Flavor Physics and CP violation

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IV. Flavor Physics beyond the SM

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From yesterday's lecture

No clear indications of New Physics effects

- in meson-antimeson mixing amplitudes (detailed exploration)
- in clean rare B and K decays such as $B_s \rightarrow \mu\mu$ (although here the exploration has only started, and the errors are still large...)

Stringent bounds on couplings and masses of possible new particles

As we have seen by means of the Effective Theory approach to New Physics:

Either NP is very heavy... or it has a non-trivial flavor-breaking pattern...
From yesterday's lecture

Either NP is very heavy... or it has a non-trivial flavor-breaking pattern...

- Can we build NP models where the alignment with the CKM occurs "naturally?"

- Does this shed light on the origin of fermion masses and CKM hierarchies?

- Can we see deviations from the SM with more precise measurements? If yes, where?

  Rare K and B decays are potentially interesting candidates
From yesterday's lecture

Not all “penguin diagrams” are the same... and correspondingly not all rare decays are equally interesting...

- Very “clean” [top quark]
  - \(b \rightarrow s W\)
  - \(e, \mu, \nu\)
  - \(B_{s,d} \rightarrow \mu\mu\)
  - \(B \rightarrow K\nu\nu, \ K \rightarrow \pi\nu\nu\)

- Less “clean” [charm quark]
  - \(u, c, t\)
  - \(e, \mu\)
  - \(B \rightarrow K\mu\mu, \ B \rightarrow K^*\mu\mu\)
  - \(B \rightarrow K^*\nu\nu, \ B \rightarrow K^*\pi\nu\nu\)

- “dirty”
  - \(u, c, t\)
  - \(e, \mu\)
  - \(B \rightarrow K^*\mu\mu, \ B \rightarrow K^*\nu\nu\)

These channels are not hopeless, but we cannot extract the interesting info directly from the BR...
Lepton Flavor Universality Tests

\[ R_{K} \]

\[ R(D^*) \]

\[ \Delta \chi^2 = 1.0 \text{ contours} \]

\[ \text{SM Predictions} \]

- LHCb
- BELLE
- Babar

- SM from CDHMV
- SM from BOS
- SM from flav.io
- SM from JC

\[ q^2 [\text{GeV}^2/c^4] \]

\[ 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \]

\[ 0.0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1.0 \quad 1.2 \]

\[ 0.25 \quad 0.3 \quad 0.35 \quad 0.4 \quad 0.45 \quad 0.5 \]

LHCb Preliminary
Generalities

We denote Lepton Flavor Universality the property that the three charged leptons \((e, \mu, \tau)\) couple in a universal way to the SM gauge bosons.

Within the SM lepton flavor physics is somehow “boring”: the only flavor non-universal terms are the three lepton masses (N.B.: by construction, neutrinos are massless within the SM)

We can turn this “boring” property into a powerful tool to discover physics beyond the SM

If physics beyond the SM couples into a non-universal way to the different families of leptons (and there is no reason why this should not happen...) then we can discover it comparing similar rare decays with different pairs of leptons [ LFU tests ]
**LFU tests in $b \to s \ell\ell$**

The process $B \to K (K^*) + \ell\ell$ are mediated by the “clean” $Z$-penguin diagrams and also by the “less clean” photon-penguin diagrams. The latter are more difficult to estimate precisely; however, in both cases one predicts the $e/\mu$ ratio to be 1 (*mass effects are negligible* $m_B >> m_\mu$)

$$
\frac{\int d\Gamma(B \to K \mu\mu)}{\int d\Gamma(B \to K ee)} \bigg|_{SM} = \frac{\int d\Gamma(B \to K^* \mu\mu)}{\int d\Gamma(B \to K^* ee)} \bigg|_{SM} = 1 \quad (\text{th. error} < 1\%)$$

![Diagram of LFU tests in $b \to s \ell\ell$](image)
**LFU tests in b → s ll**

As it often happens, what is nice theoretically is a real exp. challenge...

Electrons emit a large amount of bremsstrahlung $\rightarrow$ degraded momentum and mass resolutions $\rightarrow$ recovery procedure is in place but incomplete (calorimeter acceptance, $E_T$ of the photon > 75 MeV ...)

$\Rightarrow$ the reconstructed B mass shifts towards lower values and events migrate in and out of the $q^2$ bins

[Marie-Helene Schune [LHCb], CERN talk March '17]
LFU tests in $b \to s \ell \ell$

As it often happens, what is nice theoretically is a real exp. challenge...
... but there are ways to handle the problem

$B \to K + \psi \ (\to \mu\mu)$

(cc resonance)
**LFU tests in $b \to s \ell \ell$**

As it often happens, what is nice theoretically is a real exp. challenge...  
... *but there are ways to handle the problem*

- $R_{K^{(*)0}} = \frac{\mathcal{B}(B \to K^{(*)0} \mu^+ \mu^-)}{\mathcal{B}(B \to K^{(*)0} J/\psi (\to \mu^+ \mu^-))} / \frac{\mathcal{B}(B \to K^{(*)0} e^+ e^-)}{\mathcal{B}(B \to K^{(*)0} J/\psi (\to e^+ e^-))}$

- Selection as similar as possible between $\mu \mu$ and $e e$ for physics-related variables

*Mitigating electron/muon differences*
**LFU tests in $b \rightarrow s \ell \ell$**

### Yields:

<table>
<thead>
<tr>
<th>$q^2 = m_{\ell \ell}^2$</th>
<th>Low-$q^2$</th>
<th>Central-$q^2$</th>
<th>$J/\psi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu \mu$</td>
<td>$285 \pm 18$</td>
<td>$353 \pm 21$</td>
<td>$274k$</td>
</tr>
<tr>
<td>$ee$</td>
<td>$89 \pm 11$</td>
<td>$111 \pm 14$</td>
<td>$58k$</td>
</tr>
</tbody>
</table>

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**G. Isidori – Flavor Physics and CP violation**

**CERN Summer Student Lectures 2017**

**LFU tests in $b \to s \ell \ell$**

Finally the interesting results:

1) $R_K = \frac{\int d\Gamma(B^+ \to K^+ \mu\mu)}{\int d\Gamma(B^+ \to K^+ ee)}$ vs. $R_K^{(SM)}$ = 1.00 ± 0.01

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

2) $R_{K^*} = \frac{\int d\Gamma(B^0 \to K^* \mu\mu)}{\int d\Gamma(B^0 \to K^* ee)}$

Overall significance of the deviations from the SM ~ 3.8σ ($LFU$ ratios only)
**LFU tests in $b \rightarrow s \ell\ell$**

Finally the interesting results:

1) \[ R_K = \frac{\int d\Gamma(B^+ \rightarrow K^+\mu\mu)}{\int d\Gamma(B^+ \rightarrow K^+\ell\ell)} \]

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

\[ \left| (\text{exp}) = 0.75 \pm 0.09 \right. \]

2) \[ R_{K^*} = \frac{\int d\Gamma(B^0 \rightarrow K^*\mu\mu)}{\int d\Gamma(B^0 \rightarrow K^*\ell\ell)} \]

Overall significance of the deviations from the SM $\sim 3.8\sigma$

*(LFU ratios only)*

Actually the tension with the SM *increases* taking into account also a series of angular distributions that points to *NP in the muon modes* only
**LFU tests in \( b \rightarrow c \tau \bar{\nu} \)**

Interestingly enough, a deviation from LFU seems to emerge also in a different class of decays: the charged-current decays of B mesons into tau's

Test of LFU in charged currents

\[ [\tau \text{ vs. light leptons (}\mu, e\text{)}] : \]

\[
R(X) = \frac{\Gamma(B \rightarrow X\tau\bar{\nu})}{\Gamma(B \rightarrow X\ell\bar{\nu})}
\]

- **SM prediction quite solid** (*small theory uncertainty, but mass effect not negligible*)
**LFU tests in $b \to c \tau \nu$**

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**Test of LFU in charged currents**

[$\tau$ vs. light leptons ($\mu$, $e$)]

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- Consistent exp. results by 3 (very) different experiments
  - $3.9\sigma$ excess over SM (if D and D* combined)
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**LFU tests in $b \to c \tau \nu$**

Interestingly enough, a deviation from LFU seems to emerge also in a different class of decays: the **charged-current decays** of B mesons into tau's.

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

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

- **SM prediction quite solid**
- Consistent exp. results by 3 (very) different experiments
- 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)
Summary

This pattern of deviations from LFU is very interesting...!

However, please wait before getting super-excited... the statistical significance is high, but not high enough to claim a discovery (with many searches some anomalies are expected...).
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However, please wait before getting super-excited... the statistical significance is high, but not high enough to claim a discovery (with many searches some anomalies are expected...)

Still, while waiting for more precision studies, it is interesting to speculate a bit on what we seem to observe → two rather different classes of phenomena:

- **b → c charged currents**: τ vs. light leptons (μ, e)
  
  Large effect *(competing with SM tree-level)*

- **b → s neutral currents**: μ vs. e
  
  Small effect *(competing with a SM rare amplitude)*
Summary

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Still, while waiting for more precision studies, it is interesting to speculate a bit on what we seem to observe → two rather different classes of phenomena:

- **b → c charged currents**: τ vs. light leptons (μ, e)
  Large effect (competing with SM tree-level)

- **b → s neutral currents**: μ vs. e
  Small effect (competing with a SM rare amplitude)

This pattern is not un-natural in extensions of the SM where NP coupled predominantly to the 3rd generation → possible link to a dynamical explanation of the observed hierarchies in the Yukawa couplings
Flavor Symmetries
Either NP is very heavy... or it has a non-trivial flavor-breaking pattern...

- Can we build NP models where the alignment with the CKM occurs “naturally?

- Does this shed light on the origin of fermion masses and CKM hierarchies?

- Can we see deviations from the SM with more precise measurements? If yes, where?

Maybe we are starting to see some deviations from the SM in LFU ratios... and the (flavor) pattern is clearly non-trivial
Generalities

The flavor structure of the SM is characterized by:

- **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]

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

\[ \mathcal{L}_{\text{gauge}} = \sum_a - \frac{1}{4g_a^2} (F_{\mu\nu}^a)^2 + \sum_\psi \sum_i \bar{\psi}_i iD \psi_i \]

E.g.: \[ Q_L^i \rightarrow U^{ij} Q_L^j \]

\[ Q_L = \begin{bmatrix} u_L \\ d_L \end{bmatrix}, \quad u_R, \ d_R, \quad L_L = \begin{bmatrix} v_L \\ e_L \end{bmatrix}, \quad e_R \]

SU(3) flavor-dependent mixing matrix
Generalities

The flavor structure of the SM is characterized by:

- **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]

\[
\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}}
\]

\[
\overline{Q}_L^i Y_{U}^{ij} U_R^j \phi + \overline{Q}_L^i Y_{D}^{ij} D_R^j \phi_c
\]
**Generalities**

The flavor structure of the SM is characterized by:

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\[
\mathcal{L}_{SM} = \mathcal{L}_{gauge} + \mathcal{L}_{Higgs}
\]

This specific symmetry + symmetry-breaking pattern is responsible for the suppression of Flavor Changing Neutral Currents, the meson-antimeson mixing amplitudes,...

*all the successful SM predictions in the quark flavor sector*
The MFV hypothesis

Since the global flavor symmetry is already broken within the SM, is not consistent to impose it as an exact symmetry beyond the SM.

However, if we want to “protect” flavor mixing beyond the SM, we can do it in a consistent way “promoting” the Yukawa matrices to be the vacuum expectation values of appropriate auxiliary fields, and assume that these vacuum expectation values are the only sources of flavor symmetry breaking.

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

\[
\mathcal{L}_{\text{Yukawa}} = \overline{Q}_L Y_D D R \phi + \overline{Q}_L Y_U U R \phi_c + \overline{L}_L Y_L e_R \phi + \text{h.c.}
\]

\( (\overline{3},1,1) \) \( (3,1,\overline{3}) \) \( (1,1,\overline{3}) \)

\( (1,1,1) = \text{invariant} \)
The MFV hypothesis

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

- **Symmetry-breaking terms:**
  \[ Y_D \sim 3_Q \times 3_D \quad Y_U \sim 3_Q \times 3_U \]
  [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*
The MFV hypothesis

General principle which can be applied to any extension of the SM
**The MFV hypothesis**

- **Flavor symmetry:**
  \[ U(3)^5 = U(3)_Q \times U(3)_U \times U(3)_D \times \ldots \]

- **Symmetry-breaking terms:**
  \[ Y_D \sim \overline{3}_Q \times 3_D \quad Y_U \sim \overline{3}_Q \times 3_U \]

**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 → natural stabilization of the Higgs sector
- It leads to a rather predictive framework:

  All flavor-changing amplitudes must have the same CKM/Yukawa structure as in the SM. Only the flavor-independent magnitude of the transition amplitudes can be modified.
If we apply the MFV hypothesis to the meson-antimeson mixing amplitudes, we get exactly the “alignment” we were hoping for in order to keep a low scale of NP:

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

\[ \sim 1 \quad \text{tree/strong + generic flavor} \rightarrow \Lambda \gtrsim 2 \times 10^4 \text{ TeV} \ [K] \]

\[ \sim \frac{1}{(16\pi^2)} \quad \text{loop + generic flavor} \rightarrow \Lambda \gtrsim 2 \times 10^3 \text{ TeV} \ [K] \]

\[ \sim (V_{ti}^* V_{tj})^2 \quad \text{tree/strong + “alignment”} \rightarrow \Lambda \gtrsim 5 \text{ TeV} \ [K \ & B] \]

\[ \sim \frac{(V_{ti}^* V_{tj})^2}{16\pi^2} \quad \text{loop + “alignment”} \rightarrow \Lambda \gtrsim 0.5 \text{ TeV} \ [K \ & B] \]
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\[ \sim (V_{ti}^* V_{tj})^2 \]

\[ \sim (V_{ti}^* V_{tj})^2/(16\pi^2) \]

\[ \sim 1 \]

\[ \sim 1/(16\pi^2) \]

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\[ \sim (V_{ti}^* V_{tj})^2/(16\pi^2) \]

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\[ \text{tree/strong + generic flavor} \]

\[ \Lambda \gtrsim 2 \times 10^4 \text{ TeV [K]} \]

\[ \Lambda \gtrsim 2 \times 10^3 \text{ TeV [K]} \]

\[ \text{loop + generic flavor} \]

\[ \Lambda \gtrsim 5 \text{ TeV [K & B]} \]

\[ \text{tree/strong + “alignment”} \]

\[ \Lambda \gtrsim 0.5 \text{ TeV [K & B]} \]

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

\[
\left| \frac{A(s \rightarrow dZ)}{A(b \rightarrow sZ)} \right| = \left| \frac{V_{td}}{V_{tb}} \right|
\]

as in the SM...

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

<table>
<thead>
<tr>
<th>Operator</th>
<th>Bound on $\Lambda$</th>
<th>Observables</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H^\dagger \left( \tilde{D}<em>R Y^d Y^u Y^u u^\dagger \sigma</em>{\mu\nu} Q_L \right) (e F_{\mu\nu})$</td>
<td>6.1 TeV</td>
<td>$B \rightarrow X_s \gamma$, $B \rightarrow X_s \ell^+\ell^-$</td>
</tr>
<tr>
<td>$\frac{1}{2} (\tilde{Q}<em>L Y^u Y^u u^\dagger \gamma</em>{\mu} Q_L)^2$</td>
<td>5.9 TeV</td>
<td>$\varepsilon_K$, $\Delta m_{B_d}$, $\Delta m_{B_s}$</td>
</tr>
<tr>
<td>$H^\dagger_D \left( \tilde{D}<em>R Y^d Y^u Y^u u^\dagger \sigma</em>{\mu\nu} T^a Q_L \right) (g_s G^a_{\mu\nu})$</td>
<td>3.4 TeV</td>
<td>$B \rightarrow X_s \gamma$, $B \rightarrow X_s \ell^+\ell^-$</td>
</tr>
<tr>
<td>$(\tilde{Q}<em>L Y^u Y^u u^\dagger \gamma</em>{\mu} Q_L) (\tilde{E}<em>R \gamma</em>{\mu} E_R)$</td>
<td>2.7 TeV</td>
<td>$B \rightarrow X_s \ell^+\ell^-$, $B_s \rightarrow \mu^+\mu^-$</td>
</tr>
</tbody>
</table>
A few important comments:

1) **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]

\[
A[b \rightarrow d(s)] \sim V_{td(s)} \begin{bmatrix}
    c^{(0)}_{SM} \frac{1}{M_W^2} & + & c^{(0)}_{NP} \frac{1}{\Lambda^2}
\end{bmatrix}
\]

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

Some more rare decays not precisely measured yet could provide more useful infos → Very interesting candidates: \( B_{d,s} \rightarrow \mu \mu \ & \ K \rightarrow \pi \nu \nu \)
Beyond MFV \[ \text{from } U(3)^3 \text{ to } U(2)^3 \]
Beyond MFV

**MFV virtue**

Naturally small effects in FCNC observables

**MFV main open problem**

No explanation for $Y$ hierarchies (masses and mixing angles)
Beyond MFV

**MFV virtue**
Naturally small effects in FCNC observables

**MFV main open problem**
No explanation for $Y$ hierarchies (masses and mixing angles)

If the deviations from the SM in the LFU tests were confirmed, this would also be a problem (*they cannot be explained in MFV since the lepton Yukawa couplings are too small*)
**Beyond MFV**

*MFV virtue*

Naturally small effects in FCNC observables

*MFV main open problem*

No explanation for $Y$ hierarchies (masses and mixing angles)

To solve this issue
+ other issues on the Higgs stability
+ hints of LFU violations

↓

NP coupled mainly to 3rd gen.
+ flavor symmetry acting *only* on 1st & 2nd generations
Beyond MFV

**MFV virtue**

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No explanation for $Y$ hierarchies (masses and mixing angles)

To solve this issue

+ other issues on the Higgs stability
+ hints of LFU violations

NP coupled mainly to 3rd gen.

+ flavor symmetry acting only on 1st & 2nd generations

\[ U(2)^n = U(2)_Q \times U(2)_U \times U(2)_D \times ... \text{ flavor symmetry} \]

Not the only option, but one of the most interesting ones..
**The $U(2)^n$ flavor symmetry**

The symmetry is a good approximation to the SM quark spectrum (exact symmetry for $m_u=m_d=m_s=m_c=0$, $V_{CKM}=1$), hence we only need to introduce small breaking terms.

\[
Y_u = y_t \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \quad Y_d = y_b \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}
\]

Unbroken

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

$2 \times 2$ block of the first two generations
**The $U(2)^n$ flavor symmetry**

The symmetry is a good approximation to the SM quark spectrum (exact symmetry for $m_u = m_d = m_s = m_c = 0$, $V_{CKM} = 1$), hence we only need to introduce small breaking terms:

Minimal set of breaking terms necessary to reproduce the quark spectrum, while keeping small rare processes beyond SM:

$$V \sim (2,1,1) \quad O(|V_{ts}| \sim 0.04)$$

Leading breaking \([3^{rd} \text{ gen. } \rightarrow 1,2 \text{ gen.}]\)

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

$$Y_u = y_t \begin{bmatrix} 0 & c_u V \\ 0 & 1 \end{bmatrix} \quad Y_d = y_b \begin{bmatrix} 0 & c_d V \\ 0 & 1 \end{bmatrix} \quad \rightarrow \quad V_{CKM} \sim \begin{bmatrix} 1 & O(|V_{ts}|) \\ 0 & 1 \end{bmatrix}$$
The U(2)^n flavor symmetry

The symmetry is a good approximation to the SM quark spectrum (exact symmetry for \( m_u = m_d = m_s = m_c = 0, V_{\text{CKM}} = 1 \)), hence we only need to introduce small breaking terms:

Minimal set of breaking terms necessary to reproduce the quark spectrum, while keeping small rare processes beyond SM:

\[
V \sim (2,1,1) \quad O(|V_{ts}| \sim 0.04) \quad \text{Leading breaking} \quad [3^{\text{rd}} \text{ gen. } \rightarrow 1,2 \text{ gen.}]
\]

\[
\Delta Y_u \sim (2,2,1) \quad m_c, m_u, \theta_u \quad O(0.005)
\]

\[
\Delta Y_d \sim (2,1,2) \quad m_s, m_d, \theta_d \quad O(0.001)
\]

\[
Y_u = y_t \begin{bmatrix} \Delta Y_u & c_u V \\ 0 & 1 \end{bmatrix} \quad Y_d = y_b \begin{bmatrix} \Delta Y_d & c_d V \\ 0 & 1 \end{bmatrix} \quad \text{full } V_{\text{CKM}}
\]
The U(2)^n flavor symmetry

The symmetry is a good approximation to the SM quark spectrum (exact symmetry for $m_u=m_d=m_s=m_c=0$, $V_{CKM}=1$), hence we only need to introduce small breaking terms:

Minimal set of breaking terms necessary to reproduce the quark spectrum, while keeping small rare processes beyond SM:

\[ V \sim (2,1,1) \quad O(|V_{ts}| \sim 0.04) \quad \text{Leading breaking [3^{rd} \text{ gen. } \rightarrow 1,2 \text{ gen.}]} \]

The main idea is that the flavor symmetry is broken in two (or more) steps.

The “virtue” (from the NP point of view) is more freedom for non-standard effects → possibility to have a relatively light NP sector coupled mainly to the 3^{rd} generation.
Possible links to the recent B-physics anomalies

- Models of NP based on U(2)-type flavor symmetries (acting on both quarks and leptons) can provide a rational for the pattern of observed hints of LFU non-universality (taking into account the tight bounds from other low-energy processes)

Main idea:

- NP coupled mainly to 3rd generation (competing with SM tree-level) in $q_3 q_3 \rightarrow l_3 l_3$ \(\Rightarrow\) $V_{cb} \text{b} \text{c} \rightarrow \tau \nu_\tau$

\[ \begin{array}{c}
Q_L^{(3)} \quad Q_L^{(3)} \\
L_L^{(3)} \quad L_L^{(3)}
\end{array} \]
Possible links to the recent B-physics anomalies

- Models of NP based on U(2)-type flavor symmetries (*acting on both quarks and leptons*) can provide a rational for the pattern of observed hints of LFU non-universality (*taking into account the tight bounds from other low-energy processes*).

Main idea:

- NP coupled mainly to 3\textsuperscript{rd} generation (competing with SM tree-level) in $q_3 q_3 \rightarrow l_3 l_3 \Rightarrow V_{cb} b c \rightarrow \tau \nu_\tau$

- Small non-vanishing coupling (competing with SM FCNC) in $b s \rightarrow \mu \mu$

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G. Isidori – Flavor Physics and CP violation

Glashow, Guadagnoli, Lane '14
Bhattacharya *et al.* '14
Alonso, Grinstein, Camalich '15
Greljo, GI, Marzocca '15
Barbieri, GI, Pattori, Senia '15
...
Conclusions
**Conclusions**

The filed of flavor physics is some how old... but is also in rapid evolution. The fact we have not discovered yet new physics in flavor-physics observables, should not discourage further investigations.

- We learned that new physics has a rather non-trivial flavor structure, but *the origin of this structure is still to be discovered.*

- There are several key issues that are still open (the origin of the Yukawa couplings, etc....) and maybe we are starting to see NP effects (→ *interesting hints of LFU violations in B decays*).

We need to *continue high-precision flavor-physics experiments* and, at the same time, we need to *further improve theory tools to describe (quark) flavor-changing transitions* with higher precision.

*I hope I convinced you that this field is quite interesting...*