LHC Physics: Higgs and beyond

(*a personal selection of topics in the wast domain of LHC physics*)

Gino Isidori
[*University of Zürich*]

- Lecture I: *What we learned from run-I*
  [The SM as an effective theory & the "ghost" of the anthropic principle]

- Lecture II: *What we can hope to learn from run-II (at high-pT)*
  [Future prospects in Higgs physics and direct NP searches]

- Lecture III: *Indirect searches for NP*
  [Flavor physics beyond the SM]

Lecture III: *Indirect searches for NP*
[Flavor physics beyond the SM]

- Introduction
- The flavor sector of the SM
  - *Present status of CKM fits*
  - *The flavor structure of the SM viewed as EFT*
- The flavor problem
  - *The MFV hypothesis*
  - *Variations on the "MFV theme"*
- Speculations on the breaking of LFU in B decays
  - *Recent anomalies in B physics*
  - *Speculations on the breaking of LFU*
- Conclusions

Introduction

The SM is likely to be an *effective theory*, i.e. the limit
(*in the experimentally accessible range of energies and effective couplings*)
of a more fundamental theory, with new degrees of freedom

↓

We need to search for New Physics
[*with a broad spectrum perspective given the lack of NP signal so far...*]

↓

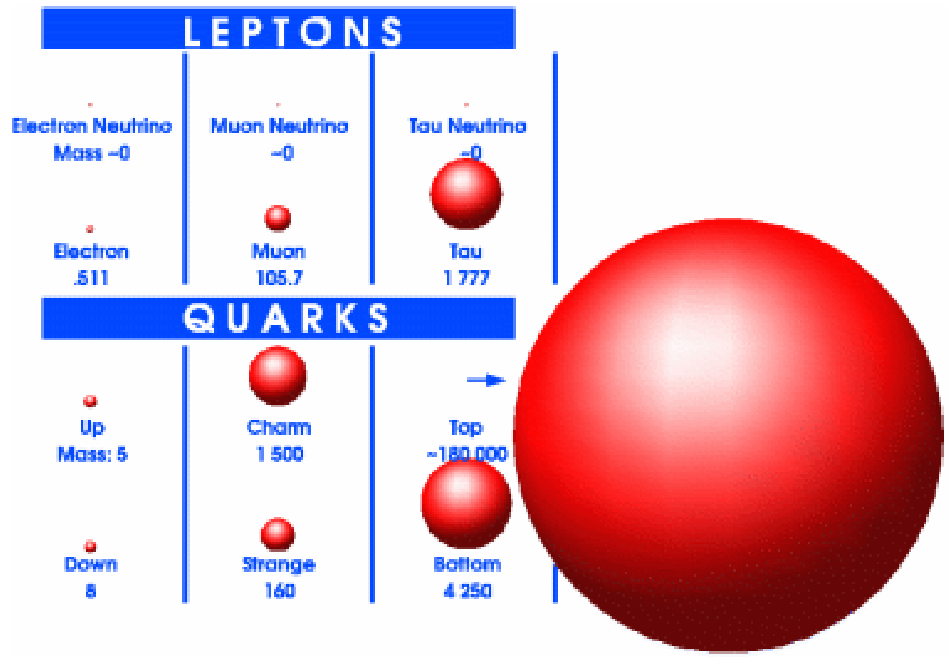
Twofold role of Flavor Physics
[= *study of flavor-changing and CPV phenomena, of both quarks and leptons*]

- Identify symmetries and symmetry-breaking patterns beyond those present in the SM
- Indirect probe of physics at energy scales not directly accessible at accelerators

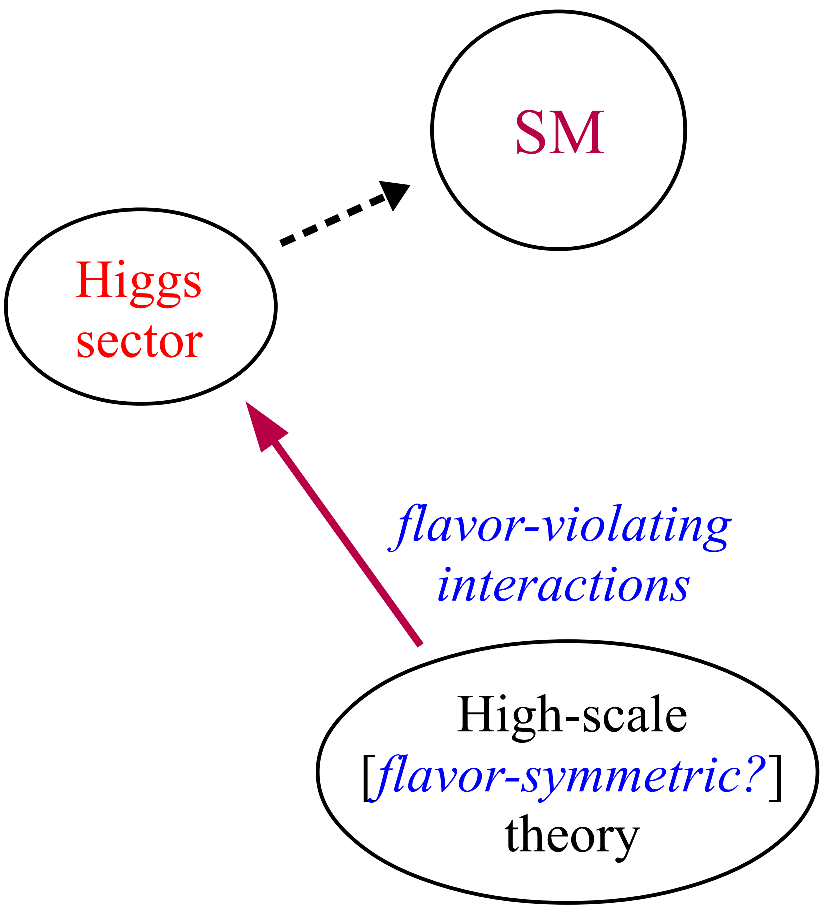
Introduction

Twofold role of Flavor Physics

- Identify symmetries and symmetry-breaking patterns beyond those present in the SM



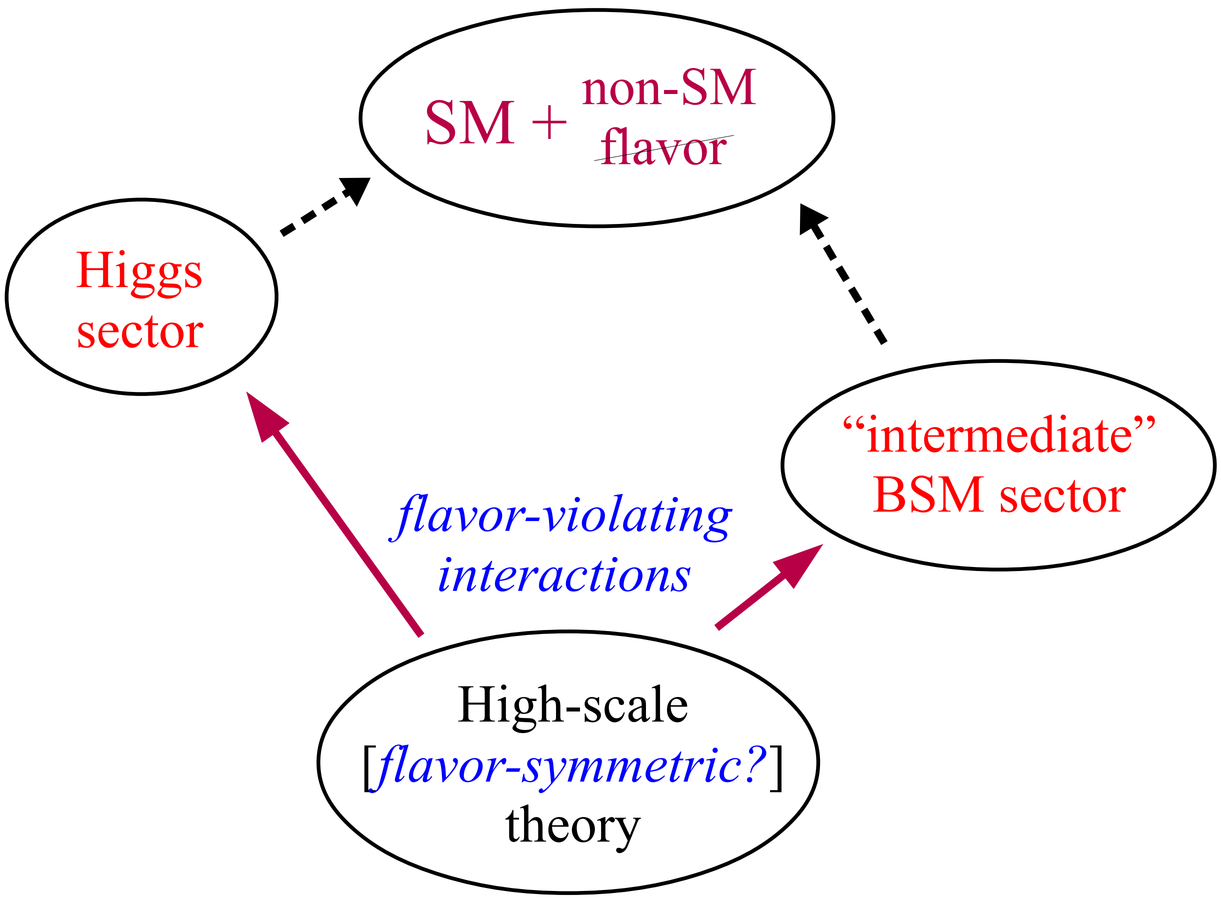
The observed pattern of fermion masses angles does not seem to be accidental !



Introduction

Twofold role of Flavor Physics

- Identify symmetries and symmetry-breaking patterns beyond those present in the SM
- Probe physics at energy scales not directly accessible at accelerators



Introduction

With flavor physics we address the second set of key questions of particle physics:

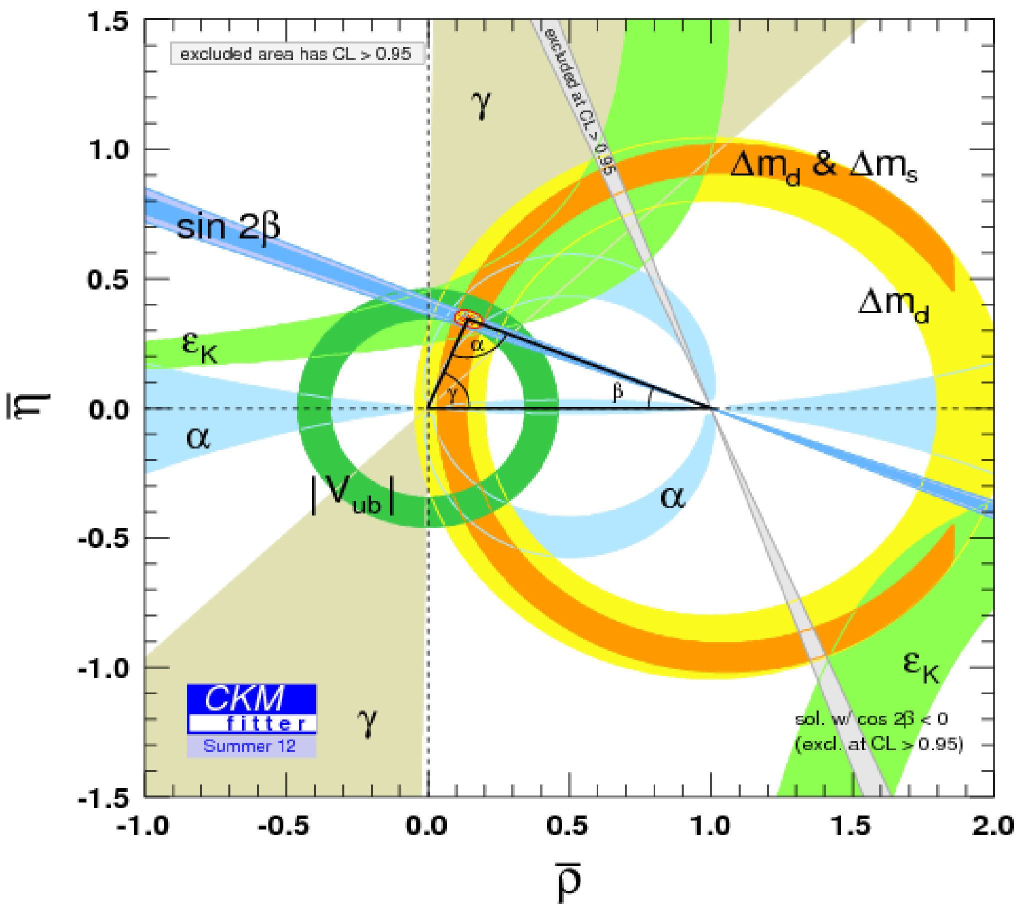
- *What determines the Higgs mass term (or the Fermi scale)?*
- *Is there anything else beyond the SM Higgs at the TeV scale?*

High-energy searches
[*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 measurements
[*the high-intensity frontier*]

The flavor sector of the SM



The flavor structure of the SM

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

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

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

The flavor structure of the SM

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

3 identical replica of the basic fermion family
$[\psi = Q_L, u_R, d_R, L_L, e_R] \Rightarrow$ huge flavor-degeneracy: $U(3)^5$ 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
Barion number
Hypercharge
Flavor mixing

The flavor structure of the SM

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

3 identical replica of the basic fermion family
$[\psi = Q_L, u_R, d_R, L_L, e_R] \Rightarrow$ huge flavor-degeneracy: $U(3)^5$ global symmetry

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

in the quark sector:

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

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

The flavor structure of the SM

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

3 identical replica of the basic fermion family
$[\psi = Q_L, u_R, d_R, L_L, e_R] \Rightarrow$ huge flavor-degeneracy: $U(3)^5$ global symmetry

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

in the quark sector:

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

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

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

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

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

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

The flavor structure of the SM

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

3 identical replica of the basic fermion family
$[\psi = Q_L, u_R, d_R, L_L, e_R] \Rightarrow$ huge flavor-degeneracy: $U(3)^5$ global symmetry

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

in the quark sector:

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

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

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

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

V= <u>unitary matrix</u>

The flavor structure of the SM

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

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

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 !

The flavor structure of the SM

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

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

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

The SM quark flavor sector is described by 10 observable parameters:

- 6 quark masses
- 3+1 CKM parameters
  - 3 real parameters (rotational angles)
  - +
  - 1 complex phase (source of CP violation)

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

The flavor structure of the SM

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

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

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

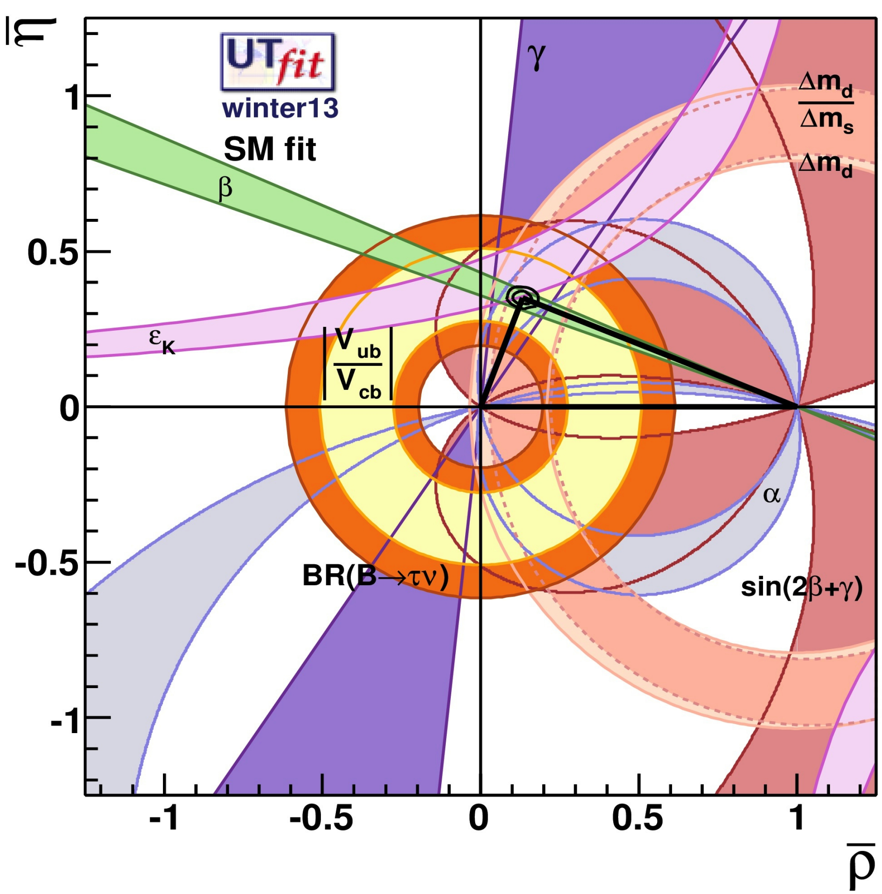
The SM quark flavor sector is described by 10 observable parameters:

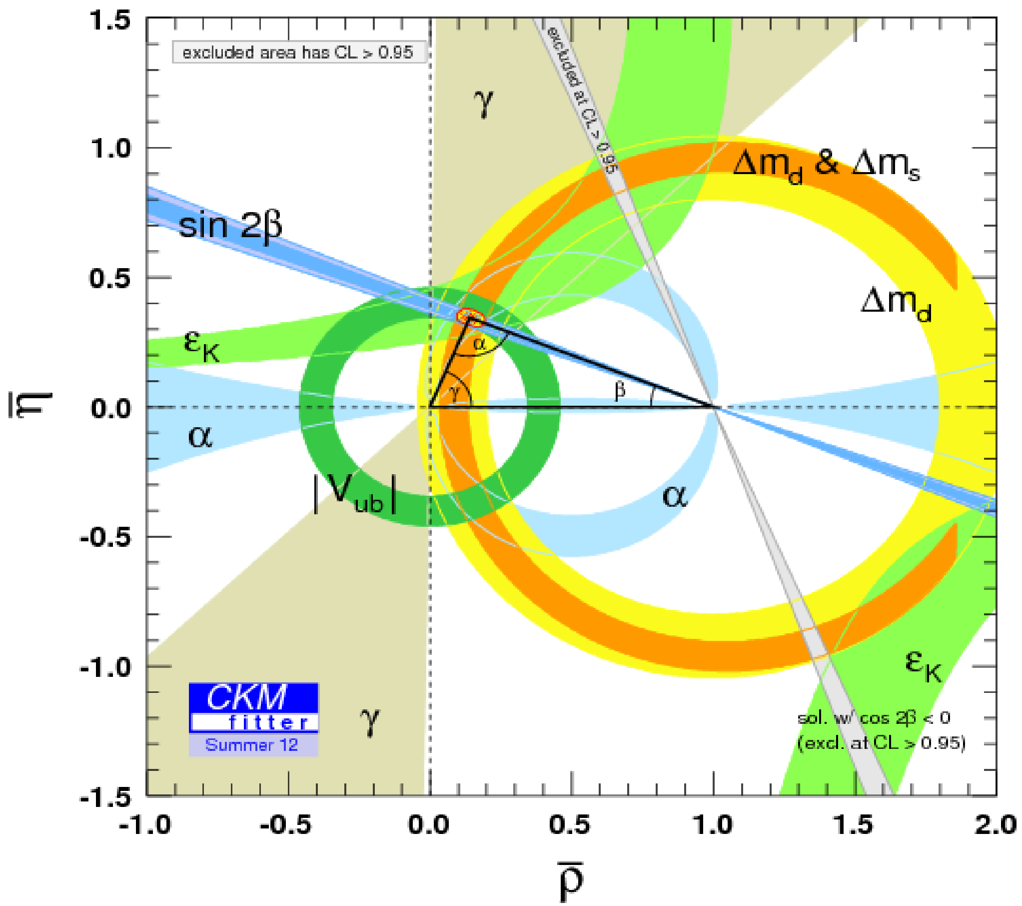
- 6 quark masses
- 3+1 CKM parameters

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

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.*





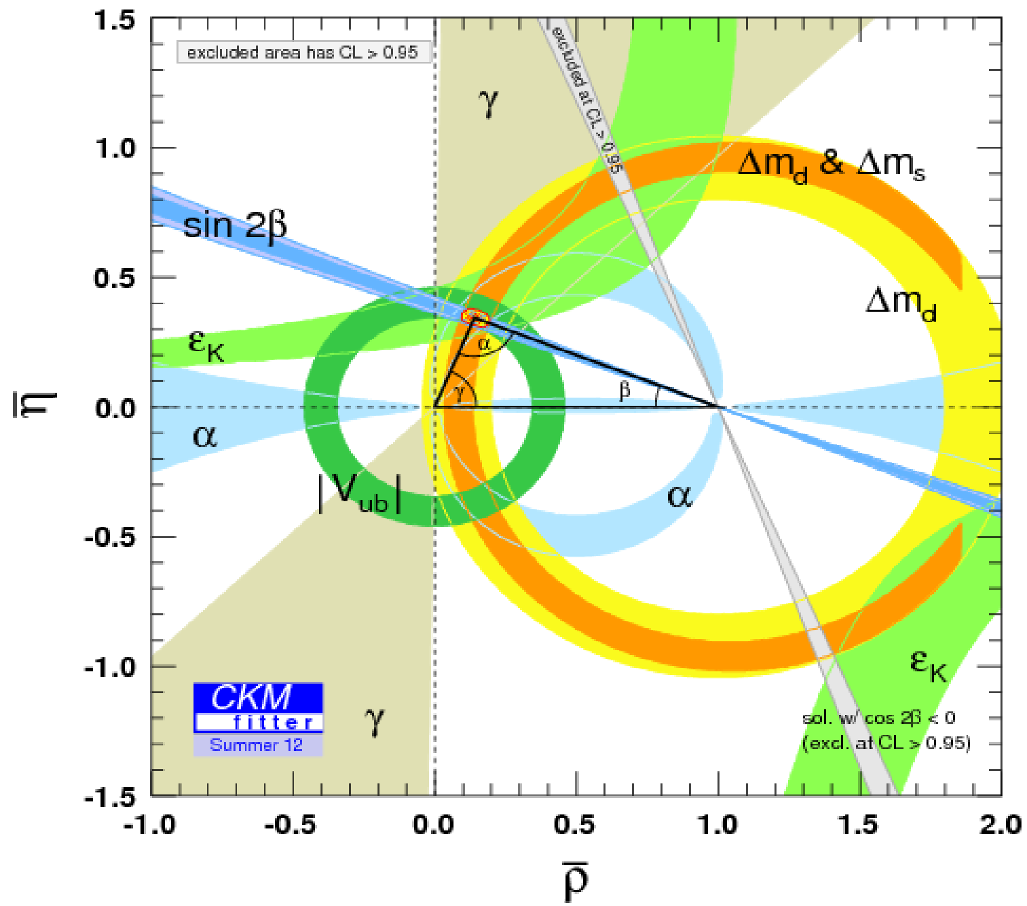
Present status of CKM fits

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.*

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

↓

Significant constraints on the flavor structure of possible new degrees of freedom



The flavor structure of the SM viewed as EFT

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

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

Flavor-degeneracy broken only by the Yukawa interaction

The redundancy of CKM fits allow us to investigate 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→u decays ($|V_{ub}|$)
- Selected non-leptonic B decays sensitive to γ

↓

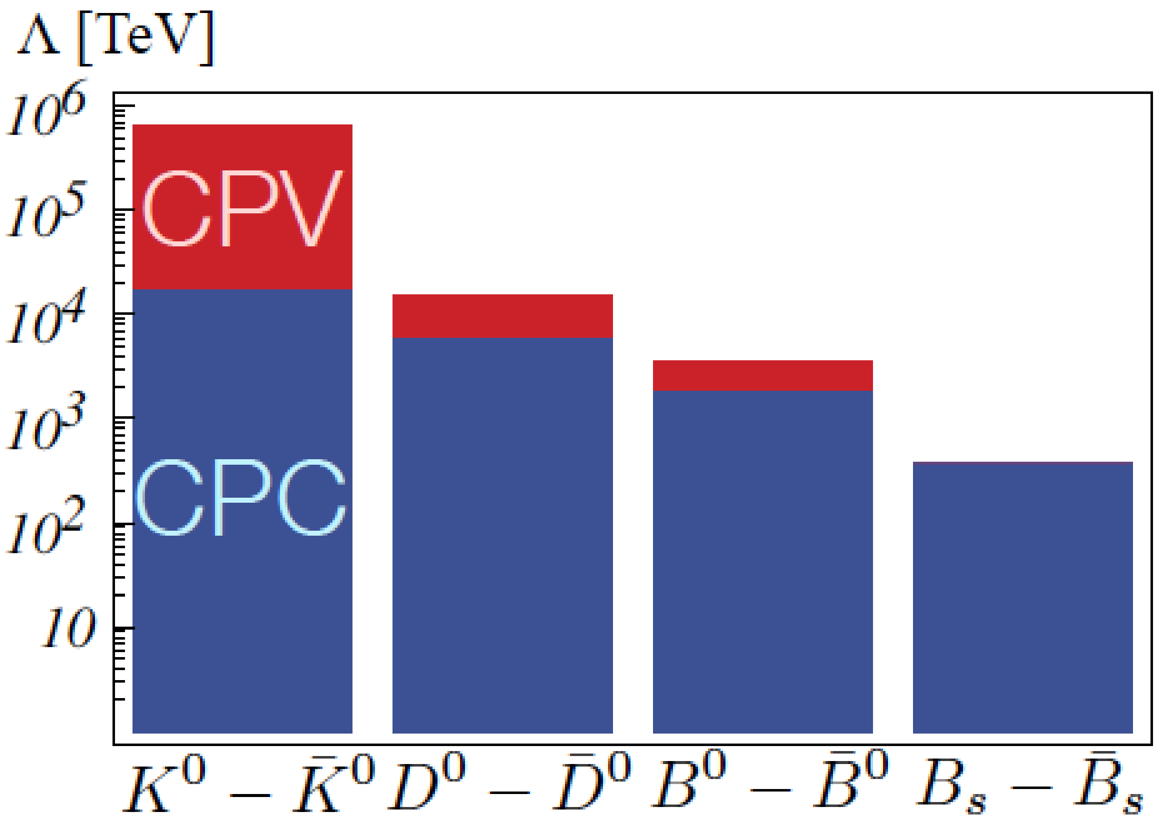
Identify processes where the SM is calculable with good accuracy using the tree-level inputs, or sufficiently suppressed for null tests.

- $\Delta F=2$ 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

↓

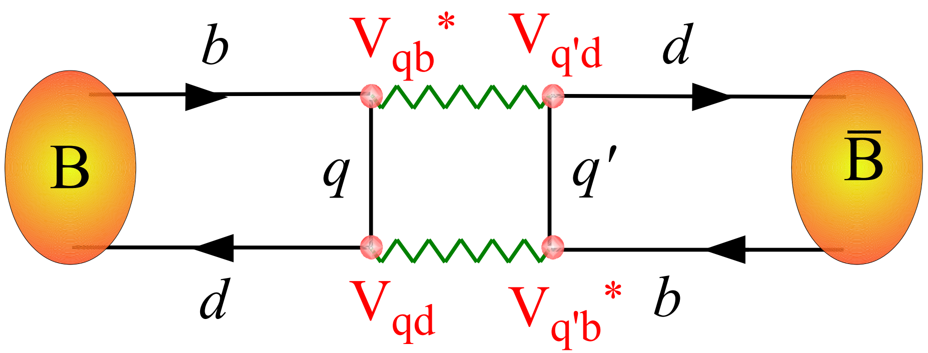
Measure with good accuracy these rare processes and determine the allowed room for new physics.

The flavor problem



The ΔF=2 bounds

The "chain" mentioned before has already been closed, with quite good accuracy, in the case of <u>down-type</u> ΔF=2 observables (K^0 and $B_{d,s}$ mixing):

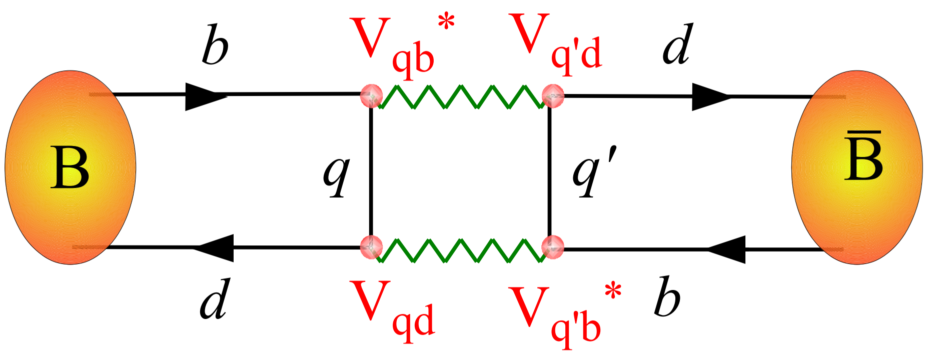


Highly suppressed amplitude potentially very sensitive to New Physics

- 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

The ΔF=2 bounds

The "chain" mentioned before has already been closed, with quite good accuracy, in the case of down-type ΔF=2 observables (K^0 and $B_{d,s}$ mixing):



power-like GIM mechanism:

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

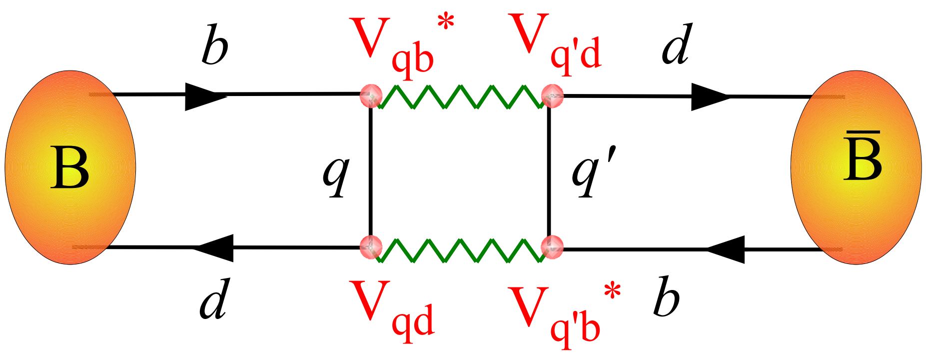
[CKM unitarity]

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

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

The $\Delta F=2$ bounds

The "chain" mentioned before has already been closed, with quite good accuracy, in the case of down-type ΔF=2 observables (K^0 and $B_{d,s}$ mixing):



power-like GIM mechanism:

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

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

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

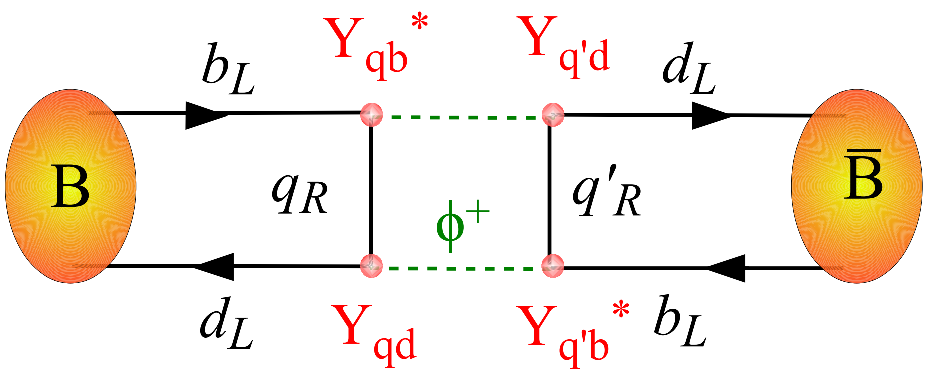
$$A_{qq'} \sim \frac{g^4}{16\pi^2 m_W^2} \left[\text{Const.} + \frac{m_q\, m_{q'}}{m_W^2} + \ldots \right] \langle \bar{B} |\, (\bar{b}_L \gamma_\mu d_L)^2 \,| B \rangle$$

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

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

The ΔF=2 bounds

The "chain" mentioned before has already been closed, with quite good accuracy, in the case of down-type ΔF=2 observables (K^0 and $B_{d,s}$ mixing):



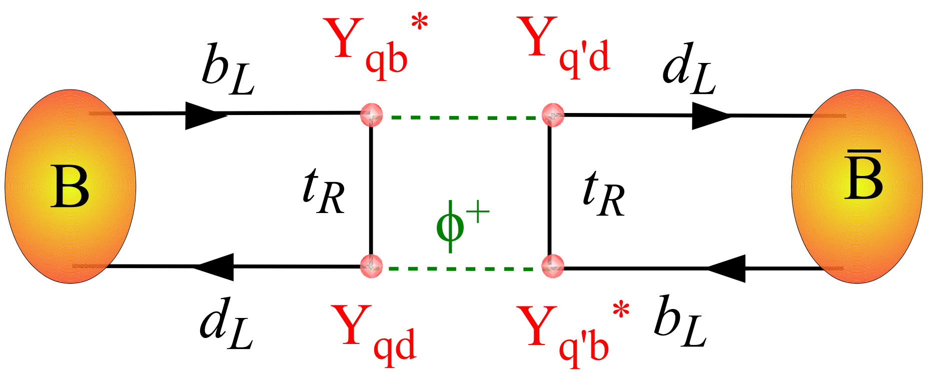
The origin of this behavior can be better understood if we *switch-off* gauge interactions ("gauge-less limit")

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

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

The ΔF=2 bounds

The "chain" mentioned before has already been closed, with quite good accuracy, in the case of down-type ΔF=2 observables (K^0 and $B_{d,s}$ mixing):



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

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

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

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

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

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

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

The flavor problem

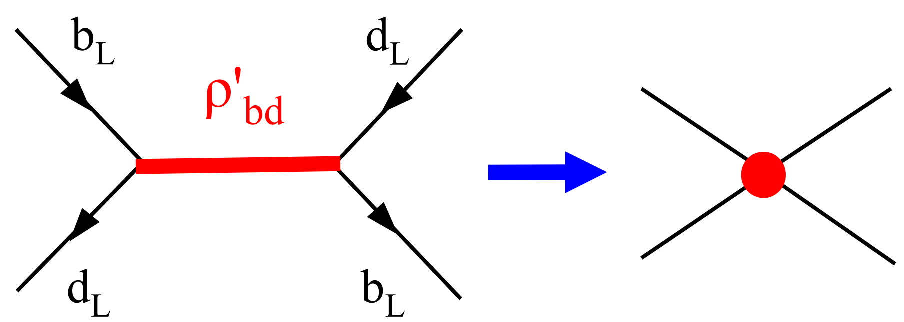
The "chain" mentioned before has already been closed, with quite good accuracy, in the case of down-type $\Delta F=2$ observables (K^0 and $B_{d,s}$ mixing), showing no significant deviations from the SM (at the 5%-30% level):

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

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

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:



The flavor problem

The "chain" mentioned before has already been closed, with quite good accuracy, in the case of down-type $\Delta F=2$ observables (K^0 and $B_{d,s}$ mixing), showing no significant deviations from the SM (at the 5%-30% level):

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

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

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

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: $V_{ts}^* V_{td} \sim \lambda^5$

The flavor problem

The "chain" mentioned before has already been closed, with quite good accuracy, in the case of down-type ΔF=2 observables (K^0 and $B_{d,s}$ mixing), showing no significant deviations from the SM (at the 5%-30% level):

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

c_{NP} $\to$ ~ 1 $\xrightarrow{\text{tree/strong + generic flavor}}$ $\Lambda \gtrsim 2\times 10^4$ TeV [K]

c_{NP} $\to$ $\sim 1/(16\pi^2)$ $\xrightarrow{\text{loop + generic flavor}}$ $\Lambda \gtrsim 2\times 10^3$ TeV [K]

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

The flavor problem

The "chain" mentioned before has already been closed, with quite good accuracy, in the case of down-type $\Delta F=2$ observables (K^0 and $B_{d,s}$ mixing), showing no significant deviations from the SM (at the 5%-30% level):

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

c_{NP}:

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

The flavor problem

The "chain" mentioned before has already been closed, with quite good accuracy, in the case of down-type $\Delta F=2$ observables (K^0 and $B_{d,s}$ mixing), showing no significant deviations from the SM (at the 5%-30% level):

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

c_{NP}:

- ~ 1 — tree/strong + generic flavor → $\Lambda \gtrsim 2\times 10^4$ TeV [K]
- $\sim 1/(16\pi^2)$ — loop + generic flavor → $\Lambda \gtrsim 2\times 10^3$ TeV [K]
- $\sim (y_t V_{ti}^* V_{tj})^2$ — 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

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

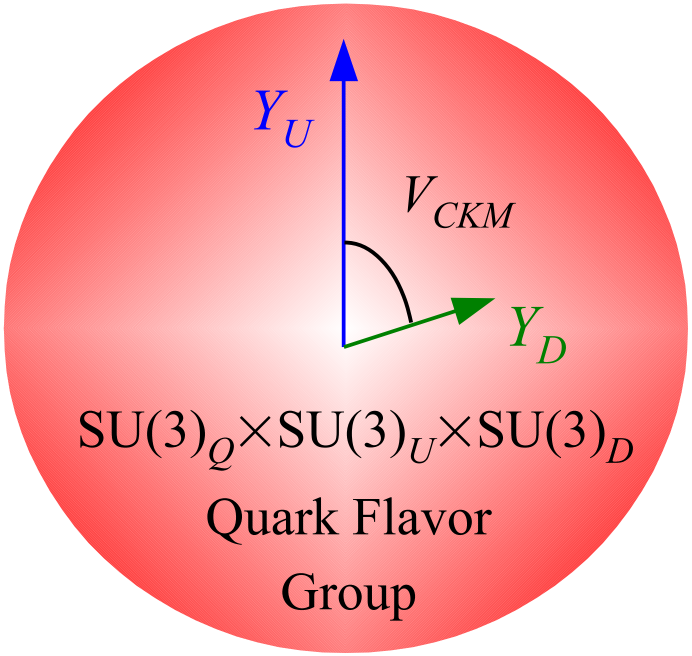
- Can we build NP models where the alignment with the CKM is "natural"?
- Is there a unique form of alignment that allows $\Lambda \sim 1$ TeV?
- Does this shed light on the origin of fermion masses and CKM hierarchies?
- Can we see deviations from the SM with more precise measurements? Where?

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

Minimal Flavor Violation

- Flavor 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_U & Y_D
  [quark Yukawa couplings]



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

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

This specific symmetry + symmetry-breaking pattern is responsible for the GIM suppression of Flavor Changing Neutral Currents, the suppression of CPV,...

all the successful SM predictions in the quark flavor sector

Minimal Flavor Violation

Since the global flavor symmetry is already broken within the SM, is not consistent to impose it as an exact symmetry beyond the SM (fine-tuning, not invariant under quantum corrections)

However, we can (formally) promote this symmetry to be an exact symmetry, assuming the Yukawa matrices are the vacuum expectation values of appropriate auxiliary fields:

E.g.: $Y_D \sim (3,1,\bar{3})$ & $Y_U \sim (3,\bar{3},1)$ under $SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$

$$\mathscr{L}_{\text{Yukawa}} = \bar{Q}_L Y_D D_R \phi + \bar{Q}_L Y_U U_R \phi_c + \bar{L}_L Y_L e_R \phi + \text{h.c.}$$

$\bar{Q}_L$: $(\bar{3},1,1)$; Y_D: $(3,1,\bar{3})$; D_R: $(1,1,3)$

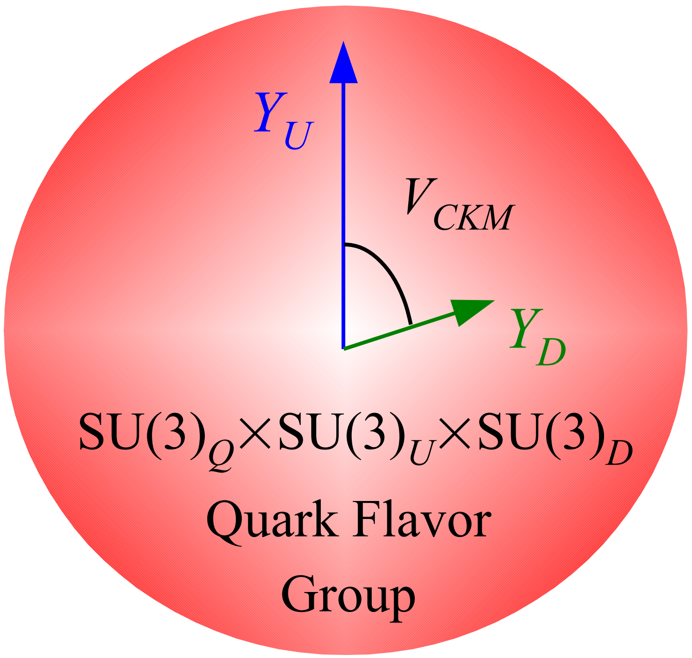
$\Downarrow$

$(1,1,1)$ = invariant

Minimal Flavor Violation

- Flavor symmetry:
  $U(3)^5 = SU(3)_Q \times SU(3)_U \times SU(3)_D \times \ldots$
  [global symmetry of the SM gauge sector]

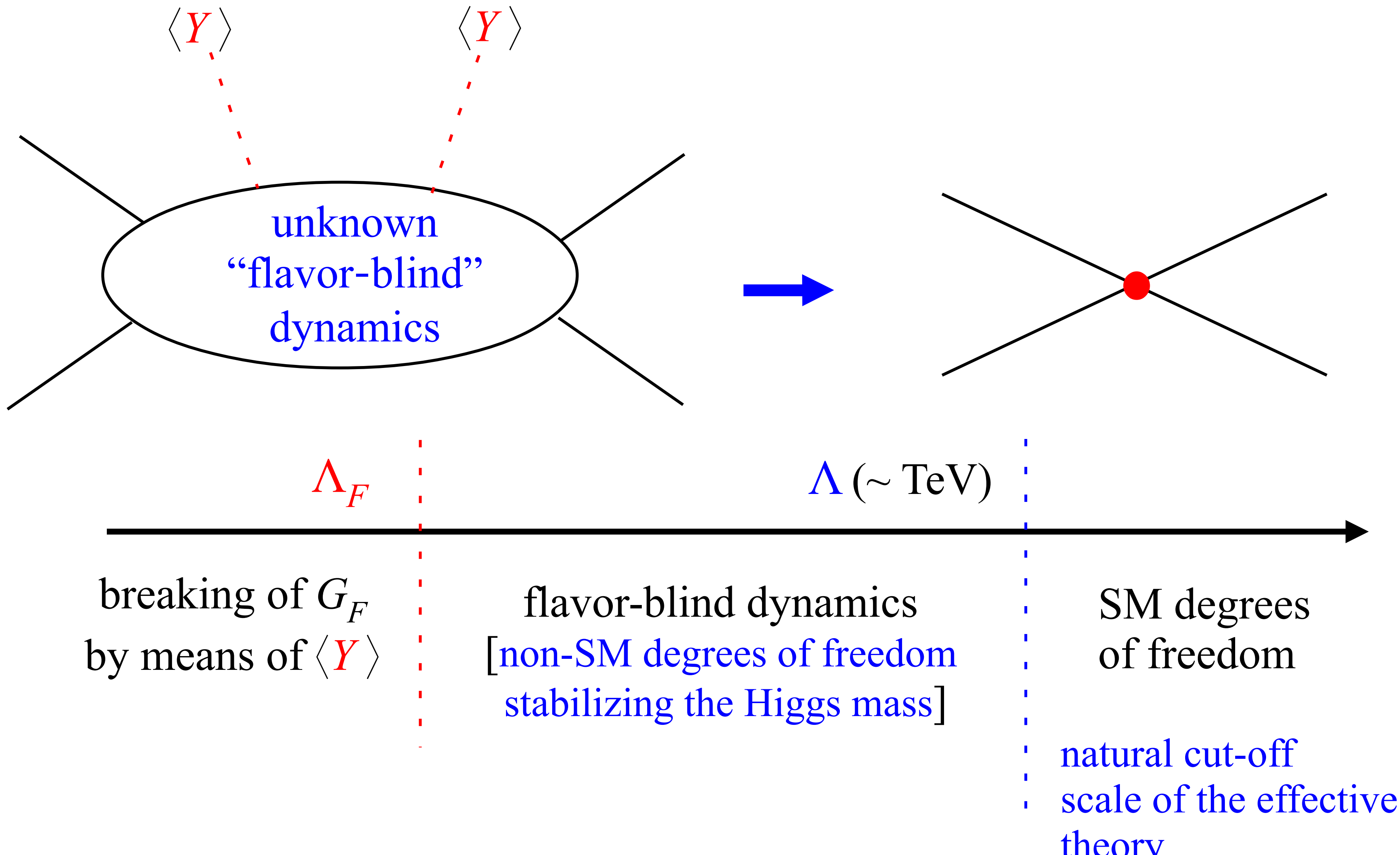
- Symmetry-breaking terms:
  $Y_D \sim 3_Q \times \bar{3}_D \qquad Y_U \sim 3_Q \times \bar{3}_U$
  [quark Yukawa couplings]



A natural mechanism to reproduce the SM successes in flavor physics -without fine tuning- is the MFV hypothesis:

Yukawa couplings = unique sources of flavor symmetry breaking also beyond SM

Minimal Flavor Violation



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

Minimal Flavor Violation

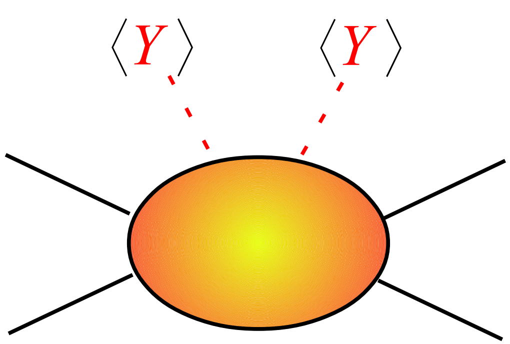
A low-energy EFT satisfies the criterion of MFV if all higher-dimensional operators, constructed from SM and Y fields, are (formally) invariant under the flavor group [$SU(3)_Q \times SU(3)_U \times SU(3)_D$]

We can always choose a quark basis where:

$$Y_D = \mathrm{diag}(y_d, y_s, y_b) \qquad Y_U = V^+ \times \mathrm{diag}(y_u, y_c, y_t) \qquad y_i = \frac{2^{1/2}\, m_{q_i}}{\langle \phi \rangle}$$

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

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



Minimal Flavor 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 flavor group [$SU(3)_Q \times SU(3)_U \times SU(3)_D$]

We can always choose a quark basis where:

$$Y_D = \mathrm{diag}(y_d, y_s, y_b) \qquad Y_U = V^+ \times \mathrm{diag}(y_u, y_c, y_t) \qquad y_i = \frac{2^{1/2}\, m_{q_i}}{\langle \phi \rangle}$$

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

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

$$\downarrow$$

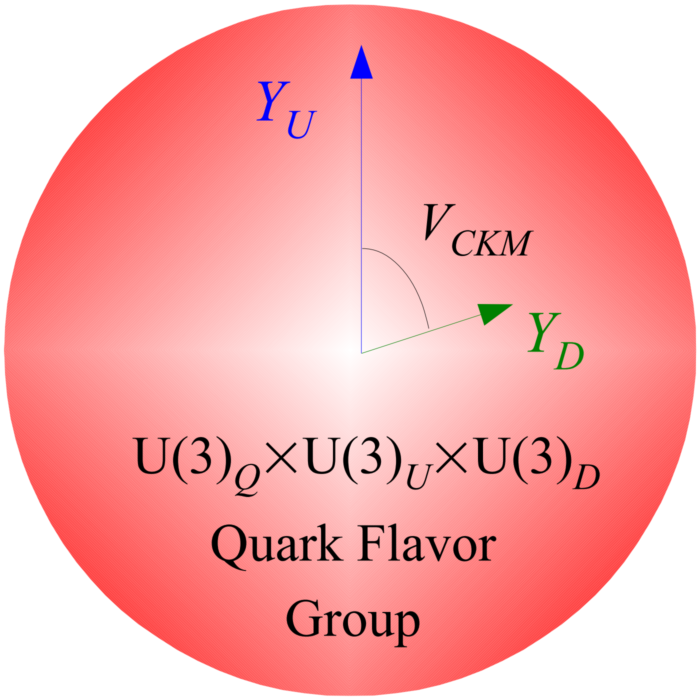
$$V^+ \times \mathrm{diag}(y_u^2, y_c^2, y_t^2) \times V$$

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

same CKM structure of the dominant (top-induced or short-distance) SM contribution !

Basic assumptions:

- Flavor symmetry:
  $U(3)^5 = U(3)_Q \times U(3)_U \times U(3)_D \times \ldots$
- Symmetry-breaking terms:
  $Y_D \sim \bar{3}_Q \times 3_D \qquad Y_U \sim \bar{3}_Q \times 3_U$

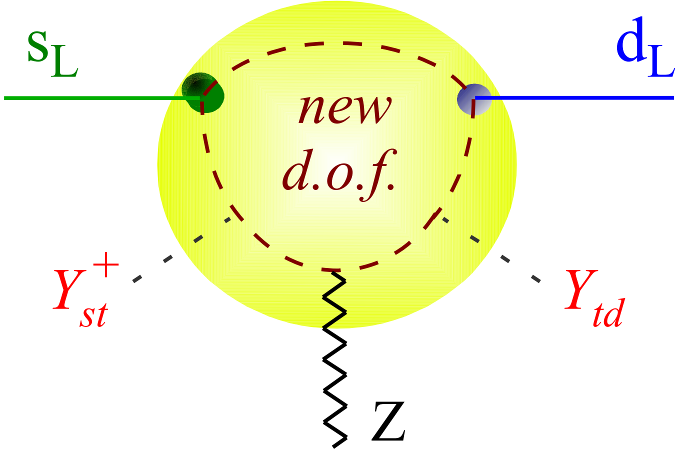


Main virtues:

- General principle that can be implemented independently of the specific high-energy completion of the theory
- Within the generic effective theory approach, the bounds on the scale of New Physics are reduced to few TeV (at most)
- It leads to a very predictive framework:

  All flavor-changing loop-induced amplitudes have the same CKM/Yukawa structure as in the SM. Only the flavor-independent magnitude of the transition amplitudes can be modified.

All flavor-changing loop-induced amplitudes have the same CKM/Yukawa structure as in the SM [e.g.: A($s\to dZ$) ~ $V_{ts}^{*}V_{td}$, A($b\to sZ$) ~ $V_{tb}^{*}V_{ts}$, …]. Only the flavor-independent magnitude can be modified



$$\left|\frac{A(s\to dZ)}{A(b\to sZ)}\right| = \left|\frac{V_{td}}{V_{tb}}\right|$$ as in the SM...

As a result, the most the tight experimental constraints on rare processes are naturally satisfied:

Operator	Bound on Λ	Observables
$H^{\dagger}\left(\bar{D}_R Y^{d\dagger} Y^{u} Y^{u\dagger}\sigma_{\mu\nu} Q_L\right)(e F_{\mu\nu})$	6.1 TeV	$B\to X_s\gamma$, $B\to X_s\ell^+\ell^-$
$\frac{1}{2}(\bar{Q}_L Y^{u} Y^{u\dagger}\gamma_\mu Q_L)^2$	5.9 TeV	ε_K, Δm_{B_d}, Δm_{B_s}
$H_D^{\dagger}\left(\bar{D}_R Y^{d\dagger} Y^{u} Y^{u\dagger}\sigma_{\mu\nu} T^a Q_L\right)(g_s G^a_{\mu\nu})$	3.4 TeV	$B\to X_s\gamma$, $B\to X_s\ell^+\ell^-$
$(\bar{Q}_L Y^{u} Y^{u\dagger}\gamma_\mu Q_L)(\bar{E}_R\gamma_\mu E_R)$	2.7 TeV	$B\to X_s\ell^+\ell^-$, $B_s\to\mu^+\mu^-$

A few important comments:

I) MFV is not a theory of flavor

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

It is a useful predictive (hence falsifiable) construction that allow us to identify which are the irreducible sources of flavor-symmetry breaking

A few important comments:

I) MFV is not a theory of flavor

II) Despite its phenomenological success, MFV is far from being "verified"

To prove MFV from data we would need to

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

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

In most of the processes measured so far we cannot go beyond the 10%-20% level of precision (even if the exp. precision is much better) because of irreducible theoretical uncertainties on evaluating the overall strength of the SM amplitude (*non-perturbative effects of strong interactions*)

Some more rare decays not observed so far could provide more useful infos. Very interesting candidates: $B_{d,s} \to l^+ l^-$ (*currently under investigation @ LHC*)

A few important comments:

I) MFV is not a theory of flavor

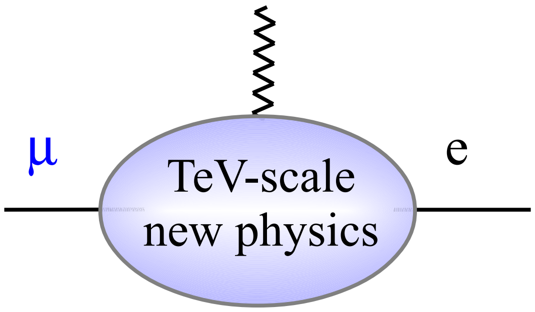
II) Despite its phenomenological success, MFV is far from being "verified"

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

Typical examples:

$B_{d,s} \to l^+ l^-$ — Sizable enhancements still possible in models with an extended Higgs sector

... 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*)

Variations on the "MFV theme"

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

- Largest flavor symmetry group compatible with the SM gauge symmetry

↓

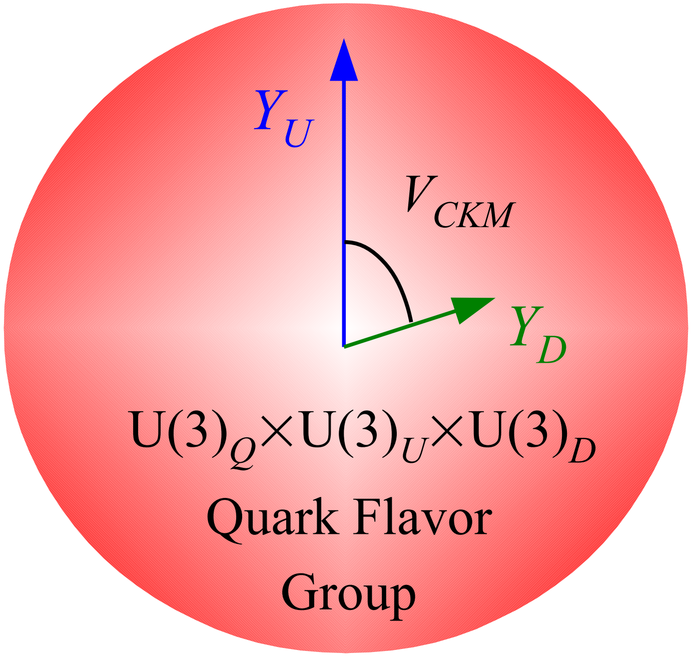
MFV hypothesis: the Yukawa couplings are the only breaking terms of this large flavor symmetry group

virtue

Small deviations from the SM in flavor-violating observables (in agreement with data)

main problem

No explanation for Y hierarchies (non-dynamical spurion analysis)



Variations on the "MFV theme"

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

- Largest flavor symmetry group compatible with the SM gauge symmetry
- MFV = minimal breaking of $U(3)^3$ by $(3,\underline{3})$ terms [*SM Yukawa couplings*]

An interesting variation of MFV is obtained considering the following subgroup:

$$U(2)^3 = U(2)_Q \times U(2)_U \times U(2)_D$$

acting on 1st & 2nd generations

Barbieri, G.I., Jones-Perez, Lodone, Straub, '11

Same protection of FCNCs

+

Additional virtue:

The exact symmetry limit is good starting point for the SM spectrum ($m_u=m_d=m_s=m_c=0$, $V_{CKM}=1$)

→ small breakings terms needed

$$Y_u = y_t \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \rightarrow \begin{bmatrix} \Delta & V \\ 0 & 1 \end{bmatrix}$$

Unbroken symmetry

$|V| \sim 0.04$

$|\Delta| \sim 0.006$

Variations on the "MFV theme"

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

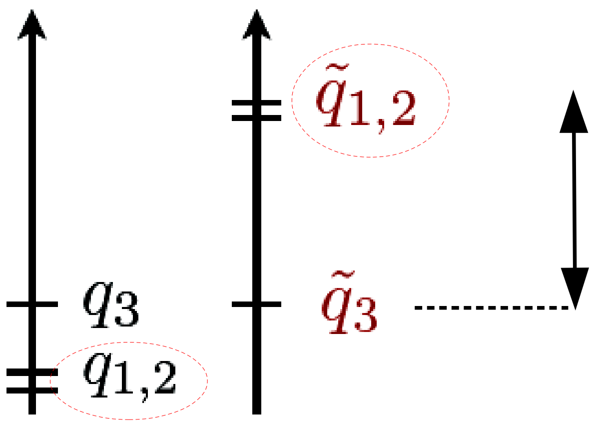
- Largest flavor symmetry group compatible with the SM gauge symmetry
- MFV = minimal breaking of $U(3)^3$ by $(3,\underline{3})$ terms [*SM Yukawa couplings*]

An interesting variation of MFV is obtained considering the following subgroup:

$$U(2)^3 = U(2)_Q \times U(2)_U \times U(2)_D$$

acting on 1st & 2nd generations

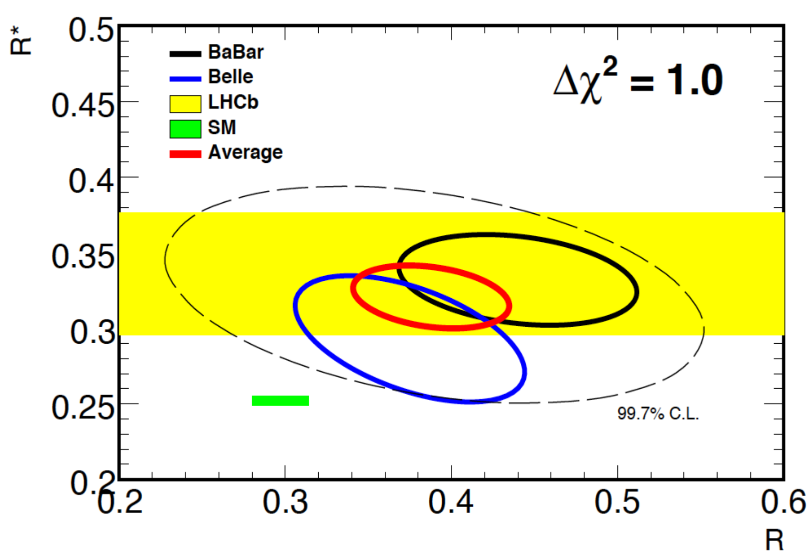
Barbieri, G.I., Jones-Perez, Lodone, Straub, '11

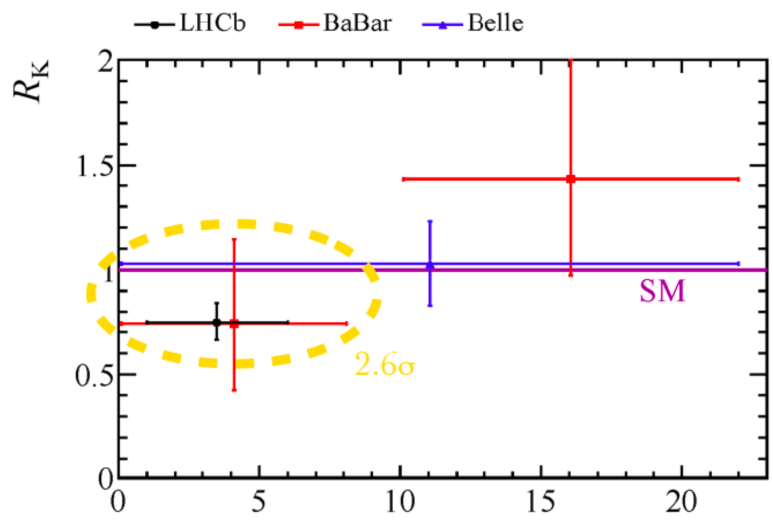


This flavor symmetry is particularly interesting in the SUSY context, since it allow to realize the "split-family" scenario discussed yesterday:

Large mass gap (several TeV) not controlled by flavor symmetries (as opposite to MFV) and fine-tuning considerations

Speculations on the breaking of LFU in B physics





[LHCb-TALK-2014-108]

Recent anomalies in B physics

A series of recent (and less recent) anomalies in B physics have received a lot of attention recently:

I. Anomalies in $B \to D^{(*)} \tau\nu$ [LHCb, Belle, Babar]

II. Anomalies in $B \to K^{(*)} \mu\mu$ / ee [LHCb]

Beside the significance of each anomaly, what makes them particularly (*at least in my opinion*) is the fact they all seem to be connected to a possible violation of Lepton Flavor Universality

I. Anomalies in B → D$^{(*)}$ τν [LHCb, Belle, Babar]

Test of LFU in charged currents
[τ vs. light leptons (μ, e)]:

$$R(X) = \frac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X\ell\bar{\nu})}$$

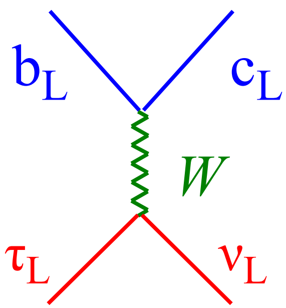
		$R(D)$	$R(D^*)$	
	BaBar	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.018$	
NEW →	Belle	$0.375^{+0.064}_{-0.063} \pm 0.026$	$0.293^{+0.039}_{-0.037} \pm 0.015$	
NEW →	LHCb		$0.336 \pm 0.027 \pm 0.030$	
	Average	0.388 ± 0.047	0.321 ± 0.021	
	SM expectation	0.300 ± 0.010	0.252 ± 0.005	
		~1.8σ	~3.2σ	

- SM prediction quite solid: f.f. uncertainty cancel (*to a good extent...*) in the ratio
- Consistent exp. results by 3 (very) different experiments

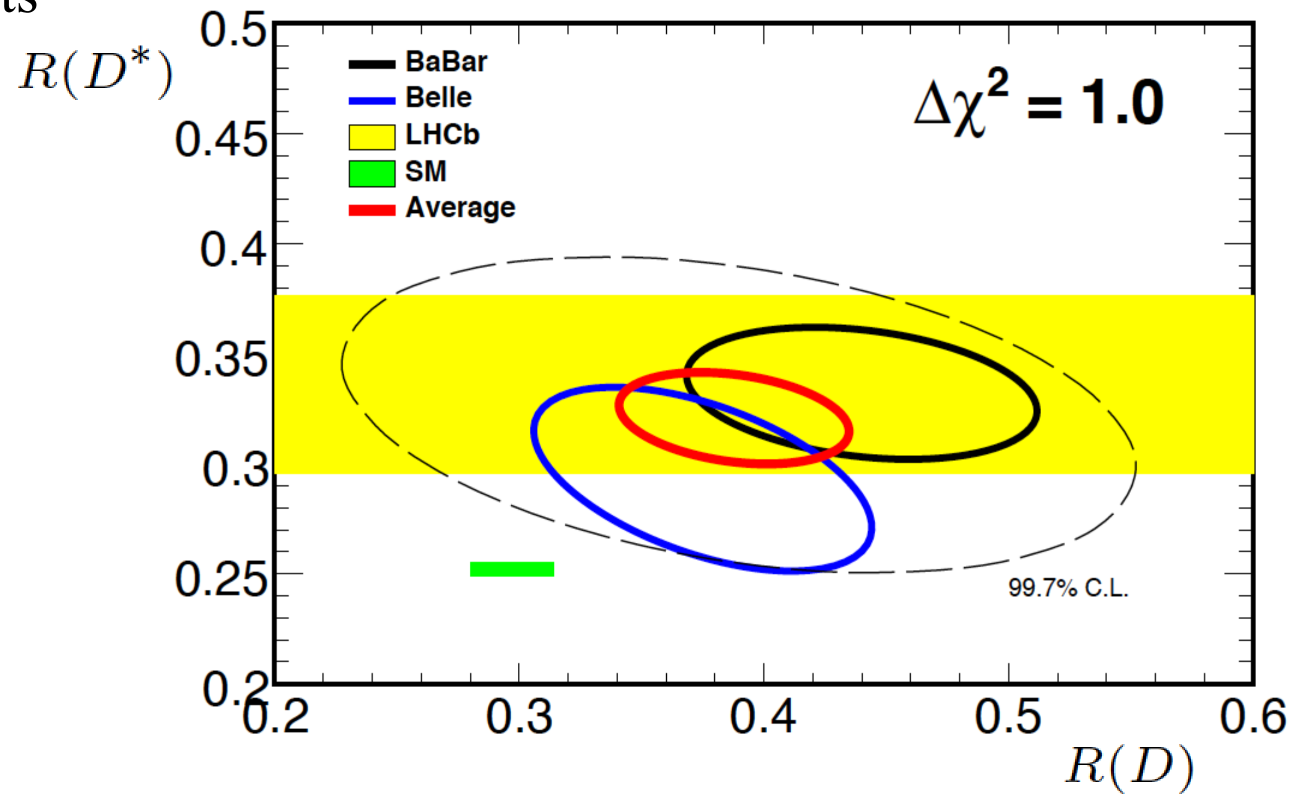
I. Anomalies in $B \to D^{(*)} \tau\nu$ [LHCb, Belle, Babar]

Test of LFU in charged currents
[τ vs. light leptons (μ, e)]:

$$R(X) = \frac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X\ell\bar{\nu})}$$



M. Rotondo



- SM prediction quite solid: f.f. uncertainty cancel (*to a good extent...*) in the ratio
- Consistent exp. results by 3 (very) different experiments
  - 4σ excess over SM (if D and D* combined)
  - The two channels are well consistent with a universal enhancement (~30%) of the SM $b_L \to c_L\, \tau_L\, \nu_L$ amplitude (*RH or scalar amplitudes disfavored*)

II. Anomalies in $B \to K^{(*)} \mu\mu$ / ee [LHCb]

The largest anomaly is the one [*obs. in 2013 and confirmed with higher stat. in 2015*] in the P_5' [$B \to K^* \mu\mu$] angular distribution.

But less significant anomalies present also in other $B \to K^* \mu\mu$ observables and also in other $b \to s\mu\mu$ channels [overall smallness of all BR($B \to$ Hadron + $\mu\mu$)]

II. Anomalies in $B \to K^{(*)} \mu\mu$ / ee [LHCb]

The largest anomaly is the one [*obs. in 2013 and confirmed with higher stat. in 2015*] in the P_5' [$B \to K^* \mu\mu$] angular distribution.

But less significant anomalies present also in other $B \to K^* \mu\mu$ observables and also in other $b \to s\mu\mu$ channels [overall smallness of all BR(B → Hadron + μμ)]

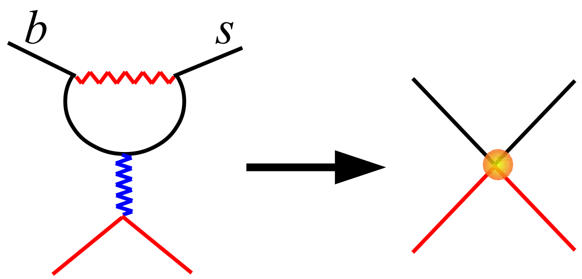
$B \to K^{(*)} ll$ are FCNC amplitudes ("natural" probes of physics beyond the SM):

- No SM tree-level contribution
- Strong suppression within the SM because of CKM hierarchy

Key point to be addressed: th. control of QCD effects

Three-step procedure to deal with the various scales of the problem:

I. Construction of a local eff. Hamiltonian at the electroweak scale



$$H_{\text{eff}} = \Sigma_i \, C_i(M_W) \, Q_i$$

- Heavy NP encoded in the $C_i(M_W)$
- No difference among all $b \to s\, ll$ decays

II. Evolution of $H_{\rm eff}$ down to low scales using RGE

FCNC operators (E.W. penguins)

$$Q_9 = Q_f (b s)_{V-A} (l l)_V$$
$$Q_{10} = Q_f (b s)_{V-A} (l l)_A$$
$$\vdots$$

$$H_{\rm eff} = \Sigma_i\, C_i(M_W)\, Q_i$$

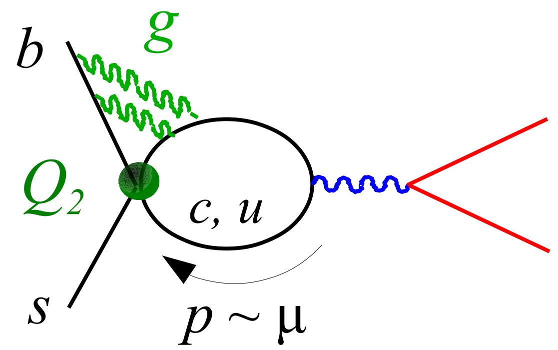
$$\downarrow$$

$$H_{\rm eff} = \Sigma_i\, C_i(\mu \sim m_b)\, Q_i$$

Four-quark (tree-level) ops.:

$$Q_1 = (b s)_{V-A} (c c)_{V-A}$$
$$Q_2 = (b c)_{V-A} (c s)_{V-A}$$
$$\vdots$$

Mixing of the four-quark Q_i into the FCNC Q_i
["dilution" of the potentially interesting NP]:



Negligible for Q_{10} [$B_{s,d} \to ll$ & $B \to K^{(*)} ll$]

Large for "photon penguins" Q_9 [$B \to K^{(*)} ll$ only]

II. Evolution of H_{eff} down to low scales using RGE

FCNC operators (E.W. penguins)

$$Q_9 = Q_f (b s)_{V-A} (l l)_V$$
$$Q_{10} = Q_f (b s)_{V-A} (l l)_A$$
$$\vdots$$

$$H_{\mathrm{eff}} = \Sigma_i\, C_i(M_W)\, Q_i$$

$$\downarrow$$

$$H_{\mathrm{eff}} = \Sigma_i\, C_i(\mu \sim m_b)\, Q_i$$

Four-quark (tree-level) ops.:

$$Q_1 = (b s)_{V-A} (c c)_{V-A}$$
$$Q_2 = (b c)_{V-A} (c s)_{V-A}$$
$$\vdots$$

III. Evaluation of the hadronic matrix elements

$$A(B \to f) = \Sigma_i\, C_i(\mu)\, \langle f | Q_i | B \rangle (\mu)$$

- sensitivity to long-distances (cc threshold...)
- distinction between different modes

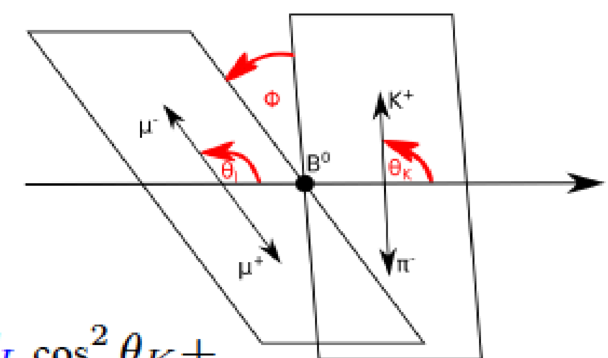
non-perturbative effects...

II. Anomalies in $B \to K^{(*)}$ $\mu\mu$ / ee [LHCb]

The largest anomaly is the one [*obs. in 2013 and confirmed with higher stat. in 2015*] in the P_5' [$B \to K^*\mu\mu$] angular distribution.

But less significant anomalies present also in other $B \to K^*\mu\mu$ observables and also in other $b\to s\mu\mu$ channels [overall smallness of all BR($B \to$ Hadron + $\mu\mu$)]

Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$



$$\frac{d^4(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell \, d\cos\theta_K \, d\phi \, dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K +$$
$$\frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell +$$
$$S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi +$$
$$S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell +$$
$$S_7\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

$$P'_{4,5} = \frac{S_{4,5}}{\sqrt{F_L(1-F_L)}}$$

observables designed to cancel f.f. dependence in the HQ limit

II. Anomalies in $B \to K^{(*)} \mu\mu$ / ee [LHCb]

The largest anomaly is the one [*obs. in 2013 and confirmed with higher stat. in 2015*] in the P_5' [$B \to K^* \mu\mu$] angular distribution.

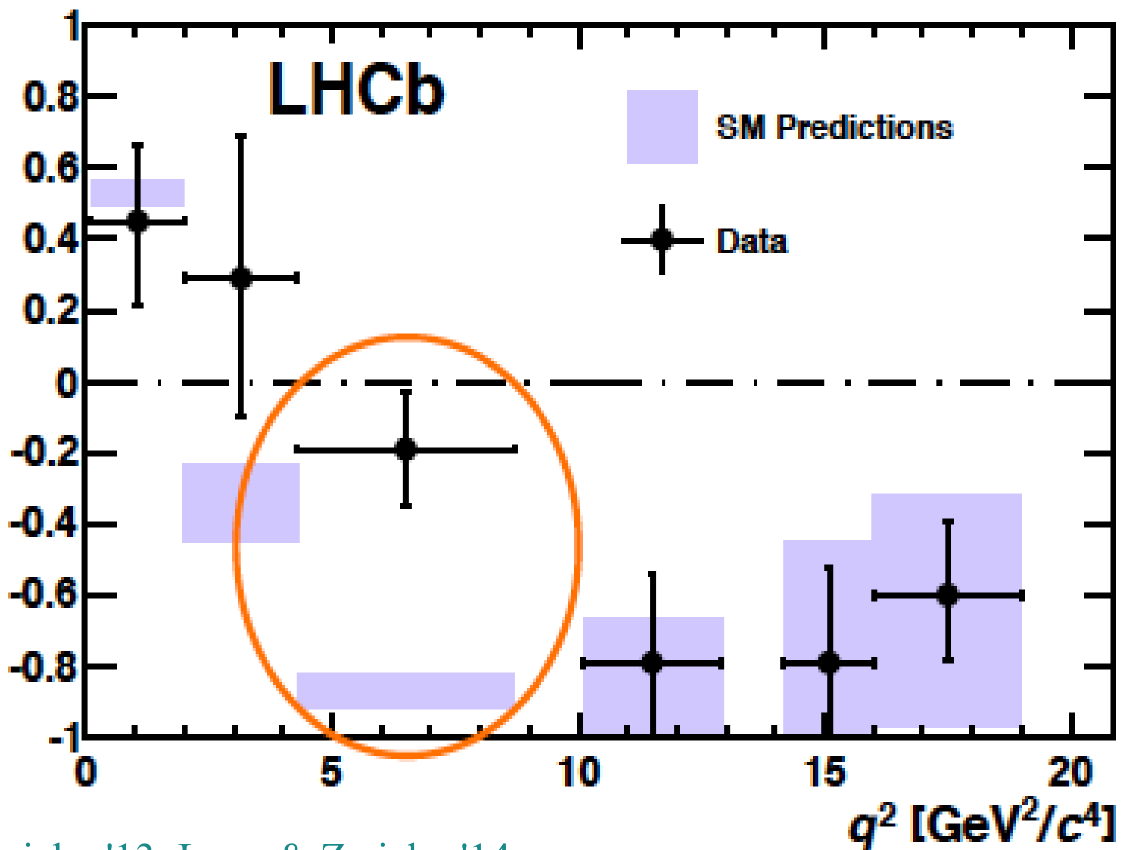
But less significant anomalies present also in other $B \to K^* \mu\mu$ observables and also in other $b \to s\mu\mu$ channels [overall smallness of all BR($B \to$ Hadron + $\mu\mu$)]

Pro NP:

- Reduced tension in <u>all the observables</u> with a unique fit of non-standard $C_i(M_W)$

Against NP:

- Main effect in P_5' not far from cc threshold
- "NP" mainly in C_9 ($\leftrightarrow$ *charm*)
- Significance reduced with conservative estimates of non-factorizable corrections



Jaeger *et al.* '12 Hambrock *et al.* '13, Hiller & Zwicky '13, Lyon & Zwicky '14

II. Anomalies in $B \to K^{(*)} \mu\mu$ / ee [LHCb]

The largest anomaly is the one [*obs. in 2013 and confirmed with higher stat. in 2015*] in the P_5' [$B \to K^* \mu\mu$] angular distribution.

But less significant anomalies present also in other $B \to K^* \mu\mu$ observables and also in other $b \to s\mu\mu$ channels [overall smallness of all BR($B \to$ Hadron + $\mu\mu$)]

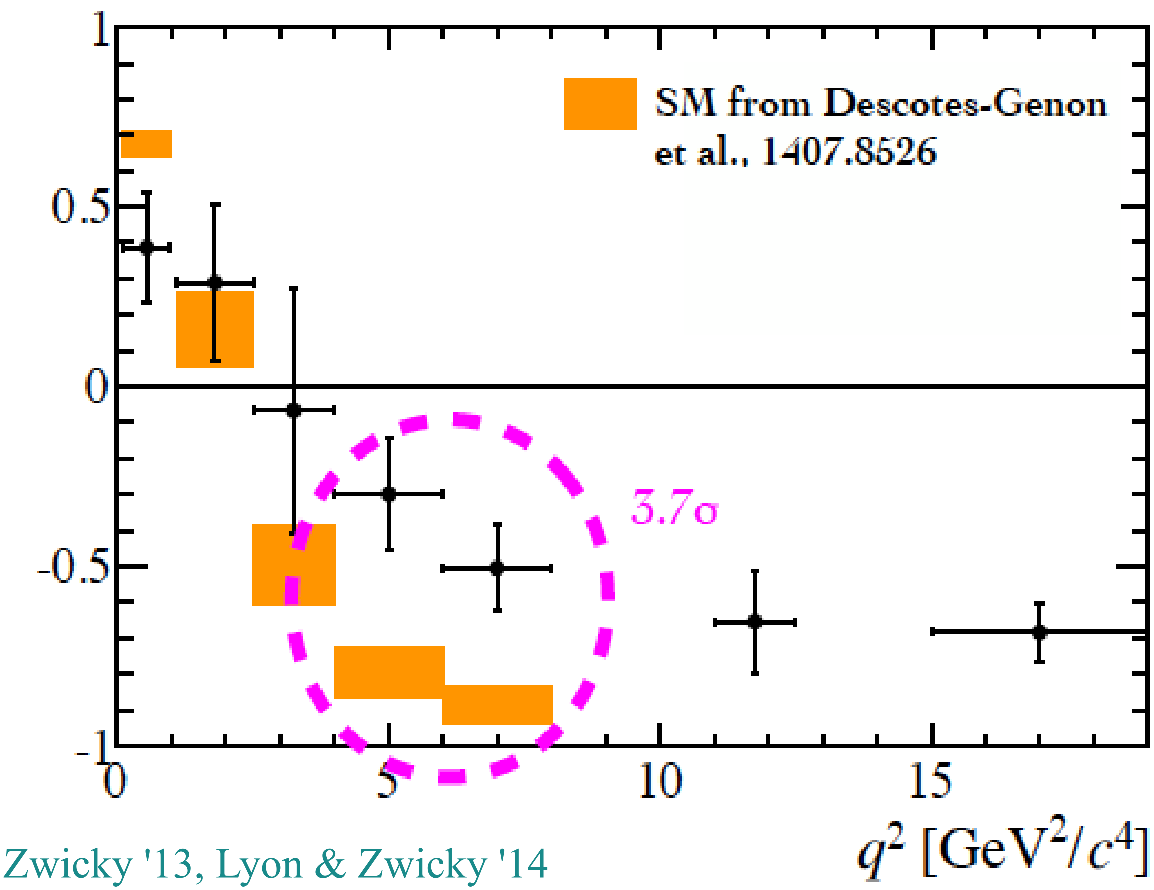
Pro NP:

- Reduced tension in <u>all the observables</u> with a unique fit of non-standard $C_i(M_W)$

Against NP:

- ~~Main effect in P_5' not far from cc threshold~~
- "NP" mainly in C_9 (↔ *charm*)
- Significance reduced with conservative estimates of non-factorizable corrections

[LHCb-CONF-2015-002]



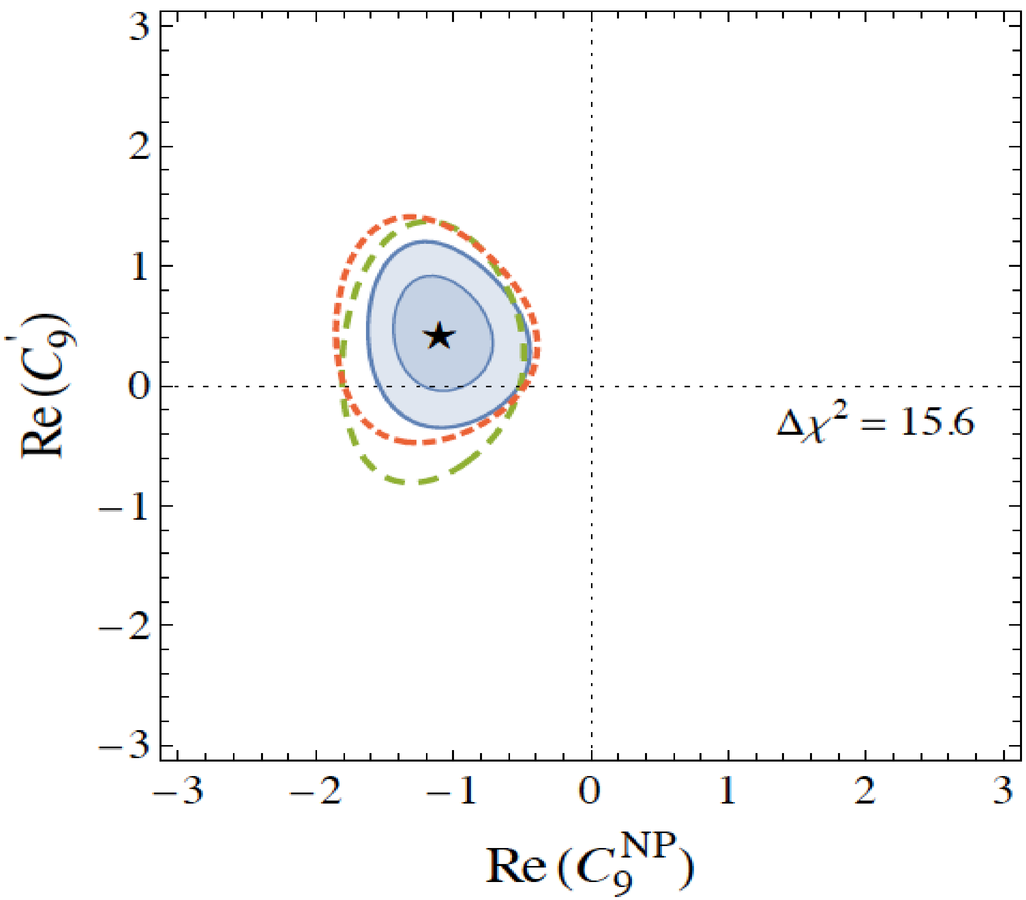
Jaeger *et al.* '12 Hambrock *et al.* '13, Hiller & Zwicky '13, Lyon & Zwicky '14

II. Anomalies in $B \to K^{(*)} \mu\mu$ / ee [LHCb]

Pro NP:

- Reduced tension in all the observables with a unique fit of non-standard short-distance Wilson coefficients

Descotes-Genon, Matias, Virto '13, '15
Altmannshofer & Straub '13, '15
Beaujean, Bobeth, van Dyk '13
Horgan *et al.* '13



Altmannshofer & Straub '15

$$O_9^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu)$$

muonic vector current

- NP contributions to C_9 give best description of the data
- (NP with $C_9 = -C_{10}$ works almost equally well)

II. Anomalies in $B \to K^{(*)} \mu\mu$ / ee [LHCb]

Last but not least, the most interesting effect in $b \to s\ell\ell$ transitions the 2.6σ deviation from the SM observed in the LFU ratio

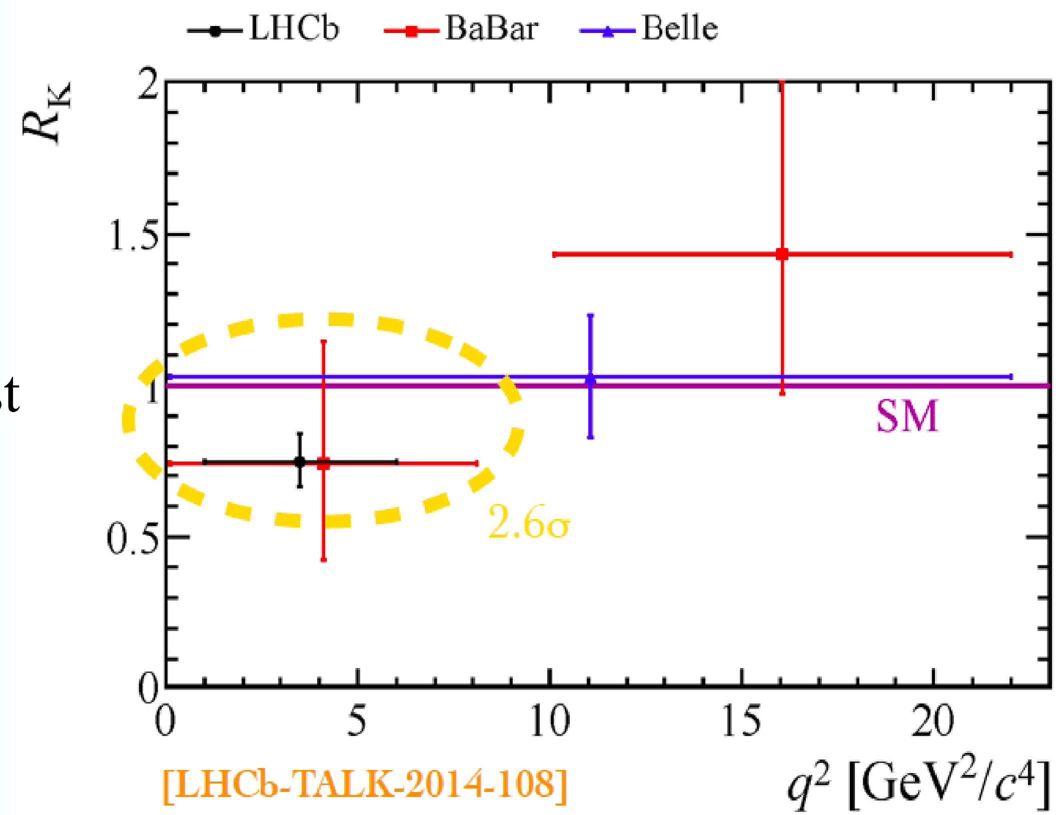
$$R_K = \frac{\int d\Gamma(B^+ \to K^+\mu\mu)}{\int d\Gamma(B^+ \to K^+ ee)}$$

$[1\text{-}6]\ \mathrm{GeV}^2$

- Negligible th. error → clean test of LFU (in neutral currents)

$$R_K = 1 \pm O(1\%)$$

Bordone *et al.* work in prog.



[LHCb-TALK-2014-108]

- This anomaly is perfectly described assuming NP only in $b \to s\mu\mu$ [*and not in* $b \to see$] consistently with the various $b \to s\mu\mu$ anomalies

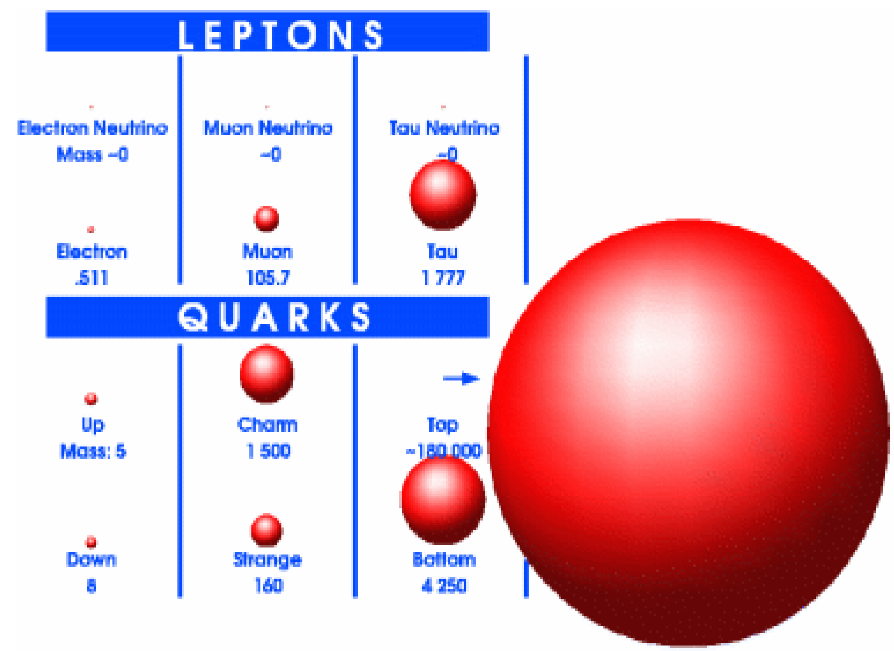
Speculations on the breaking of LFU

(Some of) these recent results have stimulated a lot of theoretical activity.

Most interesting aspect: possible breaking of LFU, both in charged currents ($b \to c\tau\nu$ vs. $b \to c\mu\nu$) and in neutral currents ($b \to s\mu\mu$ vs. $b \to see$)

A few general messages:

- LFU is not a fundamental symmetry of the SM Lagrangian (*accidental symmetry in the gauge sector, broken by Yukawas*)
- LFU tests at the Z peak are not too stringent (→ gauge sector)
- Most stringent tests of LFU involve only 1st-2nd gen. quarks & leptons



→ Natural to conceive NP models where LFU is violated more in processes with 3rd gen. quarks (↔ hierarchy in Yukawa coupl.)

Speculations on the breaking of LFU

(Some of) these recent results have stimulated a lot of theoretical activity:

S. Fajfer, J. F. Kamenik, I. Nisandzic and J. Zupan, Phys. Rev. Lett. **109** (2012) 161801 [arXiv:1206.1872].

S. Descotes-Genon, J. Matias and J. Virto, Phys. Rev. D **88** (2013) 074002 [arXiv:1307.5683].

W. Altmannshofer and D. M. Straub, Eur. Phys. J. C **73** (2013) 2646 [arXiv:1308.1501].

A. Datta, M. Duraisamy and D. Ghosh, Phys. Rev. D **89** (2014) 7, 071501 [arXiv:1310.1937].

G. Hiller and M. Schmaltz, Phys. Rev. D **90** (2014) 054014 [arXiv:1408.1627]; JHEP **1502** (2015) 055

A. Crivellin and S. Pokorski, Phys. Rev. Lett. **114** (2015) 1, 011802 [arXiv:1407.1320].

S. L. Glashow, D. Guadagnoli and K. Lane, Phys. Rev. Lett. **114** (2015) 091801 [arXiv:1411.0565].

+ many others...

...but till last summer most attempts focused only on one set of anomalies (either charged or neutral currents)

What I will discuss next are some general considerations in trying to describe both these effect within simplified (rather general) <u>semi-dynamical models.</u>

EFT-type considerations:

- Anomalies are seen only in semi-leptonic (quark×lepton) operators
- RR and scalar currents disfavored → LL current-current operators
- Necessity of at least one $SU(2)_L$-triplet effective operator (+ maybe a singlet one):

$$\frac{g_q g_\ell}{\Lambda^2} \lambda^q_{ij} \lambda^\ell_{kl} (\bar{Q}^i_L T^a \gamma_\mu Q^j_L)(\bar{L}^k_L T^a \gamma^\mu L^l_L)$$

Bhattacharya *et al.* '14
Alonso, Grinstein, Camalich '15
Greljo, GI, Marzocca '15

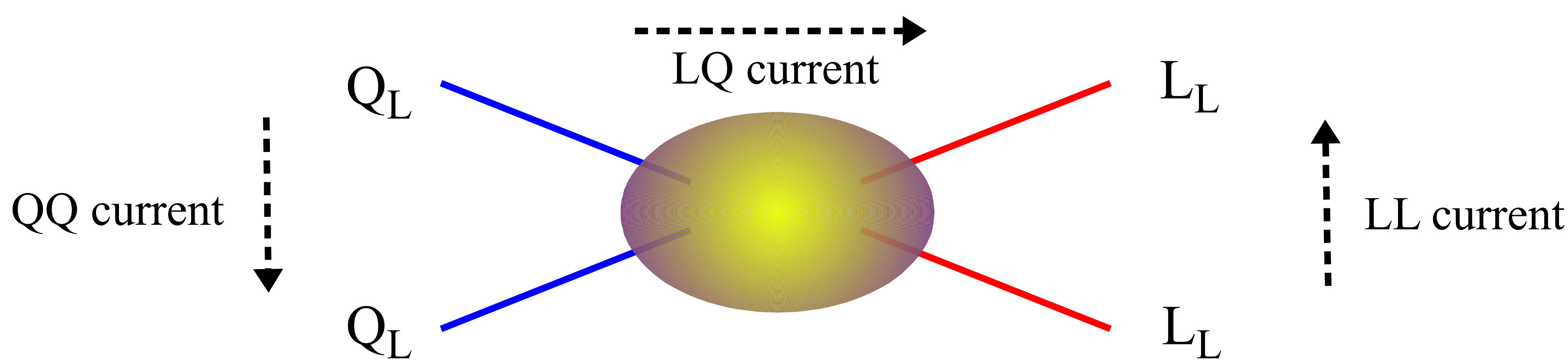
- Large coupling (competing with SM tree-level) in bc (=33_{CKM}) → $l_3\ \nu_3$
- Small non-vanishing coupling (competing with SM FCNC) in bs → $l_2\ l_2$

EFT-type considerations:

- Anomalies are seen only in semi-leptonic (quark×lepton) operators
- RR and scalar currents disfavored → LL current-current operators
- Necessity of at least one $SU(2)_L$-triplet effective operator (+ maybe a singlet one):

$$\frac{g_q g_\ell}{\Lambda^2} \lambda^q_{ij} \lambda^\ell_{kl} (\bar{Q}^i_L T^a \gamma_\mu Q^j_L)(\bar{L}^k_L T^a \gamma^\mu L^l_L)$$

Bhattacharya *et al.* '14
Alonso, Grinstein, Camalich '15
Greljo, GI, Marzocca '15



- Two natural classes of mediators, giving rise to different correlations among quark×lepton, (evidence) and quark×quark + lepton×lepton (bounds)

EFT-type considerations:

- Anomalies are seen only in semi-leptonic (quark×lepton) operators
- RR and scalar currents disfavored → LL current-current operators
- Necessity of at least one $SU(2)_L$-triplet effective operator (+ maybe a singlet one):

$$\frac{g_q g_\ell}{\Lambda^2} \lambda^q_{ij} \lambda^\ell_{kl} (\bar{Q}^i_L T^a \gamma_\mu Q^j_L)(\bar{L}^k_L T^a \gamma^\mu L^l_L)$$

Bhattacharya *et al.* '14
Alonso, Grinstein, Camalich '15
Greljo, GI, Marzocca '15

- Large coupling (competing with SM tree-level) in bc $(=33_{CKM}) \to l_3 \nu_3$
- Small non-vanishing coupling (competing with SM FCNC) in bs $\to l_2 l_2$
- Two natural classes of mediators, giving rise to different correlations among quark×lepton, (evidence) and quark×quark + lepton×lepton (bounds)

⬇

$$\lambda^{q,\ell}_{ij} = \delta_{i3}\delta_{3j}$$ + small corrections for 2nd (& 1st) generations

→ fits well with the idea of approximate $U(2)^n$ flavor symmetry

General consequences in charged currents:

$$\frac{\mathcal{A}(b \to c\, \ell^i \bar{\nu}^i)_{\rm SM+NP}}{\mathcal{A}(b \to c\, \ell^i \bar{\nu}^i)_{\rm SM}} = 1 + \boxed{R_0} \lambda^\ell_{ii} \qquad R_0 \equiv \frac{g_\ell g_q}{g^2} \frac{m_W^2}{\Lambda^2}$$

I. From R(D*) & R(D) data [$\Gamma(b \to c\tau\nu)/\Gamma(b \to c\mu\nu)$] → $\boxed{R_0 = 0.14 \pm 0.04}$

✲ *General consequences in charged currents:*

$$\frac{\mathcal{A}(b \to c\, \ell^i \bar{\nu}^i)_{\rm SM+NP}}{\mathcal{A}(b \to c\, \ell^i \bar{\nu}^i)_{\rm SM}} = 1 + R_0 \boxed{\lambda^\ell_{ii}} \qquad R_0 \equiv \frac{g_\ell g_q}{g^2} \frac{m_W^2}{\Lambda^2}$$

I. From R(D*) & R(D) data [Γ(b → cτν)/Γ(b → cμν)] → $R_0 = 0.14 \pm 0.04$

II. In principle, it should be possible to get a strong bound on the sub-leading leptonic coupling ($\lambda_{\mu\mu}$) from Γ(b → cμν)/Γ(b → ceν), but surprisingly it is not so stringent ($|\lambda_{\mu\mu}| \lesssim 0.1$) → *no dedicated studies @ B-facotries !*

⭑ *General consequences in charged currents:*

$$\frac{\mathcal{A}(b \to c\, \ell^i \bar{\nu}^i)_{\rm SM+NP}}{\mathcal{A}(b \to c\, \ell^i \bar{\nu}^i)_{\rm SM}} = 1 + R_0 \lambda^{\ell}_{ii} \qquad R_0 \equiv \frac{g_\ell g_q}{g^2}\frac{m_W^2}{\Lambda^2}$$

I. From R(D*) & R(D) data [$\Gamma(b \to c\tau\nu)/\Gamma(b \to c\mu\nu)$] $\to$ $R_0 = 0.14 \pm 0.04$

II. In principle, it should be possible to get a strong bound on the sub-leading leptonic coupling ($\lambda_{\mu\mu}$) from $\Gamma(b \to c\mu\nu)/\Gamma(b \to ce\nu)$, but surprisingly it is not so stringent ($|\lambda_{\mu\mu}| \lesssim 0.1$) $\to$ *no dedicated studies @ B-facotries !*

III. Even if it is hard to quantify, this breaking of LFU in c.c could decrease the (old) tension between exclusive & inclusive determinations of $|V_{ub}|$ & $|V_{cb}|$:

$B \to X_{c,u}\, \tau\, \nu$

$\quad\quad \tau \to \mu\nu\nu$

Irreducible bkg. for the inclusive meas. subtracted (at present) assuming SM-like $\Gamma(B \to X_{c,u}\tau\nu)$ $\Rightarrow$

if $\Gamma(B \to X_{c,u}\tau\nu)$ is enhanced over the SM $\to$ $|V_{c(u)b}|_{\rm incl.}$ are over estimated

✭ *A simplified dynamical model:*

Greljo, GI, Marzocca '15

Main assumptions:

- We assume the effective triplet operator is the result of integrating-out a heavy triplet of vector bosons (W', Z') coupled to a single current:

$$J^a_\mu = g_q \lambda^q_{ij} \left(\bar{Q}^i_L \gamma_\mu T^a Q^j_L \right) + g_\ell \lambda^\ell_{ij} \left(\bar{L}^i_L \gamma_\mu T^a L^j_L \right) \longrightarrow \frac{1}{2m_V^2} J^a_\mu J^a_\mu$$

- Non-Universal flavor structure of the currents → mainly 3rd generations

→ Coupling to 3rd generations not suppressed [*dynamical assumption*]

→ Coupling to light generations controlled by small $U(2)_q \times U(2)_l$ breaking spurions related to sub-leading terms in the Yukawa couplings

$$\lambda^q \simeq \begin{pmatrix} |\epsilon|^2 V^*_{3\alpha} V_{3\beta} & \epsilon^* V^*_{3\alpha} \\ \epsilon V_{3\beta} & 1 \end{pmatrix}$$

down-type mass basis

$$\lambda_{bd} \ll \lambda_{bs} \ll \lambda_{bb} = 1$$

$$\lambda_{ss} \sim \lambda_{bs}^2$$

A simplified dynamical model → low-energy global fit:

5 free parameters: $\epsilon_{\ell,q} \equiv \frac{g_{\ell,q}\, m_W}{g\, m_V} \approx g_{\ell,q} \frac{122\ \mathrm{GeV}}{m_V}$ $+$ $\lambda^q_{bs},\ \lambda^\ell_{\mu\mu},\ \lambda^\ell_{\tau\mu}$

several constraints:

- $R(D^*)$
- $R(D)$
- R_K
- $P_5'(B \to K^*\mu\mu)$

- $B(B \to K\nu\nu)$
- ΔM_{Bs} , ΔM_{Bd}
- CPV(D-$\underline{\text{D}}$)
- $\Gamma(B \to X\mu\nu)/\Gamma(B \to Xe\nu)$
- $\tau \to 3\mu$
- $\Gamma(\tau \to \mu\nu\nu)/\Gamma(\tau \to e\nu\nu)$

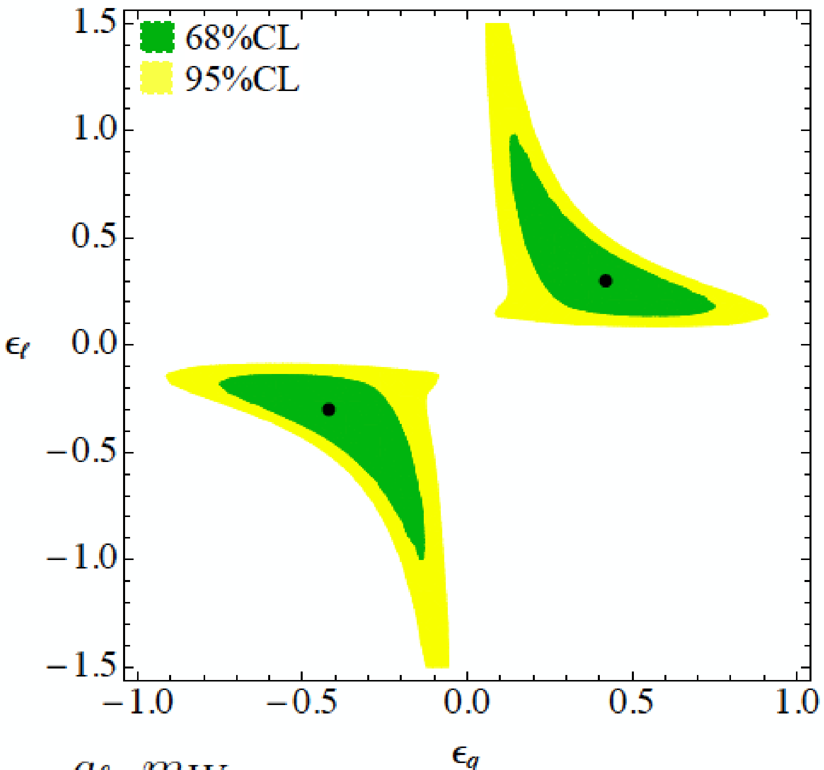
↓

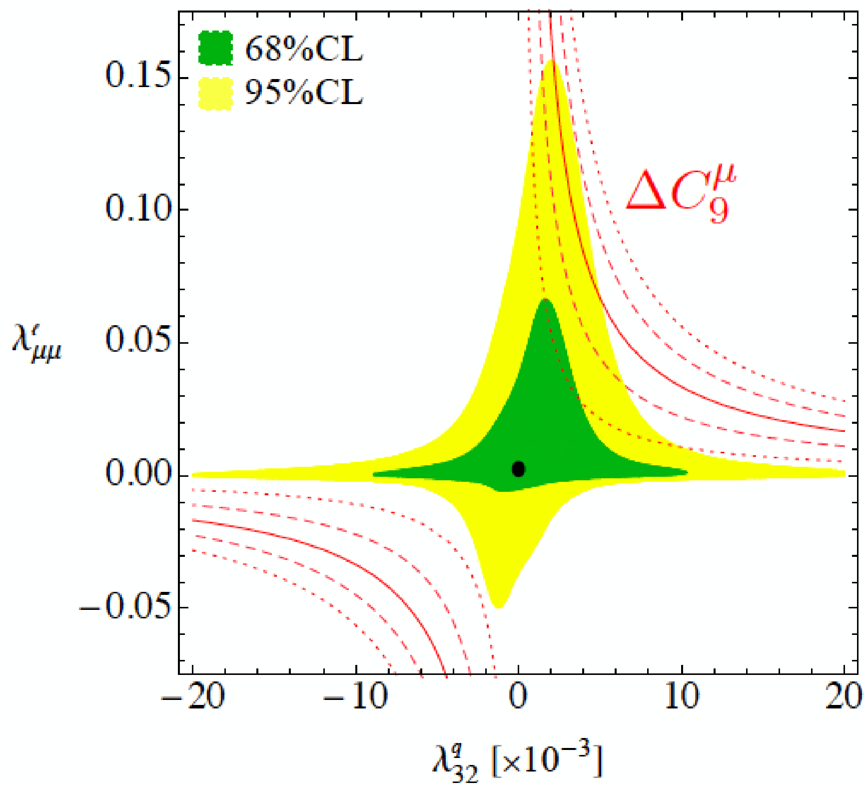
Overall good fit of low-energy data
(*non-trivial given tight constraints from ΔF=2 & LFV*)

Best fit point: $\epsilon_\ell \approx 0.37$, $\epsilon_q \approx 0.38$ *p*(SM) = 0.002

(flavor structure of the sub-leading terms not really probed)

A simplified dynamical model → low-energy global fit:





$$\epsilon_{\ell,q} = \frac{g_{\ell,q} m_W}{g m_V}$$

$\varepsilon_\ell, \varepsilon_q \lesssim 1$

$\lambda_{\mu\mu} \lesssim 0.1$

$\lambda_{bs} \lesssim 0.015$

A simplified dynamical model → further low-energy tests:

$$\mathscr{L}_{\rm eff} = -\frac{1}{2m_V^2} J_\mu^a J_\mu^a$$

works well...

… and gives several clear predictions for future low-energy data:

- b → c(u) $l\nu$ — $BR(B\to D^*\tau\nu)/BR_{SM} = BR(B\to D\tau\nu)/BR_{SM} = BR(\Lambda_b \to \Lambda_c\tau\nu)/BR_{SM}$ $= \ldots = BR(B_u \to \tau\nu)/BR_{SM}$ $\quad R^{\mu/e}(X) \sim 10\%\ R^{\tau/\mu}(X)$

- b → s μμ — $\Delta C_9^\mu = -\Delta C_{10}^\mu$, but overall size of the anom. should decrease
- b → s ττ — |NP| ~ |SM| → large enhancement (~ BR×4) or strong suppr.
- b → s νν — ~ ± 50% deviation from SM in the rate

- Meson mixing — ~ 10% deviations from SM both in ΔM_{Bs} & ΔM_{Bd}
- τ decays — τ → 3μ not far from present exp. bound

✯ A simplified dynamical model → high-energy constraints:

The dynamical model

$$\mathcal{L}_V = -\frac{1}{4} D_{[\mu} V^a_{\nu]} D^{[\mu} V^{\nu]a} + \frac{m_V^2}{2} V^a_\mu V^{\mu a} + g_H V^a_\mu (H^\dagger T^a i \overleftrightarrow{D}_\mu H) + V^a_\mu J^a_\mu$$

The "heavy vector triplet" eff. Lagrangian [Pappadopulo, Tham, Torre, Wulzer, '14] in a rather peculiar parameter range:

- W' and Z' resonances in the mass range:

$$g_{\ell,q} \sim 1 \ \to m_V \sim 250\text{GeV}$$
$$g_{\ell,q} \sim \sqrt{4\pi} \ \to m_V \lesssim 1\text{TeV}$$

- Strong constraint on g_H from e.w. precisions tests:

$$\epsilon_{\ell,q} = \frac{g_{\ell,q} m_W}{g m_V} \approx 0.3 \qquad\qquad \epsilon_H = \frac{g_H m_W}{g m_V} \lesssim 0.01$$

A simplified dynamical model → high-energy constraints:

- The heavy vectors are produced mainly from 3rd gen. quarks (bb → Z', bc → W') and decay mainly in 3rd generations quarks or leptons (Z' → ττ,bb,tt, W' →tb, τν)

↓

- Not a very easy signature...

The only really stringent constraint comes from Z' → ττ

A simplified dynamical model → high-energy constraints:

- The heavy vectors are produced mainly from 3rd gen. quarks (bb → Z', bc → W') and decay mainly in 3rd generations quarks or leptons (Z' → ττ,bb,tt, W' →tb, τν)

↓

- Not a very easy signature...

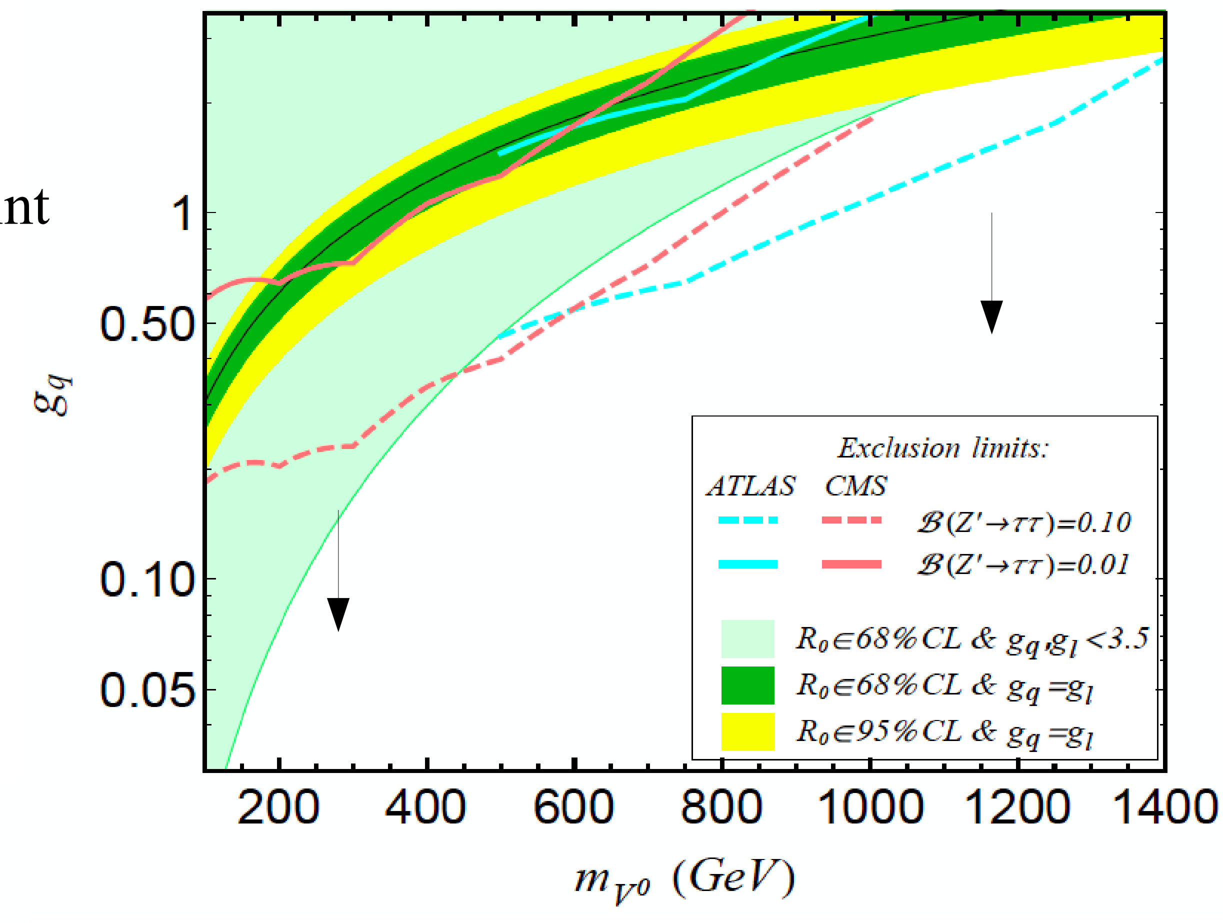
The only really stringent constraint comes from Z' → ττ

↓

Minimal version of the model (*no exotic decay channels*) ruled out by direct searches

$$BR(Z' \to \bar{\tau}\tau) = \frac{g_\ell^2}{2g_\ell^2 + 6g_q^2 + \text{extra}}$$

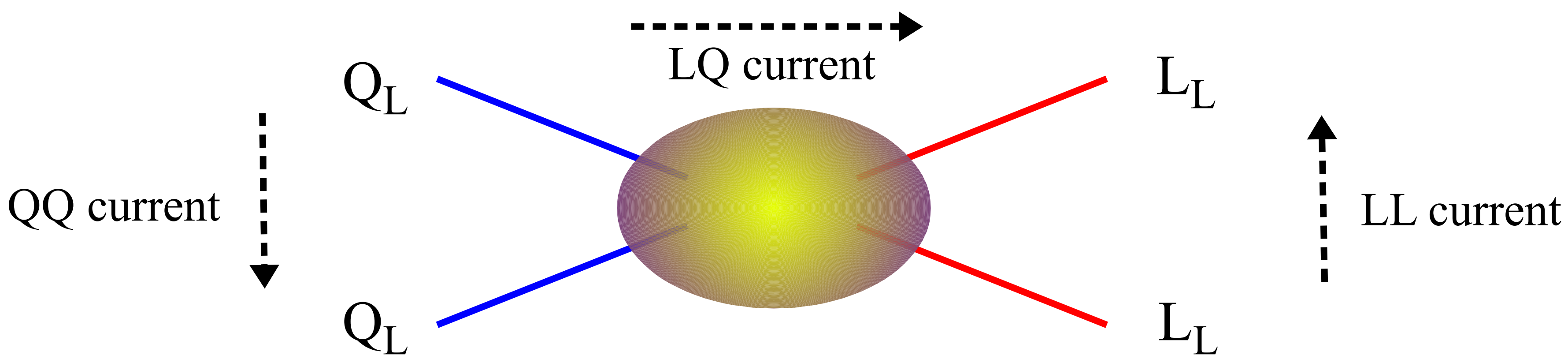
Greljo, GI, Marzocca '15



✯ *A simplified dynamical model → high-energy constraints:*

N.B.: while the low-energy consequences are almost independent from the structure of the underlying dynamical model, the high-energy consequences can be very different.

For instance, choosing the LQ mediator, we have a perfect candidate also for the mediator of the "S(750)"→γγ,gg effective couplings...



Conclusions

Conclusions

- We entered in a very special era in particle physics: the SM is a successful theory that has no intrinsic energy limitations.

- While waiting for possible clear clues for physics beyond the SM from high-energy experiments, the key (and difficult) question we face is: *what determines the precise values of SM parameters?* [*"anarchy + anthropic selection" vs. "new symmetries"*]

Conclusions

- We entered in a very special era in particle physics: the SM is a successful theory that has no intrinsic energy limitations.

- While waiting for possible clear clues for physics beyond the SM from high-energy experiments, the key (and difficult) question we face is: *what determines the precise values of SM parameters?* [*"anarchy + anthropic selection" vs. "new symmetries"*]

- We cannot exclude the anthropic principle is the right explanation for some of these couplings (e.g. for the cosmological constant), but it is definitely premature to give-up the attempt of finding dynamical explanations for most of them.

- In this perspective, (some of) the anomalies that are emerging both at high-pT and in flavor physics could be the first hints of new symmetries...