Kaons

Kaons are the lightest mesons with “non stable” quarks. They have remarkable properties and the study of those properties has (’50 →’70) has opened large new understanding of how Nature works.

$$K^+ = u\bar{s} \qquad K^0 = d\bar{s} \qquad \overline{K^0} = \bar{d}s \qquad K^- = \bar{u}s$$

mass ~ 500 MeV   weak decay by s →W^- u with W^- going to (ubar-d) or (mu,nu) or (e,nu)

Gigi.Rolandi@cern.ch

Reference: Hagedorn, relativistic Kinematics

K- cross section with matter is larger than K+

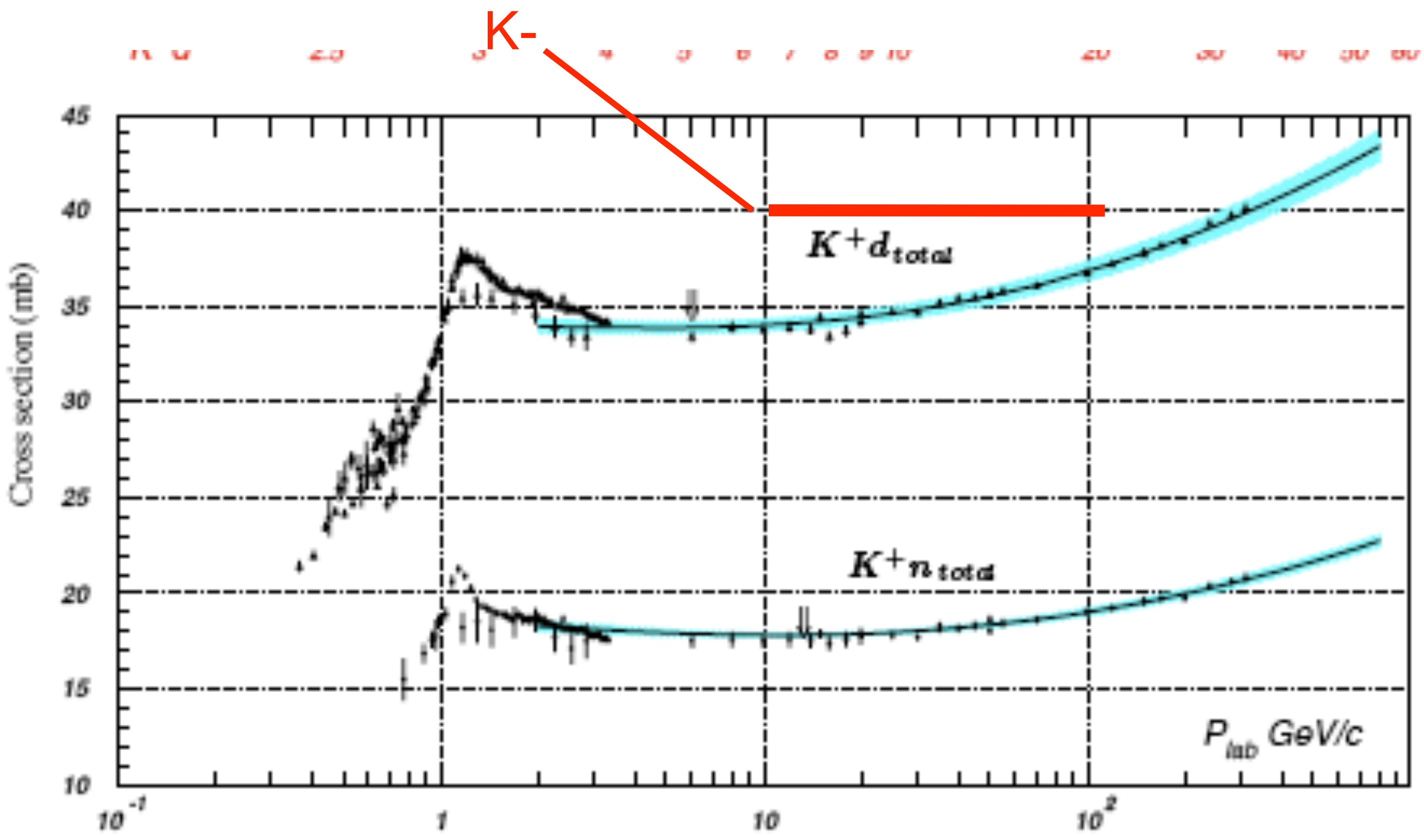


Figure 40.15: Total and elastic cross sections for K^+p and total cross sections for K^+d and K^+n collisions as a function of laboratory beam momentum and total center-of-mass energy. Corresponding computer-readable data files may be found at http://pdg.lbl.gov/xsect/contents.html. (Courtesy of the COMPAS Group, IHEP, Protvino, August 2005.)

Parity

Particles have intrinsic parity (i.e. their wavefunction is odd or even under parity transformation) and they as a conserved quantum number.

A system of two particles in the ground-state (l=0, no orbital motion) has parity equal to the product of the parities.

In QFT fermions have parity opposite to their antiparticles and bosons have the same parity of anti-particles.

We take the parity of quarks to be + and those of the anti-quarks to be minus. Pions have then negative parity . So do have Kaons.

Gigi.Rolandi@cern.ch

Tau-teta puzzle

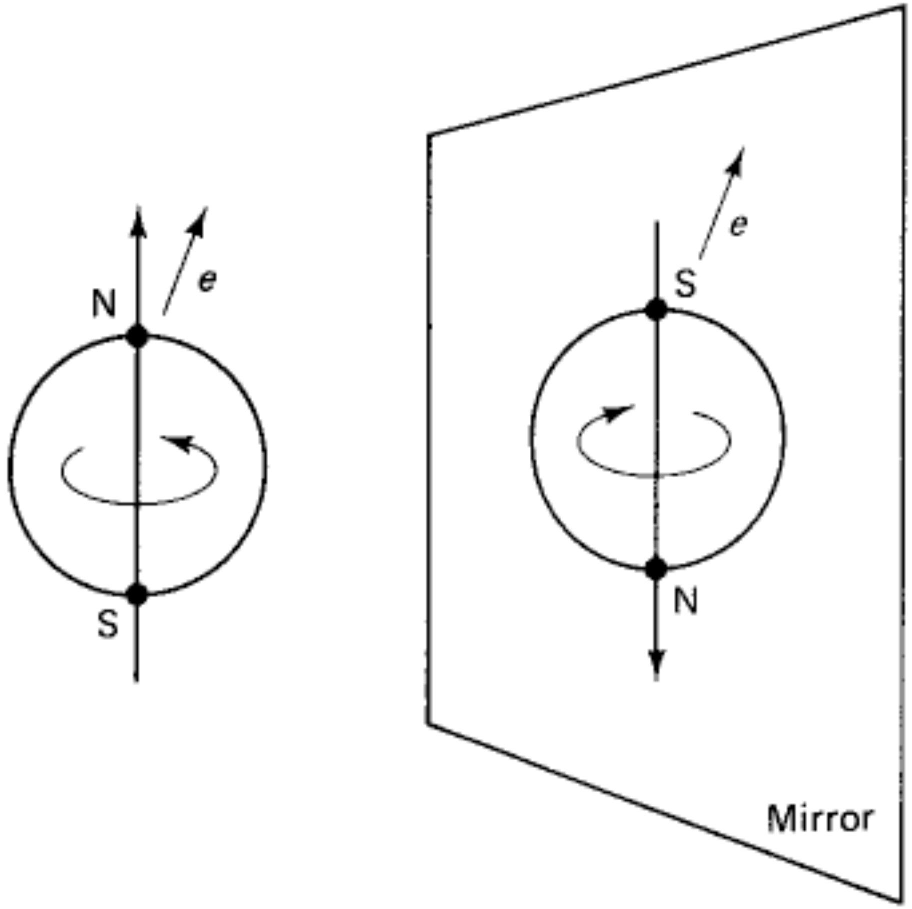
$$\vartheta \rightarrow \pi + \pi$$
$$\tau \rightarrow \pi + \pi + \pi$$

In the early ’50 bubble chamber pictures showed events of 2 and 3 prong decay in flight of a charged particle. The two mothers had the same mass and the same lifetime (in the experimental error). The puzzle was that the angular distribution of the decay product – studied by DALITZ with an innovative technique – was indicating that the parity of the two particles was different. So they could not be the same particle.

This striking contradiction, equal masses (better than 1%) and equal lifetimes (better than 10%) with a clear experimental evidence of opposite parity brought Yang and Lee to the bold hypothesis that parity was NON conserved in weak interaction and to inspire the famous ^{60}Co experiment

Gigi.Rolandi@cern.ch

Parity violation



Parity violation is MAXIMAL. In polarized W decay the muon has a distribution proportional to cos(theta) wrt to the spin direction. i.e. ¾ of the muons go forward and ¼ goes backward.

Gigi.Rolandi@cern.ch

Neutrino helicity

Helicity is the projection of he spin on the direction of motion. For massive particles this is not an invariant, however for mass-less particles are the neutrinos are (*) this is an invariant :

ALL NEUTRINOS ARE LEFT-HANDED AND ALL ANTINEUTRINOS ARE RIGHT HANDED.

The ALL is what makes parity maximally violated. No violation of parity would imply that 50% are right handed and 50% left handed

Measurement of neutrino helicity(1)

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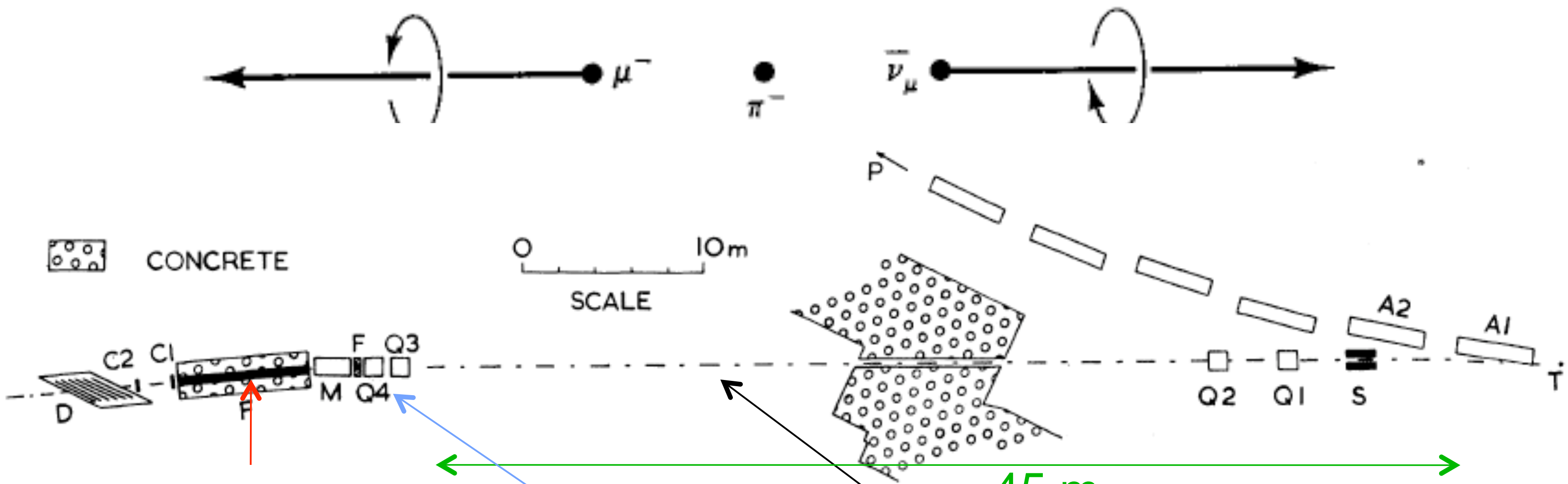


760 cm graphite filter

π^- beam 12.1±0.3 GeV

focusing system to select forward emitted muons

After the filter the pion contamination is 3 10^{-5} The muons have momentum of 11 GeV at the decay and of 8 GeV after the filter.

Calculated polarization at C2 ~ 85%

Gigi.Rolandi@cern.ch

Muon polarization(1)

In the pion rest system the muon has defined helicity. The distribution of the muons is also flat.

1) What is the muon polarization at a given angle ?
2) What is the muon polarization if I select a given angular range ?

The spin projection along the flight direction is cos(ϑ) and the distribution of events is flat in cos(ϑ),: the average projection of the component of spin along the flight direction in a given by

$$\frac{\int_1^x \cos\vartheta \cdot d\cos\vartheta}{\int_1^x d\cos\vartheta} = \frac{1}{2}(1+x)$$

Gigi.Rolandi@cern.ch

Muon Polarization (2)

A cut in momentum in the laboratory is equivalent to a cut in cosϑ the c.o.m. In the laboratory:

$$p_\mu \approx p_\pi \frac{m_\mu}{m_\pi}(1 + k\cos\vartheta)$$

$$\cos\vartheta_{cut} = \frac{1}{k}\left(\frac{p_{cut}}{p_{\max}} - 1\right) + \frac{p_{cut}}{p_{\max}}$$

$$k = \frac{30\,MeV}{m_\mu} \approx 0.3$$

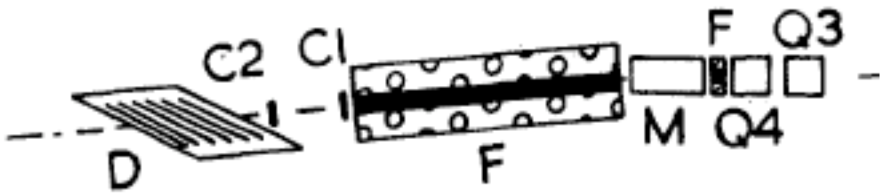
So the polarization of a given sample with momentum > p_{cut} is

$$\Pi = \frac{1}{2}\left(1 + \frac{1}{k}\left(\frac{p_{cut}}{p_{\max}} - 1\right) + \frac{p_{cut}}{p_{\max}}\right)$$

with p_{cut}/p_{max}=0.97 one gets 0.93

Gigi.Rolandi@cern.ch

Measurement of neutrino helicity(2)



The muons selected by the focusing system were scattering on an electron detector D

20 layers of magnetized iron and plastic scintillators at 30^0 wrt the beam. Magnetizing the iron one polarizes the electrons and the scattered electron produce a shower detected by absorption in the scintillator. The response in pulse height is proportional to energy. The linearity is tested on an electron beam. The scattering cross section is given by

$$\sigma(E, \vec{P}_e \cdot \vec{P}_\mu)dE = \frac{2\pi r_0^2 m_0 c^2}{\beta_\mu^2 E^2}\left\{1-\beta_\mu^2\left(\frac{E}{E_m}\right)+\frac{1}{2}\left(\frac{E}{E_\mu}\right)^2 - \vec{P}_e \cdot \vec{P}_\mu \frac{E}{E_\mu}\left(1-\frac{E}{E_m}+\frac{E}{2E_\mu}\right)\right\}dE, \quad (1)$$

E=electron energy
E_μ=muon energy
E_m= max electron energy

Gigi.Rolandi@cern.ch

Result

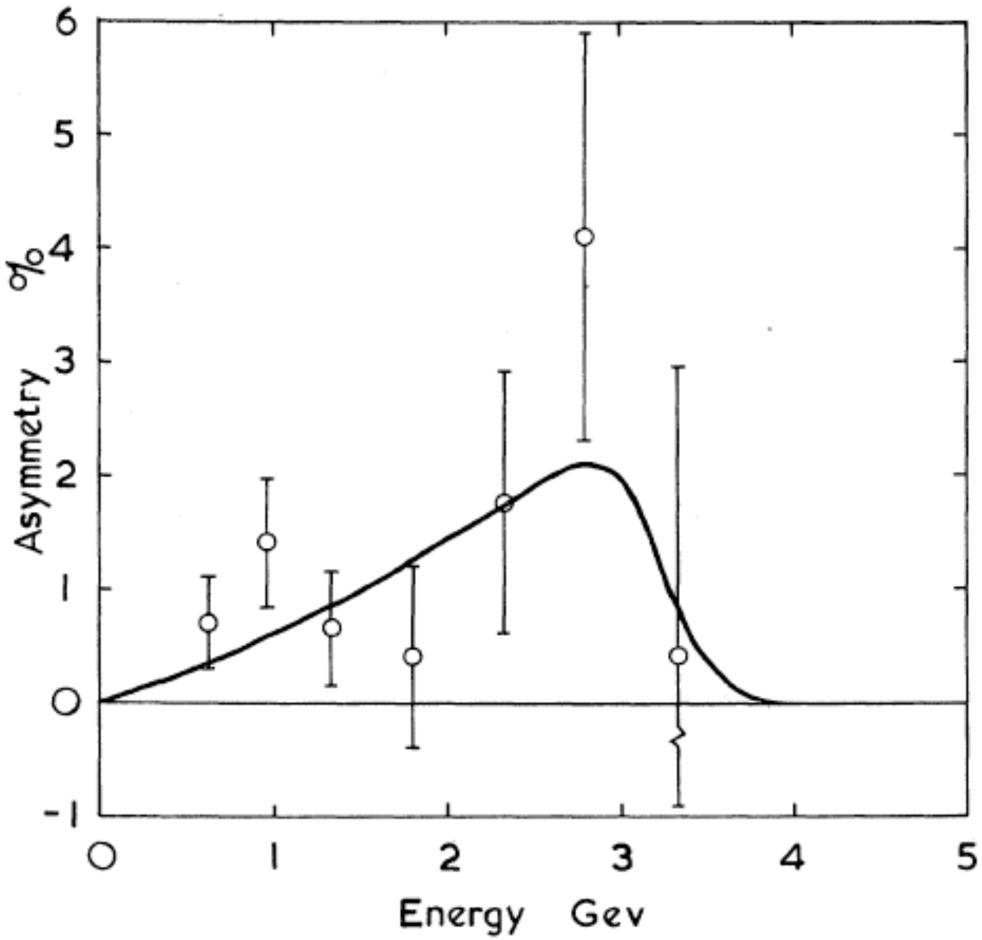


FIG 2. Asymmetry of shower production cross section, $(N_a - N_p)/(N_a + N_p)$, with magnetic field reversal vs shower energy.

Asymmetry measured inverting the iron polarization. The result is compatible to a muon helicity at decay of

$$\mathcal{H}(\mu) = +1.17 \pm 0.32 \text{ (standard deviation}$$

Gigi.Rolandi@cern.ch

Restoring the symmetry

Parity violation of the weak interaction stems from neutrino being only lefthanded. The symmetry can be restored if we introduce an operator that transforms particles in anti-particles. This is C, the charge conjugation. As parity $C^2=I$, so the eigenvalues are ±1, but differently from parity, most of the particles are not eigenstates.

The C of the photon is -1 since it is the quantum of the Electric field that changes sign under C.

A system containing a spin ½ particle and its antiparticle is an eigenstate of C with eigenvalue $(-1)^{l+s}$. This implies $C|\pi^0\rangle=|\pi^0\rangle$ and $C|J/\psi\rangle=-|J/\psi\rangle$.

Gigi.Rolandi@cern.ch

Properties of C

C is conserved in strong and electromagnetic interactions.

π^0 can decay to 2 γ, but not to 3γ.

Vector mesons cannot decay to 2γ, but can decay to 3γ.

Gluons are NOT eigeinstates of C, because they are color charged.

Gigi.Rolandi@cern.ch

Combining C and P

Thinking at parity violation as induced by neutrinos, it is obvious that if we apply a CP transformation to a reaction involving neutrinos we restore the symmetry. We restore also the belief that T invariance is a conserved symmetry. There is a theorem that says that CPT is a conserved quantity under vey general assumptions !

CP symmetry has important and bizarre consequences on the Kaon system since kaons are ground state mesons they are pseudoscalars

$$P|K^0\rangle = -|K^0\rangle, \qquad P|\bar{K}^0\rangle = -|\bar{K}^0\rangle$$

In addition they are the antiparticle of each other

$$C|K^0\rangle = |\bar{K}^0\rangle, \qquad C|\bar{K}^0\rangle = |K^0\rangle$$

then

$$CP|K^0\rangle = -|\bar{K}^0\rangle, \qquad CP|\bar{K}^0\rangle = -|K^0\rangle$$

Gigi.Rolandi@cern.ch

CP and neutral kaons

This means that they go one to the other under CP, so the eigenstates of CP are just a linear combination of the two particle and antiparticle states:

$$|K_1\rangle = (1/\sqrt{2})(|K^0\rangle - |\bar{K}^0\rangle) \quad \text{and} \quad |K_2\rangle = (1/\sqrt{2})(|K^0\rangle + |\bar{K}^0\rangle)$$

$$CP|K_1\rangle = |K_1\rangle \quad \text{and} \quad CP|K_2\rangle = -|K_2\rangle$$

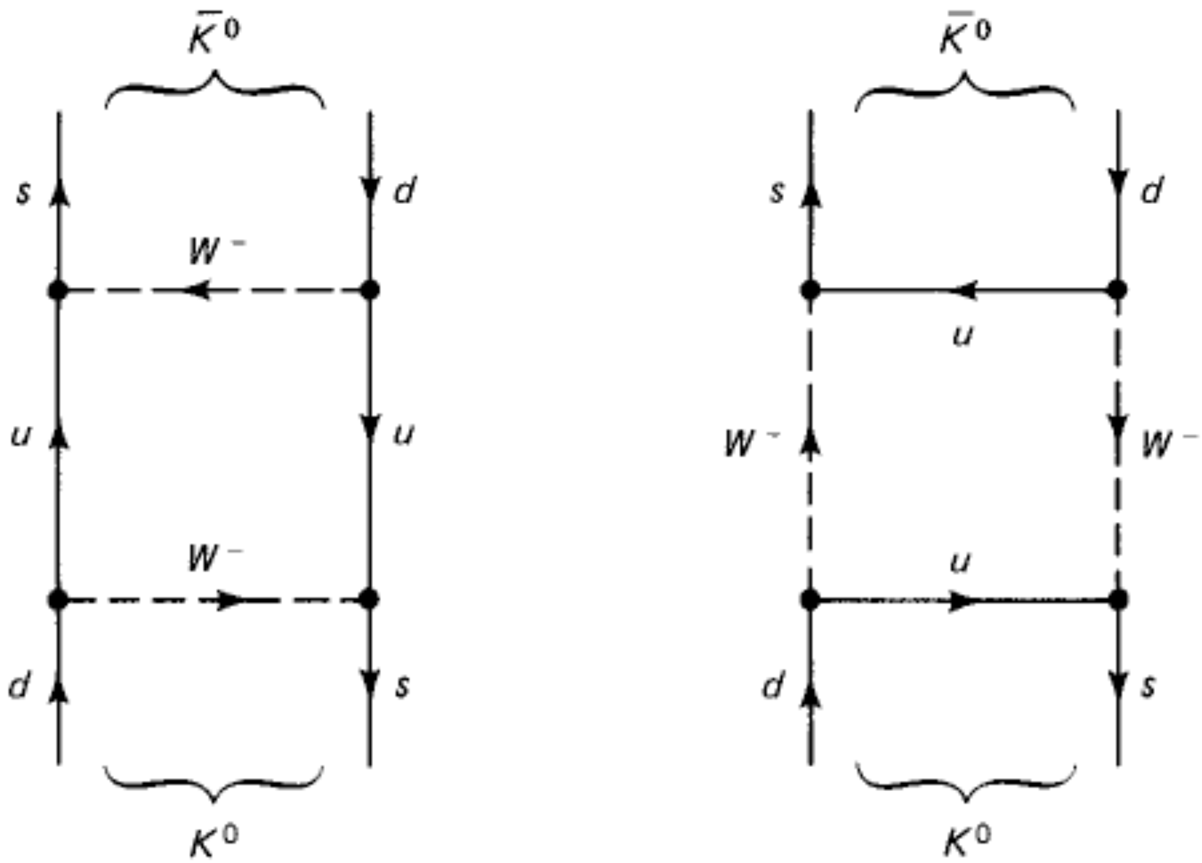
And these are the states that propagates in time: eigenstates of CP

Moreover since the CP of a 2 pions states is +1 and the CP of 3 pions state is -1 then

$$K_1 \to 2\pi, \qquad K_2 \to 3\pi$$

Kaon osclIations

Neutral kaons can oscillate one into the other via 2^{nd} order weak interaction (BOX diagram).



Gigi.Rolandi@cern.ch

Neutral Kaon beams

Since the Q value to decay to 2π is much larger than the q value to decay to 3 pions, it is expected that the lifetimes are drastically different:

$$\tau_1 = 0.89 \times 10^{-10} \text{ sec}$$
$$\tau_2 = 5.2 \times 10^{-8} \text{ sec}$$

the corresponding cτ are 3 cm and 15 m.

K_1 decay quickly and after few 10 cm there are only K_2.

If a K_2 beam interacts wit matter its' K^0-bar content will interact with matter more than its K^0 content and the outcoming beam will have again a K_1 component.

K_1 and K_2 are each its own antiparticle with C=-1 for K_1 C=+1 for K_2

Gigi.Rolandi@cern.ch

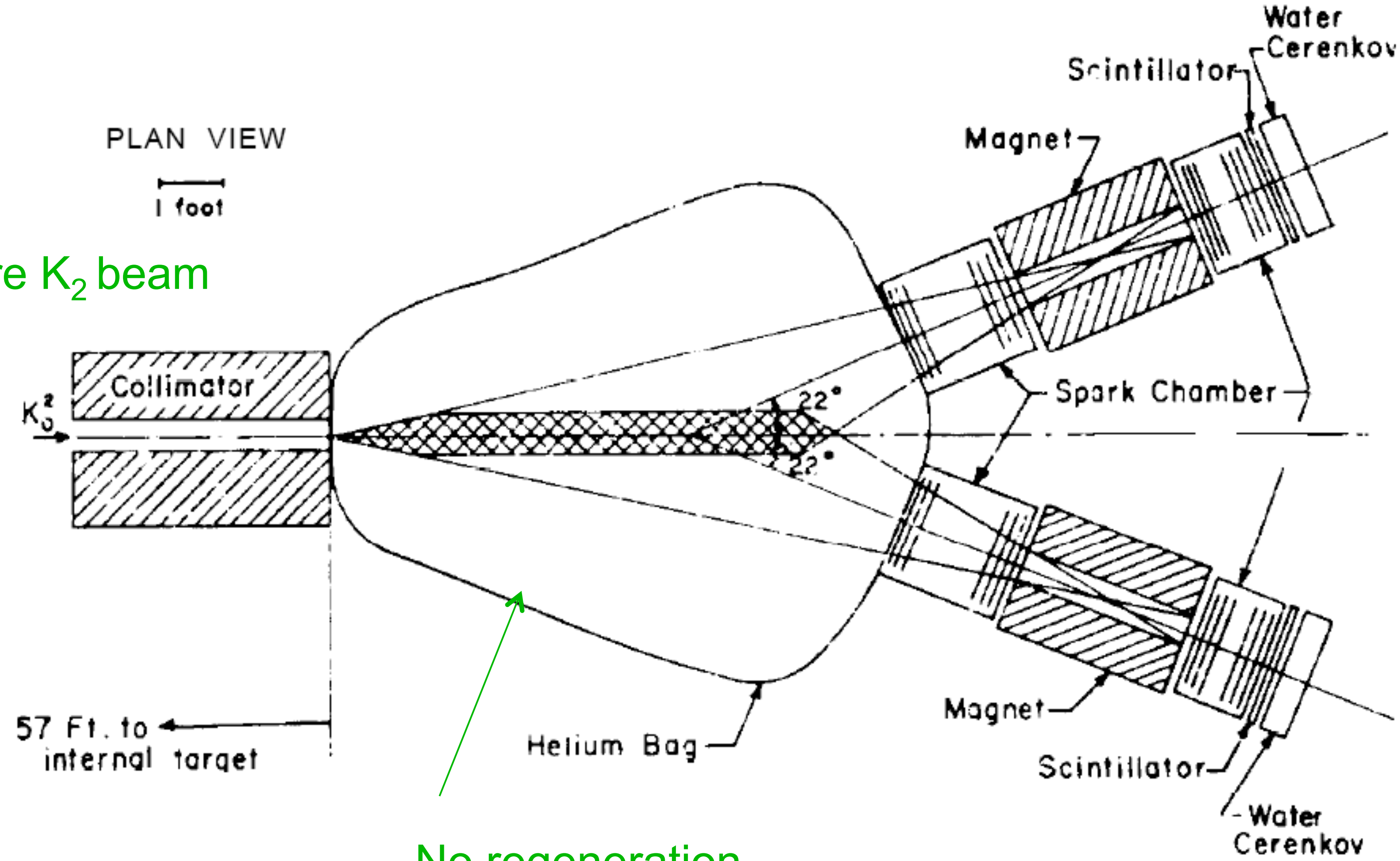
What is the particle ?

Kaons are produced in strong interactions in eigenstates of strangeness. They decay by weak interaction as eigenstates of CP. What is the particle ?

This has an analogy with polarized light: Circular polarization can be seen as superposition of two linear polarizations and vice-versa. When passing through a medium that absorbs preferentially one (linear or circular) polarization it's polarization will change as it passes through the medium. As K^0 beam turns into K_2 or back… The decision to analyze it in terms of linear of circular basis is just a question of taste.

Kronin and Fitch

pure K_2 beam

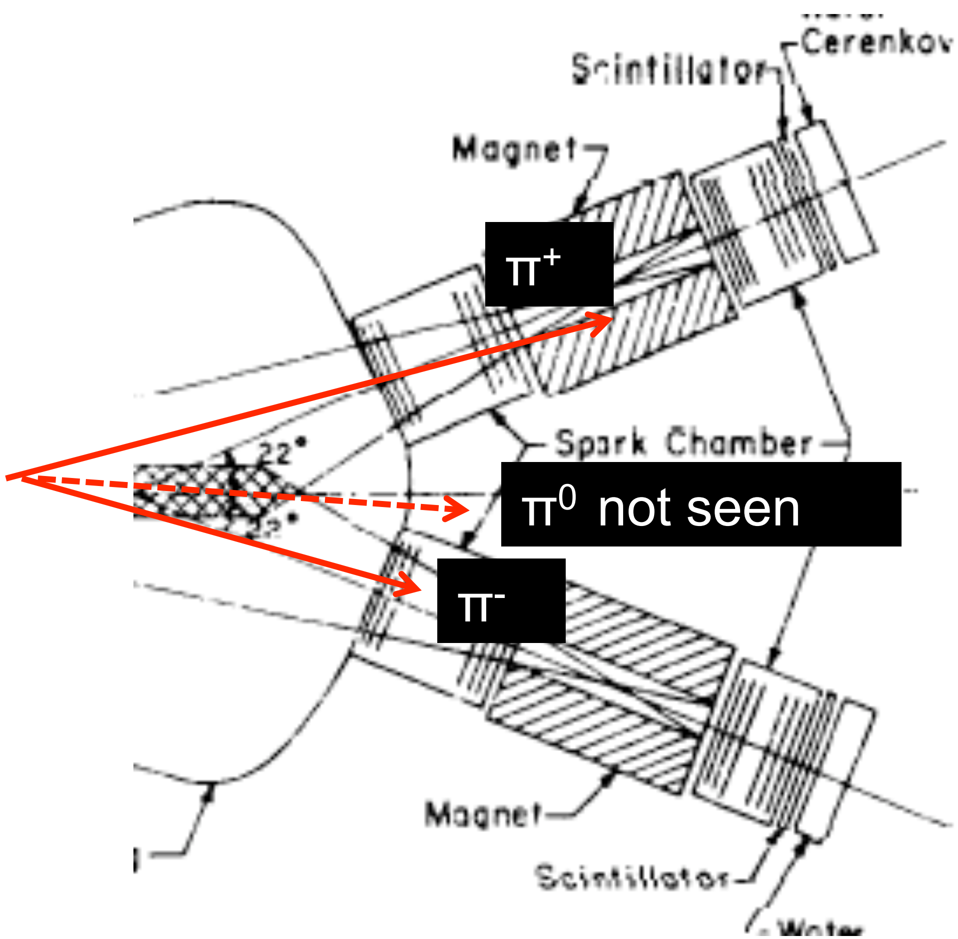


No regeneration

Gigi.Rolandi@cern.ch

Kronin and Fitch

In K_2 decays in 3 pions the two charged prongs do not point to the beam direction



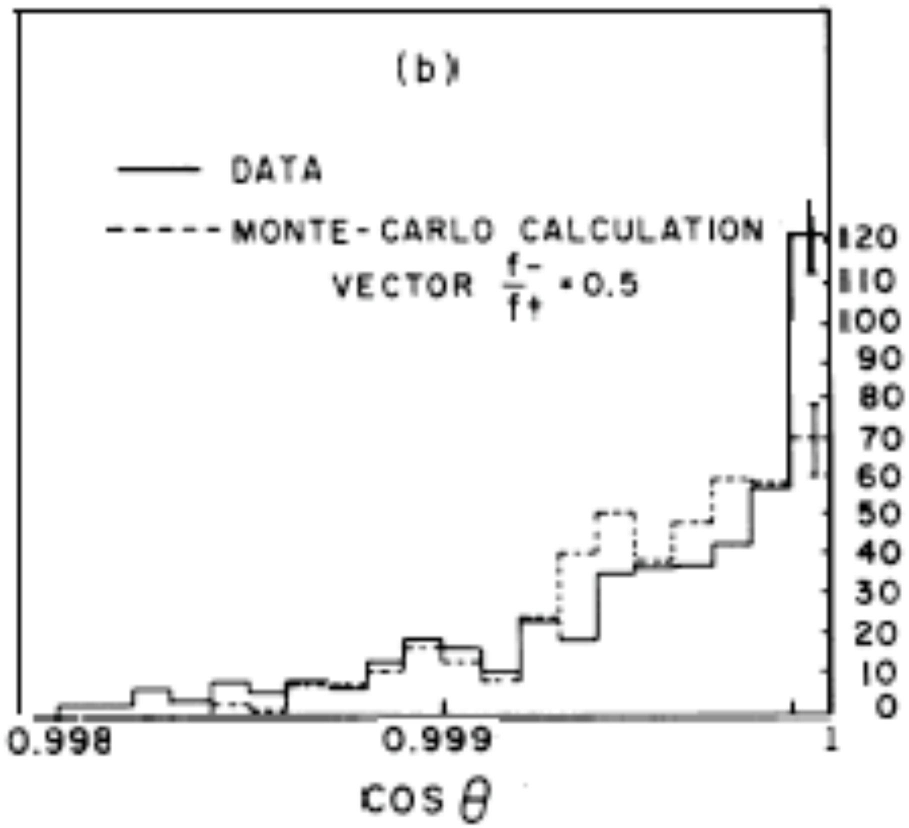
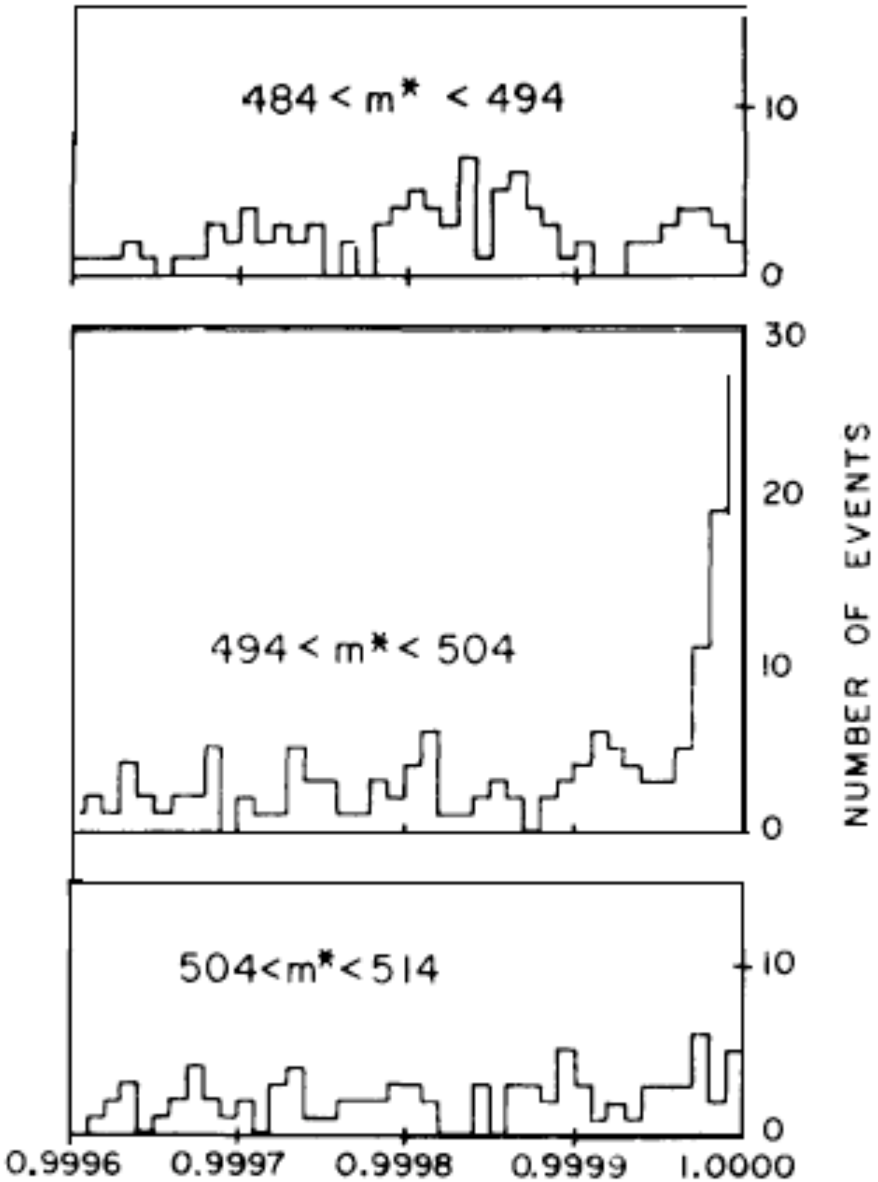


Fig. 2. Angular distributions of those events in the appropriate mass range as measured by a coarse measuring machine.

small excess of events where the sum of reconstructed momenta is in the beam direction

Gigi.Rolandi@cern.ch

The excess is correlated to kaon mass



Gigi.Rolandi@cern.ch

CP is not conserved

A small fraction 1/500 of K_2 decay in 2 π violating the CP conservation.

The K_L, the particle with long lifetime is not a pure eigenstate of CP, and contains a mixture of the two CP eigenstates

$$|K_L\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}\left(|K_2\rangle + \epsilon|K_1\rangle\right)$$

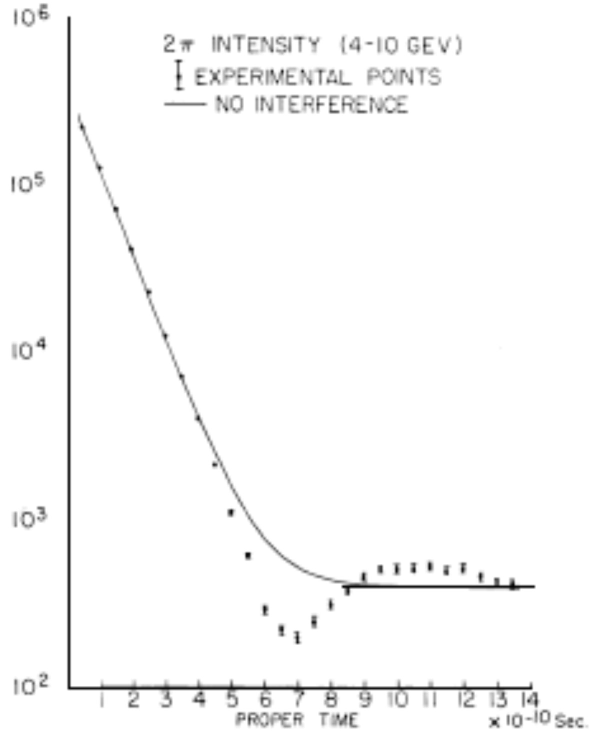


Fig. 2. Yield of $\pi^+\pi^-$ events as a function of proper time downstream from an 81 cm carbon regenerator placed in a K_L beam.

Gigi.Rolandi@cern.ch

Charge asymmetry in K_L decays

Some 40% of the K_L decay into e πν the two states are CP related. IF K_L were an eigentstate of CP then the decay rate into the two states has to be equal. Actually it is not.

$$\pi^+ + e^- + \bar{\nu}_e$$
$$\pi^- + e^+ + \nu_e$$

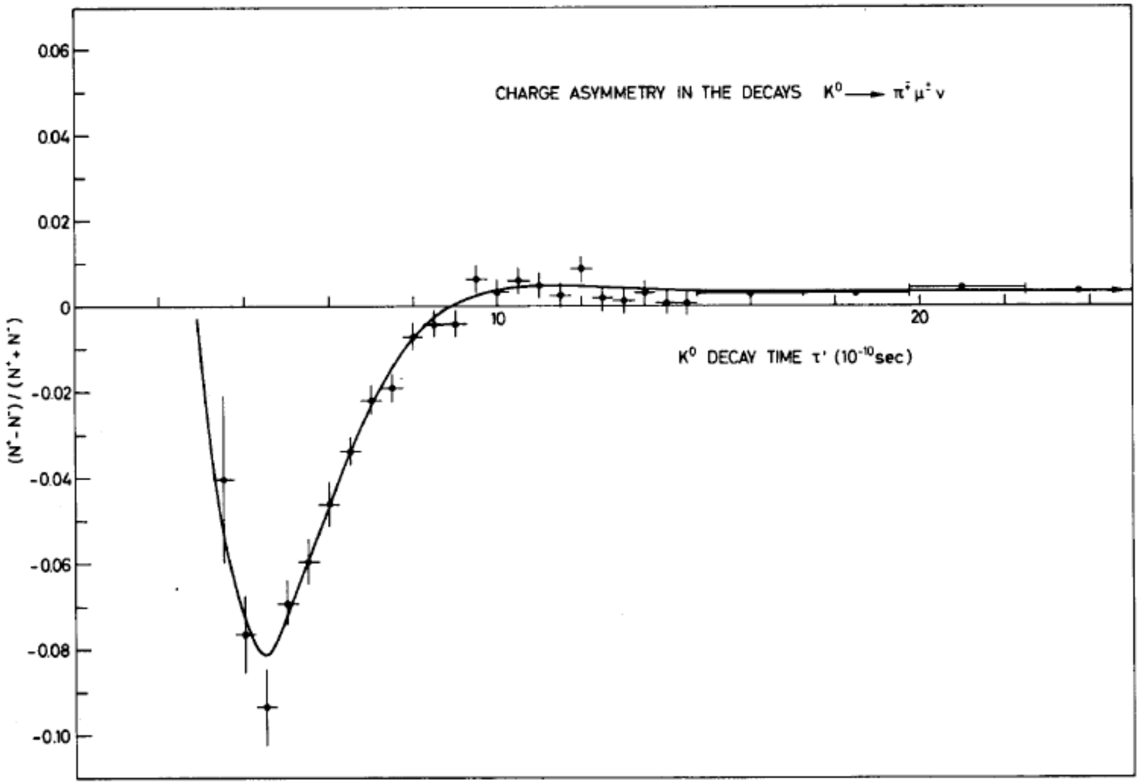
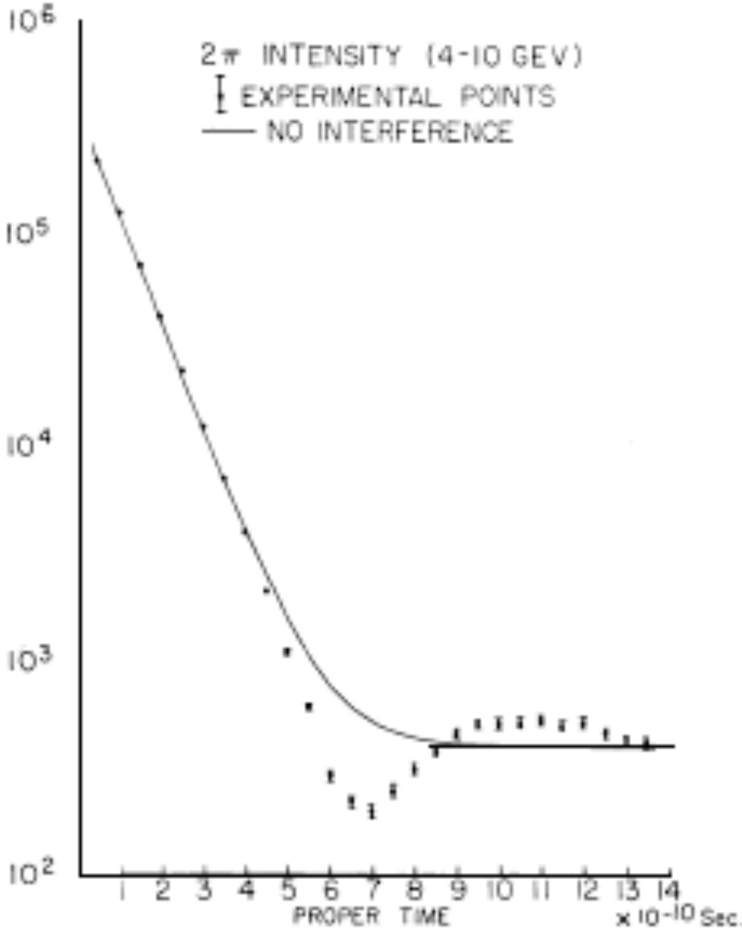


Fig. 2. The charge asymmetry as a function of the reconstructed decay time τ' for the $K_{\mu 3}$ decays. The experimental data are compared to the best fit as indicated by the solid line.

How do you tell the extra terrestrial if you are matter or anti-matter ?



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