Old and recent problems in flavor physics

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- Introduction
- The LFU anomalies: data and EFT
- Model-building considerations
- UV completions: 4321 and beyond
- Implications @ low- and high-energies
- Conclusions

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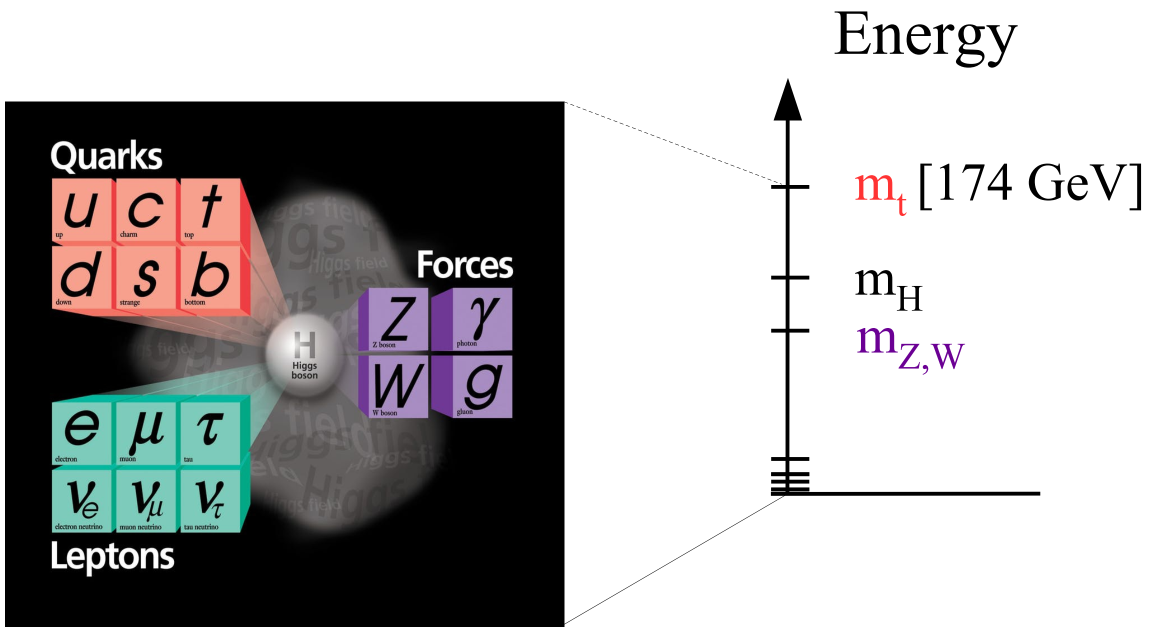
Introduction

This year we celebrated the 10th anniversary of the Higgs-boson discovery (*or the completion of the SM spectrum*).

The SM



Introduction

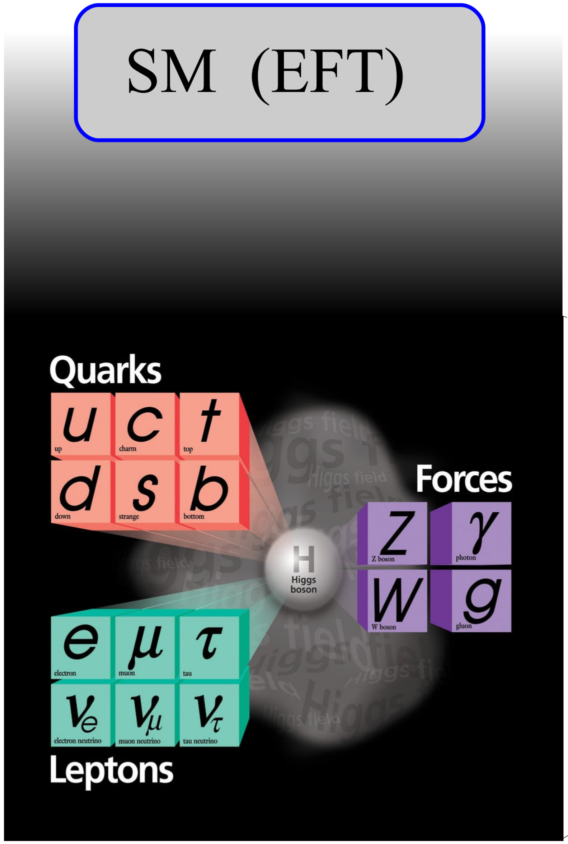
This year we celebrated the 10th anniversary of the Higgs-boson discovery (*or the completion of the SM spectrum*).

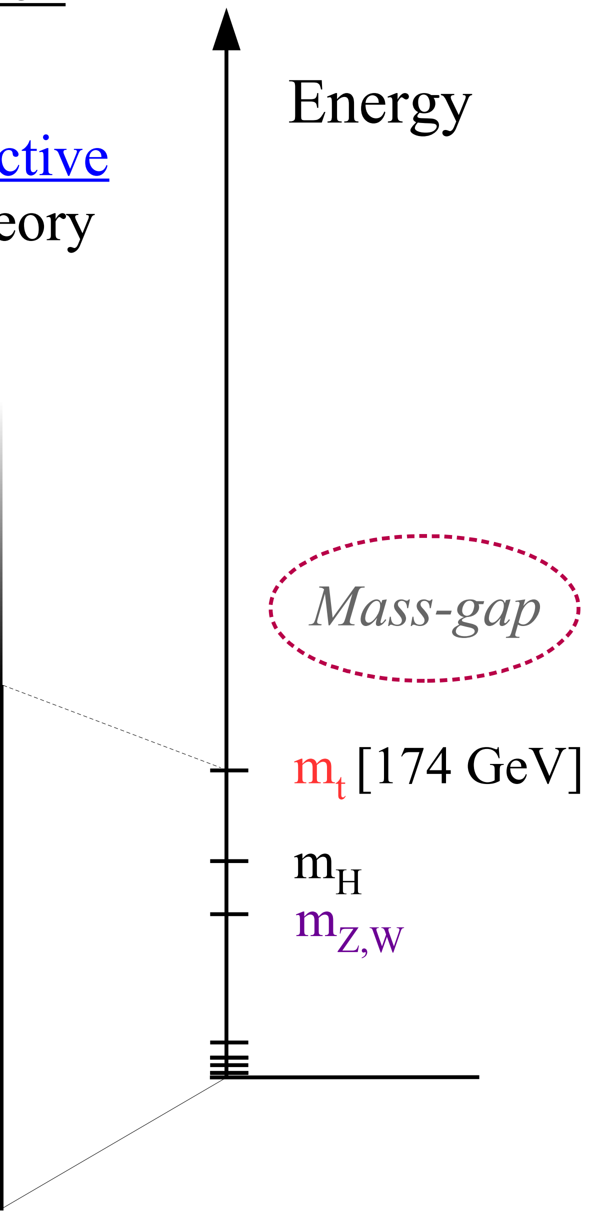
However, as for any QFT, we believe the SM is only an Effective Field Theory, i.e. the low energy limit of a more complete theory with more degrees of freedom

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

We identified the *long-range* properties of this EFT, but we struggle to understand

- *the nature of short-distance dynamics*
- *why such peculiar structure emerges at low-energies*





Introduction

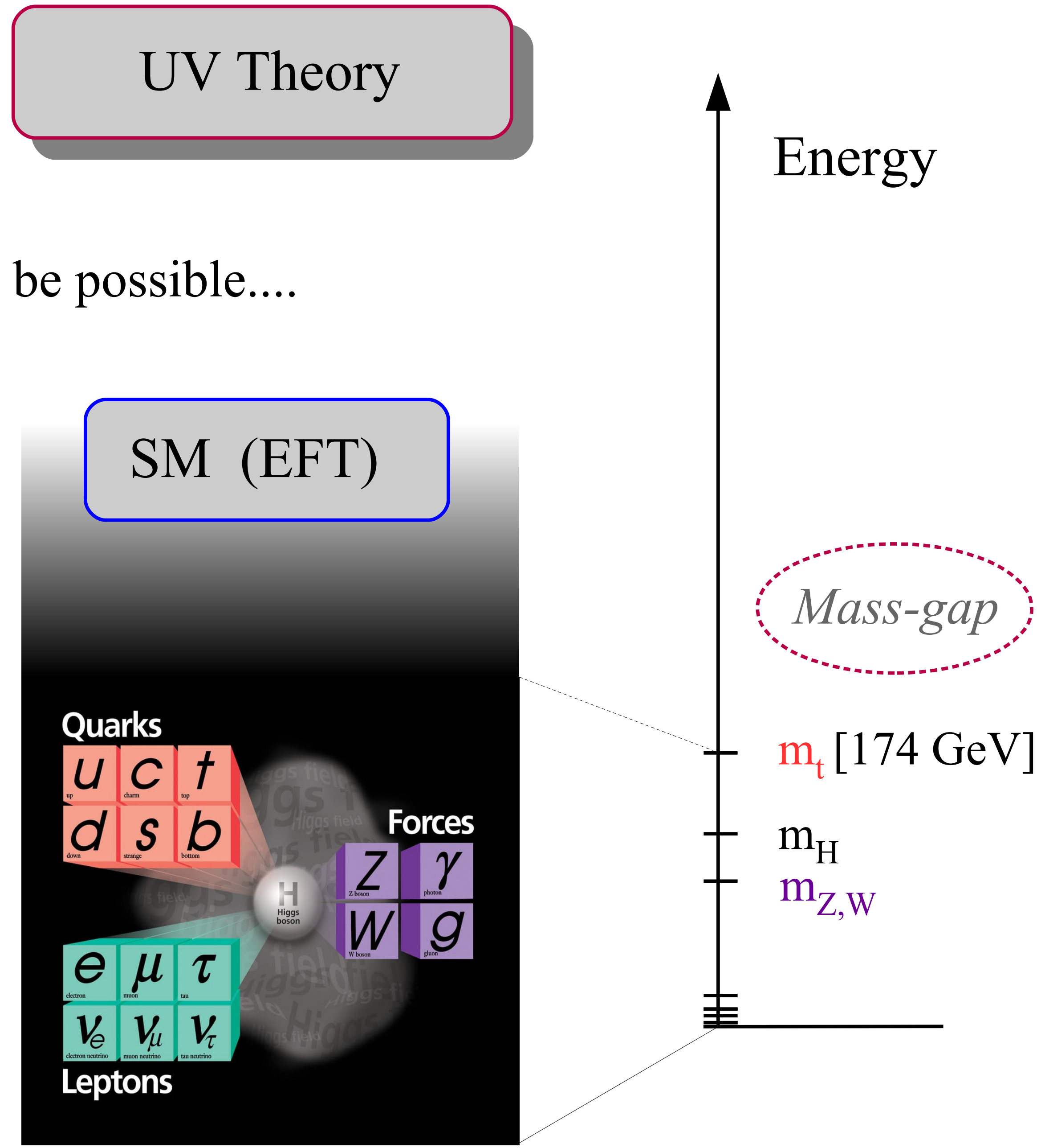
Ideally, we would like to probe the UV directly, via high-energy experiments

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 info (*bounds, but not only*), with 2 clear messages:

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



Introduction

The "old" flavor problem(s):

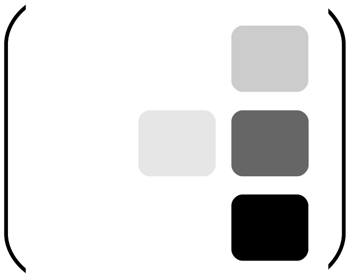
For the time being, we can only extract *indirect* UV infos exploring the low-energy limit of the EFT.

Many info (*bounds, but not only*), with 2 clear messages:

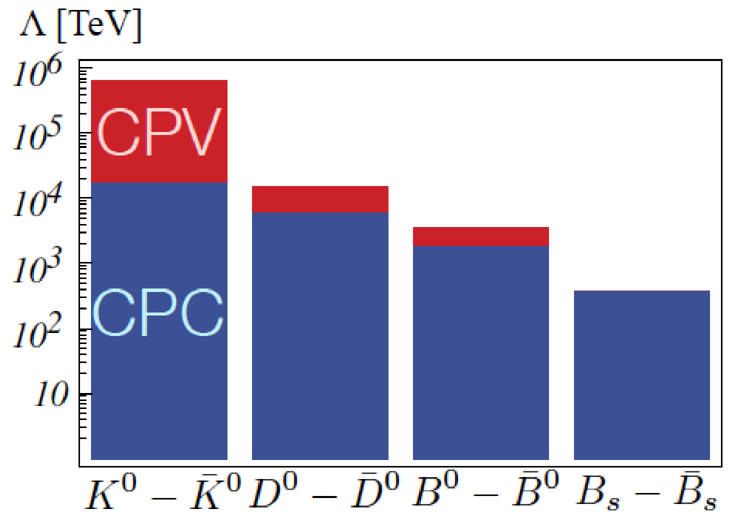
- *several tuned* (SM) *couplings* →
- *several accidental (approximate) symmetries*

- SM flavor couplings: $13 \rightarrow 4\ [> 0.01] \rightarrow 1\ [> 0.1]$

$Y \sim$



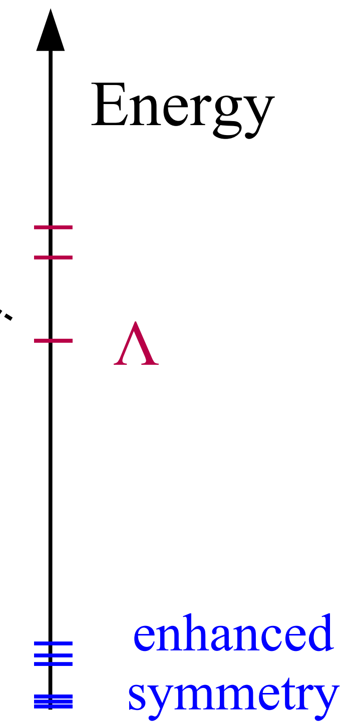
- SMEFT @ d=6: $2499 \rightarrow 47\ [U(3)^5]$



▶ Introduction

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

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



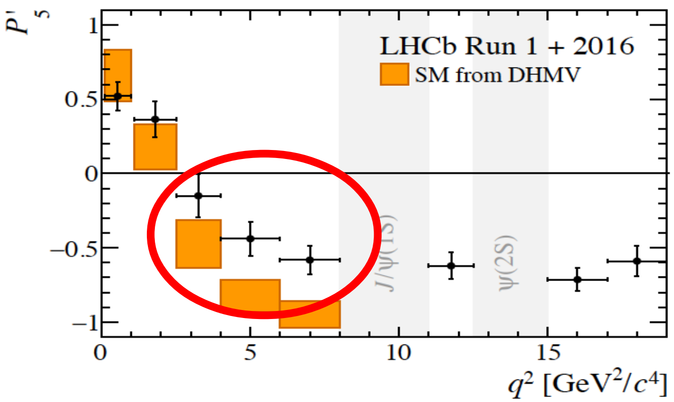
"Accidental symmetries" are symmetries which are not fundamental properties of the theory, but emerge accidentally at low energies / large distances → not enough "variables" to describe the violation of the symmetry [~ *multipole expansion*]

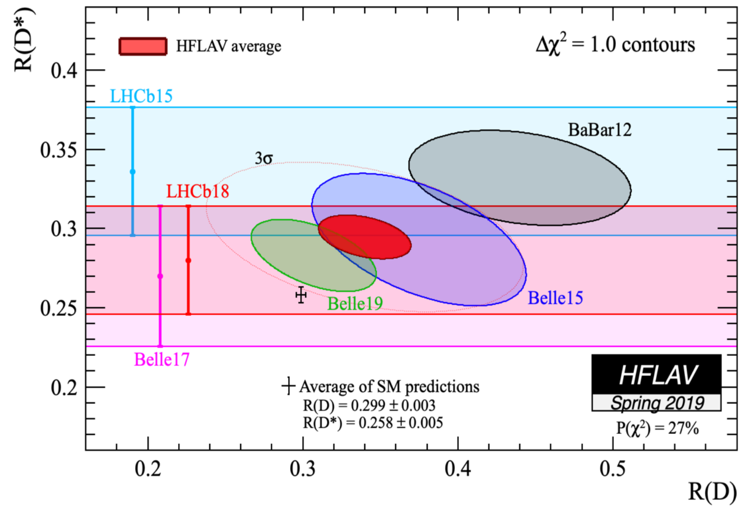
If a symmetry arises accidentally in the low-energy theory, we expect it to be violated by higher dim. ops

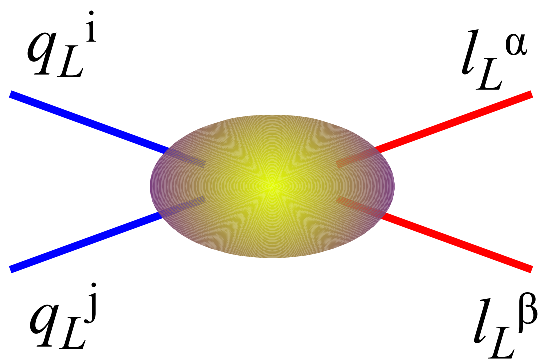
Violations of accidental symmetries

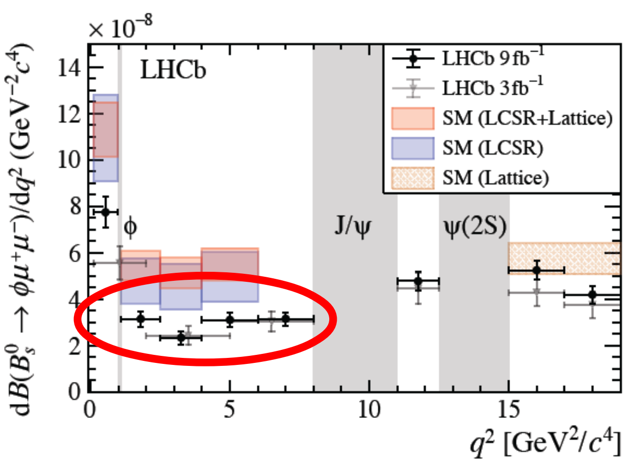
Well-known past examples... but also the hints of Lepton Flavor Universality violations recently reported in B physics belong to this category

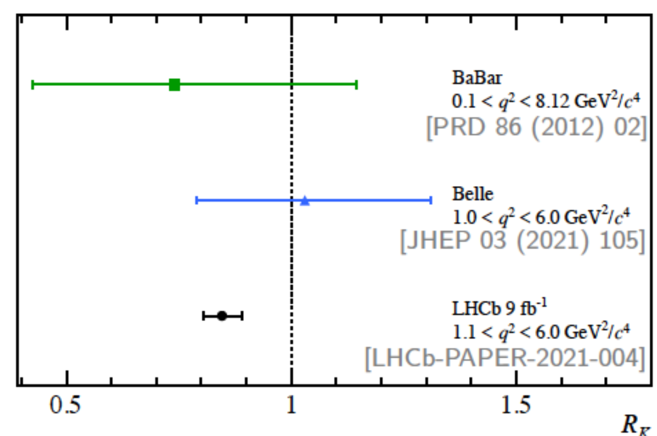
The LFU anomalies: data and EFT











The LFU 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)

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

LFU is badly broken in the Yukawa sector: $y_e \sim 3\times10^{-6}$, $y_\mu \sim 3\times10^{-4}$, $y_\tau \sim 10^{-2}$

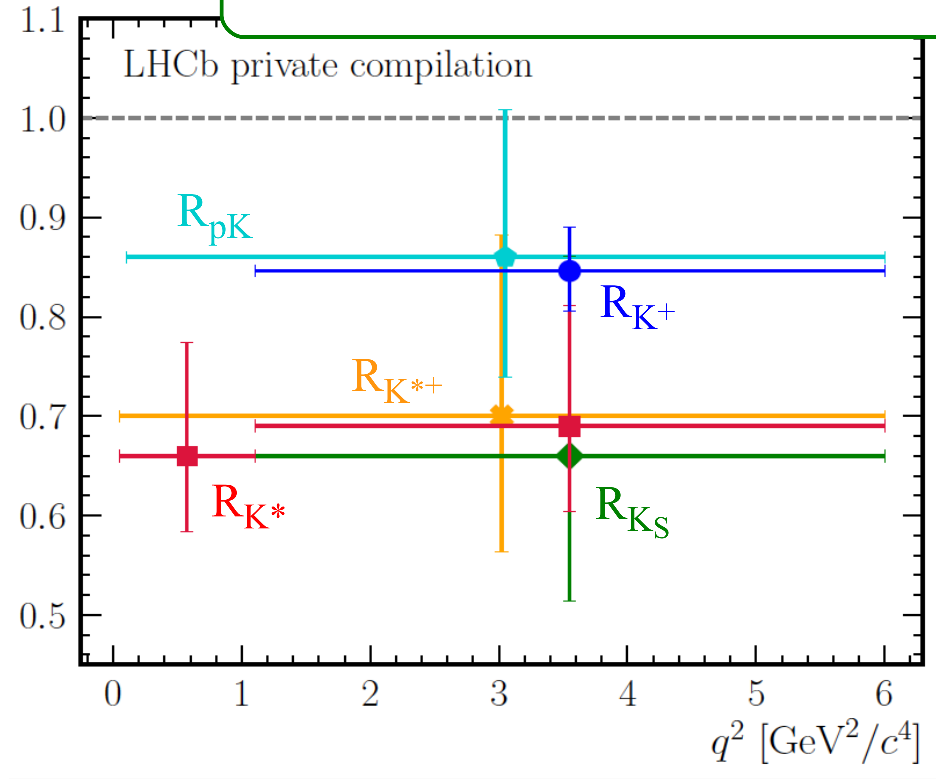
But all the lepton Yukawa couplings are small compared to SM gauge couplings, giving rise to the (*approximate*) universality of decay amplitudes which differ only by the different lepton species involved

The LFU anomalies

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

$R_H = \Gamma(H_b \rightarrow H\mu\mu)/\Gamma(H_b \rightarrow H\, ee)$

High significance: several observables pointing to the same coherent picture



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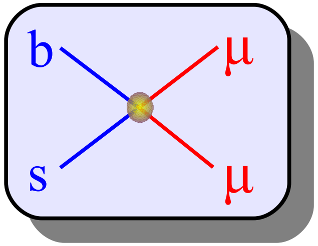

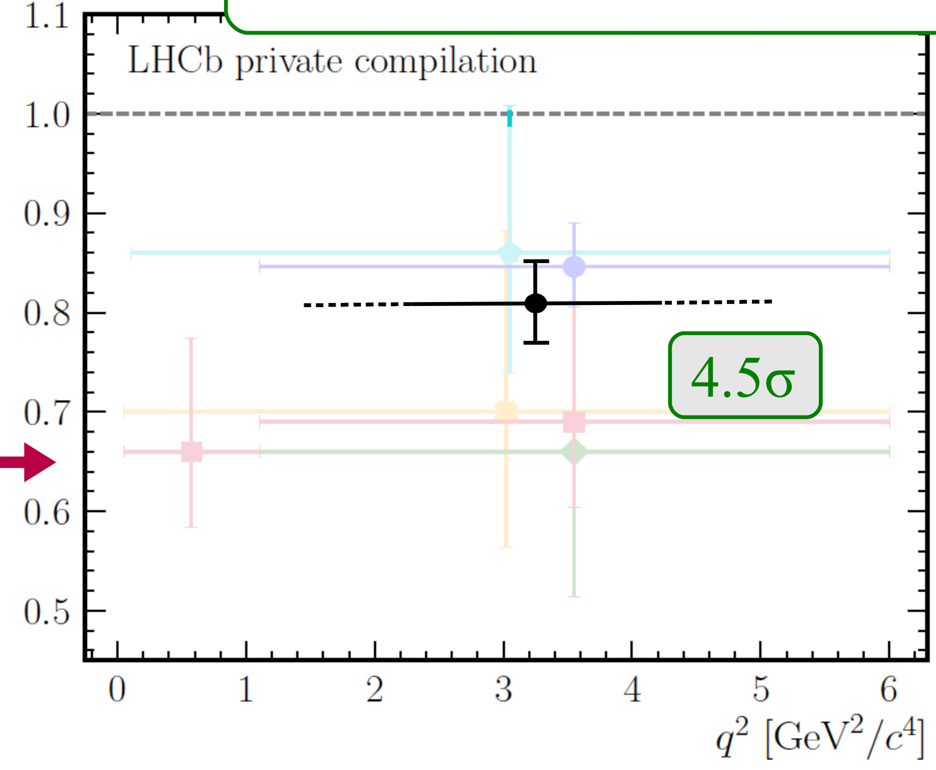

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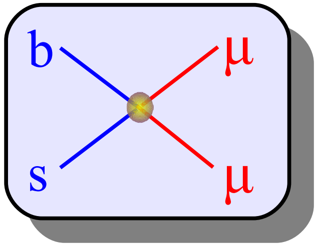

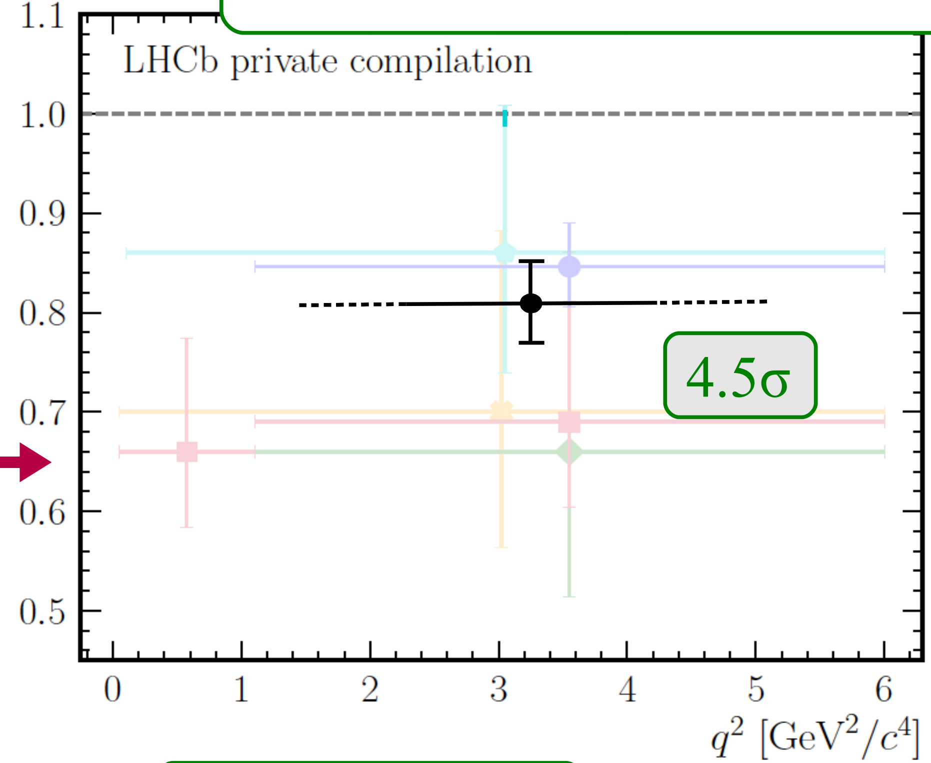

$BR(B_s \to \mu\mu)$

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

$BR_{SM} = (3.66 \pm 0.14) \times 10^{-9}$ 2.3σ

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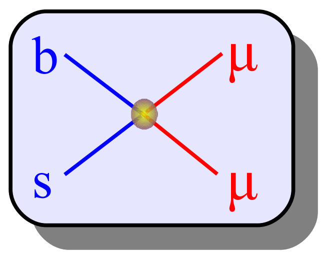

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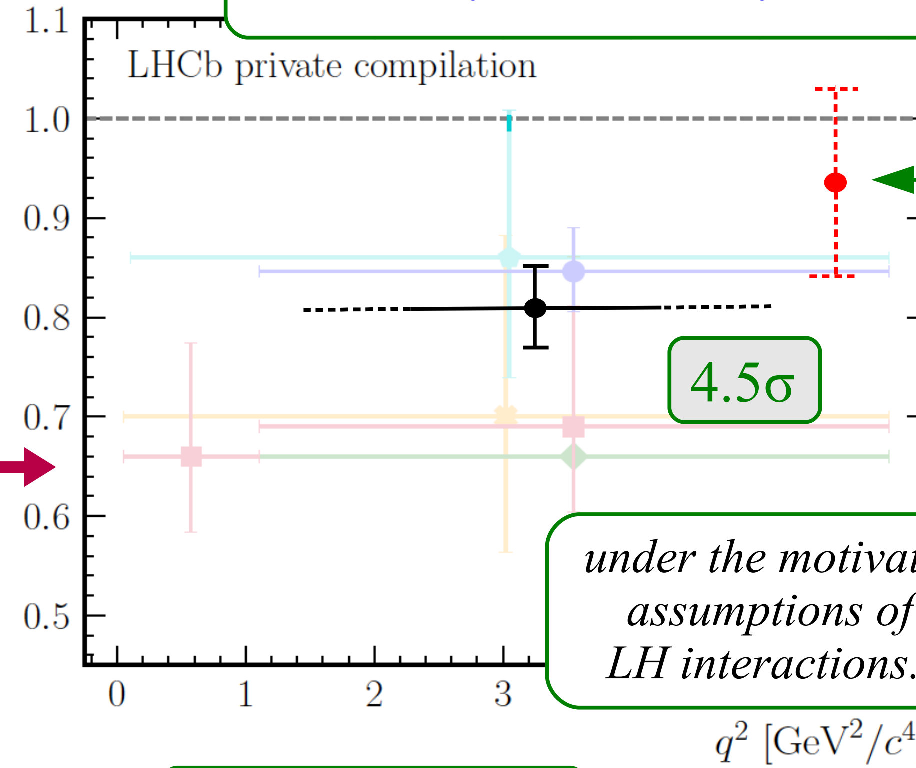


4.5σ

under the motivated assumptions of LH interactions…

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

BR_{exp} = ~~(2.85±0.32)~~ (3.42±0.29) × 10^{-9}

ATLAS+LHCb + CMS '22 (my naive average)

BR_{SM} = (3.66±0.14) × 10^{-9}

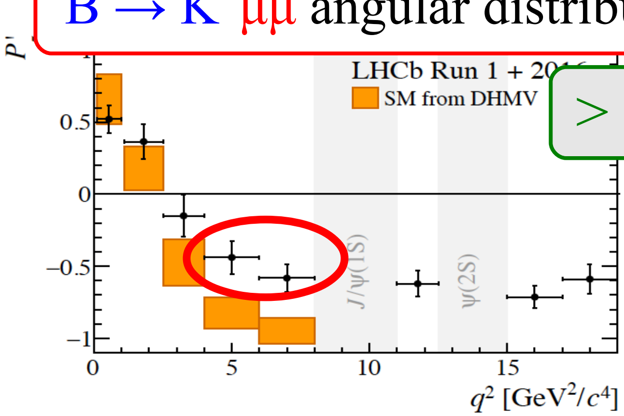
~~2.3σ~~   < 1σ

The LFU anomalies

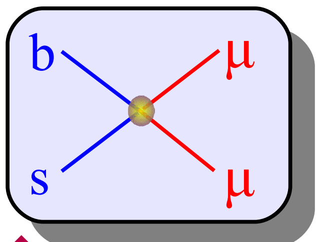
- b → s l^+l^- (neutral currents): μ vs. e

High significance: several observables pointing to the same coherent picture

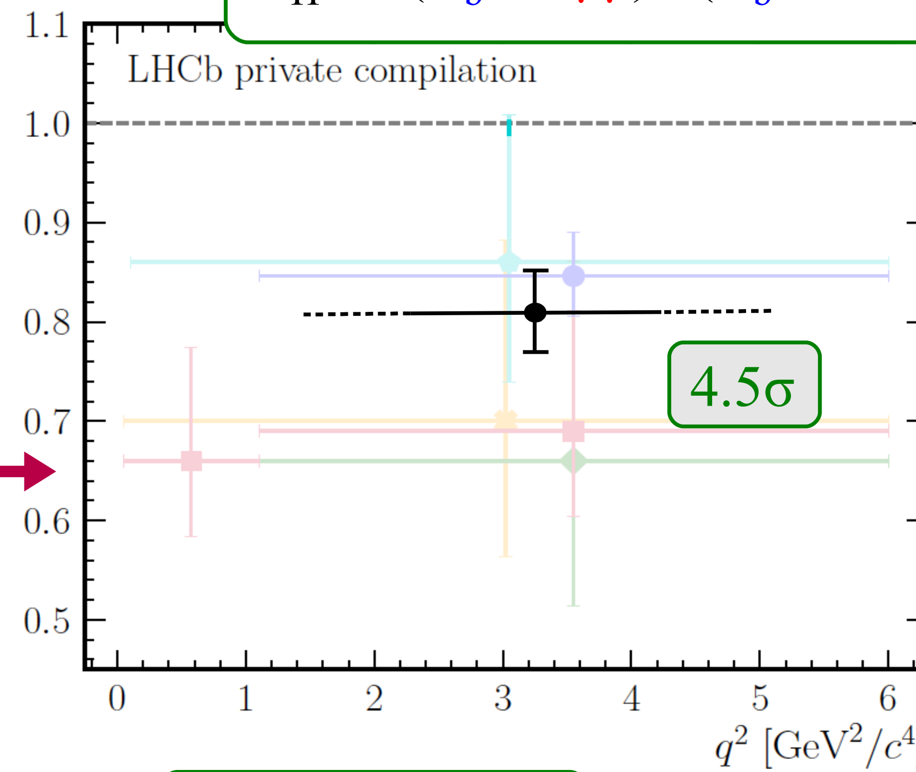
B → K^*μμ angular distribution



> 3σ

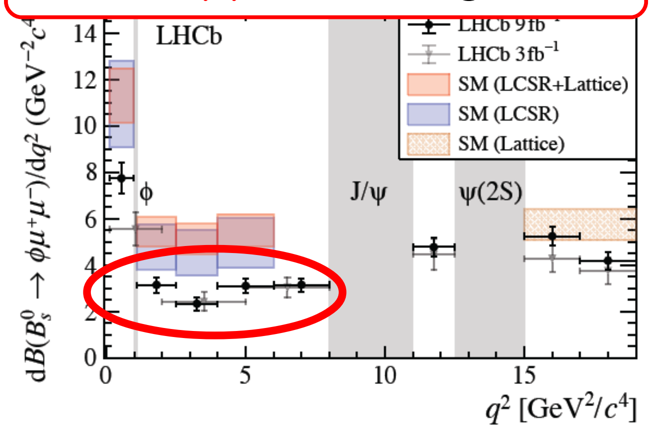


$R_H = \Gamma(H_b \to H\mu\mu)/\Gamma(H_b \to H\,ee)$



4.5σ

B → H μμ branching ratios



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~~2.3σ~~ < 1σ

The LFU anomalies

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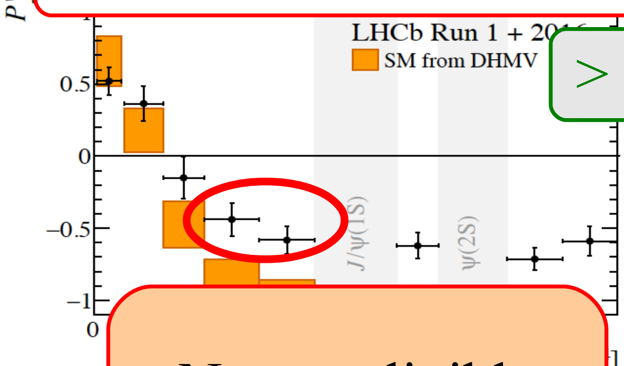
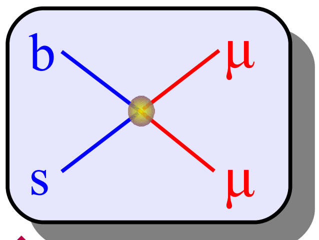
$B \to K^* \mu\mu$ angular distribution

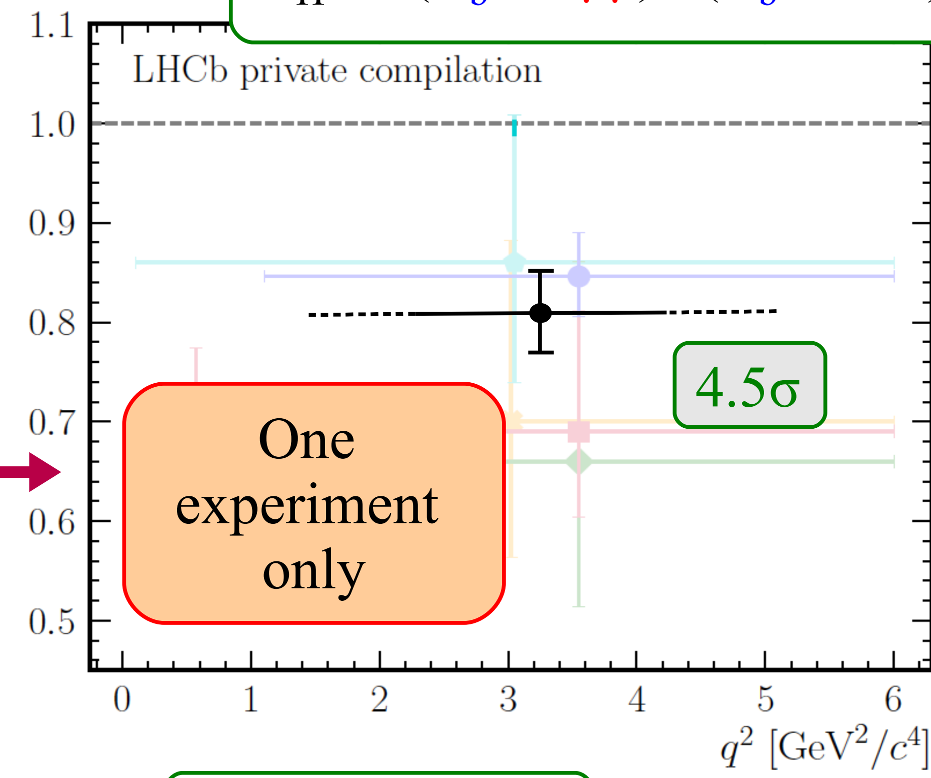


$> 3\sigma$

Non-negligible Th. errors



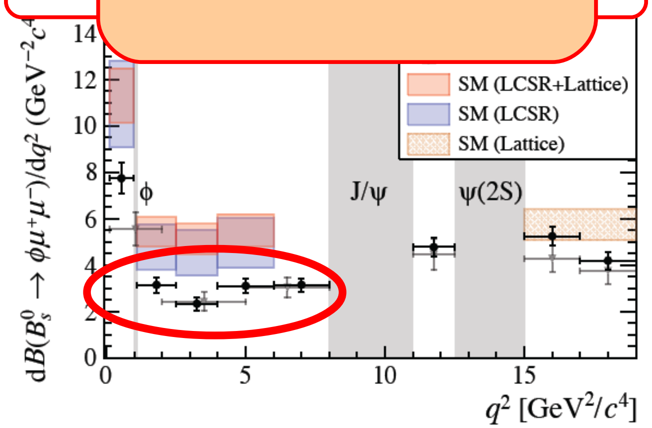
$R_H = \Gamma(H_b \to H\mu\mu)/\Gamma(H_b \to H\, ee)$



One experiment only

4.5σ

$B \to$ ... s



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Low statistics

~~2.3σ~~ $< 1\sigma$

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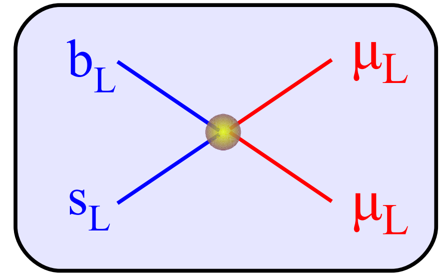

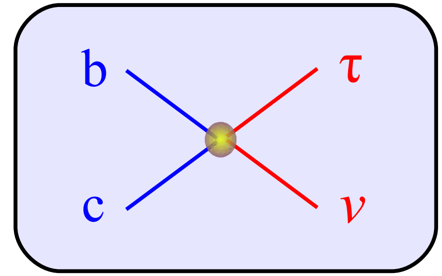

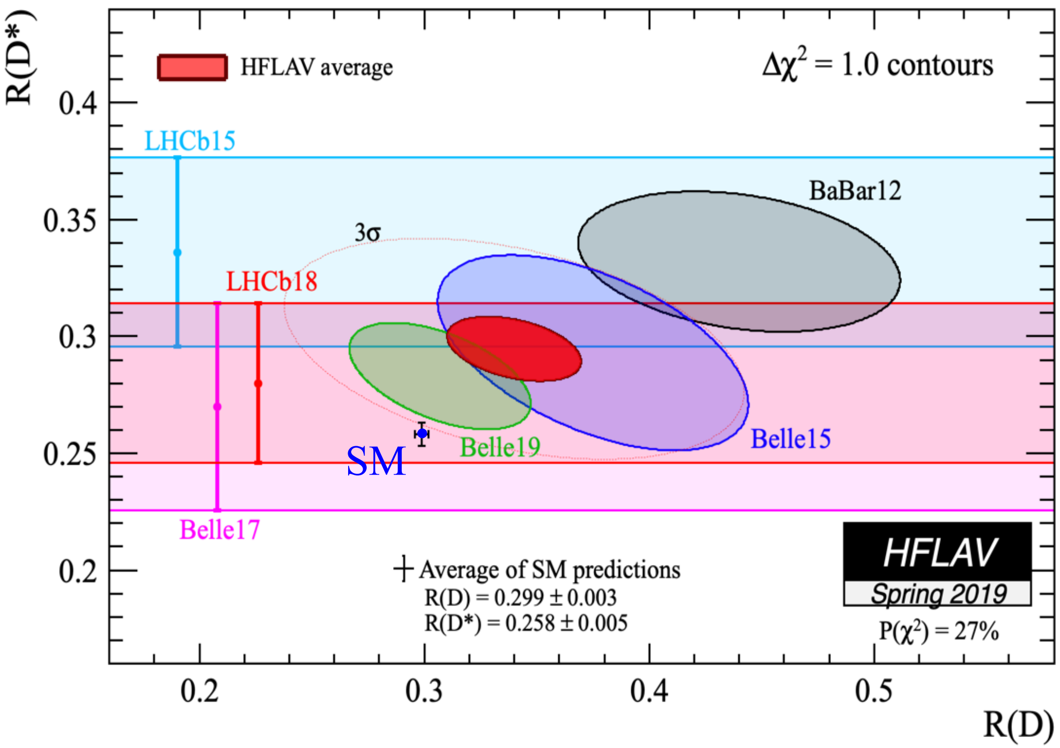

$$R(X) = \frac{\Gamma(B \to X\, \tau\nu)}{\Gamma(B \to X\, l\nu)} \quad X = D \text{ or } D^*$$

- Clean SM predictions (*uncertainties cancel in the ratios*)
- Consistent results by 3 different exp.ts: 3.1σ excess over SM
- Slower progress

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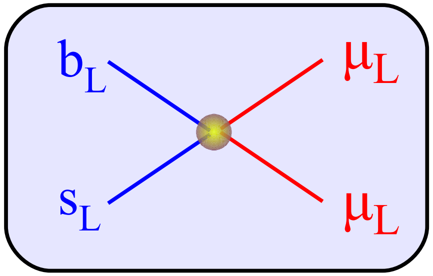

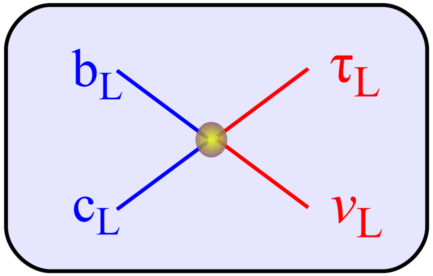

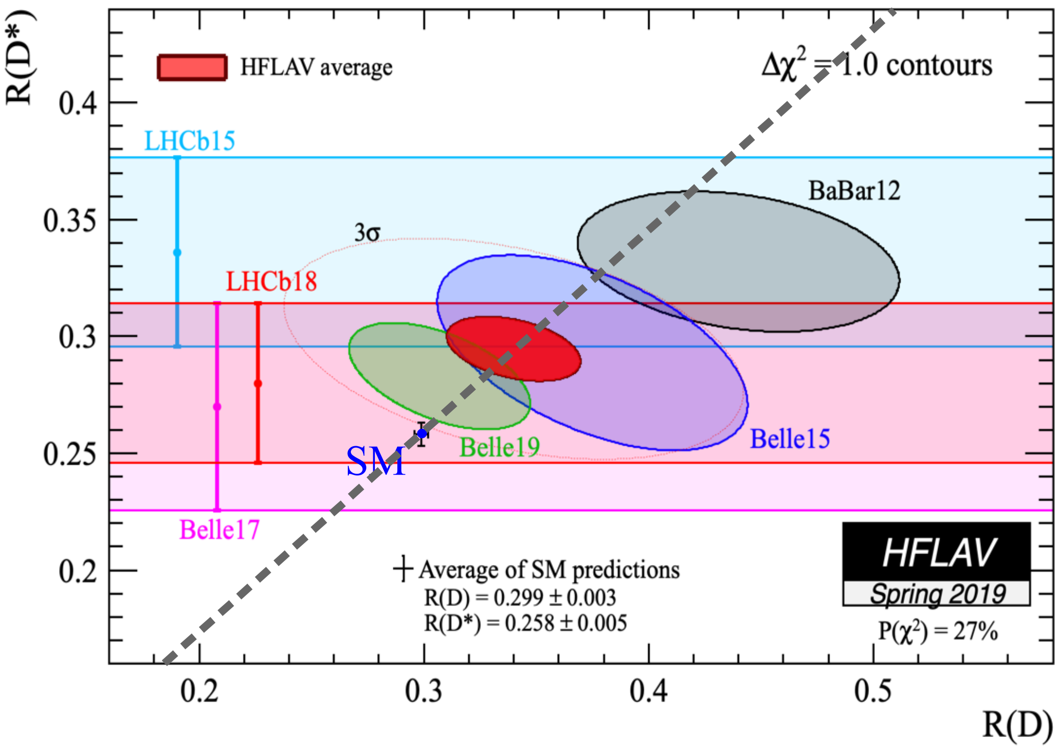

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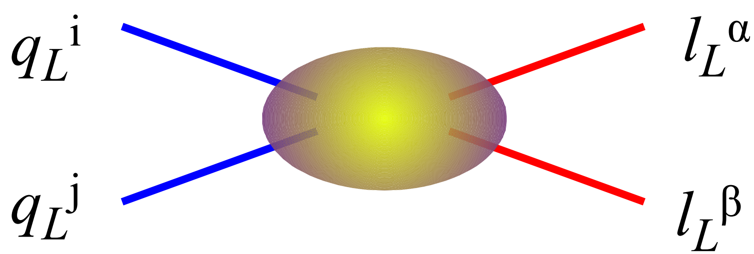
- Slower progress

- Large NP effect competing with tree-level SM amplitude
- Left-handed NP amplitude describe well data (*but other options still possible*)

General EFT considerations

- Anomalies are seen only in semi-leptonic (quark×lepton) operators
- We definitely need non-vanishing left-handed current-current operators although other contributions are also possible



Bhattacharya *et al.* '14
Alonso, Grinstein, Camalich '15
Greljo, GI, Marzocca '15
(+many others...)

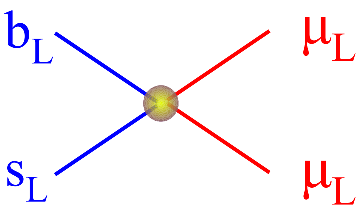
- Large coupl. [*compete with SM tree-level*] in b(3rd) c(2nd) → τ(3rd) ν_τ(3rd)
- Small coupl. [*compete with SM loop-level*] in b(3rd) s(2nd) → μ(2rd) μ(2rd)

↓

$C_{ij\alpha\beta}$ = large for 3rd generation fields + small terms for 2nd (& 1st) generations → *Link to pattern of the Yukawa couplings !*

General EFT considerations

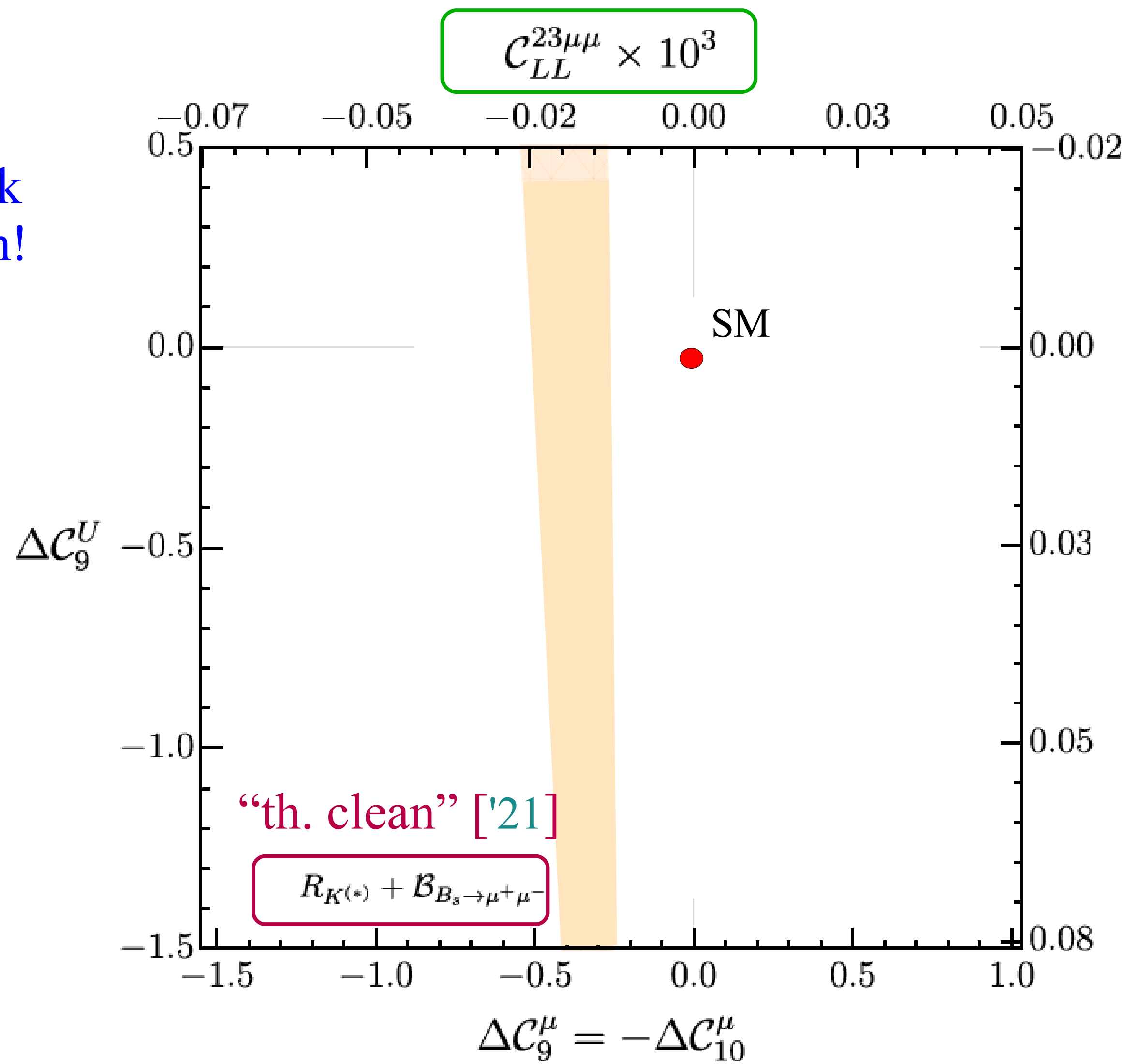
Data point to NP effects in operators of the type $\mathcal{O}_{LL}^{ij\alpha\beta} = (\bar{q}_L^i \gamma_\mu \ell_L^\alpha)(\bar{\ell}_L^\beta \gamma^\mu q_L^j)$



$\sim 4\times10^{-5}\ G_{Fermi}$

super-weak interaction!

Tiny interaction → e/μ violation



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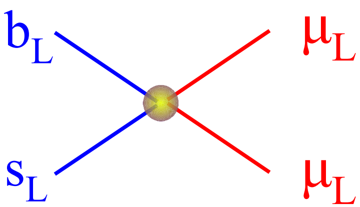

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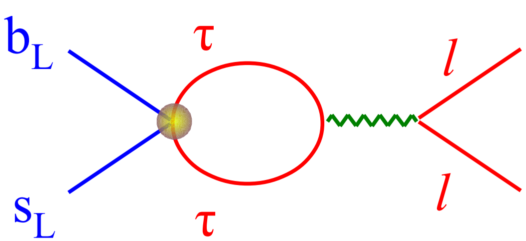
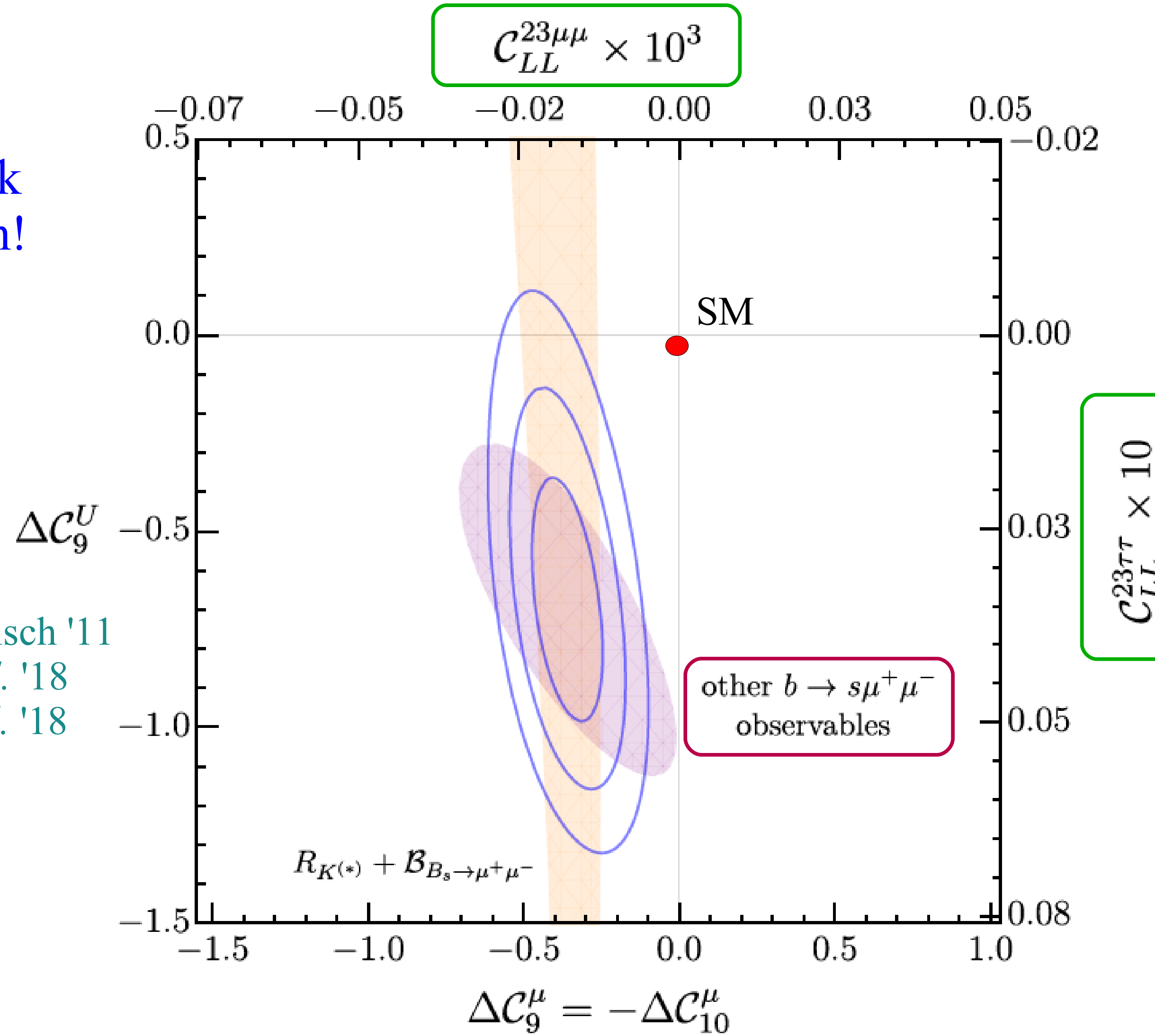


Bobeth & Haisch '11
Crivellin *et al.* '18
Alguero *et al.* '18



Stronger interaction:

- universal (loop effect) in $b \to s\, ll$

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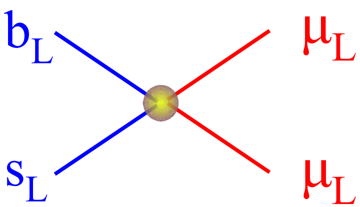

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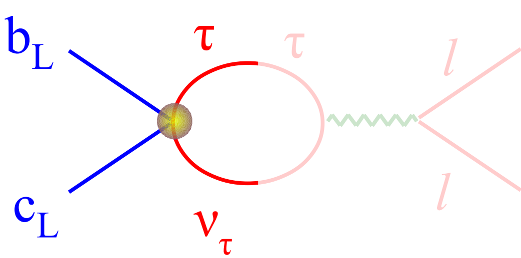
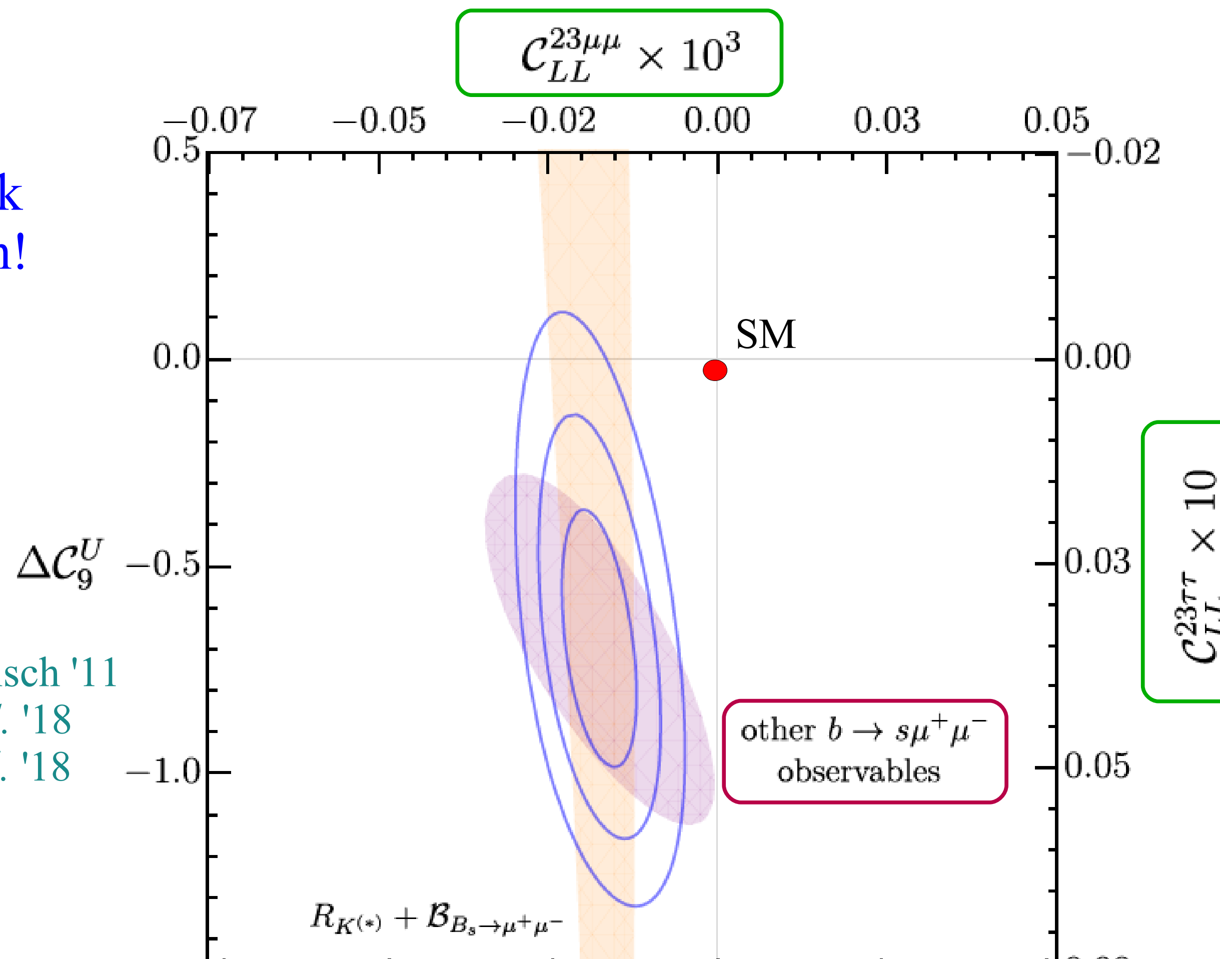


Bobeth & Haisch '11
Crivellin *et al.* '18
Alguero *et al.* '18

Stronger interaction:

- universal (loop effect) in b→s *ll*
- non-universal (tree) in b→c τν



Size (and need) of this contribution pre-dicted from CC Greljo *et al.* '17

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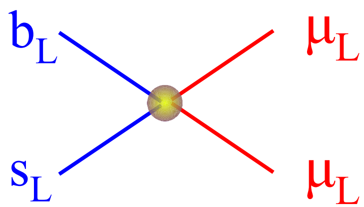

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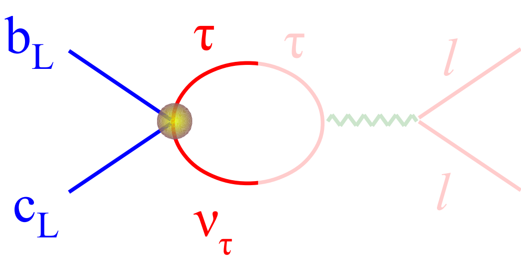

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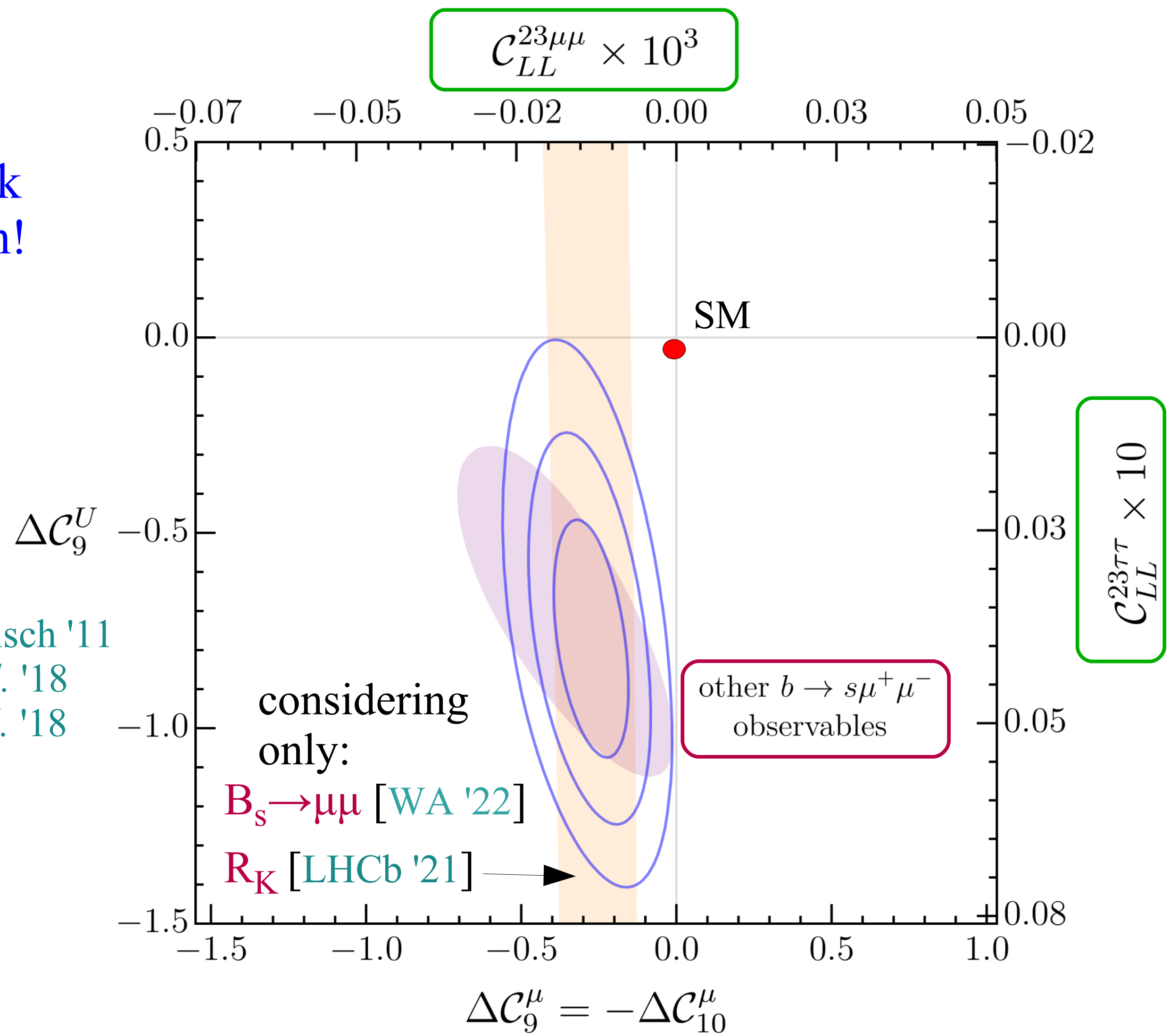
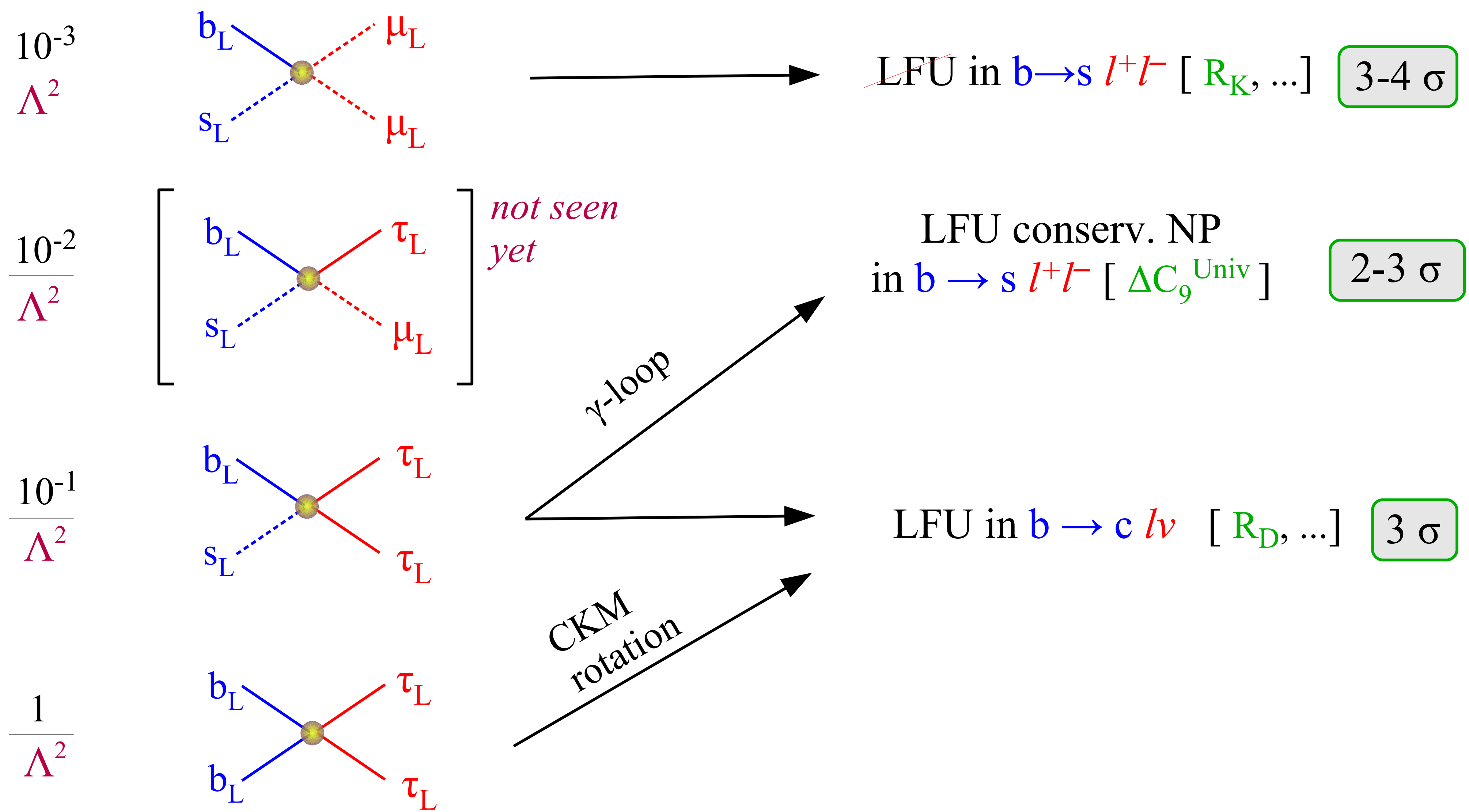


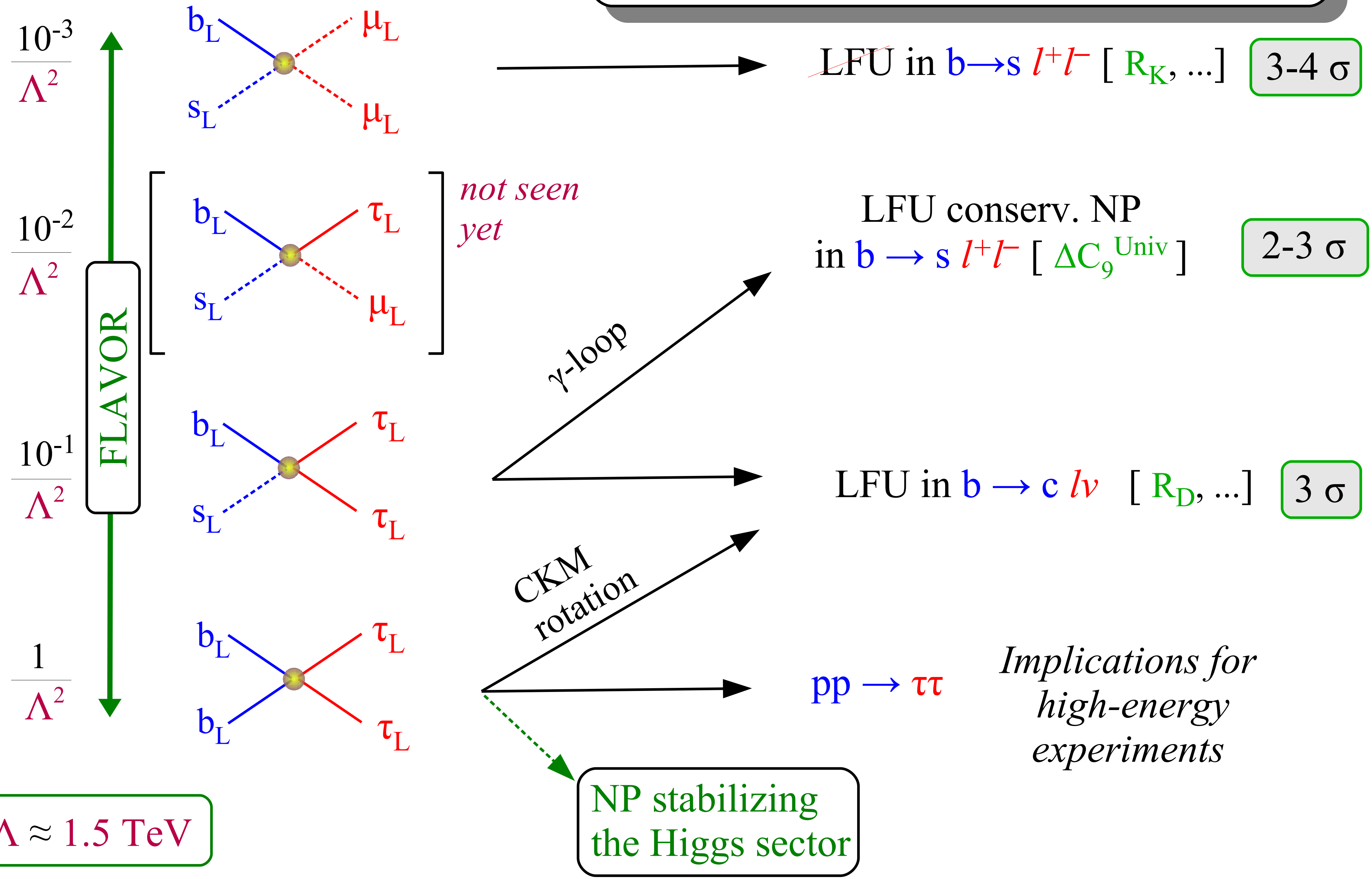
General EFT considerations



$\Lambda \approx 1.5$ TeV

General EFT considerations

An exciting "narrow path" connecting old problems and recent anomalies



Model-building considerations

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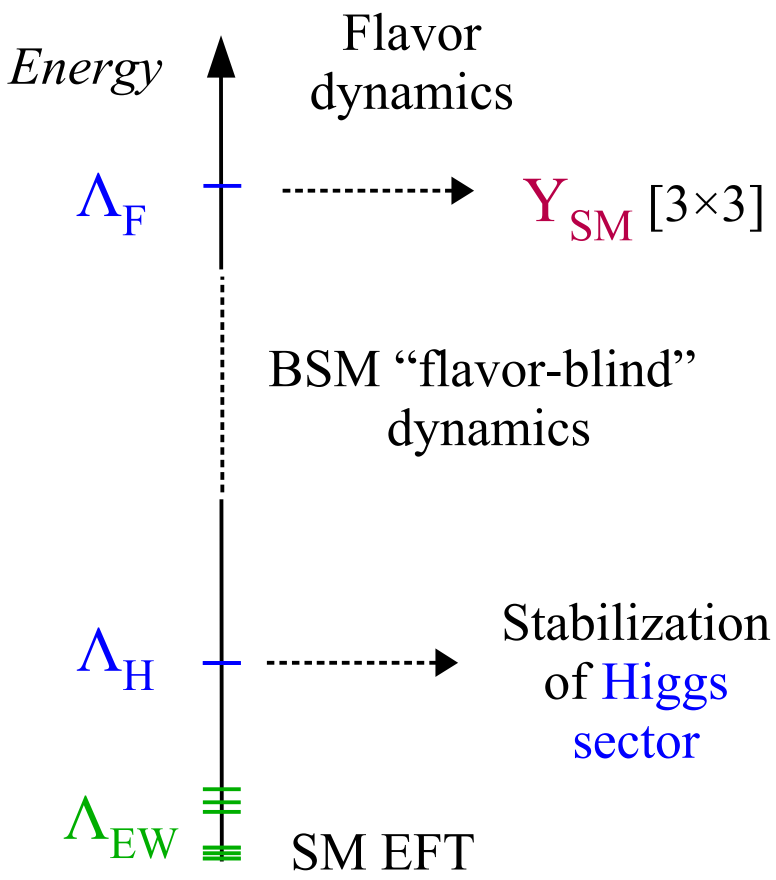
From a model-building perspective, the EFT results
challenge the "old" paradigm of flavor-universal BSM physics



The old MFV paradigm:

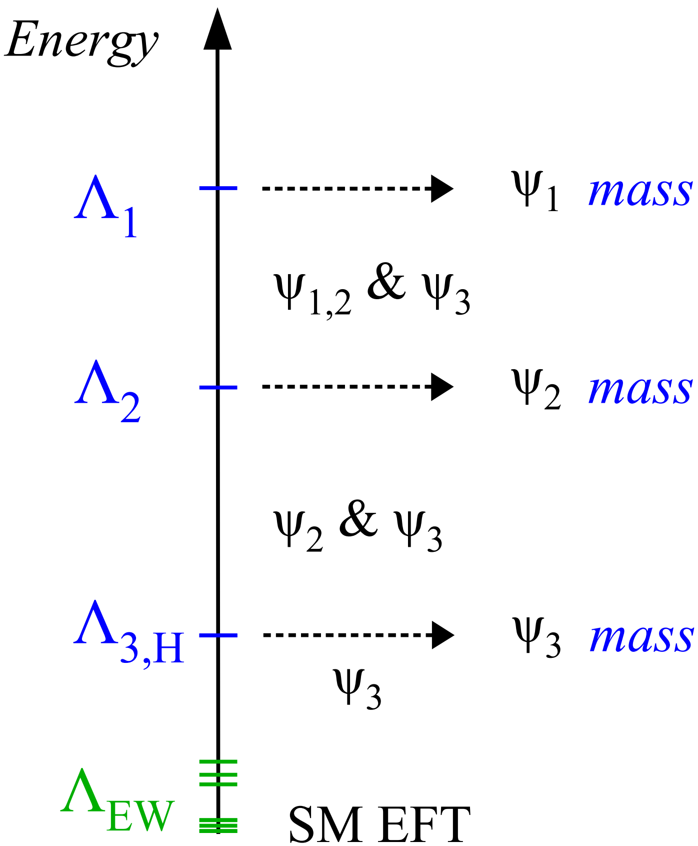
- Concentrate on the Higgs hierarchy problem
- Postpone (*ignore*) the flavor problem

⬇

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

Model-building considerations

From a model-building perspective, the EFT results *fit well with the idea of a multi-scale construction related to flavor hierarchies:*



Bordone *et al.* '17
Allwicher, GI, Thomsen '20
Barbieri '21

Panico & Pomarol '16
⋮
Dvali & Shifman '00

Main idea:

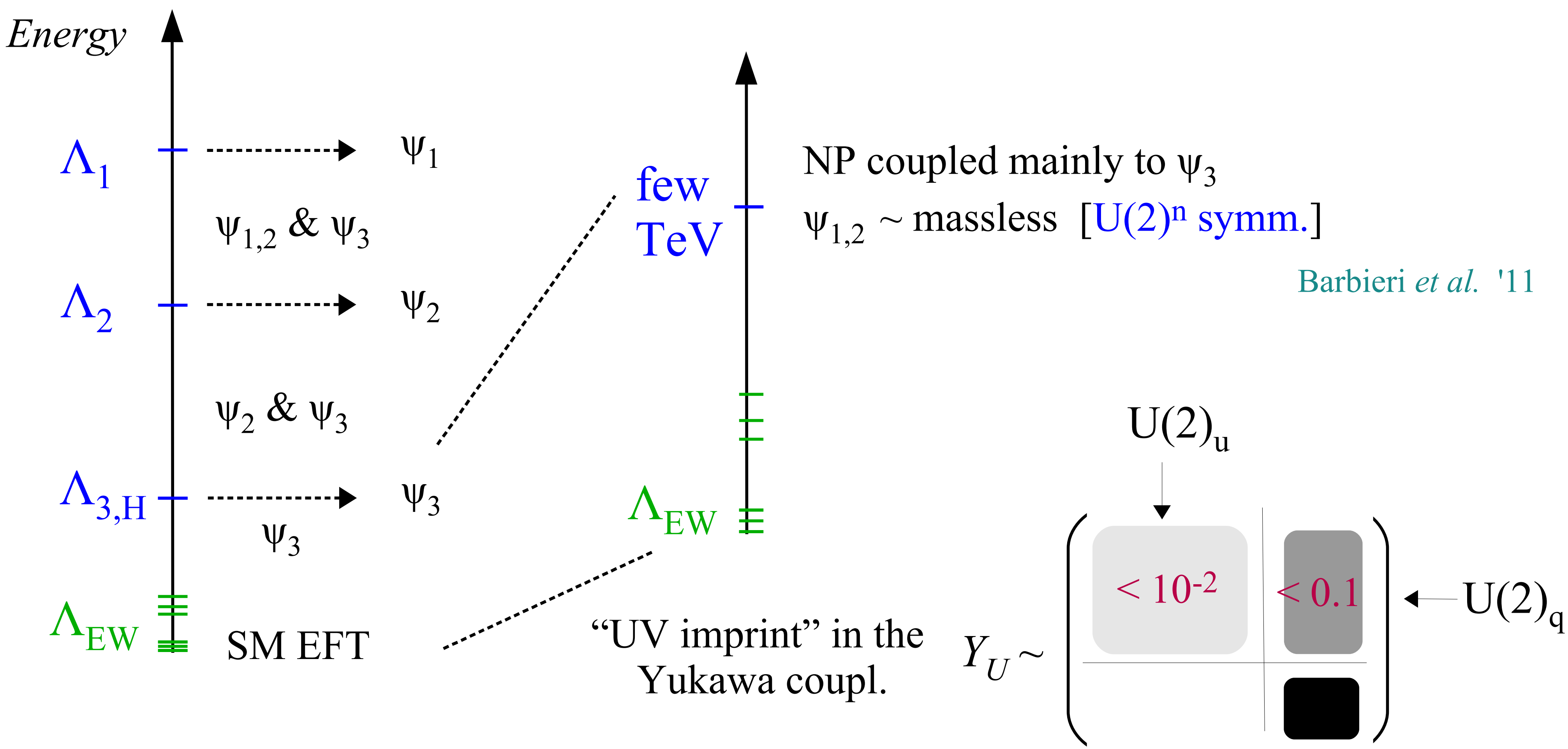
- Flavor non-universal interactions already at the TeV scale:
- 1st & 2nd gen. have small masses because they are coupled to NP at heavier scales

⬇

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

Model-building considerations

From a model-building perspective, the EFT results
fit well with the idea of a multi-scale construction related to flavor hierarchies:



Effective organizing principle for the flavor strucutre of the SMEFT

Model-building considerations

Which (tree-level) mediators can generate the effective operators required for by the EFT fit? Not many possibilities...

- ✔ We do observe "large" NP effects in semileptonic operators → ***Leptoquarks***

- ✖ What we do not see is in NP in (→ *additional loop suppression*):
  - Four-quarks ($\Delta F=2$)
  - Four-leptons ($\tau \to \mu\nu\nu$)

▶ *Model-building considerations*

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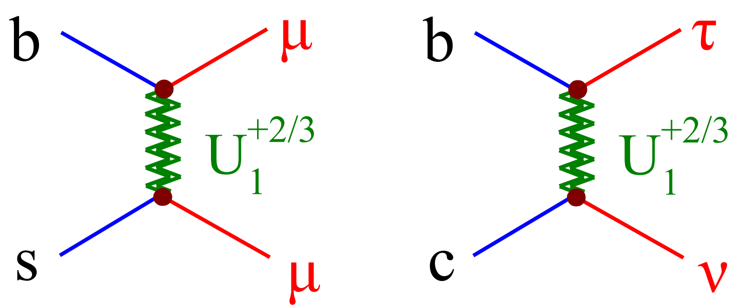
  - Four-leptons ($\tau \to \mu\nu\nu$)

Among the (few) LQ options, there is one outstanding case:



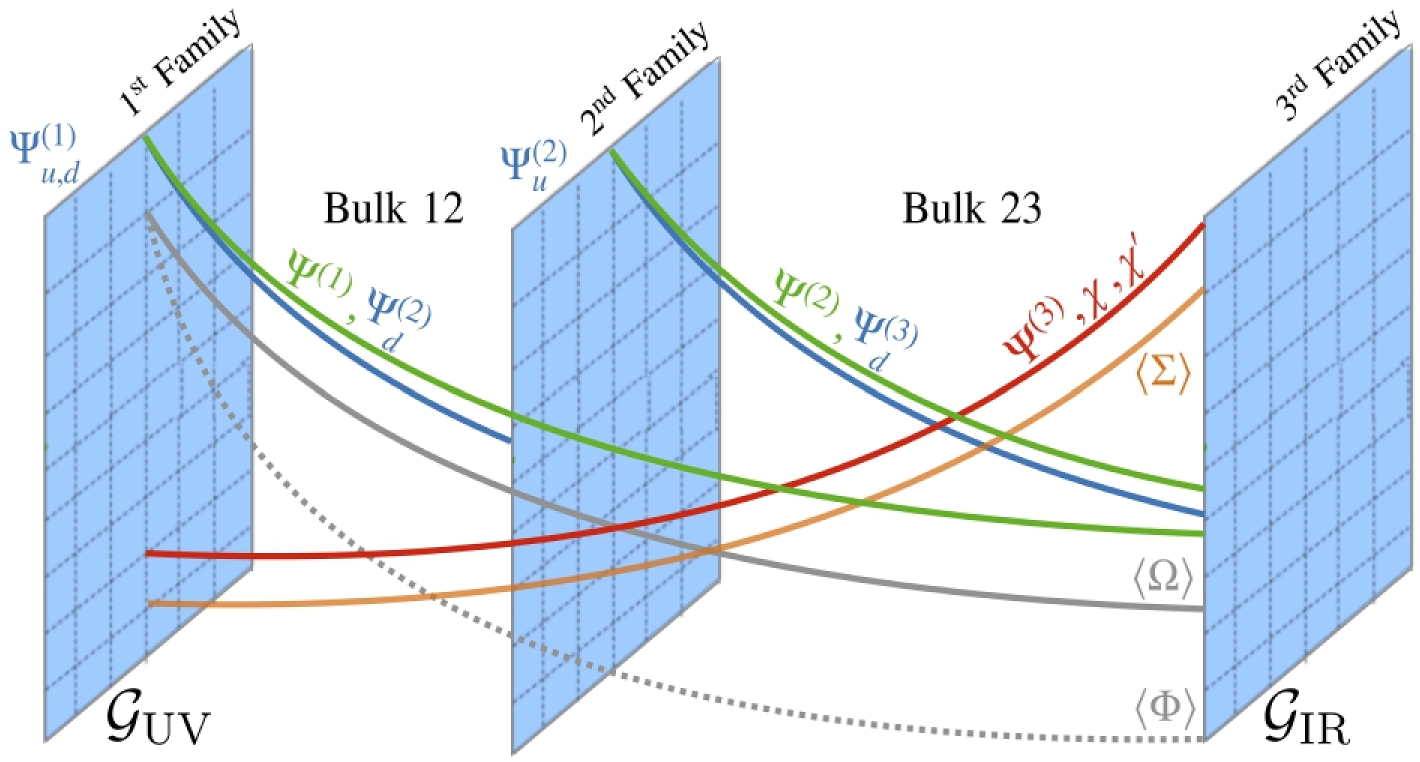
- mediator: U_1
- flavor structure: $U(2)^n$
- UV completion: SU(4)

Barbieri, GI, Pattori, Senia '15

We identified this path back in 2015, as a motivated simplified model...

...after 7 years, this is one of the very few options still in place for combined explanations & we understood much better its possible UV completion

UV completions: 4321 & beyond



UV completions: 4321 & beyond

First observation: the Pati & Salam group, proposed in the 70's to unify quarks & leptons predicts the massive LQ that is a good mediator for both anomalies:

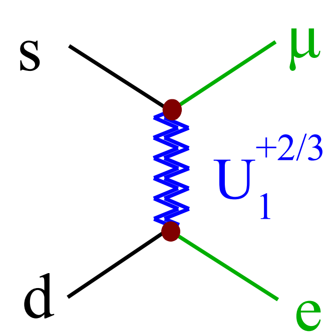
Pati-Salam group: $SU(4)\times SU(2)_L\times SU(2)_R$

Fermions in SU(4): $\begin{bmatrix} Q_L^{\alpha} \\ Q_L^{\beta} \\ Q_L^{\gamma} \\ L_L \end{bmatrix} \quad \begin{bmatrix} Q_R^{\alpha} \\ Q_R^{\beta} \\ Q_R^{\gamma} \\ L_R \end{bmatrix}$

Main Pati-Salam idea:
Lepton number as "the 4th color"

The massive LQ [U_1] arise from the breaking $SU(4) \to SU(3)_C\times U(1)_{B-L}$

The problem of the original Pati Salam model are the strong bounds on the LQ couplings to 1st & 2nd generations [e.g. $M > 200$ TeV from $K_L \to \mu e$]



Attempts to solve this problem simply adding extra fermions or scalars

Calibbi, Crivellin, Li, '17;
Fornal, Gadam, Grinstein, '18
Heeck, Teresi, '18

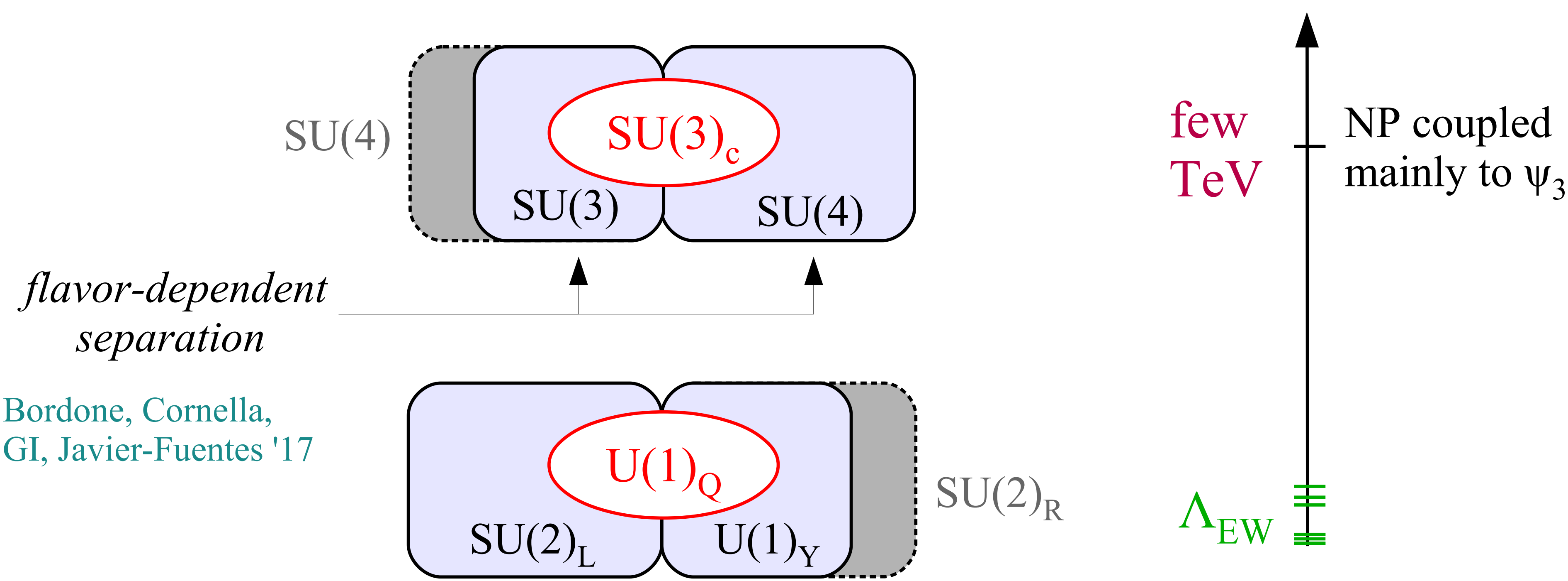
UV completions: 4321 & beyond

Second observation: we can "protect" the light families charging under SU(4) only the 3rd gen. or, more generally, "separating" the universal SU(3) component

PS group: $SU(4) \times SU(2)_L \times SU(2)_R$ • *flavor universality*

4321 models: $SU(4) \times SU(3) \times G_{EW} = \begin{cases} SU(2)_L \times SU(2)_R \\ SU(2)_L \times U(1)_Y \end{cases}$

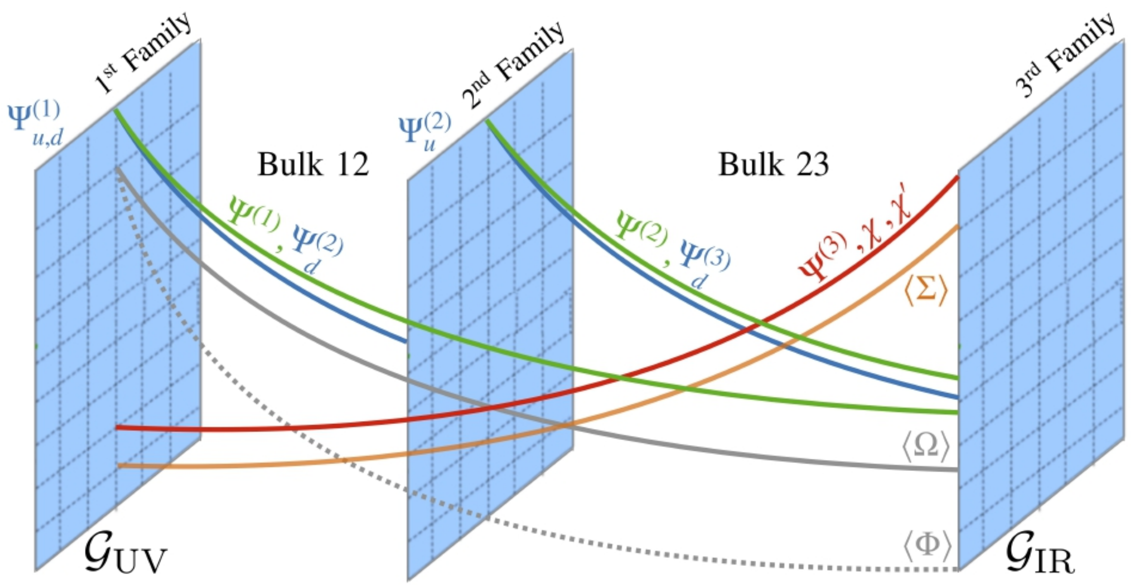
Di Luzio, Greljo, Nardecchia, '17



Bordone, Cornella, GI, Javier-Fuentes '17

UV completions: 4321 & beyond

An ambitious attempt to construct a *full theory of flavor* has been obtained embedding (a variation of the) Pati-Salam gauge group into an extra-dimensional construction:



Flavor ↔ special position (*topological defect*) in an extra (compact) space-like dimension

Dvali & Shifman, '00

Higgs and SU(4)-breaking fields with oppositely-peaked profiles, leading to the desired flavor pattern for masses & anomalies

Bordone, Cornella, GI, Javier-Fuentes '17

- Anarchic neutrino masses via inverse see-saw mechanism — Fuentes-Martin, GI, Pages, Stefanek '22
- "Holographic" Higgs from appropriate choice of bulk/brane gauge symm.
  [$G_{\text{bulk-23}} = SU(4)_3 \times SU(3)_{1,2} \times U(1) \times SO(5)$ $G_{IR} = SU(3)_c \times U(1)_{B-L} \times SO(4)$]

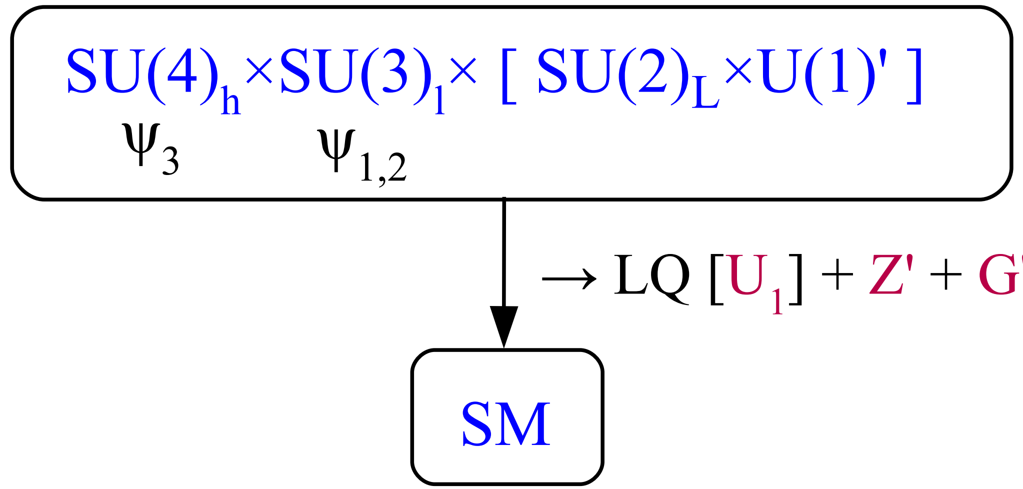
Fuentes-Martin, Stangl '20
Fuentes-Martin, GI, Lizana, Selimovic, Stefanek '22

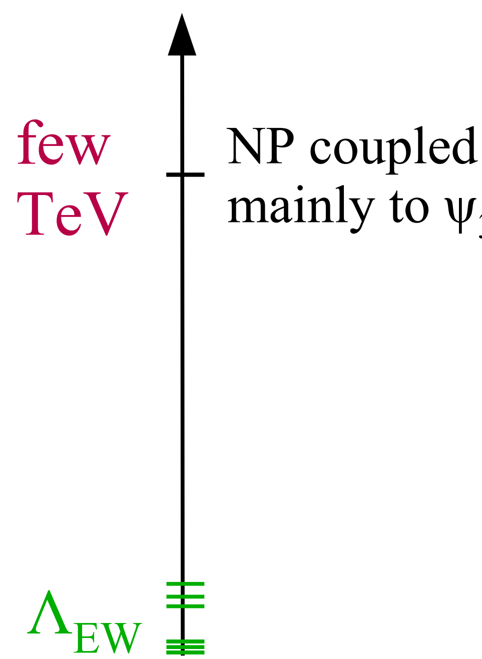
→ Light Higgs as pseudo Goldstone

Agashe, Contino, Pomarol '05

UV completions: 4321 & beyond

Even in ambitious UV completions, collider and low-energy pheno are controlled by the 4321 gauge group that rules TeV-scale dynamics
→ new heavy mediators [G' & Z']





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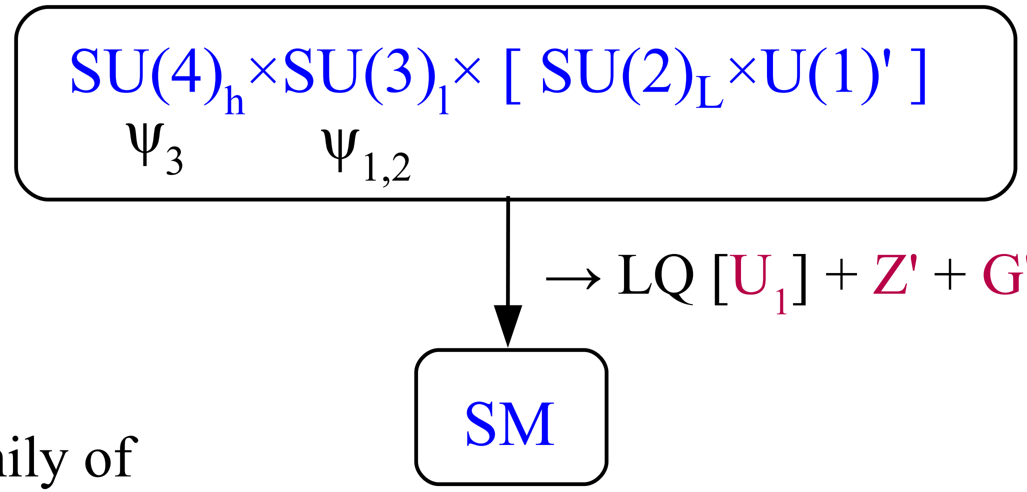
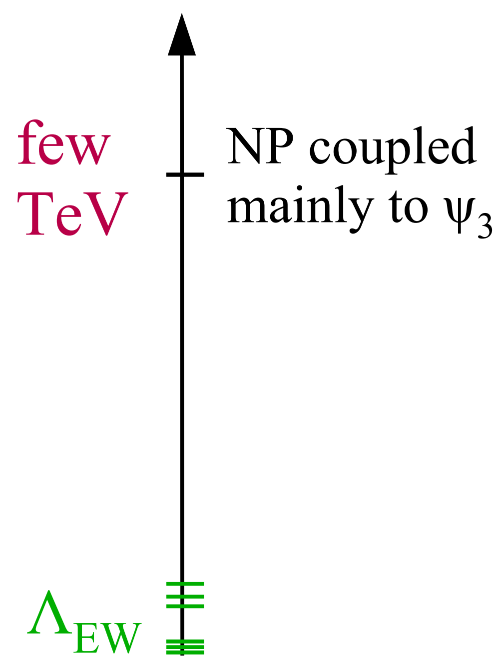


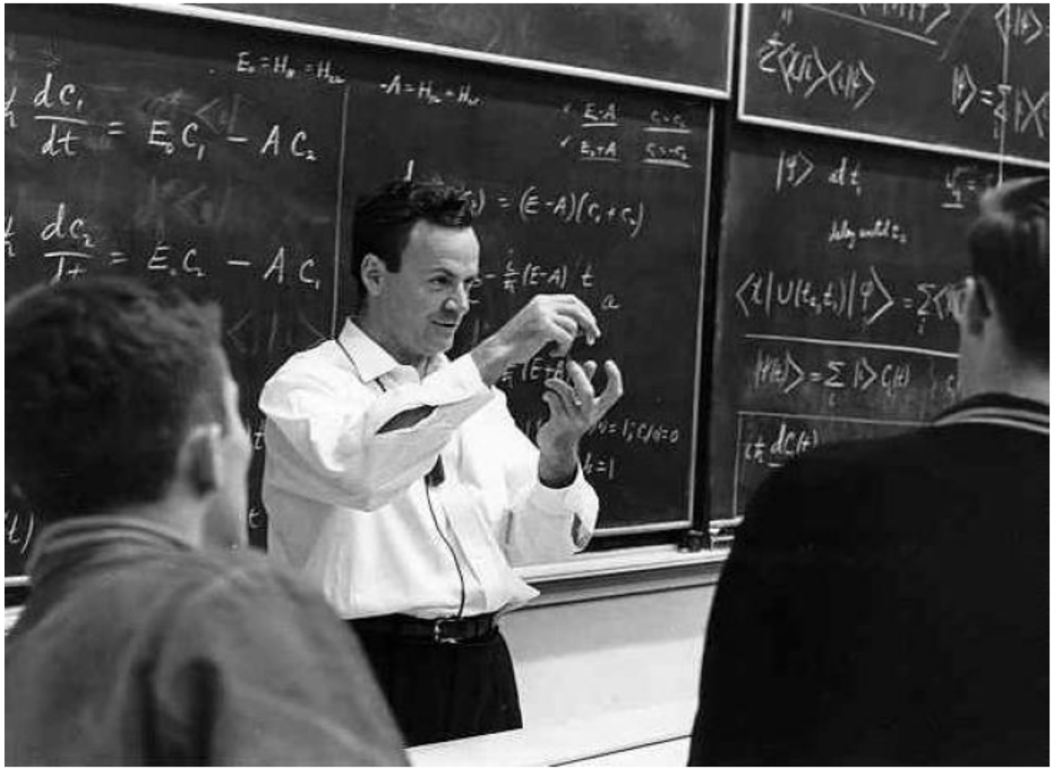
A key role is played by at least one family of
→ vector-like fermions (= fermions with both chiralities having same gauge quantum numbers) that mix with mainly with the 3rd gen. of (SM-like) chiral fermions

⬇

- Positive features the EFT reproduced
- Calculability of ΔF=2 processes
- Precise (non-trivial) predictions for high-energy physics



Implications @ low- & high-energies



"It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong." [Feynman]

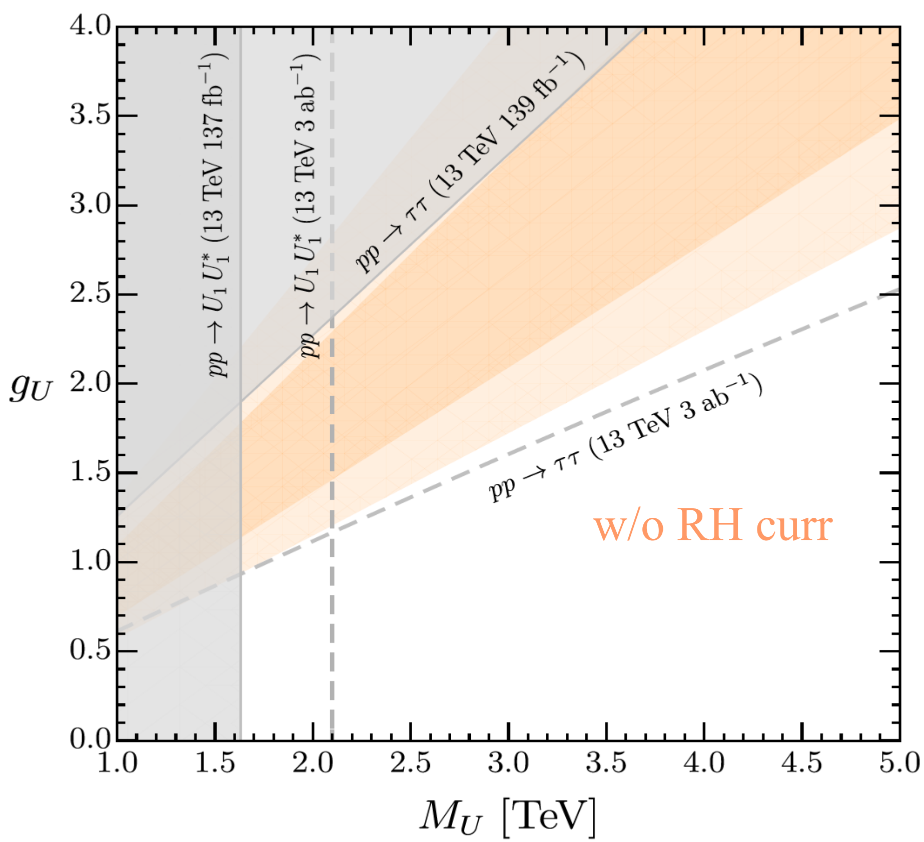
Implications @ low- & high energies

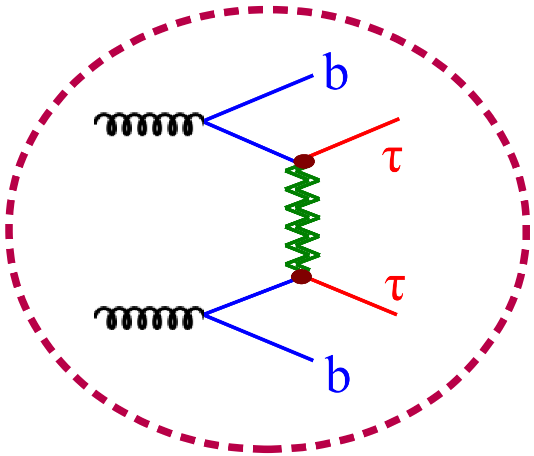
I General predictions of U_1 exchange @ high-energies

[Very general, directly connected to the EFT analysis]

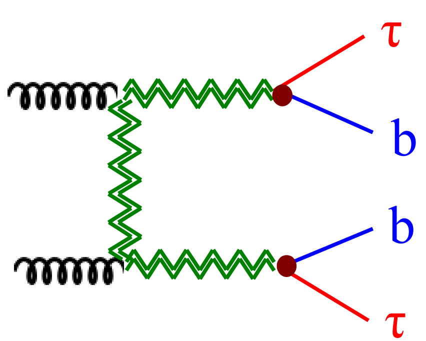
$pp \to \tau\tau$

Cornella, Fuentes-Martin, Faroughi, GI, Neubert, '21





Faroughi, Greljo, Kamenik '16



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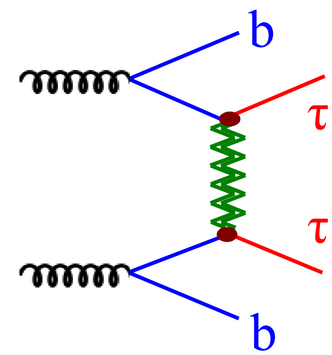
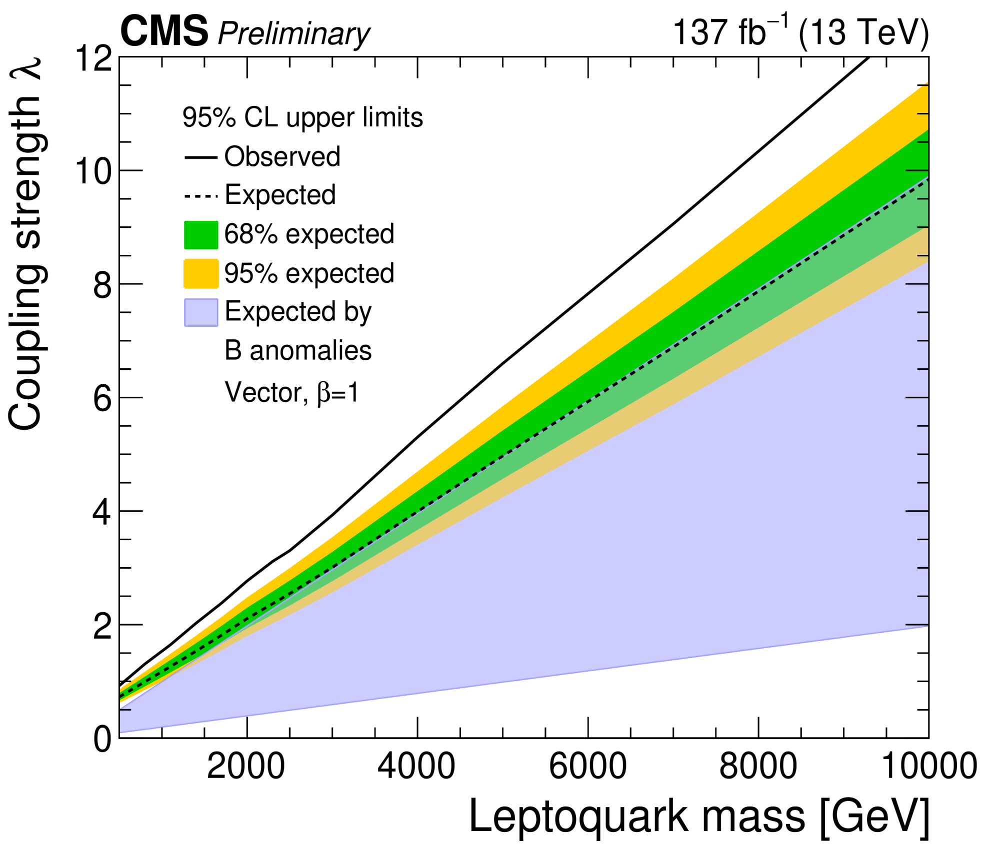
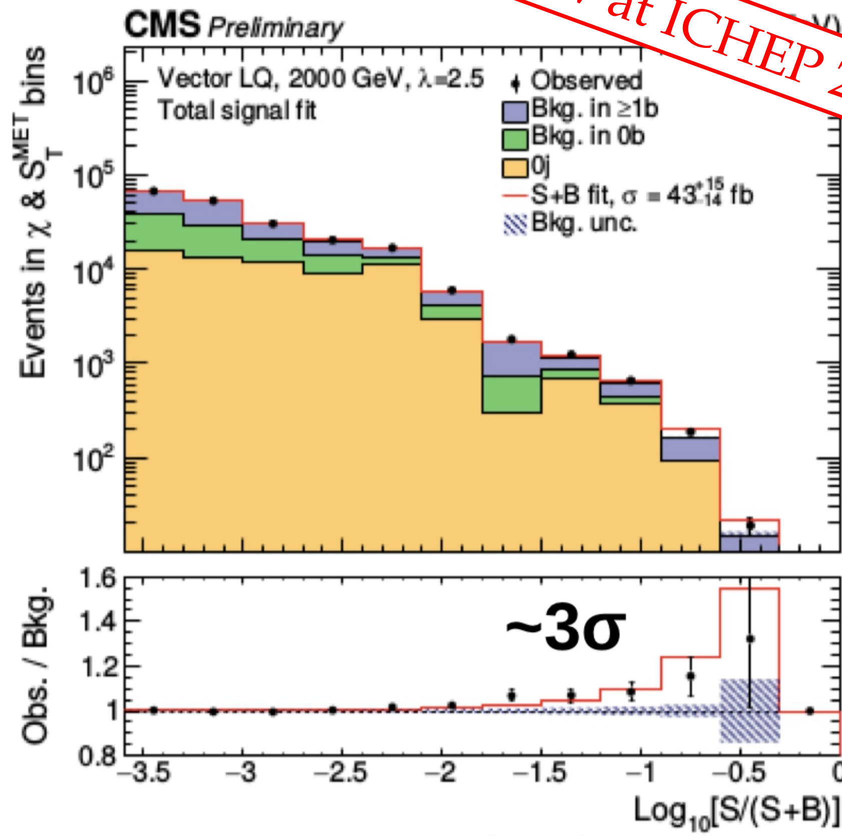


pp → ττ



New at ICHEP 2022

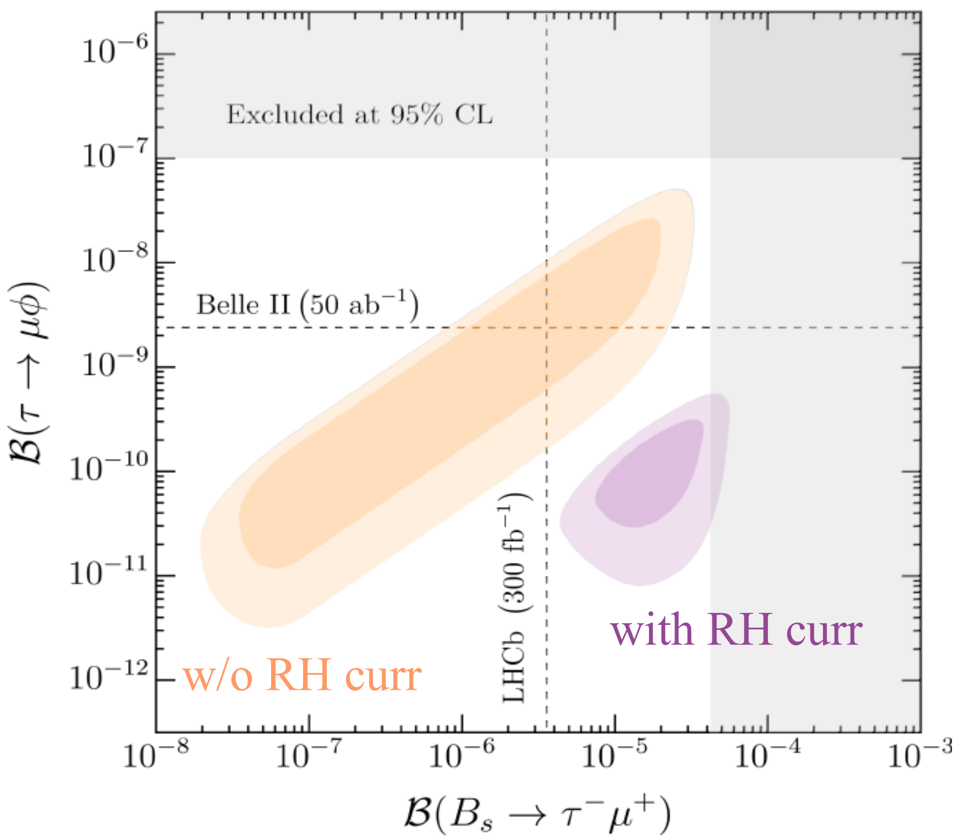


▶ Implications @ low- & high energies

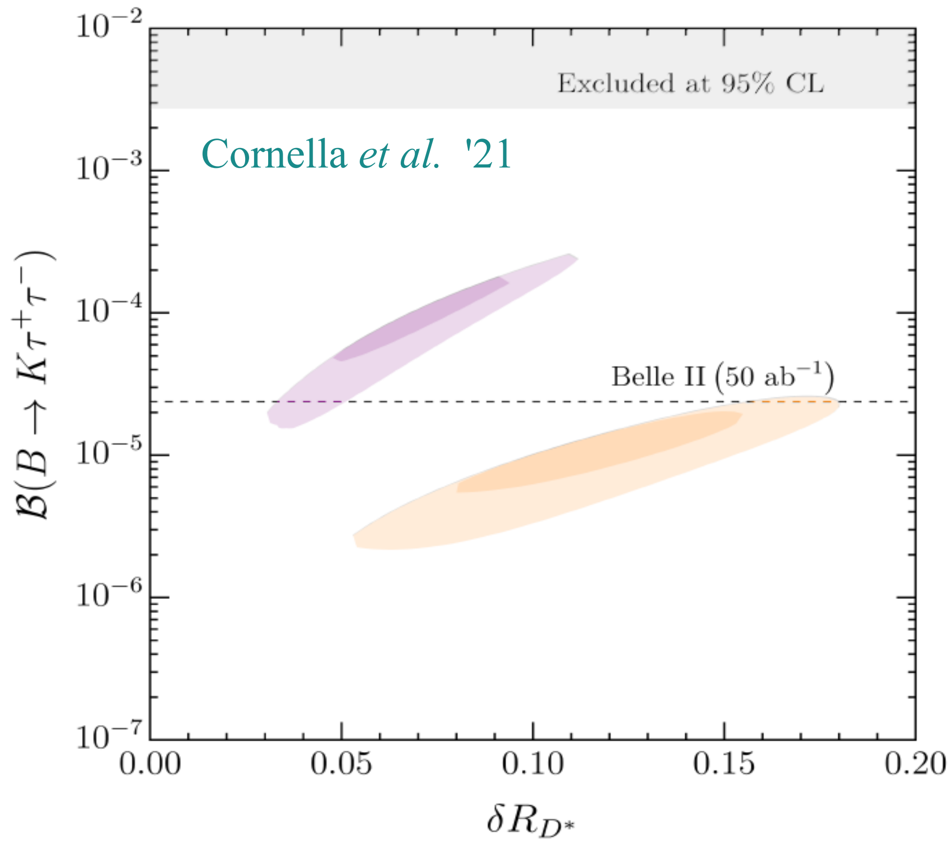
II General predictions of U_1 exchange @ low-energies

[UV insensitive observables, closely connected to the EFT analysis]

$\tau \to \mu$ LFV
(in B and tau decays)



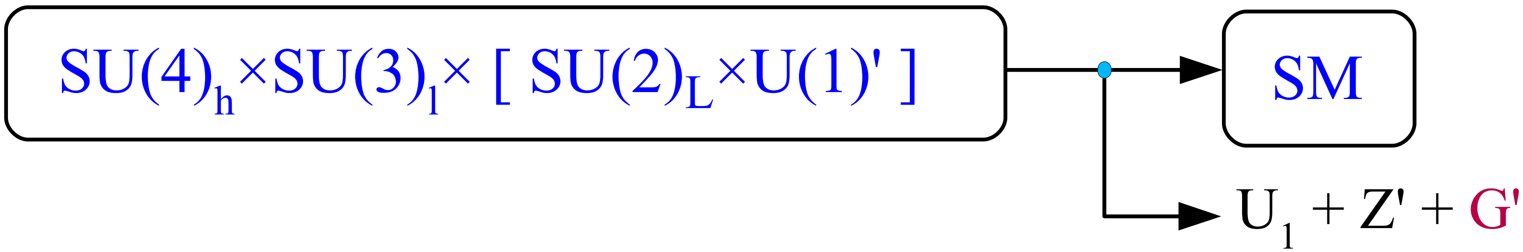
largely enhanced $b \to s\tau\tau$ rates
(in all channels)



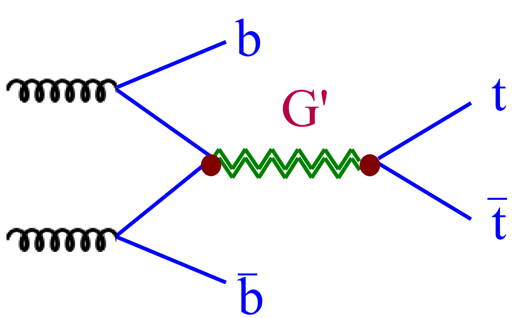
▶ Implications @ low- & high energies

III General predictions of 4321 models @ high-energies

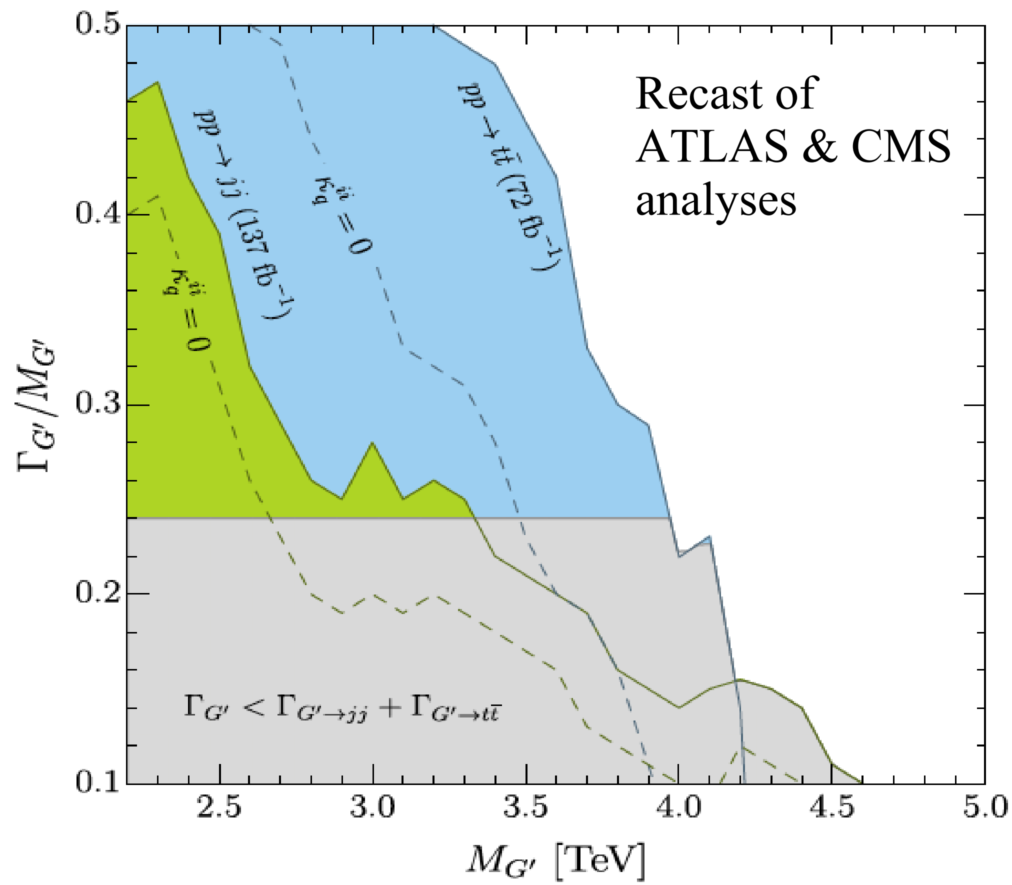
[More model dependent, not directly connected to the EFT analysis]



New striking collider signature:
G' ("*coloron*") = heavy color octet, coupled mainly to 3[rd] generation quarks

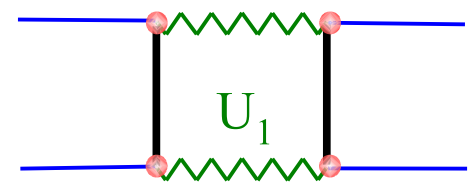


→ strongest constraint on the scale of the model from pp → $t\,\bar{t}$

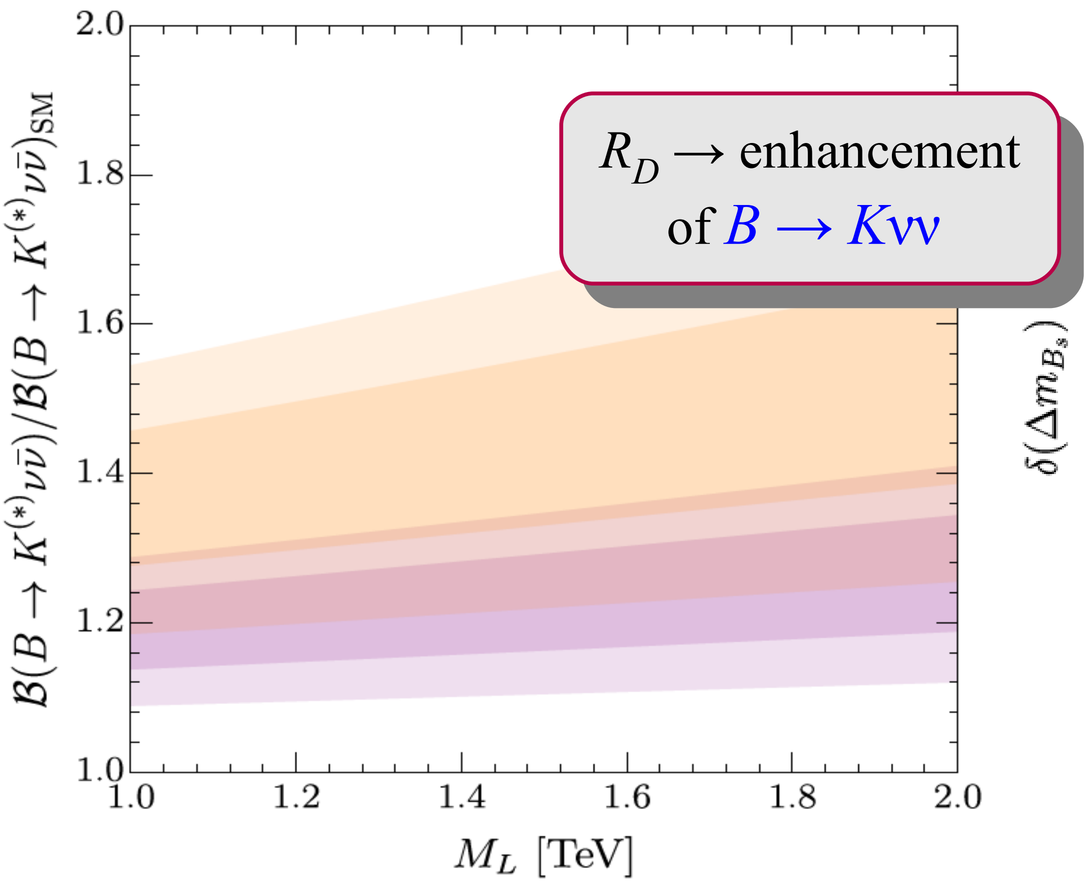


▶ *Implications @ low- & high energies*

IV Specific predictions of 4321 @ low-energies
[UV sensitive low-energy observables]

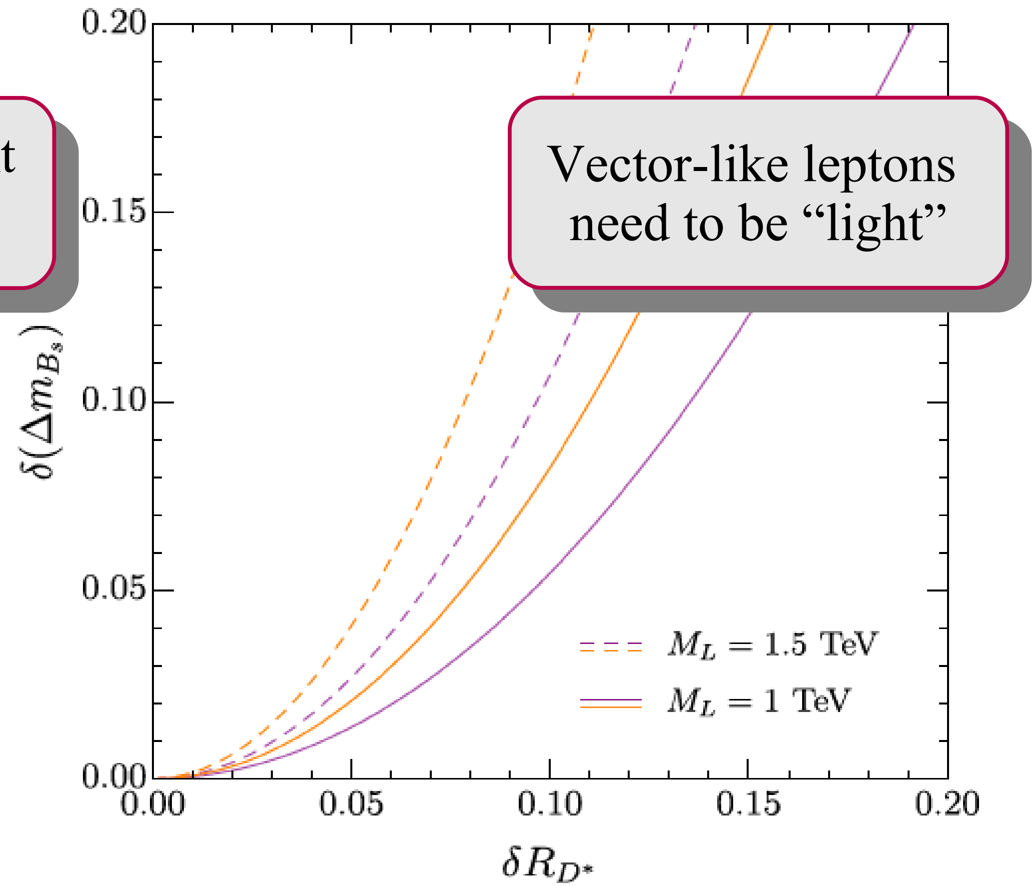


A) $B \to K\nu\nu$



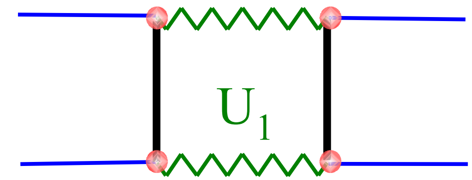
Fuentes-Martin, GI, Konig, Selimovic, '20
Cornella *et al.* '21

B) B_s mixing [ΔF=2]



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

Implications @ low- & high energies



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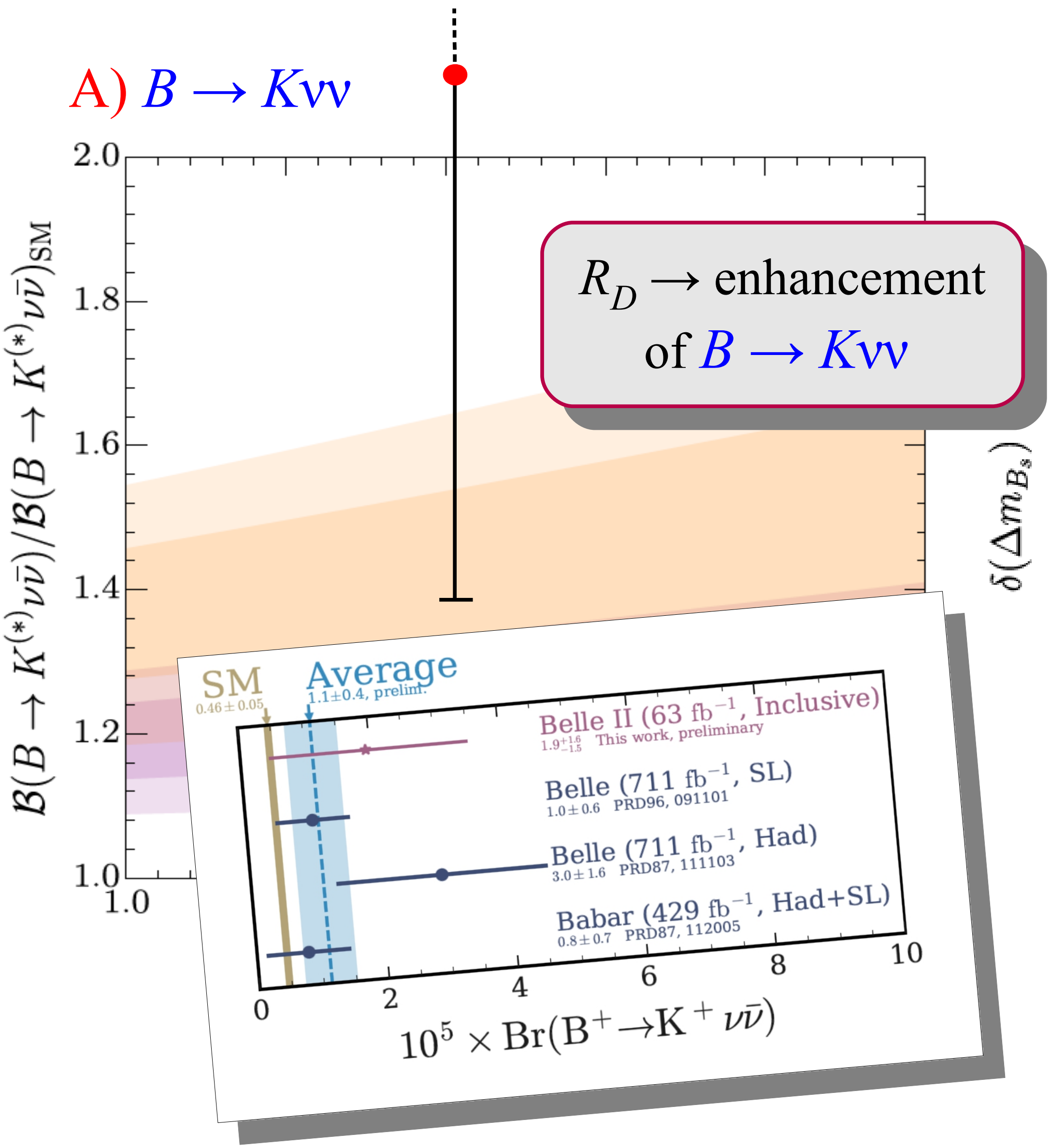

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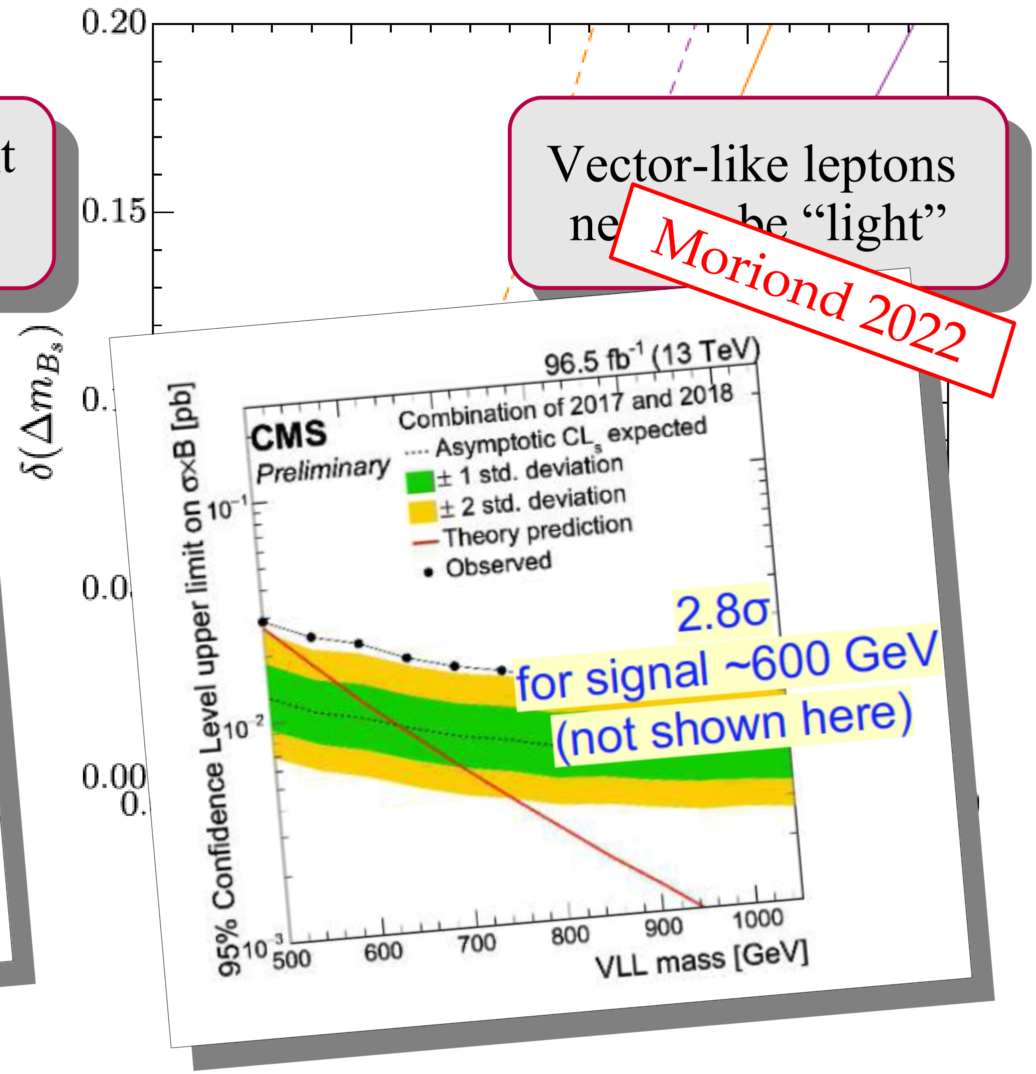


Conclusions

- The nice *picture* that emerged in 2015 of connecting the two sets of anomalies with the origin of the SM flavor hierarchies, and quark-lepton unification is still valid, and has become possibly more appealing...

- A new (theoretical) ingredient that emerged in the last few years is the possibility of connecting this picture also to a solution of the EW hierarchy problem: non-trivial flavor dynamics around the TeV scale, involving mainly the 3rd family + multi-scale picture at the origin of flavor hierarchies

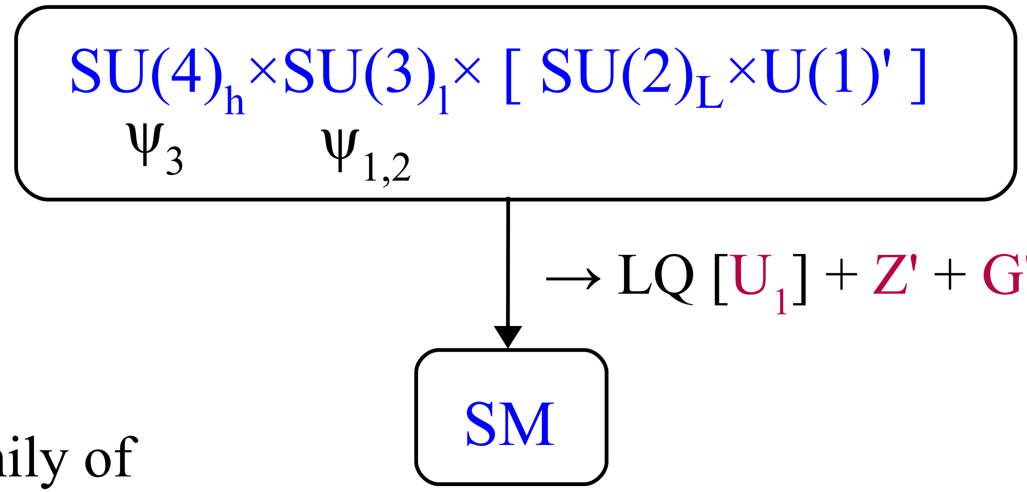
- No contradiction with existing low- & high-energy data, but new non-standard effects should emerge soon in both these areas (→ very interesting opportunities for the HL phase of the LHC).

- Important to intensify near-term experimental efforts to clarify the origin of this phenomenon (both at low & high energies) in view of future planning

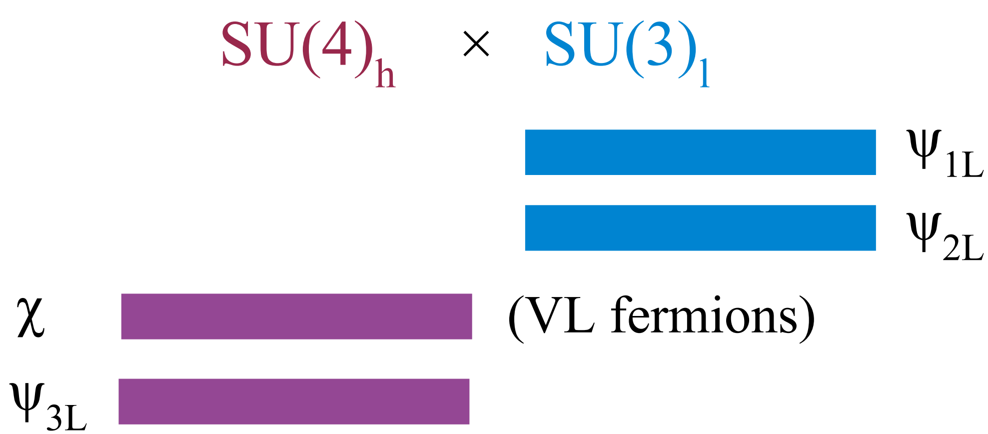

Backup

The role of vector-like fermions

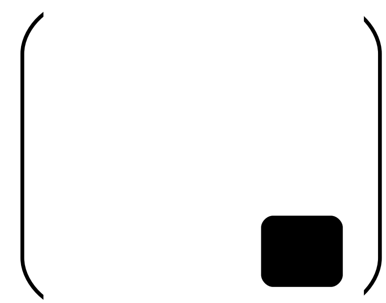
Even in ambitious UV completions, collider and low-energy pheno are controlled by the 4321 gauge group that rules TeV-scale dynamics
→ new heavy mediators [G' & Z']



A key role is played by at least one family of *vector-like fermions* (= fermions with both chiralities having same gauge quantum numbers) that mix with the 3 families of chiral fermions



SM Yukawa coupling → $Y \sim$



LQ eff. coupling → $\beta_L \sim$

$$\mathcal{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[\beta^L_{i\alpha} (\bar{q}^i_L \gamma_\mu \ell^\alpha_L) - \beta^R_{i\alpha} (\bar{d}^i_R \gamma_\mu e^\alpha_R) \right] + \text{h.c.}$$

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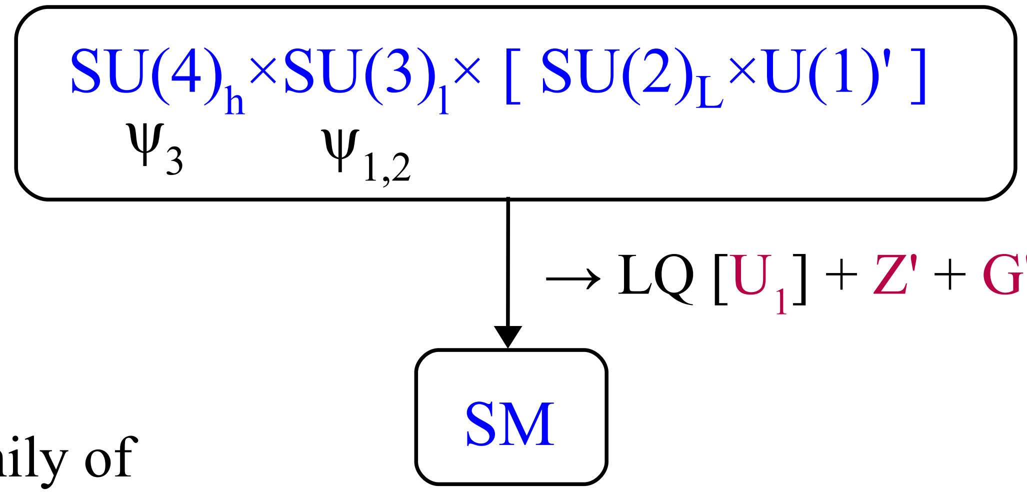

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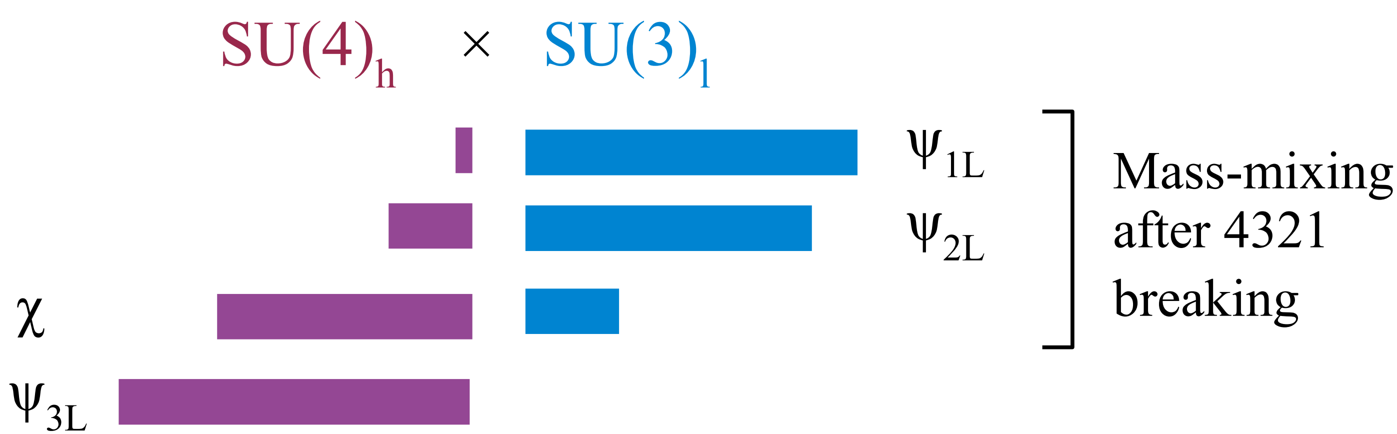

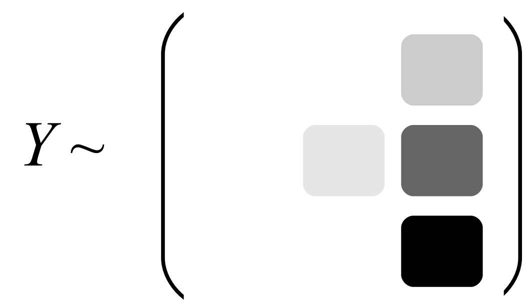

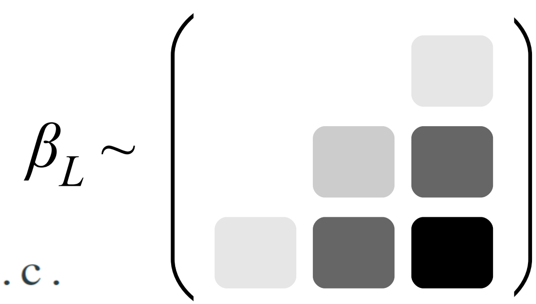

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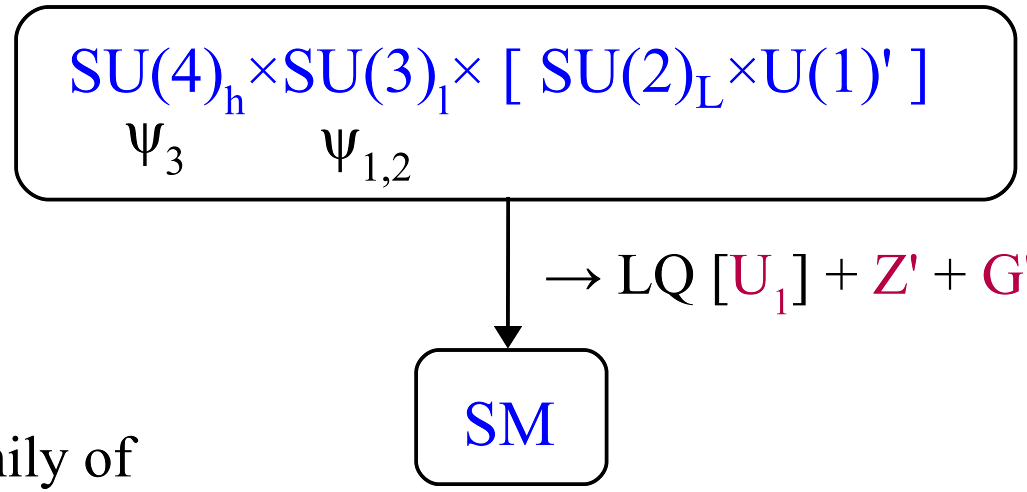

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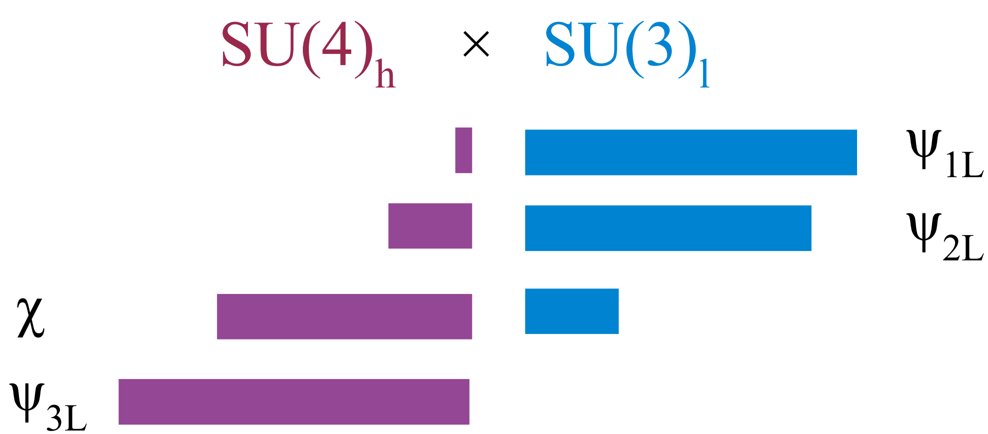
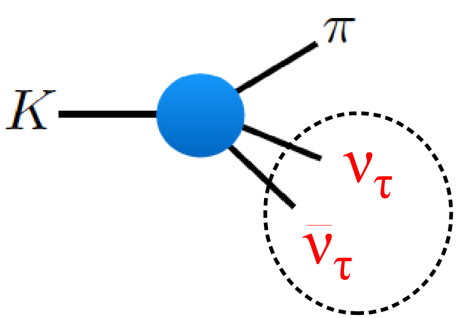


- Positive features the EFT reproduced
- Calculability of $\Delta F=2$ processes
- Precise predictions for high-pT data

} *consistent with present data*

Implications @ low- & high energies

V Last but not least: Kaon Physics



direct access to 3rd gen. leptons
as in R(D) & R(D*)

$$\Gamma(K \to \pi\nu\nu) = \Gamma(K \to \pi\nu_e\bar{\nu}_e) + \Gamma(K \to \pi\nu_\mu\bar{\nu}_\mu) + \Gamma(K \to \pi\nu_\tau\bar{\nu}_\tau)$$

SM like

few % deviation as in $b \to s\mu\mu$

O(1) deviation from SM expected in models addressing B anomalies

Bordone, Buttazzo, GI, Monnard '16
Marzocca, Trifinopulos, Venturini '21

Implications @ low- & high energies

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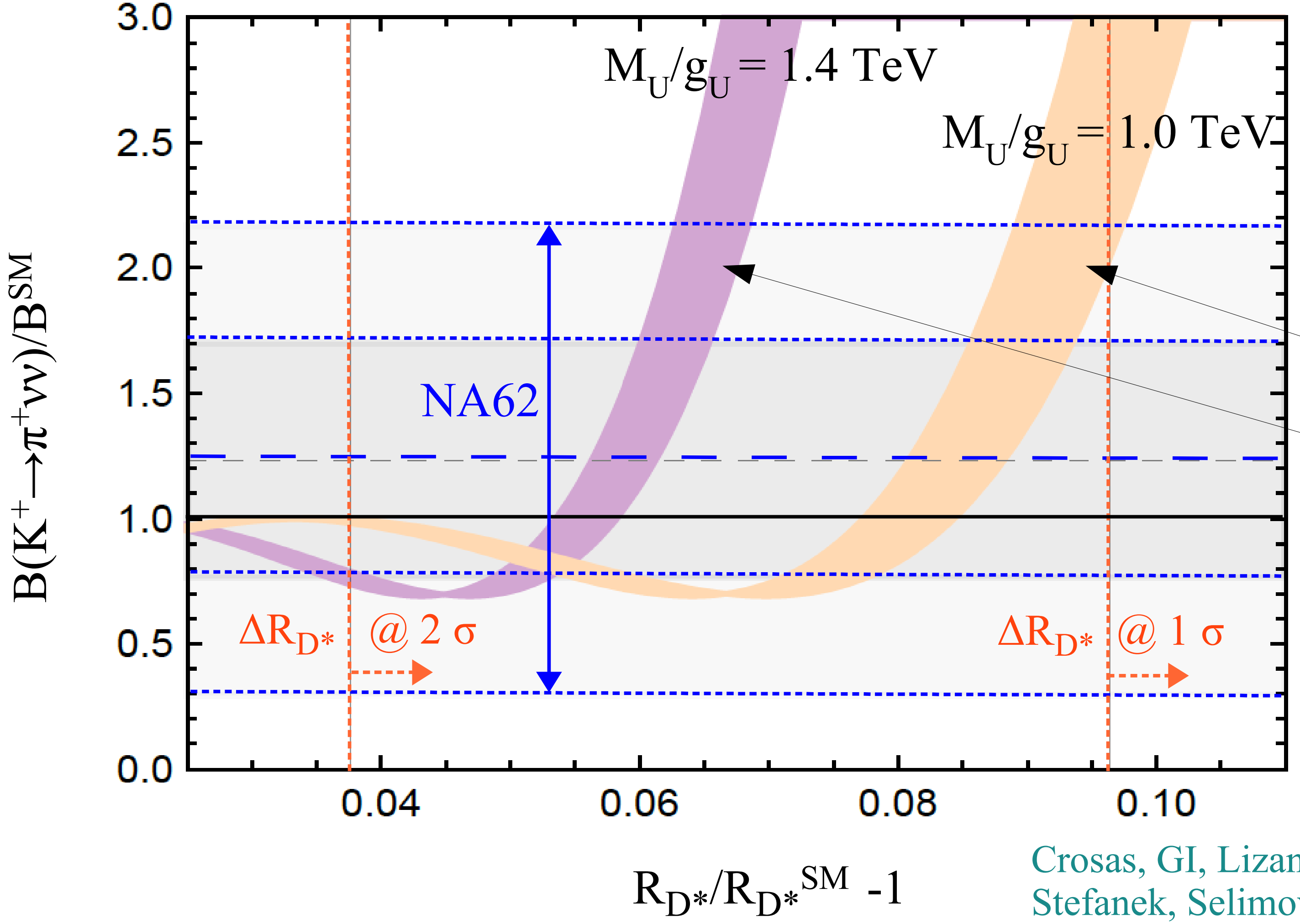

Correlations depending on high-energy parameters (LQ mass & coupling)

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

Implications @ low- & high energies

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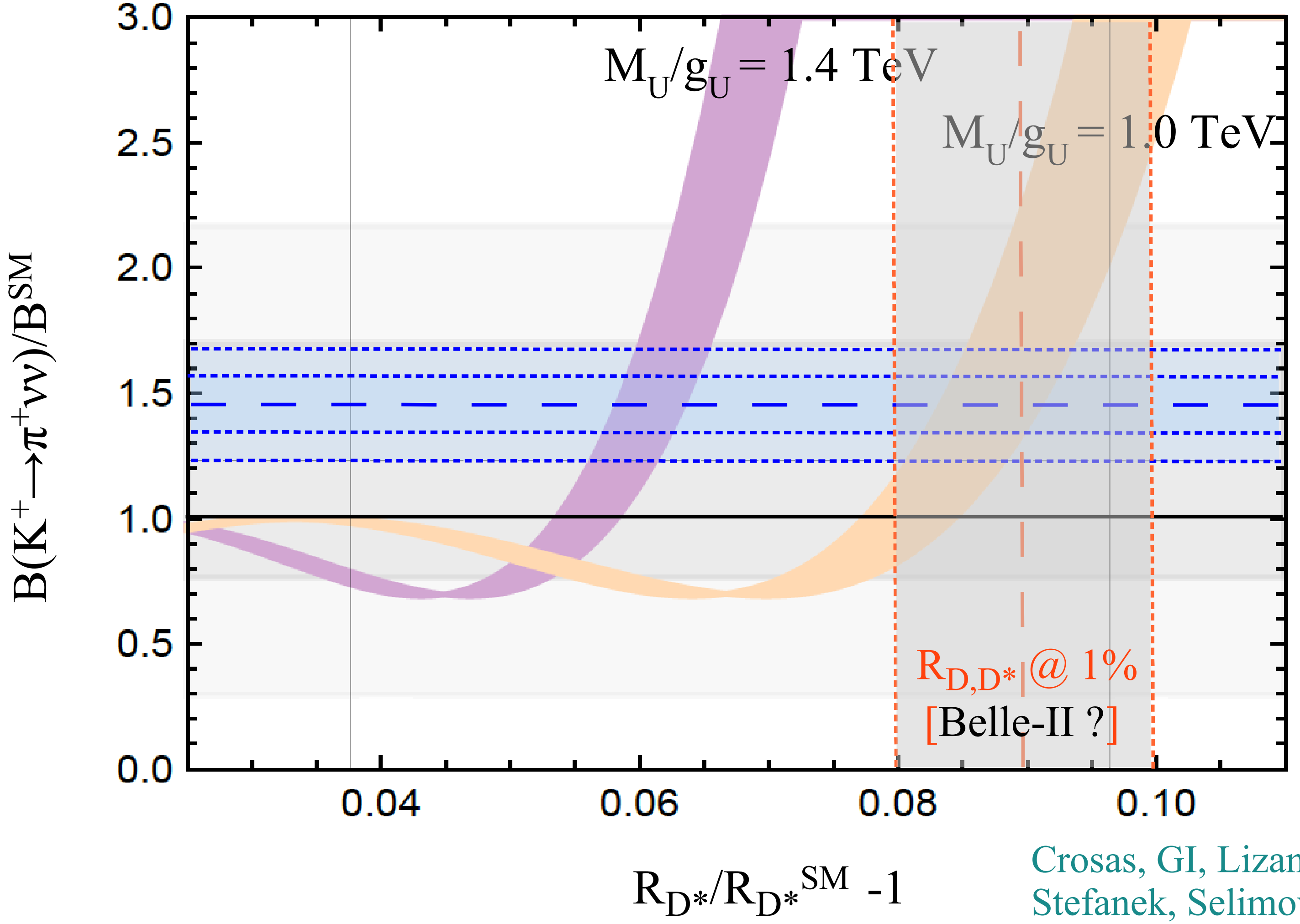

Possible impact of future measurements:

$B(K^+ \to \pi^+ \nu\nu)/B^{SM}$ @ 8%
[CERN ?]

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