Gino Isidori
[University of Zürich]

- Lecture 1: Introduction to flavor physics
- Lecture 2: Meson mixing, rare decays, universality tests
- Lecture 3: Flavor physics beyond the SM

University of Zurich UZH

European Research Council
Established by the European Commission

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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 structure of the SMEFT
- Lecture 2: Meson mixing, rare decays, universality tests
- Lecture 3: Flavor physics beyond the SM

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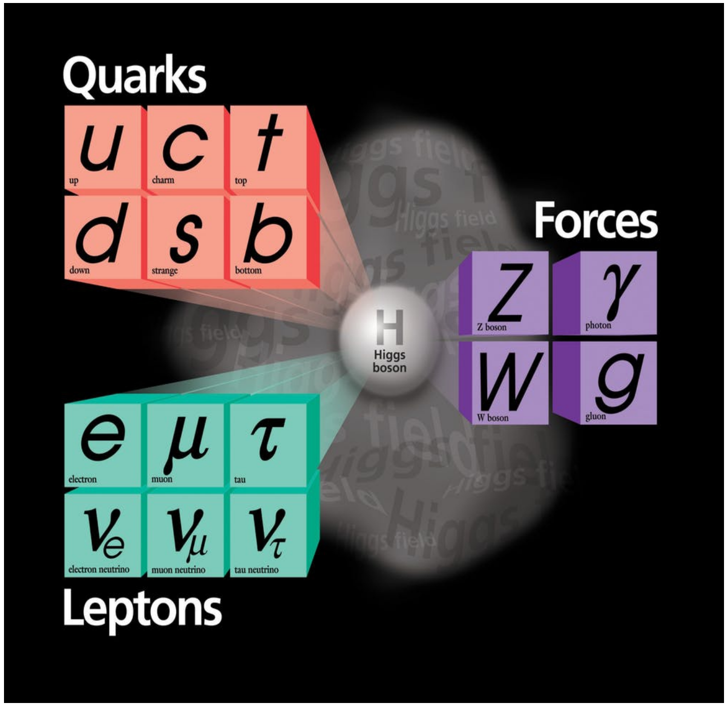
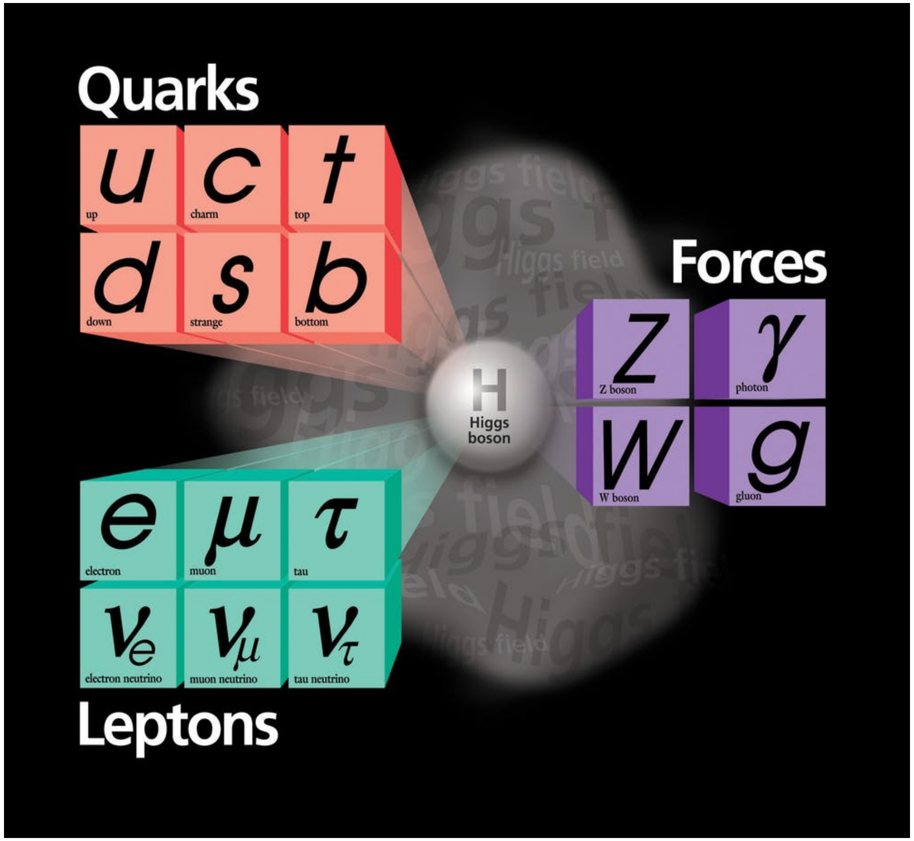
Introduction



Introduction

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

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



▶ *Introduction*

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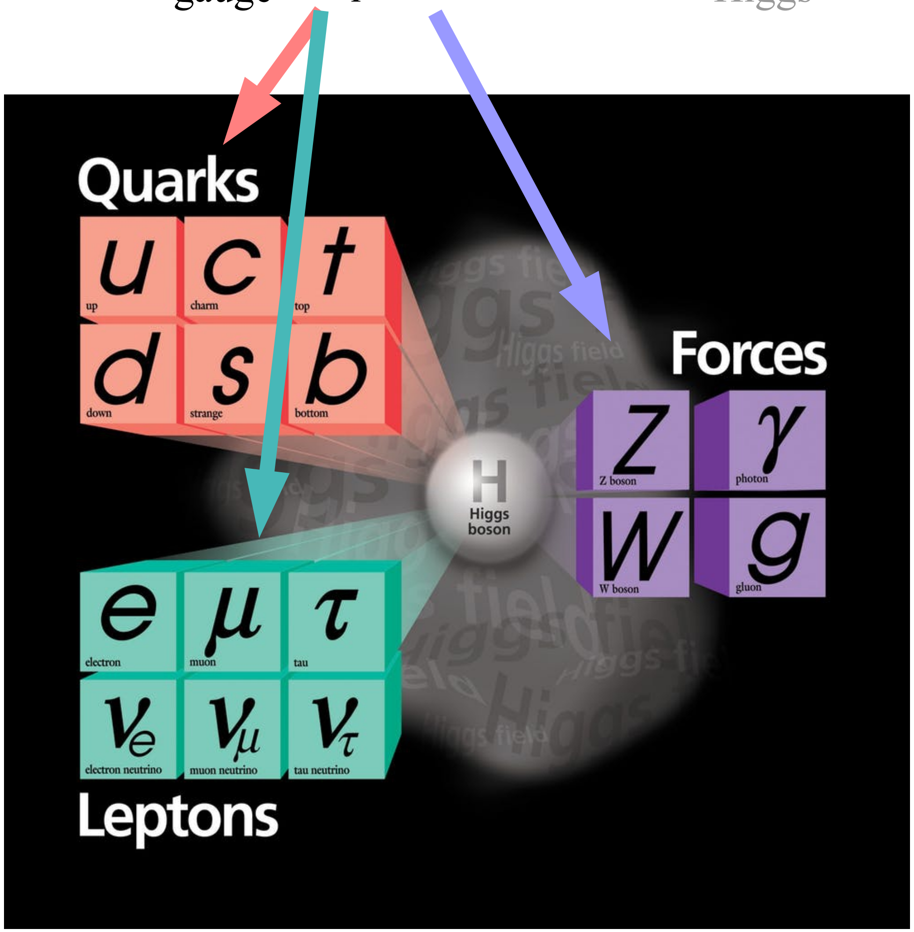

Strong
Weak
Electromagnetic
(*gauge interactions*)

Introduction

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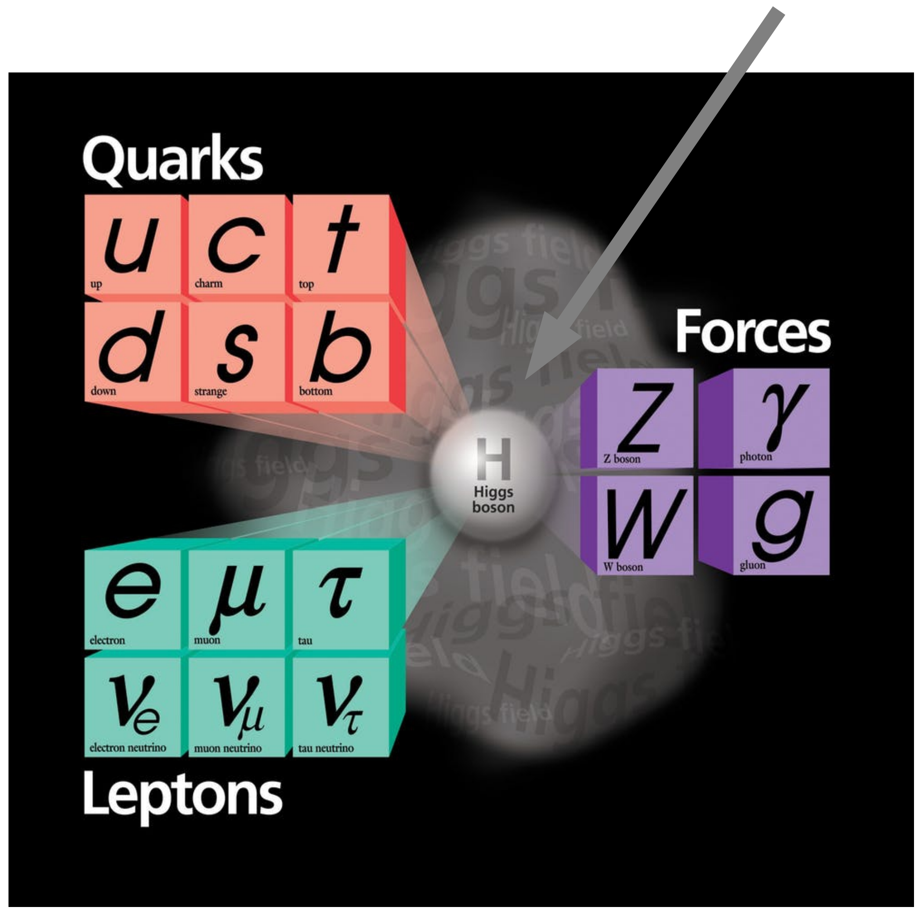


Spontaneous Symmetry Breaking

Introduction

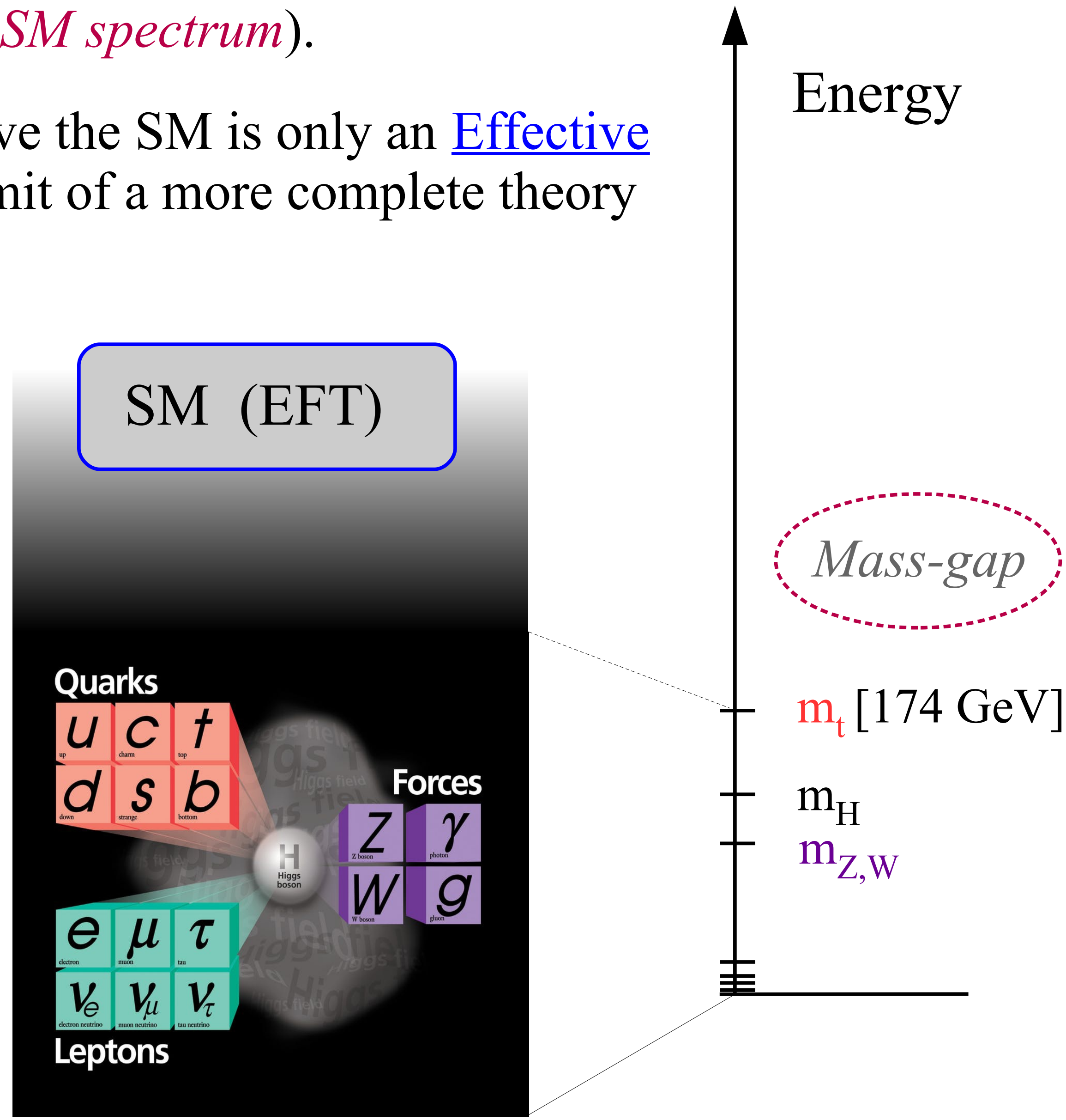
We recently celebrated the 10th anniversary of the Higgs-boson discovery (*or the completion of the SM spectrum*).

However, as for any QFT, we believe the SM is only an Effective Field Theory, i.e. the low energy limit of a more complete theory with more degrees of freedom

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \ \ldots$$

What we know after the first phase of the LHC is that: there is a mass-gap above the SM spectrum

Hence we have identified the *long-range* properties of this EFT



Introduction

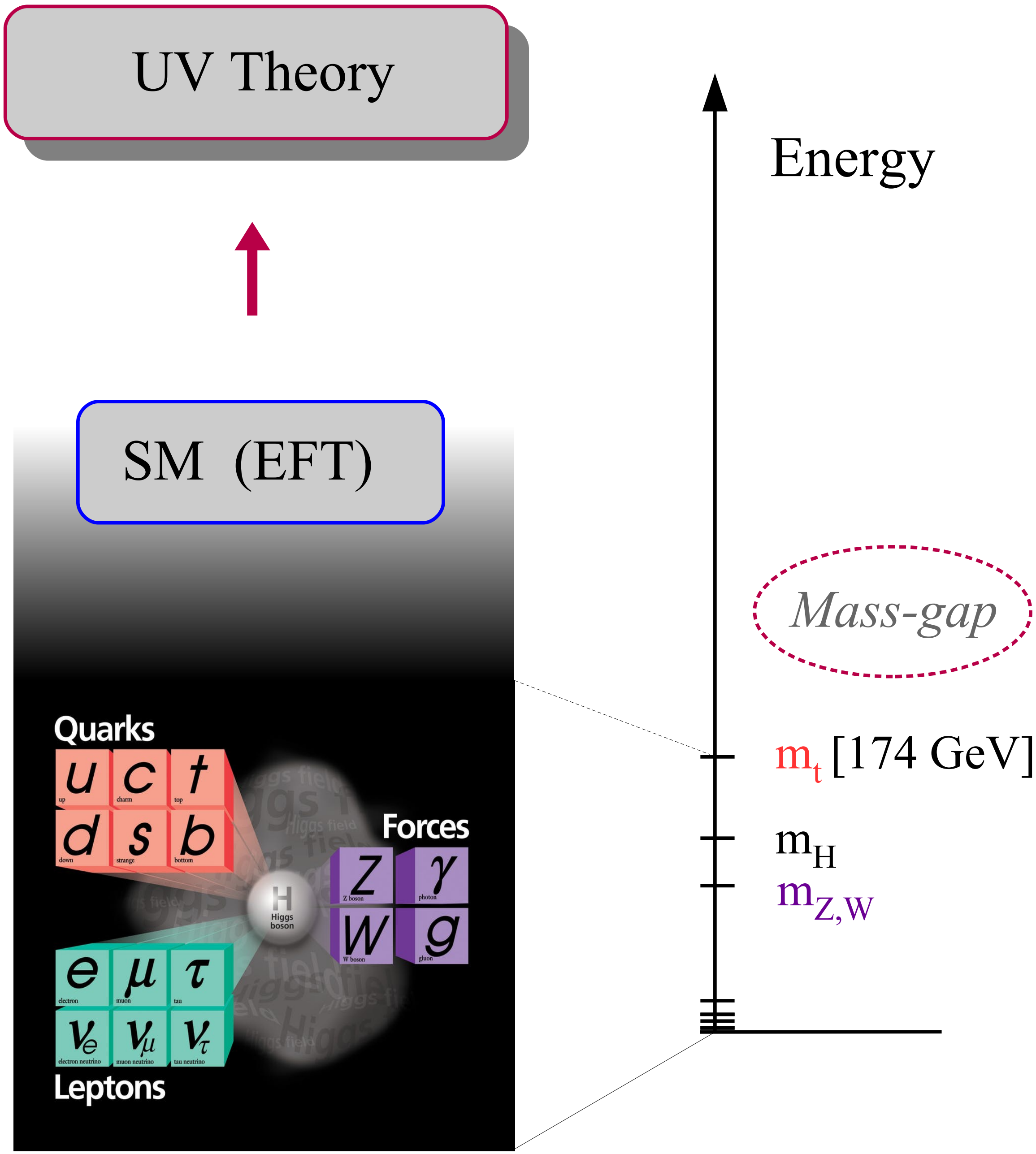
There are several reasons why we think the SM must be extended at high energies:

Electroweak hierarchy problem

Flavor puzzle
U(1) charges
Neutrino masses

Dark-matter
Dark-energy
Inflation

Quantum gravity



Introduction

There are several reasons why we think the SM must be extended at high energies:

	problem due to...	*...indicating*
Electroweak hierarchy problem	→ *Instability of the Higgs mass term*	non-trivial properties of the SM Lagrangian if interpreted as EFT ↓ Useful hints for its UV completion
Flavor puzzle U(1) charges Neutrino masses	→ *Ad hoc tuning in the model parameters*	
Dark-matter Dark-energy Inflation	→ *Cosmological implementation of the SM*	
Quantum gravity	→ *General problem of any QFT*	

Introduction

There are several reasons why we think the SM must be extended at high energies:

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U(1) charges

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Dark-energy

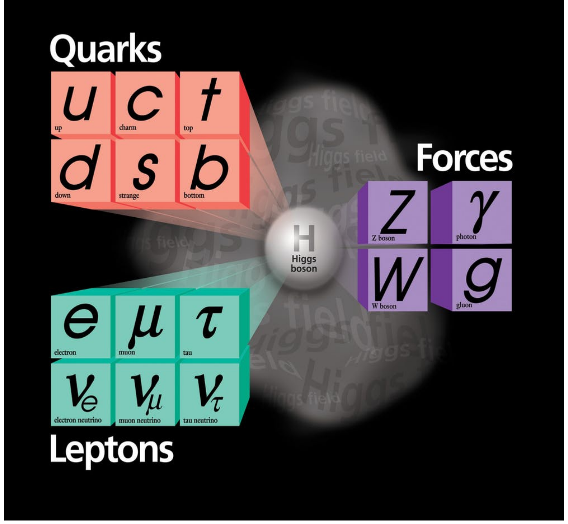
Inflation

Quantum gravity

UV Theory

↓

SM (EFT)



Messages from the UV we need to decode..

The flavor structure of the SM

The flavor structure of the SM

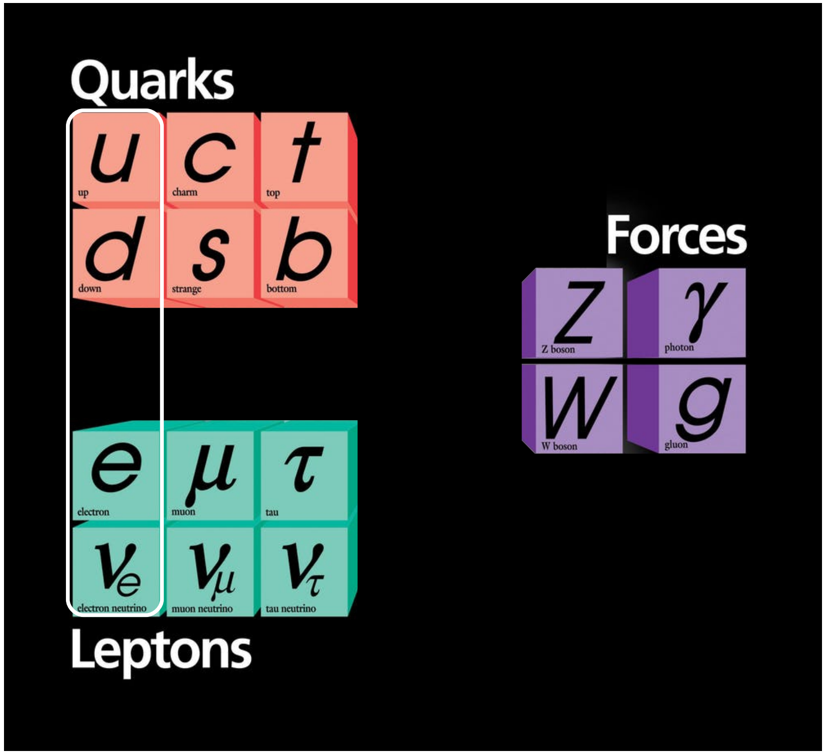
$$\mathscr{L}_{\rm SM} = \mathscr{L}_{\rm gauge}(A_a, \psi_i) + \mathscr{L}_{\rm Higgs}(H, A_a, \psi_i)$$

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 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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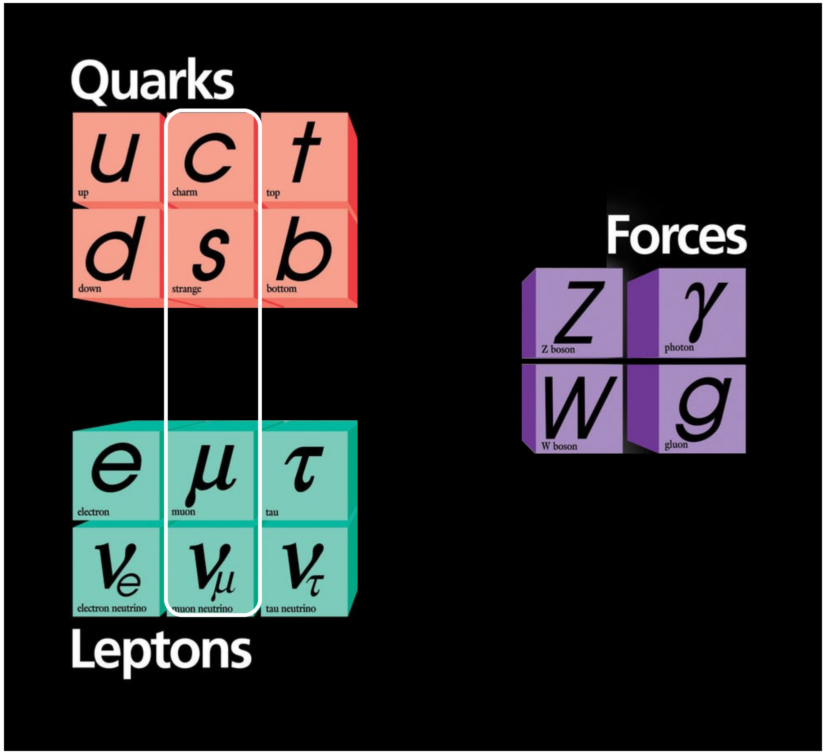

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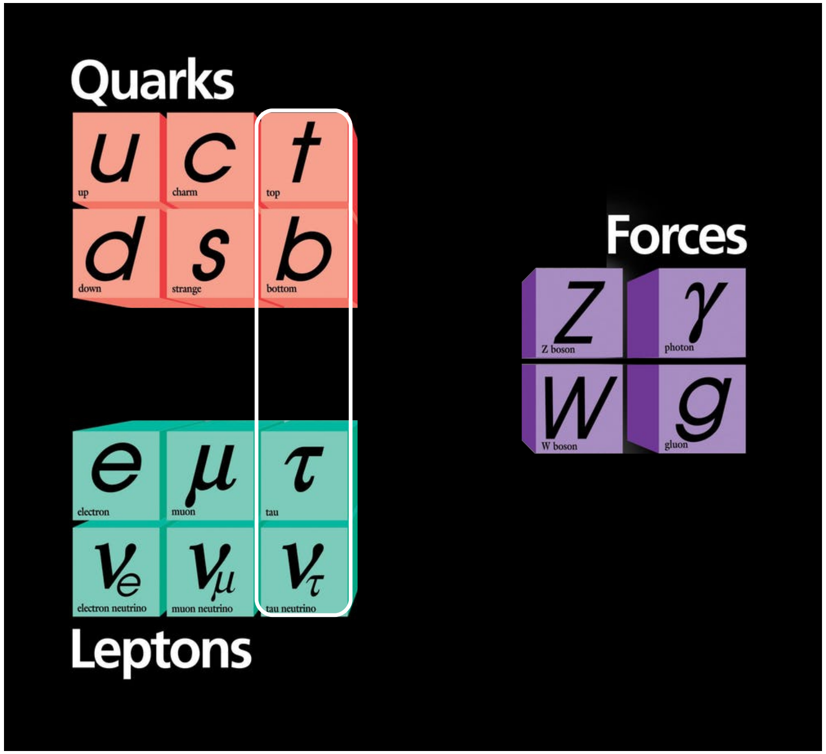

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E.g.: $Q_L^i \to U^{ij} Q_L^j$

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

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$$\mathscr{L}_{\rm SM} = \mathscr{L}_{\rm gauge}(A_{\rm a}, \psi_{\rm i}) + \mathscr{L}_{\rm Higgs}(\rm H, A_{\rm a}, \psi_{\rm i})$$

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

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

Lepton number — Baryon number — Hypercharge — *Flavor mixing*

The flavor structure of the SM

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

in the quark sector:

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

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

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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:

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

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

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

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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:

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

$$V_U^+ Y_U U_U \rightarrow (V_D^+ V_U)\, \mathrm{diag}(y_u, y_c, y_t) \qquad or \qquad \mathrm{diag}(y_u, y_c, y_t)$$

$(V_U^+ V_D) = V$

$(V_D^+ V_U)$ and V → unitary matrix

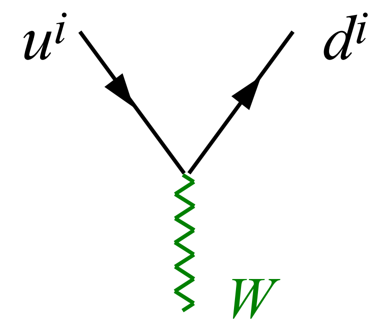
$$\bar{Q}_L^{\,i}\, Y_D^{\,ik}\, d_R^{\,k}\, \mathrm{H} \;\rightarrow\; \bar{d}_L^{\,i}\, M_D^{\,ik}\, d_R^{\,k} + \ldots \qquad M_D = \mathrm{diag}(m_d, m_s, m_b)$$

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

To diagonalize also the second mass matrix we need to rotate separately u_L & d_L (non gauge-invariant basis)

$$\mathscr{L}_{gauge} \rightarrow \frac{g}{\sqrt{2}}\, W_\mu\, J_W^{\,\mu}$$

$$J_W^{\,\mu} = u_L^{\,i}\, \gamma^{\mu}\, d_L^{\,i}$$

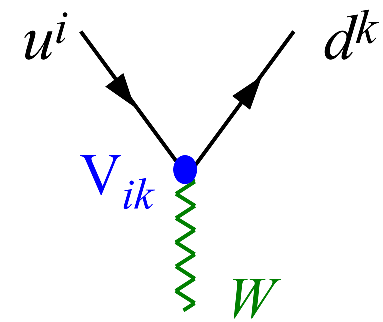


$$\bar{Q}_L{}^i\, Y_D{}^{ik}\, d_R{}^k\, \mathrm{H} \;\rightarrow\; \bar{d}_L{}^i\, M_D{}^{ik}\, d_R{}^k + \ldots \qquad M_D = \mathrm{diag}(m_d, m_s, m_b)$$

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

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:

$$\mathscr{L}_{gauge} \rightarrow \frac{g}{\sqrt{2}}\, W_\mu\, J_W{}^\mu$$



$$J_W{}^\mu = \bar{u}_L{}^i\, \gamma^\mu\, d_L{}^i \;\rightarrow\; \bar{u}_L{}^i\, V_{ik}\, \gamma^\mu\, d_L{}^k$$

→ 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 !

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

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

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:

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→ 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)

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

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

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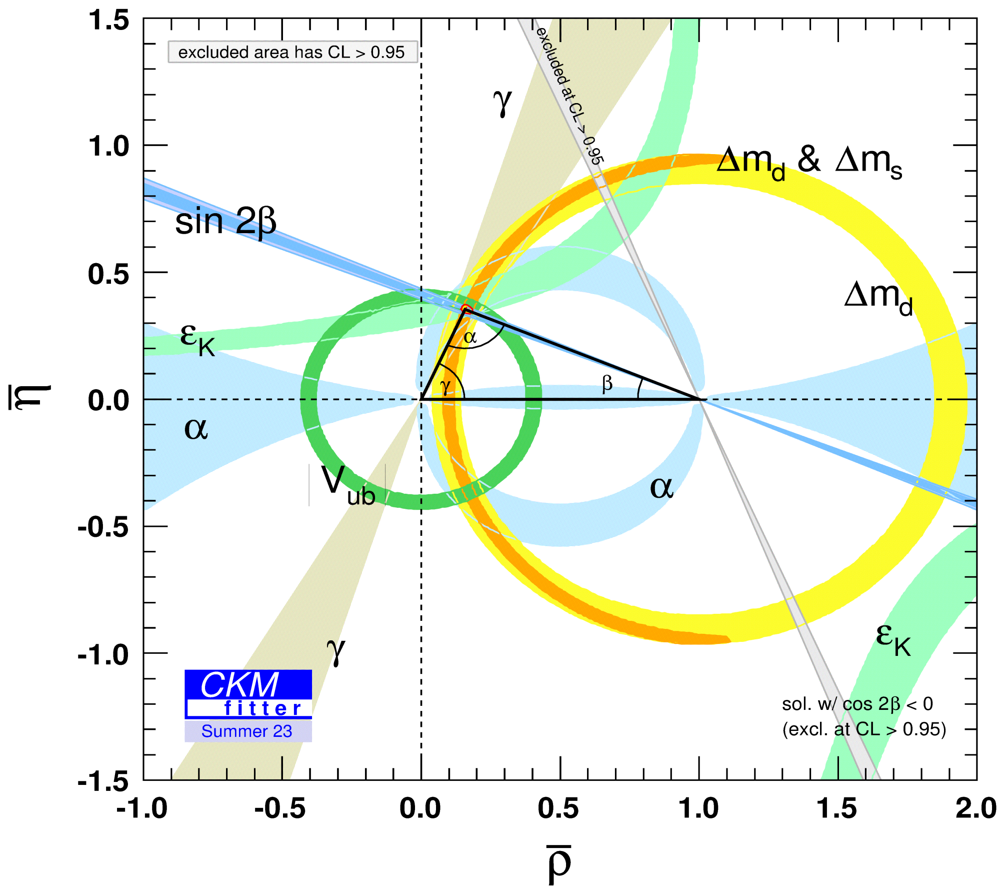
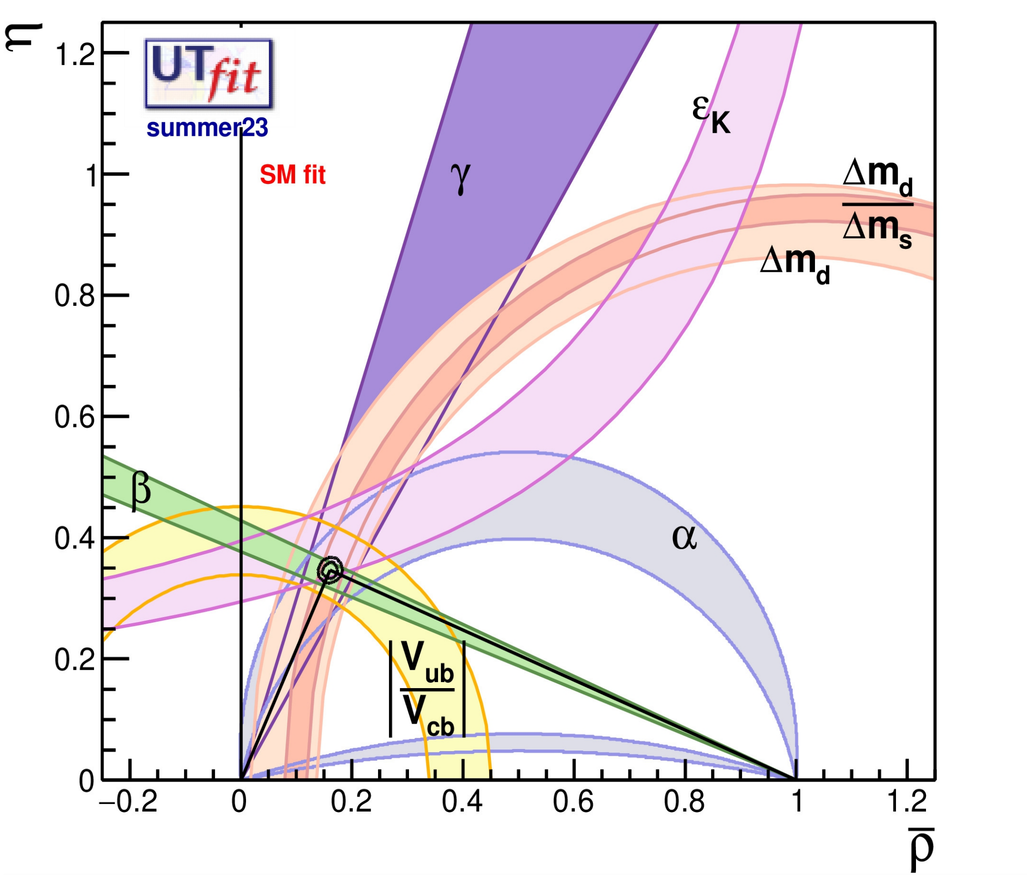
13 SM "flavor" parameters

These parameters describe the "*peculiar*" breaking of the $U(3)^5$ flavor symmetry within the SM

Properties of the CKM matrix and CKM fits





Properties of the CKM matrix & CKM fits

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

Experimental indication of a strongly hierarchical structure:

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

mixing 1-2 $\rightarrow O(\lambda)$
mixing 2-3 $\rightarrow O(\lambda^2)$
mixing 1-3 $\rightarrow O(\lambda^3)$

Wolfenstein, '83

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

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

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

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

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

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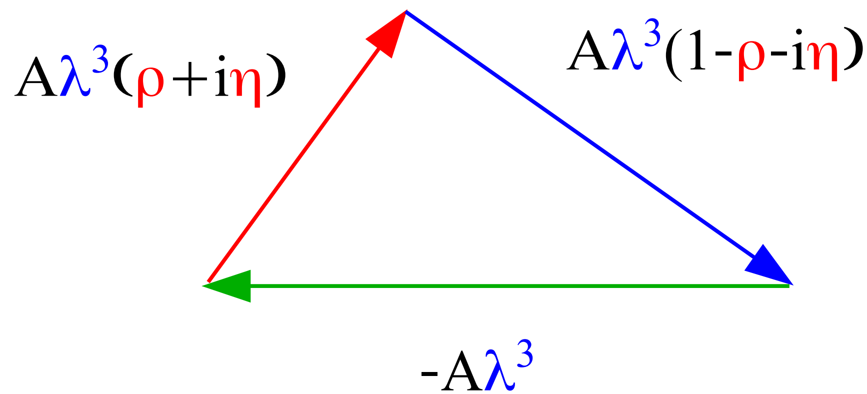
$\lambda = 0.22$ A, $|\rho+i\eta| = O(1)$



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

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

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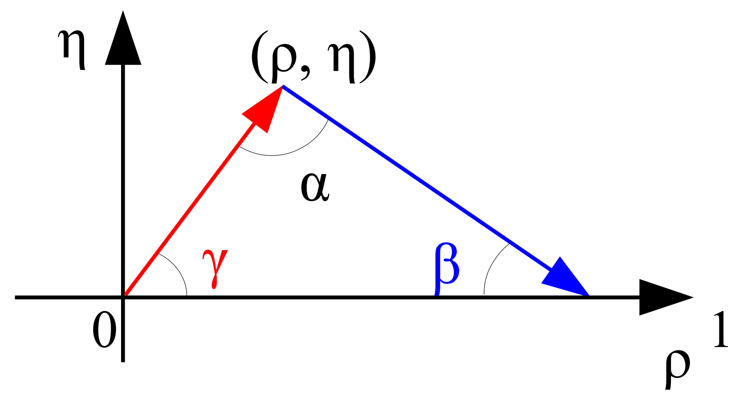

Note: *often you'll find experimental results shown as constraints in the* $\bar{\rho}, \bar{\eta}$ *plane. These new parameters are defined by* $\bar{\rho} = \rho\,(1-\lambda^2/2)^{-1/2}$ *(same for η) to keep into account higher-order terms in the expansion in powers of* λ.

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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]:

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

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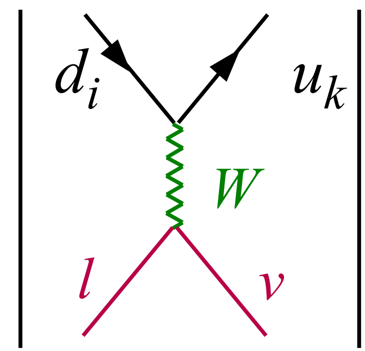
Once we assume unitarity, the CKM matrix can be completely determined using only exp. info from processes mediated by tree-level charged-current processes:

$$\mathcal{L}_{gauge} \to \frac{g}{\sqrt{2}} W_\mu \bar{u}_L^{\,i} V_{ik} \gamma^\mu d_L^{\,k} + h.c.$$



$\to |V_{ik}|$

Properties of the CKM matrix & CKM fits

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

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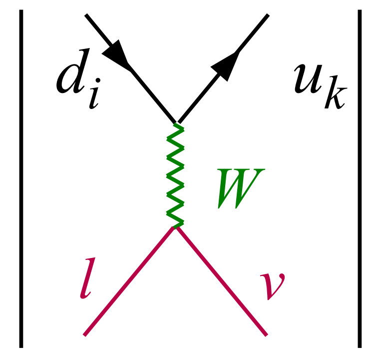
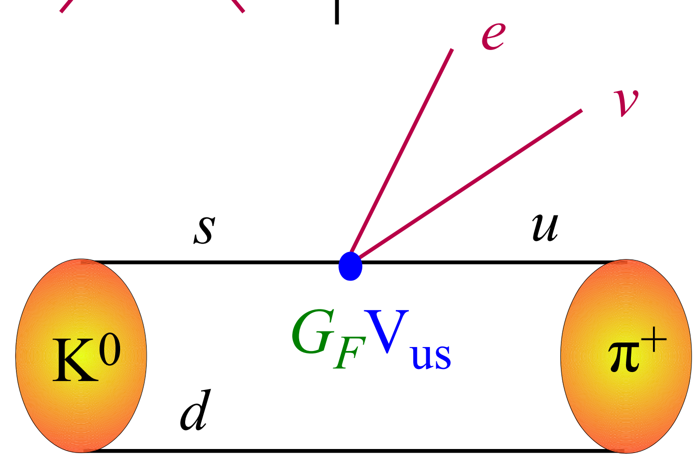


$\Rightarrow |V_{ik}|$

Actually we never observe free quarks, but we are able to compute precisely semi-leptonic weak decays (β decays) of the hadrons, e.g.:

$$\mathscr{L}_{eff} = \frac{g^2}{2M_W^2} V_{us}\ \bar{u}_L \gamma^\mu s_L\ \bar{e}_L \gamma_\mu \nu_L$$

$\frac{g^2}{2M_W^2} \leftrightarrow G_F$



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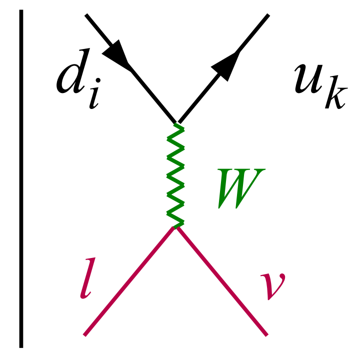

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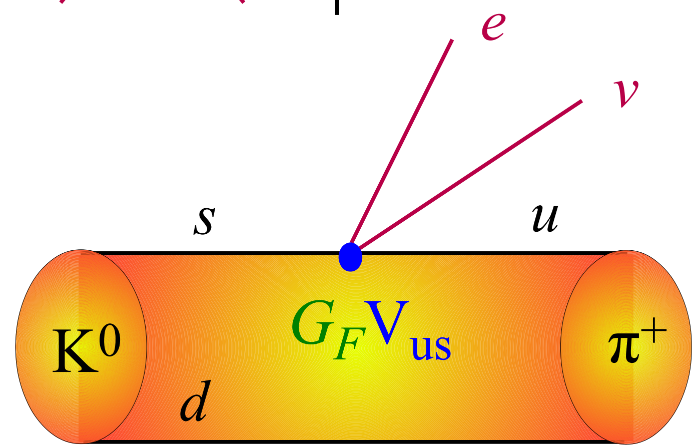
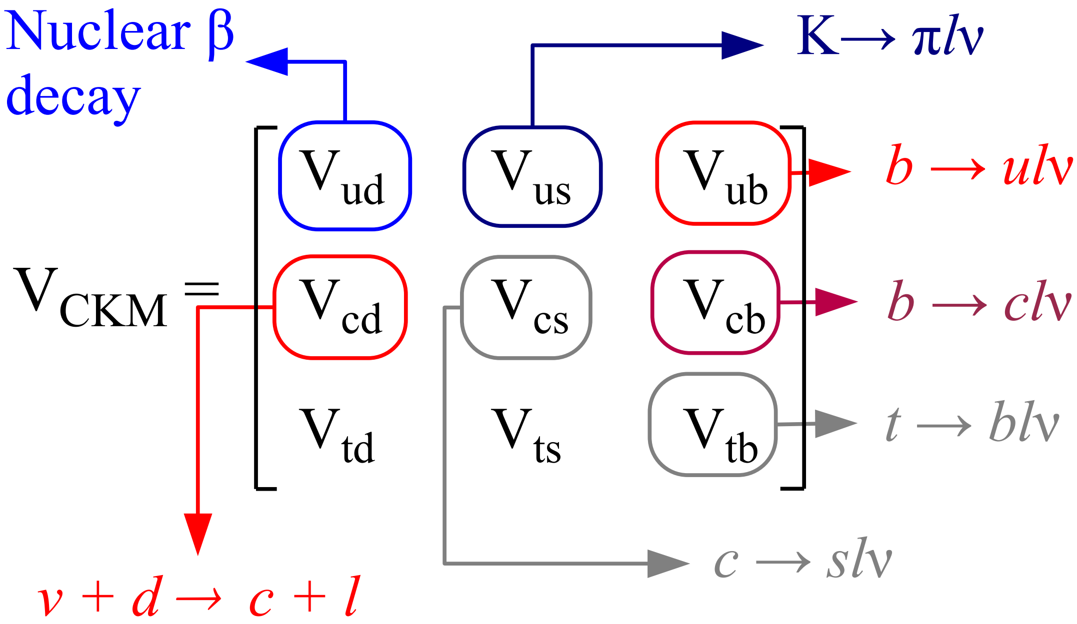


Hadronic "form factors" → *determined mainly from Lattice QCD (+ data)*



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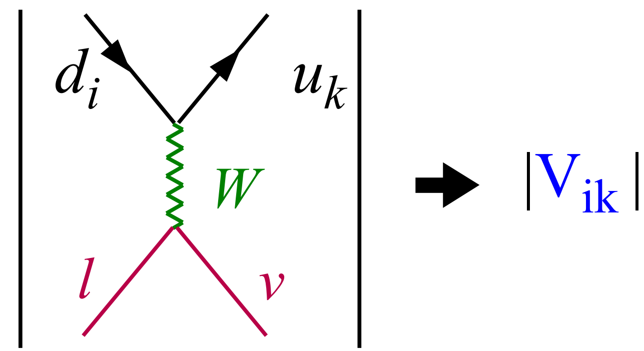

Excellent determination (error ~ 0.1%)
Very good determination (error ~ 0.5%)
Good determination (error ~ 2 %)
Sizable error (5-15 %)
Not competitive with unitarity constraints

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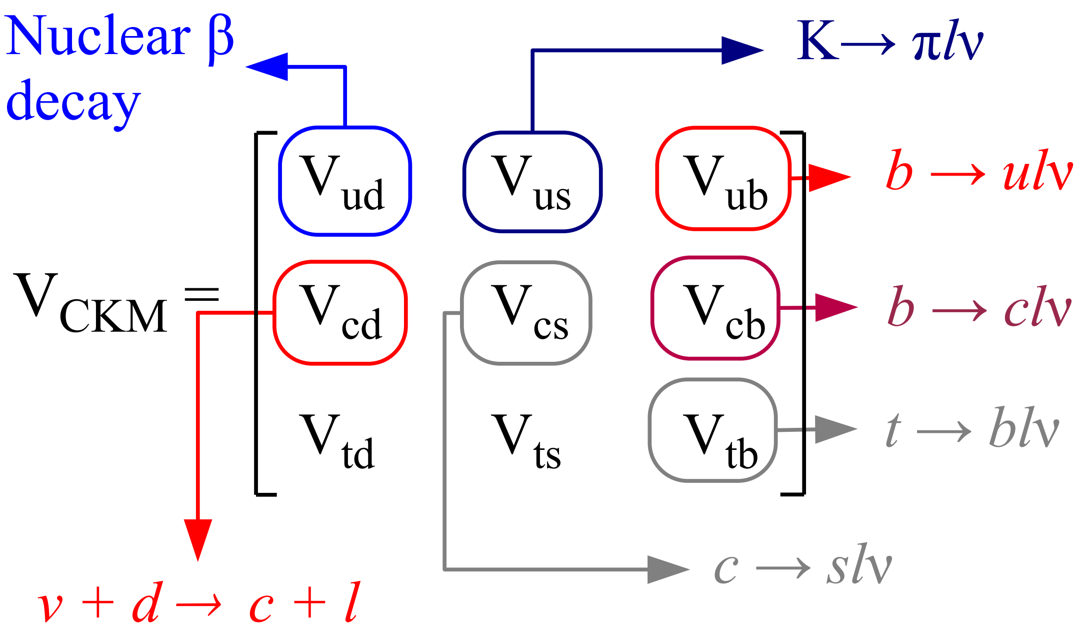

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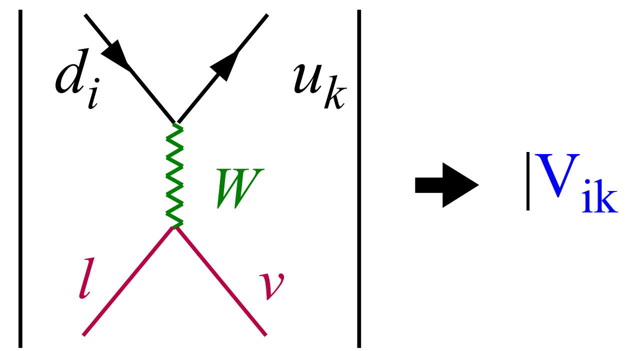

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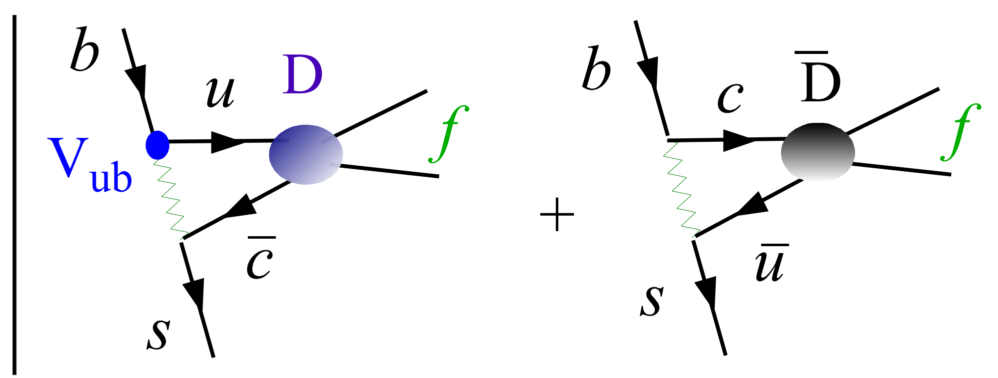
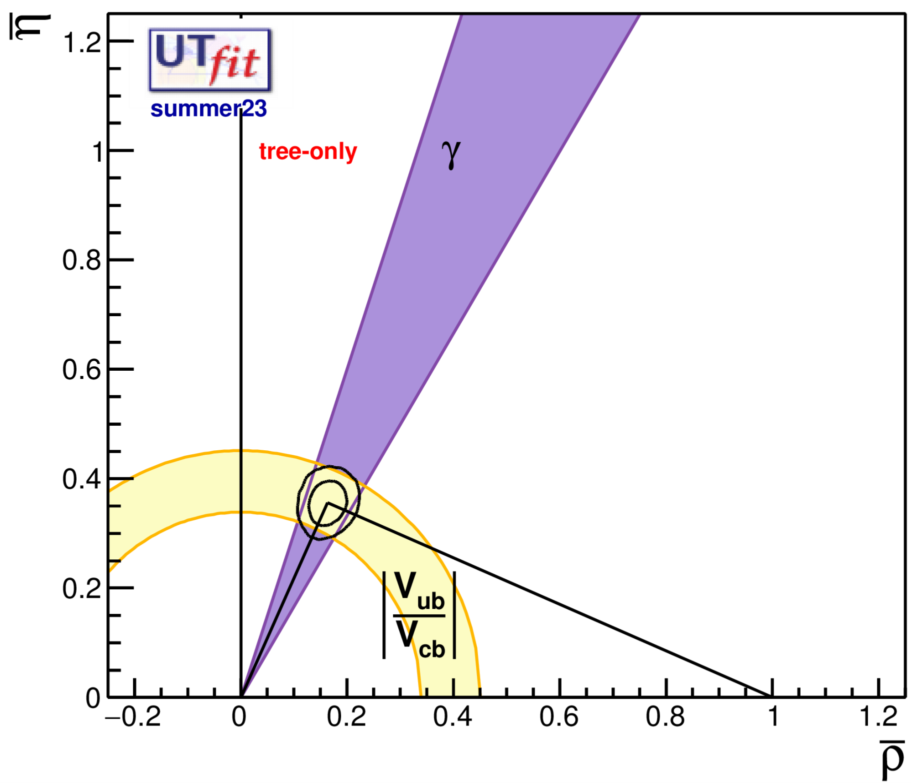
N.B.: also the phase $\gamma = \arg(V_{ub})$ can be obtained by (quasi-) tree-level processes, such as

$$B \to D\,(\bar{D}) + K \to f + K \;:$$

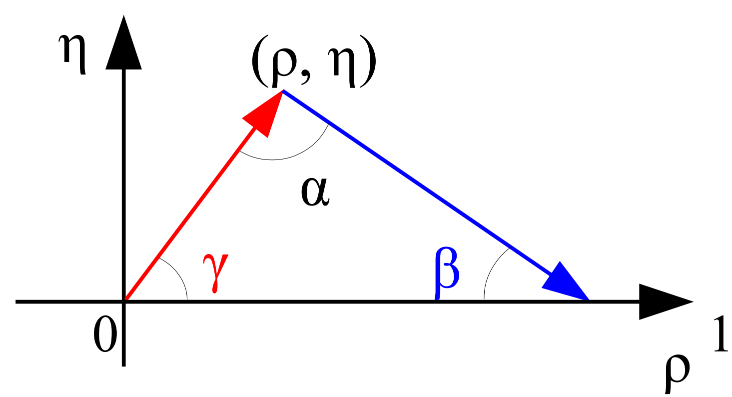


Properties of the CKM matrix & CKM fits

Beside a few 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*.



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



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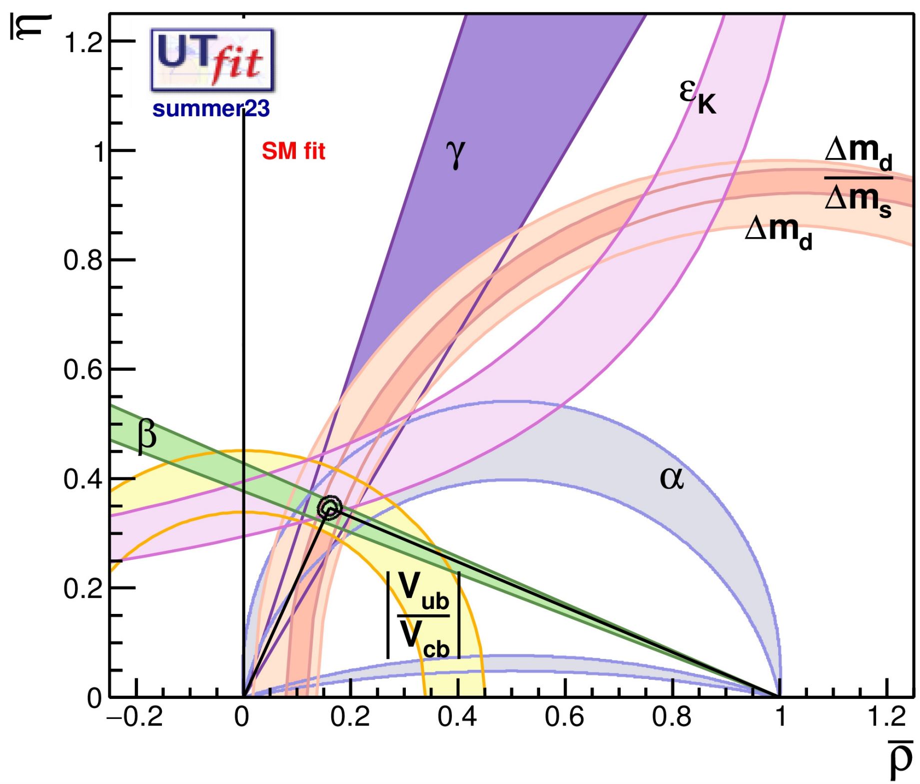

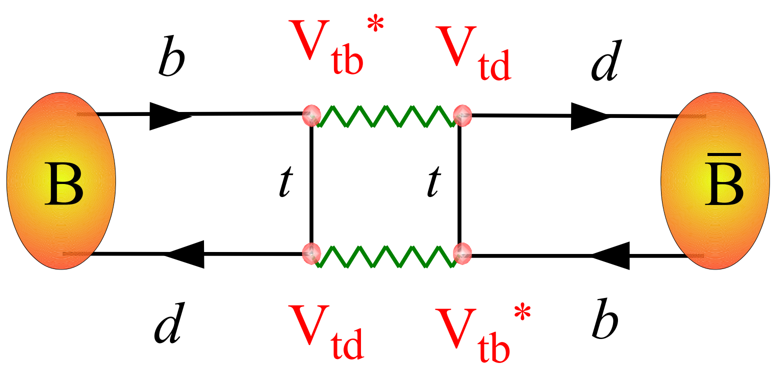

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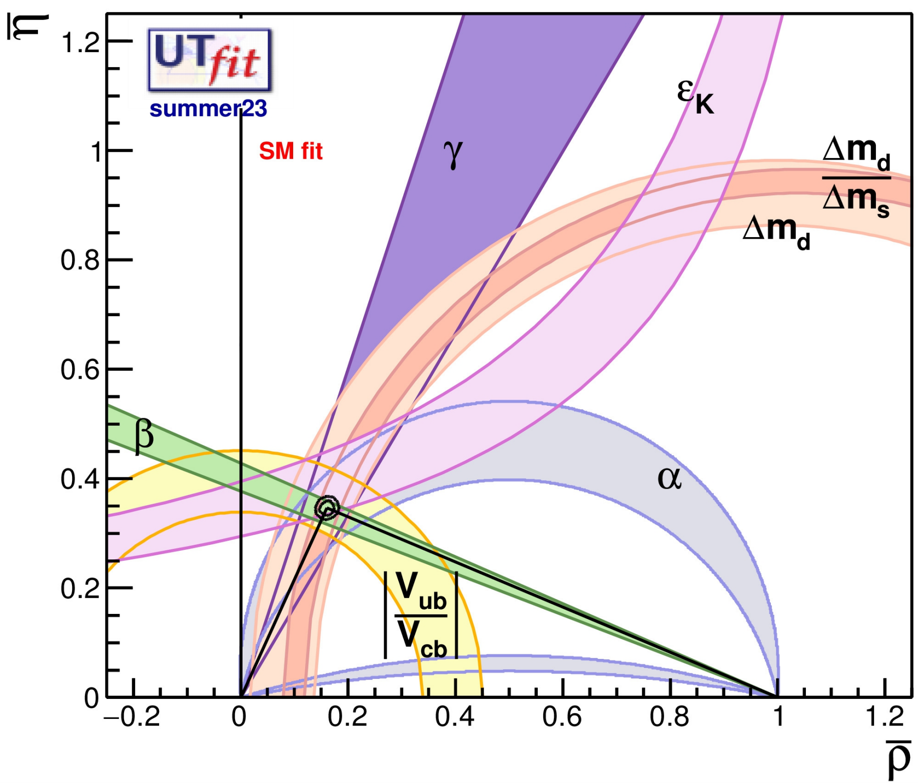


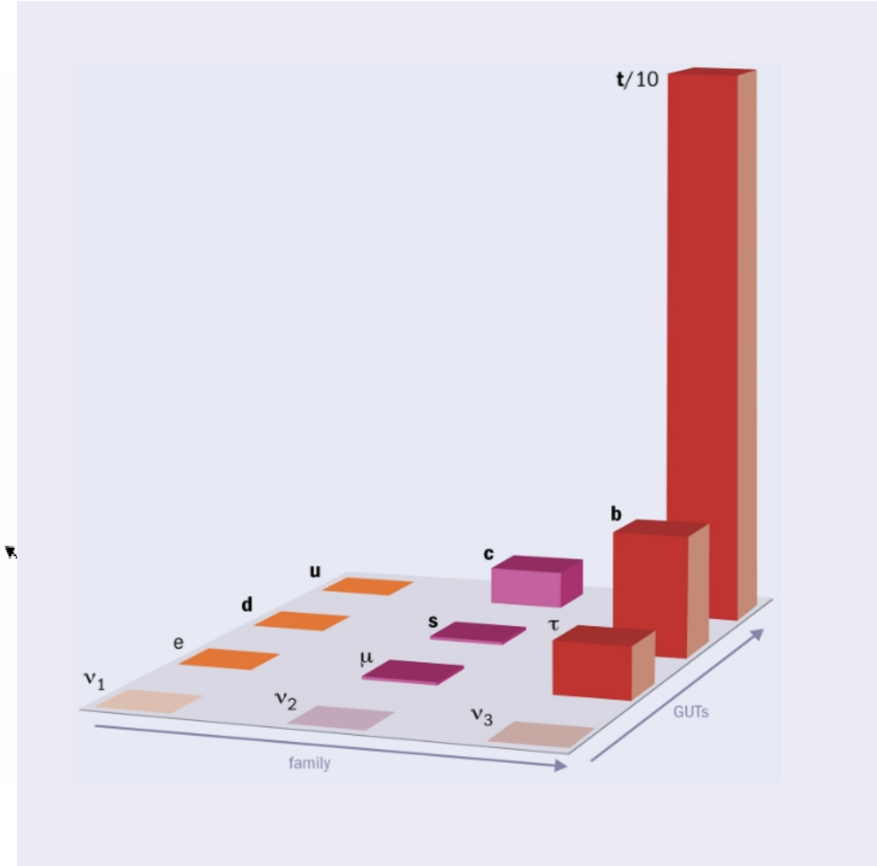
At this point one could ask:

Is it worth to push forward this type of measurements?

As we shall see, there are several good reasons, if we believe the SM is only an effective theory...

The two flavor puzzles

The two flavor puzzles



One summer I sat down and said:

"This is the summer when I'm not going to do anything but solve [the flavor] *problem"*

This was 40 years ago and I haven't solved it. No one has [...]*. That's been a frustration now for 40 years...*

[Steven Weinberg, 2013]

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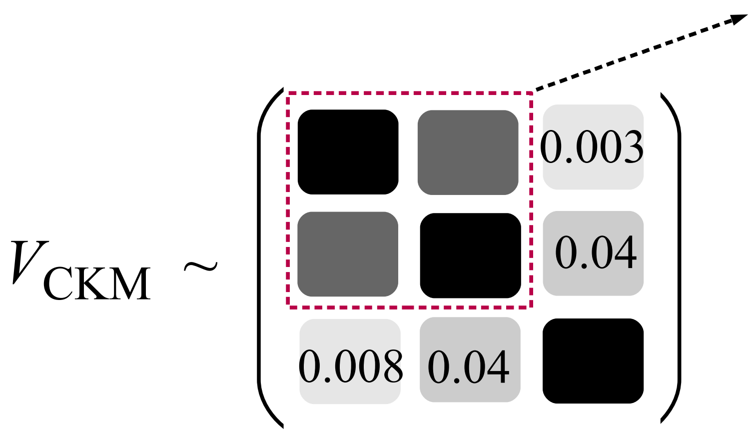
unitarity violation of the 2×2 (light) block below 10^{-3} !



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

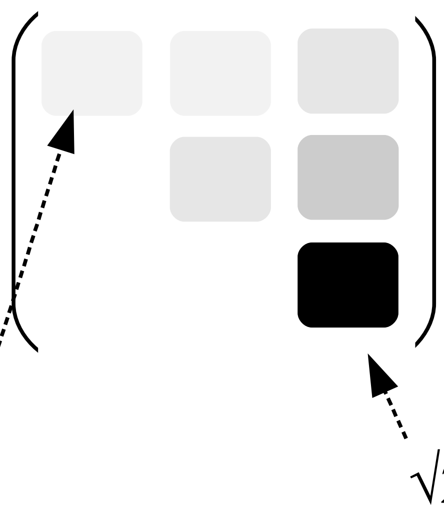
N.B.: Despite the very good knowledge we have nowadays about the CKM matrix, we are <u>not able (yet) to detect the presence of the 3rd family</u> by looking only at the 2×2 block (*as one naively would have expected...*)

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:

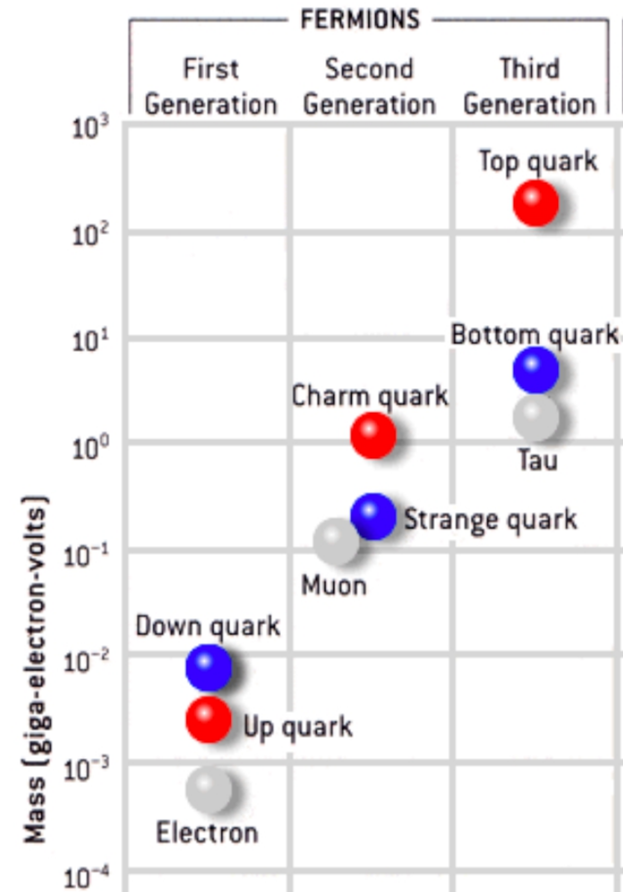
$Y_U \sim$



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

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

[Y_U in the basis where Y_D is diagonal]



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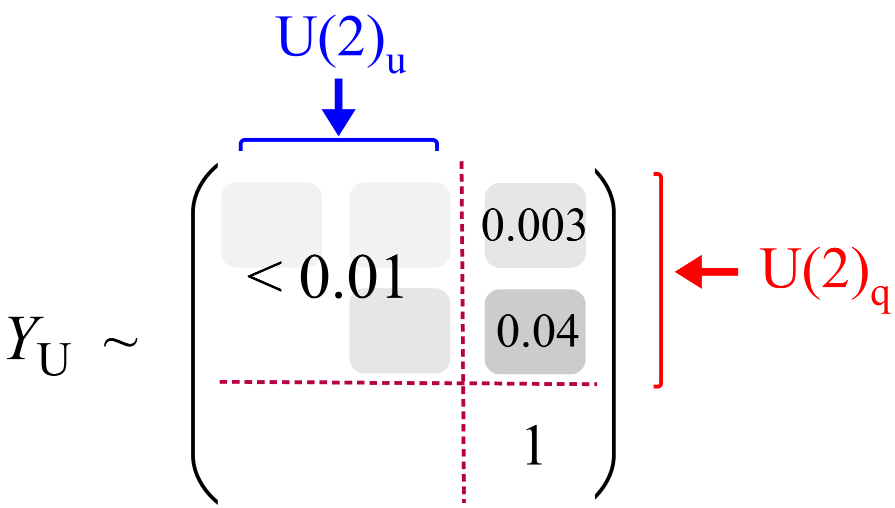


$\overline{Q}_L \, Y_U \, U_R \, H$

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

approximate $U(2)^n$ symmetry

acting on the light families

The two flavor puzzles

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

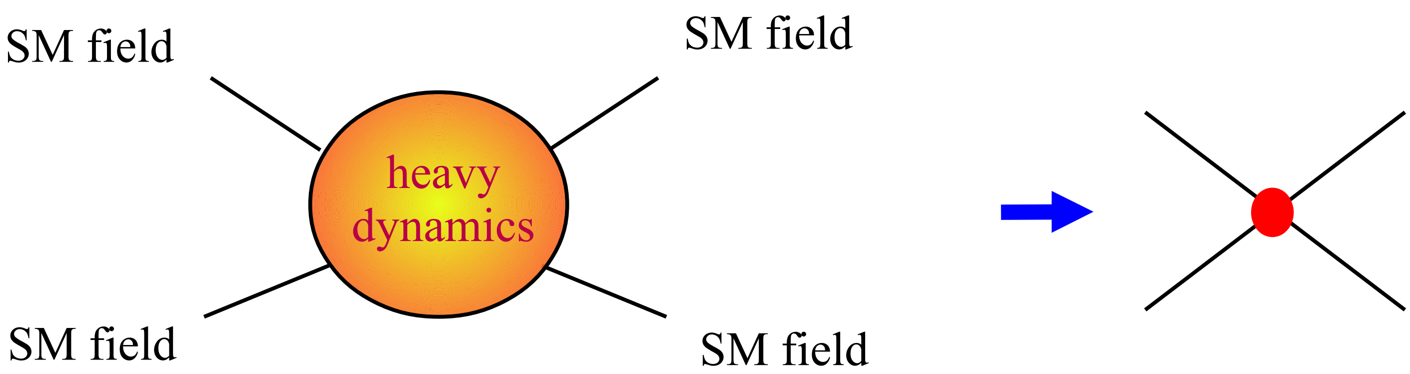
I. The observed pattern of SM Yukawa couplings does not look accidental [*SM flavor puzzle*]

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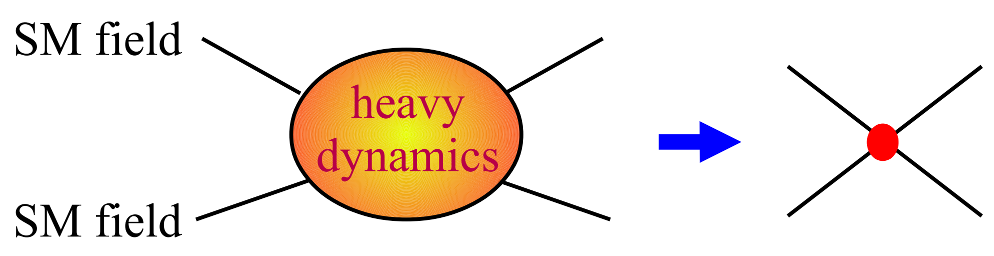
Interactions surviving @ large distances
(operators with $d \leq 4$)

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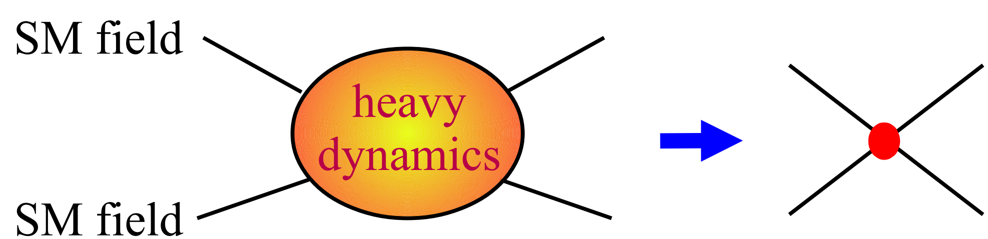
N.B.: This is the most general parameterization of the new (heavy) degrees of freedom, as long as we do not have enough energy to directly produce them.

"Remnant" of the heavy dynamics at low energies



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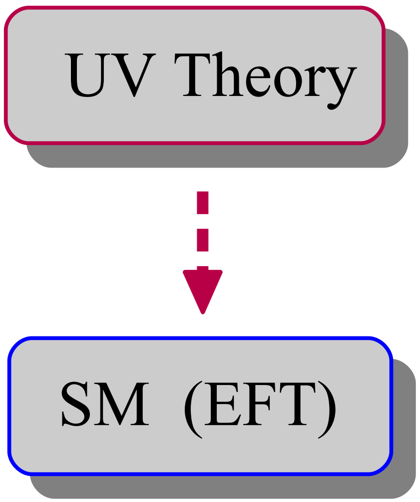
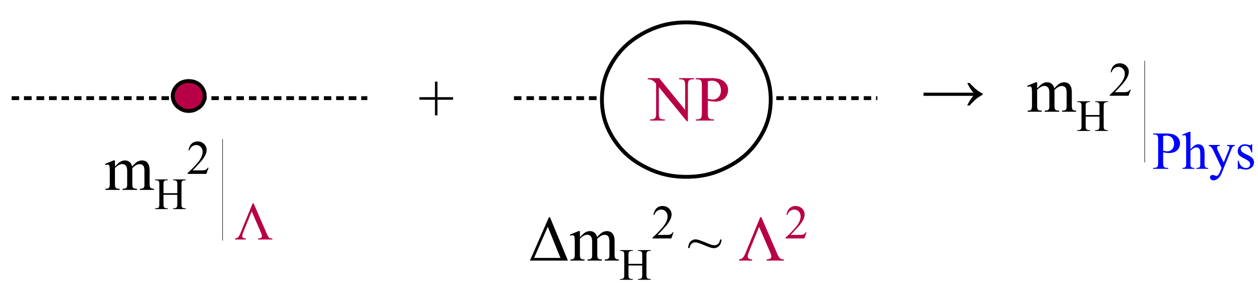
What is the cut-off scale Λ of the SMEFT?



A useful (*but somewhat vague*) indication follows from the electroweak hierarchy problem (↔ *instability of the Higgs mass under quantum corrections*):



→ (*some*) New Physics (*coupled at least to* H & t) in the TeV domain

The flavor structure of the SMEFT

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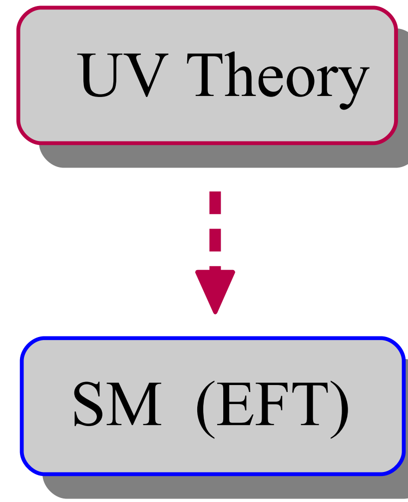
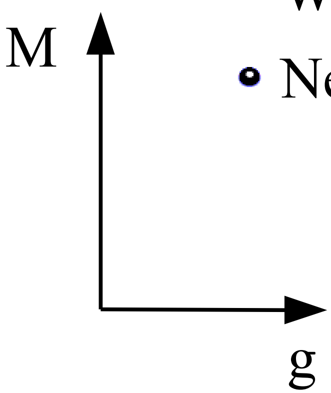
What is the cut-off scale Λ of the SMEFT?
A closer look to this question reveals more "layers"



- What is the mass scale of the new d.o.f. ?
- New dynamics weakly or strongly coupled ?



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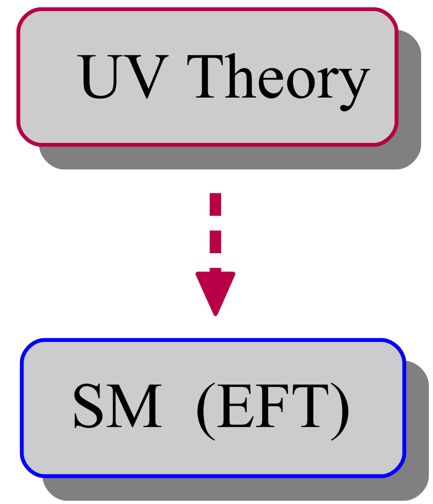
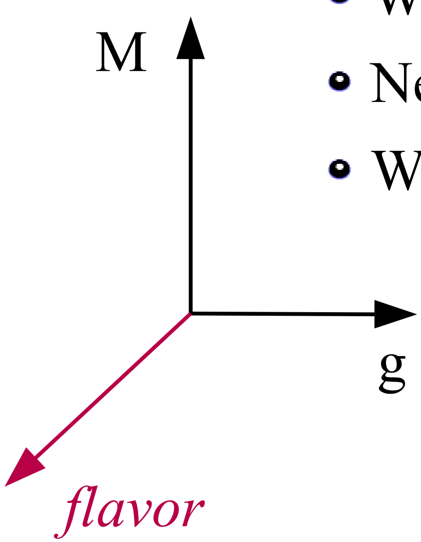


- What is the mass scale of the new d.o.f. ?
- New dynamics weakly or strongly coupled ?
- What is the *flavor structure*?



SM (Yukawa) sector → flavor is highly non trivial

- No flavor symmetry ⟶ 2499 free couplings in the SMEFT @ d=6
- Exact $U(3)^5$ ⟶ 47

Jenkins, Manohar, Trott '14
Alonso *et al.* '15

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:

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

The flavor structure of the SMEFT

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \Sigma_i \frac{1}{\Lambda_i^{d-4}} O_i^{d\geq5}$$

Large flavor symmetry → $\mathscr{L}_{\text{gauge}}$

Yukawa interaction → $\mathscr{L}_{\text{Higgs}}$

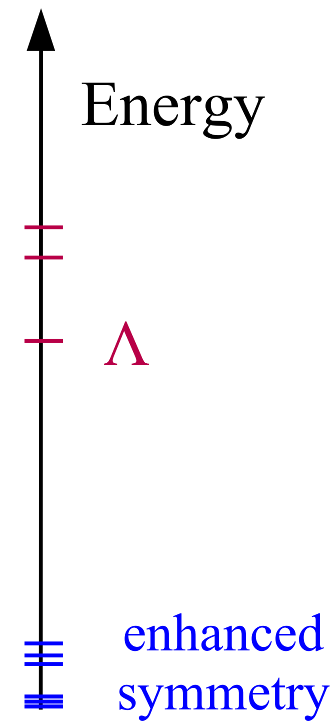
Large flavor symmetry + Yukawa interaction → Exact & approximate (*accidental* ?) symmetries

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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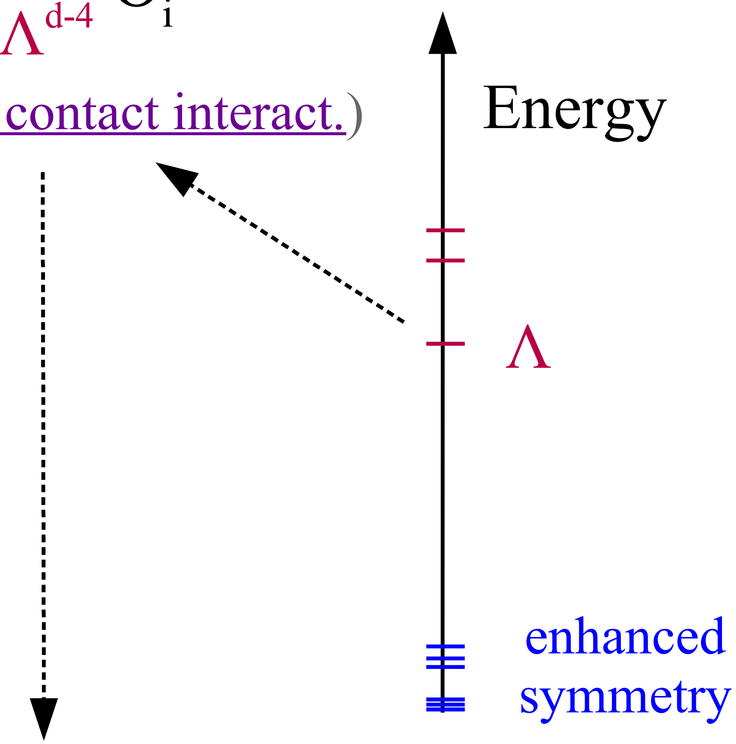

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If a symmetry arises accidentally in the low-energy theory, we expect it to be violated by higher dim. ops

Violations of accidental symmetries

Well-known examples from the past...

Accidental symmetries in QFT [a brief detour]

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

[SM-2]-EFT

Example n.1: *CP violation in the SM-2*

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

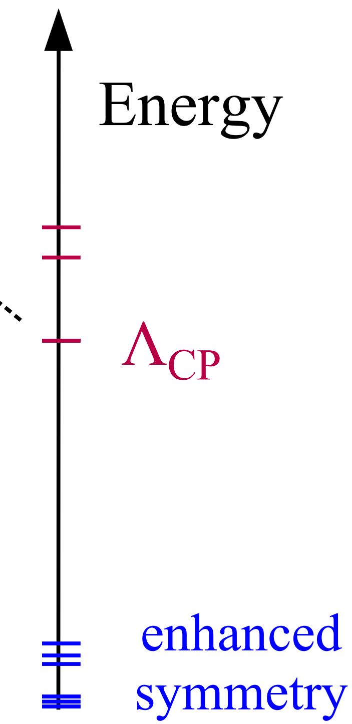
But at that time CP violation was observed in Kaon mixing [→ remnant of "heavy NP"]

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

"Super-weak" interaction

[L. Wolfenstein, '64]

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



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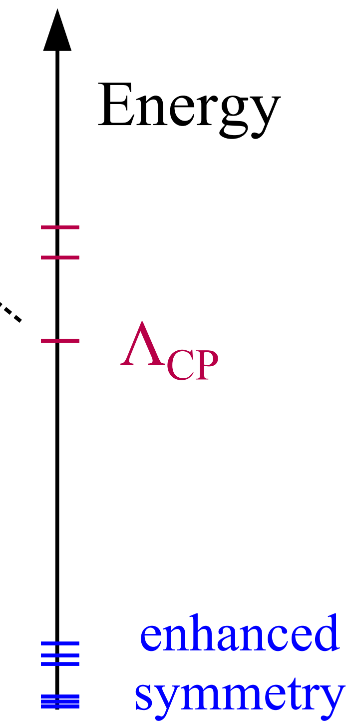
[SM-2]-EFT



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

SM-3
[KM, '73]

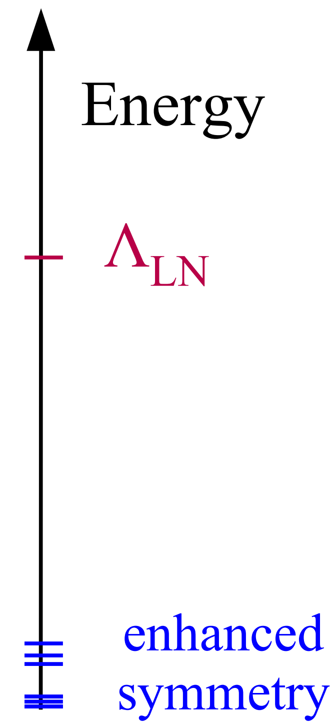
$$\frac{1}{\Lambda_{CP}^2} \sim \frac{(G_F\, m_t V_{ts} V_{td})^2}{4\pi^2}$$

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]

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



Example n.2: *Lepton Number violation & Neutrino masses*

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

This is the only d=5 operator in the SM-EFT

It violates the total Lepton Number, which is an exact accidental global symmetry of the SM

$$g_\nu^{ij} \sim 1 \quad \rightarrow \quad \Lambda_{LN} \sim 10^{14} \text{ TeV}$$

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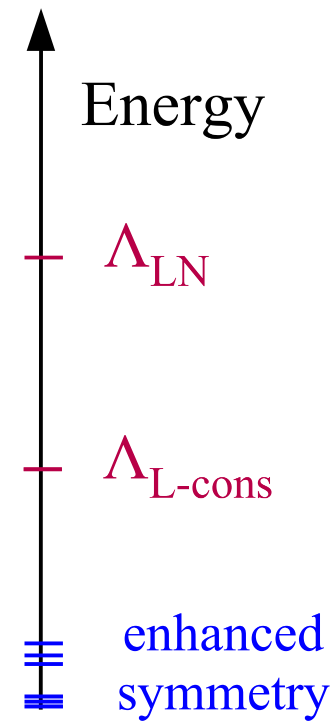

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Such a high scale would is very problematic for the Higgs hierarchy problem. However, it is consistent to assume that the stability of the Higgs sector is "cured" by new dynamcs preserving LN, characterized by $\Lambda_{L\text{-cons}} << \Lambda_{LN}$

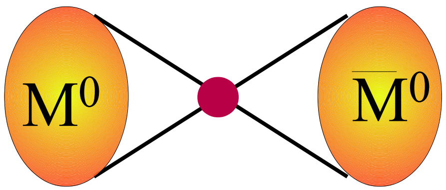
Key message: accidental symmetries allow us to separate different sectors of the EFT [stable scale separation]

N.B.: The same can be true for some of the flavor-breaking terms (*with minor differences related to approximate vs. exact symm.*)

The flavor structure of the SMEFT

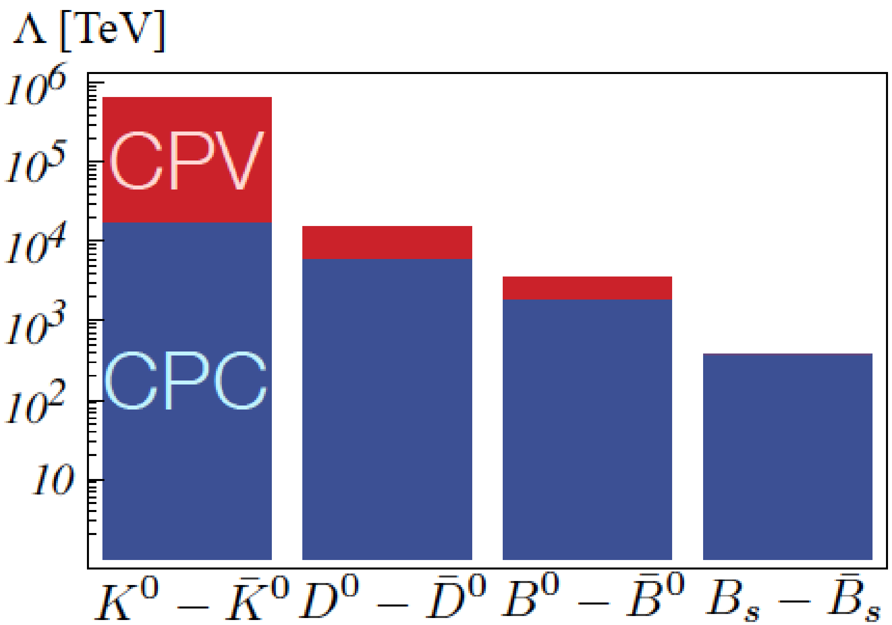
$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{d\geq5}$$

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



However, beside 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

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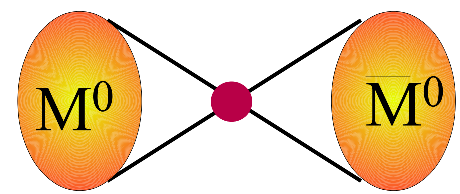

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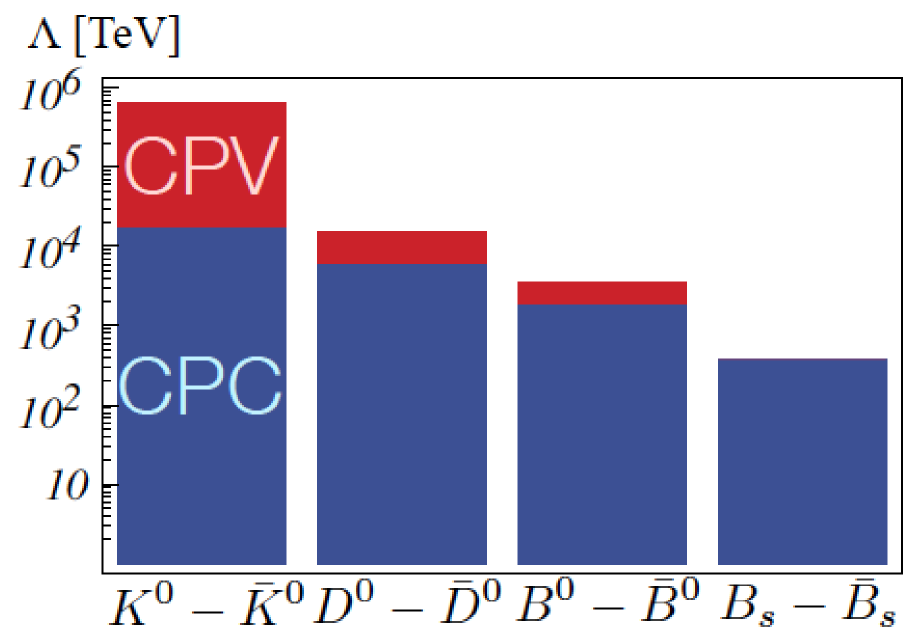
Detailed discussion in the 2nd Lecture



The NP Flavor puzzle

The flavor structure of the SMEFT

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

Yukawa couplings: $U(3)^5 \to \sim U(2)^n$ *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 flavor-physics data could provide some answers... → 3rd Lecture