LECTURE I

The SM

$$< 1930 \qquad \boxed{e} \quad \boxed{\nu_e} \quad \overset{p}{\boxed{u}} \quad \overset{n}{\boxed{d}} \quad \boxed{\gamma}$$

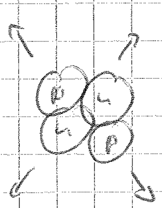
→ DIRAC : Antiparticles

→ FERMI : Neutrinos

$$\mathcal{L} = -\frac{1}{2}\frac{G_F}{\sqrt{2}}\left(j_\mu j^{\mu +} + j^{\mu +} j_\mu\right) \quad , \quad G_F \approx 10^{-5}/\mathrm{GeV}^2$$

$$j_\mu = \bar{e}_L \gamma_\mu \nu_e + \bar{d}_L \gamma_\mu u_L$$

→ YUKAWA : Exchange particle for the nuclear force



$$V(r) \propto \frac{1}{r} e^{-m_\varphi \cdot r} \Rightarrow m_\varphi \approx 100\ \mathrm{MeV}$$

→ Discovery of the muon 1937,
<u>not</u> Yukawas particle, although $m_\mu \approx 100$ MeV

$$j_\mu \to j_\mu^e + j_\mu^\mu \quad , \quad j_\mu^\mu = \bar{\mu}_L \gamma_\mu \nu_\mu$$

→ Discovery of the $\pi^\pm$, π^0 (1946, 1947)
is Yukawas particle !

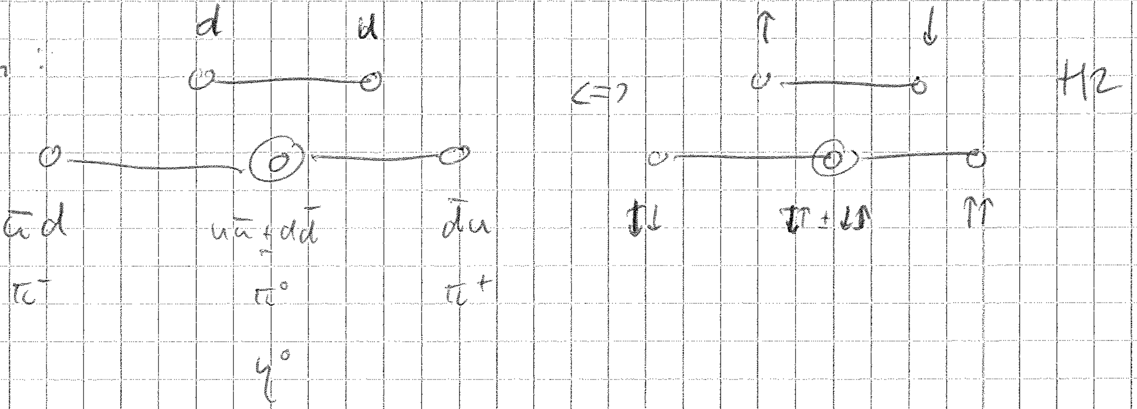
$$1940_s \qquad \begin{array}{cccccc} \boxed{e} & \boxed{\nu_e} & \boxed{u} & \boxed{d} & \boxed{\gamma} & \boxed{\pi^0} \\ \boxed{\mu} & \boxed{\nu_\mu} & p & n & & \boxed{\pi^\pm} \end{array}$$

→ Discovery of the η^0, Σ^0, Σ^+, Ω^-, Ξ^0, ...
(1950s)

did not fit in the "SM" at all
⇒ particle zoo.

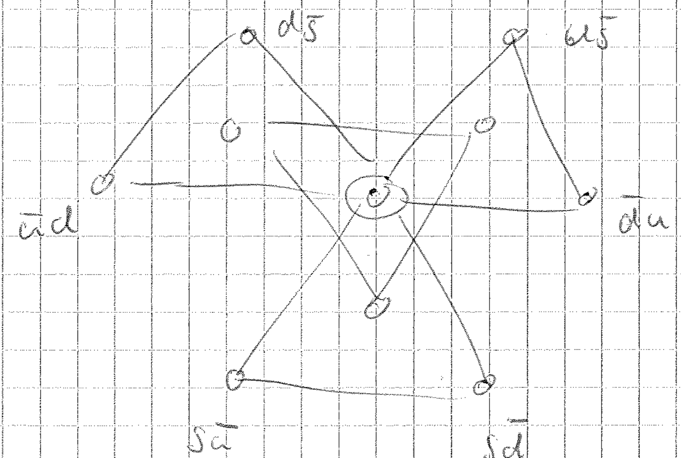
→ Gell-Mann (1961): The eightfold way

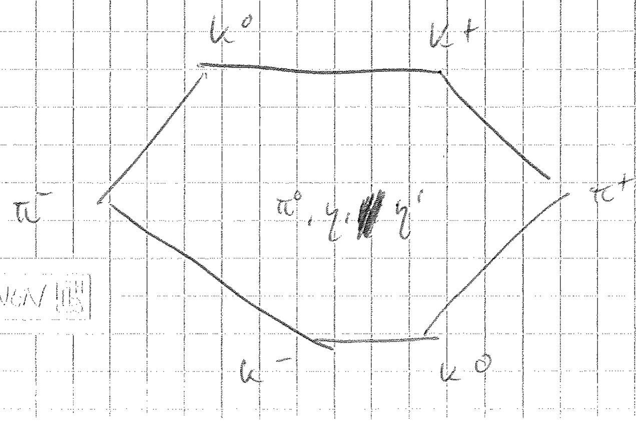
Isospin:



Add strangeness: $(u,d) \to (u,d,s)$

$$2\times 2 = 1+3 \longrightarrow 3\times 3 = 1+8$$





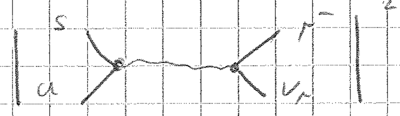
1960s $\boxed{e}$ $\boxed{\nu_e}$ $\boxed{u}$ $\boxed{d}$ $\boxed{\gamma}$

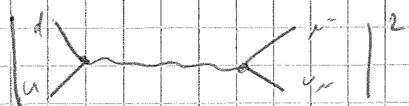
$\boxed{\mu}$ $\boxed{\nu_\mu}$ $\boxed{s}$

$$j_\mu \longrightarrow j_\mu^F + j_\mu^i + j_\mu^s \quad , \quad j_\mu^s = \bar{s}_L \gamma_\mu u_L$$

→ Problem 1: Universality

$$\frac{\Gamma(K^- \to \mu^- \bar{\nu}_\mu)}{\Gamma(\pi^- \to \mu^- \bar{\nu}_\mu)} \approx \frac{1}{20} \propto$$





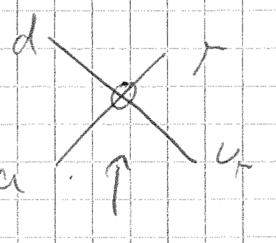
$$= \frac{\sin^2\theta_C}{\cos^2\theta_C} \Rightarrow \sin\theta_C \approx 0.22$$

CABIBBO

$$\begin{pmatrix} u \\ d' \end{pmatrix} = \begin{pmatrix} u \\ d\cos\theta_C + s\cdot\sin\theta_C \end{pmatrix}$$

→ Fermi's theory still working!

→ WEINBERG, GLASHOW, SALAM (70s)



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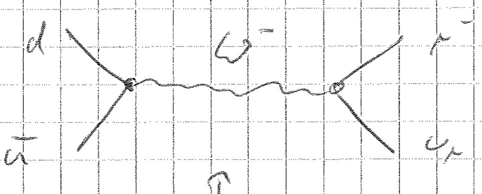
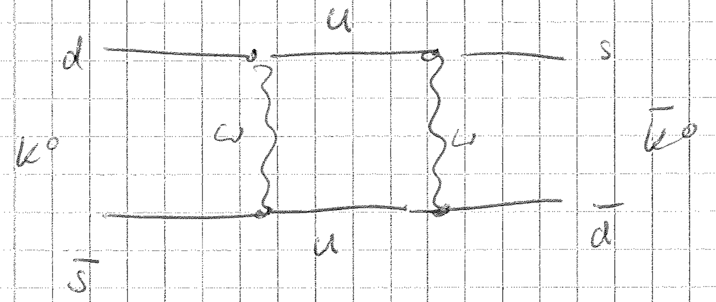


$$[G_F] = \frac{1}{GeV^2} \qquad G_F \sim \frac{1}{M^2} \leftarrow \frac{1}{p^2 - M^2}$$

Problem 2 : $\Delta m \approx 10^{-12}$ MeV experimentally



$K_S = (d\bar{s} + s\bar{d})/\sqrt{2}$, $K_L = (d\bar{s} - s\bar{d})/\sqrt{2}$

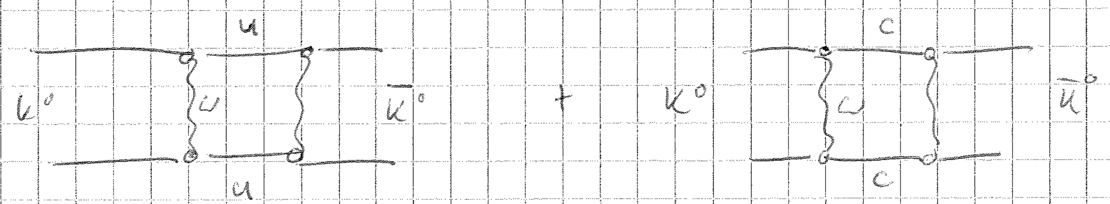
$\tau_S \approx 10^{-10}$ s $\qquad \tau_L \approx 10^{-8}$ s

$$\Delta m \propto \frac{G_F^2}{4\pi^2} M_W^2 \cos^2\theta_c \sin^2\theta_c f_K^2 m_K \approx 10^{-8} \text{ MeV}$$

$$+ \text{ —"— } m_u^2 \text{ ——"—— }$$

and divergent terms at higher order.

→ GAILLARD, LEE 1974



$$\Delta m \propto \frac{G_F^2}{4\pi^2} \cos^2\theta_c \sin^2\theta_c f_K^2 m_K^2 \left[(\cancel{M_W^2} + m_u^2) - (\cancel{M_W^2} + m_c^2) \right]$$

$$\stackrel{!}{=} 10^{-12} \text{ MeV}$$

$$\Rightarrow \frac{m_c}{M_W} \approx 10^{-2} \Rightarrow m_c \approx 1 \text{ GeV}$$

predicted the charm!

$$\mathcal{L}_F = (\bar{u} \ \bar{c}) \gamma_\mu V \begin{pmatrix} d \\ s \end{pmatrix}$$

→ Parameter Counting for V:

	Real	Imaginary
2×2	4	4
Unitarity	-3	-1
Phases absorbed	$-$	-3
	1	0

Cabibbo angle

$$V = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix}$$

→ KOBAYASHI, MASKAWA 1972

3 Generations can incorporate CP violation.

	Real	Imaginary
3×3	9	9
Unitarity	-6	-3
Phases	$-$	-5
	3	1
	angles	phase

Predicted a third generation before the charm was discovered!

Nobel prize 2008

→ Charm discovery J/ψ 1974

$\boxed{e}$ $\boxed{\nu_e}$ $\boxed{u}$ $\boxed{d}$ $\boxed{\gamma}$ $\boxed{g}$ $\boxed{H}$

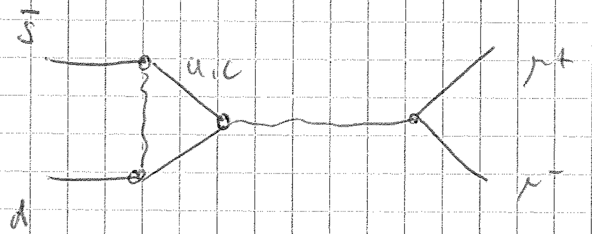
$\boxed{\mu}$ $\boxed{\nu_\mu}$ $\boxed{c}$ $\boxed{s}$ $\boxed{W^\pm}$ $\boxed{Z}$

$\boxed{\tau}$ $\boxed{\nu_\tau}$ $\boxed{t}$ $\boxed{b}$

Problem: Why are FCNCs so tiny?

$BR(K^- \to \mu^- \nu_\mu) \sim 64\%$

$BR(K_L \to \mu^+\mu^-) \sim 10^{-8}$



$$\propto V_{us} V_{ud}^* f(m_u^2) + V_{cs} V_{cd}^* f(m_c^2)$$

$$\begin{pmatrix} V_{ud}^* & V_{cd}^* \\ V_{us}^* & V_{cs}^* \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

If all quark masses were equal → No FCNCs!

GLASHOW, ILIOPOULOS, MAIANI → GIM-mechanism

→ τ Discovery 1975 → top Discovery 1995

→ b Discovery 1978 → ν_τ Discovery 2001

→ g "Discovery" 1979 → H Discovery 2012!

→ $W^\pm, Z$ 1983

↳ 3 light νs.

SM complete!