Flavor physics

Yuval Grossman

Cornell

General remarks

- I have to make assumptions about what you know
- Please ask questions (in class and outside)
- Email: yg73@cornell.edu
- Much more in
  - Book: https://www.classe.cornell.edu/∼yuvalg/
  - TASI lectures: "Just a taste” 1711.03624
  - Online lectures on the SM and on Flavor
- The plan:
  - Flavor in the SM
  - Flavor beyond the SM

Some data

$$\text{Br}(K_L \to \mu^+\mu^-)\ [s \to d\mu^+\mu^-] = 6.84 \times 10^{-9}$$
$$\text{Br}(K^- \to \mu^-\bar{\nu})\ [s \to u\mu^-\bar{\nu}] = 0.6356$$

$$\text{Br}(D^+ \to \bar{K}^0 e^+\nu)\ [c \to se^+\nu] = 8.82 \times 10^{-2}$$
$$\text{Br}(D^+ \to \bar{K}^0 \mu^+\nu)\ [c \to s\mu^+\nu] = 8.74 \times 10^{-2}$$

$$\text{Br}(B \to X_c e\nu)\ [b \to ce\nu] = 0.1086$$
$$\text{Br}(B_s \to \mu^+\mu^-)\ [b \to s\mu^+\mu^-] = 2.4 \times 10^{-9}$$
$$\text{Br}(B^- \to D^0\mu^-\bar{\nu})\ [b \to c\mu^-\bar{\nu}] = 2.27 \times 10^{-2}$$
$$\text{Br}(B^- \to \pi^0\mu^-\bar{\nu})\ [b \to u\mu^+\bar{\nu}] = 7.80 \times 10^{-5}$$

- What patterns do you see?

What we learn from the data

- **Lepton universality**. Swapping one generation of leptons with another does not appear to affect the branching ratios of these transitions.
- **Flavor-changing neutral currents are small**. Charge-neutral transitions are suppressed compared to transitions between hadrons of different charge.
- **Generation hierarchy**. Decays between third and first generation are suppressed compared to that of third to second generation.

The hope is to understand these within the SM

What is HEP?

What is HEP?

Find the basic laws of Nature

More formally

$$\mathcal{L} = ?$$

- We have quite a good answer
- It is very elegant, it is based on axioms and symmetries
- We use particles to answer this question

Building Lagrangians

- We built a Lagrangian by the following input
  - The symmetries we impose
  - The fields and their transformations
- The output is the Lagrangian such that
  - It is the most general that obeys the symmetries
  - We truncate it at some order, usually fourth

Example: A SM

(i) The symmetry is a local

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

(ii) There are three fermion generations (QUDLE)

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

$$L_L(1,2)_{-1/2}, \quad E_R(1,1)_{-1}$$

(iii) There is a single scalar multiplet

$$\phi(1,2)_{+1/2}$$

$\mathcal{L}$ for a SM

The most general $\mathcal{L}$ is given by

$$\mathcal{L} = \mathcal{L}_{\rm kin} + \mathcal{L}_\psi + \mathcal{L}_\phi + \mathcal{L}_{\rm Yuk}$$

- No mass term for the fermions: $\mathcal{L}_\psi = 0$
- Kinetic terms (with gauge interactions)
- The scalar potential that lead to SSB

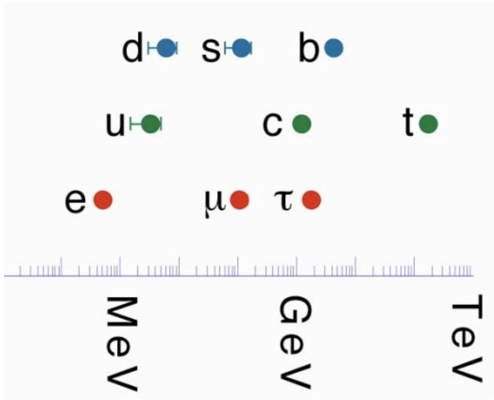
$$-\mathcal{L}_\phi = -\mu^2 \phi^\dagger \phi + \lambda \left(\phi^\dagger \phi\right)^2$$

- The Yukawas that lead to fermion masses

$$\mathcal{L}_{\rm Yuk} \sim Y^U QU\phi + Y^D QD\phi + Y^\ell LE\phi$$

A SM vs The SM

- “A SM” is the theory without the values of the parameters
- “The SM” is the one we have with a given set of values for the parameters
- The hierarchy of masses is a "The SM" thing



- "A SM" and even more "The SM" are very delicate. The fact that they work is far from trivial

The SM: Flavor physics

Moving between the bases

Flavor is about moving between the bases

Vocabulary

- Flavor basis: The couplings to the W are diagonal
- Mass basis: Where the mass matrix is diagonal

Basis choice

Consider the following three matrices

- Down-type mass
- Up-type mass
- Coupling to the W

We can at most diagonalize two out of the three matrices

- We usually choose the coupling to the W to be the non-diagonal one
- For the leptons m_ν vanishes so we have only two matrices to deal with

The CKM matrix

In the mass basis we have

$$\mathcal{L}_W \sim V_{ij}\, u_i\, d_j\, W$$

- V is called the CKM matrix
- The point is that we cannot have m_U, m_D and the couplings to the W to be diagonal in the same basis
- In the mass basis the W interaction change flavor, that is, flavor is not conserved

The CKM matrix

The CKM matrix is

- Unitary
- Four parameters: three angles and a phase

$$|V_{us}|, \quad |V_{cb}|, \quad |V_{ub}|, \quad \delta_{KM}$$

  δ_{KM} is related to CPV

- Close to a unit matrix

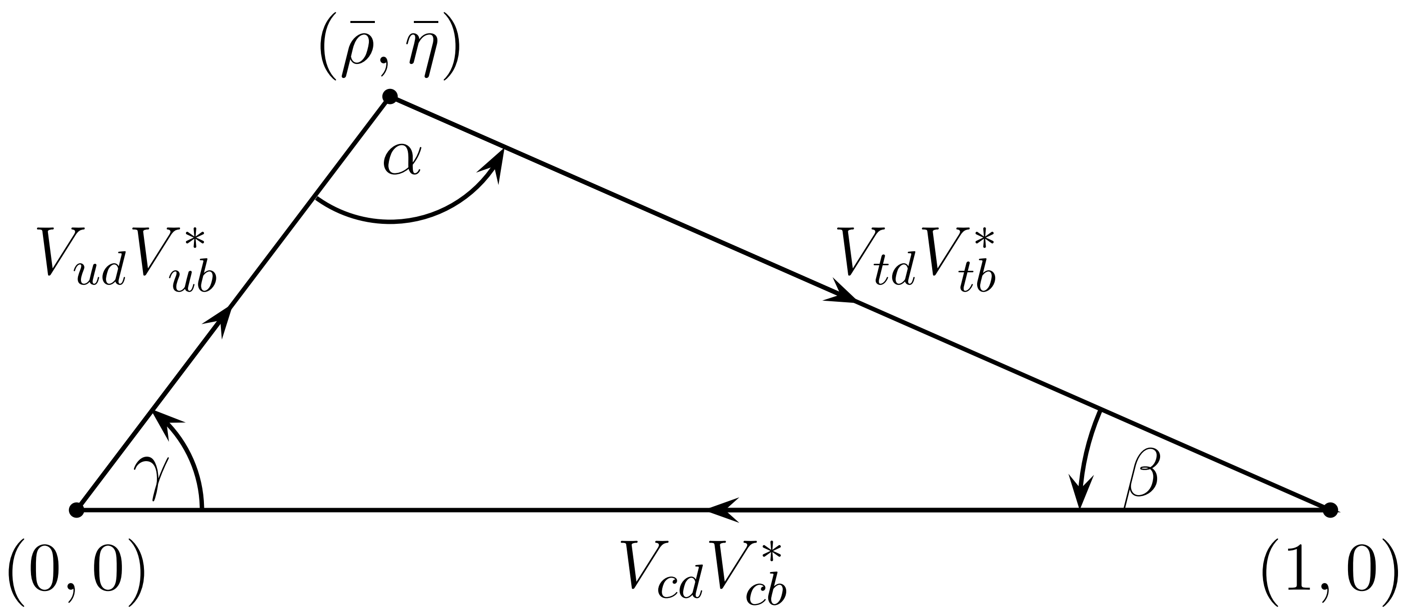
$$|V| \approx \begin{pmatrix} 0.97383 & 0.2272 & 3.96 \times 10^{-3} \\ 0.2271 & 0.97296 & 4.221 \times 10^{-2} \\ 8.14 \times 10^{-3} & 4.161 \times 10^{-2} & 0.99910 \end{pmatrix}$$

The Unitarity Triangle

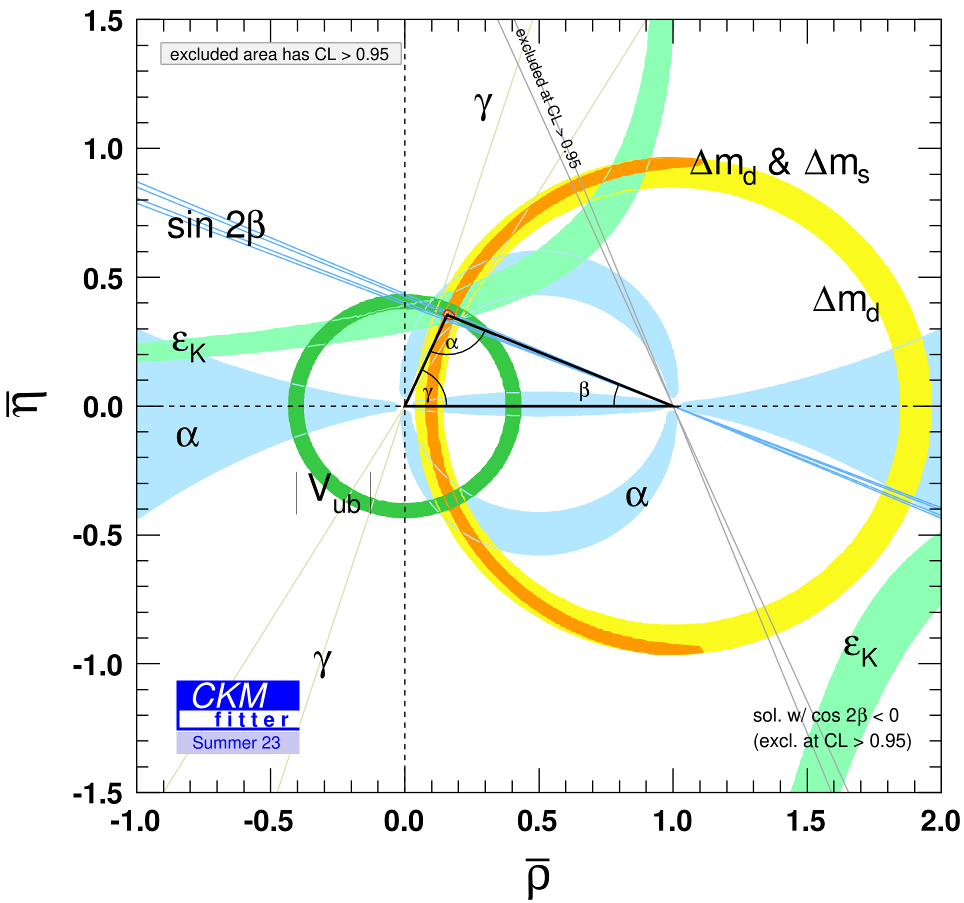
- Since the CKM is unitary its elements satisfy

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

- A nice way to describe it



The SM works



excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
|V_ub|
α
ε_K
γ
CKM fitter
Summer 23
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
η̄
ρ̄

FCNC

FCNC

Very important concept in flavor physics

- FCNC=Flavor Changing Neutral Current
- FCCC=Flavor Changing Charged Current
- For example, $b \to c\ell\nu$ vs $b \to s\ell^+\ell^-$

- Vocabulary: diagonal couplings vs universal couplings

FCNC in Nature

- In Nature FCNC are highly suppressed
  - Historically, $K \to \mu\nu$ vs $K_L \to \mu\mu$
  - The suppression was also seen in c and b decays
- In the SM there are no FCNC at tree level. Very nice!
  - 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 are always diagonal. It is part of the kinetic term

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

- Symmetries are nice...
- In any extension of the SM the photon and gluon couplings are flavor diagonal

Higgs tree level FCNC

- The Higgs is a possible source of FCNC
- With one Higgs doublet, the mass matrix is aligned with the Yukawa. $\phi \sim v + H$

$$\mathcal{L}_m \sim Y_{ij}\, v\, \bar{d}^i_L d^j_R \qquad \mathcal{L}_{int} \sim Y_{ij} H \bar{d}^i_L d^j_R$$

- With two doublets we could have tree level FCNC

Z exchange FCNC

- For broken gauge symmetry there is no FCNC when: "All the fields with the same QN in the unbroken symmetry also have the same QN 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 $SU(2) \times U(1)$
- Adding quarks with different representations can generate tree level FCNC Z couplings, like $b'_L(3,1)_{-1/3}$
- Same condition for new neutral gauge bosons (usually denoted by Z')

Tree level FCNC in "a SM"

- In a generic model we expect tree-level FCNC
- In a SM there are specific reasons for not having it
  - All fermions with the same charge also have the same hypercharge
  - There is only one Higgs doublet
- We need to be careful when extending the SM

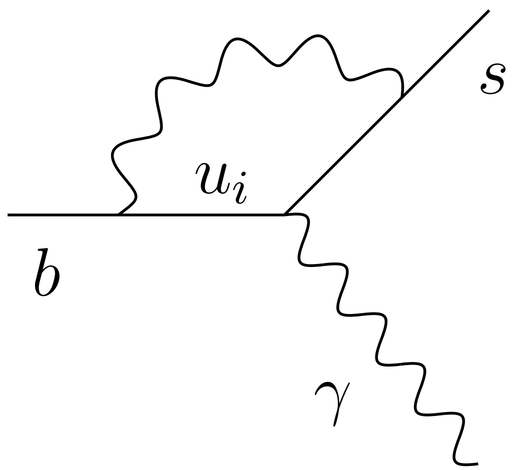
FCNC at one loop

FCNC at one loop

- We understand why FCNC are suppressed in “a SM”: There is no tree level exchange
- Yet, there are more suppression factors in “The SM”
  - CKM factors
  - Mass ratio factors: GIM mechanism
- The loop factor in “a SM” is universal
- The other factors in “the SM” are not universal, they depend on the quarks that are involved

Loop: example

$A(b \to s\gamma) \propto \sum V_{ib} V_{is}^*$



What is $\sum V_{ib} V_{is}^*$?

GIM Mechanism

What we really have is

$$A(b \to s\gamma) \propto \sum V_{ib} V_{is}^* f(m_i)$$

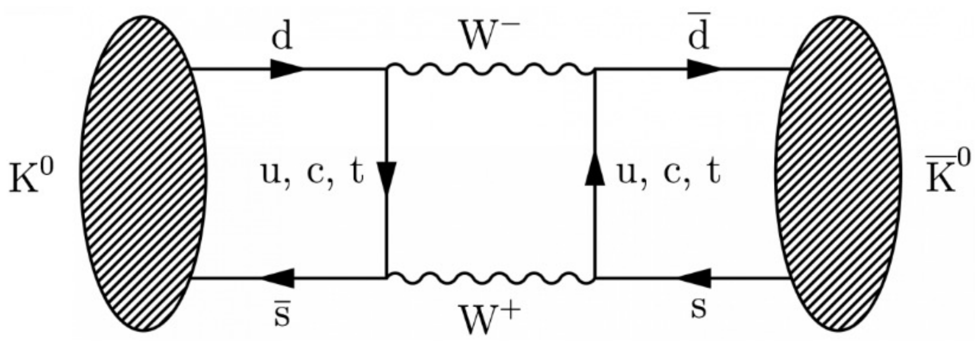
- Unitarity of the CKM $\Rightarrow$ m_i independent term in f vanishes $\Rightarrow$ The amplitude depend on the masses
- For $m_i \ll m_W^2$ we have

$$A \sim \frac{m_i^2}{m_W^2}$$

  - In s decays it gives m_c^2/m_W^2 extra suppression
  - In charm it gives m_s^2/m_W^2 extra suppression
  - Numerically, not important for b decays, $m_t \sim m_W$

Example: kaon mixing

Roughly it is giving by box diagram

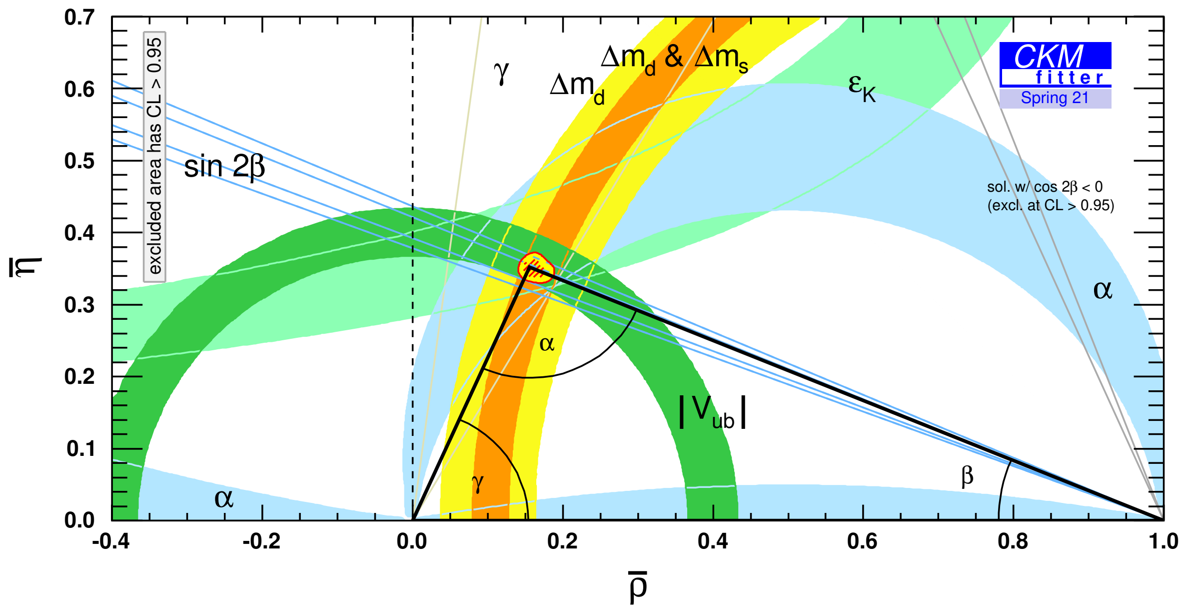


- The result is

$$\Delta m_K \sim \frac{g^4}{16\pi^2} \times \frac{m_c^2}{m_W^2} \times |V_{us}V_{ud}|^2 \sim 10^{-8}$$

- Different factors for different mesons

Summary: The SM is very special



- "A SM" is special
- "The SM" is even more special

The fact that the data confirm the SM is far from trivial