Thoughts on CP violation
- experiment -

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1) Introduction

Standard opinions;

Why do we care about CP and CPT?

Concept of symmetry is very fundamental in our understanding: conserving quantities, building blocks, interactions and space-time structure, i.e. the entire physical world.

Violation of symmetries seen at low energy reflects what happens at higher energies.

What is so special about CP?

Absence of antimatter is key to our existence; i.e. the most noticeable CP violation effect, i.e. baryogenesis:

Absence of antimatter in our universe (so far the case) cannot be explained by the baryogenesis at electroweak energy scale with only the Standard Model.

- no first order phase transition (m_{Higgs}) and not enough ~~CP~~ (~10 orders off)

Continue looking for antimatter in our universe:
AMS, PAMELA, etc. (Pohl, Nozaki, Coutu,Simon)

But if they find one $\bar{\alpha}$, may be we first re-examine early pp and pN interaction data.

(My prejudice is that we keep failing to find antimatter....)

Why did I finally got interested in CP violation?

The Standard Model $SU(3)\times SU_L(2)\times U(1)$ can generate CP violation in weak interactions (charged current)
and
QCD.

Why CP violation in the weak interactions is so large
and in the strong interaction so small?
May be they are both zero for a common reason, i.e.
observed CP violation is outside of the standard model?

My first question!

Looking back history till now

(Peyand)

It has all started with the discovery of ~~CP~~ $K_L \to \pi^+\pi^-$ decays

J.H. Christenson et al., PRL 1964

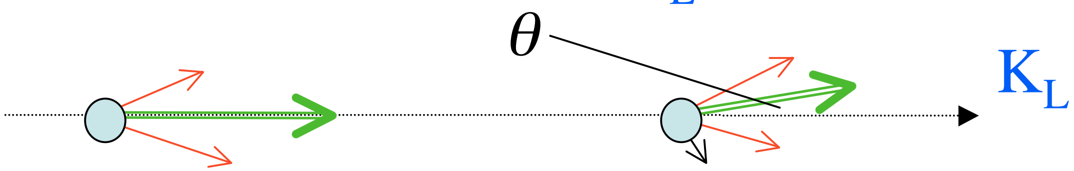
$K_L \to \pi^+\pi^- + X$

$\boldsymbol{p}_{+-} = \boldsymbol{p}_{\pi^+} + \boldsymbol{p}_{\pi^-}$

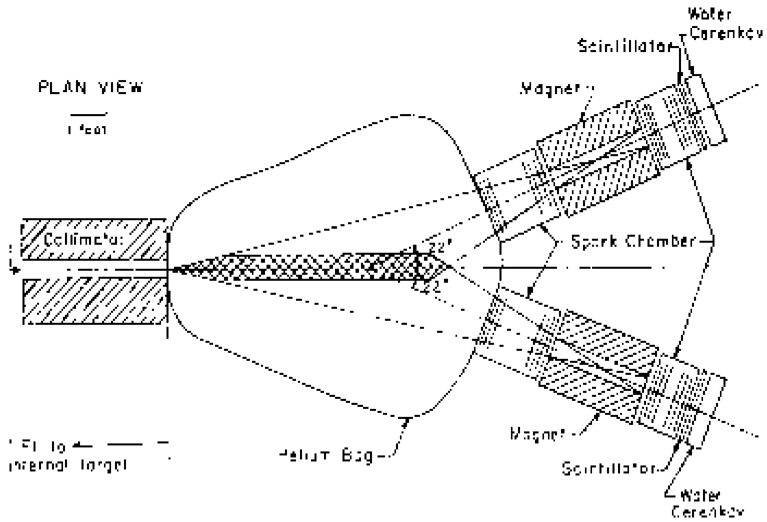
θ = angle between $\boldsymbol{p}_{K_L}$ and $\boldsymbol{p}_{+-}$

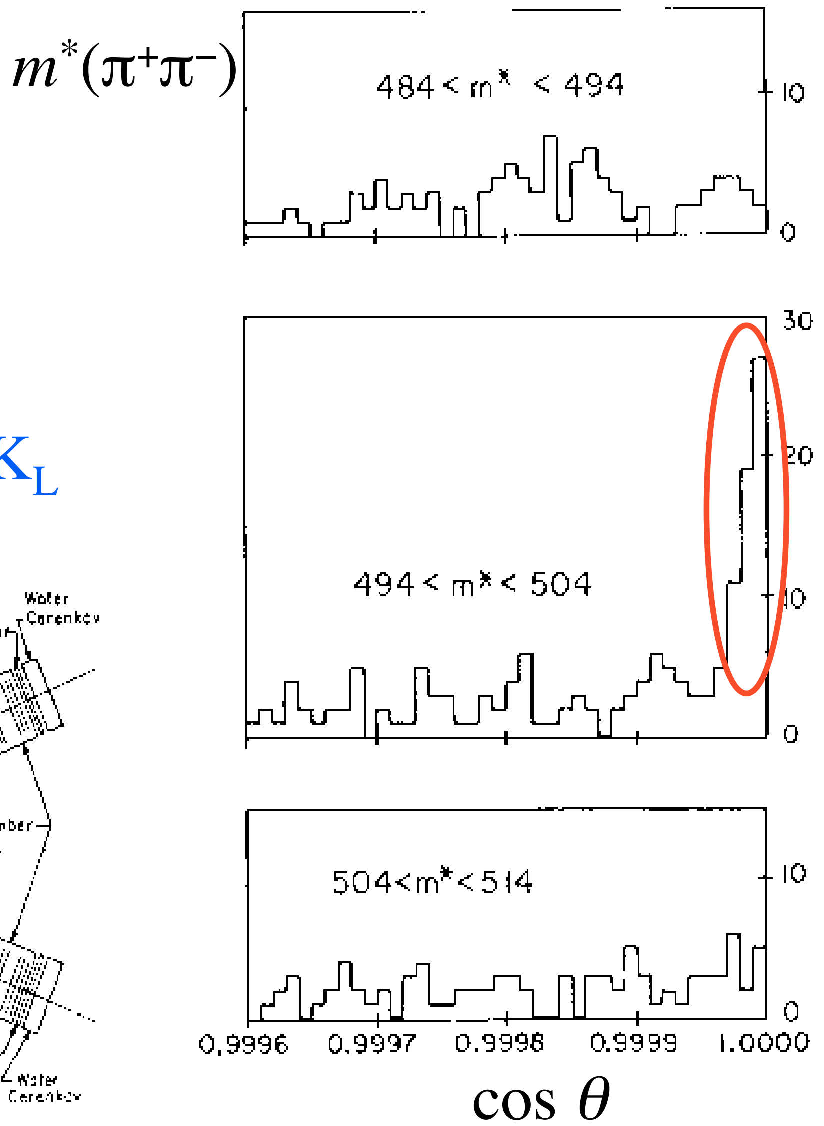
If $X = 0$, $\boldsymbol{p}_{+-} = \boldsymbol{p}_{K_L}$: $\cos\theta = 1$

If $X \neq 0$, $\boldsymbol{p}_{+-} \neq \boldsymbol{p}_{K_L}$: $\cos\theta \leq 1$



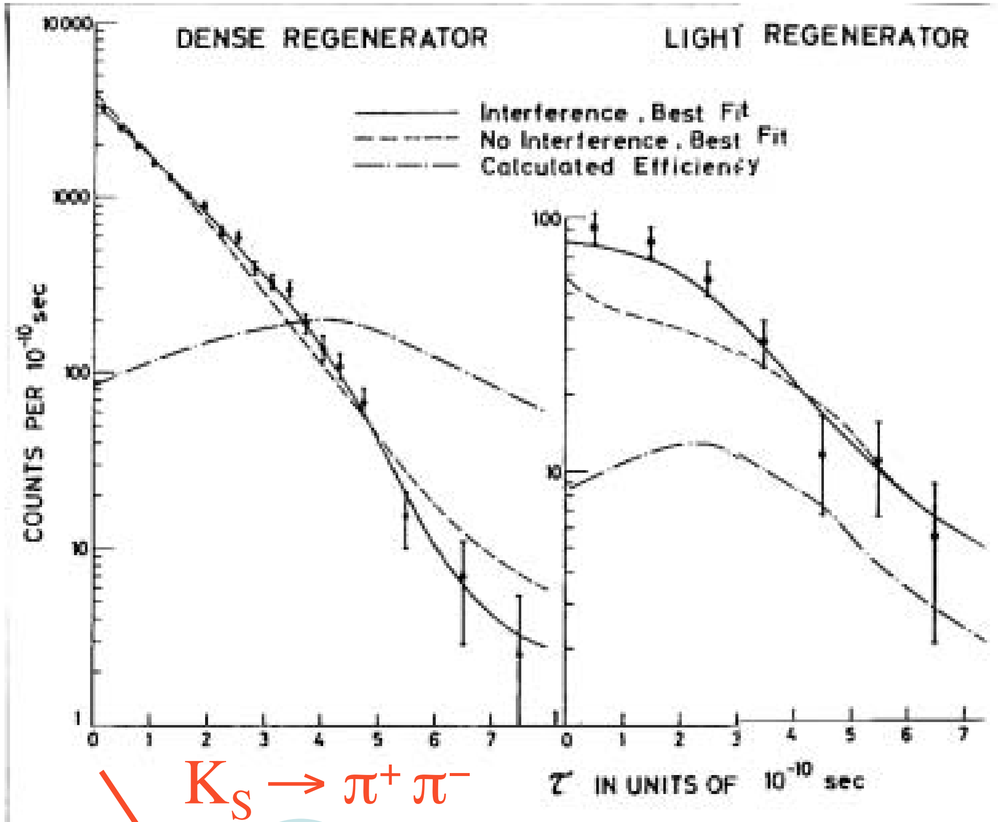
$K_L \to$





The evidence for $K_S \to \pi^+\pi^-$ was quite clear.

But CP violation was a really big deal.



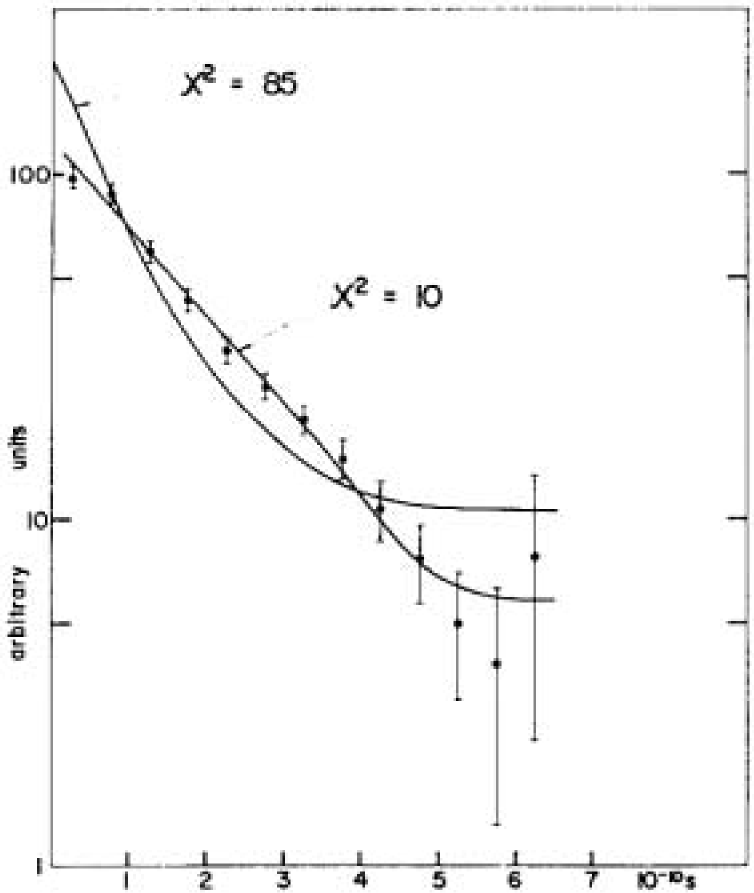
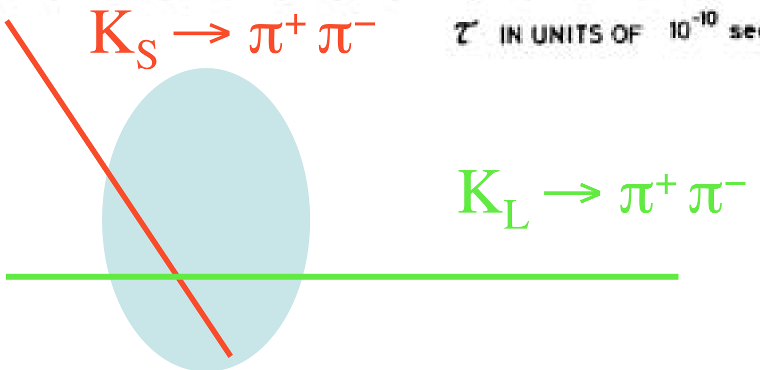


Fig. 3a. Time distribution of 2π decays observed behind a 4 cm carbon regenerator. The curve with $\chi^2 = 85$ represents the best fit assuming no interference, the curve with $\chi^2 = 10$ is the best fit assuming interference.



Observation of K_S-K_L interference

C.Alff-Steinberger et al., PL 1966

M.Bott-Bodenhausen et al., PL 1966

Framework to understand the K^0-$\bar{K}^0$ system was well developed

(Schubert)

eigenstates of
-electromagnetic and strong int.
-flavour

eigenstates
-of weak int.
-with definite masses and widths

$$\begin{pmatrix} K^0 \\ \bar{K}^0 \end{pmatrix} \longleftrightarrow \begin{pmatrix} K_S \\ K_L \end{pmatrix}$$

linear transformations
to each other

Nice demonstration of quantum mechanics!

A special situation with the kaon system

large lifetime difference; $\tau(K_S) << \tau(K_L)$

small t → practically pure*) K_S beam

intermediate t → K_S-K_L interference

large t → pure K_L beam

*) may not be pure enough for rare K_S decay studies

K_L decays = background

Solution...

observe K_S-K_L interference

or

ϕ factory, i.e. truly pure K_S beam

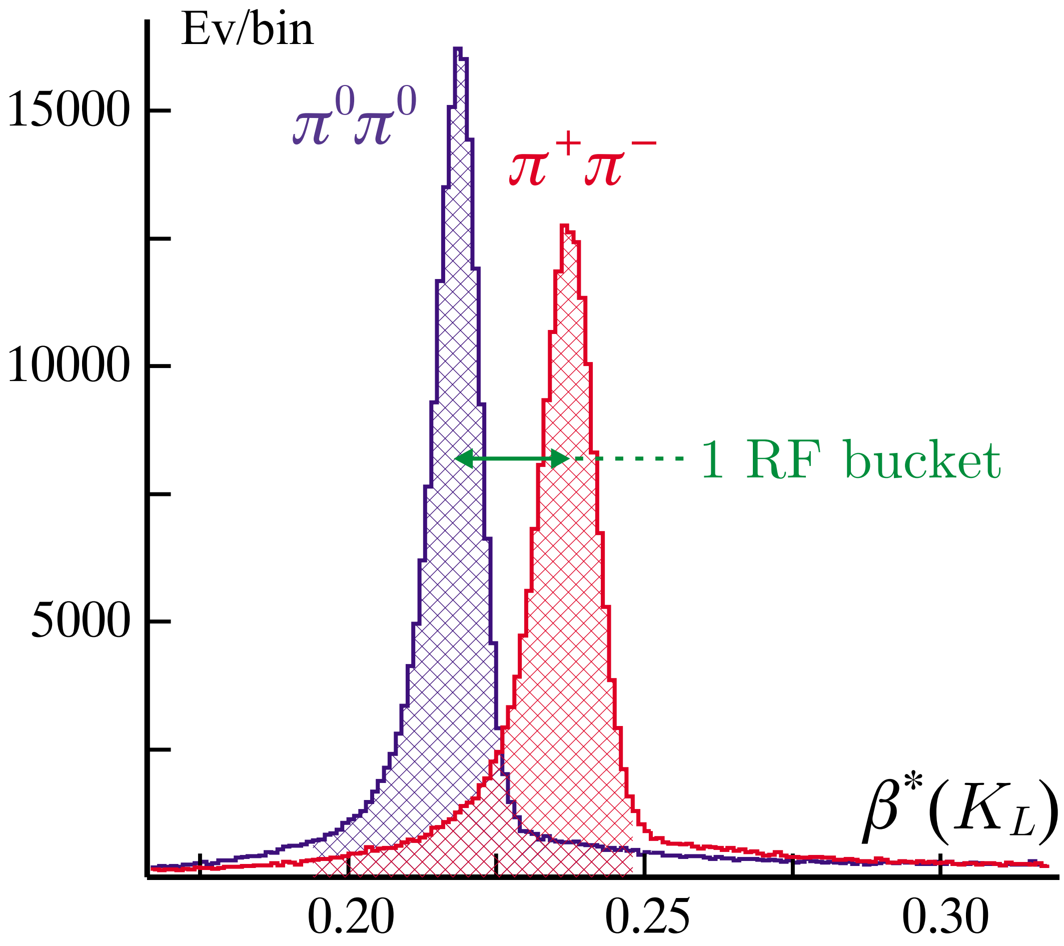
$\phi \rightarrow K_S K_L$ (Lee-Franzini)

Another approach would be, start with know initial flavour

i.e. K^0 or $\bar{K}^0$.

K_S decays

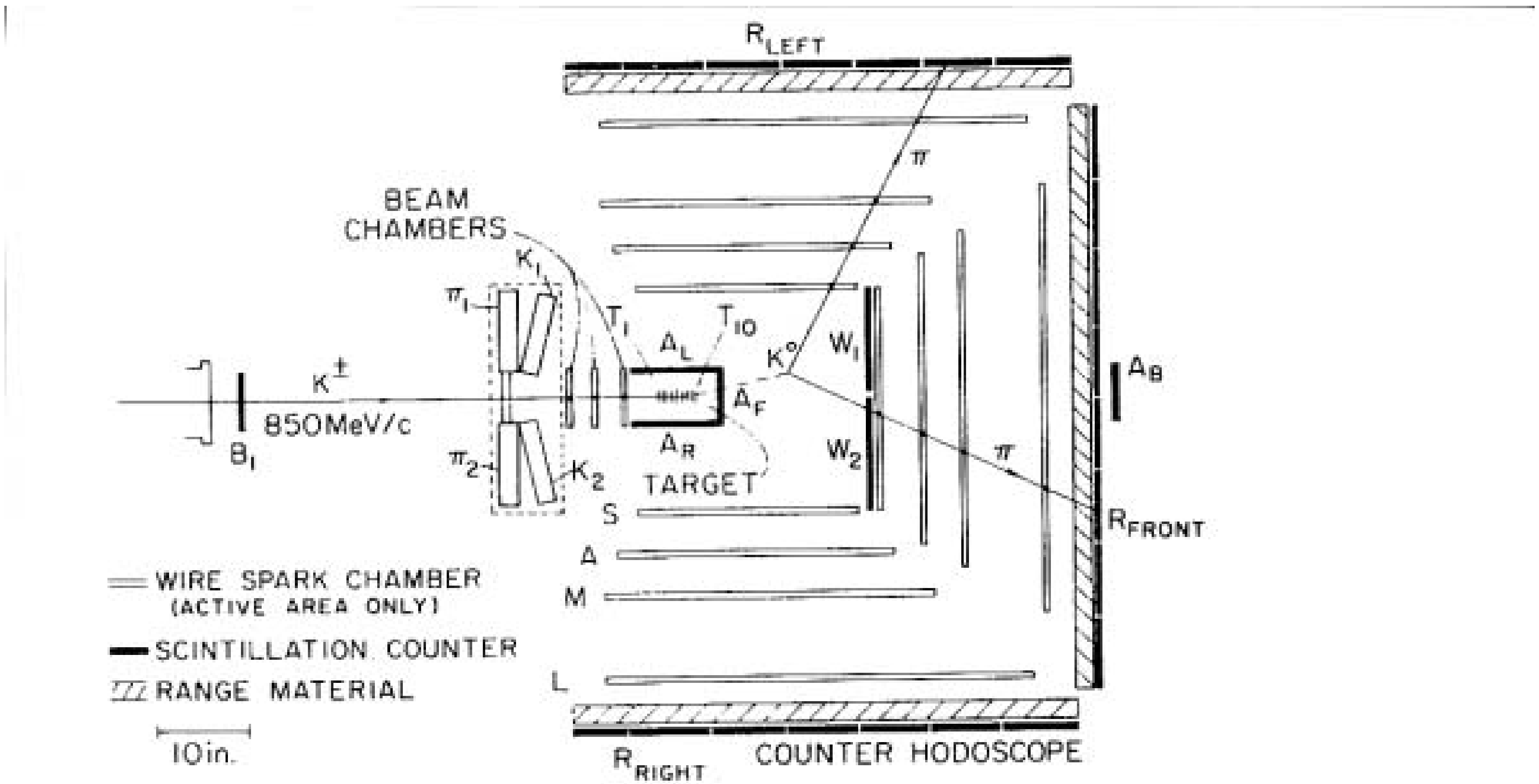
$\Gamma(K_S \to \pi^+\pi^-)/\Gamma(K_S \to \pi^0\pi^0)$



K_L interacting in the calorimeter gives an ideal K_S tag, almost independent of K_S decay mode

K$^+$ or K$^-$ beam selected K^0 or $\bar{K}^0$ initial state

$$K^+ n \to K^0 p, \quad K^- p \to \bar{K}^0 n$$



an view of the experimental arrangement. Scintillators T_1–T_{10} are the target counters. Phototubes π_1, π_2 ceive Cherenkov light from beam pions and kaons, respectively.

First "direct" matter and antimatter comparison.

D. Banner et al., PRD 1973

$K^0(t = 0) \rightarrow \pi^+\pi^-(\text{at } t)$

$\Updownarrow$ CP conjugate to each other

$\bar{K}^0(t = 0) \rightarrow \pi^+\pi^-(\text{at } t)$

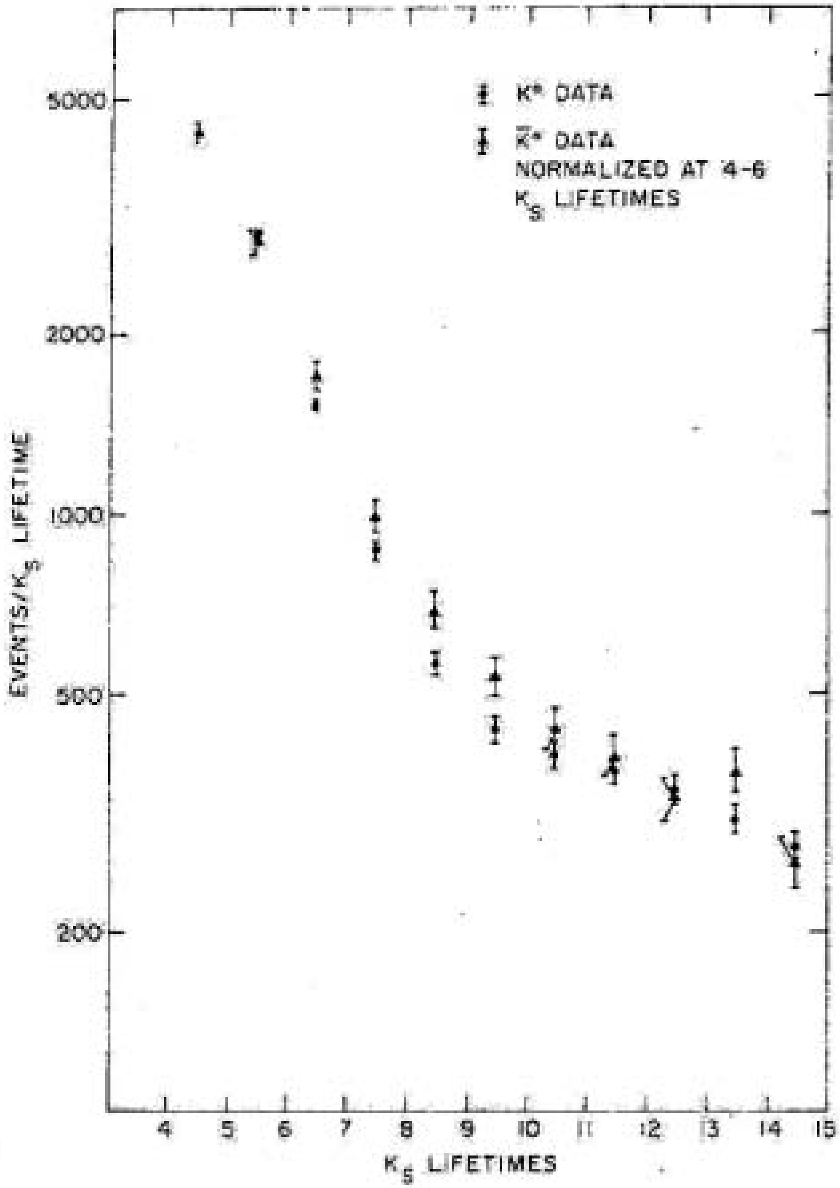
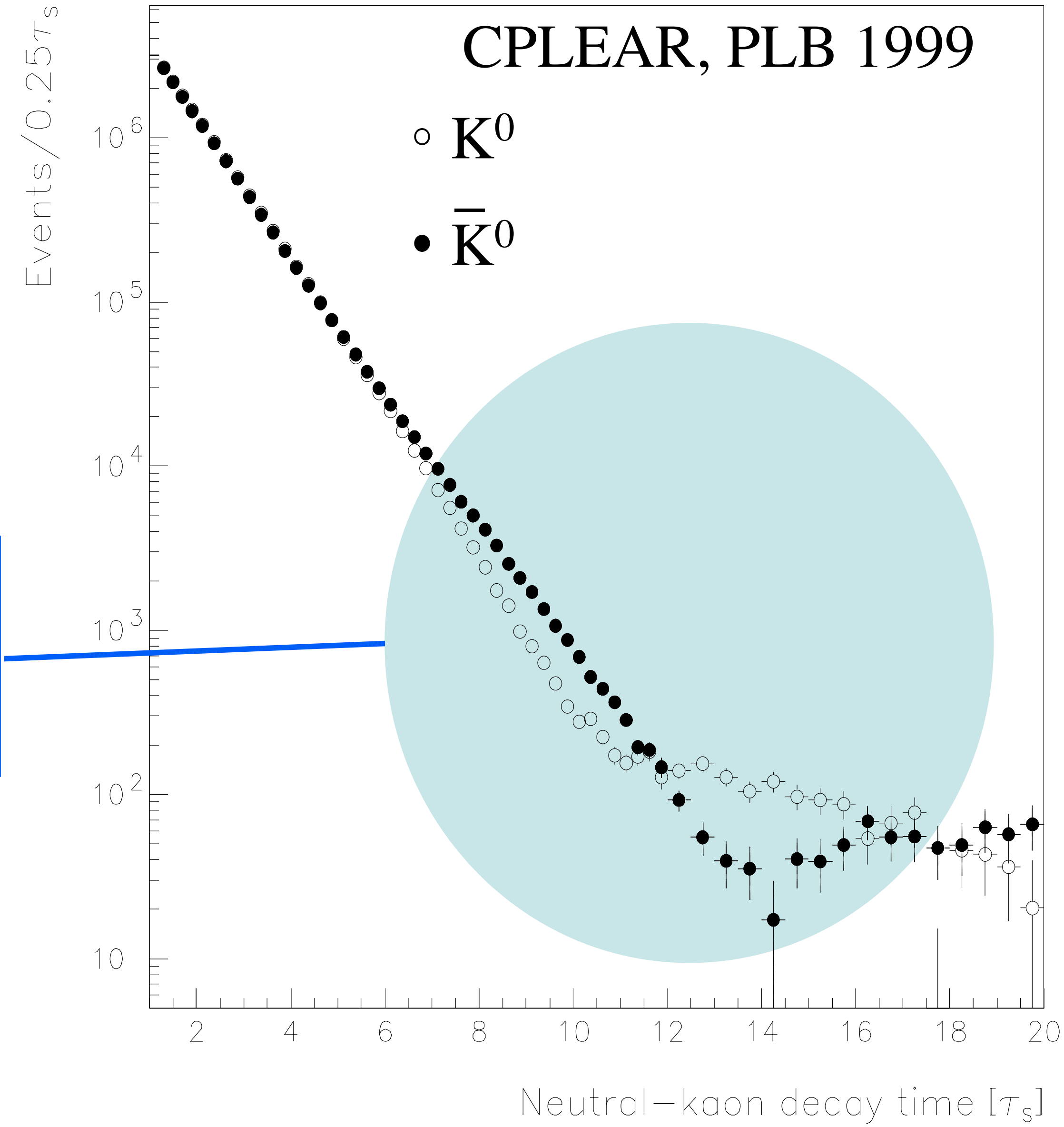


FIG. 9. Proper time distributions of K^0 and $\bar{K}^0$ decays normalized at 4 to 6 K_S lifetimes but not corrected for efficiency.

And 26 years later...

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



Opposite signs for the K_L-K_S interference terms between K^0 and $\bar{K}^0$.

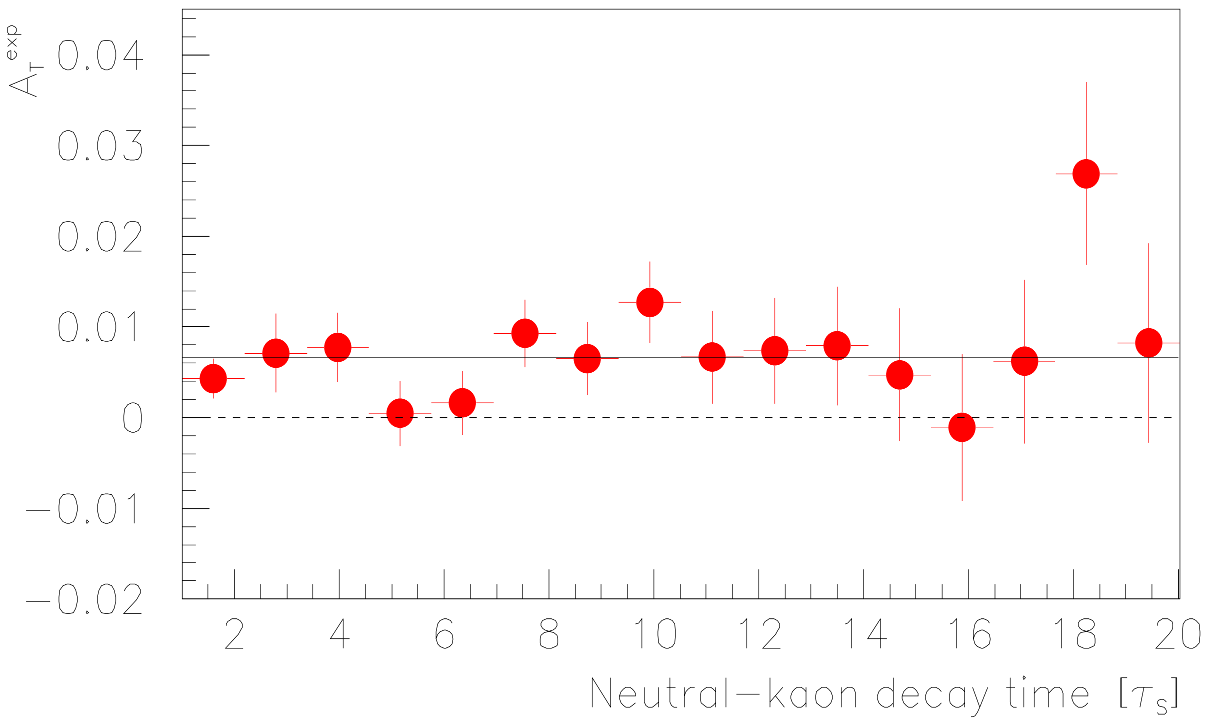
Tagged initial K^0 and $\bar{K}^0$ states are useful for testing $\not{T}$ and $\not{CPT}$ as well.

(Aslanides) To be continued with the B system.

T violation

CPLEAR

$$\frac{\overline{K}^0 \rightarrow K^0 - K^0 \rightarrow \overline{K}^0}{\overline{K}^0 \rightarrow K^0 + K^0 \rightarrow \overline{K}^0}$$



"Charged current interactions with the three families of SU(2) quark doublet can naturally generate CP violation"
1972 Kobayashi and Maskawa

This model could make an experimentally testable predictions:
CP violation effect depends on the final states,

i.e. ~~CP~~$(K_L \to \pi^+\pi^-) \neq$ ~~CP~~$(K_L \to \pi^0\pi^0)$.

Start of ε'/ε quest!!!

Now (2002) the quest is approaching to its end.

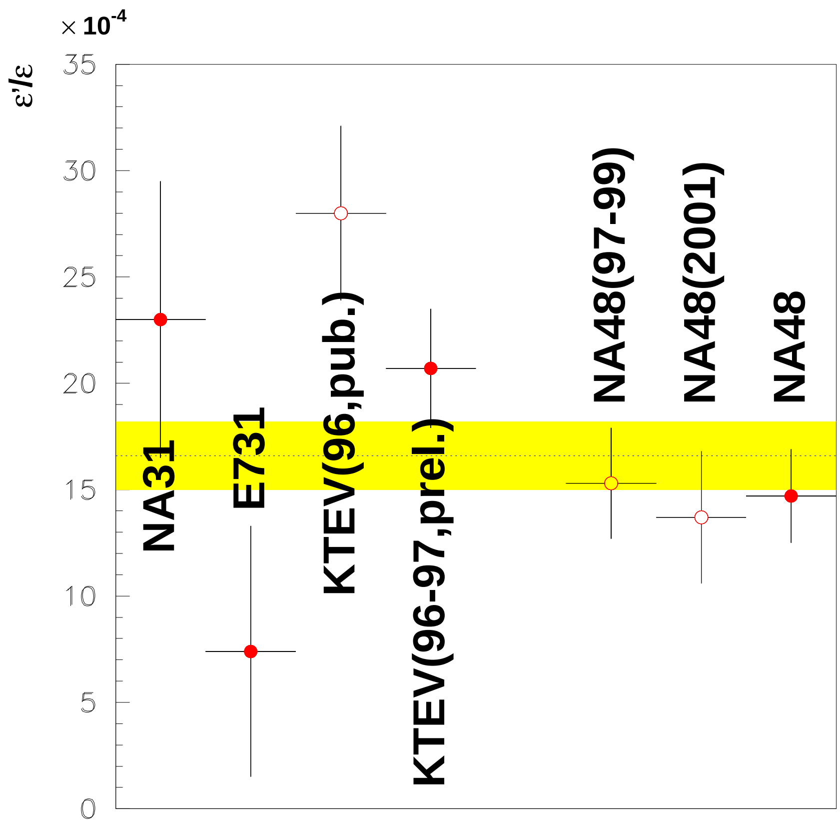
$\mathrm{Re}(\varepsilon'/\varepsilon) = (16.6 \pm 1.6) \times 10^{-4}$ (Lazzeroni)

Current average waiting for the final results from KTeV.(Turner)

Qualitative agreement with the Standard Model prediction.
Unfortunately, hadronic effects are still too difficult for a precise prediction of $\mathrm{Re}(\varepsilon'/\varepsilon)$.

-I doubt that the theoretical error can ever be reduced to the level of the experimental error.

$\mathrm{Re}(\varepsilon'/\varepsilon)$ *results*



World Average: $\mathrm{Re}(\varepsilon'/\varepsilon) = (16.6 \pm 1.6) \times 10^{-4}$
with χ^2/ndf=6.2/3

Then here comes the B system, particularly triggered by the unexpectedly long lifetime, 1984.

Now, well established “quark flavour physics” industry, i.e. determination of the CKM unitarity triangles, including:

Side measurements		
$\Gamma(B \to X_c \ell \nu)$, $\Gamma(B \to X_c h)$	tree	A
$\Gamma(B \to X_u \ell \nu)$, $\Gamma(B \to X_u h)$	tree	$\rho^2 + \eta^2$
$\Delta m(B_d)$	box (1)	$(1-\rho)^2 + \eta^2$
Angle measurements		
$\not{CP}(K^0 \Leftrightarrow K^0$ oscillations)	box (2)	$f(\rho, \eta)$
$\not{CP}(B_d \to J/\psi\ K_S)$	box and tree	$\tan^{-1} \eta/1-\rho$
	+ very small penguin (1)	

latest numbers from BABAR and BELLE
(Giorgi, Teramoto)

and other non-B data. (Kleinknecht)

Experimental input from tree-level processes

V_{ud} : beta decays of mirror nuclei $0^+ \to 0^+$

neutron decay of polarized neutrons

$|V_{ud}| = 0.9734 \pm 0.0008$

V_{us} : from K_{e3} (vector) decays

$|V_{us}| = 0.2196 \pm 0.0026$

V_{cd} : from charm production by neutrinos and antineutrinos

$|V_{cd}| = 0.224 \pm 0.016$

V_{cs} : from hadronic decays of W bosons at LEP, compared to leptonic W decays

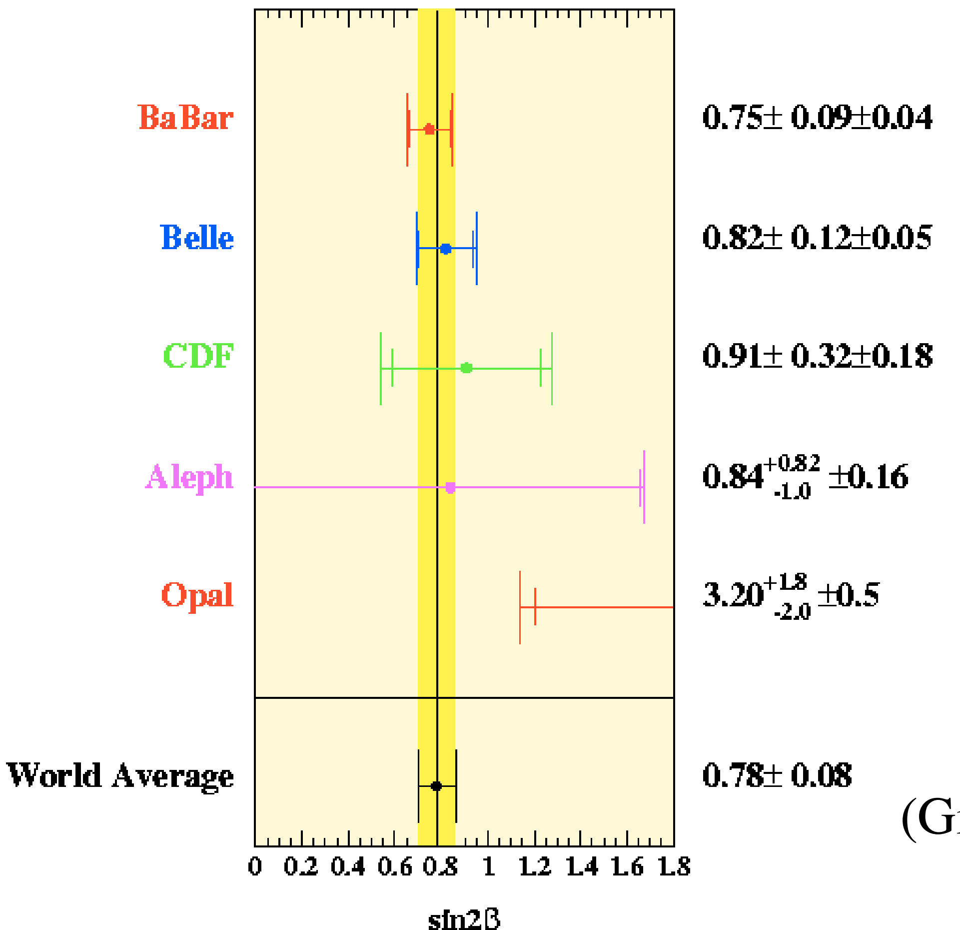
$|V_{cs}| = 0.996 \pm 0.013$

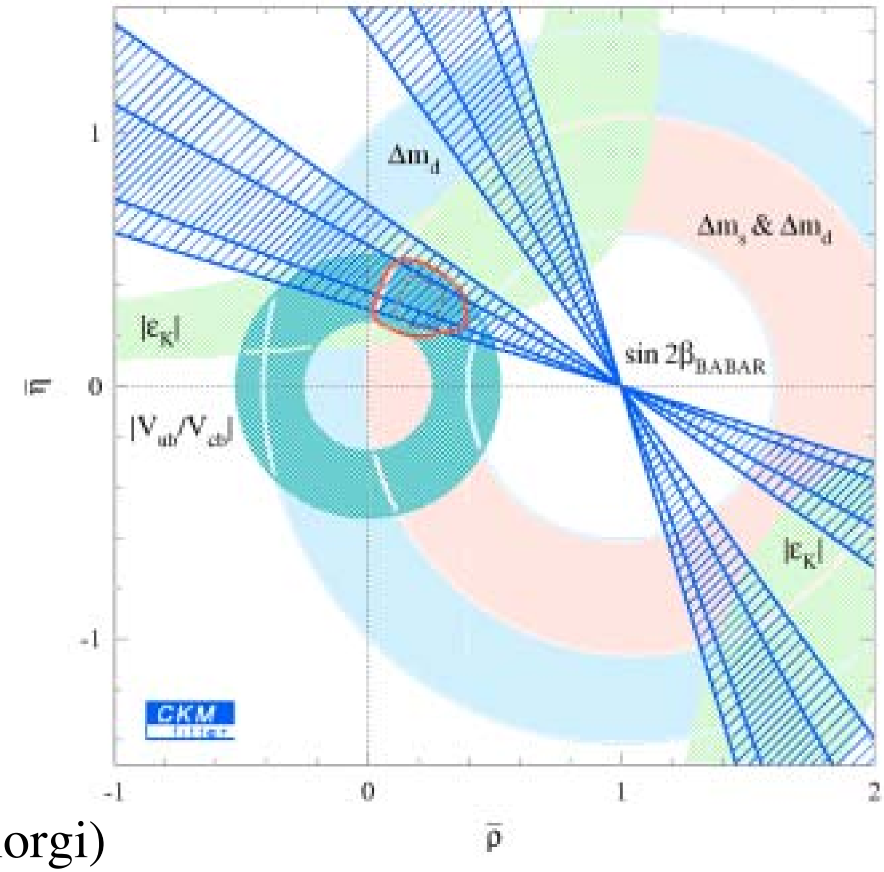
V_{cb} : average of inclusive and exclusive leptonic B decays

$|V_{cb}| = (41.2 \pm 2.0)\, 10^{-3}$

V_{ub} : inclusive and exclusive charmless B decays

$|V_{ub}| = (3.6 \pm 0.7)\, 10^{-3}$





(Giorgi)

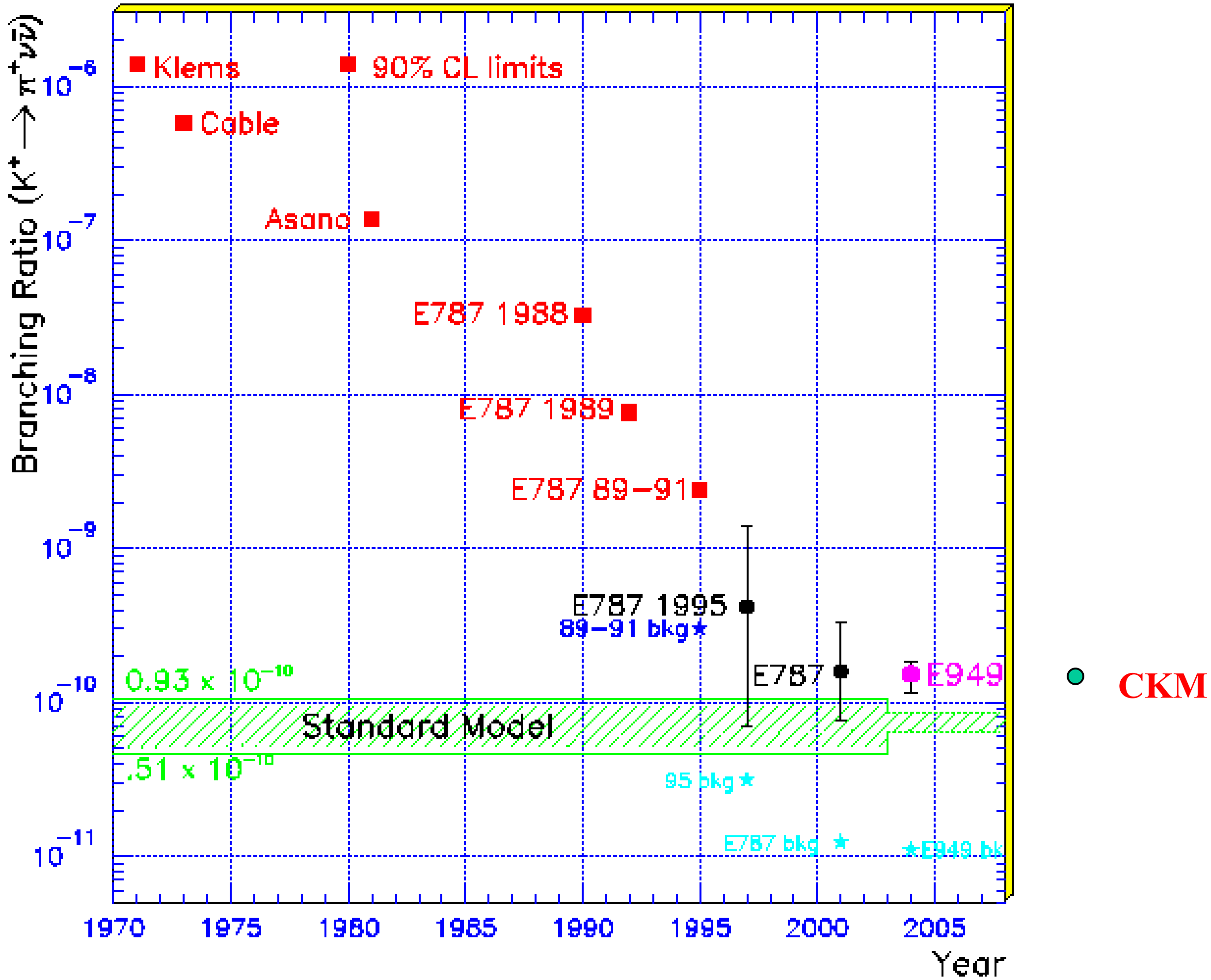
Side measurements done are in perfect agreement with the K and B CP violation measurements.

My first reaction. "It is truly amazing!"

Also no electric dipole moment see for e and n. (Hindas)
-the SM predictions are many orders below-

And also (Bryman)

$K^+ \longrightarrow \pi^+ \nu \bar{\nu}$ Measurements vs. Year



My second thoughts.

"It is really frustrating. I have now more questions than answers."

We believe (pray) that physics beyond the Standard Model,

i.e. SUSY,

is just around the corner, $O(1\ \text{TeV})$.

many theoretical goodies and

more Higgs particles and new source of CP...

which may solve the baryogenesis

Then why don't we see any effect in the box diagrams, i.e.

$\Delta m(B_d)$ and CP violations?

I still do not understand the origin of the family structure.

I still have no answer to my first question...

Only the sign of New Physics is in the neutrino sector:

Strong evidence for the neutrino oscillations. (Blondel)
(I still want to see the true oscillation curve)
→ neutrinos have different masses.

Within the next five years, this will be established.

The next step strategy

Currently observed agreement with SM
$\rightarrow$ effect of new physics is very subtle (or non).

Indirect search needs:
precise experimental measurements on
precise theoretical predictions.

NB:
Sometimes it is said that “look where SM predicts 0”.
But, 0 is as good as (or not better than) any other **precise** predictions
for the same experimental sensitivities.

Uncertainties in the Standard Model predictions are due to our limited theoretical understanding in the strong interactions.

They are in general very serious **both** for K and B.

Many “ordinary” measurements will help developing theory...

Leading to improvements on

$\Gamma(B \to X_c \ell \nu)$, $\Gamma(B \to X_c h)$	tree	A
$\Gamma(B \to X_u \ell \nu)$, $\Gamma(B \to X_u h)$	tree	$\rho^2 + \eta^2$

1) theoretical predictions with no hadronic uncertainties.

B ~~CP~~ in box □ tree: B_d□ D□, B_s□ D_sK

2) theoretical predictions with very small hadronic uncertainties.

K ~~CP~~ where hadronic effect is measured: Br(K_L □ $□^0$□□)

K Br where hadronic effect is measured: Br(K^+ □ $□^+$□□)

B ~~CP~~ in box □ (tree + one penguin): B_d□ J/□K_S,DD B_s□ J/□□(□)

Ratio of hadronic uncertainties: □m(B_d)/□m(B_s)

3) theoretical predictions with some hadronic uncertainties.

B ~~CP~~ in box □ (tree+two penguins): B_d□ □□, □□, K□ B_s□ KK,K□

B ~~CP~~ in two penguins: B_d□ □K_S B_s□ □□, □K_S

4) theoretical predictions with large hadronic uncertainties.

K and B ~~CP~~ in the decay amplitudes: □/□, etc.

My current thoughts on the
priority for the future experimental programme:

1) and 2) must be pushed as much as possible.
3) will help to test a broader consistency.

If New Physics is present, 1), 2) and 3) are differently affected.
Therefore, a combination of all should give a better signature.

4) will have only a limited contribution to precision tests of the CKM picture.

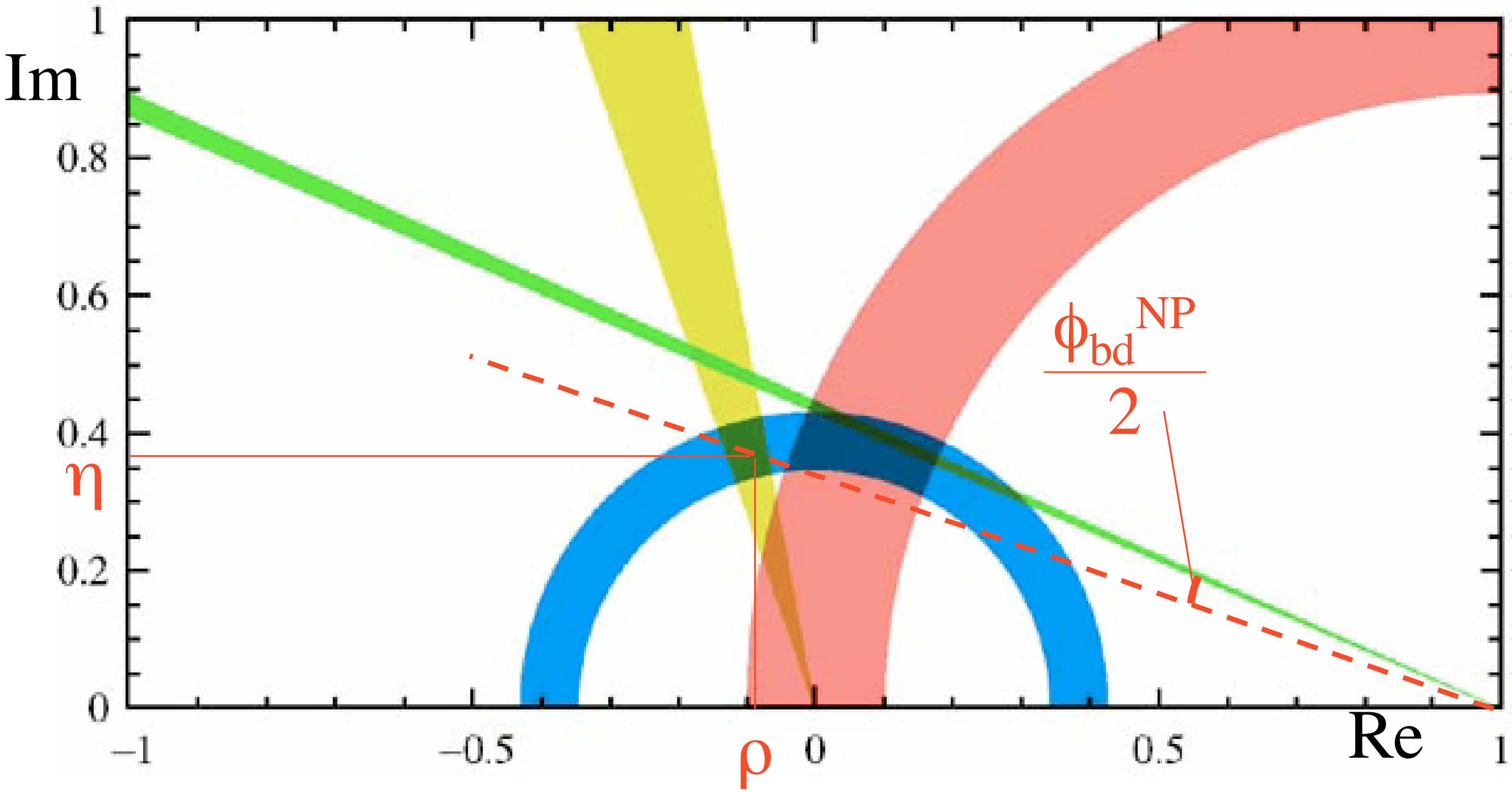
Players over the next 10 years: (Bortoletto, Tschirhrt)
Experiments accumulating data; BABAR, BELLE
Experiments just start taking data; CDF, D0
Experiments under construction; LHCb, ATLAS, CMS
Experiments approved; CKM, KOPIO, BTeV
Experiments being considered; Super BELLE, Super BABAR

~2007clean measurements

BABAR, BELLE: $|V_{cb}|$, $|V_{ub}|$, Δm_d, $\sin 2\beta_{J/\psi K_S}$,

CDF (D0): Δm_s, $\sin 2\beta_{J/\psi K_S}$,

Clean measurements of γ ($B_s \to D_s K$): ±5°



Dedicated B experiments at LHC (and Tevatron)!!!

Reflection

In the quark and gauge sectors, no sign of physics beyond the Standard Model has been seen.

Many theoretical ideas are around. But the main stream particle physics needs (desperately) experimental breakthroughs which indicate the direction to go. Such experimental breakthroughs are needed in the quark and/or gauge sectors.

For the next ten years, flavour physics (particularly CP violation and rare decays) will remain as a powerful tool to search for physics beyond the Standard Model in the quark and gauge sectors.
Till LHC, it might be indeed the most promising way; and even during depends on the nature of New Physics.

The lepton sector is only the place a deviation from the minimal Standard Model is appearing; i.e. neutrinos seem to mix and have masses.

Experimental determination of the masses and mixing angles is clearly "the must" as being done for the CKM. This would be done over the next 20 years.
However, it is not obvious (to me) how that leads to the next step of the understanding is not obvious (as it is now with the CKM).

Leptogenesis with heavy majorana neutrinos at GUT energy scale it not particularly attractive scenario for experimental physicists.

Particularly crucial experiments are those addressing:
Are ν's majorana particles?   E.g. $\beta\beta$ decays (and others?)
Does p decays?

Small experimental effort questioning the “conventional” wisdom must continue, if it brings in definite improvement.
(Kamyshkov, Gabrielse, Doser, Widmann)

All the successful experiments now had very long (agonising?) period before arriving to the present point.
This will not change.
We must be prepared, but not be discouraged!

In the end, physics is fun, to me.

Overview - Apparatus

Overview

Antiprotons

- Capture
- Cooling

Positrons

- accumulation rate
- transfer
- lifetime

Detector

- Tracking
- 511 keV

Summary

Outlook

To finish

I had a pleasure to share the summary talks with Roberto, already, at BCP conference in Taipei, December 1999.

I found the last five transparencies from the summary!

文化革命

Cultural Revolution

Taipei 1999

Superweak Model $\rightarrow$ ✕

$\alpha, \beta, \gamma \rightarrow \phi_1, \phi_2, \phi_3$

Slogans !!

No work, No food

No $\Delta I = 1/2$, No ε'/ε

No xxx, No f_{Bs}/f_{Bd}

(what could be xxx?)

Future cultural change !!

Combining many limits ⇒ A few positive precise measurements

Thanks to all the
conference secretaries
and
scientific secretaries
for helping the preparation.