Flavor mixing: a window toward new physics

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- Introduction
- The two flavor puzzles [*Two (modern) lessons from KM*]
- Flavor non-universal interactions
- Future prospects
- Conclusions

University of Zurich UZH

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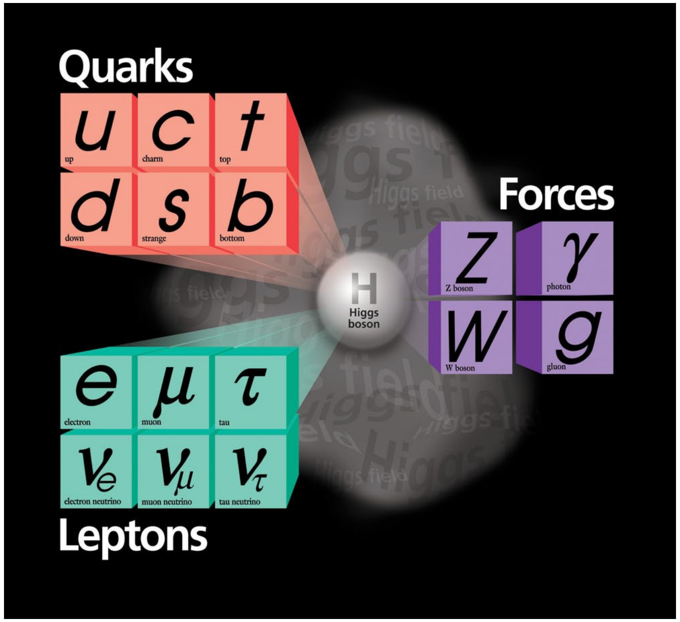
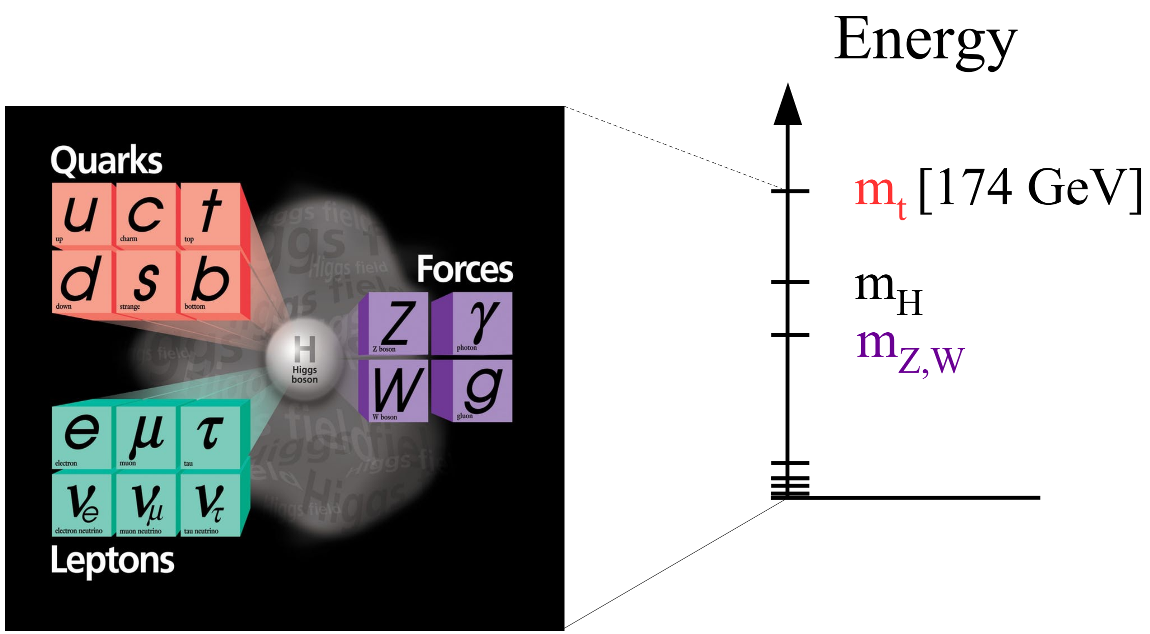
Introduction



▶ Introduction

We recently celebrated the 10th anniversary of the Higgs-boson discovery (*or the completion of the SM spectrum*).

The SM



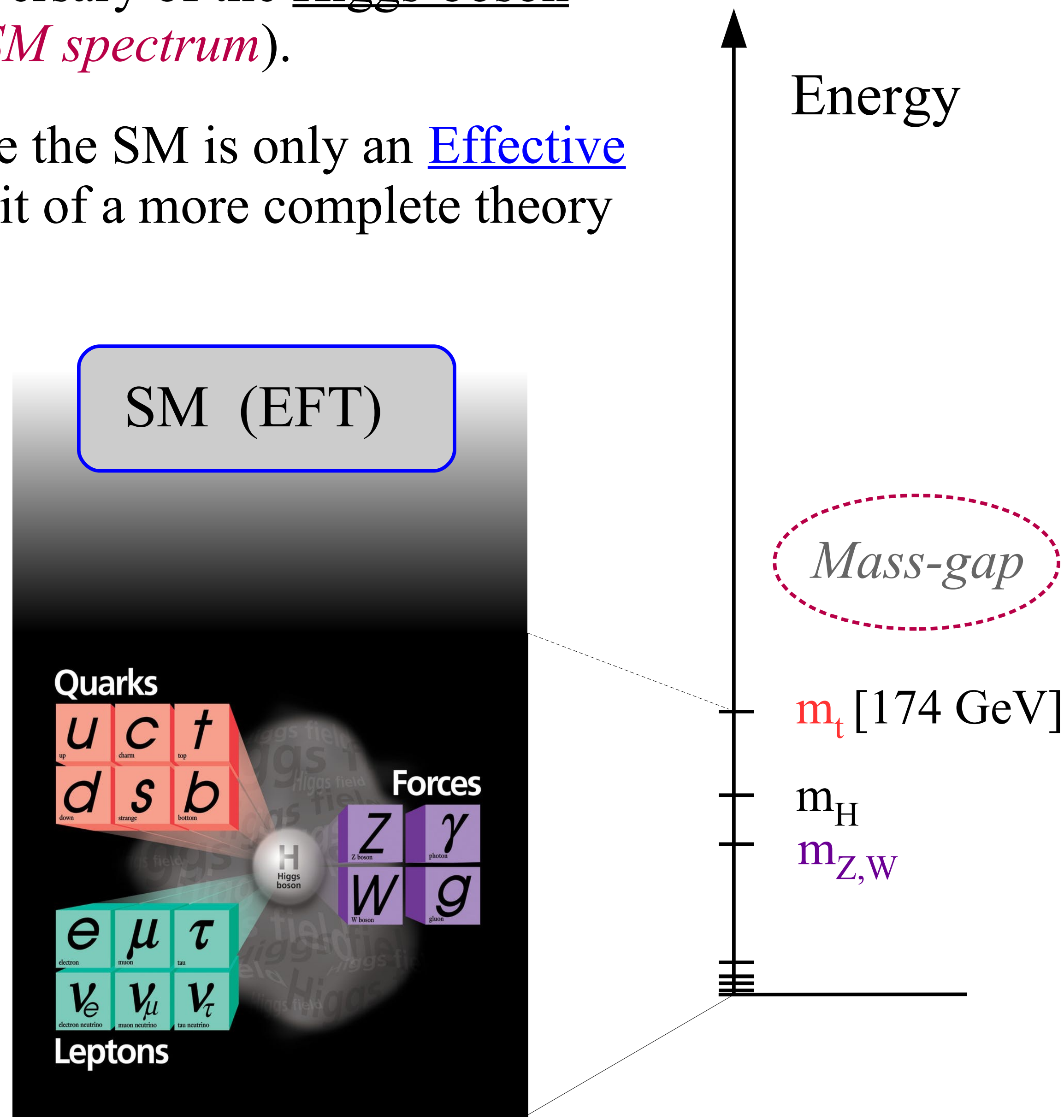
Introduction

We recently celebrated the 10th anniversary of the Higgs-boson discovery (*or the completion of the SM spectrum*).

However, as for any QFT, we believe the SM is only an Effective Field Theory, i.e. the low energy limit of a more complete theory with more degrees of freedom

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \ldots$$

We identified the *long-range* properties of this EFT



Introduction

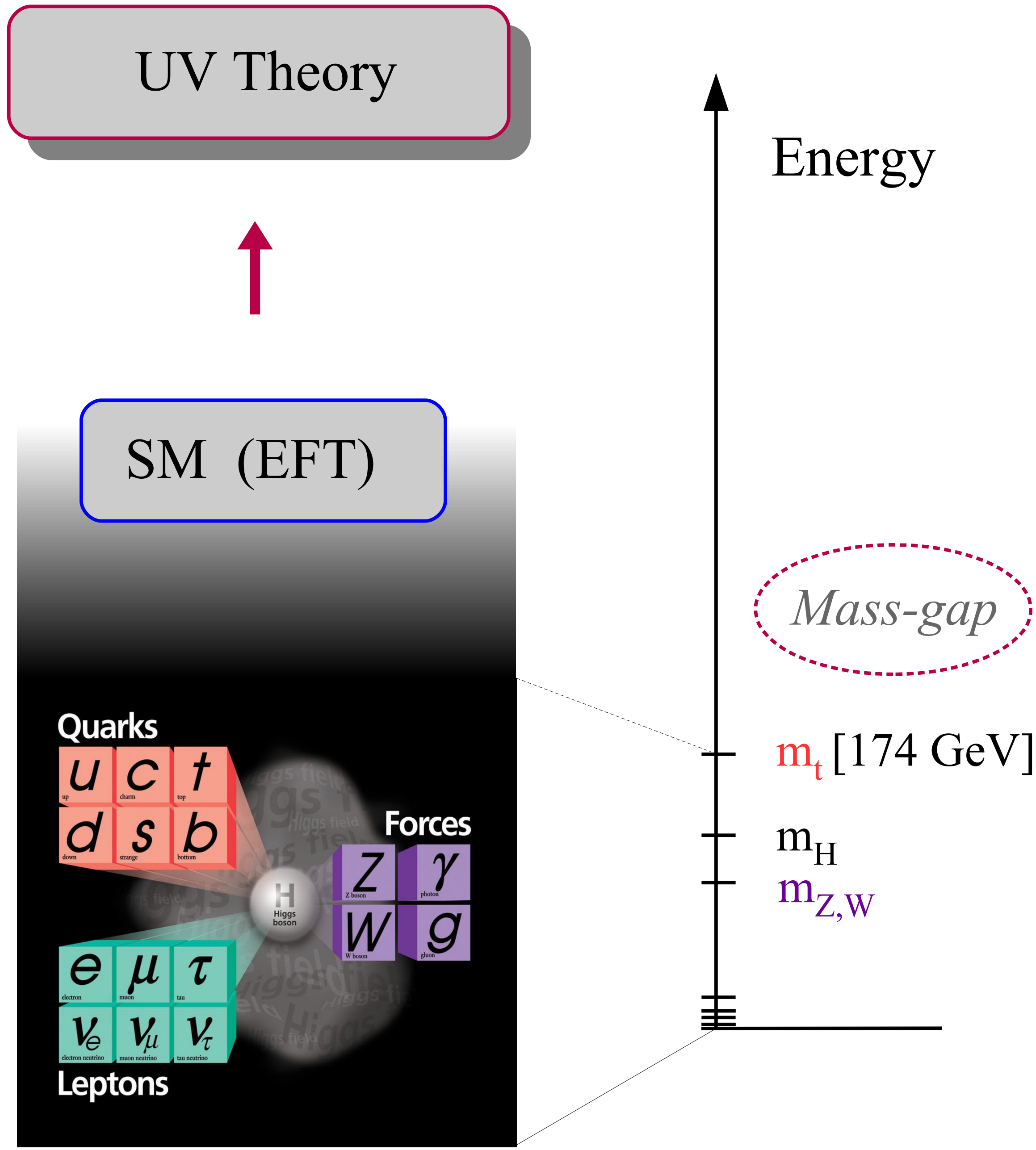
There are several reasons why we think the SM must be extended at high energies:

Electroweak hierarchy problem

Flavor puzzle
U(1) charges
Neutrino masses

Dark-matter
Dark-energy
Inflation

Quantum gravity



Introduction

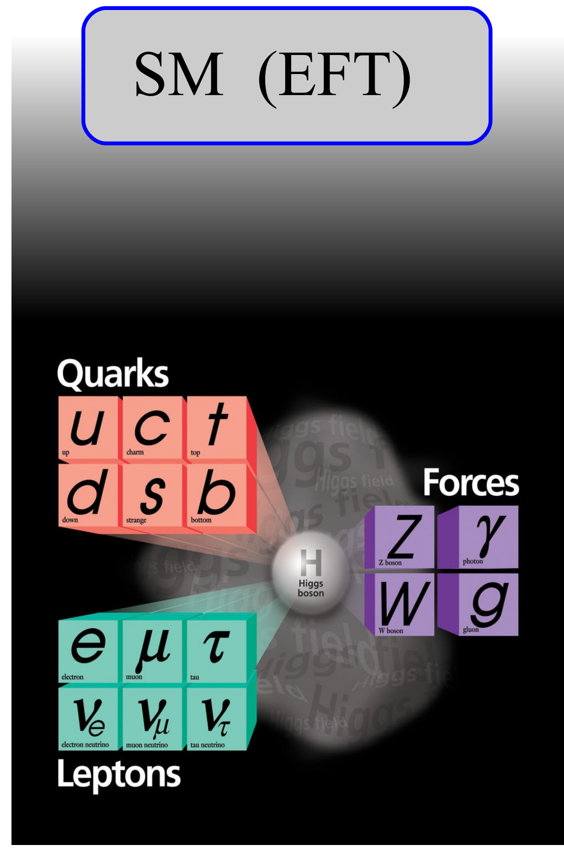
There are several reasons why we think the SM must be extended at high energies

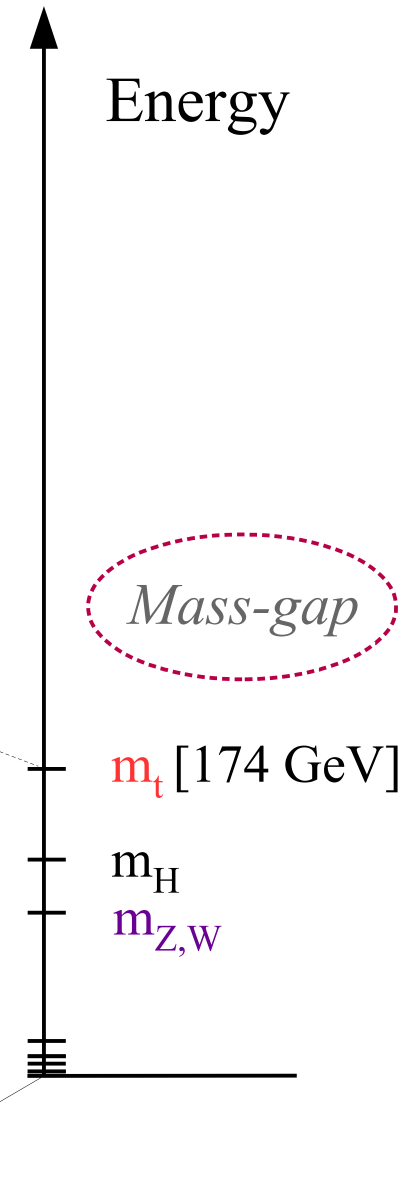
UV Theory

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

However, for a long time this will not be possible....

For the time being, the best we can do is *exploring the low-energy limit of the EFT* trying to understand better its consistency, and possibly extract indirect infos about the UV





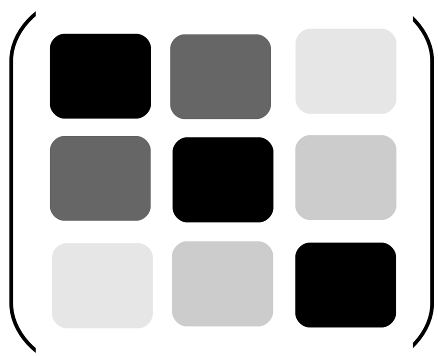
Introduction

There are several reasons why we think the SM must be extended at high energies:

	problem due to...	*...indicating*
Electroweak hierarchy problem	→ *Instability of the Higgs mass term*	non-trivial properties of the SM Lagrangian if interpreted as EFT
Flavor puzzle U(1) charges Neutrino masses	→ *Ad hoc tuning in the model parameters*	↓
Dark-matter Dark-energy Inflation	→ *Cosmological implementation of the SM*	Useful hints for its UV completion
Quantum gravity	→ *General problem of any QFT*	

The two flavor puzzles

[*Two (modern) lessons from KM*]

$V_{\rm CKM} \sim$ 

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*]

→ Is there a deeper explanation for this peculiar structures?

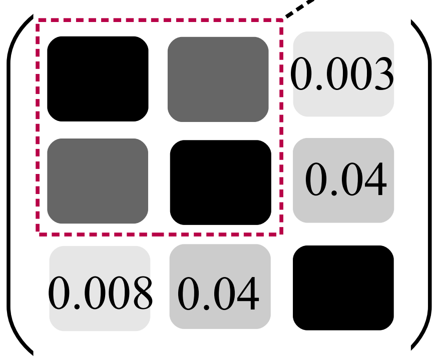
The two flavor puzzles

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:

unitarity violation of the 2×2 (light) block below 10^{-3} !

$V_{\rm CKM} \sim$



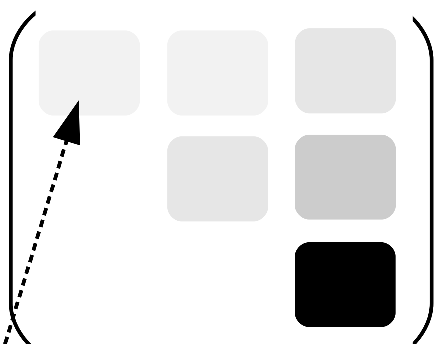
Despite the very good knowledge we have nowadays about the CKM matrix, we are not able to detect the presence of the 3rd family by looking only at the 2×2 block (*as one naively would have expected...*)

1st KM lesson: don't be discouraged to put forward new ideas (*if they are good*) by the lack of some exp. evidence and/or "tuning" in model space...

The two flavor puzzles

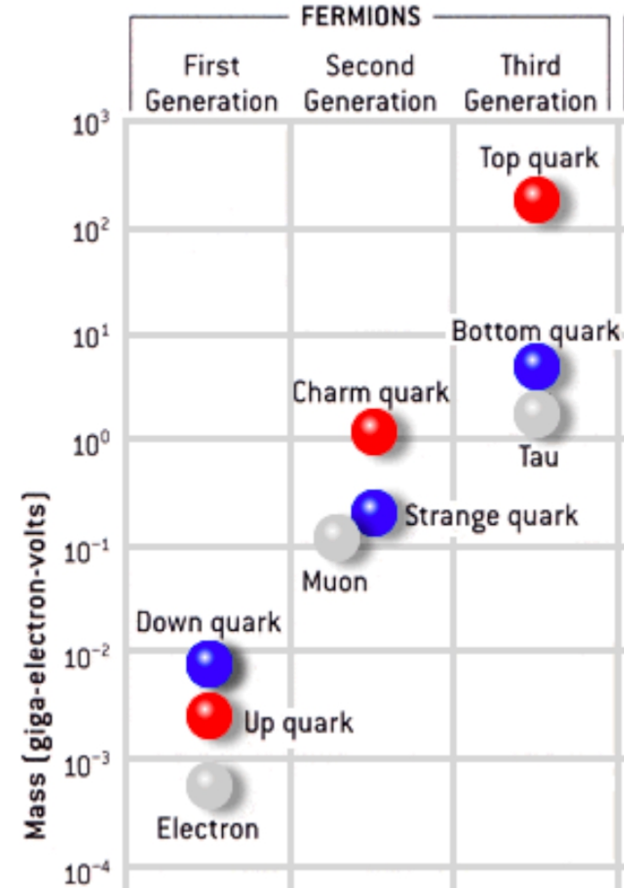
Even forgetting current anomalies, there are two (long-standing) open issues in flavor physics:

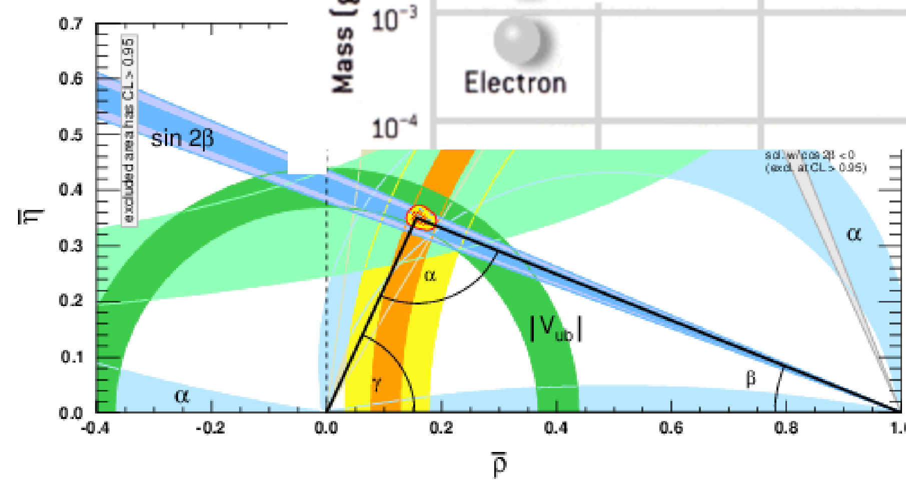
I. The observed pattern of SM Yukawa couplings does not look accidental:

$Y_U \sim$ 

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

[Y_U in the basis where Y_D is diagonal]





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*]

→ 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?

The two flavor puzzles

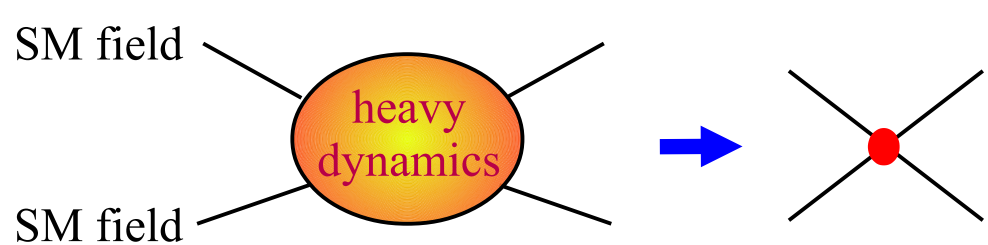
$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \Sigma_i \frac{1}{\Lambda_i^{d-4}} O_i^{d\geq 5}$$

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 two flavor puzzles

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \Sigma_i \frac{1}{\Lambda_i^{d-4}} O_i^{d\geq 5}$$

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

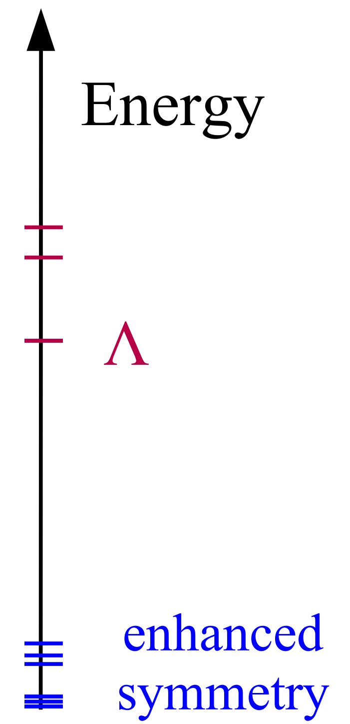
Eg:

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

Accidental symmetries in QFT [a brief detour]

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

(long-distance interactions) (local contact interact.)



"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*]

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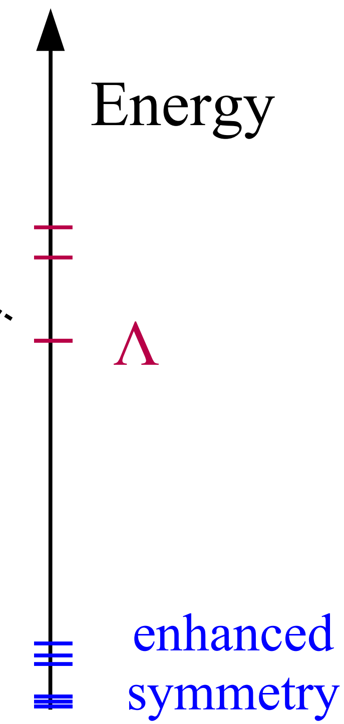

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If a symmetry arises accidentally in the low-energy theory, we expect it to be violated by higher dim. ops

Violations of accidental symmetries

How to explain CP violation in the SM, and the history of the KM mechanism, are a wonderful illustration of this effect

Accidental symmetries in QFT [a brief detour]

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[SM-2]-EFT

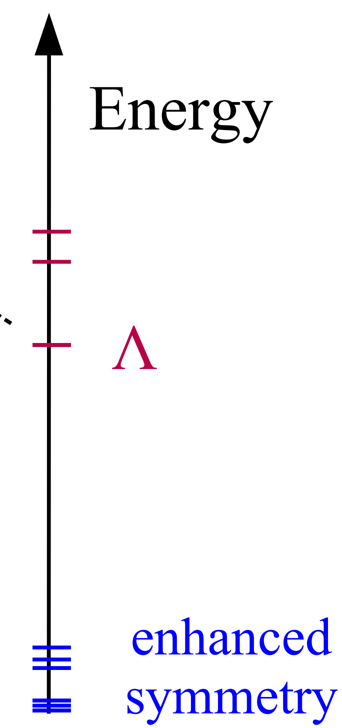
(long-distance interactions) (local contact interact.)

Back in 1973: SM with 2 generations, as "reference model" → CP violation is an accidental symmetry [KM, '73]

But CP violation is observed in K mixing [→ remnant of "heavy NP"]

$\Lambda_{CP} \sim 10^4$ TeV

$$\frac{e^{i\delta}}{\Lambda_{CP}^2} (\bar{s}\,\Gamma\, d)^2$$



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Energy

Λ

enhanced symmetry

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SM-3
[KM, '73]

"Super-weak" interaction
[L. Wolfenstein, '64]

Citations @ end of '75: 5 cit. (now ~ 10K) 130 cit. (now ~ 800)

▶ Accidental symmetries in QFT [a brief detour]

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SM-3

[KM, '73]

$$\frac{1}{\Lambda_{CP}^2} \sim \frac{(G_F m_t V_{ts} V_{td})^2}{4\pi^2}$$

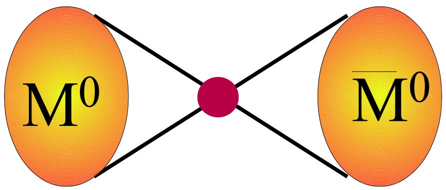
Ellis, Gaillard, Nanopulos, '76

2nd KM lesson: beware of seemingly high scales in EFT approaches: they can be a "mirage"...

The two flavor puzzles

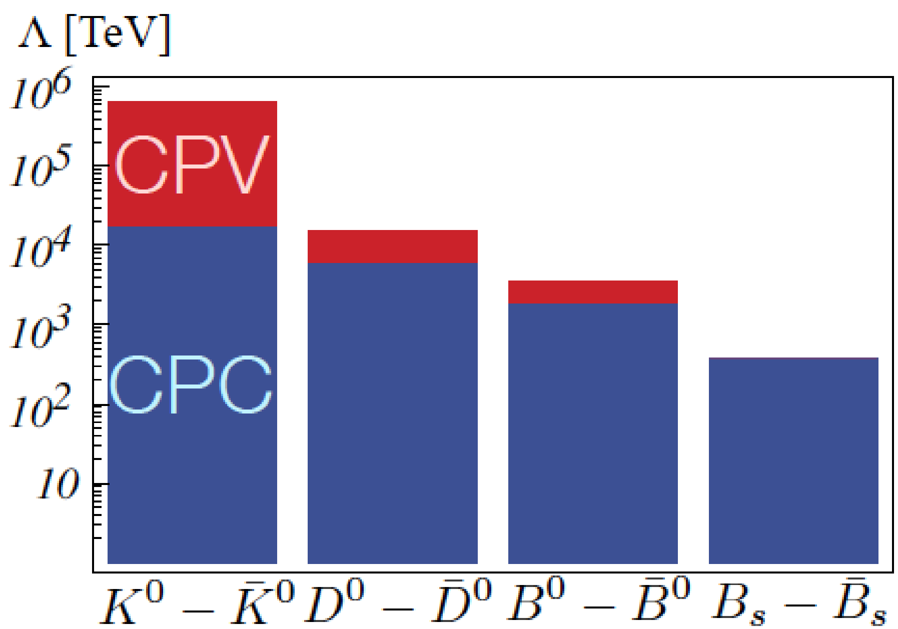
$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{d\geq 5}$$

In principle, we could expect many violations of the accidental symmetries from the heavy dynamics → *new flavor violating effects*



However, beside the B-physics anomalies we observe none

Stringent bounds on the scale of possible new flavor non-universal interactions especially from meson-antimeson mixing



The NP Flavor puzzle

The two flavor puzzles

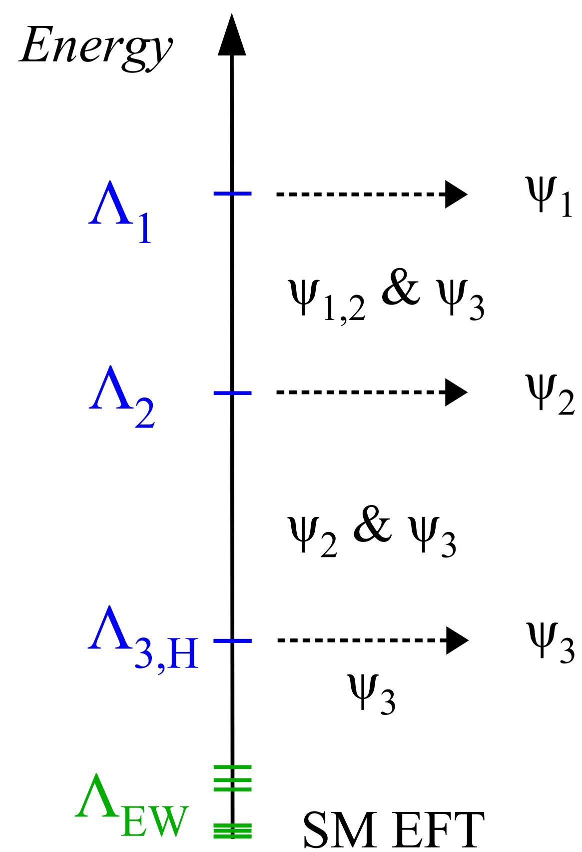
$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{d\geq 5}$$

Flavor-degeneracy: $U(3)^5$ symmetry	$U(3)^5$ symmetry broken by Yukawa couplings	Stringent bounds on generic flavor-violating ops.

The big questions in flavor physics:

- Can we find an explanation for the Yukawa hierarchies?
- Are all the the accidental flavor symmetries of the SM broken in the other sectors of the SM-EFT? If yes, at which scale(s) are they broken?
  Can be there multiple scales behind the origin of flavor?

Flavor non-universal interactions



Flavor non-universal interactions

For a long time, 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"*

"Protect" the Higgs sector with (TeV-scale) flavor universal NP (*supersymmetry or Higgs compositness*)

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 clear sign of NP from direct searches

⬇

strong bounds on NP <u>if coupled universally</u> to all SM families

⬇

<u>worsening of the Higgs hierarchy problem</u>

Flavor non-universal interactions

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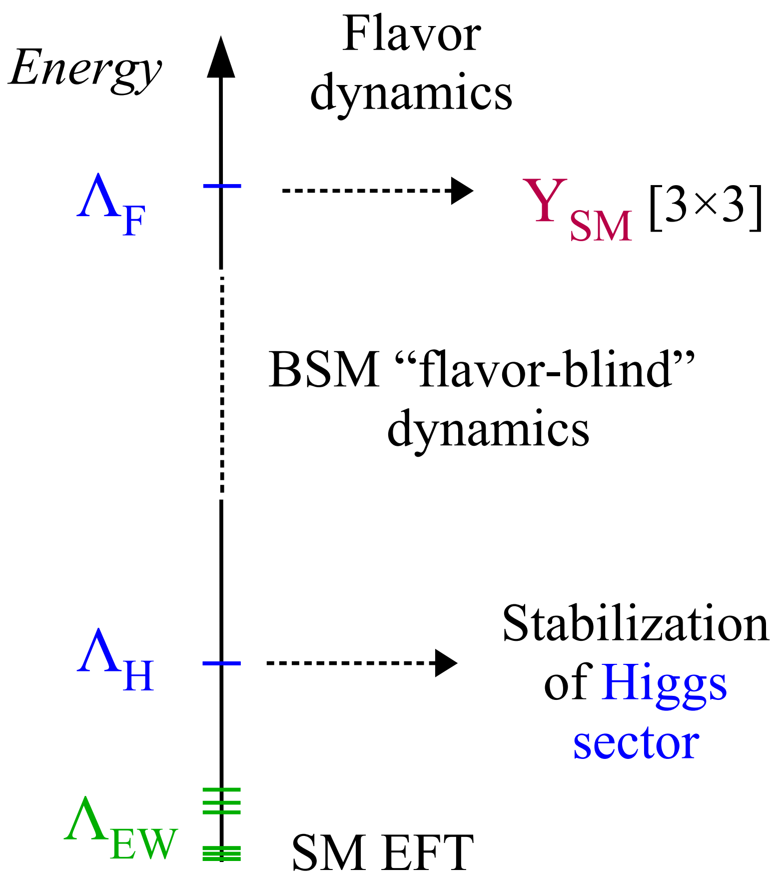
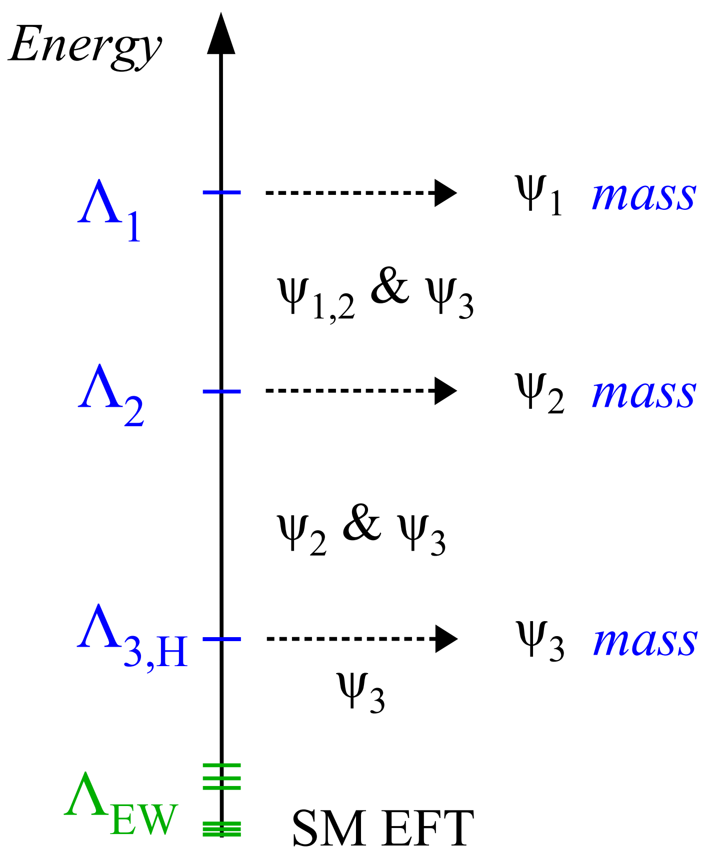


- Concentrate on the Higgs hierarchy problem
- Postpone the flavor problem to higher scales

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

Flavor non-universal interactions

New paradigm to address both the Higgs hierarchy problem and the flavor puzzle: *multi-scale* UV completion with *flavor non-universal* interactions



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

Main idea:

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

↓

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

Flavor non-universal interactions

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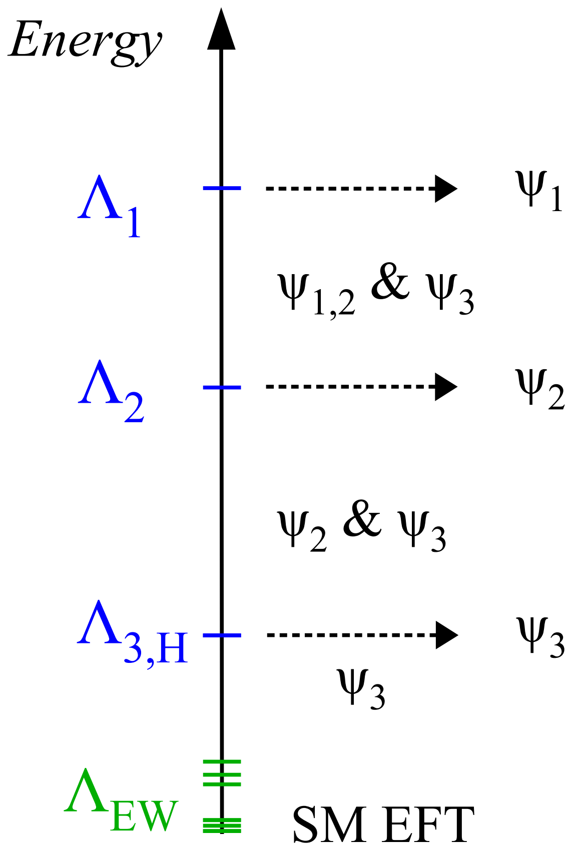

Recent phenomenological "boost" to this type of approach given but the B-physics anomalies (*hinting to violations of lepton flavor universality, mainly in 3rd generation*)

> *"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"*
>
> [G. Isidori – HL-LHC Workshop, CERN March 2019]

Flavor non-universal interactions

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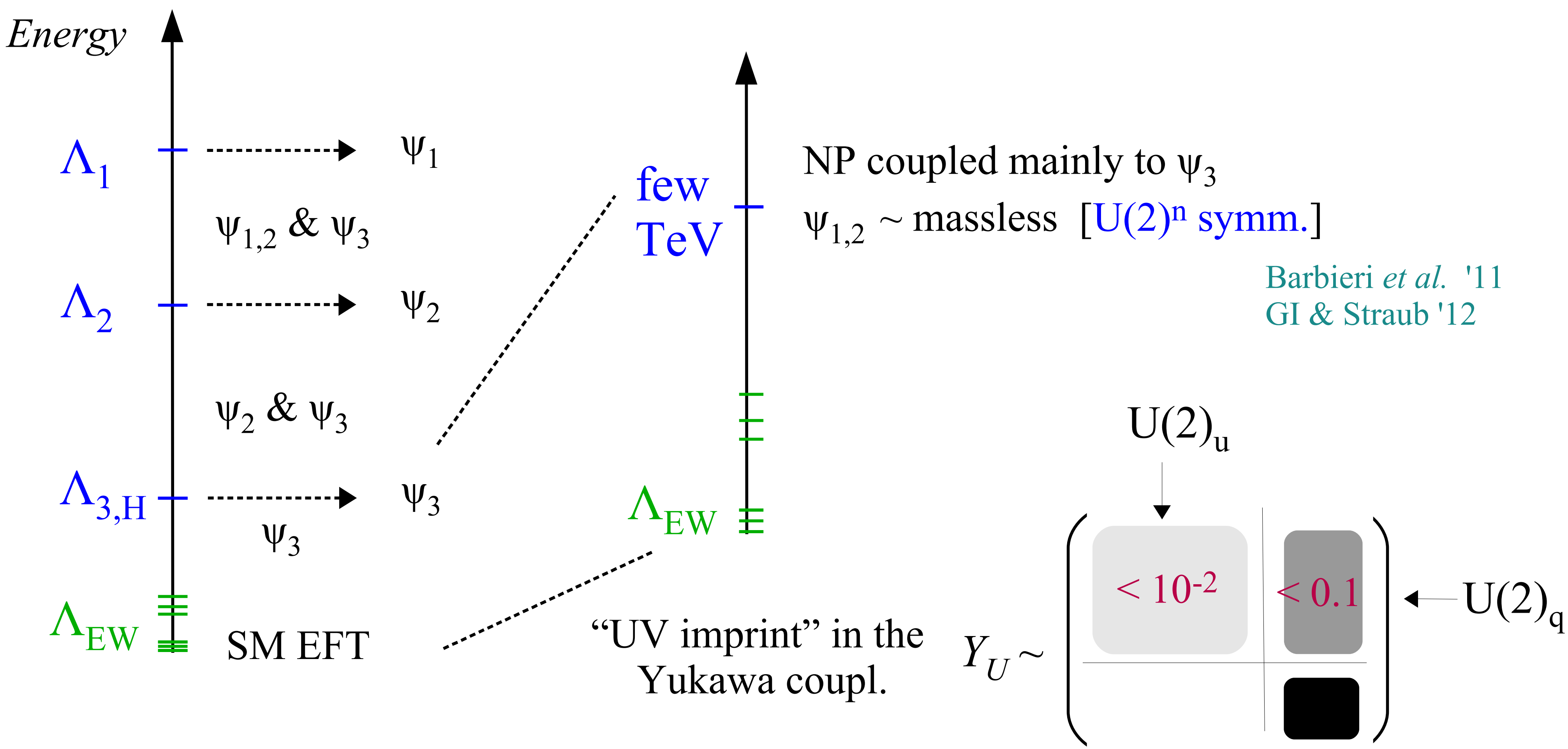


Effective organizing principle for the flavor structure of the SMEFT

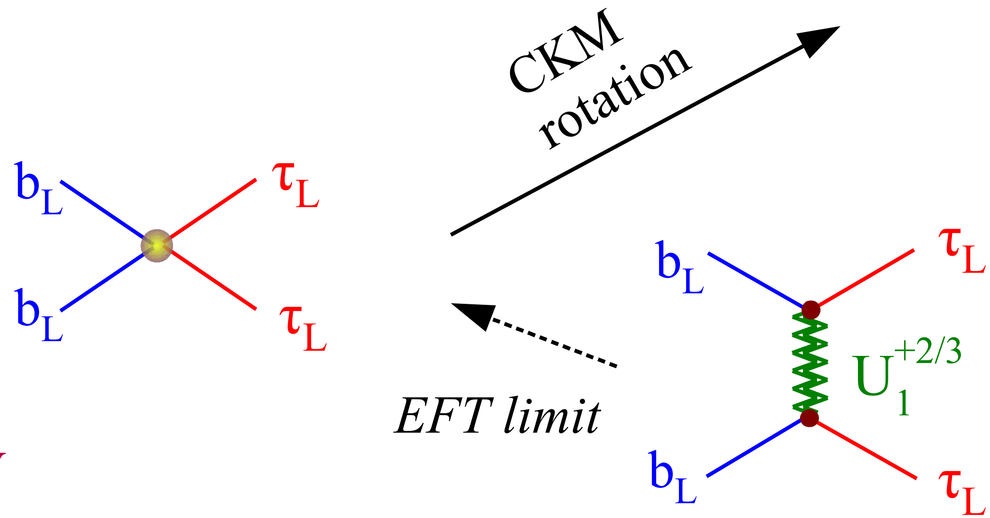
Flavor non-universal interactions

Recent phenomenological "boost" to this type of approach given but the B-physics anomalies (*hinting to violations of lepton flavor universality, mainly in 3rd generation*)

~~LFU~~ in $b \to c\ l\nu$ [R_D, ...] $\boxed{3\ \sigma}$

→ talk by Bordone

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



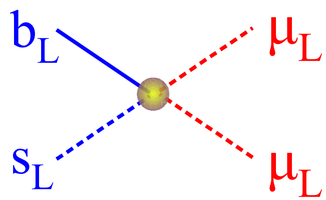
(*or similar with scalar LQ*)

$\Lambda \approx 1.5$ TeV

→ talk by Marzocca

Flavor non-universal interactions

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



~~LFU~~ in $b \to s\, l^+ l^-$ [R_K, ...] $\boxed{\sim 4\,\sigma}$
+ $B(B_s \to \mu\mu)$

Recent phenomenological "boost" to this type of approach given but the B-physics anomalies (*hinting to violations of lepton flavor universality, mainly in 3rd generation*)

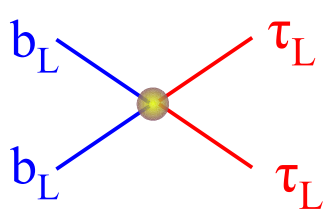
flavor mixing

~~LFU~~ in $b \to c\, l\nu$ [R_D, ...] $\boxed{3\,\sigma}$

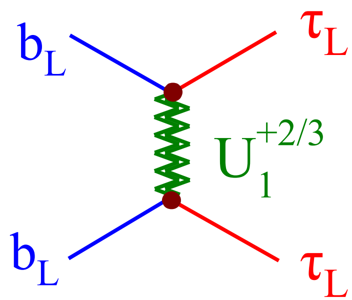
→ talk by Bordone

CKM rotation

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



EFT limit



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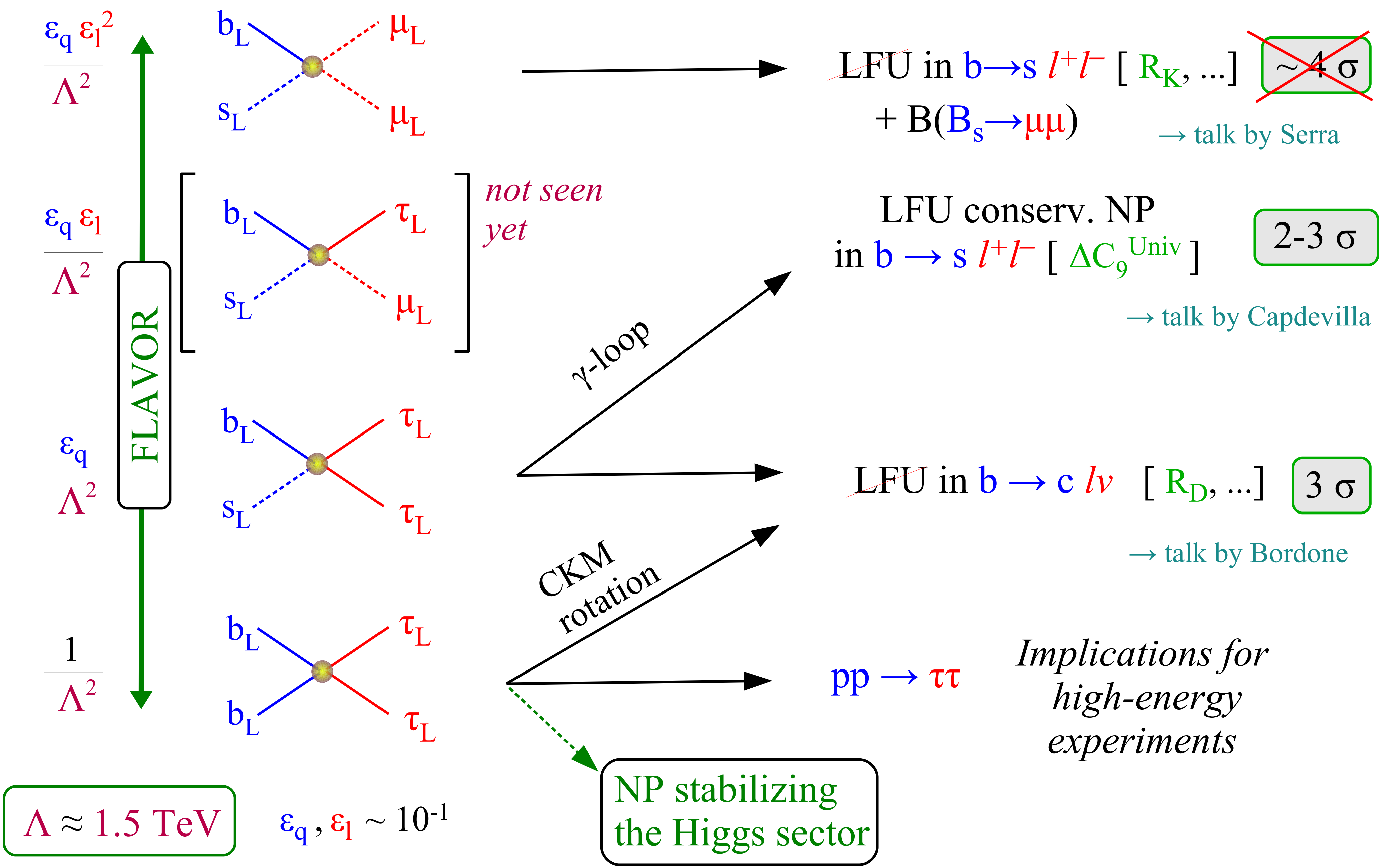
Flavor non-universal interactions



Flavor non-universal interactions

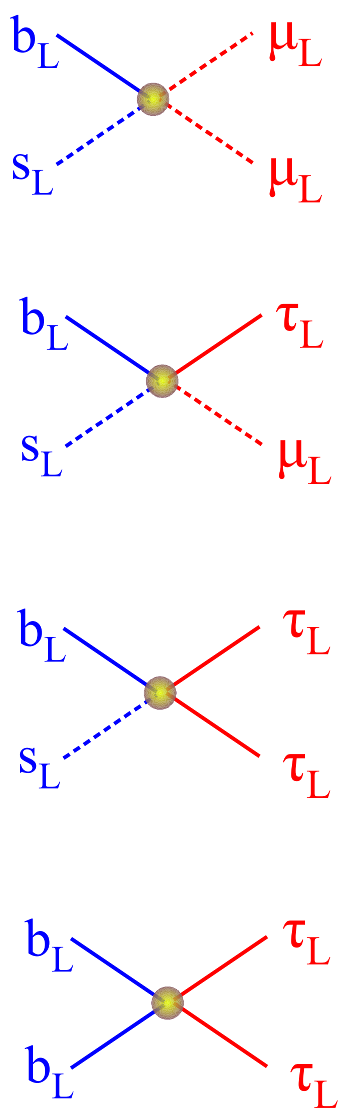
$\dfrac{\varepsilon_q \varepsilon_l^2}{\Lambda^2}$

$\dfrac{\varepsilon_q \varepsilon_l}{\Lambda^2}$

FLAVOR

$\dfrac{\varepsilon_q}{\Lambda^2}$

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



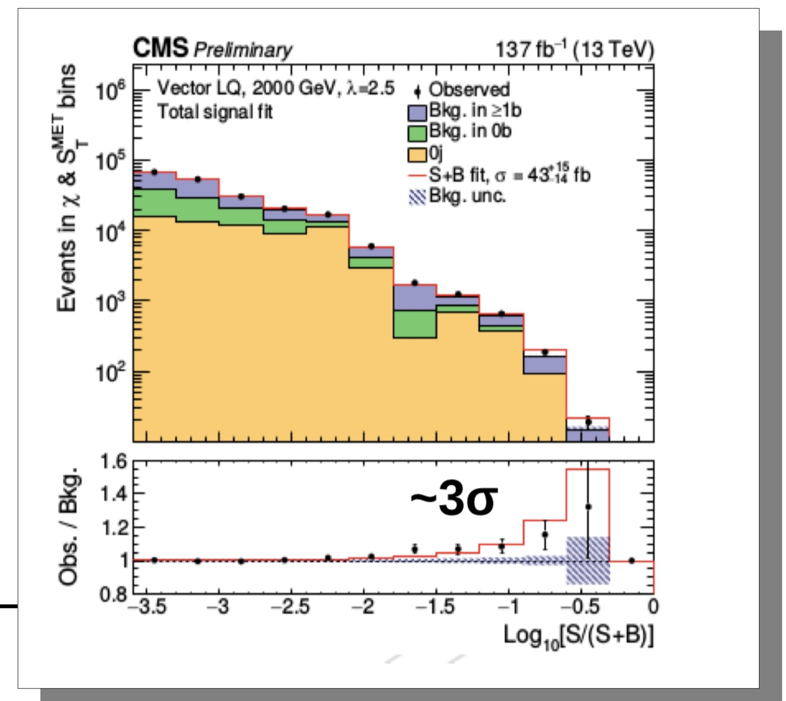
not seen yet

~~LFU~~ in $b \to s\, l^+ l^-$ [R_K, ...] $\boxed{\cancel{\sim 4\,\sigma}}$
+ $B(B_s \to \mu\mu)$

LFU conserv. NP in $b \to s\, l^+ l^-$ [$\Delta C_9^{\rm Univ}$] $\boxed{2\text{-}3\ \sigma}$

γ-loop

CKM rotation



$\boxed{pp \to \tau\tau}$

NP stabilizing the Higgs sector

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

$\varepsilon_q, \varepsilon_l \sim 10^{-1}$

Future prospects

"Prediction is very difficult, especially if it's about the future."

Niels Bohr

"As I get older, I realize being wrong isn't a bad thing like they teach you in school. It is an opportunity to learn something."

Richard Feynman

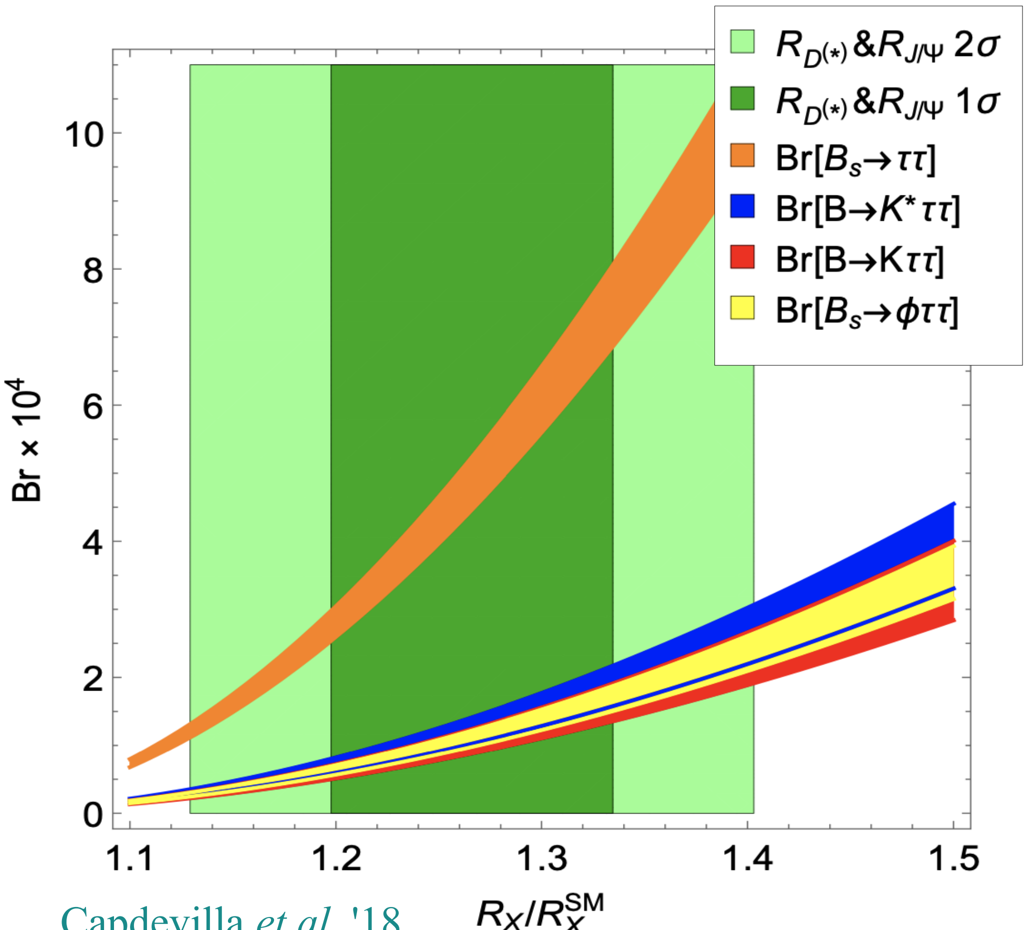
Future prospects

The idea of flavor non-universal interactions – with a 1st layer of new physics already at the TeV scale – has several interesting implications for future precision measurements (*with different degree of model-dependence*)

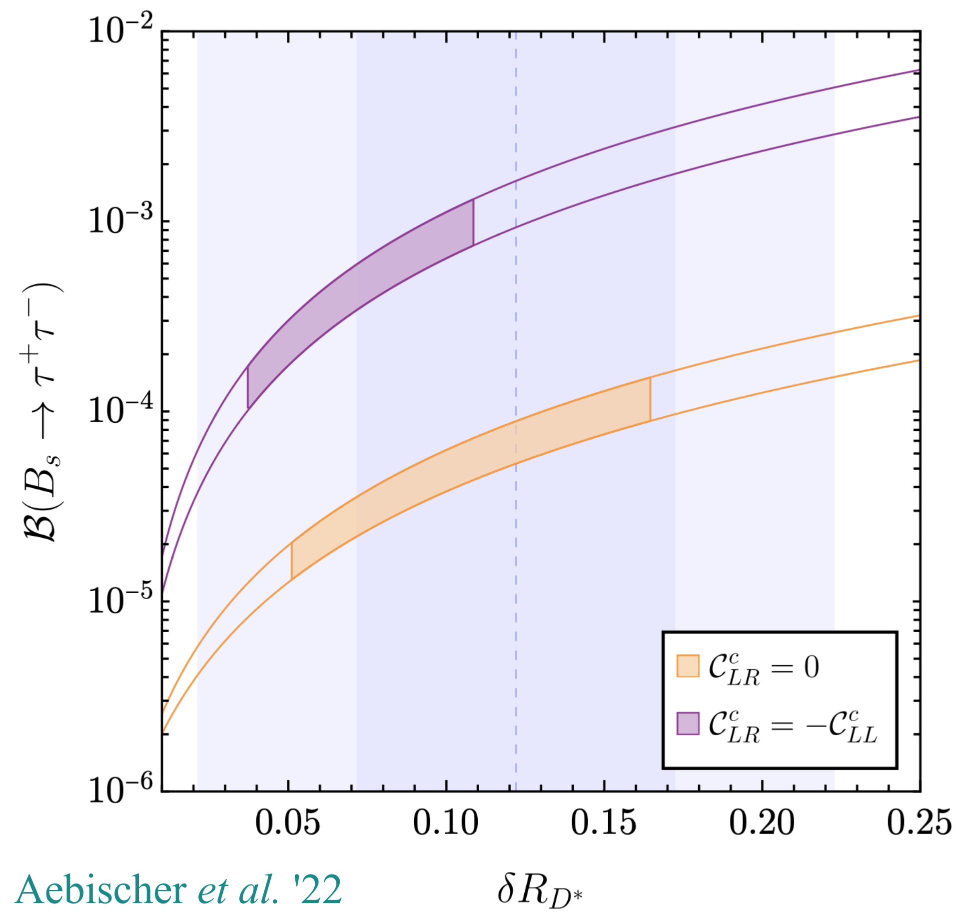
▶ *Future prospects*

The idea of flavor non-universal interactions – with a 1st layer of new physics already at the TeV scale – has several interesting implications for future precision measurements (*with different degree of model-dependence*)

E.g.: I) Possible huge enhancements in $b \to s\tau\tau$ rates



Capdevilla *et al.* '18

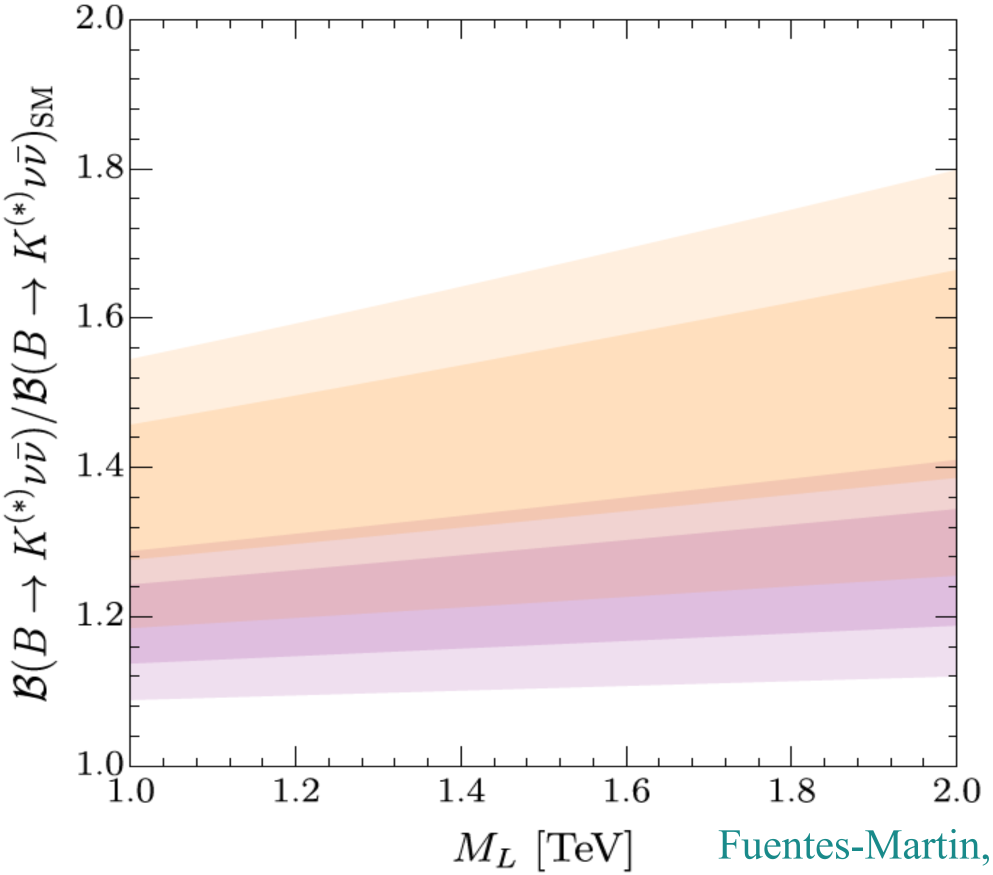


Aebischer *et al.* '22

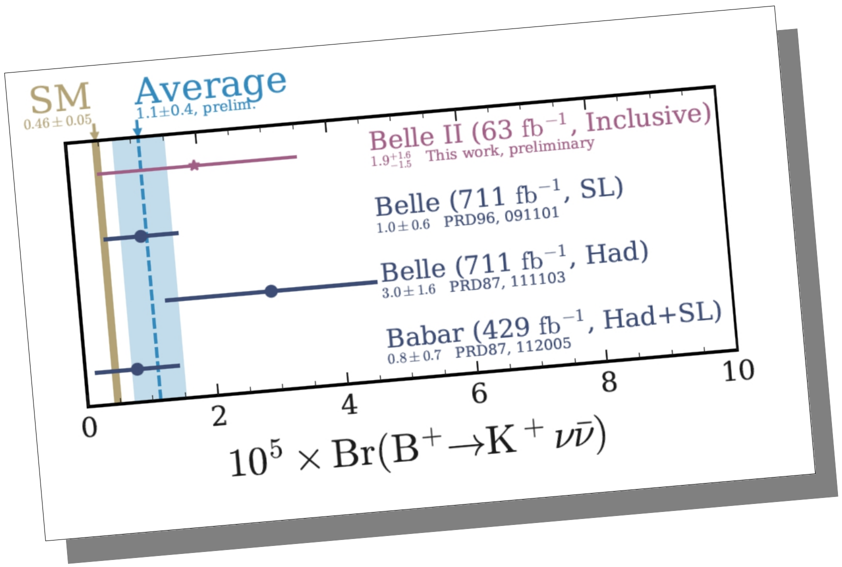
Future prospects

The idea of flavor non-universal interactions – with a 1st layer of new physics already at the TeV scale – has several interesting implications for future precision measurements (*with different degree of model-dependence*)

E.g.: II) O(10%) enhancement in $b \to s\nu\nu$ rates [3rd gen. ν in the final state]



Very interesting prospect for Belle-II, already now…

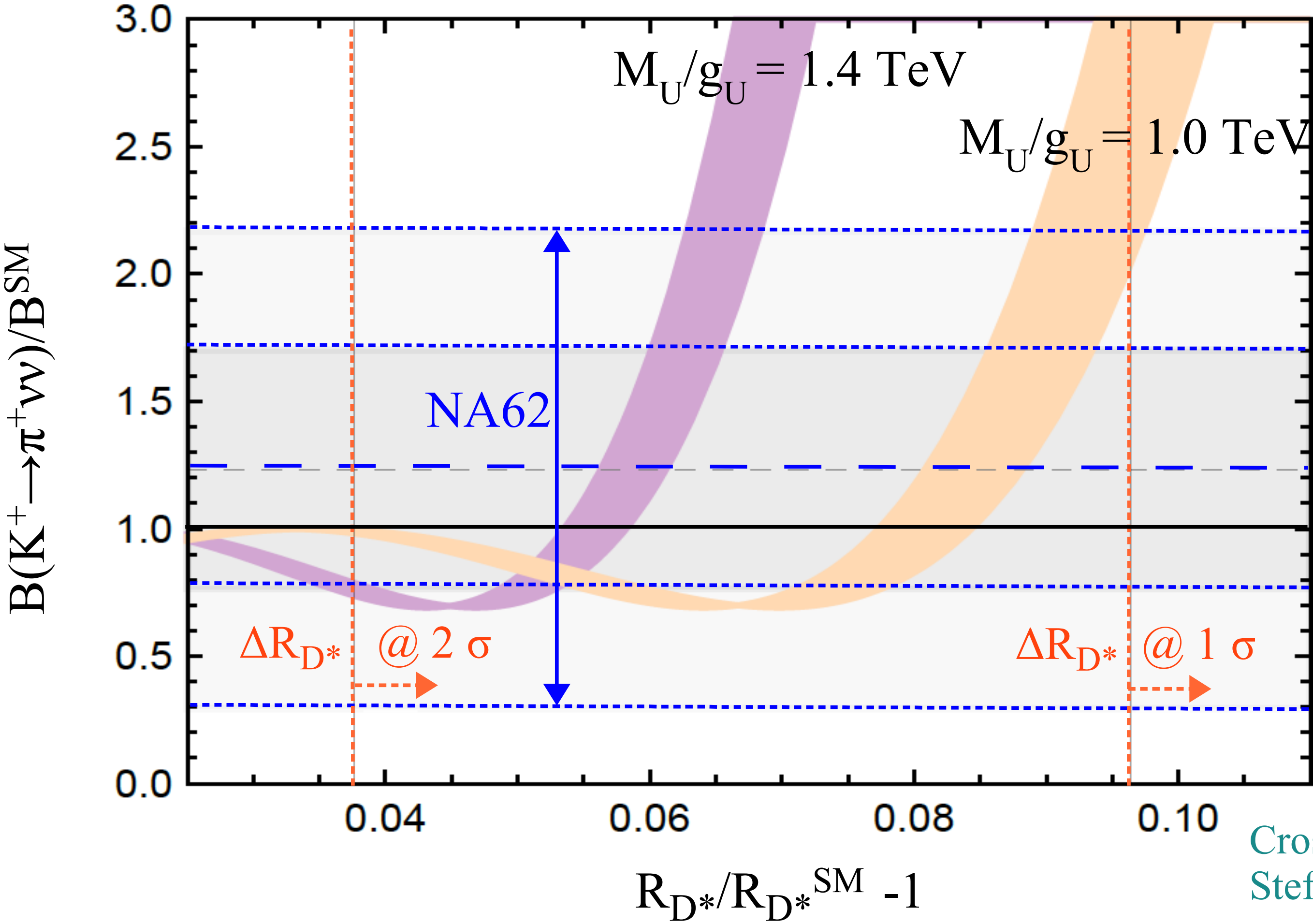


Fuentes-Martin, GI, Konig, Selimovic, '20
Cornella *et al.* '21

▶ *Future prospects*

The idea of flavor non-universal interactions – with a 1st layer of new physics already at the TeV scale – has several interesting implications for future precision measurements (*with different degree of model-dependence*)

E.g.: III) O(10%) enhancement in $s \to d\nu\nu$ rates [3rd gen. ν in the final state]

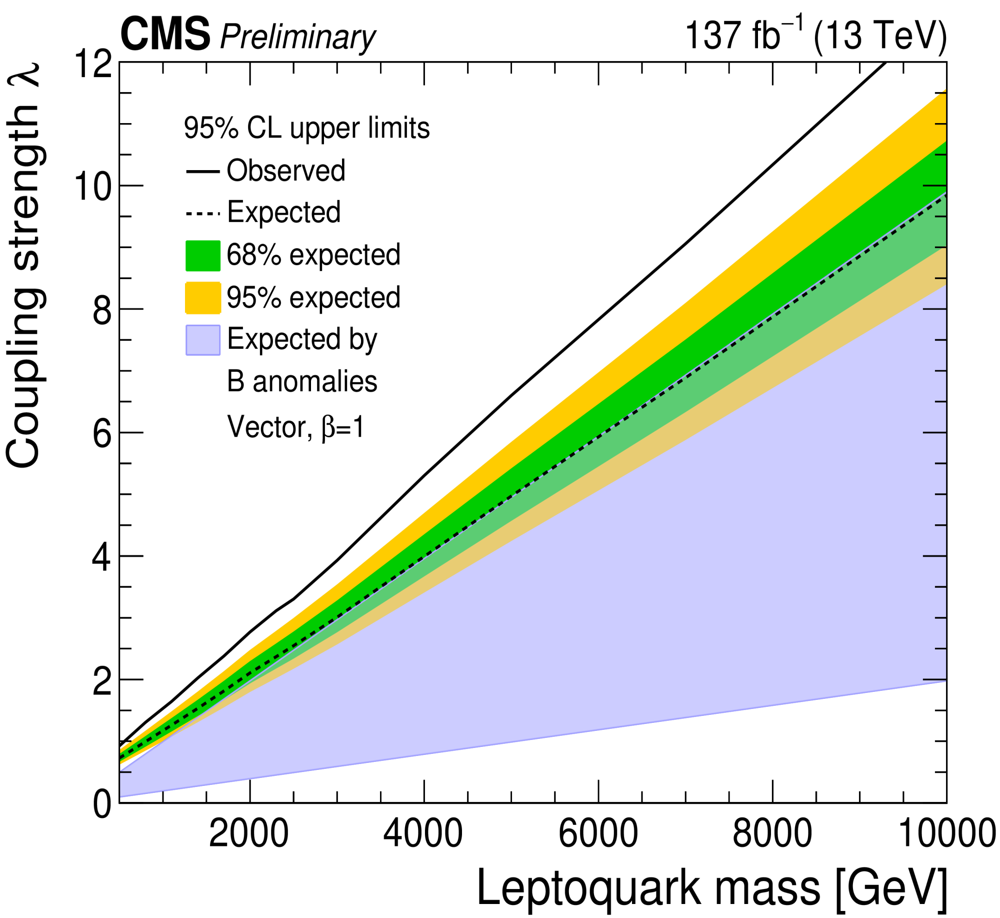


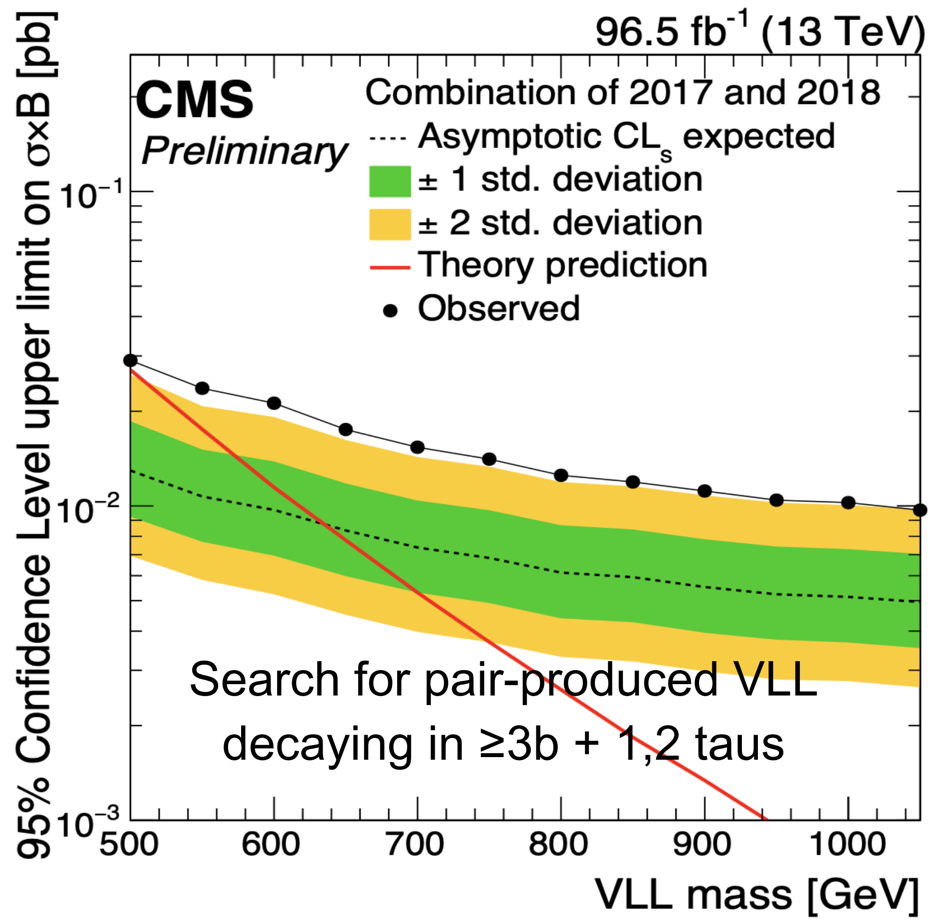
Crosas, GI, Lizana, Stefanek, Selimovic, '22

Future prospects

The idea of flavor non-universal interactions – with a 1st layer of new physics already at the TeV scale – has several interesting implications for future precision measurements + high-energy measurements

E.g.: $pp \to \tau\bar{\tau}$ $pp \to (\chi_\tau \to b\bar{b}\tau) + (\bar{\chi}_\tau \to b\bar{b}\bar{\tau})$





Future prospects

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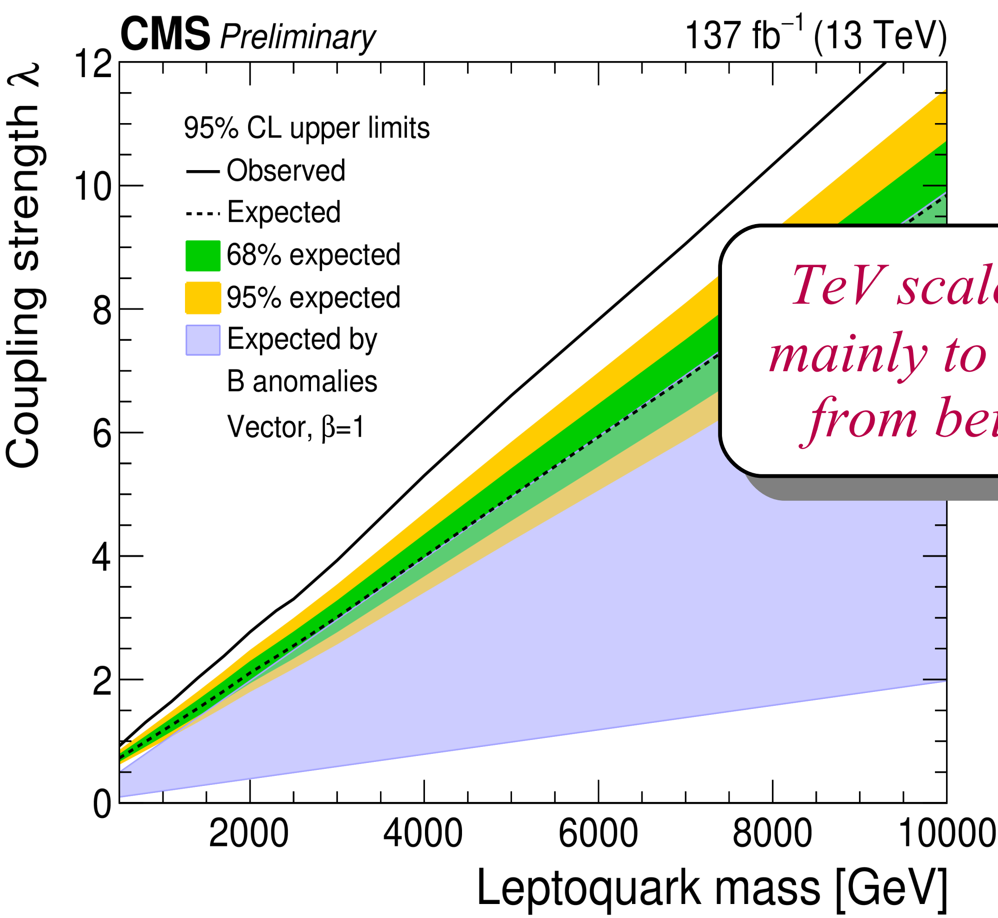
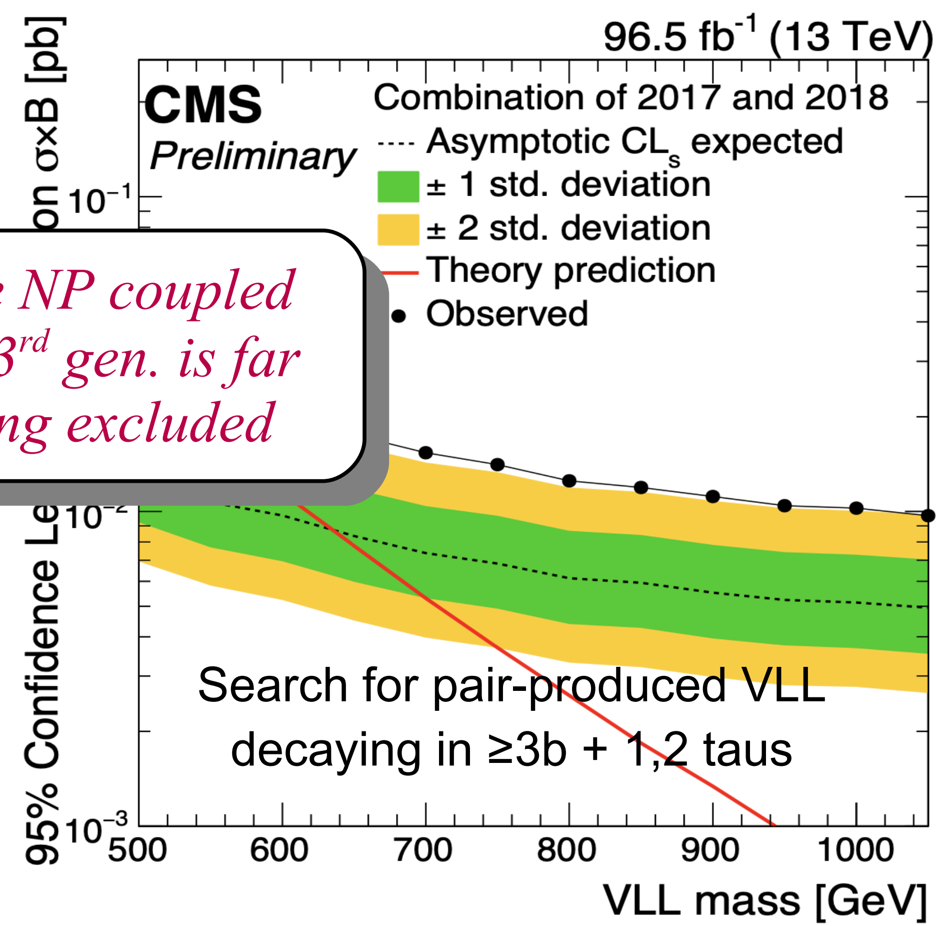


TeV scale NP coupled mainly to 3rd gen. is far from being excluded



Conclusions

- The KM mechanism has played a major role in our understanding of fundamental interactions

- As I tried to show, there are valuable lessons we can deduce from the KM paper which are still valuable today, when applied to the search for physics beyond the Standard Model

- The most general one is that *flavor physics still hides interesting puzzles* and *might be the key to understand the nature of physics above the electroweak scale*