Flavor Physics: recent progress & future prospects

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- An introduction to flavor physics
- Phenomenology of B and D decays
- Flavor physics beyond the Standard Model
  [*explicit models and interplay with high-pT physics*]

Plan of the lectures:

- An introduction to flavor physics
  - The flavor sector of the Standard Model
  - Some properties of the CKM matrix
  - Present status of CKM fits
  - The SM as an effective theory
  - Flavor physics beyond the SM
  - The flavor problem
  - Open questions
- Phenomenology of B and D decays
- Flavor physics beyond the SM

The flavor sector of the Standard Model

Particle physics is described with good accuracy by a simple and *economical* theory:

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

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- *Natural*
- Experimentally tested with high accuracy
- Stable with respect to quantum corrections
- Highly symmetric:
  - $SU(3)_c \times SU(2)_L \times U(1)_Y$ *local symmetry*
  - *Global flavor symmetry*

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

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- *Ad hoc*
- Necessary to describe data [*clear indication of a non-invariant vacuum*] weakly tested in its dynamical form
- Not stable with respect to quantum corrections
- Origin of the flavor structure of the model [*and of all the problems of the model...*]

The flavor sector of the Standard Model

Particle physics is described with good accuracy by a simple and *economical* theory:

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

- *Natural*
- Experimentally tested with high accuracy

Elegant & stable,
but also a bit boring...

- *Ad hoc*
- Necessary to describe data [*clear indication of a non-invariant vacuum*]

Ugly & unstable, but is what
makes nature interesting...!

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

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

$$\Sigma_{\psi = Q_L,\, u_R,\, d_R,\, L_L,\, e_R} \Sigma_{i=1..3}\, \bar{\psi}_i\, i\not{D}\, \psi_i$$

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

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

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

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

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$[\psi = Q_L, u_R, d_R, L_L, e_R] \Rightarrow$ 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 Hypercharge

Barion number

Flavor mixing

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

in the quark sector:

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

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

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

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

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

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

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

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

The residual flavor symmetry let us to choose a (gauge-invariant) flavor basis where <u>only one</u> of the two Yukawas 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

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

<u>unitary matrix</u>

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

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

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:

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

→ Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix

...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 !

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

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<u>Cabibbo-Kobayashi-Maskawa</u>
(CKM) mixing matrix

$$V V^{+} = \mathrm{I} \qquad V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

Several equivalent parameterizations [unobservable quark phases] in terms of

- 3 real parameters (rotational angles)

  \+

- 1 complex phase (source of CP violation)

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

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+

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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

Some properties of the CKM matrix

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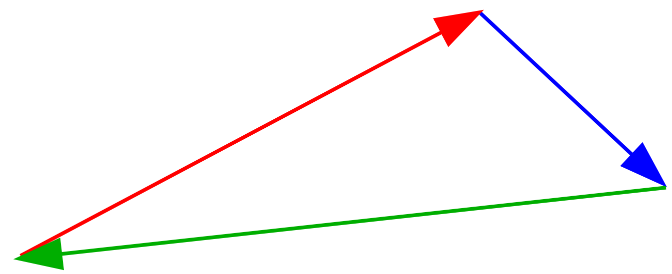
$$V_{CKM} V^{+}_{CKM} = I$$

6 triangular relations:

$$V_{a1} (V^{+})_{1b} + V_{a2} (V^{+})_{2b} + V_{a3} (V^{+})_{3b} = 0$$



the area of these triangles is:

- always the same
- phase-convention independent
- zero in absence of CP violation

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

Experimental indication of a strongly hierarchical structure:

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

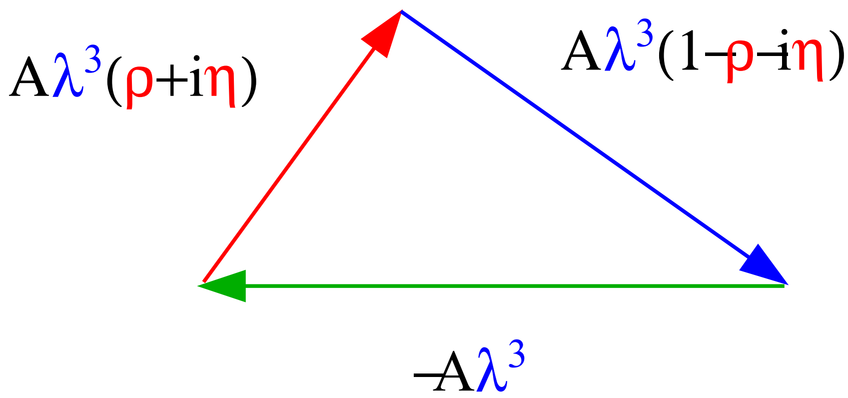
Wolfenstein, '83

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

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

The $b \rightarrow d$ 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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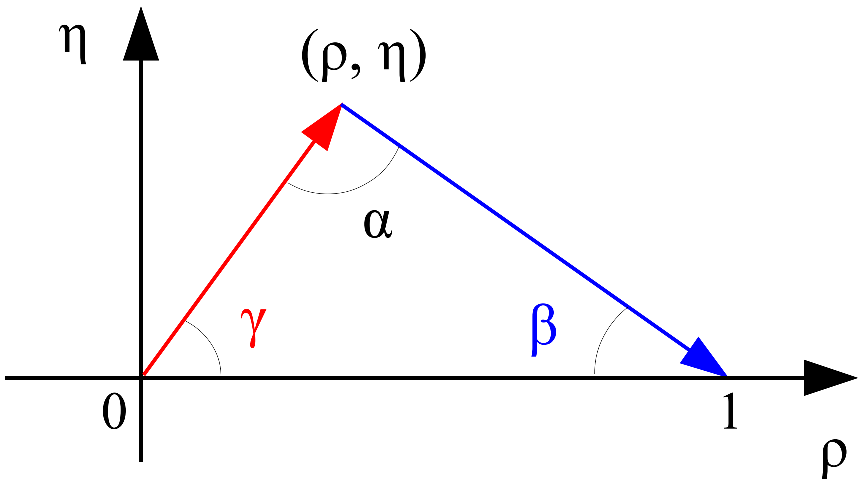
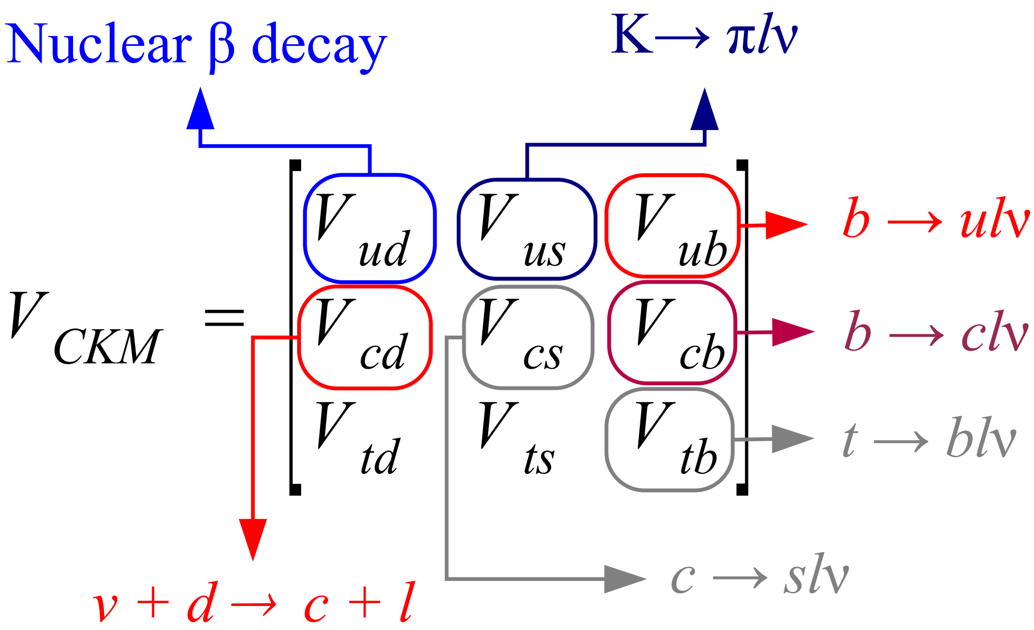
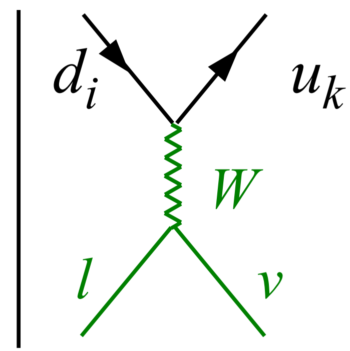


Note: *often you'll find experimental results shown as constraints in the* $\bar{\rho}, \bar{\eta}$ *plane. These new parameters are defined by* $\bar{\rho} = \rho\,(1-\lambda^2/2)^{-1/2}$ *(same for η) to keep into account higher-order terms in the expansion in powers of* λ.



Once we assume unitarity, the CKM matrix can be 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



$\rightarrow |V_{ik}|$

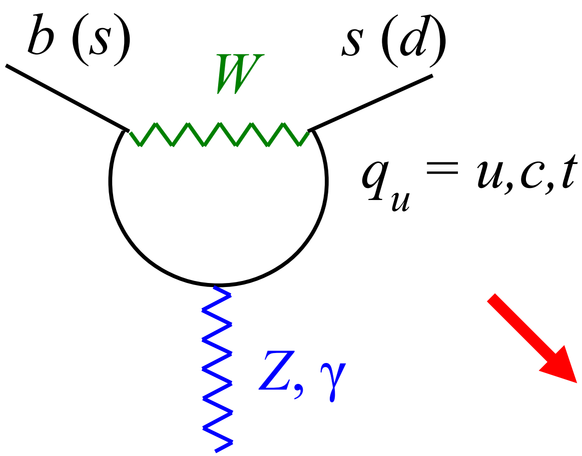
$$\begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

N.B.: Also the phase $\gamma = \arg(V_{ub})$ can be obtained by (quasi-) tree-level processes [2nd lecture]

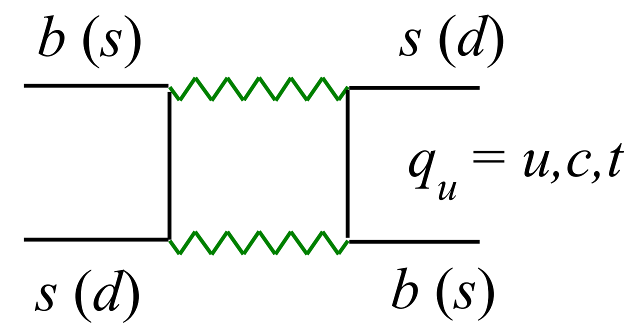
The only CKM elements we cannot access via tree-level processes are V_{ts} & V_{td}

Loop-induced amplitudes:

ΔF =1 FCNC



ΔF=2 (neutral-meson mixing)



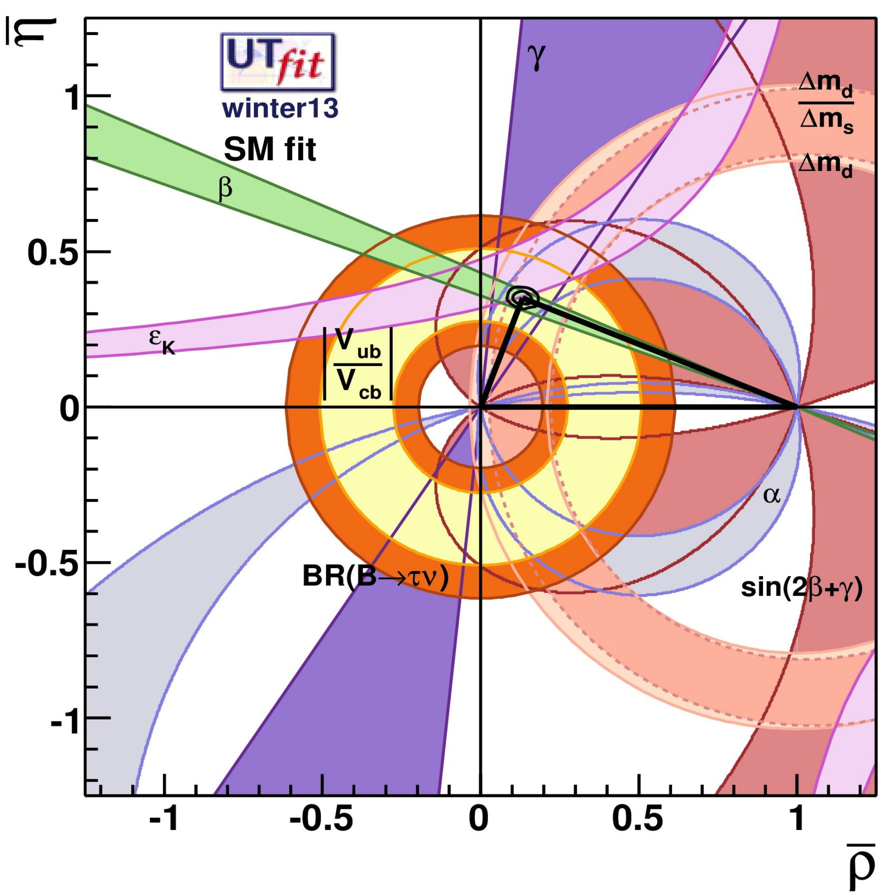
GIM mechanism

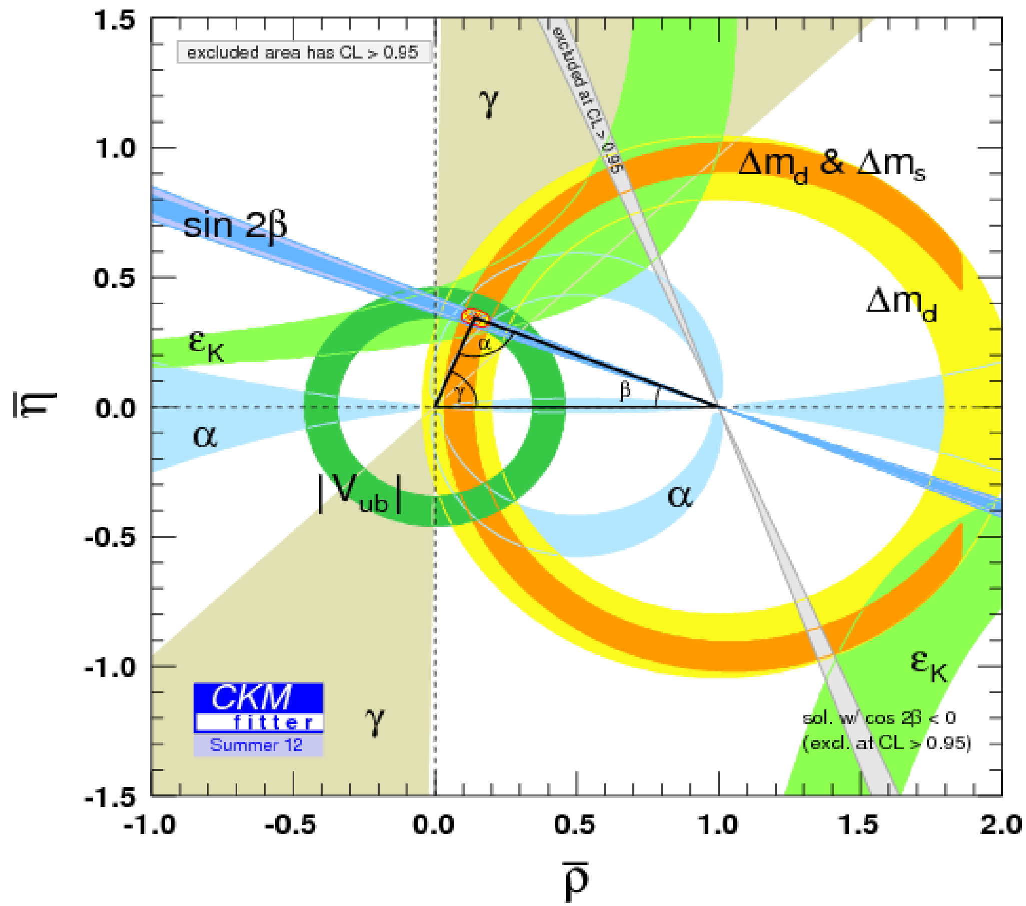
[large top-quark contribution: $A \sim m_t^2\ V_{tq}^*\, V_{tb}$]

- Rare B decays
  [$B \to X_s \gamma$, $B \to K^{(*)} l^+ l^-$, $B_{s,d} \to l^+ l^-$, ...]
- Rare K decays
  [$K \to \pi\nu\nu$, ...]
- $B_{d(s)}$- $\bar{B}_{d(s)}$ mixing
- K^0- $\bar{K}^0$ mixing

Present status of CKM fits

At present all the measurements of quark flavor-violating observables show a remarkable success of the CKM picture: we have a *redundant and consistent determination of various CKM elements.*





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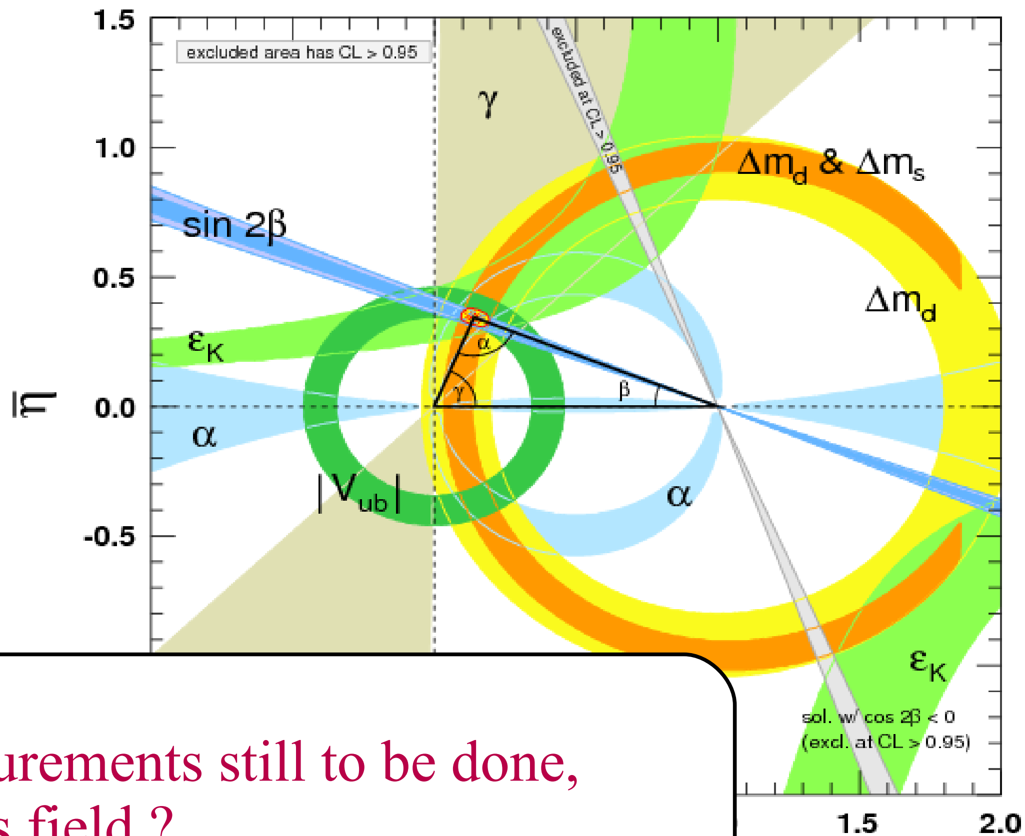
The agreement between data and SM expectations is even more striking if we consider other observables, not appearing in CKM fits, such as BR($B \to X_s \gamma$) or the B_s mixing phase



Are there interesting measurements still to be done, within this field ?

The SM as an effective theory

- Several theoretical arguments [inclusion of gravity, instability of the Higgs potential, neutrino masses, ...] and cosmological evidences [dark matter, inflation, cosmological constant, ...] point toward the existence of physics beyond the SM.

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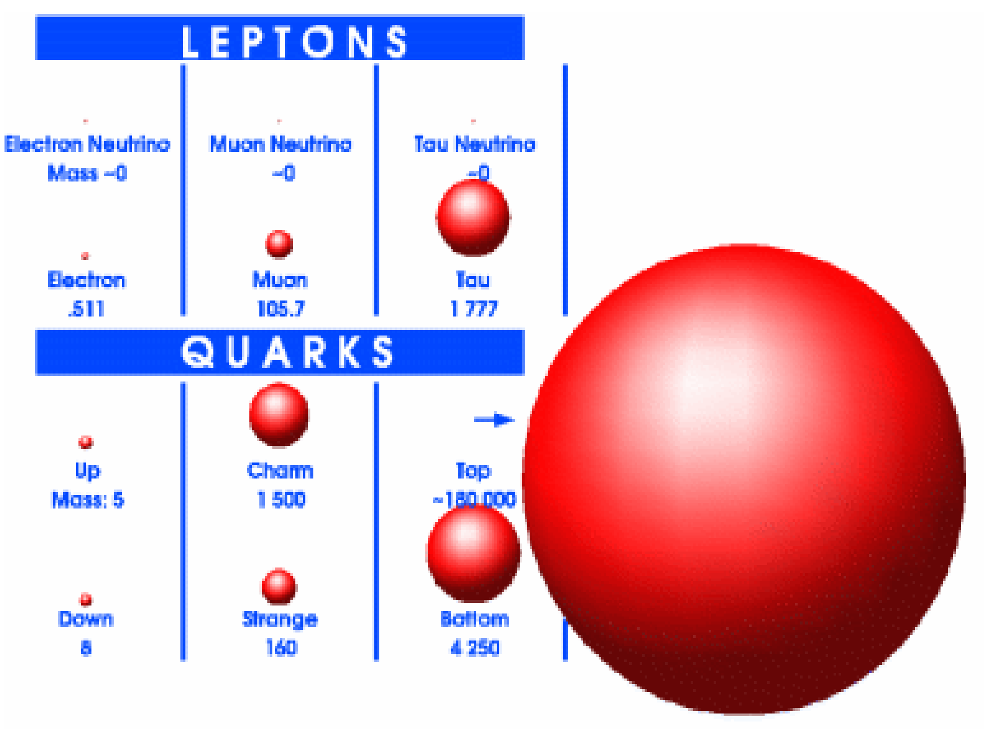
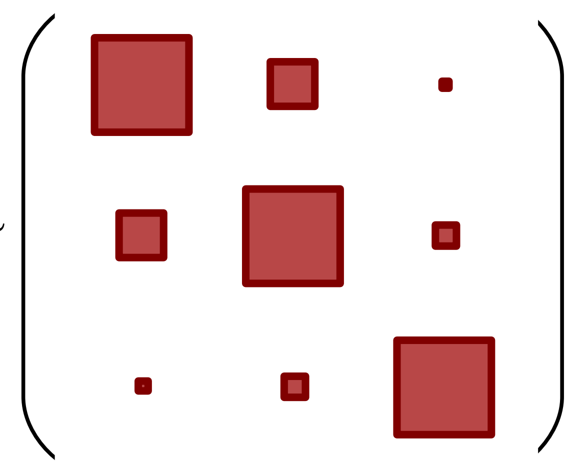


$V_{CKM} \sim$



It does not look "accidental"...

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- Even the observed hierarchical structure of quark and lepton masses, and their mixing pattern, seems to points toward some new dynamics.

- If this new dynamics is not too far from the electroweak scale, we can expect modifications of the SM predictions for a few low-energy observables in the sector of flavor physics

$\Downarrow$

still a lot of work to be done in this perspective

The SM as an effective theory

The modern point of view on the SM Lagrangian is that is only the low-energy limit of a more complete theory, or an effective theory.

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

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm gauge}(A_a, \psi_i) + \mathscr{L}_{\rm Higgs}(\phi, A_a, \psi_i) + \text{“heavy fields”}$$

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

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

✷ *Some general remarks on (effective) QFT*

$$S = \int \mathscr{L}\, d^4 x \quad = \text{ adimensional number (setting } \hbar\text{=1)}$$

All terms in the Lagrangian must have d=4.

This defines the canonical dimensions of the fields,
starting from their kinetic terms:

Scalar field: $\partial_\mu \phi\, \partial^\mu \phi \longrightarrow d[\phi] = 1$

Fermion field: $\bar{\psi}\, \partial_\mu \psi \longrightarrow d[\psi] = 3/2$

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$$\uparrow$$

d < 4 $\qquad m_\phi^{\,2}\,\phi^2, \quad m_\psi\,\bar{\psi}\,\psi, \ldots$

d=4 $\qquad g\,A_\mu\,\bar{\psi}\,\gamma_\mu\psi, \quad \lambda\,\phi^4, \ldots$

d > 4 $\qquad \dfrac{1}{\Lambda^2}\,(\bar{\psi}\,\gamma_\mu\psi)^2, \quad \dfrac{1}{\Lambda^2}\,\phi^6, \ldots$

⋆ Some general remarks on (effective) QFT

$$S = \int \mathscr{L}\, d^4x \quad = \text{adimensional number (setting } \hbar=1\text{)}$$

Contributions to scattering amplitudes:

d < 4 $\quad m_\phi^{\,2}\,\phi^2,\quad m_\psi\,\bar\psi\,\psi, \ldots \longrightarrow \dfrac{m_\phi^{\,2}}{E^2} \quad \dfrac{m_\psi}{E}$

dominant in the IR

d=4 $\quad g\,A_\mu\bar\psi\gamma_\mu\psi,\quad \lambda\,\phi^4, \ldots \longrightarrow g(E),\quad \lambda(E)$

potentially relevant at all energies

d > 4 $\quad \dfrac{1}{\Lambda^2}(\bar\psi\gamma_\mu\psi)^2,\quad \dfrac{1}{\Lambda^2}\phi^6, \ldots \longrightarrow \dfrac{E^2}{\Lambda^2}$

irrelevant at low energies,
but bad UV behavior

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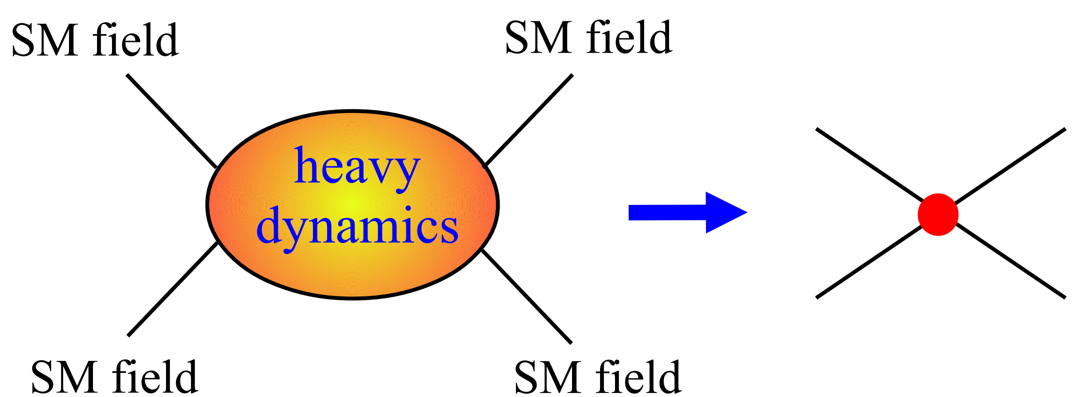
Operators of $d \geq 5$ containing SM fields only
(compatible with the SM gauge symmetry)

If we cannot directly excite the new degrees of freedom, is more efficient to *"integrate them out"*...



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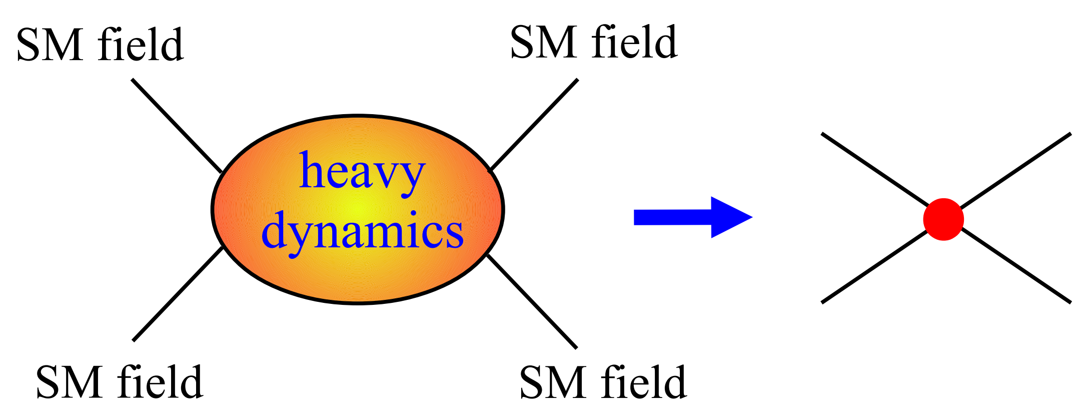
N.B. (I): This is the most general parameterization of the new (heavy) degrees of freedom, as long as we do not have enough energy to directly produce them.



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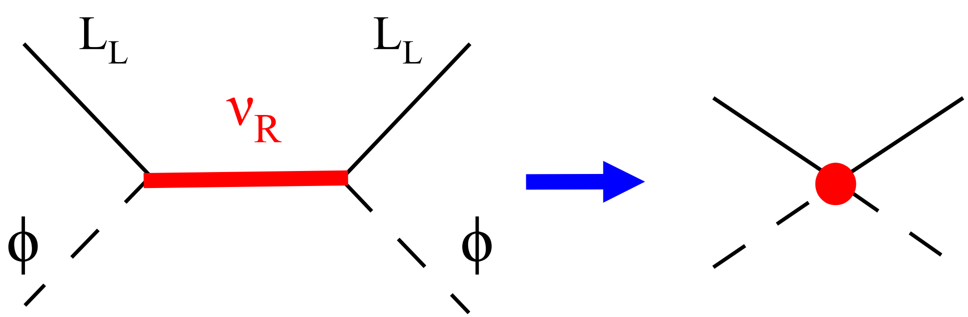
N.B. (II): So far, the only evidence of a non-vanishing term in the series of higher-dim. ops. comes from *neutrino masses.*

$$\frac{g_\nu^{ij}}{\Lambda} (L_L^{Ti} \sigma_2 \phi)(L_L^j \sigma_2 \phi^T)$$

Possible dynamical origin of this d=5 ops.:



$$(m_\nu)^{ij} = \frac{g_\nu^{ij} \, v^2}{\Lambda}$$

$$v = \langle \phi \rangle$$

The SM as an effective theory

The modern point of view on the SM Lagrangian is that is only the low-energy limit of a more complete theory, or an effective theory.

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

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm gauge}(A_a, \psi_i) + \mathscr{L}_{\rm Higgs}(\phi, A_a, \psi_i) + \sum \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \psi_i)$$

N.B. (II): So far, the only evidence of a non-vanishing term in the series of higher-dim. ops. comes from *neutrino masses.*
Neutrino masses are well described by *the only d=5 term allowed by the SM gauge symmetry.*

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Neutrino masses are well described by *the only d=5 term allowed by the SM gauge symmetry.*

$$\frac{g_\nu^{ij}}{\Lambda_{LN}} (L_L^{T\,i} \sigma_2 \phi)(L_L^j \sigma_2 \phi^T)$$

The smallness of m_ν seems to point toward a very high value of Λ. However, this ops. violates lepton number, which is global symmetry of the SM.
In this specific case, *the high value of Λ may be related to the breaking of LN*.

$$(m_\nu)^{ij} = \frac{g_\nu^{ij}\, v^2}{\Lambda_{LN}}$$

$$v = \langle \phi \rangle$$

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$$\mu^2 \ \phi^+ \phi \ \xrightarrow[\text{corrections}]{\text{quantum}} \ \Lambda^2 \ \phi^+ \phi$$

N.B. (III): An indication of a much lower value of Λ comes from *the only d=2 term in this Lagrangian*, namely from the Higgs sector:

A *"natural"* effective theory implies some new degrees of freedom (respecting SM symmetries and coupled to the Higgs sector) not far from the TeV scale to stabilize the Higgs mass term.

The SM as an effective theory

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Two key questions of particle physics today:

- Which is the <u>energy scale</u> of New Physics (*or the value of* Λ) → High-energy experiments [*the high-energy frontier*]
- Which is the <u>symmetry structure</u> of the new degrees of freedom (*or the structure of the* c_n) → High-precision low-energy exp. [*the high-intensity frontier*]

The SM as an effective theory

More precisely, on both "frontiers" we have two independent sets of questions, a *"difficult one"* and a *"more pragmatic one"*:

- *What determines the Fermi scale?*
- *Is there anything else beyond the SM Higgs at the TeV scale?*

High-energy experiments
[*the high-energy frontier*]

- *What determines the observed pattern of masses and mixing angles of quarks and leptons?*
- *Which are the sources of flavor symmetry breaking accessible at low energies?*
[Is there anything else beside SM Yukawa couplings & neutrino mass matrix?]

High-precision low-energy exp.
[*the high-intensity frontier*]

Flavor physics beyond the SM

$$\mathscr{L}_{\mathrm{eff}} = \mathscr{L}_{\mathrm{gauge}}(A_a, \psi_i) + \mathscr{L}_{\mathrm{Higgs}}(\phi, A_a, \psi_i) + \sum \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \psi_i)$$

3 identical replica of the basic fermion family
$\Rightarrow$ huge flavor-degeneracy [$U(3)^5$ symmetry]

Flavor-degeneracy broken only by the
Yukawa interaction

What we have only started to investigate is the
flavor structure of the new degrees of freedom
which hopefully will show up above the electroweak scale

Λ = *effective scale of new physics*

several new sources of
flavor symmetry breaking
are, in principle, allowed

Probing the flavor structure of physics beyond the SM requires the following three main steps:

Determine the CKM elements from theoretically clean and non-suppressed tree-level processes, where the SM is likely to be largely dominant.

- Exclusive and inclusive semi-leptonic $b \to u$ decays ($|V_{ub}|$)
- Selected non-leptonic B decays sensitive to γ

↓

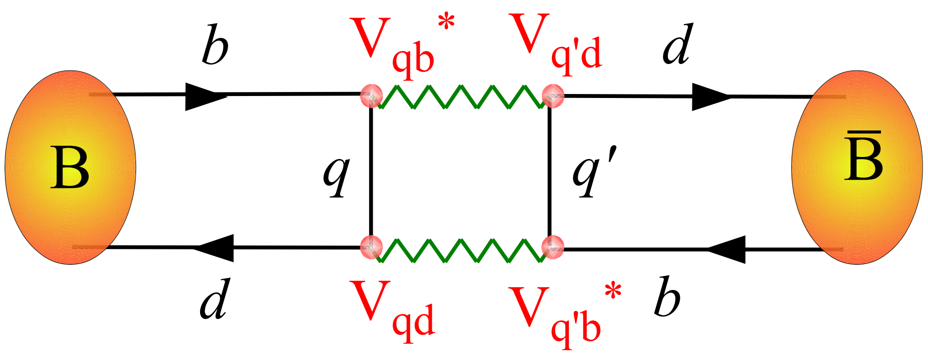
Identify processes where the SM is calculable with good accuracy using the tree-level inputs, or sufficiently suppressed for null tests.

- $\Delta F=2$ Neutral meson mixing [K, B_d, B_s + D]
- CP-violating observables
- Rare decays:
  - FCNC modes ($B \to ll$, $B \to K^* ll$,...)
  - Helicity-suppressed observables
  - Forbidden processes

↓

Measure with good accuracy these rare processes and determine the allowed room for new physics.

Such chain has already been closed, with quite good accuracy, for down-type $\Delta F=2$ observables (K and $B_{d,s}$ meson-antimeson 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 [2^{nd} lecture]

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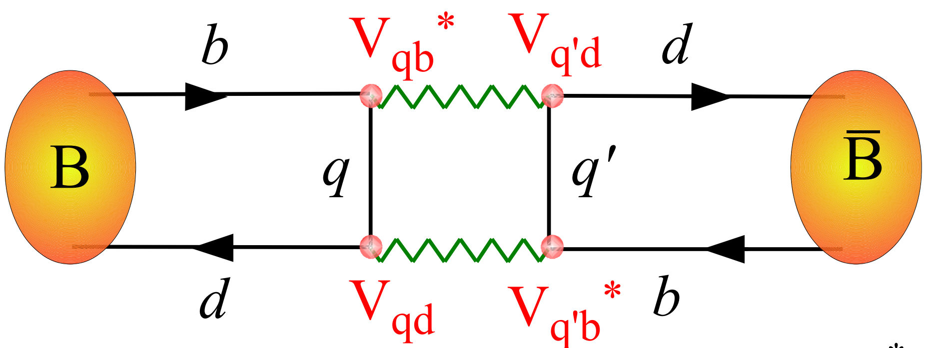

power-like GIM mechanism:

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

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

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

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

[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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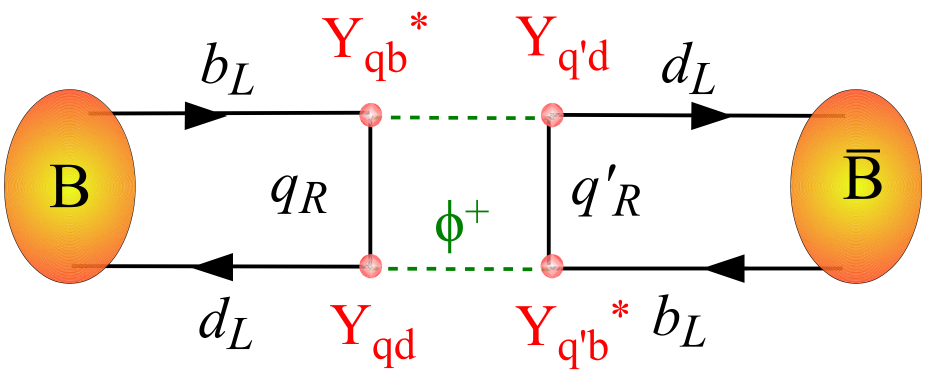

The origin of this behavior can be better understood if we *switch-off* gauge interactions ("gauge-less limit")

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

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

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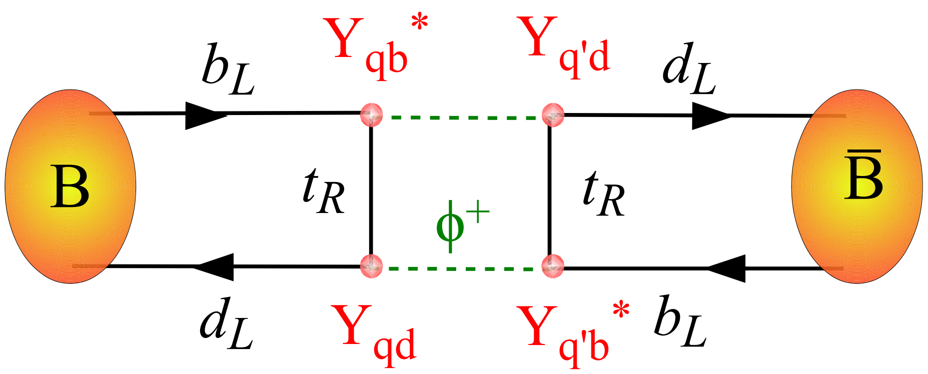

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$$Y_U = V^+ \times \mathrm{diag}(y_u, y_c, y_t) \approx V^+ \times \mathrm{diag}(0, 0, y_t)$$

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

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

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

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

The flavor problem

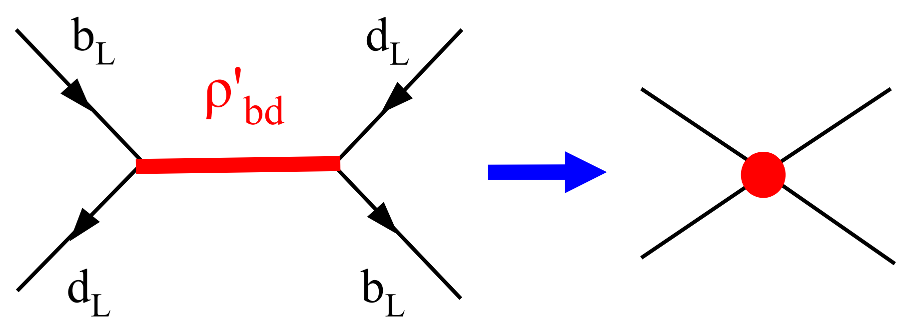
Such chain has already been closed, with quite good accuracy, for down-type $\Delta F=2$ observables (K and $B_{d,s}$ meson-antimeson mixing), showing no significant deviations from the SM (at the 5%-30% level, depending on the amplitude):

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

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

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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N.B.: In Kaon physics the CKM suppression is even stronger:

B_s-mix.: $V_{tb}^* V_{ts} \sim \lambda^2$ B_d-mix.: $V_{tb}^* V_{td} \sim \lambda^3$ K-mix: $V_{ts}^* V_{td} \sim \lambda^5$

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$$c_{NP} \begin{cases} \sim 1 & \xrightarrow{\text{tree/strong + generic flavor}} \quad \Lambda \gtrsim 2\times10^4 \text{ TeV [K]} \\ \sim 1/(16\pi^2) & \xrightarrow{\text{loop + generic flavor}} \quad \Lambda \gtrsim 2\times10^3 \text{ TeV [K]} \end{cases}$$

Serious conflict with the expectation of new physics around the TeV scale, to stabilize the electroweak sector of the SM [*The flavour problem*]

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$$c_{NP} \sim (y_t V_{ti}^* V_{tj})^2 \xrightarrow{\text{tree/strong + ``alignment''}} \Lambda \gtrsim 5 \text{ TeV [K \& B]}$$

$$c_{NP} \sim (y_t V_{ti}^* V_{tj})^2/(16\pi^2) \xrightarrow{\text{loop + ``alignment''}} \Lambda \gtrsim 0.5 \text{ TeV [K \& B]}$$

<u>*The flavor problem*</u>

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c_{NP}

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$\sim (y_t V_{ti}^* V_{tj})^2 \xrightarrow{\text{tree/strong + ``alignment''}} \Lambda \gtrsim 5$ TeV [K & B]

$\Lambda \gtrsim 0.5$ TeV [K & B]

Comparable to the scales directly probed at the LHC and/or indirectly probed in precision Higgs physics

The flavor problem

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM} + \sum \frac{c_{ij}}{\Lambda^2} O_{ij}^{(6)}$$

G.I, Nir, Perez '10

Operator	Bounds on Λ (TeV)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ε_K
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ε_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert$, ϕ_D
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert$, ϕ_D
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{B_d\to\psi K}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{B_d\to\psi K}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2	1.1×10^2	7.6×10^{-5}	7.6×10^{-5}	Δm_{B_s}
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	3.7×10^2	3.7×10^2	1.3×10^{-5}	1.3×10^{-5}	Δm_{B_s}

New flavor-breaking sources at the TeV scale (if any) are highly tuned

Open questions

New flavor-breaking sources at the TeV scale (if any) are highly tuned

- Can we build NP models where the alignment with the CKM is "natural"?
- Is there a unique form of alignment that allows $\Lambda \sim 1$ TeV?
  Do we need to impose it also in $\Delta F=1$ processes and/or up-type transitions?
- Does this shed light on the origin of fermion masses and CKM hierarchies?
- Can we have $c_{NP} = 0$ or $\Lambda \gg 10$ TeV?
- Can we see deviations from the SM with more precise measurements? Where?

Some partial answers in the rest of these lectures,
hopefully more complete answers from future flavor-physics data...