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- Lecture 1: Introduction to flavor physics
  - Introduction
  - The flavor structure of the Standard Model
  - Properties of the CKM matrix and CKM fits
  - The two flavor puzzles
  - The flavor of the SMEFT
  - New Physics bounds from meson-antimeson mixing

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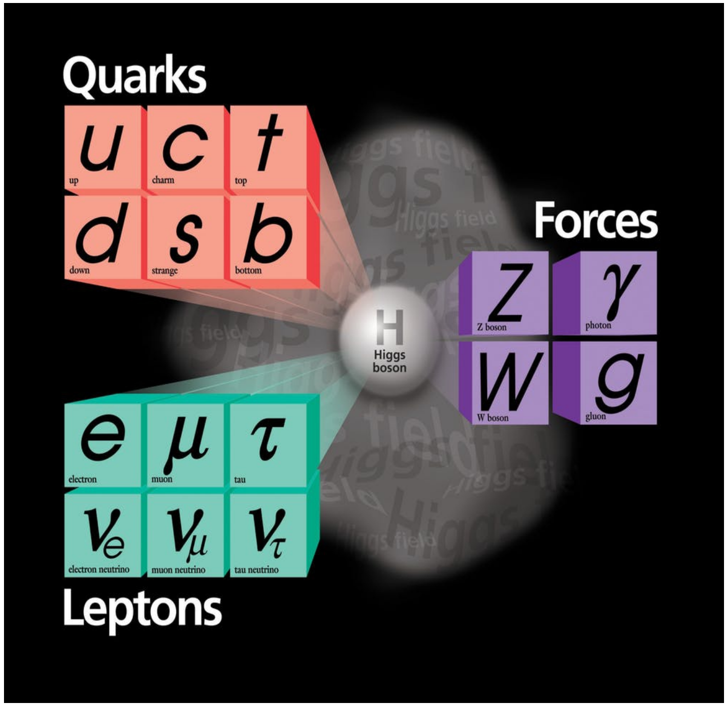
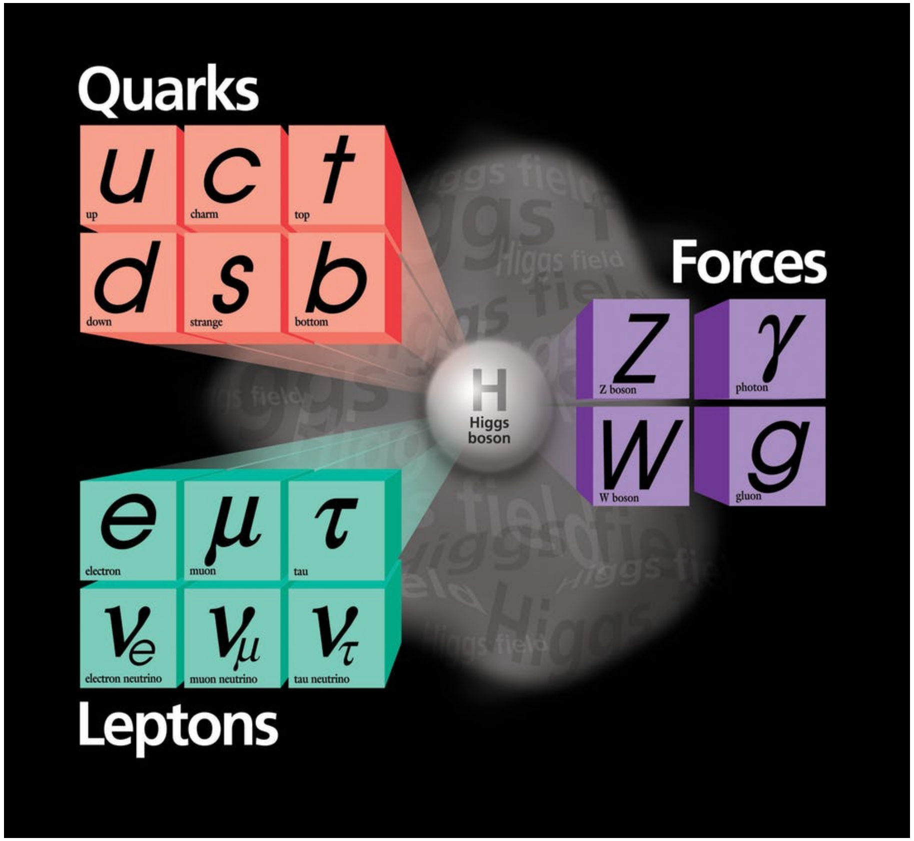
Introduction



Introduction

All microscopic phenomena seems to be well described by a remarkably simple Theory (*that we continue to call "model" only for historical reasons...*):

$$\mathscr{L}_{\text{Standard Model}} = \mathscr{L}_{\text{gauge}}(\psi_i, A_a) + \mathscr{L}_{\text{Higgs}}(\mathrm{H}, A_a, \psi_i)$$



Introduction

Despite all its phenomenological successes, this Theory has some deep unsolved problems:

Electroweak hierarchy problem

Flavor puzzle

Neutrino masses

U(1) charges

Dark-matter

Dark-energy

Inflation

Quantum gravity

$\Rightarrow$

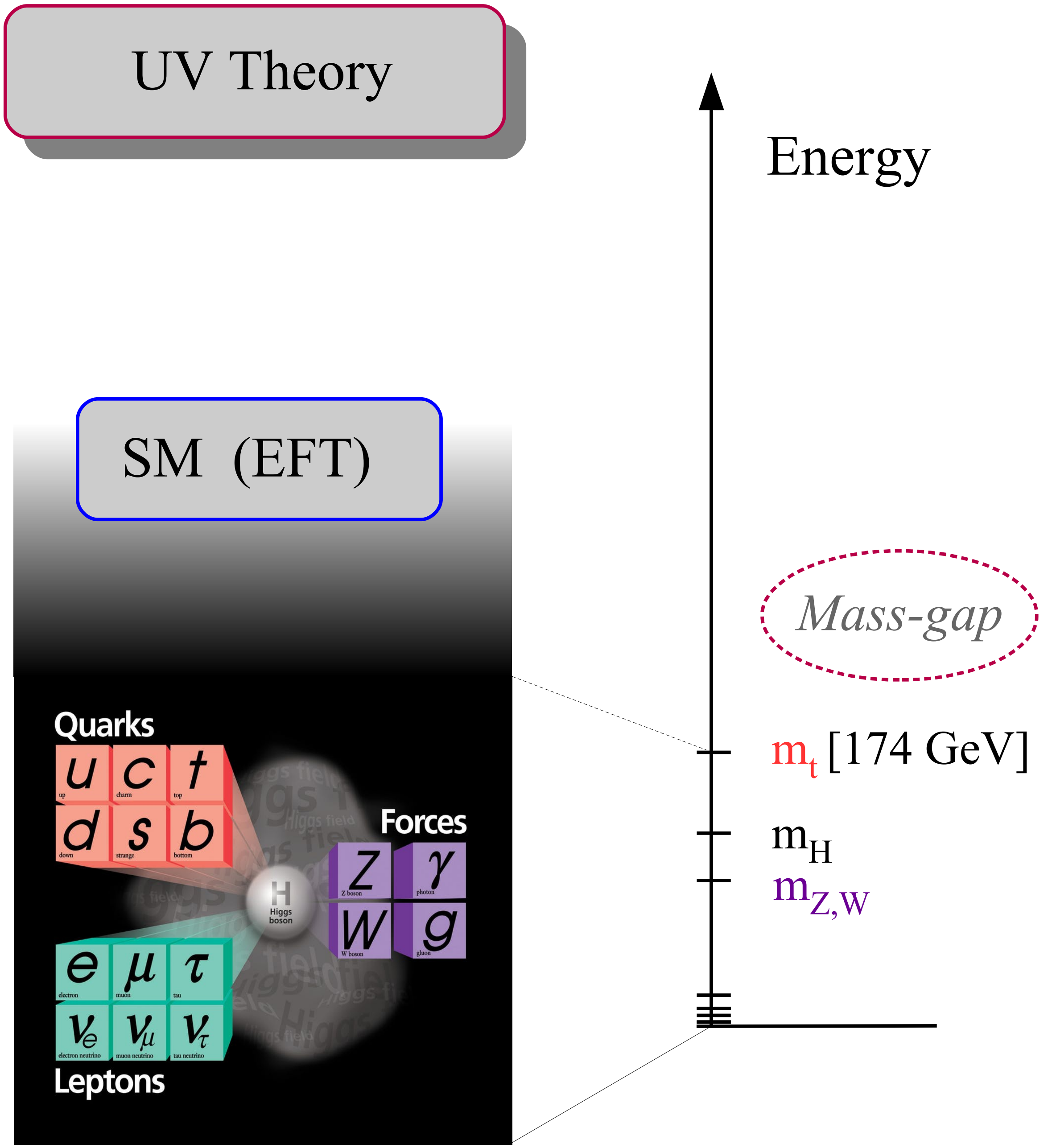
The Standard Model (SM) should be regarded as an *effective theory*

i.e. the limit (*in the range of energies and effective couplings so far probed*) of a more fundamental theory with new degrees of freedom

Introduction

What we know after the first phase of the LHC is that:

- The Higgs boson is SM-like and is "light" (*completion of the SM spectrum*)
- There is a mass-gap above the SM spectrum



Introduction

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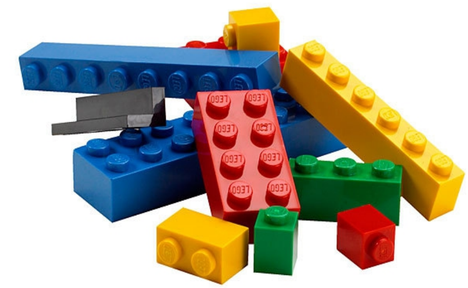
- The Higgs boson is SM-like and is "light" (*completion of the SM spectrum*)
- There is a mass-gap above the SM spectrum

We identified the *"light"* (*"large"*) pieces of our *"construction game"* & their long-range interactions →

UV Theory

$E \sim L^{-1}$



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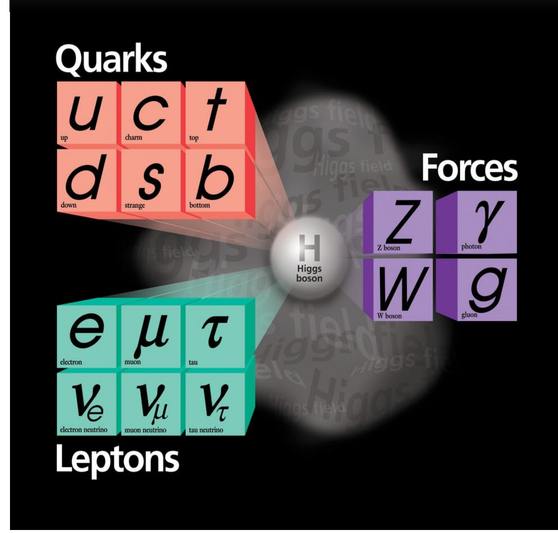
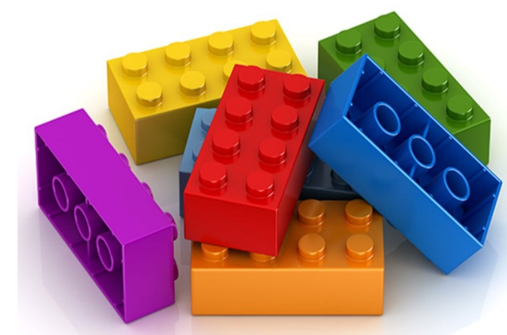
SM (EFT)





Introduction

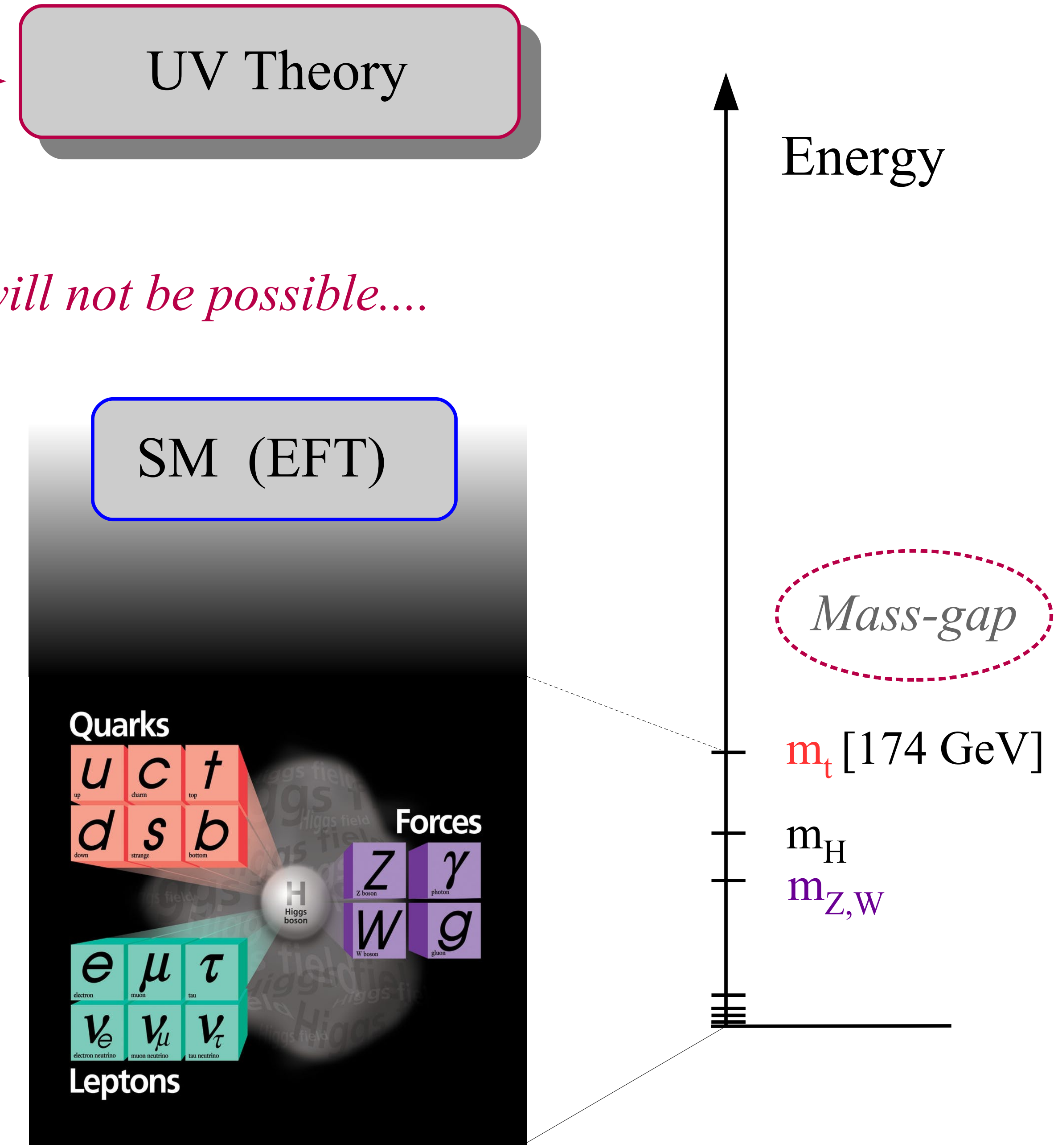
Ideally, we would like to probe the UV directly, via high-energy experiments

However, for several years this will not be possible....

For the time being, we can only extract *indirect* UV infos exploring the low-energy limit of the EFT.

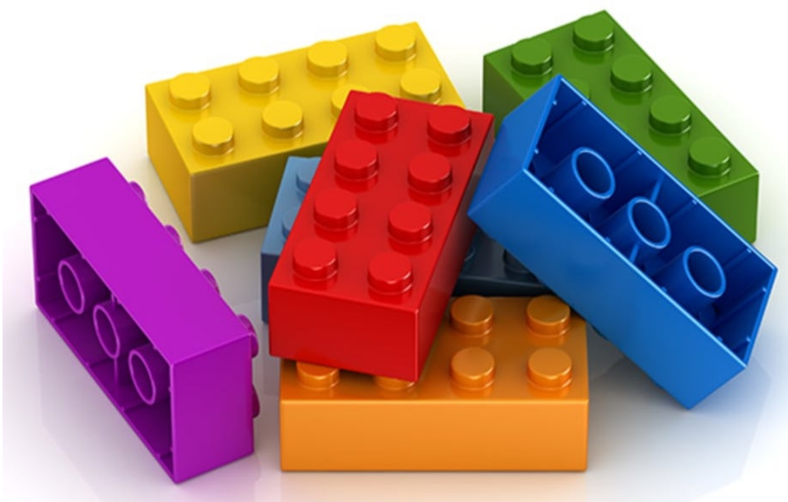
Many infos, with 2 clear messages:

- *several tuned* (SM) *couplings*
- *several accidental* (*approximate*) *symmetries*

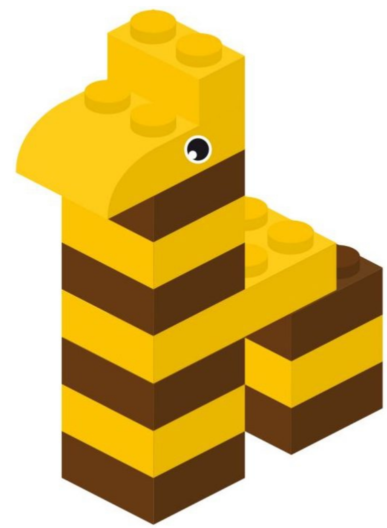


Introduction

In the next few years the best we can do to extract information about UV dynamics is trying to detect and *decode* possible *un-natural features* of the SM-EFT.



$\xrightarrow{?}$



Flavour physics is essential to this purpose

is already telling us a lot,
and might tell us much more in the near future...

The flavor structure of the SM

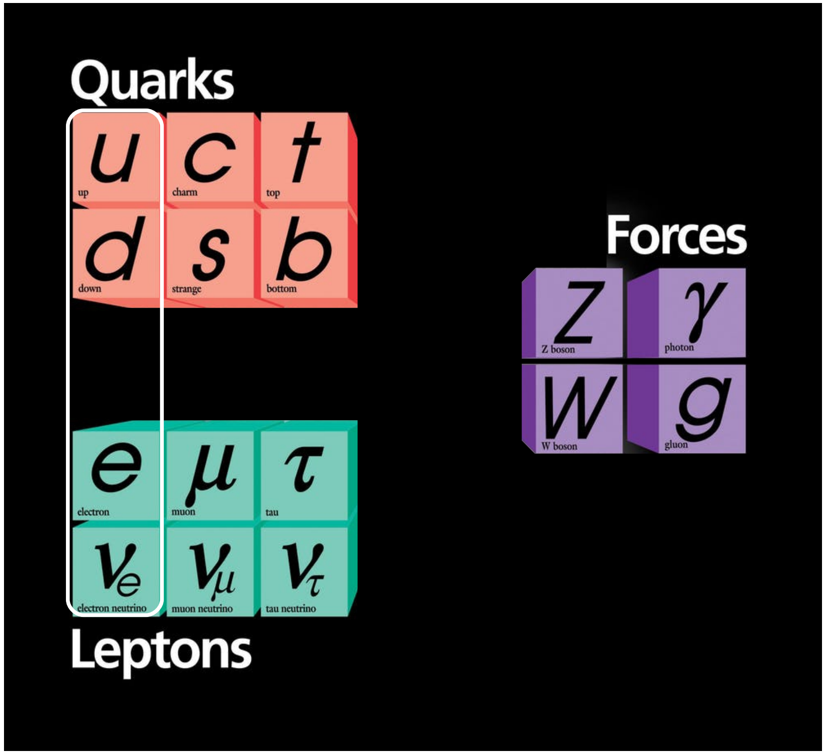
The flavor structure of the SM

$$\mathscr{L}_{\rm SM} = \mathscr{L}_{\rm gauge}(A_a, \psi_i) + \mathscr{L}_{\rm Higgs}(H, A_a, \psi_i)$$

3 identical replica of the basic fermion family
$[\psi = Q_L, u_R, d_R, L_L, e_R] \Rightarrow$ huge flavor-degeneracy

$$\mathscr{L}_{\rm gauge} = \Sigma_a -\frac{1}{4g_a^2}(F_{\mu\nu}^a)^2 + \Sigma_\psi \Sigma_{i=1..3} \bar{\psi}_i i \not{D} \psi_i$$

The gauge Lagrangian is invariant under <u>5 independent U(3) global rotations</u> for each of the 5 independent fermion fields



$$Q_L = \begin{bmatrix} u_L \\ d_L \end{bmatrix}, \quad u_R, \quad d_R, \quad L_L = \begin{bmatrix} \nu_L \\ e_L \end{bmatrix}, \quad e_R$$

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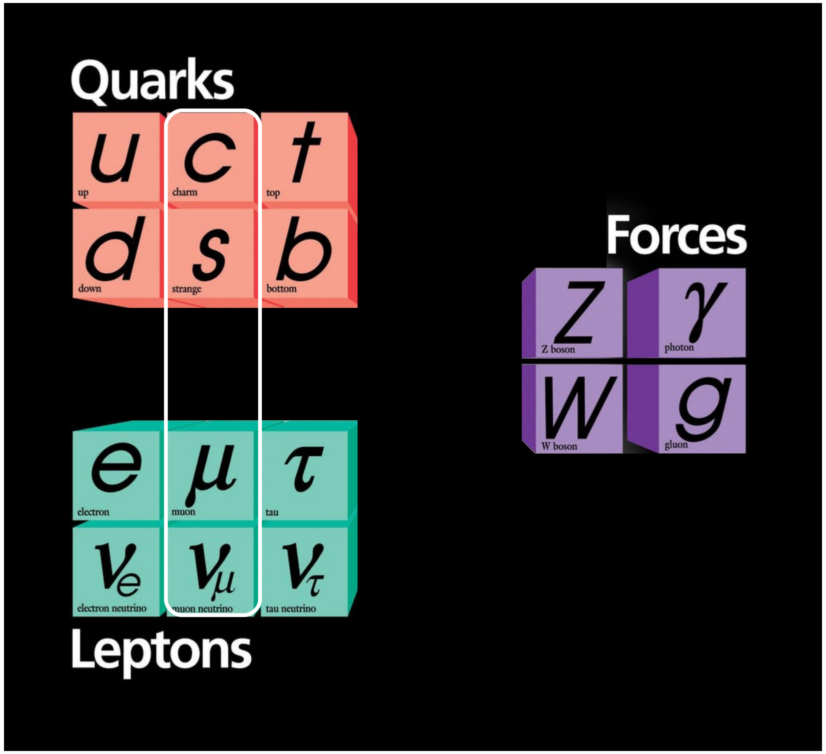

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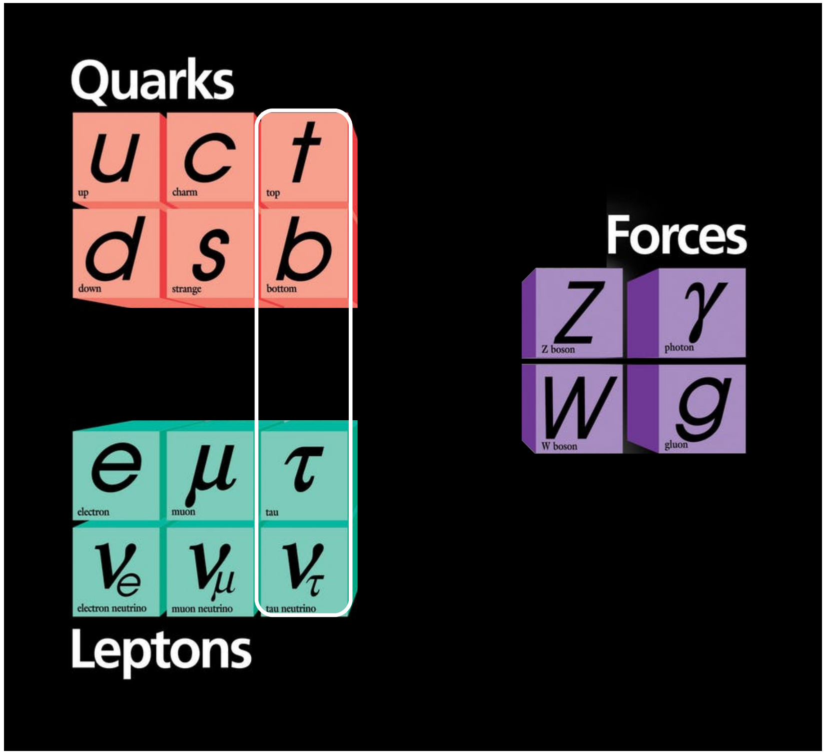

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E.g.: $Q_L^i \to U^{ij} Q_L^j$

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U(1) flavor-independent phase
+
SU(3) flavor-dependent mixing matrix

The flavor structure of the SM

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$[\psi = Q_L, u_R, d_R, L_L, e_R] \Rightarrow$ huge flavor-degeneracy: $\mathrm{U}(3)^5$ global symmetry

$$\mathrm{U}(1)_{\rm L} \times \mathrm{U}(1)_{\rm B} \times \mathrm{U}(1)_{\rm Y} \times \mathrm{SU}(3)_Q \times \mathrm{SU}(3)_U \times \mathrm{SU}(3)_D \times \ldots$$

Lepton number Hypercharge

Baryon number

Flavor mixing

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Within the SM the flavor-degeneracy is <u>broken</u> only by the Yukawa interaction:

in the quark sector:

$$\begin{cases} \bar{Q}_L{}^i\, Y_D{}^{ik}\, d_R{}^k\, \mathrm{H} + h.c. \longrightarrow \bar{d}_L{}^i\, M_D{}^{ik}\, d_R{}^k + \ldots \\ \bar{Q}_L{}^i\, Y_U{}^{ik}\, u_R{}^k\, \mathrm{H}_c + h.c. \longrightarrow \bar{u}_L{}^i\, M_U{}^{ik}\, u_R{}^k + \ldots \end{cases}$$

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in the quark sector:

$$\bar{Q}_L^{\,i}\, Y_D^{ik}\, d_R^{\,k}\, H + h.c. \rightarrow \bar{d}_L^{\,i}\, M_D^{ik}\, d_R^{\,k} + \ldots$$

$$\bar{Q}_L^{\,i}\, Y_U^{ik}\, u_R^{\,k}\, H_c + h.c. \rightarrow \bar{u}_L^{\,i}\, M_U^{ik}\, u_R^{\,k} + \ldots$$

The Y are not hermitian → diagonalized by bi-unitary transformations:

$$V_D^{+}\, Y_D\, U_D = \mathrm{diag}(y_b, y_s, y_d)$$

$$V_U^{+}\, Y_U\, U_U = \mathrm{diag}(y_t, y_c, y_u)$$

$$y_i = \frac{2^{1/2}\, m_{q_i}}{\langle H \rangle} \approx \frac{m_{q_i}}{174\ \mathrm{GeV}}$$

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in the quark sector:

$$\bar{Q}_L{}^i Y_D{}^{ik} d_R{}^k H + h.c. \rightarrow \bar{d}_L{}^i M_D{}^{ik} d_R{}^k + \ldots$$

$$\bar{Q}_L{}^i Y_U{}^{ik} u_R{}^k H_c + h.c. \rightarrow \bar{u}_L{}^i M_U{}^{ik} u_R{}^k + \ldots$$

The residual flavor symmetry let us to choose a (gauge-invariant) flavor basis where only one of the two Yukawa couplings is diagonal:

$$Y_D = \mathrm{diag}(y_d, y_s, y_b) \qquad Y_U = V^+ \times \mathrm{diag}(y_u, y_c, y_t)$$

or

$$Y_D = V \times \mathrm{diag}(y_d, y_s, y_b) \qquad Y_U = \mathrm{diag}(y_u, y_c, y_t)$$

unitary matrix

$$\bar{Q}_L{}^i \, Y_D{}^{ik} \, d_R{}^k \, \mathrm{H} \;\rightarrow\; \bar{d}_L{}^i \, M_D{}^{ik} \, d_R{}^k + \ldots \qquad M_D = \mathrm{diag}(m_d, m_s, m_b)$$

$$\bar{Q}_L{}^i \, Y_U{}^{ik} \, u_R{}^k \, \mathrm{H}_c \;\rightarrow\; \bar{u}_L{}^i \, M_U{}^{ik} \, u_R{}^k + \ldots \qquad M_U = \mathrm{V}^+ \times \mathrm{diag}(m_u, m_c, m_t)$$

To diagonalize also the second mass matrix we need to rotate separately u_L & d_L (non gauge-invariant basis) ⇒ V appears in charged-current gauge interactions:

$$J_W{}^\mu = \bar{u}_L \, \gamma^\mu \, d_L \;\rightarrow\; \bar{u}_L \, \mathrm{V} \, \gamma^\mu \, d_L$$

Cabibbo-Kobayashi-Maskawa
(CKM) mixing matrix

...however, it must be clear that this non-trivial mixing originates only from the Higgs sector: $\mathrm{V}_{ij} \rightarrow \delta_{ij}$ if we *switch-off* Yukawa interactions !

$$\bar{Q}_L^{\,i}\, Y_D^{ik}\, d_R^{\,k}\, \mathrm{H} \;\rightarrow\; \bar{d}_L^{\,i}\, M_D^{ik}\, d_R^{\,k} + \ldots \qquad M_D = \mathrm{diag}(m_d, m_s, m_b)$$

$$\bar{Q}_L^{\,i}\, Y_U^{ik}\, u_R^{\,k}\, \mathrm{H}_c \;\rightarrow\; \bar{u}_L^{\,i}\, M_U^{ik}\, u_R^{\,k} + \ldots \qquad M_U = V^{+} \times \mathrm{diag}(m_u, m_c, m_t)$$

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$$J_W^{\mu} = \bar{u}_L\, \gamma^{\mu}\, d_L \;\rightarrow\; \bar{u}_L\, V\, \gamma^{\mu}\, d_L$$

Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix

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

- 3 real parameters (rotational angles)

+

- 1 complex phase (source of CP violation)

The SM quark flavor sector is described by 10 observable parameters:

- 6 quark masses
- 3+1 CKM parameters

Note that:

- The rotation of the right-handed sector is not observable
- Neutral currents remain flavor diagonal

$$\bar{Q}_L^{\,i}\, Y_D^{\,ik}\, d_R^{\,k}\ \mathrm{H} \ \rightarrow\ \bar{d}_L^{\,i}\, M_D^{\,ik}\, d_R^{\,k} + \ldots \qquad M_D = \mathrm{diag}(m_d, m_s, m_b)$$

$$\bar{Q}_L^{\,i}\, Y_U^{\,ik}\, u_R^{\,k}\ \mathrm{H_c} \ \rightarrow\ \bar{u}_L^{\,i}\, M_U^{\,ik}\, u_R^{\,k} + \ldots \qquad M_U = V^{+} \times\ \mathrm{diag}(m_u, m_c, m_t)$$

In the lepton sector we can diagonalise the Y in a gauge invariant way

(at this level we ignore neutrino masses, which cannot be described by the SM Lagrangian introduced above)

$$L_L^{\,i}\, Y_D^{\,ik}\, e_R^{\,k}\ \mathrm{H} \ \rightarrow\ l_L^{\,i}\, M_E^{\,ik}\, e_R^{\,k} + \ldots \qquad M_E = \mathrm{diag}(m_e, m_\mu, m_\tau)$$

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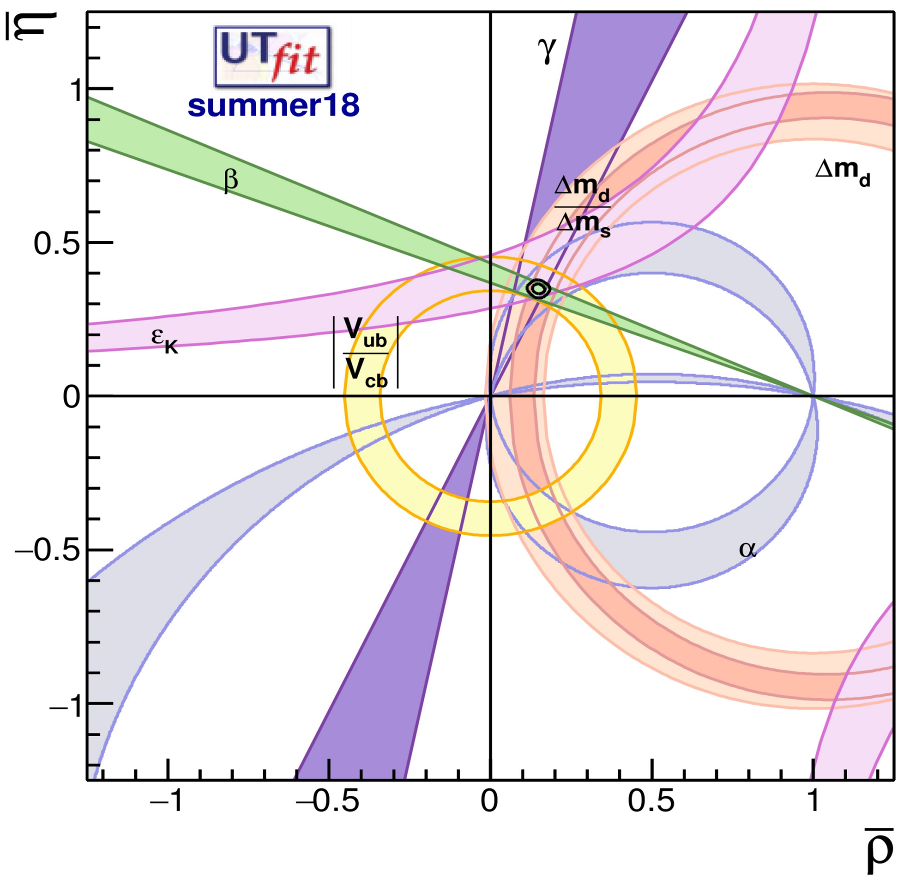
The SM lepton flavor sector is described by 3 observable parameters:

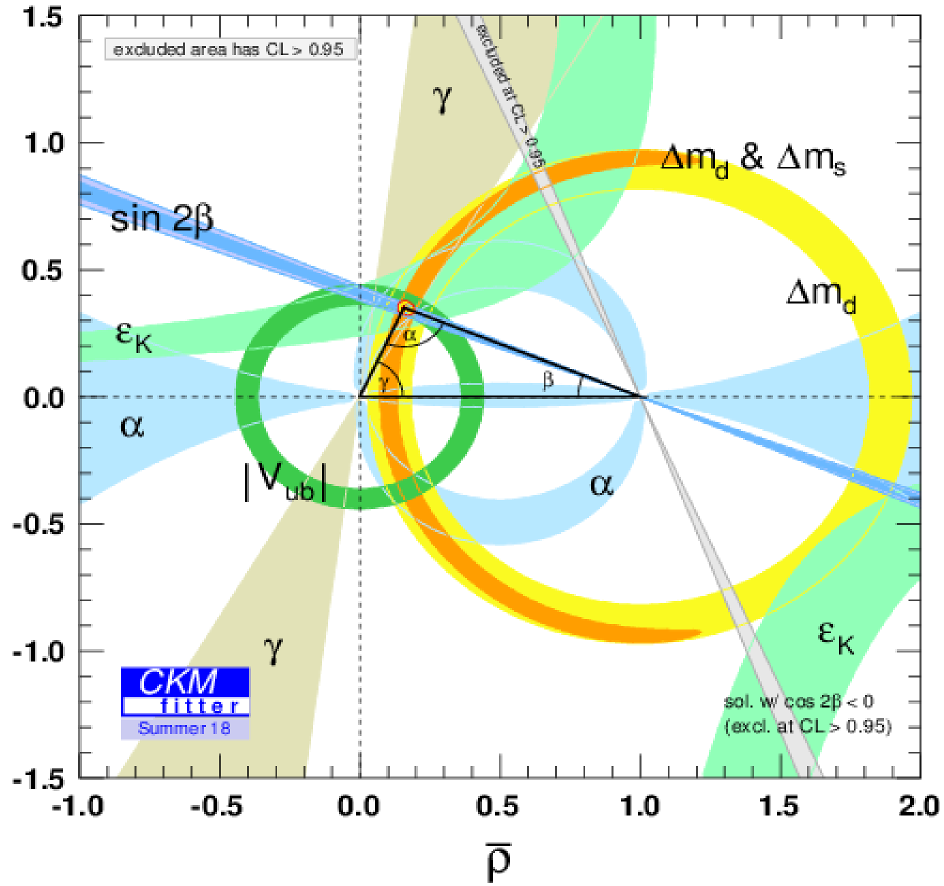
- 3 lepton masses

13 SM "flavor" parameters

- Vast majority of all SM couplings (19)
- Vast majority of all couplings involving the Higgs (15)

Properties of the CKM matrix and CKM fits





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Experimental indication of a strongly hierarchical structure:

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

Wolfenstein, '83

$\boxed{\lambda = 0.22}$ $\quad A, \;\; |\rho+i\eta| \;=\; O(1)$

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$$(V^{+} V)_{ij} = \delta_{ij}$$

Triangular relations, such as [i=b, j=d]:

$$\underline{V_{ub}^{*} V_{ud}} + \underline{V_{cb}^{*} V_{cd}} + \underline{V_{tb}^{*} V_{td}} = 0$$

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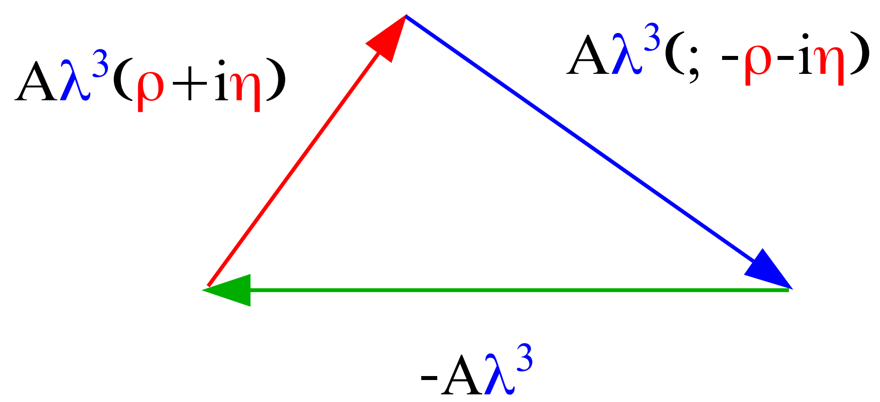

only the 3-1 triangles have all sizes of the same order in λ

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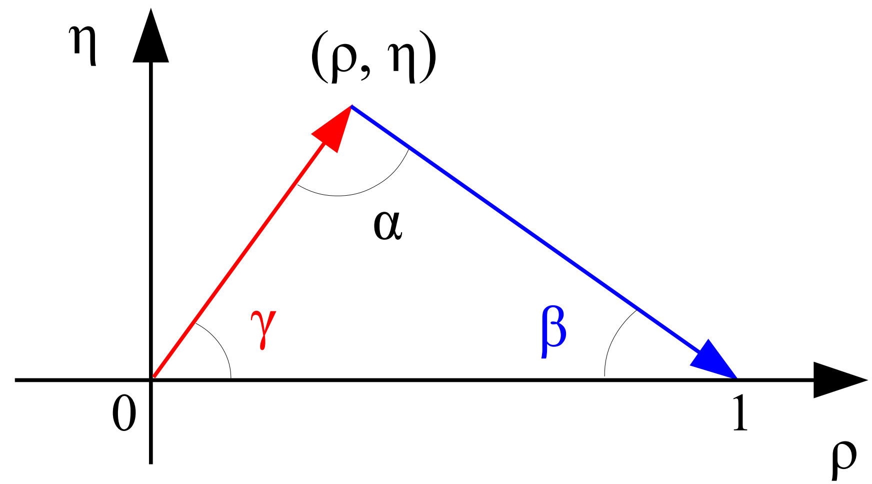

Note: *often you'll find experimental results shown as constraints in the $\bar{\rho}, \bar{\eta}$ plane. These new parameters are defined by $\bar{\rho} = \rho\,(1-\lambda^2/2)^{-1/2}$ (same for η) to keep into account higher-order terms in the expansion in powers of λ.*

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$$(V^+ V)_{ij} = \delta_{ij} = (V V^+)_{ij}$$

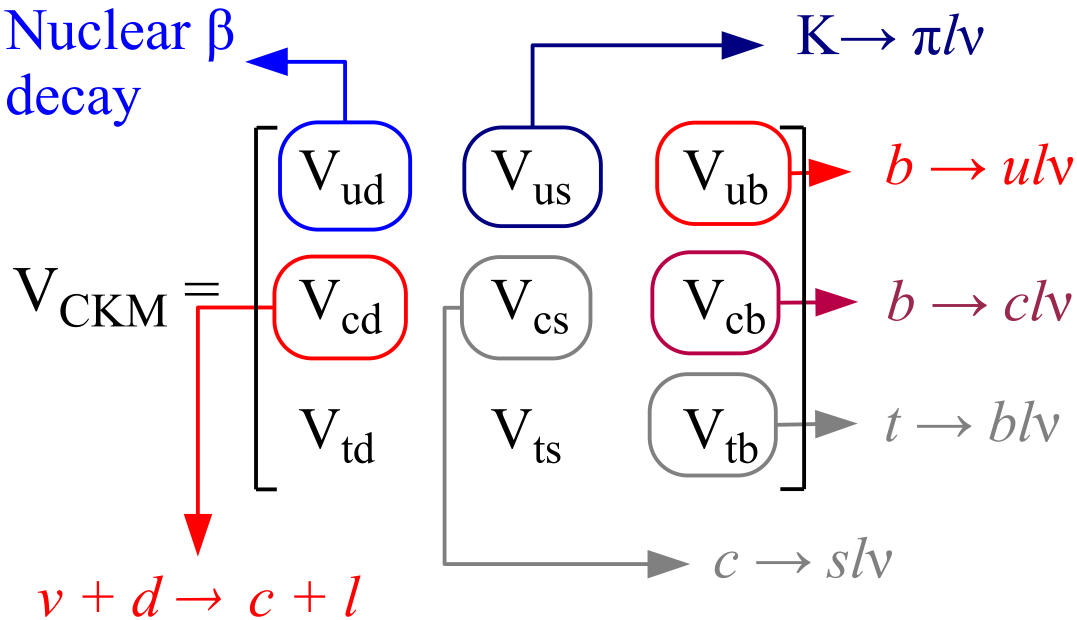
Triangular relations, such as [i=b, j=d]:

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

&

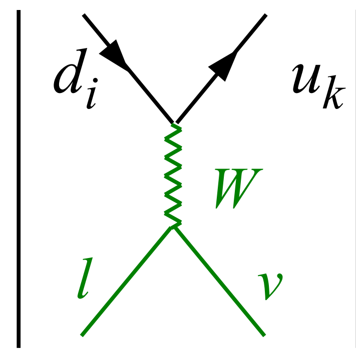
Unitarity sum rules, such as [i=u, j=u]:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$



Once we assume unitarity, the CKM matrix can be completely determined using only exp. info from processes mediated by tree-level c.c. amplitudes

Excellent determination (error ~ 0.1%)
Very good determination (error ~ 0.5%)
Good determination (error ~ 2 %)
Sizable error (5-15 %)
Not competitive with unitarity constraints



➜ $|V_{ik}|$

$$\begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

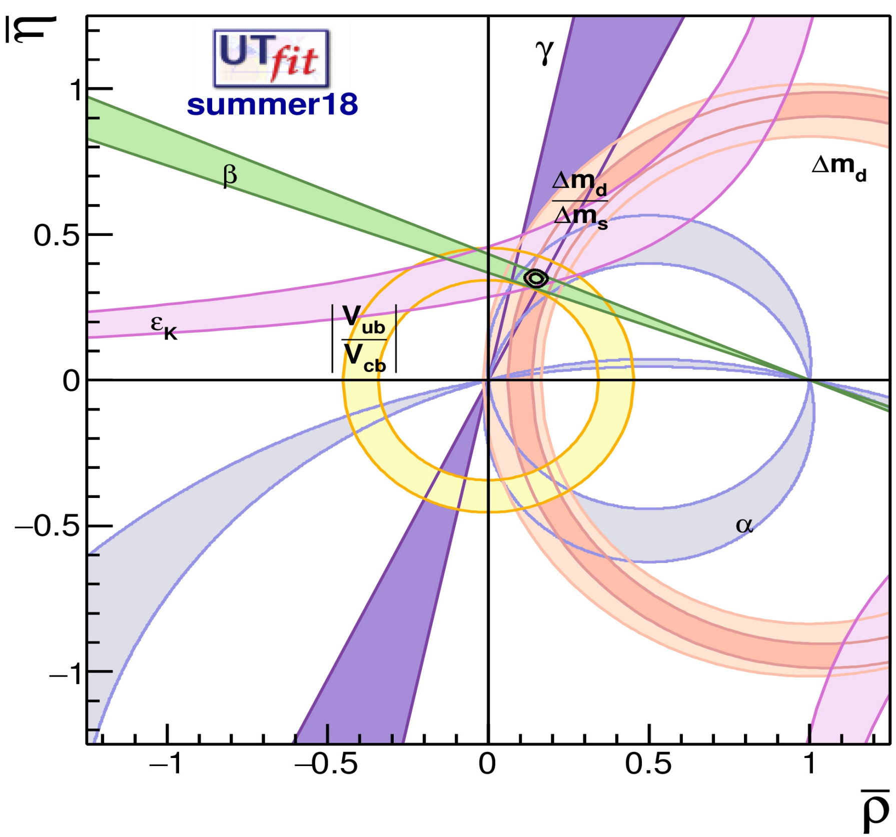
N.B.: Also the phase $\gamma = \arg(V_{ub})$ can be obtained by (quasi-) tree-level processes

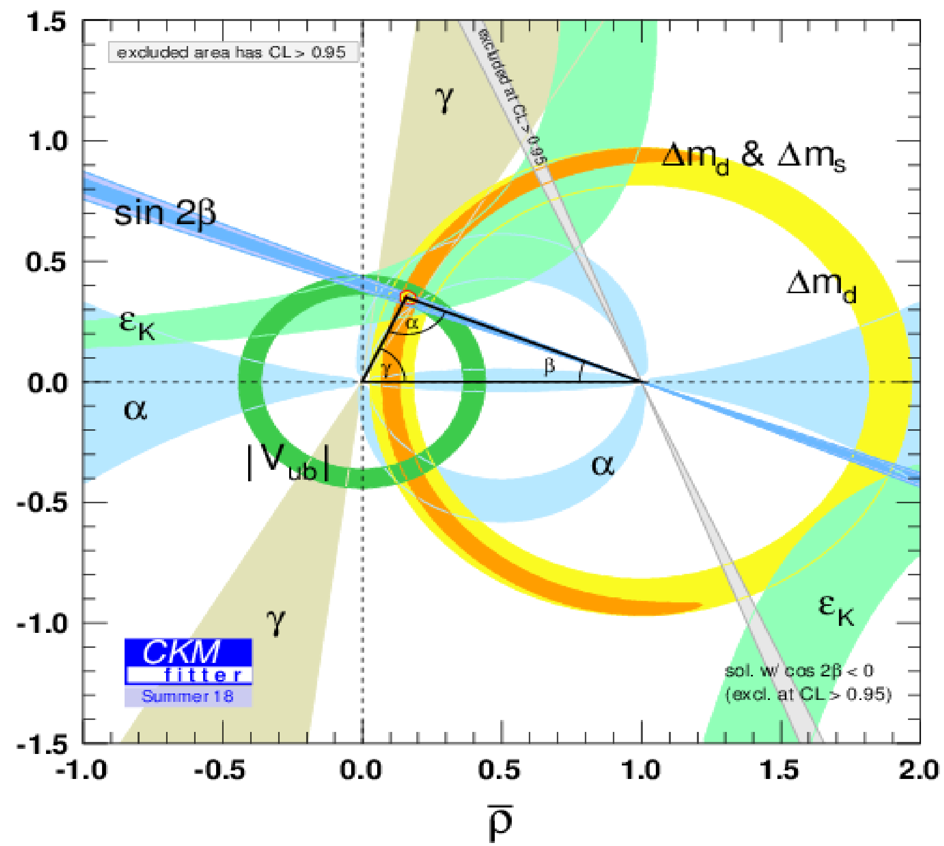
→ *lectures by Y. Amhis*

Properties of the CKM matrix & CKM fits

Beside a few anomalies [→ next lecture], most measurements of quark flavor-violating observables show a remarkable success of the CKM picture: we observe a *redundant and consistent determination of various CKM elements*.

What is particularly noteworthy in the so-called CKM fits is the consistency of the the tree-level determinations of CKM elements, with those obtained from loop observables, such as K-$\bar{K}$ or B-$\bar{B}$ mixing [→ more later]





The two flavor puzzles

The two flavor puzzles

Even forgetting current anomalies, there are two (long-standing) open issues in flavor physics:

I. The observed pattern of SM Yukawa couplings does not look accidental [*SM flavor puzzle*]

→ Is there a deeper explanation for this peculiar structures?

Historical note: this year is a special anniversary year for flavor physics:

- '60 anniversary of the Cabibbo paper (1963)
- '50 anniversary of the Kobayashi-Maskawa paper (1973)

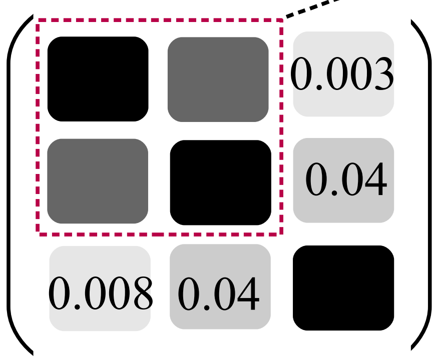
The two flavor puzzles

Even forgetting current anomalies, there are two (long-standing) open issues in flavor physics:

I. The observed pattern of SM Yukawa couplings does not look accidental [*SM flavor puzzle*]

unitarity violation of the 2×2 (light) block below 10^{-3} !

$V_{\rm CKM} \sim$



$$\underline{|V_{ud}|^2 + |V_{us}|^2} + |V_{ub}|^2 = 1$$

N.B.: Despite the very good knowledge we have nowadays about the CKM matrix, we are <u>not able (yet) to detect the presence of the 3rd family</u> by looking only at the 2×2 block (*as one naively would have expected...*)

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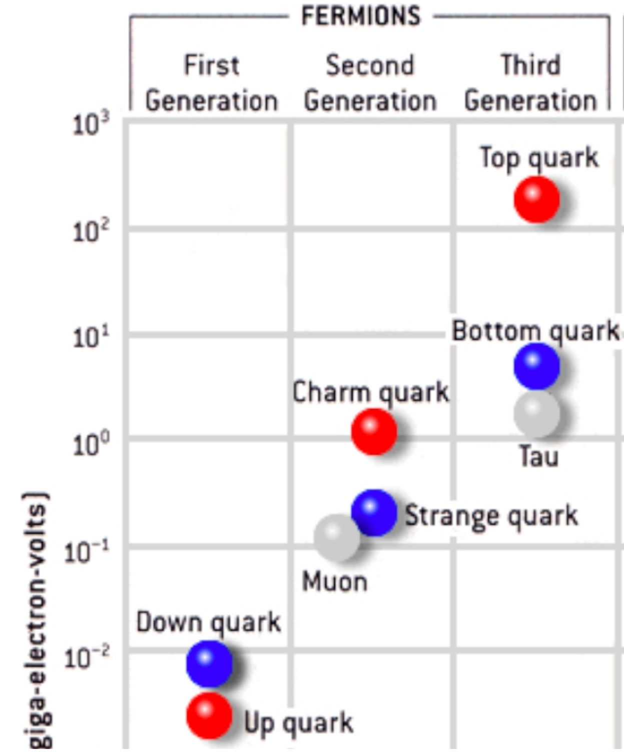
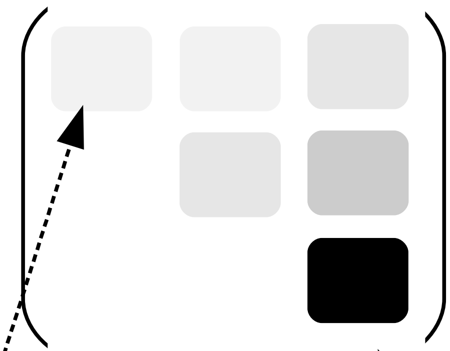
I. The observed pattern of SM Yukawa couplings does not look accidental:



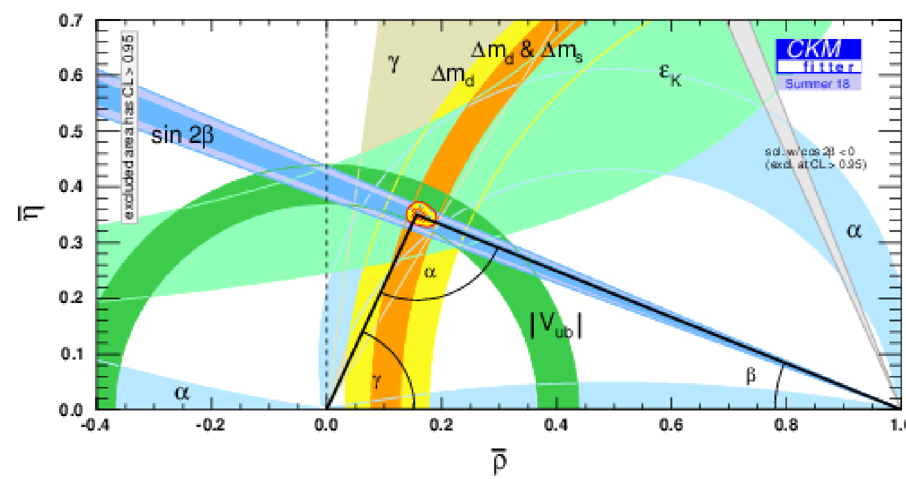
$Y_U \sim$



$$y_t = \frac{\sqrt{2}\, m_t}{\langle H \rangle} \approx 1$$

$$y_u = \frac{\sqrt{2}\, m_u}{\langle H \rangle} \approx 10^{-5}$$

[Y_U in the basis where Y_D is diagonal]



The two flavor puzzles

Even forgetting current anomalies, there are two (long-standing) open issues in flavor physics:

I. The observed pattern of SM Yukawa couplings does not look accidental:

$$Y_U \sim \begin{array}{c} \overbrace{\qquad\quad}^{U(2)_u}\qquad\qquad \\ \left(\begin{array}{cc|c} & & 0.003 \\ \multicolumn{2}{c|}{< 0.01} & 0.04 \\ \hline & & 1 \end{array}\right) \end{array} \begin{array}{l} \left.\vphantom{\begin{array}{c}0\\0\end{array}}\right] \leftarrow U(2)_q \\ \vphantom{1} \end{array} \qquad\qquad \bar{Q}_L \, Y_U \, U_R \, H$$

What we (seem to) observe in the Yukawa couplings is an

$$\boxed{\text{approximate } U(2)^n \text{ symmetry}}$$

acting on the <u>light families</u>

The two flavor puzzles

Even forgetting current anomalies, there are two (long-standing) open issues in flavor physics:

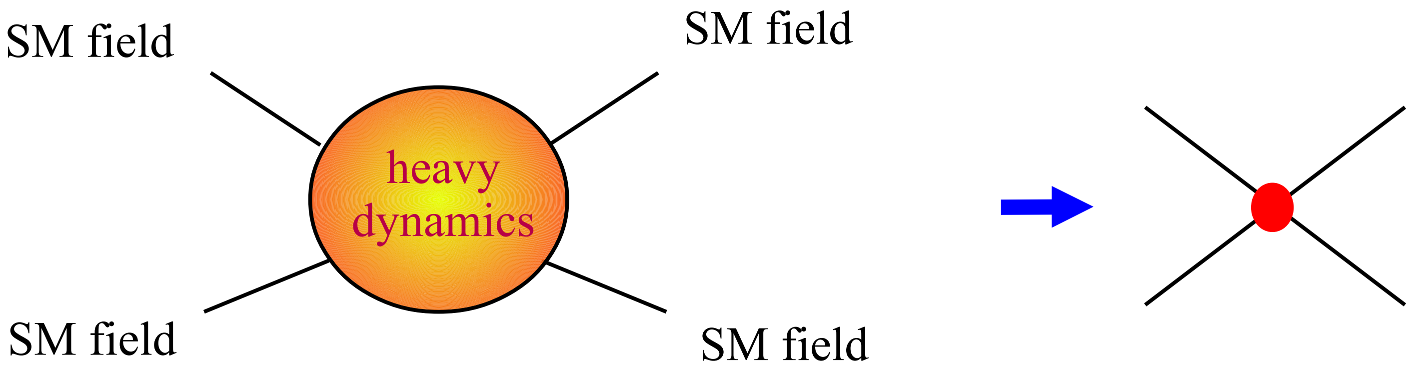
I. The observed pattern of SM Yukawa couplings does not look accidental [*SM flavor puzzle*]

→ Is there a deeper explanation for this peculiar structures?

II. If the SM is only an effective theory, valid below an ultraviolet cut-off , why we do not see any deviation from the SM predictions in the (suppressed) flavor changing processes? What constraints these observations imply on physics beyond the SM? [*NP flavor puzzle*]

→ Which is the flavor structure of physics beyond the SM?

The flavor structure of the SMEFT



The flavor structure of the SMEFT

As anticipated, the modern point of view on the SM Lagrangian is to consider it the leading part (or the low-energy limit) of a more general effective theory.

New degrees of freedom are expected at a scale Λ above the electroweak scale.

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}}(A_a, \psi_i) + \mathscr{L}_{\text{Higgs}}(\text{H}, A_a, \psi_i) + \text{“}\textit{heavy fields}\text{”}$$

$\mathscr{L}_{\text{SM}}$ = renormalizable part of $\mathscr{L}_{\text{SM-eff}}$

All possible operators with $\text{d} \leq 4$,
compatible with the gauge symmetry,
depending only on the “light fields” of the system

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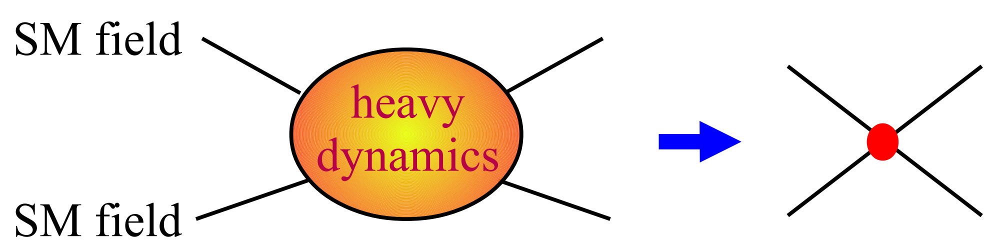
Interactions surviving @ large distances
(operators with d ≤ 4)

Long-range forces
of the SM particles
+
ground state (Higgs)

Local contact interactions
(operators with d > 4)

"Remnant" of the heavy
dynamics at low energies



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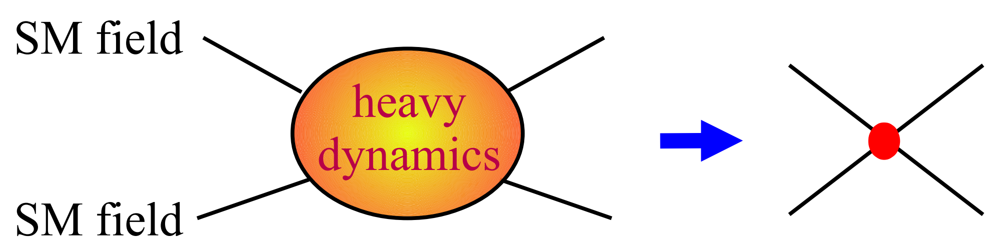
Interactions surviving @ large distances
(operators with $d \leq 4$)

Local contact interactions
(operators with $d > 4$)

“Remnant” of the heavy dynamics at low energies

N.B.: This is the most general parameterization of the new (heavy) degrees of freedom, as long as we do not have enough energy to directly produce them.



The flavor structure of the SMEFT

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \Sigma_i \frac{1}{\Lambda_i^{d-4}} O_i^{d\geq 5}$$

Large flavor symmetry

Three identical replica of the basic fermion family [U(3)^5 symmetry]

Flavor-degeneracy broken by the Yukawa interaction

$$y_{ij}\, \psi_L^{\,i}\, \psi_R^{\,j}\, H \;\rightarrow\; m_{ij}\, \psi_L^{\,i}\, \psi_R^{\,j}$$

"Peculiar" breaking structure

Exact & approximate (*accidental* ?) symmetries

Eg:

- $U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\mu}$ = (individual) Lepton Flavor [*exact symmetry*]
- $m_u \approx m_d \approx 0$ → Isospin symmetry [*approximate symmetry*]

The flavor structure of the SMEFT

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \Sigma_i \frac{1}{\Lambda_i^{d-4}} O_i^{d\geq 5}$$

Large flavor symmetry

Yukawa interaction

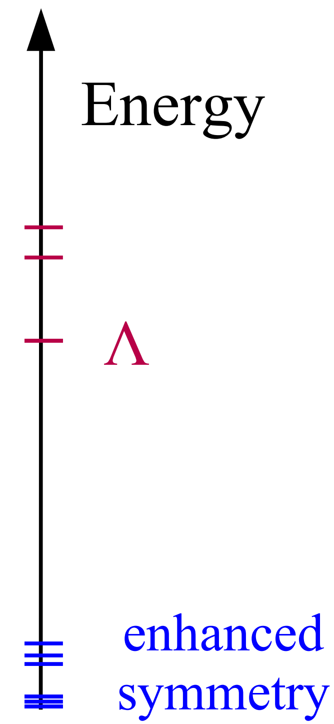
Exact & approximate (*accidental* ?) symmetries

The great interest of precision measurements in flavor physics is the possibility to tests a large number of non-standard higher-dim. operators which may correspond to rather high-energy scales, depending on the possible flavor structure of physics beyond the SM

Accidental symmetries in QFT [a brief detour]

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{d\geq 5}$$

(long-distance interactions) (local contact interact.)



"Accidental symmetries" are symmetries which are not fundamental properties of the theory, but emerge accidentally at low energies / large distances → not enough "variables" to describe the violation of the symmetry [~ *multipole expansion*]

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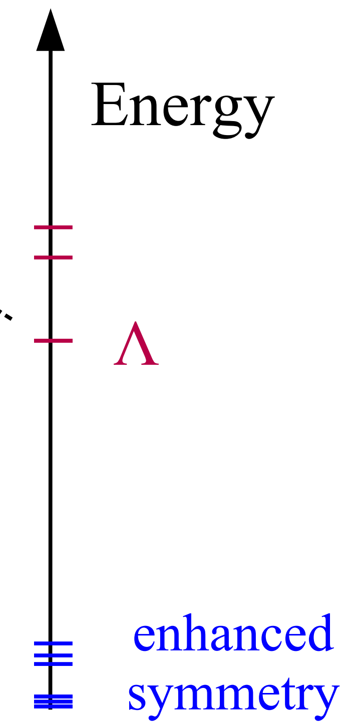


"Accidental symmetries" are symmetries which are not fundamental properties of the theory, but emerge accidentally at low energies / large distances → not enough "variables" to describe the violation of the symmetry [~ *multipole expansion*]

If a symmetry arises accidentally in the low-energy theory, we expect it to be violated by higher dim. ops

Violations of accidental symmetries

Well-known examples from the past...

Accidental symmetries in QFT [a brief detour]

$$\mathscr{L}_{\cancel{\text{SM-EFT}}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{d\geq 5}$$

[SM-2]-EFT

(long-distance interactions) (local contact interact.)

Back in 1973: SM with 2 generations, as "reference model" → CP violation is an accidental symmetry [KM, '73]

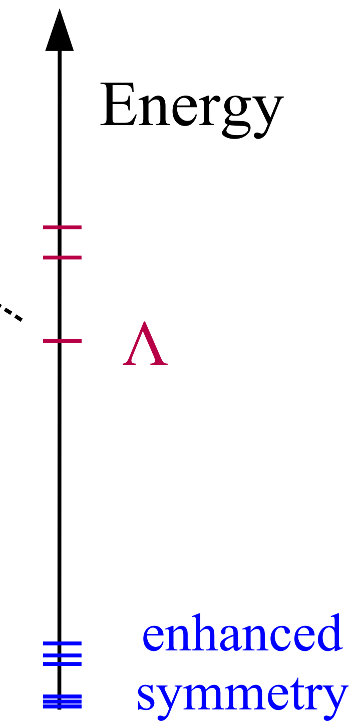
But CP violation is observed in K mixing [→ remnant of "heavy NP"]

$$\Lambda_{CP} \sim 10^4 \text{ TeV}$$

$$\frac{e^{i\delta}}{\Lambda_{CP}^2} (\bar{s}\,\Gamma\, d)^2$$

"Super-weak" interaction

[L. Wolfenstein, '64]



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[SM-2]-EFT

(long-distance interactions) (local contact interact.)

Energy

Λ

enhanced symmetry

Back in 1973: SM with 2 generations, as "reference model" → CP violation is an accidental symmetry [KM, '73]

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But CP violation is observed in K mixing [→ remnant of "heavy NP"]

$$\Lambda_{CP} \sim 10^4 \text{ TeV}$$

SM-3
[KM, '73]

$$\frac{1}{\Lambda_{CP}^2} \sim \frac{(G_F m_t V_{ts} V_{td})^2}{4\pi^2}$$

Ellis, Gaillard, Nanopulos, '76

Key message: beware of seemingly high scales in EFT approaches: they can be a "mirage"...

Accidental symmetries in QFT [a brief detour]

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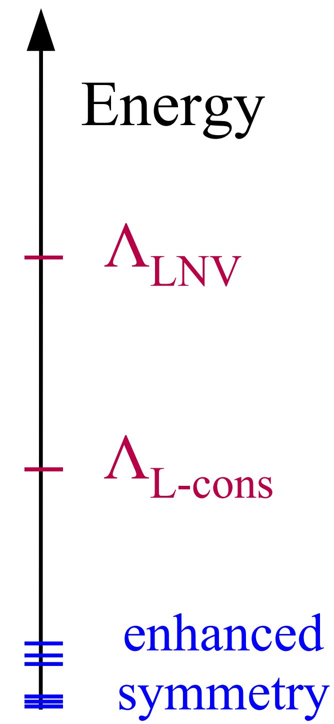


N.B. accidental symmetries allow us to separate different sectors of the EFT [stable scale separation]

Eg: *Total Lepton Number & neutrino masses*

$$\frac{g_\nu^{ij}}{\Lambda_{\text{LNV}}} (L_L^T H)(L_L H^T) \longrightarrow (m_\nu)^{ij} = \frac{g_\nu^{ij} \langle H \rangle^2}{\Lambda_{\text{LNV}}} \lesssim 0.1 \text{ eV}$$

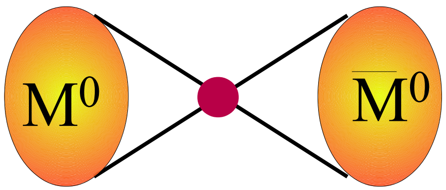
Consistent to assume d=6 ops preserving LN characterized by $\Lambda_{\text{L-cons}} << \Lambda_{\text{LN}}$

The same can be true for different sets of flavor-violating terms
(*with minor technical differences related to approximate vs. exact symmetries*)

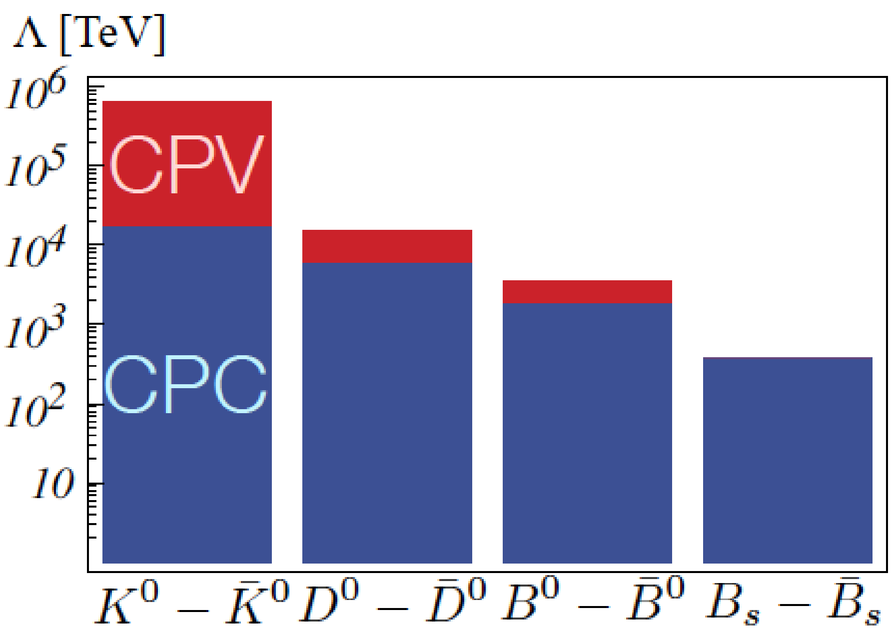
The flavor structure of the SMEFT

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{d\geq 5}$$

In principle, we could expect many violations of the accidental symmetries from the heavy dynamics → *new flavor violating effects*



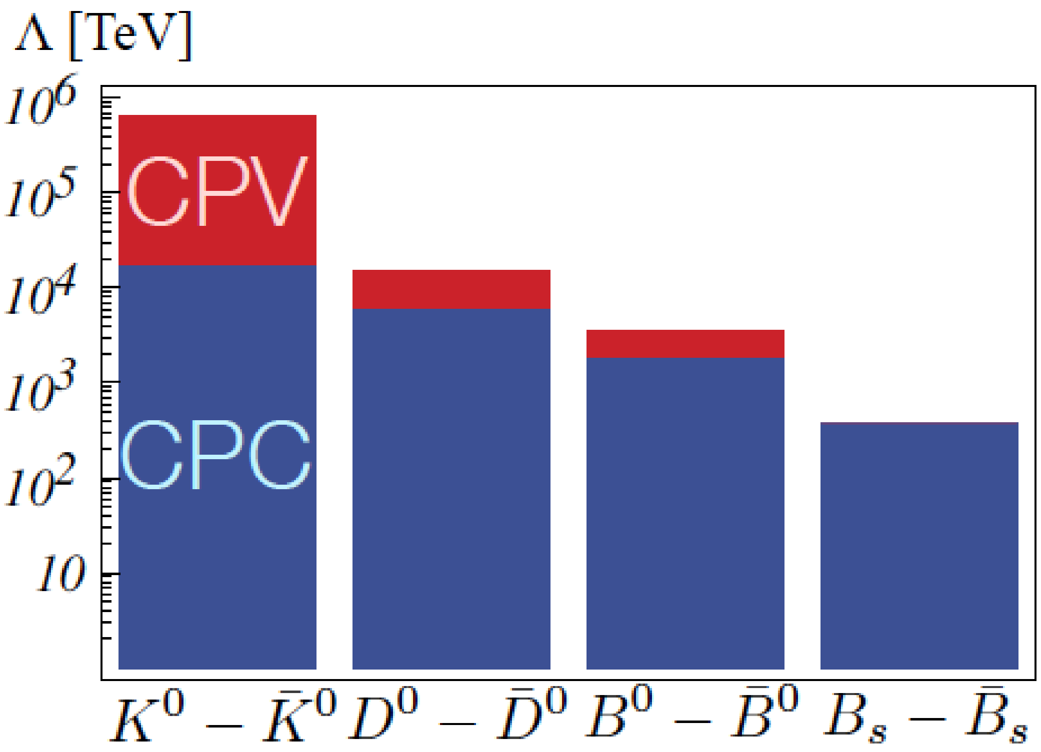
However, beside some anomalies (*still unclear...*) we observe none



Stringent bounds on the scale of possible new flavor non-universal interactions especially from meson-antimeson mixing

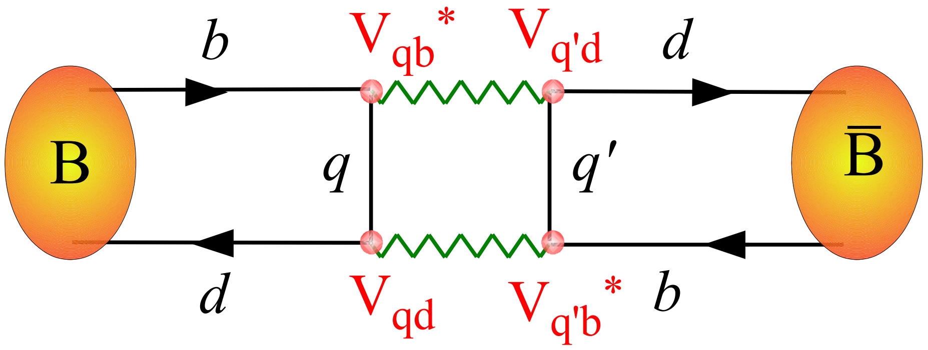
The NP Flavor puzzle

New-physics bounds from meson-antimeson mixing



NP bounds from meson-antimeson mixing

The most remarkable example of stringent NP bounds from flavor-changing observables is the case of (down-type) $\Delta F=2$ observables (K and $B_{d,s}$ mixing):



Highly suppressed amplitude
potentially very sensitive
to New Physics

- No SM tree-level contribution
- Strong suppression within the SM because of CKM hierarchy
- Calculable with good accuracy since dominated by short-distance dynamics [“power-like GIM mechanism” → top-quark dominance]
- Measurable with good accuracy from the time evolution of the neutral meson system [→ *lectures by Y. Amhis*]

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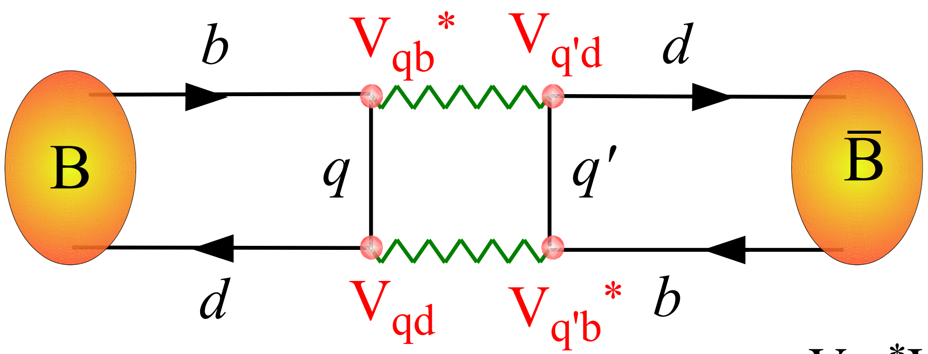

$$A_{\Delta F=2} = \Sigma_{q,q'=u,c,t} (V_{qb}{}^* V_{qd})\,(V_{q'b}{}^* V_{q'd})\, A_{q'q}$$

$$V_{ub}{}^* V_{ud} = - V_{tb}{}^* V_{td} - V_{cb}{}^* V_{cd} \qquad \text{[CKM unitarity]}$$

$$A_{\Delta F=2} = \Sigma_{q=u,c,t} (V_{qb}{}^* V_{qd}) \left[V_{tb}{}^* V_{td} \,(A_{tq} - A_{uq}) + V_{cb}{}^* V_{cd} \,(A_{cq} - A_{uq}) \right]$$

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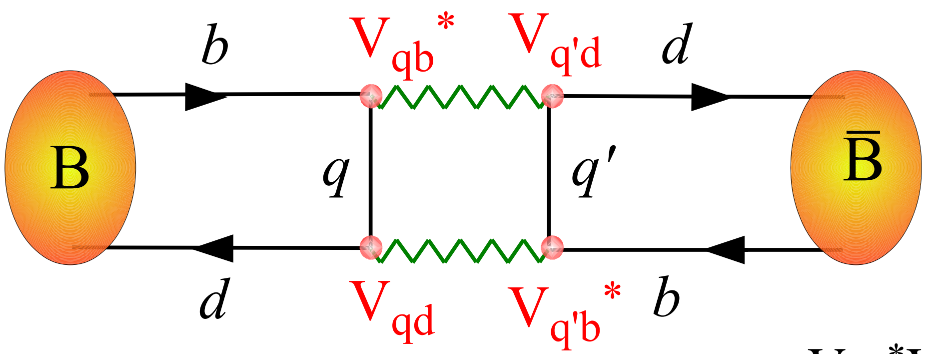

$$A_{\Delta F=2} = \Sigma_{q,q'=u,c,t} (V_{qb}^* V_{qd})(V_{q'b}^* V_{q'd}) A_{q'q}$$

$$V_{ub}^* V_{ud} = - V_{tb}^* V_{td} - V_{cb}^* V_{cd}$$ [CKM unitarity]

$$A_{\Delta F=2} = \Sigma_{q=u,c,t} (V_{qb}^* V_{qd}) [\, V_{tb}^* V_{td} (A_{tq} - A_{uq}) + V_{cb}^* V_{cd} (A_{cq} - A_{uq}) \,]$$

$$A_{qq'} \sim \frac{g^4}{16\pi^2 m_W^2} \left[\text{Const.} + \frac{m_q m_{q'}}{m_W^2} + \ldots \right] \langle \bar{B} | (\bar{b}_L \gamma_\mu d_L)^2 | B \rangle$$

[expansion of the loop amplitude for small (internal) quark masses]

$$\boxed{A_{\Delta F=2} \sim (V_{tb}^* V_{td})^2 \frac{g^4 m_t^2}{16\pi^2 m_W^4} + \ldots}$$

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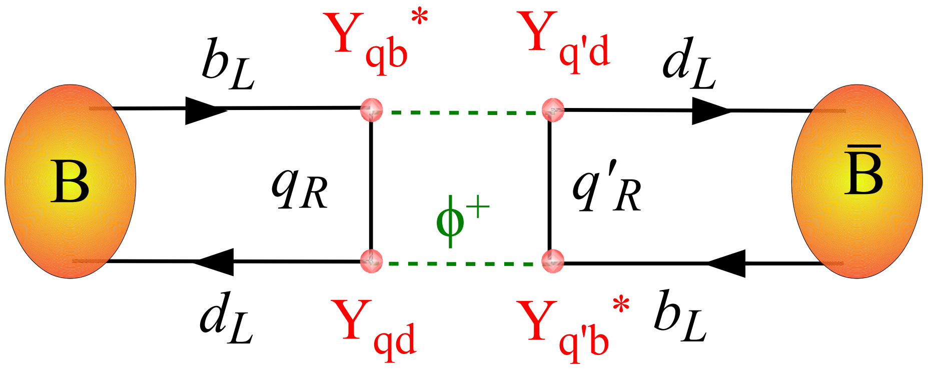

The origin of this behavior can be better understood if we *switch-off* gauge interactions ("gauge-less limit")

$$\mathscr{L}_{\text{Yukawa}} \rightarrow \bar{d}_L^{\,i}\, Y_U^{ik}\, u_R^{\,k}\, \phi^- + h.c.$$

$$\begin{aligned} Y_U &= V^+ \times \mathrm{diag}(y_u, y_c, y_t) \\ &\approx V^+ \times \mathrm{diag}(0, 0, y_t) \end{aligned}$$

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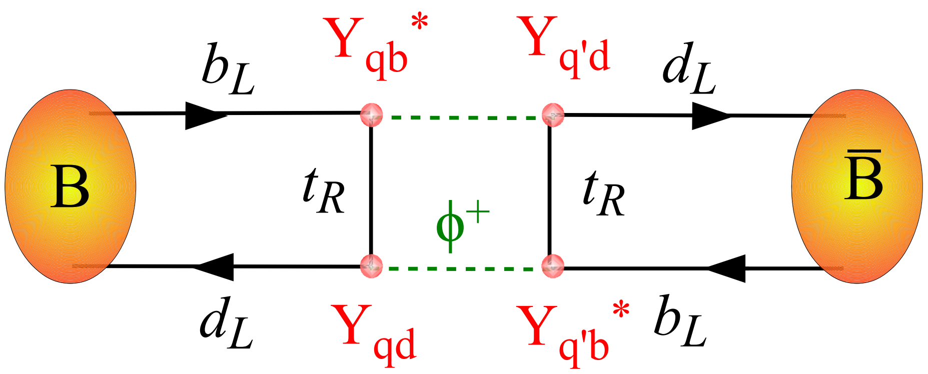

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$$\mathscr{L}_{\rm Yukawa} \to \bar{d}_L^{\,i}\, Y_U^{ik}\, u_R^k\, \phi^- + h.c.$$

$$Y_U = V^+ \times \mathrm{diag}(y_u, y_c, y_t) \approx V^+ \times \mathrm{diag}(0, 0, y_t)$$

$$A^{\rm gaugeless}_{\rm DF=2} \sim (V_{tb}^* V_{td})^2 \frac{(y_t)^4}{16\pi^2 m_t^2} \sim (V_{tb}^* V_{td})^2 \frac{g^4\, m_t^2}{16\pi^2 m_W^4}$$

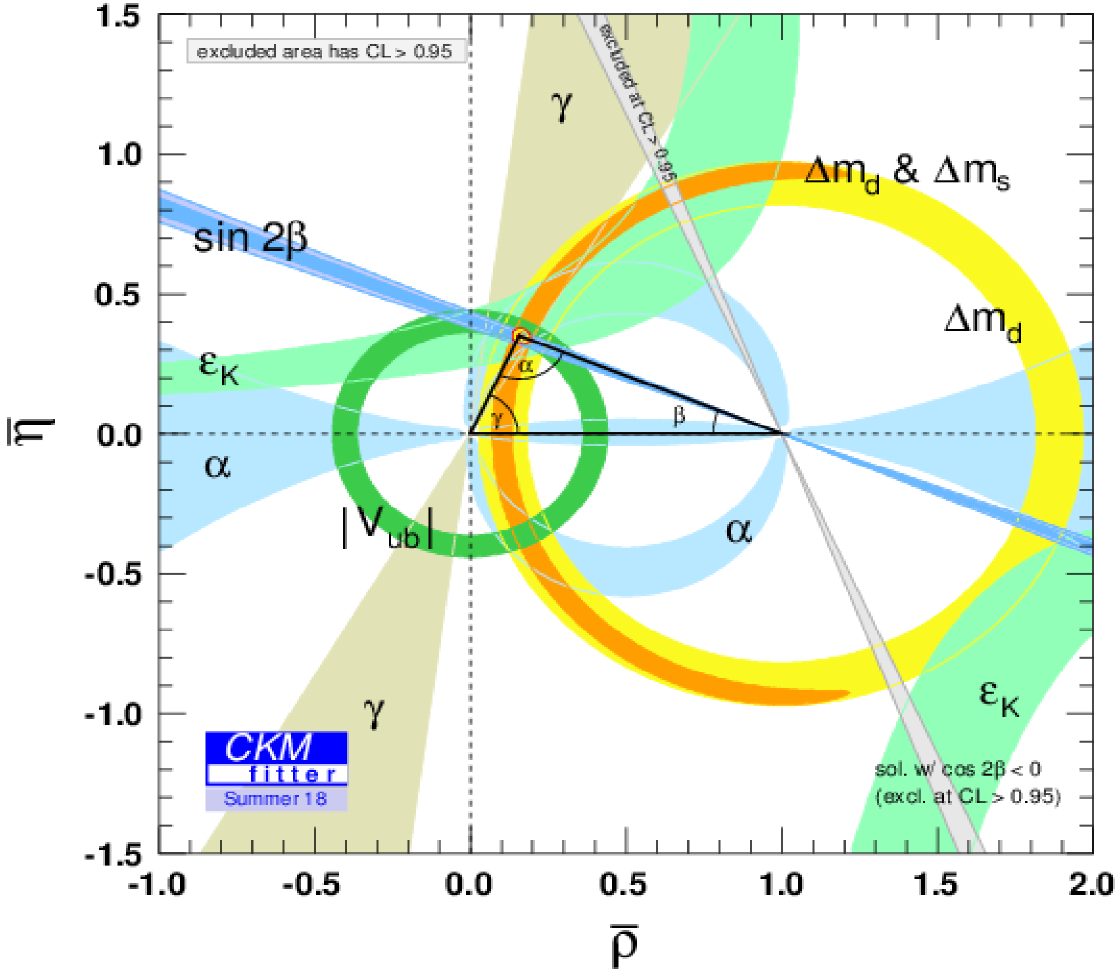
$$m_t = y_t\, v/\sqrt{2} \qquad m_W = g\, v/2$$

This way we obtain the <u>exact result</u> of the amplitude in the limit $m_t \gg m_W$:

$$A^{\rm full}_{\rm DF=2} = A^{\rm gauge\text{-}less}_{\rm DF=2} \times [\ 1 + O(g^2)\ ]$$

NP bounds from meson-antimeson mixing

Current data show no significant deviations from the SM (at the 5%-30% level, depending on the specific amplitude) on $\Delta F = 2$ observables (mass differences and CP-violating phases):



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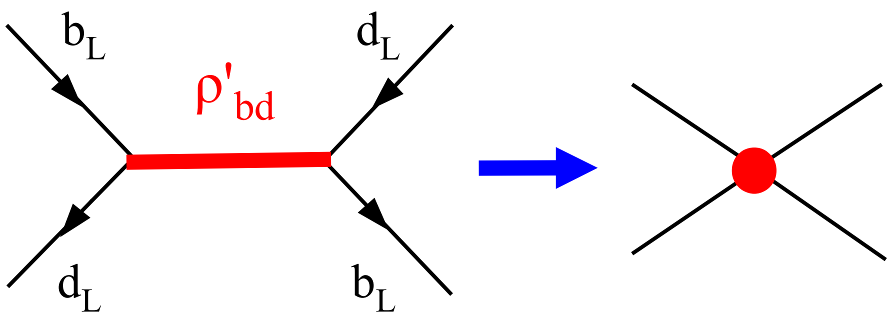
Current data show no significant deviations from the SM (at the 5%-30% level, depending on the specific amplitude) on $\Delta F = 2$ observables (mass differences and CP-violating phases) → strong bounds on possible BSM contributions:

$$M(B_d - \bar{B}_d) \sim \frac{(y_t^2 V_{tb}^* V_{td})^2}{16\pi^2 m_t^2} + c_{NP} \frac{1}{\Lambda^2}$$

$$\mathscr{L}_{eff} = \mathscr{L}_{SM} + \sum \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}$$

The list of dimension 6 ops. includes $(b_L \gamma_\mu d_L)^2$ that contributes to B_d mixing at the tree-level

Possible dynamical origin of this d=6 operator:



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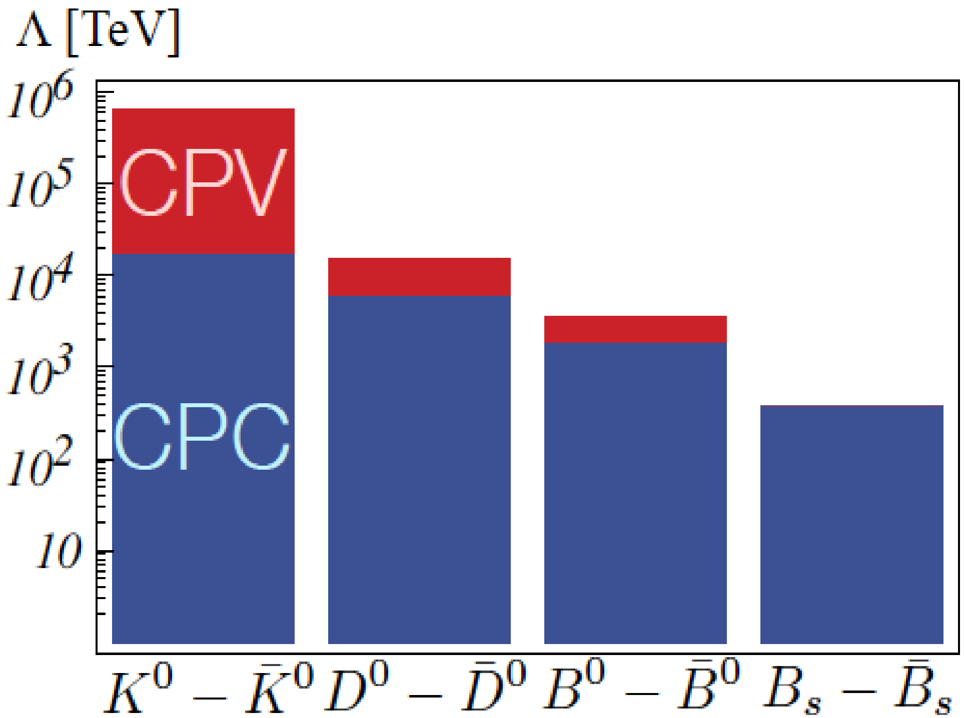
Operator	Bounds on Λ (TeV) Re	Bounds on Λ (TeV) Im
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2	1.1×10^2
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	3.7×10^2	3.7×10^2



Quite discouraging at first sight...

However, remember the lesson of the KM model to explain CP violation: these seemingly high scales could well be a “mirage”...

The flavor structure of the SMEFT

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Flavor-degeneracy:
$U(3)^5$ symmetry

Yukawa couplings:
$U(3)^5 \rightarrow \sim U(2)^n$
peculiar breaking of the flavor symm.

Stringent bounds
on generic
flavor-violating ops.

The big questions in flavor physics:

- Do we understand the origin of the approximate residual flavor symmetries giving rise to hierarchical Yukawa couplings ? — SM flavor puzzle
- Can we make sense of the tight NP bounds from flavor-violating processes and still hope to see NP signals somewhere? And in case where? — NP flavor puzzle

Future data (*rare decays*) could provide some answers... → *next lecture*