http://cplear.web.cern.ch/cplear/Welcome.html

Physics at CPLEAR, Phys. Rep. 374 (2003), 165-270

T and CPT Measurements with the CPLEAR Experiment

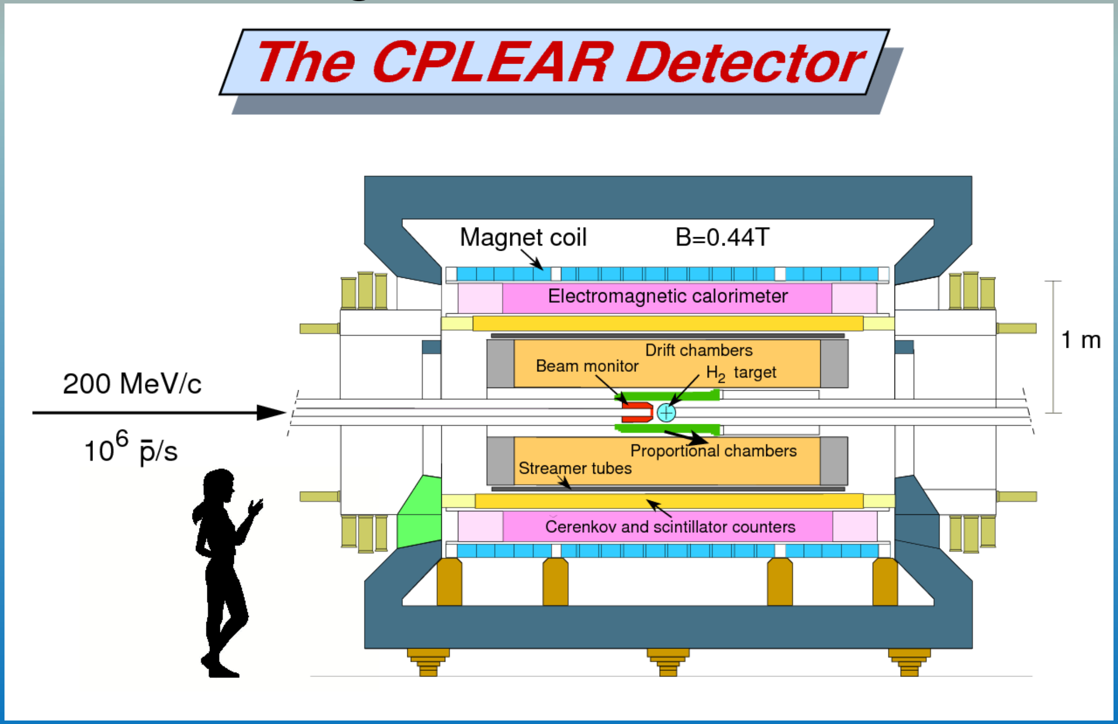
Thomas Ruf

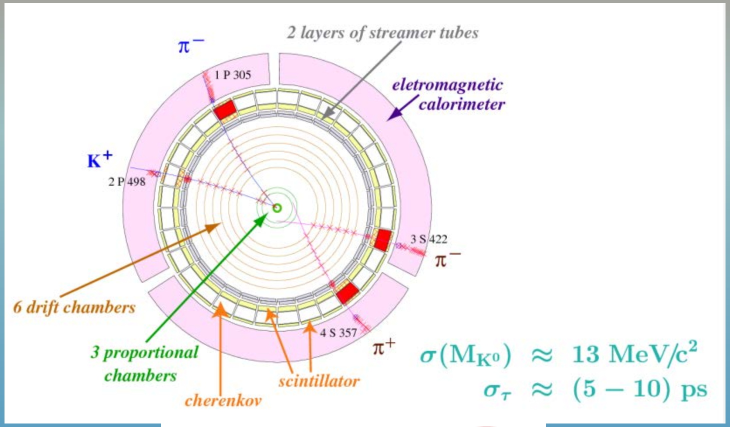
Workshop on T violation and CPT tests in neutral-meson systems, Mainz, April 15-16

- **The CPLEAR experimental setup**
- **(Some formalism)** for the afternoon
- **The CPLEAR results**
  - ***CP*, *T* and *CPT*, and others**

The CPLEAR Experiment PS195

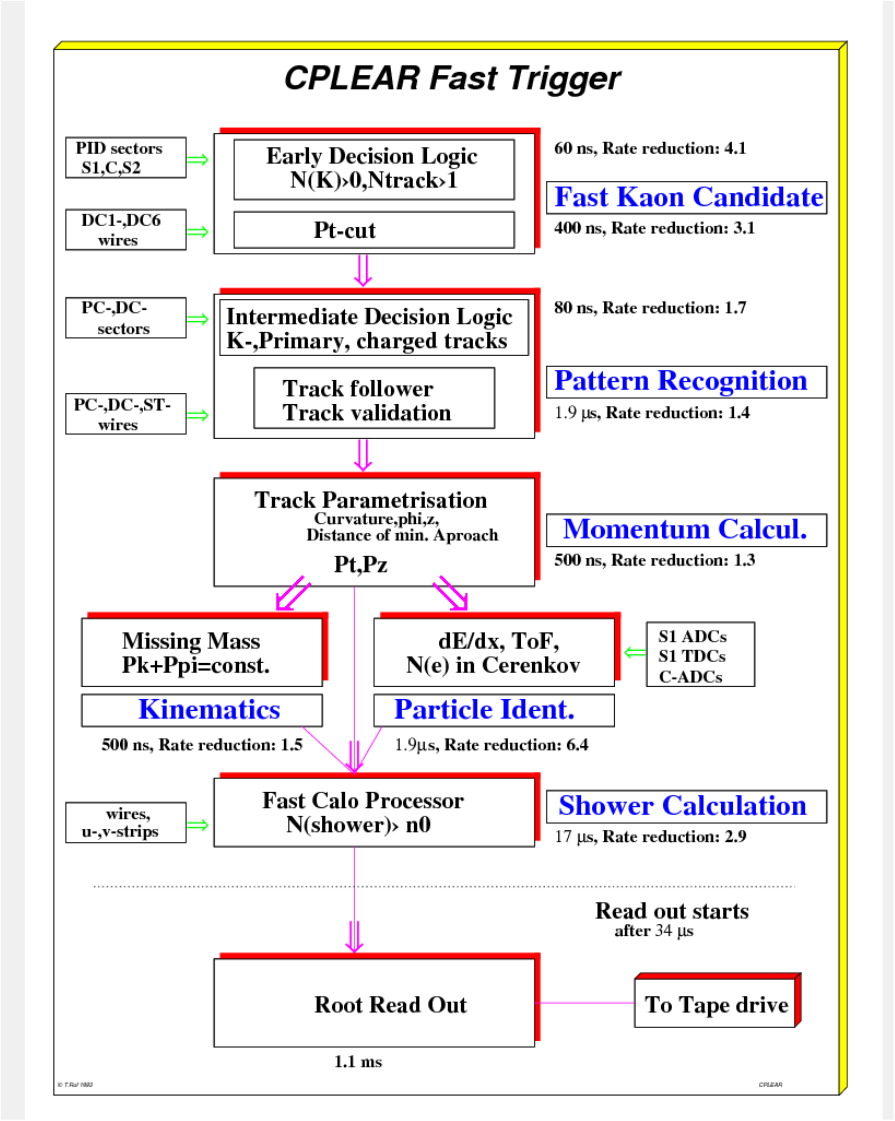
- Data taking from ~1990 until 8th July 1996, 08:21:33
- Using antiprotons from CERN de-accelarator LEAR
- 1MHz $\bar{p}$ rate, stopped in hydrogen target, $p\bar{p} \rightarrow K^{\pm}\pi^{\mp}K^{0}$
- Flavour of neutral kaon at production tagged by charge of charged kaon





The CPLEAR Experiment PS195

- Very sophisticated first and higher level trigger processing at high rates.



- $7 \times 10^7 \quad \pi^+\pi^- \quad t > 1\tau_S$
- $2 \times 10^6 \quad \pi^0\pi^0$
- $1.3 \times 10^6 \quad e\pi\nu$
- $5 \times 10^5 \quad \pi^+\pi^-\pi^0$
- $1.7 \times 10^4 \quad \pi^0\pi^0\pi^0$

Principle of the Experiment

- Measurement of time dependent decay rate asymmetries:

$$A_f(\tau) = \frac{R_{\overline{K}^0\to\overline{f}}(\tau) - R_{K^0\to f}(\tau)}{R_{\overline{K}^0\to\overline{f}}(\tau) + R_{K^0\to f}(\tau)}$$

acceptances cancel

Production and Tagging:

$$p\overline{p}\ (\text{at rest}) \to \begin{array}{ll} K^-\pi^+K^0 & 2\cdot 10^{-3} \\ K^+\pi^-\overline{K}^0 & 2\cdot 10^{-3} \end{array}$$

BR

The *Strangeness* of the neutral kaon K^0 ($\overline{K}^0$) at time $\tau = 0$ is defined by the charged kaon K^- (K^+).

Strong interaction

Tagging at decay time:

$K^0 \to e^+\nu\pi^-$ $\qquad$ $\overline{K}^0 \to e^-\overline{\nu}\pi^+$

The *Strangeness* of the neutral kaon K^0 ($\overline{K}^0$) at the decay time is defined by the charge of the lepton ($\Delta S = \Delta Q$).

Weak interaction

Principle of the Experiment

- **Measurement of time dependent decay rate asymmetries:**

$$A_f(\tau) = \frac{R_{\overline{K}^0 \to \overline{f}}(\tau) - R_{K^0 \to f}(\tau)}{R_{\overline{K}^0 \to \overline{f}}(\tau) + R_{K^0 \to f}(\tau)}$$

acceptances cancel

Production and Tagging:

$$p\bar{p} \text{ (at rest)} \to \begin{array}{ll} & \text{BR} \\ K^-\pi^+K^0 & 2 \cdot 10^{-3} \\ K^+\pi^-\overline{K}^0 & 2 \cdot 10^{-3} \end{array}$$

The *Strangeness* of the neutral kaon K^0 ($\overline{K}^0$) at time $\tau = 0$ is defined by the charged kaon K^- (K^+).

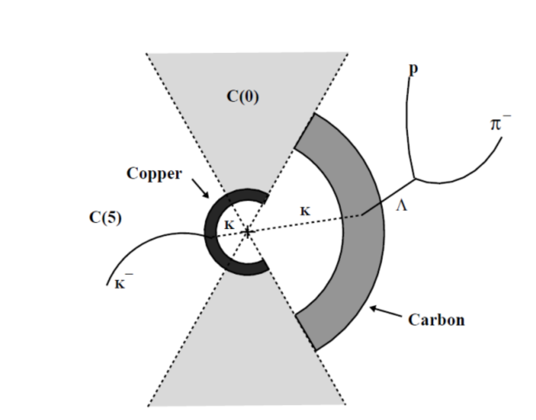
Tagging after production:

Through charge exchange with absorber material.

$$\overline{K}^0(p,n) \to \Lambda X$$

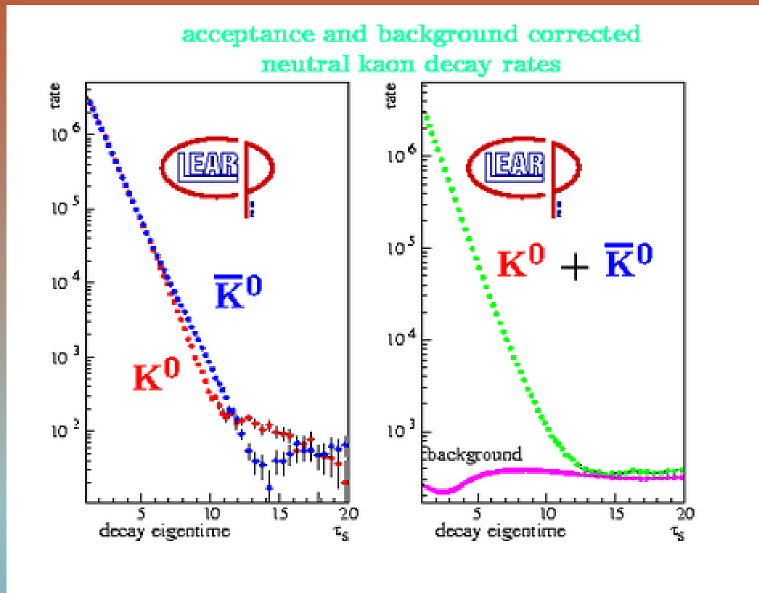
$$\hookrightarrow \Lambda \to p\pi^-$$

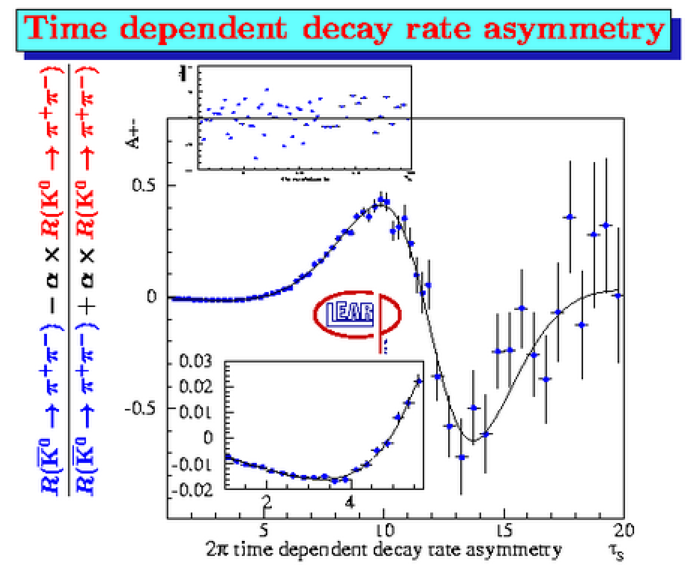
$$\overline{K}^0/K^0(p,n) \to K^-/K^+X$$



Strong interaction

2π Final State, Measurement of η_{+-}





$$A_{+-}(\tau) = -\frac{2|\eta_{+-}|e^{\frac{1}{2}(1/\tau_S - 1/\tau_L)\tau}\cos(\Delta m \cdot \tau - \varphi_{+-})}{1 + |\eta_{+-}|^2 e^{(1/\tau_S - 1/\tau_L)\tau}}$$

$$|\eta_{+-}| = (2.264 \pm 0.023_{sta.} \pm 0.026_{sys.} \pm 0.007_{\tau_S}) \times 10^{-3}$$
$$\varphi_{+-} = 43.19^\circ \pm 0.53^\circ_{sta.} \pm 0.28^\circ_{sys.} \pm 0.42^\circ_{\Delta m}$$

with $\Delta m = (530.1 \pm 1.4) \times 10^7 \hbar s^{-1}$ PDG '98

published in Phys. Lett. B 458 (1999) 545

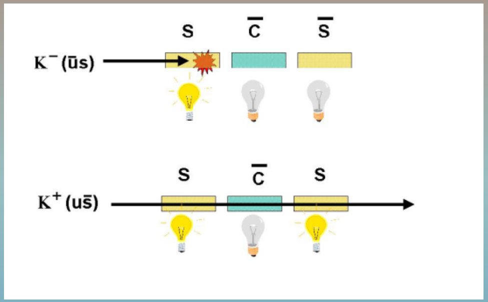
$$A_{2\pi} = \frac{R(\overline{K}^0 \to \pi\pi)(\tau) - \alpha \times R(K^0 \to \pi\pi)(\tau)}{R(\overline{K}^0 \to \pi\pi)(\tau) + \alpha \times R(K^0 \to \pi\pi)(\tau)}$$
$$= -2|\eta_{\pi\pi}|\cos(\Delta m\tau - \varphi_{\pi\pi})\frac{e^{\frac{1}{2}(\Gamma_S - \Gamma_L)\tau}}{1 + |\eta_{\pi\pi}|^2 e^{(\Gamma_S - \Gamma_L)\tau}}$$

- α is a free parameter in the fit, $\alpha = \frac{\varepsilon(K^+)}{\varepsilon(K^-)}[1 + 4\mathbb{R}(\varepsilon_T + \delta)]$ used as rate normalization in other decay channels

With Δm free in the fit, not assuming CPT,
$\Delta m = (524.0 \pm 4.4 \pm 3.3) \times 10^7 \hbar s^{-1}$

Rate Normalizations

- Different charged kaon reconstruction efficiencies due to non-perfect geometry
  - Solved by frequent changes of magnet polarity
- Different charged kaon reconstruction efficiencies due to strong interaction with matter, usage of threshold Cherenkov counter for kaon ID

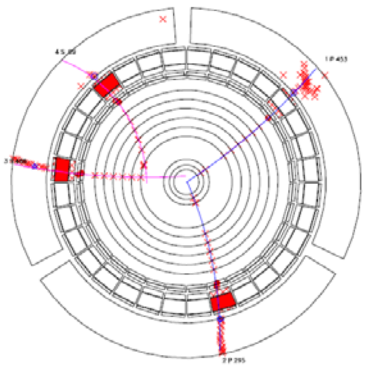


  - Normalization factor $\alpha = \frac{\varepsilon(K^+)}{\varepsilon(K^-)} \times [1 + 4\mathbb{R}(\varepsilon_T + \delta)]$ extracted from high statistics 2π channel, as function of charged kaon momentum.
  - K_L charge asymmetry, external to CPLEAR: $\delta_L = 2\mathbb{R}(\varepsilon_T + \delta - 2x_- - y)$
- Different $e^-\pi^+$ and $e^+\pi^-$ efficiencies
  - Obtained from pure electron and pion samples
- Note, for small asymmetries: $A_{phys} = A_{meas} - A_{detector}$

- y = CPT violation in semileptonic $\Delta S = \Delta Q$ allowed amplitudes
- x_- CP violation in $\Delta S = \Delta Q$ forbidden amplitudes

Physics with semileptonic decays

Analysis of $K^0 \to \pi^{\mp} e^{\pm} \nu$



- kinematical constraints
- electron identification based on:
- dE/dx in the scintillators,
- number of photo-electrons in the Čerenkov,
- number of hits in the calorimeter

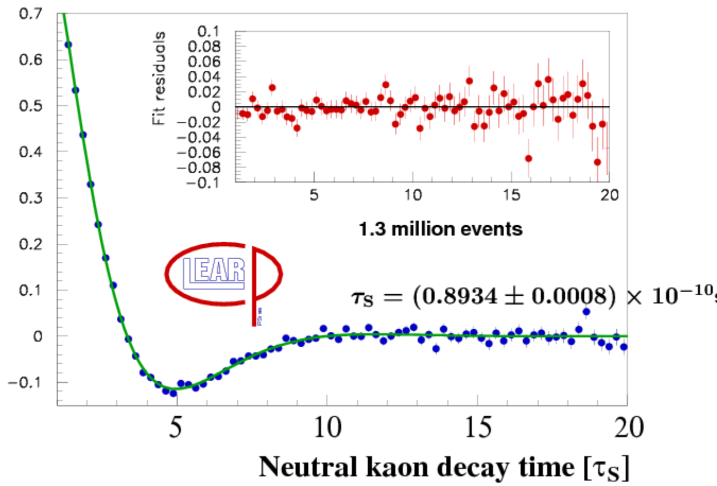
Precise measurement of the oscillation frequency Δm (setting $\Im(x_-)$=0) :

Δm and $\Im(x_-)$ are strongly correlated, >0.99.
With $\Delta m = (530.1 \pm 1.4) \times 10^7 \hbar s^{-1}$ obtain
$\Im(x_-) = (-0.8 \pm 3.5) \times 10^{-3}$

$K_L - K_S$ Mass Difference

$$A_{\Delta m} = \frac{N_{K^0 \leftarrow K^0, \overline{K}^0 \leftarrow \overline{K}^0} - N_{\overline{K}^0 \leftarrow K^0, K^0 \leftarrow \overline{K}^0}}{N_{K^0 \leftarrow K^0, \overline{K}^0 \leftarrow \overline{K}^0} + N_{\overline{K}^0 \leftarrow K^0, K^0 \leftarrow \overline{K}^0}}$$

$$= 2 \frac{e^{-\overline{\Gamma}\tau} \cos \Delta m \tau + 2\Im(x_-) e^{-\overline{\Gamma}\tau} \sin \Delta m \tau}{[1 + 2\Re(x_+)] e^{-\Gamma_S \tau} + [1 - 2\Re(x_+)] e^{-\Gamma_L \tau}}$$



$$\Delta m = (529.5 \pm 2.0_{stat.} \pm 0.3_{syst.}) \times 10^7 \hbar s^{-1}$$

$$\Delta m = (348.5 \pm 1.3) \times 10^{-9} \text{ eV}/c^2$$

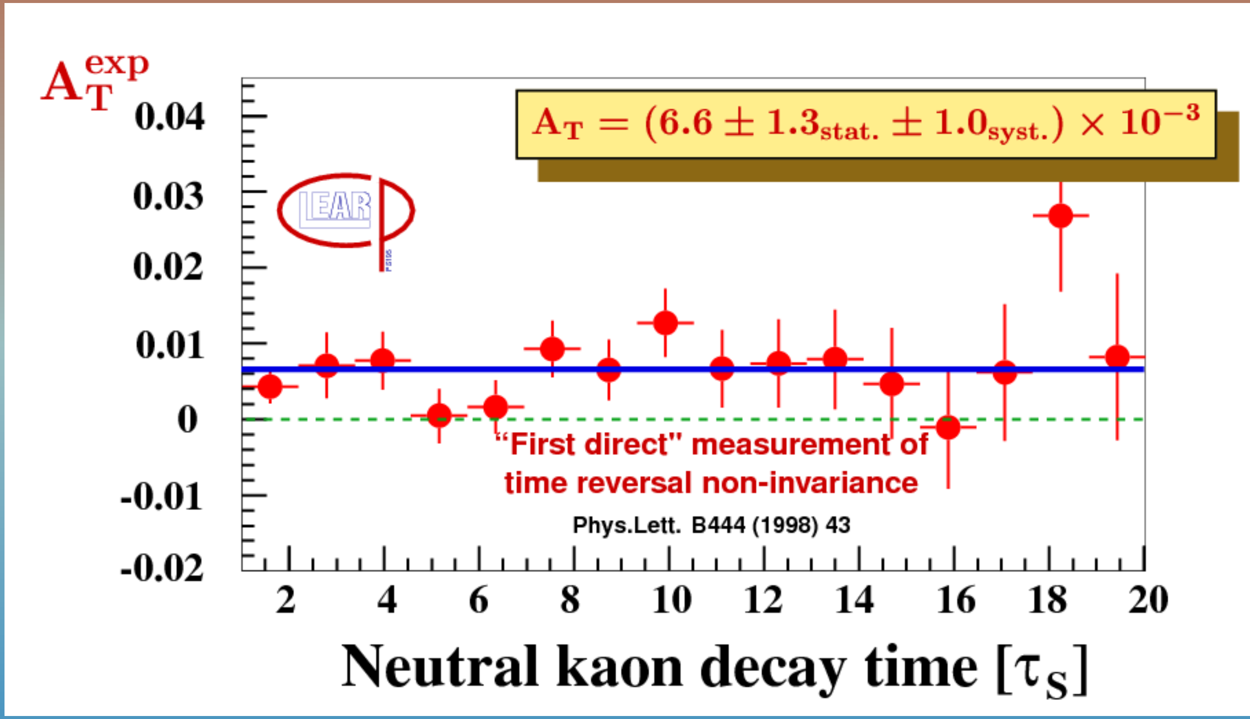
$\Delta S = \Delta Q$ violating decays or wrong tagging:

$$\Re e\, x_+ = (-1.8 \pm 4.1_{stat.} \pm 4.5_{syst.}) \times 10^{-3}$$

Best single measurements: Phys.Lett. B444 (1998) 38

T Violation, CPLEAR Result

$$A_T = \frac{R(\overline{K}^0 \to K^0) - R(K^0 \to \overline{K}^0)}{R(\overline{K}^0 \to K^0) + R(K^0 \to \overline{K}^0)} = 4\Re e\, \varepsilon_T$$



- CPT conservation in semileptonic decay amplitudes is assumed.
- ΔS=ΔQ forbidden decays allowed.

$$4\mathrm{Re}(\epsilon) = (6.2 \pm 1.4) \times 10^{-3}$$
$$\mathrm{Im}(x_+) = (1.2 \pm 1.9) \times 10^{-3}$$

"Direct" Measurement of T Violation

- $$A_T = \frac{\overline{R}_+(\tau) - R_-(\tau)}{\overline{R}_+(\tau) + R_-(\tau)} = 4\Re(\varepsilon_T) + 2\Re(y) + 2\frac{\Re(x_-)\sinh[\frac{t\Delta\Gamma}{2}] - \Im(x_+)\sin[\Delta m t]}{\cos[\Delta m t] - \cosh[\frac{t\Delta\Gamma}{2}]}$$

  Valid for $\frac{t}{\tau_S} \gg \mathcal{R}(x_-), \Im(x_+)$

- $$A^{exp} \approx A^{phys} + A^{K^+/K^-} + A^{e^+\pi^-/e^-\pi^+}$$

  from pure electron/pion samples

  from 2π asymmetry: $\alpha = \frac{\varepsilon(K^+)}{\varepsilon(K^-)}[1 + 4\mathcal{R}(\varepsilon_T + \delta)]$

  Rewriting using $\delta_l = 2\mathcal{R}(\varepsilon_T + \delta + y - x_-)$:

  $A_{K^\pm} = \frac{1-\alpha}{2}[\delta_l + 2\,\mathcal{R}(y) - \Re(x_-)\,]$

  CPLEAR specific

- $$A_T^{exp} - A^{K^+/K^-} - A^{e^+\pi^-/e^-\pi^+} = 4\Re(\varepsilon_T) + 4\Re(y) - 2\Re(x_-) - 2\frac{\Re(x_-)\sinh[\frac{t\Delta\Gamma}{2}] - \Im(x_+)\sin[\Delta m t]}{\cosh[\frac{t\Delta\Gamma}{2}] - \cos[\Delta m t]} = 4\Re(\varepsilon_T) + 4\Re(y) - 4\Re(x_-) \quad \text{for } t \to \infty$$

- For the final result, CPT violation in semileptonic decay amplitudes, y and x_- are set to zero.

$$4\mathrm{Re}(\epsilon) = (6.2 \pm 1.4) \times 10^{-3}$$
$$\mathrm{Im}(x_+) = (1.2 \pm 1.9) \times 10^{-3}$$

From a global fit: $\mathcal{R}(y - x_-) = (-0.2 \pm 0.3) \times 10^{-3}$

Direct Measurement of CPT Violation

$$A_{CPT} = \frac{\overline{R}_-(\tau) - R_+(\tau)}{\overline{R}_-(\tau) + R_+(\tau)}$$

$$\mathbf{A_{CPT}} = \frac{R\left(\overline{\mathrm{K}}^0 \to \overline{\mathrm{K}}^0\right) - R\left(\mathrm{K}^0 \to \mathrm{K}^0\right)}{R\left(\overline{\mathrm{K}}^0 \to \overline{\mathrm{K}}^0\right) + R\left(\mathrm{K}^0 \to \mathrm{K}^0\right)}$$

$$= -2\Re(y) - 2\frac{(2\Im(\delta) - \Im(x_+))\sin[\Delta m t] + (2\Re(\delta) - \Re(x_-))\sinh[\frac{t\Delta\Gamma}{2}]}{\cos[\Delta m t] + \cosh[\frac{t\Delta\Gamma}{2}]}$$

$$= -4\Re(\delta) + 2\Re(x_-) - 2\Re(y) \quad \text{for } t \to \infty$$

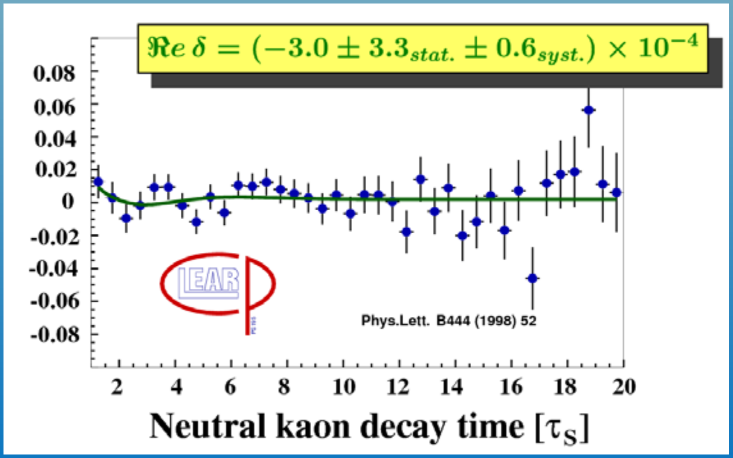
- More direct, using normalization from 2π:

$$A_T^{exp} + A_{CPT}^{exp} - 2A^{K^+/K^-} - 2A^{e^+\pi^-/e^-\pi^+}$$

$$= -4\Re(\delta) + \frac{4}{\cos[2\Delta m t] - \cosh[t\Delta\Gamma]}\Big[\Re(\delta) - \Im(\delta)\sin[2\Delta m t]$$

$$+2\cos[\Delta m t]\sinh[\frac{t\Delta\Gamma}{2}](\Re(x_-) - \Re(\delta)) + 2\sin[\Delta m t]\cosh[\frac{t\Delta\Gamma}{2}](\Im(\delta) - \Im(x_+))\Big]$$

$$= -8\Re(\delta) \quad \text{for } t \to \infty$$



Additional results from short lifetime region:

$$\Im m\,\delta = (1.5 \pm 2.3_{stat.} \pm 0.3_{syst.}) \times 10^{-2}$$
$$\Re e\,x_- = (0.2 \pm 1.3_{stat.} \pm 0.3_{syst.}) \times 10^{-2}$$
$$\Im m\,x_+ = (1.2 \pm 2.2_{stat.} \pm 0.3_{syst.}) \times 10^{-2}$$

$\Delta S = \Delta Q$:

$$\mathrm{Re}(\delta) = (2.9 \pm 2.6_{stat} \pm 0.6_{syst}) \times 10^{-4},$$
$$\mathrm{Im}(\delta) = (-0.9 \pm 2.9_{stat} \pm 1.0_{syst}) \times 10^{-3},$$

Some recent criticisms about the CPLEAR measurement of T violation

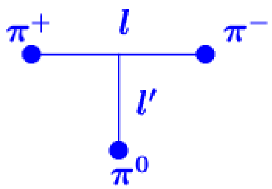
- A_T is also violating CP
  - So what ? $A_T \neq 0$ ⇒ T violation of H_{weak}
- ε_T becomes zero for $\Delta\Gamma = 0$
  - So what ? No T violation in mixing, no measurement
- A_T is independent of decay time
  - ? Don't understand why this is a problem
- My personal opinions:
  - Only criticism could be about the assumption of CPT conservation in the decay amplitudes. (Which by the way is also assumed in the recent Babar measurement.) However, with a global fit of all measurements, in can be shown that the contribution of direct CPT violation, $4\mathcal{R}(y) - 4\Re(x_{-})$, is negligible.
  - I find it more interesting to put limits on CPT violation, rather than performing "direct" observations of T violation. After all, the real sensation would be to measure a deviation from CPT invariance.

$$\varepsilon_B = -\frac{1}{4}\frac{\Gamma_{12}}{M_{12}}\sin(\phi_M - \phi_\Gamma)$$

H. J. Gerber, Eur. Phys. J. C **35**, 195 (2004)

3π Final State

$\mathcal{CP}$-violation in $\mathrm{K}^0 \to 3\pi$ Decays



$$\begin{array}{rlll} \pi^0\pi^0\pi^0: & I=1 & \mathcal{CP}=-1 & l=l'=0 \\ \pi^+\pi^-\pi^0: & I=1 & \mathcal{CP}=-1 & l=l'=0 \\ & I=0 & \mathcal{CP}=+1 & l=l'=1 \end{array}$$

Bose statistic, $\Delta \mathrm{I} = 1/2$ and phase space

$\mathrm{K_S} \to \pi^0\pi^0\pi^0$ is $\not{\mathcal{CP}}$: $\eta_{000} = \dfrac{A(\mathrm{K_S} \to \pi^0\pi^0\pi^0)}{A(\mathrm{K_L} \to \pi^0\pi^0\pi^0)}$

$$\mathrm{R}\left(\mathrm{K} \to \pi^+\pi^-\pi^0\right) \sim \mathrm{e}^{-\tau/\tau_\mathrm{L}} + \frac{\Gamma(\mathrm{K_S} \to \pi^+\pi^-\pi^0)}{\Gamma(\mathrm{K_L} \to \pi^+\pi^-\pi^0)} \mathrm{e}^{-\tau/\tau_\mathrm{S}}$$
$$\pm 2|\eta_{+-0}|\mathrm{e}^{-\frac{1}{2}(1/\tau_\mathrm{S}+1/\tau_\mathrm{L})\tau} \cos(\Delta m \tau + \varphi_{+-0})$$

$$\eta_{+-0} = \frac{\int d\Omega A(\mathrm{K_S} \to \pi^+\pi^-\pi^0) \times A^*(\mathrm{K_L} \to \pi^+\pi^-\pi^0)}{\int d\Omega |A(\mathrm{K_L} \to \pi^+\pi^-\pi^0)|^2}$$

Only the I=1 amplitude contributes to CP violation. By neglecting CPT violation in decay amplitudes:

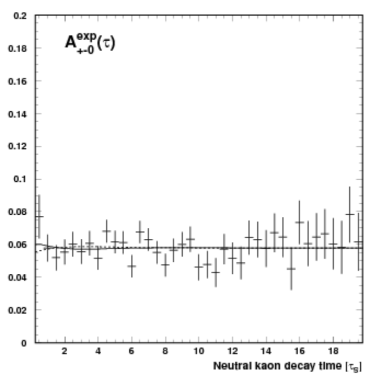
$$\eta_{3\pi} = \varepsilon_\mathrm{T} - \delta + \frac{i}{2}\left(\varphi_\Gamma - \arg \int\int A^*_{3\pi} \overline{A}_{3\pi} dX dY\right)$$

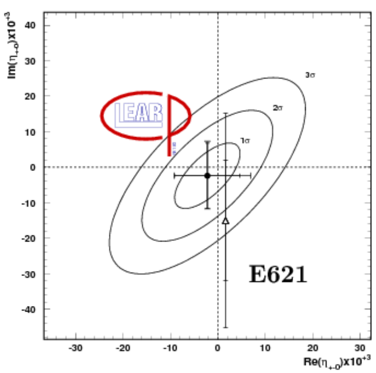
3π Final State CPLEAR Results

Search for $\mathcal{CP}$ violation in $K_S \to \pi^+\pi^-\pi^0$

$$A_{+-0}(\tau) = \frac{R_{\overline{K}^0 \to \pi^+\pi^-\pi^0}(\tau) - R_{K^0 \to \pi^+\pi^-\pi^0}(\tau)}{R_{\overline{K}^0 \to \pi^+\pi^-\pi^0}(\tau) + R_{K^0 \to \pi^+\pi^-\pi^0}(\tau)}$$

$$= C - 2e^{-\frac{1}{2}(\frac{1}{\tau_S} - \frac{1}{\tau_L})\tau} [\Re e\,(\eta_{+-0}) cos(\Delta m \tau) - \Im m\,(\eta_{+-0}) sin(\Delta m \tau)]$$





$0.5 \cdot 10^6$ selected events

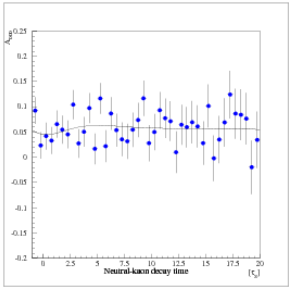
$$\Re e\,(\eta_{+-0}) = (-2 \pm 7_{sta.}\ {}^{+4}_{-1}\ {}_{sys.}) \times 10^{-3}$$
$$\Im m\,(\eta_{+-0}) = (-2 \pm 9_{sta.}\ {}^{+2}_{-1}\ {}_{sys.}) \times 10^{-3}$$

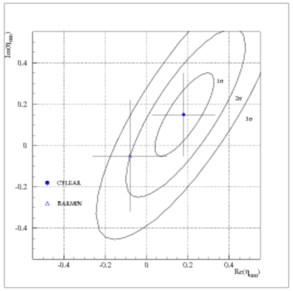
Published in Phys.Lett. B407 (1997) 193.

Search for $\mathcal{CP}$ violation in $K_S \to \pi^0\pi^0\pi^0$

$$A_{000}(\tau) = \frac{R_{\overline{K}^0 \to \pi^0\pi^0\pi^0}(\tau) - R_{K^0 \to \pi^0\pi^0\pi^0}(\tau)}{R_{\overline{K}^0 \to \pi^0\pi^0\pi^0}(\tau) + R_{K^0 \to \pi^0\pi^0\pi^0}(\tau)}$$

$$= C - 2e^{-\frac{1}{2}(\frac{1}{\tau_S} - \frac{1}{\tau_L})\tau} [\Re e\,(\eta_{000}) cos(\Delta m \tau) - \Im m\,(\eta_{000}) sin(\Delta m \tau)]$$





Final result with 17×10^3 selected signal events:

$$\Re e\,(\eta_{000}) = 0.18 \pm 0.14_{sta.} \pm 0.06_{sys.}$$
$$\Im m\,(\eta_{000}) = 0.15 \pm 0.20_{sta.} \pm 0.03_{sys.}$$

Fixing $\Re e\,(\eta_{000})$ to $\delta_L/2$:

$$\Im m\,(\eta_{000}) = -0.05 \pm 0.12_{sta.} \pm 0.05_{sys.}$$
$$B_{K_S \to \pi^0\pi^0\pi^0} < 1.9 \times 10^{-5} \quad (90\% CL)$$

Published in Phys.Lett. B425 (1998) 391.

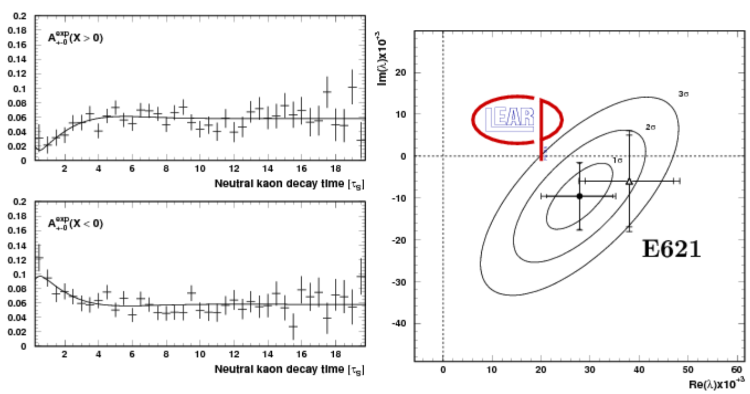
3π Final State, CP allowed

$\mathcal{CP}$ allowed decays of $K_S \rightarrow \pi^+\pi^-\pi^0$

$$A(X>0) = \frac{R_{\overline{K}^0 \rightarrow \pi\pi\pi}(p_{\pi^+} > p_{\pi^-}) - R_{K^0 \rightarrow \pi\pi\pi}(p_{\pi^+} > p_{\pi^-})}{R_{\overline{K}^0 \rightarrow \pi\pi\pi}(p_{\pi^+} > p_{\pi^-}) + R_{K^0 \rightarrow \pi\pi\pi}(p_{\pi^+} > p_{\pi^-})}$$

$$A(X<0) = \frac{R_{\overline{K}^0 \rightarrow \pi\pi\pi}(p_{\pi^+} < p_{\pi^-}) - R_{K^0 \rightarrow \pi\pi\pi}(p_{\pi^+} < p_{\pi^-})}{R_{\overline{K}^0 \rightarrow \pi\pi\pi}(p_{\pi^+} < p_{\pi^-}) + R_{K^0 \rightarrow \pi\pi\pi}(p_{\pi^+} < p_{\pi^-})}$$

$$= C - 2e^{-\frac{1}{2}(\frac{1}{\tau_S}-\frac{1}{\tau_L})\tau}[\Re e\,(\eta_{+-0} \pm \lambda)cos(\Delta m\tau) - \Im m\,(\eta_{+-0} \pm \lambda)sin(\Delta m\tau)]$$



$$\Re e\,(\lambda) = (28 \pm 7_{sta.} \pm 3_{sys.}) \times 10^{-3}$$
$$\Im m\,(\lambda) = (-10 \pm 8_{sta.} \pm 2_{sys.}) \times 10^{-3}$$
$$B_{K_S \rightarrow \pi^+\pi^-\pi^0} = (2.5\ ^{+1.3}_{-1.0}\ sta.\ ^{+0.5}_{-0.6}\ sys.) \times 10^{-7}$$

Published in Phys.Lett. B407 (1997) 193.

Unitarity, Bell-Steinberger, Indirect test of CPT, ...

- Back to CP violation in the $\pi\pi$ channel

$$\eta_{+-} = \varepsilon_T + \delta + \varepsilon' + \frac{|\overline{A}_0|^2 - |A_0|^2}{|A_0|^2 + |\overline{A}_0|^2} + \frac{i}{2}\left(\varphi_\Gamma - \arg A_0^* \overline{A}_0\right)$$
$$\eta_{+-} = \varepsilon_T + \delta_\perp + \varepsilon' + \frac{i}{2}\left(\varphi_\Gamma - \arg A_0^* \overline{A}_0\right)$$
$$\eta_{00} = \varepsilon_T + \delta_\perp - 2\varepsilon' + \frac{i}{2}\left(\varphi_\Gamma - \arg A_0^* \overline{A}_0\right)$$

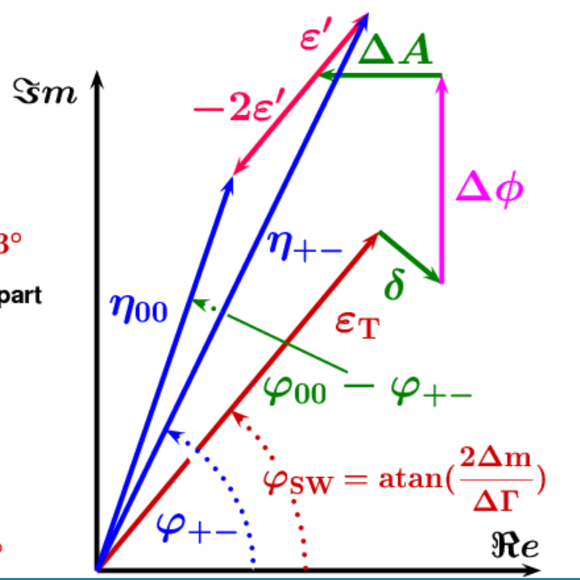
$$\delta_\perp \equiv \delta + \frac{|\overline{A}_0|^2 - |A_0|^2}{|A_0|^2 + |\overline{A}_0|^2}$$
$$\approx \delta - \frac{\Gamma_{22} - \Gamma_{11}}{2\Delta\Gamma}$$
$$= \frac{i\Delta\Gamma - 2\Delta m}{4\Delta m^2 + \Delta\Gamma^2}\left[(M_{22} - M_{11}) + \frac{\Delta m}{\Delta\Gamma}(\Gamma_{22} - \Gamma_{11})\right]$$

  - $\Delta\phi = \frac{1}{2}\left(\varphi_\Gamma - \arg A_0^* \overline{A}_0\right)$ CP violation through interference of mixing and decay.
    Major source of CP violation in the B^0 system

measurements of $\Im m\,(\eta_{3\pi})$, $\Im m\,(x)$, ...:

$$\Delta\phi = (-5.8 \pm 8.1) \times 10^{-6}$$
$$\cong \pm 0.15°$$

- $\varphi_{00} - \varphi_{+-}$
  ~~CPT~~ in $I = 2$ amplitude
  $\varphi_{00} - \varphi_{+-} = 0.62° \pm 1.03°$
  contribution of CP conserving part $< 0.3°$
- $\varphi_{+-} - \varphi_{SW}$
  ~~CPT~~ in mixing or in $I = 0$ amplitude
  $\varphi_{+-} - \varphi_{SW} = 0.1° \pm 0.6°$



Unitarity, Bell-Steinberger, Indirect test of CPT, ...

- Unique in the kaon system, explore additional constraints

$$\begin{aligned}\Gamma_{12}e^{i\varphi_\Gamma} &= A_\circ^*\overline{A}_\circ + A_2^*\overline{A}_2 + \int d\Omega A^*_{\pi\pi\gamma}\overline{A}_{\pi\pi\gamma} + \int d\Omega[A^*_{\pi^+\pi^-\pi^\circ}\overline{A}_{\pi^+\pi^-\pi^\circ} \\ &\quad + A^*_{\pi^\circ\pi^\circ\pi^\circ}\overline{A}_{\pi^\circ\pi^\circ\pi^\circ}] + \sum_{\vec{s}}\int d\Omega[A_+^*\overline{A}_+ + A_-^*\overline{A}_-] + \ldots\end{aligned}$$

$$\begin{aligned}\frac{\Gamma_{22}-\Gamma_{11}}{2\Delta\Gamma} &= -\Re\left(\frac{b_0}{a_0}\right) - |\frac{A_2}{A_0}|^2\Re\left(\frac{b_2}{a_2}\right) \\ &\quad -\frac{\Gamma_L}{\Gamma_S}\left[\mathrm{BR}(K_L\to 3\pi)\Re\left(\frac{b_1}{a_1}\right) + 2\mathrm{BR}(K_L\to\pi l\nu)\Re(y)\right] \\ &\approx -\Re\left(\frac{b_0}{a_0}\right)\end{aligned}$$

  by using measurements. Possible, because of limited number of final states.

  - $I = 2$ and direct emmission $\pi\pi\gamma$ amplitudes can be neglected

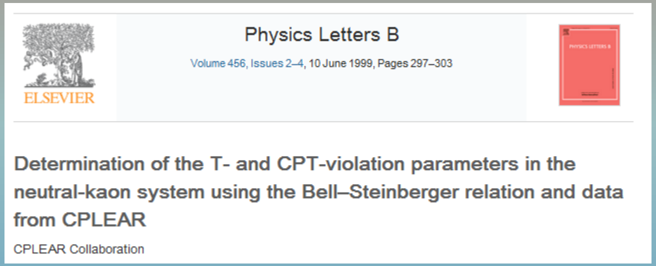
$$\begin{aligned}\varphi_\Gamma - \arg(A_\circ^*\overline{A}_\circ) &= \frac{\Gamma_L}{\Gamma_S}\Big(8\mathrm{BR}(K_L\to l^+\pi^-\nu)\Im(x_+) \\ &\quad -2\mathrm{BR}(K_L\to\pi^+\pi^-\pi^\circ)\Im(\varepsilon_T-\delta-\eta_{+-\circ}) \\ &\quad -2\mathrm{BR}(K_L\to\pi^\circ\pi^\circ\pi^\circ)\Im(\varepsilon_T-\delta-\eta_{\circ\circ\circ})\Big)\end{aligned}$$

  - = phase difference of $I = 0$ and the mixing amplitudes (Major source of CP violation in the B^0 system)

- CPLEAR contributions: improved limits on η_{000} and η_{+-0} and $\Delta S = \Delta Q$ forbidden decays

Putting all together

- Adding external measurement of $\boldsymbol{\delta_l}$
  - $\mathcal{R}(\varepsilon_T) = (164.9 \pm 2.5_{stat} \pm 0.1_{sys}) \times 10^{-5}$
  - $\mathfrak{I}(\delta) = (-2.4 \pm 5.0_{stat} \pm 0.1_{sys}) \times 10^{-5}$
  - $\mathcal{R}(\delta) = (-2.4 \pm 2.7_{stat} \pm 0.6_{sys}) \times 10^{-4}$
  - $\mathcal{R}(y) = (0.3 \pm 3.0_{stat} \pm 0.6_{sys}) \times 10^{-3}$
  - $\mathcal{R}(x_-) = (-0.5 \pm 3.0_{stat} \pm 0.3_{sys}) \times 10^{-3}$
  - $\mathfrak{I}(x_+) = (-2.0 \pm 2.6_{stat} \pm 0.5_{sys}) \times 10^{-3}$
  - $\mathcal{R}(y + x_-) = (-0.2 \pm 0.3) \times 10^{-3}$


Physics Letters B

Volume 456, Issues 2–4, 10 June 1999, Pages 297–303

Determination of the T- and CPT-violation parameters in the neutral-kaon system using the Bell–Steinberger relation and data from CPLEAR

CPLEAR Collaboration

- **T violation established with 66σ !**
- **Translating CPTV in mixing to mass and lifetime differences of neutral kaons:**

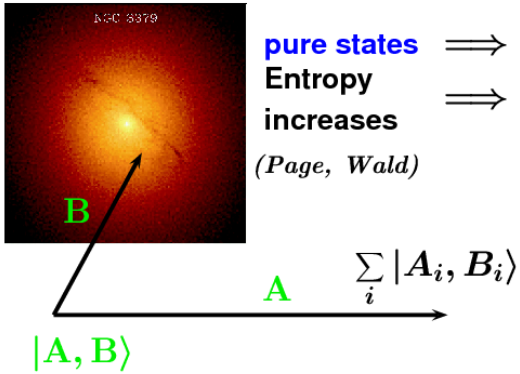
$$M_{\bar{K}^0} - M_{K^0} = (1.5 \pm 2.0) \times 10^{-18}\ \mathrm{GeV}$$
$$\Gamma_{\bar{K}^0} - \Gamma_{K^0} = (-3.9 \pm 4.2) \times 10^{-18}\ \mathrm{GeV}$$

assuming no CPTV in decay amplitudes $\Rightarrow$ $M_{\bar{K}^0} - M_{K^0} = (0.7 \pm 2.8) \times 10^{-19}\ \mathrm{GeV}$

Arrow of Time

Quantum Gravitation

Macroscopic: Loss of information at the horizon of a black hole (*Hawking*)



pure states $\Longrightarrow$ mixed States

Entropy increases $\Longrightarrow$ Arrow of Time, $\mathcal{CPT}$-violation

(Page, Wald)

Microscopic: Could fluctuations of the space-time (virtual black holes) be responsible for the Arrow of Time ?

Consequence: Loss of quantum coherence

Could be tested in the neutral kaon system using Quantum Mechanics of open systems $\frac{\partial}{\partial t}\rho = i[\rho, H] + \delta H \rho$

Ellis, Mavromatos, Nanopoulos, ...

Precise measurements of K^0 and $\overline{K}^0$ decay rates as function of the decay time yield information about the loss of quantum coherence

Open Quantum Mechanics

Space-Time fluctuations cause loss of quantum coherence

$$\dot{\rho} = i[\rho, H] + \delta H \rho$$

With unitarity and $\Delta S = \Delta Q \Longrightarrow \alpha, \beta, \gamma$

Best guess: $\mathcal{CPT}$-violation $\sim \mathcal{O}\left(\frac{M_K^2}{M_{Pl}}\right)$

otherwise effect too small to be off any importance

Some examples:

$$A_{2\pi}(\tau) = \Big\{ 2|\varepsilon|\cos\phi + 4\widehat{\beta}\sin\phi\cos\phi - 8\widehat{\alpha}\sin\phi\cos\phi(|\varepsilon|\sin\phi - 2\widehat{\beta}\cos^2\phi)$$
$$-2\sqrt{|\varepsilon|^2 + 4\widehat{\beta}^2\cos^2\phi}\; e^{\frac{1}{2}(1/\tau_S - 1/\tau_L)\tau}\left[\cos(\Delta m\tau - \phi - \delta\phi) + 2\frac{\widehat{\alpha}}{\tan\phi}X_\alpha\right]\Big\}$$
$$/\left\{1 + e^{(1/\tau_S - 1/\tau_L)\tau}\left[\widehat{\gamma} + |\varepsilon|^2 - 4\widehat{\beta}^2\cos^2\phi - 4\widehat{\beta}|\varepsilon|\sin\phi\right]\right\}$$

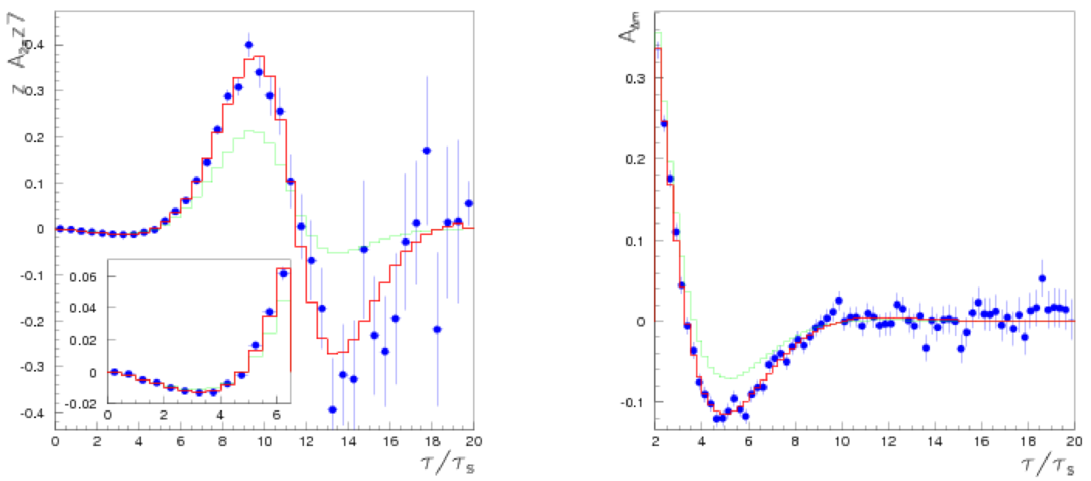
$$A_{\Delta m}(\tau) = \frac{2e^{-\frac{1}{2}(1/\tau_S + 1/\tau_L)\tau}\left[\cos\Delta m\tau + \frac{2\widehat{\alpha}}{\tan\phi}(\sin\Delta m\tau - \Delta m\tau\cos\Delta m\tau)\right]}{e^{-\tau/\tau_L}(1 + 2\widehat{\gamma}) + e^{-\tau/\tau_S}(1 - 2\widehat{\gamma})}$$

with $\widehat{\alpha}, \widehat{\beta}, \widehat{\gamma}$ scaled variables $\alpha/\Delta\Gamma, \beta/\Delta\Gamma, \gamma/\Delta\Gamma$

Is the observed $\mathcal{CP}$-violation in the kaon system entirely explained by $\mathcal{CPT}$-violation ?

$M_{Pl} = \sqrt{\hbar c/G_N} = 1.22 \times 10^{19}\ \mathrm{GeV}/c^2 \quad = 22\ \mu g$

CPLEAR Result



additional constraints: η_{+-} measured at long lifetimes; δ_l measured at long lifetimes

perform global fit:

$$\begin{aligned}
\alpha &= (-0.5 \pm 2.8 &< 4.0) \times 10^{-17} \;\; \mathrm{GeV}/c^2 \\
\beta &= (2.5 \pm 2.3 &< 2.3) \times 10^{-19} \;\; \mathrm{GeV}/c^2 \\
\gamma &= (1.1 \pm 2.5 &< 3.7) \times 10^{-21} \;\; \mathrm{GeV}/c^2 \\
|\varepsilon| &= (2.32 \pm 0.06) & \times 10^{-3}
\end{aligned}$$

Phys.Lett.B 364 (1995) p239.

Ellis/Mavromatos, private communication:

With these limits, our model is not anymore interesting.

EPR Correlations

EPR Paradox

A. Einstein, B. Podolsky and N. Rosen, Phys. Rev. 47 (1935) 777.

Look at $p\bar{p}_{\text{at rest}} \rightarrow K^0\overline{K}^0$

2-particle wave function: $|\psi\rangle = |K^0{}_{\vec{p}}\rangle|\overline{K}^0{}_{-\vec{p}}\rangle \mp |K^0{}_{-\vec{p}}\rangle|\overline{K}^0{}_{\vec{p}}\rangle$

'−' $\equiv J^{PC} = 1^{--}$ $\Upsilon(4S) \rightarrow B^0\bar{B}^0$

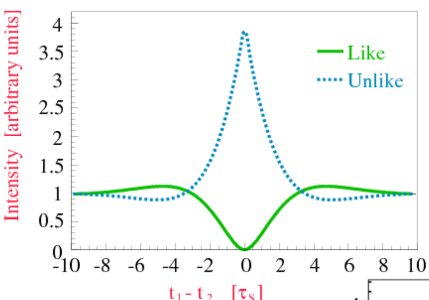
'+' $\equiv J^{PC} = 0^{++},\ 2^{++}$

$\frac{(0^{++},2^{++})}{1^{--}} = 7.4\%$ Phys.Lett. B403 (1997) 383.

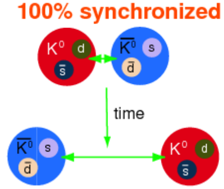
Strangeness correlations for $J^{PC} = 1^{--}$:

like $\equiv$ K^0K^0 or $\overline{K}^0\overline{K}^0$ at times t_1 and t_2

unlike $\equiv$ $\overline{K}^0K^0$ or $K^0\overline{K}^0$ at times t_1 and t_2

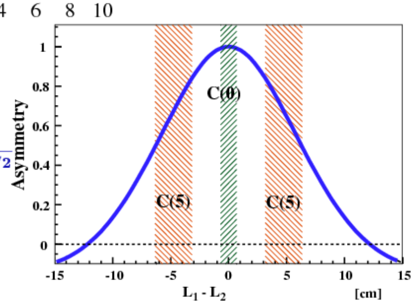


The two kaons oscillate 100% synchronized !



$$A = \frac{\text{unlike} - \text{like}}{\text{unlike} + \text{like}} = \frac{2\cos\{\Delta m(t_2 - t_1)\}}{e^{-\Delta\Gamma(t_2-t_1)/2} + e^{\Delta\Gamma(t_2-t_1)/2}}$$

without long distance correlations: $A = 0$

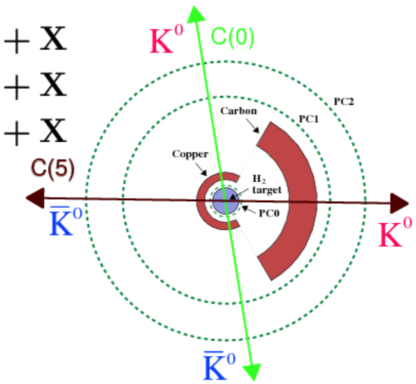


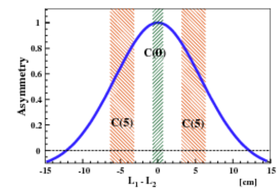
Another Strangeness Tagging Method

$K^0 + N \rightarrow K^+ + X$

$\overline{K}^0 + N \rightarrow K^- + X$

$\overline{K}^0 + N \rightarrow \Lambda + X$





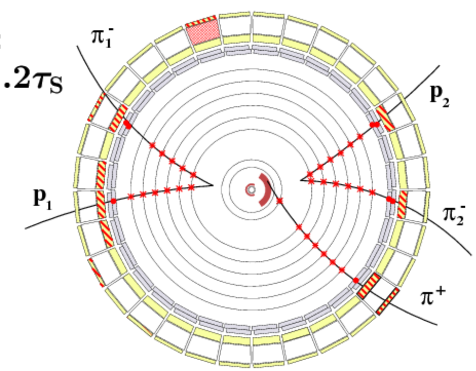
Position of the absorbers allows to measure two constellations:

C(0) $t_1 \approx t_2$

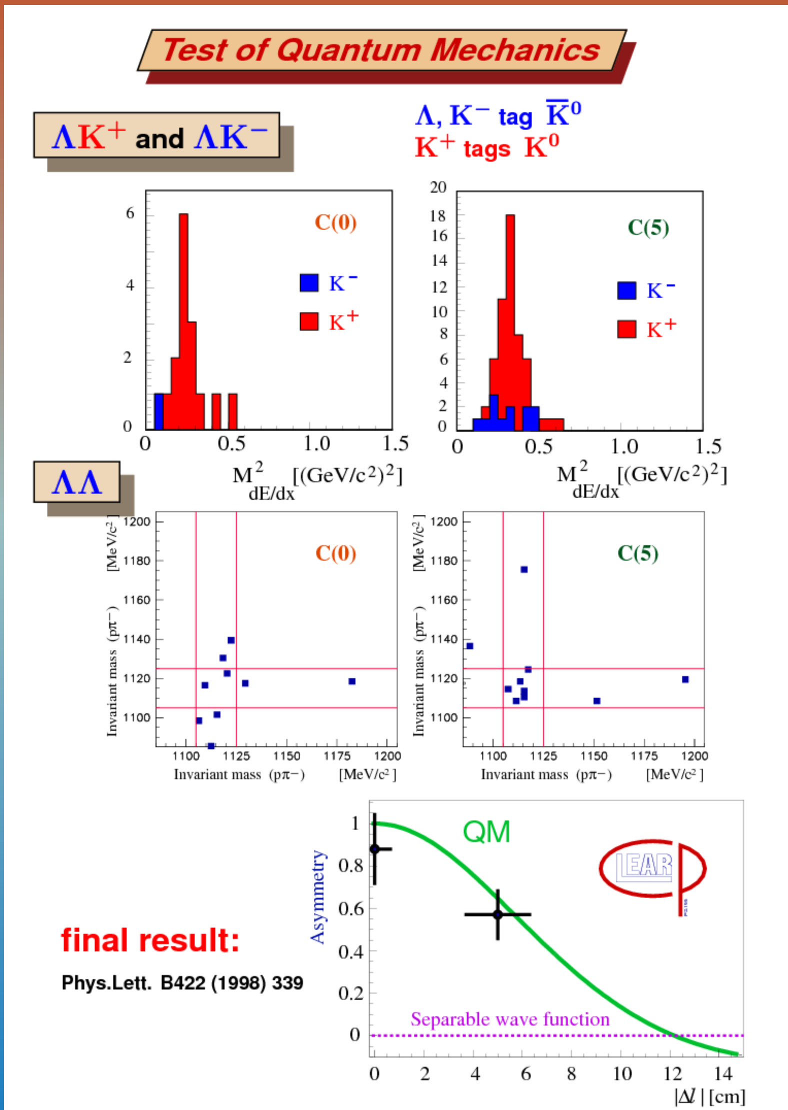
C(5) $|t_1 - t_2| \approx 1.2\tau_S$

$\Lambda\Lambda(\overline{K}^0\overline{K}^0)$ event:

with $|t_1 - t_2| \approx 1.2\tau_S$



EPR Correlations



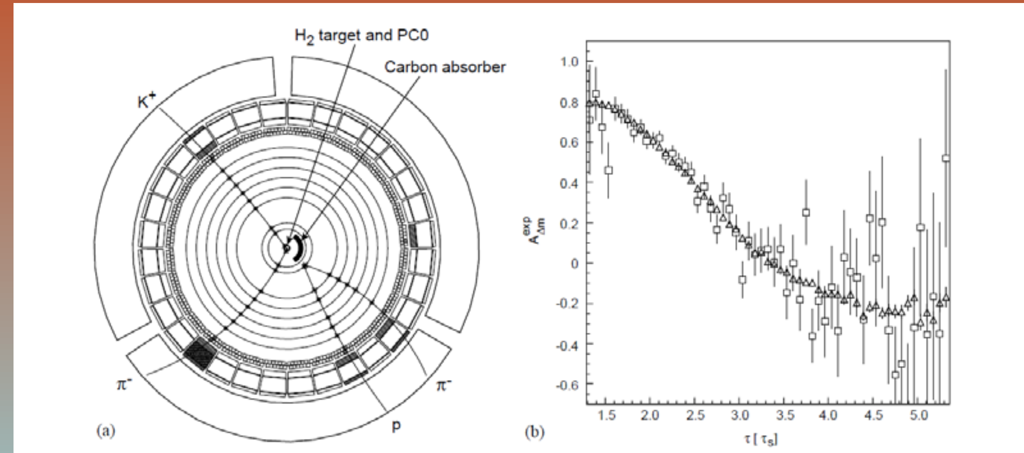


Fig. 41. (a) Display of an event (transverse view): the $K^+\pi^-$ pair produced in a $\bar{p}p$ annihilation together with a $\bar{K}^0$ is shown. The $\bar{K}^0$, interacting in the carbon absorber, produces a Λ subsequently decaying to $p\pi^-$ (also shown). (b) $A^{exp}_{\Delta m}(\tau)$: the data points (squares) of the $(K^- + \Lambda)$ sample are fitted with the simulated asymmetries (triangles), see text.

$$\Delta m = (534.3 \pm 6.3_{stat} \pm 2.5_{syst}) \times 10^7\ \hbar/s$$

Strangeness tagging through strong interactions. Does not require any assumptions about CPT violation in decay amplitudes.

Phys.Lett. B 422 (1998), 339

Conclusions

- The kaon system exhibits all kinds of CP violation
  - T and CPT violation in mixing
  - CP violation through interference of decay amplitudes, called direct CP violation, ε'
  - CP violation through interference of mixing and decay amplitudes
- CPLEAR had been the pionneer experiment for precise T & CPT measurements using flavour tagging at production
  - **Many textbook measurements**
  - **Most measurements are still among the world best measurements**
- **CPT tests in the kaon system put world's best limits on mass and lifetime differences of particles and antiparticles**
- Other CPLEAR achievements:
  - Strangeness tagging via strong interactions instead of weak decays used to test EPR entanglement in neutral meson system (before B-factories)
  - New method to measure regeneration

Formalism

Some Formalism

- Wigner-Weisskopf formalism, $\mathcal{H}_{weak} \ll \mathcal{H}_{st} + \mathcal{H}_{em}$
  - Stationary states $|\mathrm{K}^0>$ and $|\overline{\mathrm{K}}^0>$ are mass eigenstates of the strong and electromagnetic interactions: $(\mathcal{H}_{st} + \mathcal{H}_{em})|\mathrm{K}^0> = m_0|\mathrm{K}^0>$

$$|\psi(t)\rangle = a(t)|\mathrm{K}^0\rangle + b(t)|\overline{\mathrm{K}}^0\rangle$$

  - "Effective" Schrödinger equation: $i\frac{\partial}{\partial\tau}\begin{pmatrix} a(\tau) \\ b(\tau) \end{pmatrix} = \Lambda \begin{pmatrix} a(\tau) \\ b(\tau) \end{pmatrix}$

  - Parametrization of Λ, avoiding unnecessary phase conventions:

not adopted by CPLEAR in general

$$\Lambda = \begin{pmatrix} M_{11} & M_{12}\mathrm{e}^{\mathrm{i}\varphi_{\mathrm{M}}} \\ M_{12}\mathrm{e}^{-\mathrm{i}\varphi_{\mathrm{M}}} & M_{22} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11} & \Gamma_{12}\mathrm{e}^{\mathrm{i}\varphi_{\Gamma}} \\ \Gamma_{12}\mathrm{e}^{-\mathrm{i}\varphi_{\Gamma}} & \Gamma_{22} \end{pmatrix}$$

hermitian part = mass matrix, anti-hermitian part = decay matrix

  - Matrix elements are given by:

$$M_{ij} = m_o\delta_{ij} + \langle i|\mathcal{H}_{weak}|j\rangle + \sum_f \mathcal{P}r\left(\frac{\langle i|\mathcal{H}_{weak}|f\rangle\langle f|\mathcal{H}_{weak}|j\rangle}{m_o - E_f}\right)$$

$$\Gamma_{ij} = 2\pi\sum_f \langle i|\mathcal{H}_{weak}|f\rangle\langle f|\mathcal{H}_{weak}|j\rangle\delta(m_o - E_f)$$

Some Formalism II

$$^{\dagger}\mathcal{CP}|K^0\rangle = -e^{i\phi_C}|\overline{K^0}\rangle \qquad \mathcal{CP}|\overline{K^0}\rangle = -e^{-i\phi_C}|K^0\rangle$$
$$\mathcal{T}|K^0\rangle = e^{i\phi_T}|K^0\rangle \qquad \mathcal{T}|\overline{K^0}\rangle = e^{i\bar{\phi}_T}|\overline{K^0}\rangle$$

- Discrete Symmetries
  - CPT invariance of $\mathcal{H}_{weak}$ requires:
    - $M_{11} = M_{22}$ and $\Gamma_{11} = \Gamma_{22}$ [*CPT(CPT)=1* $\Rightarrow 2\phi_C = \bar{\phi}_T - \phi_T$]
    - **Equal masses and lifetimes of K^0 and $\bar{K}^0$**
  - From T invariance of $\mathcal{H}_{weak}$ follows:
    - $|\Lambda_{12}| = |\Lambda_{21}|$ and $\phi_C = -\phi_\Gamma + n \cdot \pi$
      identical to $\sin(\varphi_M - \varphi_\Gamma) = 0$
      T violation caused by phase difference between Γ_{12} and M_{12}
  - From CP invariance of $\mathcal{H}_{weak}$ follows:
    - $|\Lambda_{12}| = |\Lambda_{21}|$ and $\Lambda_{11} = \Lambda_{22}$
    - **Which means, if T or CPT is violated, then also CP is violated.**

† To look for a symmetry violation makes only sense if there exists a part of the Hamilton operator which is invariant under this symmetry. This allows to define the symmetry operator.

Some Formalism III

- Time Dependence
  - Solving the "effective" Schrödinger equation

Eigenvalues $\lambda_{L,S}$

$$|\psi(\tau)\rangle = T(t) \cdot |\psi(0)\rangle$$

$$T(t) = \begin{pmatrix} \frac{\Lambda_{22}-\Lambda_{11}}{\Delta\lambda} f_-(t) + f_+(t) & -2\frac{\Lambda_{12}}{\Delta\lambda} f_-(t) \\ -2\frac{\Lambda_{21}}{\Delta\lambda} f_-(t) & -\frac{\Lambda_{22}-\Lambda_{11}}{\Delta\lambda} f_-(t) + f_+(t) \end{pmatrix}$$

$$T(t_1) \cdot T(t_2) = T(t_2) \cdot T(t_1) = T(t_1 + t_2)$$

$$\lambda_{L,S} = \frac{\Lambda_{11} + \Lambda_{22}}{2} \pm \sqrt{\frac{(\Lambda_{22} - \Lambda_{11})^2}{4} + \Lambda_{12}\Lambda_{21}}$$

$$\lambda_L - \lambda_S = \Delta\lambda = \sqrt{(\Lambda_{22} - \Lambda_{11})^2 + 4\Lambda_{12}\Lambda_{21}}$$

$$f_\pm(t) = \frac{e^{-i\lambda_S t} \pm e^{-i\lambda_L t}}{2}$$

$$\overline{\Gamma} = \frac{\Gamma_S + \Gamma_L}{2}$$

$$\Delta m = m_L - m_S$$
$$\Delta\Gamma = \Gamma_S - \Gamma_L$$

  - For small T and CPT violation, $\Delta\Lambda = 2M_{12} + i\Gamma_{12}$ it is convenient to write:

$m_L > m_S$ but $\Gamma_S > \Gamma_L$

$$\frac{\Lambda_{22} - \Lambda_{11}}{\Delta\lambda} = -2\frac{i\Delta\Gamma - 2\Delta m}{4\Delta m^2 + \Delta\Gamma^2}(\Lambda_{22} - \Lambda_{11}) = -2\delta$$

$$\frac{\Lambda_{21}}{\Delta\lambda} \approx -\frac{e^{-i\varphi_\Gamma}}{2}(1 - 2\varepsilon_T) \qquad \frac{\Lambda_{12}}{\Delta\lambda} \approx -\frac{e^{i\varphi_\Gamma}}{2}(1 + 2\varepsilon_T)$$

$$\varepsilon_T \equiv \frac{2i\Delta m^2 + \Delta m\Delta\Gamma}{4\Delta m^2 + \Delta\Gamma^2}\sin(\varphi_M - \varphi_\Gamma)$$

$$\delta \equiv \frac{i\Delta\Gamma - 2\Delta m}{4\Delta m^2 + \Delta\Gamma^2}(\Lambda_{22} - \Lambda_{11})$$

$$\varepsilon_T \equiv \sin(\varphi_{SW}) \frac{|\Lambda_{12}|^2 - |\Lambda_{21}|^2}{\Delta\Gamma\Delta m} e^{i\varphi_{SW}}$$

$$\delta \equiv \cos(\varphi_{SW}) \frac{\Lambda_{22} - \Lambda_{11}}{\Delta\Gamma} e^{i(\varphi_{SW} + \pi/2)}$$

$$\varphi_{SW} = \mathrm{atan}(2\Delta m/\Delta\Gamma)$$

(
  - In case of $\Gamma_{12} \ll M_{12}$:

$$\varepsilon_b = -\frac{1}{4}\frac{\Gamma_{12}}{M_{12}}\sin(\phi_M - \phi_\Gamma) \qquad \delta_B = \frac{\Lambda_{22} - \Lambda_{11}}{4M_{12}}$$
)

Some Formalism IV

- Decay rate into CP eigenstates, $\boldsymbol{2\pi}$ $(\boldsymbol{CP = +1})$ example
  - $\boldsymbol{A = \mathrm{A}(K^0 \to 2\pi)}$ and $\boldsymbol{\bar{A} = \mathrm{A}(\bar{K}^0 \to 2\pi)}$

$$R_{\pi\pi}(t) = \left|\frac{\Lambda_{21}}{\Delta\lambda}\left(e^{-i\lambda_L t}\left(r_L A_{\pi\pi} + \overline{A}_{\pi\pi}\right) - e^{-i\lambda_S t}\left(r_S A_{\pi\pi} + \overline{A}_{\pi\pi}\right)\right)\right|^2$$

$$\eta_{\pi\pi} = -\frac{1 + r_L \frac{A_{\pi\pi}}{\overline{A}_{\pi\pi}}}{1 + r_S \frac{A_{\pi\pi}}{\overline{A}_{\pi\pi}}}$$

$$r_S = \frac{2\Lambda_{12}}{\Lambda_{22} - \Lambda_{11} - \Delta\lambda} = -\frac{\Lambda_{22} - \Lambda_{11} + \Delta\lambda}{2\Lambda_{21}}$$
$$r_L = \frac{2\Lambda_{12}}{\Lambda_{22} - \Lambda_{11} + \Delta\lambda} = -\frac{\Lambda_{22} - \Lambda_{11} - \Delta\lambda}{2\Lambda_{21}}$$

The p/q used by the B-factories extended to account for CPT violation

$$R_{\pi\pi}(t) = B_{\pi\pi}\left[\mathrm{e}^{-\Gamma_S\tau} + |\eta_{\pi\pi}|^2\mathrm{e}^{-\Gamma_L\tau} + 2|\eta_{\pi\pi}|\mathrm{e}^{-\overline{\Gamma}\tau}\cos(\Delta m\tau - \varphi_{\pi\pi})\right]$$
$$\overline{R}_{\pi\pi}(t) = \overline{B}_{\pi\pi}\left[\mathrm{e}^{-\Gamma_S\tau} + |\overline{\eta}_{\pi\pi}|^2\mathrm{e}^{-\Gamma_L\tau} - 2|\overline{\eta}_{\pi\pi}|\mathrm{e}^{-\overline{\Gamma}\tau}\cos(\Delta m\tau - \overline{\varphi}_{\pi\pi})\right]$$

No assumptions about small CP violation yet

$$\overline{\eta}_{\pi\pi} = -\frac{r_S}{r_L}\eta_{\pi\pi} \qquad \overline{B}_{\pi\pi} = |r_L|^2 B_{\pi\pi}$$

Some 2nd order terms become important for long decay times

- With small CP violation
  $\boldsymbol{\overline{\eta}_{\pi\pi} \approx (1 - 4\delta)\eta_{\pi\pi} \approx \eta_{\pi\pi}}$ **and** $\boldsymbol{\overline{B}_{\pi\pi} \approx [1 + 4\Re(\varepsilon + \delta)]B_{\pi\pi}}$

CPLEAR

$$A_{\pi\pi} := \frac{\overline{R}_{\pi\pi}(t) - \frac{\overline{B}_{\pi\pi}}{B_{\pi\pi}} \times R_{\pi\pi}(t)}{\overline{R}_{\pi\pi}(t) + \frac{\overline{B}_{\pi\pi}}{B_{\pi\pi}} \times R_{\pi\pi}(t)} = -2|\eta_{\pi\pi}|\frac{\cos(\Delta m t - \varphi_{\pi\pi})}{e^{-\frac{1}{2}\Delta\Gamma t} + |\eta_{\pi\pi}|^2 e^{\frac{1}{2}\Delta\Gamma t}}$$

- Most of the work is now to estimate the different contributions to $\boldsymbol{\eta_{\pi\pi}}$

Some Formalism V

- Decay Amplitudes for CP eigenstates,
  CPT conserving and non-conserving:
  - In case of CPT conservation in the decay, and f being an eigenstate of strong and electroweak interaction, i.e. one decay amplitude:

$$\bar{A} = n_{CP} e^{i2\delta} A^* \qquad CP\,|f> = n_{CP}|f>$$

  - $f = 2\pi\ I = 0, CP = +1,\ \bar{A} - e^{i2\delta} A^*$ is CPT violating

$$\begin{aligned} A &= (a+b)\,e^{i\delta} \quad \overline{A} = (a^*-b^*)\,e^{i\delta} \\ |A|^2 - |\overline{A}|^2 &= 4\Re(ab^*) \quad \text{CPT violation} \end{aligned}$$

$$y = \frac{b}{a} \qquad \frac{|A|^2 - |\overline{A}|^2}{|A|^2 + |\overline{A}|^2} = 2\Re(y)$$

  - Otherwise: $\bar{A}_{+-} = \sqrt{\frac{1}{3}} e^{i\delta_2}(a_2^* - b_2^*) + \sqrt{\frac{2}{3}} e^{i\delta_0}(a_0^* - b_0^*)$
  - And then even in case of CPT conservation

$$|A_{+-}|^2 - |\bar{A}_{+-}|^2 = -\frac{4}{3}\sqrt{2}\sin(\delta_0 - \delta_2)\sin(\psi_0 - \psi_2)|a_0||a_2| \neq 0$$

Semileptonic Amplitudes and Rates

- Amplitudes

$$\begin{aligned} A_+ &= \langle \pi^-(\vec{p}_\pi), l^+(\vec{p}_l, \vec{s}), \nu(\vec{p}_\nu) | H_{weak} | \mathrm{K}^0 \rangle \\ \overline{A}_+ &= \langle \pi^-(\vec{p}_\pi), l^+(\vec{p}_l, \vec{s}), \nu(\vec{p}_\nu) | H_{weak} | \overline{\mathrm{K}^0} \rangle \\ A_- &= \langle \pi^+(\vec{p}_\pi), l^-(\vec{p}_l, -\vec{s}), \overline{\nu}(\vec{p}_\nu) | H_{weak} | \mathrm{K}^0 \rangle \\ \overline{A}_- &= \langle \pi^+(\vec{p}_\pi), l^-(\vec{p}_l, -\vec{s}), \overline{\nu}(\vec{p}_\nu) | H_{weak} | \overline{\mathrm{K}^0} \rangle \end{aligned}$$

$\Delta S = \Delta Q$ **allowed**
$\Delta S = \Delta Q$ **forbidden**
$\Delta S = \Delta Q$ **forbidden**
$\Delta S = \Delta Q$ **allowed**

- Time dependent rates

$$A_+ \gg \overline{A}_+ \text{ and } \overline{A}_- \gg A_-$$

$$\begin{aligned} R_+(t) &= \int d\Omega \sum_{\vec{s}} \left| \left[\frac{\Lambda_{22} - \Lambda_{11}}{\Delta\lambda} f_-(t) + f_+(t) \right] A_+ - 2\frac{\Lambda_{21}}{\Delta\lambda} f_-(t) \overline{A}_+ \right|^2 \\ &\approx \left| -2\delta f_-(t) + f_+(t) \right|^2 \int d\Omega \sum_{\vec{s}} |A_+|^2 - 2\Re \left(f_+^*(t) f_-(t) \int d\Omega \sum_{\vec{s}} \mathrm{e}^{-i\varphi_\Gamma} A_+^* \overline{A}_+ \right) \end{aligned}$$

- Neglecting terms proportional to
  - $\Delta S = \Delta Q$ forbidden amplitudes times T-violation in mixing ε_T or CPT-violation in mixing δ
  - $\Delta S = \Delta Q$ forbidden amplitudes squared

$$B_+ = \int d\Omega \sum_{\vec{s}} |A_+|^2 \qquad \overline{B}_- = \int d\Omega \sum_{\vec{s}} |\overline{A}_-|^2$$

$$\overline{x} = \frac{\int d\Omega \sum_{\vec{s}} \mathrm{e}^{-i\varphi_\Gamma} A_+^* \overline{A}_+}{\int d\Omega \sum_{\vec{s}} |A_+|^2} \qquad x = \frac{\int d\Omega \sum_{\vec{s}} \mathrm{e}^{-i\varphi_\Gamma} A_-^* \overline{A}_-}{\int d\Omega \sum_{\vec{s}} |\overline{A}_-|^2}$$

$$\begin{aligned} = \; & B_+ \Big\{ \left[1 - 4\Re(\delta) + 2\Re(\overline{x}) \right] \mathrm{e}^{-\Gamma_S \tau} + \left[1 + 4\Re(\delta) - 2\Re(\overline{x}) \right] \mathrm{e}^{-\Gamma_L \tau} \\ & + 2\mathrm{e}^{-\overline{\Gamma}\tau} \cos \Delta m t + \left[8\Im(\delta) - 4\Im(\overline{x}) \right] \mathrm{e}^{-\overline{\Gamma}\tau} \sin \Delta m t \Big\} \end{aligned}$$

no phase convention !

CPLEAR $x \leftrightarrow \overline{x}$
$x_- \leftrightarrow -x_-$

The Four Semileptonic Decay Rates

- $R_+(t)$: K^0 at $t=0$ and decay to $l^+\pi^-\nu$ at time t:

$$\begin{aligned} R_+(t) &= B_+ \Big\{ [1 - 4\Re(\delta) + 2\Re(\overline{x})]\, \mathrm{e}^{-\Gamma_\mathrm{S}\tau} + [1 + 4\Re(\delta) - 2\Re(\overline{x})]\, \mathrm{e}^{-\Gamma_\mathrm{L}\tau} \\ &\quad + 2\mathrm{e}^{-\overline{\Gamma}\tau} \cos\Delta m t + [8\Im(\delta) - 4\Im(\overline{x})]\, \mathrm{e}^{-\overline{\Gamma}\tau} \sin\Delta m t \Big\} \end{aligned}$$

$\overline{R}_-(t)$: $\overline{\mathrm{K}}^0$ at $t=0$ and decay to $l^-\pi^+\overline{\nu}$ at time t:

$$\begin{aligned} \overline{R}_-(t) &= \overline{B}_- \Big\{ [1 + 4\Re(\delta) + 2\Re(x)]\, \mathrm{e}^{-\Gamma_\mathrm{S}\tau} + [1 - 4\Re(\delta) - 2\Re(x)]\, \mathrm{e}^{-\Gamma_\mathrm{L}\tau} \\ &\quad + 2\mathrm{e}^{-\overline{\Gamma}\tau} \cos\Delta m t - [8\Im(\delta) - 4\Im(x)]\, \mathrm{e}^{-\overline{\Gamma}\tau} \sin\Delta m t \Big\} \end{aligned}$$

$R_-(t)$: K^0 at $t=0$ and decay to $l^-\pi^+\overline{\nu}$ at time t:

$$\begin{aligned} R_-(t) &= \overline{B}_- \Big\{ [1 - 4\Re(\varepsilon_\mathrm{T}) + 2\Re(x)]\, \mathrm{e}^{-\Gamma_\mathrm{S}\tau} + [1 - 4\Re(\varepsilon_\mathrm{T}) - 2\Re(x)]\, \mathrm{e}^{-\Gamma_\mathrm{L}\tau} \\ &\quad - 2\,[1 - 4\Re(\varepsilon_\mathrm{T})]\, \mathrm{e}^{-\overline{\Gamma}\tau} \cos\Delta m t - 4\Im(x) \mathrm{e}^{-\overline{\Gamma}\tau} \sin\Delta m t \Big\} \end{aligned}$$

$\overline{R}_+(t)$: $\overline{\mathrm{K}}^0$ at $t=0$ and decay to $l^+\pi^-\nu$ at time t:

$$\begin{aligned} \overline{R}_+(t) &= B_+ \Big\{ [1 + 4\Re(\varepsilon_\mathrm{T}) + 2\Re(\overline{x})]\, \mathrm{e}^{-\Gamma_\mathrm{S}\tau} + [1 + 4\Re(\varepsilon_\mathrm{T}) - 2\Re(\overline{x})]\, \mathrm{e}^{-\Gamma_\mathrm{L}\tau} \\ &\quad - 2\,[1 + 4\Re(\varepsilon_\mathrm{T})]\, \mathrm{e}^{-\overline{\Gamma}\tau} \cos\Delta m t + 4\Im(\overline{x}) \mathrm{e}^{-\overline{\Gamma}\tau} \sin\Delta m t \Big\} \end{aligned}$$

"Direct" Measurement of T Violation

- $$A_T = \frac{\overline{R}_+(\tau) - R_-(\tau)}{\overline{R}_+(\tau) + R_-(\tau)} = 4\Re(\varepsilon_T) + 2\Re(y) + 2\frac{\Re(x_-)\sinh[\frac{t\Delta\Gamma}{2}] - \Im(x_+)\sin[\Delta m t]}{\cos[\Delta m t] - \cosh[\frac{t\Delta\Gamma}{2}]}$$

  Valid for $\frac{t}{\tau_S} \gg \mathcal{R}(x_-), \Im(x_+)$

- $$A^{exp} \approx A^{phys} + A^{K^+/K^-} + A^{e^+\pi^-/e^-\pi^+}$$

  from pure electron/pion samples

  from 2π asymmetry: $\alpha = \frac{\varepsilon(K^+)}{\varepsilon(K^-)}[1 + 4\mathcal{R}(\varepsilon_T + \delta)]$

  CPLEAR specific

  Rewriting using $\delta_l = 2\mathcal{R}(\varepsilon_T + \delta + y - x_-)$**:**

  $$A_{K^\pm} = \frac{1-\alpha}{2}[\delta_l + 2\,\mathcal{R}(y) - \Re(x_-)\,]$$

- $$A_T^{exp} - A^{K^+/K^-} - A^{e^+\pi^-/e^-\pi^+} = 4\Re(\varepsilon_T) + 4\Re(y) - 2\Re(x_-) - 2\frac{\Re(x_-)\sinh[\frac{t\Delta\Gamma}{2}] - \Im(x_+)\sin[\Delta m t]}{\cosh[\frac{t\Delta\Gamma}{2}] - \cos[\Delta m t]}$$
  $$= 4\Re(\varepsilon_T) + 4\Re(y) - 4\Re(x_-) \quad \text{for } t \to \infty$$

- For the final result, CPT violation in semileptonic decay amplitudes, y and x_- are set to zero.

$$4\mathrm{Re}(\epsilon) = (6.2 \pm 1.4) \times 10^{-3}$$
$$\mathrm{Im}(x_+) = (1.2 \pm 1.9) \times 10^{-3}$$

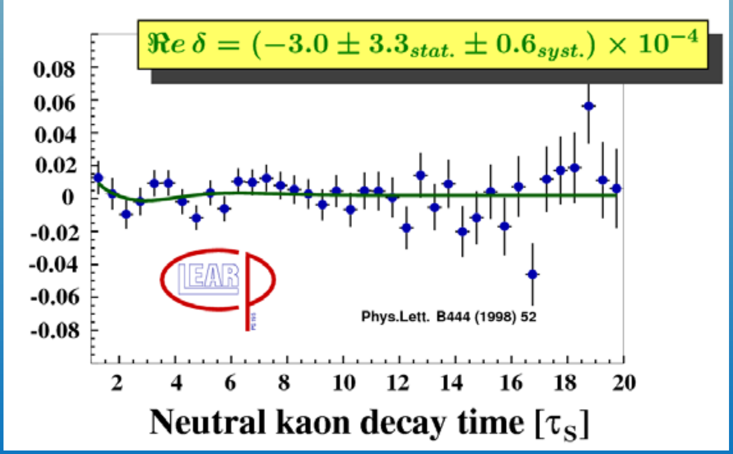
From a global fit: $\mathcal{R}(y - x_-) = (-0.2 \pm 0.3) \times 10^{-3}$

Direct Measurement of CPT Violation

- $$\begin{aligned} A_{CPT} &= \frac{\overline{R}_-(\tau) - R_+(\tau)}{\overline{R}_-(\tau) + R_+(\tau)} \\ &= -2\Re(y) - 2\frac{(2\Im(\delta) - \Im(x_+))\sin[\Delta m t] + (2\Re(\delta) - \Re(x_-))\sinh[\frac{t\Delta\Gamma}{2}]}{\cos[\Delta m t] + \cosh[\frac{t\Delta\Gamma}{2}]} \\ &= -4\Re(\delta) + 2\Re(x_-) - 2\Re(y) \quad \text{for } t \to \infty \end{aligned}$$

- More direct, using normalization from 2π:

$$\begin{aligned} & A_T^{exp} + A_{CPT}^{exp} - 2A^{K^+/K^-} - 2A^{e^+\pi^-/e^-\pi^+} \\ = & -4\Re(\delta) + \frac{4}{\cos[2\Delta m t] - \cosh[t\Delta\Gamma]}\left[\Re(\delta) - \Im(\delta)\sin[2\Delta m t]\right. \\ & \left. +2\cos[\Delta m t]\sinh[\frac{t\Delta\Gamma}{2}](\Re(x_-) - \Re(\delta)) + 2\sin[\Delta m t]\cosh[\frac{t\Delta\Gamma}{2}](\Im(\delta) - \Im(x_+))\right] \\ = & -8\Re(\delta) \quad \text{for } t \to \infty \end{aligned}$$



Additional results from short lifetime region:

$$\begin{aligned} \Im m\,\delta &= (1.5 \pm 2.3_{stat.} \pm 0.3_{syst.}) \times 10^{-2} \\ \Re e\,x_- &= (0.2 \pm 1.3_{stat.} \pm 0.3_{syst.}) \times 10^{-2} \\ \Im m\,x_+ &= (1.2 \pm 2.2_{stat.} \pm 0.3_{syst.}) \times 10^{-2} \end{aligned}$$

$\Delta S = \Delta Q$:

$$\begin{aligned} \mathrm{Re}(\delta) &= (2.9 \pm 2.6_{stat} \pm 0.6_{syst}) \times 10^{-4}, \\ \mathrm{Im}(\delta) &= (-0.9 \pm 2.9_{stat} \pm 1.0_{syst}) \times 10^{-3}, \end{aligned}$$

Parametrization of direct CP Violation

- $\Delta S = \Delta Q$ allowed: $\dfrac{B_+}{\overline{B}_-} = 1 + 4\Re(y)$ **CPT violating**

- $\Delta S = \Delta Q$ forbidden:

$$x_- = \frac{\overline{x} - x}{2}$$

CPT violating

$$x_+ = \frac{\overline{x} + x}{2}$$

CPT conserving

Unitarity, Bell-Steinberger, Indirect test of CPT, ...

- Back to CP violation in the $\pi\pi$ channel

$$\eta_{+-} = \varepsilon_T + \delta + \varepsilon' + \frac{|\overline{A}_0|^2 - |A_0|^2}{|A_0|^2 + |\overline{A}_0|^2} + \frac{i}{2}\left(\varphi_\Gamma - \arg A_0^* \overline{A}_0\right)$$

$$\eta_{+-} = \varepsilon_T + \delta_\perp + \varepsilon' + \frac{i}{2}\left(\varphi_\Gamma - \arg A_0^* \overline{A}_0\right)$$

$$\eta_{00} = \varepsilon_T + \delta_\perp - 2\varepsilon' + \frac{i}{2}\left(\varphi_\Gamma - \arg A_0^* \overline{A}_0\right)$$

$$\delta_\perp \equiv \delta + \frac{|\overline{A}_0|^2 - |A_0|^2}{|A_0|^2 + |\overline{A}_0|^2}$$

$$\approx \delta - \frac{\Gamma_{22} - \Gamma_{11}}{2\Delta\Gamma}$$

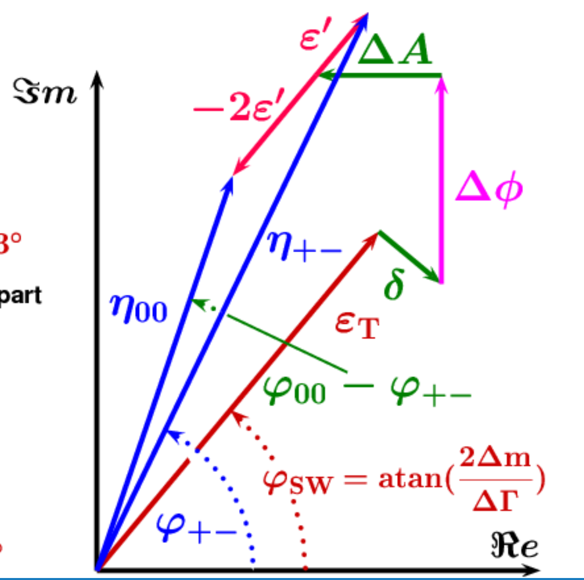
$$= \frac{i\Delta\Gamma - 2\Delta m}{4\Delta m^2 + \Delta\Gamma^2}\left[(M_{22} - M_{11}) + \frac{\Delta m}{\Delta\Gamma}(\Gamma_{22} - \Gamma_{11})\right]$$

- $\Delta\phi = \frac{1}{2}\left(\varphi_\Gamma - \arg A_0^* \overline{A}_0\right)$ CP violation through interference of mixing and decay.
  Major source of CP violation in the B^0 system

measurements of $\Im m\,(\eta_{3\pi})$, $\Im m\,(x)$, ...:

$$\Delta\phi = (-5.8 \pm 8.1) \times 10^{-6}$$
$$\cong \pm 0.15^\circ$$

- $\varphi_{00} - \varphi_{+-}$
  CPT in $I = 2$ amplitude
  $\varphi_{00} - \varphi_{+-} = 0.62^\circ \pm 1.03^\circ$
  contribution of CP conserving part
  $< 0.3^\circ$
- $\varphi_{+-} - \varphi_{SW}$
  CPT in mixing or
  in $I = 0$ amplitude
  $\varphi_{+-} - \varphi_{SW} = 0.1^\circ \pm 0.6^\circ$



More on η_{+-} and η_{00}

$$A_{+-} = \sqrt{\frac{1}{3}}A_2 + \sqrt{\frac{2}{3}}A_0, \qquad A_{00} = \sqrt{\frac{2}{3}}A_2 - \sqrt{\frac{1}{3}}A_0$$

$$A_{0,2} \equiv \sqrt{2\pi}\langle \pi\pi, \mathrm{I}=0,2|T|\mathrm{K}^0\rangle$$

$$A_{0,2} = (a_{0,2} + b_{0,2})e^{i\delta_{0,2}}$$

$$\overline{A}_{0,2} = (a_{0,2}^* - b_{0,2}^*)e^{i\delta_{0,2}}e^{i(\phi_{CP}-\overline{\phi}_T)}$$

$$\eta_f = \varepsilon_\mathrm{T} + \delta + \frac{1}{2}\left(1 - \frac{\overline{A}_f}{A_f}e^{-i\varphi_\Gamma}\right)$$

$$\approx \varepsilon_\mathrm{T} + \delta + \frac{1}{2}\frac{|A_{\pi\pi}| - |\overline{A}_{\pi\pi}|}{|A_{\pi\pi}|} + \frac{i}{2}\left(\varphi_\Gamma - \arg A^*_{\pi\pi}\overline{A}_{\pi\pi}\right)$$

- $\frac{i}{2}\left(\varphi_\Gamma - \arg A^*_{\pi\pi}\overline{A}_{\pi\pi}\right)$, a purely imaginary part from a possible phase difference of the decay amplitude compared to φ_Γ,
- $\frac{1}{2}\frac{|A_{\pi\pi}| - |\overline{A}_{\pi\pi}|}{|A_{\pi\pi}|}$, a real part which can either come directly from $\mathcal{CPT}$ violation of the decay amplitudes or from an interference of two decay amplitudes with a different phase. In the case of only one contributing amplitude, this term is $\mathcal{CPT}$ violating.

$$\eta_{+-} = \varepsilon_\mathrm{T} + \delta + \varepsilon' + \Re e\,\frac{b_2}{a_0} + \frac{i}{2}\left(\varphi_\Gamma - \arg A_0^*\overline{A}_0\right)$$

$$\eta_{00} = \varepsilon_\mathrm{T} + \delta - 2\varepsilon' + \Re e\,\frac{b_2}{a_0} + \frac{i}{2}\left(\varphi_\Gamma - \arg A_0^*\overline{A}_0\right)$$

$$\varepsilon' = \frac{1}{2\sqrt{2}}\left(\frac{A_2}{A_0} - \frac{\overline{A}_2}{\overline{A}_0}\right)$$

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

Backups

CPT Invariance

$$\mathcal{CPT}|\mathrm{K}^0\rangle = -e^{i(\phi_C+\phi_T)}|\overline{\mathrm{K}}^0\rangle$$

$$\mathcal{CPT}|\overline{\mathrm{K}}^0\rangle = -e^{i(-\phi_C+\overline{\phi}_T)}|\mathrm{K}^0\rangle$$

$$\Lambda = \Lambda' = \left(\mathcal{CPT}\Lambda(\mathcal{CPT})^{-1}\right)^\dagger \qquad \text{Invariance}$$

$$\langle a|\Lambda|b\rangle = \langle b'|\Lambda'|a'\rangle \qquad \text{Identity}$$

$$b = a = K^\circ \rightarrow \Lambda_{11} = \Lambda_{22}$$

$$b = a = \overline{K}^\circ \rightarrow \Lambda_{22} = \Lambda_{11}$$

$$a = K^\circ, b = \overline{K}^\circ \rightarrow \Lambda_{12} = e^{i(2\phi_C+\phi_T-\overline{\phi}_T)}\Lambda_{12}$$

$$a = \overline{K}^\circ, b = K^\circ \rightarrow \Lambda_{21} = e^{-i(2\phi_C+\phi_T-\overline{\phi}_T)}\Lambda_{21}$$

$$(\mathcal{CPT})(\mathcal{CPT}) = 1$$

$$\rightarrow 2\phi_C = \overline{\phi}_T - \phi_T$$

T Invariance

$$
\begin{aligned}
\mathcal{T}|\mathrm{K}^0\rangle &= e^{i\phi_T}|\mathrm{K}^0\rangle \\
\mathcal{T}|\overline{\mathrm{K}}^0\rangle &= e^{i\overline{\phi}_T}|\overline{\mathrm{K}}^0\rangle \\
\Lambda' &= \left(\mathcal{T}\Lambda\mathcal{T}^{-1}\right)^\dagger \\
\langle a|\Lambda|b\rangle &= \langle b'|\Lambda'|a'\rangle \\
b = a = K^\circ &\rightarrow \Lambda_{11} = e^{i\phi_T - i\phi_T}\Lambda_{11} = \Lambda_{11} \\
b = a = \overline{K}^\circ &\rightarrow \Lambda_{22} = \Lambda_{22} \\
a = K^\circ, b = \overline{K}^\circ &\rightarrow \Lambda_{12} = e^{i\phi_T}e^{-i\overline{\phi}_T}\Lambda_{21} = e^{-2i\phi_C}\Lambda_{21} \\
a = \overline{K}^\circ, b = K^\circ &\rightarrow \Lambda_{21} = e^{2i\phi_C}\Lambda_{12} \\
&\quad |M_{12}|\mathrm{e}^{-\mathrm{i}\varphi_\mathrm{M}} - \frac{i}{2}|\Gamma_{12}|\mathrm{e}^{-\mathrm{i}\varphi_\Gamma} = |M_{12}|e^{i(2\phi_C+\varphi_M)} - \frac{i}{2}|\Gamma_{12}|e^{i(2\phi_C+\varphi_\Gamma)} \\
&\quad = e^{i(2\phi_C+2\varphi_M)}\left(|M_{12}|\mathrm{e}^{-\mathrm{i}\varphi_\mathrm{M}} - \frac{i}{2}|\Gamma_{12}|\mathrm{e}^{-\mathrm{i}\varphi_\Gamma}e^{2i(\varphi_\Gamma-\varphi_M)}\right)
\end{aligned}
$$

T/CPT Violation, Systematic Errors

Table 1
Summary of systematic errors

Source	Known precision	$\langle A_T^{exp} \rangle [10^{-3}]$	$\mathrm{Im}(x_+) [10^{-3}]$
background level	$\pm 10\%$	± 0.03	± 0.2
background asymmetry	$\pm 1\%$	± 0.02	± 0.5
ξ	$\pm 4.3 \times 10^{-4}$	± 0.2	± 0.1
η	$\pm 2.0 \times 10^{-3}$	± 1.0	± 0.4
decay-time resolution	10%	negligible	± 0.6
regeneration	Ref. [8]	± 0.1	± 0.1
Total syst.		± 1.0	± 0.9

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Information | References (11) | Citations (66) | Files | Plots

Determination of the T and CPT violation parameters in the neutral kaon system using the Bell-Steinberger relation and data from CPLEAR - CPLEAR Collaboration (Apostolakis, A. *et al.*) Phys.Lett. B456 (1999) 297-303 CERN-EP-99-051, CERN-EP-99-51

Cited by: 66 records

- Search for T, CP and CPT violation in B0 anti-B0 mMixing with inclusive dilepton events - BABAR Collaboration (Aubert, Bernard *et al.*) Phys.Rev.Lett. 96 (2006) 251802 hep-ex/0603053 SLAC-PUB-11787, BABAR-PUB-06-11
- Study of the branching ratio and charge asymmetry for the decay K(s) ---> pi e nu with the KLOE detector - KLOE Collaboration (Ambrosino, F. *et al.*) Phys.Lett. B636 (2006) 173-182 hep-ex/0601026
- Search for T and CP violation in $B^0-\overline{B}^0$ mixing with inclusive dilepton events - BABAR Collaboration (Aubert, Bernard *et al.*) Phys.Rev.Lett. 88 (2002) 231801 hep-ex/0202041 SLAC-PUB-9149, BABAR-PUB-01-20
- Limits on the decay rate difference of neutral$-B$ mesons and on CP, T, and CPT violation in $B^0\overline{B}^0$ oscillations - BABAR Collaboration (Aubert, Bernard *et al.*) Phys.Rev. D70 (2004) 012007 hep-ex/0403002 SLAC-PUB-10364, BABAR-PUB-04-001
- Limits on the lifetime difference of neutral B mesons and on CP, T, and CPT violation in B0 anti-B0 mixing - BABAR Collaboration (Aubert, Bernard *et al.*) hep-ex/0303043 SLAC-PUB-9696, BABAR-CONF-03-08

more

... of which self-citations: 3 records

- A measurement of K0 anti-K0 ---> 3 pi0 and an improved test of CPT - Bargassa, P. CERN-THESIS-99-067, CERN-THESIS-99-67, DISS-ETH-13246
- T-violation and CPT-invariance measurements in the CPLEAR experiment: A detailed description of the analysis of neutral-kaon decays to e pi nu - CPLEAR Collaboration (Angelopoulos, A. *et al.*) Eur.Phys.J. C22 (2001) 55-79 CERN-EP-2001-060
- Physics at CPLEAR - CPLEAR Collaboration (Angelopoulos, A. *et al.*) Phys.Rept. 374 (2003) 165-270

Co-cited with: 1381 records

- First direct observation of time reversal noninvariance in the neutral kaon system - CPLEAR Collaboration (Angelopoulos, A. *et al.*) Phys.Lett. B444 (1998) 43-51 CERN-EP-98-153
- Evidence for the 2 pi Decay of the k(2)0 Meson - Christenson, J.H. *et al.* Phys.Rev.Lett. 13 (1964) 138-140
- A Determination of the CPT violation parameter Re(delta) from the semileptonic decay of strangeness tagged neutral kaons - CPLEAR Collaboration (Angelopoulos, A. *et al.*) Phys.Lett. B444 (1998) 52-60 CERN-EP-98-154
- Observation of direct CP violation in K(S,L) ---> pi pi decays - KTeV Collaboration (Alavi-Harati, A. *et al.*) Phys.Rev.Lett. 83 (1999) 22-27 hep-ex/9905060 EFI-99-25, FERMILAB-PUB-99-150-E
- CP Violation in the Renormalizable Theory of Weak Interaction - Kobayashi, Makoto *et al.* Prog.Theor.Phys. 49 (1973) 652-657 KUNS-242

more

Citation history:

PDG Online 2013

$|\eta_{+-}| = |A(K^0_L \to \pi^+\pi^-) / A(K^0_S \to \pi^+\pi^-)|$

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
2.232±0.011 OUR FIT		Error includes scale factor of 1.8.			
2.226±0.007		BRFIT	12		
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.223±0.012		[1] LAI	07	NA48	
2.219±0.013		[2] AMBROSINO	06F	KLOE	
2.228±0.010		[3] ALEXOPOU...	04	KTEV	
2.286±0.023±0.026	70M	[4] APOSTOLA...	99C	CPLR	K^0-$\overline{K}^0$ asymmetry
2.310±0.043±0.031		[5] ADLER	95B	CPLR	K^0-$\overline{K}^0$ asymmetry
2.32 ±0.14 ±0.03	10^5	ADLER	92B	CPLR	K^0-$\overline{K}^0$ asymmetry
2.30 ±0.035		GEWENIGER	74B	ASPK	

VALUE (°)	EVTS	DOCUMENT ID		TECN	COMMENT
43.51±0.05 OUR FIT		Error includes scale factor of 1.2. Assuming *CPT*			
43.4 ±0.5 OUR FIT		Error includes scale factor of 1.2. Not assuming *CPT*			
42.9 ±0.6 ±0.3	70M	[1] APOSTOLA...	99C	CPLR	K^0-$\overline{K}^0$ asymmetry
42.9 ±0.8 ±0.2		[2,3] SCHWINGEN...	95	E773	$CH_{1.1}$ regenerator
41.4 ±0.9 ±0.2		[3,4] GIBBONS	93	E731	B_4C regenerator
44.5 ±1.6 ±0.6		[5] CAROSI	90	NA31	Vacuum regen.
43.3 ±1.0 ±0.5		[6] GEWENIGER	74B	ASPK	Vacuum regen.

$x = A(\overline{K}^0 \to \pi^-\ell^+\nu)/A(K^0 \to \pi^-\ell^+\nu) = A(\Delta S{=}-\Delta Q)/A(\Delta S{=}\Delta Q)$

REAL PART OF x

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.0018±0.0041±0.0045		ANGELOPO...	98D	CPLR	K_{e3} from K^0
• • • We do not use the following data for averages, fits, limits, etc. • • •					

IMAGINARY PART OF x

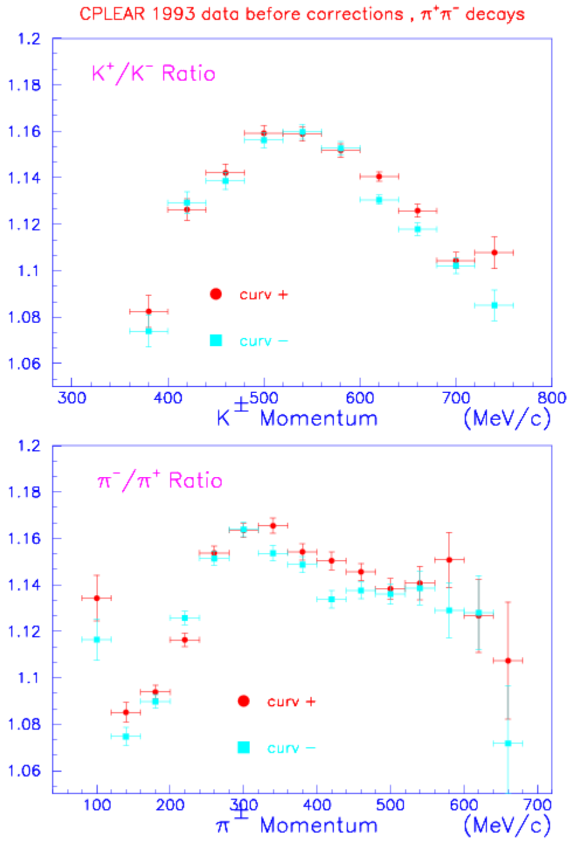
Assumes $m_{K^0_L} - m_{K^0_S}$ positive. See Listings above.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0012±0.0019±0.0009	640k	ANGELOPO...	01B	CPLR	K_{e3} from K^0

VALUE (10^{10} $\hbar$ s^{-1})	DOCUMENT ID		TECN	COMMENT
0.5293 ±0.0009 OUR FIT	Error includes scale factor of 1.3. Assuming *CPT*			
0.5289 ±0.0010 OUR FIT	Not assuming *CPT*			
0.52797±0.00195	[1,2] ABOUZAID	11	KTEV	Not assuming *CPT*
0.52699±0.00123	[1,3] ABOUZAID	11	KTEV	Assuming *CPT*
0.5240 ±0.0044 ±0.0033	APOSTOLA...	99C	CPLR	K^0-$\overline{K}^0$ to $\pi^+\pi^-$
0.5297 ±0.0030 ±0.0022	[4] SCHWINGEN...	95	E773	20–160 GeV K beams
0.5286 ±0.0028	[5] GIBBONS	93	E731	Assuming *CPT*
0.5257 ±0.0049 ±0.0021	[4] GIBBONS	93C	E731	Not assuming *CPT*
0.5340 ±0.00255±0.0015	[6] GEWENIGER	74C	SPEC	Gap method
0.5334 ±0.0040 ±0.0015	[6,7] GJESDAL	74	SPEC	Assuming *CPT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.5261 ±0.0015	[8] ALAVI-HARATI	03	KTEV	Assuming *CPT*
0.5288 ±0.0043	[9] ALAVI-HARATI	03	KTEV	Not assuming *CPT*
0.5343 ±0.0063 ±0.0025	[10] ANGELOPO...	01	CPLR	
0.5295 ±0.0020 ±0.0003	[11] ANGELOPO...	98D	CPLR	Assuming *CPT*
0.5307 ±0.0013	[12] ADLER	96C	RVUE	

$\mathcal{P}$- and $\mathcal{C}$-Symmetry of the Experiment

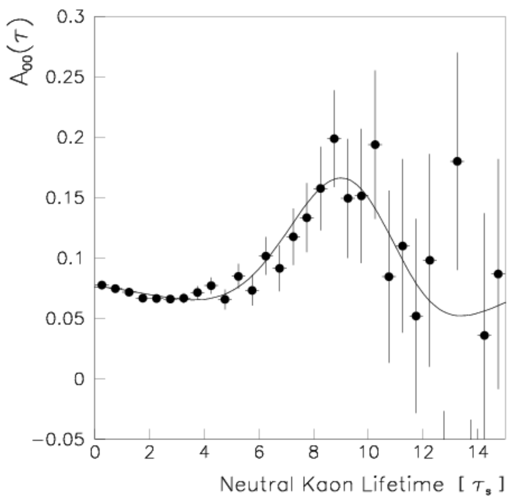
$$\frac{\mathbf{K}^+, \pi^+\,(\text{curv}^-)}{\mathbf{K}^-, \pi^-\,(\text{curv}^-)} = \frac{\mathbf{K}^+, \pi^+\,(\text{curv}^+)}{\mathbf{K}^-, \pi^-\,(\text{curv}^+)}$$



$\mathcal{CP}$ violation in $\pi^0\pi^0$

$$A_{00}(\tau) = \frac{R_{\overline{K}^0\to\pi^0\pi^0}(\tau) - R_{K^0\to\pi^0\pi^0}(\tau)}{R_{\overline{K}^0\to\pi^0\pi^0}(\tau) + R_{K^0\to\pi^0\pi^0}(\tau)}$$

$$= C - \frac{2|\eta_{00}|e^{\frac{1}{2}(\frac{1}{\tau_S}-\frac{1}{\tau_L})\tau}\cos(\Delta m\tau - \varphi_{00})}{1+|\eta_{00}|^2 e^{(\frac{1}{\tau_S}-\frac{1}{\tau_L})\tau}}$$



2×10^6 reconstructed events

$$|\eta_{00}| = (2.47 \pm 0.31_{sta.} \pm 0.24_{sys.}) \times 10^{-3}$$
$$\varphi_{00} = 42.0^\circ \pm 5.6^\circ_{sta.} \pm 1.9^\circ_{sys.}$$

Published in Phys.Lett. B420 (1998) 191.

Regeneration

Measurement of Regeneration through Interference

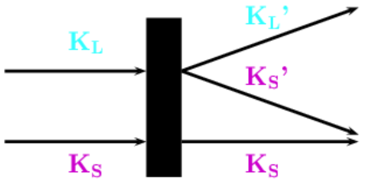
$$i\frac{\partial}{\partial\tau}\psi(\tau) = \left[\Lambda - \frac{2\pi N}{m}\begin{pmatrix} f(0) & 0 \\ 0 & \bar{f}(0)\end{pmatrix}\right]\psi(\tau)$$

Regeneration appears as an effective $\mathcal{CPT}$ –violation.

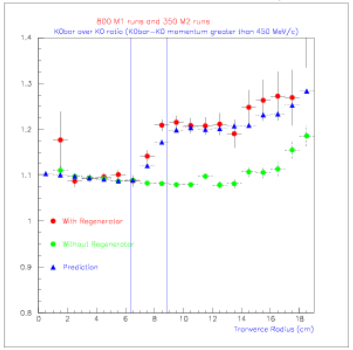
Modification to the CPLEAR experiment:

add 2.5 cm carbon at 7.5 cm from the interaction region, covering 110° of the azimuth angle

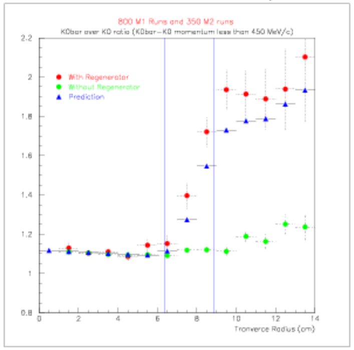
CPLEAR is sensitive to the interference of K_S with K_S' regenerated from K_L:



$P_{K^0} > 450$ MeV/c

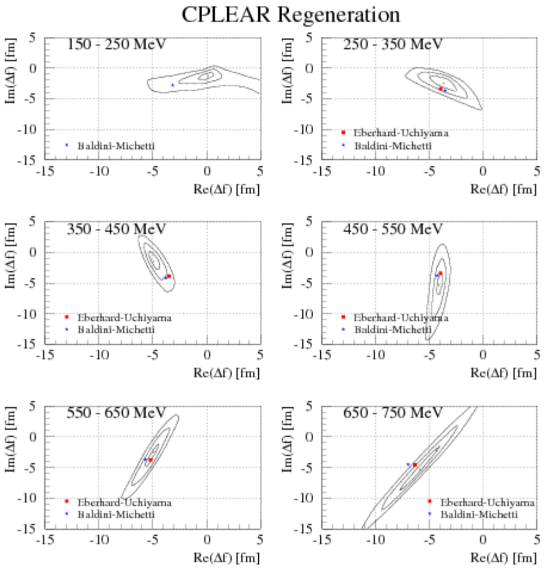


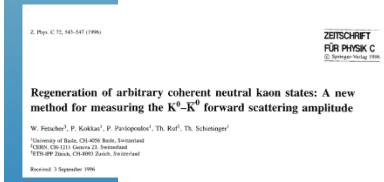
$P_{K^0} < 450$ MeV/c



$\frac{\bar{K}^0 \to \pi^+\pi^-}{K^0 \to \pi^+\pi^-}$

Results of the Regeneration Measurement




Z. Phys. C 72, 543–547 (1996)

ZEITSCHRIFT FÜR PHYSIK C
© Springer-Verlag 1996

Regeneration of arbitrary coherent neutral kaon states: A new method for measuring the K^0–$\bar{K}^0$ forward scattering amplitude

W. Fetscher[3], P. Kokkas[1], P. Pavlopoulos[1], Th. Ruf[2], Th. Schietinger[1]

[1]University of Basle, CH-4056 Basle, Switzerland
[2]CERN, CH-1211 Geneva 23, Switzerland
[3]ETH-IPP Zürich, CH-8093 Zurich, Switzerland

Received: 3 September 1996

Systematic error of φ_{+-} measurement reduced from $\pm 0.6°$ to $\pm 0.2°$

Phys.Lett. B413 (1997) 422

Formalism applied to B System

Flavour tagged rates, use $\Delta = -\Re(y)$:

with $K_{\pm}$ = final state with CP= ± 1

$$
\begin{aligned}
R1(\mathrm{B^0}_{t=0};\overline{\mathrm{B}^0}_{t=0} \to K_+)(t) &= \frac{|\overline{A}|^2}{4}\left|-2\delta_b f_-(t) + f_+(t) + \frac{A}{\overline{A}}e^{i\phi_M}\left(1+2\varepsilon_b\right) f_-(t)\right|^2 \\
&= \overline{\mathrm{P}}\mathrm{e}^{-\overline{\Gamma}\tau}\{2\left(-\varepsilon_b + \Delta + \Re(\delta_b)\cos\Omega + \Im(\delta_b)\sin\Omega\right)\cos[\Delta\mathrm{m}t] \\
&\quad + \left(2\Im(\delta_b) - (1+2\varepsilon_b-2\Delta)\sin\Omega\right)\sin[\Delta\mathrm{m}t] \\
&\quad + \left(1+2\varepsilon_b - 2\Delta - 2\Re(\delta_b)\cos\Omega - 2\Im(\delta_b)\sin\Omega\right)\cosh[\tfrac{\Delta\Gamma t}{2}] \\
&\quad + \left(-2\Re(\delta_b) + (1+2\varepsilon_b-2\Delta)\cos\Omega\right)\sinh[\tfrac{\Delta\Gamma t}{2}]\} \\
&= \overline{\mathrm{P}}\mathrm{e}^{-\overline{\Gamma}\tau}\left(1 + 2\left(\varepsilon_b - \Delta - \Re(\delta_b)\cos\Omega - \Im(\delta_b)\sin\Omega\right)\left(1-\cos[\Delta\mathrm{m}t]\right)\right. \\
&\quad \left. + \left(-2\Im(\delta_b) + (1-2\varepsilon_b+2\Delta)\sin\Omega\right)\sin[\Delta\mathrm{m}t]\right) \\
&\approx \overline{\mathrm{P}}\mathrm{e}^{-\overline{\Gamma}\tau}\left(1 - \sin\Omega\sin[\Delta\mathrm{m}t]\right)
\end{aligned}
$$

with $\Delta\Gamma = 0$

with $\Delta\Gamma = \delta = \varepsilon = 0$

$$
\begin{aligned}
R1(\overline{\mathrm{B}^0}_{t=0};\mathrm{B^0}_{t=0} \to K_+)(t) &= \frac{|\overline{A}|^2}{4}\left|\frac{A}{\overline{A}}e^{i\phi_M}\left(2\delta_b f_-(t) + f_+(t)\right) + \left(1-2\varepsilon_b\right) f_-(t)\right|^2 \\
&= \overline{\mathrm{P}}\mathrm{e}^{-\overline{\Gamma}\tau}\{2\left(\varepsilon_b - \Delta - \Re(\delta_b)\cos\Omega + \Im(\delta_b)\sin\Omega\right)\cos[\Delta\mathrm{m}t] \\
&\quad + \left(-2\Im(\delta_b) + (1-2\varepsilon_b-2\Delta)\sin\Omega\right)\sin[\Delta\mathrm{m}t] \\
&\quad + \left(1-2\varepsilon_b - 2\Delta + 2\Re(\delta_b)\cos\Omega - 2\Im(\delta_b)\sin\Omega\right)\cosh[\tfrac{\Delta\Gamma t}{2}] \\
&\quad + \left(2\Re(\delta_b) + (1-2\varepsilon_b-\Delta)\cos\Omega\right)\sinh[\tfrac{\Delta\Gamma t}{2}]\} \\
&= \overline{\mathrm{P}}\mathrm{e}^{-\overline{\Gamma}\tau}\left(1 - 4\Delta + 2\left(\varepsilon_b - \Delta - \Re(\delta_b)\cos\Omega + \Im(\delta_b)\sin\Omega\right)\left(\cos[\Delta\mathrm{m}t]-1\right)\right. \\
&\quad \left. + \left(-2\Im(\delta_b) + (1-2\varepsilon_b-2\Delta)\right)\sin\Omega\right)\sin[\Delta\mathrm{m}t]) \\
&\approx \overline{\mathrm{P}}\mathrm{e}^{-\overline{\Gamma}\tau}\left(1 + \sin\Omega\sin[\Delta\mathrm{m}t]\right)
\end{aligned}
$$

with $\Delta\Gamma = 0$

with $\Delta\Gamma = \delta = \varepsilon = 0$

Formalism applied to B System, cont.

$$
\begin{aligned}
R1(\mathrm{B^0}_{t=0};\overline{\mathrm{B}}^0{}_{t=0}\to K_-)(t) &= \frac{|\overline{A}|^2}{4}\left|-2\delta_b f_-(t)+f_+(t)-\frac{A}{\overline{A}}e^{i\phi_M}\,(1+2\varepsilon_b)\,f_-(t)\right|^2\\
&= \overline{\mathrm{P}}\mathrm{e}^{-\overline{\Gamma}\tau}\,\{2\,(\varepsilon_b-\Delta+\Re(\delta_b)\cos\Omega+\Im(\delta_b)\sin\Omega)\cos[\Delta\mathrm{mt}]\\
&\quad+(2\Im(\delta_b)+(1+2\varepsilon_b-2\Delta)\sin\Omega)\sin[\Delta\mathrm{mt}]\\
&\quad+(1+2\varepsilon_b-2\Delta+2\Re(\delta_b)\cos\Omega+2\Im(\delta_b)\sin\Omega)\cosh[\tfrac{\Delta\Gamma t}{2}]\\
&\quad-(2\Re(\delta_b)+(1+2\varepsilon_b-2\Delta)\cos\Omega)\sinh[\tfrac{\Delta\Gamma t}{2}]\}\\
&= \overline{\mathrm{P}}\mathrm{e}^{-\overline{\Gamma}\tau}\,(1+2\,(\varepsilon_b-\Delta+\Re(\delta_b)\cos\Omega+\Im(\delta_b)\sin\Omega)\,(1-\cos[\Delta\mathrm{mt}])\\
&\quad+(2\Im(\delta_b)+(1+2\varepsilon_b-2\Delta)\sin\Omega)\sin[\Delta\mathrm{mt}])\\
&\approx \overline{\mathrm{P}}\mathrm{e}^{-\overline{\Gamma}\tau}\,(1+\sin\Omega\sin[\Delta\mathrm{mt}])
\end{aligned}
$$

with $\Delta\Gamma = 0$

with $\Delta\Gamma = \delta = \varepsilon = 0$

$$
\begin{aligned}
R1(\overline{\mathrm{B}}^0{}_{t=0};\mathrm{B^0}_{t=0}\to K_-)(t) &= \frac{|\overline{A}|^2}{4}\left|-\frac{A}{\overline{A}}e^{i\phi_M}\,(2\delta_b f_-(t)+f_+(t))+(1-2\varepsilon_b)\,f_-(t)\right|^2\\
&= \overline{\mathrm{P}}\mathrm{e}^{-\overline{\Gamma}\tau}\,\{2\,(\varepsilon_b-\Delta+\Re(\delta_b)\cos\Omega-\Im(\delta_b)\sin\Omega)\cos[\Delta\mathrm{mt}]\\
&\quad+(-2\Im(\delta_b)-(1-2\varepsilon_b-2\Delta)\sin\Omega)\sin[\Delta\mathrm{mt}]\\
&\quad+(1-2\varepsilon_b-2\Delta-2\Re(\delta_b)\cos\Omega+2\Im(\delta_b)\sin\Omega)\cosh[\tfrac{\Delta\Gamma t}{2}]\\
&\quad+(2\Re(\delta_b)-(1-2\varepsilon_b-\Delta)\cos\Omega)\sinh[\tfrac{\Delta\Gamma t}{2}]\}\\
&= \overline{\mathrm{P}}\mathrm{e}^{-\overline{\Gamma}\tau}\,(1-4\Delta+2\,(\varepsilon_b-\Delta+\Re(\delta_b)\cos\Omega-\Im(\delta_b)\sin\Omega)\,(\cos[\Delta\mathrm{mt}]-1)\\
&\quad-(2\Im(\delta_b)+(1-2\varepsilon_b-\Delta)\sin\Omega)\sin[\Delta\mathrm{mt}])\\
&\approx \overline{\mathrm{P}}\mathrm{e}^{-\overline{\Gamma}\tau}\,(1-\sin\Omega\sin[\Delta\mathrm{mt}])
\end{aligned}
$$

with $\Delta\Gamma = 0$

with $\Delta\Gamma = \delta = \varepsilon = 0$

CP Asymmetries

$$
\begin{aligned}
A^{CP}(J/\psi K_L) &= \frac{R1(\mathrm{B^0}_{t=0} \to K_+)(t) - R1(\overline{\mathrm{B}}^0{}_{t=0} \to K_+)(t)}{R1(\mathrm{B^0}_{t=0} \to K_+)(t) + R1(\overline{\mathrm{B}}^0{}_{t=0} \to K_+)(t)} \\
&= \frac{\sin[\Delta\mathrm{mt}]\sin\Omega}{\cosh[\frac{\Delta\Gamma t}{2}] + \cos\Omega\sinh[\frac{\Delta\Gamma t}{2}]} \\
&\quad +2(\varepsilon_b - \Re(\delta_b))\,(\cos[\Delta\mathrm{mt}] - 1) - 2\Delta\cos[\Delta\mathrm{mt}] - 2\Im(\delta_b)\sin[\Delta\mathrm{mt}] \\
&\quad +2\Re(\delta_b)(1 - \cos[\Delta\mathrm{mt}])(1 - \cos\Omega) + 2\Delta\sin\Omega\sin[\Delta\mathrm{mt}] \\
A^{CP}(J/\psi K_S) &= \frac{R1(\mathrm{B^0}_{t=0} \to K_-)(t) - R1(\overline{\mathrm{B}}^0{}_{t=0} \to K_-)(t)}{R1(\mathrm{B^0}_{t=0} \to K_-)(t) + R1(\overline{\mathrm{B}}^0{}_{t=0} \to K_-)(t)} \\
&= -\frac{\sin[\Delta\mathrm{mt}]\sin\Omega}{\cosh[\frac{\Delta\Gamma t}{2}] - \cos\Omega\sinh[\frac{\Delta\Gamma t}{2}]} \\
&\quad +2(\varepsilon_b + \Re(\delta_b))\,(\cos[\Delta\mathrm{mt}] - 1) - 2\Delta\cos[\Delta\mathrm{mt}] - 2\Im(\delta_b)\sin[\Delta\mathrm{mt}] \\
&\quad -2\Re(\delta_b)(1 - \cos[\Delta\mathrm{mt}])(1 - \cos\Omega) - 2\Delta\sin\Omega\sin[\Delta\mathrm{mt}]
\end{aligned}
$$

$\Delta\Gamma = 0$:

$$
\begin{aligned}
A^{CP}(J/\psi K_S) - A^{CP}(J/\psi K_L) &= -2(1 - 2\Delta)\sin\Omega\sin[\Delta\mathrm{mt}] - 4\Re(\delta_b)\cos\Omega(1 - \cos[\Delta\mathrm{mt}]) \\
A^{CP}(J/\psi K_S) + A^{CP}(J/\psi K_L) &= 4(\varepsilon_b - \Delta)\cos[\Delta\mathrm{mt}] - 4(\varepsilon_b + \Im(\delta_b)\sin[\Delta\mathrm{mt}])
\end{aligned}
$$

EPR CP Tagged Rates

$$
\begin{aligned}
R2(K_{-(t=0)}; B_+ \to \mathrm{B}^0)(t) &= \frac{|\overline{A}|^2}{4}\left|-\frac{A}{\overline{A}}e^{i\phi_M}(1+2\varepsilon_b)f_-(t) - [2\delta_b f_-(t) + f_+(t)]\right|^2 \\
&= \overline{\mathrm{P}}\mathrm{e}^{-\overline{\Gamma}\tau}\,\{-2\,(\varepsilon_b - \Delta + \Re(\delta_b)\cos\Omega + \Im(\delta_b)\sin\Omega)\cos[\Delta\mathrm{m}t] \\
&\quad - (2\Im(\delta_b) + (1+2\varepsilon_b - 2\Delta)\sin\Omega)\sin[\Delta\mathrm{m}t] \\
&\quad + (1 + 2\varepsilon_b - 2\Delta + 2\Re(\delta_b)\cos\Omega + 2\Im(\delta_b)\sin\Omega)\cosh[\tfrac{\Delta\Gamma t}{2}] \\
&\quad + (2\Re(\delta_b) + (1+2\varepsilon_b - 2\Delta)\cos\Omega)\sinh[\tfrac{\Delta\Gamma t}{2}]\Big\} \\
&\approx \overline{\mathrm{P}}\mathrm{e}^{-\overline{\Gamma}\tau}\,(1 - \sin\Omega\sin[\Delta\mathrm{m}t]) \\
R2(K_{-(t=0)}; B_+ \to \overline{\mathrm{B}}^0)(t) &= \frac{|\overline{A}|^2}{4}\left|-\frac{A}{\overline{A}}e^{i\phi_M}[-2\delta_b f_-(t) + f_+(t)] - (1-2\varepsilon_b)f_-(t)\right|^2 \\
&= \overline{\mathrm{P}}\mathrm{e}^{-\overline{\Gamma}\tau}\,\{2\,(\varepsilon_b - \Delta + \Re(\delta_b)\cos\Omega - \Im(\delta_b)\sin\Omega)\cos[\Delta\mathrm{m}t] \\
&\quad + (2\Im(\delta_b) + (1-2\varepsilon_b - 2\Delta)\sin\Omega)\sin[\Delta\mathrm{m}t] \\
&\quad + (1 - 2\varepsilon_b - 2\Delta - 2\Re(\delta_b)\cos\Omega + 2\Im(\delta_b)\sin\Omega)\cosh[\tfrac{\Delta\Gamma t}{2}] \\
&\quad + (-2\Re(\delta_b) + (1-2\varepsilon_b - 2\Delta)\cos\Omega)\sinh[\tfrac{\Delta\Gamma t}{2}]\Big\} \\
&\approx \overline{\mathrm{P}}\mathrm{e}^{-\overline{\Gamma}\tau}\,(1 + \sin\Omega\sin[\Delta\mathrm{m}t]) \\
R2(K_{+(t=0)}; B_- \to \mathrm{B}^0)(t) &= \frac{|\overline{A}|^2}{4}\left|\frac{A}{\overline{A}}e^{i\phi_M}(1+2\varepsilon_b)f_-(t) - [2\delta_b f_-(t) + f_+(t)]\right|^2 \\
&= \overline{\mathrm{P}}\mathrm{e}^{-\overline{\Gamma}\tau}\,\{-2\,(\varepsilon_b - \Delta - \Re(\delta_b)\cos\Omega - \Im(\delta_b)\sin\Omega)\cos[\Delta\mathrm{m}t] \\
&\quad - (2\Im(\delta_b) - (1+2\varepsilon_b - 2\Delta)\sin\Omega)\sin[\Delta\mathrm{m}t] \\
&\quad + (1 + 2\varepsilon_b - 2\Delta - 2\Re(\delta_b)\cos\Omega - 2\Im(\delta_b)\sin\Omega)\cosh[\tfrac{\Delta\Gamma t}{2}] \\
&\quad + (2\Re(\delta_b) - (1+2\varepsilon_b - 2\Delta)\cos\Omega)\sinh[\tfrac{\Delta\Gamma t}{2}]\Big\} \\
&\approx \overline{\mathrm{P}}\mathrm{e}^{-\overline{\Gamma}\tau}\,(1 + \sin\Omega\sin[\Delta\mathrm{m}t]) \\
R2(K_{+(t=0)}; B_- \to \overline{\mathrm{B}}^0)(t) &= \frac{|\overline{A}|^2}{4}\left|\frac{A}{\overline{A}}e^{i\phi_M}[-2\delta_b f_-(t) + f_+(t)] - (1-2\varepsilon_b)f_-(t)\right|^2 \\
&= \overline{\mathrm{P}}\mathrm{e}^{-\overline{\Gamma}\tau}\,\{2\,(\varepsilon_b - \Delta - \Re(\delta_b)\cos\Omega + \Im(\delta_b)\sin\Omega)\cos[\Delta\mathrm{m}t] \\
&\quad + (2\Im(\delta_b) - (1-2\varepsilon_b + 2\Delta)\sin\Omega)\sin[\Delta\mathrm{m}t] \\
&\quad + (1 - 2\varepsilon_b - 2\Delta + 2\Re(\delta_b)\cos\Omega - 2\Im(\delta_b)\sin\Omega)\cosh[\tfrac{\Delta\Gamma t}{2}] \\
&\quad - (2\Re(\delta_b) + (1-2\varepsilon_b - 2\Delta)\cos\Omega)\sinh[\tfrac{\Delta\Gamma t}{2}]\Big\} \\
&\approx \overline{\mathrm{P}}\mathrm{e}^{-\overline{\Gamma}\tau}\,(1 - \sin\Omega\sin[\Delta\mathrm{m}t])
\end{aligned}
$$

"T" Violating Asymmetries

$$\begin{aligned}
A(\overline{\mathrm{B}}^0 \to B_-) &= \sin\Omega\sin[\Delta\mathrm{mt}] + \frac{1}{4}t\Delta\Gamma\sin 2\Omega\sin[\Delta\mathrm{mt}] \\
&\quad +2\varepsilon_b\,(1-\cos[\Delta\mathrm{mt}]) - \Delta\cos[\Delta\mathrm{mt}] \\
&\quad -2\sin\Omega(1-\cos[\Delta\mathrm{mt}])\,(\Re(\delta_b)\cos\Omega\sin[\Delta\mathrm{mt}] + \varepsilon_b\sin\Omega + (\Im(\delta_b) + \varepsilon_b\sin\Omega)\cos[\Delta\mathrm{mt}]) \\
A(\overline{\mathrm{B}}^0 \to B_+) &= -\sin\Omega\sin[\Delta\mathrm{mt}] + \frac{1}{4}t\Delta\Gamma\sin 2\Omega\sin[\Delta\mathrm{mt}] \\
&\quad +2\varepsilon_b\,(1-\cos[\Delta\mathrm{mt}]) - \Delta\cos[\Delta\mathrm{mt}] \\
&\quad -2\sin\Omega(1-\cos[\Delta\mathrm{mt}])\,(\Re(\delta_b)\cos\Omega\sin[\Delta\mathrm{mt}] + \varepsilon_b\sin\Omega + (-\Im(\delta_b) + \varepsilon_b\sin\Omega)\cos[\Delta\mathrm{mt}]) \\
A(B_+ \to \mathrm{B}^0) &= -\sin\Omega\sin[\Delta\mathrm{mt}] + \frac{1}{4}t\Delta\Gamma\sin 2\Omega\sin[\Delta\mathrm{mt}] \\
&\quad +2\varepsilon_b\,(1-\cos[\Delta\mathrm{mt}]) - \Delta\cos[\Delta\mathrm{mt}] \\
&\quad -2\sin\Omega(1-\cos[\Delta\mathrm{mt}])\,(-\Re(\delta_b)\cos\Omega\sin[\Delta\mathrm{mt}] + \varepsilon_b\sin\Omega + (\Im(\delta_b) + \varepsilon_b\sin\Omega)\cos[\Delta\mathrm{mt}]) \\
A(B_- \to \mathrm{B}^0) &= \sin\Omega\sin[\Delta\mathrm{mt}] + \frac{1}{4}t\Delta\Gamma\sin 2\Omega\sin[\Delta\mathrm{mt}] \\
&\quad +2\varepsilon_b\,(1-\cos[\Delta\mathrm{mt}]) - \Delta\cos[\Delta\mathrm{mt}] \\
&\quad +2\sin\Omega(1-\cos[\Delta\mathrm{mt}])\,(\Re(\delta_b)\cos\Omega\sin[\Delta\mathrm{mt}] - \varepsilon_b\sin\Omega + (\Im(\delta_b) - \varepsilon_b\sin\Omega)\cos[\Delta\mathrm{mt}])
\end{aligned}$$

"CPT" Violating Asymmetries

$$\frac{R(\overline{\mathrm{B}}^0 \to B_-) - R(B_- \to \mathrm{B}^0)}{R(\overline{\mathrm{B}}^0 \to B_-) + R(B_- \to \mathrm{B}^0)} = 2\left(\Re(\delta_b)\left(1-\cos[\Delta\mathrm{mt}]\right) + \Im(\delta_b)\sin[\Delta\mathrm{mt}]\right)$$

$$-2\left(1-\cos[\Delta\mathrm{mt}]\right)\frac{\left(\Re(\delta_b)(1-\cos\Omega) + (\Im(\delta_b)\cos[\Delta\mathrm{mt}] + \Re(\delta_b)\sin[\Delta\mathrm{mt}])\sin\Omega\right)}{1+\sin[\Delta\mathrm{mt}]\sin\Omega}$$

$$\frac{R(B_+ \to \mathrm{B}^0) - R(\overline{\mathrm{B}}^0 \to B_+)}{R(B_+ \to \mathrm{B}^0) + R(\overline{\mathrm{B}}^0 \to B_+)} = 2\left(\Re(\delta_b)\left(1-\cos[\Delta\mathrm{mt}]\right) - \Im(\delta_b)\sin[\Delta\mathrm{mt}]\right)$$

$$-2\left(1-\cos[\Delta\mathrm{mt}]\right)\frac{\left(\Re(\delta_b)(1-\cos\Omega) + (\Im(\delta_b)\cos[\Delta\mathrm{mt}] - \Re(\delta_b)\sin[\Delta\mathrm{mt}])\sin\Omega\right)}{1-\sin[\Delta\mathrm{mt}]\sin\Omega}$$

$$\frac{R(\mathrm{B}^0 \to B_-) - R(B_- \to \overline{\mathrm{B}}^0)}{R(\mathrm{B}^0 \to B_-) + R(B_- \to \overline{\mathrm{B}}^0)} = -2\left(\Re(\delta_b)\left(1-\cos[\Delta\mathrm{mt}]\right) + \Im(\delta_b)\sin[\Delta\mathrm{mt}]\right)$$

$$-2\left(1-\cos[\Delta\mathrm{mt}]\right)\frac{\left(-\Re(\delta_b)(1-\cos\Omega) + (\Im(\delta_b)\cos[\Delta\mathrm{mt}] + \Re(\delta_b)\sin[\Delta\mathrm{mt}])\sin\Omega\right)}{1-\sin[\Delta\mathrm{mt}]\sin\Omega}$$

$$\frac{R(B_+ \to \overline{\mathrm{B}}^0) - R(\mathrm{B}^0 \to B_+)}{R(B_+ \to \overline{\mathrm{B}}^0) + R(\mathrm{B}^0 \to B_+)} = -2\left(\Re(\delta_b)\left(1-\cos[\Delta\mathrm{mt}]\right) - \Im(\delta_b)\sin[\Delta\mathrm{mt}]\right)$$

$$+2\left(1-\cos[\Delta\mathrm{mt}]\right)\frac{\left(\Re(\delta_b)(1-\cos\Omega) - (\Im(\delta_b)\cos[\Delta\mathrm{mt}] - \Re(\delta_b)\sin[\Delta\mathrm{mt}])\sin\Omega\right)}{1+\sin[\Delta\mathrm{mt}]\sin\Omega}$$

Semiletponic Asymmetries

$$A_T(t) = \frac{R(\overline{\mathrm{B}}^0 \to \mathrm{B}^0) - R(\mathrm{B}^0 \to \overline{\mathrm{B}}^0)}{R(\overline{\mathrm{B}}^0 \to \mathrm{B}^0) + R(\mathrm{B}^0 \to \overline{\mathrm{B}}^0)} = 4\varepsilon_b$$

$$A_{CPT}(t) = \frac{R(\mathrm{B}^0 \to \mathrm{B}^0) - R(\overline{\mathrm{B}}^0 \to \overline{\mathrm{B}}^0)}{R(\mathrm{B}^0 \to \mathrm{B}^0) + R(\overline{\mathrm{B}}^0 \to \overline{\mathrm{B}}^0)} = 4\frac{\Re(\delta_b)\sinh(\frac{\Delta\Gamma t}{2}) - \Im(\delta_b)\sin[\Delta \mathrm{mt}]}{\cos[\Delta \mathrm{mt}] + \cosh(\frac{\Delta\Gamma t}{2})}$$

The untagged semileptonic asymmetry:

$$A_2(t) = \frac{R(\overline{\mathrm{B}}^0, \mathrm{B}^0 \to \mathrm{B}^0) - R(\overline{\mathrm{B}}^0, \mathrm{B}^0 \to \overline{\mathrm{B}}^0)}{R(\overline{\mathrm{B}}^0, \mathrm{B}^0 \to \mathrm{B}^0) - R(\overline{\mathrm{B}}^0, \mathrm{B}^0 \to \overline{\mathrm{B}}^0)}$$

$$= -2\varepsilon_b \left(\cos[\Delta \mathrm{mt}] + \cosh(\frac{\Delta\Gamma t}{2})\right) - 2\Im(\delta_b)\sin[\Delta \mathrm{mt}] + 2\Re(\delta_b)\sinh(\frac{\Delta\Gamma t}{2})$$