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The Flavour Problem

Gino ISIDORI

Laboratori Nazionali di Frascati
INFN Edificio Alte Energie Gruppo Teorico
Via Enrico Fermi, 40, 00044 Frascati
Roma
Italy

The flavour problem

Gino Isidori
[*INFN - Frascati*]

- Introduction: the SM as an effective theory
- Flavour symmetry breaking in the quark sector
- Minimal Flavour Violation
- Flavour protection in warped space
- Flavour symmetry breaking in the lepton sector
- Conclusions

Introduction: the SM as an effective theory

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

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

- *Natural*

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

- 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*
  - $U(3)^5$ *global flavour symmetry* [3 *identical replica of the* 5 *basic basic fermion fields*]

Introduction: the SM as an effective theory

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

- *Natural*
- Experimentally tested with high accuracy
- Stable with respect to quantum corrections
- 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

Introduction: the SM as an effective theory

Particle physics is described with good accuracy by a simple and *economical* theory. However, this is likely to be only the low-energy limit of a more fundamentaly theory:

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

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

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 (LHC) [*the high-energy frontier*]
- Which is the symmetry structure of the new degrees of freedom → High-precision low-energy exp. [*the high-intensity frontier*]

Introduction: the SM as an effective theory

Particle physics is described with good accuracy by a simple and *economical* theory. However, this is likely to be only the low-energy limit of a more fundamentaly theory:

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Two key questions of particle physics today:

- Which is the energy scale of New Physics → High-energy experiments (LHC) [*the high-energy frontier*]

Strong theoretical prejudice that some new degrees of freedom need to appear around or below 1 TeV to stabilise the electroweak symmetry breaking mechanism [$\langle\phi\rangle \approx 246$ GeV]

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

Flavour symmetry breaking in the quark sector

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

3 identical replica of the basic fermion family

[$\psi_i = Q_L, u_R, d_R, L_L, e_R$] $\Rightarrow$ huge flavour-degeneracy [$U(3)^5$ group]

$$U(1)_L \times U(2)_B \times SU(3)_Q \times SU(3)_U \times SU(3)_D \times \ldots$$

Lepton number Barion number *Flavour mixing*

Flavour symmetry breaking in the quark sector

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3 identical replica of the basic fermion family
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Within the SM the flavour-degeneracy is broken only by the Yukawa interaction:

in the quark sector:

$$\bar{Q}_L{}^i\, Y_D{}^{ik}\, d_R{}^k\, \phi \;\rightarrow\; \bar{Q}_L{}^i\, M_D{}^{ik}\, d_R{}^k$$

$$\bar{Q}_L{}^i\, Y_U{}^{ik}\, u_R{}^k\, \phi_c \;\rightarrow\; \bar{Q}_L{}^i\, M_U{}^{ik}\, u_R{}^k$$

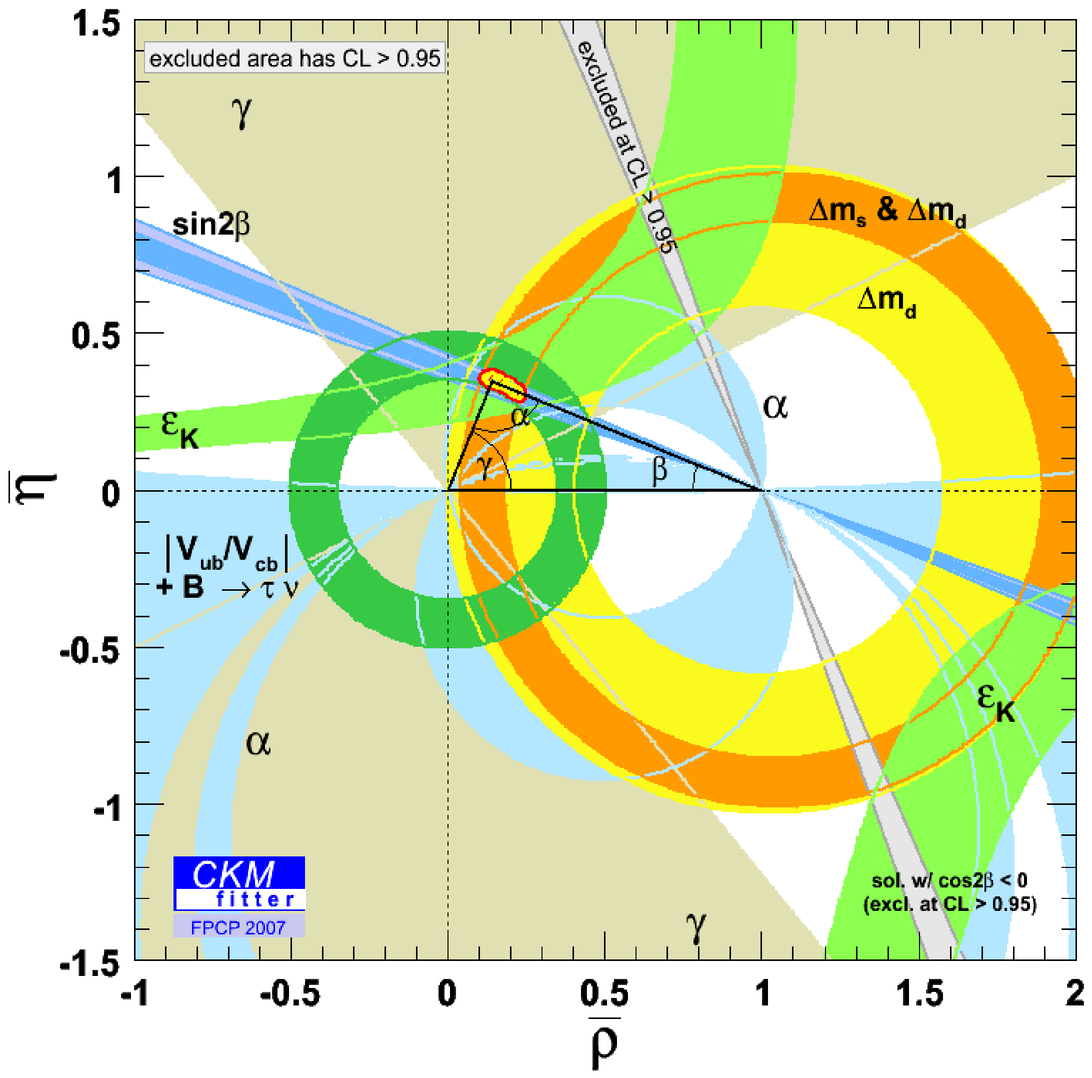
the residual flavour sym. let us to rotate the phases of the fields such that one of the two mass matrix is diagonal, e.g.:

$$M_D = \mathrm{diag}(m_d, m_s, m_b)$$

$$M_U = V \times \mathrm{diag}(m_u, m_c, m_t)$$

The CKM matrix

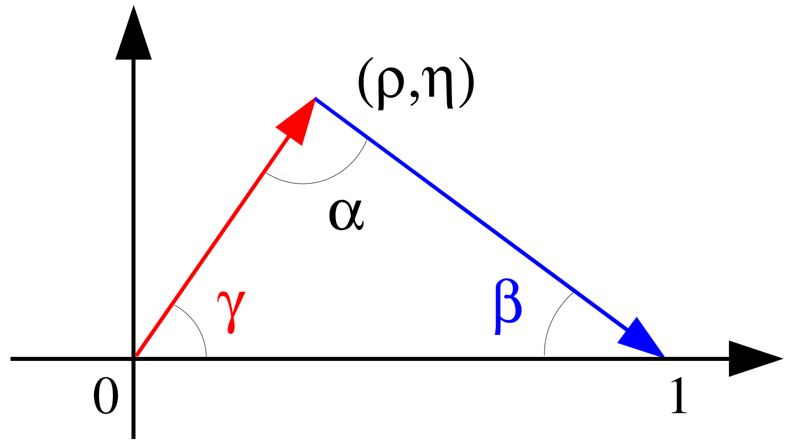
The consistency of this mechanism in describing all flavour-mixing phenomena has been sucesfully verified by B- and K-meson factories:



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

Triangular relations, such as

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

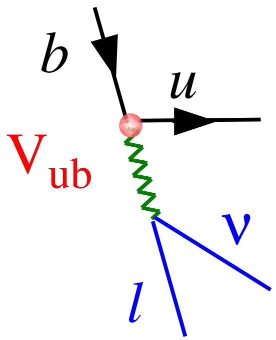


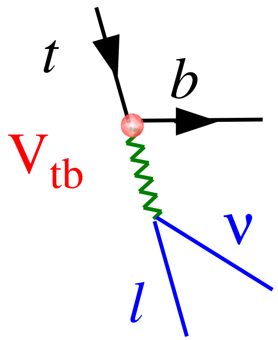
⇒ Lectures by Silvestrini

What is particularly remarkable is the consistency between tree-level and loop-induced observables:

E.g.:

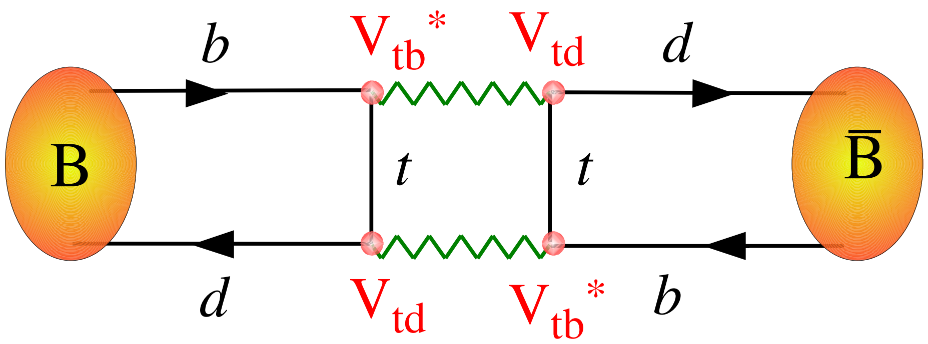
Tree-level
semilptonic decays





vs.

$\Delta F = 2$ neutral-meson mixing



$$\Rightarrow \quad \frac{(y_t V_{tb}^* V_{td})^2}{16\,\pi^2 M_W^2}$$

Highly suppressed amplitude potentially
much more sensitive to New Physics

⇒ Lectures by Silvestrini

An efficient way to quantify the success of the SM in the flavour sector is to derive bounds on the effective scale of new physics:

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

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

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

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

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

An efficient way to quantify the success of the SM in the flavour sector is to derive bounds on the effective scale of new physics:

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

$$c_{NP} \to \sim 1 \xrightarrow{\text{tree/strong + generic flavor}} \Lambda \gtrsim 2\times10^4\ \text{TeV}\ [K]$$

$$c_{NP} \to \sim 1/(16\,\pi^2) \xrightarrow{\text{loop + generic flavor}} \Lambda \gtrsim 2\times10^3\ \text{TeV}\ [K]$$

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

The problem is not only in the $\Delta F=2$ sector...

	$b \to s$ $(\sim\lambda^2)$	$b \to d$ $(\sim\lambda^3)$	$s \to d$ $(\sim\lambda^5)$
$\Delta F=2$ box	$(b_L \Gamma s_L)^2$	$(b_L \Gamma d_L)^2$	$(s_L \Gamma d_L)^2$
$\Delta F=1$ 4-quark box	$\vdots$		
gluon penguin			
γ penguin			
Z^0 penguin			
H^0 penguin			

The FCNC matrix:

each box correspond to an indep. combination of dim.-6 $SU(3)\times SU(2)\times U(1)$-invariant operators

The problem is not only in the ΔF=2 sector...

	$b \to s$ $(\sim\lambda^2)$	$b \to d$ $(\sim\lambda^3)$	$s \to d$ $(\sim\lambda^5)$
ΔF=2 box		$\Lambda \gtrsim 2\times10^3$ TeV from $A_{CP}(B_d \to \psi K)$	$\Lambda \gtrsim 2\times10^4$ TeV from ε_K
ΔF=1 4-quark box			
gluon penguin	$\Lambda \gtrsim 80$ TeV from $B(B \to X_s\gamma)$		$\Lambda \gtrsim 10^3$ TeV from $\varepsilon'/\varepsilon_K$
γ penguin	$\Lambda \gtrsim 150$ TeV from $B(B \to X_s\gamma)$		
Z^0 penguin	$\Lambda \gtrsim 20$ TeV from $B(B \to X_s l^+ l^-)$		
H^0 penguin			

(at leat some of) the new eff. couplings must be quite small if $\Lambda \sim$ TeV

An efficient way to quantify the success of the SM in the flavour sector is to derive bounds on the effective scale of new physics:

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

c_{NP}

- ~ 1 $\xrightarrow{\text{tree/strong + generic flavor}}$ $\Lambda \gtrsim 2\times 10^4$ TeV [K]
- $\sim 1/(16\,\pi^2)$ $\xrightarrow{\text{loop + generic flavor}}$ $\Lambda \gtrsim 2\times 10^3$ TeV [K]
- $\sim (y_t V_{ti}^{*} V_{tj})^2$ $\xrightarrow{\text{tree/strong + “alignment”}}$ $\Lambda \gtrsim 5$ TeV [K & B]
- $\sim (y_t V_{ti}^{*} V_{tj})^2/(16\,\pi^2)$ $\xrightarrow{\text{loop + “alignment”}}$ $\Lambda \gtrsim 0.5$ TeV [K & B]

We must find a mechanism to “align” (in flavour space) the new-physics contribution to the SM one

Minimal Flavour violation

- Flavour symmetry:

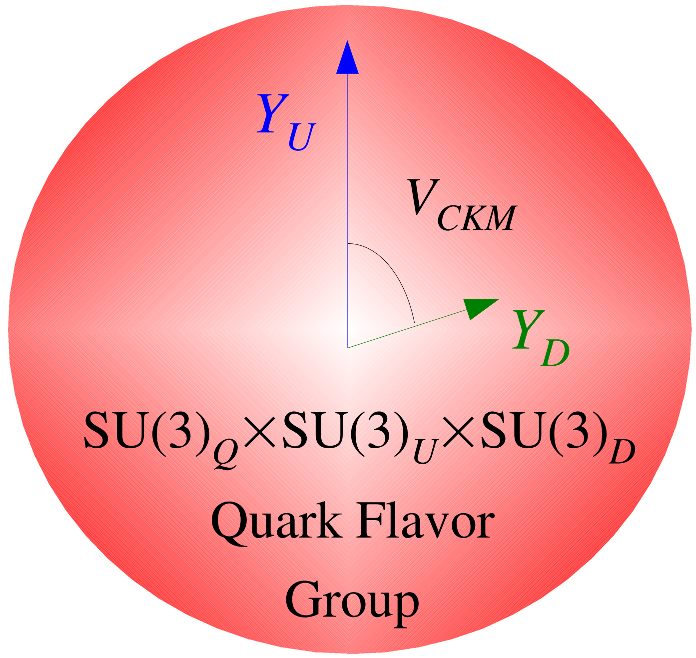
  $U(3)^5 = SU(3)_Q \times SU(3)_U \times SU(3)_D \times \ldots$

  [global symmetry of the SM gauge sector]

- Symmetry-breaking terms:

  $Y_D \sim \bar{3}_Q \times 3_D \qquad Y_U \sim \bar{3}_Q \times 3_U$

  [quark Yukawa couplings]



$$\mathscr{L}_{\rm SM} = \mathscr{L}_{\rm gauge} + \mathscr{L}_{\rm Higgs}$$

$$\mathscr{L}_{\rm Higgs} \longrightarrow \bar{Q}_L^{\,i}\, Y_U^{ij}\, U_R^{\,j}\, \phi + \bar{Q}_L^{\,i}\, Y_D^{ij}\, D_R^{\,j}\, \phi_c$$

This specific symmetry + symmetry-breaking pattern is responsible for the GIM suppression of FCNCs, the suppression of CPV,...
all the successful SM predictions in the quark flavour sector

<u>*Minimal Flavour violation*</u>

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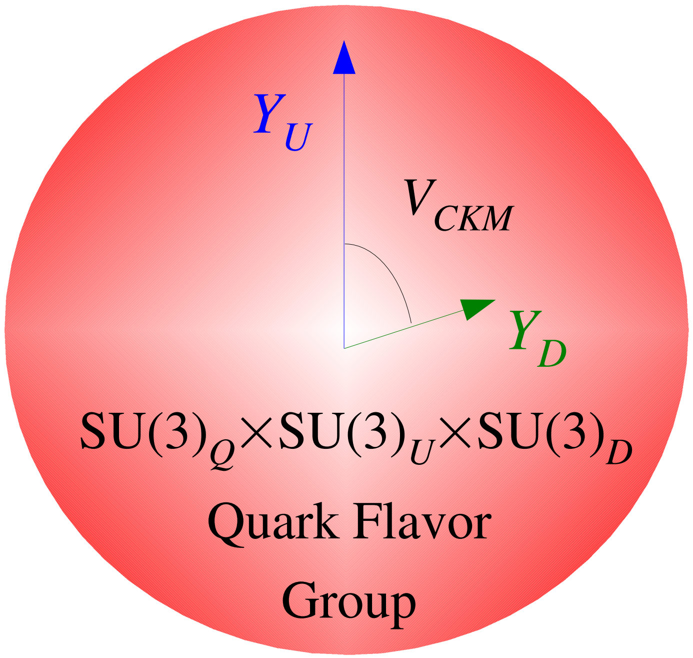
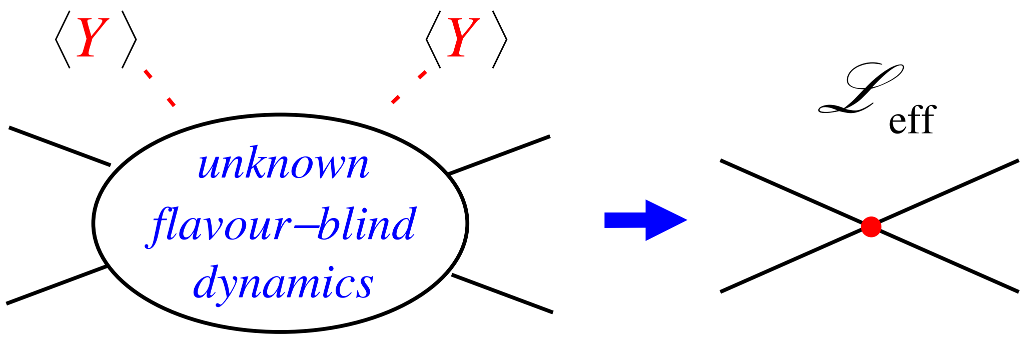


A natural mechanism to reproduce the SM successes in flavour physics -without fine tuning- is the <u>MFV hypothesis</u>:
Yukawa couplings = unique sources of flavour symmetry breaking also beyond SM

General principle (RGE invariant) which can be applied to any TeV-scale new-physics model



Minimal Flavour violation

A low-energy EFT satisfies the criterion of MFV if all higher-dimensional operators, constructed from SM and Y fields, are (formally) invariant under the flavour group [$SU(3)_Q \times SU(3)_U \times SU(3)_D$]

We can always choose a quark basis where:

$Y_D = \mathrm{diag}(y_d, y_s, y_b)$ $Y_U = V^+ \times \mathrm{diag}(y_u, y_c, y_t)$ $y_q = m_q / \langle \phi \rangle$

Typical FCNC dim.-6 operator: $\bar{Q}_L^{\,i}\, (Y_U Y_U^{+})_{ij}\, Q_L^{\,j} \times \bar{L}_L L_L$

$$(3,\bar{3},1) \qquad (\bar{3},3,1)$$

$$\Downarrow$$

$$(1,1,1)$$

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Typical FCNC dim.-6 operator: $\bar{Q}_L{}^i \, (Y_U Y_U{}^+)_{ij} \, Q_L{}^j \times \bar{L}_L L_L$

$$(Y_U Y_U{}^+)_{ij} \approx y_t^2 V_{3i} V_{3j}^*$$

$$\downarrow$$

$$V^+ \times \mathrm{diag}(y_u^2, y_c^2, y_t^2) \times V$$

$$\approx V^+ \times \mathrm{diag}(0, 0, y_t^2) \times V$$

same CKM - Yukawa structure of the SM short-distance contribution !

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Typical FCNC dim.-6 operator: $\bar{Q}_L^{\,i} \, (Y_U Y_U^{+})_{ij} \, Q_L^{\,j} \times \bar{L}_L \, L_L$

In principle we can consider higher powers of the Y.
However, because of their hierarchical nature this does not change the picture:

$$[\,(Y_U\, Y_U^{+})^n\,]_{ij} \approx (Y_U\, Y_U^{+})_{ij} \approx y_t^2\, V_{3i} V_{3j}^{*}$$

Basic MFV:

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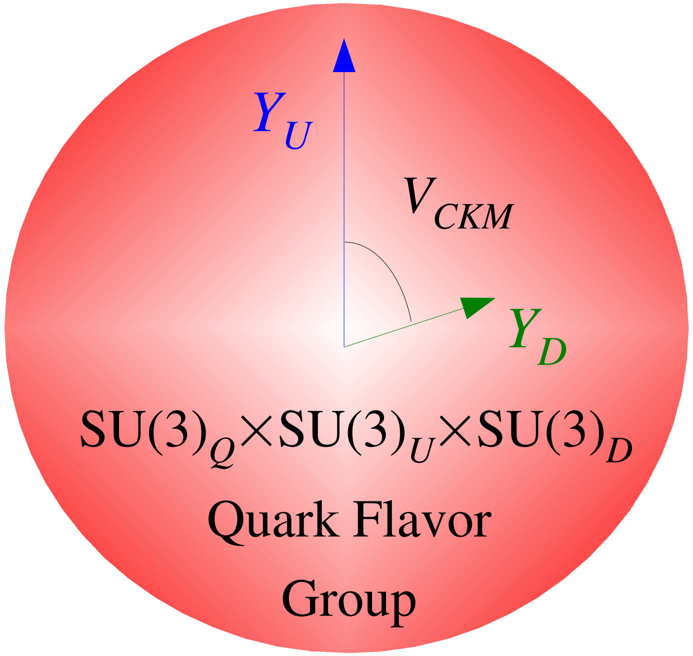

Main virtues:

- Bounds on NP scales range from few×TeV (for strongly interacting theories) to few×100 GeV (for weakly interacting theories)

- Very predictive framework:
  - All FCNC amplitudes have the same CKM structure as in the SM [e.g.: $A(b \to s\gamma) \propto V_{bt}V_{ts}$, $A(s \to d\gamma) \propto V_{st}V_{td}$, ...] and only the flavour–independent magnitude can be modified
  - *Phase measurements* [e.g.: $A_{CP}(B \to \psi K_S)$, $A_{CP}(B \to \phi K_S)$, $\Delta M_{B_d}/\Delta M_{B_s}$] are completely unaffected by new physics

Basic MFV:

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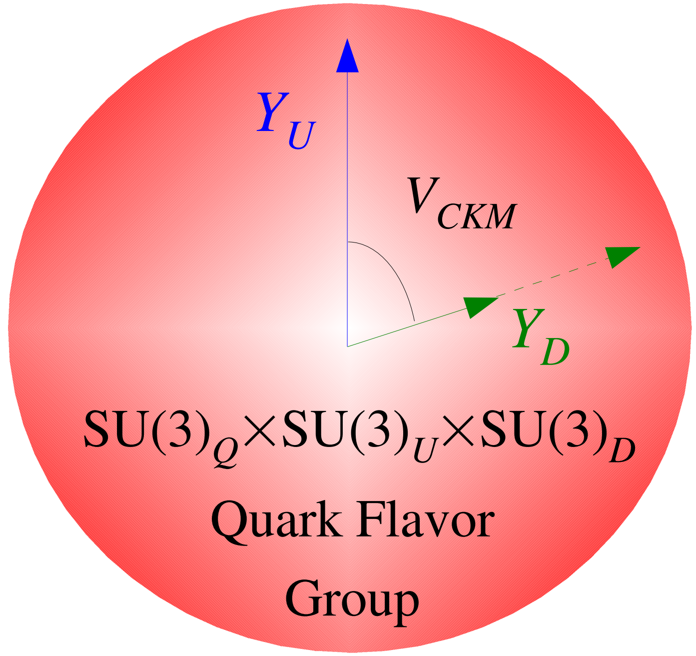

Interesting extension/variation in case of more than one Higgs doublet:

- With two Higgs doublets we can change the relative normalization of Y_U & Y_D (controlled by $\tan\beta = \langle \phi_U \rangle / \langle \phi_D \rangle$)

$$\mathscr{L}_{\text{q-Yukawa}} = \bar{Q}_L Y_D D_R \phi_D + \bar{Q}_L Y_U U_R \phi_U + \text{h.c.}$$

$$y_u = m_u / \langle \phi_U \rangle$$

$$y_d = m_d / \langle \phi_D \rangle = \tan\beta \, m_d / \langle \phi_U \rangle$$

$$\Downarrow$$

Interesting phenomenological signatures in *helicity-suppressed* observables

A few important comments:

I) MFV is not a theory of flavour

It does not allow us to compute the Yukawa couplings in terms of some more fundamental parameters

A few important comments:

I) MFV is not a theory of flavour

II) There is still room for non-MFV effects

According to recent CDF & D0 results on the time-dependent CP asymmetry in $B_s \to \psi\phi$, there is even a ~2.5σ deviation from the SM (and MFV) in the phase of B_s mixing.

If confirmed, this would rule out both SM and MFV hypothesis.
But we have to wait...

A few important comments:

I) MFV is not a theory of flavour

II) There is still room for non-MFV effects

III) Even if we forget about B_s mixing, MFV is far from being "verified"

To prove MFV from data we would need to

- observe some deviation form the SM in FCNCs
- observe the CKM pattern predicted by MFV [within same type of FCNCs]

$$A_{FCNC}\,[b \to d(s)] \sim V_{td(s)} \left[c^{(0)}_{SM} \frac{1}{M_W^{\,2}} + c^{(0)}_{NP} \frac{1}{\Lambda^2} \right]$$

$\Delta F = 2$ processes are in principle good candidates to prove MFV, but so far we are limited by theoretical (Lattice) uncertainties

Some $\Delta F=1$ rare decays could provide more useful infos to proof (or disproof) the MFV hypothesis from data (very interesting candidates: $B_{d,s} \to l^+ l^-$)

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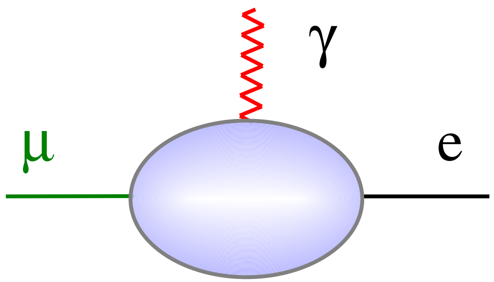
IV) Even within the "pessimisic" MFV hypothesis, we can still expect sizable deviations from the SM in various B physics observables...

Typical examples:

$B_{d,s} \to l^+ l^-$ up to order of magnitude enhancements if $\tan\beta$ is large

... and, hopefully, spectacular NP effects in the charged lepton sector:



$B(\mu \to e\gamma)$ could reach values in the $10^{-12} - 10^{-13}$ range, within the reach of MEG

A few important comments:

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II) There is still room for non-MFV effects

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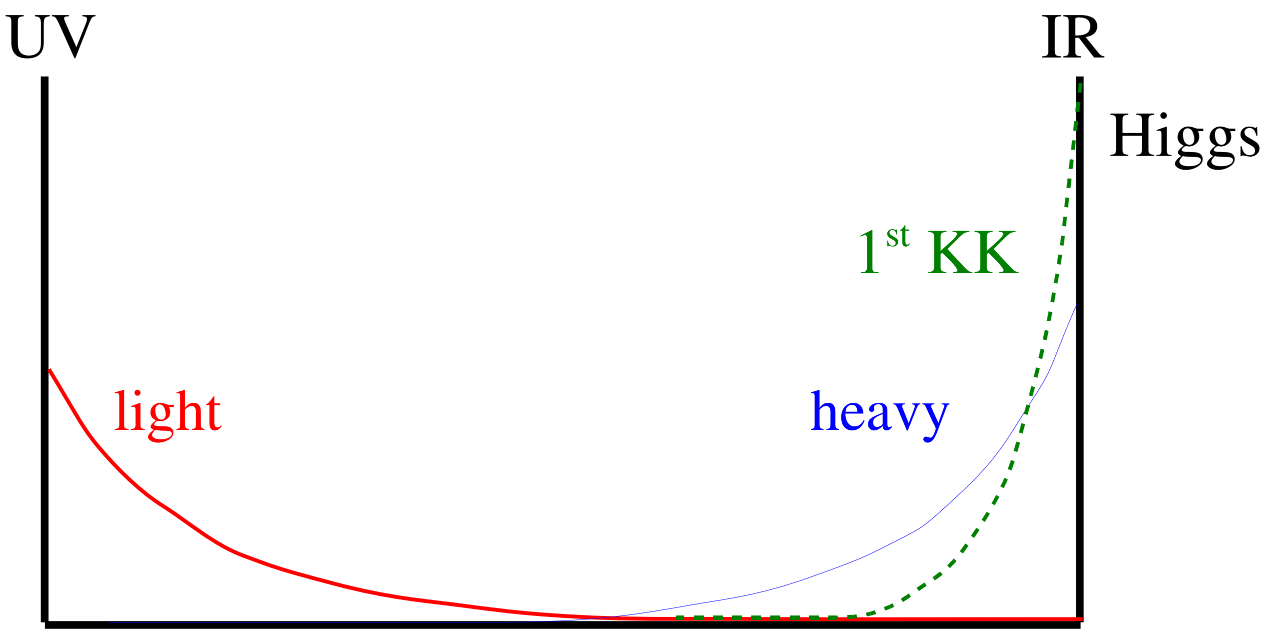
Three main direction of research in quark-flavour physics:

- Theoretical justification of MFV (or alternative “protective criteria”) from explicit new-physics models (SUSY, SUSY-GUTS, Extra-dimensions...)
- Identifications of signals/observables which could falsify the MFV scenario from data
- Connections with the lepton sector

Flavour protection from warped space

An interesting approach to explain the hierarchy of the Yukawa couplings, in the context of models with extra space-time dimensions, is to attribute this hierarchy to the different overlap of fermion wave-functions (spread along a 5D bulk) with the Higgs wave function (localised on the IR brane)



In 5D models with warped geometry, this construction provides a potentially interesting alternative to MFV to explain the suppression of FCNCs beyond the SM

Flavour protection from warped space

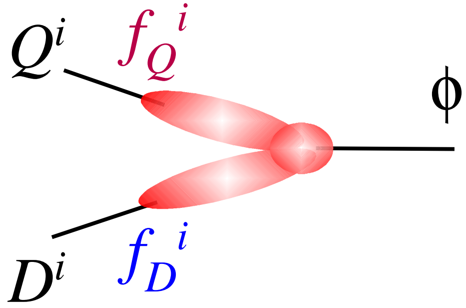
The model can be formulated in terms of the following 4D effective theory:

- SM fermions couples to the new-physics sector via some hierarchical wave funcions f_Q, f_D, f_U (in the quark sector), such that

$$Y_D^{ij} = f_Q^{\,i}\,(\mathbf{Y}_D^{5D})\,f_D^{\,j} \approx f_Q^{\,i} f_D^{\,j} \qquad Y_U^{ij} = f_Q^{\,i}\,(\mathbf{Y}_U^{5D})\,f_U^{\,j} \approx f_Q^{\,i} f_U^{\,j}$$

anarchic

hierarchical



$$f_Q^{\,3} \gg f_Q^{\,2} \gg f_Q^{\,1}$$
$$f_D^{\,3} \gg f_D^{\,2} \gg f_D^{\,1}$$
$$f_U^{\,3} \gg f_U^{\,2} \gg f_U^{\,1}$$

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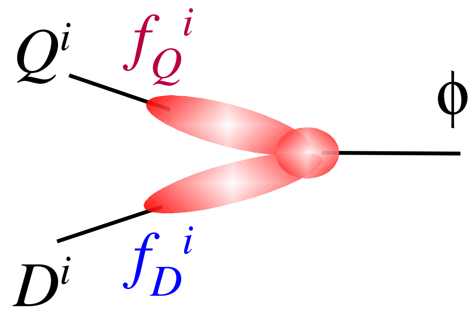
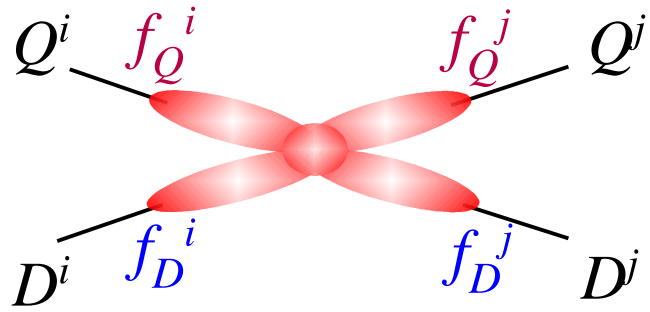


- There is no underlying flavour symmetry (complete anarchy) in the new strongly interacting sector:
  dim.-6 FCNC operators suppressed only by the light-fermion wave functions
  (= *mixing with the new heavy states*)



Flavour protection from warped space

This construction works remarkably well in various cases:

- The condition on the (4D) Yukawa couplings implies

$$f_Q^1 / f_Q^3 \sim |V_{31}| \quad \& \quad f_Q^2 / f_Q^3 \sim |V_{32}| \quad \xrightarrow{\text{predict}} \quad \boxed{f_Q^1 / f_Q^2 \sim |V_{21}| \sim |V_{31}/V_{32}|}$$

- All the left-handed FCNC operators (the leading ones in the SM) have the same suppression as in MFV:

$$f_Q^i f_Q^j \, \bar{Q}_L^i \, Q_L^j \quad \sim \quad V_{3i} V_{3j} \, \bar{Q}_L^i \, Q_L^j$$

to be compared with

$$\bar{Q}_L^i \, (Y_U Y_U^+)_{ij} \, Q_L^j \; = \; y_t^2 \, V_{3i}^* V_{3j} \, \bar{Q}_L^i \, Q_L^j$$

Flavour protection from warped space

This construction works remarkably well in various cases:

- The condition on the (4D) Yukawa couplings implies

$$f_Q^{\,1} / f_Q^{\,3} \sim |V_{31}| \quad \& \quad f_Q^{\,2} / f_Q^{\,3} \sim |V_{32}| \quad \xrightarrow{\text{predict}} \quad \boxed{f_Q^{\,1} / f_Q^{\,2} \sim |V_{21}| \sim |V_{31}/V_{32}|}$$

- All the left-handed FCNC operators (the leading ones in the SM) have the same suppression as in MFV
- However, some problem arieses with helicity-suppressed operators, in 2 →1 transitions (kaon physics):

$$f_D^{\,i} f_Q^{\,j}\ \bar{D}_R^{\,i} Q_L^{\,j} = f_D^{\,i} f_Q^{\,i} f_Q^{\,j} / f_Q^{\,i}\ \bar{D}_R^{\,i} Q_L^{\,j} \quad \begin{cases} \sim y_b V_{ts}\,(b_R s_L) \\ \boxed{\sim y_s V_{us}\,(s_R d_L)} \end{cases}$$

big difference !

to be compared with

$$\bar{D}_R^{\,i} (Y_D Y_U Y_U^{\,+})_{ij}\ Q_L^{\,j} = y_{d_i}\, y_t^{\,2} V_{3i}^{\,*} V_{3j}\ \bar{Q}_R^{\,i} Q_L^{\,j} \quad \begin{cases} \sim y_b y_t^{\,2} V_{tb}^{\,*} V_{ts}\,(b_R s_L) \\ \boxed{\sim y_s y_t^{\,2} V_{ts}^{\,*} V_{td}\,(s_R d_L)} \end{cases}$$

Flavour protection from warped space

The constraints from ε and ε'/ε in the kaon system imply that this simple construction has to be improved with some sort of alignment, at least in the down sector.

This discussion has allowed to illustrate two rather general points:

- MFV is not the only allowed solution to the flavour problem
- The most natural place to look for deviations from MFV are helicity-suppressed observables and/or clean kaon-physics observables (because of their strong suppression in MFV)

The breaking of flavour symmetry in the lepton sector

Do we need a MFV hypothesis also in the lepton sector ?

A severe lepton-FCNC problem exists:

$$\mathscr{L}_{\rm eff} \supset \frac{c_{\mu e}}{\Lambda^2} \bar{e}_L \sigma^{\mu\nu} \mu_R \phi F_{\mu\nu} \quad \Rightarrow \quad \Lambda > 10^5 \text{ TeV} \times (c_{\mu e})^{1/2}$$

from $\mathrm{BR}(\mu \to e\gamma)^{\rm exp} < 1.2\times 10^{-11}$

However, in the lepton sector is not so easy to identify the irreducible sources of (lepton) flavor symmetry breaking.

⇓

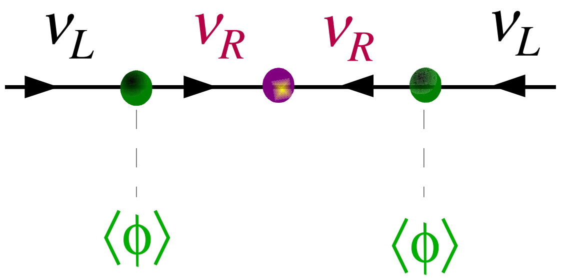
extra assumptions needed
in order to define an effective theory
approach similar to the quark sector

In the lepton sector we have the only clear indication of a non-vanishing effective operator beyond the SM: <u>the d=5 effective neutrino mass matrix</u>

$$\boxed{\frac{g_\nu}{\Lambda_{LN}} \; L_L{}^T L_L \;\; \phi^T \phi}$$

$$\downarrow$$

$$m_\nu \;\; \nu_L{}^T \nu_L$$



completely equivalent (but more general) with respect to the usual see-saw mechanism

$[M_{\nu_R} \sim \Lambda_{LN} \gg \langle\phi\rangle\,]$

$\Rightarrow$ <u>Lectures by Vissani</u>

In the lepton sector we have the only clear indication of a non-vanishing effective operator beyond the SM: <u>the d=5 effective neutrino mass matrix</u>

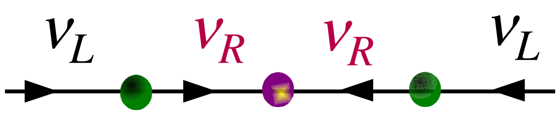
This operator s quite special since it violates *lepton number*

$$\frac{g_\nu^{ik}}{\Lambda_{LN}} (L_L^T)^i L_L^k \, \phi^T \phi$$

$$m_\nu^{ik} (\nu_L^T)^i \nu_L^k$$

Natural to assume that this symmetry of the pure SM Lagrangian is broken at very high scales:

if $\Lambda_{LN} \sim 10^{15}$ GeV some g_ν^{ik} can be O(1) $\Rightarrow$ *natural* effective theory [no fine-tuning for the smallness of m_ν]



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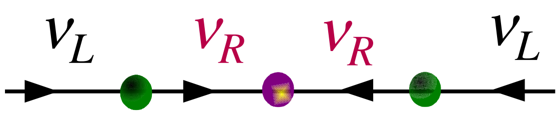

$$m_\nu = \frac{Y_\nu^T Y_\nu v^2}{M_R}$$

$$\frac{g_\nu^{ik}}{\Lambda_{LN}} (L_L^T)^i L_L^k \phi^T \phi$$

Two useful working assumptions for a predictive framework (similar to MFV) in the lepton sector:

1st assumption (very natural)

Decoupling of $U(1)_L$ and $SU(3)_{L_L}$ breaking

2nd assumption (more model dependent)

The neutrino mass matrix allow to determine completely the flavor-breaking structures (*e.g. trivial right-handed sector*)

This predictive M(L)FV scheme is a useful working hypothesis to investigate some general properties of FCNC in the lepton sector [link between neutrino masses (& mixing) and lepton-flavor violating rare decays]

▶ If the scale of $U(1)_L$ breaking is sufficiently high, we should observe soon $\mu \to e\gamma$: $M_R \gtrsim 10^{12}\,\mathrm{GeV} \times (\Lambda / 10\,\mathrm{TeV})^2$ ⟷ $B(\mu \to e\gamma) \gtrsim 10^{-13}$

$$B(\mu \to e\gamma) \approx 10^{-13} \left[\frac{10\ \mathrm{TeV}}{\Lambda}\right]^4 \left[\frac{M_R}{10^{12}\ \mathrm{GeV}}\right]^2$$

[general conclusion, essentially independent from the specific strucutre of the flavour symmetry breaking terms]

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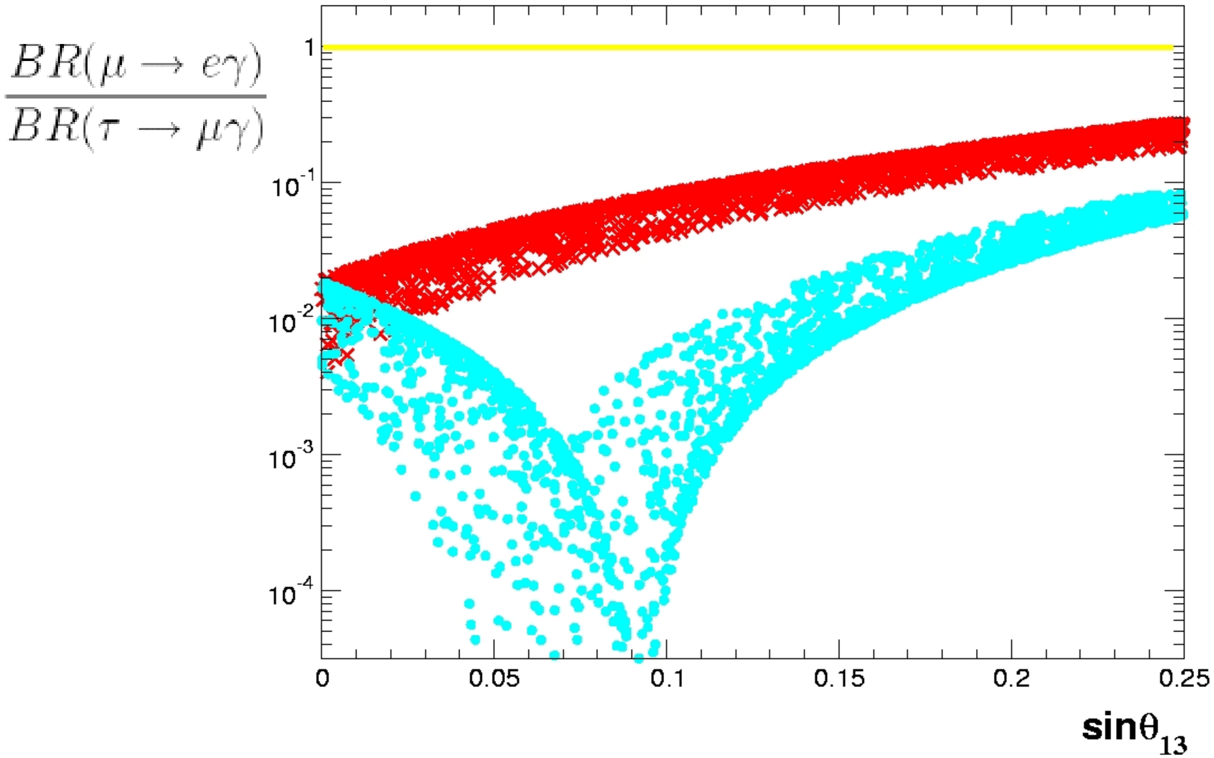
- Clear pattern for FCNC ratios [dictated by the flavour structure of m_ν]
  $B(\tau \to \mu\gamma) : B(\tau \to e\gamma) : B(\mu \to e\gamma) \sim [\,500 - 10\,] : 1 : 1$



[violations of these predictions would unambiguously signal the presence of additional lepton-flavour symmetry-breaking terms]

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- If the neutrino Yukawa couplings contain non-trivial CP-violating phases (as naturally expected) the observed matter-antimatter asymmetry of the universe can be generated via leptogenesis

$$\Delta L \neq 0 \xrightarrow[\textit{sfalerons}]{} \Delta B \neq 0$$

[general conclusion, almost independent from the specific strucutre of the flavour symmetry breaking terms]

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No need to invoke non-trivial right-handed flavour structures and/or new CPV phase beyond the Yukawas to explain the matter-antimatter asymmetry: the MFV scheme for both quarks & leptons is phenomenologically consistent

Conclusions

The fact we have not discovered yet new physics in flavour-physics observables, and that the minimalistic scenario of MFV is consistent with data, should not discourage further searches:

we learned that new physics has a rather non-trivial flavour structure (MFV like), but *the origin of this structure has still to be discovered* (several key issues are still open)

The MFV hypothesis has not been clearly established from data and is unlikely to be exact:

- not compatible (in its more constrained form) with GUTs $\Rightarrow$ at some level we should expect some *contamination from the lepton Yukawa couplings* in the quark sector
- it could well be only an approximate infrared property of the underlying theory $\Rightarrow$ some *deviations* could appear *in the most suppressed processes*

Conclusions

We learned that new physics has a rather non-trivial flavour structure (MFV like), but *the origin of this structure has still to be discovered* (several key issues are still open)

The MFV hypothesis has not been clearly established from data and is unlikely to be exact.

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Important to continue high-precision flavour physics in the LHC era

There is not a unique (or a unique class) of outstanding observable(s), we need to improve in several directions, especially on the very suppressed theoretically-clean observables. My favourite shopping list:

- LFV [$\mu \to e\gamma$, $\mu N \to eN$, $\tau \to \mu\gamma$, ...]
- Rare K decays [$K \to \pi\nu\nu$]
- Helicity-suppressed B decays [$B_{d,s} \to \mu\mu$, $B_u \to l\nu$]