Flavour Physics and CP Violation

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

Plan of the lectures:

- An introduction to flavour physics
  - The flavour sector of the Standard Model
  - Some properties of the CKM matrix
  - Present status of CKM fits
  - The SM as an effective theory
  - Flavour physics beyond the SM
  - The flavour problem
  - Open questions

- Phenomenology of B and D decays
- Flavour physics beyond the SM

The flavour sector of the Standard Model

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

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

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

- *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 flavour symmetry*

$$\mathcal{L}_{\mathrm{gauge}} = \Sigma_{\mathrm{a}} - \frac{1}{4g_{\mathrm{a}}^{2}} (F_{\mu\nu}^{\mathrm{a}})^2 + \Sigma_{\psi} \Sigma_{\mathrm{i}} \overline{\psi}_{\mathrm{i}}\, i \not{D}\, \psi_{\mathrm{i}}$$

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- Highly symmetric

- *Ad hoc*
- Necessary to describe data [*clear indication of a non-invariant vacuum*] so far, weakly tested in its dynamical form
- Not stable with respect to quantum corrections
- Origin of the flavour structure of the model

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

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

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

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

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

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

Lepton number Hypercharge *Flavour mixing*

Barion number

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Within the SM the flavour-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:

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

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

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

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but the residual flavour symmetry let us to choose a (gauge-invariant) flavour basis where one of the two Yuwawas is diagonal:

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

or

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

V → unitary matrix

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

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To diagonalize also the second mass matrix we need to rotate separately u_L & d_L (non gauge-invariant basis) $\Rightarrow$ 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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$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

Several equivalent parameterizations [unobservable quark phases] in terms of

- 3 real parameters (rotational angles)

+

- 1 complex phase (source of CP violation)

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The SM quark flavour 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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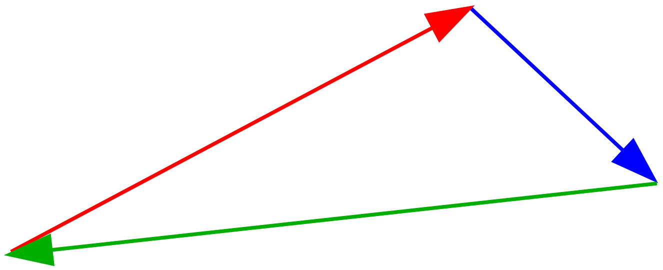
$$V_{CKM} V^{+}_{CKM} = I$$

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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Experimental indication of a strongly hierarchical structure:

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

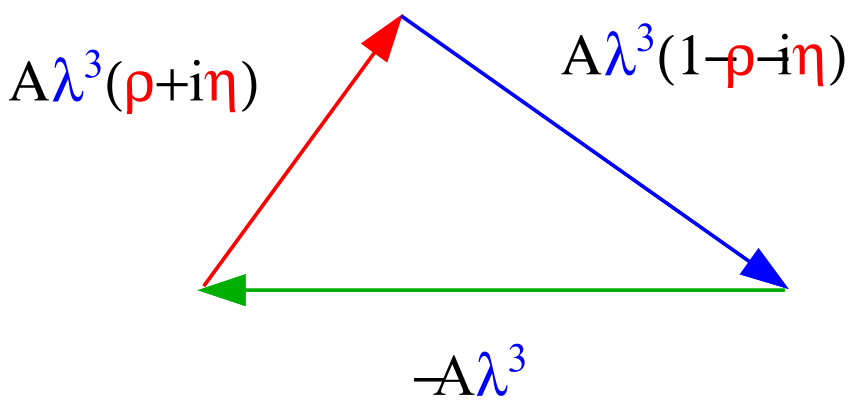
Wolfenstein, '83

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

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

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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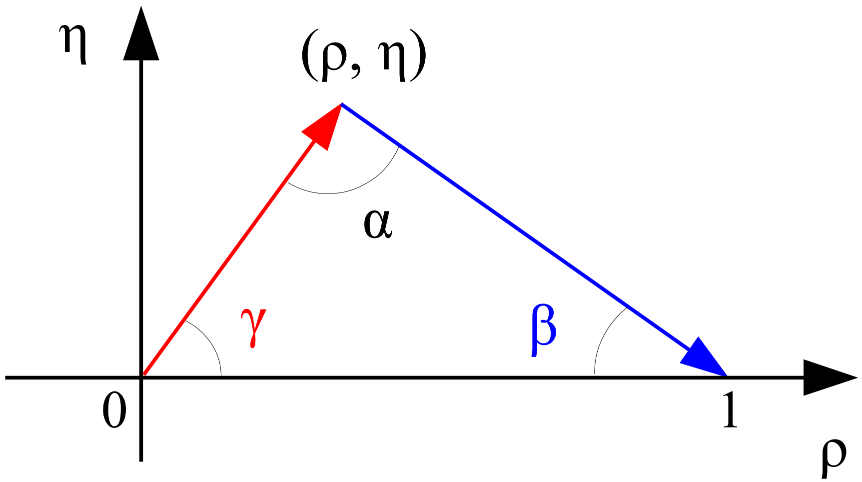
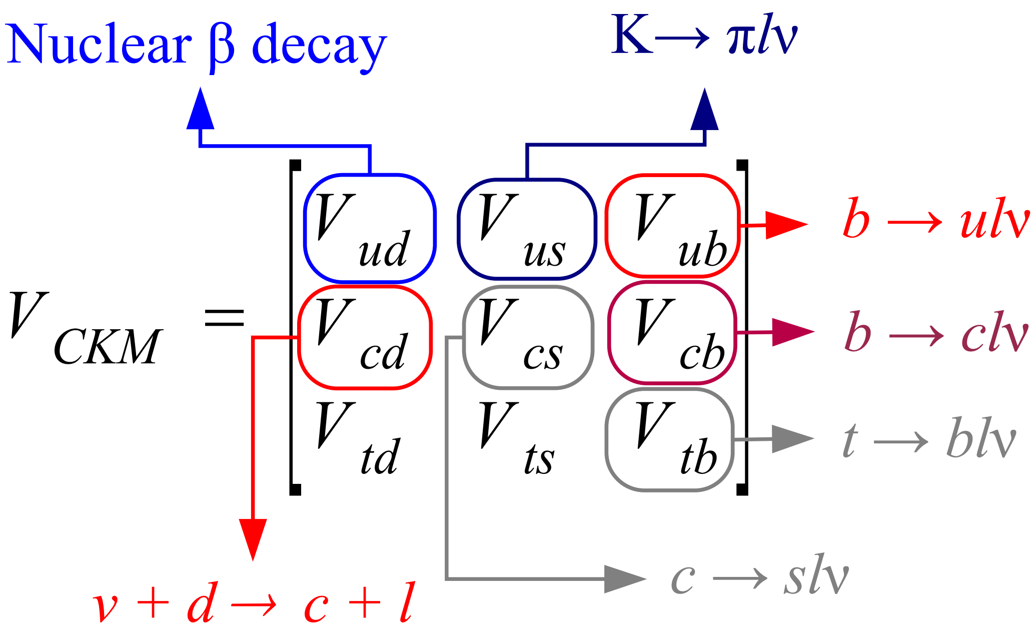
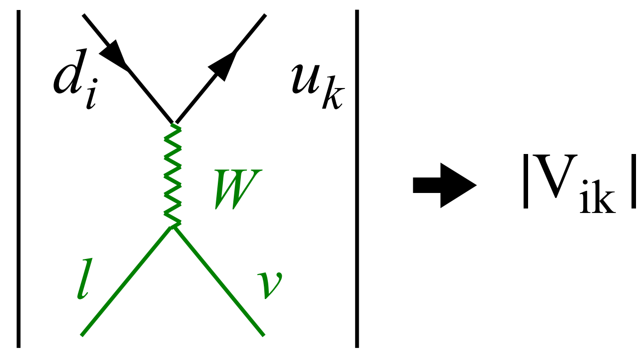


Note: *often you'll find experimental results shown as constraints in the* $\bar\rho, \bar\eta$ *plane. These new parameters are defined by* $\bar\rho = \rho\,(1-\lambda^2/2)^{-1/2}$ *(same for η) to keep into account higher-order terms in the expansion in powers of* λ.



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

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



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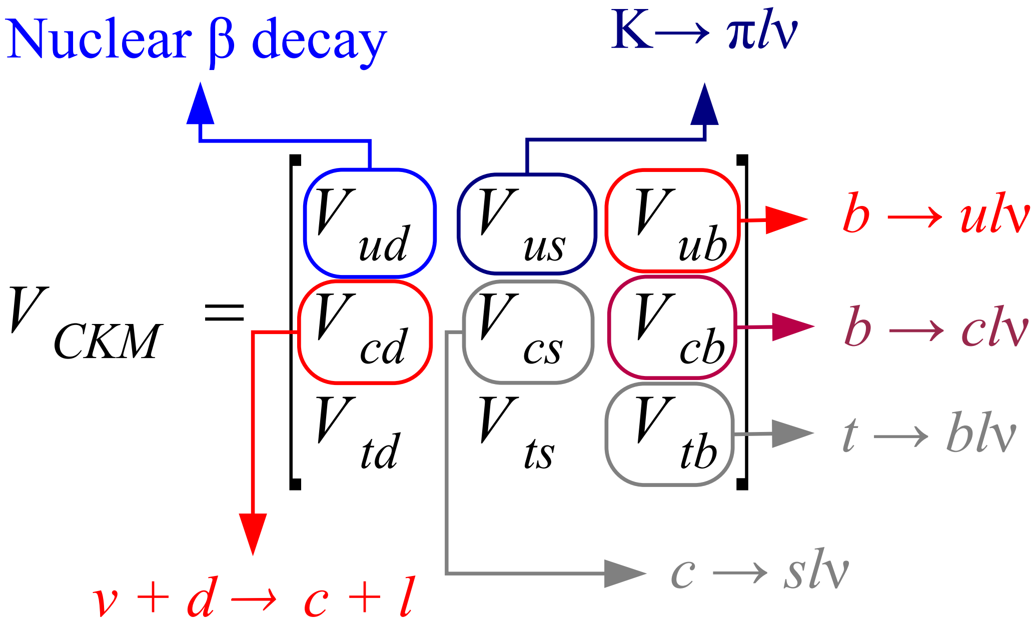

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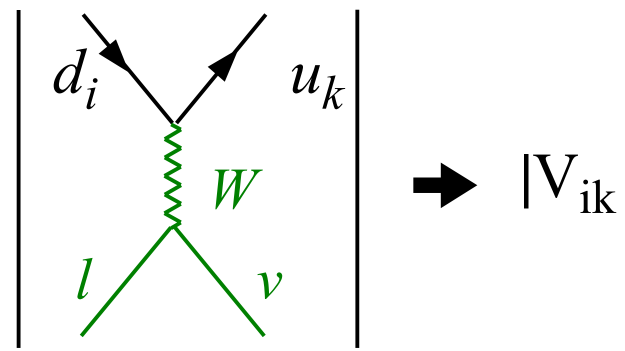
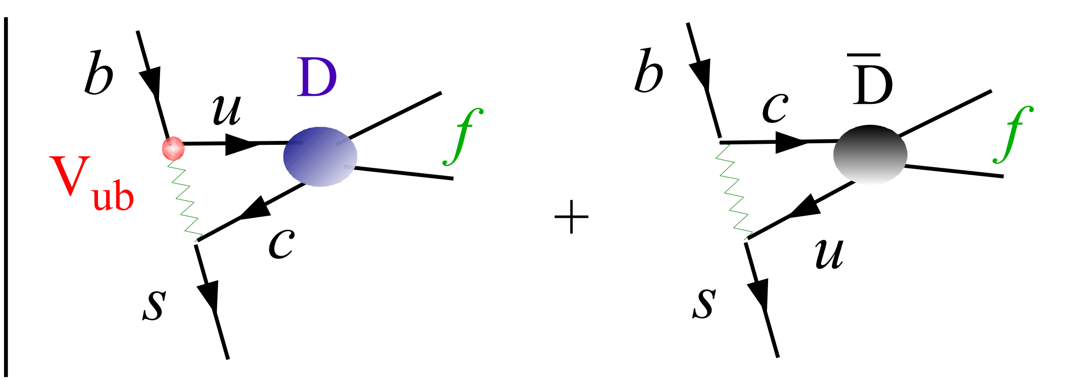


Also the phase $\gamma = \arg(V_{ub})$ can be obtained by (quasi-) tree-level processes, such as

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

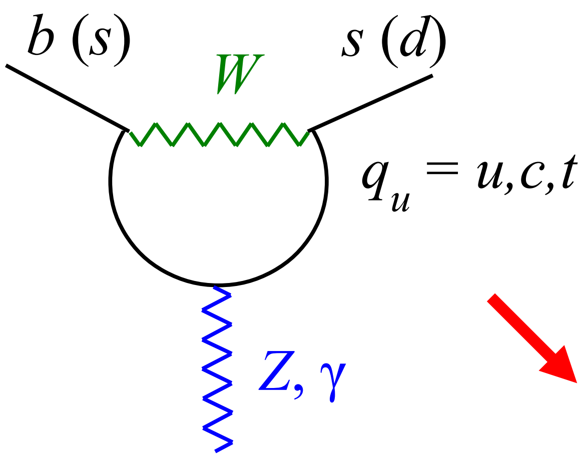


The only CKM elements we cannot access via tree-level processes are V_{ts} & V_{td}

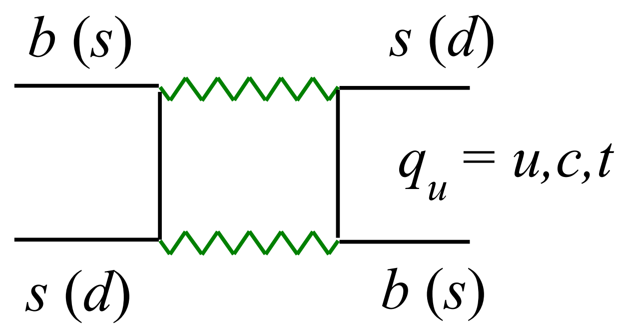
↓

Loop-induced amplitudes:

$\Delta F = 1$ FCNC



$\Delta F = 2$ (neutral-meson mixing)



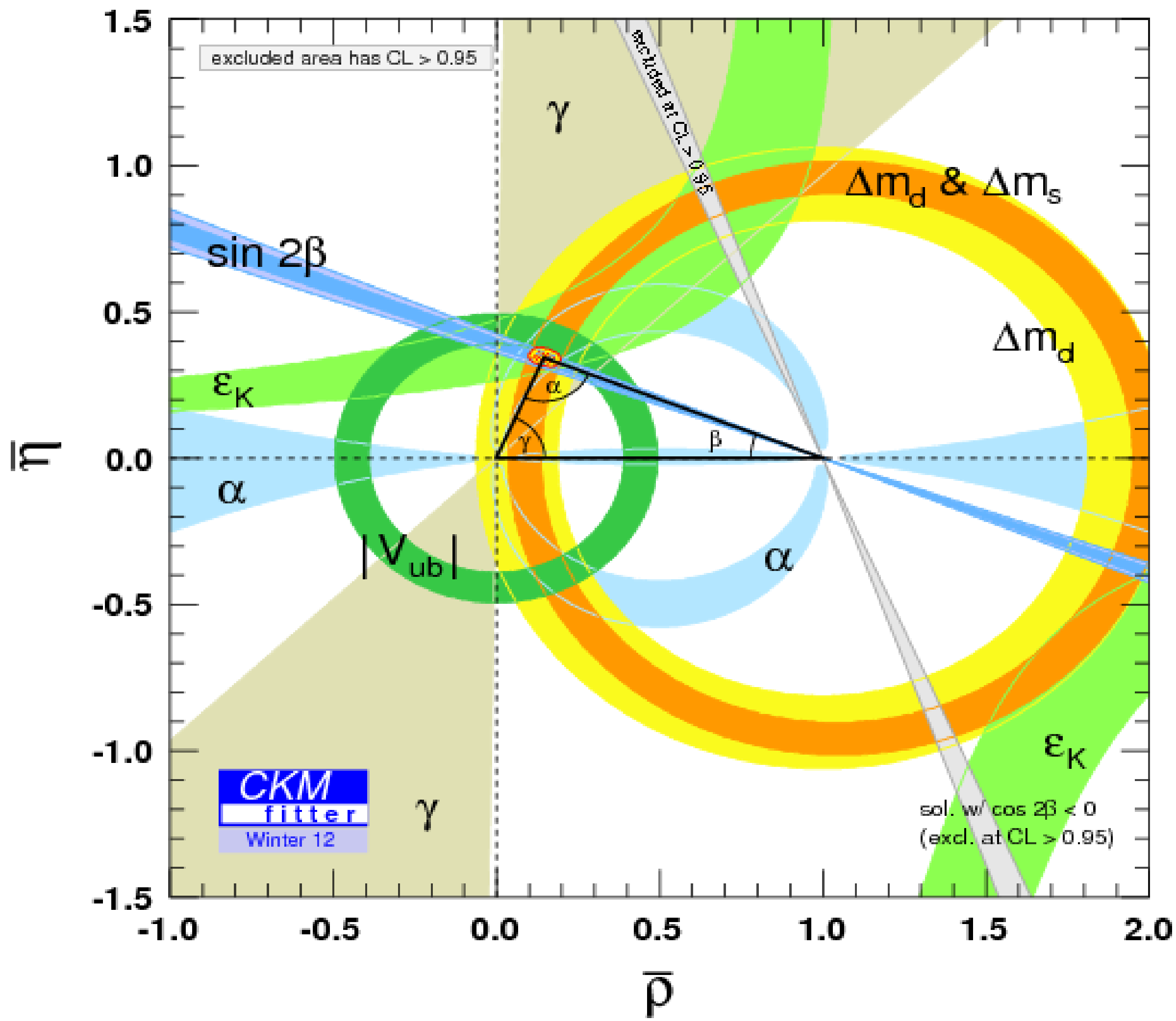
GIM mechanism

[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*

Beside a few "anomalies" (*on which I'll come back...*) the measurements of quark flavor-violating observables show a remarkable success of the CKM picture: we have redundant and consistent determinations of various CKM elements



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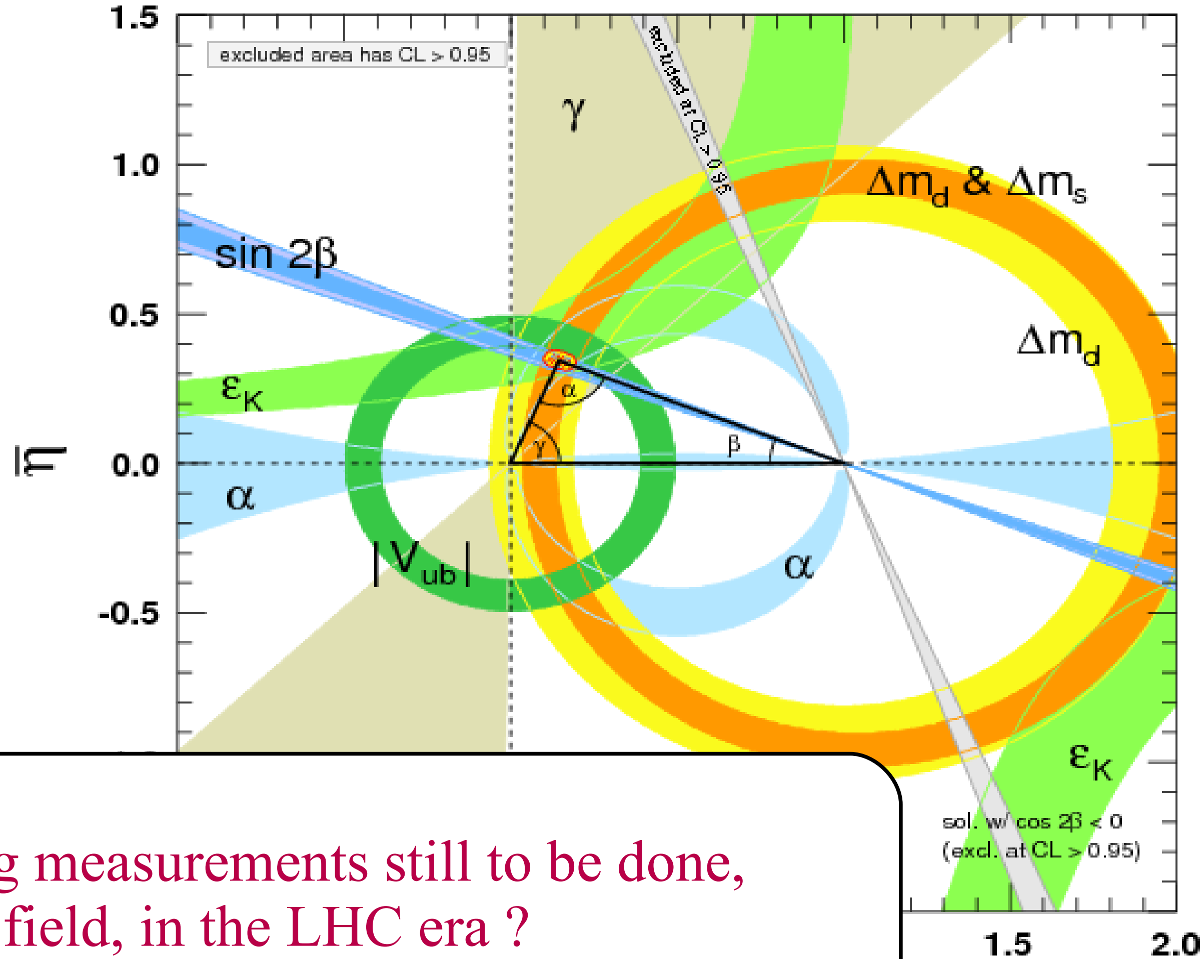

The agreement between data and SM expectations is even more striking if we consider other observables, not appearing in CKM fits, such as $B(B \to X_s \gamma)$ or the B_s mixing phase

Are there interesting measurements still to be done, within this field, in the LHC era ?

The SM as an effective theory

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

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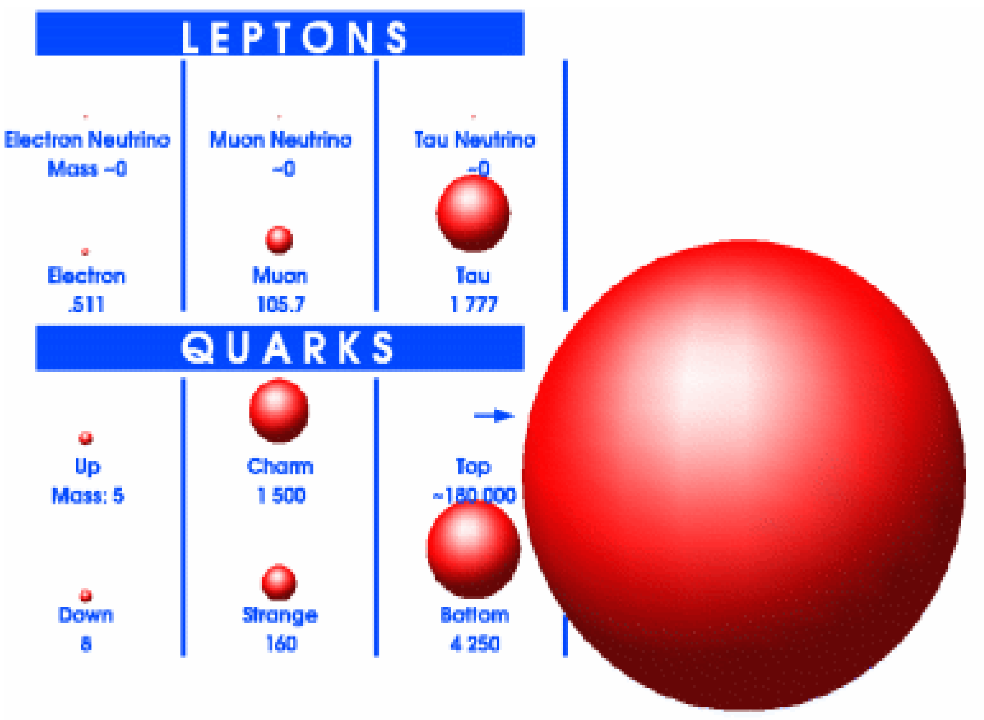
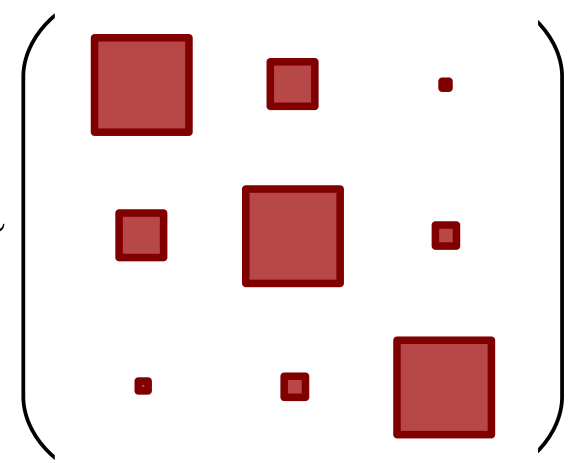


$V_{CKM} \sim$



It does not look "accidental"...

The SM as an effective theory

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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 flavour physics

⬇

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.

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm gauge}(A_a, \psi_i) + \mathcal{L}_{\rm Higgs}(\phi, A_a, \psi_i) + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \psi_i)$$

$\mathcal{L}_{\rm SM}$ = renormalizable part of $\mathcal{L}_{\rm eff}$
[= all possible operators with $d \leq 4$ compatible with the gauge symmetry]

operators of $d \geq 5$ containing SM fields only and compatible with the SM gauge symmetry

N.B. (I): This is the most general parameterization of the new degrees of freedom, (*assuming* Λ *above the electroweak scale*), as long as we perform low-energy experiments

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

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

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

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

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

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*.

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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.

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Two key questions of particle physics today:

- Which is the energy scale of New Physics (*or the value of* Λ) → High-energy experiments [*the high-energy frontier*]
- Which is the symmetry structure 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 flavour 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*]

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↕

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 flavour 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*]

▸ *Flavour physics beyond the SM*

$$\mathscr{L}_{eff} = \mathscr{L}_{gauge}(A_a, \psi_i) + \mathscr{L}_{Higgs}(\phi, A_a, \psi_i) + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \psi_i)$$

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

Flavour-degeneracy broken only by the Yukawa interaction

What we have only started to investigate is the flavour 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 flavour symmetry breaking are, in principle, allowed

Probing the flavour 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→u decays ($|V_{ub}|$)
- Selected non-leptonic B decays sensitive to γ

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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 ($B \to Kll$,..)
  - Helicity-suppressed observables
  - Forbidden processes

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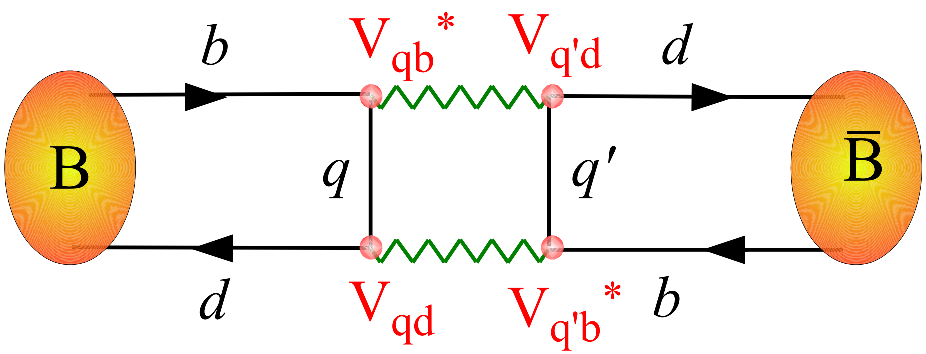
Measure with good accuracy these rare processes and determine the allowed room for new physics.

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 [next lecture]

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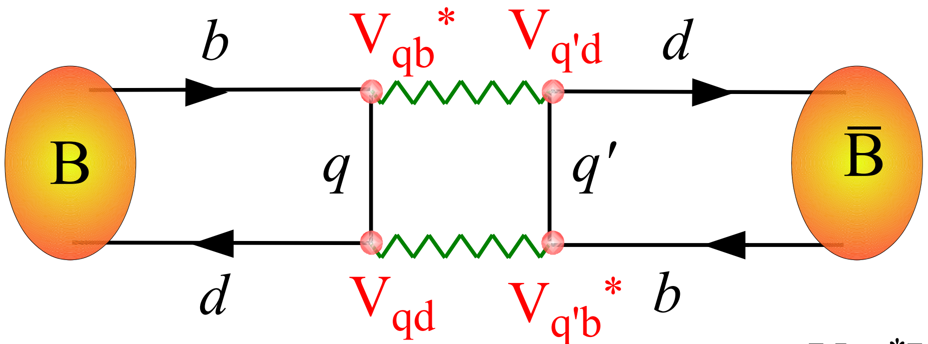


power-like GIM mechanism:

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

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

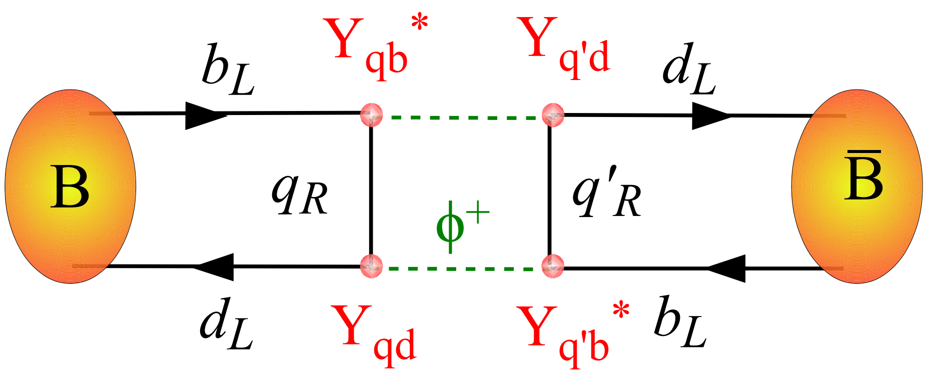
$$A_{\Delta F=2} = \Sigma_{q=u,c,t} (V_{qb}{}^* V_{qd}) [\, V_{tb}{}^* V_{td} (A_{tq} - A_{uq}) + V_{cb}{}^* V_{cd} (A_{cq} - A_{uq}) \,]$$

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

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

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

Such chain has already been closed, with quite good accuracy, for <u>down-type</u> $\Delta F=2$ observables (K and $B_{d,s}$ meson-antimeson mixing):



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

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

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

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

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

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

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

The flavour 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):

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

$$\mathscr{L}_{eff} = \mathscr{L}_{SM} + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}$$

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

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We can extract some info about new physics

The flavour problem

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

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

▶ The flavour problem

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c_{NP}:

- ~ 1 — tree/strong + generic flavor → $\Lambda \gtrsim 2\times10^4$ TeV [K]
- $\sim 1/(16\pi^2)$ — loop + generic flavor → $\Lambda \gtrsim 2\times10^3$ TeV [K]
- $\sim (y_t V_{ti}^* V_{tj})^2$ — tree/strong + “alignment” → $\Lambda \gtrsim 5$ TeV [K & B]
- $\sim (y_t V_{ti}^* V_{tj})^2/(16\pi^2)$ — loop + “alignment” → $\Lambda \gtrsim 0.5$ TeV [K & B]

The flavour 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 flavour-physics data...