Flavor physics: old problems and recent developments

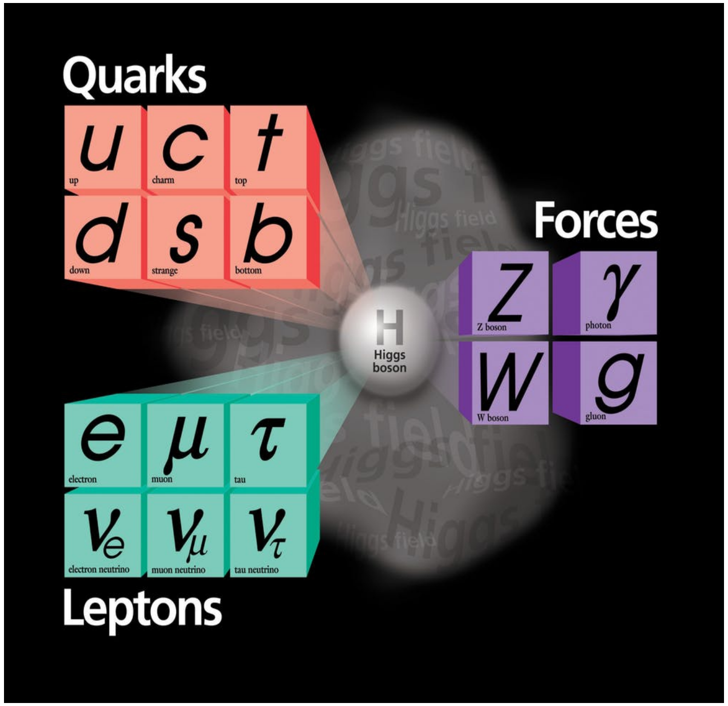
Gino Isidori
[*University of Zürich*]

- Introduction
- The flavor structure of the SM-EFT
- The B-physics anomalies
- A (possible) new paradigm in particle physics
- Paolo & Juliet

University of Zurich UZH

European Research Council
Established by the European Commission

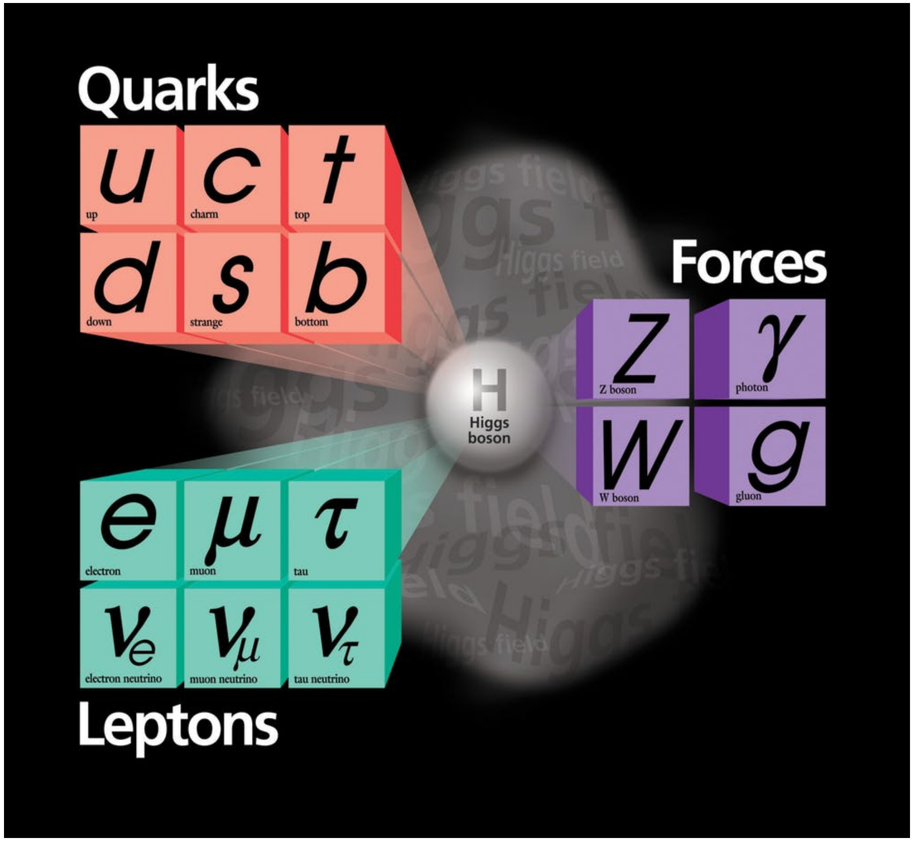
Introduction



Introduction

All microscopic phenomena seems to be well described by a remarkably simple Theory (*that we continue to call "model" only for historical reasons...*):

$$\mathscr{L}_{\text{Standard Model}} = \mathscr{L}_{\text{gauge}}(\psi_i, A_a) + \mathscr{L}_{\text{Higgs}}(H, A_a, \psi_i)$$



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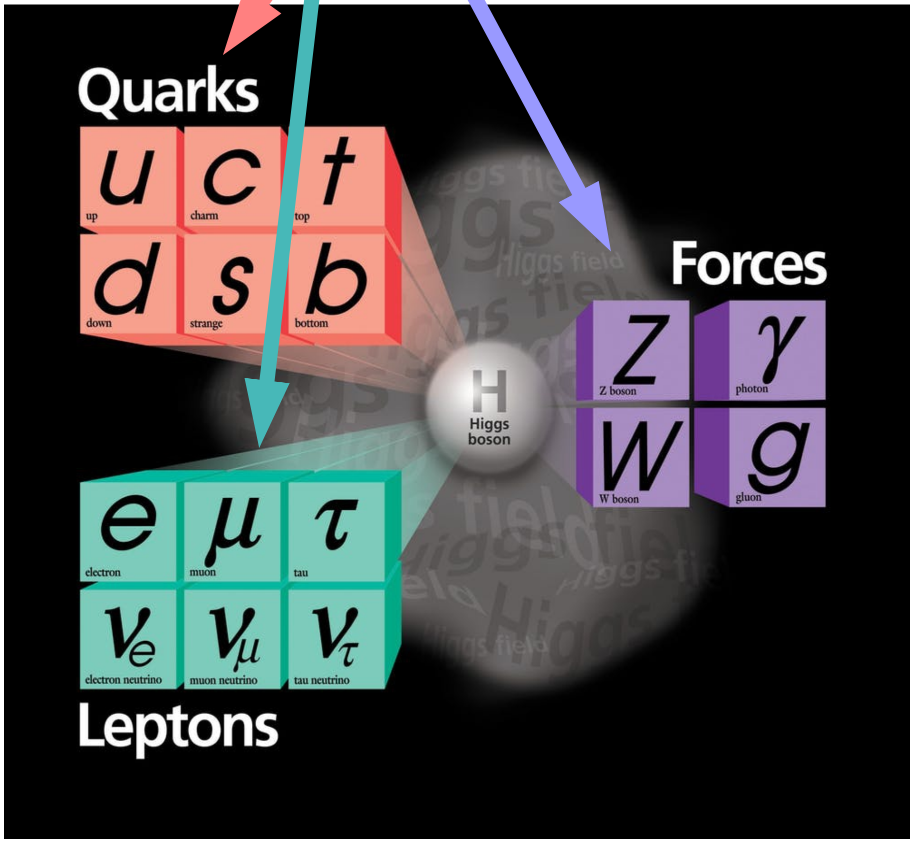

Strong
Weak
Electromagnetic
(*gauge interactions*)

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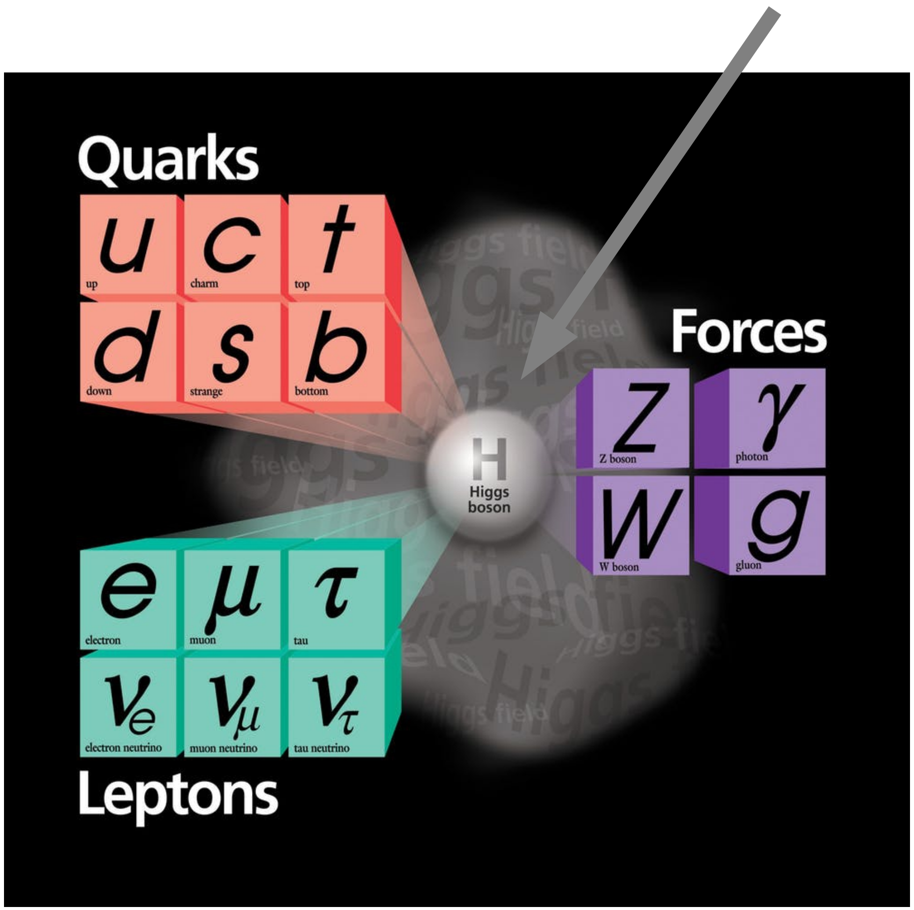


Spontaneous Symmetry Breaking

Introduction

Despite all its phenomenological successes, this Theory has some deep unsolved problems:

Electroweak hierarchy problem

Flavor puzzle
Neutrino masses
U(1) charges

Dark-matter
Dark-energy
Inflation

Quantum gravity

→

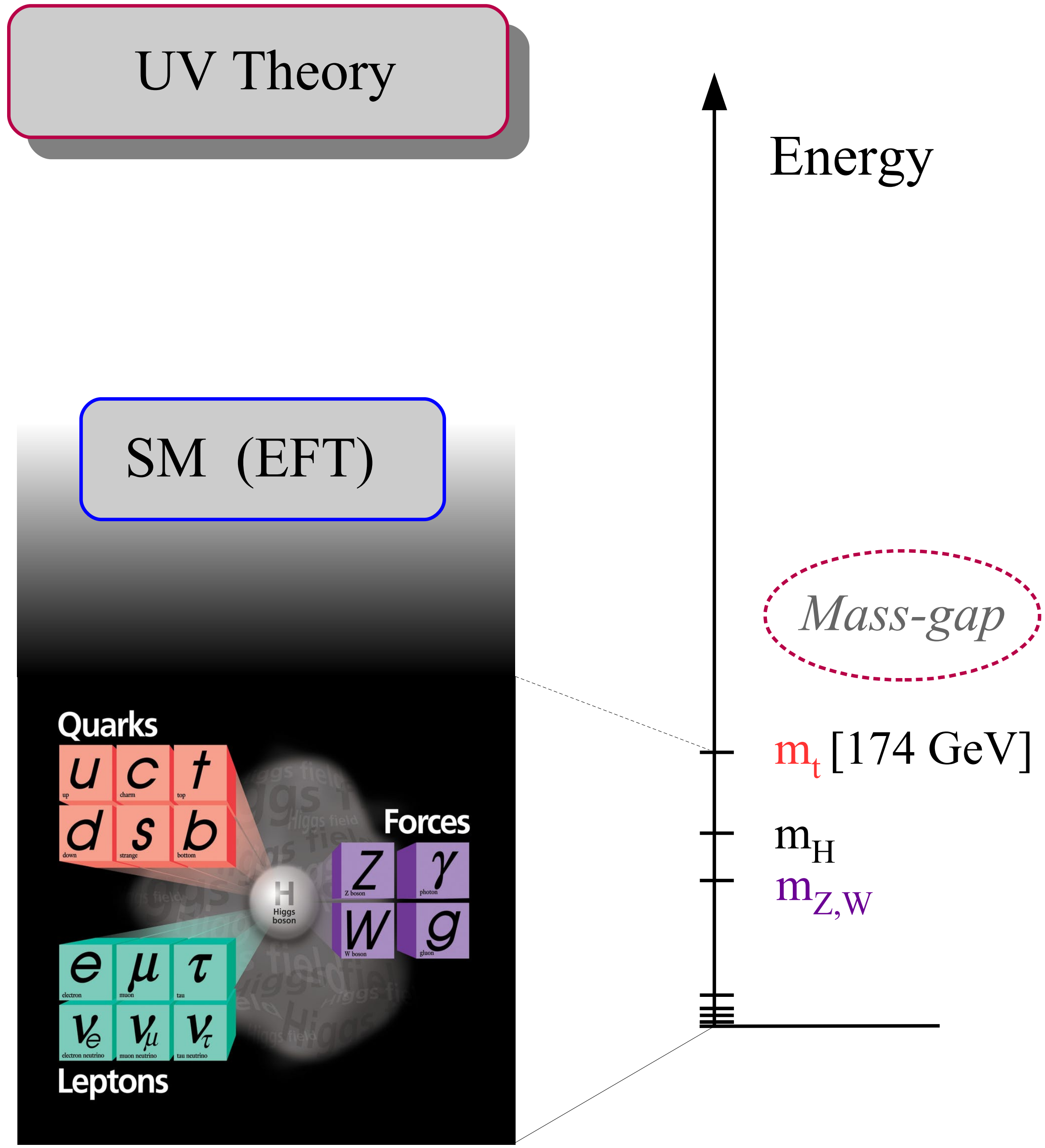
The Standard Model (SM) should be regarded as an *effective theory*

i.e. the limit (*in the range of energies and effective couplings so far probed*) of a more fundamental theory with new degrees of freedom

Introduction

What we know after the first phase of the LHC is that:

- The Higgs boson is SM-like and is "light" (*completion of the SM spectrum*)
- There is a mass-gap above the SM spectrum



Introduction

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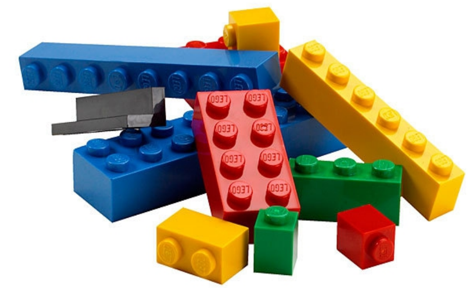
UV Theory

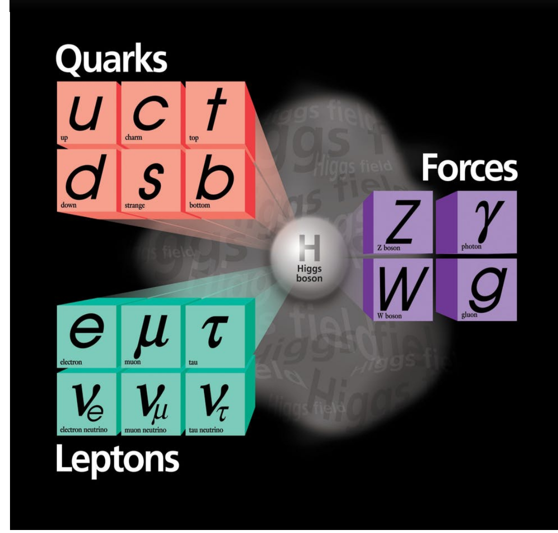
$E \sim L^{-1}$

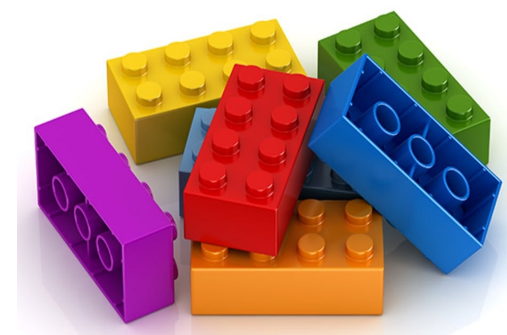


?

SM (EFT)

We identified the *“light”* (*“large”*) pieces of our *“construction game”* & their long-range interactions





Introduction

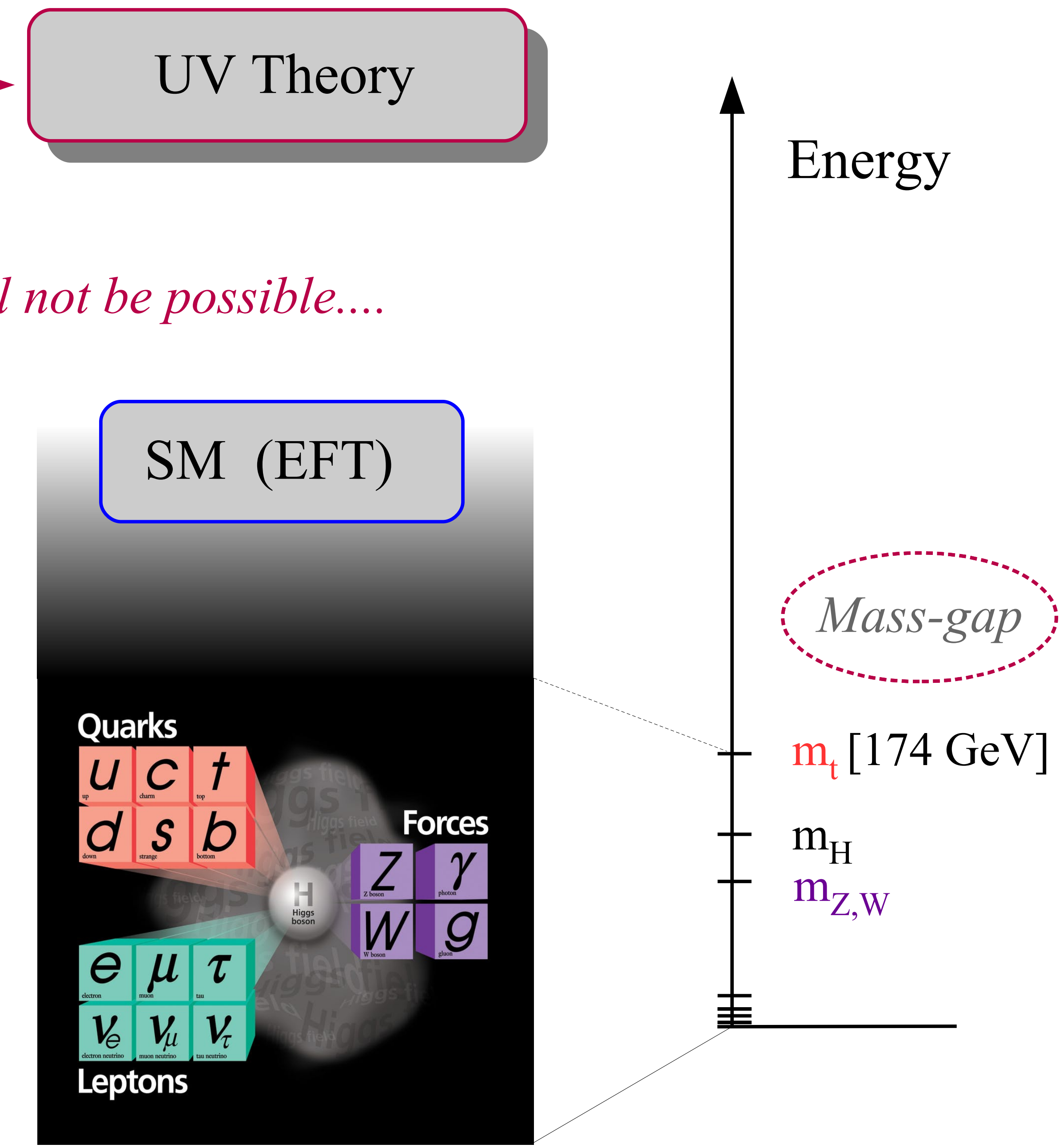
Ideally, we would like to probe the UV directly, via high-energy experiments

However, for > 30 years this will not be possible....

For the time being, we can only extract *indirect* UV infos exploring the low-energy limit of the EFT.

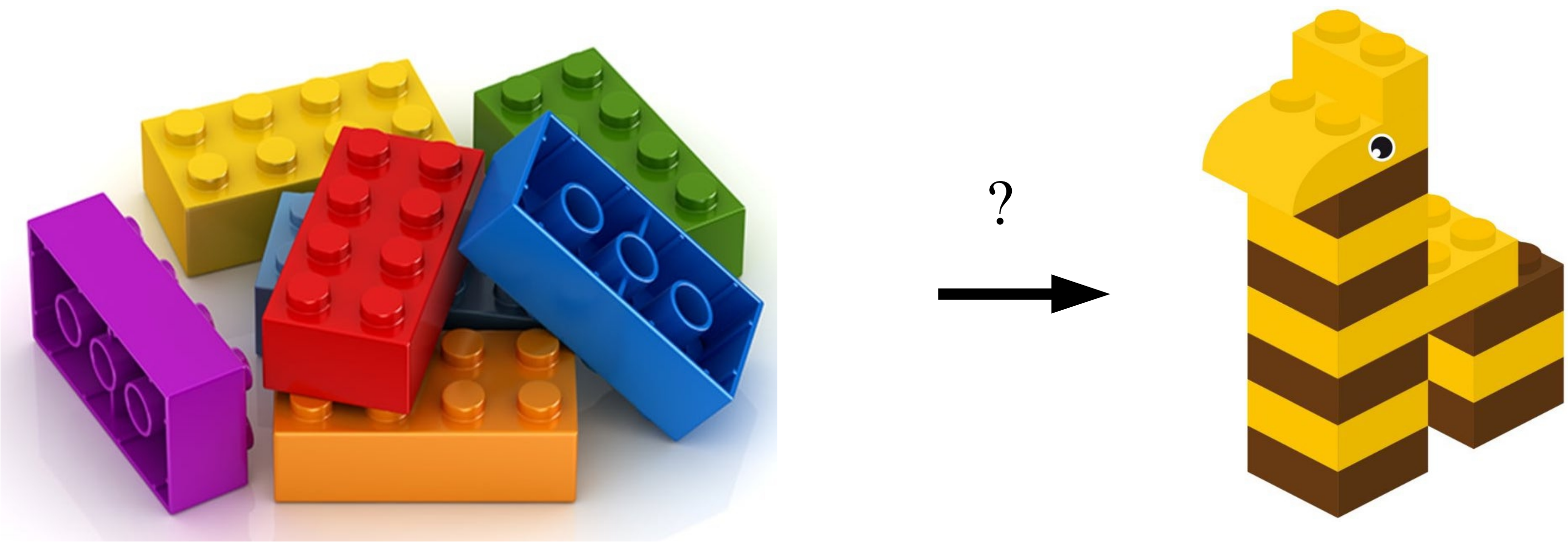
Many infos, with 2 clear messages:

- *several tuned* (SM) *couplings*
- *several accidental* (*approximate*) *symmetries*



Introduction

In the next few years the best we can do to extract information about UV dynamics is trying to detect and *decode* possible *un-natural features* of the SM-EFT.



Flavour physics is essential to this purpose

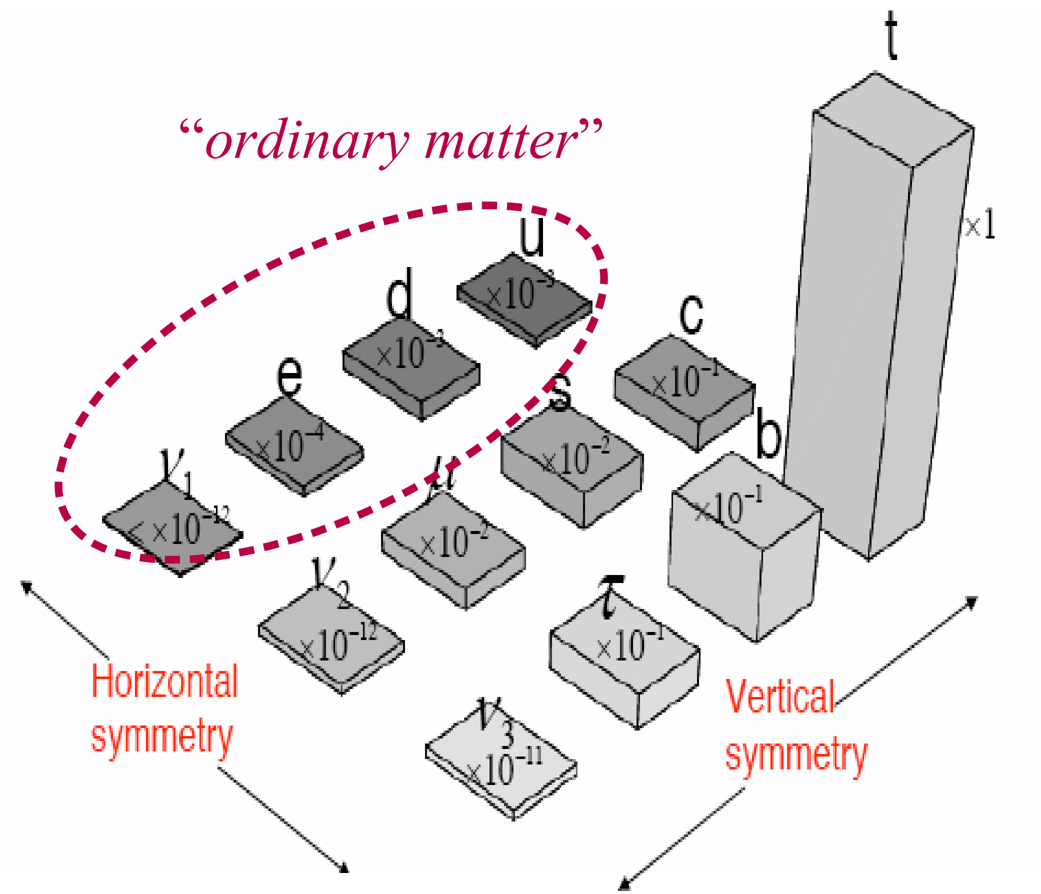
is already telling us a lot,
and might tell us much more in the near future...

The flavor structure of the SM

The flavor structure of the SM

The mystery of why we have three generations of quarks and leptons, and what distinguish them, is one of the most old, fascinating and, to a large extent, still open problems in particle physics

Paolo's contribution to this field, for more than 40 years been essential...



TEST OF THE CONSERVED VECTOR CURRENT HYPOTHESIS IN $\Sigma^{\pm} \to \Lambda^0$ LEPTONIC DECAYS

N. CABIBBO and P. FRANZINI *
CERN, Geneva

Received 13 December 1962

It has been proposed [1,2] that the decay processes

$$\Sigma^- \to \Lambda^0 + e^- + \bar{\nu}\,, \quad (1a)$$

$$\Sigma^+ \to \Lambda^0 + e^+ + \nu \quad (1b)$$

could provide a test of the conserved vector current hypothesis [3].

In the present work we show how such a test can be performed through the combined measurement of the branching ratio for the above decays, the average Λ^0 polarisation from unpolarised Σ's ** and the Λ^0 hyperon spectrum. The matrix element for process (1a) can be written as form factors; for the case of even $\Sigma\Lambda$ parity we have

$$(2\pi)^3 \langle \Lambda^0 | J_\mu^V | \Sigma^- \rangle = \bar{u}^{\Lambda^0}[a(q^2)\gamma_\mu + b(q^2)\sigma_{\mu\nu}q_\nu + b'(q^2)q_\mu]\, u^{\Sigma^-}\,, \quad (3)$$

$$(2\pi)^3 \langle \Lambda^0 | J_\mu^A | \Sigma^- \rangle = \bar{u}^{\Lambda^0}[c(q^2)\gamma_\mu\gamma_5 + d(q^2)\sigma_{\mu\nu}q_\nu\gamma_5 + d'(q^2)q_\mu\gamma_5]\, u^{\Sigma^-}\,, \quad (4)$$

$$q_\mu = p_e^\mu + p_{\bar{\nu}}^\mu\,.$$

It is convenient to classify contributions according to forbiddenness: the terms with γ_μ and $\gamma_\mu\gamma_5$ give allowed contributions if $a(0)$ and respectively

Important ingredient for the formulation of Cabibbo's theory in 1963

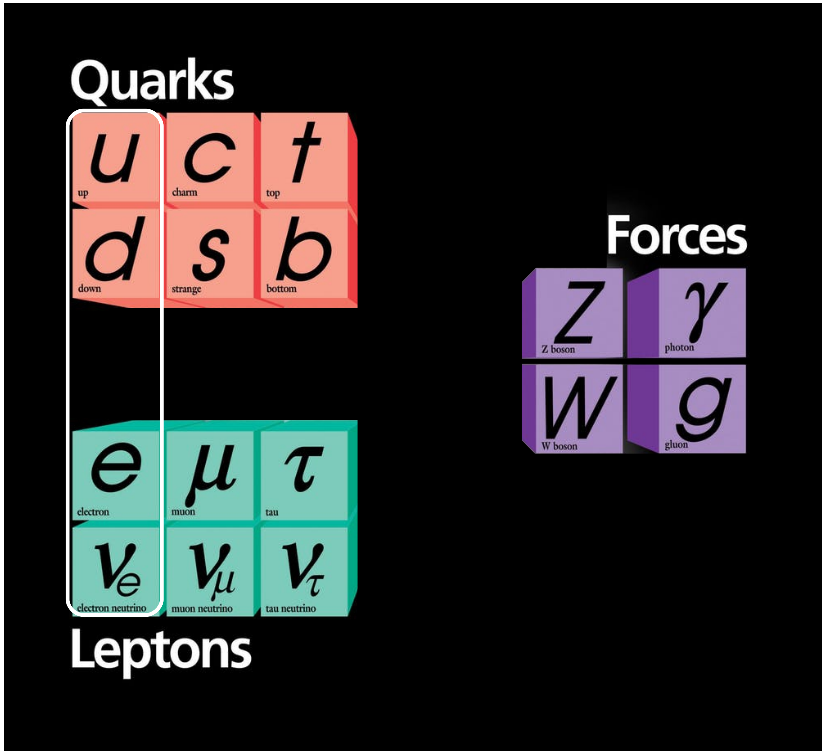
The flavor structure of the SM

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

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

$$\mathscr{L}_{gauge} = \Sigma_a -\frac{1}{4g_a^2}(F_{\mu\nu}^a)^2 + \Sigma_\psi \Sigma_{i=1..3} \bar{\psi}_i i \not{D} \psi_i$$

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



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

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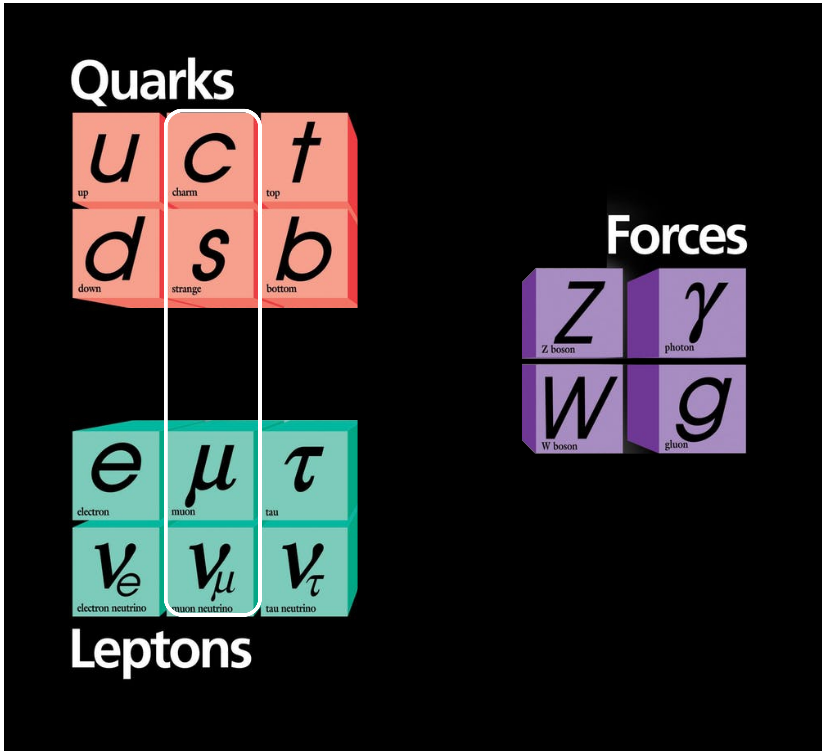

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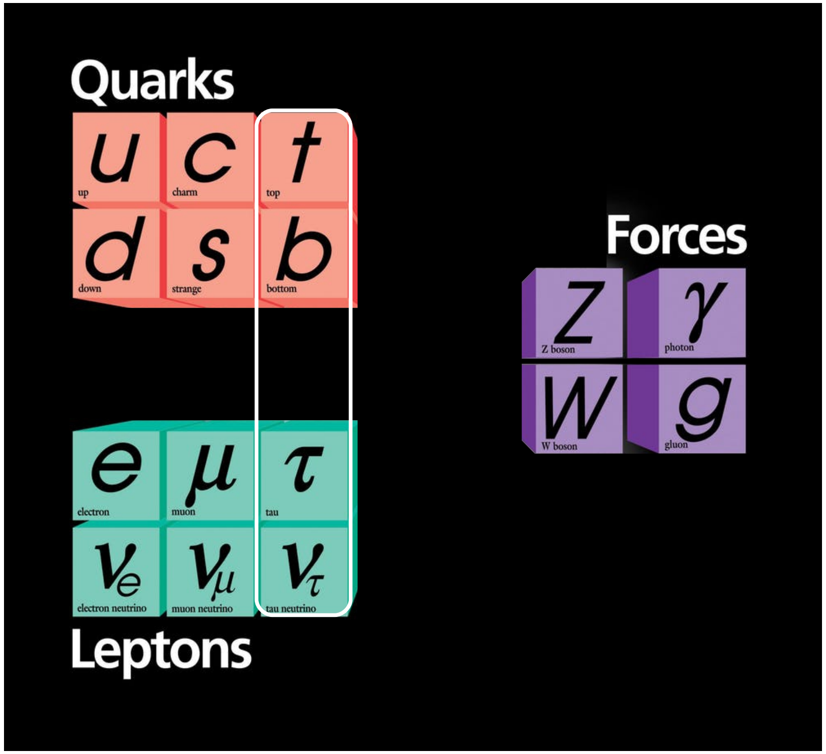

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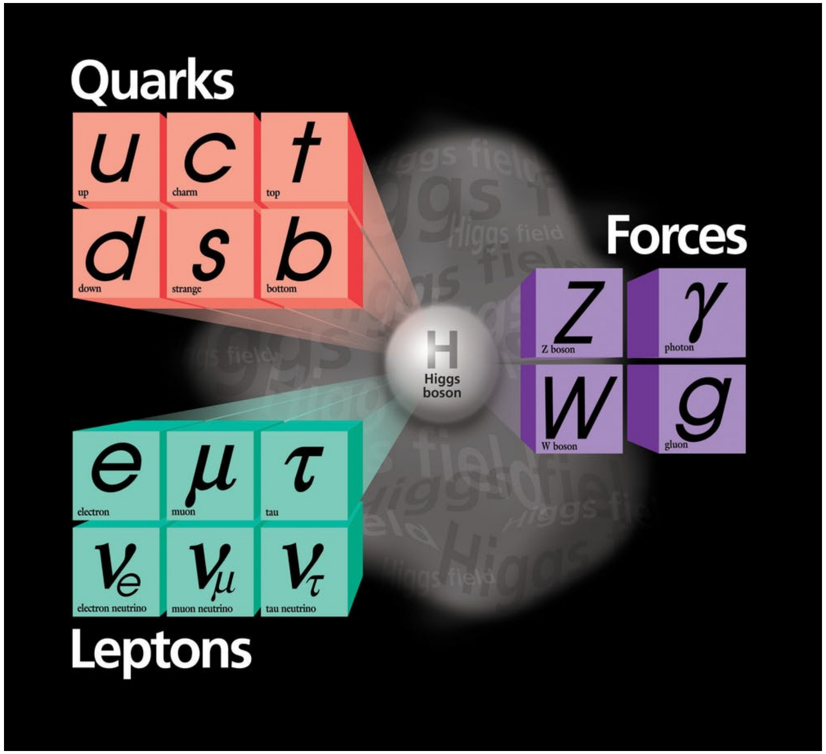
Within the SM the flavor-degeneracy is broken only by the Yukawa interaction:

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

$$\bar{Q}_L^{\,i}\, Y_U^{ik}\, u_R^{\,k}\, H_c \rightarrow \bar{u}_L^{\,i}\, M_U^{ik}\, u_R^{\,k} + \ldots$$

$$\bar{L}_L^{\,i}\, Y_E^{ik}\, e_R^{\,k}\, H \rightarrow \bar{l}_L^{\,i}\, M_E^{ik}\, l_R^{\,k} + \ldots$$



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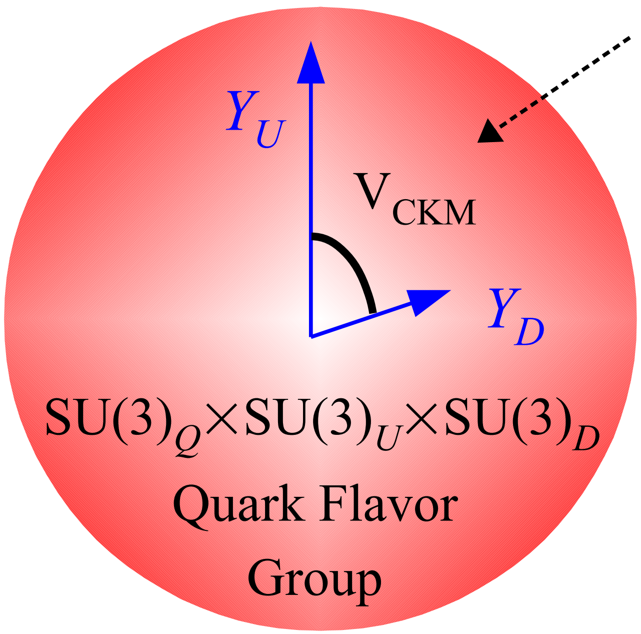
Cabibbo
Kobayashi
Maskawa



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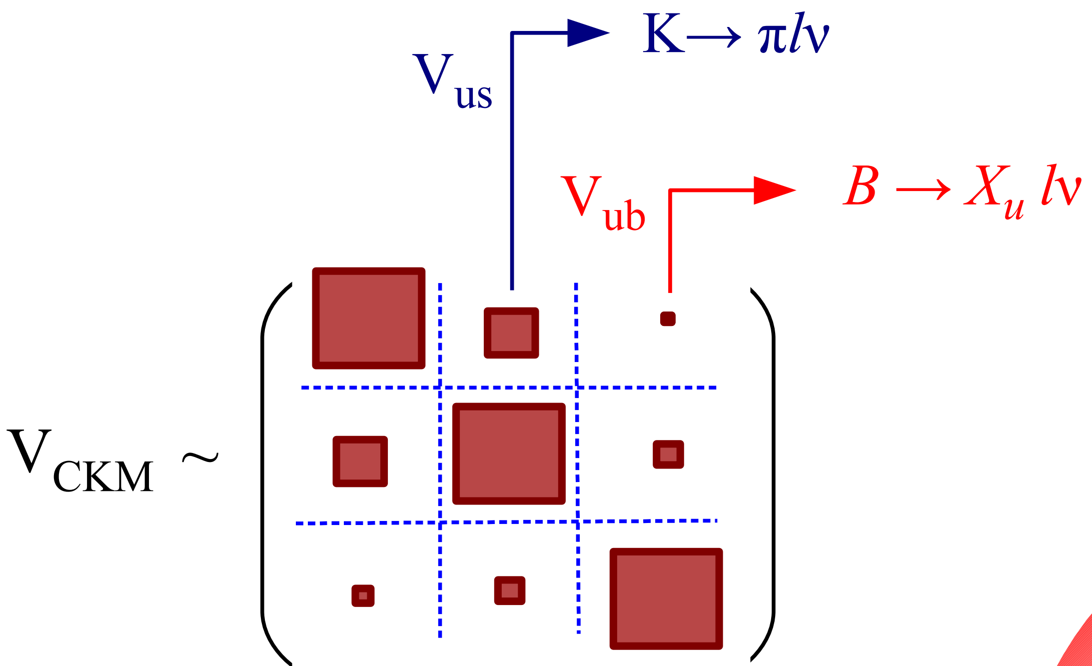
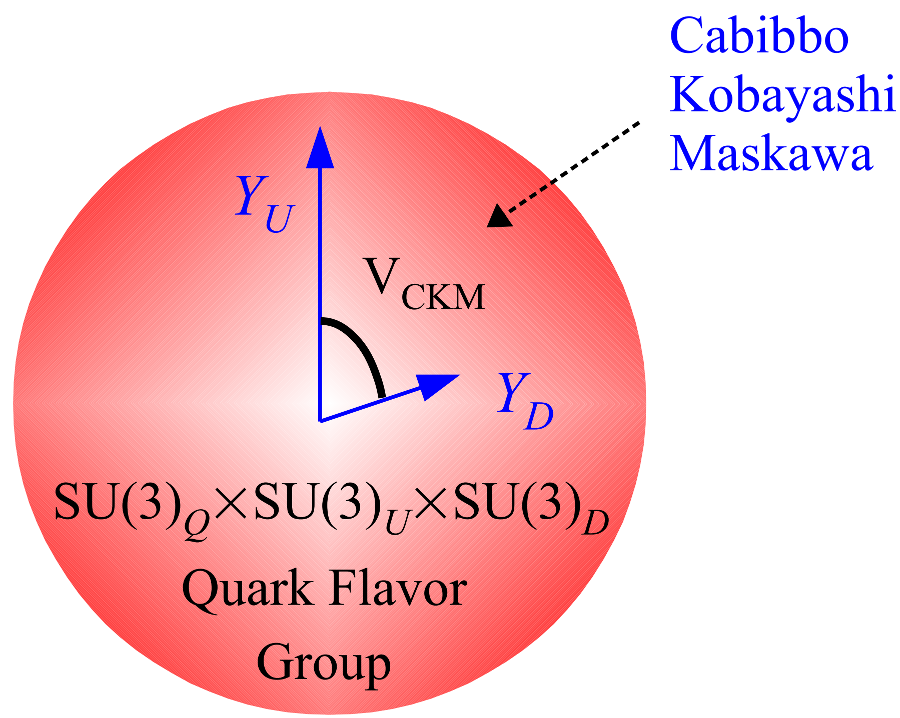
Paolo's contribution to this field, for more than 40 years, been essential...





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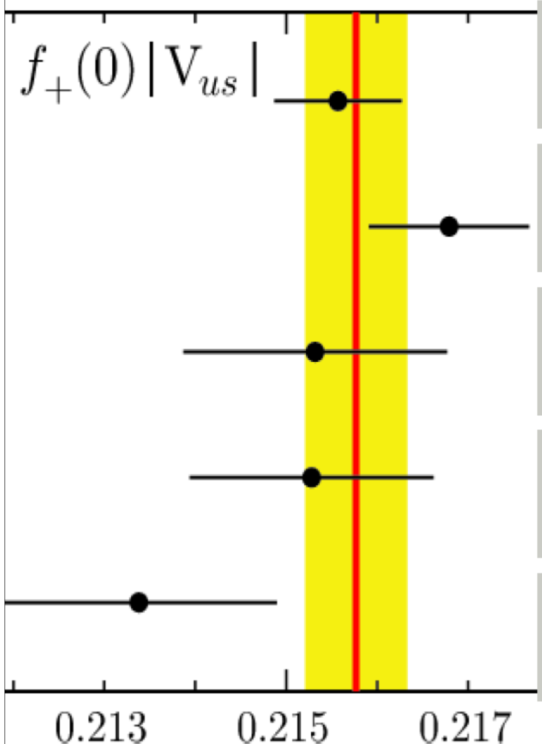
V_{us} from KLOE K_{l3} data

JHEP 0804:059



		% err
$K_L e3$	0.2155(7)	0.3
$K_L \mu 3$	0.2167(9)	0.4
$K_S e3$	0.2152(14)	0.7
$K^\pm e3$	0.2152(13)	0.6
$K^\pm \mu 3$	0.2132(15)	0.7

$|V_{us}| f_+(0)$

KLOE Avg:
0.2157(6)
χ^2/ndf = 7/4 (13%)

World Avg:
0.2166(5)

$f_+(0)$=0.964(5) **RBC/UKQCD**

$\Rightarrow$ **V_{us} = 0.2237(13)**

M. Antonelli @ La Thuile 2009

The flavor structure of the SM

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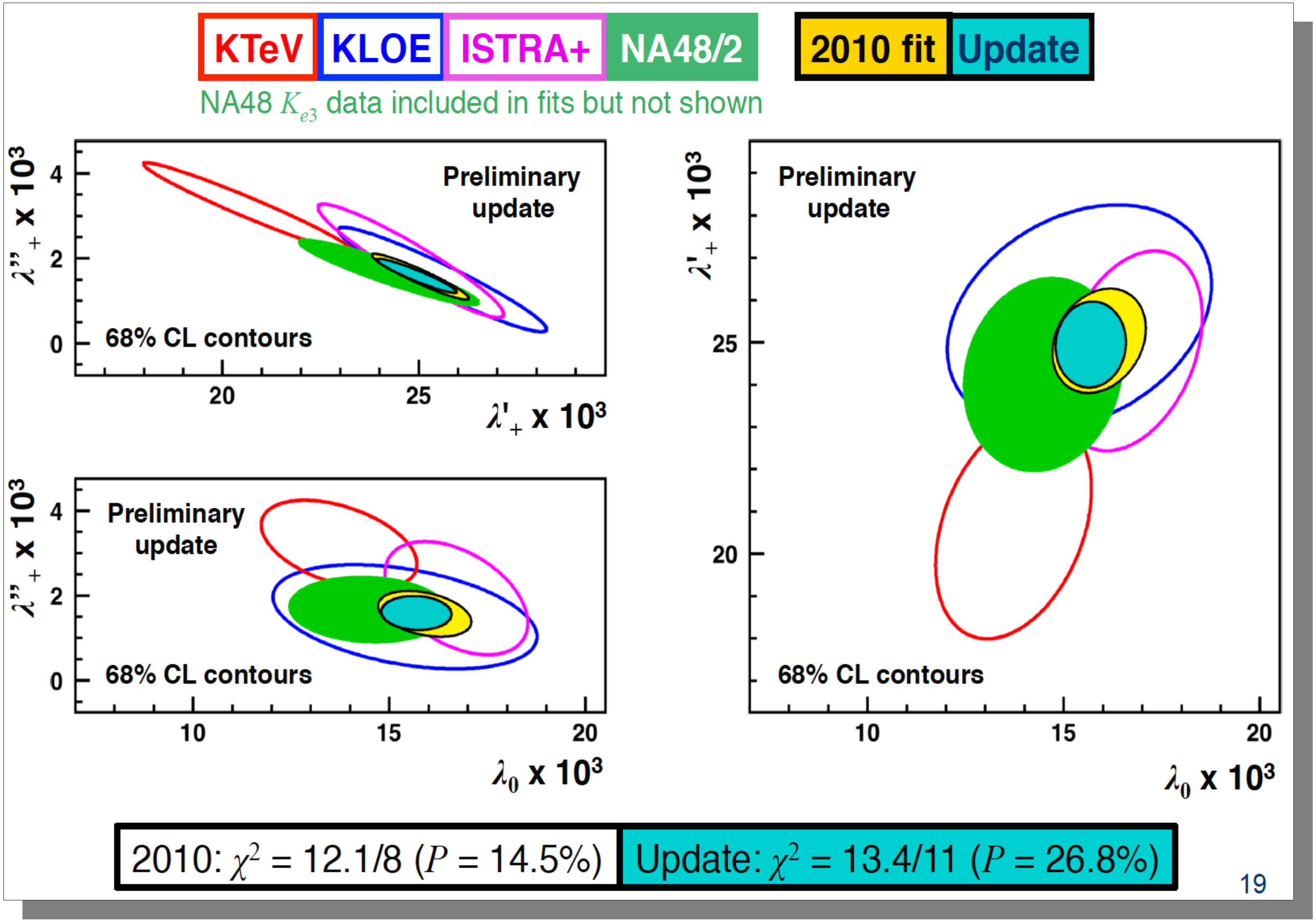

E. Passemar @ Kaon 2019

The flavor structure of the SM

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SEMILEPTONIC DECAY OF THE B MESON

C. KLOPFENSTEIN, J.E. HORSTKOTTE, J. LEE-FRANZINI, R.D. SCHAMBERGER
M. SIVERTZ, L.J. SPENCER [1], P.M. TUTS
The State University of New York at Stony Brook, Stony Brook, NY 11794, USA

P. FRANZINI, K. HAN, E. RICE [2], D. SON, S. YOUSSEF
Columbia University, New York, NY 10027, USA

S.W. HERB
Cornell University, Ithaca, NY 14853, USA

R. IMLAY, G. LEVMAN, W. METCALF, V. SREEDHAR
Louisiana State University, Baton Rouge, LA 70803, USA
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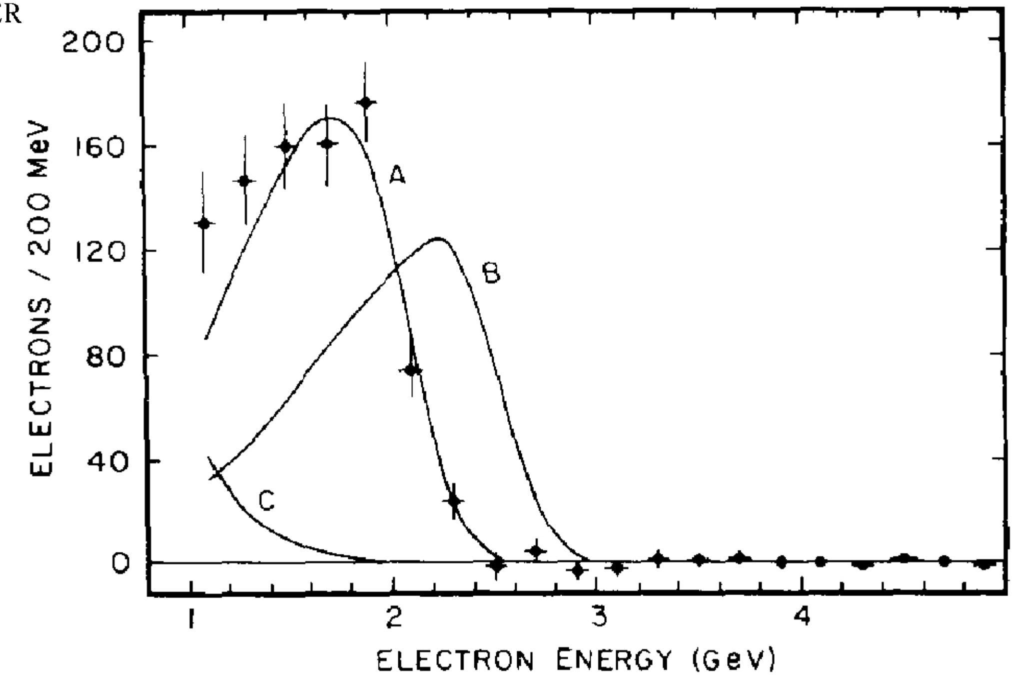
H. DIETL, G. EIGEN, E. LORENZ, G. MAGERAS, F. PAUSS [3] and H. VOGEL
Max Planck Institut für Physik, D-8000 Munich 40, Fed. Rep. Germany

Received 3 August 1983



PLB
Nov. '83

Using the CUSB detector we have measured the production of electrons from the decay $B \to e\nu X$. We obtain a branching ratio for $B \to e\nu X$ of $(13.2 \pm 0.8 \pm 1.4)\%$. The observed energy spectrum of the electrons implies that the coupling (bc)W dominates over (bu)W. An upper limit $\Gamma(B \to e\nu X_u)/\Gamma(B \to e\nu X_c) < 5.5\%$ at 90% confidence level is obtained, where X_c contains a c-quark and X_u contains no charmed particles.

$\downarrow$

$$|V_{ub}|/|V_{cb}| < 0.2$$

The two flavor puzzles

Even forgetting current anomalies, there are two (long-standing) open issues in flavor physics:

I. The observed pattern of SM Yukawa couplings does not look accidental [*SM flavor puzzle*]

$\rightarrow$ Is there a deeper explanation for this peculiar structures?

The two flavor puzzles

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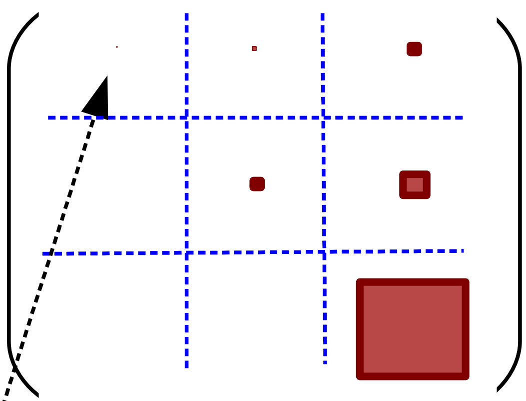
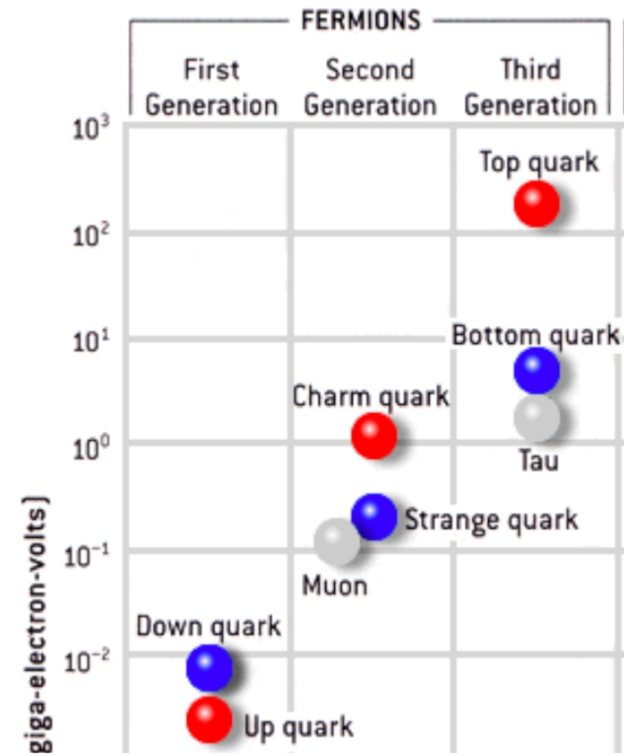
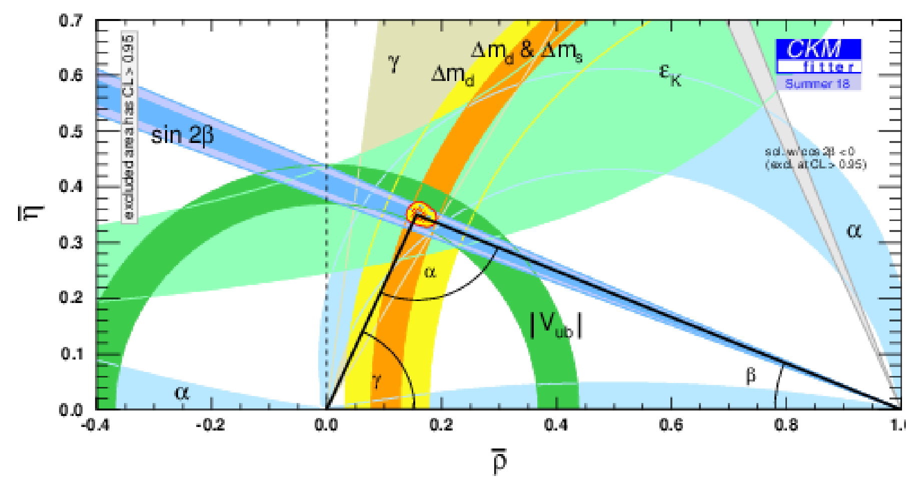
E.g.:

$Y_U \sim$ 

$$y_u = \frac{\sqrt{2}\, m_u}{\langle H \rangle} \approx 10^{-5} \qquad y_t = \frac{\sqrt{2}\, m_t}{\langle H \rangle} \approx 1$$

[Y_U in the basis where Y_D is diagonal]





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I. The observed pattern of SM Yukawa couplings does not look accidental [*SM flavor puzzle*]

→ Is there a deeper explanation for this peculiar structures?

II. If the SM is only an effective theory, valid below an ultraviolet cut-off , why we do not see any deviation from the SM predictions in the (suppressed) flavor changing processes? What constraints these observations imply on physics beyond the SM? [*NP flavor puzzle*]

→ Which is the flavor structure of physics beyond the SM?

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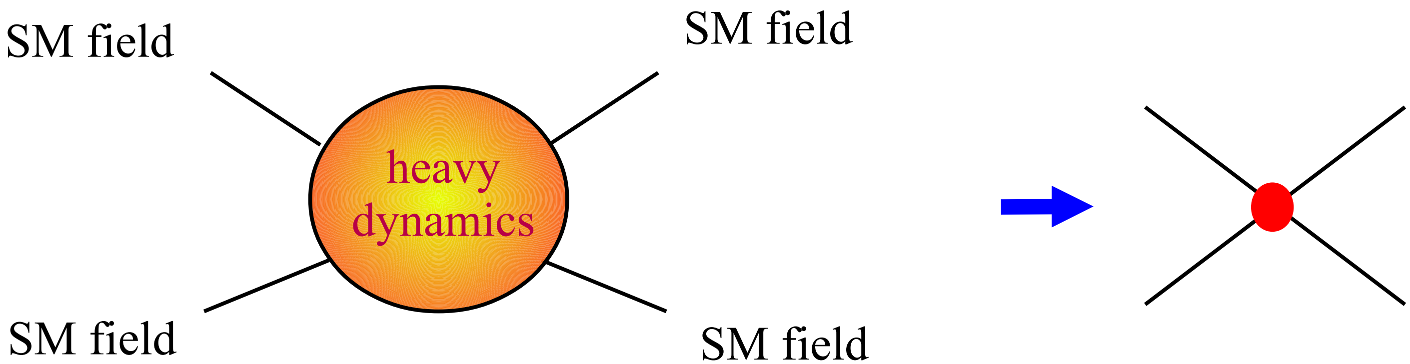
Recent data "hints" to possible answers..

The flavor structure of the SMEFT



The flavor structure of the SMEFT

As anticipated, the modern point of view on the SM Lagrangian is to consider it the leading part (or the low-energy limit) of a more general effective theory.

New degrees of freedom are expected at a scale Λ above the electroweak scale.

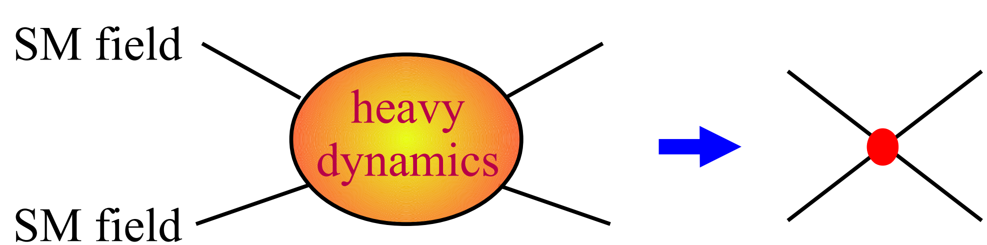
$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}}(A_a, \psi_i) + \mathscr{L}_{\text{Higgs}}(H, A_a, \psi_i) + \sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{d\geq 5}(H, A_a, \psi_i)$$

Interactions surviving @ large distances
(operators with $d \leq 4$)

Long-range forces
of the SM particles
+
ground state (Higgs)

Local contact interactions
(operators with $d > 4$)

"Remnant" of the heavy
dynamics at low energies



The flavor structure of the SMEFT

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Large flavor symmetry

Three identical replica of the basic fermion family [$U(3)^5$ symmetry]

Flavor-degeneracy broken by the Yukawa interaction

$$y_{ij}\, \psi_L^{\ i}\, \psi_R^{\ j}\, H \;\rightarrow\; m_{ij}\, \psi_L^{\ i}\, \psi_R^{\ j}$$

"Peculiar" breaking structure

Exact & approximate (*accidental* ?) symmetries

Eg:

- $U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\mu}$ = (individual) Lepton Flavor [*exact symmetry*]
- $m_u \approx m_d \approx 0$ $\rightarrow$ Isospin symmetry [*approximate symmetry*]

The flavor structure of the SMEFT

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Large flavor symmetry

Yukawa interaction

Exact & approximate (*accidental* ?) symmetries

The great interest of precision measurements in flavor physics is the possibility to tests a large number of non-standard higher-dim. operators which may correspond to rather high-energy scales, depending on the possible flavor structure of physics beyond the SM

▸ *Accidental symmetries in QFT* [a brief detour]

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{d\geq 5}$$

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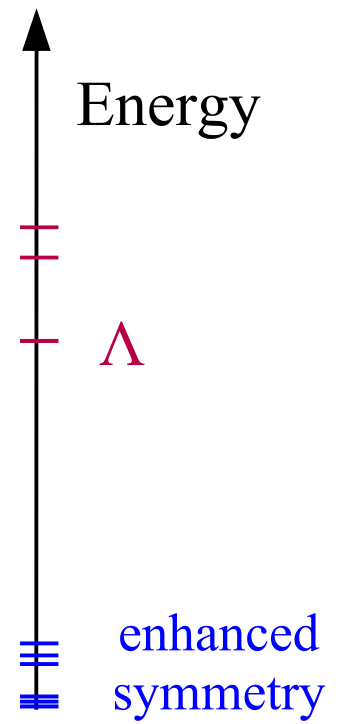

"Accidental symmetries" are symmetries which are not fundamental properties of the theory, but emerge accidentally at low energies / large distances → not enough "variables" to describe the violation of the symmetry [~ *multipole expansion*]

Accidental symmetries in QFT [a brief detour]

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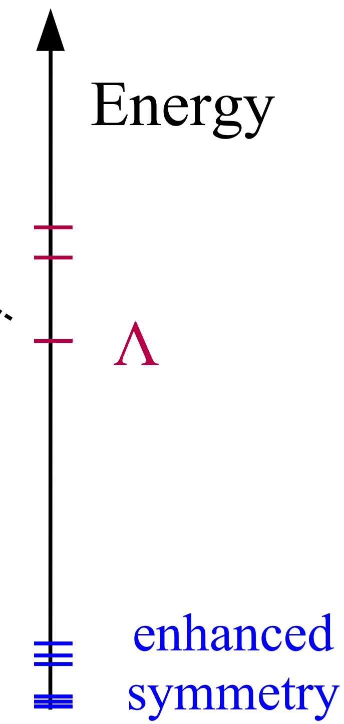

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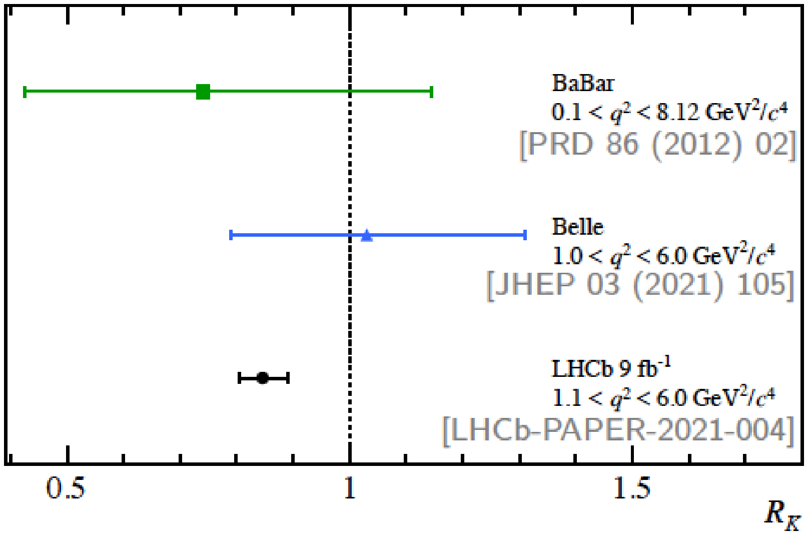
If a symmetry arises accidentally in the low-energy theory, we expect it to be violated by higher dim. ops

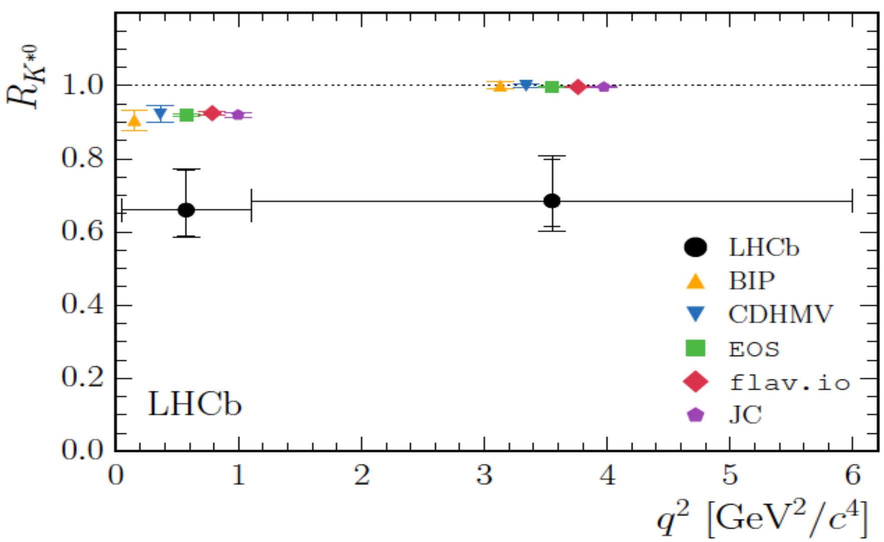
Violations of accidental symmetries

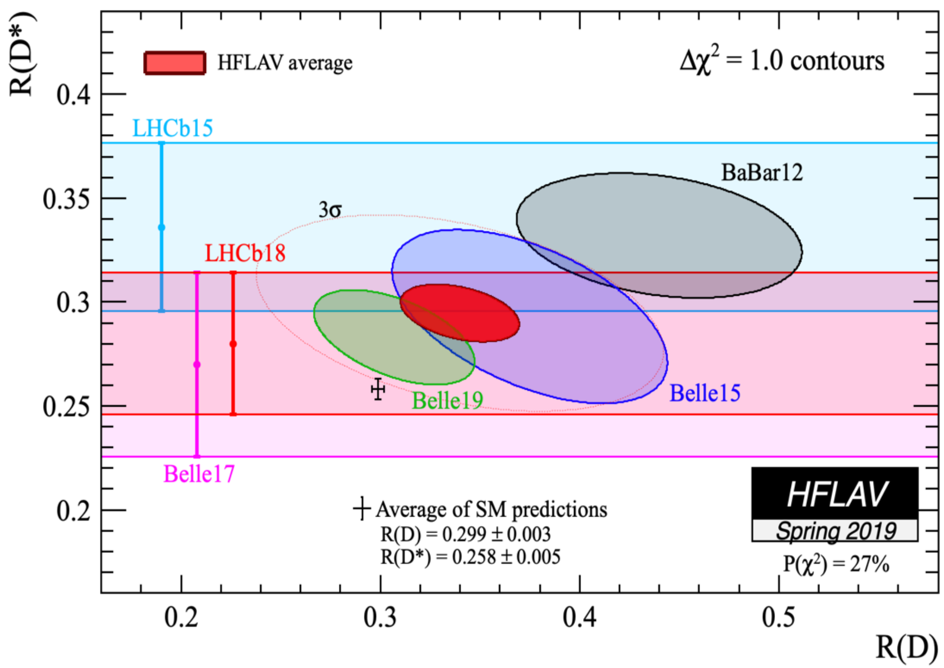
Well-known examples from the past...

…the "anomalies" reported in recent data belong to this category

The B-physics anomalies







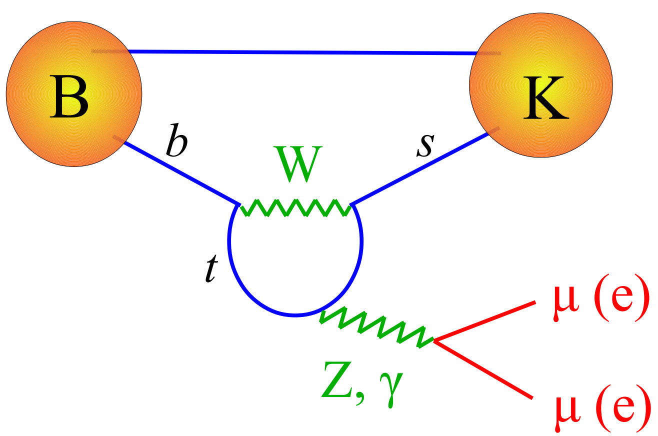
The B-physics anomalies

Since 2013 results in semi-leptonic B decays started to exhibit tensions with the SM predictions connected to a possible violation of Lepton Flavor Universality

More precisely, we seem to observe a different behavior (*beside pure kinematical effects*) of different lepton species in the following processes:

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

E.g.:



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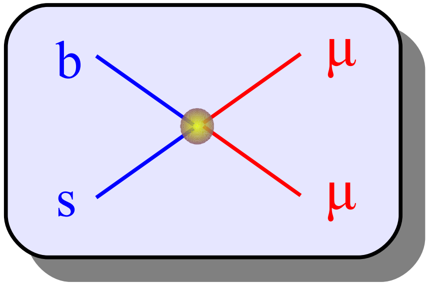
N.B: LFU is an accidental symmetry of the SM Lagrangian in the limit where we neglect the lepton Yukawa couplings (or the lepton masses).

Since all lepton masses are small (*more precisely, the lepton Yukawa couplings are small compared to the SM gauge couplings*), within the SM we expect all leptons to behave in the same manner (except pure kinematical effects due to their different masses)

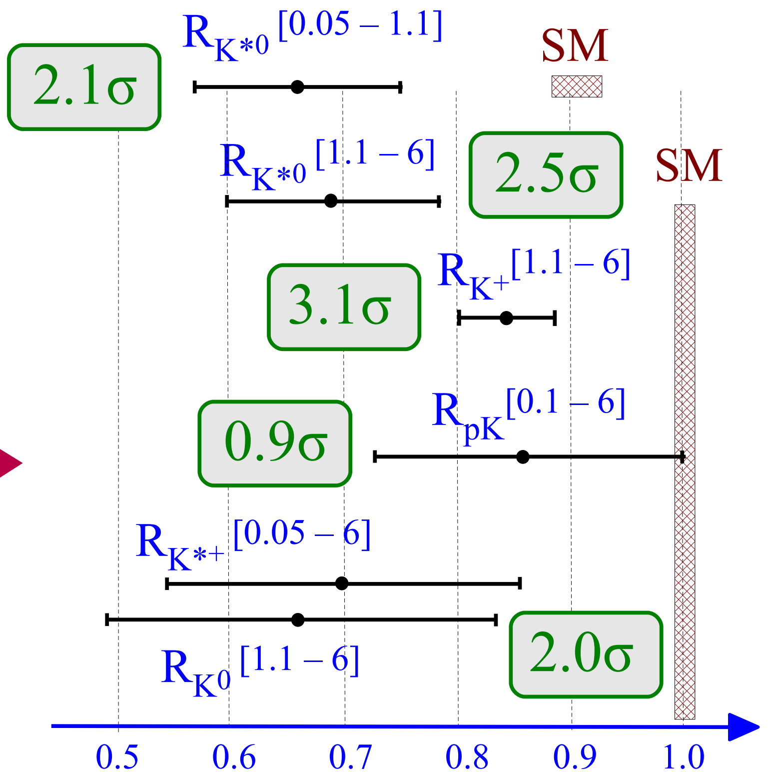
The B-physics anomalies

- $b \to s\, l^+ l^-$ (neutral currents): μ vs. e

High significance: several observables pointing to the same coherent picture [several new results in 2021]



$\Gamma(H_b \to H_s\, \mu\mu)/\Gamma(H_b \to H_s\, ee)$



LFU ratios

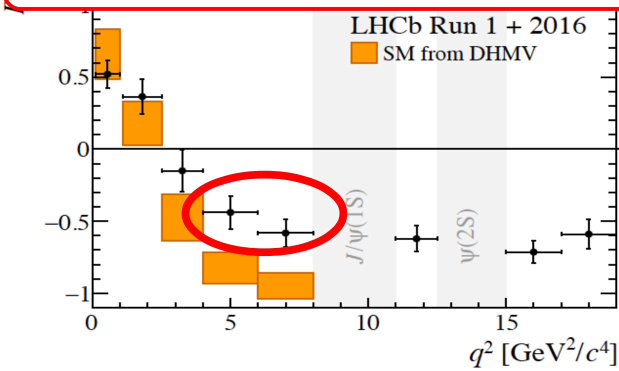
[LHCb – Autumn 2021]

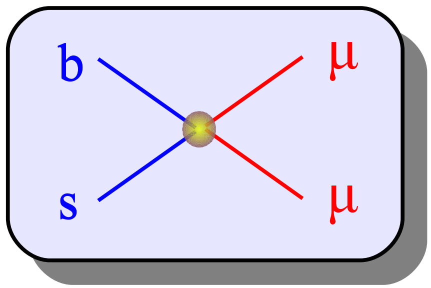
The B-physics anomalies

$b \to s\, l^+ l^-$ (neutral currents): μ vs. e

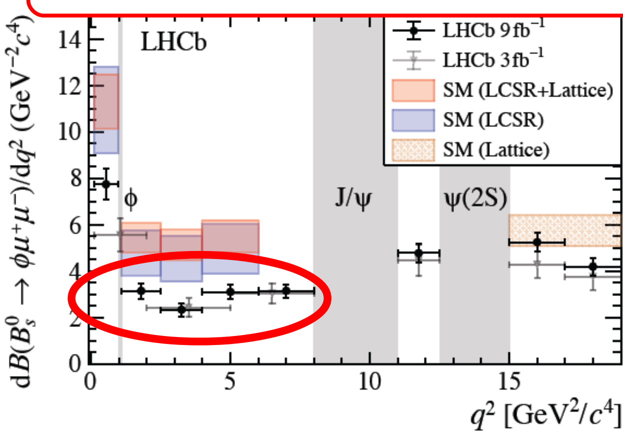
High significance: several observables pointing to the same coherent picture [several new results in 2021]

$B \to K^* \mu\mu$ angular distribution

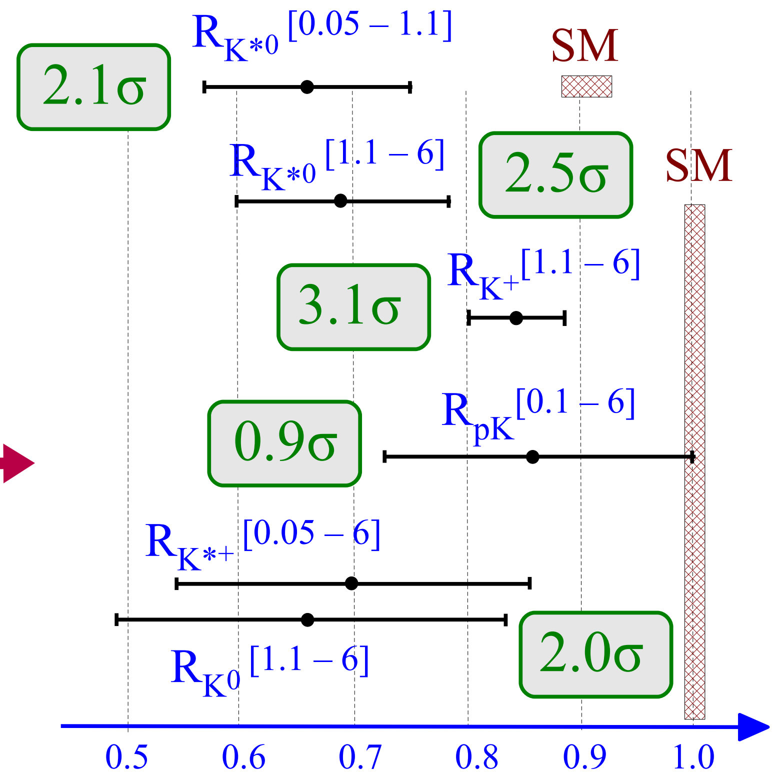




$B \to H\, \mu\mu$ branching ratios



$\Gamma(H_b \to H_s\, \mu\mu)/\Gamma(H_b \to H_s\, ee)$



$BR(B_s \to \mu\mu)$

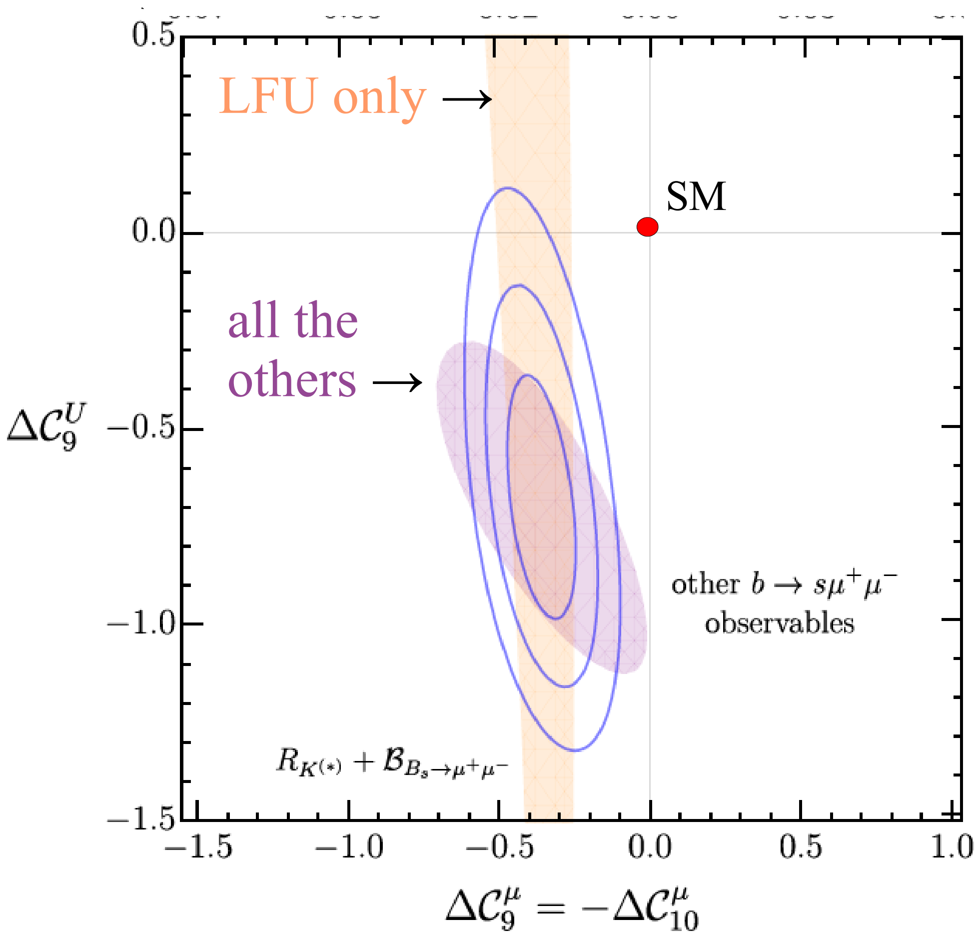
$BR_{exp} = (2.85 \pm 0.32) \times 10^{-9}$ ATLAS+CMS+LHCb '21

$BR_{SM} = (3.66 \pm 0.14) \times 10^{-9}$

2.3σ

The B-physics anomalies

- $b \to s\, l^+ l^-$ (neutral currents): μ vs. e



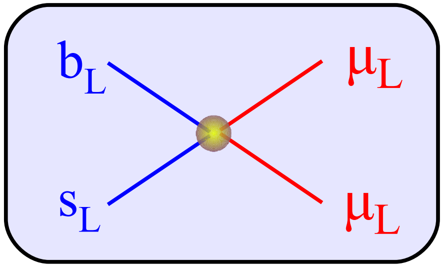
$$\mathcal{O}_{10}^\ell = (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$
$$\mathcal{O}_9^\ell = (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\ell)$$

Significance from global fits:

$\boxed{5.0\sigma}$ Conservative fit
"clean obs." only,
SM vs. best New Physics model

>> 5σ Including all observables
(*with best estimate of non-perturbative contributions*)

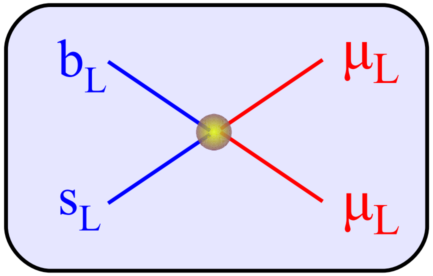
$\boxed{4.2\sigma}$ Global significance of NP
(*probing any type of NP model*)



Alguero *et al.* '19
Ciuchini *et al.* '20
Li-Sheng *et al.* '21
Altmanshofer & Stangl '21
Cornella *et al.* '21
GI, Lancierini *et al.* '21

The B-physics anomalies

- $b \to s\, l^+ l^-$ (neutral currents): μ vs. e



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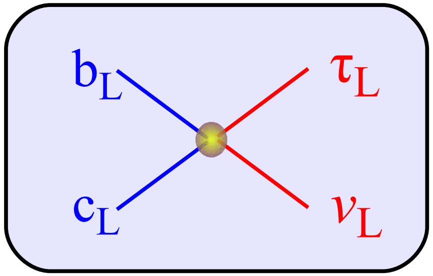
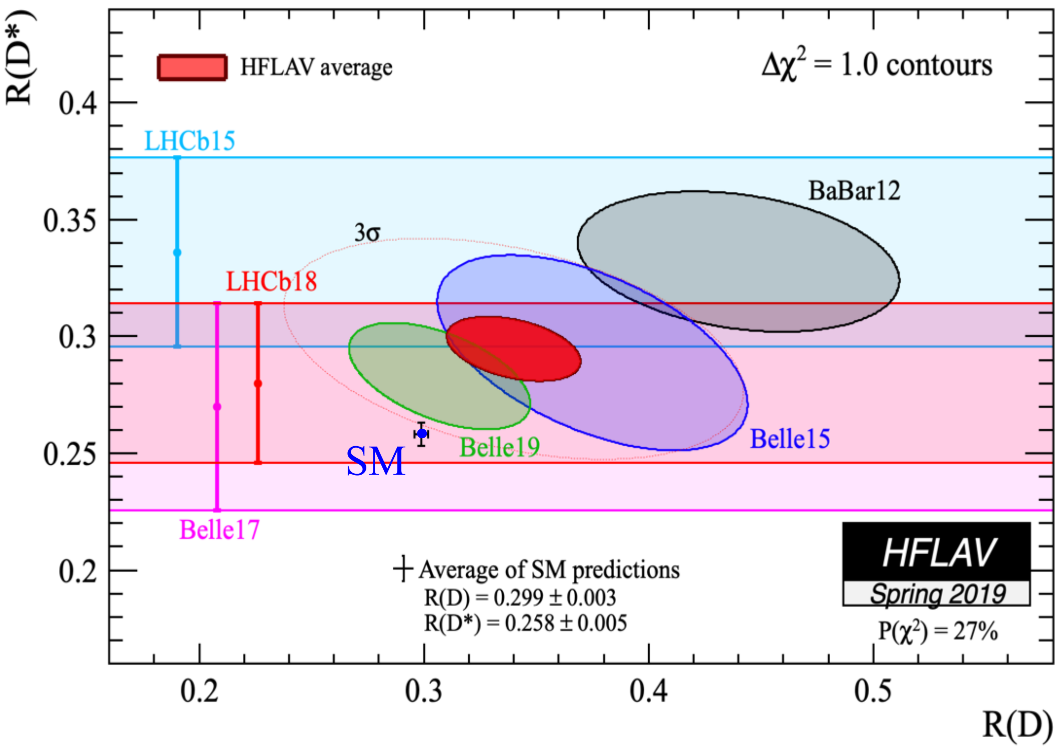




$$R(X) = \frac{\Gamma(B \to X\, \tau\nu)}{\Gamma(B \to X\, l\nu)}$$

X = D or D*

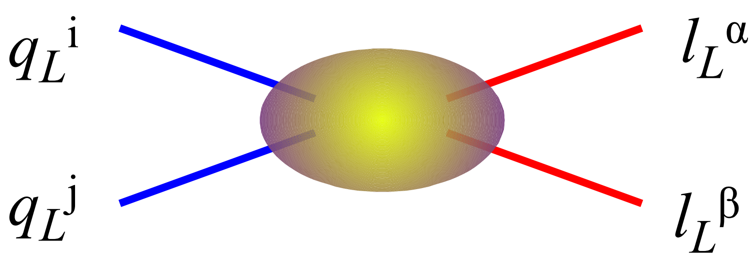
- Clean SM predictions (*uncertainties cancel in the ratios*)
- Consistent results by 3 different exp.ts: $\boxed{\sim 3\sigma}$ excess over SM
- Slower progress...

➔ Large New Physics effect competing with large SM amplitude

The B-physics anomalies

Summary:

- Anomalies are seen only in semi-leptonic (quark×lepton) operators



- Large coupling in b (3^{rd}) c (2^{nd}) $\rightarrow$ τ (3^{rd}) ν_τ (3^{rd})
- Small coupling in b (3^{rd}) s (2^{nd}) $\rightarrow$ μ (2^{rd}) μ (2^{rd})

$\Downarrow$

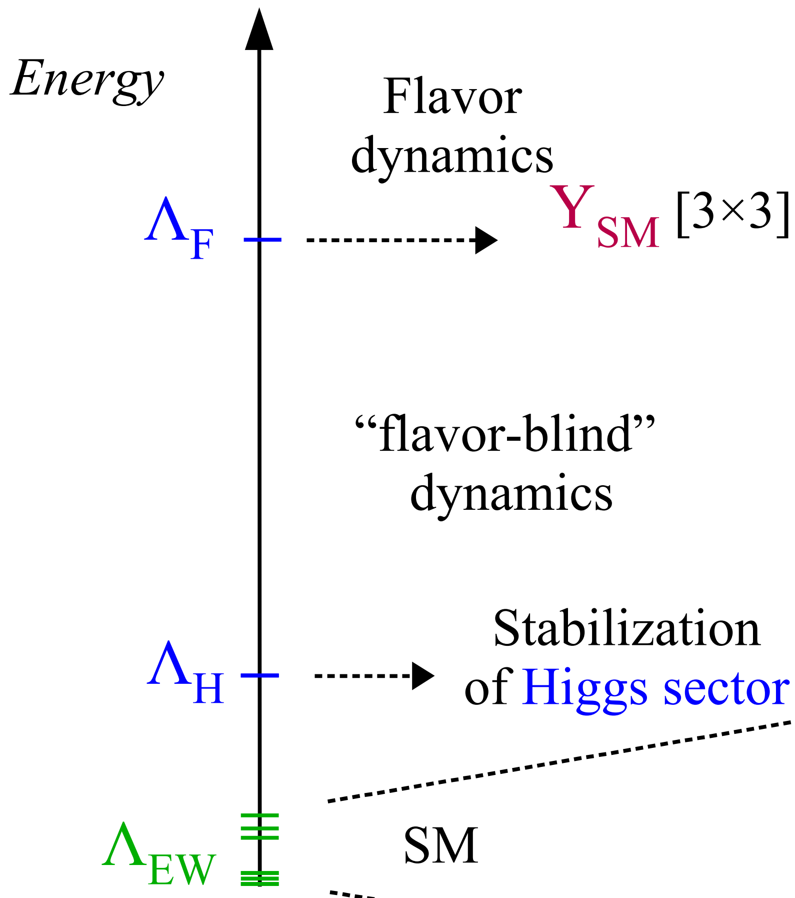
$C_{ij\alpha\beta}$ = large for 3^{rd} generation fields + small terms for 2^{nd} (& 1^{st}) generations $\rightarrow$

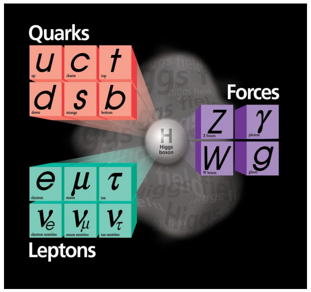
Same pattern of the SM Yukawa couplings !

A (possible) new paradigm in particle physics

▸ A (possible) new paradigm in particle physics

The old paradigm (*Minimal Flavor Violation*):





Main idea:

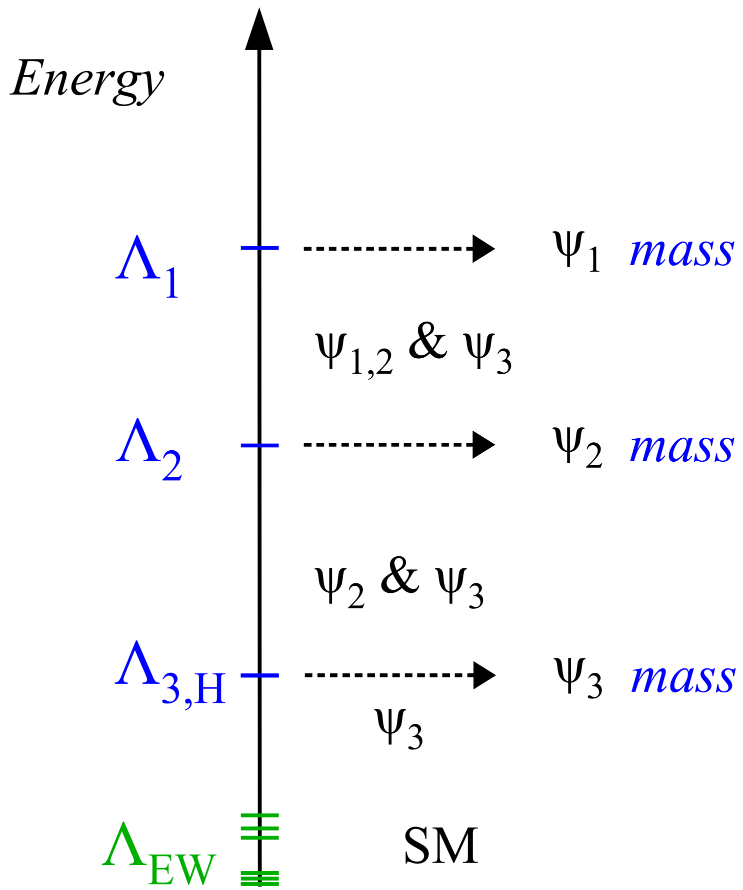
- Concentrate on the Higgs hierarchy problem
- Postpone (*ignore*) the flavor problem

⬇

3 gen. = "identical copies"
up to high energies

A (possible) new paradigm in particle physics

~~The MFV paradigm~~ Multi-scale picture @ origin of flavor:



Barbieri '21
Allwicher, GI, Thomsen '20
⋮
Bordone *et al.* '17
Panico & Pomarol '16
⋮
Dvali & Shifman '00

Main idea:

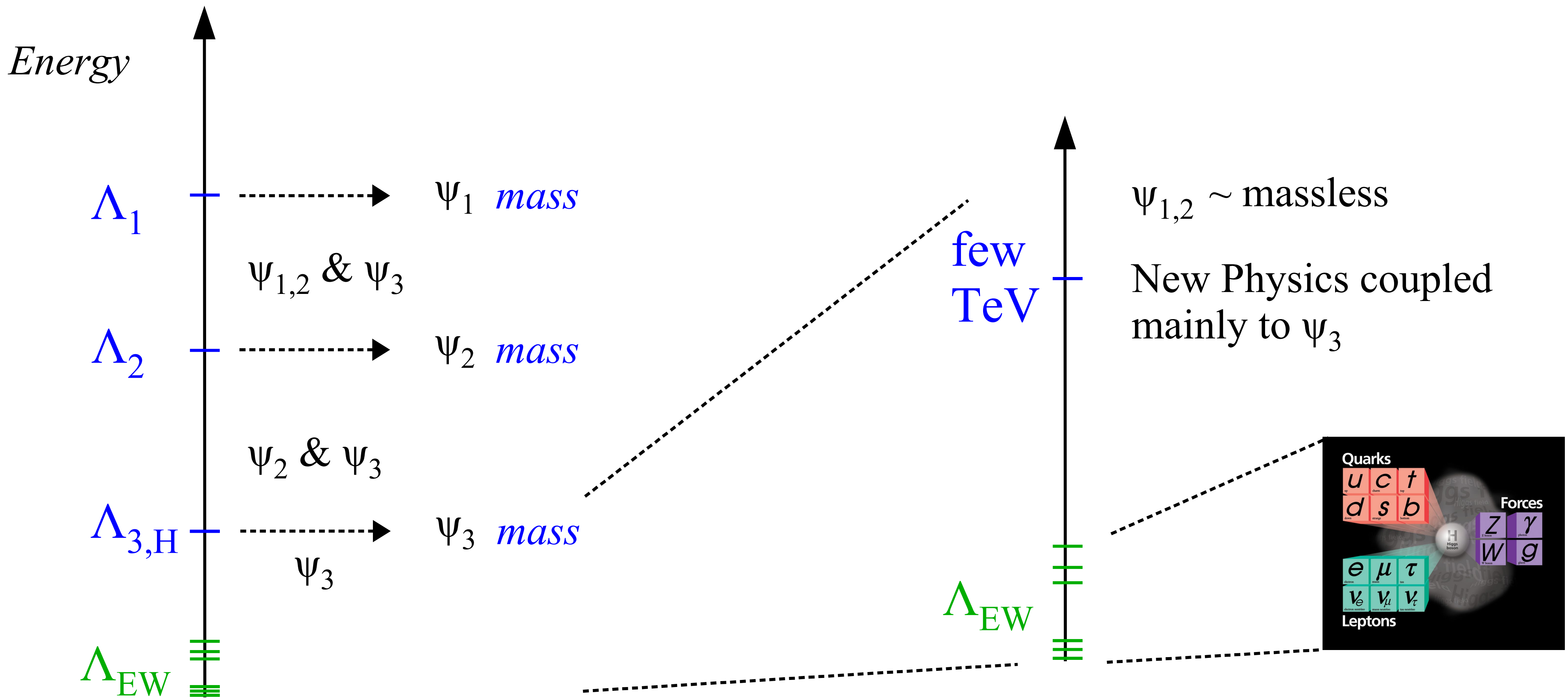
- Flavor non-universal interactions already at the TeV scale:
- 1^{st} & 2^{nd} gen. have small masses because they are coupled to NP at heavier scales

⬇

~~3 gen. = "identical copies" up to high energies~~

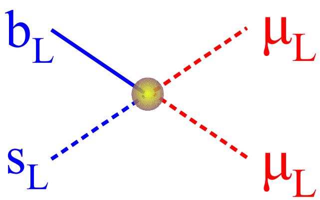
A (possible) new paradigm in particle physics

~~The MFV paradigm~~ *Multi-scale picture @ origin of flavor*:



EFT considerations on the anomalies

$$\frac{10^{-3}}{\Lambda^2}$$

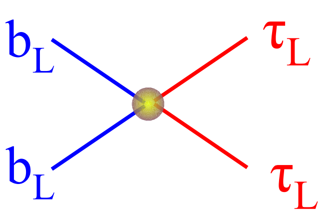


~~LFU~~ in $b \to s\, l^+ l^-$ [R_K, ...] $\boxed{5\,\sigma}$

Violation of the accidental symmetry "seen" depsite occurring at apparently high energy scales

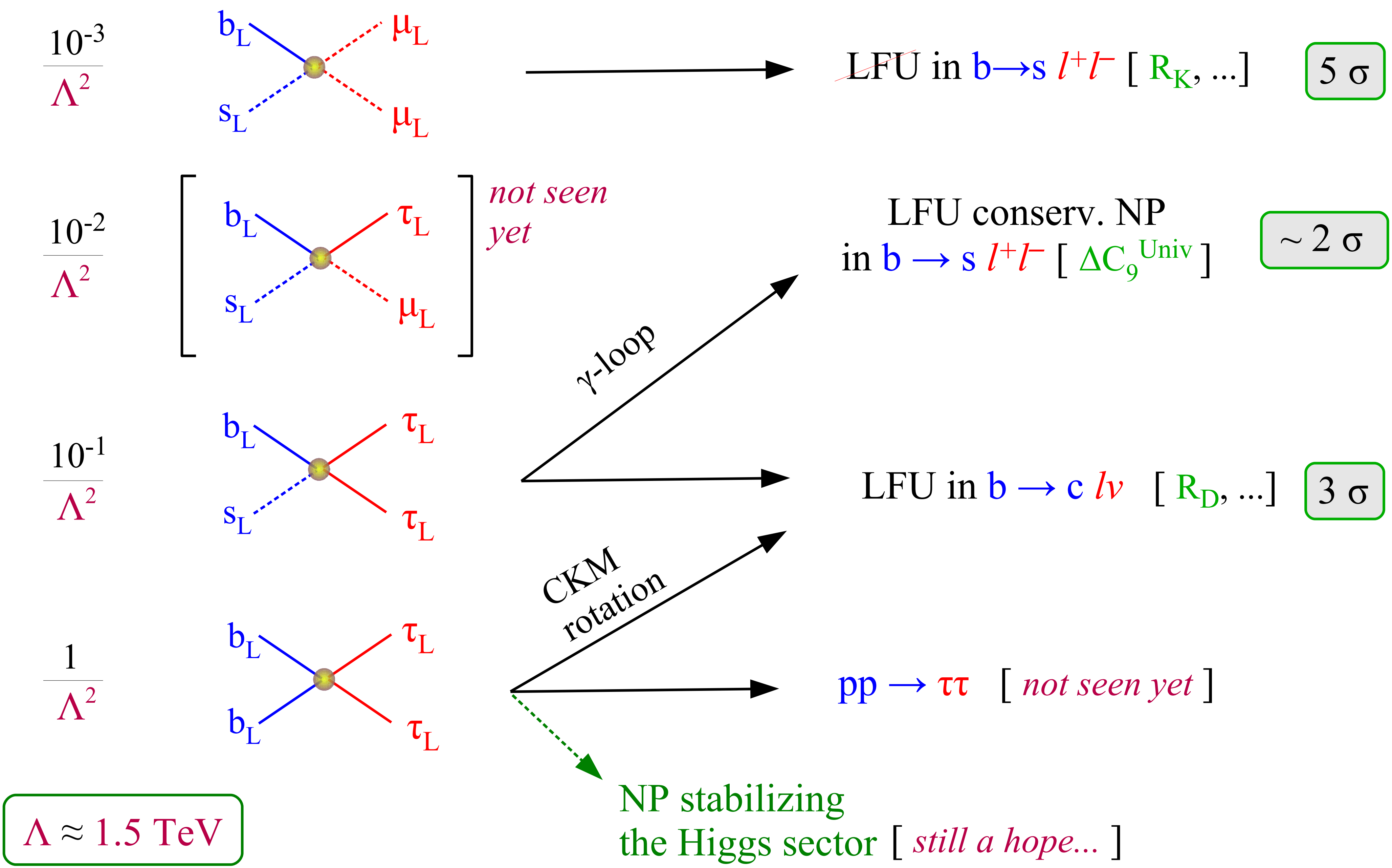
"*natural*" flavor connection

$$\frac{1}{\Lambda^2}$$



$\boxed{\Lambda \approx 1.5\ \text{TeV}}$

EFT considerations on the anomalies



EFT considerations on the anomalies

A promising "tale" connecting old and recent anomalies

FLAVOR

$\frac{10^{-3}}{\Lambda^2}$: $b_L\, s_L \to \mu_L\, \mu_L$ → ~~LFU~~ in $b \to s\, l^+ l^-$ [R_K, ...] $\boxed{5\,\sigma}$

$\frac{10^{-2}}{\Lambda^2}$: [$b_L\, s_L \to \tau_L\, \mu_L$] *not seen yet*

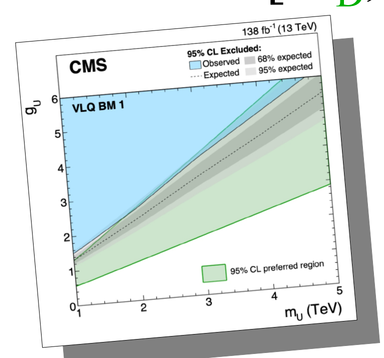
$\frac{10^{-1}}{\Lambda^2}$: $b_L\, s_L \to \tau_L\, \tau_L$ → LFU in $b \to c\, l\nu$ [R_D, ...] $\boxed{3\,\sigma}$

γ-loop → LFU conserv. NP in $b \to s\, l^+ l^-$ [$\Delta C_9^{\rm Univ}$] $\boxed{\sim 2\,\sigma}$

$\frac{1}{\Lambda^2}$: $b_L\, b_L \to \tau_L\, \tau_L$

CKM rotation

→ $pp \to \tau\tau$ $\boxed{\sim 1\,\sigma}$



→ NP stabilizing the Higgs sector

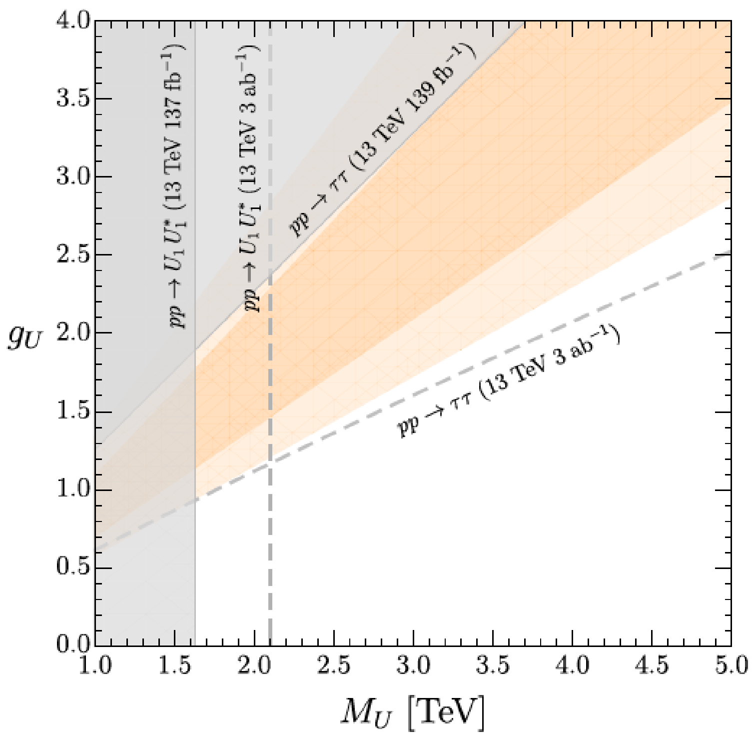
Higgs = pNGB of the new dynamics (↔ LQ mass)

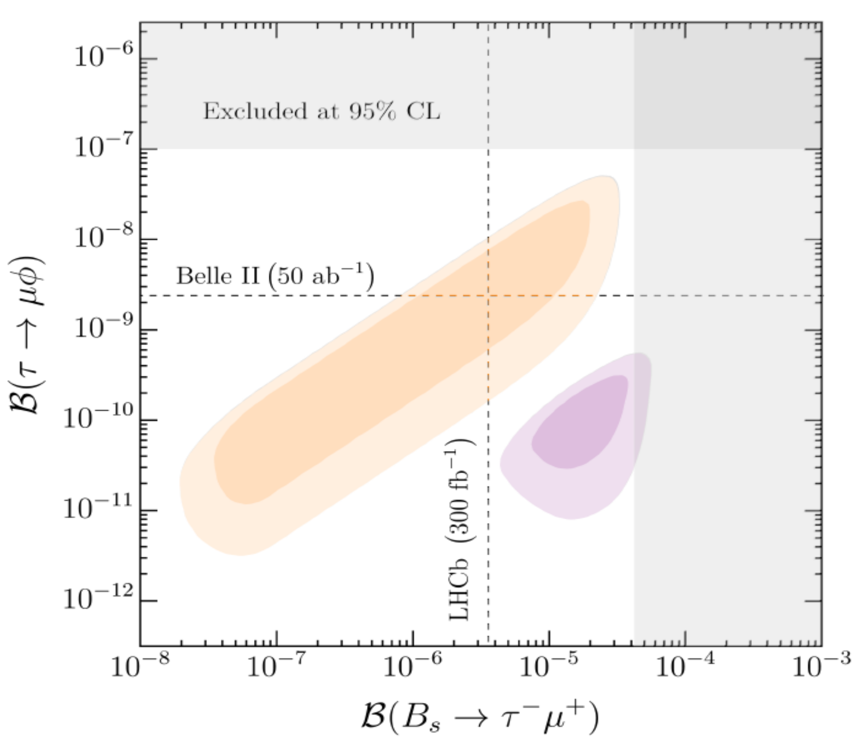
$\boxed{\Lambda \approx 1.5 \text{ TeV}}$

▶ EFT considerations on the anomalies

A promising "tale" connecting old and recent anomalies

- *If confirmed & combined...* the two sets of anomalies point to non-trivial flavor dynamics around the TeV scale, involving mainly the 3rd family that might be connected to the origin of the flavor flavor hierachies [multi-scale picture at the origin of flavor hierarchies]
- No contradiction with existing low- & high-energy data, but new non-standard effects should emerge soon in both these areas





Paolo & Juliet

Paolo & Juliet

It has been a great pleasure and a honor to discuss physics (*and beyond*...) with Paolo & Juliet over the many years I spent in Frascati.

- *Paolo's numerous contributions to flavor physics are a cornerstone of this field*

- As many others, I learned a lot from him. I learned in particular that precision physics is a tough business... which require a deep understanding of both theory and experiments.

- I will never forget his intuition that semileptonic weak decays are still a formidable tool to test the SM at an incredible degree of precision: *a message these recent "anomalies" seem to confirm...*

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But what I adimire more in Paolo & Juliet has been their passion for physics and their dedication in training an incredible new generation of scientists... [*their "legacy" is very visible in this lab, and beyond...*]

Sorry if you don't find yourself in this picture...

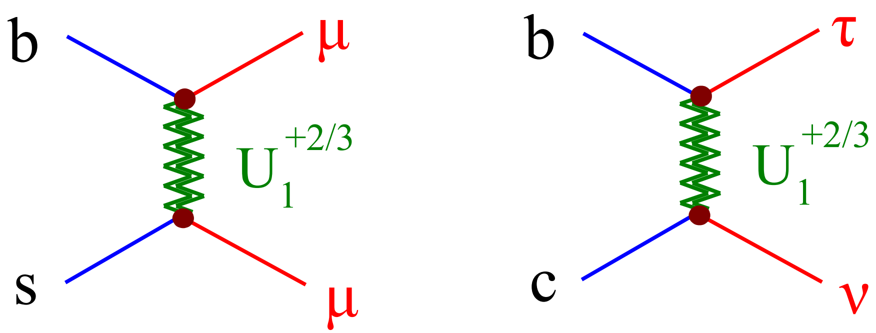
Goodbye !


Backup

UV completions & leptoquarks

To move toward more complete/ambitious models, we need to address the nature of the *mediators* of the New Physics at the TeV coupled mainly to the 3rd generation

Best option: new force mediated by a leptoquark field



- "Large" contributions to the anomalous processes
- Suppressed contribution where we do not see deviations from SM

UV completions & leptoquarks

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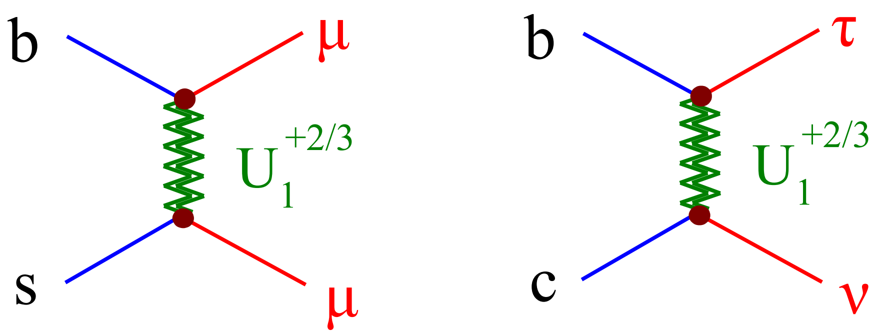


- "Large" contributions to the anomalous processes
- Suppressed contribution where we do not see deviations from SM

This mediator fits well with the old idea of unifying quarks and leptons into a single type of matter field [Pati & Salam, '74]:

$$\begin{bmatrix} Q^{\alpha} \\ Q^{\beta} \\ Q^{\gamma} \\ L \end{bmatrix}$$

Main idea: Lepton number as "the 4th color"

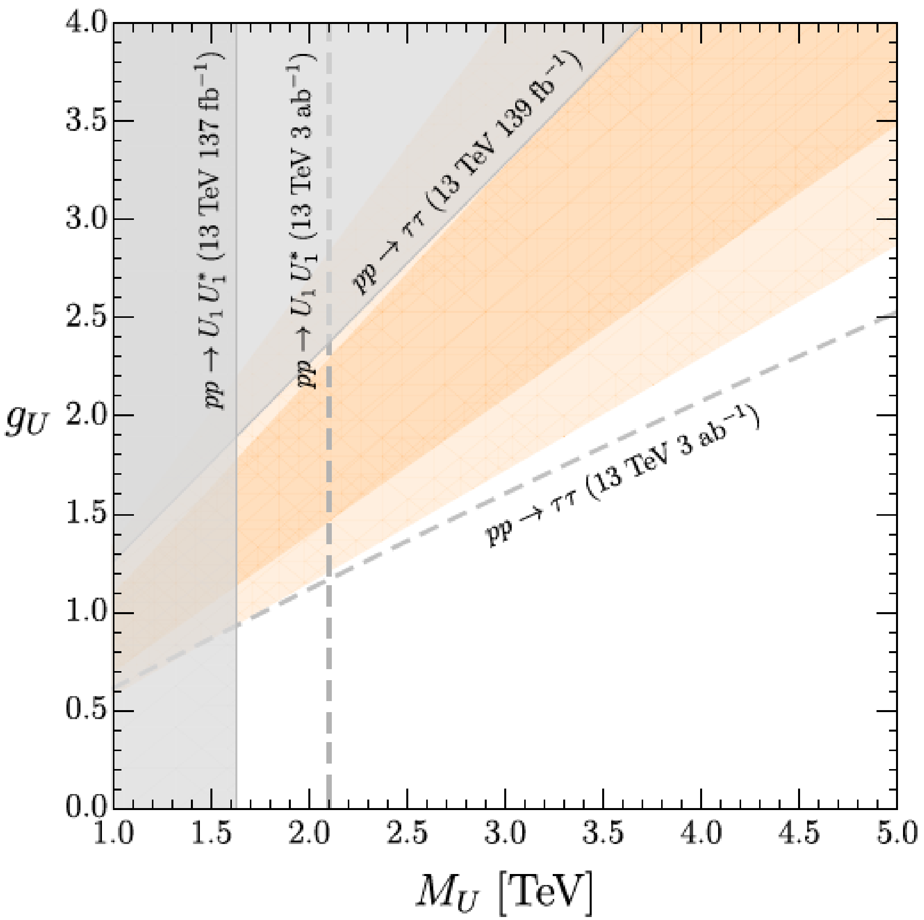
→ *natural explanation of the electric-charge ratios of quark & leptons*

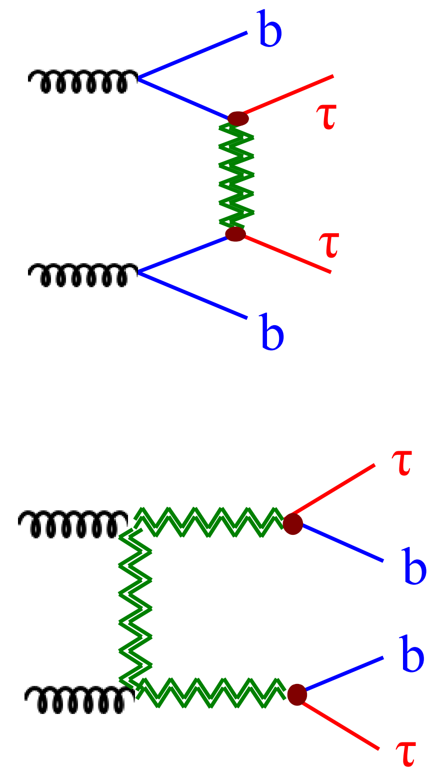
The massive leptoquark is a heavy "cousin" of the gluon, that couples with different strength to different families

UV completions & leptoquarks

If these ideas are correct, we should observe soon other “traces” of the leptoquark elsewhere, both at high energies...

E.g.: pp → ττ [at ATLAS or CMS]

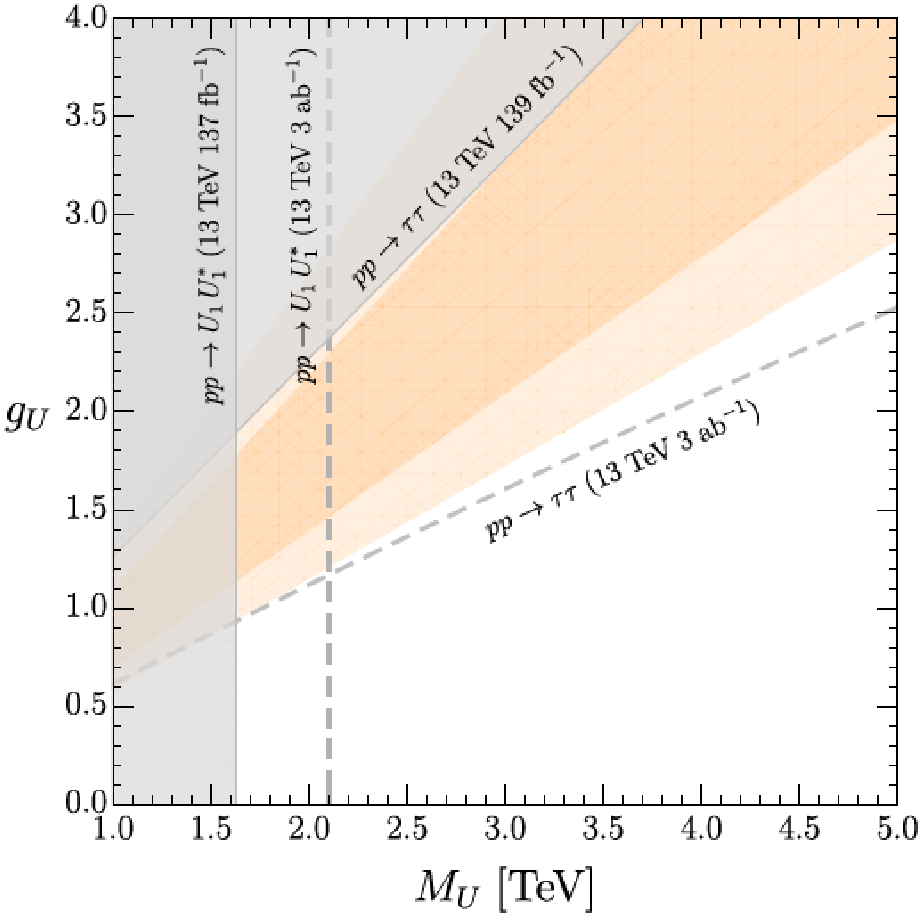




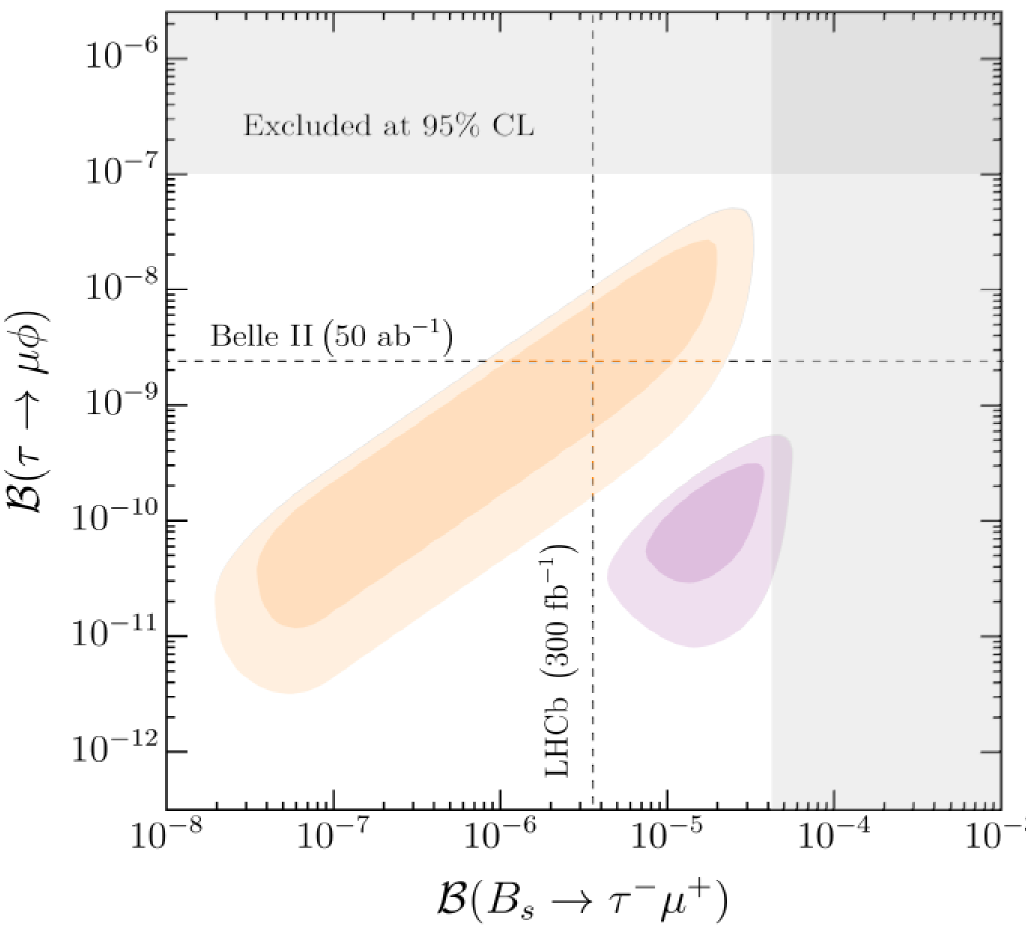
UV completions & leptoquarks

If these ideas are correct, we should observe soon other "traces" of the leptoquark elsewhere, both at high energies, and at low energies:

E.g.: pp → ττ [at ATLAS or CMS]

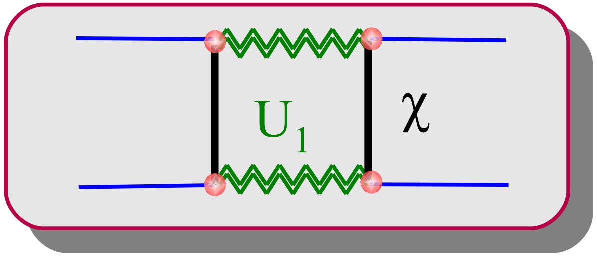


E.g.: LFV processes in B and τ decays

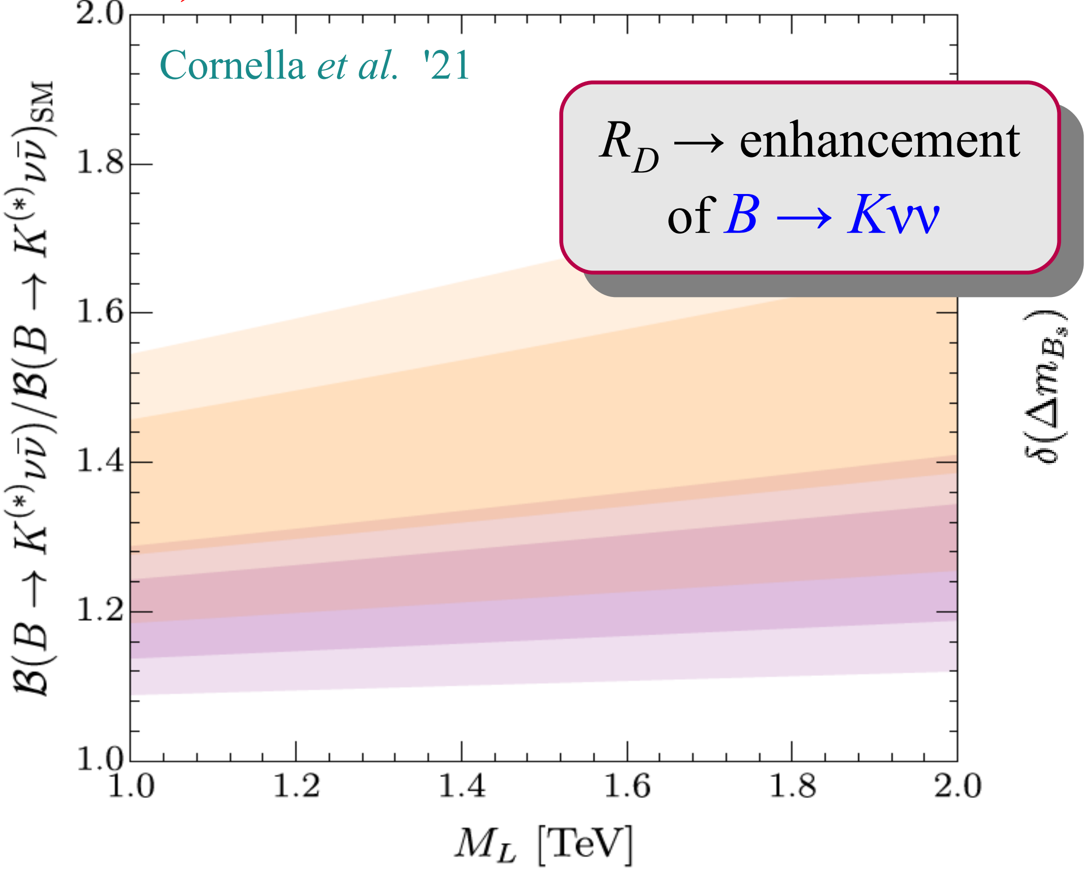


UV completions & leptoquarks

In all explicit models, leptoquarks are accompained by heavy (vector-like) fermions, which are responsible for the generation mixing → other low-energy effects

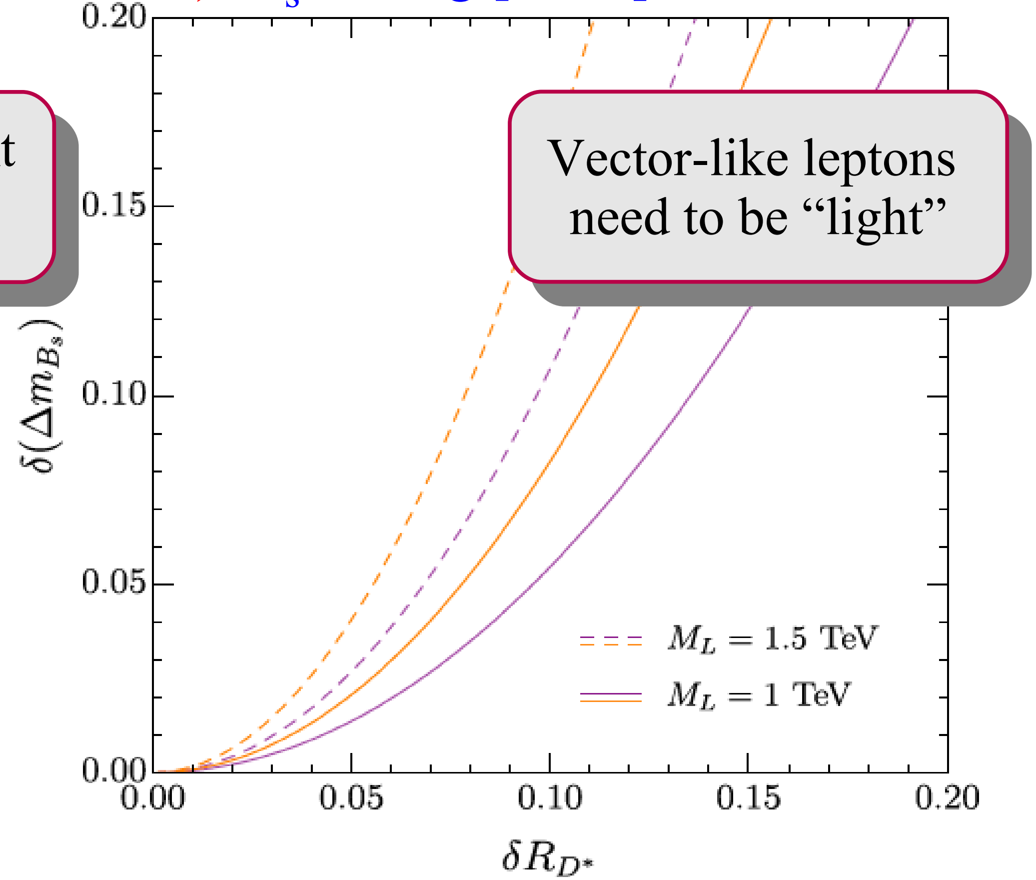


A) $B \to K\nu\nu$



Fuentes-Martin, GI, Konig, Selimovic, '20

B) B_s mixing [$\Delta F=2$]



Di Luzio, Fuentes-Martin, Greljo, Nardecchia, Renner '18

UV completions & leptoquarks

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