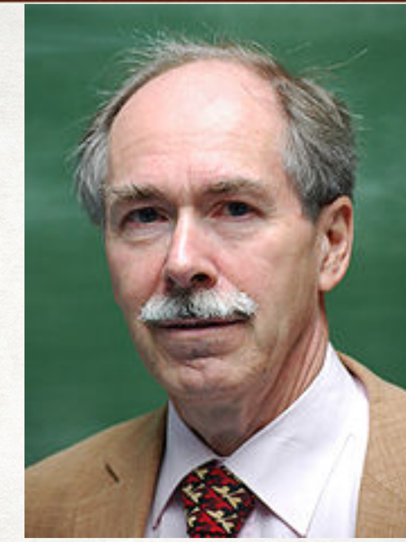
FISICA DE LAS INTERACCIONES FUNDAMENTALES

1ER CUATRIMESTRE 2026

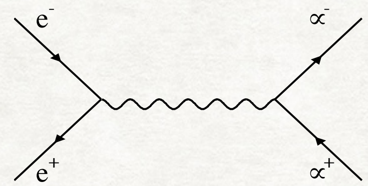
CLASE 18

RODOLFO SASSOT

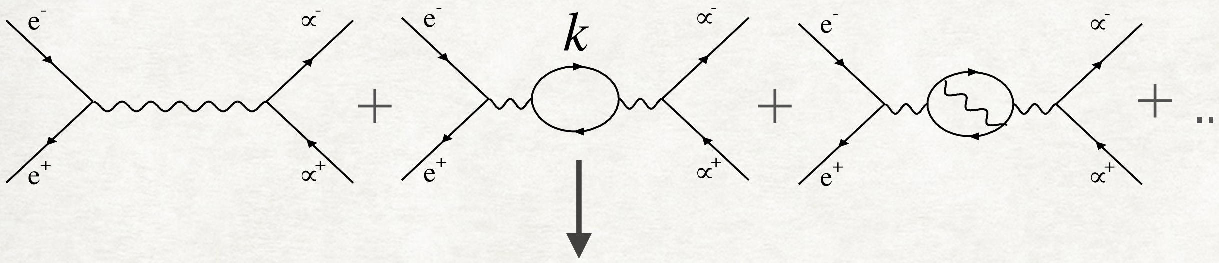
CLASE 18: Generación de masas en la teoría electrodébil.


G. 't Hooft

renormalizabilidad:

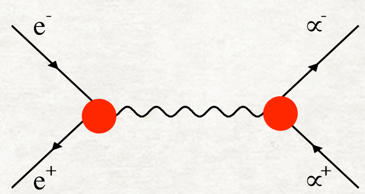


$$\sigma = \frac{4\pi}{3s}\alpha_0^2 \qquad s = (p_{e^-} + p_{e^+})^2$$

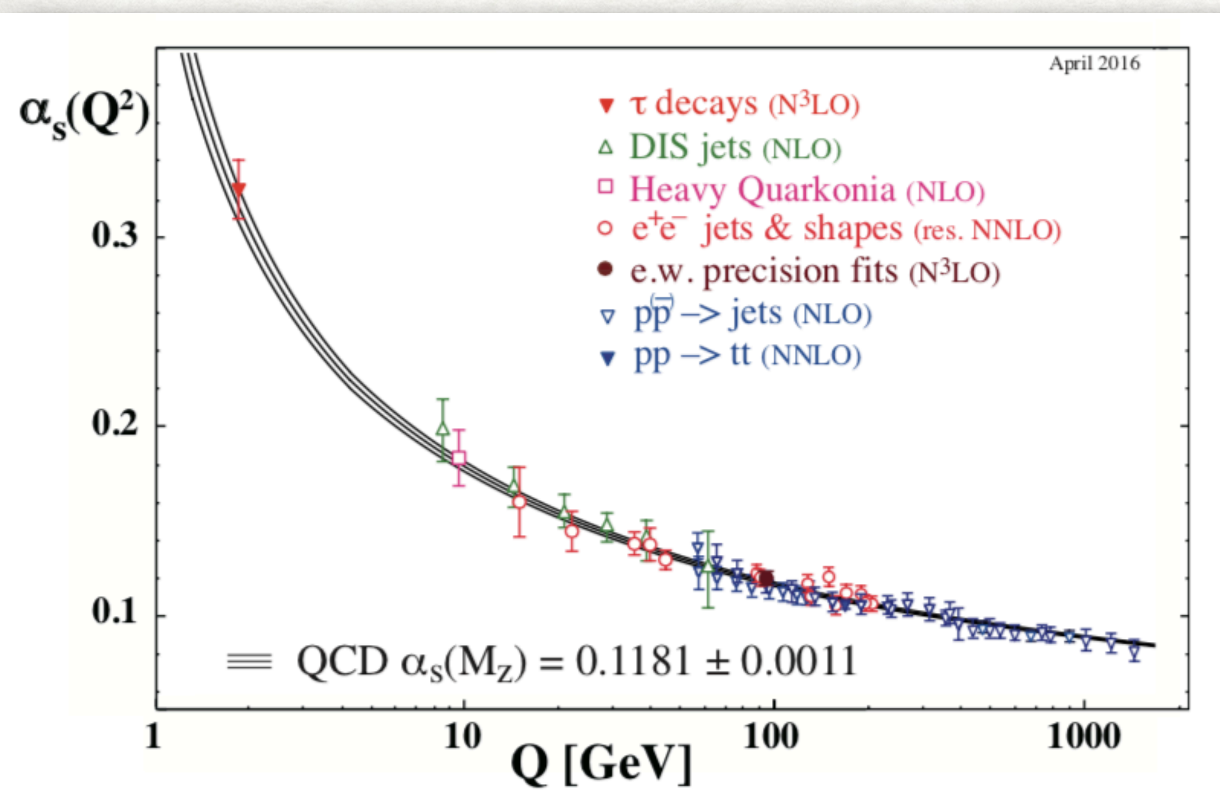


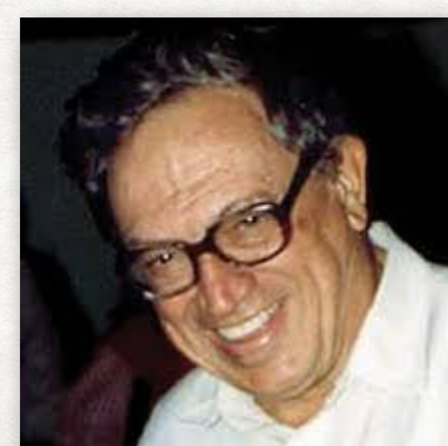
$$\sigma = \frac{4\pi}{3s}\alpha_0^2(1 + \alpha_0\sigma^{(1)}(s) + \alpha_0^2\sigma^{(2)}(s) + \ldots)$$

$$\int \frac{d^4k}{(2\pi)^4}\frac{1}{(k^2+m^2)^2}$$



$$\sigma = \frac{4\pi}{3s}\alpha_{\text{eff}}^2(s)$$



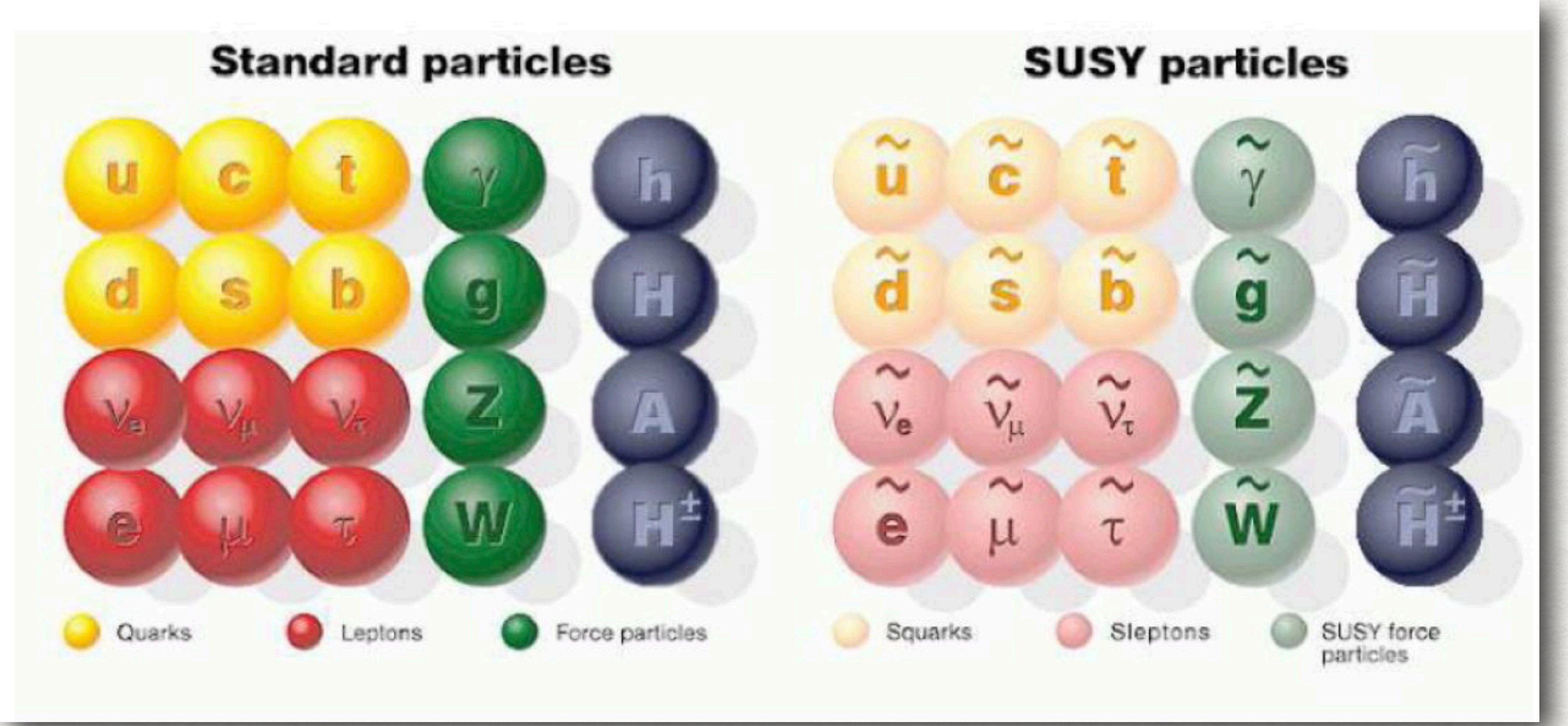


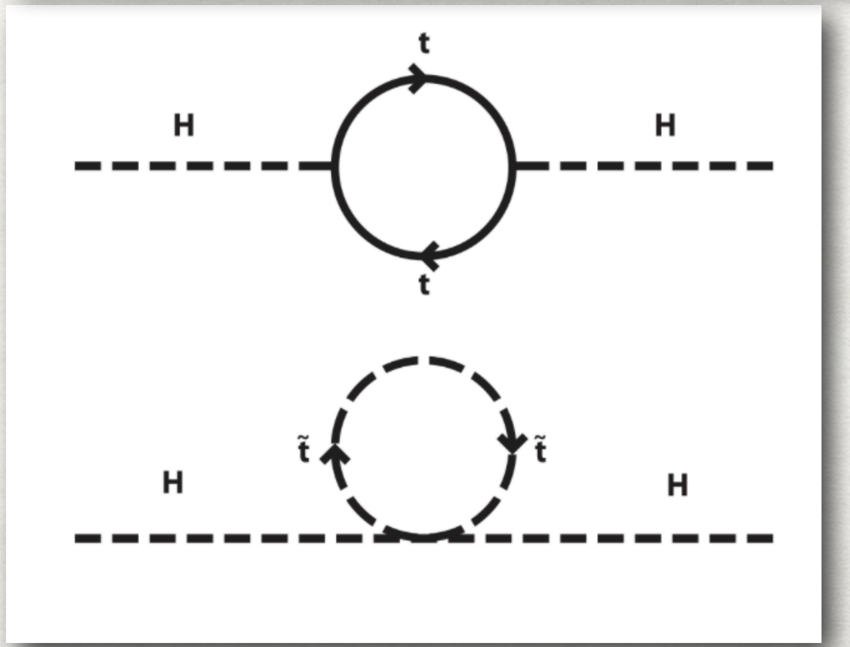
J.J. Giambiaggi G. Bollini

CLASE 18: Generación de masas en la teoría electrodébil.

Supersimetria:

cuantización (clase 11): spin semi-entero = fermiones





CLASE 18: Masas de quarks y de neutrinos

$$\mathscr{L}_4 = -G_e \left[(\overline{\nu}_e, \overline{e})_L \, \Phi \, e_R + \overline{e}_R \overline{\Phi} \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \right] \qquad \Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

$$= -\underbrace{\frac{G_e}{\sqrt{2}}}_{m_e} v \underbrace{(\overline{e}_L e_R + \overline{e}_R e_L)}_{\overline{\psi_e}\psi_e} - \frac{G_e}{\sqrt{2}} h (\overline{e}_L e_R + \overline{e}_R e_L) \qquad m_\nu = 0$$

$$\mathscr{L}_5 = -G_d \left[\left(\overline{u}, \overline{d}'\right)_L \Phi \, d_R + \overline{d}_R \overline{\Phi} \begin{pmatrix} u \\ d' \end{pmatrix}_L \right] - G_u \left[\left(\overline{u}, \overline{d}'\right)_L \tilde{\Phi} \, u_R + \overline{u}_R \overline{\tilde{\Phi}} \begin{pmatrix} u \\ d' \end{pmatrix}_L \right]$$

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \qquad \tilde{\Phi} = \frac{1}{\sqrt{2}} \begin{pmatrix} -\overline{\phi^0} \\ \phi^- \end{pmatrix} = \frac{-1}{\sqrt{2}} \begin{pmatrix} v + h(x) \\ 0 \end{pmatrix}$$

CLASE 18: Masas de quarks y de neutrinos

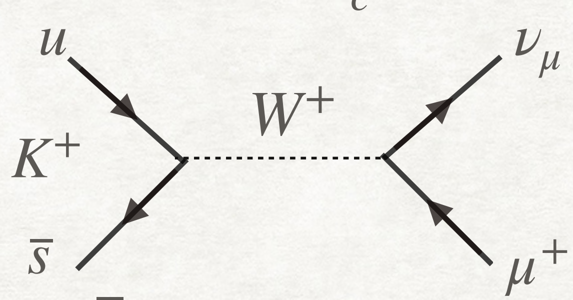
mecanismo de ruptura espontánea debería generar masas para los quarks físicos!

(y no para los autoestados débiles d', s', b')

de la clase 14

$$\begin{pmatrix}\nu_e \\ e^-\end{pmatrix}\begin{pmatrix}\nu_\mu \\ \mu^-\end{pmatrix}\begin{pmatrix}\nu_\tau \\ \tau^-\end{pmatrix}\begin{pmatrix}u \\ d\end{pmatrix}\begin{pmatrix}c \\ s\end{pmatrix}\begin{pmatrix}t \\ b\end{pmatrix}$$

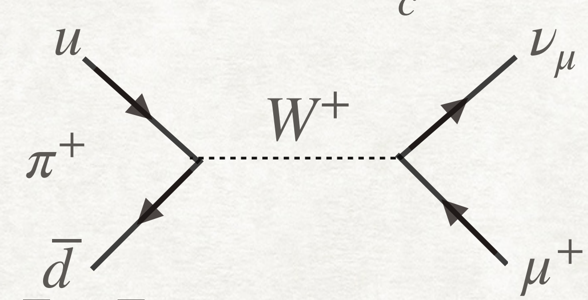
$\sim \sin\theta_c$



$\bar{s} = \bar{d}' \sin\theta_c + \bar{s}' \cos\theta_c$

$\ll$

$\sim \cos\theta_c$



$\bar{d} = \bar{d}' \cos\theta_c - \bar{s}' \sin\theta_c$

Cabibbo Kobayashi Maskawa

$$\begin{pmatrix}u \\ d'\end{pmatrix}\begin{pmatrix}c \\ s'\end{pmatrix}\begin{pmatrix}t \\ b'\end{pmatrix} \qquad \begin{cases} d' \equiv d\cos\theta_c + s\sin\theta_c \\ s' \equiv -d\sin\theta_c + s\cos\theta_c \end{cases} \qquad \begin{cases} d \equiv d'\cos\theta_c - s'\sin\theta_c \\ s \equiv d'\sin\theta_c + s'\cos\theta_c \end{cases}$$

$\theta_c \simeq 13^o$

$\sin^2\theta_c \simeq 0.05$

$$\begin{pmatrix}d' \\ s' \\ b'\end{pmatrix} = \begin{pmatrix}U_{dd} & U_{ds} & U_{db} \\ U_{sd} & U_{ss} & U_{sb} \\ U_{bd} & U_{bs} & U_{bb}\end{pmatrix}\begin{pmatrix}d \\ s \\ b\end{pmatrix}$$

$$m_d = 4.7\ ^{+0.5}_{-0.3}\, MeV$$

$$m_s = 95\ ^{+9}_{-6}\, MeV$$

$$m_b = 4180\ ^{+40}_{-30}\, MeV$$

CLASE 18: Masas de quarks y de neutrinos

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} U_{dd} & U_{ds} & U_{db} \\ U_{sd} & U_{ss} & U_{sb} \\ U_{bd} & U_{bs} & U_{bb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$m_d = 4.7 \,{}^{+0.5}_{-0.3}\, MeV$$
$$m_s = 95 \,{}^{+9}_{-6}\, MeV$$
$$m_b = 4180 \,{}^{+40}_{-30}\, MeV$$

$$d'_1 \equiv d' = U_{dd}\, d + U_{ds}\, s + U_{db}\, b \qquad d'_i = \sum_{j=1}^{3} U_{ij}\, d_j$$
$$d'_2 \equiv s'$$
$$d'_3 \equiv b'$$

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \qquad \tilde{\Phi} = \frac{1}{\sqrt{2}}\begin{pmatrix} \overline{\phi^0} \\ \phi^- \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} v + h(x) \\ 0 \end{pmatrix}$$

$$\mathscr{L}_4 = -G_e \left[(\overline{\nu}_e, \overline{e})_L\, \Phi\, e_R + \overline{e}_R \overline{\Phi} \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \right] = -\frac{G_e}{\sqrt{2}}\, v\, (\overline{e}_L e_R + \overline{e}_R e_L) - \frac{G_e}{\sqrt{2}}\, h\, (\overline{e}_L e_R + \overline{e}_R e_L)$$

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \longrightarrow \begin{pmatrix} u \\ d' \end{pmatrix}$$

$$\mathscr{L}_5 = \underbrace{-G_d^{ij}\left[(\overline{u}_i, \overline{d}'_i)_L\, \Phi\, d_R^j + \overline{d}_R^j \overline{\Phi} \begin{pmatrix} u_i \\ d'_i \end{pmatrix}_L \right]}_{genera\ masas\ para\ d',\, s',\, b'} \underbrace{- G_u^{ij}\left[(\overline{u}_i, \overline{d}'_i)_L\, \tilde{\Phi}\, u_R^j + \overline{u}_R^j \overline{\tilde{\Phi}} \begin{pmatrix} u_i \\ d'_i \end{pmatrix}_L \right]}_{genera\ masas\ para\ u,\, c,\, t}$$

$$v\, G_d^{ij}\, \overline{d}'^i_L\, d_R^j = \underbrace{v\, G_d^{ij}\, U^\dagger_{ik}}_{m_i \delta_{kj}} \overline{d}^k_L\, d_R^j$$

$$\sim -m_d^i\, \overline{d}_i\, d_i \left(1 + \frac{h}{v}\right) - m_d^i\, \overline{u}_i\, u_i \left(1 + \frac{h}{v}\right)$$

CLASE 18: Masas de quarks y de neutrinos

$(\nu_e, \nu_\mu, \nu_\tau)_L$ son autoestados débiles, qué pasa si se generaran masas a (ν_1, ν_2, ν_3)?

$\Longrightarrow$ consecuencias medibles: $\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$ interacción con h

oscilaciones cuánticas $|\Psi(t) > = e^{-i/\hbar E_1 t}|\phi_1 > + e^{-i/\hbar E_2 t}|\phi_2 > + \ldots$

(R. Davies M. Koshiba Nobel 2002, A. McDonald T. Kajita 2015)

CLASE 18: Masas de quarks y de neutrinos

el problema de los neutrinos solares (~1968)

$$4p \longrightarrow {}^4He + 2e^+ + 2\nu_e \qquad \phi_{\nu_e} \sim 10^{11}\,\frac{\nu_e}{cm^2\,s}$$

1964 R. Davies, J. Bahcall

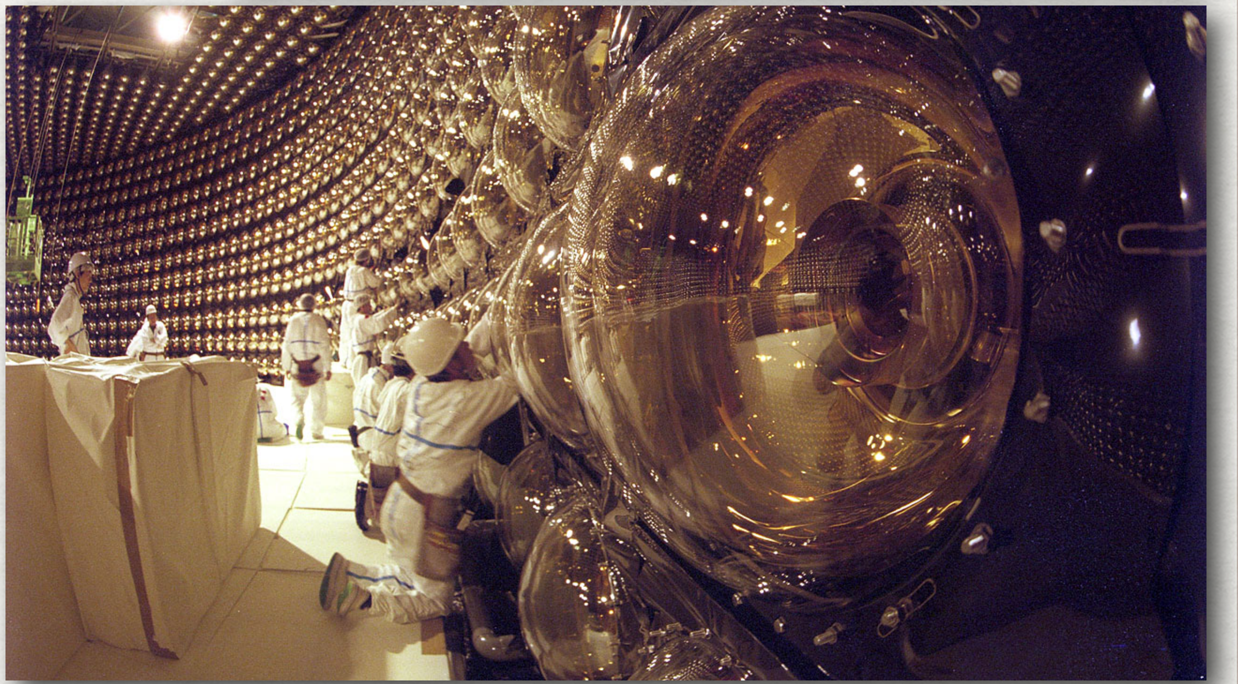
40.000 l ^{37}Cl

$$\nu_e + {}^{37}Cl \longrightarrow {}^{37}Ar + e^-$$

1968 $\sim 1/3$ 'deficit'

1989 Kamiokande

3.000.000 l H_2O



CLASE 18: Masas de quarks y de neutrinos

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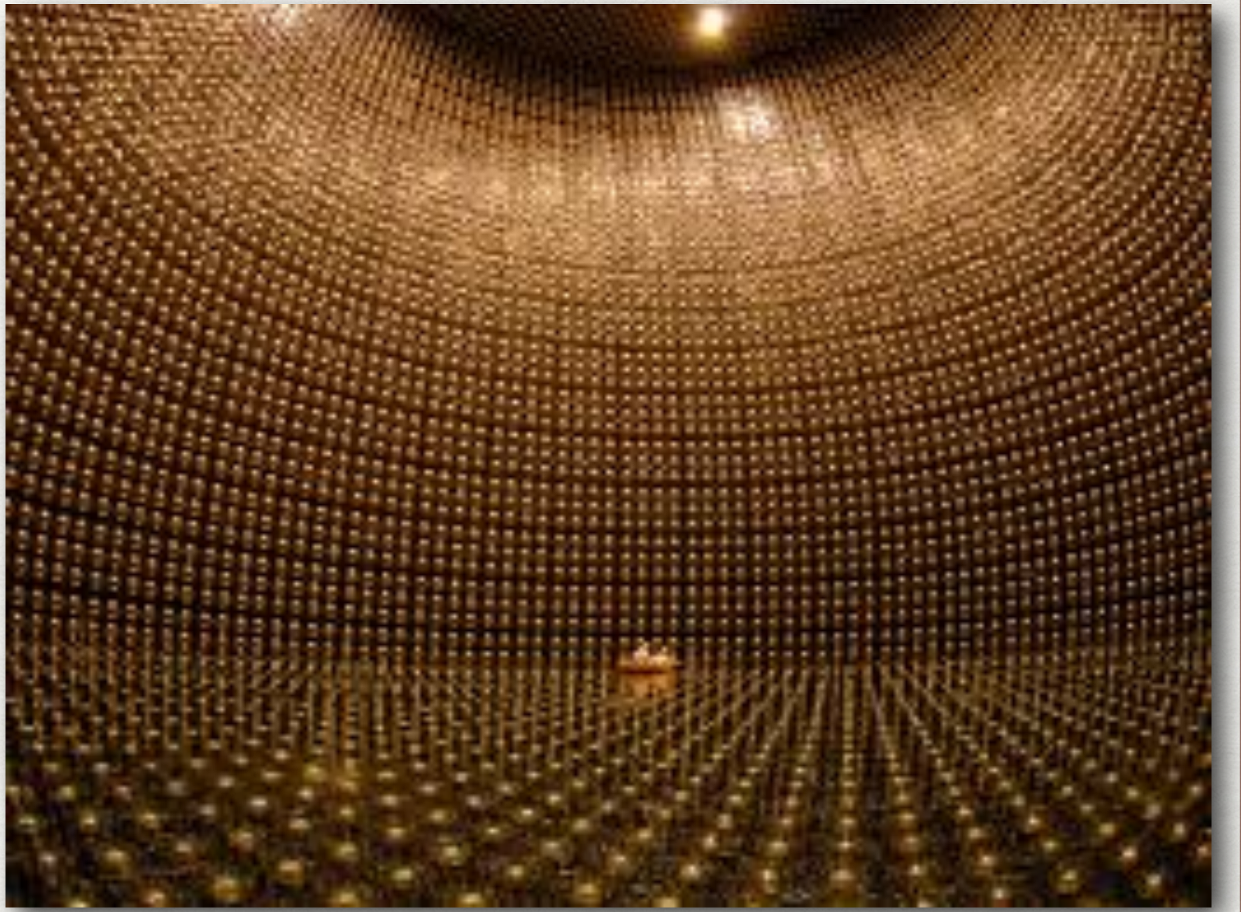

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40.000 l ^{37}Cl

$$\nu_e + {}^{37}Cl \longrightarrow {}^{37}Ar + e^-$$

1968 $\sim 1/3$ 'deficit'

1989 Kamiokande

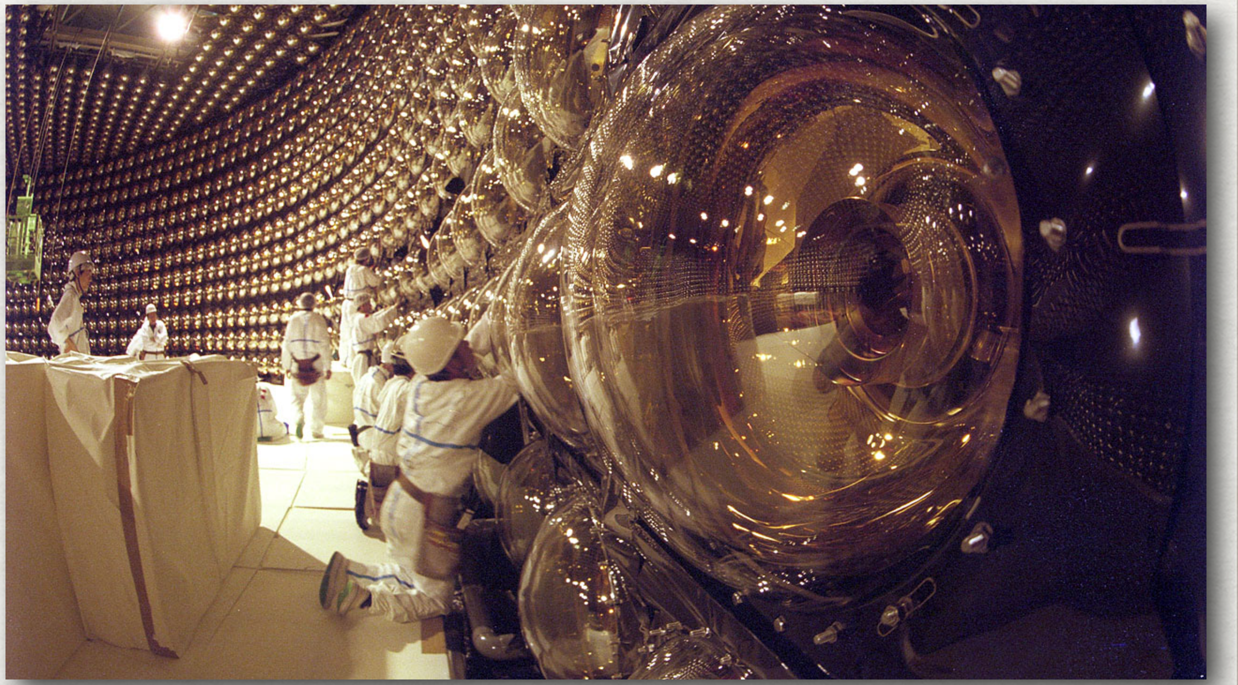
3.000.000 l H_2O

1996 Super-Kamiokande

50.000.000 l H_2O

2001 Subdury

1.000.000 l D_2O 'esquizofrenia'



CLASE 18: Masas de quarks y de neutrinos

B. Pontecorvo (1957)

oscilaciones de neutrinos:

$$\begin{pmatrix} \nu_\mu \\ \nu_e \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\begin{cases} \nu_\mu = \nu_1 \cos\theta + \nu_2 \sin\theta \\ \nu_e = -\nu_1 \sin\theta + \nu_2 \cos\theta \end{cases} \qquad \begin{cases} \nu_1 = \nu_\mu \cos\theta - \nu_e \sin\theta \\ \nu_2 = \nu_\mu \sin\theta + \nu_e \cos\theta \end{cases} \qquad \begin{matrix} \nu_1(t) = \nu_1(0)\, e^{-iE_1 t} \\ \nu_2(t) = \nu_2(0)\, e^{-iE_2 t} \end{matrix}$$

si se generan con p fijo $\quad E_i \simeq p + \dfrac{m_i^2}{2p} \quad (E_i \gg m_i)$

si a $t = 0$ $\quad \nu_\mu(0) = 1 \quad \nu_1(0) = \nu_\mu(0)\cos\theta \quad \nu_2(0) = \nu_\mu(0)\sin\theta$

$$\nu_\mu(t) = \nu_1(t)\, \cos\theta + \nu_2(t)\, \sin\theta \; = \nu_\mu(0)\, \cos^2\theta\, e^{-iE_1 t} + \nu_\mu(0)\, \sin^2\theta\, e^{-iE_2 t}$$

$$A_\mu = \frac{\nu_\mu(t)}{\nu_\mu(0)} = \cos^2\theta\, e^{-iE_1 t} + \sin^2\theta\, e^{-iE_2 t}$$

$$A_\mu A_\mu^* = 1 - \sin^2(2\theta)\, \sin^2\left(\frac{E_2 - E_1}{2} t\right)$$

CLASE 18: Masas de quarks y de neutrinos

B. Pontecorvo (1957)

oscilaciones de neutrinos:

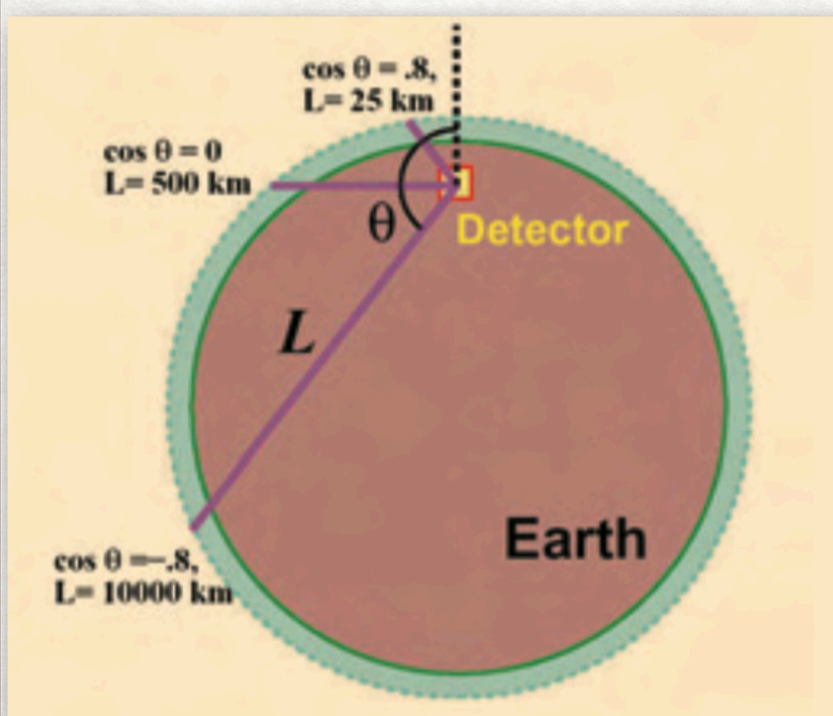
$$A_\mu A_\mu^* = 1 - \sin^2(2\theta)\ \sin^2\left(\frac{E_2 - E_1}{2} t\right)$$

$$\Delta m^2 \equiv m_2^2 - m_1^2 \ \simeq 2p(E_2 - p) - 2p(E_1 - p) \qquad E_i \simeq p + \frac{m_i^2}{2p}$$

$$\simeq 2p(E_2 - E_1)$$

$$P(\nu_\mu \to \nu_\mu) = A_\mu A_\mu^* = 1 - \sin^2(2\theta)\ \sin^2\left(\frac{\Delta m^2}{4p} t\right) \ = 1 - \sin^2(2\theta)\ \sin^2\left(\frac{\Delta m^2 c^4 L}{4E\hbar c}\right)$$

$$E_i \gg m_i \quad v \simeq c \quad E \simeq p \quad t \simeq \frac{L}{c}$$



$$\Delta m_{12}^2 = 7.53 \pm 0.18\ 10^{-5}\, eV^2$$

$$\Delta m_{23}^2 = 2.546 \pm 0.034\ 10^{-3}\, eV^2$$

$$\theta_{12} \simeq 17.89^o$$

$$\theta_{23} \simeq 9.17^o$$

CLASE 18: Masas y CP

V. Fitch J. Cronin (Nobel 1980)

oscilaciones de kaones: violación de CP

$$\Gamma(\pi^+ \longrightarrow \mu^+ + \nu_L) \underset{P}{\neq} \Gamma(\pi^+ \longrightarrow \mu^+ + \nu_R) \underset{C}{\neq} \Gamma(\pi^- \longrightarrow \mu^- + \bar{\nu}_R)$$

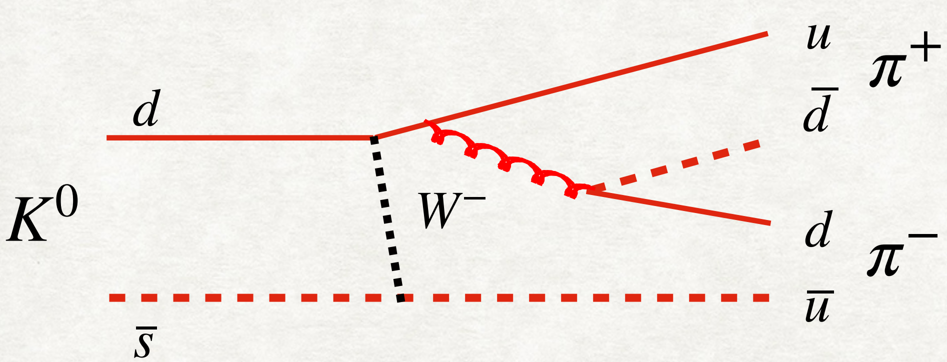
(CP relaciona el primer y el tercer proceso)

teorema CPT : invariancia Lorentz + causalidad + QFT implican que CPT es buena simetría

1964 Violación de CP oscilaciones de kaones neutros ($K^0 \equiv d\bar{s}$, $\overline{K}^0 \equiv s\bar{d}$)

2001 en mesones B (SLAC) ($B^0 \equiv d\bar{b}, \overline{B}^0 \equiv b\bar{d}$)

2019 en mesones D (LHC) ($D^0 \equiv c\bar{u}, \overline{D}^0 \equiv u\bar{c}$)



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

$$|K_L> = \frac{1}{\sqrt{2}}\left[\,|K^0> + |\overline{K}^0>\,\right] \qquad CP\,|K_L> = -\,|K_L>$$

$$|K_S> = \frac{1}{\sqrt{2}}\left[\,|K^0> - |\overline{K}^0>\,\right] \qquad CP\,|K_S> = +\,|K_S>$$

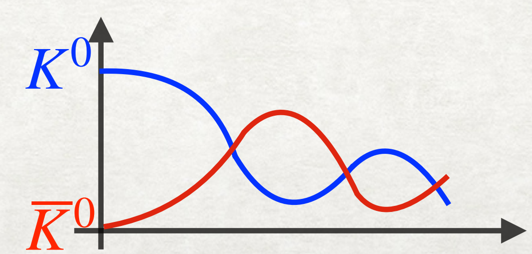
$$\pi^- + p \longrightarrow K^0 + \Lambda^0$$

$$\pi^+ + p \longrightarrow \overline{K}^0 + p + K^+$$

$$K_L \longrightarrow 3\pi \qquad (\tau_L \simeq 0.517\,10^{-7}s) \qquad CP = -1$$

$$K_S \longrightarrow 2\pi \qquad (\tau_S \simeq 0.893\,10^{-10}s) \qquad CP = +1$$

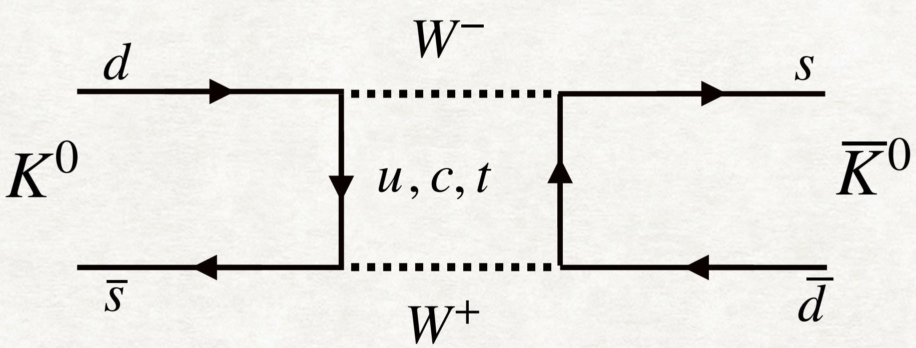
$$|K_0> = \frac{1}{\sqrt{2}}\left[\,|K_L> + |K_S>\,\right]$$



CLASE 18: Masas y CP

oscilaciones de kaones: violación de CP

$$\frac{K_L \longrightarrow \pi^0\pi^0}{K_S \longrightarrow \pi^0\pi^0} = (2.28 \pm 0.02)\ 10^{-3}$$



$$\Gamma(K^0 \longrightarrow \overline{K}^0) \neq \Gamma(\overline{K}^0 \longrightarrow K^0)$$

$$\begin{cases} K_L \longrightarrow e^+ + \nu_e + \pi^- \\ K_L \longrightarrow e^- + \overline{\nu}_e + \pi^+ \end{cases}$$

materia/anti-materia

asimetría bariónica

$$\frac{\Gamma(K_L \longrightarrow e^+ + \nu_e + \pi^-) - \Gamma(K_L \longrightarrow e^- + \overline{\nu}_e + \pi^+)}{\Gamma(K_L \longrightarrow e^+ + \nu_e + \pi^-) + \Gamma(K_L \longrightarrow e^- + \overline{\nu}_e + \pi^+)} = (3.32 \pm 0.06)\ 10^{-3}$$