Flavor physics

Yuval Grossman

Cornell

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

\[ \mathcal{L} = ? \]

Not a very simple answer

Basics of model building

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
  $$\phi(1,2)_{+1/2} \quad \langle \phi \rangle = \left( \begin{array}{c} 0 \\ v/\sqrt{2} \end{array} \right)$$
  $$\Rightarrow \quad SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$$
- This model has a $U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$ global symmetry

Yukawa terms

$$Y_{ij}^L \: (\bar{L}_L)_i \phi(E_R)_j + Y_{ij}^D \: (\bar{Q}_L)_i \phi(D_R)_j + Y_{ij}^U \: (\bar{Q}_L)_i \tilde{\phi}(U_R)_j$$

- The Yukawa matrix, $Y_{ij}^F$, 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

Then Nature is given by...

the most general $\mathcal{L}$

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

- 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

CP violation

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

- It is all in the $+h.c.$ term
  $$Y_{ij} \: (\bar{Q}_L)_i \phi(D_R)_j + Y_{ij}^* \: (\bar{D}_R)_j \phi^\dagger(\bar{Q}_L)_i$$
- Under CP
  $$Y_{ij} \: (\bar{D}_R)_j \phi^\dagger(\bar{Q}_L)_i + Y_{ij}^* \: (\bar{Q}_L)_i \phi(\bar{D}_R)_j$$
- 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
  \[ \mathcal{L}_\gamma \sim \bar{d}_i \delta_{ij} d_i \rightarrow \bar{d}_i V_{\text{CKM}} \delta_{ij} V^\dagger d_i \]

CKM: Remarks

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

- \( V_{\text{CKM}} \) 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 \( V_L^U \) 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

CKM, \( W \) couplings

- For the \( W \) the rotation to the mass basis is important
  \[ \mathcal{L}_W \sim \bar{u}_i \delta_{ij} d_i \rightarrow \bar{u}_i V_L^U \delta_{ij} V_L^D d_i \sim \bar{u}_i V_{\text{CKM}} d_i \]
  where
  \[ V_{\text{CKM}} = V_L^U V_L^D \]
- 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

FCNC

FCNC = Flavor Changing Neutral Current

- Very important concept in flavor physics
- Important: Diagoal couplings vs univeral 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)

Photon and gluon tree level FCNC

For exact gauge interactions the couplings are always diagonal. It is part of the kinetic term

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

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

$$\mathcal{L}_m \sim Y v d_L d_R \quad \mathcal{L}_{int} \sim Y H d_L d_R$$

With two doublets we have tree level FCNC

$$\mathcal{L}_m \sim d_L (Y_1 v_1 + Y_2 v_2) d_R \quad \mathcal{L}_{int} \sim H_1 d_L Y_1 d_R$$

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

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

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

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