Flavor physics

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General remarks

- Please ask questions
- I will tell you things that you know. But if you do not know them, ask...
- Do your “homeworks”
- I will cover only the main ideas. For details look at reviews and books

Some references
- Y. Nir, hep-ph/0510413
- Branco, Lavora, and Silva, CP violation (book)
Outline

1. First lecture
   - The SM (or how we built models)
   - The flavor sector of the SM

2. Second lecture
   - Meson mixing and decays
   - CP violation

3. Third lecture
   - Measurements of CP violation
   - The big picture (how all this related to HEP...)
What is HEP?
What is HEP

Very simple question

\[ \mathcal{L} = ? \]
What is HEP

Very simple question

$L = ?$

Not a very simple answer
Basics of model building

\[ \mathcal{L} = ? \]

Axioms of physics

1. Gauge symmetry
2. representations of the fermions and scalars (irreps)
3. SSB (relations between parameters)

Then $\mathcal{L}$ is the most general normalizable one
Remarks

- We impose Lorentz symmetry (in a way it is a local symmetry)
- We assume QFT (that is, quantum mechanics is also an axiom)
- We do not impose global symmetries. They are “accidental,” that is, they are there only because we do not write NR terms
- The basic fields are two components Weyl spinors
- A model has a finite number of parameters. In principle, they need to be measured and only after that the model can be tested
A working example: the SM

- Symmetry: $SU(3)_C \times SU(2)_L \times U(1)_Y$
- irreps: 3 copies of QUDLE fermions

\[
Q_L(3, 2)^{1/6}, \quad U_R(3, 1)^{2/3}, \quad D_R(3, 1)^{-1/3},
\]
\[
L_L(1, 2)^{-1/2}, \quad E_R(1, 1)^{-1}
\]
- SSB: one scalar

\[
\phi(1, 2)^{+1/2}, \quad \langle \phi \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}
\]

$\Rightarrow$ $SU(2)_L \times U(1)_Y \rightarrow U(1)_{\text{EM}}$

- This model has a $U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$ global symmetry
Then Nature is given by...

the most general $\mathcal{L}$

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

- Kinetic terms give rise to the gauge interactions.
- The Gauge interactions are universal (better emphasis that!)
- 3 parameters, $g$, $g'$ and $g_s$
- In the SM only LH fields participate in the weak interaction
- The Higgs part gives the vev and the Higgs mass. 2 parameters. I will not discuss this part
- Yukawa terms: $H\bar{\psi}_L\psi_R$. This is where flavor is. 13 parameters
Yukawa terms

\[ Y^L_{ij} (\bar{L}_L)_i \phi (E_R)_j + Y^D_{ij} (\bar{Q}_L)_i \phi (D_R)_j + Y^U_{ij} (\bar{Q}_L)_i \tilde{\phi} (U_R)_j \]

- The Yukawa matrix, $Y^F_{ij}$, is a general complex matrix.

- After the Higgs acquires a vev, the Yukawa terms give masses to the fermions. Also, after the breaking we can talk about $U_L$ and $D_L$, not about $Q_L$.

- If $Y$ is not diagonal, flavor is not conserved (soon we will go over the subtleties here).

- If $Y$ carries a phase, $CP$ is violated (soon we will understand). $C$ and $P$ is violated to start with.
CP violation

A simple “hand wave” argument of why CP violation is given by a phase

- It is all in the $+h.c.$ term

$$Y_{ij} \left(\bar{Q}_L\right)_i \phi \left(D_R\right)_j + Y^*_{ji} \left(\bar{D}_R\right)_j \phi^\dagger \left(Q_L\right)_i$$

- Under CP

$$Y_{ij} \left(\bar{D}_R\right)_j \phi^\dagger \left(Q_L\right)_i + Y^*_{ji} \left(\bar{Q}_L\right)_j \phi \left(D_R\right)_i$$

- CP is conserved if $Y_{ij} = Y^*_{ij}$

- Not a full proof, since there is still a basis choice...
The CKM matrix

It is all about moving between bases...

- We can diagonalize the Yukawa matrices

\[ Y_{\text{diag}} = V_L Y V_R^\dagger, \quad V_L, V_R \text{ are unitary} \]

- The mass basis is defined as the one with \( Y \) diagonal, and this is when

\[ (d_L)_i \rightarrow (V_L)_{ij} (d_L)_j, \quad (d_R)_i \rightarrow (V_R)_{ij} (d_R)_j \]

- The couplings to the photon is not modifies by this rotation

\[ \mathcal{L}_\gamma \sim \bar{d}_i \delta_{ij} d_i \rightarrow \bar{d}_i V \delta_{ij} V^\dagger d \sim \bar{d}_i \delta_{ij} d_i \]
CKM, $W$ couplings

- For the $W$ the rotation to the mass basis is important

\[ \mathcal{L}_W \sim \bar{u}_L^i \delta_{ij} d_L^i \rightarrow \bar{u}_i V^U_L \delta_{ij} V^D_{L\dagger} d \sim \bar{u}_i V_{CKM} d_i \]

where

\[ V_{CKM} = V^U_L V^D_{L\dagger} \]

- The point is that we cannot have $Y_U$, $Y_D$ and the couplings to the $W$ diagonal at the same basis

- In the mass basis the $W$ interaction change flavor, that is flavor is not conserved
CKM: Remarks

\[ V_{CKM} = V_L^U V_L^{D\dagger} \]

- \( V_{CKM} \) is unitary

- The CKM matrix violates flavor only in charge current interactions, for example, in transition from \( u \) to \( d \)

\[ V_{us} \bar{u} s W^+, \]

- In the lepton sector without RH neutrinos \( V = 1 \) since \( V_L^\nu \) is arbitrary. This is in general the case with degenerate fermions

- When we add neutrino masses the picture is the same as for quarks. Yet, for leptons it is usually not the best to work in the mass basis
FCNC

FCNC = Flavor Changing Neutral Current

- Very important concept in flavor physics
- Important: Diagonal couplings vs universal couplings
In the SM there is no FCNC at tree level. Very nice since in Nature FCNC are highly suppressed

- Historically, $K \rightarrow \mu \nu$ vs $K_L \rightarrow \mu \mu$
- The suppression was also seen in charm and $B$
- In the SM we have four neutral bosons, $g, \gamma, Z, h$. Their couplings are diagonal
- The reasons why they are diagonal, and what it takes to have FCNC, is not always trivial
- Of course we have FCNC at one loop (two charged current interactions give a neutral one)
For exact gauge interactions the couplings are always diagonal. It is part of the kinetic term

$$\partial_\mu \delta_{ij} \to (\partial_\mu + iq_\mu)\delta_{ij}$$

Symmetries are nice...
Higgs tree level FCNC

- The Higgs is a possible source of FCNC. With one Higgs doublet, the mass matrix is aligned with the Yukawa:

\[ \mathcal{L}_m \sim Y v \bar{d}_L d_R \quad \mathcal{L}_{int} \sim Y H \bar{d}_L d_R \]

- With two doublets we have tree level FCNC:

\[ \mathcal{L}_m \sim \bar{d}_L (Y_1 v_1 + Y_2 v_2) d_R \quad \mathcal{L}_{int} \sim H_1 \bar{d}_L Y_1 d_R \]

- There are “ways” to avoid it, by imposing extra symmetries.
For broken gauge symmetry there is no FCNC when: “All the fields with the same irreps if the unbroken symmetry also have the same irreps in the broken part”

In the SM the $Z$ coupling is diagonal since all $q = -1/3$ RH quarks are $(3, 1)_{-1/3}$ under $SU(2) \times U(1)$

What we have in the couplings is

$$\bar{d}_i (T_3)_{ij} d_j \rightarrow \bar{d} V (T_3)_{ij} V^\dagger d_j, \quad VT_3 V^\dagger \propto I \text{ if } T_3 \propto I$$

Adding quarks of different irreps generate tree level FCNC $Z$ couplings

It is the same for new neutral gauge bosons (usually denoted by $Z'$)
A little conclusion

- In the SM flavor is the issue of the 3 generations of quarks
- Flavor is violated by the charged current weak interactions only
- There is no FCNC at tree level. Not trivial, and very important
- All flavor violation is from the CKM matrix
Parameter counting
How many parameters we have?

How many parameters are physical?

- “Unphysical” parameters are those that can be set to zero by a basis rotation
- General theorem

\[ N(\text{Phys}) = N(\text{tot}) - N(\text{broken}) \]

- \( N(\text{Phys}) \), number of physical parameters
- \( N(\text{tot}) \), total number of parameters
- \( N(\text{broken}) \), number of broken generators

- Without the new terms the global symmetry is large, and the new terms break part of it. It is the breaking that can be “used” to find a better basis
Example: Zeeman effect

A hydrogen atom with weak magnetic field

- The magnetic field add one new physical parameter, $B$

$$V(r) = \frac{-e^2}{r} + B \hat{z}$$

- But there are 3 total parameters

$$V(r) = \frac{-e^2}{r} + B_x \hat{x} + B_y \hat{y} + B_z \hat{z}$$

- The magnetic field break the symmetry $SO(3) \rightarrow SO(2)$

- 2 broken generators, can be “used” to define the $z$ axis

$$N(\text{Phys}) = N(\text{tot}) - N(\text{broken}) \quad \Rightarrow \quad 1 = 3 - 2$$