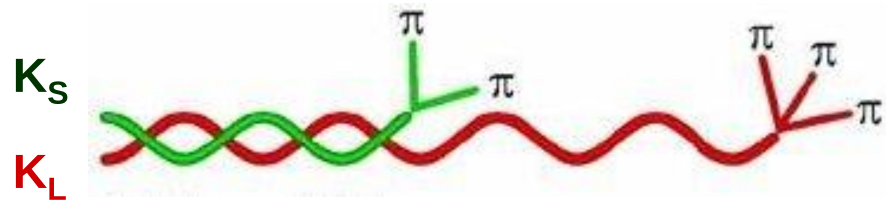
CP violation

From Schrödinger eqn:

$$|K_{S,L}(t)\rangle = e^{-im_{S,L}t}\, e^{-\Gamma_{S,L}t/2}\, |K_{S,L}(0)\rangle$$



3 types of CP violation:

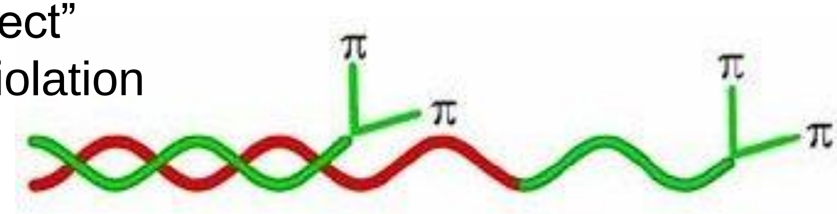
violation in mixing

$$\text{Prob}(K^0 \to \bar{K}^0) \neq \text{Prob}(\bar{K}^0 \to K^0)$$

violation in interference

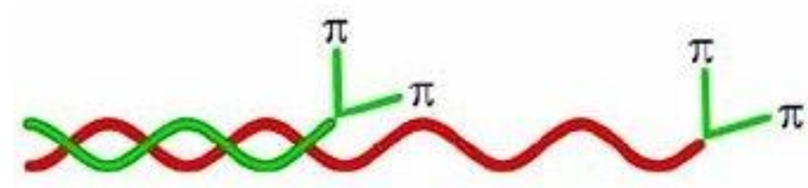
$$\text{Prob}(K^0(t) \to \pi^+\pi^-) \neq \text{Prob}(\bar{K}^0(t) \to \pi^+\pi^-)$$

} Parameter ε
"indirect"
CP violation



violation in decays

$$\text{Prob}(K \to f) \neq \text{Prob}(\bar{K} \to \bar{f})$$



"direct"
CP violation
Parameter ε'

Observables for direct ~~CP~~

CPV effect small, direct CPV expected to be even smaller or zero

If no direct CPV then the observable ratios of $K_{L,S}$ to $\pi^+\pi^-$ and $\pi^0\pi^0$ should both equal ε:

$$\eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = \varepsilon + \varepsilon' \qquad \eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} = \varepsilon - 2\varepsilon'$$

The ratio between the rates related to the ratio of direct to indirect CPV:

$$\mathrm{Re}(\varepsilon'/\varepsilon) \cong \frac{1}{6}\left[\left|\frac{\eta_{+-}}{\eta_{00}}\right|^2 - 1\right] \cong \frac{1}{6}\left[\frac{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)} - 1\right]$$

Rare decays **"normal" decays**

From theory:

- Standard Model: Re(ε'/ε) ~ 0 – 30 × 10^{-4}
- Superweak theory: Re(ε'/ε) = 0

A=amplitude
Γ=decay rate

Exploring direct CP violation

Need to measure **ε'/ε** at the 1-2 × 10^{-4} level. It took several experiments and **decades** of effort to establish the existence of direct CPV!

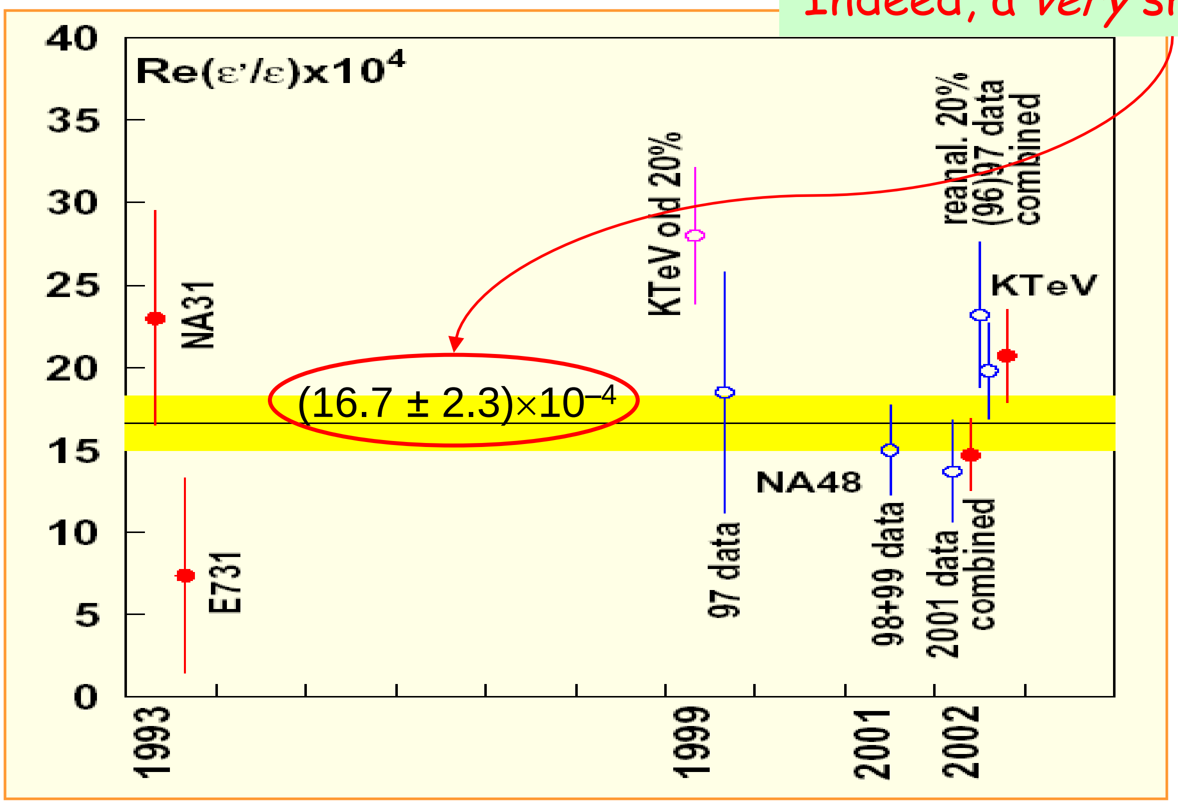
Experimental average

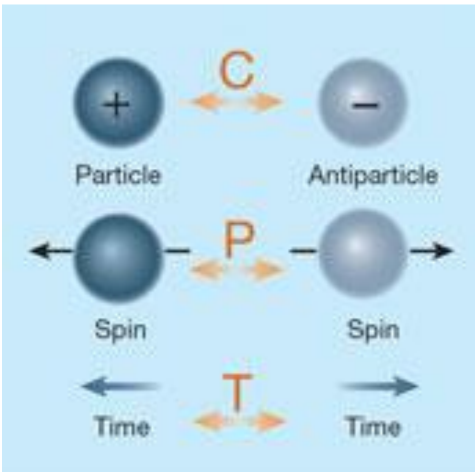
Indeed, a *very* small CPV effect !

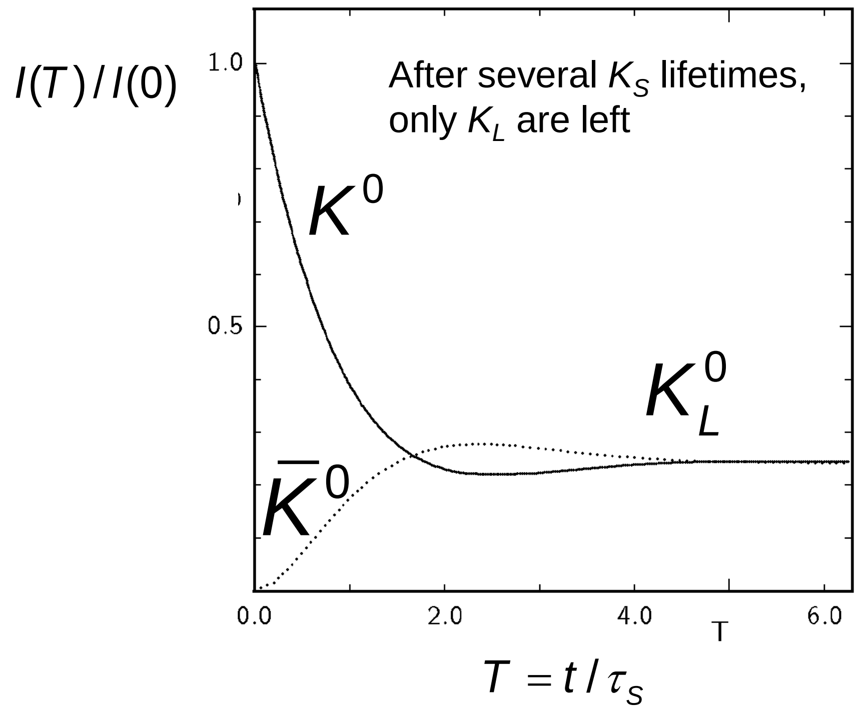
1987 (E731a): Re(ε'/ε)≅0

1988 (NA31): Re(ε'/ε) ~ 30×10^{-4}

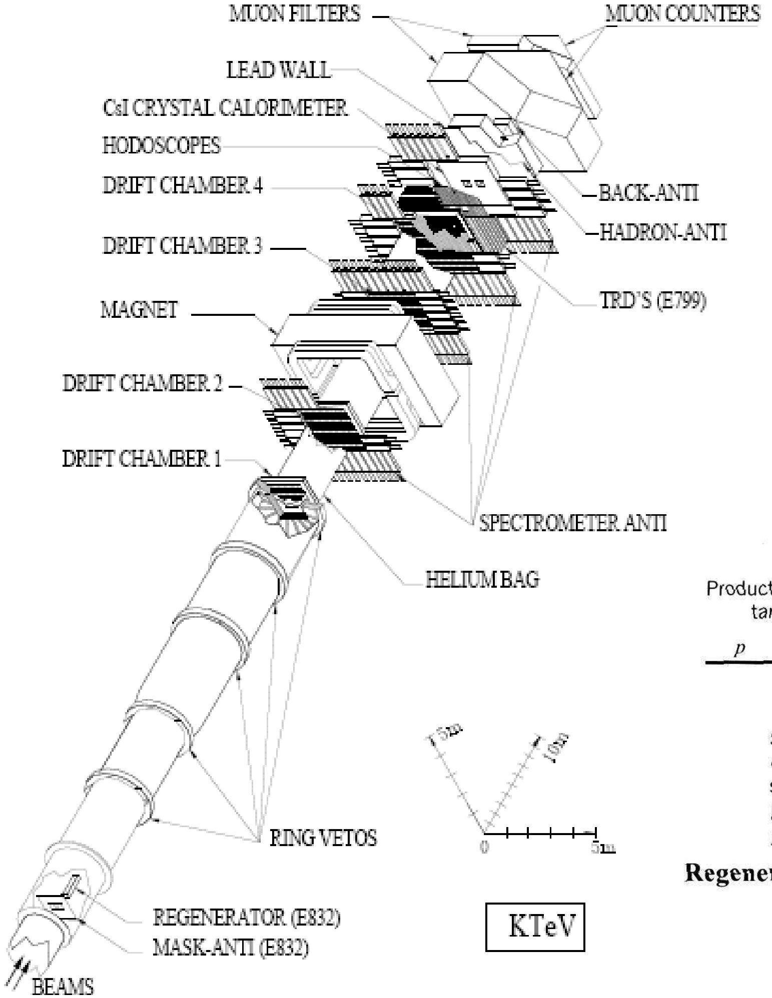
1992 (E7310: Re(ε'/ε)≅0

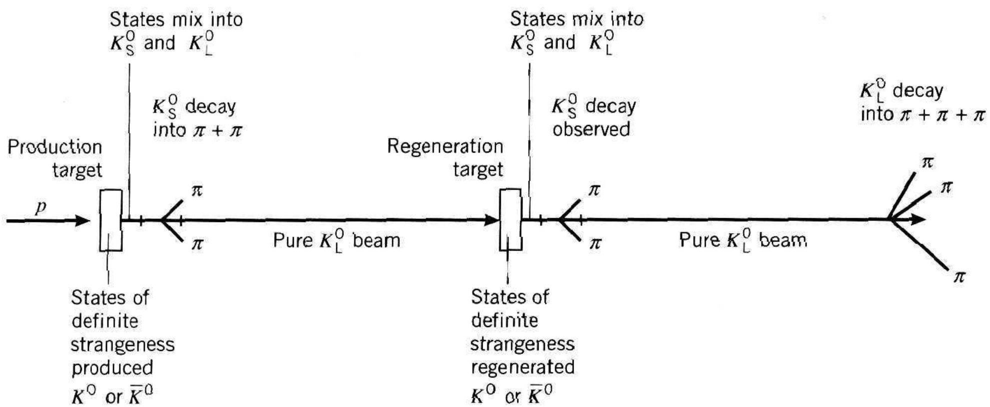



C
Particle
Antiparticle
P
Spin
Spin
T
Time
Time


$I(T)/I(0)$
After several K_S lifetimes, only K_L are left
K^0
$\overline{K}^0$
K_L^0
1.0
0.5
0.0
2.0
4.0
6.0
T
$T = t/\tau_S$

KTeV more plots





Regeneration in the neutral kaon system.

The *CPT* Theorem

The *CPT* theorem (1954): **"Any Lorentz-invariant local quantum field theory is invariant under the successive application of *C*, *P* and *T*"**

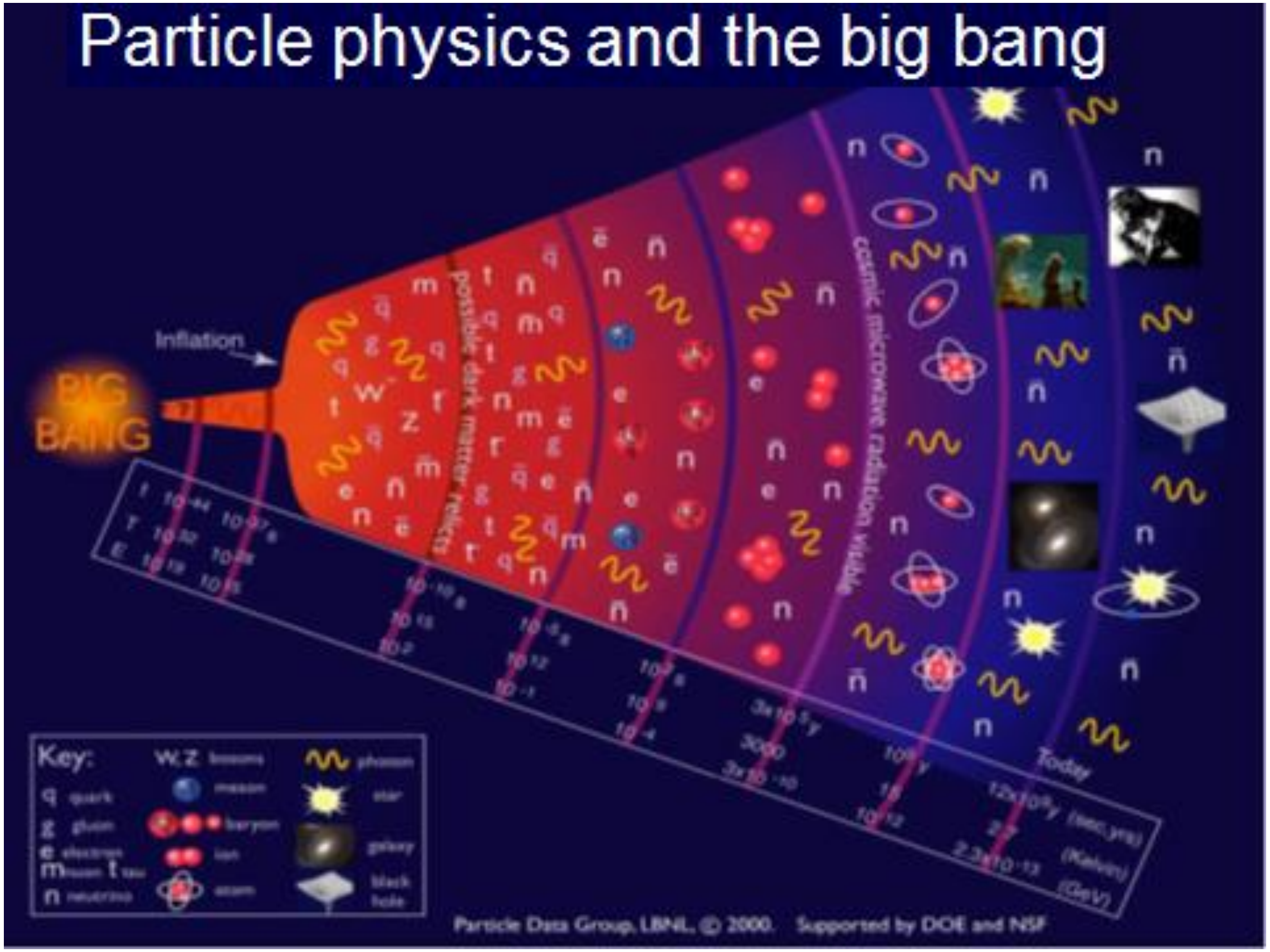
Proofs: G. Lüders, W. Pauli (1954);
J. Schwinger (1951)
Derived from Lorentz invariance and the "principle of locality"

- Fundamental consequences:
  - Relation between spin and statistics: fields with integer spin ("bosons") commute and fields with half-numbered spin ("fermions") anticommute → Pauli exclusion principle
  - Particles and antiparticles have **equal mass and lifetime**, equal magnetic moments with opposite sign, and **opposite quantum numbers**
- Best experimental test: $\left|\left(m_{K^0} - m_{\bar{K}^0}\right)/m_{K^0}\right| < 10^{-18}$

CPV lessons

- No *CP* violation without antimatter !
- *CP* violation is a vital ingredient for the creation of a matter universe
- *CPT* Symmetry is a fundamental property of quantum field theories
- *P*, *C*, *T* are good symmetries of electromagnetic and strong interactions
- *P*, *C* are maximally violated in weak interaction
- *CP*, *T* are broken symmetries of weak interaction
- *CP* violation has been first discovered in the kaon system, and both, direct and indirect *CP* violation have been observed
- No other source of *CP* violation has been found so far

Beyond the Standard Model



Tuning the higgs couplings example

$$
\begin{aligned}
100^2 \quad = \quad & 16419971512763993607881093447038089115 \\
& -19402031160008016677277886179991476752 \\
& +24412810990665599549438182257396371 42 \\
& +5407785481774631144529745072137514 95
\end{aligned}
$$