Determination of CP and CPT violation parameters in the neutral kaon system using the Bell-Steinberger relation and WA data

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The CPT symmetry

CPT symmetry is linked to the basic mathematical tools that we use in particle physics:

QFT + Lorentz invariance + Locality ⇒ CPT

These tools have intrinsic limitations (we're not able to include gravity in a consistent way) ⇒ we should expect CPT viol. at some level (hard to predict a reference scale/size for CPT viol.)

Phenomenologically driven search

Neutral kaon system
ideal testing ground

$$|m_K - m_{\overline{K}}| < 10^{-18}\, m_K \sim O(m_K^2/M_{PL})$$

With this system, the most powerful and simple phenomenological tool for CPT tests is the Bell-Steinberger relation

Time evolution of the neutral kaons

$$i \frac{d}{dt}\begin{pmatrix} K^0 \\ \overline{K}^0 \end{pmatrix} = \left(M - i\,\Gamma/2\right)\begin{pmatrix} K^0 \\ \overline{K}^0 \end{pmatrix}$$

CPT invariance

$$M_{11} = M_{22} \quad \Gamma_{11} = \Gamma_{22}$$

Diagonalization

$$K_{S,L} = N\left[\left(1+\varepsilon_{S,L}\right) K^0 \pm \left(1-\varepsilon_{S,L}\right)\overline{K}^0\right]$$

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

$$\delta = \frac{i\,(m_K - m_{\overline{K}}) + (\Gamma_K - \Gamma_{\overline{K}})/2}{\Gamma_S - \Gamma_L} \cos\phi_{SW}\; e^{\,i\phi_{SW}}$$

⇓ $\Delta\Gamma=0$

$$\phi_{SW} = \tan^{-1}\frac{2\left(m_L - m_S\right)}{\Gamma_S - \Gamma_L} = 43.5°$$

$$\left|\frac{m_K - m_{\overline{K}}}{m_K}\right| \cong 3 \times 10^{-14}\,\left|\,\mathrm{Im}\delta\,\right|$$

Unitarity and Bell Steinberger relation

Even if CPT is violated, we can assume that **unitarity** is preserved

$$\Gamma_{11} = \Sigma_f A^*(K^0 \to f)\, A(K^0 \to f)$$

$$\Gamma_{12} = \Sigma_f A^*(\bar{K}^0 \to f)\, A(K^0 \to f)$$

Expressing the decay amplitudes in the K_S K_L basis and using the definitions of ε and δ

$$\left(\frac{\Gamma_S + \Gamma_L}{\Gamma_S - \Gamma_L} + i \tan\phi_{SW}\right)\left(\frac{\mathrm{Re}\,\varepsilon}{1+|\varepsilon|^2} - i\,\mathrm{Im}\,\delta\right) = \frac{1}{\Gamma_S - \Gamma_L}\Sigma_f A^*(K_S \to f)\, A(K_L \to f)$$

Exp. inputs

Two outputs

Exp. Inputs: only ππ, 3π and πlν give appreciable contribution, ≥ 10^{-7}

Im δ ≠ 0 **could only be due to: violation of CPT, violation of unitarity, new exotic invisible final states**

A bit of recent history

- CPLEAR '99 First pioneer work
- PDG (~2000) quote the CPLEAR result
- KLOE , G. D'Ambrosio and G. Isidori JHEP 12 (2006) 011
- First WA result in 2007 (online in PDG07) published in

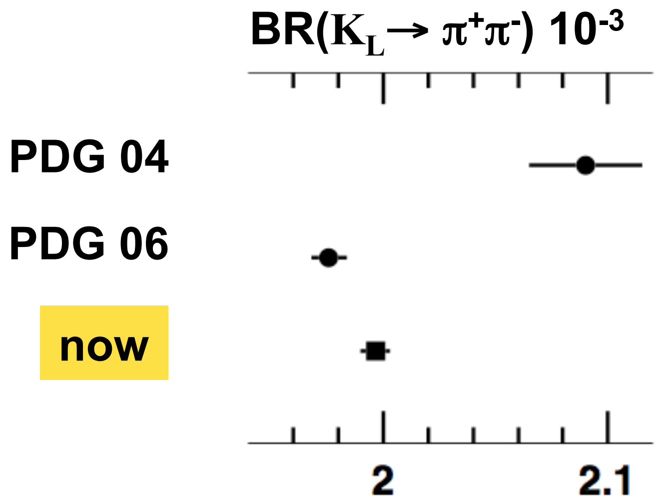
PDG08

- KTeV, Phys.Rev.D83 (2011)
- WA update including new KTeV result PDG12

$\pi^+\pi^-(\gamma)$, $\pi^0\pi^0$ decays (1)

$$\alpha_{\pi\pi} = \frac{1}{\Gamma_S} \langle A^*(K_S \to \pi\pi)\, A(K_L \to \pi\pi) \rangle = \eta_{\pi\pi}\, BR(K_S \to \pi\pi)$$

- $|\eta_{\pi+\pi-}|$ from KTeV, NA48 and KLOE BRs



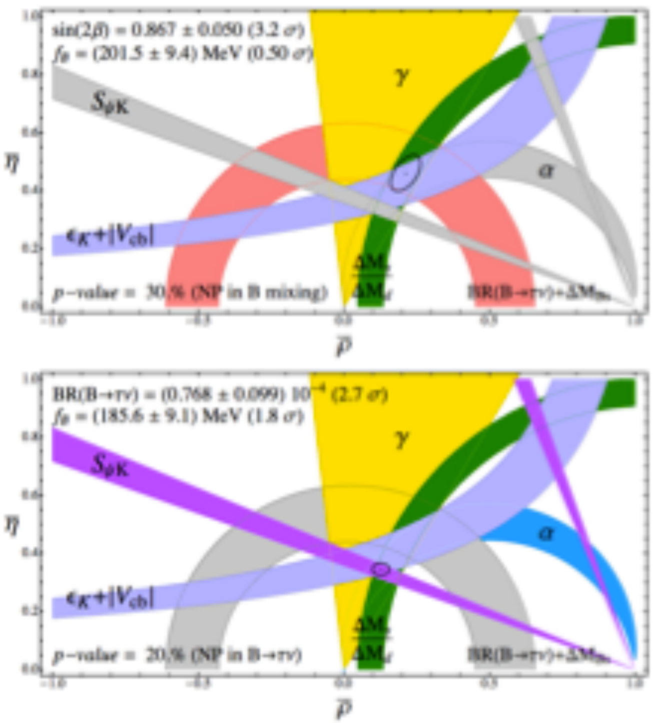
KTeV BR($\pi^+\pi^-$/Ke3) = 4.856(29) x10^{-3}

NA48 BR($\pi^+\pi^-$/Ke3) = 4.826(27) x10^{-3}

KLOE BR($\pi^+\pi^-$/Kμ3) = 7.275(68) x10^{-3}

DE contribution of **1.52(7)%*** subtracted

- fundamental ingredient for CKM
- Renewed relevance thanks to improvements in B_K determinations
- One of the “tension” in UT analysis:



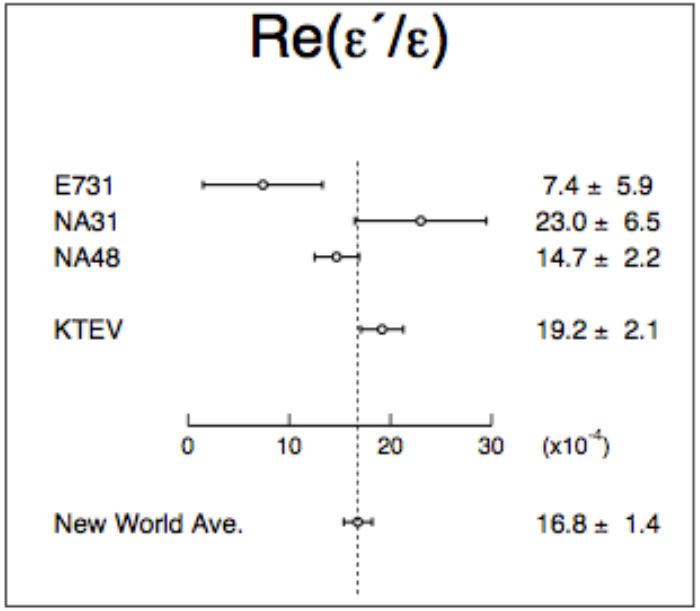
[E Lunghi, A Soni,arXiv:1104.2117]

$\pi^+\pi^-(\gamma)$, $\pi^0\pi^0$ decays (2)

$$\alpha_{\pi\pi} = \frac{1}{\Gamma_S} \langle A^*(K_S \to \pi\pi)\, A(K_L \to \pi\pi) \rangle = \eta_{\pi\pi}\, BR(K_S \to \pi\pi)$$

new KTeV CP, CPT measurement [Phys.Rev.D83 (2011)]
$\phi_{+-} = (43.76 \pm 0.64)°$, $\phi_{00} = (44.06 \pm 0.68)°$

"bonus" from direct CP measurement:



- improved average :

PDG10 fit to ΔM, τ_S, ϕ_{+-} , ϕ_{00}
(without assuming CPT)

$$\phi_{+-} = (43.4 \pm 0.7)°$$
$$\phi_{00} = (43.7 \pm 0.8)°$$

PDG12 fit to ΔM, τ_S, ϕ_{+-} , ϕ_{00}
(without assuming CPT)

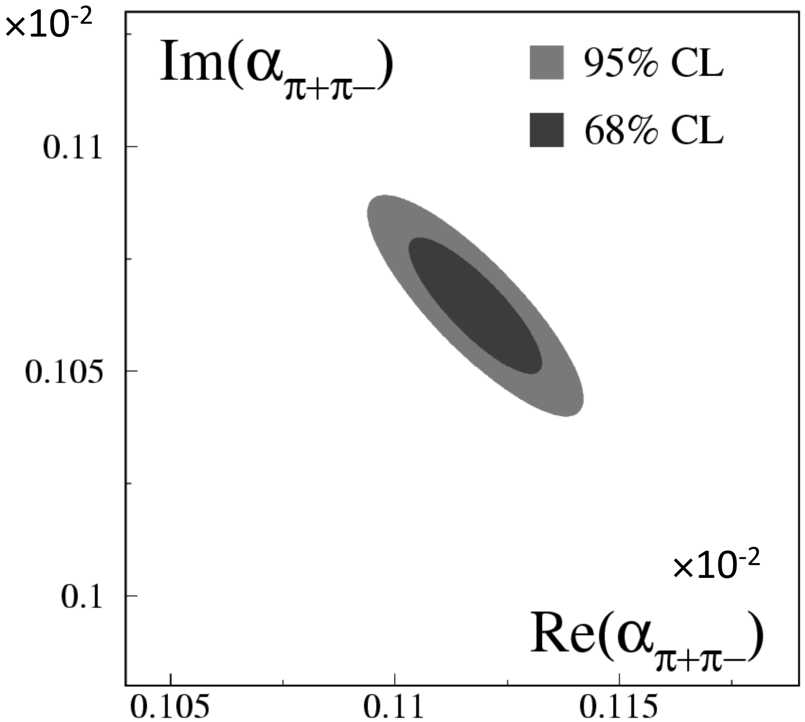
$$\phi_{+-} = (43.4 \pm 0.5)°$$
$$\phi_{00} = (43.7 \pm 0.6)°$$

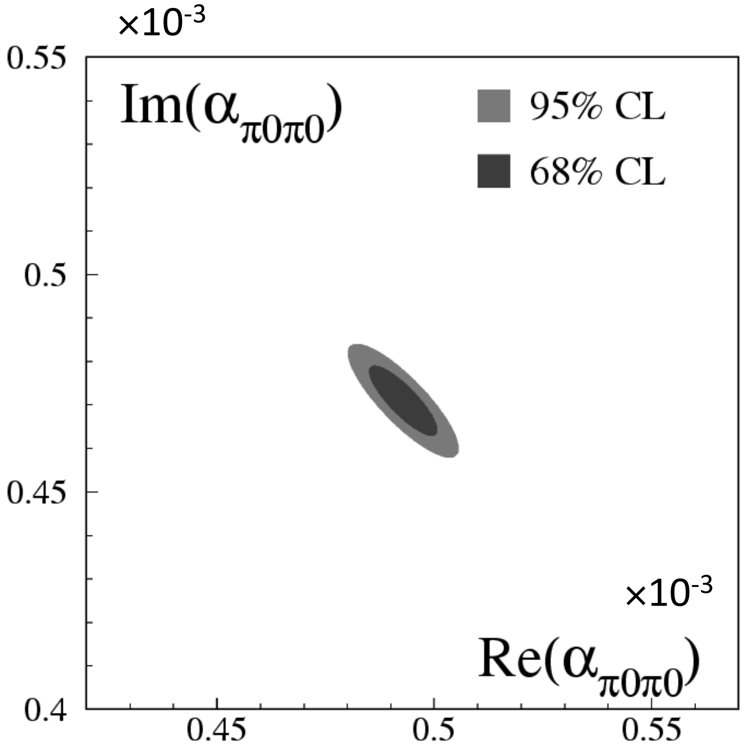
[C.-J. Lin PDG team]

$\pi^+\pi^-(\gamma)$, $\pi^0\pi^0$ decays (3)

$|\eta_{\pi\pi}|$ from KTeV, NA48 and KLOE BRs; $\phi_{\pi\pi}$ from PDG12 fit

$\alpha_{\pi+\pi-}$ = (1.11 ± 0.01 + i (1.06 ± 0.01)) ×10^{-3} $\alpha_{\pi0\pi0}$ = (0.493 ± 0.005 + i (0.471 ± 0.005)) ×10^{-3}

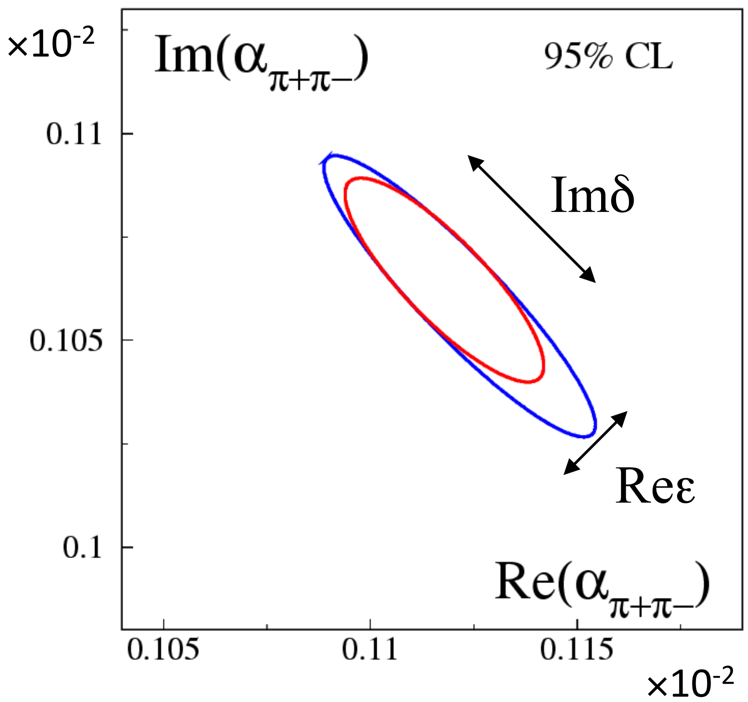


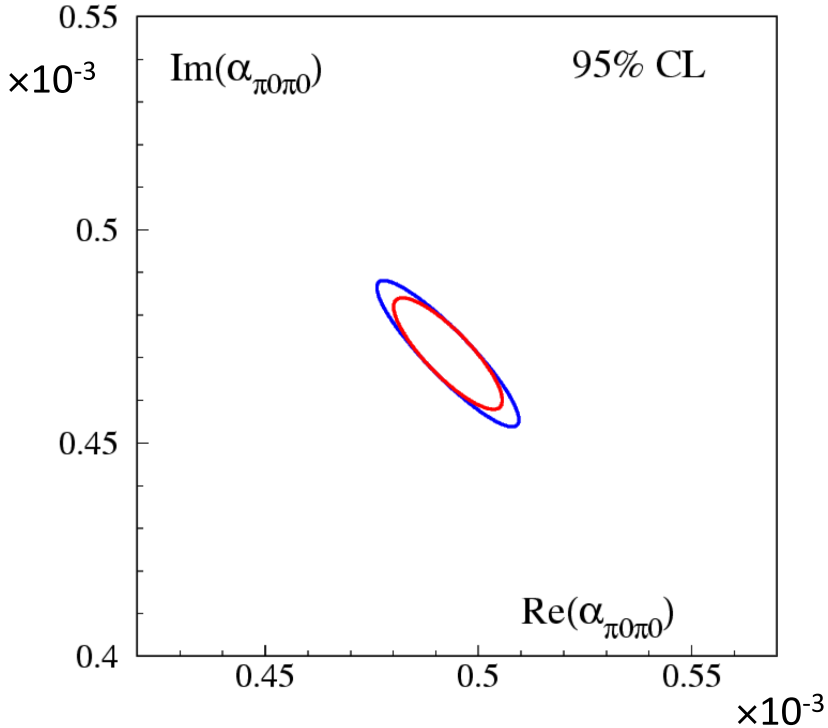


$\pi^+\pi^-(\gamma)$, $\pi^0\pi^0$ decays (3)

PDG10 fit $\phi_{+-} = (43.4 \pm 0.7)°$ $\phi_{00} = (43.7 \pm 0.8)°$

PDG12 fit $\phi_{+-} = (43.4 \pm 0.5)°$ $\phi_{00} = (43.7 \pm 0.6)°$





Semileptonic decays (1)

Decay amplitudes

$$A(K^0 \to \pi^- l^+ \nu) = A_0 (1 - y)$$

$$A(K^0 \to \pi^+ l^- \nu) = A_0^* (1 + y^*)(x_+ - x_-)^*$$

$$A(\overline{K}^0 \to \pi^+ l^- \nu) = A_0^* (1 + y^*)$$

$$A(\overline{K}^0 \to \pi^- l^+ \nu) = A_0 (1 - y)(x_+ - x_-)$$

y: ~~CPT~~; x_+: $\Delta S \neq \Delta Q$; x_-: $\Delta S \neq \Delta Q$ and ~~CPT~~

$$A_S - A_L = 4(\mathrm{Re}\,\delta + \mathrm{Re}\,x_-)$$

direct test of CPT

$$A_S + A_L = 4(\mathrm{Re}\,\varepsilon - \mathrm{Re}\,y)$$

key input for BSR

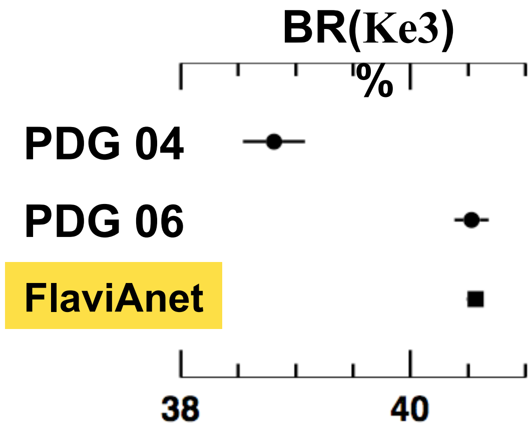
$$\frac{1}{\Gamma_S}\langle A_S(\pi l\nu) A_L(\pi l\nu)\rangle = 2\frac{\tau_S}{\tau_L} BR(K_L \to \pi l\nu)\left(\mathrm{Re}\,\varepsilon - \mathrm{Re}\,y - i(\mathrm{Im}\,x_+ + \mathrm{Im}\,\delta)\right)$$

$$= 2\frac{\tau_S}{\tau_L} BR(K_L \to \pi l\nu)\left(\underbrace{(A_S + A_L)/4 - i(\mathrm{Im}\,x_+ + \mathrm{Im}\,\delta)}_{\alpha_{\pi l\nu}}\right)$$

Semileptonic decays (2)

$$\frac{1}{\Gamma_S}\langle A_S(\pi l\nu)\, A_L^*(\pi l\nu)\rangle = 2\,\frac{\tau_S}{\tau_L} BR(K_L \to \pi l\nu) \underbrace{\left((A_S + A_L)/4 - i\,(\mathrm{Im}x_+ + \mathrm{Im}\delta) \right)}_{\alpha_{\pi l\nu}}$$

- BR_L from KLOE, KTeV and NA48



- $\tau_S = 0.08958(5)$ **ns,** constrained by **NA48 '02** and **KTeV '03** values
- $\tau_L = 50.84(23)$ **ns,** from **KLOE '06**

- $A_L = (3.34 \pm 0.07) \times 10^{-3}$ from **KTeV**
- $A_S = (1.5 \pm 10.0) \times 10^{-3}$ from **KLOE**
- $\mathrm{Im}x_+$ from CPLEAR time-dependent asymmetries:

$$A_\delta = \frac{P(\bar{K}^0 \to \bar{K}^0(t)) - P(K^0 \to K^0(t))}{P(\bar{K}^0 \to \bar{K}^0(t)) + P(K^0 \to K^0(t))}$$

$$= 4\,\mathrm{Re}\delta + f\,(\mathrm{Im}\,x_+ , \mathrm{Im}\delta , \mathrm{Re}\,x_- , t)$$

Semileptonic decays (3)

$$A_T^{\exp}(\tau) \approx \frac{\bar{R}_+(\tau) - R_-(\tau)}{\bar{R}_+(\tau) + R_-(\tau)} - 2\mathrm{Re}(y) - 2\mathrm{Re}(x_-) = 4(\mathrm{Re}(\epsilon - y) - \mathrm{Re}(x_-)) + 2\frac{\mathrm{Re}(x_-)\left(e^{-\frac{1}{2}\Delta\Gamma\tau} + \cos(\Delta m\tau)\right) + \mathrm{Im}(x_+)\sin(\Delta m\tau)}{\cosh\left(\frac{1}{2}\Delta\Gamma\tau\right) - \cos(\Delta m\tau)},$$

$$\mathbf{A_T} = \frac{N(\overline{K^0} \to e^+\pi^-\nu)(t) - N(K^0 \to e^-\pi^+\nu)(t)}{N(\overline{K^0} \to e^+\pi^-\nu)(t) + N(K^0 \to e^-\pi^+\nu)(t)}$$

Combined fit to:
A_S,(KLOE) A_l (~KTeV), A_T and A_δ (CPLEAR)

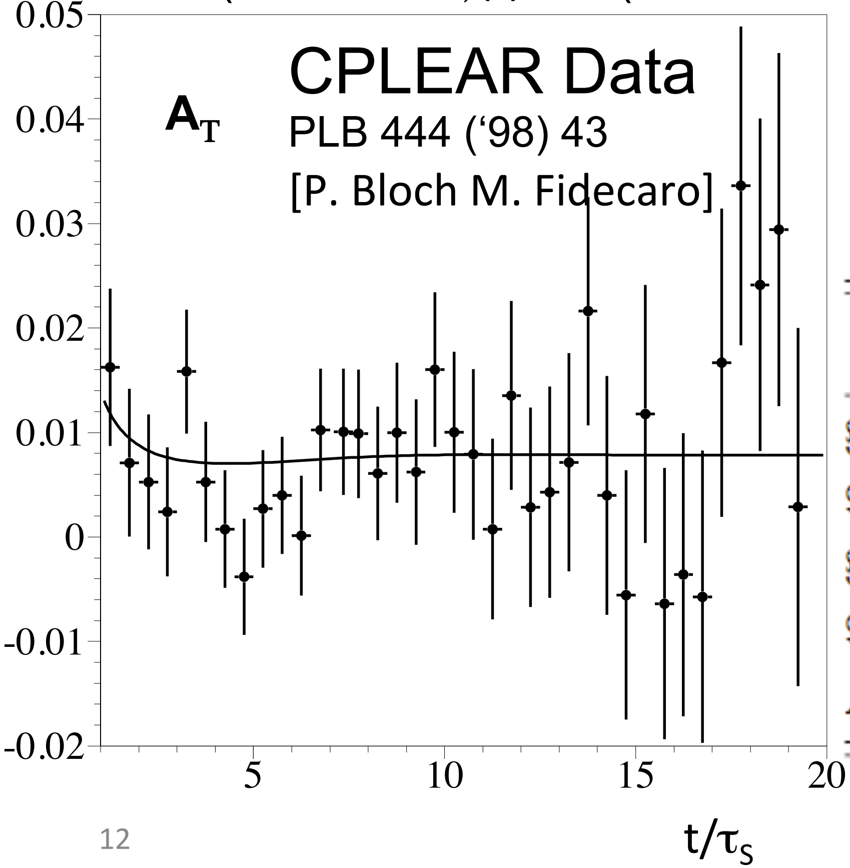


Table 1: Values, errors, and correlation coefficients for $\Re(\delta)$, $\Im(\delta)$, $\Re(x_-)$, $\Im(x_+)$, and $A_S + A_L$ obtained from a combined fit, including KLOE [4] and CPLEAR [13].

	value	Correlations coefficients				
$\Re(\delta)$	$(3.0 \pm 2.3) \times 10^{-4}$	1				
$\Im(\delta)$	$(-0.66 \pm 0.65) \times 10^{-2}$	-0.21	1			
$\Re(x_-)$	$(-0.30 \pm 0.21) \times 10^{-2}$	-0.21	-0.60	1		
$\Im(x_+)$	$(0.02 \pm 0.22) \times 10^{-2}$	-0.38	-0.14	0.47	1	
$A_S + A_L$	$(-0.40 \pm 0.83) \times 10^{-2}$	-0.10	-0.63	0.99	0.43	1

Semileptonic decays (4)

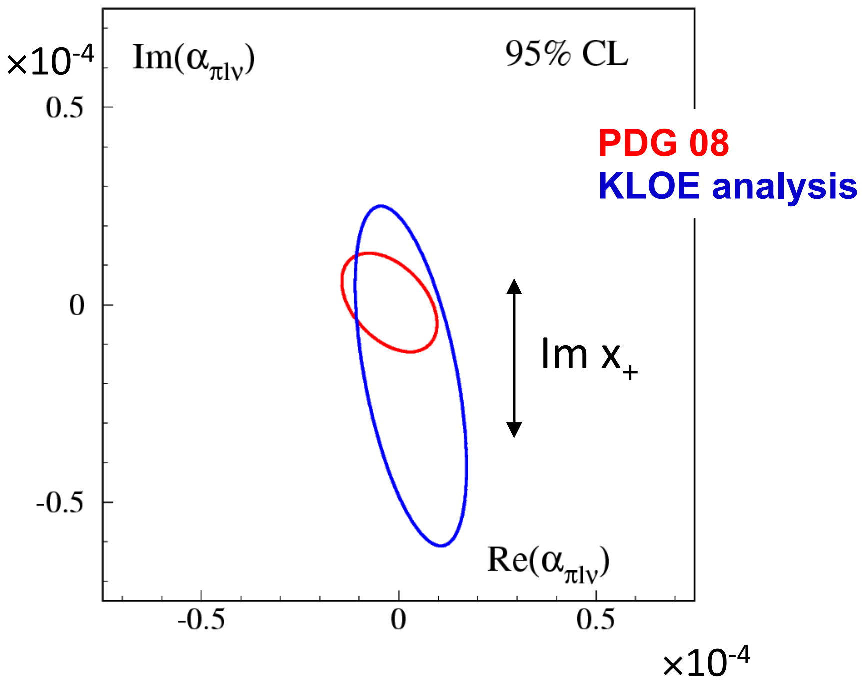
Improved determination of **Imx$_+$** from a combined fit of CPLEAR time-dependent asymmetries and A_L and A_S from KTeV and KLOE

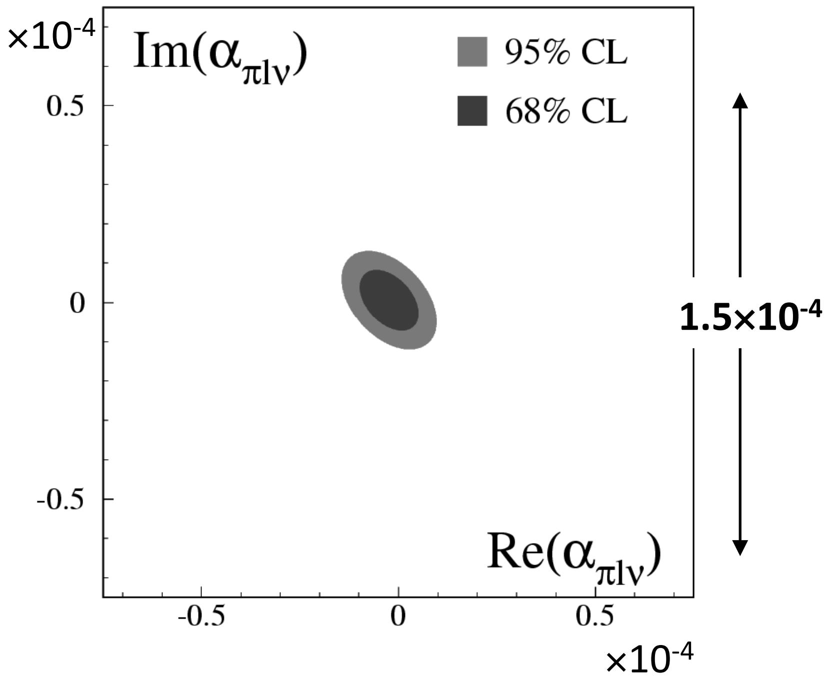
Im x_+ = 1.2(2.2)×10^{-2}

original CPLEAR result

→ **Im x_+ = 0.8(0.7)×10^{-2}** **KLOE analysis 2006**

→ **Im x_+ = 0.02(0.22)×10^{-2}** **update for PDG08**





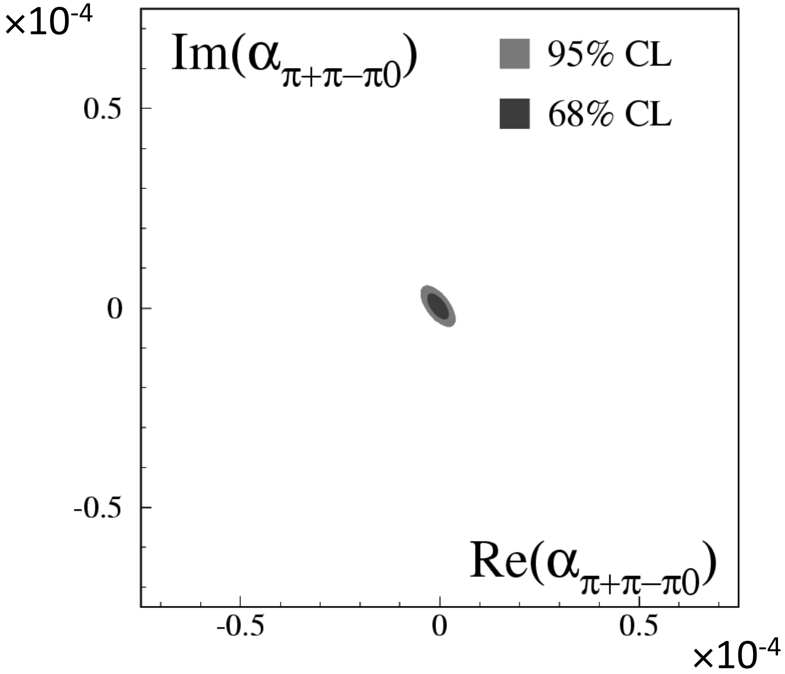
$$\alpha_{\pi l \nu} = (-2.3 \pm 4.9 \; + \; i\,(1.0 \pm 5.1)) \;\times 10^{-6}$$

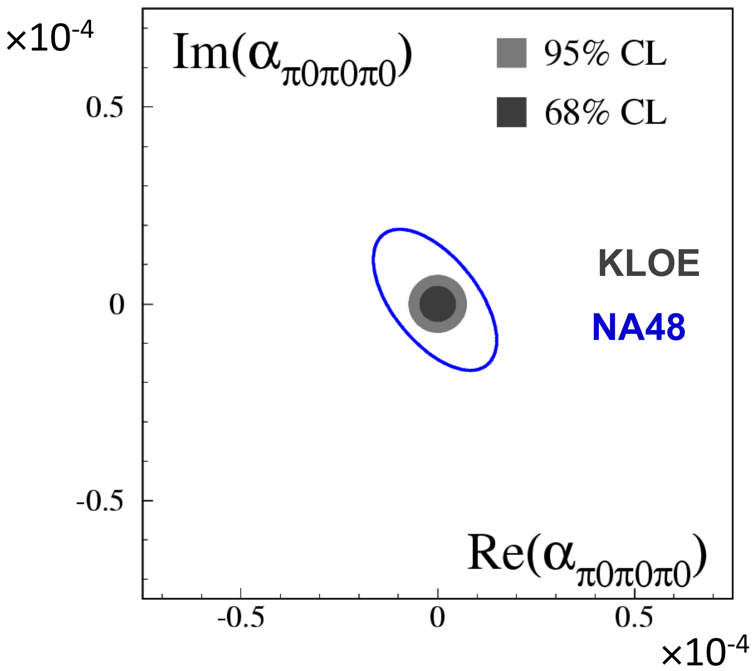
3π decays

$$\alpha_{3\pi} = \frac{1}{\Gamma_S} \langle A^*(K_S \to 3\pi)\, A(K_L \to 3\pi) \rangle = \frac{\tau_S}{\tau_L} \eta^*_{3\pi} BR(K_L \to 3\pi)$$

$Re(\eta_{+-0})$, $Im(\eta_{+-0})$ from CPLEAR

$|\eta_{000}|$ from KLOE UL on $BR(K_S \to 3\pi^0)$
$\times 2$ improvement w.r.t. NA48 η_{000}





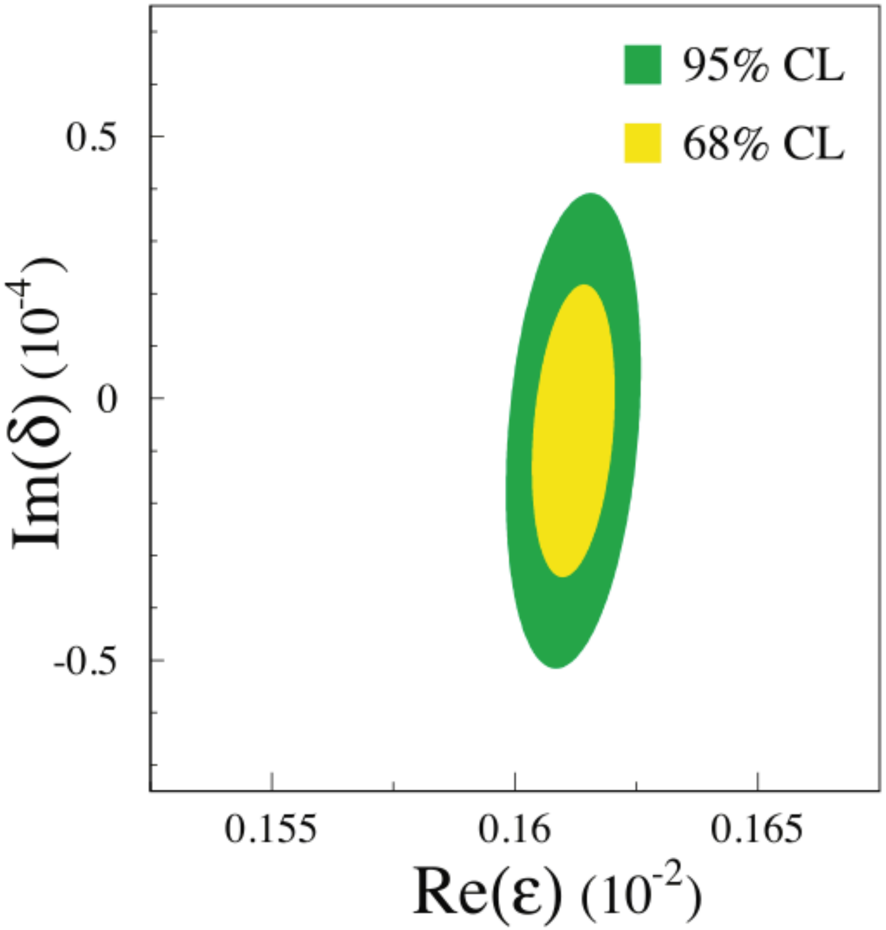
$\alpha_{\pi+\pi-\pi0}$ = $(0\pm2 + i(0\pm2)) \times 10^{-6}$

$|\alpha_{3\pi0}| < 7\times10^{-6}$ at 95% CL

Results for Reε and Imδ

$$\mathrm{Re}\,\varepsilon \propto \cos\phi_{SW} \sum_f \mathrm{Re}\,\alpha_f + \sin\phi_{SW} \sum_f \mathrm{Im}\,\alpha_f$$

$$\mathrm{Im}\,\delta \propto \cos\phi_{SW} \sum_f \mathrm{Re}\,\alpha_f - \sin\phi_{SW} \sum_f \mathrm{Im}\,\alpha_f \quad \rightarrow |\alpha_{+-}| \times (\phi_{+-} - \phi_{SW})$$



$\mathrm{Re}\,\varepsilon = (161.1 \pm 0.5) \times 10^{-5}$

$\mathrm{Im}\,\delta = (-0.7 \pm 1.4) \times 10^{-5}$

$$\sigma(\mathrm{Im}\,\delta) = \underset{\pi\pi}{1.3} \oplus \underset{\pi l \nu}{0.6}$$

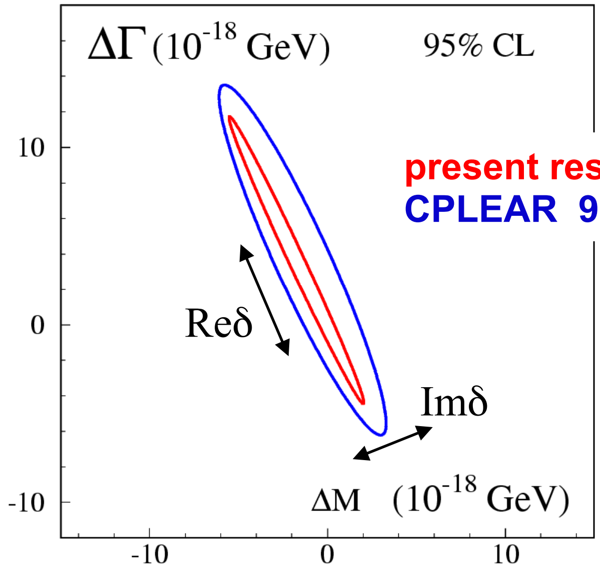
A bit of history: results

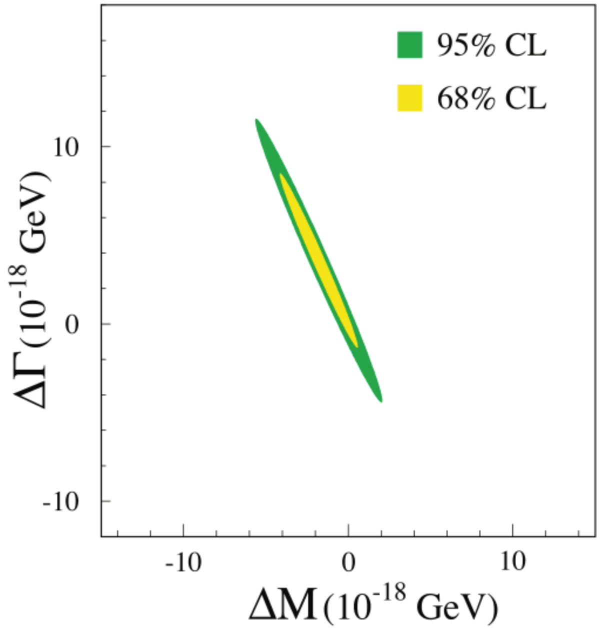
	CPLEAR99	KLOE06	PDG08	**Present result**
Analysis strategy	**fit to BSR and $\pi l\nu$ asymm.**	**Evaluation of α's**		
Im δ ($\times 10^5$)	**2.4 ± 5.0**	**0.4 ± 2.1**	**-0.6 ± 1.9**	**-0.1 ± 1.4**
σ(Im δ)	**4.5 $\oplus$ 2.1** 3π $\pi\pi$, $\pi l\nu$	**1.8 $\oplus$ 1.2** $\pi\pi$ $\pi l\nu$	**1.8 $\oplus$ 0.6** $\pi\pi$ $\pi l\nu$	**1.3 $\oplus$ 0.6** $\pi\pi$ $\pi l\nu$
Comments	**$\pi l\nu$ vs time**	**new $K_L \to \pi\pi$, $K_S \to 3\pi^0$, A_S and A_L**	**better treatment of CPLEAR data**	**new $\phi_{\pi\pi}$**
Re ε ($\times 10^5$)	**164.9 ± 2.5**	**159.6 ± 1.3**	**161.2 ± 0.6**	**161.2 ± 0.6**

CPT test: m(K)-m($\overline{K}$)

$$\delta = \frac{1}{2} \frac{M_{11} - M_{22} - i(\Gamma_{11} - \Gamma_{22})/2}{m_S - m_L - i(\Gamma_S - \Gamma_L)/2} \Rightarrow \begin{cases} \Delta M \propto -\sin\phi_{SW} \, \mathrm{Re}\,\delta + \cos\phi_{SW} \, \mathrm{Im}\,\delta \\ \Delta\Gamma \propto \cos\phi_{SW} \, \mathrm{Re}\,\delta + \sin\phi_{SW} \, \mathrm{Im}\,\delta \end{cases}$$

$\mathrm{Im}\delta = (-0.1 \pm 1.4) \times 10^{-5}$ from BSR; $\mathrm{Re}\delta = (2.5 \pm 2.3) \times 10^{-4}$ essentially from CPLEAR





Assuming CPT violation only in the mass matrix:

	CPLEAR99	KLOE06	PDG08	Present result
ΔM at $\Delta\Gamma=0$ (10^{-19} GeV)	3.3 ± 7.0	0.5 ± 3.0	-0.9 ± 2.6	-0.1 ± 2.0

Conclusions

- The Bell-Steinberger relation is a very powerful tool to probe some of the basic principles of fundamental interactions (CPT + unitarity)

- Remarkable step forward thanks to new data ($K_L \rightarrow \pi\pi$, $K_S \rightarrow 3\pi^0$, A_S, A_L, ϕ_{+-} and ϕ_{00}) + re-analysis of old CPLEAR data on semileptonic time-asymmetries

- Present uncertainty on **Imδ** is dominated by 2π channels (ϕ_{+-})

$$| m_K - m_{\overline{K}}| < 4\times10^{-19}\ m_K \quad \text{at 95\% CL if } \Delta\Gamma=0$$