II] The Standard Model of Particle Physics

1) Symmetries, conservation laws and the Noether theorem

× Symmetries are fundamental in our understanding in Nature

ex : - continuous & discrete | space-time / external symmetries (space rotat° & parity tf $(\vec{x} \to -\vec{x})$)

- ———— internal ———— (U(1) gauge tf & charge conjugaison ie φ. rotat° of wave function)

× The importance of symmetries in Nature is to a large extent due to the Noether th. :

= to any continuous symmetry of a physical system, it corresponds a conserved current and an associate conserved charge =

× ex : Symmetry $\Longleftrightarrow$ Conserved charge

- T-translation — Energy

(classical partical mechanics : if $\frac{\partial \mathcal{L}}{\partial t} = 0$ (no explicit dep) $\Rightarrow \frac{dH}{dt} = 0$ Energy)

- Space-translation — Momentum
- Rotations — angular momentum
- phase rotations of wave function — electric charge

× Proof of Noether th. in classical field theory :

$$\mathcal{L}(\phi, \partial_\mu \phi), \; S(\phi, \partial_\mu \phi)$$

field tf : $\delta\phi = \alpha_a(x) T^a \phi$

$$\mathcal{L}(\phi, \partial_\mu\phi) \longrightarrow \hat{\mathcal{L}}(\phi, \alpha_a, \partial_\mu\phi, \partial_\mu\alpha_a)$$

variation of the action functional under field variations : $\delta S = \int d^4x \left[\frac{\partial \hat{\mathcal{L}}}{\partial \alpha_a} \alpha_a + \frac{\partial \hat{\mathcal{L}}}{\partial(\partial_\mu \alpha_a)} (\partial_\mu \alpha_a) \right] \overset{IBP}{=} \int d^4x \left[\frac{\partial \hat{\mathcal{L}}}{\partial \alpha_a} - \partial_\mu J^\mu_a \right] \alpha_a$

$$J^\mu_a \equiv \frac{\partial \hat{\mathcal{L}}}{\partial(\partial_\mu \alpha_a)}$$

$$\delta S = 0 \Rightarrow \partial_\mu J^\mu_a = \frac{\partial \hat{\mathcal{L}}}{\partial \alpha_a}$$

- if field variation is a symmetry of $\mathcal{L}$: $\frac{\partial \hat{\mathcal{L}}}{\partial \alpha_a} = 0$

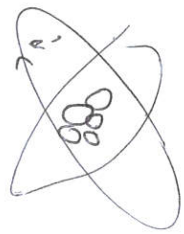
$\Rightarrow \partial_\mu J^\mu_a = 0$: J^μ_a is a conserved current associated to the invariance def by $\delta\phi = \alpha_a(x) T^a \phi$

$$\Rightarrow \frac{dQ_a}{dt} = \int d^3x \, \partial_\mu J_a^\mu = 0 \,, \quad Q_a = \underbrace{\int d^3x}_{\text{space}} \, \underbrace{J_a^0}_{t\text{-component}} \text{ is a conserved charge}$$

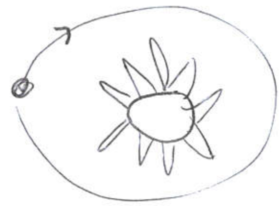
* in QM: study of symmetry simplify greatly the dynamics (angular of mom...)
* Now, we will see that, Local (space-time dependant, $\alpha(\vec{x},t)$) symmetries determine the structure of all the fundamental interactions in Nature.
* Indeed, all 4 fundamental forces (EM, weak, strong ; gravity) can be found as consequences of local symmetries call $\boxed{\text{gauge symmetries}}$

weak force in radioactive decay ;

strong force bounds the nucleus ;



EM force binds atoms ;



gravitational force binds the solar system

2) Gauge theories

1. Gauge invariance of Schrödinger equation

* particle of mass m & EM charge q in Q.M.:

$$H = \frac{1}{2m}(\vec{p} - q\vec{A})^2 + qV$$

$V \longrightarrow$ scalar potential, $\vec{A} \longrightarrow$ vector pot. } not observables but related to

Maxwell eq. of EM:
$$\begin{cases} \vec{E} = -\nabla V - \dfrac{\partial \vec{A}}{\partial t} \\ \vec{B} = \nabla \times \vec{A} \end{cases}$$

inv. under the "gauge tf":
$$\begin{cases} \vec{A} \longrightarrow \vec{A}' = A + \nabla\alpha(\vec{x},t) \\ V \longrightarrow V' = V - \dfrac{\partial\alpha}{\partial t}(\vec{x},t) \end{cases}$$

* the dynamics (Schrödinger eq.) is covariant meaning:

$$i\frac{\partial\psi}{\partial t} = H(\vec{A},V)\psi \longrightarrow i\frac{\partial\psi'}{\partial t} = H'(\vec{A}',V')\psi'$$

if
$$\psi(\vec{x},t) \longrightarrow \psi'(\vec{x},t) = e^{i\underbrace{q}_{\text{e-charge}}\alpha(\vec{x},t)}\psi(\vec{x},t)$$

Gauge princip: postulate that physical laws are invariant under

$\Rightarrow H$ is unique

* these tf define a $U(1)$ tf

$\Rightarrow U(1)$ gauge inv. determines the E.M interaction

2. From Maxwell & Dirac equations to Quantum Electro Dynamics (QED)

× Relativistic fermions is described by a 4-component spinor ψ via Dirac eq:

$$i\gamma^\mu \partial_\mu \psi - m\psi = 0 \quad , \quad \gamma^\mu \text{ Dirac matrices}$$

pb: not inv. under gauge tf $\begin{cases} A_\mu \to A'_\mu = A_\mu - \partial_\mu \alpha \\ \psi(x) \to \psi'(x) = e^{iq\alpha(x)}\psi(x) \end{cases}$ $\quad (\partial_\mu \alpha(x) \neq 0)$

• "Tricks": $\partial_\mu \psi \xrightarrow[\text{by}]{\text{replaced}} D_\mu \psi \equiv (\partial_\mu + iqA_\mu)\psi \xrightarrow[\text{tf.}]{\text{gauge}} (D_\mu\psi)' = (\partial_\mu + iqA'_\mu)\psi'$

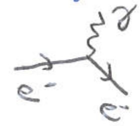
$$= e^{iq\alpha(x)}(D_\mu \psi)$$

covariant derivative

(i.e. $D_\mu\psi$ tf as ψ)

× Dirac eq in an EM field becomes:

$$(i\gamma^\mu D_\mu - m)\psi = (i\gamma^\mu \partial_\mu - q\gamma^\mu A_\mu - m)\psi = 0$$

NEW: 

(γ-e) interact° term

× EM + matter (γ + e^-, Maxwell + Dirac) $\longrightarrow \mathcal{L}_{QED} = \bar\psi(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$

↳ $\bar\psi = \psi^\dagger \gamma^0$

↳ $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ (tensor field strength) $= -\frac{i}{e}[D_\mu, D_\nu]$

Rq: × Feynman rules of QED: - quantizat° of free Dirac + free EM eq.

- switching a int. term by applying perturbation theory

× Euler-Lagrange eq°: $\partial^\mu F_{\mu\nu} = q\bar\psi\gamma_\nu\psi \equiv j_\nu$: EM current (conserved)

$$\Rightarrow \partial^\mu j_\mu = 0 \Rightarrow \frac{dQ}{dt} = 0 \text{ with } Q = \int d^3x\, j_0(x) = q \text{ : conserved charge}$$

× photon mass term would be: $\mathcal{L}_{\gamma,mass} = \frac{M_A^2}{2}A_\mu^2$ pb: break gauge inv! ($\Rightarrow$ no mass then)

3. Non-Abelian gauge theories

- EM : described by $U(1)$ (Unitary abelian) tg.
- What about interactions described by "Non Abelian" tg ?
  $\hookrightarrow SU(N)$: $N\times N$ matrices U, $U^+U = UU^+ = \mathbb{1}$ & $\det U = 1$
- Let's start with $SU(2)$ [Yang-Mills, 1954]

• simplest representation in a doublet : $\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} \longrightarrow \psi' = U(\alpha)\psi$ with $U(\alpha) = e^{\frac{i}{2} g \alpha_a \tau_a}$ ← Pauli matrices

g : $SU(2)$ gauge coupling (charge in $U(1)$) ; α_a : from tg

• Nb of gauge bosons = Nb of generators of tg. $\rightarrow$ 3 for $SU(N)$ ($\rightarrow 1$ for $U(1)$, γ)

$$W_\mu = W_\mu^a \frac{\tau_a}{2} = \begin{pmatrix} W_\mu^3 & W_\mu^1 - iW_\mu^2 \\ W_\mu^1 + iW_\mu^2 & -W_\mu^3 \end{pmatrix} \underset{\text{change of basis}}{=} \begin{pmatrix} W_\mu^3 & \sqrt{2}W^+ \\ \sqrt{2}W^- & -W_\mu^3 \end{pmatrix}$$

• as before we define D_μ :
$$D_\mu \psi = \left(\partial_\mu - igW_\mu\right)\psi$$
$$\left(\text{QED} : +iqA_\mu \mathbb{1}\right)$$

• $D_\mu\psi \rightarrow (D_\mu\psi)' = U(D_\mu\psi)$ i.e. $D_\mu\psi$ tg as ψ

(tg) : $W_\mu \rightarrow W_\mu' = UW_\mu U^{-1} - \frac{i}{g}(\partial_\mu U)U^{-1}$

• we can build the field strength :

$$[D_\mu, D_\nu] = -igF_{\mu\nu}, \quad F_{\mu\nu} = F_{\mu\nu}^a \frac{\tau^a}{2} = \partial_\mu W_\nu - \partial_\nu W_\mu \underbrace{-ig[W_\mu, W_\nu]}_{\text{new non abelian term}}$$

• gauge invariant $\mathcal{L}$:

$$\mathcal{L}_{YM} = -\frac{1}{4}F_{\mu\nu}^a F^{a,\mu\nu} = -\frac{1}{4}\left(\partial_\mu W_\nu^a - \partial_\nu W_\mu^a\right)^2 \underbrace{- \text{``}g\partial W_\nu^a W^{b,\mu} W^{c,\nu}\text{''} - \text{``}g^2 W_\mu^b W_\nu^c W^{d,\mu} W^{e,\nu}\text{''}}_{\text{self interaction in non ab. gauge boson } (\neq \gamma)}$$

• YM + charge matter :

$$\mathcal{L} = \bar{\psi}\left(i\gamma^\mu D_\mu - m\right)\psi - \frac{1}{4}F_{\mu\nu}^a F^{a,\mu\nu}$$

$$\left(SU(2) \rightarrow U(1) : \quad \frac{\tau_a}{2} \rightarrow q \ ; \ g \rightarrow e \ ; \ \varepsilon_{abc} \rightarrow 0 \right)$$

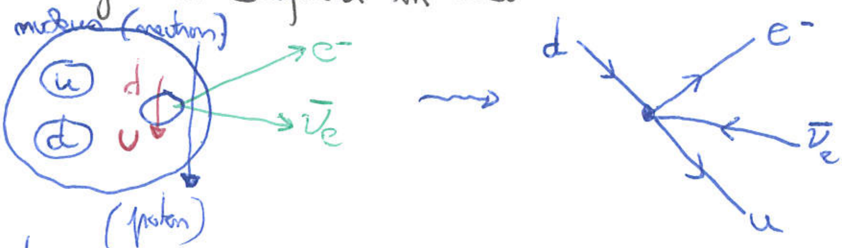
4. From radioactivity to the weak force

* radioactivity: • process by which an unstable atomic nucleus loses energy by emitting radiat°

  (ex: $\underset{He^{2+}}{\alpha}$, $\underset{e^{\mp}}{\beta^{\mp}}$ with ν or $\bar{\nu}$)

  • discovered by Henri Becquerel in 1896

ex: β^- decay



* can't be explain by E.M.
* Enrico Fermi proposed a theory in 1933: 4-fermion contact interaction

contact at the same space-time point = force with no range

$$\mathcal{L}_{Fermi} = -\frac{G_F}{\sqrt{2}}\left[\bar{p}\,\gamma_\mu\, n\right]\left[\bar{e}\,\gamma^\mu \nu_e\right] + h.c.$$

hadronic current — leptonic current

• $G_F = 1,167 \times 10^{-5}\ GeV^{-2}$ → new coupling = new force! (great role in things falling apart, decaying)

↳ small → probability of interact° small → "weak force"

• Perturbation theory based on this $\mathcal{L}$ described pretty well β-decay

Problem: inconsistencies in the theory when considering scattering at high energy

P_{tot}(weak process) > 1 (unitarity violat° pb)

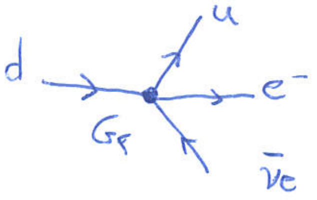
→ serious pb and clearly the theory cannot be used at high energy

→ Effective Field Theory or low energy theory (attached to a regime of validity cut-off in energy Λ)

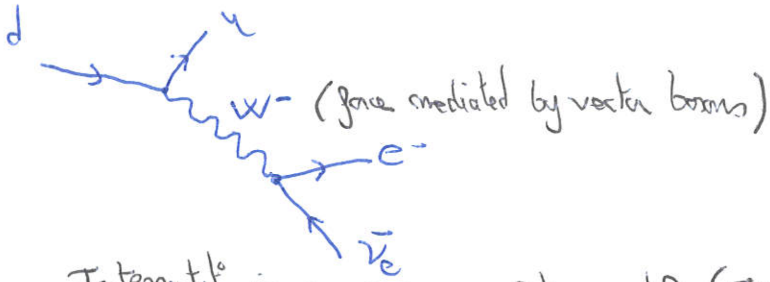
→ meaning this is an approximation of a more general theory

Rq: 4-fermion int.: not renormalizable int. → divergences in calculat° .... serious issue

× Non contact force with finite range induced by massive bosons



Fermi Theory



Interpretat° in a more complete model (SM)

- the weak nuclear force has a limit range of $\sim 10^{-18}$ m $(\neq 0)$
  $\Rightarrow$ force carrier should have a mass ($\neq$ EM, $m_\gamma = 0 \Rightarrow$ infinite range)
- 3 carrier particles: $W^\pm$ (91 GeV), Z (80 GeV) [directly discovered in 1983 at CERN]
- Link with virtue of QED and gauge theories?

  Weak force comes from gauge invariance ~~of non~~ under non-abelian gauge tf.
  (Yang-Mills theory with $SU(2)$ local tf)

- Rq: - called "weak" but $g \sim 0{,}6$ (of $D_\mu = (\partial_\mu - igW_\mu)$)

  but $G_F = \frac{\sqrt{2}}{8}\frac{g^2}{M_W^2}$
  $\longrightarrow$ W, Z are so big they travel is limited to short distance.

× The mass problem:

- YM theory: massless gauge fields: force with ∞ range
- Experimentally: $M_{W,Z} \neq 0$ and heavy $\Rightarrow$ weak force has a short range
- Need to give these gauge bosons a mass pb: by hand term as $m^2 W_\mu W^\mu$ breaks explicitly gauge invariance!

$\longrightarrow$ We need another way to generate gauge boson masses in a more subtle way

3) Spontaneous symmetry breaking and the Higgs mechanism

1. Vacuum Expectation Values (VEV)

× scalar fields in QFT:

$$\phi(x) = \int d^3k \left[a_k e^{-ikx} + a_k^\dagger e^{ikx} \right]$$

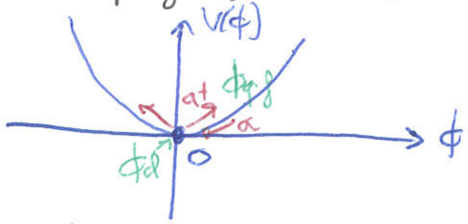
$|0\rangle$: ground state of the theory

$\langle 0|a|0\rangle = \langle 0|a^\dagger|0\rangle \Rightarrow \langle 0|\phi|0\rangle = 0$ (No VEV)

ϕ : quantum fluctuation $\xrightarrow[\text{general}]{\text{in}}$ $\phi = \phi_{\text{classical}} + \phi_{q.f.}$

• What about if $\langle 0|\phi_{cl}|0\rangle \neq 0$?

× ex: (scalar free field) $\mathcal{L}_{KG} = \frac{1}{2}\left[\partial_\mu\phi\partial^\mu\phi \underbrace{- m^2\phi^2}_{V(\phi)}\right]$

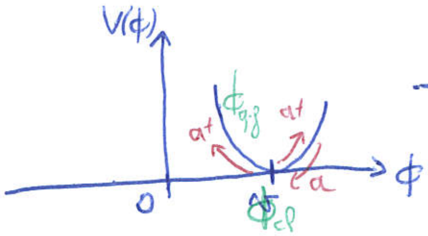


• ground state at the minimum of the potential : $\langle 0|\phi_{cl}|0\rangle = 0$

• When we quantize a theory, one considers fluctuations of fields around minima of the potential

• fluctuations define a set of harmonic $(a, a^\dagger)$ oscillators

• Suppose $\langle 0|\phi_{cl}|0\rangle \neq 0$: non trivial ground state of the theory



⟶ we have to expand the theory around <u>that</u> vacuum (def. $\phi_{q.f}$)

× In general for $\phi_{cl} \neq 0$ there will be fewer symmetries than with $\phi_{cl} = 0$

× So, if a symmetry operator changes the classical vacuum, then this is not going to be a symmetry of the theory expanded around that vacuum!

× ex: $U(1)$ tf: $\phi \to e^{i\alpha(x)}\phi$

$\phi_{cl} = 0$: inv under $U(1)$ + $\mathcal{L}$ inv under $U(1)$: $U(1)$ symmetry ✓

$\phi_{cl} \neq 0$: <u>not</u> inv. under $U(1)$ + ——— : $U(1)$ not a symmetry

× If there is a symmetry of the $\mathcal{L}$ that is not realized by the vacuum

$\longrightarrow$ spontaneous symmetry breaking of the theory

2. The Higgs mechanism

× abelian $U(1)$ gauge theory :

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}^2 + \left| D_\mu \Phi \right|^2 - V(\Phi)$$

$\longrightarrow$ let's not specify it

$\Phi = \frac{1}{\sqrt{2}}(\Phi_1 + i\Phi_2)$: complex scalar field

but designed to have $\langle 0 | \Phi | 0 \rangle = \frac{v}{\sqrt{2}} \neq 0$

× ~~R~~ ~~ws~~ Need to perturbe the theory around the minima and write the theory with ϕ such as $\underset{\phi_{q.f}}{\langle 0 | \phi | 0 \rangle} = 0$: $\phi(x) = \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2) = \Phi - \frac{1}{\sqrt{2}} v$

× $$\left| D_\mu \Phi \right|^2 = \frac{1}{2}(\partial_\mu \phi_i)^2 + e v A_\mu \partial_\mu \phi_2 + \frac{e^2 v^2}{2} A_\mu^2 + \dots$$

mass term for gauge boson

× $$\mathcal{L} \supset -\frac{1}{4}(\partial_\mu B_\nu - \partial_\nu B_\mu)^2 + \frac{e^2 v^2}{2} B_\mu^2$$

after the change of variable : $A_\mu \rightarrow B_\mu = A_\mu + \frac{1}{ev} \partial_\mu \phi_2$

1 new d.o.f.

× ϕ_2 ~~has~~ absorbed by the gauge boson B_μ

↳ longitudinal polarization of B_μ responsible of the mass

× $$A_\mu (M_A = 0) + \phi_2 \longrightarrow A_\mu (M_A \neq 0)$$
$$(\ 2 \text{ dof} \quad + \quad 1 \quad = \quad 3 \text{ dof}\ )$$

× $\langle 0 | \phi_{cl} | 0 \rangle \neq 0 + SSB \overset{\text{induces}}{\Longrightarrow} M_{\substack{\text{gauge}\\\text{boson}}} \neq 0$ (~~then breaks gauge invariance~~)

$\longrightarrow$ this is called the Higgs mechanism

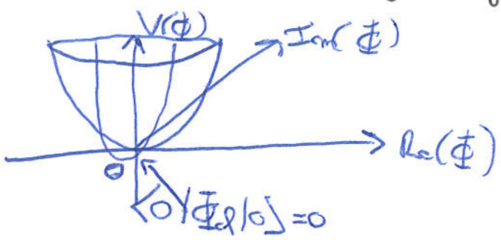
× Rq : apply to non abelian symmetry

3. The mexican hat potential

× so far we have not specified $V(\Phi)$, only the "generic feature" to design $\langle 0|\Phi_{cl}|0\rangle \neq 0$

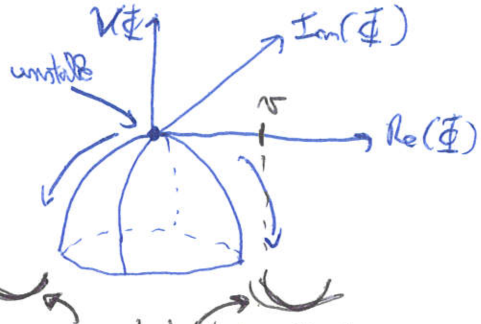
• $V(\Phi) = m^2 |\Phi|^2$

(a mass term)



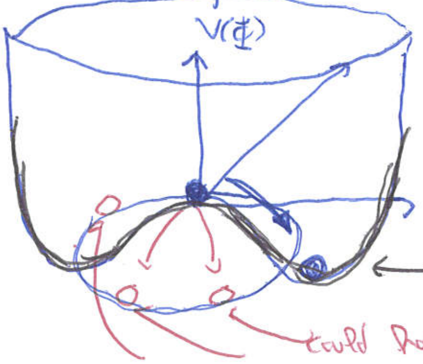
• $V(\Phi) = -m^2 |\Phi|^2$

(imaginary mass ⇝ tachyon (pb))



we want to design that shape to enable a VEV

• $V(\Phi) = -\mu^2 |\Phi|^2 + \lambda |\Phi|^4$ (inv. under U(1) $\Phi \to e^{i\alpha(x)}\Phi$ ✓)



choice of vacuum ⇒ not inv by $e^{i\alpha}$ ⇝ <u>SSB</u>

could have been this one, ...

× $\frac{dV}{d\Phi} = 0 \Rightarrow$ $\Phi = 0$: unstable

$\Phi = \sqrt{\frac{\mu^2}{2\lambda}} \equiv \frac{v}{\sqrt{2}}$: stable

× remember : $\phi = \frac{\phi_1 + i\phi_2}{\sqrt{2}}$

ϕ_2 ⟶ long. pol. of A_μ

ϕ_1 ⟶ $\frac{m_1^2}{2}\phi_1^2$ with $m_1^2 = \sqrt{2}\,\lambda v = \sqrt{2\mu^2}$

when applied to breaking of $SU(2)_L \times U(1)_Y$: ϕ_1 : Higgs boson ⟶ $U(1)_{EM}$

m_1 : Higgs mass

$m_\gamma = 0$
$M_{W^\pm, Z} \neq 0$
+ Higgs

× $V = -\mu^2 |\Phi|^2 + \lambda |\Phi|^4$

↳ by continuously changing μ^2 we can go from a symmetric vacuum to the vacuum with broken symmetry

not included in SM, need BSM...

4) The Standard Model

1. Gauge group and matter content

$$SU(3)_c \times \overbrace{SU(2)_L \times U(1)_Y} \xrightarrow{EWSB} SU(3)_c \times U(1)_{EM}$$

gauge bosons: G_μ^a (8 gluons) $\quad A_\mu^a$ (3) $\quad B_\mu$ (1) $\quad | \quad A_\mu$ (1)

* <u>matter fermions</u>:
* Leptons $\begin{pmatrix}\nu_{eL}\\ e^-_L\end{pmatrix}, \begin{pmatrix}\nu_{\mu L}\\ \mu^-_L\end{pmatrix}, \begin{pmatrix}\nu_{\tau L}\\ \tau^-_L\end{pmatrix}$: $(1,2)_{Y=-1}$ $\quad (\ell_L + \ell_R = \ell)$

e^-_R, μ^-_R, τ^-_R : $(1,1)_{Y=-2}$

No $\nu_{eR}, \nu_{\mu R}, \nu_{\tau R}$! why?

⊕ anti particles: $\begin{pmatrix}e^+_L\\ \bar\nu_{eL}\end{pmatrix}, \begin{pmatrix}\mu^+_L\\ \bar\nu_{\mu L}\end{pmatrix}, \begin{pmatrix}\tau^+_L\\ \bar\nu_{\tau L}\end{pmatrix}$: $(1,2)_{Y=1}$

e^+_R, μ^+_R, τ^+_R

* Quarks: $\begin{pmatrix}u_L\\ d_L\end{pmatrix}, \begin{pmatrix}c_L\\ s_L\end{pmatrix}, \begin{pmatrix}t_L\\ b_L\end{pmatrix}$: $(3,2)_{Y=1/3}$

u_R, c_R, t_R : $(3,1)_{Y=4/3}$

d_R, s_R, b_R : $(3,1)_{Y=-2/3}$

⊕ anti particles

⟶ only left-handed quarks & leptons interact with $SU(2)_L$ gauge fields.

* <u>Higgs</u> (scalar): $\Phi = \begin{pmatrix}\Phi^+\\ \Phi^0\end{pmatrix}$: $(1,2)_{Y=1}$

* $\mathcal{L}_{SM} = \mathcal{L}_{kinetic} - V(\Phi) + \mathcal{L}_{YUKAWA}$ ↳ (see later on)

$$\hookrightarrow = -\frac{1}{4}\left(F^a_{\mu\nu}\right)^2 - \frac{1}{4}f_{\mu\nu}^2 + |D_\mu\Phi|^2 + \bar\Psi_L i\gamma^\mu D_\mu\Psi_L + \bar\Psi_R i\gamma^\mu D_\mu\Psi_R$$

$(\times 2)$

<u>ex leptons</u>:

$$D_\mu\Psi_L = \left(\partial_\mu - ig\frac{\tau_a}{2}A_\mu - ig'\frac{Y_L}{2}B_\mu\right)\Psi_L$$

$$D_\mu\Psi_R = \left(\partial_\mu \qquad - ig'\frac{Y_R}{2}B_\mu\right)\Psi_R$$

(only L.H fermion couple to $SU(2)_L$ gauge fields)

$$V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4$$

~~needed to~~ Higgs doublet VEV breaks the EW group down to the electric charge: $SU(2)_L \times U(1)_Y \longrightarrow U(1)_Q$

2. Fermion masses and Yukawa interactions

* $\mathcal{L}_{Dirac} = \bar{\Psi}(i\gamma^\mu \partial_\mu \Psi - m)\Psi$

  γ^μ ↳ Dirac matrices

  $\bar\Psi$ ↳ $\Psi^+\gamma^0$

  Ψ ↳ 4x4 matrix in Dirac rep. (bi-spinor)

* Chirality operator: $\gamma^5 = i\gamma_0\gamma_1\gamma_2\gamma_3$ use to define $\begin{cases}\text{Left}\\ \text{Right}\end{cases}$ - handed chirality fermion

$$\begin{cases}\gamma^5(\Psi_L) = -\Psi_L \\ \gamma^5(\Psi_R) = +\Psi_R\end{cases} \longrightarrow \begin{cases}\Psi_L = \frac{1-\gamma^5}{2}\Psi \\ \Psi_R = \frac{1+\gamma^5}{2}\Psi\end{cases}$$

$$\mathcal{L}_{Dirac} = \bar\Psi_L i\gamma^\mu\partial_\mu\Psi_L + \bar\Psi_R i\gamma^\mu \partial_\mu \Psi_R \underbrace{- m(\bar\Psi_L\Psi_R + \bar\Psi_R\Psi_L)}_{\text{Dirac mass term}}$$

• no $\bar\Psi_L\Psi_L = \Psi_L^+\gamma^0\Psi_L$ $\quad \gamma^{5+} = \gamma^5$ (hermitian)

$= \overline{\Psi_L}\gamma^0\Psi_L$ $\quad \gamma^5\gamma^0 = -\gamma^0\gamma^5$

$= \gamma^0 \underbrace{\Psi_R\Psi_L}_{=0}$

* In QED: $e^{-i\alpha(x)}e^{i\alpha(x)} = 1 \Rightarrow$ Dirac mass terms are gauge invariant!

* In SM: fermion also charged under $SU(2)_L$, ex: $e_L^- \xrightarrow{SU(2)_L} \nu_L$

$$m\,\bar{e}_L^- e_R^- \longrightarrow m\,\bar\nu_L e_R^-$$

(doesn't tf) — Clearly not invariant under $SU(2)_L$ tf.!

$\Rightarrow$ pb: Dirac masses in the SM are not gauge invariant! due to chiral nature of EW interaction.

$\longrightarrow$ Let's use the Higgs field to generate Dirac fermion masses:

$$-\mathcal{L}_{YUKAWA} = h_{ij}^{(u)}\,\bar q_L^i\, u_R^j\,\tilde\Phi + h_{ij}^{(d)}\,\bar q_L^i\, d_R^j\,\Phi + h_{ij}^{(e)}\,\bar l_L^i\, e_R^j\,\Phi$$

flavor indices

$\boxed{\text{u-type quarks } (u,c,t)}$ $\quad$ $\boxed{\text{d-type quarks } (d,s,b)}$ $\quad$ $\boxed{\text{leptons}}$

with $\tilde\Phi = i\,\tau_2\,\Phi^* = \begin{pmatrix}\bar\Phi^0 \\ -\bar\Phi^+\end{pmatrix}$ [charge conjugate of Higgs field]

× after EWSB, $\langle 0|\Phi^0|0\rangle \neq 0$
$$= \frac{v}{\sqrt{2}}$$

$$\longrightarrow -\mathcal{L}_{\text{Yukawa}} \longrightarrow -\mathcal{L}_{\text{mass}} = m^u_{ij}\,\bar{u}^i_L u^j_R + m^d_{ij}\,\bar{d}^i_L d^j_R + m^e_{ij}\,\bar{e}^i_L e^j_R + c.c.$$

with $m^{u,d,e}_{ij} = h^{u,d,e}_{ij}\,\frac{v}{\sqrt{2}}$

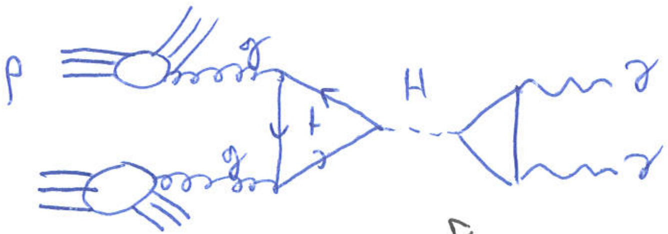
$$-\mathcal{L}_{\text{mass}} = \bar{u}_L m^u u_R + \bar{d}_L m^d d_R + \bar{e}_L m^e e_R + c.c.$$

3×3 mass matrix in the flavor space

Rq: see Diego's flavor lecture

5) Discovery of the Higgs boson

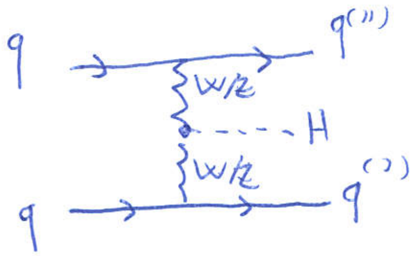
× in 2012: ATLAS & CMS (LHC @ CERN) discovered:



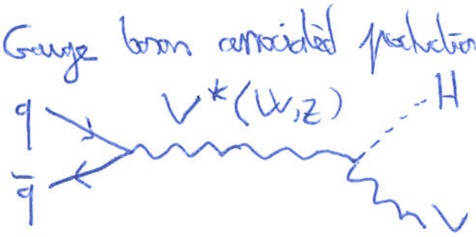
$M_H \sim 125$ GeV

other production modes:

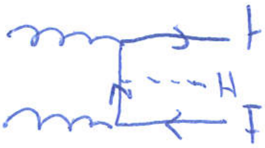
- gluon fusion
- Vector boson fusion:



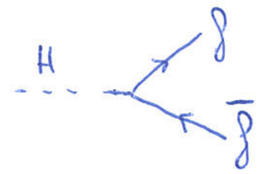
- Gauge boson associated production



- associated product° with top quark pair (ttH)



other decay modes:

- 

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