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 great 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

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

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

$$Q_L(3,2)_{1/6} \quad U_R(3,1)_{2/3} \quad D_R(3,1)_{-1/3}$$
$$L_L(1,2)_{-1/2} \quad E_R(3,1)_{-1}$$

- SSB: one scalar

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

- 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
- 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

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

- The Yukawa matrix, Y_{ij}^F, is a general complex matrix
- After the Higss 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

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

  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 ass 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

$$\partial_\mu \delta_{ij} \to (\partial_m u + i q_\mu) \delta_{ij}$$

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

$$\bar{d}_i \, (T_3)_{ij} \, d_j \;\rightarrow\; \bar{d} V \, (T_3)_{ij} \, V^\dagger d_j, \qquad VT_3V^\dagger \propto I \text{ if } T_3 \propto I$$

- 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

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

Back to the flavor sector

Without the Yukawa interaction, a model with N copies of the same field has a $U(N)$ global symmetry (the symmetry of the kinetic term). It has N^2 generators

- First example, leptons in the “old” SM: L, E
- One Yukawa matrix: $N_T = 18$
- Global symmetries: $U(3)^2$, 18 generators
- Exact accidental symmetries: $U(1)^3$, 3 generators
- Broken generators due to the Yukawa: $N_B = 18 - 3 = 15$
- Physical parameters: $N_P = 18 - 15 = 3$. They are the 3 charged lepton masses

Two generations of quarks

Q_i, D_i, U_i, $i = 1, 2$

Do it yourself...

Two generations of quarks

Q_i, D_i, U_i, $i = 1, 2$

Do it yourself...

$$N_T = 2 \times 8 = 16$$
$$N_G = 3 \times 4 = 12$$
$$N_U = 1$$
$$N_B = 12 - 1 = 11$$

So we have

$$N_P = 16 - 11 = 5$$

4 masses and 1 mixing angle

The SM flavor sector

Back to the SM with three generations

- $N_T = 2 \times 18 = 36$
- $N_G = 3 \times 9 = 27$
- $N_U = 1$
- $N_B = 27 - 1 = 26$
- $N_P = 36 - 26 = 10$
- 6 quark masses, 3 mixing angles and one CPV phase
- Remark: The broken generators are 17 Im and 9 Re. We have 18 to “start with” so the physical ones are $18 - 17 = 1$ and $18 - 9 = 9$

Homework

Consider a model with the same gauge symmetry and SSB as in the SM. The fermions, however, are

$$Q_L(3,2)_{1/6}, \quad S_L(3,1)_{-1/3}, \quad Q_R(3,2)_{1/6}, \quad S_R(3,1)_{-1/3}$$

- What is the spectrum of this model? That is, what are the quarks after SSB. Note that you can also have "bare masses" in this model. Also, there is no flavor index
- How many physical parameters there are, and what are they?
- Are there W exchange flavor changing interactions?
- Is there tree level-FCNC in this model?

The CKM matrix

The flavor parameters

- The 6 masses. We kind of know them. There is a lot to discuss, but I will not do it in these lectures
- The CKM matrix has 4 parameters
  - 3 mixing angles (the orthogonal part of the mixing)
  - One phase (CP violating)
- Thus we concentrate on trying to find ways to determine the CKM mixing angle and phase

The CKM matrix

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} \overline{U_L} V \gamma^\mu D_L W_\mu^+ + \text{h.c.}$$

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- CKM is unitary

$$\sum V_{ij} V_{ik}^* = \delta_{jk}$$

- Experimentally, $V \sim 1$. Off diagonal terms are small
- Many (infinite) ways to parametrize the matrix

CKM parametrization

- The standard parametrization

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

  where $c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$.

- In general there are 5 entries that carry a phase
- Experimentally: (will explain later how these measurements were done)

$$|V| \approx \begin{pmatrix} 0.97383 & 0.2272 & 3.96 \times 10^{-3} \\ 0.2271 & 0.97296 & 4.221 \times 10^{-2} \\ 8.14 \times 10^{-3} & 4.161 \times 10^{-2} & 0.99910 \end{pmatrix}$$

The Wolfenstein parametrization

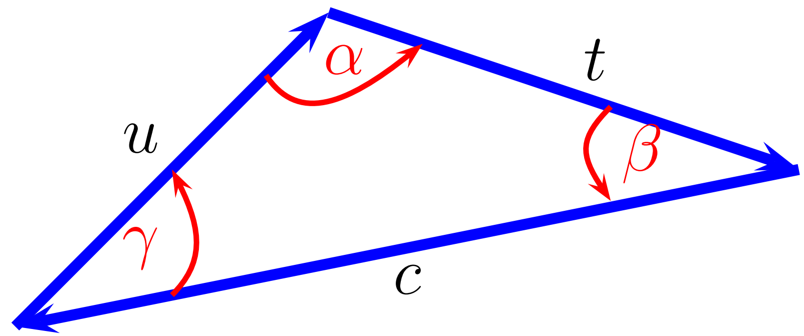
- Since $V \sim 1$ it is useful to expand it

$$V \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- One small parameter $\lambda \sim 0.2$, and three that are roughly $O(1)$
- As always, be careful (unitarity...)
- Note that to this order only V_{13} and V_{31} have a phase

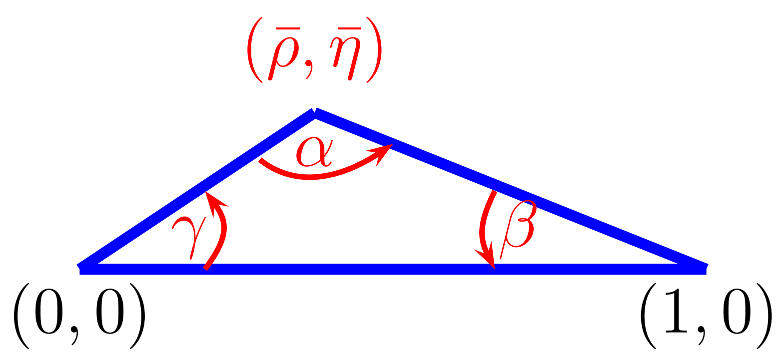
The unitarity triangle

A geometrical presentation of $V_{ub}^* V_{ud} + V_{tb}^* V_{td} + V_{cb}^* V_{cd} = 0$



Rescale by the c size and rotated

$$A\lambda^3 \left[(\rho + i\eta) + (1 - \rho - i\eta) + (-1) \right] = 0$$



Where are we?

- The SM is about measuring all the parameters and using more measurements to check it
- Flavor physics is: Make 4 measurements and from the 5th on we check the model
- But it is a bit more exciting...

The NP flavor problem

The flavor problems

- “Problem” is not a problem. It is a hint for something more fundamental
- The SM flavor problems
  - Why there are 3 generations?
  - Why the mass ratios and mixing angles are small and hierarchical?
- The NP flavor problem is different

The SM is not perfect...

- We know the SM does not describe gravity
- At what scale it breaks down?

We parametrize the NP scale as the denominator of an effective higher dimension operator. The weak scale is roughly

$$\mathcal{L}_{\text{eff}} = \frac{\mu\, e\nu\bar{\nu}}{\Lambda_W^2} \Rightarrow \Lambda_W \sim 100 \text{ GeV}$$

- The effective scale is roughly the masses of the new fields times unknown couplings
- Flavor bounds give $\Lambda \gtrsim 10^4 \text{ TeV}$

Flavor and the hierarchy problem

There is tension:

- The hierarchy problem $\Rightarrow$ $\Lambda \sim 1$ TeV
- Flavor bounds $\Rightarrow$ $\Lambda \gtrsim 10^4$ TeV

Any TeV scale NP has to deal with the flavor bounds

$$\Downarrow$$

Such NP cannot have a generic flavor structure

> Flavor is mainly an input to model building, not an output

Summary

- The SM flavor sector is minimal
  - FCNC only at one loop and thus suppressed
  - CPV from one source
- In general NP give too large correction to this picture
- Flavor physics is a way to look for physics beyond the SM

We need to measure flavor parameters in many ways to look for discrepancies