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)
  - Y. Grossman, arXiv:1006.3534

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

$$\boxed{\mathcal{L} = ?}$$

What is HEP

Very simple question

$$\boxed{\mathcal{L} = ?}$$

Not a very simple answer

Basics of model building

$$\boxed{\mathcal{L} = ?}$$

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

$$\phi(1,2)_{+1/2} \qquad \langle\phi\rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$
$$\Rightarrow \quad SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$$

- 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 Higss 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

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

- 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

$$Y_{diag} = V_L Y V_R^\dagger, \qquad V_L, V_R \text{ are unitary}$$

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

$$(d_L)_i \to (V_L)_{ij}(d_L)_j, \qquad (d_R)_i \to (V_R)_{ij}(d_R)_j$$

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

$$\mathcal{L}_\gamma \sim \bar{d}_i \delta_{ij} d_i \;\to\; \bar{d}_i V \delta_{ij} V^\dagger d \sim \bar{d}_i \delta_{ij} d_i$$

CKM, W couplings

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

$$\mathcal{L}_W \sim \bar{u}_L^i \delta_{ij} d_L^i \;\to\; \bar{u}_i V_L^U \delta_{ij} V_L^{D\dagger} d \sim \bar{u}_i V_{CKM} d_i$$

where

$$V_{CKM} = V_L^U V_L^{D\dagger}$$

- 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^ν 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: Diagoal couplings vs univeral couplings

FCNC

In the SM there is no FCNC at tree level. Very nice since in Nature FCNC are highly suppressed

- Historically, $K \to \mu\nu$ vs $K_L \to \mu\mu$
- The suppression was also seen in charm and B
- In the SM we have four neutral bosons, g, γ, 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)

Photon and gluon tree level FCNC

- For exact gauge interactions the couplings arep 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 align with the Yukawa

$$\mathcal{L}_m \sim Y\, v\, \bar{d}_L d_R \qquad \mathcal{L}_{int} \sim Y H \bar{d}_L d_R$$

- With two doublets we have tree level FCNC

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

- There are "ways" to avoid it, by imposing extra symmetries

Z exchange FCNC

- 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

$$\bar{d}_i \,(T_3)_{ij}\, d_j \;\to\; \bar{d} V \,(T_3)_{ij}\, V^\dagger d_j, \qquad V T_3 V^\dagger \propto I \text{ if } T_3 \propto I$$

- 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 batter 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 $SO(3) \to SO(2)$
- 2 broken generators, can be "used" to define the z axis

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