B Physics

Gino Isidori [INFN - Frascati]

Selected aspects of **B Physics** *in the LHC era*

Gino Isidori [*INFN - Frascati*]

- Flavour physics in the LHC era
- B-physics phenomenology: mixing, CP violation, and rare decays
- Flavour physics beyond the SM: models and predictions

Plan of the lectures:

- Flavour physics in the LHC era
  - 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
- B-physics phenomenology: mixing, CP violation, and rare decays
- Flavour physics beyond the SM: models and predictions

The flavour sector of the Standard Model

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

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

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

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

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- Higly symmetric

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

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

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

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

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

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

U(1) flavour-independent phase

×

SU(3) flavour-dependent mixing matrix

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

3 identical replica of the basic fermion family

$[\ \psi = Q_L,\ u_R,\ d_R,\ L_L,\ e_R\ ]$ $\Rightarrow$ huge flavour-degeneracy: $U(3)^5$ global symm.

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

Lepton number

Barion number

Hypercharge

Flavour mixing

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

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[$\psi = Q_L, u_R, d_R, L_L, e_R$] $\Rightarrow$ huge flavour-degeneracy: $U(3)^5$ global symm.

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

in the quark sector:

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

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

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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 → diagonalised by bi-unitary transformations:

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

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

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

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

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

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

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

V, V^+ → unitary matrix

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

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

To diagonalize also the second mass matrix we need to rotate separately u_L & d_L (non gauge-invariant basis) $\Rightarrow$ 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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The CKM matrix:

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

Several equivalent parameterizations [unobservable quark phases] in terms of

- 3 real parameters (rotational angles)

+

- 1 complex phase (source of CP violation)

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

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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

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

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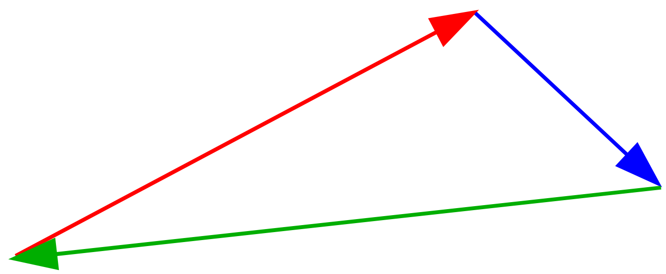
$$V_{CKM} V_{CKM}^{+} = I$$

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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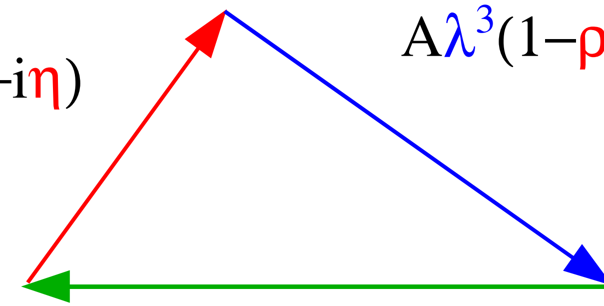
The $b \to d$ UT triangle:

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



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

$\lambda = 0.22$

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

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

Some properties of the CKM matrix

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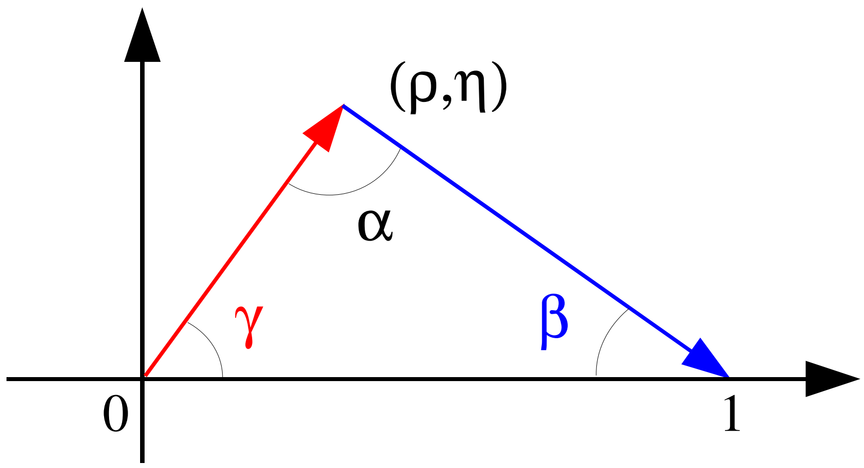

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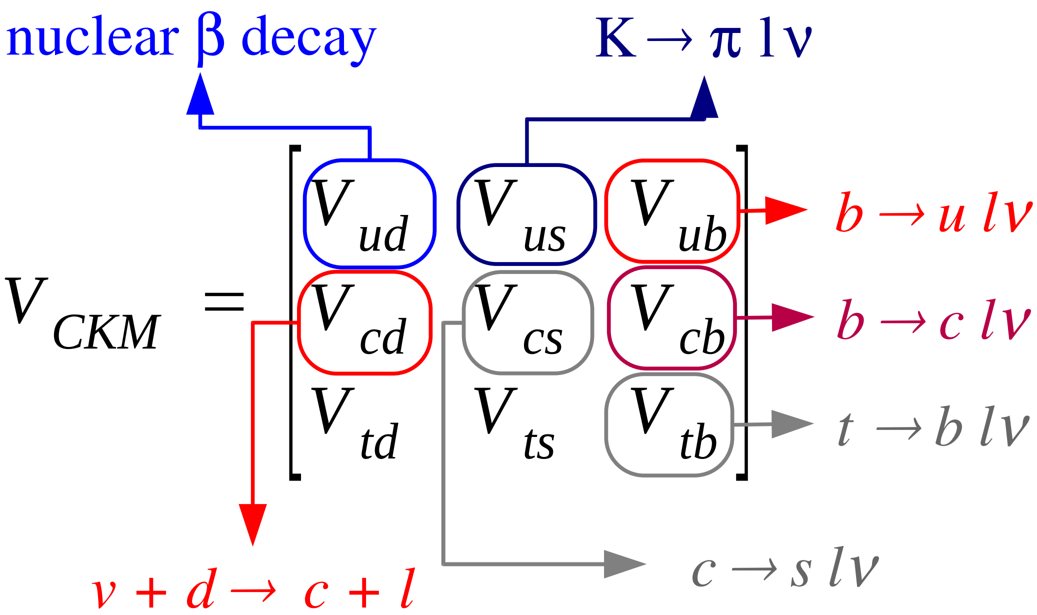
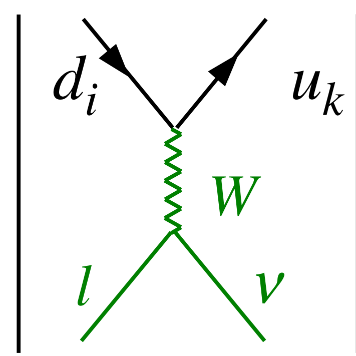


Once we assume unitarity, the CKM matrix can be <u>completely determined</u> using only exp. info from processes mediated <u>by tree-level</u> c.c. amplitudes

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



➡ $|V_{ik}|$

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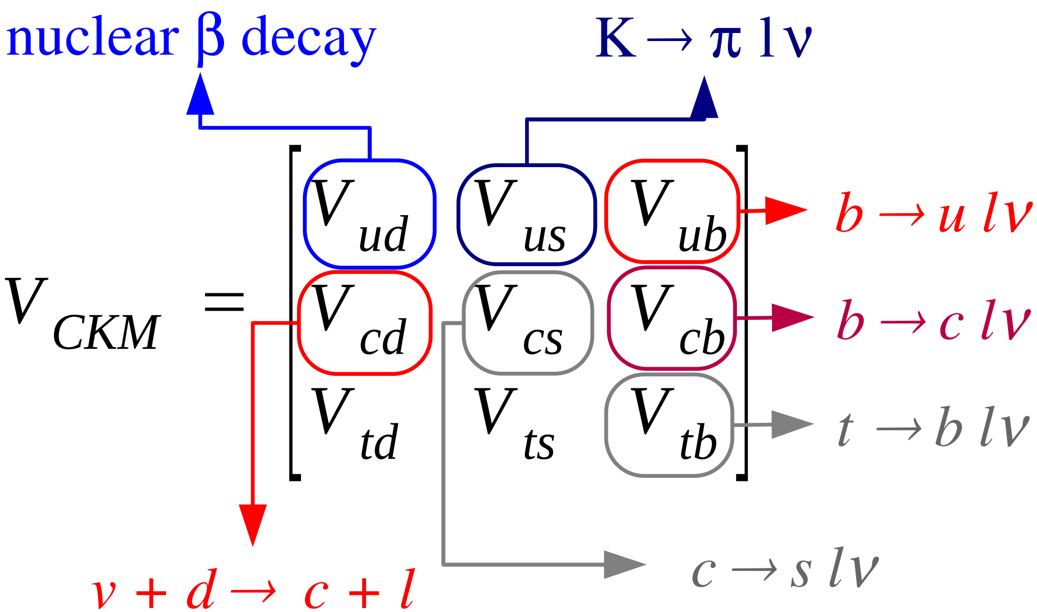

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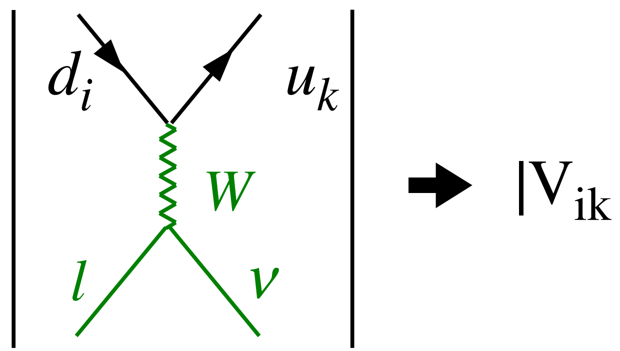
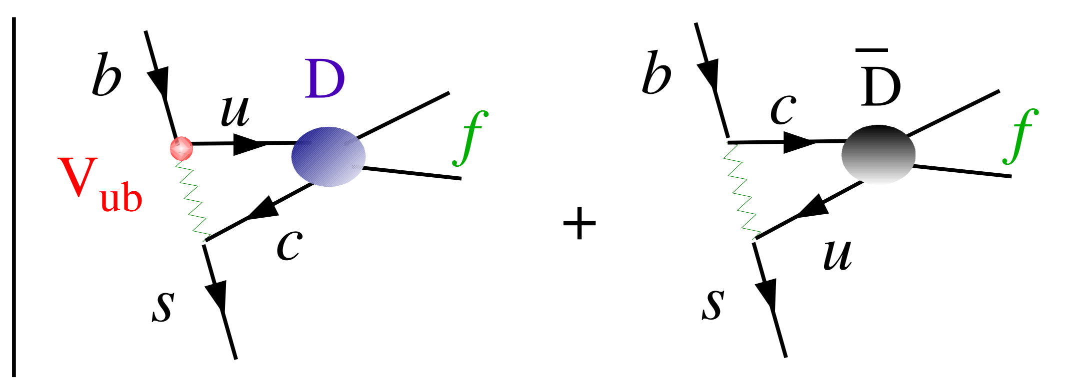


➡ $|V_{ik}|$

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

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

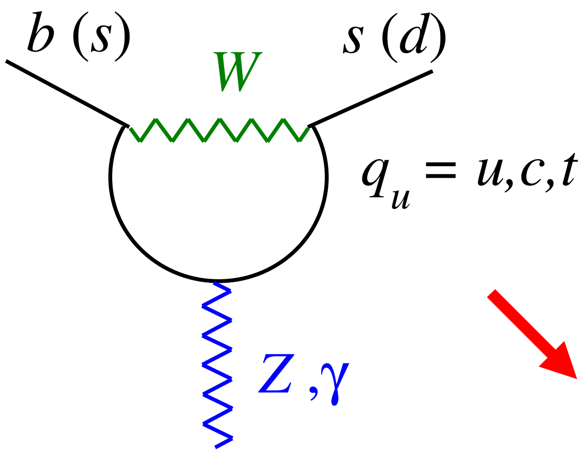


The only CKM elements we cannot access via tree-level processes are V_{ts} & V_{td}

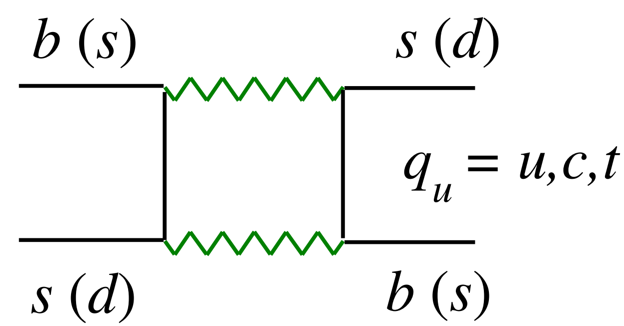
↓

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

  [$B \to X_s \gamma$, $B \to X_s l^+ l^-$, $B_s \to l^+ l^-$, ...]

- Rare K decays

  [$K \to \pi \nu\nu$, $K \to \pi l^+ l^-$, ...]

- $B_{d(s)}$- $\bar{B}_{d(s)}$ mixing

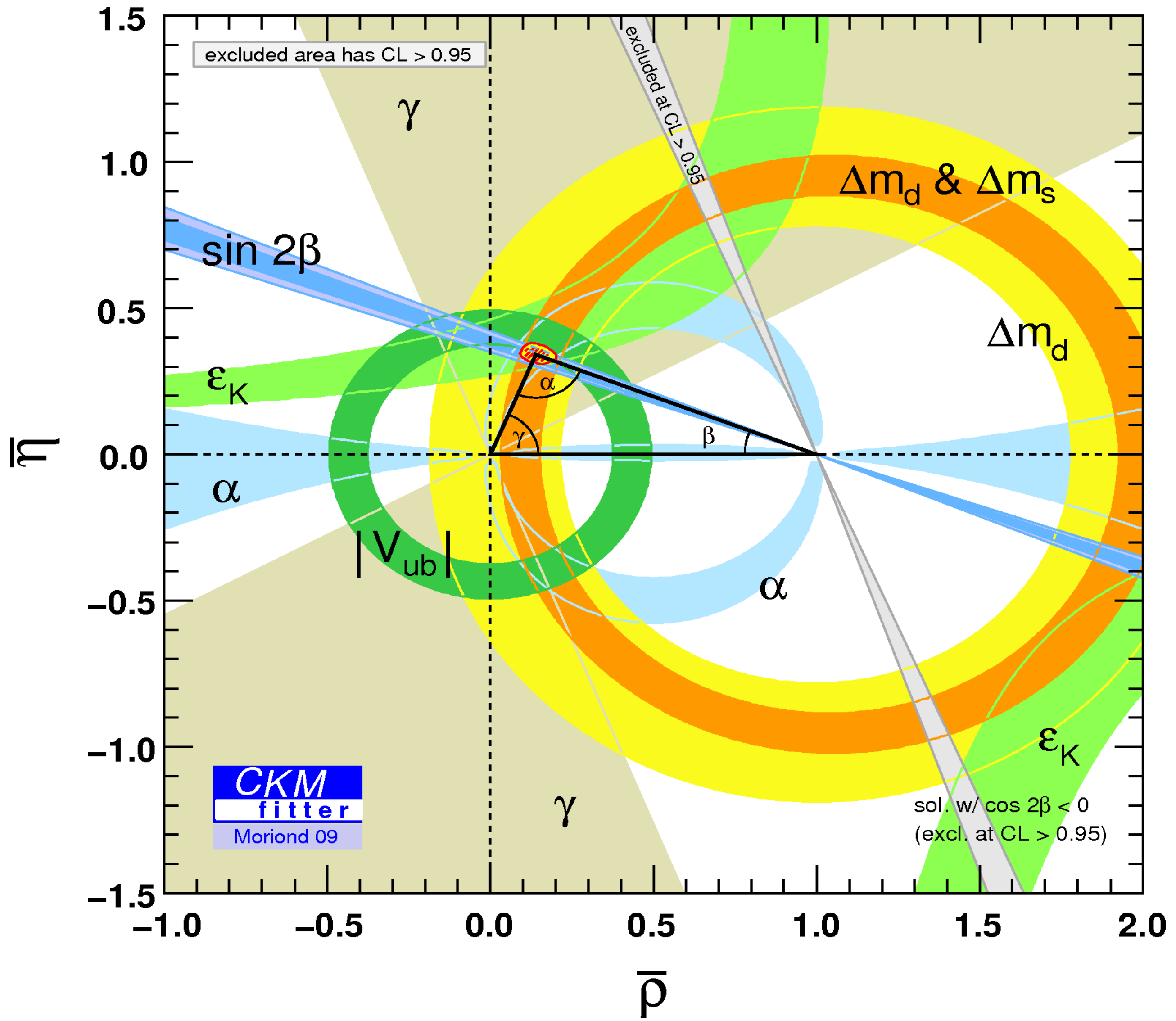
  [Δm_{Bd}, $a_{CP}(\psi K)$, Δm_{Bs}, $a_{CP}(\psi \phi)$]

- K^0- $\bar{K}^0$ mixing

  [Δm_K, ε_K]

Present status of CKM fits

Thanks to the recent results from B factories (+ Tevatron & Kaon factories), at present we have a good consistency check of the SM picture (redundant determinations of various CKM elements)



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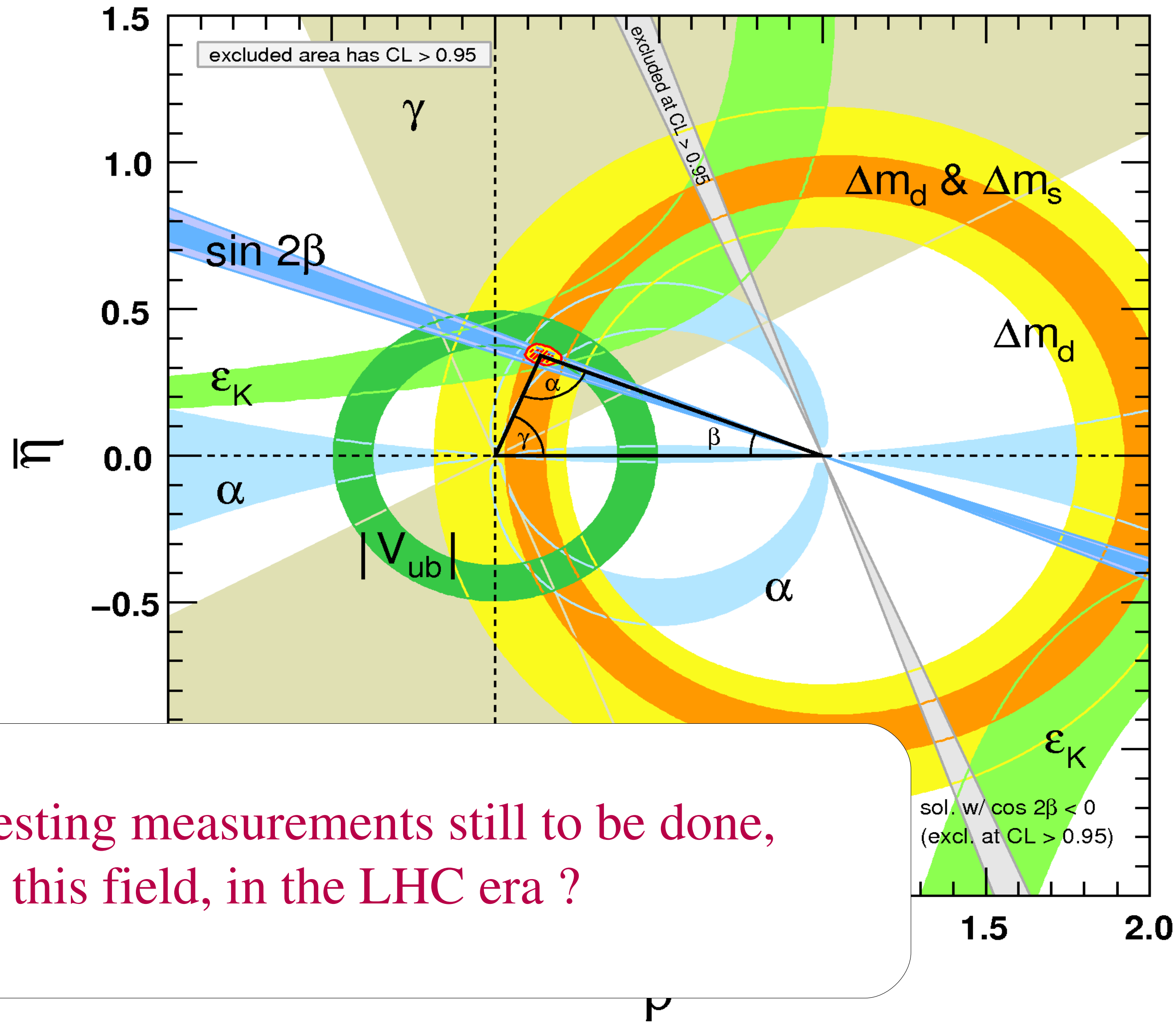

The agreement between data and SM expectations is even more striking if we consider other observables, not appearing in CKM fits, such as $B(B \to X_s \gamma)$

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

- If this new physics 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 [$\Lambda > \langle\phi\rangle \approx 250$ GeV]

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

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

[=most general parameterization of the new (heavy) degrees of freedom, as long as we perform low-energy experiments]

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Two key questions of particle physics today:

- Which is the energy scale of New Physics → High-energy experiments [*the high-energy frontier*]
- Which is the symmetry structure of the new degrees of freedom → High-precision low-energy exp. [*the high-intensity frontier*]

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Two key questions of particle physics today:

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Strong theoretical prejudice that some new degrees of freedom need to appear around or below 1 TeV to stabilise the electroweak symmetry breaking mechanism

Can we reconcile this expectation with the tight constraints of flavour physics ?

Flavour physics beyond the SM

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

3 identical replica of the basic fermion family

⇒ 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.

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

↓

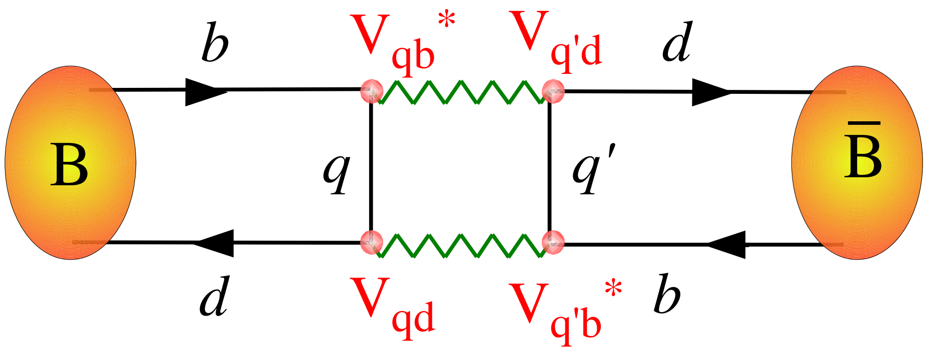
Identify processes where the SM is suppressed and calculable with good accuracy using the tree-level inputs

- $\Delta F=2$ Neutral meson mixing [K, B_d, B_s]
- Rare decays:
  - FCNC modes ($B \to X_s \gamma$,..)
  - Helicity-suppressed observables
  - Forbidden processes

↓

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

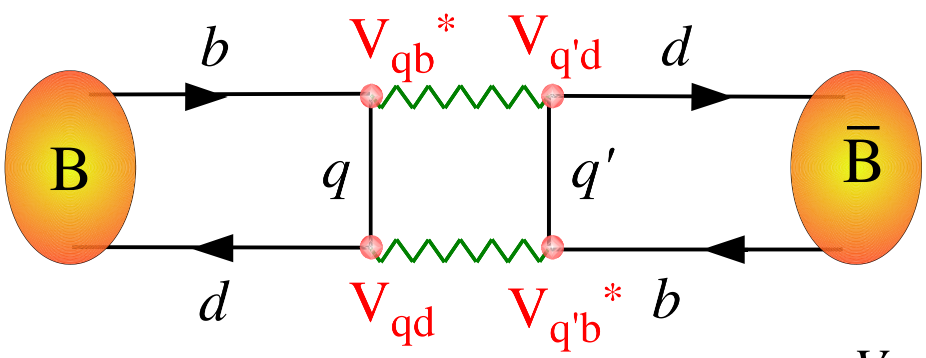
Such chain has already been closed, with good accuracy, for b→d and s→d ΔF=2 observables (K and B_d meson-antimeson mixing):



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 [tomorrow's lecture]

Such chain has already been closed, with good accuracy, for b→d and s→d $\Delta F=2$ observables (K and B_d meson-antimeson mixing):



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]

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

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

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

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

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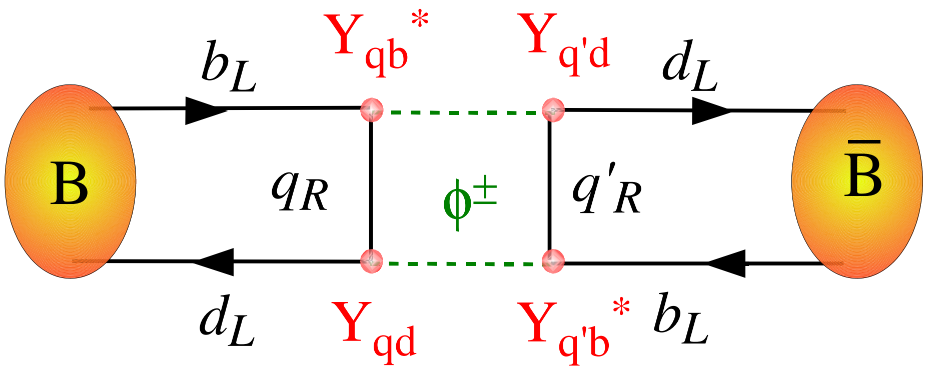

The origin of this behaviour can be better understood if we *switch-off* gauge interactions (gauge-less limit)

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

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

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

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

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

$$A^{\rm full}_{\Delta F=2} = A^{\rm gaugeless}_{\Delta F=2} \times [\, 1 + O(g^2)\,]$$

The flavour problem

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

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

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

The list of dim.6 ops inlcudes $(\bar{b}_L \gamma_\mu d_L)^2$ which contributes to B_d mixing at the tree-level

↓

We can extract some info about new physics

The flavour problem

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The list of dim.6 ops inlcudes $(\bar{b}_L \gamma_\mu d_L)^2$ which contributes to B_d mixing at the tree-level

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

B-physics: $V_{tb}^{*}V_{td} \sim \lambda^3$ K-physics: $V_{ts}^{*}V_{td} \sim \lambda^5$

The flavour problem

Such chain has already been closed, with good accuracy, for b→d and s→d ΔF=2 observables (*K* and B_d meson-antimeson mixing), showing no significant deviations from the SM (at the 5%-30% level, depending on the amplitude):

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

c_{NP} → ~ 1 —(tree/strong + generic flavor)→ $\Lambda \gtrsim 2\times10^4$ TeV [K]

c_{NP} → ~ $1/(16\pi^2)$ —(loop + generic flavor)→ $\Lambda \gtrsim 2\times10^3$ TeV [K]

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

▸ *The flavour problem*

Such chain has already been closed, with good accuracy, for b→d and s→d ΔF=2 observables (K and B_d meson-antimeson mixing), showing no significant deviations from the SM (at the 5%-30% level, depending on the amplitude):

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

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]

▸ *Open questions* (*a personal point of view...*)

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]

Can we build NP models with such alignment ?

Do we need to impose it also in $\Delta F=1$ processes ?

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 exp.ts in flavour physics...