(\bar{K}^0 \to \pi^- e^+ \nu) - R(K^0 \to \pi^+ e^- \nu)}{R(\bar{K}^0 \to \pi^- e^+ \nu) + R(K^0 \to \pi^+ e^- \nu)}$$

T violation and tests of CPT with neutral Kaons

This was the ideal situation !

1) There can be a violation of $\Delta S = \Delta Q$ rule: we introduce

$$x = \frac{\langle \pi^- l^+ \nu | T | \bar{K}^0 \rangle}{\langle \pi^- l^+ \nu | T | K^0 \rangle} \equiv \frac{(\Delta S = -\Delta Q)}{(\Delta S = \Delta Q)}$$

and similar for $\bar{x}$

2) It is also possible to have direct CPT violation in semi-leptonic decays.

<u>in the main amplitude</u>:

$$y \equiv \frac{\langle \pi^+ l^- \nu | T | \bar{K}^0 \rangle^* - \langle \pi^- l^+ \nu | T | K^0 \rangle}{\langle \pi^+ l^- \nu | T | \bar{K}^0 \rangle^* + \langle \pi^- l^+ \nu | T | K^0 \rangle} \equiv \text{difference}(\bar{K}^0 - K^0)$$

<u>in $\Delta S = -\Delta Q$,</u> $\bar{x} - x \neq 0$ $\quad x_+ = \left(\frac{\bar{x} + x}{2}\right) \quad x_- = \left(\frac{x - \bar{x}}{2}\right)$

we get more complicated equations

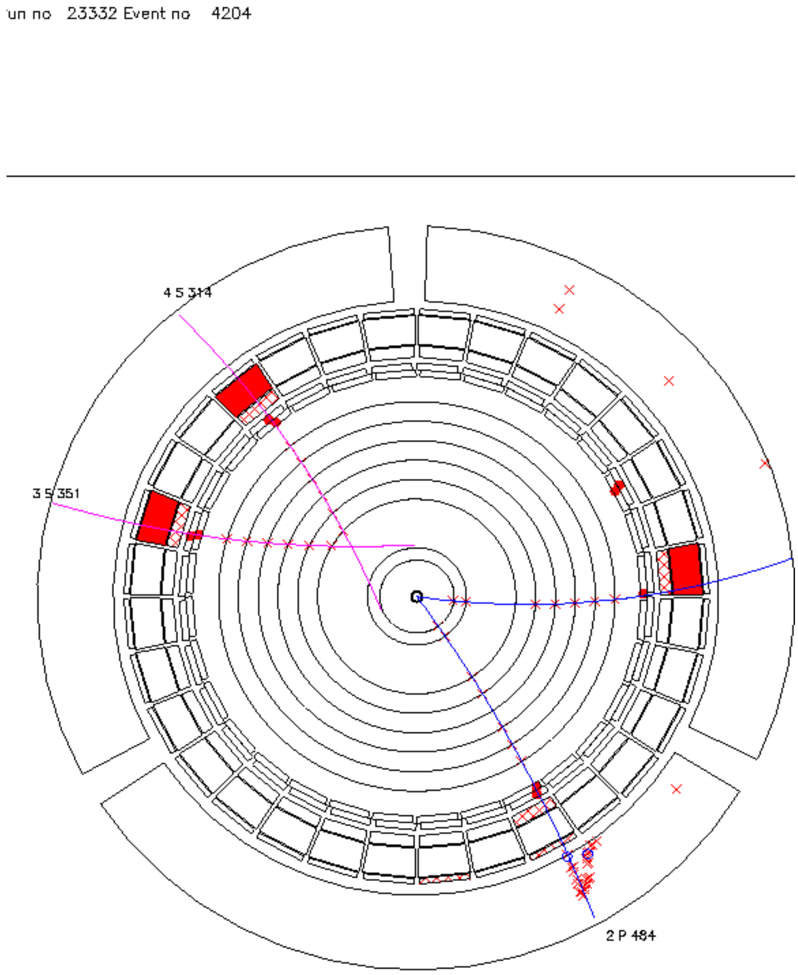
$$\boxed{A_l = 4\Re(\varepsilon_T) - 2\Re(x_-) - 2\Re(y) (\text{ for } \tau \gg \tau_S)}$$

+ additional terms at short lifetimes

$$\boxed{A_l = 4\Re(\varepsilon_T) - 2\Re(x_-) - 2\Re(y) - 2\frac{\Re(x_-)\left(e^{-\frac{1}{2}\Delta\Gamma\tau} + \cos(\Delta m t)\right) + \Im(x_+)\sin(\Delta m\tau)}{\cosh\left(\frac{1}{2}\Delta\Gamma\tau\right) - \cos(\Delta m t)}}$$

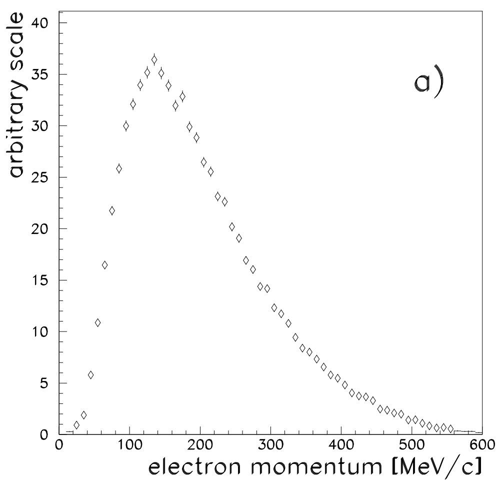
The CPLEAR experiment

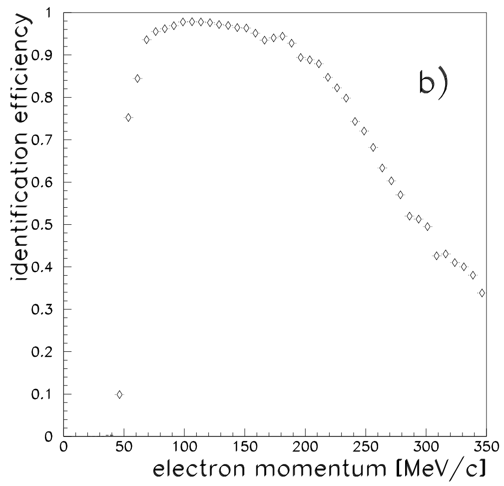
- $\bar{p}$ annihilation at rest
- $p\ \bar{p} \to K^{-}\pi^{+}K^{0}$ and $p\ \bar{p} \to K^{+}\pi^{-}K^{0}$
- the charge of the kaon tags the strangeness of the K^{0} event by event



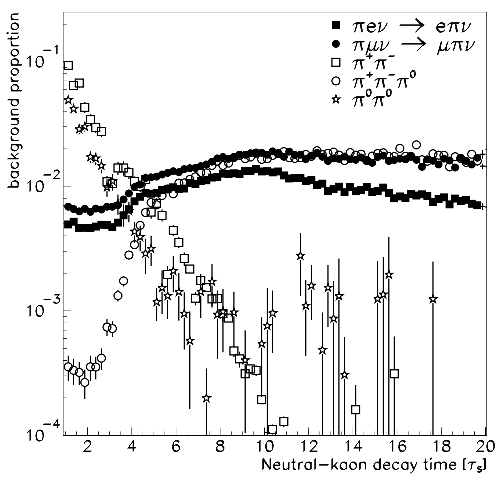
measures $N(\bar{K}^{0} \to e^{+}\pi^{-}\nu)(\tau)$ and $N(K^{0} \to e^{-}\pi^{+}\bar{\nu})(\tau)$

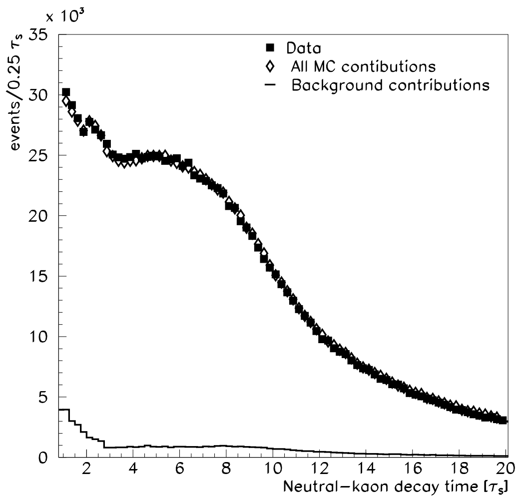
Properties of Semileptonic events in CPLEAR





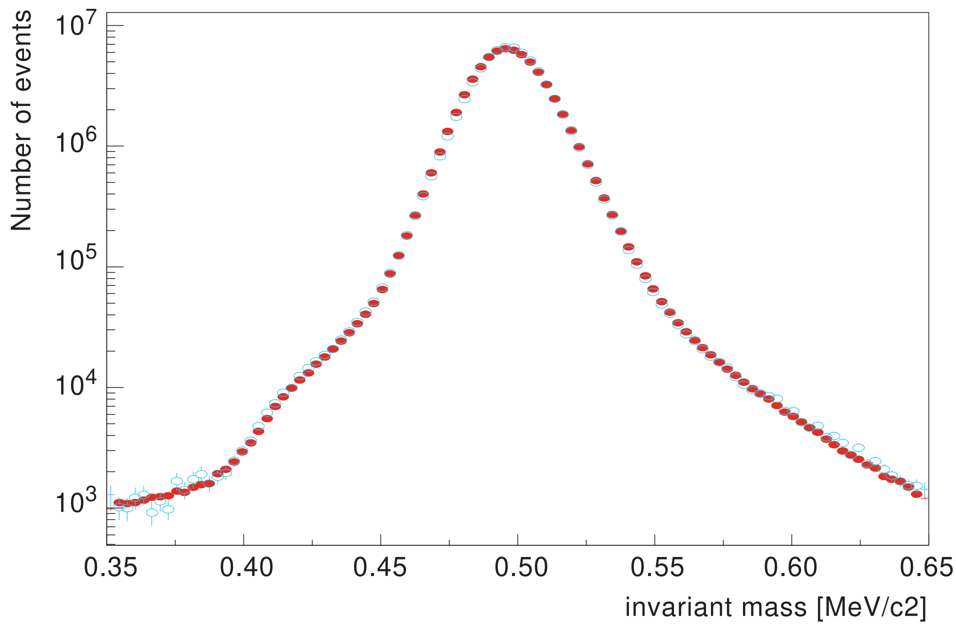
Momentum spectrum Electron id efficiency





Background composition Data-MonteCarlo comparaison

Data-Simulation quality checks

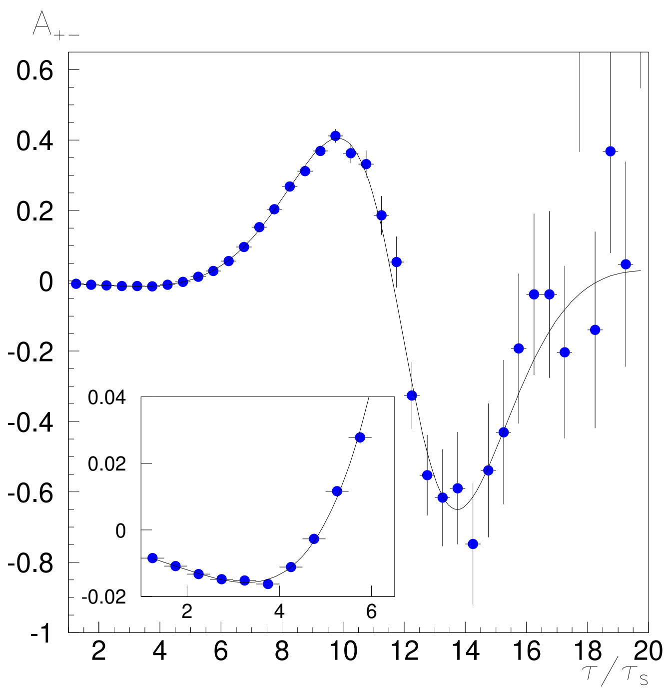


Reconstructed vs simulated invariant mass of the $\pi^+\pi^-$ sample

K^0 to $\overline{K}^0$ rate normalisation in CPLEAR

The initial ($\tau = 0$) numbers of K^0 and $\overline{K}^0$ are different due to difference in tagging efficiency (different strong interactions)

From the high statistics $\pi^+\pi^-$ data , we can find the ratio ξ of tagging efficiency



$$\xi \times \frac{N(K^0_{t=0} \rightarrow \pi\pi_{t=\tau})}{N(\overline{K}^0_{t=0} \rightarrow \pi\pi_{t=\tau})} = (1 - 4\Re(\varepsilon_T - \delta))\left(1 + 4|\eta_{+-}|e^{\frac{1}{2}1/\tau_S}\cos(\Delta m\tau - \varphi_{+-})\right)$$

small at short τ (~ 1%) , can be corrected with experimental η value at 10^{-4} level

This procedure can only determine $\xi(1+4\Re(\varepsilon_T-\delta))$

Important remarks

☞ **Only for the T violation analysis**, CPLEAR infers $\Re(\varepsilon_T-\delta)$ from an external measurement : K_L charge asymmetry δ_L

For all other measurements ($\pi^+\pi^-$, $\pi^+\pi^-\pi^0$, $Re(\delta)$) published by CPLEAR , the fitted asymmetries are defined such as to incorporate $\xi(1+4\Re(\varepsilon_T-\delta))$

☞ This procedure does not imply any assumption on (direct) CPT violation in the $\pi^+\pi^-$decay

if CPT is violated , it will be contained in the experimental value of η_{+-}

☞ For the T violation analysis, direct CPT violation in the semileptonic decay can be taken into account :

$$\delta_L = 2\Re(\varepsilon_T-\delta)-2\Re(x_-)-2\Re(y)$$

as a consequence , the measured A_l asymmetry is modified and becomes

$$\boxed{A_l^{exp} = 4\Re(\varepsilon_T)-4\Re(x_-)-4\Re(y)(\text{ for } \tau \gg \tau_S)}$$

☞ $\Re(\varepsilon_T-\delta)$ does not distinguish between T and CPT violation (no circularity).

☞ In practice ξ is determined as function of the kinematical variables of the tagging particles (p_T^K, p_Z^K , p^π)

Look-up tables applied event by event . (Takes into account the primary particles phase space difference between different decay channels)

Final state identification / efficiency normalisation

Identification of electrons with Neural Network using

Measured momentum

Cerenkov light

DeDx in scintillator S1

Time Of Flight

Evaluate background from Monte Carlo simulation

small (< 1%) if $\tau > 1\ \tau_S$; almost no effect

Correct for the different reconstruction efficiencies of final state using unbiased pure electron/pion samples

e from γ conversions

π from minimum bias events or 2π decays

$$\varepsilon(\pi^+ e^-)/\varepsilon(\pi^- e^+) = 1.014 \pm 0.002$$

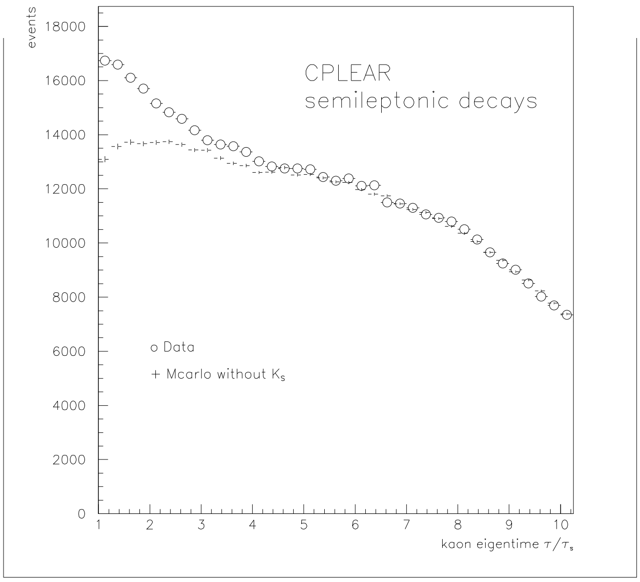
$$\text{shifts } A_l \text{ by } (7 \pm 1)\times 10^{-3}$$

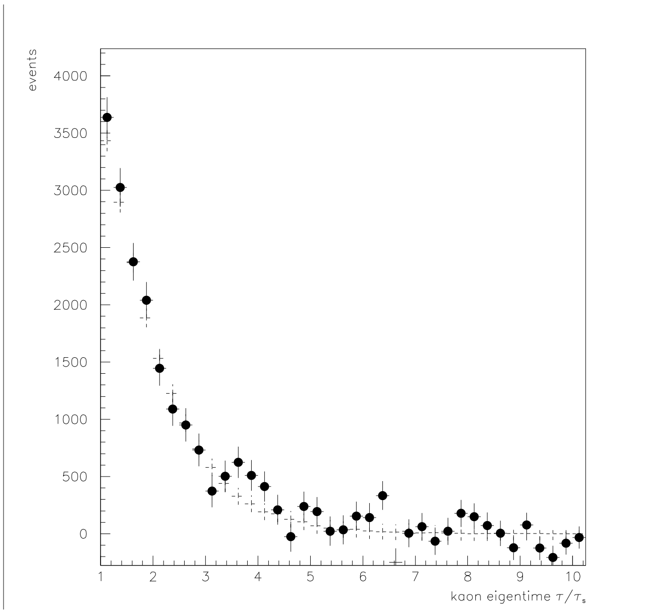
Apply regeneration correrctions using CPLEAR measured amplitudes

$$\text{shifts } A_l \text{ by } \quad 0.3\times 10^{-3}$$

check(not using kaon strangeness) : $\delta_L = (2.8 \pm 1.3)\times 10^{-3}$

a quality check: observation of the Ks semileptonic decay

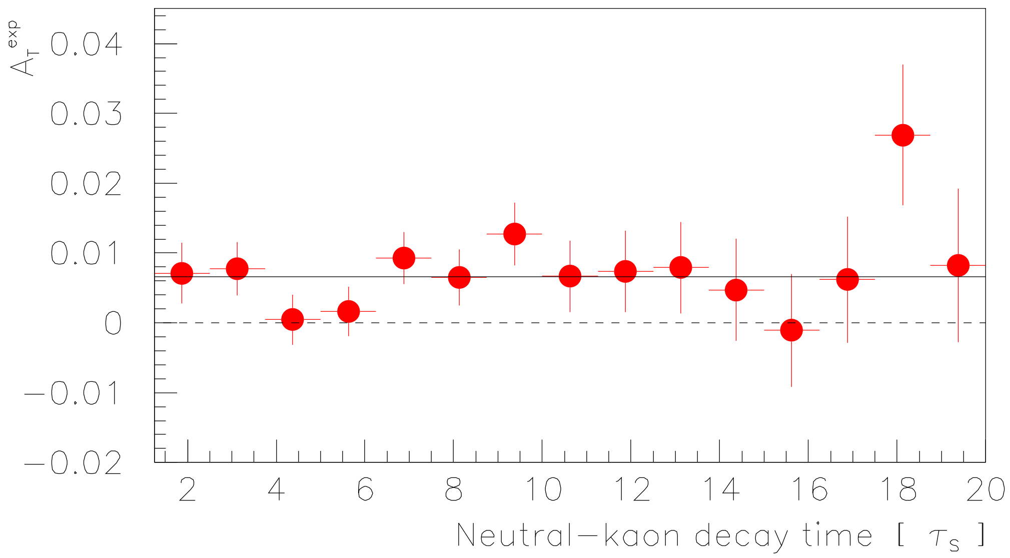




my very preliminary analysis :

$$\frac{N(K_S \rightarrow \pi e \nu)_{data}}{N(K_S \rightarrow \pi e \nu)_{Mcarlo}} = 1.03 \pm 0.03 \pm ?$$

First direct measurement of time reversal non-invariance



$$\boxed{A_l^{exp} = (6.6 \pm 1.3_{stat} \pm 1.0_{syst}) \cdot 10^{-3}}$$

Systematic errors on A_l

background level : from Monte Carlo 10%

background charge asymmetry (different probabiity of misendification for π^+ and π^-) : use π from minimum bias events $(3 \pm 1)\times10^{-2}$

tagging efficiency: statistical error from 2π sample $\pm4.3\times10^{-4}$

different reconstruction efficiency of final states: $\pm2.0\times10^{-3}$

decay time resolution

regeneration corrections : uncertainty of CPLEAR measurement

systematic errors on A_T

source	$\langle A_T^{exp} \rangle [\times10^{-3}]$
background level	±0.03
background asym.	±0.02
tagging efficiency	±0.2
reconstruction final state	±1.0
decay time resolution	negligible
regeneration	±0.1
total	±1.0

Discussion

☞Relaxing on $\Delta S = \Delta Q$

Fit the formula, including the $\Delta S = \Delta Q$ violation

$$A_1(\tau) = \frac{R(\bar{K}^0 \to e^+\pi^-\nu)(\tau) - R(K^0 \to e^-\pi^+\bar{\nu})(\tau)}{R(\bar{K}^0 \to e^+\pi^-\nu)(\tau) + R(K^0 \to e^-\pi^+\bar{\nu})(\tau)}$$

$$= \left(4\Re(\varepsilon_T) + \frac{2\Im(x_+)\sin(\Delta m t)}{\cosh(0.5 \times \Delta\Gamma) - \cos(\Delta m t)}\right)$$

gives

$$4\Re(\varepsilon_T) = (6.2 \pm 1.4)\times 10^{-3}$$

$$\Im(x_+) = (1.2 \pm 1.9)\times 10^{-3}$$

note : $\Im(x_+)$ was T violating anyway !

☞The value obtained is exactly what is expected to compensate CP violation

☞If we do not assume CPT violation in decay, then what we have measured at large lifetime is

$$A_1^{exp} = 4\Re(\varepsilon_T - y - x_-)$$

In full generality , the measurement, taken in isolation can not be taken as evidence for T violation.

T odd terms in K_L decay
KTEV experiment at FNAL

$K_L \to \pi^+\pi^- e^+ e^-$ BR (3.2 +-0.6 +-0.4)e-7

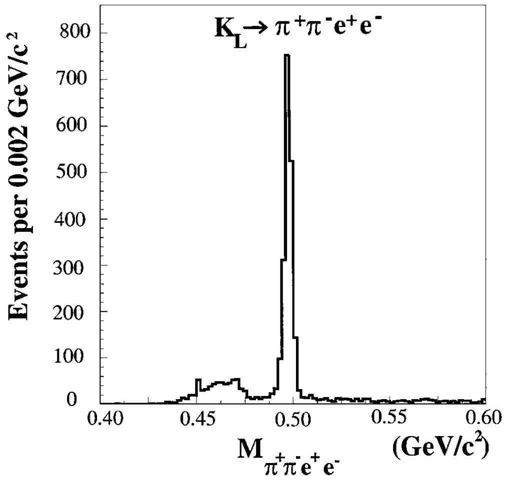
$$\vec{n}_\pi = \left(\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}\right) / \left|\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}\right|$$
$$\vec{n}_e = \left(\vec{p}_{e^+} \times \vec{p}_{e^-}\right) / \left|\vec{p}_{e^+} \times \vec{p}_{e^-}\right|$$
$$\vec{z} = \left(\vec{p}_{\pi^+} + \vec{p}_{\pi^-}\right) / \left|\vec{p}_{\pi^+} + \vec{p}_{\pi^-}\right|$$
$$\sin\phi = \vec{n}_\pi \times \vec{n}_e \cdot \vec{z} \qquad \text{CPodd} \qquad \text{Todd}$$
$$\cos\phi = \vec{n}_\pi \cdot \vec{n}_e \qquad \text{CPeven} \qquad \text{Teven}$$

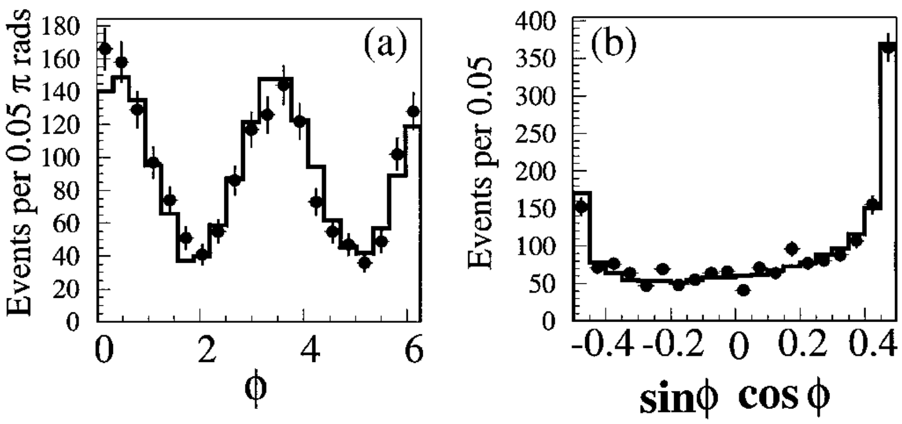
Observed asymmetry

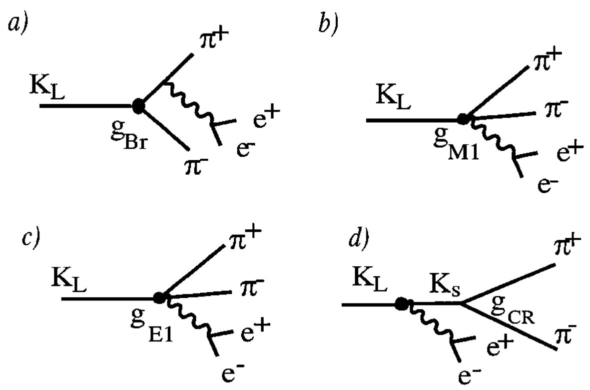
$$[13.6 \pm 2.5\text{stat} \pm 1.2\text{syst}] \times 10^{-2}$$

Remarks:
- CP asymmetry, very similar to η_{+-}
- a T odd correlation is only evidence for T violation
  if final state interactions are small and CPT invariant
  if unitarity holds
- (*Direct T violation measurements and Todd effects in decay experiments L. Alvarez Gaume et al. CERN TH/99-80 , and Moriond 99)*

T odd term in $K_L \to \pi^+\pi^-e^+e^-$







What do we learn on CPT from 2π sector?

The observables are the amplitude ratios

$$\eta_{\pi\pi} = |\eta_{\pi\pi}| e^{i\varphi_{\pi\pi}} = \frac{\langle\pi\pi|T|K_L\rangle}{\langle\pi\pi|T|K_S\rangle} \equiv \frac{\text{CPforbidden}}{\text{CPallowed}}$$

the phases carry important information

One defines the isospin amplitudes (I=0 or I=2):

$$A_I = (a_I + b_I)e^{i\delta_I} \qquad \bar{A}_I = (a_I^* - b_I^*)e^{i\delta_I} \qquad (b_I \text{ are } \underline{\text{CPT violating}})$$

One obtains:

$$\eta_{+-} = \frac{\langle\pi\pi|T|K_L\rangle}{\langle\pi\pi|T|K_S\rangle} = \tilde{\varepsilon} + \varepsilon' \qquad \eta_{00} = \frac{\langle\pi\pi|T|K_L\rangle}{\langle\pi\pi|T|K_S\rangle} = \tilde{\varepsilon} - 2\varepsilon'$$

with:

$$\boxed{\tilde{\varepsilon} = \varepsilon_T - \delta + i\Delta\phi + \Re\left(\frac{b_0}{a_0}\right)}$$

$$\boxed{\varepsilon' = \frac{1}{\sqrt{2}} e^{i(\delta_2 - \delta_0)}\left[i\Im\left(\frac{a_2}{a_0}\right) + \Re\left(\frac{a_2}{a_0}\right)\left\{\Re\left(\frac{b_2}{a_2}\right) - \Re\left(\frac{b_0}{a_0}\right)\right\}\right]}$$

$$\Delta\phi = \frac{1}{2}[\phi_\Gamma - \arg(A_0^* \bar{A}_0)]$$

$$\Delta\phi = \frac{\Gamma_L}{\Gamma_S}(4Br(K_L \to \pi^- l^+ \nu) \cdot \Im(x) - Br(K_L \to 3\pi) \cdot \Im(\varepsilon_T + \delta - \eta_{3\pi})$$

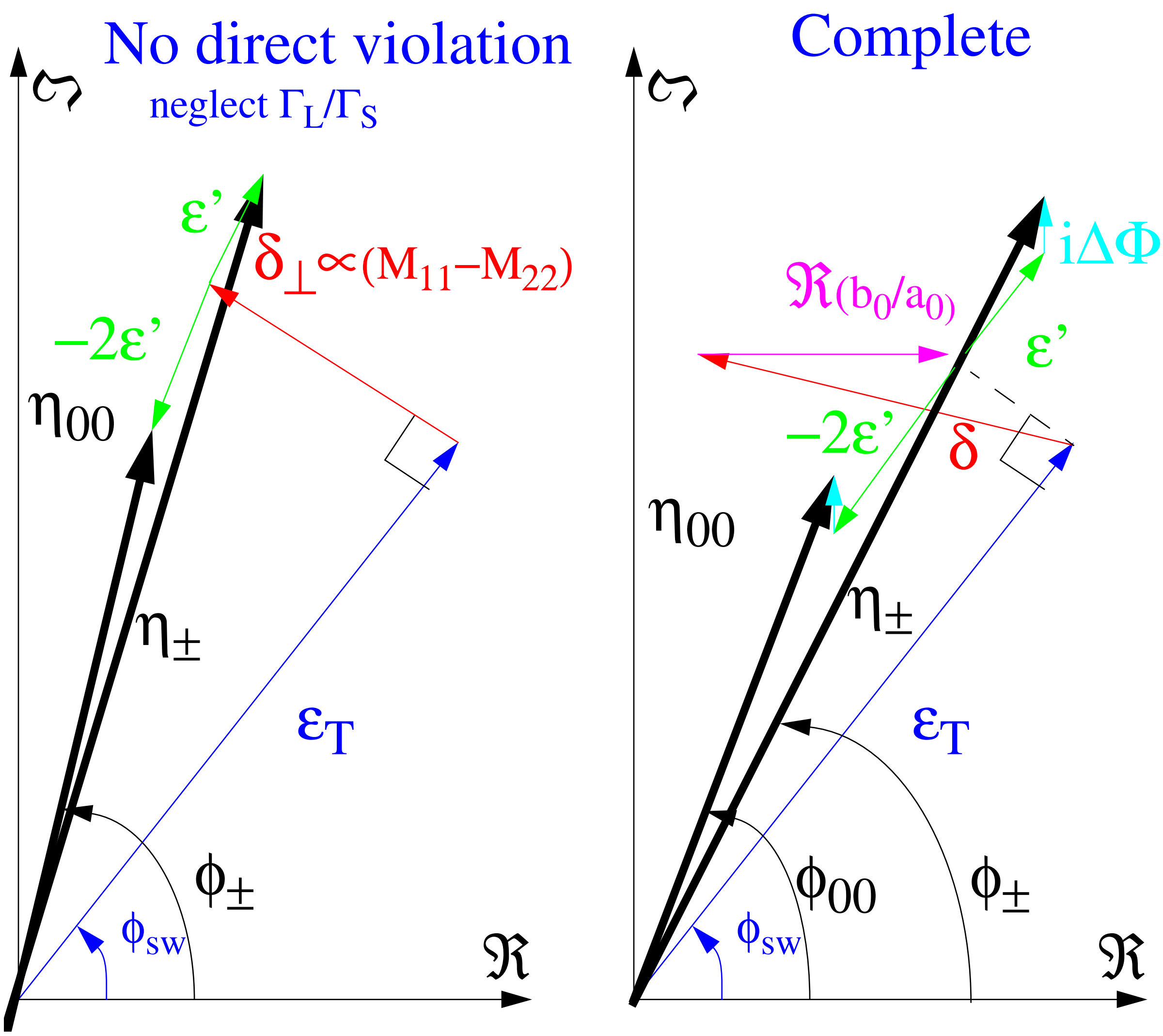
can be neglected if one assumes $\eta_{000} = \eta_{+-0}$

Since $\delta_2 - \delta_0 + 90^\circ = (48 \pm 4)^\circ$, in absence of CPT violation,
all phases ϕ_{+-} , ϕ_{00} , ϕ_{SW} are equal

The reverse is not true : there can be cancelations (Peccei 92)

$\phi_{+-} - \phi_{00}$ gives $\Im(\varepsilon'/\varepsilon)$ "direct" CPT violation: difference I=0 and I=2

$\phi_{+-} - \phi_{SW}$ cancelations between $\Re(b_0/a_0)$ and $\Re(\delta)$ $(\Gamma_{11}-\Gamma_{22}\ \#0)$



Other measurements are essential !

Direct measurement of CPT invariance

analysis very similar as for T violation

$$A_{CPT}(\tau) = \frac{R(\bar{K}^0 \to \bar{K}^0)(\tau) - R(K^0 \to K^0)(\tau)}{R(\bar{K}^0 \to \bar{K}^0)(\tau) + R(K^0 \to K^0)(\tau)}$$
$$= 4\Re(\delta) \ \text{ for } \tau » \tau_s$$

To extract the CPT parameter in a optimal way , we define

$$A_\delta(\tau) = \frac{R\left(\bar{K}^0 \to e^+\right)(\tau) - (1+4\Re(\varepsilon_L))R(K^0 \to e^-)(\tau)}{R\left(\bar{K}^0 \to e^+\right)(\tau) + (1+4\Re(\varepsilon_L))R(K^0 \to e^-)(\tau)} + \frac{R\left(\bar{K}^0 \to e^-\right)(\tau) - (1+4\Re(\varepsilon_L))R(K^0 \to e^+)(\tau)}{R\left(\bar{K}^0 \to e^-\right)(\tau) + (1+4\Re(\varepsilon_L))R(K^0 \to e^+)(\tau)}$$

which has several nice features:

-does not depend on parameter y (CPT violation in kaon decay)

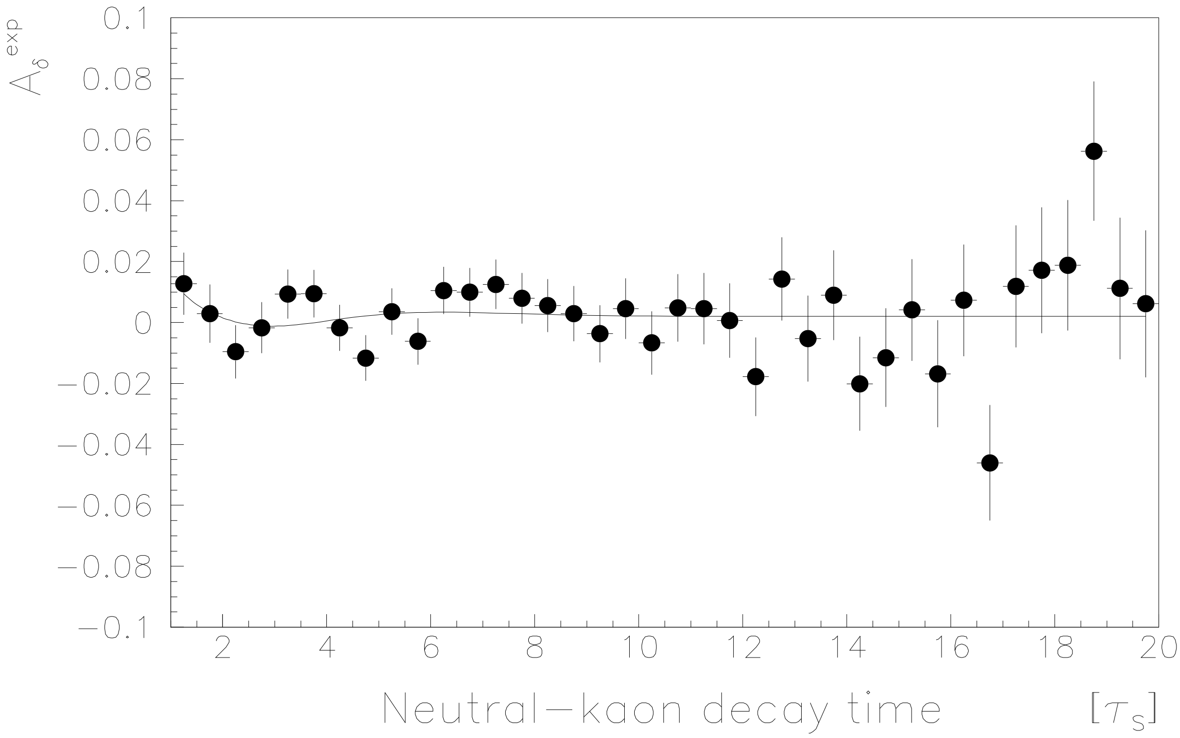
-the factor $(1+4\Re(\varepsilon_L))$ is absorbed in our 2π normalisation factor

no need to use external parameters (as δ_L for T study)

-all other parameters $\Im(\delta), \Im(x+\bar{x}), \Re(x-\bar{x})$ are damped and do not contribute after few lifetimes . At large lifetimes

$$\boxed{A_\delta = 8\Re(\delta)}$$

without any assumption on direct CPT violation in semileptonic decay



$$\Re(\delta) = (3.0 \pm 3.3_{stat} \pm 0.6_{syst}) \cdot 10^{-4}$$

we also get in the fit

$$\Im(\delta) = (-1.5 \pm 2.3 \pm 0.3) \times 10^{-2}$$

$$\Im(x_+) = (1.2 \pm 2.2 \pm 0.3) \times 10^{-2}$$

$$\Re(x_-) = (0.2 \pm 1.3 \pm 0.3) \times 10^{-2}$$

Systematic errors on $\Re(\delta)$

background level : from Monte Carlo   10%

background charge asymmetry   (different probabiity of misendification for π^+ and π^-) : use π from minimum bias events $(3 \pm 1)\times 10^{-2}$

tagging efficiency: statistical error from 2π sample $\pm 4.3\times 10^{-4}$

different reconstruction efficiency of final states: $\pm 2.0\times 10^{-3}$

decay time resolution: vary by 10%

regeneration corrections : uncertainty of CPLEAR measurement

systematic errors on $\Re(\delta)$

source	$[\ \times 10^{-4}]$
background level	± 0.1
background asym.	± 0.2
tagging efficiency	± 0.5
reconstruction final state	± 0.02
decay time resolution	negligible
regeneration	± 0.25
total	± 0.6

Fit of CPLEAR semileptonic data with Bell-Steinberger unitarity constraint

Parameter	value	reference
η_{+-}	$2.276 \pm 0.024)\times 10^{-3}$	CPLEAR
ϕ_{+-}	43.6 ± 0.6^{o}	CPLEAR global fit
Δm	$(530.19 \pm 1.54)\times 10^{7}$	CPLEAR fit without CPT
$\phi_{+-} - \phi_{00}$	-0.3 ± 0.8^{o}	PDG (E731/NA31)
$r = \eta_{00} / \eta_{+-}$	0.993 ± 0.002	PDG (NA31/E731)
$\mathrm{Re}(\eta_{+-0})$	$(-2 \pm 8)\times 10^{-3}$	CPLEAR
$\mathrm{Im}(\eta_{+-0})$	$(-2 \pm 9)\times 10^{-3}$	CPLEAR
$\mathrm{Re}(\eta_{000})$	$(7 \pm 11)\times 10^{-2}$	CPLEAR
$\mathrm{Im}(\eta_{000})$	$(8 \pm 16)\times 10^{-2}$	CPLEAR
Br ($K_S \to 2\pi^0$)	$(31.39 \pm 0.28)\%$	PDG
Br ($K_L \to \pi^+\pi^-\pi^0$)	$(12.56 \pm 0.20)\%$	PDG
Br ($K_L \to 3\pi^0$)	$(21.12 \pm 0.27)\%$	PDG
Br ($K_s \to \pi l \nu$)	$(65.95 \pm 0.37)\%$	PDG
τ_S	$0.8934 \pm 0.0008)\times 10^{-10}$	PDG

Apply unitarity relations (Bell Steinberger)

$$\left(-i\Delta m + \frac{\gamma_L + \gamma_S}{2}\right)\langle K_L|K_S\rangle = \sum_F A_L^* A_S$$

$$\Re(\varepsilon_T) - i\Im(\delta) = \frac{1}{2\left(i\Delta m + \frac{\gamma_L + \gamma_S}{2}\right)} \mathrm{x} \left(\sum |A_S|^2 \eta_{\pi\pi} + \sum |A_L|^2 \eta^*{}_{\pi\pi\pi} + 2[\Re(\varepsilon) - \Re(y) - i(\Im(x)) + \Im(\delta)]|f|^2\right)$$

where

$$|A_S|^2 = \Gamma_S Br(K_S \to \pi\pi)$$

$$|A_L|^2 = \Gamma_L Br(K_L \to \pi\pi\pi)$$

$$|f|^2 = \Gamma_L Br(K_L \to \pi l \nu)$$

and fit simultaneously our A'_T and A_δ

we obtain

$$\Im(\delta) = (-2.4 \pm 4.2)\times 10^{-5}$$

$$\Re(\delta) = (2.4 \pm 2.8)\times 10^{-4}$$

$$\Im(x_+) = (1.2 \pm 2.2)\times 10^{-2}$$

$$\Re(x_-) = (-0.6 \pm 3.1)\times 10^{-3}$$

$$\Re(\varepsilon_T) = (165.0 \pm 4.1)\times 10^{-5}$$

$$\Re(y) = (0.4 \pm 3.1)\times 10^{-3}$$

T violation and tests of CPT with neutral Kaons

Case with $\eta_{000} = \eta_{+-0}$

$$\Im(\delta) = (-0.2 \pm 2.0)\times 10^{-3}$$

$$\Re(\varepsilon_T) = (164.9 \pm 2.0)\times 10^{-5}$$

correlation matrix

	Re(y)	**Re(δ)**	**Re(x_)**	**Re(ε)**	**Im(δ)**
Im(x)	-0.624	-0.555	0.651	-0.086	0.090
Re(y))		0.279	-0.997	-0.097	-0.090
Re(δ)			-0.349	0.024	-0.062
Re(x_)				0.036	0.131
Re(ε)					0.004

Note the very strong anticorrelation between $\Re(x\_)$ and $\Re(y)$

such that $\left(\Re(x\_) + \Re(y) = (-0.2 \pm 0.3)\times 10^{-3}\right)$

This is what entered in the T violating A_L asymmetry

K0 $\overline{\text{K0}}$ mass and width differences

$$\delta_{//} = \frac{1}{4}\frac{\Gamma_{11} - \Gamma_{22}}{\sqrt{\Delta m^2 + (\Delta\Gamma/2)^2}} = \Re(\delta)\cos\varphi_{SW} + \Im(\delta)\sin\varphi_{SW}$$

$$\delta_{\perp} = \frac{1}{2}\frac{M_{11} - M_{22}}{\sqrt{\Delta m^2 + (\Delta\Gamma/2)^2}} = -\Re(\delta)\sin\varphi_{SW} + \Im(\delta)\cos\varphi_{SW}$$

$$\boxed{\frac{M_{K^0} - M_{\overline{K}^0}}{M_K} = (-1.5 \pm 2.0)\times 10^{-18}}$$

$$\boxed{\Gamma_{K^0} - \Gamma_{\overline{K}^0} = (3.9 \pm 4.2)\times 10^{-18} \quad \text{GeV}}$$

with a correlation factor ρ=-0.94, or

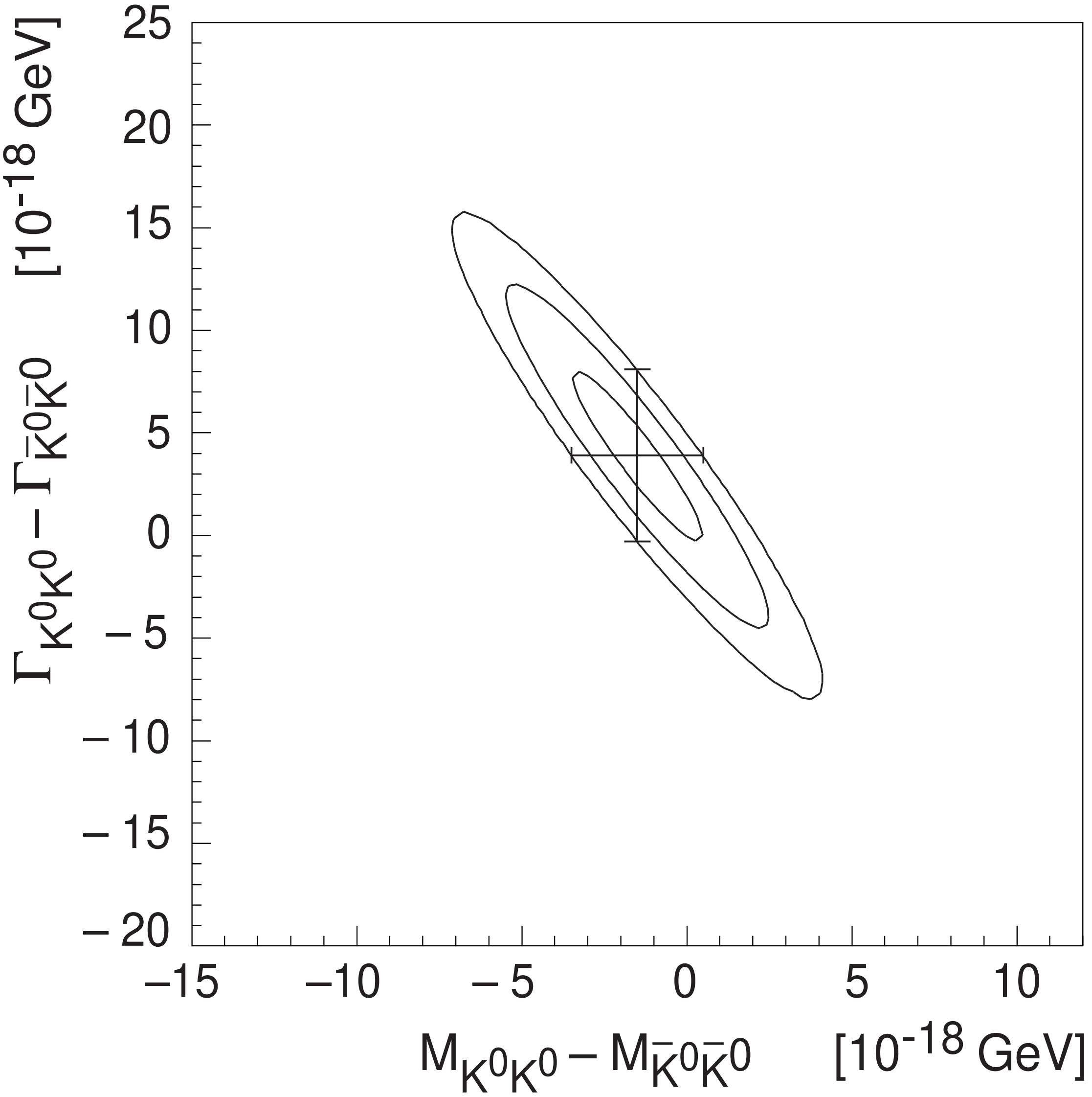
$$\boxed{\frac{\Gamma_{K^0} - \Gamma_{\overline{K}^0}}{\Delta\Gamma} = (5.3 \pm 5.7)\times 10^{-4}}$$

Assuming CPT invariance in the decay amplitudes

$$M_{K^0} - M_{\overline{K}^0} = (3.3 \pm 7.0)\times 10^{-19} < 12.7\times 10^{-19}\,\text{GeV}$$

assuming same CP violation in 3p0 than p+p-p0

$$M_{K^0} - M_{\overline{K}^0} = (-0.7 \pm 2.8)\times 10^{-19} < 4.8\times 10^{--19}\,\text{GeV}$$


$\Gamma_{K^0K^0} - \Gamma_{\bar{K}^0\bar{K}^0}$ [10^{-18} GeV]
$M_{K^0K^0} - M_{\bar{K}^0\bar{K}^0}$ [10^{-18} GeV]
25
20
15
10
5
0
– 5
– 10
– 15
– 20
–15
–10
– 5
0
5
10

Coming back to the 2π system

$$\boxed{\begin{aligned}\Re\left(\frac{b_0}{a_0}\right) &= \Re(\eta_{+-}) - \Re(\varepsilon_T) + \Re(\delta) + \Re(\varepsilon') \\ &= (2.6 \pm 2.9)\times 10^{-4}\end{aligned}}$$

and from $\phi_{+-} - \phi_{00}$

$$\Rightarrow \quad \boxed{\varepsilon'_\perp \approx \frac{1}{\sqrt{2}}\left[\Re\left(\frac{a_2}{a_0}\right)\left\{\Re\left(\frac{b_2}{a_2}\right) - \Re\left(\frac{b_0}{a_0}\right)\right\}\right] = (-0.4 \pm 1.2\times 10^{-5})}$$

we obtain

$$\boxed{\Re\left(\frac{b_2}{a_2}\right) - \Re\left(\frac{b_0}{a_0}\right) = (-1.3 \pm 3.4)\times 10^{-4}}$$

Conclusions

☞CPLEAR experiment has , for the first time, directly observed a violation of time-reversal by comparing two time conjugate processes.

$$A_l^{exp} = (6.6 \pm 1.3_{stat} \pm 1.0_{syst}) \cdot 10^{-3}$$

independently of the $\Delta S = \Delta Q$ rule.

Taking this measurement in isolation, this conclusion is only valid in the limit of CPT symmetry for the neutral kaon beta decay.

,Combining this measurement with the other neutral kaon data and assuming unitarity shows that it can only be due do T violation

☞The precise CPLEAR measurement of R(δ) with tagged semi-leptonic decays

$$\Re(\delta) = (3.0 \pm 3.3_{stat} \pm 0.6_{syst}) \cdot 10^{-4}$$

opens for the first time the possibility to measure the CPT violation parameters of the neutral kaon system in a general way.

☞Combining this measurement with other neutral kaon data -with the assumption of unitarity-, we have obtained limits on the yet unmeasured K^0 $\bar{K}^0$ width difference and on several CPT violating amplitudes for semi-leptonic and 2π decays.

☞ The precision on Im(δ) -mostly obtained from 2π and 3π decays- is still one order of magnitude better than the precision of R(δ) . It is therefore important to improve this last measurement . Then the largest limitation will come from the poor precision on η_{000} .