Particle Physics

Juliet Lee-Franzini

Laboratori Nazionali Frascati

Karlsruhe University

Karlsruhe - Fall 2001

url: www-ttp.physik.uni-karlsruhe.de/~juliet/

1. Introduction

In this series of lectures, interspersed with specialized seminars, I would like to give you a view of the state of Particle Physics, HEP, in mid 2001.

The snapshots I'm going to use are taken mostly from the presentations given at the XXth International Symposium on Lepton and Photon Interactions at High Energies, LP01, which took place in Rome from the 23rd to the 28th of July 2001.
http://www.lp01.infn.it, click Program click, Slides.
It so happens that it was a particularly serendipitious moment to take a time slice photograph of HEP, because several events which took decades to mature, seem to have conspired to be announced within weeks of each other.

For example, the question of the existence of direct CP violation in the kaon system, a puzzle since about 1964, was finally experimentally verified by two experiments separated by the Atlantic Ocean, simultaneously almost, with the announcement of CP violation being observed in a totally new system, that of the neutral B mesons, this time by two independent laboratories lying on opposite sides the Pacific Ocean.

It is amusing that the kaon system was discovered some half a century ago, while the B mesons are, shall we say, only twenty years young. And while the accelerators which produced the kaons for the super accurate measurement have been built for some fifty years, the colliders which produced the B's are 'particle factories', a new sort of beasts which were commissioned only as recently as in the last two years.

An area which shows amazing conceptual consistency, despite its being notoriously difficult to compute, is QCD.

This year we not only saw that the strong coupling constant that has been extracted from an e^+e^- collider is equal to that obtained from colliding leptons with hadrons, but that at 'low energies', quark-quark molecules get formed at meson production thresholds, much the same way a deuteron gets formed from a neutron and a proton.

However, as far as hardiness is concerned, 1100 LEP papers, and probably many more LEP physicists in twelve years, have not been able to pierce the intricately constructed armor of the 'Standard Model', one can only admire its resilience even as one peers desperately through any possible escape outlet.

Thus the ‘g-2 discrepancy’ announcement this year was greeted with enthusiasm despite its shaky nature.

What is not uncertain, instead, is the fact the solar neutrino deficit is real, that neutrinos oscillate, that they may have a tiny amount of mass. So we really are standing at the dawn of detailed studies of the neutrino system.

From a machine builders’ point of view, this means not only higher luminosity, higher energy, but totally different particle colliders such as muon colliders as neutrino factories, which could be fascinating.

Theorists, instead, seem to be more concerned that supersymmetric particles have not been found yet (they seem to think the light HIGGS is a sure thing at the Tevatron and LHC). I find the tying down of string ends to branes enchanting, *albeit* I'd feel more comfortable if it manifests signs in my 4-dimensional world.

Cosmologists and astrophysicists apparently are going through a revolution of their own, in fact they belong in the same picture with us HEP's because they just found experimental evidence (acoustic peaks) to construct their own SM, they have signals (UH energy gammas) they can't explain, and they invent a vacuum which actually has energy! So we are both not lacking in fantasy.

So I think I have shown you that this is a good time to take a tour of HEP, and for each subject I'll provide some background notes on the history, formalism and techniques which will help the appreciation of the contemporary findings.

Summary of Proposed Talks

In the first four lectures, CP violation in the K–B systems are pedagogically reviewed: their manifestations in the neutral K–B meson systems, in rare K meson decays and in decays of charged K mesons, and results from classical and current experiments, are discussed. In the third lecture, the CKM matrix will be discussed, and in the fourth the consequences in the B system will be discussed..

Prerequisite Knowledge and References

Three years of study at university level with good knowledge of quantum theory. See:

"CP Violation in the K-System", J. Lee-Franzini and P. Franzini, Surveys in High Energy Physics, Vol. 13, pp 1-44 (1998).

2. Strange mesons

I chose to begin our discussion with the discovery of K mesons, because these particles, from the first day to the present, were responsible for the introduction into particle physics many concepts: *flavor*, parity violation, the $\Delta I = 1/2$ rule in non-leptonic decays, $\Delta S = \Delta Q$, FCNC suppression, to CP violation, which I will describe in sections of this chapter.

From them we built up the so called 'Flavor Physics' sector, one which, while seemingly is not as central to HEP as the QCD and Electroweak (EW) sectors, in fact has enriched them by posing lots of puzzles, and has given experimentalists a wealth of technical challenges, thus has really made physics more *flavorful*.

2.1 Discovery and strangeness

Kaons were probably discovered in 1944 in cosmic rays, and their decays were first observed in 1947. In old cloud chamber pictures, from their topology, they were called V particles. They seem to appear out of nowhere, or suddenly exhibit a kink, just look at the pair of photos on the website
http://hepweb.rl.ac.uk/ppUKpics/pr_971217.html
also shown in fig. 1.

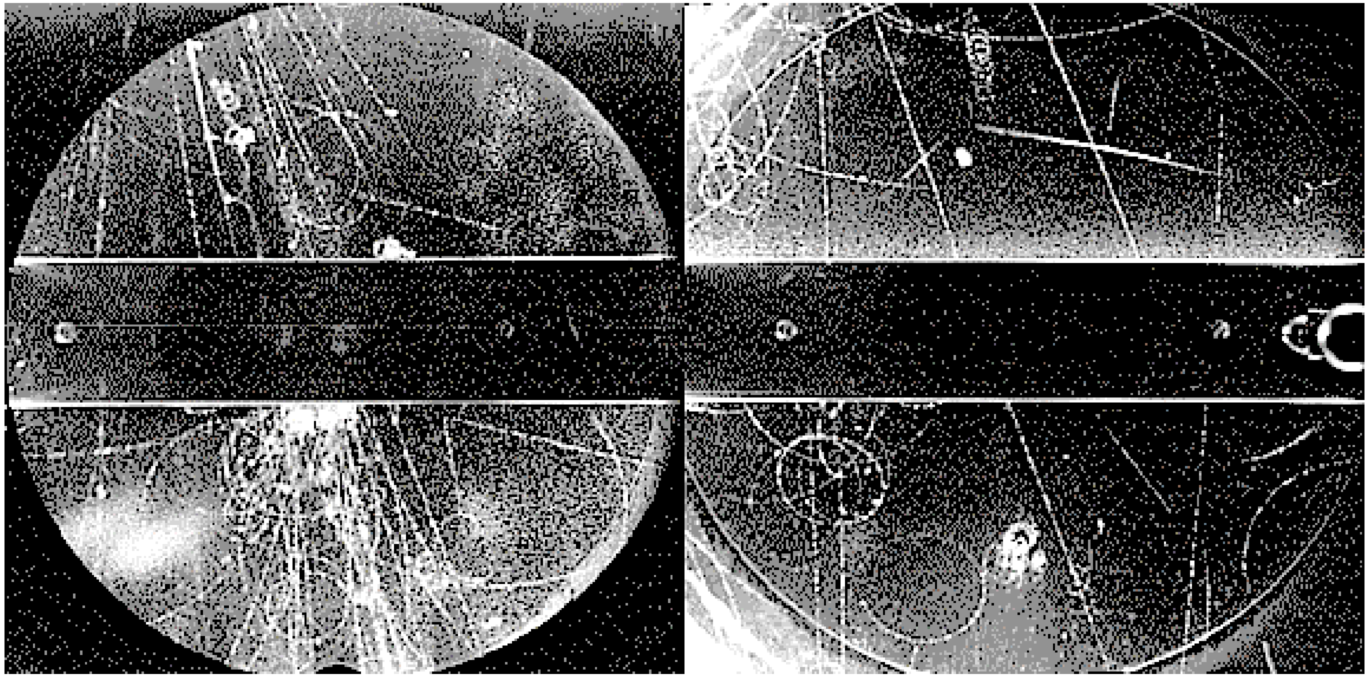


Fig. 1. K discovery.

It was in December 1947 that Rochester and Butler (Nature **106**, 885 (1947)) published these Wilson chamber pictures which we interpret now as (on the left) a $K^0_{\pi 2}{\to}\pi^+\pi^-$ and (on the right) a $K^+_{\pi 2}{\to}\pi^+\pi^0$ (where we do not see the neutral pion decaying into two photons).

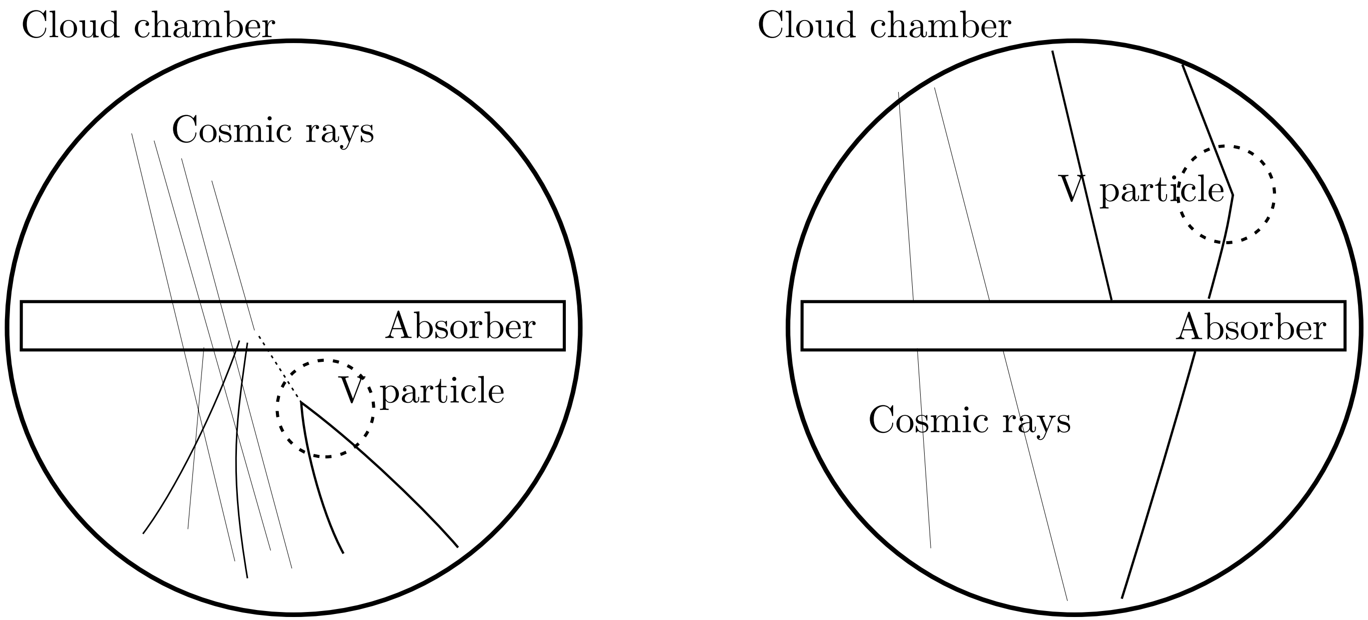


Fig. 2. Production and decay of V particles.

It was quite a puzzle that in a $\sim$1000 triggered pictures corresponding to $\sim$1000 nuclear interactions, one could observe the production of a few particles which decayed in few cm.

A typical strong interaction cross section is (1 fm)^2=10^{-26} cm^2, corresponding to the production in a 1 g/cm^2 plate of:

$$N_{\text{events}} = N_{\text{in}} \times \sigma \times \frac{\text{nucleons}}{\text{cm}^2} = 10^3 \times 10^{-26} \times 1 \times 6 \times 10^{23} = 6.$$

Assuming the V-particles travel a few cm with $\gamma\beta{\sim}3$, their lifetime is $\mathcal{O}(10^{-10}$ s), typical of weak interactions. Thus we conclude that the decay of V-particles is weak while the production is strong, strange indeed since pions and nucleons appear at the beginning and at the end!!

This strange property of K mesons and other particles, the hyperons, led to the introduction of a new quantum number, the strangeness, S.[(1)]

Strangeness is conserved in strong interactions, while the first order weak interaction can induce transitions in which strangeness is changed by one unit.

2.2 Quarks and flavors

Today we describe these properties in terms of quarks with different "flavors", first suggested in 1964 independently by Gell-Mann and Zweig,[(2)] reformulating the $SU(3)$ flavor, approximate, global symmetry. The "normal particles" are bound states of quarks: $q\bar{q}$, the mesons, or qqq, baryons, where

$$q = \begin{pmatrix} u \\ d \end{pmatrix} = \begin{pmatrix} \text{up} \\ \text{down} \end{pmatrix}.$$

K's, hyperons and hypernuclei contain the strange quark, s:

$$\begin{array}{ll} K^0 = d\bar{s} & \overline{K^0} = \bar{d}s \\ K^+ = u\bar{s} & K^- = \bar{u}s \\ S = +1 & S = -1. \end{array}$$

The assignment of negative strangeness to the s quark is arbitrary but maintains today the convenient original assignment of positive strangeness for K^0, K^+ and negative for the Λ and Σ hyperons and for $\overline{K}^0$ and K^-. Like, somehow, calling negative the charge of the electron and referring to it as a particle.

An important consequence of the fact that K mesons carry strangeness, a new additive quantum number, is that *the neutral K and anti neutral K meson are distinct particles, even though they carry no baryon number!!!*

$$C|\,K^0\,\rangle = |\,\overline{K}^0\,\rangle,\;\; S|\,K^0\,\rangle = |\,K^0\,\rangle,\;\; S|\,\overline{K}^0\,\rangle = -|\,\overline{K}^0\,\rangle$$

This is not the case for π^0, γ, η^0 etc.

An apocryphal story says that upon hearing of this hypothesis, Fermi challenged Gell-Mann to devise an experiment which shows an observable difference between the K^0 and the $\overline{K}^0$. We don't know what Gell-Mann answered, but today we know that it is trivial to do so. For example, the process $p\bar{p} \to \pi^- K^+ \overline{K^0}$, produces $\overline{K^0}$'s which in turn can produce Λ hyperons while the K^0's produced in $p\bar{p} \to \pi^+ K^- K^0$ cannot.

Another of Fermi's question was:
if you observe a $K \to 2\pi$ decay, how do you tell whether it is a K^0 or a $\overline{K^0}$? The answer here is complicated as we shall see.

Since the '50's K mesons have been produced at accelerators, first amongst them was the Cosmotron.

2.3 Parity Violation

Parity violation, $P\!\!\!\!\backslash$, was first observed through the θ-τ decay modes of K mesons. Incidentally, the τ there is not the heavy lepton of today, but is a charged particle which decays into three pions, $K^+ \to \pi^+\pi^+\pi^-$ in today's language. The θ there refers to a neutral particle which decays into a pair of charged pions, today $K^0 \to \pi^+\pi^-$.

This puzzle was originally not so apparent until Dalitz advanced an argument which says that one could determine the spin of τ by looking at the decay distribution of the three pions in a "Dalitz" (what he calls phase space) plot, which was in fact consistent with J=0.

The spin of the θ was inferred to be zero because it did not like to decay into a pion and a photon (a photon cannot be emitted in a 0→0 transition). For neutral K's two of the principal decay modes are two or three pions.

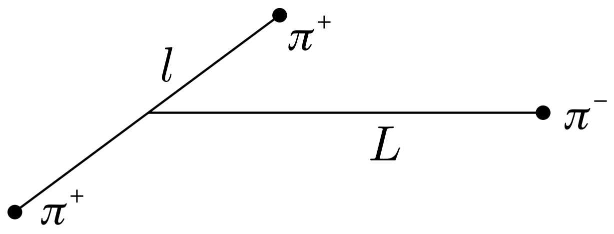


Fig. 3. Definition of l and L for three pion decays of τ^+.

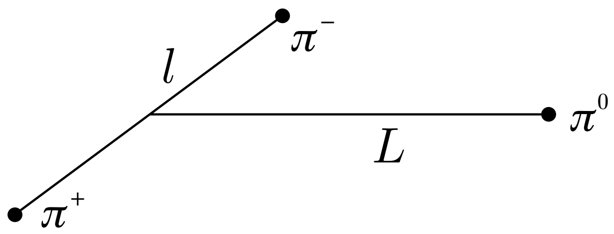


Fig. 4. Definition of l and L for $K^0 \to \pi^+\pi^-\pi^0$.

The relevant properties of the neutral two and three pion systems with zero total angular momentum are given below.

1. $\ell = L = 0,\ 1,\ 2\ldots$
2. $\pi^+\pi^-$, $\pi^0\pi^0$: $P = +1,\ C = +1,\ CP = +1$.
3. $\pi^+\pi^-\pi^0$: $P = -1,\ C = (-1)^l,\ CP = \pm 1$, where l is the

angular momentum of the charged pions in their center of mass. States with $l > 0$ are suppressed by the angular momentum barrier.

4. $\pi^0\pi^0\pi^0$: $P = -1$, $C = +1$, $CP = -1$. Bose statistics requires that l for any identical pion pair be even in this case.

Note that the two pion and three pion states have opposite parity, except for $\pi^+\pi^-\pi^0$ with ℓ, L odd.

2.4 Mass and CP eigenstates

While the strong interactions conserve strangeness, the weak interactions do not. In fact, not only do they violate S with $\Delta S = 1$, they also violate charge conjugation, C, and parity, P, as we have just seen.

However, at the end of the 50's, the weak interaction does not manifestly violate the combined CP symmetry. For now let's assume that CP is a symmetry of the world: $[H, CP] = 0$. We define an arbitrary, unmeasurable phase by:

$$CP|\,K^0\,\rangle = |\,\overline{K^0}\,\rangle$$

Then the simultaneous mass and CP eigenstates are:[(3)]

$$|\,K_1\,\rangle \equiv \frac{|\,K^0\,\rangle + |\,\overline{K^0}\,\rangle}{\sqrt{2}} \qquad |\,K_2\,\rangle \equiv \frac{|\,K^0\,\rangle - |\,\overline{K^0}\,\rangle}{\sqrt{2}}, \tag{1}$$

where K_1 has CP=+1 and K_2 has CP=−1.

2.4.1 K_1 *and* K_2 *lifetimes and mass difference*

While K^0 and $\overline{K^0}$ are degenerate states in mass, as required by CPT invariance, the weak interactions, which induces to second order $K^0 \leftrightarrow \overline{K^0}$ transitions, removes the degeneracy resulting in a small mass difference, Δm, between K_1 and K_2.

The $K_{1(2)}$ mass is the expectation value

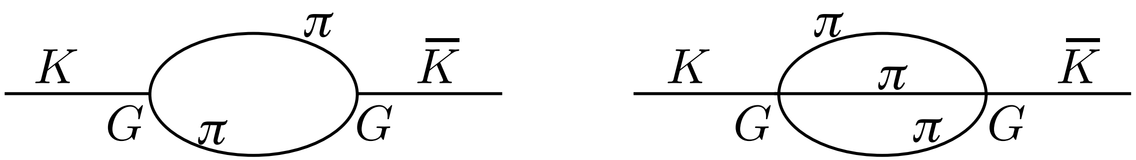
$$\langle K_1 | H | K_1 \rangle.$$

With $K_1 = (K^0 + \overline{K^0})/\sqrt{2}$ and analogously for K_2, we find

$$m_1 - m_2 = \langle K^0 | H | \overline{K^0} \rangle + \langle \overline{K^0} | H | K^0 \rangle,$$

δm is due to $K^0 \leftrightarrow \overline{K^0}$ transitions induced by a $\Delta S{=}2$ interaction.

Contributions to $H(|\Delta S| = 2)$ are like:



i.e. second order in the weak interaction. Thus $\Delta m \propto G^2$.

— — $G \equiv G_F = 1.166 \times 10^{-5}$ GeV^{-2} — —

If the interaction is CP invariant, *i.e.* $[H, CP] = 0$, the decays of K_1's and K_2's must conserve CP. Thus the K_1's with $CP = 1$, must decay into two pions (and three pions in an $L = \ell = 1$ state, surmounting an angular momentum barrier - $\sim(kr)^2(KR)^2\sim1/100$ and suppressed by phase space, $\sim1/1000$), while the K_2's with $CP = -1$, must decay into three pion final states. The decay amplitudes are illustrated in the figure.

Fig. 5. K_1 and K_2 decay amplitudes.

The decay widths are also $\propto G^2$.

Phase space for 3 pion decay is smaller by $32\pi^2$ plus some, since the energy available in 2π decay is ~220 MeV, while for a 3 π decay is ~90 MeV. Thus the lifetime of the K_1 ought to be much shorter than that of the K_2 or $\Gamma_1 \gg \Gamma_2$. Experimentally $\Gamma 1 \sim 600 \times \Gamma 2$

From the above arguments we expect $\Delta m{\sim}\Gamma_1$, apart from some mathematical *trivial* complications (real and imaginary parts of the amplitudes, principal values, etc.)

On dimensional grounds, $\Gamma_1{=}\Delta m{=}G^2 m_\pi^5{=}\ 5.3 \times 10^{-15}$ GeV, in good agreement with measurements. The use here of the pion mass is not rigorous, but $m_\pi \sim M_K - 2m_\pi$ and mnemonically m_π is convenient.

Lederman *et al.*[4] observed long lived neutral kaons in 1956, in a diffusion cloud chamber at the Cosmotron.

Today we have $\tau_1 = (0.8959 \pm 0.0006) \times 10^{-10}$ s and :

$$\begin{aligned} \Gamma_1 &= (1.1162 \pm 0.0007) \times 10^{10}\ \mathrm{s}^{-1} \\ \Gamma_2 &= (1.72 \pm 0.02 \times) 10^{-3} \times \Gamma_1 \\ \Delta m = m(K_2) - m(K_1) &= (0.5296 \pm 0.0010) \times 10^{10}\ \mathrm{s}^{-1} \\ \Delta m/(\Gamma_1 + \Gamma_2) &= 0.4736 \pm 0.0009. \end{aligned} \tag{2}$$

We use throughout natural units, *i.e.* $\hbar = c = 1$. Conversion is obtained from $\hbar c$=197.3... MeV×fm.

Unit Conversion

To convert from	to	multiply by
1/MeV	s	6.58×10^{-22}
1/MeV	fm	197
1/GeV^2	mb	0.389

2.4.2 Strangeness oscillations

The mass eigenstates K_1 and K_2 evolve in vacuum and in their rest frame according to

$$|\,K_{1,2},\ t\,\rangle = |\,K_{1,2},\ t=0\,\rangle e^{-i\,m_{1,2}\,t-(\Gamma_{1,2}/2)\,t} \qquad (3)$$

If the initial state has definite strangeness, say it is a K^0 as the one produced in the process $\pi^- p \to K^0\Lambda^0$, it must first be rewritten in terms of the mass eigenstates K_1 and K_2 which then evolve in time as above. Since the K_1 and K_2 amplitudes change phase differently in time, the pure S=1 state at t=0 acquires an S=−1 component at $t > 0$.

From (1) the wave function at time t is:

$$\Psi(t) = \sqrt{1/2}[e^{(i\,m_1 - \Gamma_1/2)t}|\,K_1\,\rangle + e^{(i\,m_2 - \Gamma_1/2)t}|\,K_2\,\rangle] =$$
$$1/2[(e^{(i\,m_1 - \Gamma_1/2)t} + e^{(i\,m_2 - \Gamma_2/2)t})|\,K^0\,\rangle +$$
$$(e^{(i\,m_1 - \Gamma_1/2)t} - e^{(i\,m_2 - \Gamma_2/2)t})|\,\overline{K^0}\,\rangle].$$

The intensity of K^0 ($\overline{K^0}$) at time t is given by:

$$I(K^0\ (\overline{K^0}), t) = |\langle K^0\ (\overline{K^0})|\,\Psi(t)\,\rangle|^2 =$$
$$\frac{1}{4}[e^{-t\Gamma_1} + e^{-t\Gamma_2} + (-)2e^{-t(\Gamma_1+\Gamma_2)/2}\cos\Delta m\,t]$$

which exhibits oscillations whose frequency depends on the mass difference, see fig. 6.

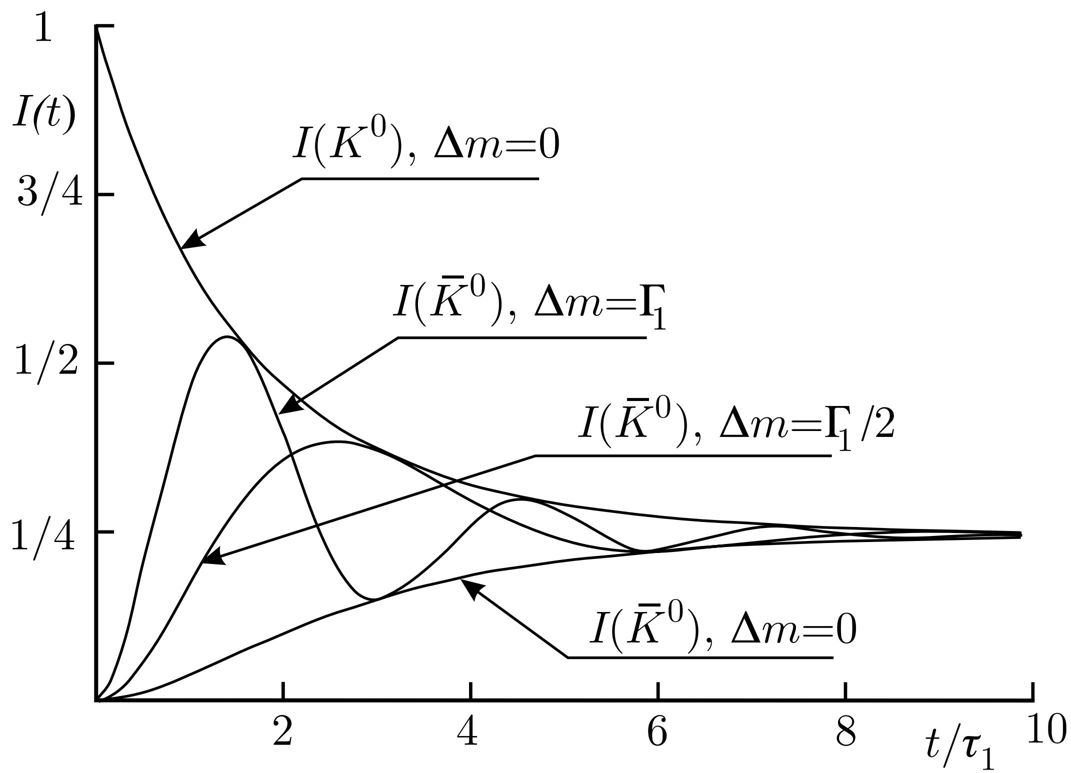


Fig. 6. Evolution in time of a pure S=1 state at time t=0

The appearance of $\overline{K^0}$'s from an initially pure K^0 beam can be detected by the production of hyperons, according to the reactions:

$$\bar{K}^0 p \to \pi^+ \Lambda^0, \quad \to \pi^+ \Sigma^0, \quad \to \pi^0 \Sigma^+,$$
$$\bar{K}^0 n \to \pi^0 \Lambda^0, \quad \to \pi^0 \Sigma^0, \quad \to \pi^+ \Sigma^-, \quad \to \pi^- \Sigma^+.$$

The K_L-K_S mass difference can also be measured, for instance from the oscillation frequency of the hyperon production.

2.4.3 Regeneration

Another interesting, and extremely useful phenomenon, is that it is possible to regenerate K_1's by placing a piece of material in the path of a K_2 beam.

Let's take our standard reaction,

$$\pi^- p \to K^0 \Lambda^0,$$

the initial state wave function of the K^0's is

$$\Psi(t=0) \equiv |\,K^0\,\rangle = \frac{|\,K_1\,\rangle + |\,K_2\,\rangle}{\sqrt{2}}.$$

Note that it is composed equally of K_1's and K_2's. The K_1 component decays away quickly via the two pion decay modes, leaving a virtually pure K_2 beam.

A K_2 beam has equal K^0 and $\bar{K}^0$ components, which interact differently in matter. For example, the K^0's undergo elastic scattering, charge exchange etc. whereas the $\bar{K}^0$'s also produce hyperons via strangeness conserving transitions. Thus we have an apparent rebirth of K_1's emerging from a piece of material placed in the path of a K_2 beam! See fig. 7.

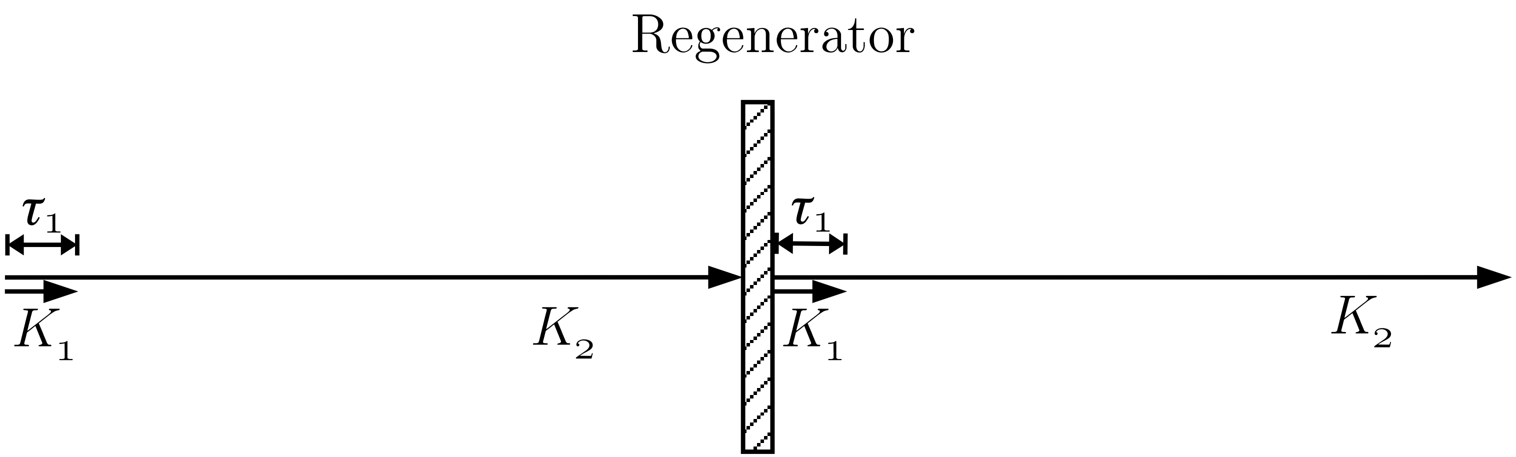


Fig. 7. K_1 regeneration

Virtually all past and present experiments, with the exception of a couple which will be mentioned explicitly, use this method to obtain a source of K_1's (or K_S's, as we shall see later).

Denoting the amplitudes for K^0 and $\overline{K^0}$ scattering on nuclei by f and $\bar{f}$ respectively, the scattered amplitude for an initial K_2 state is given by:

$$\sqrt{1/2}(f|\,K^0\,\rangle - \bar{f}|\,\overline{K^0}\,\rangle) = \frac{f+\bar{f}}{2\sqrt{2}}(|\,K^0\,\rangle - |\,\overline{K^0}\,\rangle) + \frac{f-\bar{f}}{2\sqrt{2}}(|\,K^0\,\rangle + |\,\overline{K^0}\,\rangle)$$
$$= 1/2(f+\bar{f})|\,K_2\,\rangle + 1/2(f-\bar{f})|\,K_1\,\rangle.$$

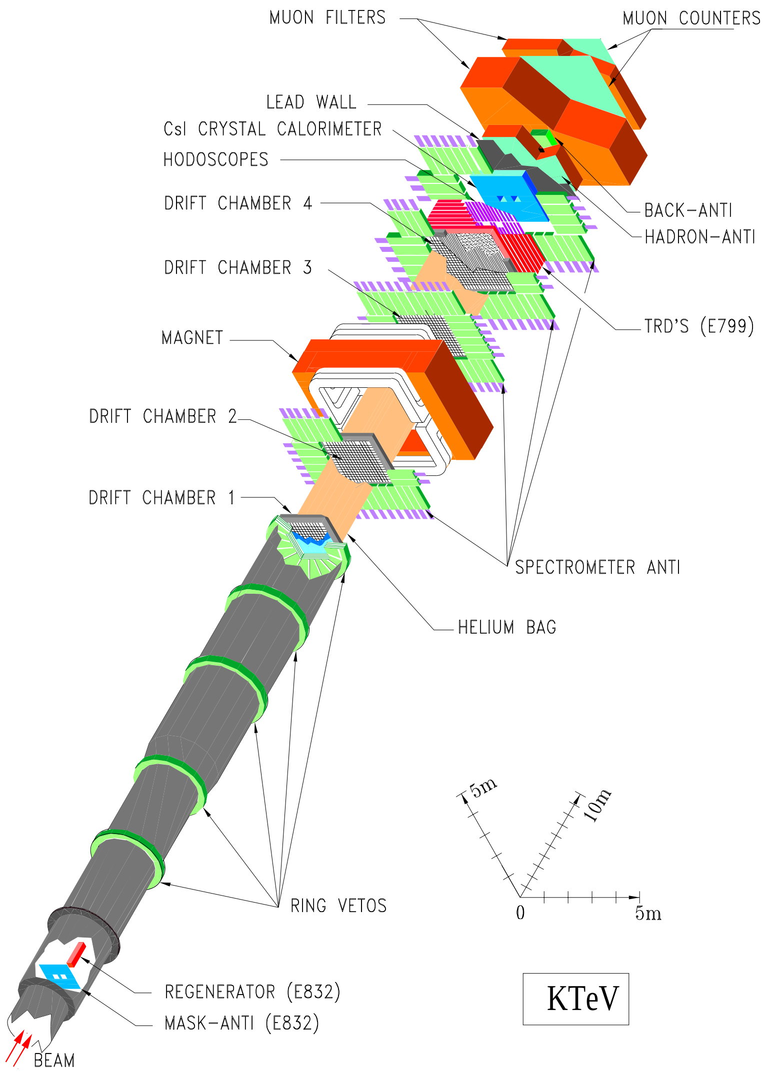
The so called regeneration amplitude for $K_2 \rightarrow K_1$, f_{21} is given by $1/2(f-\bar{f})$ which of course would be 0 if $f=\bar{f}$, which is true at infinite energy.

Another important property of regeneration is that when the K_1 is produced at non-zero angle to the incident K_2 beam, regeneration on different nuclei in a regenerator is incoherent, while at zero degree the amplitudes from different nuclei add up coherently.

The intensity for coherent regeneration depends on the K_1, K_2 mass difference. Precision mass measurements have been performed by measuring the ratio of coherent to diffraction regeneration. The interference of K_1 waves from two or more regenerators has also allowed us to determine that the K_2 meson is heavier than the K_1 meson. This perhaps could be expected, but it is nice to have it measured.

Finally we note that the K_1 and K_2 amplitudes after regeneration are coherent and can interfere if CP is violated.

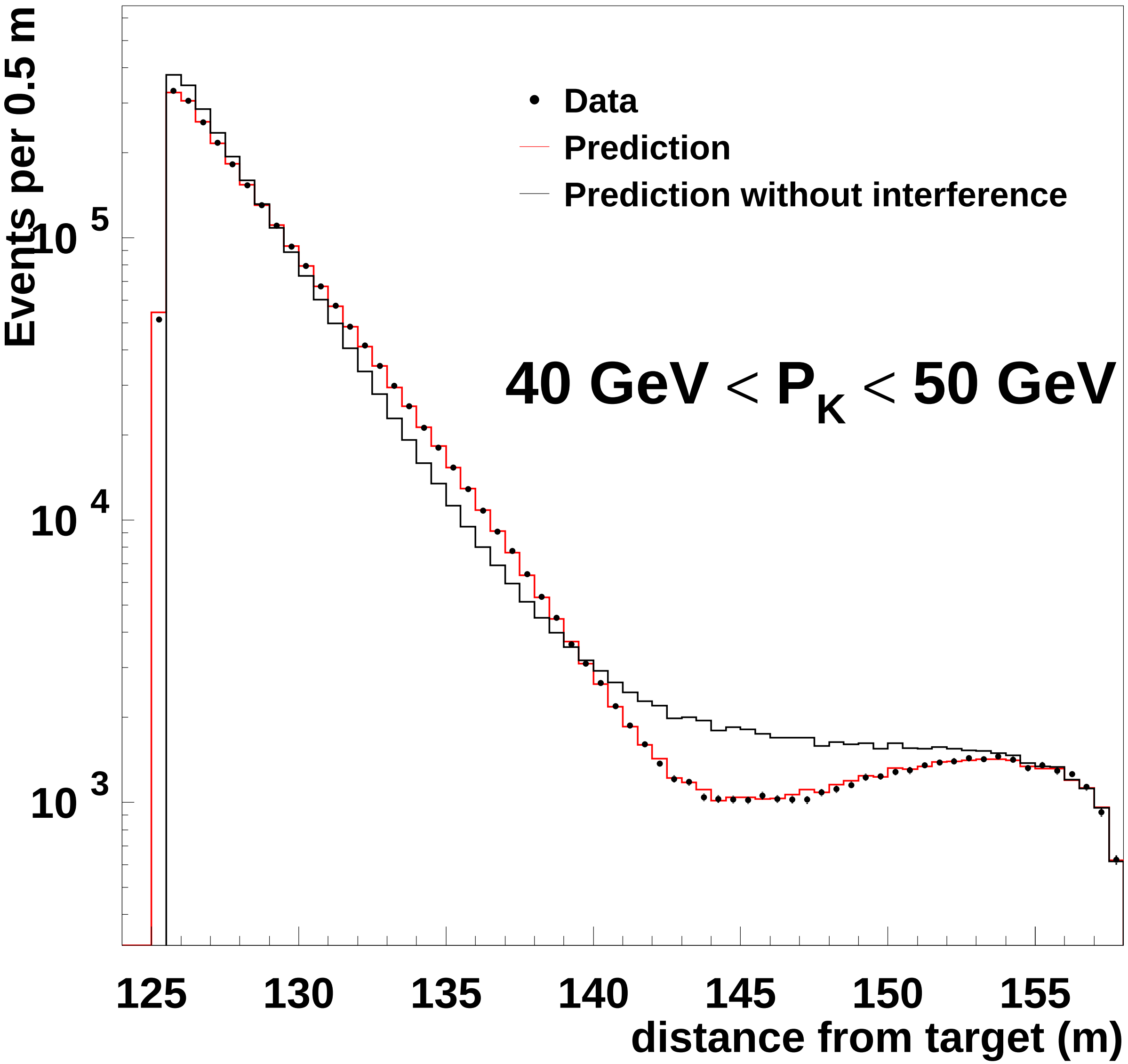
KTEV Detector



Vacuum beam: K_L

Regenerator beam:
$K_L + \rho K_S$, $\rho \sim 0.03$
(2π mainly from K_S)

Key to systematics control:
simultaneous collection
of K_L and K_S decays.



Regenerator Vertex Z distribution

Extract:

- τ_S (lifetime)
- Δm (oscill. width)
- $\Phi_{+-} - \phi_\rho$ (oscill. phase)
- $\Delta\Phi = \Phi_{00} - \Phi_{+-}$ (CPT test)

2.5 CP Violation in Two Pion Decay Modes

2.5.1 Discovery

For some years after the discovery that C and P are violated in the weak interactions, it was thought that CP might still be conserved.

CP violation was discovered in '64,[5] through the observation of the unexpected decay $K_2 \rightarrow \pi^+\pi^-$. This beautiful experiment is conceptually very simple, see fig. 8.

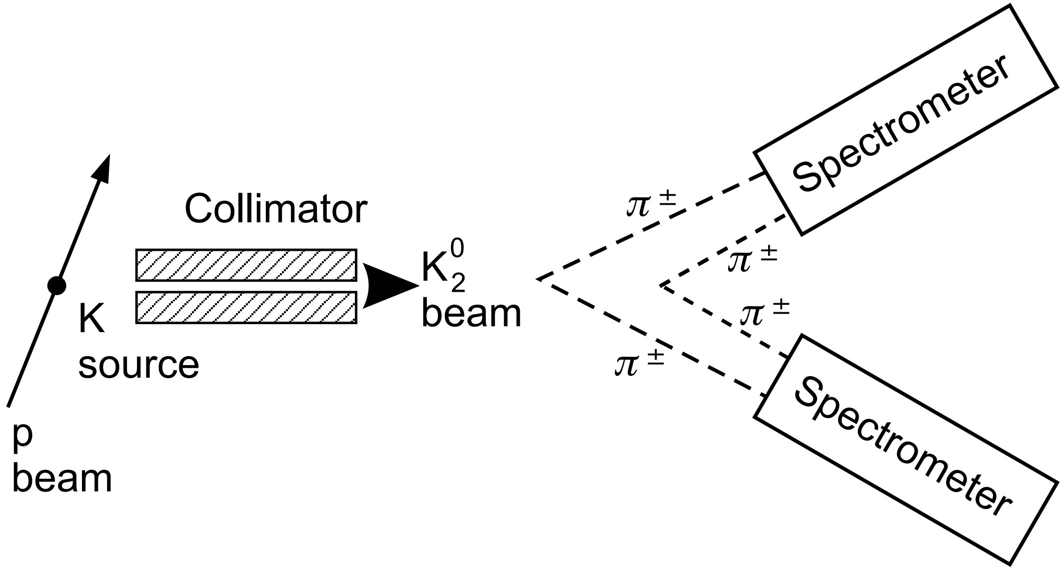


Fig. 8. The setup of the experiment of Christenson *et al.*.

Let a K beam pass through a long collimator and decay in an empty space (actually a big helium bag) in front of two spectrometers. We have made a K_2 beam. The K_2 decay products are viewed by spark chambers and scintillator hodoscopes in the spectrometers placed on either side of the beam.

Two pion decay modes are distinguished from three pion and leptonics decay modes by the reconstructed invariant mass $M_{\pi\pi}$, and the direction θ of their resultant momentum vector relative to the beam.

In the mass interval 494-504 MeV an excess of 45 events collinear with the beam ($\cos\theta > 0.99997$) is observed. For the intervals 484-494 and 504-514 there is no excess, establishing that K_2's decay into two pions, with a branching ratio of the order of 2×10^{-3}.

CP is therefore shown to be violated!

The CP violating decay $K_L \to \pi^0\pi^0$ has also been observed.

2.5.2 K^0 Decays with CP Violation

Since CP is violated in K decays, the mass eigenstates are no more CP eigenstate and can be written, assuming CPT invariance, as:

$$K_S = ((1+\epsilon)|\,K^0\,\rangle + (1-\epsilon)|\,\overline{K^0}\,\rangle)/\sqrt{2(1+|\epsilon|^2)}$$
$$K_L = ((1+\epsilon)|\,K^0\,\rangle - (1-\epsilon)|\,\overline{K^0}\,\rangle)/\sqrt{2(1+|\epsilon|^2)}$$

Another equivalent form, in terms of the CP eigenstate K_1 and K_2 is:

$$|\,K_S\,\rangle = \frac{|\,K_1\,\rangle + \epsilon|\,K_2\,\rangle}{\sqrt{1+|\epsilon|^2}} \qquad |\,K_L\,\rangle = \frac{|\,K_2\,\rangle + \epsilon|\,K_1\,\rangle}{\sqrt{1+|\epsilon|^2}} \tag{4}$$

with $|\epsilon| = (2.259 \pm 0.018) \times 10^{-3}$ from experiment. Note that the K_S and K_L states are not orthogonal states, contrary to the case of K_1 and K_2. If we describe an arbitrary state $a|\,K^0\,\rangle + b|\,\overline{K^0}\,\rangle$ as

$$\psi = \begin{pmatrix} a \\ b \end{pmatrix}.$$

its time evolution is given by

$$i\frac{\mathrm{d}}{\mathrm{dt}}\psi = (\mathbf{M} - i\mathbf{\Gamma}/2)\psi$$

where **M** and **Γ** are 2×2 hermitian matrices which can be called the mass and decay matrix.

CPT invariance requires $M_{11} = M_{22}$, *i.e.* $M(K^0) = M(\overline{K^0})$, and $\Gamma_{11} = \Gamma_{22}$. CP invariance requires $\arg(\Gamma_{12}/M_{12})=0$. The relation between ϵ and **M**, **Γ** is:

$$\frac{1+\epsilon}{1-\epsilon} = \sqrt{\frac{M_{12} - \Gamma_{12}/2}{M_{12}^* - \Gamma_{12}^*/2}}.$$

K_S and K_L satisfy

$$(\mathbf{M} - i\mathbf{\Gamma})|\,K_{S,\,L}\,\rangle = (M_{S,L} - i\Gamma_{S,L})|\,K_{S,\,L}\,\rangle$$

where $M_{S,L}$ and $\Gamma_{S,L}$ are the mass and width of the physical neutral kaons, with values given earlier for the K_1 and K_2 states.

Equation (3) is rewritten as:

$$|\, K_{S,L},\ t\,\rangle = |\, K_{S,L},\ t=0\,\rangle e^{-i\, M_{S,L}\, t - \Gamma_{S,L}/2\, t}$$

$$\frac{\mathrm{d}}{\mathrm{dt}}|\, K_{S,L}\,\rangle = -i\mathcal{M}_{S,L}|\, K_{S,L}\,\rangle$$

with

$$\mathcal{M}_{S,L} = M_{S,L} - i\Gamma_{S,L}/2$$

and the values of masses and decay widths given in eq. (2) belong to K_S and K_L, rather than to K_1 and K_2. We further introduce the so called superweak phase ϕ_{SW} as:

$$\phi_{\mathrm{SW}} = \mathrm{Arg}(\epsilon) = \tan^{-1}\frac{2(M_{K_L} - M_{K_S})}{\Gamma_{K_S} - \Gamma_{K_L}} = 43.63^\circ \pm 0.08^\circ.$$

A superweak theory, is a theory with a ΔS=2 interaction, whose sole effect is to induce a CP impurity ϵ in the mass eigenstates. Since 1964 we have been asking the question: is CP violated directly in K^0 decays, *i.e.* is the $|\Delta S|$=1 amplitude $\langle \pi\pi | K_2 \rangle \neq 0$ or the only manifestation of $\not{C}\not{P}$ is to introduce a small impurity of K_1 in the K_L state, via $K^0 \leftrightarrow \overline{K^0}$, $|\Delta S|$=2 transitions?

2.5.3 Wu and Yang formalism, $\Delta I = 1/2$ rule

Wu and Yang,[(6)] have analyzed the two pion decays of K_S, K_L in term of the isospin amplitudes:

$$A(K^0 \to 2\pi, I) = A_I e^{i\delta_I}$$
$$A(\overline{K^0} \to 2\pi, I) = A_I^* e^{i\delta_I}$$

where δ_I are the $\pi\pi$ scattering phase shifts in the I=0, 2 states. W-Y chose an arbitrary phase, by defining A_0 real.

A_0, due to a $\Delta I = 1/2$ contribution, is about 22 times larger than $\Re A_2$, from $\Delta I = 3/2$ transitions.

The dominance of the $\Delta I = 1/2$ transition is true in non leptonic decays of kaons and all strange particles, and still is not understood. In fact, in LP01 it was singled out by Barbieri as one of the problems 'that could hide new interactions'.

Problems that could hide new interactions?

$\Delta I = 1/2$ in K-decays

$\frac{\tau(\Lambda_b)}{\tau(B_d)} = 0.794 \pm 0.053(\text{exp})$ v.s. $0.88 \div 1.0$ (theory)

$$\begin{cases} y_D & = (3.42 \pm 1.39 \pm 0.74)\% \text{ FOCUS, but see E791, BELLE, CLEO} \\ y'_D & = -x_D \sin\delta + y_D \cos\delta = (-2.5^{+1.4}_{-1.6} \pm 0.3)\% \text{ CLEO} \end{cases}$$

W&Y also introduce the ratios of the amplitudes for K decay to a final state f_i, $\eta_i = A(K_L \to f_i)/A(K_S \to f_i)$:

$$\eta_{+-} \equiv |\eta_{+-}|e^{-i\phi_{+-}} = \frac{\langle \pi^+\pi^- |\, K_L \,\rangle}{\langle \pi^+\pi^- |\, K_S \,\rangle} = \epsilon + \epsilon'$$

$$\eta_{00} \equiv |\eta_{00}|e^{-i\phi_{00}} = \frac{\langle \pi^0\pi^0 |\, K_L \,\rangle}{\langle \pi^0\pi^0 |\, K_S \,\rangle} = \epsilon - 2\epsilon',$$

with

$$\epsilon' = \frac{i}{2\sqrt{2}}\, e^{i(\delta_2-\delta_0)}\, \frac{\Im A_2}{A_0}$$

Since $\delta_2 - \delta_0 \sim 45°$, Arg$(\epsilon')\sim 135°$ *i.e.* ϵ' is orthogonal to ϵ. Therefore, in principle, only two real quantities need to be measured: $\Re\epsilon$ and $\Re(\epsilon'/\epsilon)$, *with sign*.

In terms of the measurable amplitude ratios, η, ϵ and ϵ' are given by:

$$\epsilon = (2\eta_{+-} + \eta_{00})/3$$
$$\epsilon' = (\eta_{+-} - \eta_{00})/3$$
$$\text{Arg}(\epsilon) = \phi_{+-} + (\phi_{+-} - \phi_{00})/3.$$

ϵ' is a measure of direct CP violation and its magnitude is $\mathcal{O}(A(K_2 \to \pi\pi)/A(K_1 \to \pi\pi))$.

Our question above is then the same as: is $\epsilon' \neq 0$? Since 1964, experiments searching for a difference in η_{+-} and η_{00} have been going on.

If $\eta_{+-} \neq \eta_{00}$ the ratios of branching ratios for $K_{L,S} \to \pi^+\pi^-$ and $\pi^0\pi^0$ are different.

The first measurement of BR($K_L \to \pi^0\pi^0$), *i.e.* of $|\eta_{00}|^2$ was announced by Cronin in 1965.......

Most experiments measure the quantity $\mathcal{R}$, the so called double ratio of the four rates for $K_{L,S}\to\pi^0\pi^0$, $\pi^+\pi^-$, which is given, to lowest order in ϵ and ϵ' by:

$$\mathcal{R} \equiv \frac{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)}{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)} \equiv |\frac{\eta_{00}}{\eta_{+-}}|^2 = 1 - 6\Re(\epsilon'/\epsilon).$$

Observation of $\mathcal{R}\neq 1$ is proof that $\Re(\epsilon'/\epsilon)\neq 0$ and therefore of "direct" CP violation, *i.e.* that the amplitude for $|\Delta S|=1$, CP violating transitions

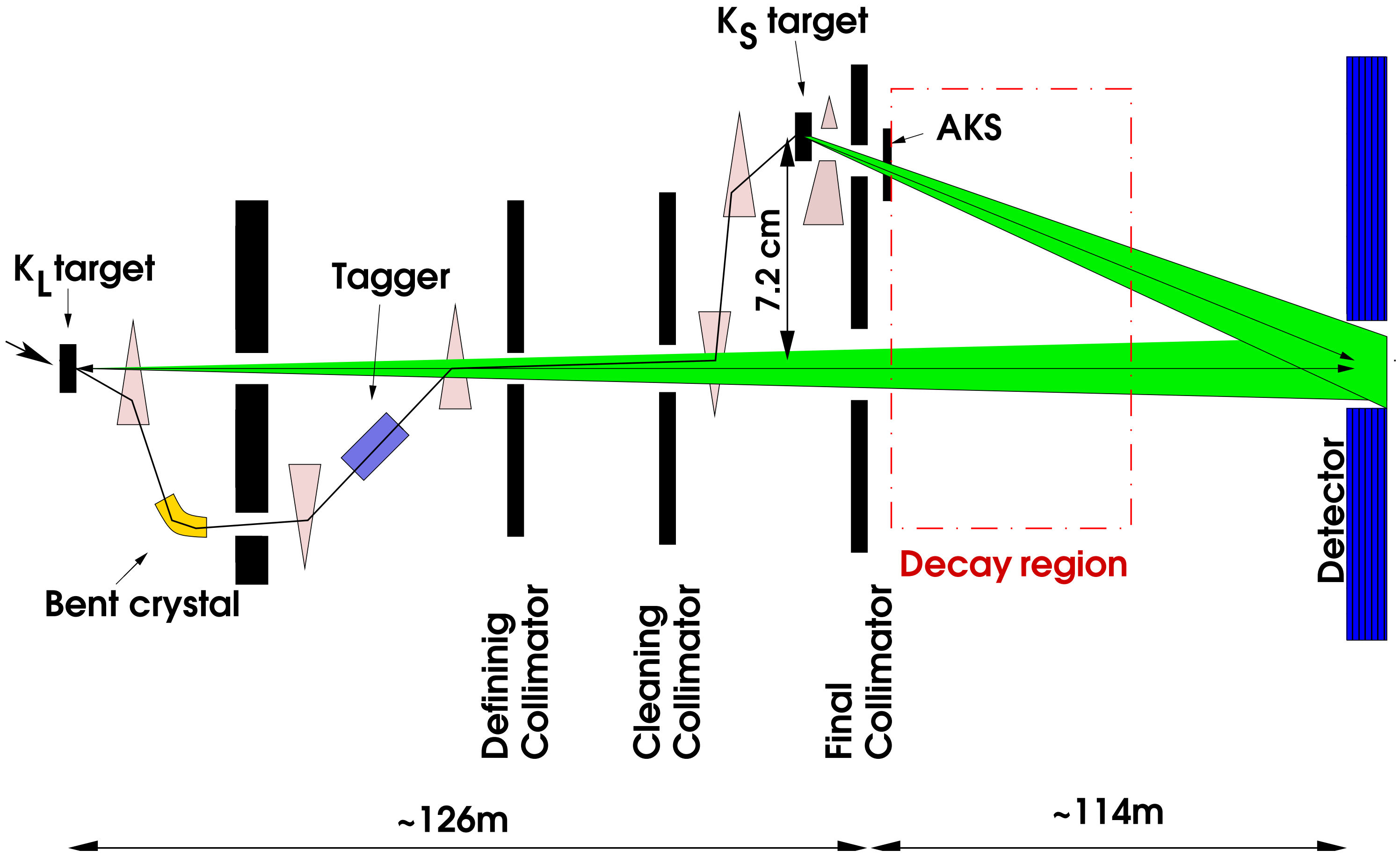
$$A(K_2 \to 2\pi) \neq 0.$$

Note that all observations of CP violation, $\not{C}\not{P}$, prior to about 1999, *i.e.* the decays $K_L\to 2\pi$, $\pi^+\pi^-\gamma$ and the charge asymmetries in $K_{\ell 3}$ decays are examples of so called "indirect" violation, due to $|\Delta S|$=2 $K^0 \leftrightarrow \overline{K}^0$ transitions introducing a small CP impurity in the mass eigenstates K_S and K_L.

Incidentally, because of the smallness of ϵ (and ϵ'), most results and parameter values given earlier for K_1 and K_2 remain valid after the substitution $K_1 \to K_S$ and $K_2 \to K_L$.

We will have a seminar dedicated to the experimental measurements of $\Re(\epsilon'/\epsilon)$, which had a real roller coaster history for the last some thirty years until it finally settled down this summer in 2001.

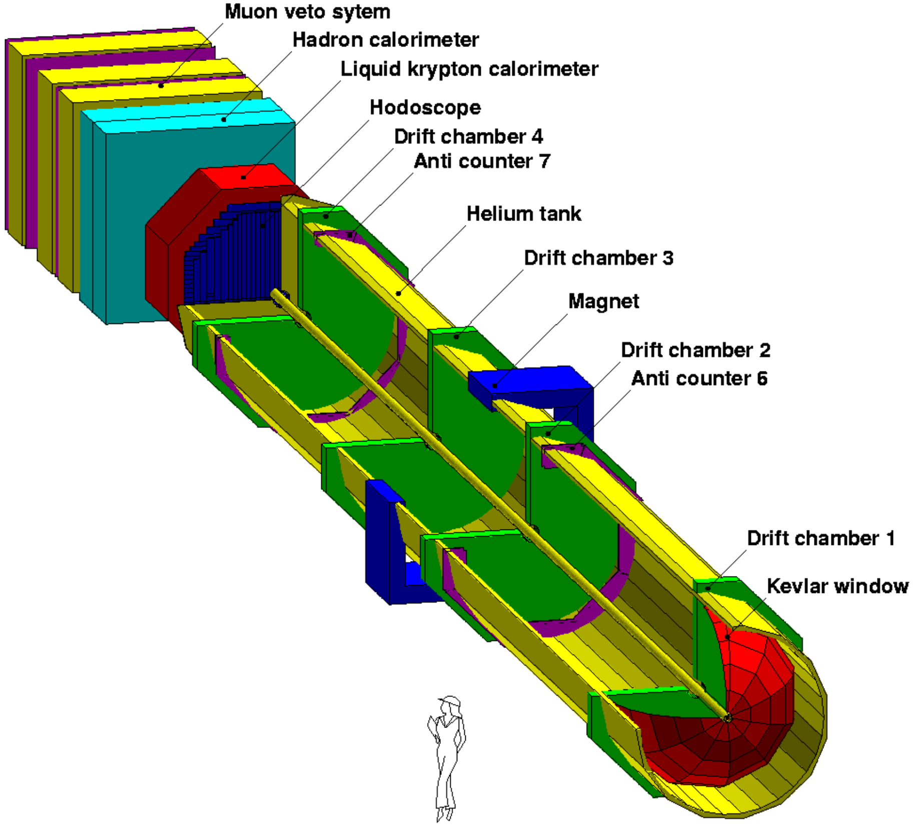
PRESENTATION of NA48:The Beams



Simultaneous K_S and K_L beams.

Sligthly converging, to hit the same detector region.

PRESENTATION of NA48:The Detector

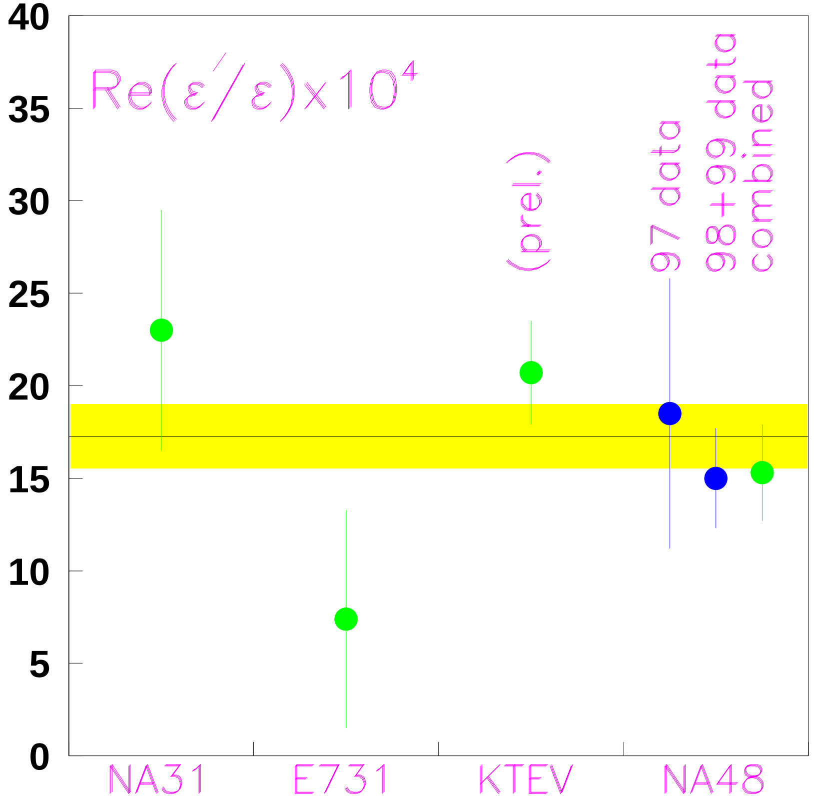


High resolution detectors to identify 3body background

- $\pi^+\pi^-$:Magnetic Spectrometer with P_T kick=265MeV/c
- $\pi^0\pi^0$: Liquid Krypton Calorimeter leading to $\sigma(\pi^0)\sim$1MeV
- Decay time known to $\sim$200ps allows an accurate K_S–K_L identification

LP01 *Lydia ICONOMIDOU-FAYARD* Results on CP Violation from NA48 experiment **13**

CONCLUSIONS



Combined NA48 result :

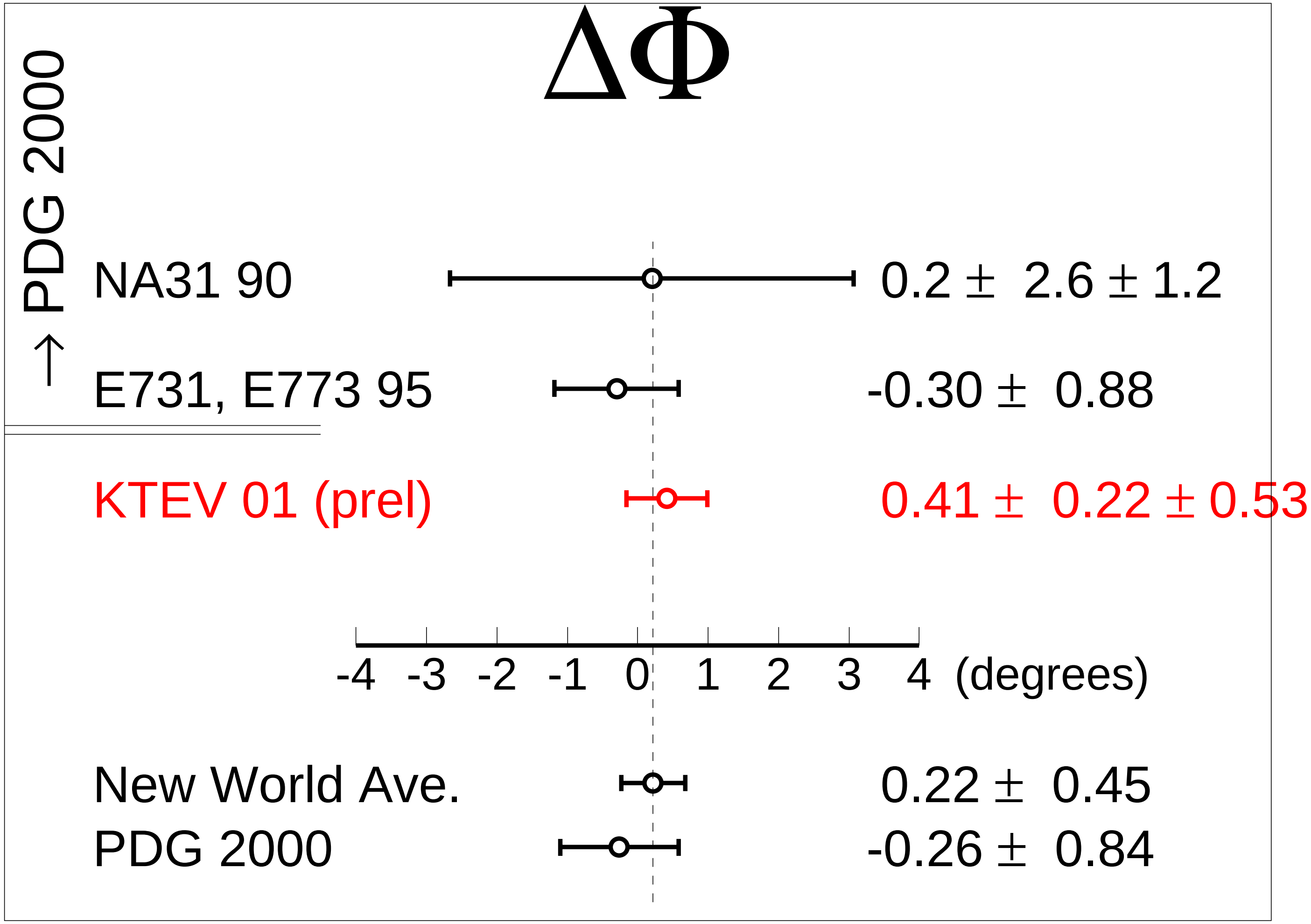
$$Re(\varepsilon'/\varepsilon) = (15.3 \pm 2.6) \times 10^{-4}$$

World average of NA31, E731, KTeV and NA48:

$$Re(\varepsilon'/\varepsilon) = (17.2 \pm 1.8) \times 10^{-4}$$

⇒ Both Indirect and Direct CP Violation components discovered, measured and confirmed in the kaon system

LP01 *Lydia ICONOMIDOU-FAYARD* Results on CP Violation from NA48 experiment **38**

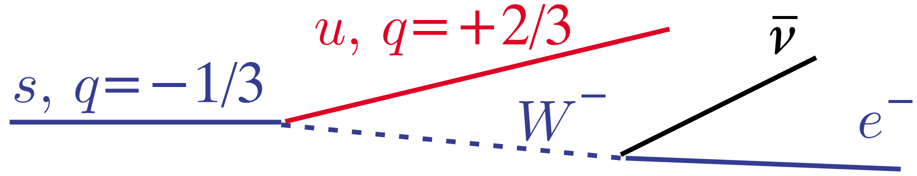


KTEV systematic dominated by neutral energy reconstruction.

2.6 Semileptonic decays and the $\Delta S = \Delta Q$ rule

K-mesons also decay semileptonically, into a hadron with charge Q and strangeness zero, and a pair of lepton-neutrino. These decays at quark levels are due to the elementary processes

$$s \to W^- u \to \ell^- \bar{\nu} u$$
$$\bar{s} \to W^+ \bar{u} \to \ell^+ \nu \bar{u}.$$



Physical K-mesons could decay as:

$$K^0 \to \pi^- \ell^+ \nu,\ \Delta S = -1,\ \Delta Q = -1$$
$$\overline{K^0} \to \pi^+ \ell^- \bar{\nu},\ \Delta S = +1,\ \Delta Q = +1$$
$$\overline{K^0} \to \pi^- \ell^+ \nu,\ \Delta S = +1,\ \Delta Q = -1$$
$$K^0 \to \pi^+ \ell^- \bar{\nu},\ \Delta S = -1,\ \Delta Q = +1.$$

In the standard model, SM, K^0 decay only to ℓ^- and $\overline{K^0}$ to ℓ^+. This is commonly referred to as the $\Delta S = \Delta Q$ rule, experimentally established in the very early days of strange particle studies.

Semileptonic decays enable one to know the strangeness of the decaying meson - and for the case of pair production to "tag" the strangeness of the other meson of the pair.

Assuming the validity of the $\Delta S = \Delta Q$ rule, the leptonic asymmetry

$$\mathcal{A}_\ell = \frac{N_{\ell+} - N_{\ell-}}{N_{\ell+} + N_{\ell-}}$$

in K_L or K_S decays is

$$2\Re\epsilon \simeq \sqrt{2}|\epsilon| = (3.30 \pm 0.03) \times 10^{-3}.$$

The measured value of $\mathcal{A}_\ell$ for K_L decays was $(0.327 \pm 0.012)\%$, in good agreement with the above result, the first proof that CP violation is, mostly, in the mass term.

$K_L \to \pi e \nu$ Charge Asymmetry

$$\delta_{Ke3} \equiv \frac{N(K_L \to \pi^- e^+ \nu) - N(K_L \to \pi^+ e^- \nu)}{sum}$$

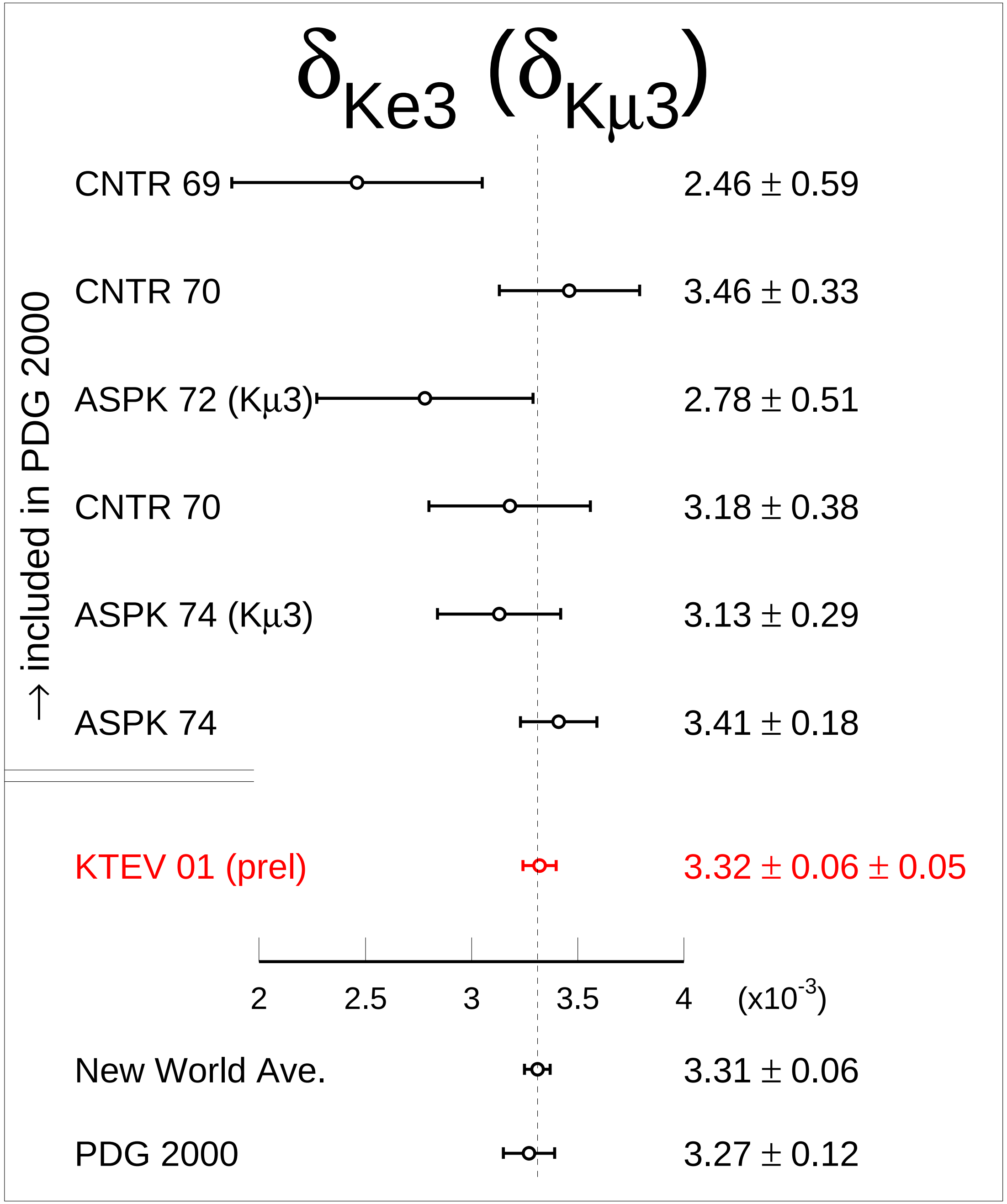
$$= 2Re(\epsilon - \Delta - Y - X_-)$$

$$\epsilon = \not{C}\not{P} \quad in \ mixing.$$

$$\Delta = \not{C}\not{P}\not{T} \ in \ mixing \ (\Delta S = \Delta Q).$$

$$Y = \not{C}\not{P}\not{T} \ in \ decay \ amplitude \ (\Delta S = \Delta Q).$$

$$X_- = \not{C}\not{P}\not{T} \ in \ decay \ amplitude \ (\Delta S \neq \Delta Q).$$



KTeV Result:

- 298 million Ke3
- No MC correction
- $\times 2.4$ more precise than previous best
- world avg $\times 2$ more precise

Dominant σ_{syst} $(\times 10^{-3})$:

- π-punch to μ-veto: 0.04
- e^+/e^- diff in CsI: 0.018
- π^+/π^- diff in CsI: 0.014

In strong interactions strangeness is conserved. The strangeness of neutral K-mesons can be tagged by the sign of the charge kaon (pion) in the reaction

$$p + \bar{p} \to K^0(\overline{K^0}) + K^{-(+)} + \pi^{+(-)}.$$

This of course is valid if the rule $\Delta S = \Delta Q$ is correct. In fact, the validity of the rule can be checked in experiments of this kind. (In KLOE we can tag S using $K^{\pm}$'s)

2.7 CP Violation at a ϕ–factory

2.7.1 ϕ (Υ''') production and decay in e^+e^- annihilations

The cross section for production of a bound $q\bar{q}$ pair of mass M and total width Γ with $J^{PC} = 1^{--}$, a so called vector meson V, (ϕ in the following and the $\Upsilon(4S)$ later) in e^+e^- annihilation, see fig. 9, is given by:

$$\sigma_{\mathrm{res},(q\bar{q})} = \frac{12\pi}{s}\frac{\Gamma_{ee}\Gamma M^2}{(M^2-s)^2+M^2\Gamma^2} = \frac{12\pi}{s}B_{ee}\frac{M^2\Gamma^2}{(M^2-s)^2+M^2\Gamma^2}$$

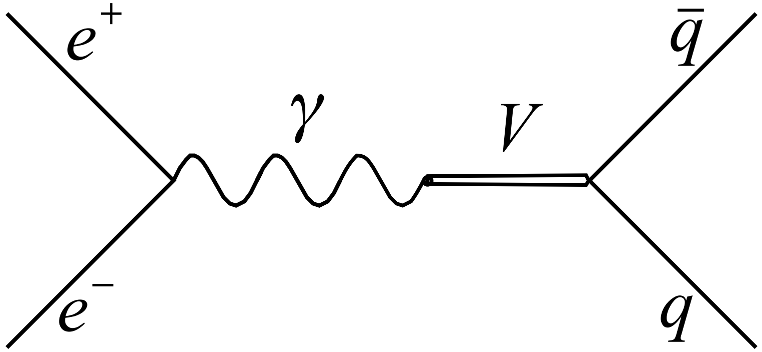


Fig. 9. Amplitude for production of a bound $q\bar{q}$ pair

The ϕ meson is an $s\bar{s}$ $^3\mathrm{S}_1$ bound state with J^{PC}=1^{--}, just as a photon and the cross section for its production in e^+e^- annihilations at 1020 MeV is

$$\sigma_{s\bar{s}}(s = (1.02)^2\ \mathrm{GeV}^2) \sim \frac{12\pi}{s}B_{ee}$$

$$= 36.2 \times (1.37/4430) = 0.011\ \mathrm{GeV}^{-2} \sim 4000\ \mathrm{nb},$$

compared to a total hadronic cross section of $\sim$(5/3) $\times$87$\sim$100 nb, from $\sigma(q\bar{q}) = \sum e_i^2 \times (4\pi\alpha^2/3s) = 5/3 \times (86.85 \text{ nb})/(s \text{ GeV}^2)$.

The production cross section for the $\Upsilon(4S)$ at W=10,400 MeV is $\sim$1 nb (resolution!), over a background of $\sim$3.1 nb ($11/3\times\sigma_{\mu\mu}$).

The Frascati ϕ–factory, DAΦNE, will have a luminosity $\mathcal{L} = 10^{33}$ cm^{-2} s^{-1} = 1 nb^{-1}s^{-1}.

Collecting data for 10^7 seconds corresponds to the production at DAΦNE of $\sim 4000 \times 10^7 = 4 \times 10^{10}$ ϕ meson per year or approximately 1.3×10^{10} K^0, $\overline{K^0}$ pairs.

However a B-factory has to have a luminosity around 10^{34} cm^{-2} s^{-1} just to start.

One of the advantages of studying K, B mesons at with e^+e^-, is that they are produced in a well defined quantum state. Neutral K (B) mesons are produced as collinear pairs, with $J^{PC} = 1^{--}$ and opposite momenta, thus detection of one $K(B)$ announces the presence of the other and gives its direction.

Since in the reaction:

$$e^+e^- \to \text{``}\gamma\text{''} \to \phi \to K^0\overline{K}^0$$

we have

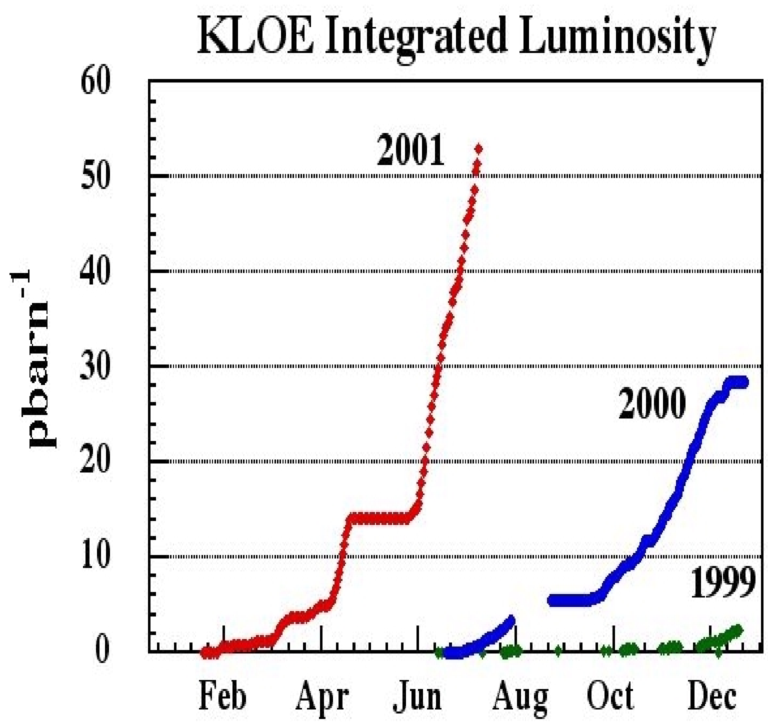
$$C(K^0\overline{K}^0) = C(\phi) = C(\gamma) = -1.$$

we can immediately write the 2-K state. Define $|\, i\,\rangle = |\, K\overline{K},\ t = 0,\ C = -1\,\rangle$. Then $|\, i\,\rangle$ must have the form:

$$|\, i\,\rangle = \frac{|\, K^0, \mathbf{p}\,\rangle |\, \overline{K}^0, -\mathbf{p}\,\rangle - |\, \overline{K}^0, \mathbf{p}\,\rangle |\, K^0, -\mathbf{p}\,\rangle}{\sqrt{2}}$$

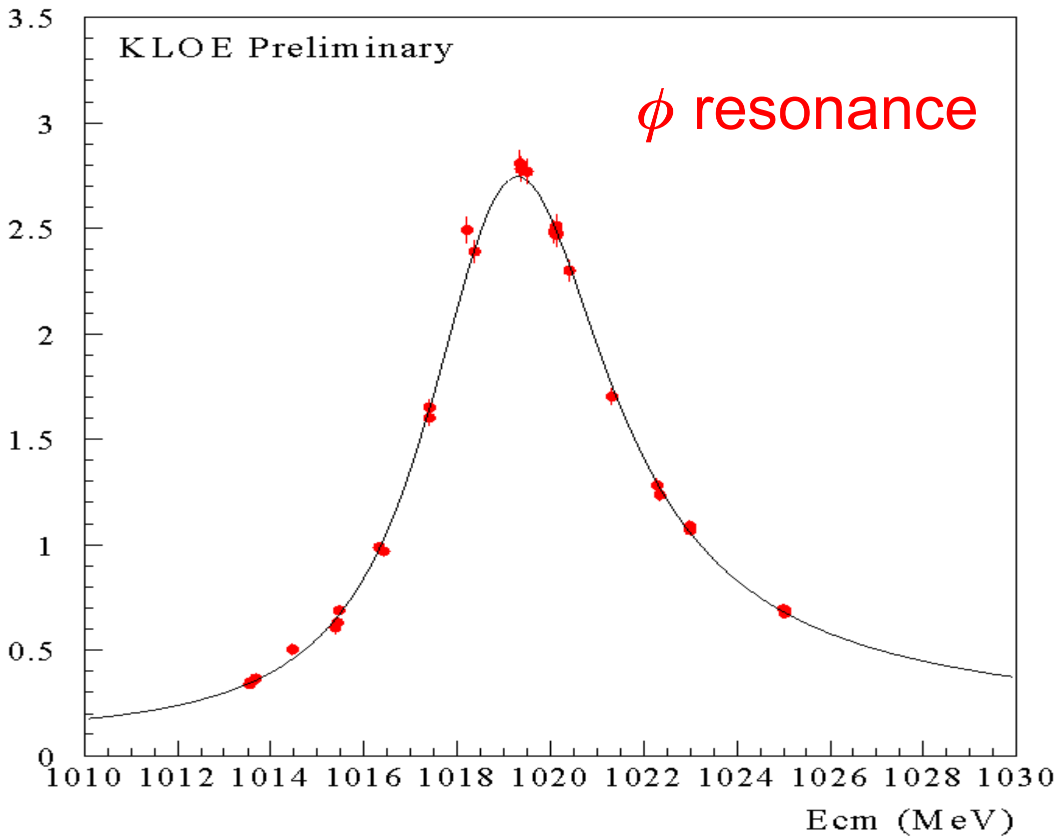
From eq. (4), the relations between K_S, K_L and K^0, $\overline{K}^0$, to

THE ACTUAL PERFORMANCES



Present day performances:

← $\int L dt_{TOT} \approx 80\ pb^{-1}$



lowest order in ϵ, we find:

$$|\,K_S\ (K_L)\,\rangle = \frac{(1+\epsilon)|\,K^0\,\rangle + (-)(1-\epsilon)|\,\overline{K^0}\,\rangle}{\sqrt{2}}.$$

$$|\,K^0\ (\overline{K^0})\,\rangle = \frac{|\,K_S\,\rangle + (-)|\,K_L\,\rangle}{(1+(-)\epsilon)\sqrt{2}}$$

from which

$$|\,i\,\rangle = \frac{1}{\sqrt{2}}(|\,K_S, -\mathbf{p}\,\rangle|\,K_L, \mathbf{p}\,\rangle - |\,K_S, \mathbf{p}\,\rangle|\,K_L, -\mathbf{p}\,\rangle)$$

so that the neutral kaon pair produced in e^+e^- annihilations is a pure K^0, $\overline{K^0}$ as well as a pure K_S, K_L for *all times,* in vacuum. What this means, is that if at some time t a K_S (K_L, K^0, $\overline{K^0}$) is recognized, the other kaon, if still alive, is a K_L (K_S, $\overline{K^0}$, K^0).

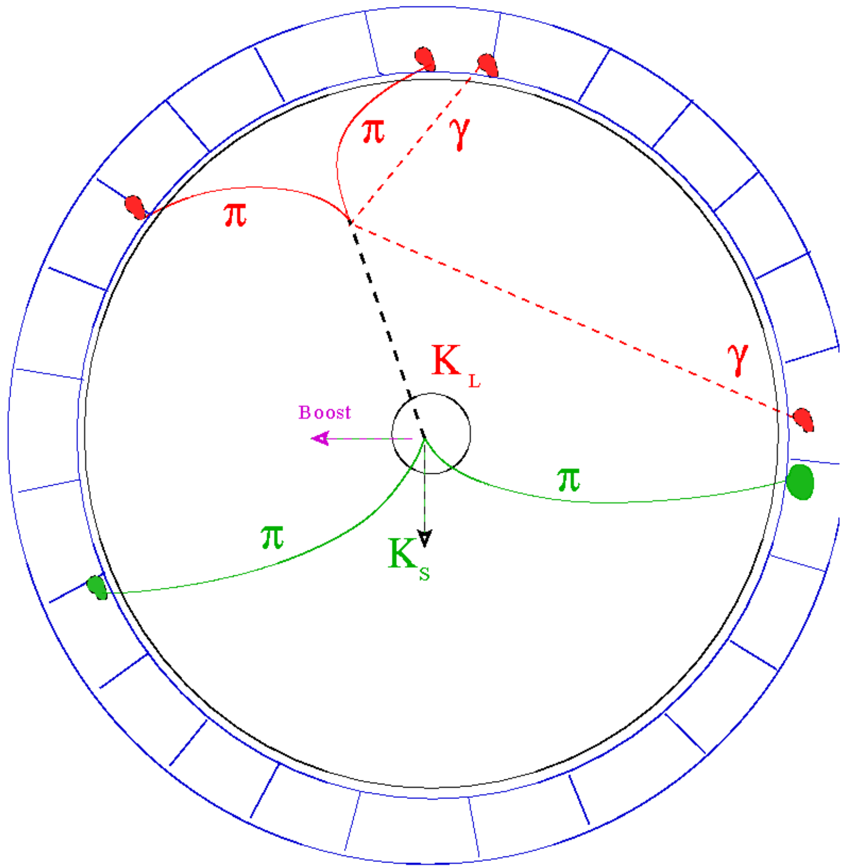
KAONS AT A Φ-FACTORY : TAGGING

The two kaon state from ϕ meson decay can be written as:

$$\frac{K_S(p)K_L(-p) - K_S(-p)K_L(p)}{\sqrt{2}}$$

↓

The observation of a $K_S(K_L)$ ***tags*** the presence of the other particle



A ***pure*** (to 10^{-5}) ***tagged*** K_S beam available only at DAΦNE

KAONS AT A Φ-FACTORY : TAGGING

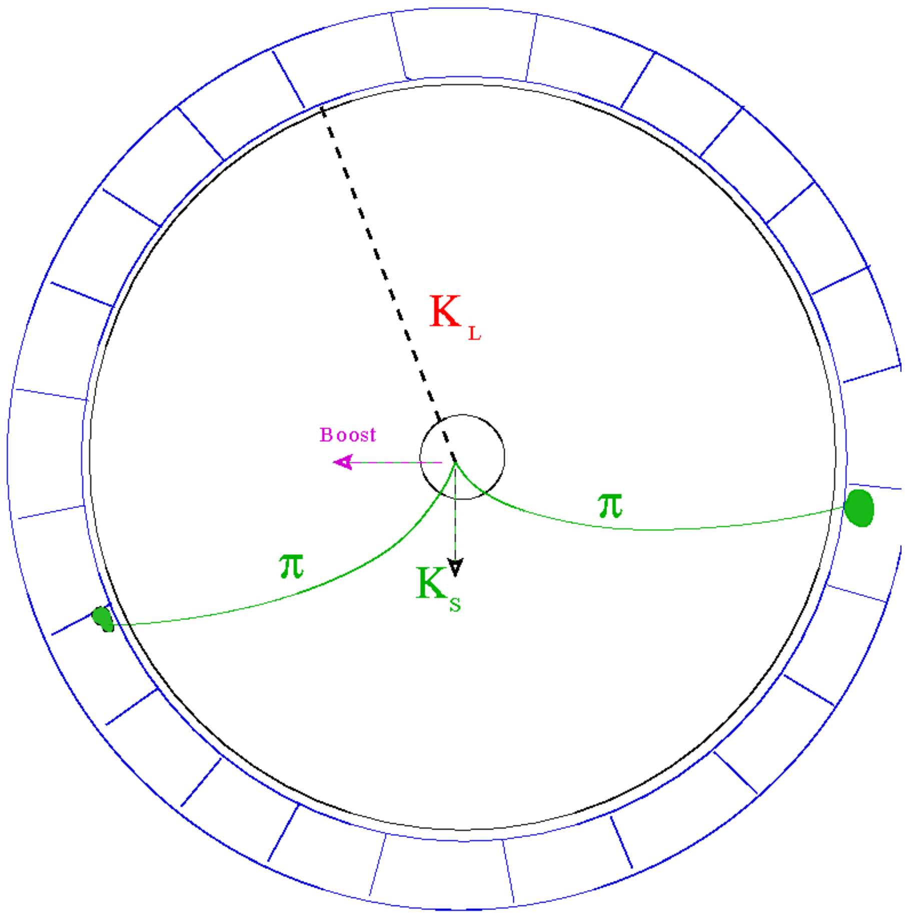
The two kaon state from ϕ meson decay can be written as:

$$\frac{K_S(p)K_L(-p) - K_S(-p)K_L(p)}{\sqrt{2}}$$

↓

The observation of a $K_S(K_L)$ ***tags*** the presence of the other particle

A ***pure*** (to 10^{-5}) ***tagged*** K_S beam available only at DAΦNE



KAONS AT A Φ-FACTORY : TAGGING

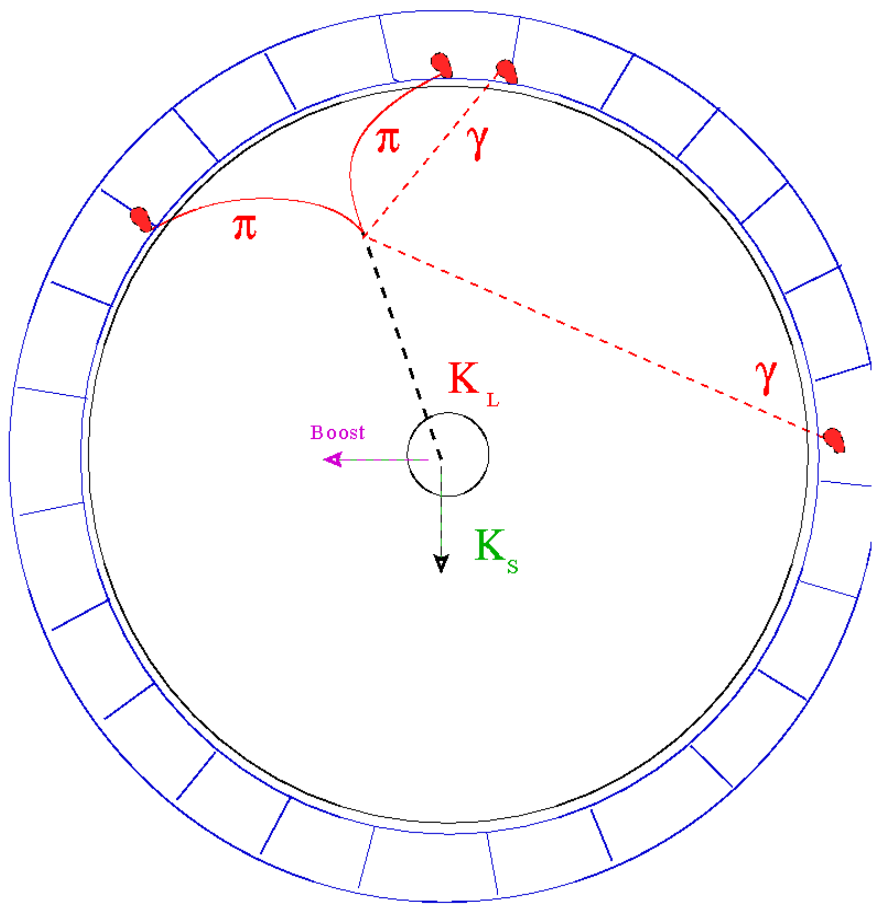
The two kaon state from ϕ meson decay can be written as:

$$\frac{K_S(p)K_L(-p) - K_S(-p)K_L(p)}{\sqrt{2}}$$

↓

The observation of a $K_S(K_L)$ ***tags*** the presence of the other particle

A ***pure*** (to 10^{-5}) ***tagged*** K_S beam available only at DAΦNE



The result above is correct to all orders in ϵ, apart from a normalization constant, and holds even without assuming CPT invariance.

The result also applies to $e^+e^-\to B^0\overline{B}^0$ at the $\Upsilon(4S)$.

2.7.2 *Correlations in K_S, K_L decays*

To obtain the amplitude for decay of $K(\mathbf{p})$ into a final state f_1 at time t_1 and of $K(-\mathbf{p})$ to f_2 at time t_2, see the diagram below, we time evolve the initial state in the usual way:

$$|\,t_1,\ \mathbf{p};\ t_2,\ -\mathbf{p}\,\rangle = \frac{1+|\epsilon^2|}{(1-\epsilon^2)\sqrt{2}}\times$$
$$(|\,K_S(-\mathbf{p})\,\rangle|\,K_L(\mathbf{p})\,\rangle e^{-i(\mathcal{M}_S t_2+\mathcal{M}_L t_1)} -$$
$$|\,K_S(\mathbf{p})\,\rangle|\,K_L(-\mathbf{p})\,\rangle e^{-i(\mathcal{M}_S t_1+\mathcal{M}_L t_2)})$$

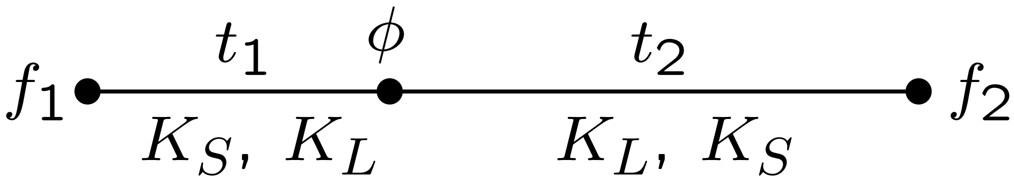


Fig. 10. $\phi\to K_L,\ K_S\to f_1,\ f_2$.

where $\mathcal{M}_{S,L} = M_{S,L} - i\Gamma_{S,L}/2$ are the complex K_S, K_L masses.

In terms of the previously mentioned ratios $\eta_i = \langle\, f_i |\, K_L\,\rangle / \langle\, f_i |\, K_S\,\rangle$ and defining $\Delta t = t_2 - t_1$, $t = t_1 + t_2$, $\Delta\mathcal{M} = \mathcal{M}_L - \mathcal{M}_S$ and $\mathcal{M} = \mathcal{M}_L + \mathcal{M}_S$ we get the amplitude for decay to states 1 and 2:

$$
\begin{aligned}
A(f_1, f_2, t_1, t_2) = \langle\, f_1 |\, K_S\,\rangle \langle\, f_2 |\, K_S\,\rangle e^{-i\mathcal{M}t/2} \times \\
(\eta_1 e^{i\Delta\mathcal{M}\Delta t/2} - \eta_2 e^{-i\Delta\mathcal{M}\Delta t/2})/\sqrt{2}.
\end{aligned}
\tag{5}
$$

This implies $A(e^+e^- \to \phi \to K^0\overline{K}^0 \to f_1 f_2) = 0$ for $t_1 = t_2$ and $f_1 = f_2$ (Bose statistics).

For $t_1 = t_2$, $f_1 = \pi^+\pi^-$ and $f_2 = \pi^0\pi^0$ instead, $A \propto \eta_{+-} - \eta_{00} = 3 \times \epsilon'$ which suggest a (unrealistic) way to measure ϵ'.

The intensity for decay to final states f_1 and f_2 at times t_1 and t_2 obtained taking the modulus squared of eq. (5) depends on magnitude and argument of η_1 and η_2 as well as on $\Gamma_{L,S}$ and ΔM. The intensity is given by

$$I(f_1, f_2, t_1, t_2) = |\langle\, f_1 |\, K_S\,\rangle|^2 |\langle\, f_2 |\, K_S\,\rangle|^2 e^{-\Gamma_S t/2} \times$$
$$(|\eta_1|^2 e^{\Gamma_S \Delta t/2} + |\eta_2|^2 e^{-\Gamma_S \Delta t/2} - 2|\eta_1||\eta_2| \cos(\Delta m\, t + \phi_1 - \phi_2))$$

where we have everywhere neglected Γ_L with respect to Γ_S.

Thus the study of the decay of K pairs at a ϕ–factory offers the unique possibility of observing interference pattern in time, or space, in the intensity observed at two different points in space.

This fact is the source of endless excitement and frustration to some people.

Rather than studying the intensity above, which is a function of two times or distances, it is more convenient to consider the once integrated distribution. In particular one can integrate the intensity over all times t_1 and t_2 for fixed time difference $\Delta t = t_1 - t_2$, to obtain the intensity as a function of Δt. Performing the integrations yields, for $\Delta t > 0$,

$$I(f_1,\ f_2;\ \Delta t) = \frac{1}{2\Gamma}|\langle f_1|\, K_S\,\rangle\langle f_2|\, K_S\,\rangle|^2 \times \\ (|\eta_1|^2 e^{-\Gamma_L \Delta t} + |\eta_2|^2 e^{-\Gamma_S \Delta t} - \\ 2|\eta_1||\eta_2| e^{-\Gamma \Delta t/2} \cos(\Delta m \Delta t + \phi_1 - \phi_2))$$

and a similar expression is obtained for $\Delta t < 0$. The interference pattern is quite different according to the choice of f_1 and f_2 as illustrated in fig. 11.

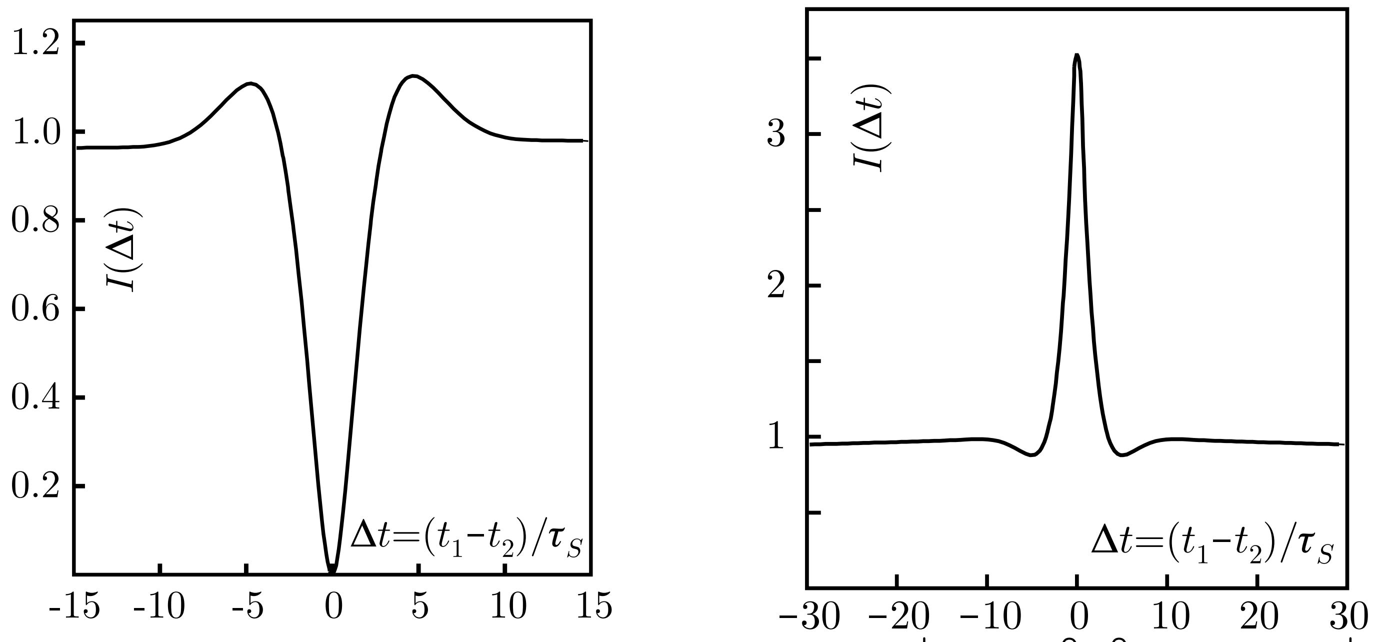


Fig. 11. Interference pattern for $f_{1,2}{=}\pi^+\pi^-$, $\pi^0\pi^0$ and ℓ^-, ℓ^+.

The strong destructive interference at zero time difference is due to the antisymmetry of the initial KK state, decay amplitude phases being identical. The destructive interference at zero time difference becomes constructive because the amplitude for $K^0{\to}\ell^-$ has opposite sign to that for $\overline{K}^0{\to}\ell^+$ thus making the overall amplitude symmetric. One can perform a whole spectrum of precision "kaon-interferometry" experiments at DAΦNE by measuring the above decay intensity distributions for appropriate choices of the final states f_1, f_2. Four examples are listed below.

- With f_1=f_2 one measures Γ_S, Γ_L and Δm, since all phases cancel. Rates can be measured with a $\times$10 improvement in accuracy and Δm to $\sim\times 2$.

- With $f_1=\pi^+\pi^-$, $f_2=\pi^0\pi^0$, one measures $\Re(\epsilon'/\epsilon)$ at large time differences, and $\Im(\epsilon'/\epsilon)$ for $|\Delta t| \leq 5\tau_s$. Fig. 11 shows the interference pattern for this case.

- With $f_1 = \pi^+\ell^-\nu$ and $f_2 = \pi^-\ell^+\nu$, one can measure the CPT–violation parameter δ, see our discussion later concerning tests of CPT. Again the real part of δ is measured at large time differences and the imaginary part for $|\Delta t| \leq 10\tau_s$. Fig. 11 shows the interference pattern

For $f_1 = 2\pi$, $f_2 = \pi^+\ell^-\nu$ or $\pi^-\ell^+\nu$ small time differences yield Δm, $|\eta_{\pi\pi}|$ and $\phi_{\pi\pi}$, while at large time differences, the asymmetry in K_L semileptonic decays provides tests of T and CPT. The *vacuum regeneration* interference is shown in fig. 12.

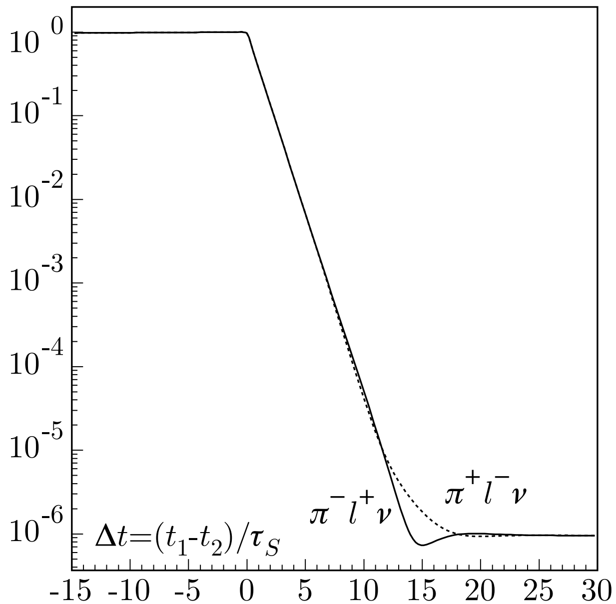


Fig. 12. Interference pattern for $f_1 = 2\pi, f_2 = \ell^{\pm}$

2.8 CP violation in K_S decays

CP violation has only been seen in K_L decays ($K_L \to \pi\pi$ and semileptonic decays). This is because, while it is easy to prepare an intense, pure K_L beam, thus far it has not been possible to prepare a pure K_S beam.

However, if the picture of $\not{C}\not{P}$ we have developed so far is correct, we can predict quite accurately the values of some branching ratios and the leptonic asymmetry.

It is quite important to check experimentally such predictions especially since the effects being so small, they could be easily perturbed by new physics outside the standard model.

2.8.1 $K_S \to \pi^0\pi^0\pi^0$

At a ϕ–factory such as DAΦNE, where $\mathcal{O}(10^{10})$ tagged K_S/y will be available, one can look for the $\not{C}\not{P}$ decay $K_S \to \pi^0\pi^0\pi^0$, the counterpart to $K_L \to \pi\pi$.

The branching ratio for this process is proportional to $|\epsilon + \epsilon'_{000}|^2$ where ϵ'_{000} is a quantity similar to ϵ', signalling direct CP violation. While ϵ'_{000}/ϵ might not be as suppressed as the ϵ'/ϵ, we can neglect it to an overall accuracy of a few %. Then $K_S{\to}\pi^0\pi^0\pi^0$ is due to the K_L impurity in K_S and the expected BR is 2×10^{-9}. The signal at DAΦNE is at the 30 event level. There is here the possibility of observing the CP impurity of K_S, never seen before. The current limit on BR($K_S{\to}\pi^+\pi^-\pi^0$) is 3.7×10^{-5}.

2.8.2 BR($K_S \to \pi^{\pm}\ell^{\mp}\nu$) and $\mathcal{A}_\ell(K_S)$

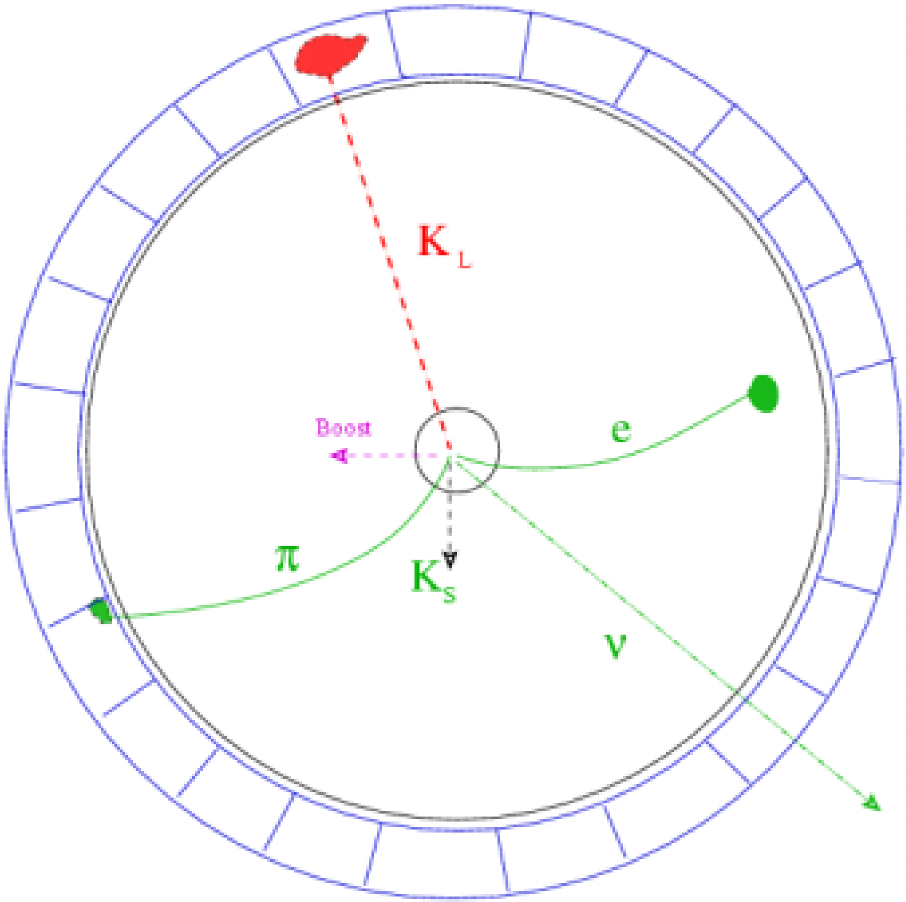
The branching ratio for $K_S \to \pi^{\pm}\ell^{\mp}\nu$ can be obtained from that of K_L and the K_S-K_L lifetime's ratio, since the two amplitudes are equal, assuming CPT invariance. In this way we find

$$\mathrm{BR}(K_S \to \pi^{\pm}e^{\mp}\nu) = (6.70 \pm 0.07) \times 10^{-4}$$
$$\mathrm{BR}(K_S \to \pi^{\pm}\mu^{\mp}\nu) = (4.69 \pm 0.06) \times 10^{-4}$$

The leptonic asymmetry in K_S (as for K_L) decays is $2\Re\epsilon = (3.30 \pm 0.03) \times 10^{-3}$.

KLOE has recently collected some 600 such decays, the BR is in agreement with expectation. The leptonic asymmetry $\mathcal{A}_\ell$ in K_S decays will be determined in the future.

$K_S \rightarrow \pi e \nu$



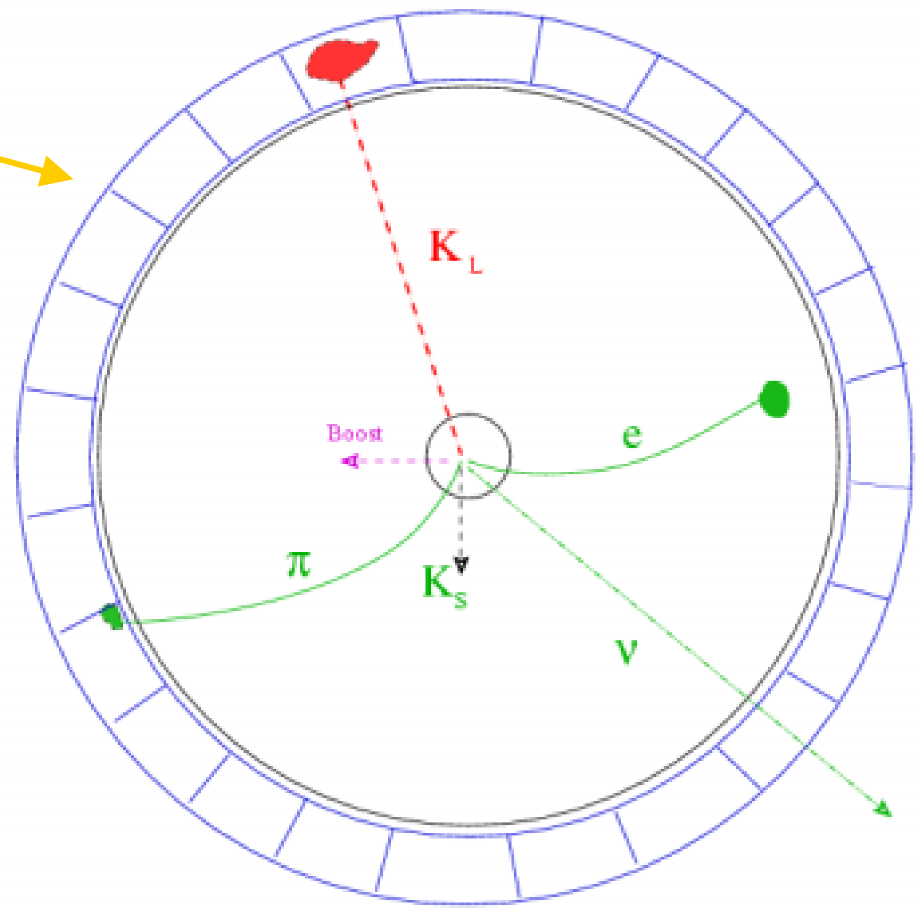
Selection Recipe:

- K crash
- Kinem. preselection
- TOF particle id
- Close kinematics

Kinematic identification

K_S momentum estimated by

K_L direction and ϕ boost



Energy and momentum of the neutrino given by:

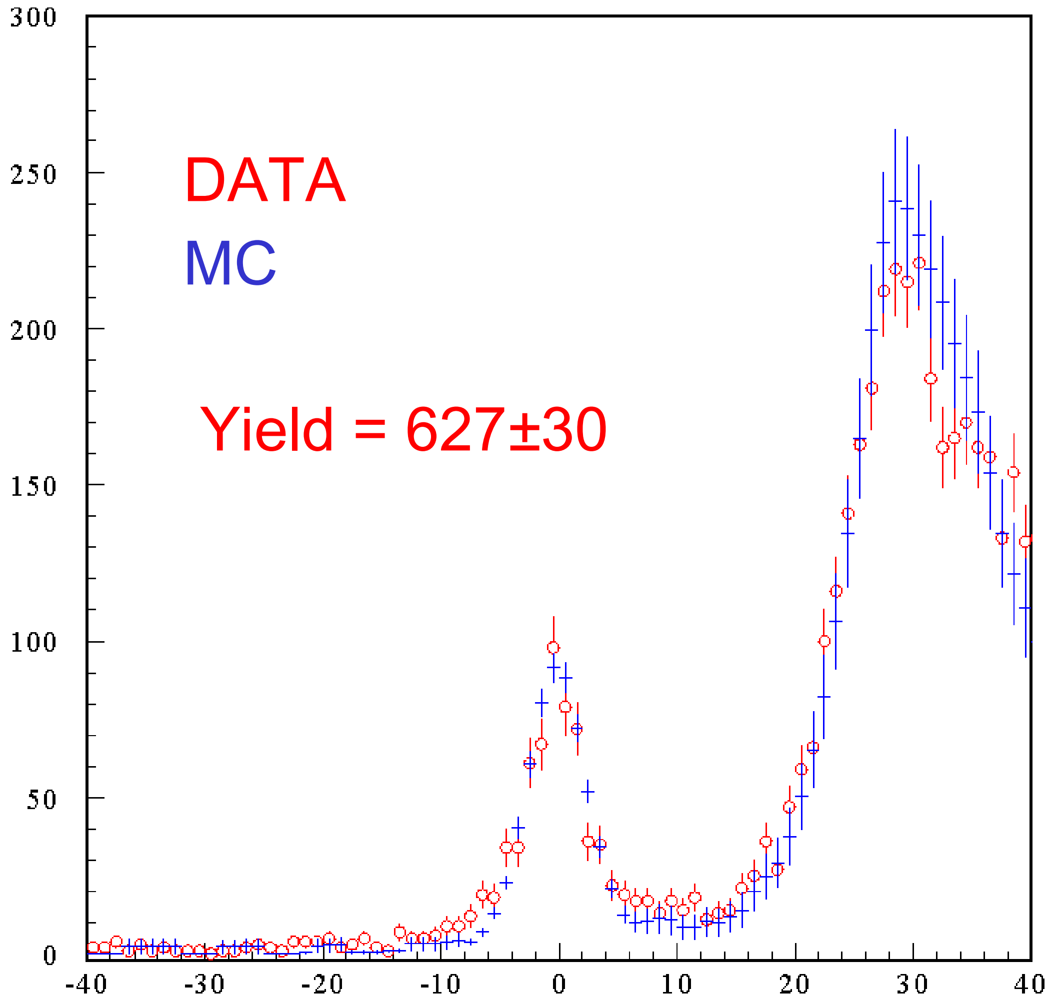
$$E(\text{missing})_{\pi e} = E_S - E_\pi - E_e$$

$$\vec{P}(\text{missing})_{\pi e} = \vec{P}_S - \vec{P}_\pi - \vec{P}_e$$

Kinematic identification

Signal yield estimation:

- Plot E_{MISS}–P_{MISS} variable
- Data fit using MC spectra for background and signal
- Log-likelihood function takes into account contribution due to finite MC statistics



$E_{miss}(\pi e)$-P_{miss} (MeV)

$K_S \rightarrow \pi e \nu$ results

Data: 2000 ~ 17 pb^{-1}

overall efficiency $\varepsilon_{TOT} = (21.8 \pm 0.3)\%$

Yield $N(K_S \rightarrow \pi e \nu) = 627 \pm 30$ events

PDG 2000* $BR(K_S \rightarrow \pi e \nu) = [7.2 \pm 1.2] \times 10^{-4}$ (75 ± 13 events)

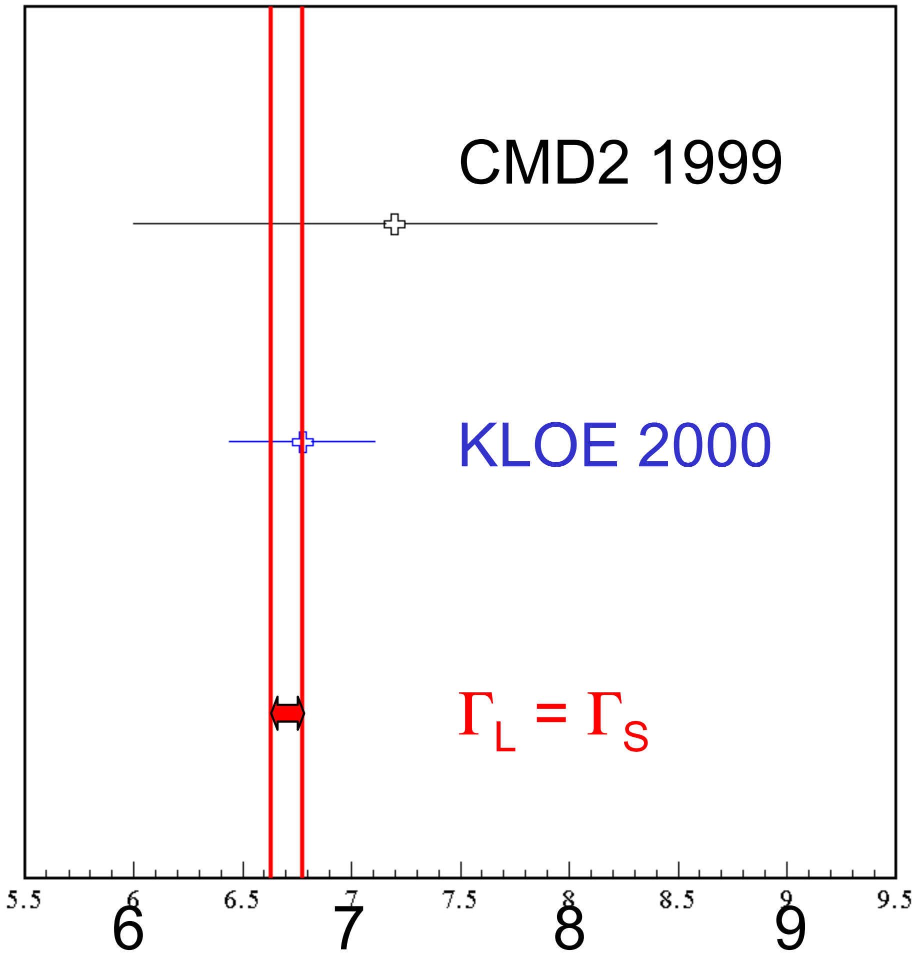
$\Gamma_S = \Gamma_L$ $BR(K_S \rightarrow \pi e \nu) = [6.70 \pm 0.07] \times 10^{-4}$

KLOE 2000 $BR(K_S \rightarrow \pi e \nu) = [6.8 \pm 0.3(stat)] \times 10^{-4}$

preliminary

***CMD-2 @ VEPP-2M** Phys. Lett. **B456**(1999)90-94

$K_S \to \pi e \nu$ results



$B(K_S \to \pi e \nu) \cdot 10^{-4}$

2.9 CP violation in charged K decays

Evidence for direct CP violation can be also be obtained from the decays of charged K mesons. CP invariance requires equality of the partial rates for $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ ($\tau^{\pm}$) and for $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ ($\tau'^{\pm}$).

With the luminosities obtainable at DAΦNE one can improve the present rate asymmetry measurements by two orders of magnitude, although *alas* the expected effects are predicted from standard calculations to be woefully small.

One can also search for differences in the Dalitz plot distributions for K^{+} and K^{-} decays in both the τ and τ' modes and reach sensitivities of $\sim 10^{-4}$.

Finally, differences in rates in the radiative two pion decays of $K^{\pm}$, $K^{\pm}\to\pi^{\pm}\pi^{0}\gamma$, are also proof of direct CP violation. Again, except for unorthodox computations, the effects are expected to be very small.

You have heard about our beginnings in these studies from Claudia Lecci seminar here a few weeks ago.

3. The fourth Quark

3.1 FCNC suppression

It is a well known fact for decades that flavor changing neutral weak currents, FCNC are very suppressed. The neutral weak current which causes reactions such as $\nu p \rightarrow \nu p$, leaves the flavor of the particles intact. Neutral weak currents cannot be observed in pion decays since the electromagnetic decay $\pi^0 \rightarrow \gamma\gamma$ is much too fast.

With kaons the situation is more favorable. The decays $K \rightarrow \pi\nu\bar{\nu}$ and $K \rightarrow \mu\bar{\mu}$ could be expected to proceed via a four fermion interaction suppressed by a factor $\sin^2\theta$ *i.e.* with a decay rate about equal to that of other channels. This was clearly not the case.

It was therefore necessary to assume that flavor changing neutral currents are forbidden. Of course a second order process with two charged currents can make up an effective neutral current.

The reaction $K_L \to \mu^+\mu^-$ can proceed through an effective strangeness changing neutral current as depicted in the figure

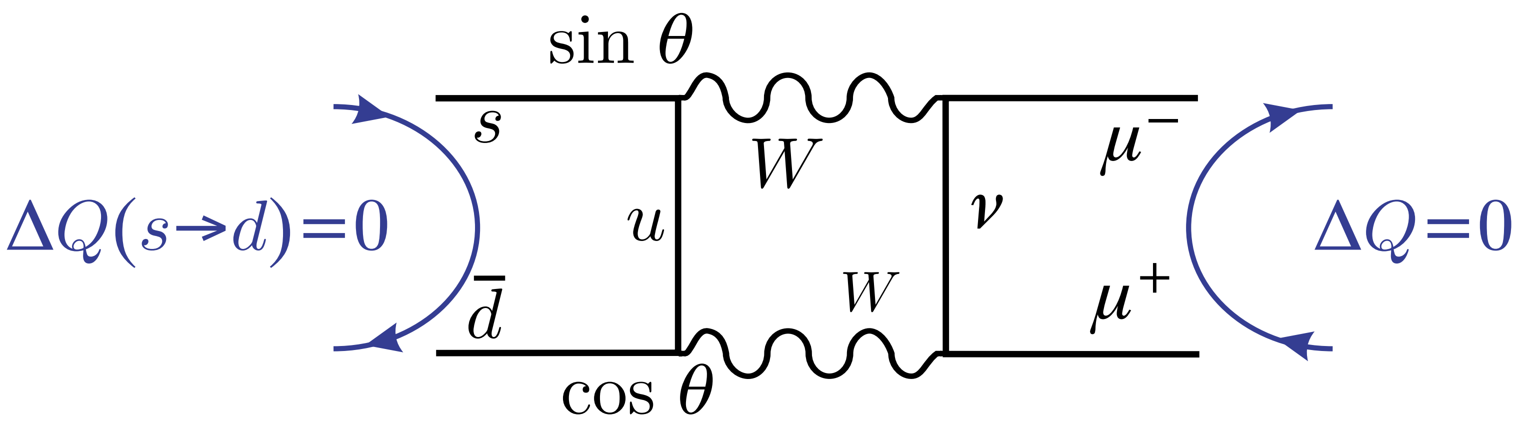


Fig. 28. $K^0 \to \mu^+\mu^-$.

which is a second order process in the weak interaction. Still the BR should be much larger than the (then, '70) observed value of $\sim 10^{-8}$. Today: BR($K_L \to \mu^+\mu^-$)=$(7.18 \pm 0.17) \times 10^{-9}$!

To be precise, the amplitude in fig. 28 diverges badly integrating on the loop.

In 1970, Glashow, Iliopoulos and Maiani showed that by postulating a fourth quark, it could provide a mechanism to decrease drastically the $K^0 \to \mu^+\mu^-$ decay rate. The complete amplitude is shown in the following diagram (the divergence is cancelled!):

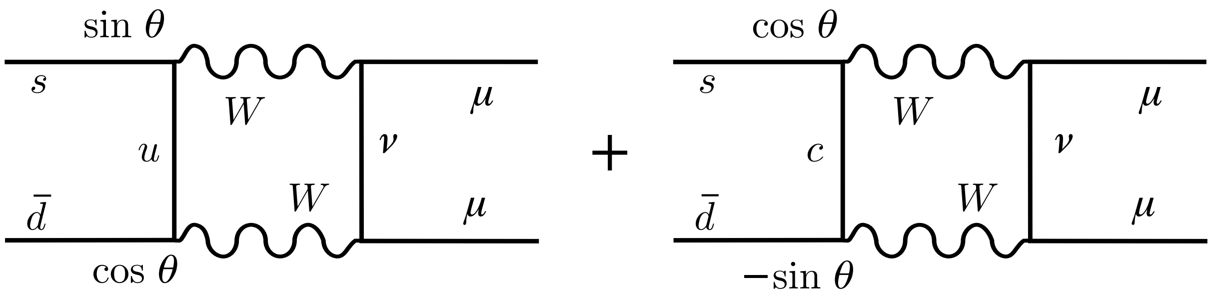


Fig. 29. $K^0 \to \mu^+\mu^-$.

In the second piece, a c quark appears instead of the u quark.

The quark structure of the currents which contribute to the decay is:

$$\bar{u}(\cos\theta_C d + \sin\theta_C s) + \bar{c}(-\sin\theta_C d + \cos\theta_C s) =$$
$$\begin{pmatrix} \bar{u} & \bar{c} \end{pmatrix} \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

In the four quark scheme, the Cabibbo angle, θ_C, mixes the d and s quarks via a rotation, and the amplitude for the $K^0 \to \mu^+ \mu^-$ has two terms proportional to $\sin\theta_C \cos\theta_C$ of opposite sign which cancel each other, leaving terms which are not in the lowest order of weak interaction.

Meanwhile, many processes due to effective FCNC have been observed since then, as summarized by Riccardo Barbieri in LP01.

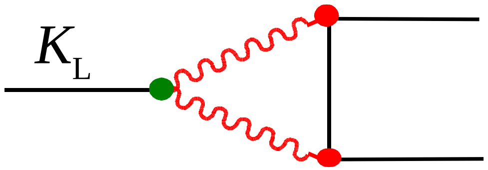
Observed Genuine FCNCs

	Exp	Th
ϵ	$(2.271 \pm 0.017)10^{-3}$	$\simeq \eta(A-\rho)$
$\frac{\epsilon\prime}{\epsilon}$	$(17.2 \pm 1.8)10^{-4}$	$(1 \div 30)10^{-4}$
$BR(B \to \chi_s \gamma)$	$(3.11 \pm 0.39)10^{-4}$	$(3.50 \pm 0.50)10^{-4}$
Δm_{B_d}	$(0.487 \pm 0.014)ps^{-1}$	$\simeq (1-\rho)^2 + \eta^2$
$A(B_d \to J/\Psi K_S)$	0.61 ± 0.12	$\frac{2\eta(1-\rho)}{(1-\rho)^2+\eta^2}$
$[BR(K^+ \to \pi^+ \nu\bar{\nu})$	$(1.5^{+3.4}_{-1.2})10^{-10}$	$(0.8 \pm 0.3)10^{-10}]$
$[\frac{\Delta m_{B_s}}{\Delta m_{B_d}}$	$\geq 30(95\% C.L.)$	$[(1-\rho)^2 + \eta^2]^{-1}]$

As we shall see, the study of FCNC plays a central role in determining some parameters in the flavor sector of the SM.

Experiments are still trying to determine the $K^0 \rightarrow \mu^+ \mu^-$ rate to higher and higher accuracy. Its computation has gotten more sophisticated, as seen in the following transparency presented by Gino Isidori in LP01.

$K_L \to l^+ l^-$



+ clean s.d. terms (as in $K^+ \to \pi^+ \nu\bar{\nu}$)

$B(K_L \to e^+ e^-) = (8.7^{+5.7}_{-4.1}) \times 10^{-12}$

$B(K_L \to \mu^+ \mu^-) = (7.18 \pm 0.17) \times 10^{-9}$

BNL−E871 ’98, ’00

$$|A(K_L \to l^+ l^-)|^2 = |\Im A_{\gamma\gamma}|^2 + |\Re A_{\gamma\gamma} + \Re A_{short}|^2$$

fixed by $\Gamma(K_L \to \gamma\gamma)$

$\xrightarrow{\mu^+\mu^-}$ $(7.07 \pm 0.18) \times 10^{-9}$

depends on the $K_L \to \gamma^* \gamma^*$ form factor (at all energies)

known @ NLO, $\propto \Re(V_{td})$

Buchalla & Buras ’94

$K_L \to e^+ e^-$

dispersive integral large & dominated by the low−energy region

$\Rightarrow$ reliable th. prediction: $B(K_L \to e^+ e^-)^{\text{th}} \simeq 10^{-11}$

Valencia, ’98
Pich & Dumm, ’98

$K_L \to \mu^+ \mu^-$

disp. integral smaller but more uncertain

- theoretical constr. @ high q^2
- exp. info from $K_L \to \gamma l^+ l^-$ & $K_L \to e^+ e^- \mu^+ \mu^-$

[work in prog. @ KTeV & NA48]

Littenberg ’96

D’Ambrosio, G.I., Potoles ’98

$\Rightarrow$ interesting prospects to extract $\Re(V_{td})$; more work needed [th.+exp.]

3.2 The Charm quark today

The charm quark was discovered officially (there were possible hints in cosmic ray events in emulsion exposures) in 1973, in a $\bar{c}c$ bound state called J/ψ. Since then hundreds and maybe thousands of papers have been devoted to its study, the most charming recent picture is taken from Patrik Roudeau's report in LP01.

Somehow it and τ, the lepton of similar weight (literally), never had a particle accelerator dedicated to their production. Suddenly, in 2001, two are proposed, CESR-c and BEPC-II, they are "upgrades" in luminosity of an older generation Υ, the former, and J/ψ, the latter, *factories*. They were scientifically approved and are awaiting funding.

Charm Physics

- Testing QCD Technologies
  - $f_D \leftrightarrow f_B$
  - $D \to \ell^+ \nu_\ell \pi(\rho) \leftrightarrow B \to \ell^- \overline{\nu}_\ell \pi(\rho)$
  - $\Gamma(\mathrm{D}^*)$
  - spectroscopy
- New Physics

- rare decays, oscillations, CP violation in c-hadrons
- in other fields (B) $\leftrightarrow$ QCD monitoring