Quark and Lepton Flavor connections

Gino Isidori
[ INFN, Frascati ]

- Introduction
- SUSY & Flavor
- Selected examples in the quark sector
- What determines the observed pattern of quark & lepton masses?
- Conclusions
Introduction

[direct vs. indirect searches of New Physics]
Introduction

After the discovery of a “Higgs-like” boson with mass around 126 GeV [consistent with e.w. precision tests & stability bounds], the SM couldn't be in better shape...
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Still, this theory suffers of a series of theoretical & cosmological problems:

- Fine-tuning/UV sensitivity of the Higgs-mass term [“hierarchy problem”]
- Unexplained hierarchical structure of the Yukawa couplings [“flavor puzzle”]
- No explanation for the quantization of the U(1) charges [hint of unification?]
- Non coherent inclusion of gravity at the quantum level
- No good candidate for dark matter
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The SM is likely to be an effective theory, or the low-energy limit of a more fundamental theory, with new degrees of freedom around or above the electroweak scale (i.e. around or above 1 TeV).
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The only (qualitative) indication of NP around 1 TeV:

\[
\Delta m_h^2 \sim \Lambda^2
\]
Introduction

The SM is likely to be an effective theory, or the low-energy limit of a more fundamental theory, with new degrees of freedom around or above $\sim 1$ TeV.

These structures do not seem to be accidental...
Introduction

The SM is likely to be an effective theory, or the low-energy limit of a more fundamental theory, with new degrees of freedom around or above \( \sim 1 \) TeV

one of the arguments why we believe the SM is not a complete theory

key tool to investigate the nature of physics beyond the SM

\[
L_{\text{SM}+\nu} = L_{\text{gauge}} (A_a, \psi_i) + D\phi^+ D\phi - V_{\text{eff.}} (\phi, A_a, \psi_i)
\]

\[
V_{\text{eff.}} = - \mu^2 \phi^+ \phi + \lambda (\phi^+ \phi)^2 + Y^{ij} \psi_L^i \psi_R^j \phi + \frac{g^{ij}}{\Lambda} \psi_L^i \psi_L^j T_j \phi \phi^T + \ldots
\]

• From \( \nu \) masses we already know the SM is an effective theory
• The vast majority (and the less tested) couplings of the Higgs boson are “flavor couplings”
\[ V(\phi) = -\mu^2 \phi^+\phi + \lambda (\phi^+\phi)^2 + Y^{ij} \psi_L^i \psi_R^j \phi + \frac{g^{ij}}{\Lambda} \psi_L^i \psi_L T^j \phi \phi^T + ... \]

Beside the direct searches of new degrees of freedom at high energies, the main goal now is to understand if, and how large, are the additional terms in this series

*(natural to expect non-vanishing couplings in operators involving \(\phi\))

---

**Higgs physics**

&

**Flavor physics**
Beside the direct searches of new degrees of freedom at high energies, the main goal now is to understand if, and how large, are the additional terms in this series 

\[ V(\phi) = - \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 + Y^{ij} \psi_L^i \psi_R^j \phi + \frac{g^{ij}}{\Lambda} \psi_L^i \psi_L^T \phi \phi^T + \ldots \]

(natural to expect non-vanishing couplings in operators involving $\phi$)

the (relatively) small value of $m_h$ + compatibility of the $h$ couplings with SM + absence of NP signals so far

\[ \downarrow \]

NP is likely to be weakly coupled with a non-negligible mass gap (hopefully not too large..) between NP and SM degrees of freedom

\[ \downarrow \]

Indirect searches of NP require high precision, but are a fundamental ingredient in searching for physics beyond the SM
Under very general assumptions (gauge symmetry + absence of new light states) flavor and e.w. observables used for indirect NP searches can be decomposed as follows:

\[ A = A_0 \left[ c_{SM} \frac{1}{M_W^2} + c_{NP} \frac{1}{\Lambda^2} \right] \]

This decomposition is very general: it holds both for forbidden processes (e.g.: $\mu \to \epsilon \gamma$) and precision measurements (e.g.: $B_s \to \mu \mu$)

- The interest of a given obs. depends on the magnitude of $c_{SM}$ vs. $c_{NP}$ and on the theoretical error of $c_{SM}$ → concentrate on clean & rare processes
- No way to disentangle $\Lambda$ & $c_{NP}$, but fully complementary to direct searches at high-$p_T$ → symmetry-structure of NP & possible access to high scale dynamics
The present lack of direct signals of NP at the high-energy frontier has reinforced the interest of indirect searches, given their potential sensitivity to high scales:

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}+\nu} + \frac{c_{\text{NP}}}{\Lambda^2} O_{ij} \]

\[ (6) \]

G.I., Perez, Nir '10
(2013 update)

<table>
<thead>
<tr>
<th>Operator</th>
<th>Bounds on $\Lambda$ in TeV ($c_{\text{NP}} = 1$)</th>
<th>Bounds on $c_{\text{NP}}$ ($\Lambda = 1$ TeV)</th>
<th>Observables</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\left( \bar{s}_L \gamma^\mu d_L \right)^2$</td>
<td>$\text{Re} = 9.8 \times 10^2$, $\text{Im} = 1.6 \times 10^4$</td>
<td>$\text{Re} = 9.0 \times 10^{-7}$, $\text{Im} = 3.4 \times 10^{-9}$</td>
<td>$\Delta m_K; \epsilon_K$</td>
</tr>
<tr>
<td>$\left( \bar{s}_R d_L \right) \left( \bar{s}_L d_R \right)$</td>
<td>$\text{Re} = 1.8 \times 10^4$, $\text{Im} = 3.2 \times 10^5$</td>
<td>$\text{Re} = 6.9 \times 10^{-9}$, $\text{Im} = 2.6 \times 10^{-11}$</td>
<td>$\Delta m_K; \epsilon_K$</td>
</tr>
<tr>
<td>$\left( \bar{c}_L \gamma^\mu u_L \right)^2$</td>
<td>$\text{Re} = 1.2 \times 10^3$, $\text{Im} = 2.9 \times 10^3$</td>
<td>$\text{Re} = 5.6 \times 10^{-7}$, $\text{Im} = 1.0 \times 10^{-7}$</td>
<td>$\Delta m_D;</td>
</tr>
<tr>
<td>$\left( \bar{c}_R u_L \right) \left( \bar{c}_L u_R \right)$</td>
<td>$\text{Re} = 6.2 \times 10^3$, $\text{Im} = 1.5 \times 10^4$</td>
<td>$\text{Re} = 5.7 \times 10^{-8}$, $\text{Im} = 1.1 \times 10^{-8}$</td>
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<tr>
<td>$\left( \bar{b}_L \gamma^\mu d_L \right)^2$</td>
<td>$\text{Re} = 6.6 \times 10^2$, $\text{Im} = 9.3 \times 10^2$</td>
<td>$\text{Re} = 2.3 \times 10^{-6}$, $\text{Im} = 1.1 \times 10^{-6}$</td>
<td>$\Delta m_{B_d}; S_{\psi K_S}$</td>
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<td>$\left( \bar{b}_R d_L \right) \left( \bar{b}_L d_R \right)$</td>
<td>$\text{Re} = 2.5 \times 10^3$, $\text{Im} = 3.6 \times 10^3$</td>
<td>$\text{Re} = 3.9 \times 10^{-7}$, $\text{Im} = 1.9 \times 10^{-7}$</td>
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<tr>
<td>$\left( \bar{b}_L \gamma^\mu s_L \right)^2$</td>
<td>$\text{Re} = 1.4 \times 10^2$, $\text{Im} = 2.5 \times 10^2$</td>
<td>$\text{Re} = 5.0 \times 10^{-5}$, $\text{Im} = 1.7 \times 10^{-5}$</td>
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<tr>
<td>$\left( \bar{b}_R s_L \right) \left( \bar{b}_L s_R \right)$</td>
<td>$\text{Re} = 4.8 \times 10^2$, $\text{Im} = 8.3 \times 10^2$</td>
<td>$\text{Re} = 8.8 \times 10^{-6}$, $\text{Im} = 2.9 \times 10^{-6}$</td>
<td>$\Delta m_{B_s}; S_{\psi \phi}$</td>
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If NP is not around the corner, flavor-changing processes might allow to probe high scales (if the flavor structure of the theory is not trivial)

N.B.: if NP contributes only at the loop level, then $\Lambda_{\text{NP}} \sim 4\pi m_{\text{NP}}$
The present lack of direct signals of NP at the high-energy frontier has reinforced the interest of indirect searches, given their potential sensitivity to high scales:

\[
\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM} + \nu} + \frac{c_{\text{NP}}}{\Lambda^2} O_{ij}^{(6)}
\]

This is of course true also in the lepton sector:

\[
\frac{c_{\mu e}}{\Lambda^2} \bar{e}_L \sigma^{\mu \nu} \mu_R \phi F_{\mu \nu}
\]

\[\Lambda > 4 \times 10^5 \text{ TeV} \times (c_{\mu e})^{1/2} \text{ from } \frac{\text{BR(\mu\rightarrow e\gamma)}}{\exp} < 5.7 \times 10^{-13}\]

MEG '13
However, we should keep in mind that the constraints on the scale of NP become much less severe in realistic/motivated models where the mechanisms of \textit{flavor-mixing} and \textit{fermion masses} are linked together.

E.g.: \textit{Minimal Flavor Violation}

Yukawa couplings as unique sources of flavor symmetry breaking

\begin{itemize}
\item SU(3)$^3$
\item Quark Flavor Symmetry
\item \textbf{Y}^{ik} \ldots \textbf{Y}^{jl}
\item $q^i_L$, $q^j_L$, $q^k_R$, $q^l_R$
\end{itemize}

SU(3)$_Q \times$SU(3)$_U \times$SU(3)$_D$

Quark Flavor Group

Chivukula & Georgi, '89
D'Ambrosio, Giudice, G.I., Strumia, '02
However, we should keep in mind that the constraints on the scale of NP become much less severe in realistic/motivated models where the mechanisms of *flavor-mixing* and *fermion masses* are linked together.

E.g.: *Minimal Flavor Violation* or *Partial Compositeness*

-Yukawa couplings as unique sources of flavor symmetry breaking

-“Elementary-composite mixing” as unique source of fermion mass hierarchies
### Mass scale of New Physics (new colored & flavored particles)

<table>
<thead>
<tr>
<th>Flavor Structure</th>
<th>$&lt; 1$ TeV</th>
<th>few TeV</th>
<th>$&gt; 1$ TeV</th>
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<tbody>
<tr>
<td><strong>Anarchic</strong></td>
<td>huge [$&gt; O(1)$]</td>
<td>sizable [$O(1)$]</td>
<td>sizable/small [$&lt; O(1)$]</td>
</tr>
<tr>
<td>Small misalignment</td>
<td>sizable [$O(1)$]</td>
<td>small [$O(10%)$]</td>
<td>small/tiny [$O(1-10%)$]</td>
</tr>
<tr>
<td>(e.g. partial compositeness)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aligned to SM ($MFV$)</td>
<td>small [$O(10%)$]</td>
<td>tiny [$O(1%)$]</td>
<td>not visible [$&lt; 1%$]</td>
</tr>
</tbody>
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### Direct New Physics searches @ high pT:
- NP within direct reach @ 8 TeV
- NP within reach @ 14 TeV
- NP beyond direct searches @ LHC
Mass scale of New Physics (new colored & flavored particles)

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Direct New Physics searches @ high pT:

NP effects in Quark Flavor Physics:

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There is still a wide range of “NP parameter space” that can and need to be explored (without strong theoretical prejudices) in quark & lepton flavor physics.
SUSY & Flavor

I ♥ Susy
A (very) concise summary about direct searches for New Physics

Despite several efforts, no non-standard state has been discovered so far at the LHC. Rough summary of the present status of high-energy searches:

- **The Higgs boson is around 125 GeV**
  - within the “SUSY” region, despite a bit heavier than expected
  - technicolor and most composite-Higgs models somehow disfavored*

- Bounds on generic “colored” new states typically above 1 TeV
- Colored new states coupled only to 3\textsuperscript{rd} gen. quarks still allowed below 1 TeV
- Bounds on colorless new states still in the few 100 GeV domain

* but definitely not ruled out !

[wide literature...]
A (very) concise summary about direct searches for New Physics

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- **Supersymmetry remains a good candidate**: weakly coupled theory + light Higgs (+ dark-matter & unification)
- **The SUSY spectrum is less trivial than expected**: only a few new states below the TeV
- **Some tuning in $m_h$ is unavoidable**: *do we really care if the fine-tuning is ~1%?*
A (very) concise summary about direct searches for New Physics

The strongest bounds on the SUSY spectrum are on gluinos and 1\textsuperscript{st}-2\textsuperscript{nd} gen. squarks.

They imply an overall heavy SUSY spectrum only in simplified models, with a MFV structure (such as the CMSSM).

- Supersymmetry remains a good candidate: weakly coupled theory + light Higgs (+ dark-matter & unification)

- The SUSY spectrum is less trivial than expected: only a few new states below the TeV

- Some tuning in $m_h$ is unavoidable: \textit{do we really care if the fine-tuning is $\sim1\%$}?
“Split-family” SUSY

Possible SUSY spectrum still compatible with present data that minimizes the fine-tuning problem in $m_h$

- Only 3\textsuperscript{rd} gen. squarks + Higgsinos need to be “light” to minimize the tuning in $m_h$
- A large stop-mixing term is needed to explain $m_h \sim 125$ GeV → large splitting among the stops → one of the two mass eigenstates (an almost RH stop) could well be in the few 100 GeV region, with all other colored states above 1 TeV
- The splitting of the 3\textsuperscript{rd} family can be well motivated in flavor models (connection with large top mass)
“Split-family” SUSY

A scenario that LHC experiments have only started to explore, where **flavor physics definitely plays a key role** given the non-trivial flavor structure of the SUSY spectrum → interesting non-standard effects mediated by the exchange of the 3\(^{rd}\) generation of squarks and leptons:

Possible “visible” effects in
- CPV in K mixing ($\varepsilon_K$)
- CPV in $B_{s,d}$ mixing ($\phi_{s,d}$)

Possible “visible” effects in
- Direct CPV in charm ($\Delta a_{CP}$)
- Rare B decays ($B_s \rightarrow \mu\mu$)
- LFV ($\mu \rightarrow e\gamma$) & EDMs
“Mini-Split” SUSY

If we give-up the goal of minimizing the fine-tuning in $m_h$, retaining other appealing features of SUSY (such as unification), other options become possible. A particularly interesting one is the so-called “mini-split” scenario:

- “loop-splitting” between gauginos ($\sim$TeV) and sfermions ($\sim$10-100 TeV)

- Possible generic flavor structure (no “flavor-tuning” on squarks).

Giudice, Luty, Muraya, Rattazzi, '98
Arvanitaki et al. '12
+ many others...
“Mini-Split” SUSY

Also in this case flavor observables may play a key role in finding-evidences or constraining the model:

Present bounds:
- on specific sfermion masses by corresponding low-energy observables

Possible Future reach:

Althmanshofer, Harnik, Zupan, '13
High-quality flavor physics requires a good selection...
Example I: $B_{s,d} \rightarrow \mu\mu$

These modes are a unique source of information about flavor physics beyond the SM:
- theoretically very clean (virtually no long-distance contributions)
- particularly sensitive to FCNC scalar currents and FCNC Z penguins

Leading SM diagrams (unitary gauge):

- Good approx. to the full SM amplitude
Example I: $B_{s,d} \rightarrow \mu\mu$

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- theoretically very clean (virtually no long-distance contributions)
- particularly sensitive to FCNC scalar currents and FCNC Z penguins

Leading SM diagrams (unitary gauge):

Possible non-SM contributions:

Relevant for $\text{BR} = O(\text{SM})$

Possible large enhancement (e.g. SUSY @ large tan$\beta$)
Recent developments both on the theory and on the experimental side:

\[ \overline{\text{BR}}_{s,\text{SM}} = (3.65 \pm 0.23) \times 10^{-9} \]  
(time-integrated average)

Bobeth, Gorbahn, Hermann, Misiak, Stamou, Steinhauser '13  
+  
progress from Lattice QCD

\[ \overline{\text{BR}}_{s}^{\text{(exp)}} = (2.9 \pm 0.7) \times 10^{-9} \]  
LHCb + CMS '13

\[ \text{BR}_{d,\text{SM}} = (1.06 \pm 0.09) \times 10^{-10} \]

\[ \text{BR}_{d}^{\text{(exp)}} = (3.6 \pm 1.5) \times 10^{-10} \]

An overall th. error below 5% is definitely within the reach in the next few years

At this stage there is perfect compatibility, but we are only at the beginning...
The preferred regions (68% & 95% CL) do not take into account the new measurement.

...and the good agreement with SM has important implications:

E.g.: Impact of the present experimental bound on \( \text{BR}(B_s \rightarrow \mu^+\mu^-) \) in constrained versions of the MSSM.'
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E.g.: Impact of the present experimental bound on $\text{BR}(B_s \rightarrow \mu^+\mu^-)$ in constrained versions of the MSSM

$$\text{BR}^{(\text{exp})} = (3.5 \pm 1.0) \times 10^{-9}$$

Shift in the preferred regions (68% & 95% CL) with an hypothetical measurement:

The impact of $B_s \rightarrow \mu\mu$ is even more pronounced in scenarios such as “split-family” SUSY, if the stop is not too heavy.
Example II: $\Delta F=2$ amplitudes

Despite the overall consistency of the CKM picture, looking more closely the agreement of the various constraints is not perfect. Long-standing tension between $\varepsilon_K$ (CPV in $K^0$ mixing) & $S_{\psi K} = \sin(2\beta)$ (CPV in $B_d$ mixing)

SM fit, no $\varepsilon_K$ (no K-meson mix. phase)

SM fit, no $\phi_\delta$ (no Bd mix. phase)

The discrepancy does not exceed the $2\sigma$ level, but is “intriguing”, since it appears in two amplitudes particularly sensitive to NP.

Lunghi & Soni '08
Buras & Guadagnoli '08
Lenz et al. '12
Example II: $\Delta F=2$ amplitudes

Best way to clarify the situation: improve the precision on $\gamma$ and $|V_{ub}| \rightarrow$ CKM from pure tree-level observables (*not easy...*)

Alternative route: compare CKM constraints from $\Delta F=2$ with $K \rightarrow \pi \nu\nu$ (*not easy*)

Two ways to disentangle NP in kaon mixing
(as expected in the “split-family” or “mini-split” SUSY models)
**Example II: ΔF=2 amplitudes**

Best way to clarify the situation: improve the precision on $\gamma$ and $|V_{ub}|$ → CKM from pure tree-level observables (*not easy...*)

Alternative route: compare CKM constraints from ΔF=2 with $K \rightarrow \pi\nu\nu$ (*not easy*

Quite interesting to see also what happens in the ΔF=2 $b \rightarrow s$ mixing amplitude (CPV in $B_s$ mixing), where the SM prediction is more precise (*easier in the short term, but less conclusive...*):

$$\sin(2\beta_s)^{\text{SM}} = 0.036 \pm 0.01$$
$$\sin(2\beta_s)^{\text{exp}} = -0.01 \pm 0.07 \pm 0.01$$

LHCb '13

So far, no signs of deviations from the SM, but the precision is not conclusive yet
Example III: CP-violation in the charm system

The physics of charm mixing and charm decays ($c \to u$ transitions) is quite different with respect to the $B_{s,d}$ ($b \to s,d$) and $K$ ($s \to d$) systems.

No top-enhancement of FCNC amplitudes (both $\Delta F=2$ & $\Delta F=1$):

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

- In all CP-conserving amplitudes we can safely approximate the CKM matrix to a 2x2 real mixing matrix, and long-distance contributions are largely dominant.

- CP-violating amplitudes are not calculable with high-accuracy within the SM, but are expected to be very small because of the CKM hierarchy ⇒ possible interesting null-tests of the SM.
Example III: CP-violation in the charm system

The “quasi-evidence” (4σ!) of CP violation in two-body Cabibbo-suppressed charm decays $D \rightarrow KK, \pi\pi$ ($c \rightarrow u + ss, dd$) reported by LHCb & other experiments in 2012 was a big surprise:

$$\Delta a_{CP} = a_{CP}(K^{+}K^{-}) - a_{CP}(\pi^{+}\pi^{-}) = (0.67 \pm 0.16)\%$$

- Unambiguous evidence of direct CP violation:

$$a^{(\text{dir})}_{CP} = \frac{\Gamma(D \rightarrow PP) - \Gamma(\bar{D} \rightarrow PP)}{\Gamma(D \rightarrow PP) + \Gamma(\bar{D} \rightarrow PP)}$$

- Totally unexpected, at least according to (most of the) pre-LHCb predictions
Example III: CP-violation in the charm system

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After the 2013 LHCb results this evidence is much weaker...

- New HFAG average [March ‘13]
  \[ \Delta a_{CP}^{dir} = (-0.33 \pm 0.12)\% \]

...but the basic question of what can we expect in the SM (and what can we learn about BSM) from direct CP-violation in Cabibbo-suppressed modes remains interesting.
Example III: CP-violation in the charm system

A value of $\Delta a_{CP} > 0.5\%$ is definitely too large compared to its “natural” SM expectation, but is not large enough, compared to SM uncertainties, to be considered a clear signal of NP:

$$\Delta a_{CP} \approx (0.13\%) \, \text{Im}(\Delta R^{SM})$$

CKM suppression:

matrix-element ratio:

“penguin”

“tree”

$$\arg \left( \frac{V_{cs}^* V_{us}}{V_{cd}^* V_{ud}} \right) = O(\lambda^4)$$

$\Delta R > 1$ is not what we expect for $m_c >> \Lambda_{QCD}$, but is not impossible treating the charm as a light quark (possible connection with the $\Delta I=1/2$ rule in Kaons)

More work (and especially more observables) needed in order to clarify the situation.
Example III: CP-violation in the charm system

A value of $\Delta a_{\text{CP}} > 0.5\%$ is definitely too large compared to its “natural” SM expectation, but is not large enough, compared to SM uncertainties, to be considered a clear signal of NP.

A value of $\Delta a_{\text{CP}} > 0.5\%$ fits well in a wide class of NP models predicting sizable CPV in *chromo-magnetic* operators ($Q_8$).

- Stringent bounds from D meson mixing naturally satisfied
- Easily generated in various well-motivated models (SUSY with partial compositness,...)
- Open window on flavor-mixing in the up sector (about which we know very little...)
Example III: CP-violation in the charm system

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A value of $\Delta a_{\text{CP}} > 0.5\%$ fits well in a wide class of NP models predicting sizable CPV in chromo-magnetic operators ($Q_8$).

Unavoidable large CPV (model-independent connection via QCD) also in the electric-dipole operators ($Q_7$):

The best way to distinguish SM vs. NP is to look at radiative Cabibbo-suppressed decays, especially $D \rightarrow V \gamma$ or $D \rightarrow V l^+l^-$ where the hadronic matrix element of $Q_7$ is enhanced [$\Delta a_{\text{CP(radiative)}} \sim 10 \times \Delta a_{\text{CP(non-leptonic)}}$]
What determines the observed pattern of quark & lepton masses?

$V_{\text{CKM}} \sim \begin{pmatrix} 1 & \cdot & \cdot & \cdot \\ \cdot & 1 & \cdot & \cdot \\ \cdot & \cdot & 1 & \cdot \\ \cdot & \cdot & \cdot & 1 \end{pmatrix}$
What determines the observed pattern of quark & lepton masses?

Two main roads:

Anarchy

+  

Anthropic selection

(“Chance & Necessity” [J. Monod])

The symmetric way

(“The book of nature is written in terms of circles, triangles and other geometrical figures...” [G. Galilei])
What determines the observed pattern of quark & lepton masses?

Two main roads:

- Anarchy + Anthropic selection
  
  (“Chance & Necessity” [J. Monod])

- The symmetric way
  
  (“The book of nature is written in terms of circles, triangles and other geometrical figures...” [G. Galilei])

Many unanswered questions:

- It works well for $m_{u,d}$
- maybe also for $m_t$ & $\nu$ mixing,
- but what about CKM and the other masses? Why 3 generations?
- ....

- Main road of particle physics so far.
- It works well in the Yukawa sector (several possible options), less evident, but not excluded, in the neutrino case
- “large” flavor symmetry + “small” breaking is the best way to explain the absence of NP signals so far [and often implies visible NP signals with higher precision].

- No clear direction for future searches
The symmetric way [a possible option]

Minimally-broken $U(2)^3 = U(2)_{QL} \times U(2)_{UR} \times U(2)_{DR}$
acting on the 1$^{\text{st}}$ & 2$^{\text{nd}}$ generations of quarks

- The exact symmetry limit is good starting point for the SM quark spectrum ($m_u=m_d=m_s=m_c=0$, $V_{\text{CKM}}=1$) → we only need to introduce small breaking terms

\[ Y \propto (0,0,1) \]

This symmetry accommodates “naturally” heavy squarks for the first 2 generations (in the SUSY context)

The “small & minimal breaking” ensures small effects in rare processes (in agreement with present data)
The symmetric way [a possible option]

Minimally-broken $U(2)^3 = U(2)_{QL} \times U(2)_{UR} \times U(2)_{DR}$ acting on the 1st & 2nd generations of quarks

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A potential problem of this approach and, more generally, of any approach attributing a special role to the hierarchies in the Yukawa sector, is the problem of neutrino masses (under the hypothesis we are interested to describe in a unified way quark and lepton sectors):

- Why neutrino mixing angles are not as small as in the quark sector?
- Why the mass hierarchies in the neutrino sector are not as large as in the quark/charged-lepton sector?
The symmetric way [a possible option]

The only possibility of extending this idea to the neutrino sector, is to assume a different initial symmetry for Dirac and Majorna sectors (or a different initial breaking of some larger flavor symmetry)

The only two small parameters in the neutrino (Majorana) mass matrix are

\[ \zeta = \left| \frac{\Delta m^2_{\text{sol}}}{\Delta m^2_{\text{atm}}} \right|^{1/2} = 0.174 \pm 0.007, \]
\[ s_{13} = |(U_{\text{PMNS}})_{13}| = 0.15 \pm 0.02, \]

\[
\begin{align*}
M^+_\nu M_\nu & \xrightarrow{\zeta, s_{13} \to 0} \quad m_\nu^2 I + \Delta m_{\text{atm}}^2 \Sigma \\
\Sigma & \approx \frac{1}{2} \begin{pmatrix}
0 & 0 & 0 \\
0 & 1 & 1 \\
0 & 1 & 1
\end{pmatrix}
\end{align*}
\]

\[
\begin{align*}
\Delta m_{\text{atm}}^2 & \ll m_\nu^2 \\
m_\nu^2 I & \to \text{diagonal mass matrix}
\end{align*}
\]
The symmetric way \textit{[a possible option]}

Let's assume the Yukawa couplings and the neutrino mass matrix are \textit{dynamical fields} of the the MFV flavor group, and that their values are determined by a \textit{minimization principle} (e.g. the potential minimum)

\begin{align*}
Y \propto (0,0,1) & \quad \text{[ unbroken $U(2)_L \times U(2)_R$]} \\
M_\nu \propto (1,1,1) & \quad \text{[ unbroken $O(3)_L$]}
\end{align*}

“natural solutions” = configurations preserving maximally unbroken subgroups.

Michel & Radicati, '69
Cabibbo & Maiani, '69
The symmetric way [a possible option]

\[ \begin{align*}
Y & \propto (0,0,1) \quad [\text{unbroken } U(2)_L \times U(2)_R] \\
M_\nu & \propto (1,1,1) \quad [\text{unbroken } O(3)_L]
\end{align*} \]

A “natural orientation” of \( O(3)_L \) vs. \( U(2)_L \) preserving an unbroken \( U(1) \) symmetry implies a \( \pi/4 \) mixing angle in the PMNS matrix.
The symmetric way \textit{[a possible option]}

\[ Y \propto (0,0,1) \quad [\text{unbroken } U(2)_L \times U(2)_R] \]

\[ U(3)^5 \]

\[ M_v \propto \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \quad \text{unbroken } O(3)_L \]

same basis
The symmetric way [a possible option]

\[ Y \propto (0,0,1) \quad [\text{unbroken } U(2)_L \times U(2)_R] \]

\[ m_{\mu} \frac{1}{m_{\tau}} = O(\varepsilon) \]

\[ \frac{m_{\mu}}{m_{\tau}} \sim 0.06 < \frac{\Delta m_{\text{atm}}^2}{m_{\nu}^2} = O(\varepsilon) < |s_{13}| \sim 0.2 \]

\[ M_\nu \propto \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \quad (\text{unbroken } O(3)_L) \]

Alonso, Gavela, Isidori, Maiani, '13
The symmetric way \([a \text{ possible option}]\)

\(\text{U}(3)^5\)

\[ M_\nu \propto \begin{pmatrix}
1 & 0 & 0 \\
0 & 0 & 1 \\
0 & 1 & 0
\end{pmatrix} \quad \text{(unbroken)}
\]

\[ \text{O}(3)_L \]

\[ \frac{\Delta m_{\text{atm}}^2}{m_\nu^2} = O(\epsilon) \]

If all this is correct... 0ν2β decay experiments (and maybe KATRIN) should be very close to observe a positive signal...
Conclusions

- Despite we have not seen any clear NP signal yet, it is still likely (and experimentally allowed) to expect some new degrees of freedom around the TeV scale.

- The absence of NP signal so far fits well with the idea of a *weakly interacting extension of the SM + little hierarchy around the e.w. scale + mildly broken flavor symmetry* (coherent picture of precision tests + light Higgs + lack of deviations from SM at high-pT) → *Low-scale supersymmetry remains a good candidate.*

- We have understood that the flavor structure of this weakly interacting extension of the SM is not trivial, but we have not clearly identified this structure yet → *Improved experiments/searches in flavor physics play a key role in uncovering the nature of physics beyond the SM*
If all this is correct...
→ $0\nu2\beta$ decay experiments should be very close to observe a positive signal

… and if we add (low-energy) SUSY
→ LFV in charged leptons ($\mu \rightarrow e\gamma$) may also be close to present exp. bounds:

N.B.: LFV rates affected by a larger uncertainty
[ $BR \sim 1/m^4$]
**Flavor-violating Higgs couplings**

If we consider the SM as a low-energy effective theory, it is natural to include possible flavor-violating couplings of the physical Higgs boson.

h-mediated FCNCs are unavoidable in models with more Higgs doublets and, more generally, can be viewed as the effect of higher-dimensional operators (in the EFT approach):

\[ Y^{ij} \psi_L^i \psi_R^j \phi + \varepsilon^{ij} \psi_L^i \psi_R^j \phi^3 + ... \]

\[ \varepsilon^{ij} = \frac{c^{ij}}{\Lambda^2} \]

\[ (vY^{ij} + v^3 \varepsilon^{ij}) \psi_L^i \psi_R^j + (Y^{ij} + 3v^2 \varepsilon^{ij}) \psi_L^i \psi_R^j h + ... \]

\[ vY_{\text{eff}} \]

h FCNC couplings if \( Y^{ij} \neq c \varepsilon^{ij} \)
Flavor-violating Higgs couplings

\[ \mathcal{L}_{\text{eff}} = \sum_{i,j=d,s,b \ (i \neq j)} c_{ij} \bar{d}_L^i d_R^j h + \sum_{i,j=u,c,t \ (i \neq j)} c_{ij} \bar{u}_L^i u_R^j h + \sum_{i,j=e,\mu,\tau \ (i \neq j)} c_{ij} \bar{\ell}_L^i \ell_R^j h + \text{H.c.} \]

(fermion mass-eigenstate basis)

Strongly bounded by \( \Delta F=2 \)
(except for terms involving the top)

| Operator | Eff. couplings | 95% C.L. Bound \( |c_{\text{eff}}| \) | 95% C.L. Bound \( |\text{Im}(c_{\text{eff}})| \) | Observables |
|----------|----------------|-----------------|-----------------|-------------|
| \((\bar{s}_R d_L)(\bar{s}_L d_R)\) | \(c_{sd} \ c_{ds}^*\) | 1.1 \( \times 10^{-10}\) | 4.1 \( \times 10^{-13}\) | \(\Delta m_K; \epsilon_K\) |
| \((\bar{s}_R d_L)^2, (\bar{s}_L d_R)^2\) | \(c_{2d}, c_{2sd}^*\) | 2.2 \( \times 10^{-10}\) | 0.8 \( \times 10^{-12}\) | \(\Delta m_K; |q/p|, \phi_D\) |
| \((\bar{c}_R u_L)(\bar{c}_L u_R)\) | \(c_{cu} \ c_{uc}^*\) | 0.9 \( \times 10^{-9}\) | 1.7 \( \times 10^{-10}\) | \(\Delta m_D; |q/p|, \phi_D\) |
| \((\bar{c}_R u_L)^2, (\bar{c}_L u_R)^2\) | \(c_{2uc}, c_{2cu}^*\) | 1.4 \( \times 10^{-9}\) | 2.5 \( \times 10^{-10}\) | \(\Delta m_D; |q/p|, \phi_D\) |
| \((\bar{b}_R d_L)(\bar{b}_L d_R)\) | \(c_{bd} \ c_{db}^*\) | 0.9 \( \times 10^{-9}\) | 2.7 \( \times 10^{-9}\) | \(\Delta m_{B_d}; S_{B_d \to \psi K}\) |
| \((\bar{b}_R d_L)^2, (\bar{b}_L d_R)^2\) | \(c_{2db}, c_{2bd}^*\) | 1.0 \( \times 10^{-9}\) | 3.0 \( \times 10^{-9}\) | \(\Delta m_{B_d}; S_{B_d \to \psi K}\) |
| \((\bar{b}_R s_L)(\bar{b}_L s_R)\) | \(c_{bs} \ c_{sb}^*\) | 2.0 \( \times 10^{-7}\) | 2.0 \( \times 10^{-7}\) | \(\Delta m_{B_s}\) |
| \((\bar{b}_R s_L)^2, (\bar{b}_L s_R)^2\) | \(c_{2sb}, c_{2bs}^*\) | 2.2 \( \times 10^{-7}\) | 2.2 \( \times 10^{-7}\) | \(\Delta m_{B_s}\) |
Flavor-violating Higgs couplings

\[ \mathcal{L}_{\text{eff}} = \sum_{i,j,d,s,b \ (i \neq j)} c_{ij} d^i_L d^j_R h + \sum_{i,j=u,c,t \ (i \neq j)} c_{ij} u^i_L u^j_R h + \sum_{i,j=e,\mu,\tau \ (i \neq j)} c_{ij} \ell^i_L \ell^j_R h + \text{H.c.} \]

The bounds are significantly less severe in the lepton sector, especially for the $\tau\mu$ and $\tau e$ effective couplings:

<table>
<thead>
<tr>
<th>Eff. couplings</th>
<th>Bound</th>
<th>Constraint</th>
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<td>c_{e\tau} c_{\mu e}</td>
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<td>c_{\mu \tau}</td>
<td>^2$, $</td>
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Flavor-violating Higgs couplings

$$\mathcal{L}_{\text{eff}} = \sum_{i,j=d,s,b \ (i \neq j)} c_{ij} \bar{d}_L^i d_R^j h + \sum_{i,j=u,c,t \ (i \neq j)} c_{ij} \bar{u}_L^i u_R^j h + \sum_{i,j=e,\mu,\tau \ (i \neq j)} c_{ij} \bar{\ell}_L^i \ell_R^j h + \text{H.c.}$$

The bounds are significantly less severe in the lepton sector, especially for the $\tau\mu$ and $\tau e$ effective couplings.

Taking into account also the smallness of the Higgs width for $m \sim 125$ GeV (dominant partial width controlled by $y_b \sim 0.02$)

Flavor-changing decays into lepton pairs -with one tau- are not strongly constrained: $\text{BR}(h \rightarrow \tau\mu, \tau e) \lesssim 10\% \rightarrow \text{worth a direct search !!}$

ATLAS & CMS already have the sensitivity to set bounds on $\text{BR}(h \rightarrow \tau\mu) \lesssim 1\%$

Blankenburg, Ellis, G.I. '12

Harnik, Kopp, Zupan, '12
Davidson, Verdier, '12