Flavor physics

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Extra HW

You can find some notes and HW at

www.lepp.cornell.edu/$\sim$yuvalg/p645

Yesterday...

- Parameter counting
- The CKM matrix and its determination
- Started meson mixing

Today we will talk about meson mixing and CPV

Meson mixing

Meson mixing

$$|f_1\rangle(t) = \exp\left[i\Delta E t/2\right]|1\rangle + \exp\left[-i\Delta E t/2\right]|2\rangle$$

The probability to measure flavor f_i at time t is

$$|\langle f_1|f_1\rangle|^2 = \frac{1+\cos\Delta E t}{2}$$

$$|\langle f_1|f_2\rangle|^2 = \frac{1-\cos\Delta E t}{2}$$

- Oscillations with frequency ΔE
- In the rest frame it is just Δm
- The relevant time scale is $x \equiv \Delta m/\Gamma$

Calculations of Δm

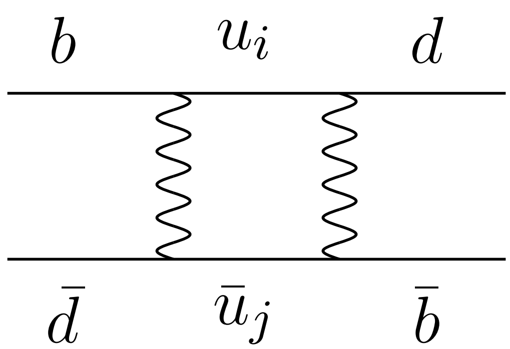
- There are 4 neutral mesons: $K(\bar{s}d)$, $B(\bar{b}d)$, $B_s(\bar{b}s)$, $D(c\bar{u})$
  - Why not charged mesons?
  - Why not the neutral pion?
  - Why not the K^*
- The two flavor eigenstate B and $\bar{B}$ mix via the weak interactions. It is an FCNC process $m_{weak} = A(B \to \bar{B})$
- In the SM it is a loop process, and it gives an effect that is much smaller than the mass

$$M = \begin{pmatrix} m_B & m_{weak} \\ m_{weak} & m_B \end{pmatrix} \quad \Rightarrow \quad M_{H,L} = m_B \pm m_{weak}/2$$

$$\Delta M = m_{weak}$$

The box diagram

- In the SM the mixing is giving by the box diagram



- The result is

$$\Delta M \propto \sum_{i,j} V_{is}V_{id}^{*}V_{js}V_{jd}^{*} f(m_i, m_j)$$

- To leading order $f \sim m_i^2/m_W^2$ so for K mixing m_c^2/m_W^2 suppression

Meson mixing: remarks

- Mixing can be used to determined magnitude of CKM elements. The heavy fermion is the dominant one. For example B mixing is used to get $|V_{td}|$
- There are still hadronic uncertainties. We calculate at the quark level and we need the meson. Lattice QCD is very useful here
- My treatment was very simplistic, there are more effects
- Each meson have its own set of approximations

Meson mixing

In general we have also width different between the two eigenstates. They are due to common final states.

$$x \equiv \frac{\Delta m}{\Gamma} \qquad y \equiv \frac{\Delta \Gamma}{2\Gamma}$$

K	$x \sim 1$	$y \sim 1$
D	$x \sim 10^{-2}$	$y \sim 10^{-2}$
B_d	$x \sim 1$	$y \sim 10^{-2}$
B_s	$x \sim 10$	$y \sim 10^{-1}$

Mixing measurements

How this is done?

- Need the flavor of the initial state. Usually the mesons are pair produced
  - Same side tagging ($D^* \to D\pi$)
  - Other side tagging (semileptonic B decays)
- The final flavor
  - Use time dependent (easier for highly boosted mesons)
  - Use time integrated signals
  - The final state may not be a flavor eigenstate, but we still can have oscillations as long as it is not a mass eigenstate

CPV

What is CP

- A symmetry between a particle and its anti-particle
- CP is violated if we have

$$\Gamma(A \to B) \neq \Gamma(\bar{A} \to \bar{B})$$

- It is a very small effect in Nature, and thus sensitive to NP
- In the SM it is closely related to flavor
- We do not discuss the strong CP problem that is not directly related to flavor
- We also do not discuss the need for CP for baryogenesis

How to find CPV

It is not easy to detect CPV

- Always need interference of two (or more) amplitudes
- CPT implies that the total widths of a particles and it anti-particles are the same, so we need at least two modes with CPV
- To see CPV we need 2 amplitudes with different weak and strong phases

All these phases

- Weak phase (CP-odd phase)
  - Phase in $\mathcal{L}$
  - In the SM they are only in the weak part so they are called weak phases

$$CP(Ae^{i\phi}) = Ae^{-i\phi}$$

Strong phase

- Strong phase (CP-even phase). Do not change under CP

$$CP(Ae^{i\delta}) = Ae^{i\delta}$$

  - Due to time evolution

$$\psi(t) = e^{iHt}\psi(0)$$

  - They are also due to intermediate real states, and have to do with “rescattering” of hadrons
  - Such strong phases are very hard to calculate

Why we need the two phases?

Intuitive argument

- If we have only one $|A|^2 = |\bar{A}|^2$
- Two but with a different of only weak phase

$$\left|A + be^{i\phi}\right|^2 = \left|A + be^{-i\phi}\right|^2$$

- When both are not zero it is not the same (do it for HW!)

CPV remarks

- The basic idea is to find processes where we can measure CPV
- In some cases they are clean so we get sensitivity to the phases of the UT (or of the CKM matrix)
- We can be sensitive to the CP phase without measuring CP violation
- Triple products and EDMs are also probes of CPV. I will not talk about that
- So far CPV was only found in meson decays, K_L, B_d and $B^{\pm}$, and we will concentrate on that

The three classes of CPV

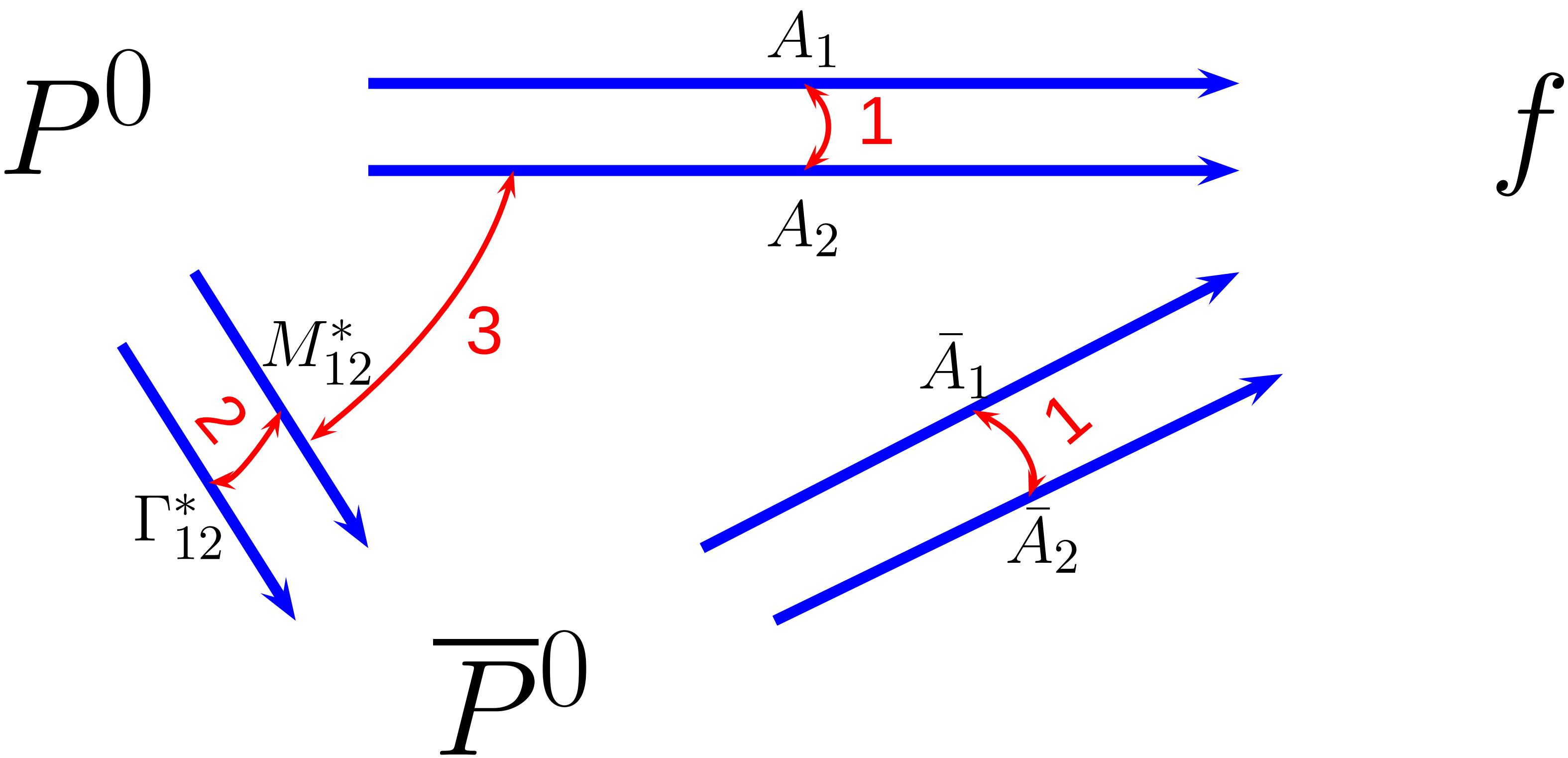
We need to find processes where we have two interfering amplitudes

- Two decay amplitudes
- Two oscillation amplitudes
- One decay and one oscillation amplitudes

Where the phases are coming from?

- Weak phases from the decay or mixing amplitudes (SM or NP)
- Strong phase is the time evolution (mixing) or the rescattering (decay)

The 3 classes



- 1: Decay 2: Mixing 3: Mixing and decay

Type 1: CPV in decay

Two decay amplitudes

$$|A(B \to f)| \neq |A(\bar{B} \to \bar{f})|$$

- The way to measure it is via

$$a_{CP} \equiv \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)} = \frac{|\bar{A}/A|^2 - 1}{|\bar{A}/A|^2 + 1}$$

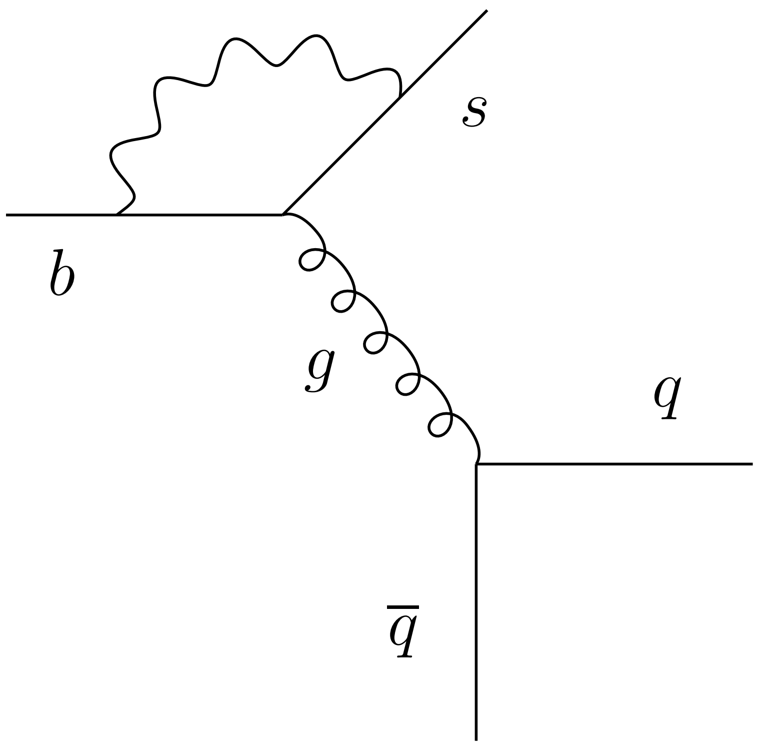
- If we write $A = A\,(1 + r\exp[i(\phi + \delta)])$

$$a_{CP} = r \sin\phi \sin\delta$$

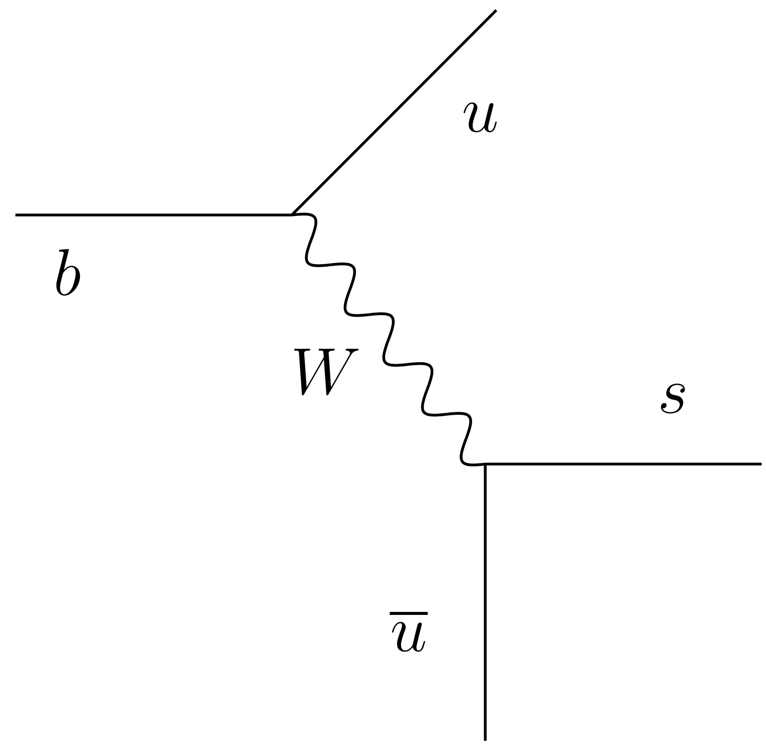
- We like r, δ and ϕ to be large
- Work for decays of both charged and neutral hadrons

CPV in decay, example: $B \to K\pi$

(P) + (P_{EW})



(T)



P is a loop amplitude, but due to CKM factors $P/T \sim 3$. We also have a strong phase difference

One more example: $B \to DK$

- A bit ore “sophisticated” example of CPV in decay
- Theoretically by far the cleanest measurement of any CKM parameter

Mixing formalism with CPV

When there is CPV the mixing formalism is more complicated. Diagonalizing the Hamiltonian we get

$$B_{H,L} = p|B\rangle \pm q|\bar{B}\rangle$$

- In general B_H and B_L are not orthogonal
- This is because they are “resonances” not asymptotic states. Open system
- The condition for the non orthogonality is CPV

2: CPV in mixing

The second kind of CPV is when it is pure in the mixing

$$|q| \neq |p| \qquad (B_{H,L} = p|B\rangle \pm q|\bar{B}\rangle)$$

We measure it by semileptonic asymmetries

- It was measured in

$$\frac{\Gamma(K_L \to \pi\ell^+\nu) - \Gamma(K_L \to \pi\ell^-\bar{\nu})}{\Gamma(K_L \to \pi\ell^+\nu) + \Gamma(K_L \to \pi\ell^-\bar{\nu})} = (3.32 \pm 0.06) \times 10^{-3}$$

- This is so far the only way we can define the electron microscopically!

3: CPV in interference mixing & decay

Interference between decay and mixing amplitudes

$$A(B \to f_{CP}) \qquad A(B \to \bar{B} \to f)$$

- Best with one decay amplitude
- Very useful when f is a CP eigenstate
- In that case $|A(B \to f_{CP})| = |A(\bar{B} \to f_{CP})|$

Some definitions

$$\lambda \equiv \frac{q}{p}\frac{\bar{A}}{A}$$

In the case of a CP final state

- $\lambda \neq \pm 1 \;\Rightarrow$ CPV
  - $|\lambda| \neq 1$ because $|A| \neq |\bar{A}|$. CPV in decay
  - $|\lambda| \neq 1$ because $|q| \neq |p|$. CPV in mixing
  - The cleanest case $|\lambda| \approx 1$ and $Im(\lambda) \neq 0$. Interference between mixing and decay
- We can have several classes at the same time
- In the clean cases we have one dominant source

Formalism

B at $t = 0$ compared to a $\bar{B}$ and let them evolve

$$a_{CP}(t) \equiv \frac{\Gamma(B(t) \to f) - \Gamma(\bar{B}(t) \to f)}{\Gamma(B(t) \to f) + \Gamma(\bar{B}(t) \to f)}$$

Consider the case where $|\lambda| = 1$

$$A_{CP}(t) = -Im\lambda \sin \Delta m t$$

- We know Δm so we can measure $Im\lambda$
- $Im\lambda$ is the phase between mixing and decay amplitudes
- When we have only one dominant decay amplitude all the hadronic physics cancel (YES!!!)
- In some cases this phase is $O(1)$

Example: $B \to \psi K_S$

Reminder ψ is a $\bar{c}c$, K_S is s and d

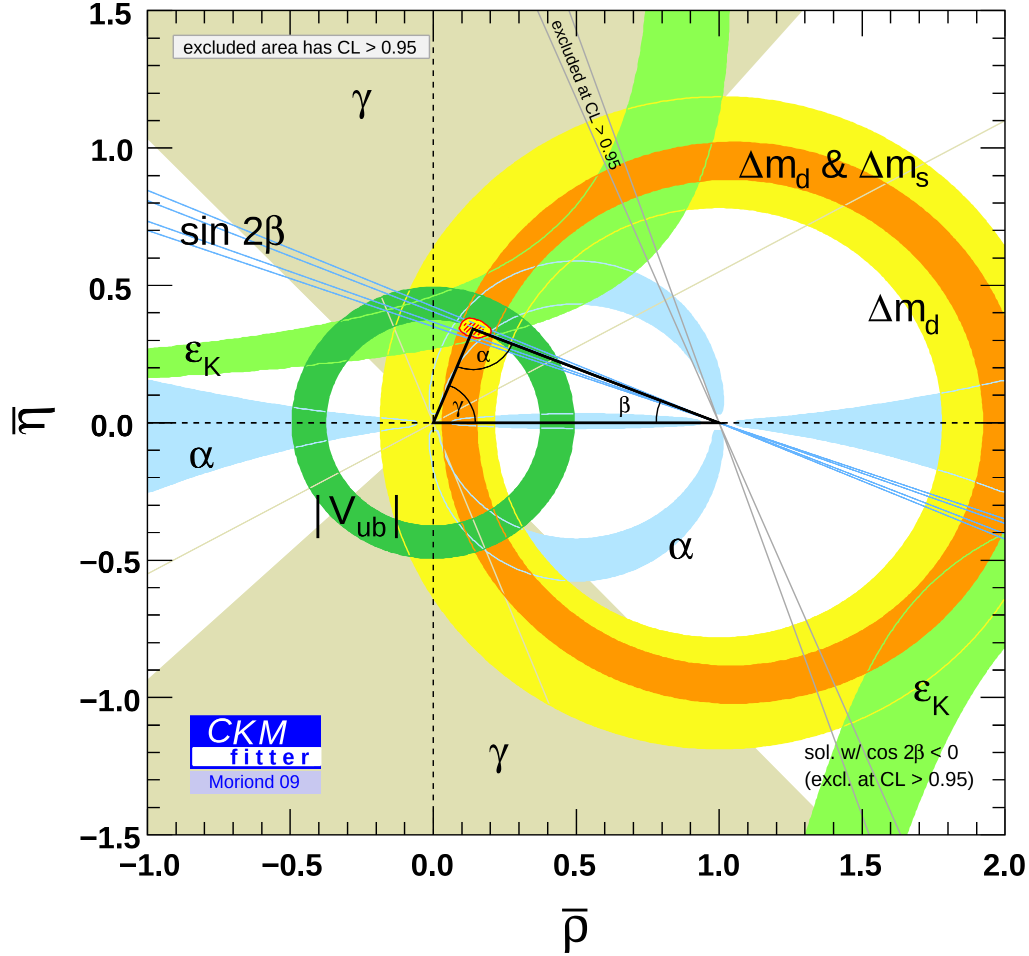
- One decay amplitude, tree level $A \propto V_{cb}V_{cs}^*$. In the standard parametrization it is real
- Very important: $|A| = |\bar{A}|$ to a very good approximation.
- In the standard parametrization $q/p = \exp(2i\beta)$ to a very good approximation
- We then get

$$Im\lambda = Im\left[\frac{q}{P}\frac{\bar{A}}{A}\right] = \sin 2\beta$$

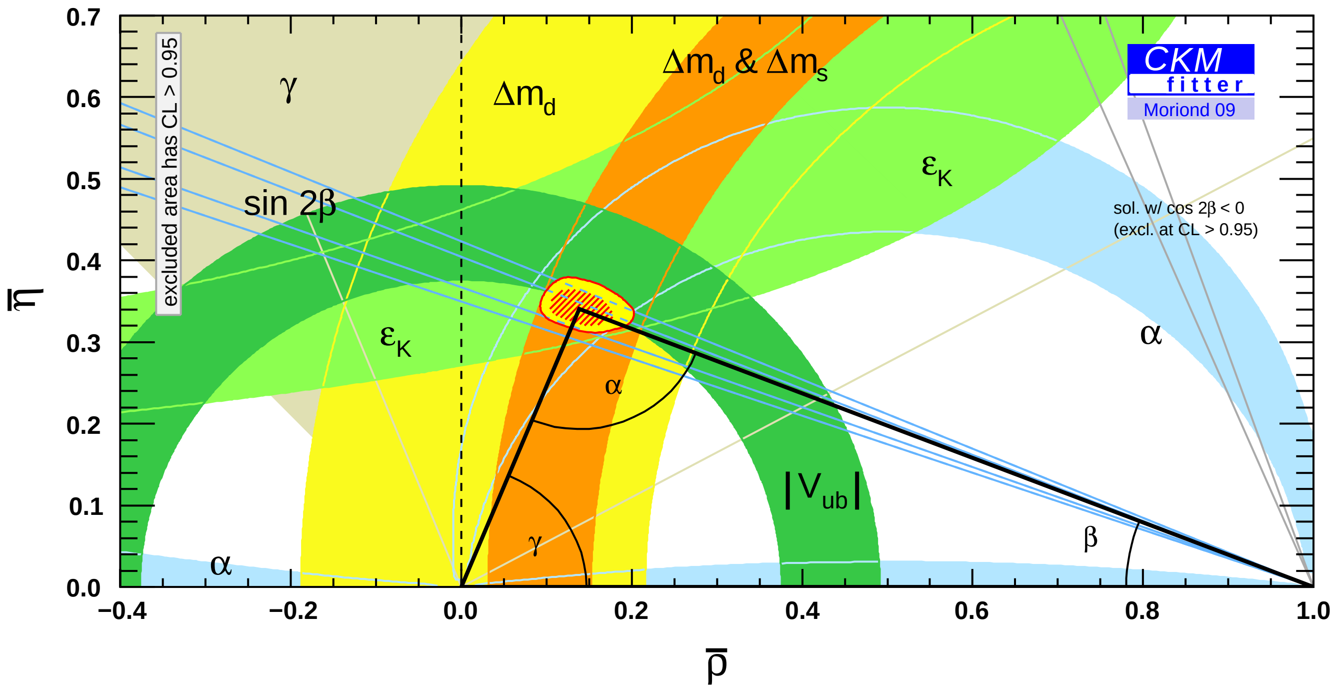
- For HW do some other decays: D^+D^-, $\pi^+\pi^-$, ϕK_S and $B_s \to \psi\phi$ (Ignore the subtleties)

Instead of summary

All together now



Zoom in



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$\bar{\eta}$
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excluded area has CL > 0.95
γ
Δm_d
Δm_d & Δm_s
CKM
fitter
Moriond 09
ε_K
sin 2β
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
α
|V_ub|
β

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

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

- 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