Mysteries in flavor physics

[*Old problems, recent hopes, and new challenges*]

Monica Altarelli (CERN) & Gino Isidori (Zürich)

- Lecture 1 (Monday - Gino):
  Introduction to flavor physics

- Lecture 2 & 3 (Wednesday & Thursday - Monica):
  Experimental aspects of B physics & recent results

- Lecture 4 (Friday - Gino):
  Theoretical models addressing the B-physics anomalies

Gino Isidori
[*University of Zürich*]

- 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
  - LFU and $b \to sll$ decays

University of Zurich[UZH]

European Research Council
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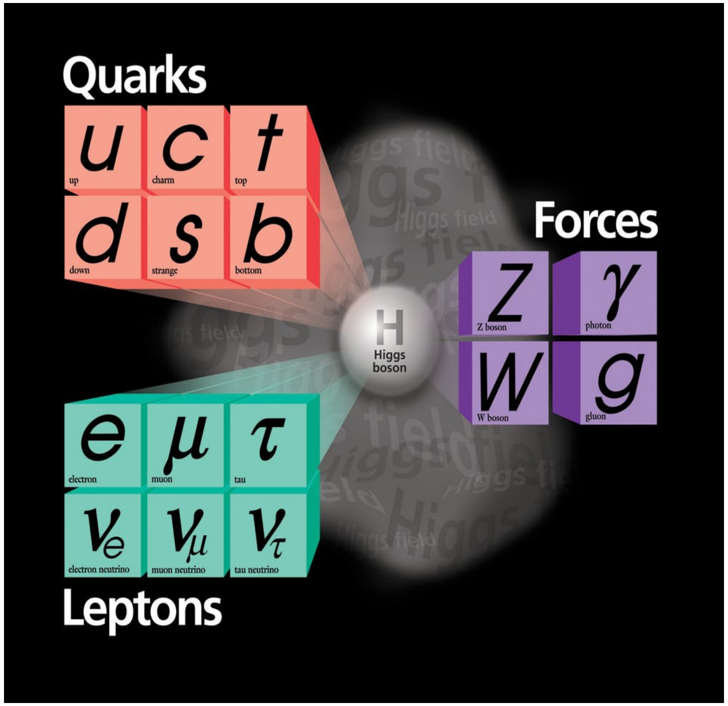
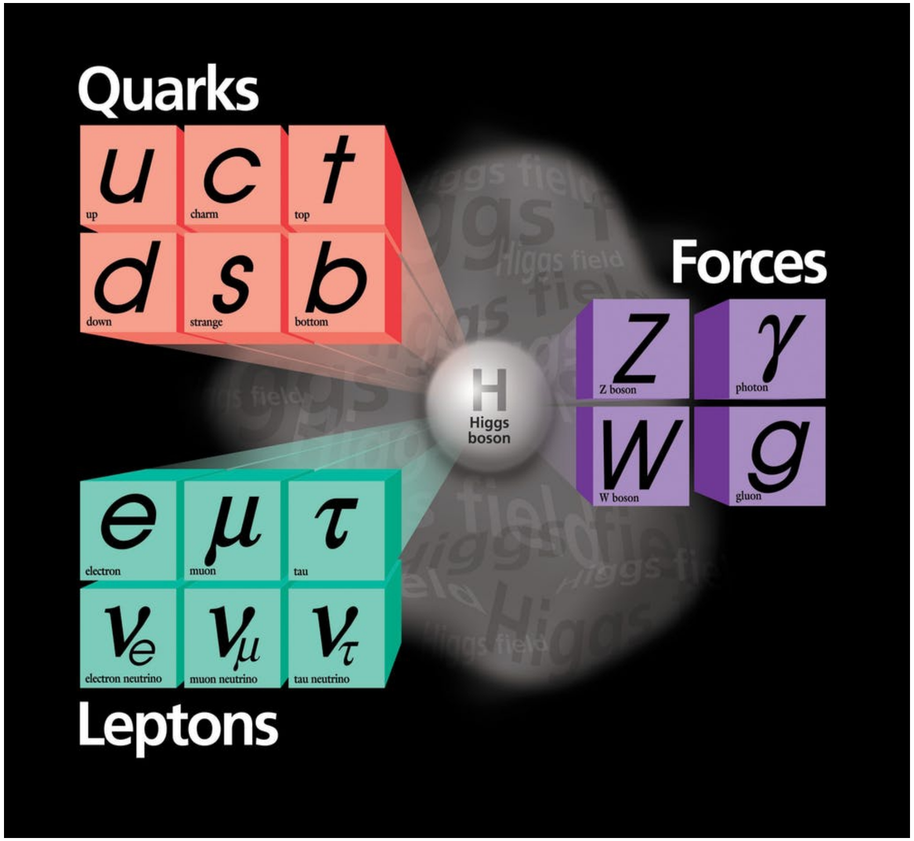
Introduction



Introduction

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

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



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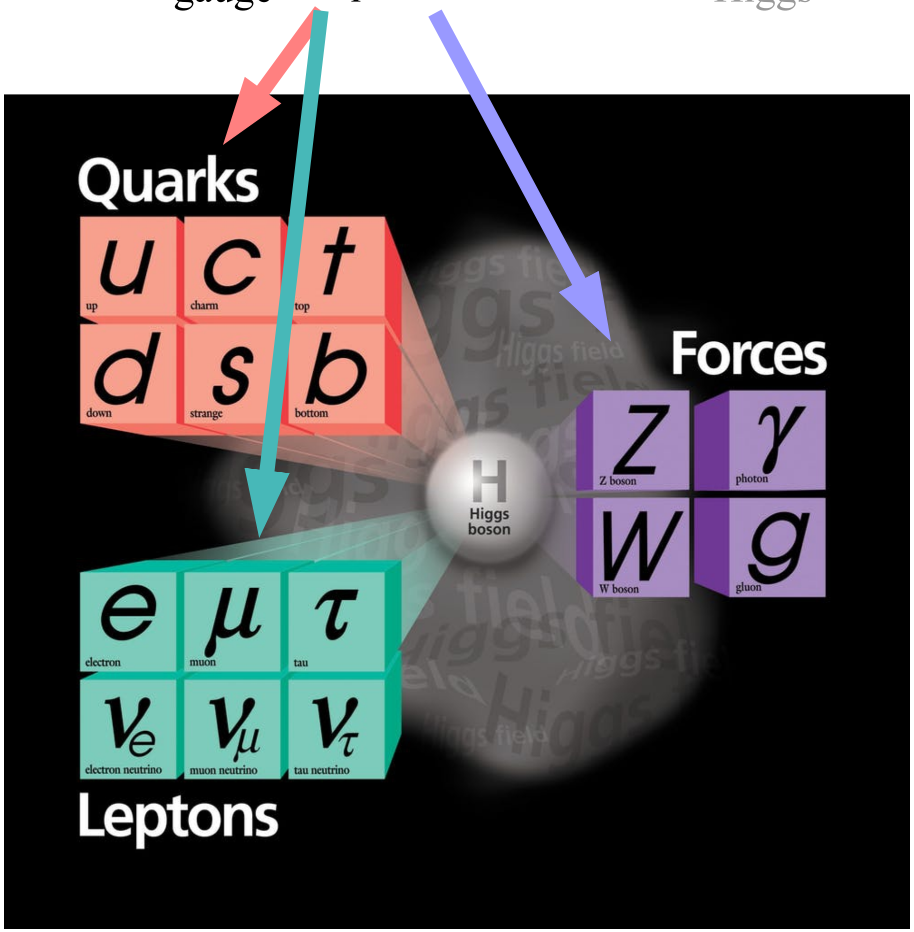

Strong
Weak
Electromagnetic
(*gauge interactions*)

Introduction

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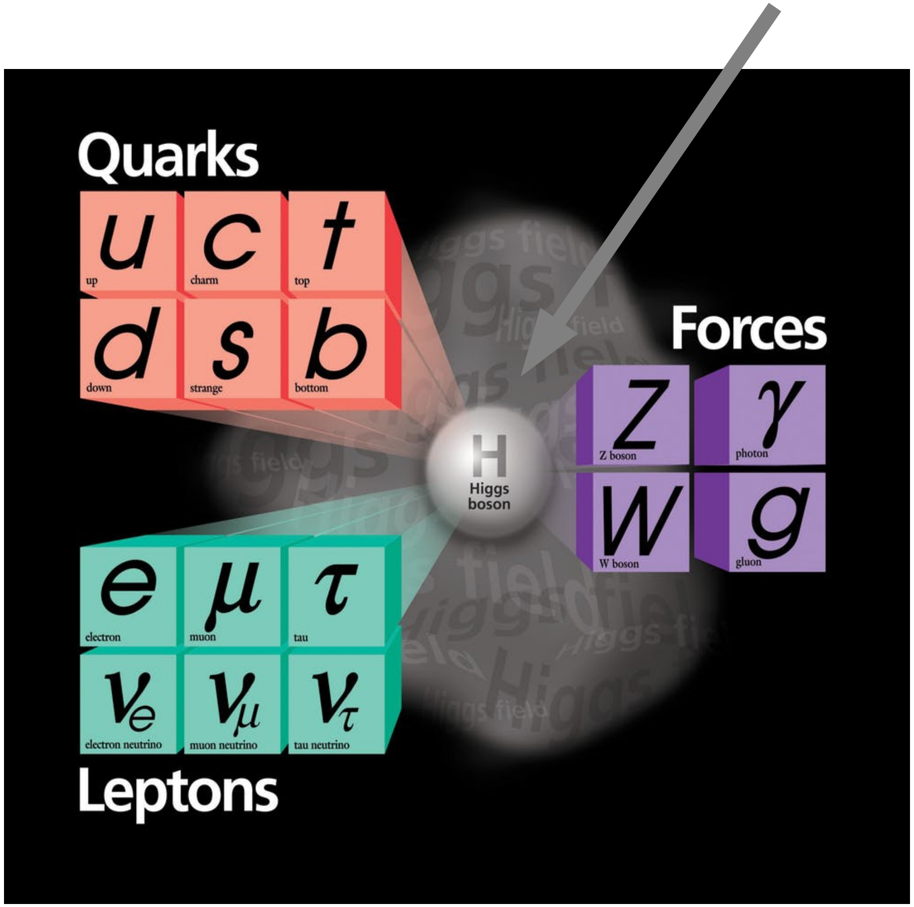


Spontaneous Symmetry Breaking

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

→

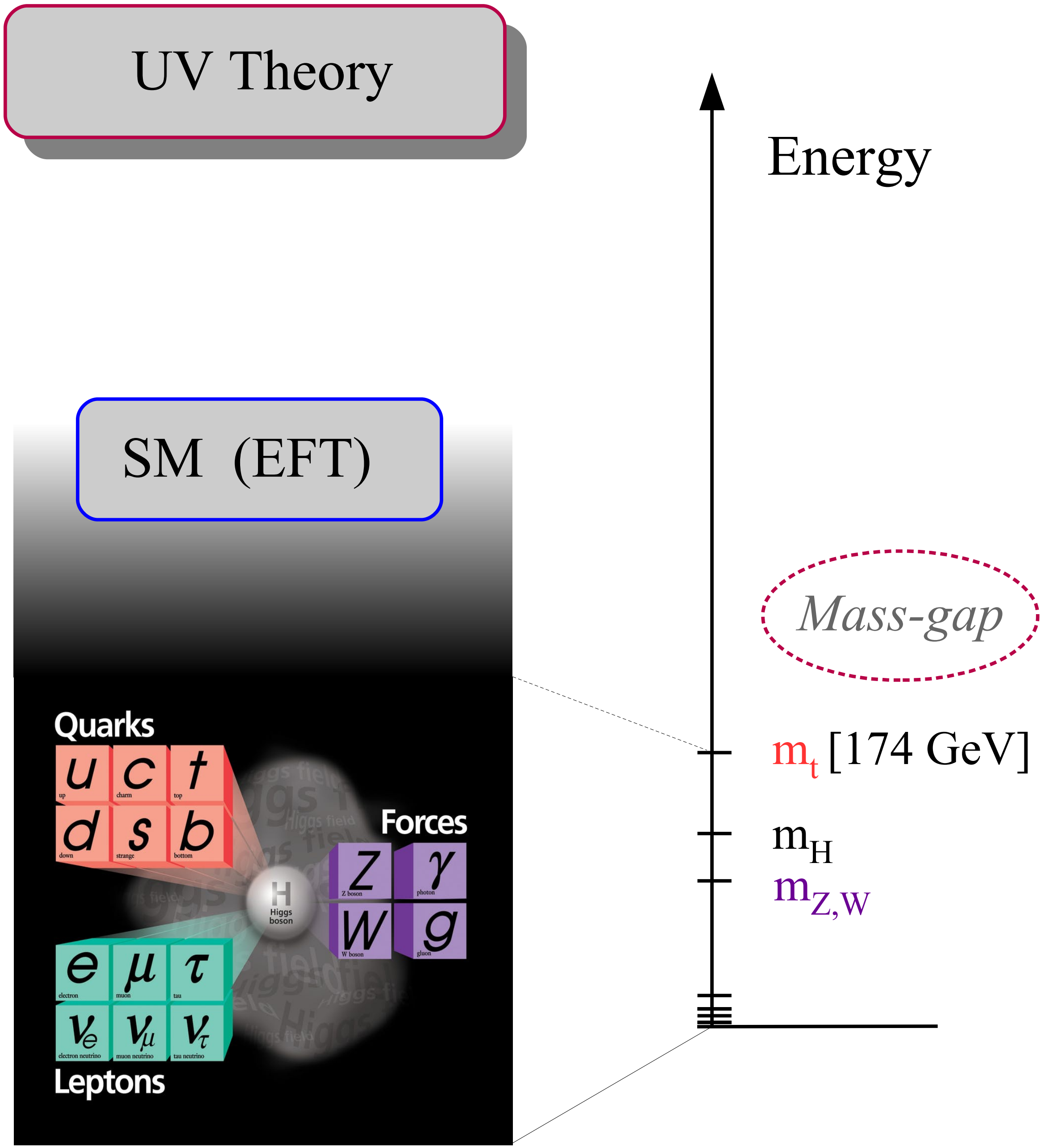
The Standard Model (SM) should be regarded as an *effective theory*

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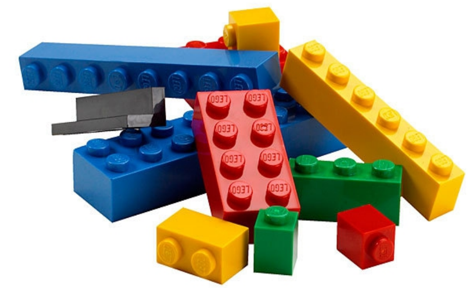
We identified the *"light"* (*"large"*) pieces of our *"construction game"* & their long-range interactions

UV Theory

$E \sim L^{-1}$



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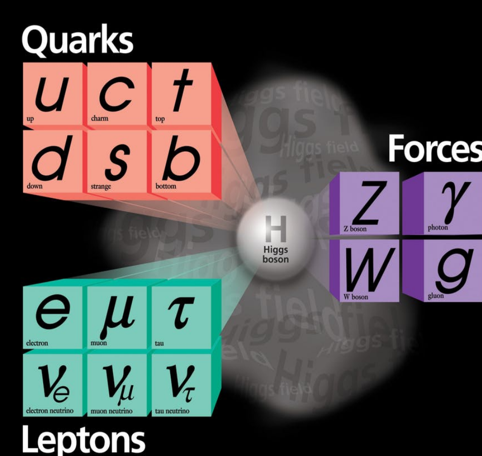
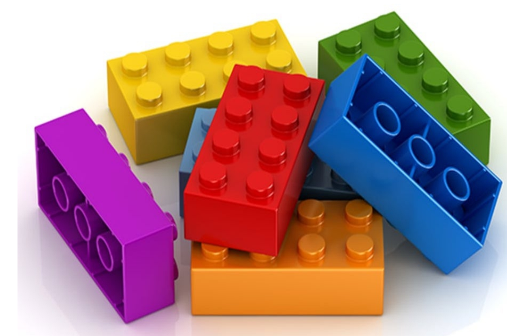
SM (EFT)





Introduction

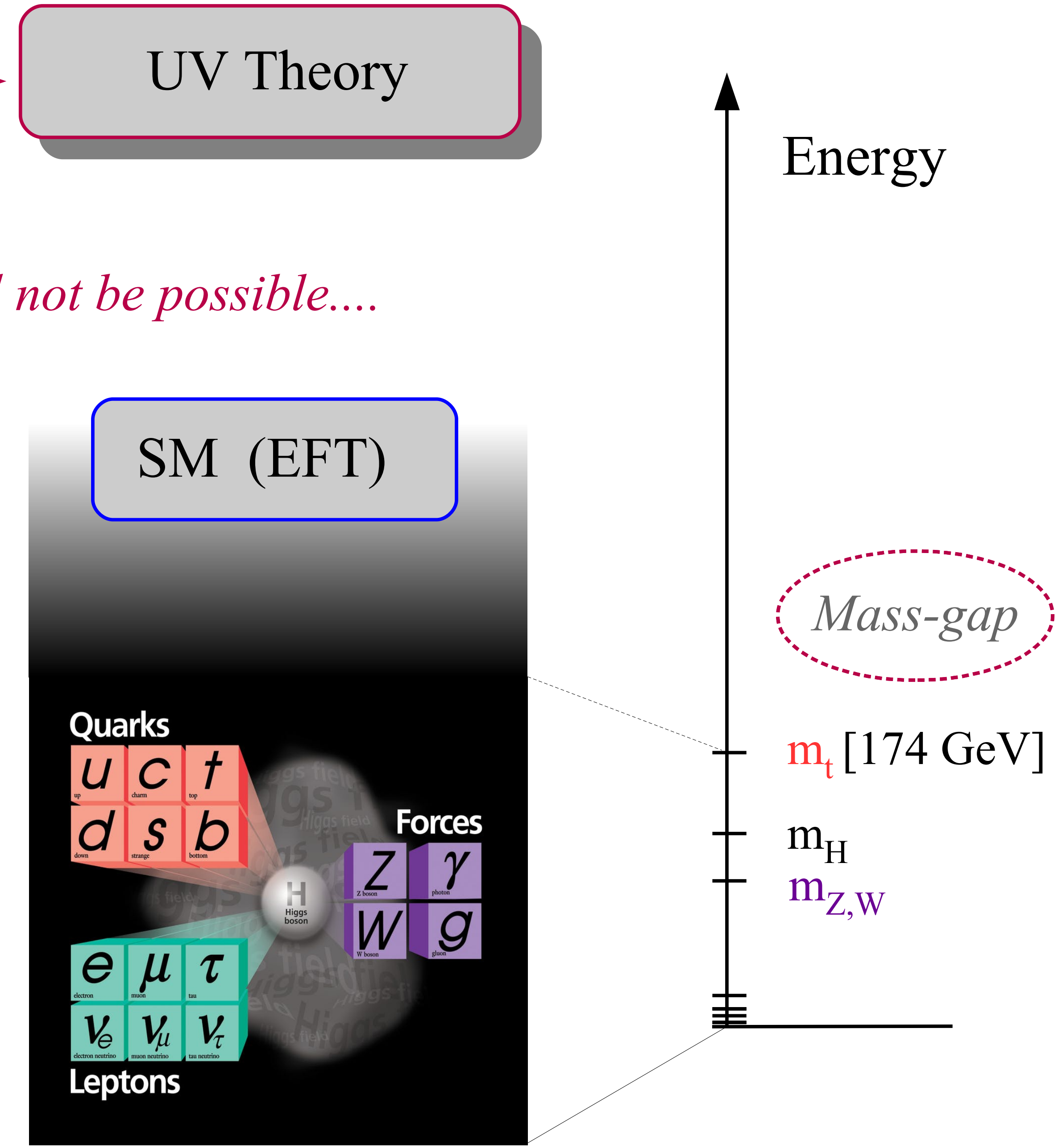
Ideally, we would like to probe the UV directly, via high-energy experiments

However, for > 30 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.

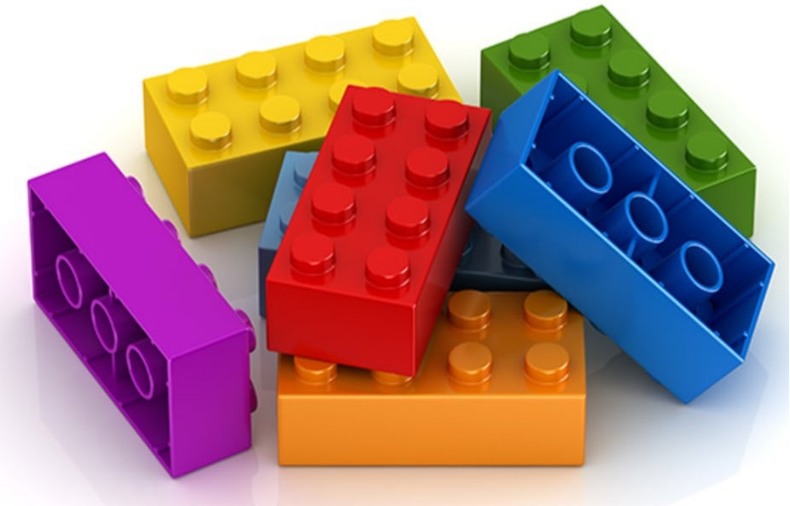
Many infos, with 2 clear messages:

- *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.



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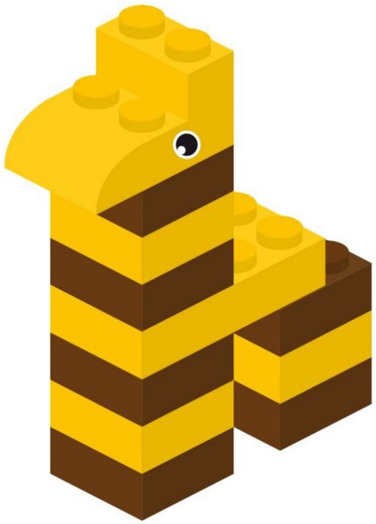


Flavour physics is essential to this purpose

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

The flavor structure of the SM

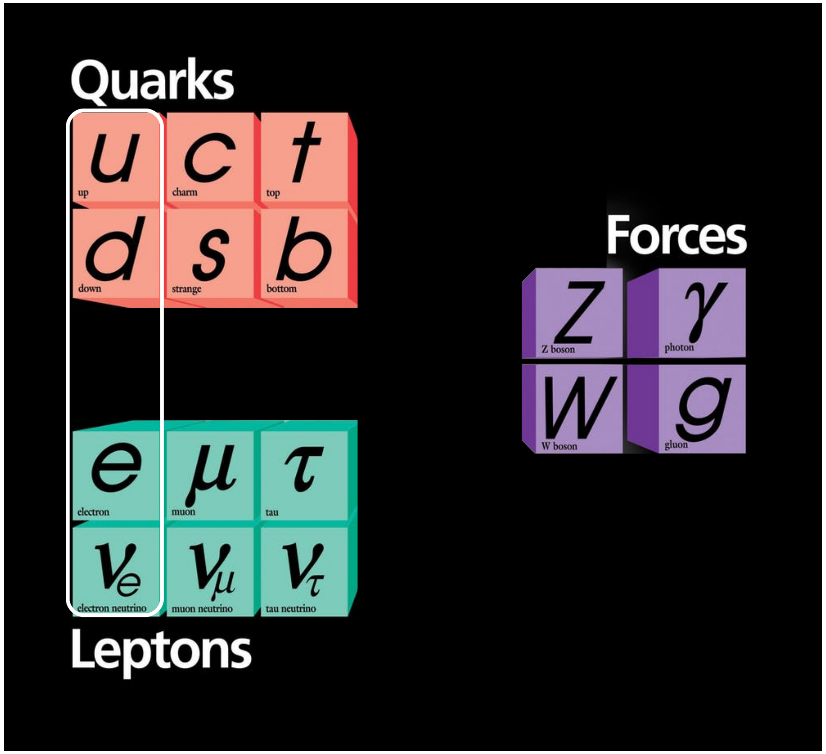
The flavor structure of the SM

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

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

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

The gauge Lagrangian is invariant under 5 independent U(3) global rotations 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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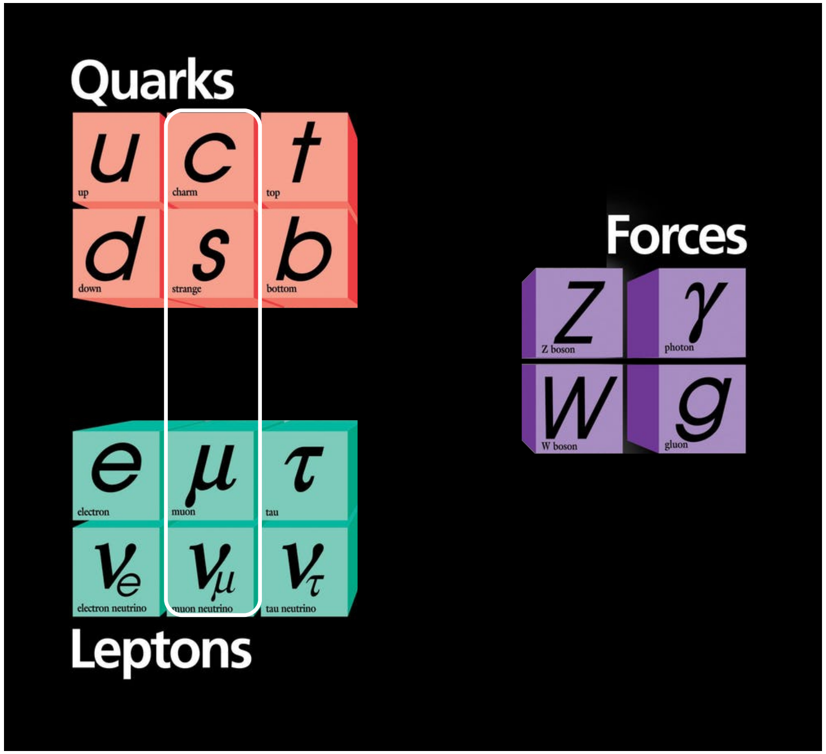

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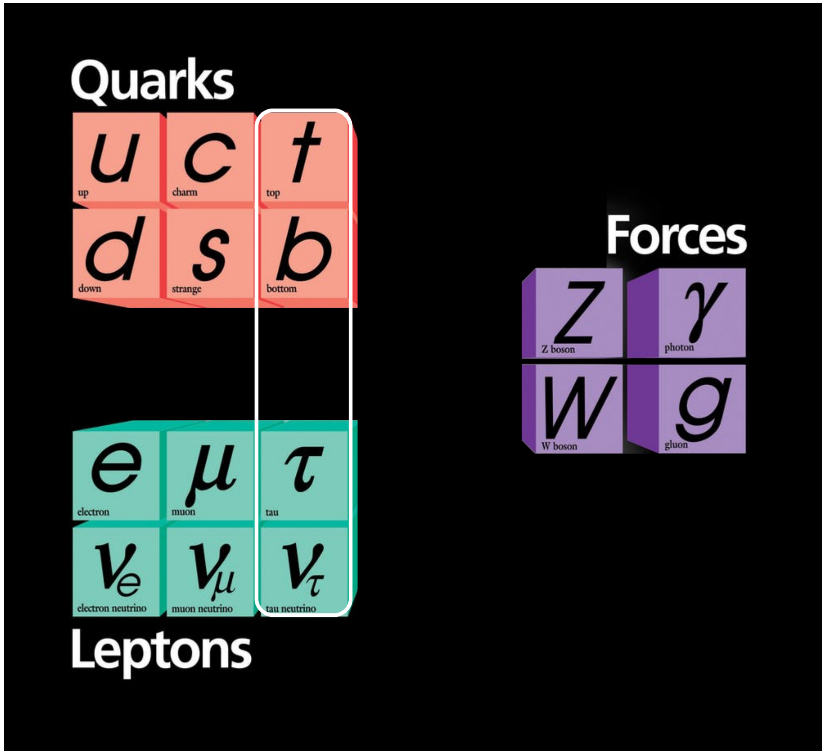

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E.g.: $Q_L^i \to U^{ij} Q_L^j$

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

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$$U(1)_L \times U(1)_B \times U(1)_Y \times SU(3)_Q \times SU(3)_U \times SU(3)_D \times \ldots$$

Lepton number
Baryon number
Hypercharge
Flavor mixing

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Within the SM the flavor-degeneracy is broken only by the Yukawa interaction:

in the quark sector:

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

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

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

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

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

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

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

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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

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

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

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:

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

→ Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix

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

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

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

- 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:

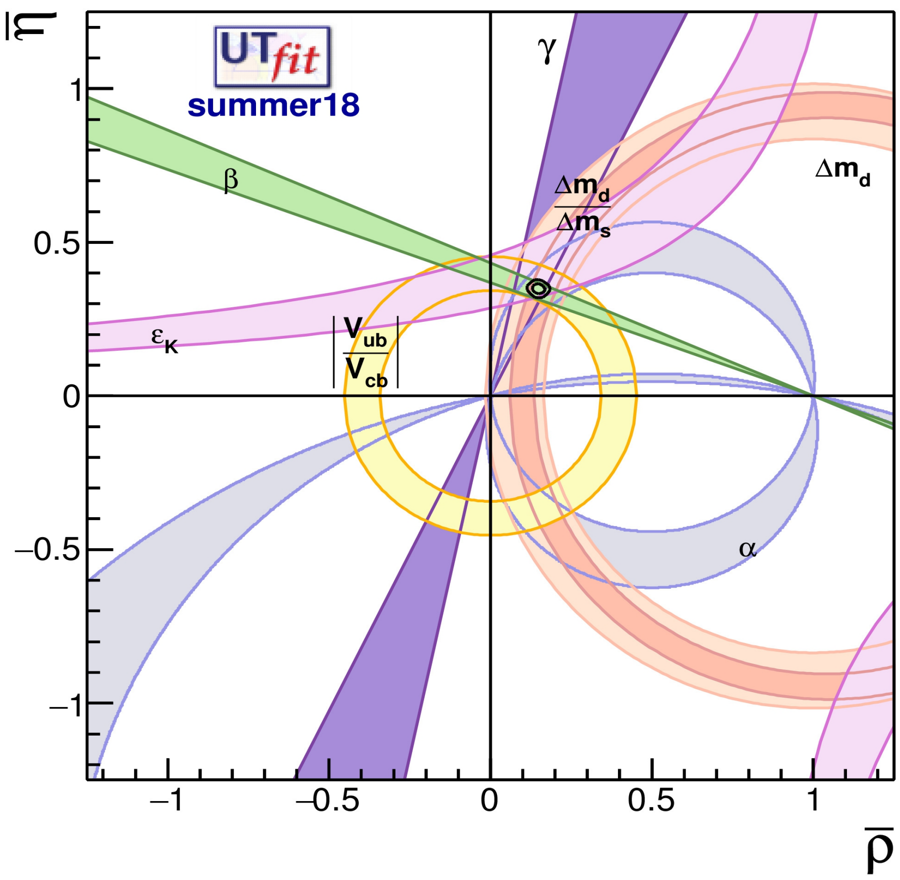
- 3 lepton masses

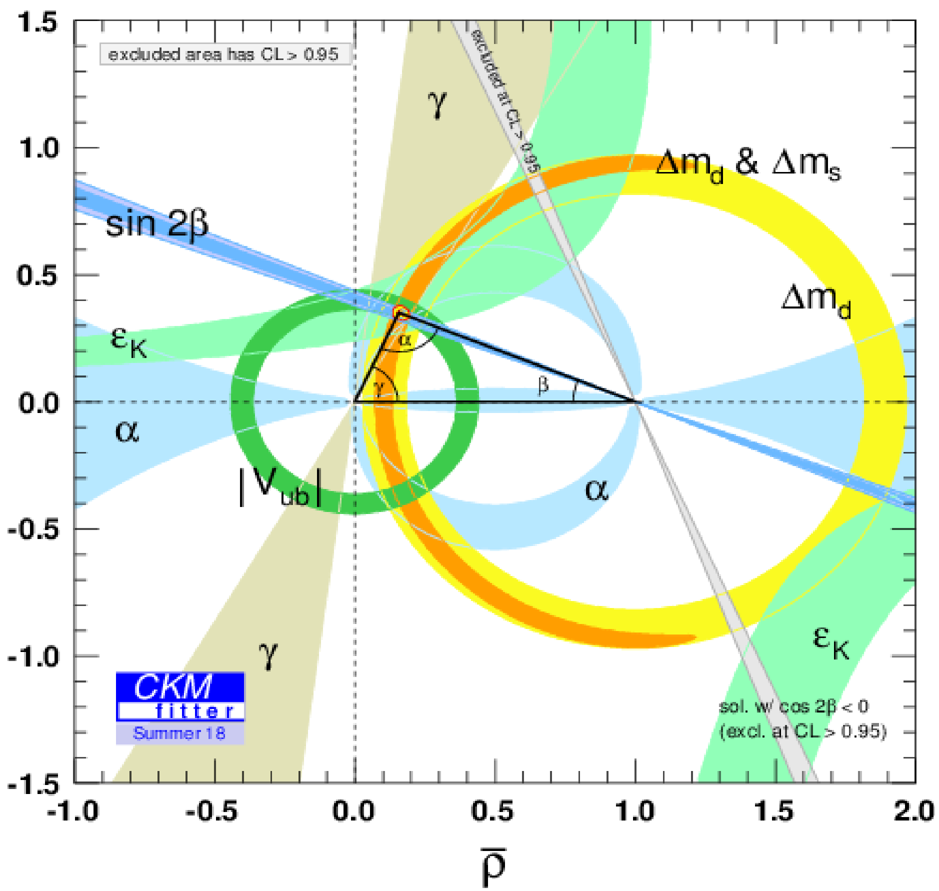
↘ ↙

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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$$V_{CKM} V_{CKM}^{+} = I$$

Experimental indication of a strongly hierarchical structure:

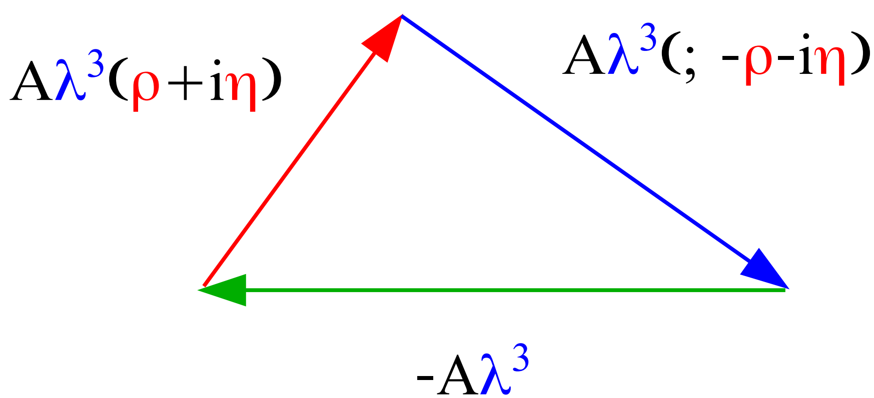
$$\approx \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

Wolfenstein, '83

$\lambda = 0.22$ A, $|\rho+i\eta| = O(1)$

The $b \to d$ UT triangle:

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



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

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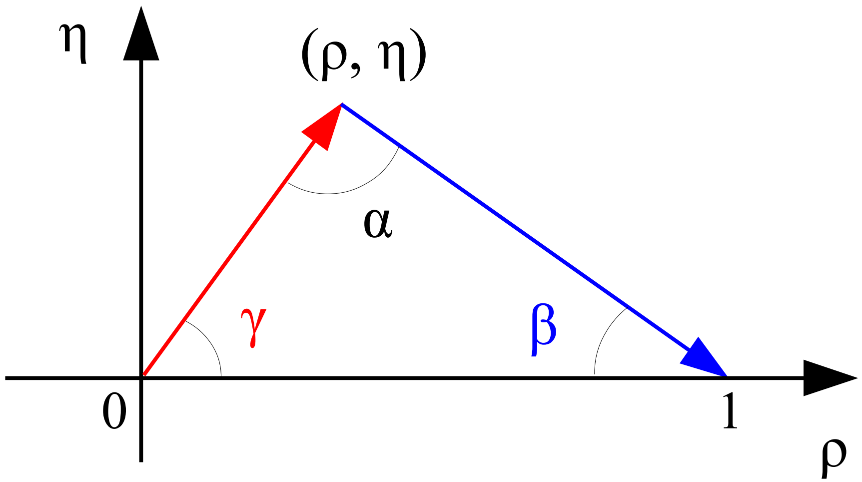
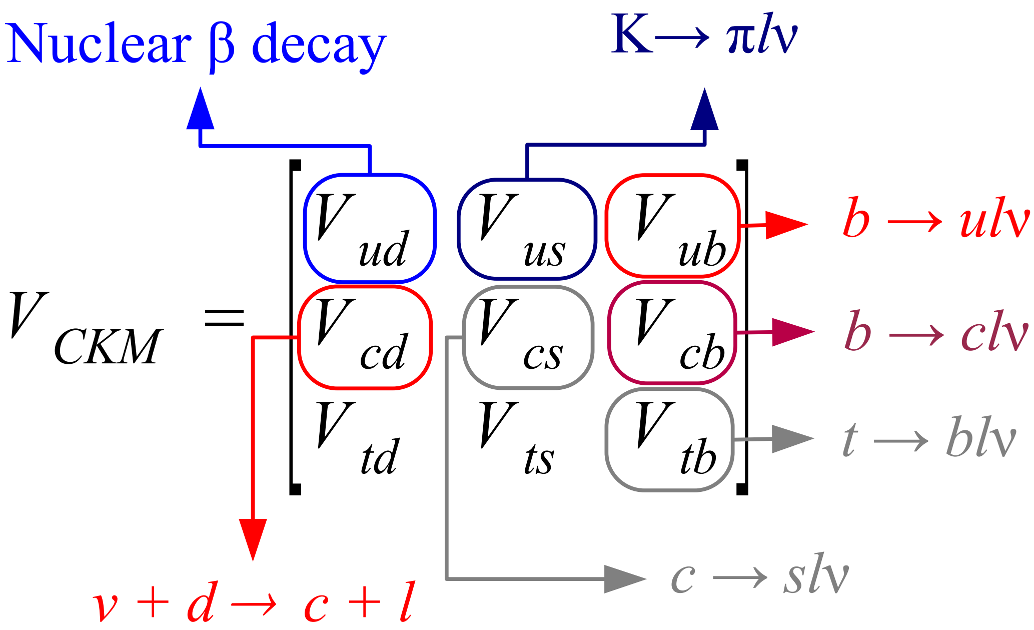
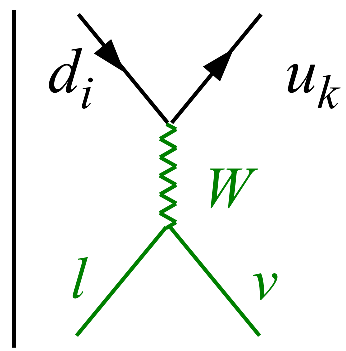


Note: *often you'll find experimental results shown as constraints in the* $\bar\rho, \bar\eta$ *plane. These new parameters are defined by* $\bar\rho = \rho\,(1-\lambda^2/2)^{-1/2}$ *(same for η) to keep into account higher-order terms in the expansion in powers of* λ.



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



$\Rightarrow |V_{ik}|$

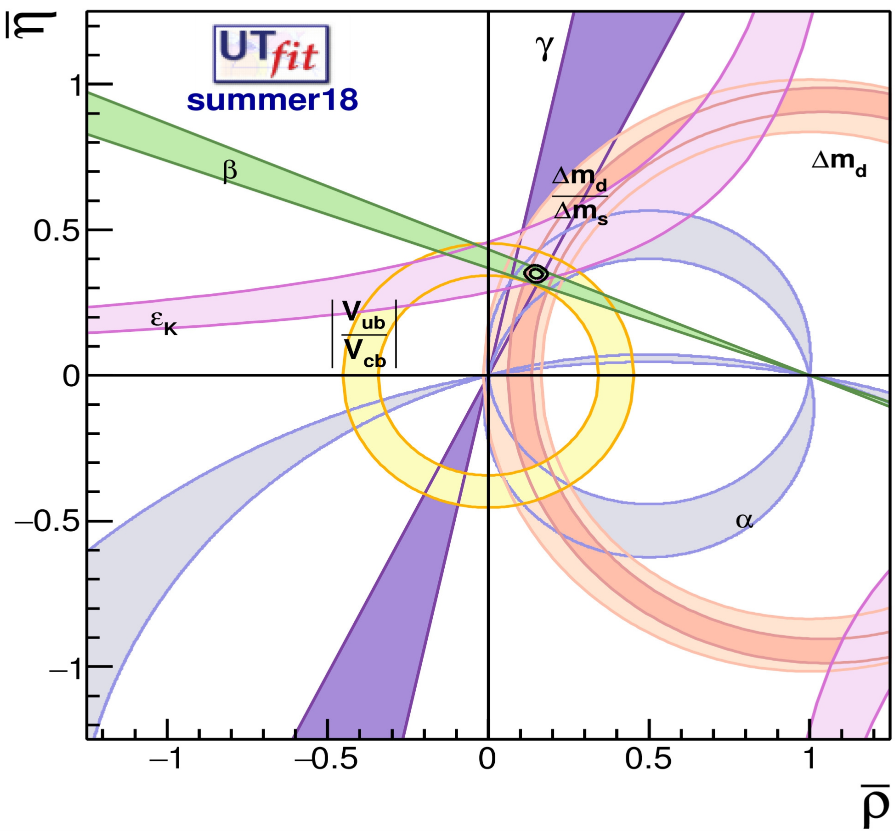
$$\begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

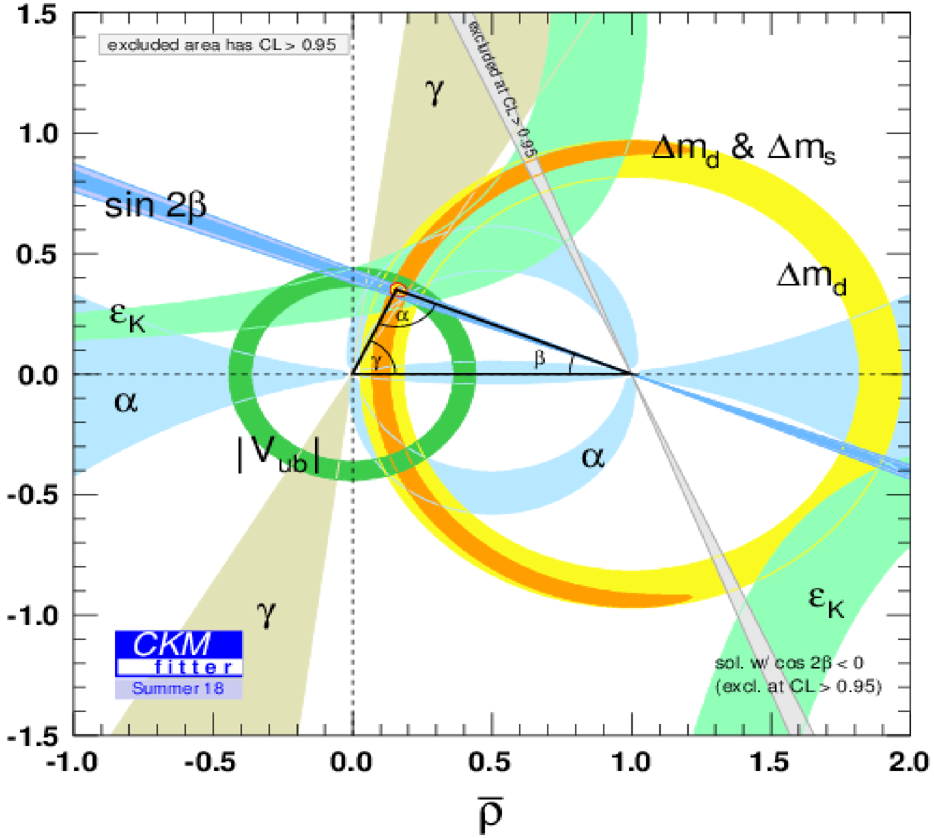
N.B.: Also the phase $\gamma = \arg(V_{ub})$ can be obtained by (quasi-) tree-level processes

Properties of the CKM matrix & CKM fits

Beside a series of recent anomalies [→ next lectures], 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?

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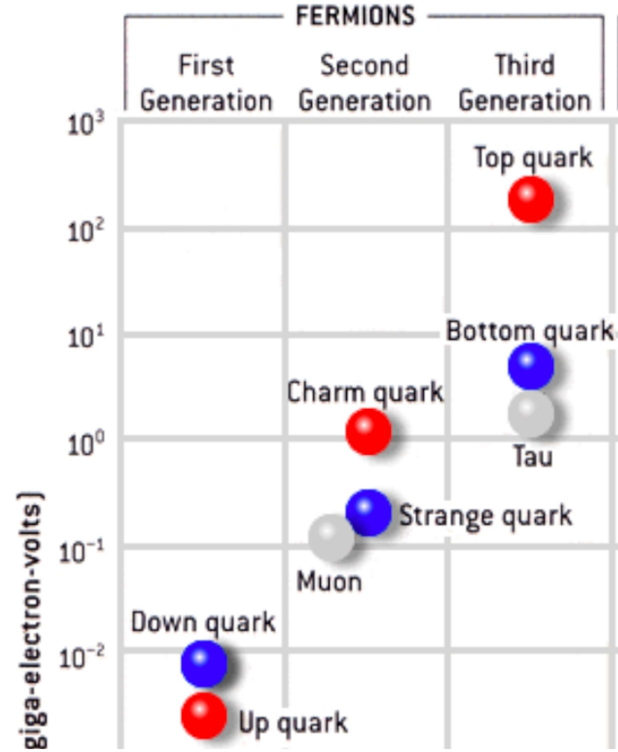
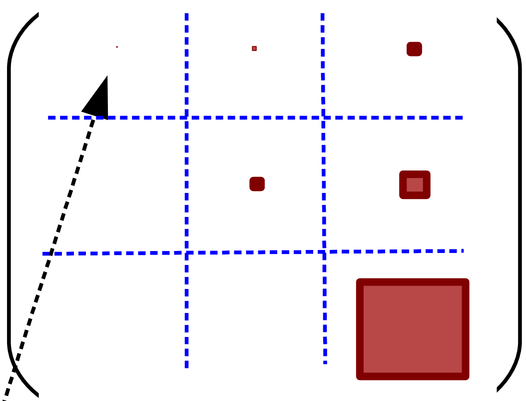
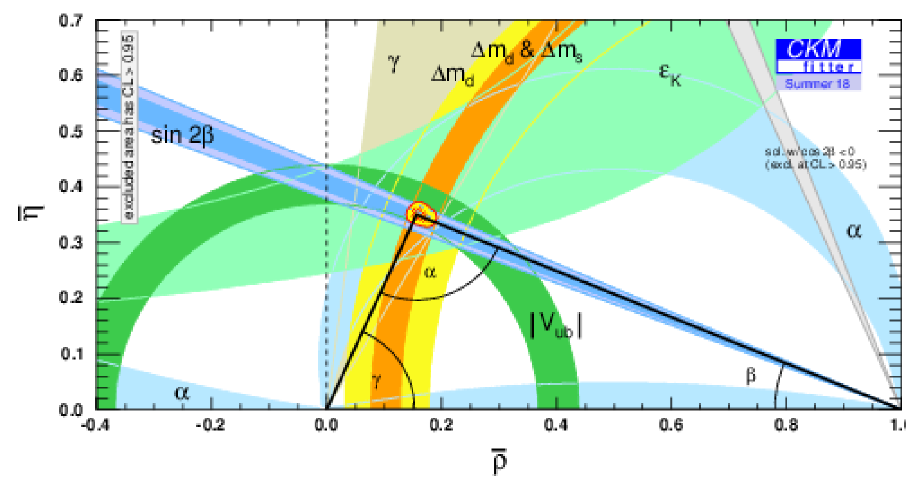


E.g.:

$Y_U \sim$ 

$$y_u = \frac{\sqrt{2}\, m_u}{\langle H \rangle} \approx 10^{-5} \qquad y_t = \frac{\sqrt{2}\, m_t}{\langle H \rangle} \approx 1$$

[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:

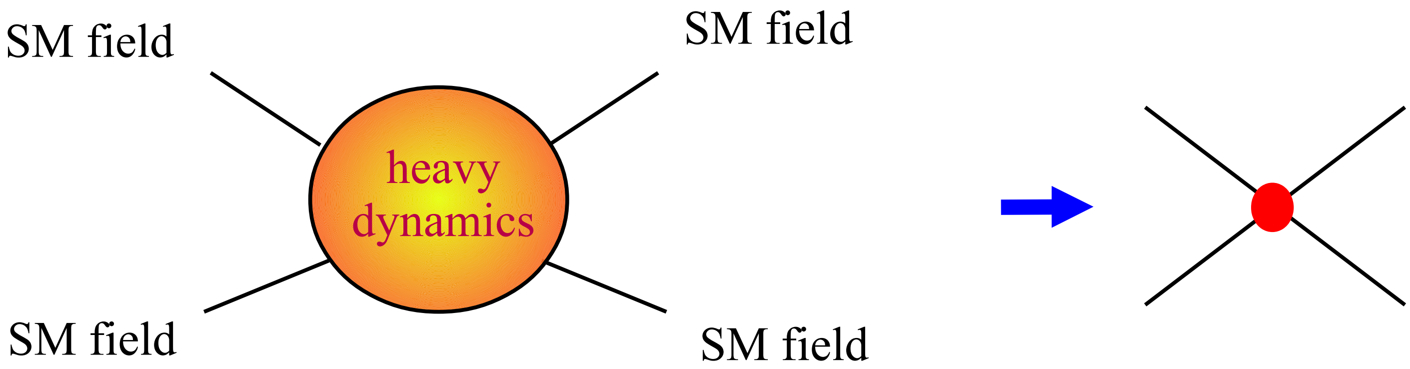
I. The observed pattern of SM Yukawa couplings does not look accidental [*SM flavor puzzle*]

→ 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.

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

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

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

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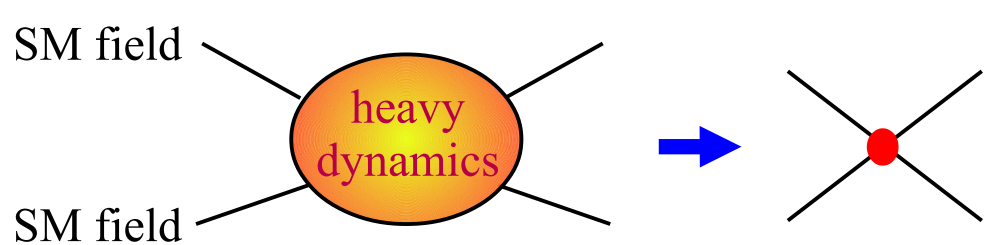
Interactions surviving @ large distances
(operators with $d \leq 4$)

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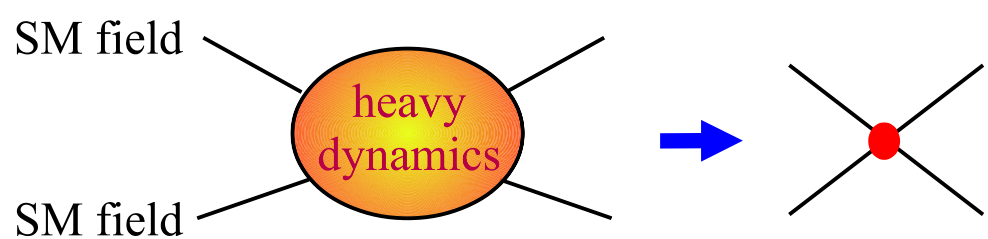
Interactions surviving @ large distances
(operators with $d \leq 4$)

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*]
- $m_u \approx m_d \approx 0 \rightarrow$ Isospin symmetry [*approximate symmetry*]

The flavor structure of the SMEFT

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Large flavor symmetry

Yukawa interaction

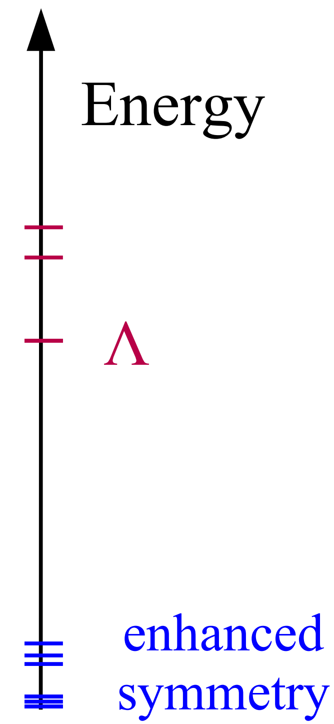
Exact & approximate (*accidental* ?) symmetries

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]

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

(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*]

▶ Accidental symmetries in QFT [a brief detour]

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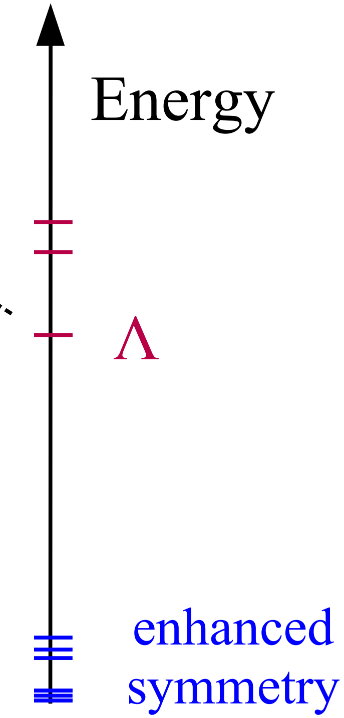


"Accidental symmetries" are symmetries which are not fundamental properties of the theory, but emerge accidentally at low energies / large distances → not enough "variables" to describe the violation of the symmetry [~ *multipole expansion*]

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

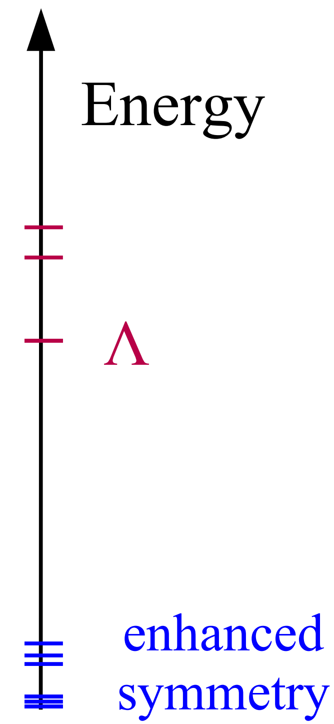
Violations of accidental symmetries

Accidental symmetries in QFT [a brief detour]

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

$\mathcal{L}_{\text{[QCD+QED]-EFT}}$ $\qquad$ $\mathcal{L}_{mf}$

Violations of accidental symmetries



Well-known examples from the past...

Eg: *Low-energy theory:* QED + QCD

Accidental symm.: Flavor [$U(1)^{n_f}$]

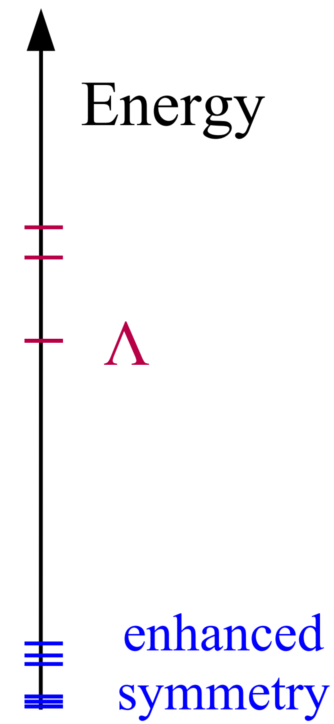
Violated by: Weak interactions $\rightarrow G_F \sim (250\ \text{GeV})^{-2}$

Accidental symmetries in QFT [a brief detour]

$$\mathcal{L}_{\text{SM-EFT}} \to \mathcal{L}_{\text{[SM-2]-EFT}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{d\geq 5}$$

(SM-EFT crossed out, replaced by [SM-2]-EFT)

Violations of accidental symmetries



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Eg: *Low-energy theory:* QED + QCD
Accidental symm.: Flavor [$U(1)^{n_f}$]
Violated by: Weak interactions → $G_F \sim (250 \text{ GeV})^{-2}$

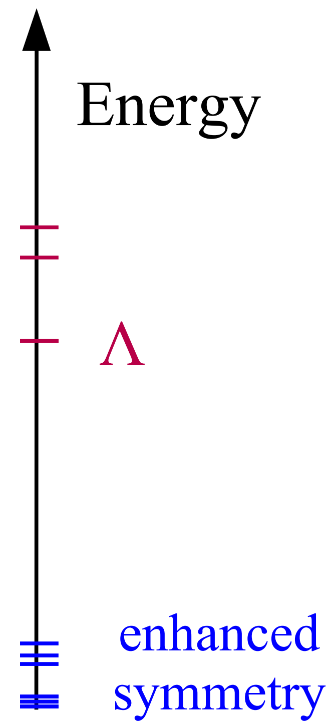
Eg: *Low-energy theory:* SM, 2 generations
Accidental symm.: CP
Violated by: "Super-weak" interaction [L. Wolfenstein]:

$$\frac{e^{i\delta}}{\Lambda^2} (\bar{s}\,\Gamma\, d)^2 \qquad \frac{1}{\Lambda^2} \sim (10^4 \text{ TeV})^{-2} \sim \frac{(G_F m_t V_{ts} V_{td})^2}{4\pi^2}$$

Accidental symmetries in QFT [a brief detour]

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

Violations of accidental symmetries

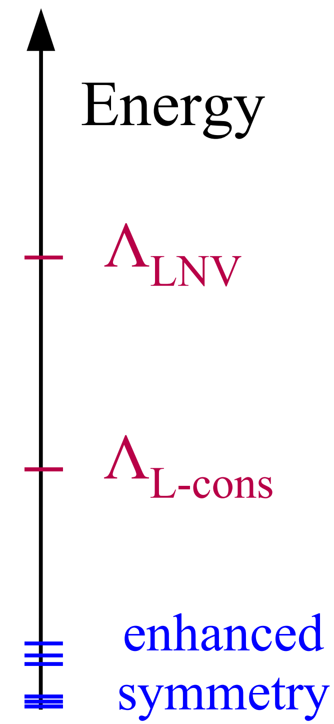


Well-known examples from the past...

…the violations of Lepton Flavor Universality recently reported by experiments (B-physics *anomalies*) belong to this category

Accidental symmetries in QFT [a brief detour]

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



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

Eg: *Total Lepton Number & neutrino masses*

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

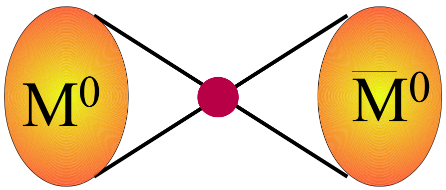
Consistent to assume d=6 ops preserving LN characterized by $\Lambda_{L\text{-cons}} \ll \Lambda_{LN}$

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

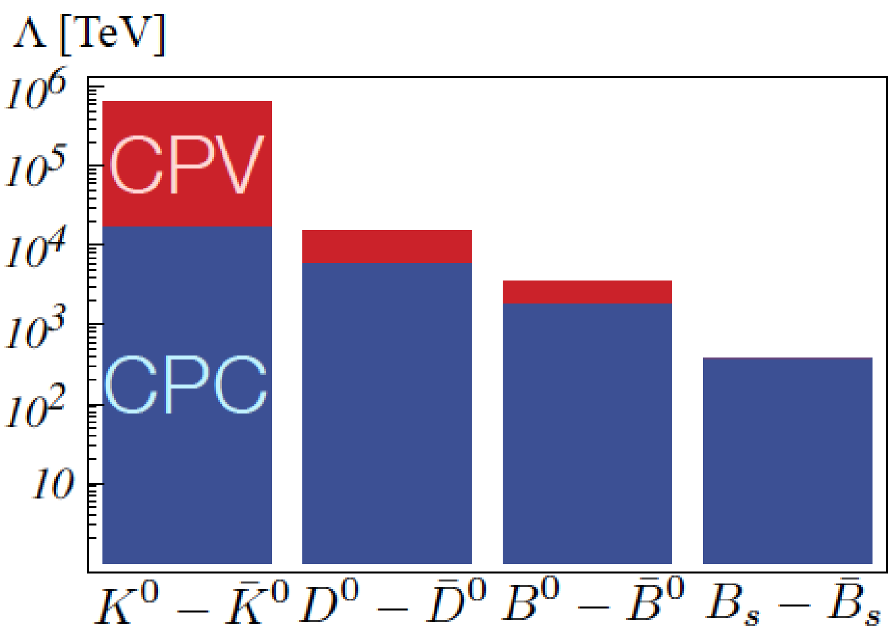
$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{d\geq5}$$

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



However, beside the B-physics anomalies we observe none

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



The NP Flavor puzzle

The flavor structure of the SMEFT

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

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

$U(3)^5$ symmetry broken by Yukawa couplings

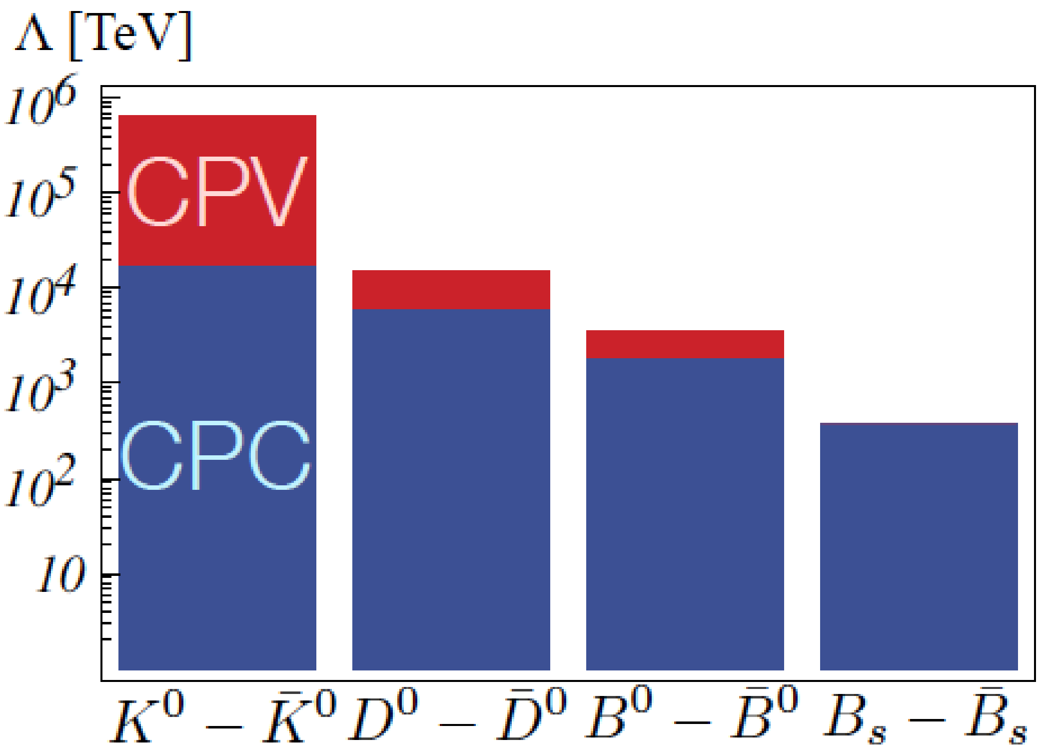
Stringent bounds on generic flavor-violating ops.

The big questions in flavor physics:

- Are all the the accidental flavor symmetries of the SM broken in the other sectors of the SM-EFT ?
- 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?

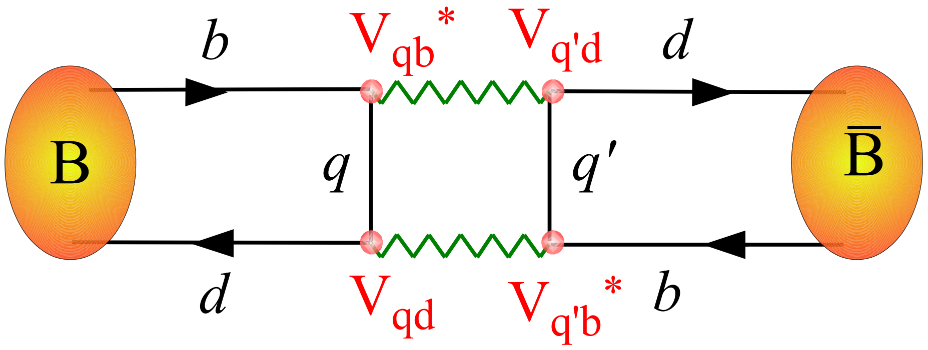
Recent data start to provide some answers...

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) ΔF=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 [e.g. from the time evolution of the neutral meson system]

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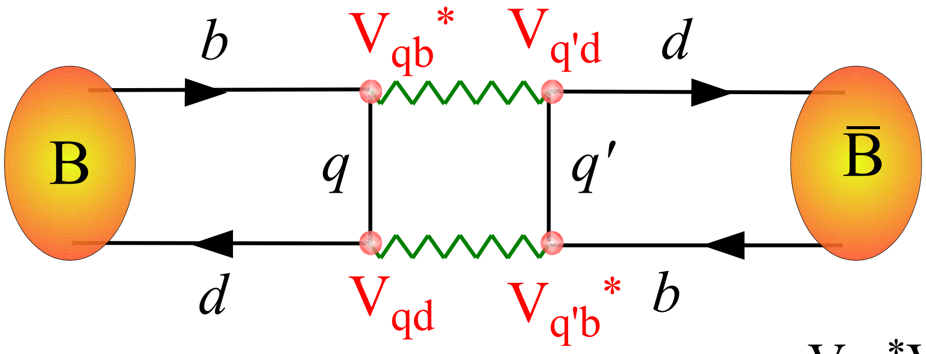

$$A_{\Delta F=2} = \Sigma_{q,q'=u,c,t} (V_{qb}{}^* V_{qd}) (V_{q'b}{}^* V_{q'd}) A_{q'q}$$

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

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

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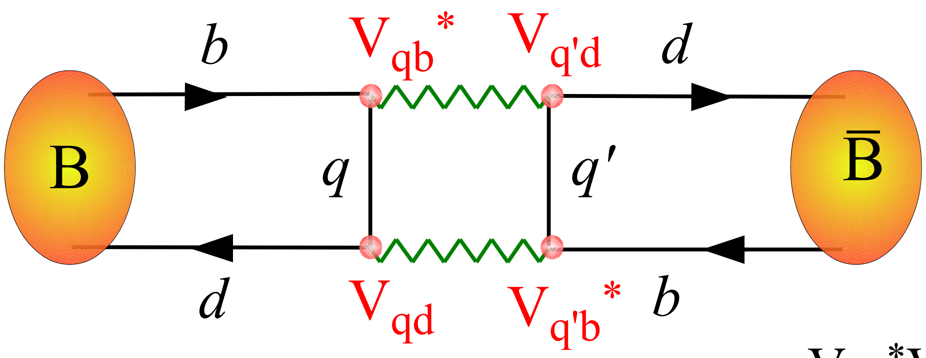

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$$A_{qq'} \sim \frac{g^4}{16\pi^2 m_W{}^2} \left[\text{Const.} + \frac{m_q\, m_{q'}}{m_W{}^2} + \ldots \right] \langle \overline{B} |\, (\bar{b}_L \gamma_\mu d_L)^2\, | B \rangle$$

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

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

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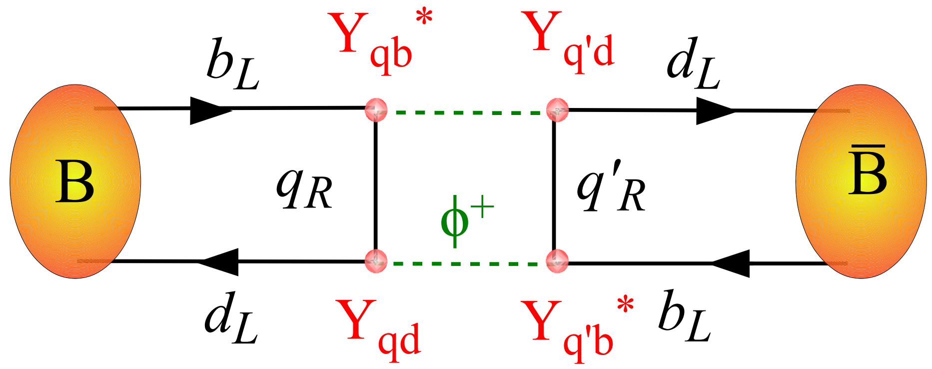

The origin of this behavior can be better understood if we *switch-off* gauge interactions ("gauge-less limit")

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

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

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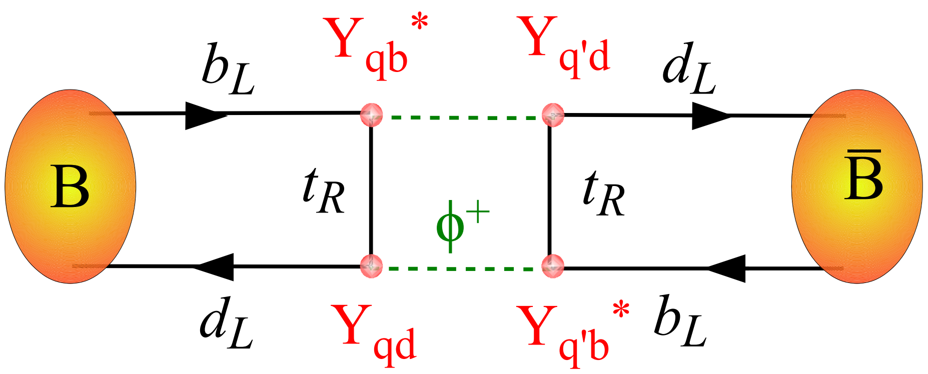

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$$Y_U = V^+ \times \mathrm{diag}(y_u, y_c, y_t) \approx V^+ \times \mathrm{diag}(0, 0, y_t)$$

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

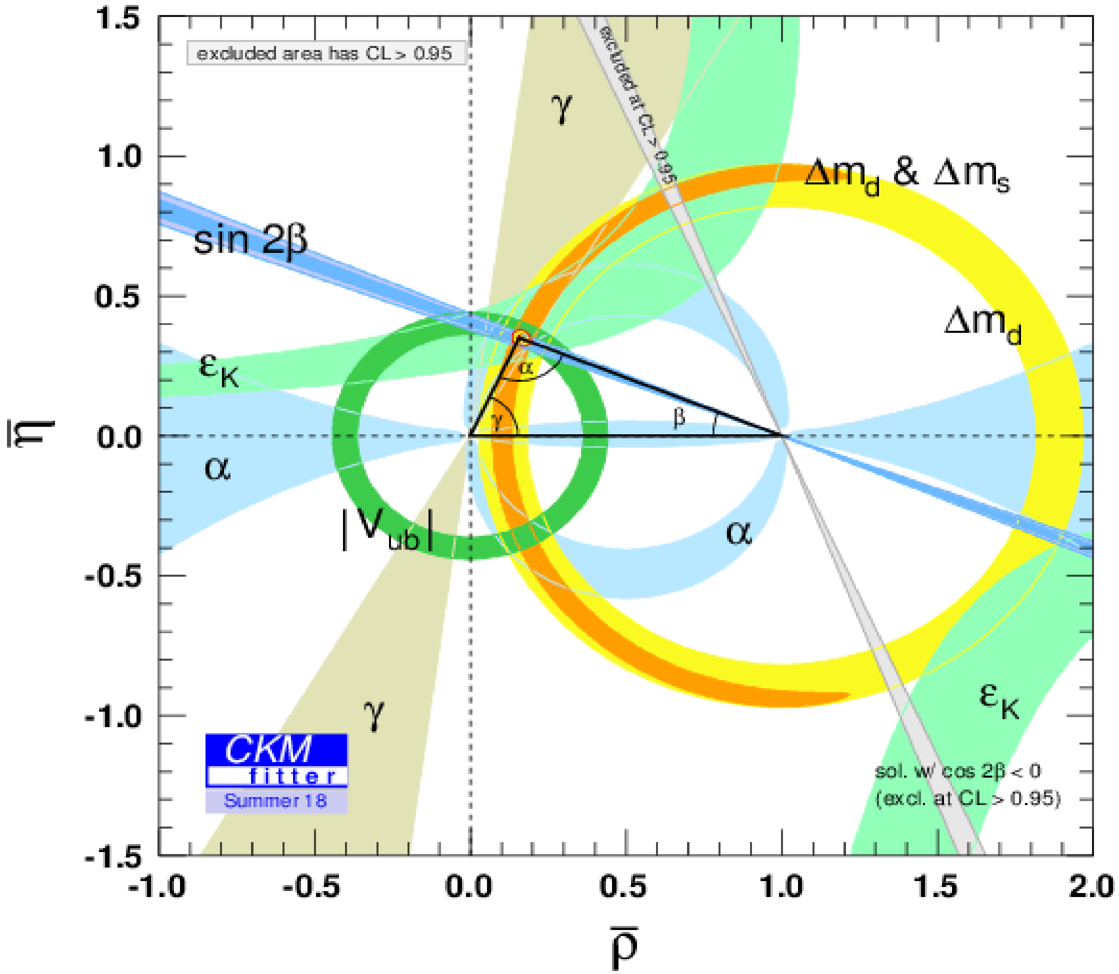
$$m_t = y_t\, v / \sqrt{2} \qquad m_W = g\, v / 2$$

This way we obtain the exact result 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):



▸ NP bounds from meson-antimeson mixing

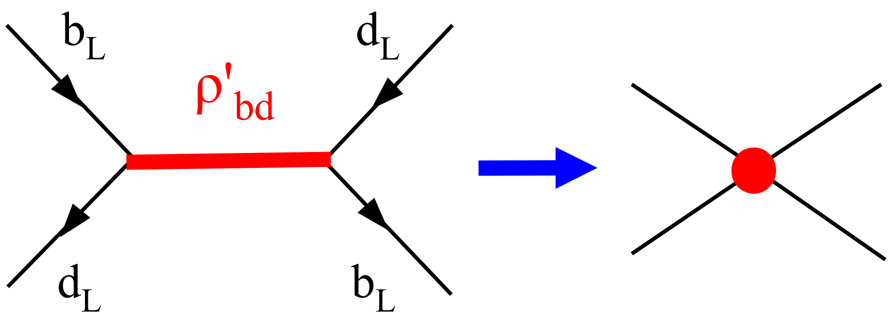
Current data show no significant deviations from the SM (at the 5%-30% level, depending on the specific amplitude) on $\Delta F = 2$ observables (mass differences and CP-violating phases) → strong bounds on possible BSM contributions:

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

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

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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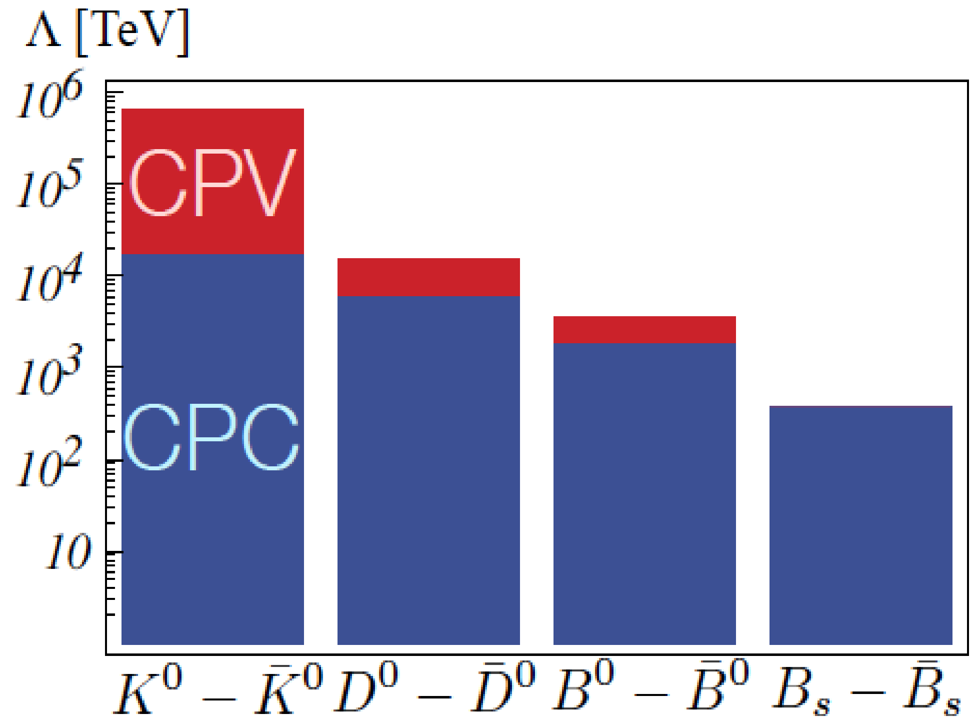
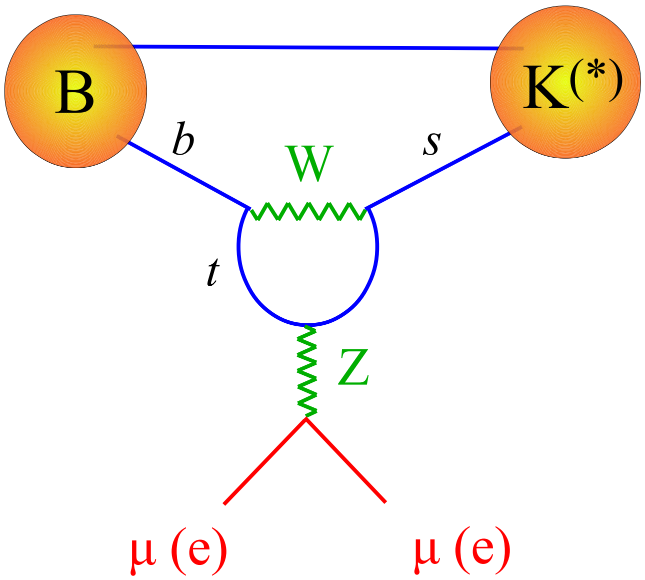
Operator	Bounds on Λ (TeV)	
	Re	Im
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	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, these bounds can be missleading in terms of physical scales [c.f. the case of CP-violation in SM-2] and accidental symmetries in the EFT might hide a multi-scale strucutre in the underlying theory [→ lecture 4]

LFU and $b \to s\ell\ell$ decays



What is LFU?

Since 2013 results in semi-leptonic B decays started to exhibit tensions with the SM predictions connected to a possible violation of Lepton Flavor Universality

More precisely, we seem to observe a different behavior (*beside pure kinematical effects*) of different lepton species in the following processes:

- $b \to s\, l^+ l^-$ (neutral currents): μ vs. e
- $b \to c\, l\nu$ (charged currents): τ vs. light leptons (μ, e)

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LFU is an accidental symmetry of the SM Lagrangian in the limit where we neglect the lepton Yukawa couplings.

LFU is badly broken in the Yukawa sector: $y_e \sim 3\times10^{-6}$, $y_\mu \sim 3\times10^{-4}$, $y_\tau \sim 10^{-2}$
but all the lepton Yukawa couplings are small compared to SM gauge couplings

$$(y_{e,y,\tau})^2 \ll (g_i)^2 \qquad [e \sim 1/3,\ g \sim 2/3]$$

This is why – within the SM – we expect to a very good accuracy the universality of decay amplitudes which differ only by the different lepton species involved

Rare $b \to s$ decays: generalities

The *anomalies* (= deviations from SM) are statistically more significant in $b \to s\, l^+ l^-$ transitions [$l = \mu, e$] and in these processes do not involve only LFU violations:

- P'_5 anomaly [$B \to K^* \mu\mu$ angular distribution]
- Smallness of all $B \to H_s \mu\mu$ rates [H_s=K, K^*, ϕ (from B_s)]
- LFU ratios (μ vs. e) in $H_b \to H_s\, ll$ decays
- Smallness of BR($B_s \to \mu\mu$)

chronological order

Lectures 2 & 3 by Monica Altarelli

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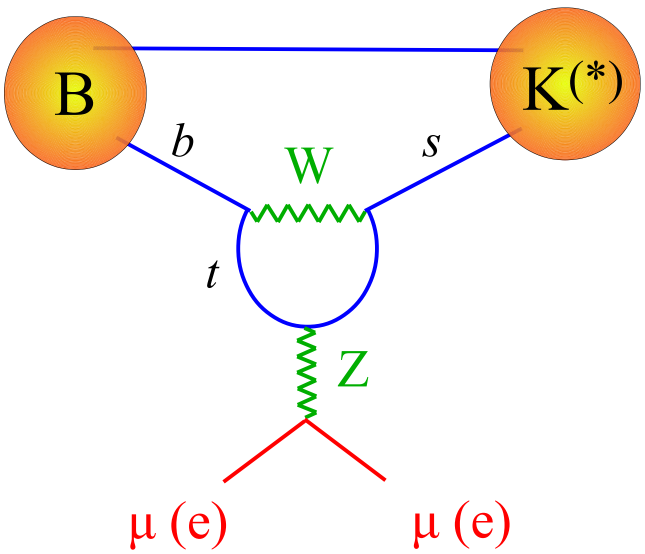
chronological order

$b \to s\, l^+l^-$ transitions are Flavor Channing Neutral Current amplitudes

- No SM tree-level contribution
- Strong suppression within the SM because of CKM hierarchy
- Sizable hadronic uncertainties in the rates

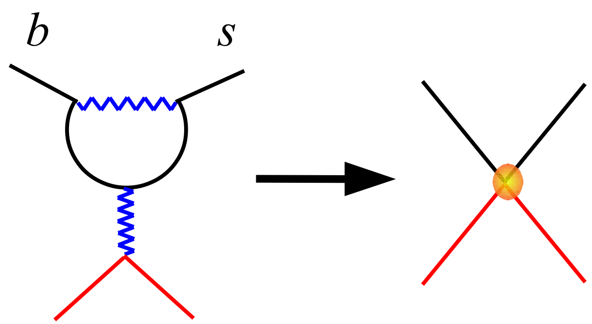
→ *detailed th. discussion needed*



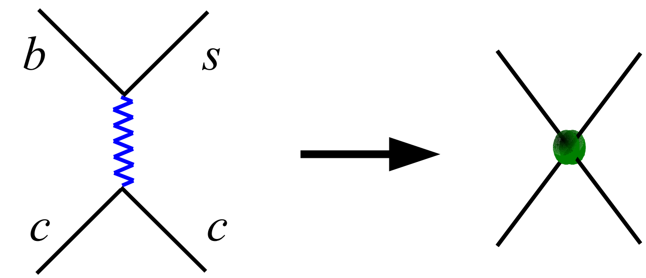
Rare b → s decays: generalities

In order to describe these processes within the SM & beyond, we use a 3-step procedure which allows us to separate the different scales involved:

1st step: Construction of an effective Lagrangian at the electroweak scale integrating out all the heavy fields around m_W (including the heavy SM fields)



$$\mathscr{L}_{\text{eff}} = \Sigma_i \, C_i(M_W) \, Q_i$$



FCNC operators:

$$\mathcal{O}_{10}^{\ell} = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell) \quad \text{[Z penguin \& box]}$$

$$\mathcal{O}_{9}^{\ell} = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell) \quad [\gamma \text{ \& Z penguin}]$$

$$Q_7 = m_b(\bar{s}_L \sigma^{\mu\nu} b_R) F_{\mu\nu} \quad [\gamma \text{ penguin}]$$

Four-quark operatros:

$$Q_1^c = (\bar{s}_L \gamma_\mu T^a c_L)(\bar{c}_L \gamma^\mu T^a b_L)$$

$$Q_2^c = (\bar{s}_L \gamma_\mu c_L)(\bar{c}_L \gamma^\mu b_L)$$

$$\vdots$$

- The interesting short-distance info (sensitive to NP) is encoded in the $C_i(M_W)$ (*initial conditions*) of the Wilson coefficients of the FCNC operators (especially C_9 & C_{10})
- In generic extensions of the SM, the basis of FCNC operators can be larger

Rare $b \to s$ decays: generalities

In order to describe these processes within the SM & beyond, we use a 3-step procedure which allows us to separate the different scales involved:

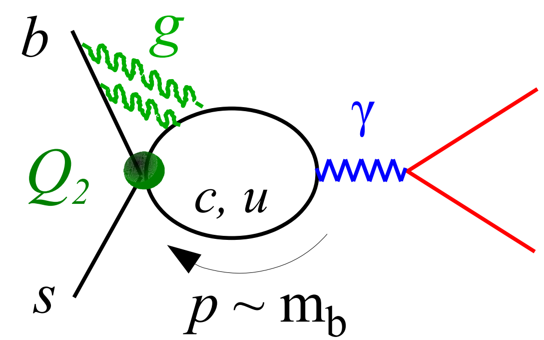
2nd step: Evolution of $\mathscr{L}_{\text{eff}}$ down to low scales using RGE

$$\mathscr{L}_{\text{eff}} = \Sigma_i\, C_i(M_W)\, Q_i \longrightarrow \mathscr{L}_{\text{eff}} = \Sigma_i\, C_i(\mu \sim m_b)\, Q_i$$

Potential dilution of the interesting short-distance information:

Mixing of the four-quark Q_i into the FCNC Q_i [perturbative long-distance contribution]

e.g.:



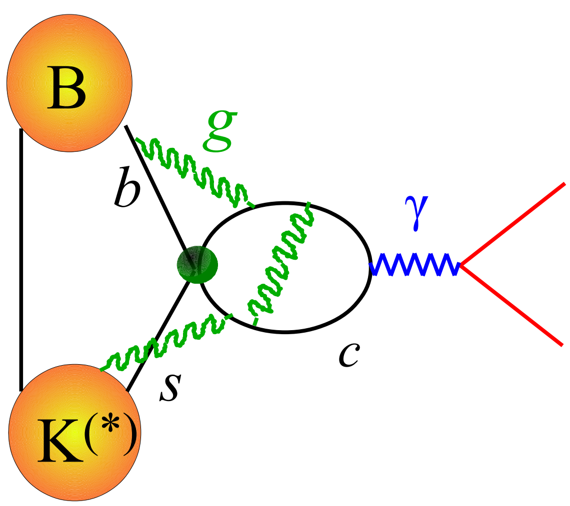
- Small in the case of the Z penguin (Q_{10}) because of the power-like GIM mechanism [mixing parametrically suppressed by $O(m_c^2/m_t^2)$]
- Large for most other operators; however, the effect can be computed with high accuracy

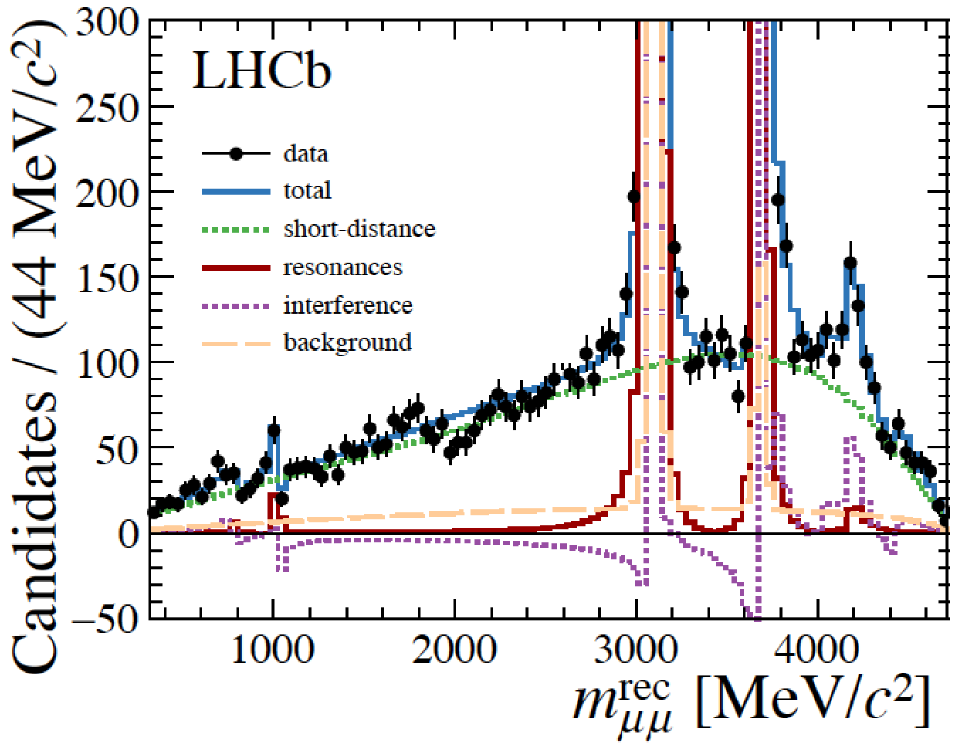
Rare b → s decays: generalities

3rd step: Evaluation of the hadronic matrix elements

$$A(B \to f) = \Sigma_i\, C_i(\mu)\, \langle f |\, Q_i\, | B \rangle (\mu) \qquad [\, \mu \sim m_b\,]$$

- Hadronic uncertainty due to form factors (as in all exclusive decays)
- Irreducible th. error due to long-distance effects not included in f.f. (*charm* threshold → particularly large close to $c\bar{c}$ resonances)





Rare $b \to s$ decays: generalities

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Despite the difficulties of estimating precisely long-distance dynamics, there are two properties which are very simple/clean:

- cannot induce LFU breaking terms ($\to$ LFU ratios *"clean"*)
- cannot induce axial-current contributions ($\to$ $B_s \to \mu\mu$ *"clean"*)

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- P'_5 anomaly [$B \to K^*\mu\mu$ angular distribution]
- Smallness of all $B \to H_s\, \mu\mu$ rates
- LFU ratios (μ vs. e) in $H_b \to H_s\, ll$ decays
- Smallness of BR($B_s \to \mu\mu$)

= th. error $\lesssim$1%

= th. error few %