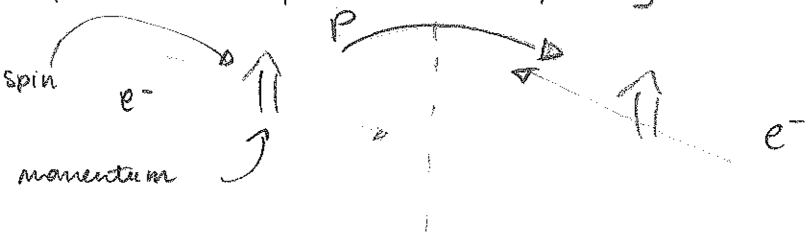
CP violation in neutral B^0 meson mixing

tentative plan

1. Neutral meson mixing
2. CP violation in B system
3. Measurement of a_{sl}^{d} (semileptonic asymmetry in $B^0-\overline{B^0}$ mixing) at LHCb

1) Discrete symmetries

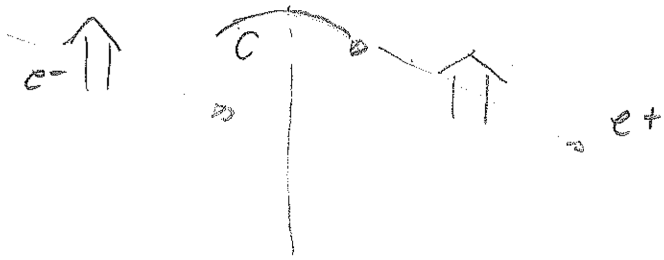
* space reflection or parity



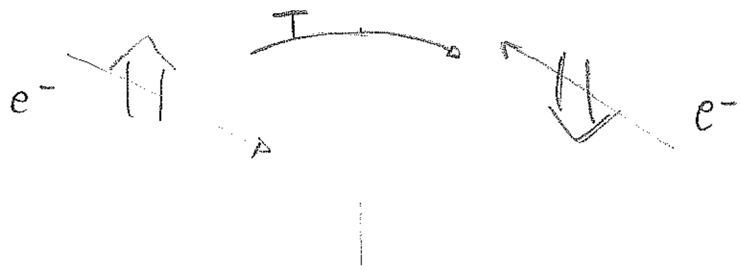
$$\vec{p} \rightarrow \vec{p}\,' = -\vec{p}$$
$$\vec{L} \rightarrow \vec{L}' = \vec{L}$$

Helicity $\lambda = \frac{\vec{J}\cdot\vec{p}}{|\vec{p}|}$ $\quad \lambda' = -\lambda$

* charge conjugation



* time reversal



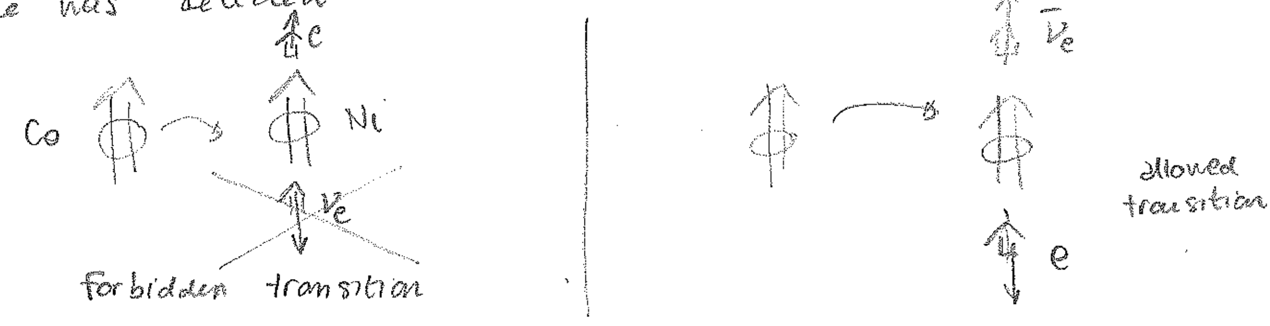
CPT needs to be conserved (to guarantee Lorentz invariance)

In <u>weak interactions</u> :

- P is maximally violated, since SU(2) couples only to left-chiral fields

Wu experiment exploiting β decays: ${}^{60}_{27}Co \longrightarrow {}^{60}_{28}Ni + e^- + \overline{\nu_e}$

By inverting the magnetic field direction (and therefore the polarization of the cobalt nucleus, a difference in counting rate was detected



Analogous example: the muon decays in air FP13 lab course

- C is also maximally violated in weak interactions

$$C\,|\nu(\lambda=-1/2)\rangle = |\bar{\nu}(\lambda=-1/2)\rangle \text{ does not exist}$$

For example, when considering neutrinos

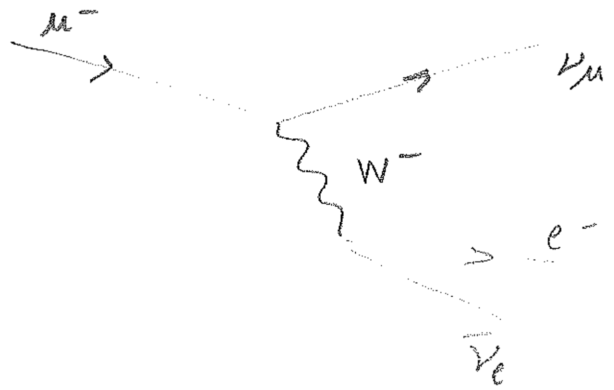
What about CP?

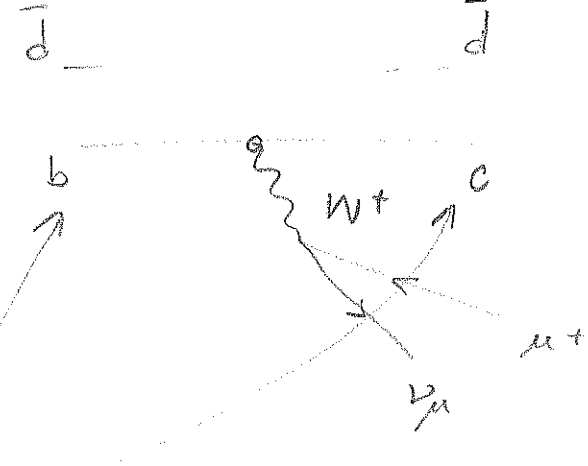
2) quarks and charged weak current interactions

3 generations of fundamental particles:

$$\begin{array}{lcccc} & \mathrm{I} & \mathrm{II} & \mathrm{III} & Q\,[e] \\ \text{quarks} & \begin{pmatrix} u \\ d \end{pmatrix} & \begin{pmatrix} c \\ s \end{pmatrix} & \begin{pmatrix} t \\ b \end{pmatrix} & \begin{pmatrix} +2/3 \\ -1/3 \end{pmatrix} \\ \hline \text{leptons} & \begin{pmatrix} \nu_e \\ e \end{pmatrix} & \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} & \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} & \begin{pmatrix} 0 \\ 1 \end{pmatrix} \end{array}$$

Examples of charged current interactions





Quarks can change flavor through these processes

SM Lagrangian: $\mathcal{L}_{SM} = \mathcal{L}_{kin} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa}$

$$-\mathcal{L}_{Yukawa} = Y_{ij}\,(\underbrace{\psi_{L_i}\ \phi}_{\text{doublets (Left handed)}})\ \psi_{R_i} + h.c.$$

singlet (Right handed)

For the charge current interactions $\mathcal{L}_{cc}$:

$$-\mathcal{L}_{cc} = \frac{g}{\sqrt{2}} \overline{U^I_L} \gamma^\mu W_\mu D^I_L$$ in the interaction eigenstate basis

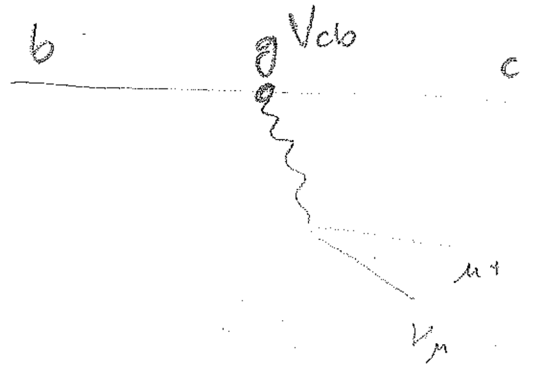
$+ \dots$

$$= \frac{g}{\sqrt{2}} (\bar{u}, \bar{c}, \bar{t})_L \left(V_{CKM} \right) \begin{pmatrix} d \\ s \\ b \end{pmatrix} \gamma^\mu W_\mu$$ using the mass eigenstates.

CKM matrix:

$1-\frac{1}{2}\lambda^2$ $\quad \lambda \quad$ $A\lambda^3(\rho - i\eta)$ $\quad A\lambda^2$

$$\begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} \boxed{V_{ud}} & \square & \square \\ \square & \boxed{V_{cs}} & \square \\ \square & \square & \boxed{V_{tb}} \end{pmatrix} \end{array}$$

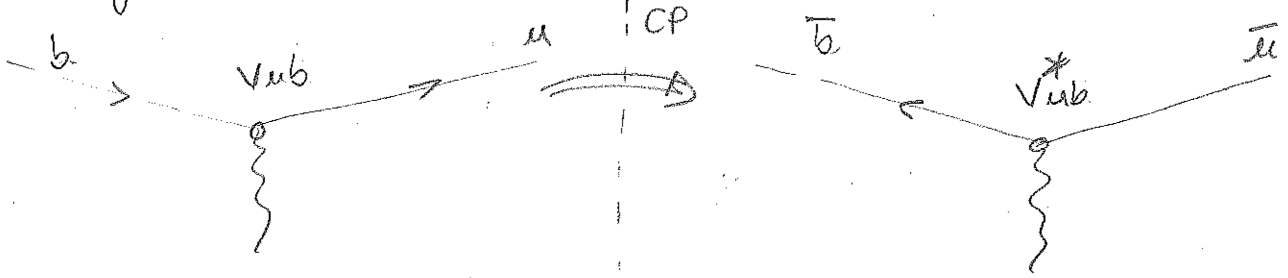


different parametrization used. The drawn matrix shows the size of the different elements (as the values reported in terms of λ, Wolfenstein parameter)

Properties: The CKM matrix is complex and unitary.

4 free parameters with 3 generations: 3 angles and 1 phase

Meaning of the phase:



Zero phase ($V_{ij} = V_{ij}^*$) means CP conservation in weak interactions

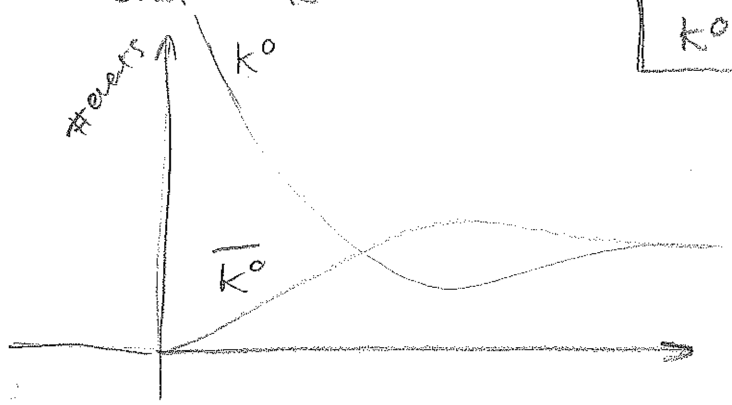
Unitarity condition: unique constraint from SM

CP thought to be conserved in weak interactions until 1964: CP violation observed in neutral $K^0 - \overline{K^0}$ oscillations

3) Neutral mesons oscillations

* Experimentally : Starting from a beam of pure K^0, after some time the beam contains a mixture of K^0 and $\overline{K^0}$ mesons.

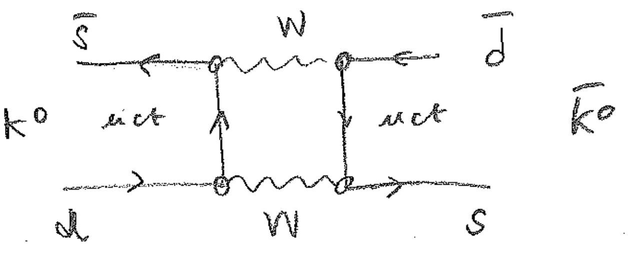
$$\boxed{K^0 = d\bar{s} \qquad \overline{K^0} = \bar{d}s}$$

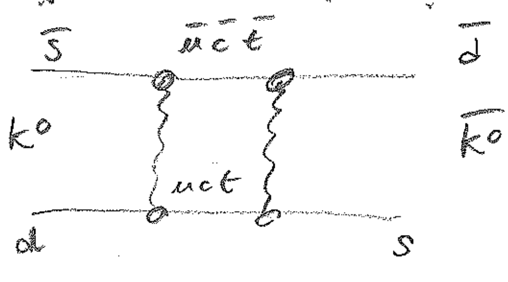


* Formalism used : effective formalism to describe the meson system. $|P\rangle$ and $|\overline{P}\rangle$ are the flavor eigenstates of the 2-state system (valid for kaons, B and D mesons. The time evolution is described by the differential equation :

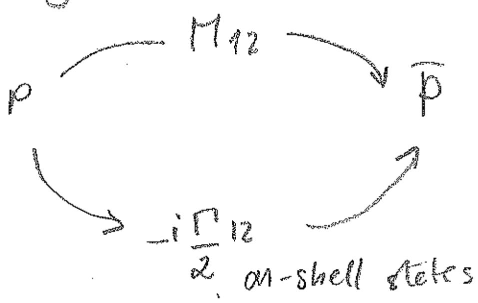
$$i\frac{\partial}{\partial t}\begin{pmatrix}|P\rangle\\|\overline{P}\rangle\end{pmatrix} = \underbrace{\left(M - i\frac{\Gamma}{2}\right)}_{H_{eff}}\begin{pmatrix}|P\rangle\\|\overline{P}\rangle\end{pmatrix}$$

M_{12} and Γ_{12} describe the different ways for the $P \to \overline{P}$ transition. M_{12} accounts for the short distance contributions, i.e. the following box diagrams :





Γ_{12} accounts for the contributions from virtual intermediate decays to a state f :



(2π dominat for kaons)

$$P \to \overset{2\pi}{\underset{3\pi}{f}} \to \overline{P}$$

Diagonalizing the Hamiltonian, we find the mass eigenstates, superpositions of the flavor eigenstates

$$|P_L\rangle = p\,|P\rangle + q\,|\bar{P}\rangle$$
$$|P_H\rangle = p\,|P\rangle - q\,|\bar{P}\rangle$$

We can now calculate the probability of having a $\overline{K^0}$ at the time t, given a beam of K^0_s at $t=0$

$$|P\rangle = \frac{1}{2p}\left[|P_H\rangle + |P_L\rangle\right] \; ; \quad |\bar{P}\rangle = \frac{1}{2q}\left[|P_H\rangle - |P_L\rangle\right]$$

and the usual evolution from the mass eigenstates:

$$|P_H(t)\rangle = e^{-im_H t - \frac{1}{2}\Gamma_H t}\,|P_H(0)\rangle$$
$$|P_L(t)\rangle = e^{-im_L t - \frac{1}{2}\Gamma_L t}\,|P_L(0)\rangle$$

$$|P(t)\rangle = \frac{1}{2}\left(e^{-im_H t - \frac{1}{2}\Gamma_H t} + e^{-im_L t - \frac{1}{2}\Gamma_L t}\right)|P\rangle + \frac{1}{2}\frac{q}{p}\left(e^{-im_H t - \frac{1}{2}\Gamma_H t} - e^{-im_L t - \frac{1}{2}\Gamma_L t}\right)|\bar{P}\rangle$$

$|\bar{P}(t)\rangle = \ldots$ similarly

We can define $\Delta m = m_H - m_L$

$\Delta\Gamma = \Gamma_L - \Gamma_H$ difference of decay widths

$$|\langle\bar{P}|P(t)\rangle|^2 = \frac{e^{-\Gamma t}}{2}\left(\cosh\left(\frac{\Delta\Gamma t}{2}\right) - \cos(\Delta m t)\right)\left|\frac{q}{p}\right|^2$$

$$|\langle P|\bar{P}(t)\rangle|^2 = \frac{e^{-\Gamma t}}{2}\left(\cosh\left(\frac{\Delta\Gamma t}{2}\right) + \cos(\Delta m t)\right)\left|\frac{p}{q}\right|^2$$

Note: in case of CP conservation:

for instance: $p = q = 1$

$$|P_+\rangle = |P\rangle - |\bar{P}\rangle$$
$$|P_-\rangle = |P\rangle + |P\rangle$$

$$CP|P_+\rangle = -|\bar{P}\rangle + |P\rangle = +1\,|P_+\rangle$$
$$CP|P_-\rangle = -|\bar{P}\rangle - |P\rangle = -1\,|P_-\rangle$$

4) CP violation in kaon mixing

Assuming CP conservation:

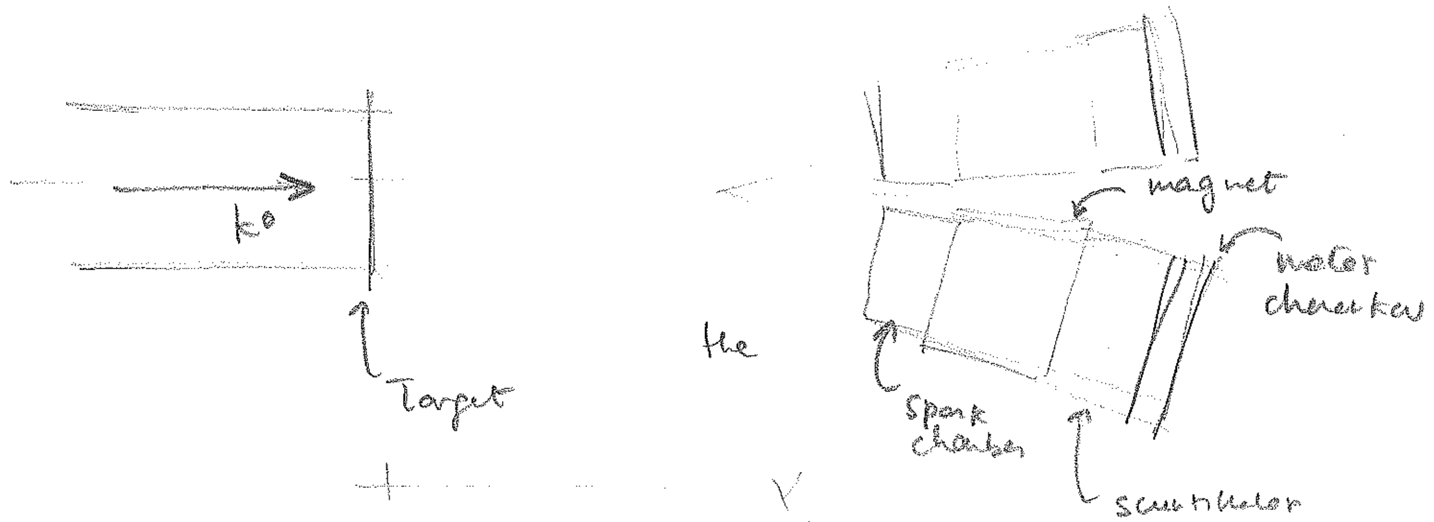
$$|K_S\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\bar{K}^0\rangle\right) \qquad CP|K_S\rangle = +1\,|K_S\rangle$$
CP even

$$|K_L\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\bar{K}^0\rangle\right) \qquad CP|K_L\rangle = -1\,|K_L\rangle$$
CP odd

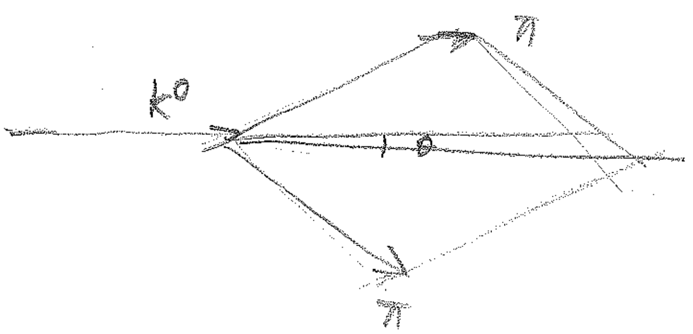
$|\pi\pi\rangle$ CP even, $|\pi\pi\pi\rangle$ CP odd

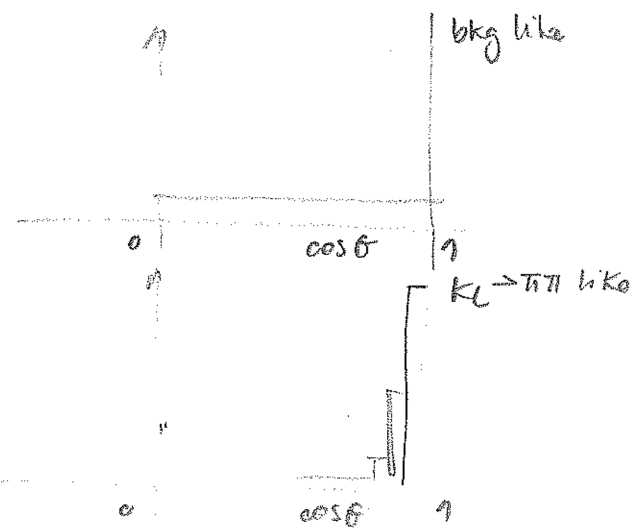
$\Rightarrow$ in a ONLY K_L beam, we expect only $\pi\pi\pi$ final states.

Cronin-Fitch experiment:



analysis detail:





Result:

$$\frac{\Gamma(K_L^0 \to \pi^+\pi^-)}{\Gamma(K_L^0 \to \text{all other charged mode})} = (2.0 \pm 0.4)\cdot 10^{-3}$$

Formally introduced ε: Mass eigenstates are <u>almost</u> CP eigenstates:

$$|K_L\rangle = \frac{1}{\sqrt{1+|\varepsilon|^2}}\left(|K_-\rangle + \varepsilon\,|K_+\rangle\right)$$

$$|K_S\rangle = \frac{1}{\sqrt{1+|\varepsilon|^2}}\left(|K_+\rangle - \varepsilon\,|K_-\rangle\right)$$

which is equivalent to say $|q/p| \neq 1$.

$|q/p| = |(1-\varepsilon)/(1+\varepsilon)|$. (approximation)

Another experimental footnote: <u>Regeneration</u>.
(example of effect competing with CPV)

K^0 and $\overline{K^0}$ are absorbed differently from the material:
process $\overline{K^0} + n \longrightarrow \Lambda + \pi^0$ (Λ strange baryon)
possible only for $\overline{K^0}$

$$|K_L\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\overline{K^0}\rangle\right)$$

In Cronin experiment the effect of the material interaction needed to be studied: The Helium was replaced by liquid hydrogen (enhancement expected ×10, found ~0.2)