Theoretical Prospects in Flavor Physics

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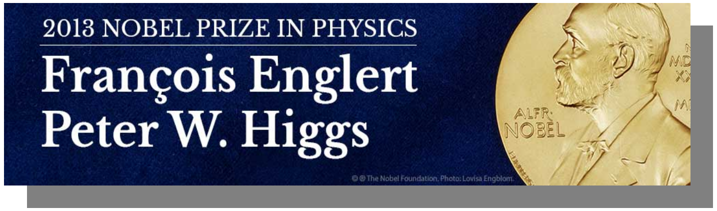
- Introduction
- Old problems & new hopes in Flavor Physics
- Some concrete examples in view of HL-LHC
- Conclusions

Introduction

[some general considerations]

Introduction

Oversimplifying, the three most important messages we learned so far from LHC run-I & II are:



- The Higgs boson has been found
  (the SM is a d=4 renormalizable QFT)

- The Higgs boson is "light"
  ($m_h \sim 125$ GeV → not the heaviest SM particle)

→ No clear UV cut-off on the SM view as an effective theory

- There is a "mass-gap" above the SM spectrum
  (i.e. no unambiguous sign of NP up to ~ 1 TeV)

Apparently a not too encouraging scenario…

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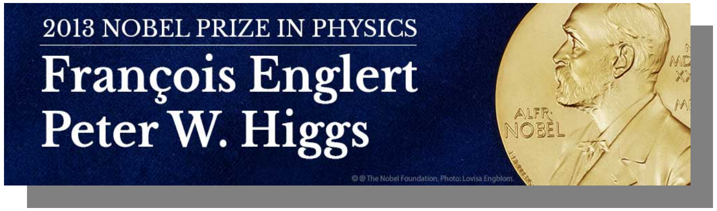

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Apparently a not too encouraging scenario...

However....

All SM problems (*hierarchy problem, flavor pattern, dark-matter, dark energy, inflation*...) are still there unsolved

→

Strong motivation to purse a diversified (broad spectrum) search for New Physics (difficult, given the lack of clear clues, but at the same time exciting !)

→

Key role of

Flavor Physics

[@ HL-LHC & beyond]

Introduction

Flavor physics has a long history full of interesting, sometime unexpected, results (= *indirect discoveries*), that anticipated *direct discoveries* at the high energy frontier.

Two most notable/simple examples:

- K-mixing, $K \to \mu\mu$ (GIM) ['70] $\to$ charm (J/psi) ['74]
- B-mixing + small $|V_{ub}|$ ['87] $\to$ (large) top ['95]

It could well be that, similarly to the past, also in the future new high-precision results in flavor physics will anticipate the discovery of new heavy particles.

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The fact that no new particle has been "signaled" by flavor physics since a long time should not be surprising: starting from the B-factory era (2000's) the experimental results in flavor physics *anticipated* the completeness of the SM and the existence of a mass gap above the SM spectrum.

Triumph of the CKM mechanism ['01] $\dashrightarrow$ Triumph of the Higgs mechanism ['12]

Introduction

A posteriori, I think we can admit that the three key LHC results,

- The Higgs discovery
- The Higgs boson is "light"
- Existence of a "mass-gap" above the SM spectrum

are "the most natural" outcome of the pre-LHC results of "indirect searches" of NP via EWPO + Flavor

Easy to say now... but not too unfair...

The indirect search for NP is somehow like the search for precursor signals that "tell us in advance" when a given status is going to change...

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Interestingly enough, the situation of indirect searches of NP has changed in the last few years → appearance of a series of coherent anomalies in various flavor observables (*certainly the most exciting time in flavor physics since decades*...)

The statistical significance of these anomalies is still limited, but is definitely a promising situation (*as it has never been in the past*...)

Introduction

Leaving aside the anomalies, there is no doubt that HL-LHC will offer a unique opportunity of improvement in flavor observables that could allow us to cover unexplored regions of realistic NP models where we can hope to listen some "precursor" NP signal...

General decomposition (based on gauge symmetry + absence of new light states) of flavor and e.w. amplitudes used for indirect NP searches:

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

trivial kinematical factors

(a-dimensional) effective couplings

Very general decompositions: valid for both for forbidden processes (e.g.: $\mu \to e\gamma$) and precision meas. (e.g.: $B_s \to \mu\mu$)

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Twofold advantage of flavor physics:

- Enhanced NP sensitivity due to smallness of c_{SM} [loop + CKM/Yukawa suppression + many null SM tests]
- Specific advantage in the HL-LHC context: potential huge increase in statistics compare to present status (*significantly higher, compared to the one expected in Higgs Physics and EWPO*)

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Twofold advantage of flavor physics:

- Enhanced NP sensitivity due to smallness of c_{SM}
- Specific advantage in the HL-LHC context:

Λ	$\longrightarrow$	$3\times\Lambda$
c_{NP} now		$0.1\times c_{NP}$ HL-LHC

(for th. clean observables)

Old problems & new hopes in Flavor Physics

The flavor structure of the SM

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

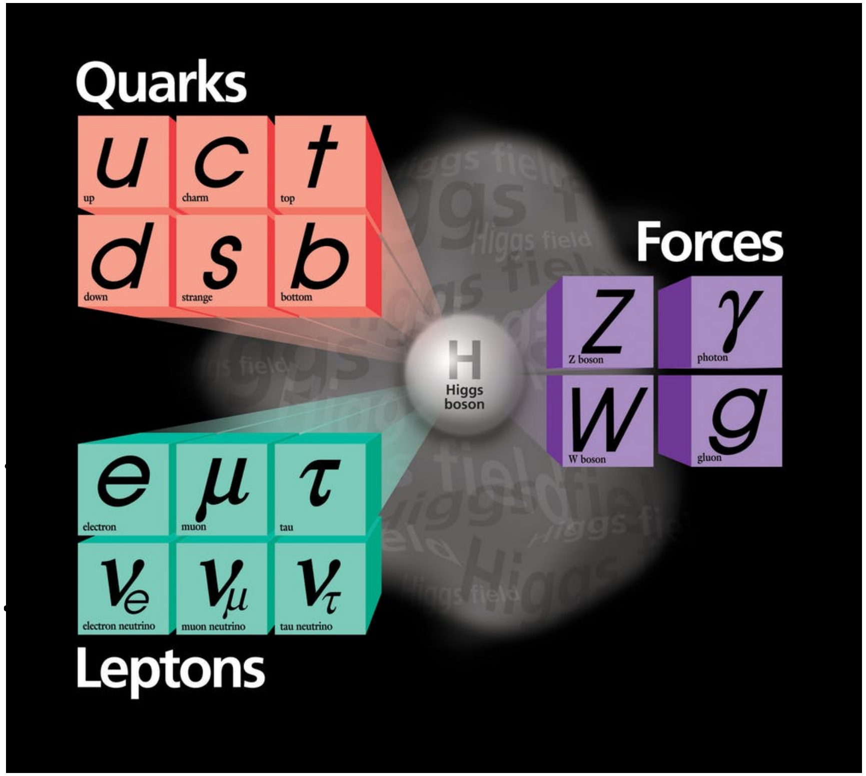
3 identical replica of the basic fermion family $[\psi = Q_L, u_R, d_R, L_L, e_R] \Rightarrow$ huge flavor-degeneracy

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

$$\bar{L}_L^{\,i}\, Y_L^{ik}\, e_R^{\,k}\, {\rm H} \quad + \; h.c.$$

$$\bar{Q}_L^{\,i}\, Y_D^{ik}\, d_R^{\,k}\, {\rm H} \quad + \; h.c.$$

$$\bar{Q}_L^{\,i}\, Y_U^{ik}\, u_R^{\,k}\, {\rm H_c} \quad + \; h.c.$$



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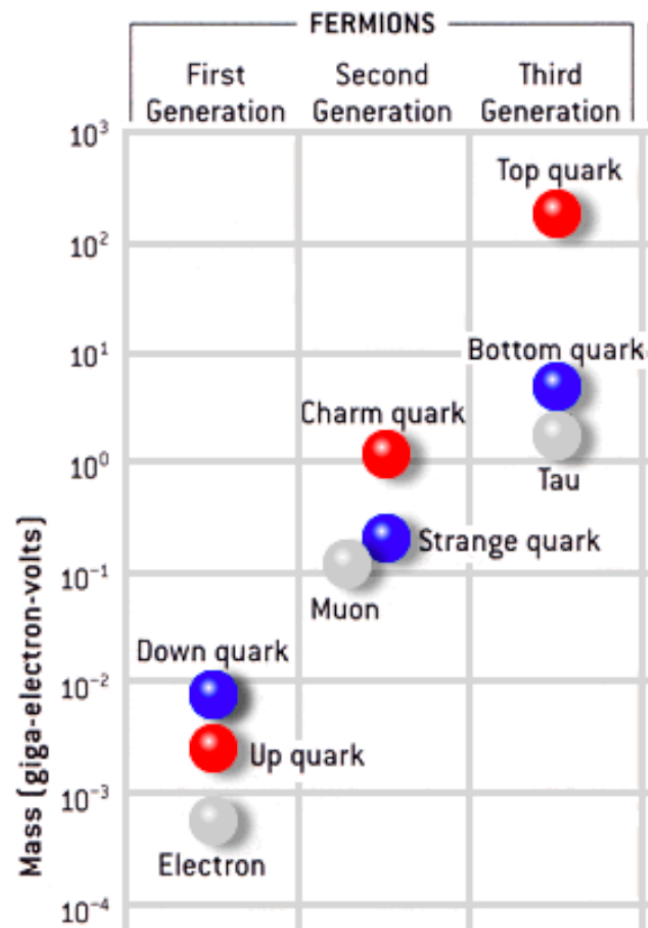
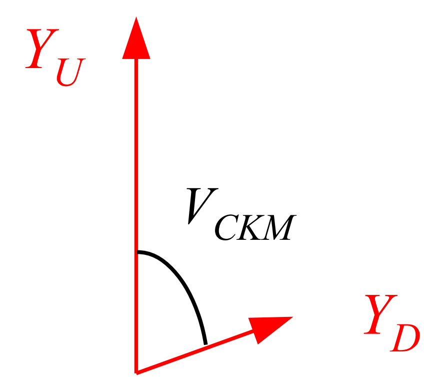
$$\bar{L}_L^{\,i}\, Y_L^{ik}\, e_R^{\,k}\, \mathrm{H} \;\rightarrow\; l_L^{\,i}\, M_L^{ii}\, \bar{l}_R^{\,i} + \ldots$$

$$\bar{Q}_L^{\,i}\, Y_D^{ik}\, d_R^{\,k}\, \mathrm{H} \;\rightarrow\; d_L^{\,i}\, M_D^{ik}\, \bar{d}_R^{\,k} + \ldots$$

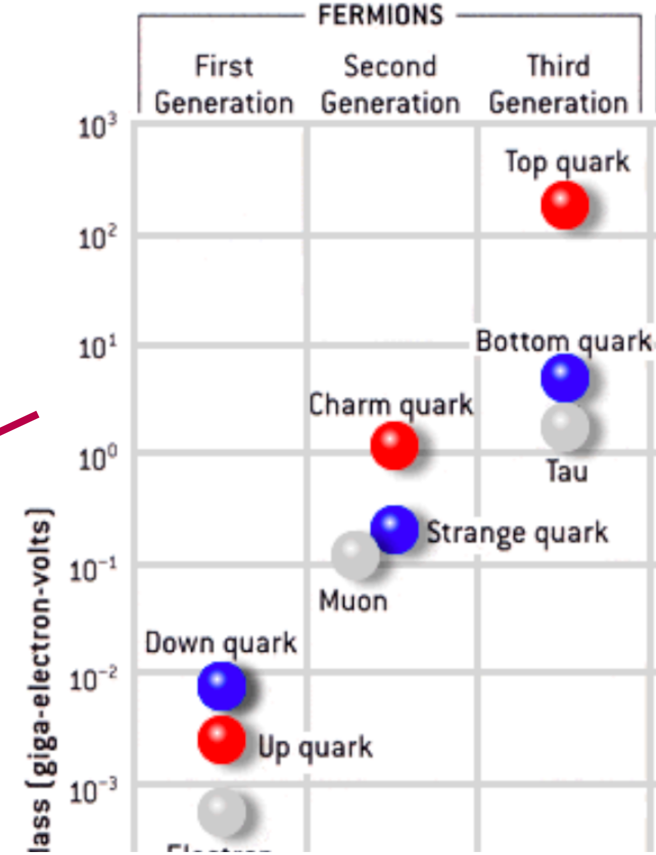
$$\bar{Q}_L^{\,i}\, Y_U^{ik}\, u_R^{\,k}\, \mathrm{H}_{\rm c} \;\rightarrow\; u_L^{\,i}\, M_U^{ik}\, \bar{u}_R^{\,k} + \ldots$$





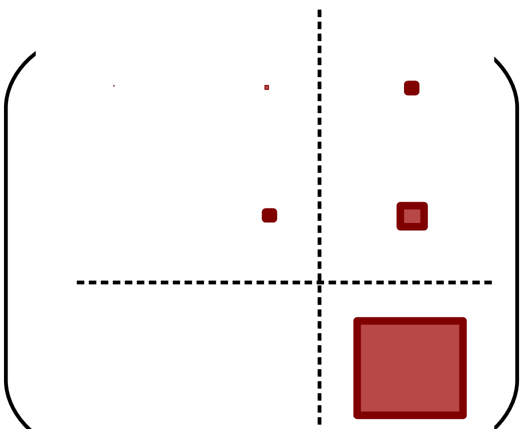
The Flavor Puzzle

The SM flavor sector (= *the Yukawa sector*) contains a large number of free parameters (fermion masses & mixing angles), which *do not look at all accidental...*

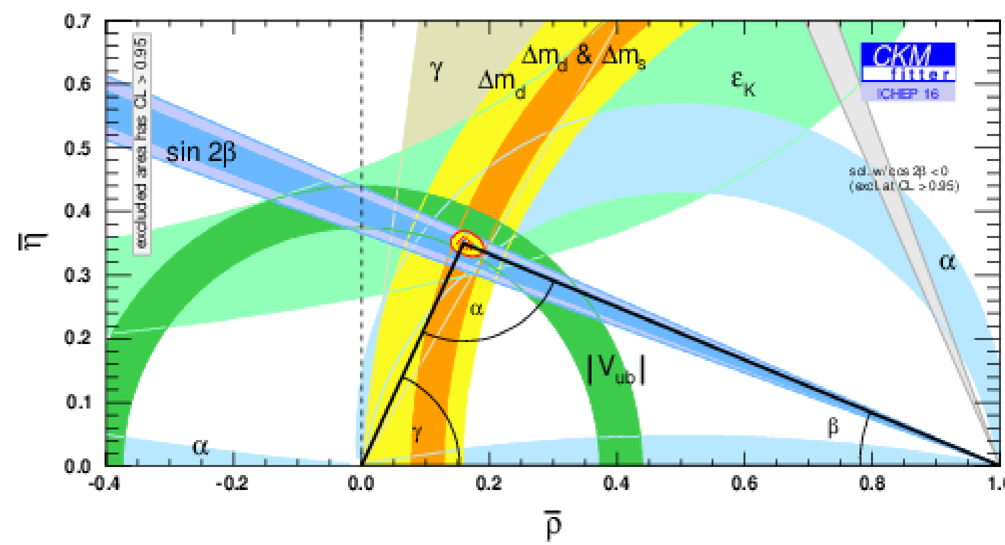


E.g.:

$Y_U \sim$



$$y_t = \frac{\sqrt{2}\, m_t}{\langle H \rangle} \approx 1$$



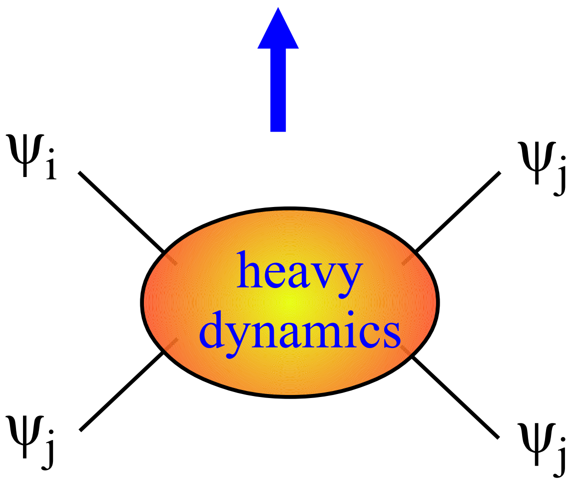
The "old" Flavor Puzzle...

The NP Flavor Problem

Given the SM is an effective theory, we should ask the following question:
Are there other sources of flavor symmetry breaking [beside the SM Yukawas] ?

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \sum_n \frac{c_n}{\Lambda^2} O_n^{d=6} \longrightarrow$$

Possible large impact on rare flavor-changing processes, such as meson-antimeson mixing



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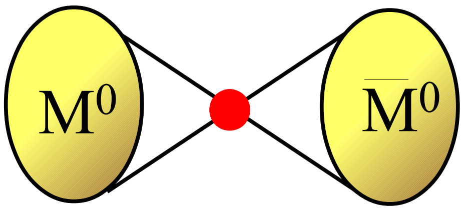
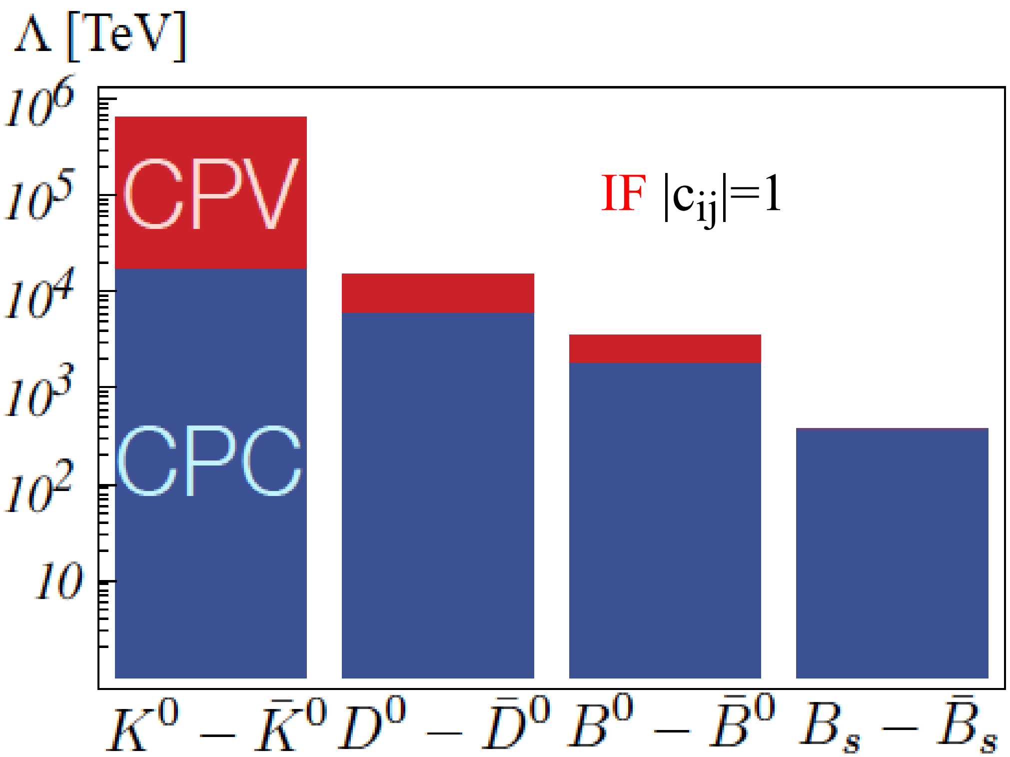


So far (*almost*) everything fits well with the SM→ Strong limits on NP

The NP Flavor Problem

We would like to have NP ~ few TeV to solve the hierarchy problem



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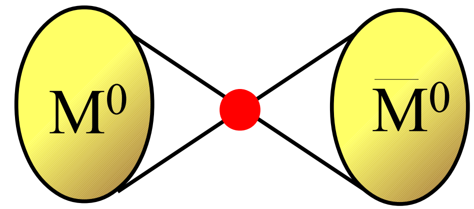

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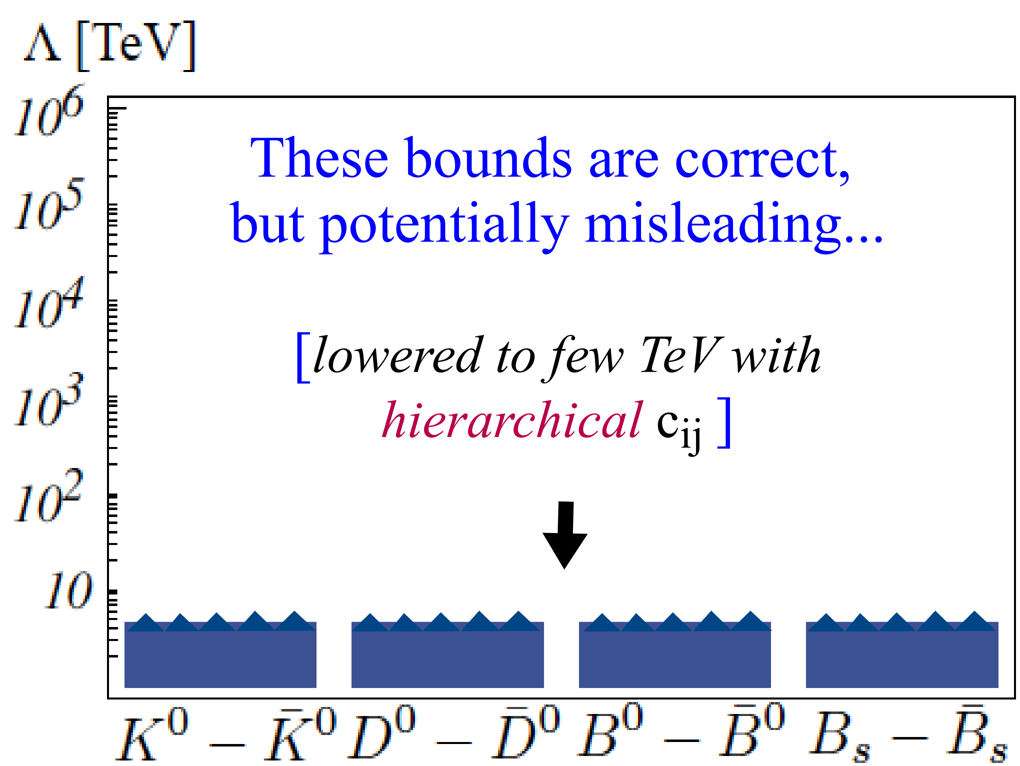

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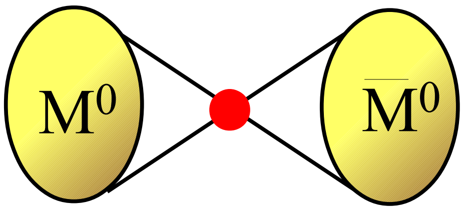

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↓

The NP Flavor Problem ➡ *The MFV hypothesis*

The Yukawa couplings are generated at some very heavy energy scale and there is *no chance to probe their dynamical origin*

A rather pessimistic approach...

A change of paradigm...

So far, the vast majority of model-building attempts to extend the SM was based on the following two (*implicit*) hypotheses:

- Concentrate on the Higgs hierarchy problem
- Postpone (*ignore*) the flavor problem

→ *The "MFV paradigm"*

While this was a very motivated option in the pre-LHC era, it has become a less and less compelling case after the high-pT results from run-I and run-II (*no sign of flavor universal NP at the TeV scale*)

A change of paradigm...

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→ *not very successful...*

Beside the lack of success in high-pT physics, this point of view is challenged at low-energies by the recent "anomalies", i.e. the observation of a different (*non-universal*) behavior of different lepton species in specific semi-leptonic processes:

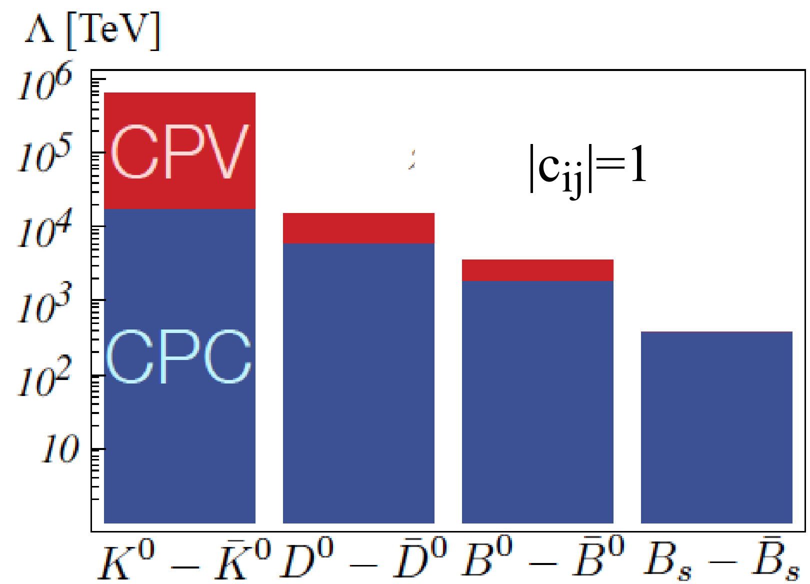
- $b \to c$ charged currents: τ vs. light leptons (μ, e)
- $b \to s$ neutral currents: μ vs. e

What is particularly interesting, is that these anomalies are challenging an assumption (Lepton Flavor Universality), that we gave for granted for many years (*without many good theoretical reasons...*)

A change of paradigm...

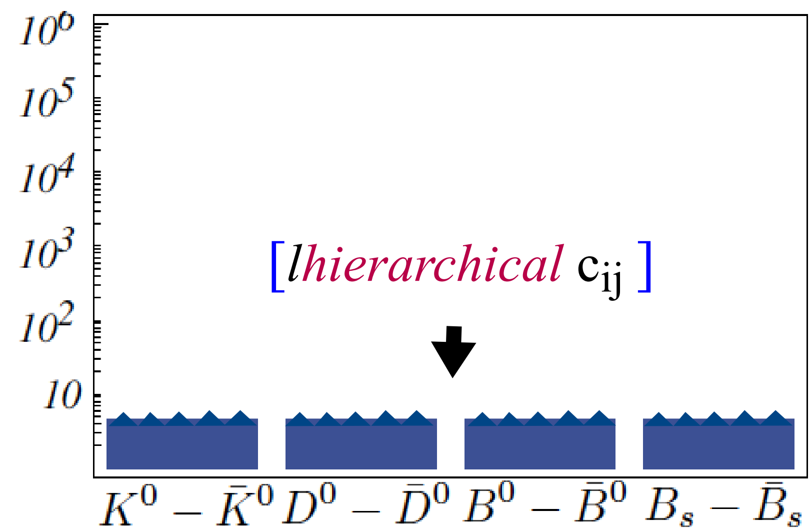
Even if (some of the) anomalies will go away in the future, they have had a very beneficial impact in enlarging our horizon on flavor physics BSM

I. It is now clear that there are many (*less pessimistic...*) alternatives to MFV which predict to new (non-Yukawa) sources of flavor-symmetry breaking at accessible energies



II. It is misleading to give for granted the flavor universality of gauge interactions

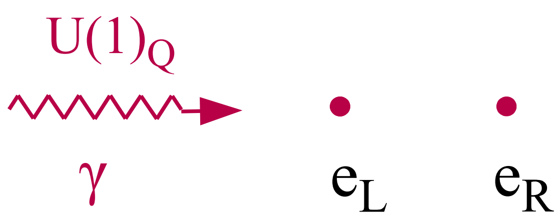
- *built-in in the SM,*
- *well tested for light generations,*
- *but it may well be only an accidental low-energy property...*



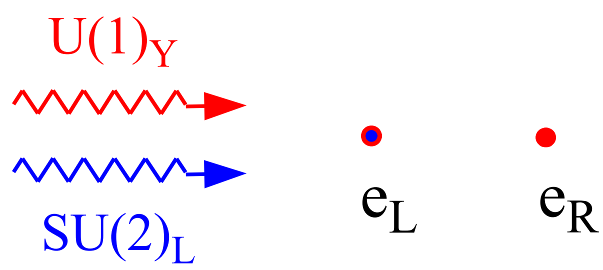
Clean NP signals accessible in flavor physics with higher precision...

A change of paradigm [on possible flavor non-universal gauge interactions]

We have no problem in accepting that the photon is not a fundamental field...

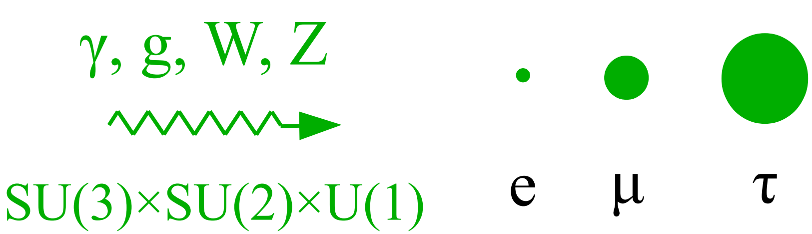


Low energies



High energies

In a similar fashion, the apparent flavor symmetry of the SM gauge interactions could well be only an accidental low-energy property...



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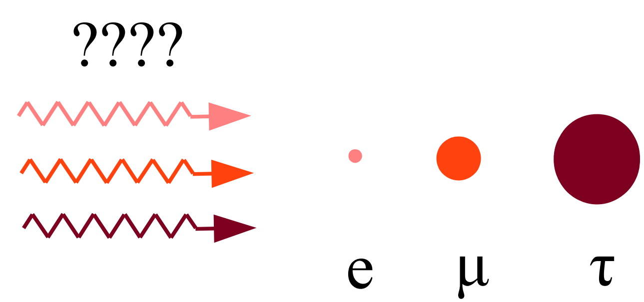

High energies

A change of paradigm...

So far, the vast majority of model-building attempts to extend the SM was based on the following two (*implicit*) hypotheses:

- Concentrate on the Higgs hierarchy problem
- Postpone (*ignore*) the flavor problem ➡ ~~The 3 gen. as "identical" copies (*but for Yukawa-type interactions*)~~

Both high-pT data and low-energy anomalies seem to suggest to consider different approaches:

- We should not ignore the flavor problem
  → *still hope to observe new (non-Yukawa) interactions at the TeV scale distinguishing the different families*

- A (very) different behavior of the 3 families (with special role for 3rd gen.) may be the key to solve/understand also the gauge hierarchy problem
  → *Higgs mostly coupled to 3rd gen.*
  → *TeV-scale NP mainly coupled to 3rd gen. could have escaped direct searches*

Some concrete examples

Back to the master formula

The list of observables where we can expect a significant progress (with a corresponding impact on motivated NP searches) is very long (→ see the report...!) I will limit myself to mention only a few simple cases.

It is clear from the master formula, that significant improvement can be expected only if we have a good control on the the SM predictions:

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

Even for *lazy theoreticians...* there are many interesting options:

- LFU tests in the μ/e sector in FCNCs (R_K, R_K + many more...)
- LFU tests in the τ/μ sector in CC (R_D, R_{D*} + many more...)
- LFV observables in B decays (B → Kτμ, ...)
- LFV observables in tau decays (τ → φμ, ...)
- CPV in the charm system
- Search for RH currents in FCNC B decays (from angular analysis)

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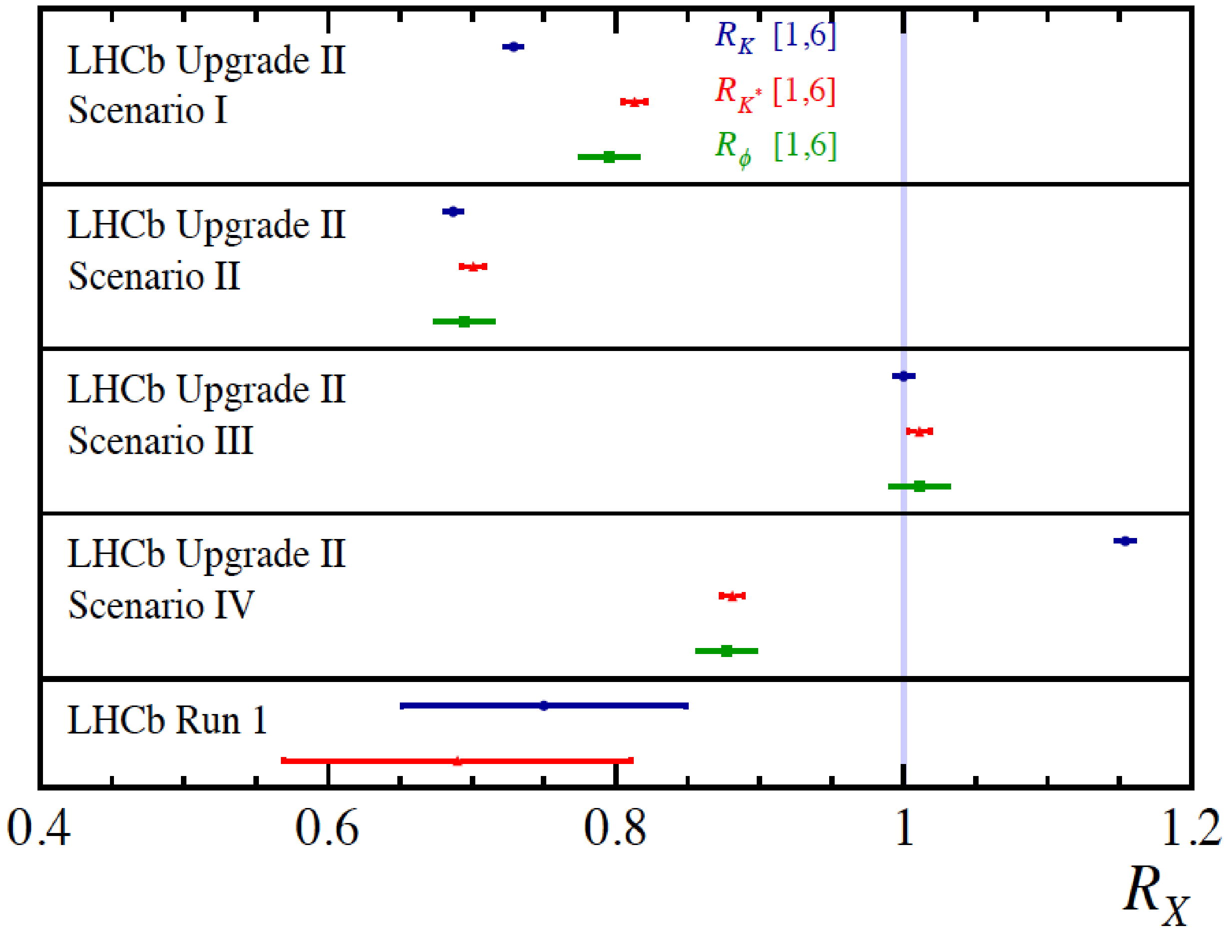
- LFV observables in B decays
- LFV observables in tau decays
- CPV in the charm system
- Search for RH currents in FCNC

For most of these observables we are close to the ideal scaling:

Λ, c_{NP} (now) $\longrightarrow$ $3\times\Lambda$, $0.1\times c_{NP}$ (HL-LHC)

Some concrete examples

E.g.: LFU tests in the μ/e sector in FCNCs (R_K, R_K + many more...)



Even in the pessimistic case of scenario III, this would be a tremendous improvement in our understanding of flavor physics BSM

Some concrete examples

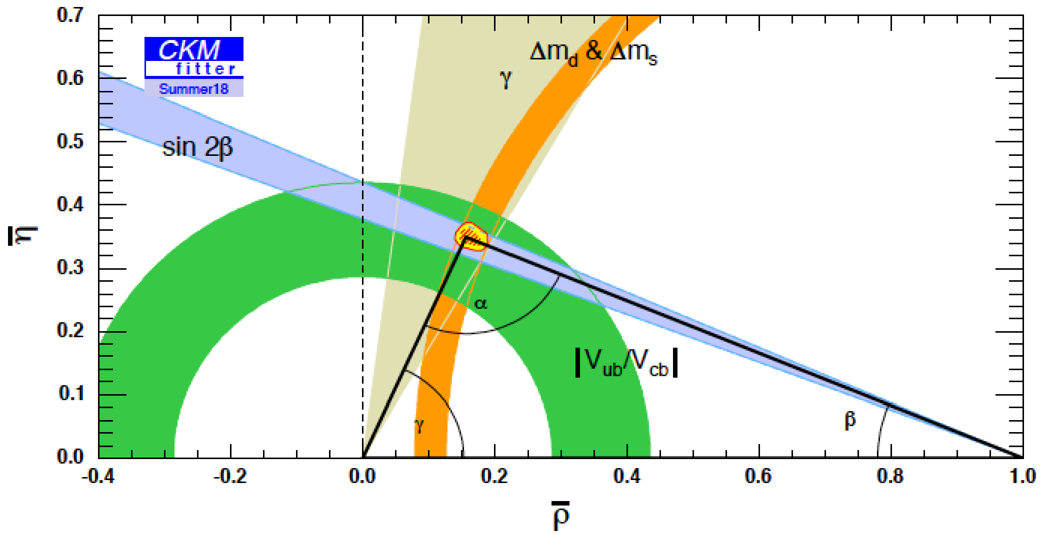
N.B.: if the anomalies are due to NP, we should expect to see several other BSM effects in low-energy observables

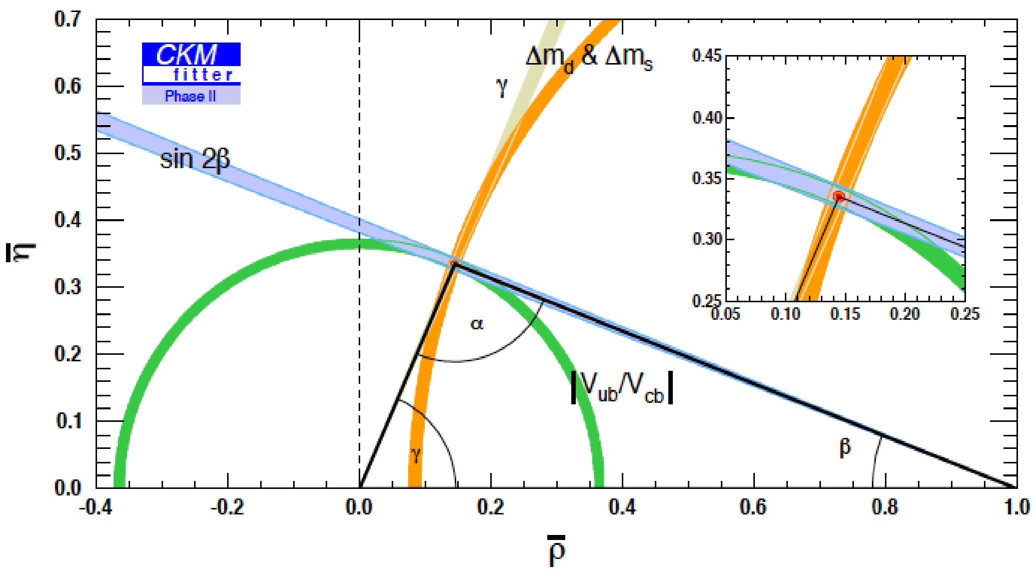
E.g.: correlations among down-type FCNCs [*using* U(2)*-based EFT, starting from present anomalies*]:

	$\mu\mu$ (ee)	$\tau\tau$	$\nu\nu$	$\tau\mu$	μe
$b \to s$	R_K, R_{K^*} O(20%)	$B \to K^{(*)}\,\tau\tau$ $\to$ 100×SM	$B \to K^{(*)}\,\nu\nu$ O(1)	$B \to K\,\tau\mu$ $\to \sim 10^{-6}$	$B \to K\,\mu e$???
$b \to d$	$B_d \to \mu\mu$ $B \to \pi\,\mu\mu$ $B_s \to K^{(*)}\,\mu\mu$ O(20%) [R_K=R_π]	$B \to \pi\,\tau\tau$ $\to$ 100×SM	$B \to \pi\,\nu\nu$ O(1)	$B \to \pi\,\tau\mu$ $\to \sim 10^{-7}$	$B \to \pi\,\mu e$???
$s \to d$	*long-distance pollution*	*NA*	$K \to \pi\,\nu\nu$ O(1)	*NA*	$K \to \mu e$???

Some concrete examples

For *less lazy theoreticians* (*key help from Lattice QCD...*), more options open up





→ One order of magnitude improvements in bounds on possible CPV phases of non SM origin...

Conclusions

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

- Motivations for NP still there (*including the puzzling structure of quark and lepton masses matrices, or the origin of flavor...*) → flavor physics remains a very privileged observatory from where we can hopefully observe "precursor signals" of NP → <u>unique opportunity offered by HL-LHC</u>

- While "classical studies" of rare decays remains well motivated, recent data have helped us to identify a very rich "new frontier" in flavor physics: the study of LFU (*whose interest will remain high even if present anomalies will disappear*)