# The Flavor Problem

(*on the connections between quark-flavor physics and other fields*)

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- Introduction
- Flavor symmetries & connections with neutrino physics
- Recent anomalies & connections with hight-pT physics
- Conclusions

# Introduction

All known phenomena in particle physics (*leaving aside a few cosmological observations...*) can be described with good accuracy by a remarkably simple (*effective*) theory:

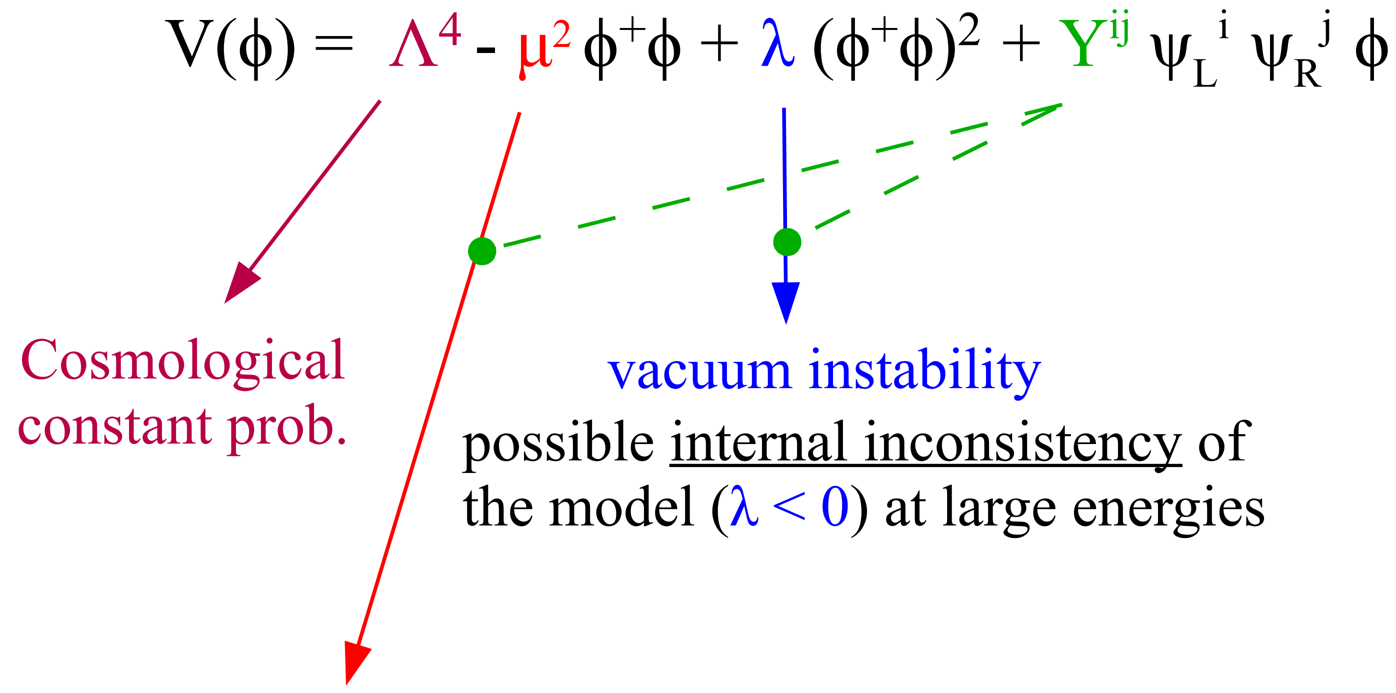
$$\mathscr{L}_{\text{SM}} = \mathscr{L}_{\text{gauge}}(A_a, \psi_i) + \mathscr{L}_{\text{Higgs}}(\phi, A_a, \psi_i)$$

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

- *Ad hoc*
- Necessary to describe data [*clear indication of a non-invariant vacuum*] weakly tested in its dynamical form
- Not stable with respect to quantum corrections
- Origin of the flavor structure of the model [*and of all the problems of the model...*]

# Introduction

The “disturbing” (*but interesting...*) features of the theory are associated to the structure (and the various couplings) appearing in the Higgs potential:



$$V(\phi) = \Lambda^4 - \mu^2 \phi^+\phi + \lambda\, (\phi^+\phi)^2 + Y^{ij}\, \psi_L{}^i\, \psi_R{}^j\, \phi$$

Cosmological
constant prob.

vacuum instability

possible <u>internal inconsistency</u> of the model ($\lambda < 0$) at large energies

Hierarchy problem
(*quadratic sensitivity to the cut-off*)

$$\Delta\mu^2 \sim \Delta m_h{}^2 \sim \Lambda^2$$

(indication of *new physics*
close to the electroweak scale ?)

*Main open questions*
*in HEP and cosmology...*

## Introduction

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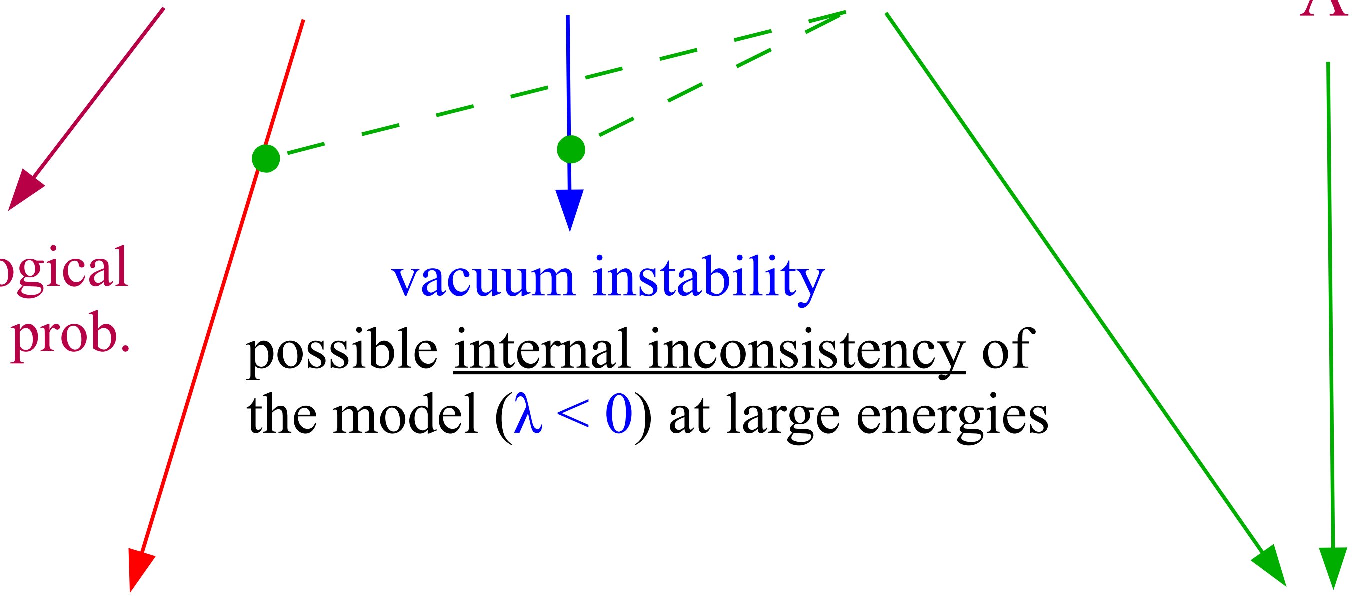
$$V(\phi) = \Lambda^4 - \mu^2 \phi^+\phi + \lambda (\phi^+\phi)^2 + Y^{ij} \psi_L{}^i \psi_R{}^j \phi + \frac{g^{ij}}{\Lambda} \psi_L{}^i \psi_L{}^{Tj} \phi \phi^T$$

*effective neutrino mass term*



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<u>flavor problem</u>

(unexplained span over several orders of magnitude and strongly hierarchical structure of the Yukawa coupl.)

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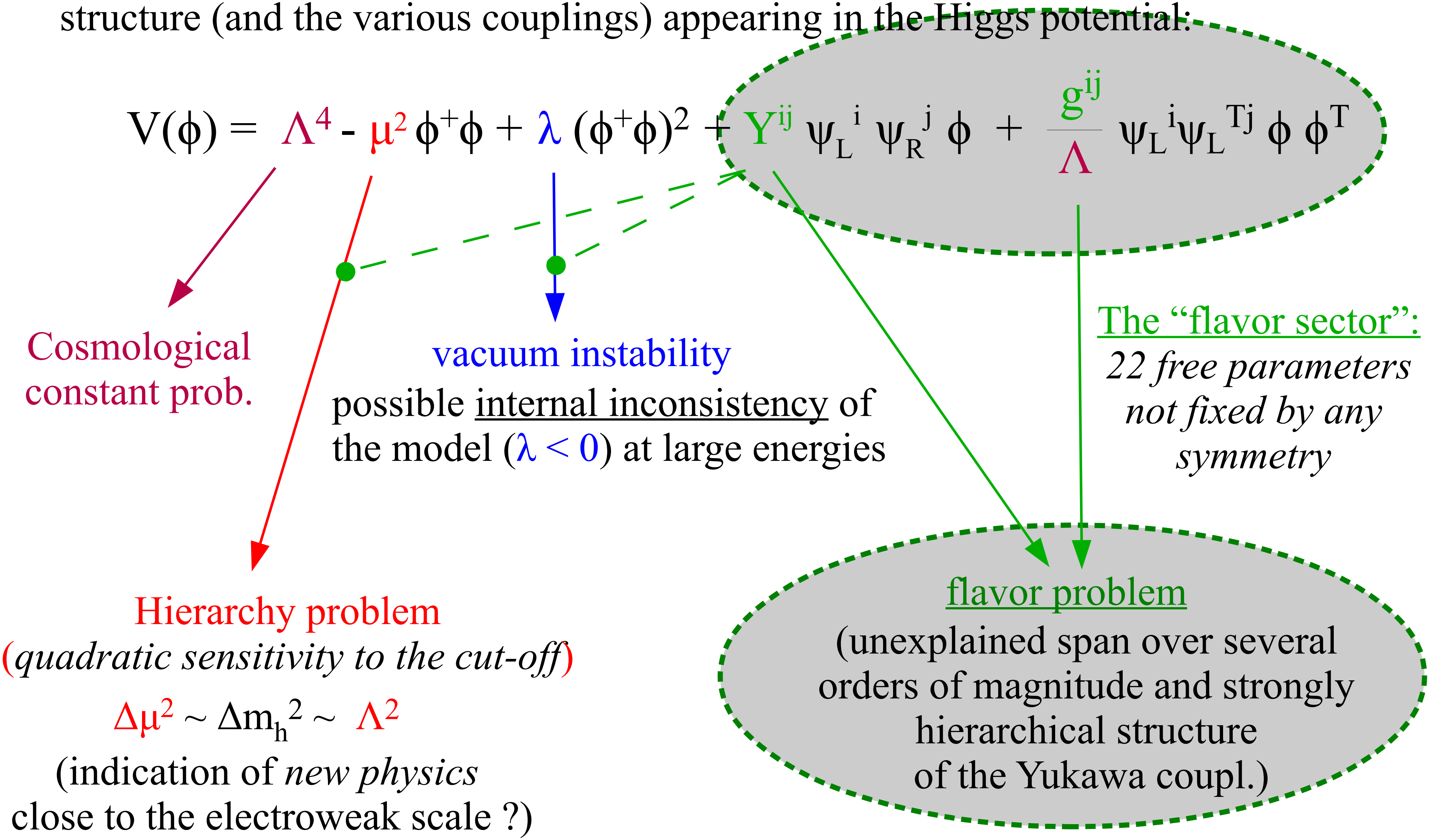

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Cosmological constant prob.

vacuum instability

possible internal inconsistency of the model ($\lambda < 0$) at large energies

The “flavor sector”:

*22 free parameters not fixed by any symmetry*

Hierarchy problem

(*quadratic sensitivity to the cut-off*)

$$\Delta\mu^2 \sim \Delta m_h^{\ 2} \sim \Lambda^2$$

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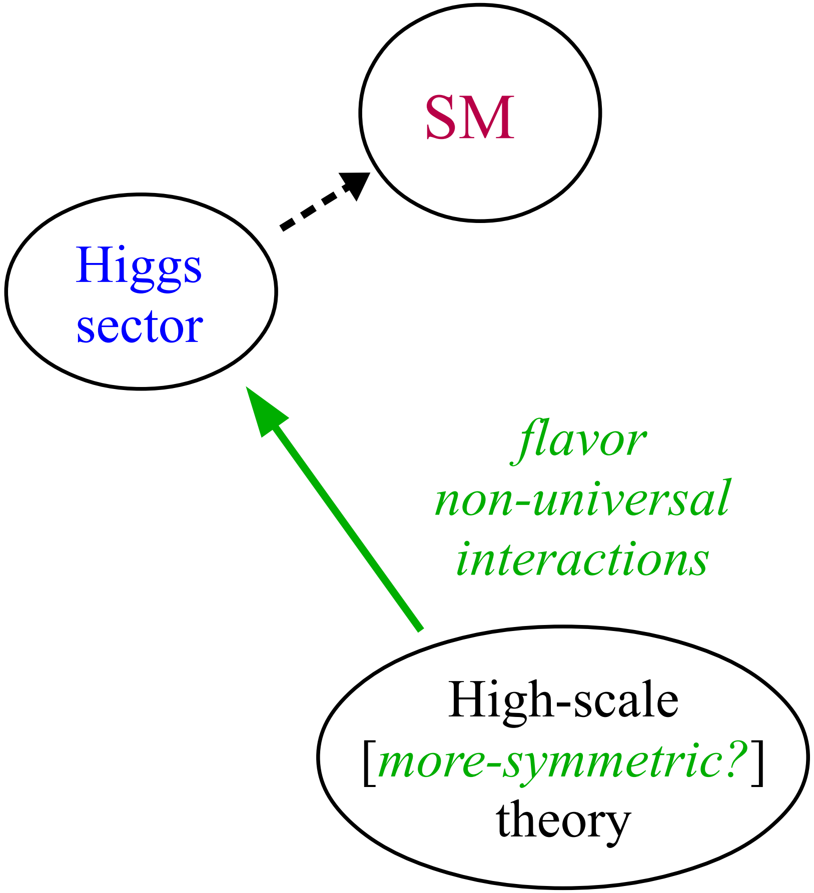
## *Introduction*

Key role of flavor physics → 
- Identify symmetries and symmetry-breaking patterns beyond those present in the SM



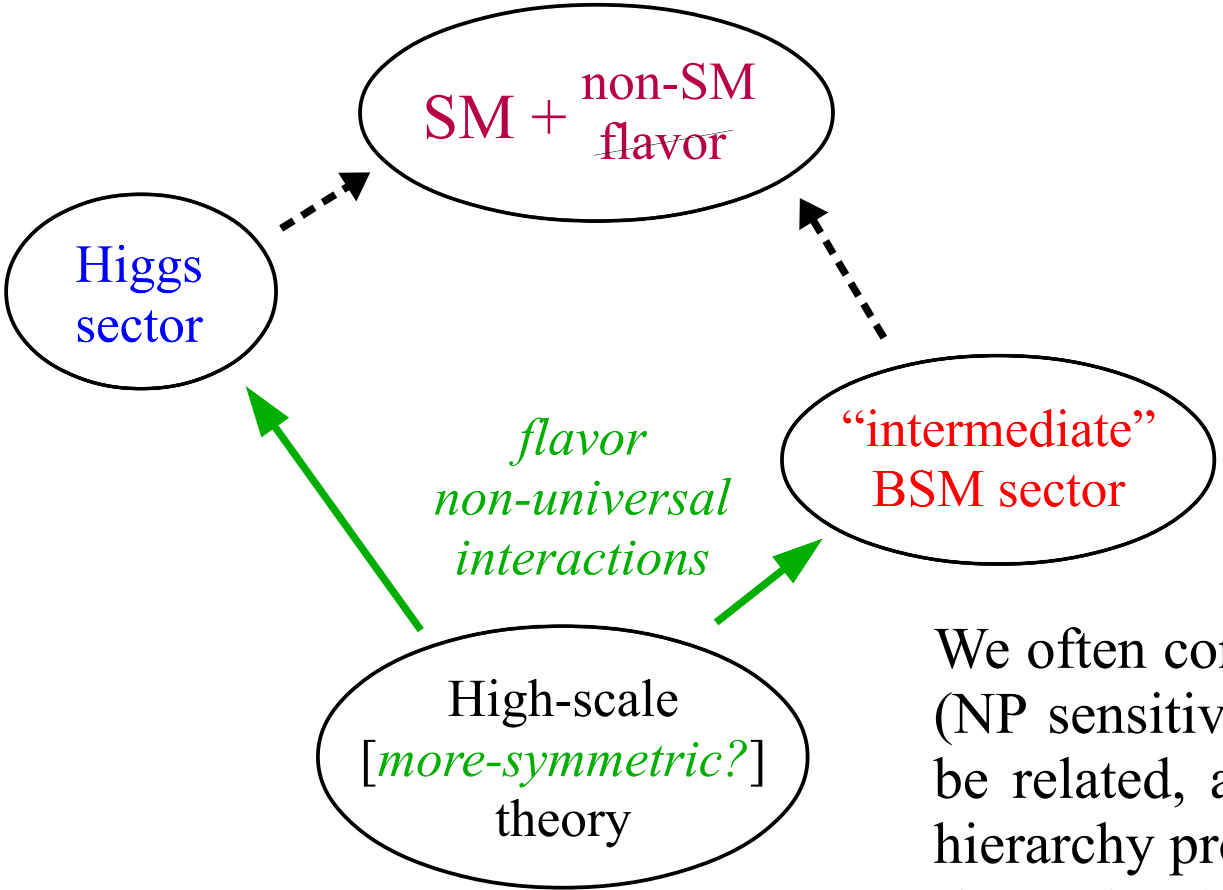
Key open question:

- *What determines the observed pattern of quark & lepton mass matrices?*

# *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



SM + non-SM ~~flavor~~

Higgs sector

*flavor non-universal interactions*

“intermediate” BSM sector

High-scale [*more-symmetric?*] theory

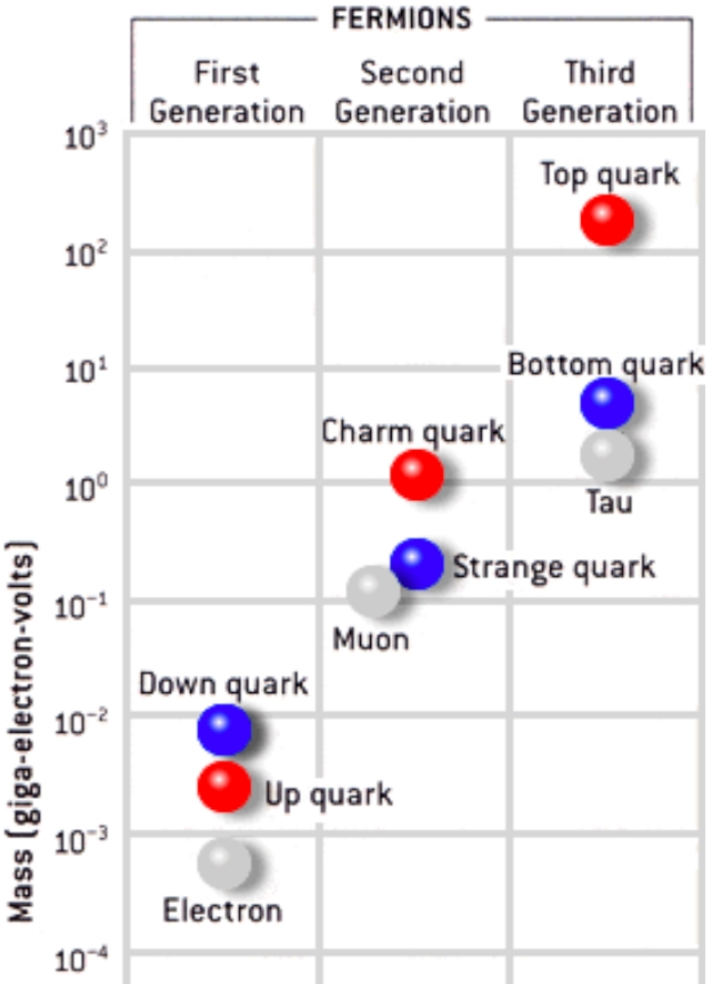
Two key open questions:

- *What determines the observed pattern of quark & lepton mass matrices?*
- *Are there other sources of flavor symmetry breaking?*

We often concentrate only on the second aspect (NP sensitivity), but the two issues could well be related, and possibly be related also to the hierarchy problem of the Higgs potential (key role of the 3rd generation)

# Speculations about Flavor Symmetries

# ▸ *The data:* (I) *quark & lepton masses*

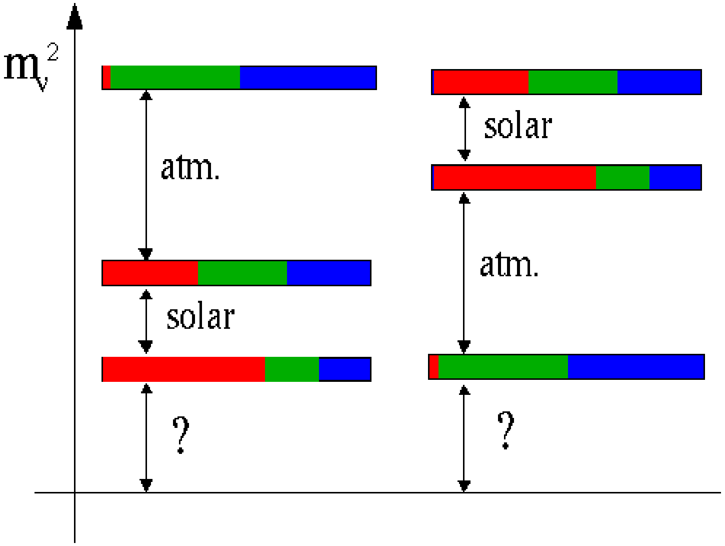


$$V_{CKM} \sim \begin{pmatrix} 1.0 & 0.2 & 3\times10^{-3} \\ 0.2 & 1.0 & 0.04 \\ 9\times10^{-3} & 0.04 & 1.0 \end{pmatrix}$$

- Strong hierarchical pattern of quark and charged-lepton masses ($m_1/m_3 \ll m_2/m_3 \ll 1$)
- Almost diagonal CKM (quark-mixing) matrix
- Large mixing angles in the neutrino sector
- Neutrino spectrum not fully known yet, but certainly not very hierarchical

$$\left|\frac{\Delta m^2_{\rm sol}}{\Delta m^2_{\rm atm}}\right|^{1/2} \sim 1/6$$

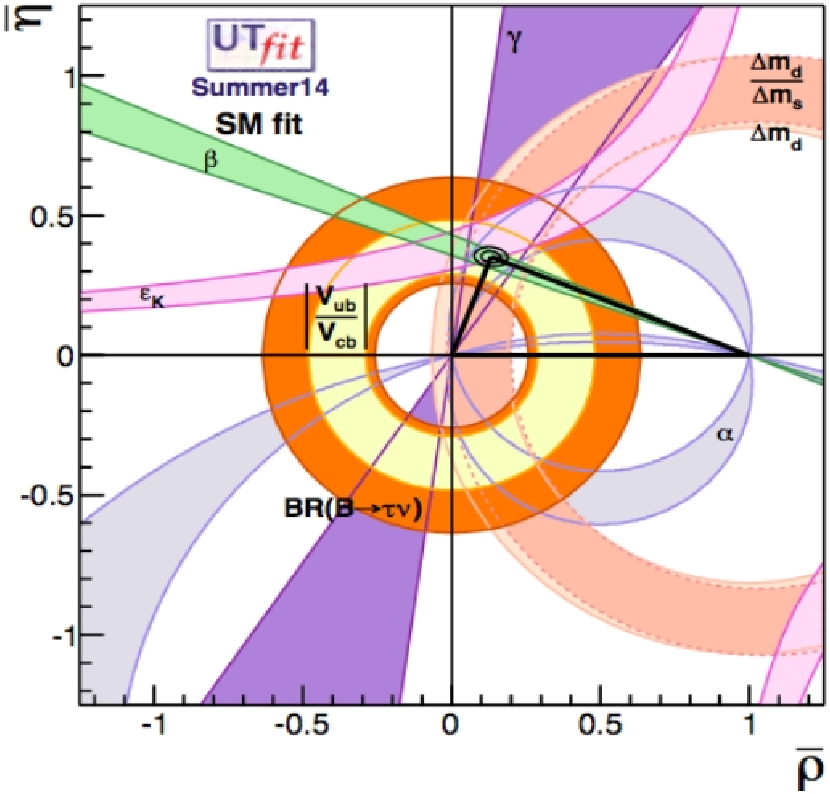
🟥 $\nu_e$
🟩 $\nu_\mu$
🟦 $\nu_\tau$



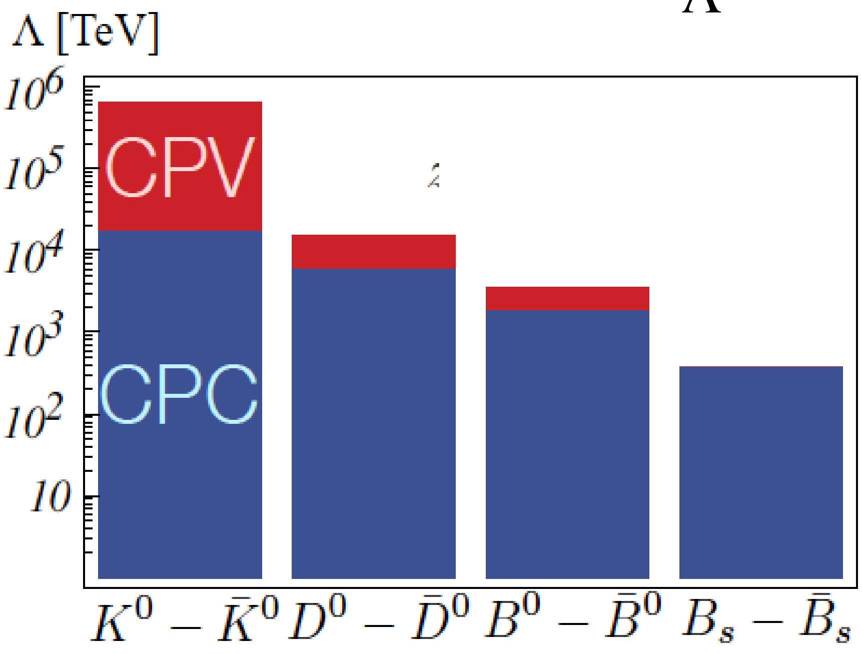
## *The data:* (II) *the suppression of FCNCs*

- *Are there other sources of flavor symmetry breaking (beside SM Yukawa couplings & neutrino mass matrix)?*

That's the question addressed by precision measurements (& searches) of flavor-changing processes of quarks & charged-leptons → So far (almost) everything seems to fit well with the SM→ Strong limits on NP



$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda^2} O_{\Delta F=2}$$



## The MFV hypothesis (& variations)

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

- Largest flavor symmetry group compatible with the SM gauge symmetry

↓

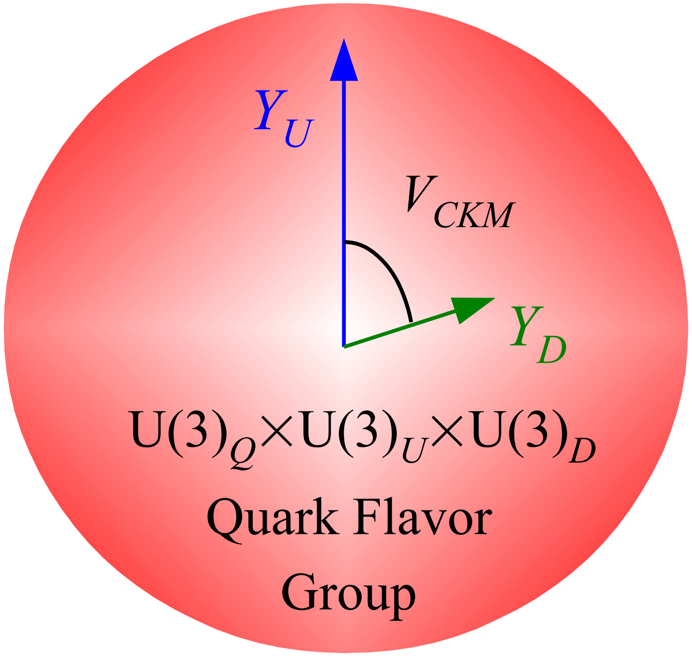
MFV hypothesis: the Yukawa couplings are the only breaking terms of this large flavor symmetry group

*virtue*

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

*unsolved problem*

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



## The MFV hypothesis (& variations)

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

- 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*

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

$$Y_u = y_t \left[\begin{array}{c|c} 0 & 0 \\ \hline 0 & 1 \end{array}\right] \longrightarrow \left[\begin{array}{c|c} \Delta & V \\ \hline 0 & 1 \end{array}\right]$$

*Unbroken symmetry*

$|V| \sim 0.04$

$|\Delta| \sim 0.006$

## ▸ Open problems

I. A potential problem of the U(2)$^3$ approach and, more generally, of any approach attributing a special role to the hierarchies in the Yukawa sector, is the problem of neutrino masses:

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?

II. Most important, the breaking terms and, in the U(2)$^3$ case, also the group structure are put in "by hands" (*non-dynamical "spurion" analysis*)

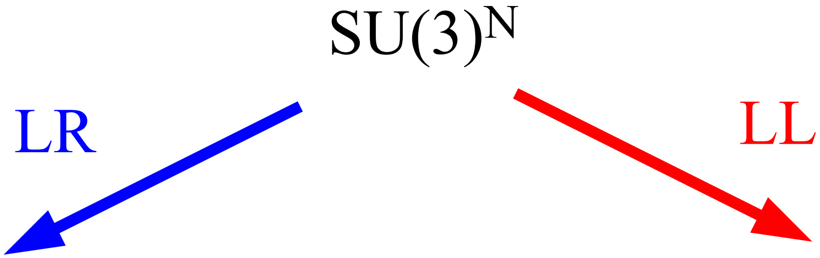
↓

*Yukawa couplings*
(or part of them)
*as dynamical fields*

## *Dynamical Yukawa's*

The main idea is that of a large flavor symmetry, spontaneously broken by the dynamical *Y* preserving maximally invariant sub-groups (*stable solution of the minimization problem*)

E.g.:



$SU(3)^N$

LR

LL

$Y_{E,D,U} \propto \mathrm{diag}(0,0,1) \quad \left(\begin{array}{c}\text{unbroken}\\ SU(2)_L \times SU(2)_R\end{array}\right)$

$|M_\nu \propto Y_\nu Y_\nu^T| \propto \mathrm{diag}(1,1,1) \quad \left(\begin{array}{c}\text{unbroken}\\ O(3)_L\end{array}\right)$

- Vanishing masses for the 1st & 2nd generations (compared to 3rd one)
- $V_{CKM} = 1$

- Degenerate neutrino spectrum
- One maximal and one large mixing angle

## Dynamical Yukawa's

The main idea is that of a large flavor symmetry, spontaneously broken by the dynamical $Y$ preserving maximally invariant sub-groups (*stable solution of the minimization problem*) + further broken down to realistic $Y$ by small breaking terms

E.g.:

$$\begin{tikzcd} & \mathrm{SU}(3)^N \arrow[dl, "\mathrm{LR}"'] \arrow[dr, "\mathrm{LL}"] & \\ Y_{E,D,U} \propto \mathrm{diag}(0,0,1) \left( \begin{array}{c} \text{unbroken} \\ \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \end{array} \right) & & |M_\nu \propto Y_\nu Y_\nu^T| \propto \mathrm{diag}(1,1,1) \left( \begin{array}{c} \text{unbroken} \\ \mathrm{O}(3)_L \end{array} \right) \end{tikzcd}$$

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- $V_{CKM} = 1$

$$Y_u = y_t \begin{bmatrix} O(\varepsilon') & O(\varepsilon) \\ 0 & 1 \end{bmatrix}$$

- Degenerate neutrino spectrum
- One maximal and one large mixing angle

$$\frac{\Delta m_{atm}^2}{m_\nu^2} = O(\varepsilon)$$

$$\boxed{\langle m_\nu \rangle \approx 0.1 \text{ eV}}$$

## Dynamical Yukawa's

*If these speculations are correct…* → 0ν2β decay experiments should be very close to observe a positive signal + neutrino mass well-within reach of CMB analyses + signals of $U(2)^N$ symmetry breaking in B physics → fascinating link between flavor physics + neutrino + cosmology

$$Y_{E,D,U} \propto \mathrm{diag}(0,0,1) \quad \left( \begin{array}{c} \text{unbroken} \\ SU(2)_L \times SU(2)_R \end{array} \right)$$

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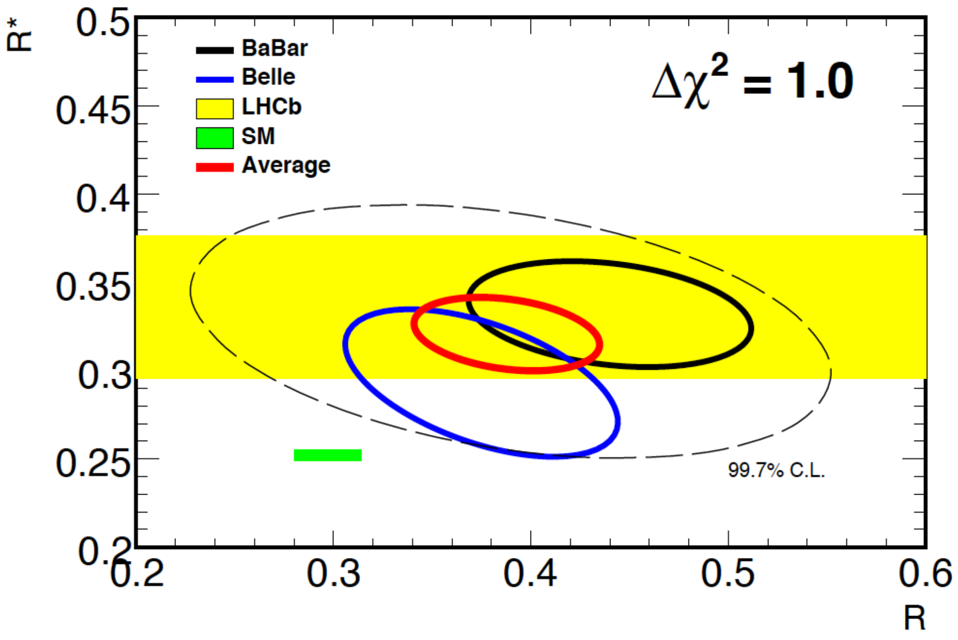
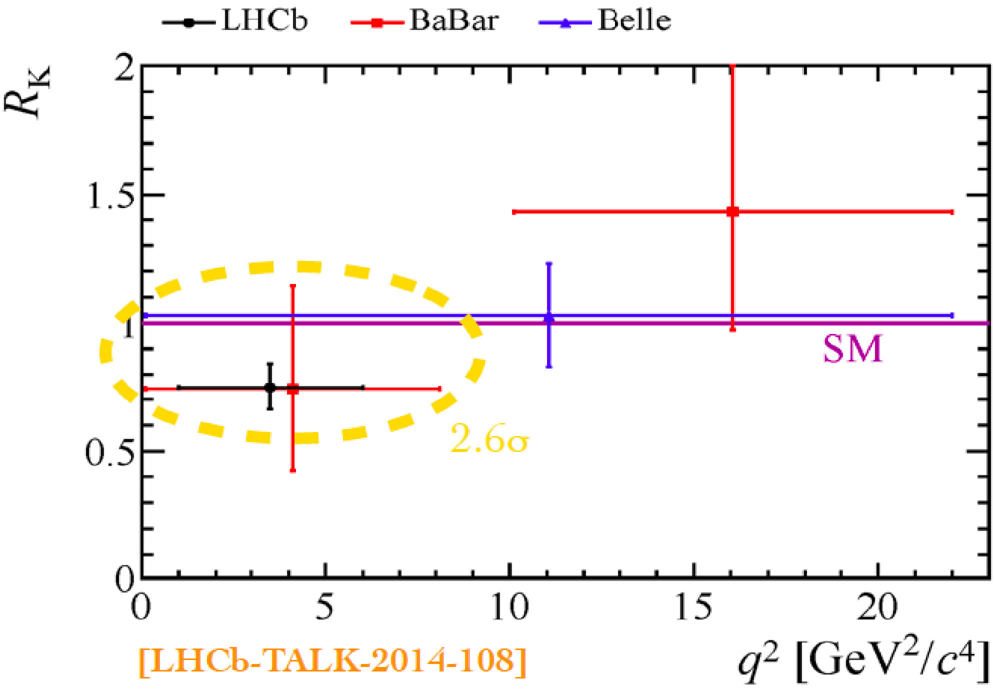
# On the flavor anomalies





[LHCb-TALK-2014-108]

## *General considerations about the breaking of LFU*

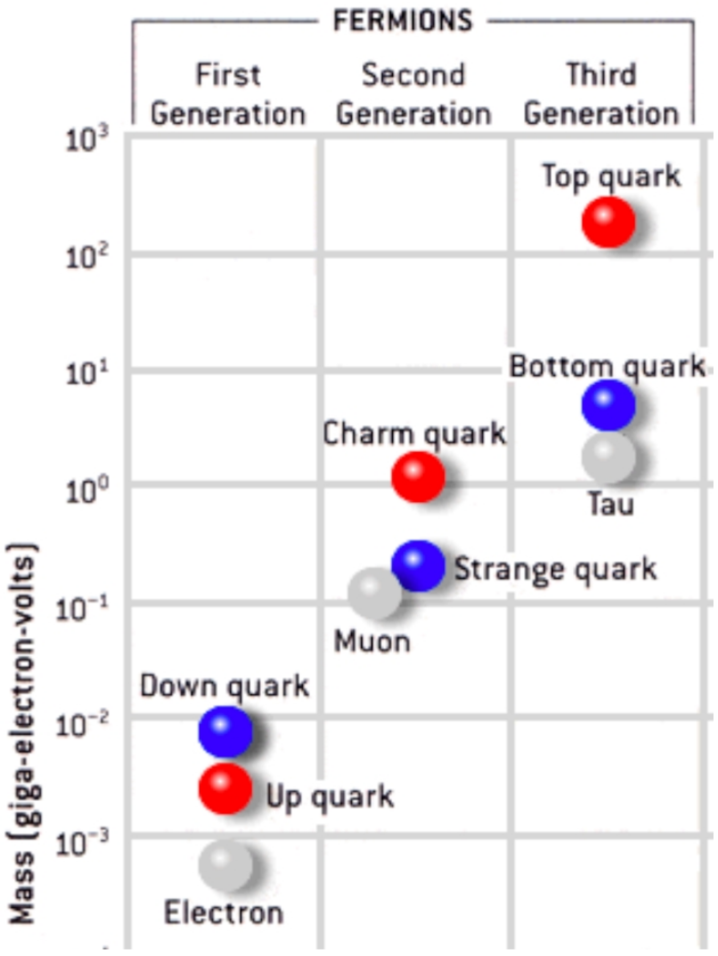
Recent results by LHCb and other B-physics experiments seems to indicate a (*somehow surprising...*) breaking of Lepton Flavor Universality, both in charged currents ($b \to c\tau\nu$ vs. $b \to c\mu\nu$) and in neutral currents ($b \to s\mu\mu$ vs. $b \to see$)

A few general messages:

- LFU is not a fundamental symmetry of the SM Lagrangian (*accidental symmetry in the gauge sector, badly broken by Yukawa interactions*)
- Most stringent tests of LFU involve only 1st-2nd gen. quarks & leptons

↓

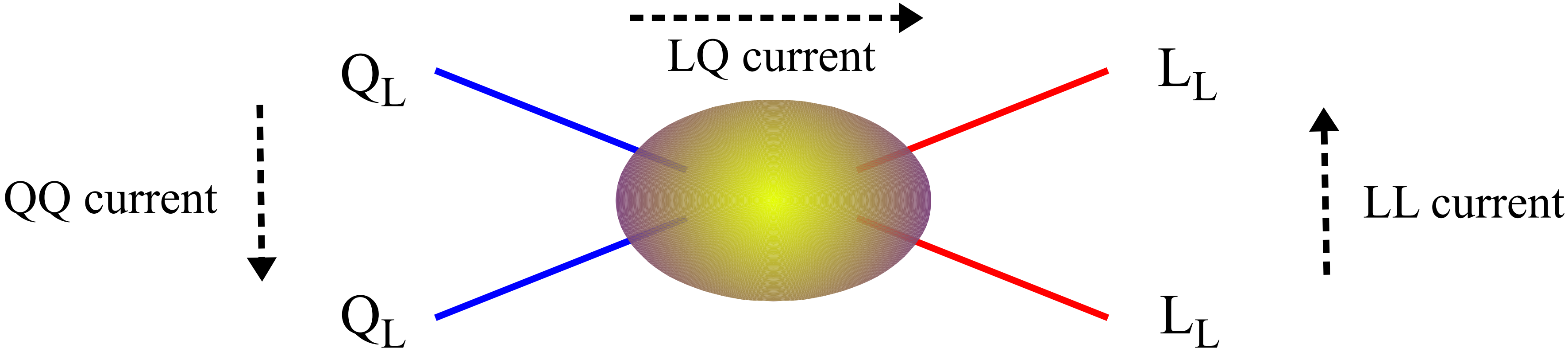
Natural to conceive NP models where
LFU is violated more in processes
with 3rd gen. quarks
(↔ hierarchy in Yukawa coupl.)



## General considerations about the breaking of LFU

- 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 (*as in the Fermi theory*):

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



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

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

## *Simplified dynamical models*

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

⬇

- Both color-less (W', Z') and lepto-quark (LQ) mediators provide a good fit of data, provided these are vector-like particles coupled mainly to 3rd gen.
- Non-universal flavor structure based on the approximate $U(2)_q \times U(2)_l$ flavor symmetry works well (→ *connection to models addressing mass hierarchies*)

⬇

| | | | |
|---|---|---|---|
| Vector-mediator mass: | 200 GeV<br>(weak coupl.) | ⟷ | 2 TeV<br>(strong coup.) |

## A possible "coherent" explanation with F(750)

SM

$SU(3)\times SU(2)\times U(1)_Y$

$f_i^{\mathrm{SM,chiral}}$

New sector

$SU(N_{TC})_{TC}$

$\Psi_{L,R}$ [ different SM charges ]

$SU(N_F)_L\times SU(N_F)_R\times U(1)_V$

$\downarrow$

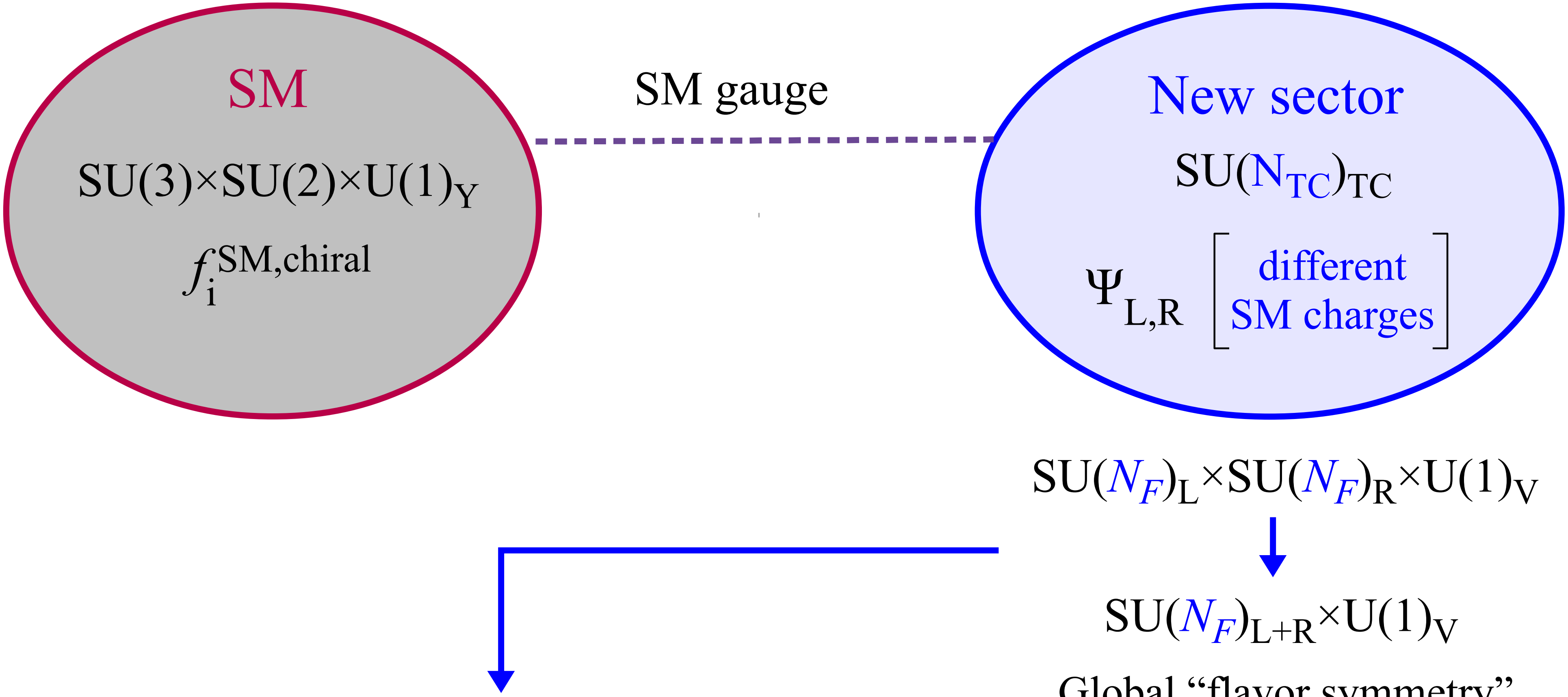
$SU(N_F)_{L+R}\times U(1)_V$

Global "flavor symmetry"
Spontaneously broken as in QCD
at a scale $\Lambda_{TC}\sim$ TeV

The basic construction is based on the idea of "*Vector-like confinement*"

- Very similar to the old idea of technicolor
- Key difference is that the SSB of the new sector preserves the SM gauge symmetry, that is broken in a 2nd step by an appropriate Higgs field

## *A possible "coherent" explanation with F(750)*



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$f_i^{SM,chiral}$

SM gauge

New sector

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↓

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Global "flavor symmetry"
Spontaneously broken as in QCD
at a scale $\Lambda_{TC} \sim$ TeV

[ $\Lambda_{TC}$ & $m_{TC}$ fixed
→ $M_V \sim$ 1.5-2.5 TeV ]

Lowest-lying spectrum of resonances:

pseudo-GB

π, η, ...

pp → η(750) → γγ

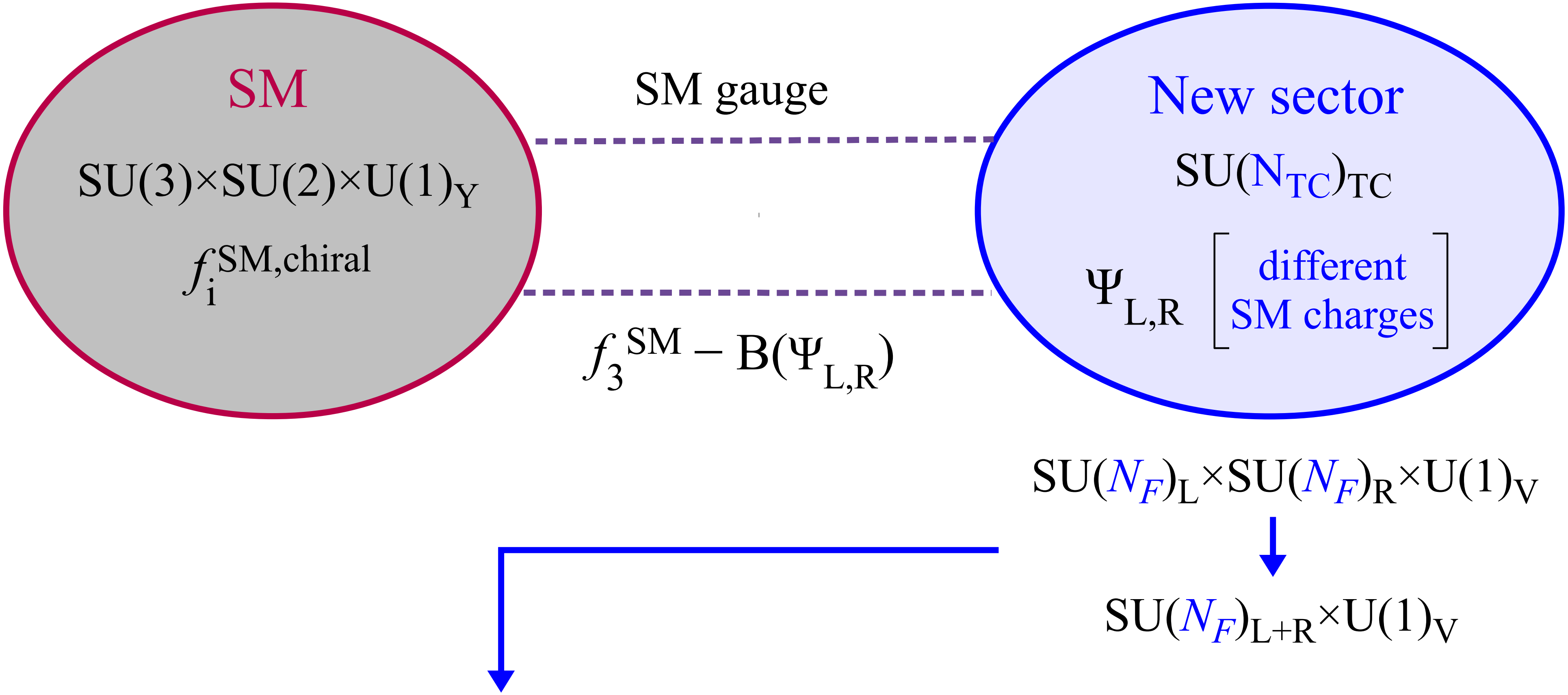
[wide literature]

Heavy vectors

ρ, ω, φ, …

( + possibly LQ )

## A possible "coherent" explanation with F(750)



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$SU(3)\times SU(2)\times U(1)_Y$

$f_i^{\mathrm{SM,chiral}}$

SM gauge

$f_3^{\mathrm{SM}} - B(\Psi_{L,R})$

New sector

$SU(N_{TC})_{TC}$

$\Psi_{L,R}$ [different SM charges]

$SU(N_F)_L\times SU(N_F)_R\times U(1)_V$

↓

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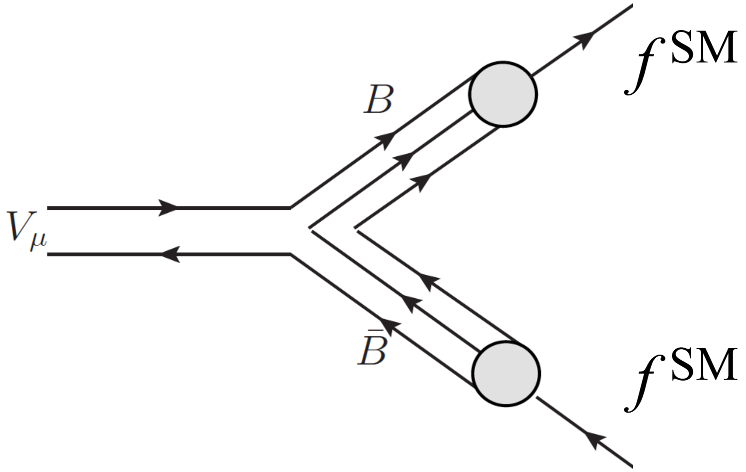
[wide literature]

Heavy vectors

ρ, ω, φ, ...

4f ops. that solve flavor anomalies

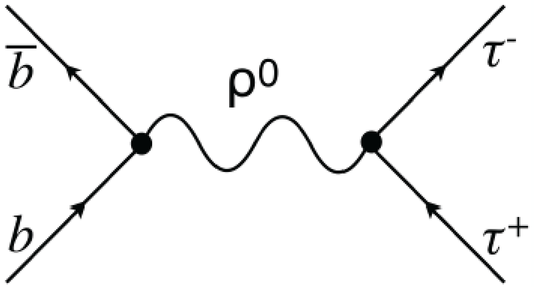


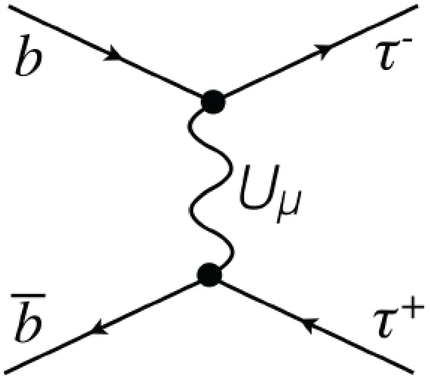
## *A possible "coherent" explanation with F(750)*

Within this class of models one expects a rich phenomenology, both at low energies (*notable cases:* $\tau \to 3\mu$ & $\mu \to 3e$) and at high energies.

Some general features for high-pT signatures:

- Vector mesons are expected to have large widths and to decay predominantly in pNGB (difficult signatures)
- The mixing of the heavy vectors with SM gauge bosons (hence light SM fermions) is very suppressed → dominant coupling to SM via 3rd generation
- Almost model-independent expectation of sizable (broad) excess in $pp \to \tau\tau$ & $pp \to bb$, $tt$ that should be accessible in run-II





# 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 very interesting, and we must search for NP with an "open-mind" perspective, given the lack of a clear preferred direction in "model space".

- Quark-flavor physics has potential deep implications and connections with the other "frontiers" of particle physics (neutrino physics & high-pT physics)

- 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*) → possible improved performances on tau leptons (also in high-pT physics) should be carefully investigated.