Toward UV complete models

[addressing the B-physics anomalies]

Gino Isidori
[*University of Zürich*]

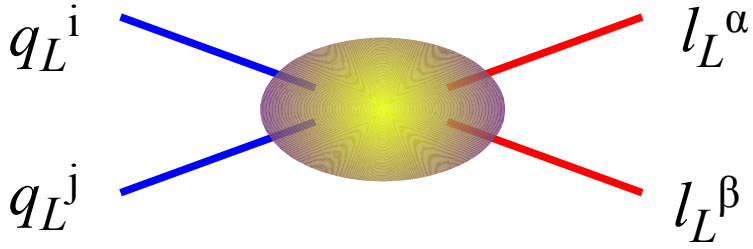
- General EFT considerations
- General model-building considerations
- UV completions: 4321 and beyond
- Predictions @ low- & high-energies
- Conclusions

University of Zurich[UZH]

European Research Council
Established by the European Commission

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 $b(3^{rd})$ $c(2^{nd})$ → $\tau(3^{rd})$ $\nu_\tau(3^{rd})$
- Small coupl. [*compete with SM loop-level*] in $b(3^{rd})$ $s(2^{nd})$ → $\mu(2^{rd})$ $\mu(2^{rd})$

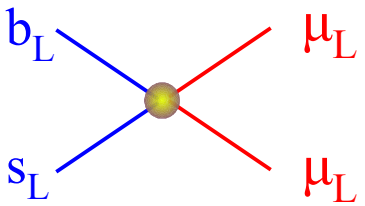
$$C_{ij\alpha\beta} = \begin{array}{c}\text{large for}\\ 3^{rd}\text{ generation}\\ \text{fields}\end{array} + \begin{array}{c}\text{small terms}\\ \text{for } 2^{nd}\ (\&\ 1^{st})\\ \text{generations}\end{array} \rightarrow$$

Link to pattern of the Yukawa couplings !

General EFT considerations

Data point to (short-distance) NP effects in operators of the type

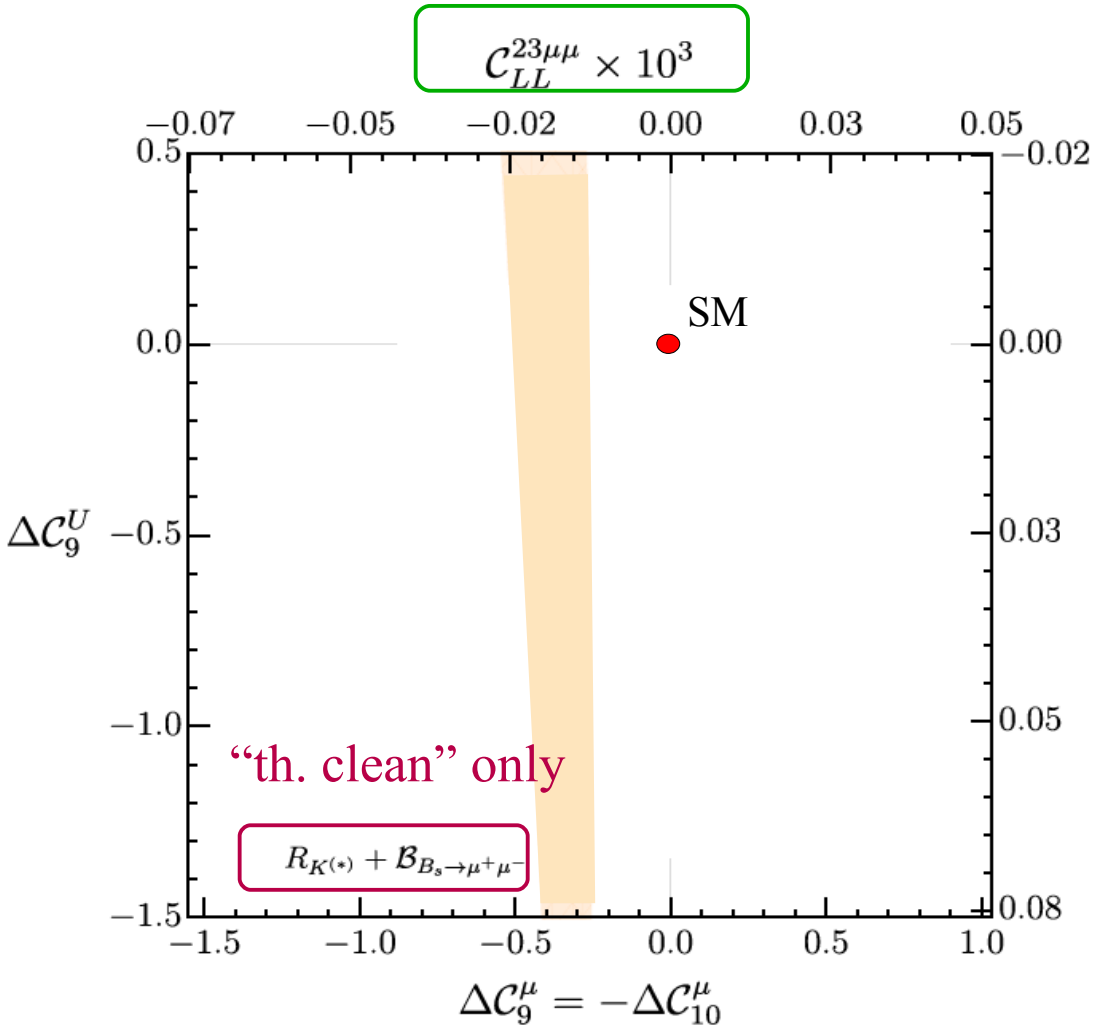
$$\mathcal{O}_{LL}^{ij\alpha\beta} = (\bar{q}_L^i \gamma_\mu \ell_L^\alpha)(\bar{\ell}_L^\beta \gamma_\mu q_L^j)$$



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

super-weak interaction!

$C_{LL}^{23\mu\mu} \rightarrow \Delta C_9^\mu = -\Delta C_{10}^\mu$



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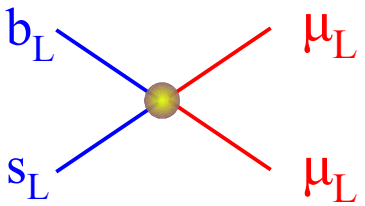
- $O(10^{-1})$ suppress. for each 2nd gen. l_L



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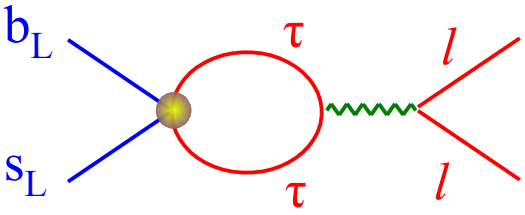
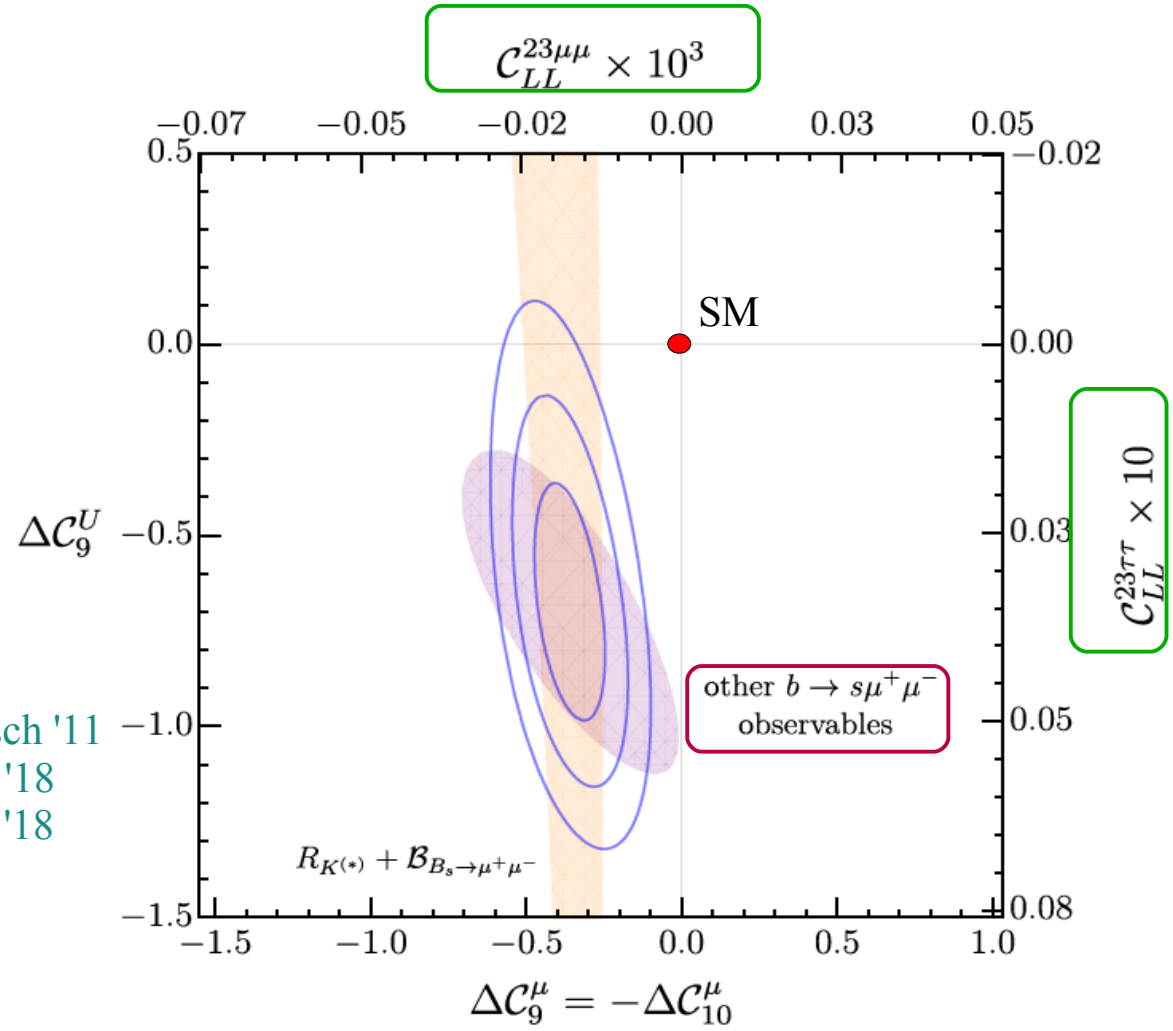


$C_{LL}^{23\tau\tau} \rightarrow \Delta C_9^{\text{Univ}}$

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



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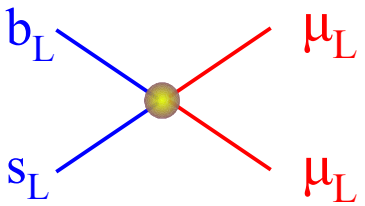

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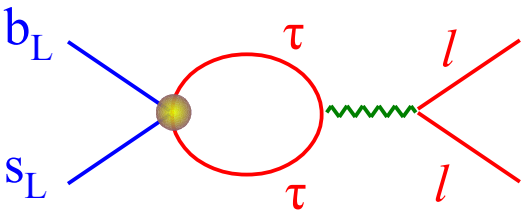

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Link to CC anomaly

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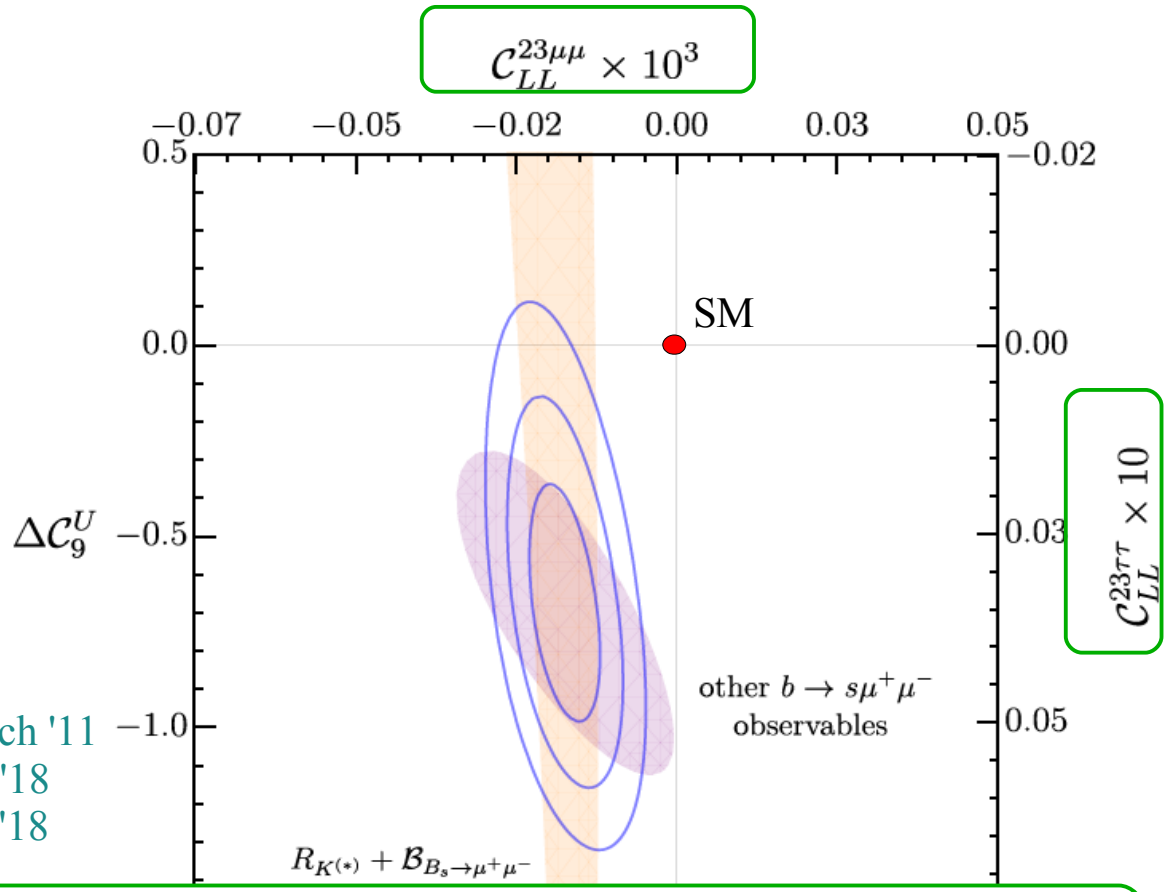

Size (and need) of $C^{23\tau\tau}$ pre-dicted from CC before this effect was observed in NC

Greljo *et al.* '17

General EFT considerations

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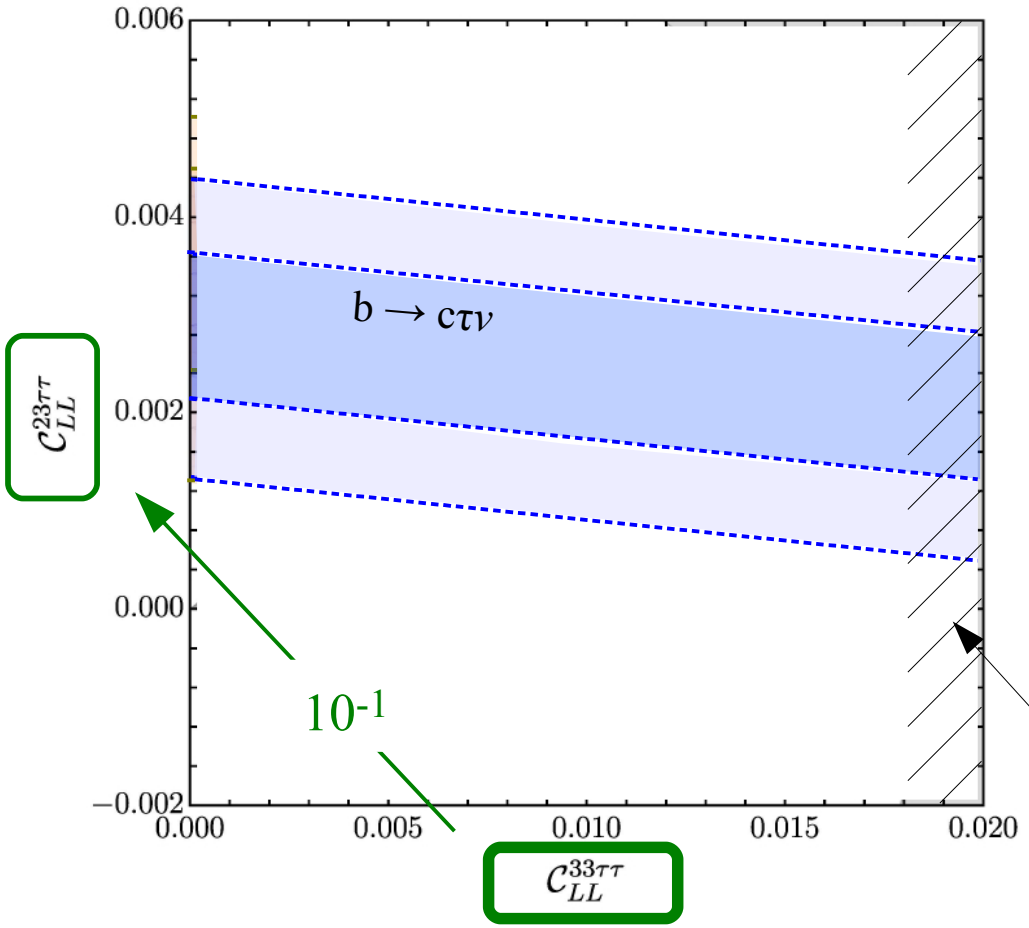
- $O(10^{-1})$ suppress. for each 2nd gen. q_L or l_L

We have chosen down-type quarks as flavor basis

charged-currents:

$$\frac{V_{cb}\,\mathcal{C}_{LL}^{33\tau\tau} + V_{cs}\,\mathcal{C}_{LL}^{23\tau\tau}}{V_{cb}}$$

CKM rotation to get the charm



bounds from high-pT searches

General EFT considerations

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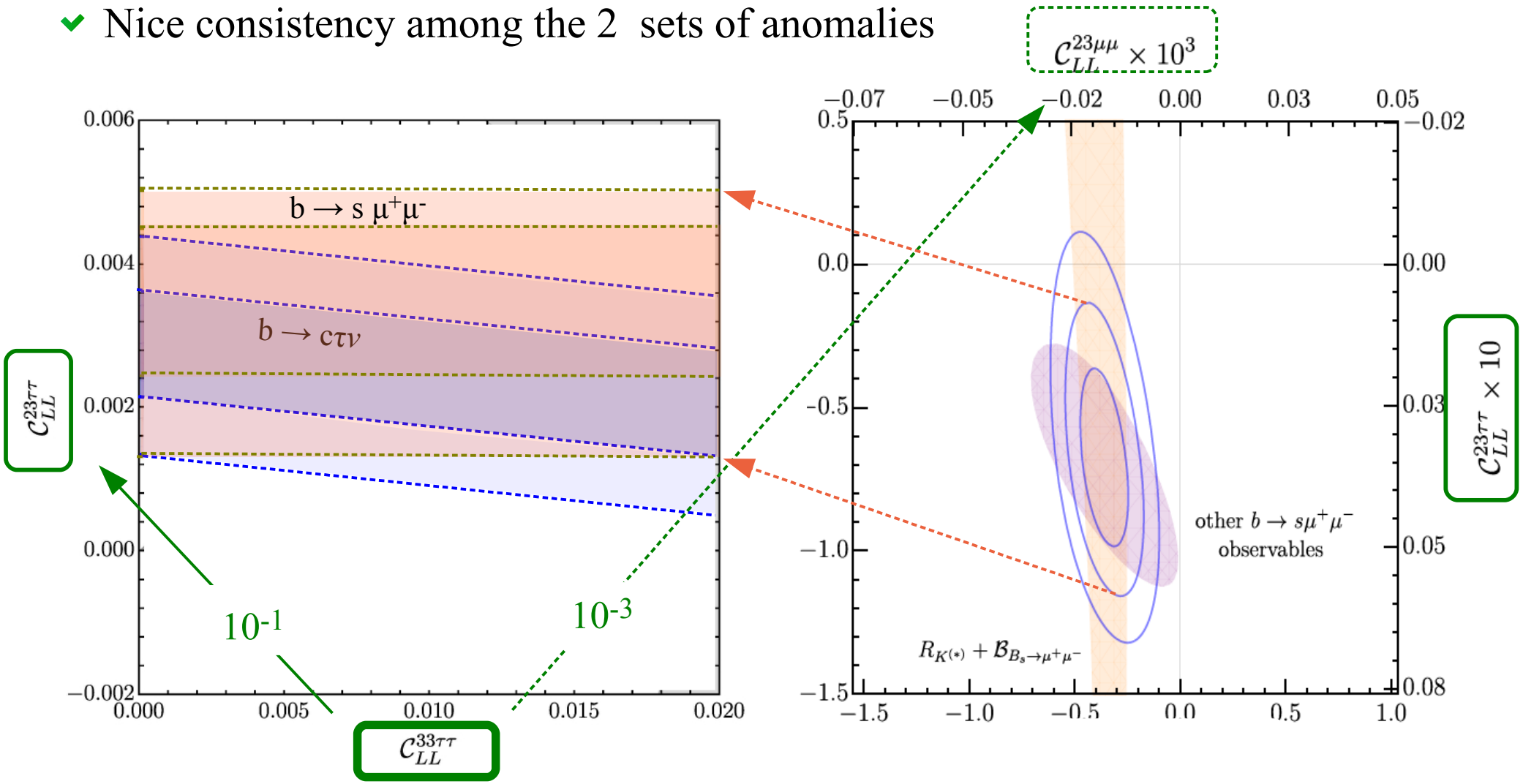
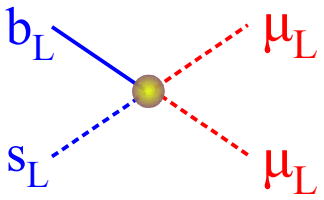
- Nice consistency among the 2 sets of anomalies



General EFT considerations

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

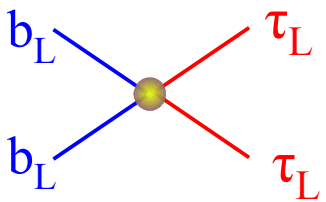


~~LFU~~ in $b \to s\, l^+ l^-$ [R_K, ...] $> 4\,\sigma$

"*natural*" flavor connection (*main theoretical hypothesis*)

LFU in $b \to c\, l\nu$ [R_D, ...]

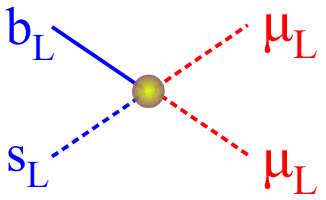
$\frac{1}{\Lambda^2}$



CKM rotation

$\Lambda \approx 1.5$ TeV

General EFT considerations

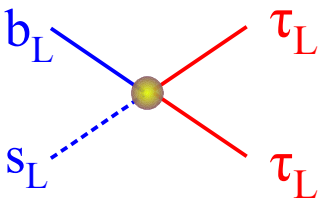
$\frac{10^{-3}}{\Lambda^2}$ 

→ ~~LFU~~ in $b \to s\, l^+ l^-$ [R_K, ...] **> 4 σ**

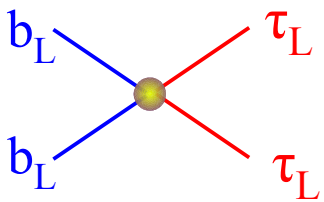
$\frac{10^{-2}}{\Lambda^2}$ [

] *not seen yet*

→ LFU conserv. NP in $b \to s\, l^+ l^-$ [ΔC_9^{Univ}] **~ 2 σ**

$\frac{10^{-1}}{\Lambda^2}$ 

γ-loop → LFU in $b \to c\, l\nu$ [R_D, ...] **3 σ**

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

CKM rotation → $pp \to \tau\tau$ [*not seen yet*]

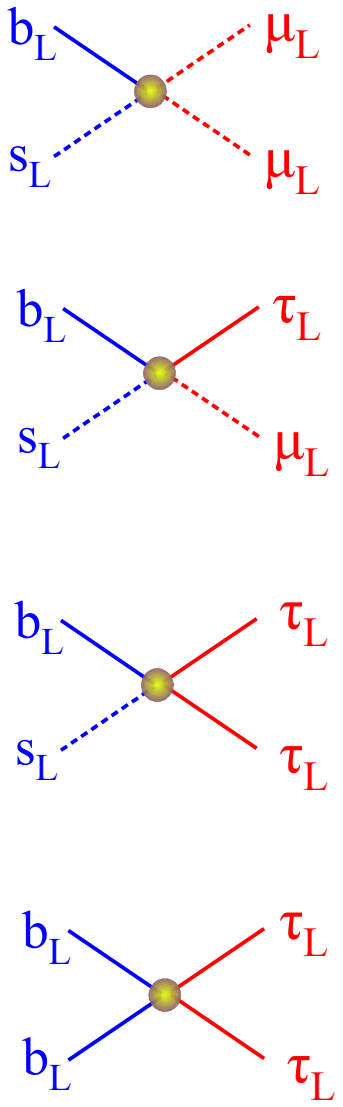
→ NP stabilizing the Higgs sector [*still a hope...*]

$\Lambda \approx 1.5$ TeV

General EFT considerations

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

$\frac{10^{-3}}{\Lambda^2}$ $\frac{10^{-2}}{\Lambda^2}$ $\frac{10^{-1}}{\Lambda^2}$ $\frac{1}{\Lambda^2}$ FLAVOR



not seen yet

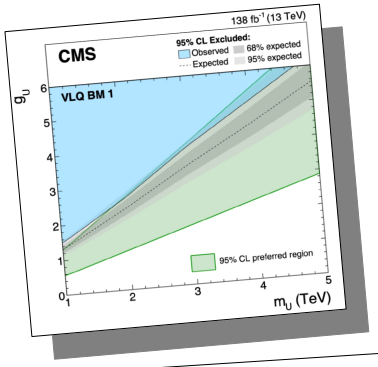
LFU in $b \to s\, l^+l^-$ [R_K, ...] — $> 4\,\sigma$

LFU conserv. NP in $b \to s\, l^+l^-$ [ΔC_9^{Univ}] — $\sim 2\,\sigma$

γ-loop

LFU in $b \to c\, l\nu$ [R_D, ...] — $3\,\sigma$

CKM rotation



$pp \to \tau\tau$ — $\sim 1\,\sigma$

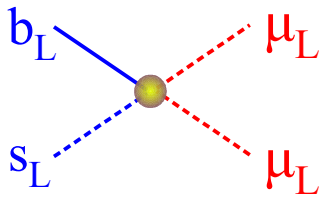
$\Lambda \approx 1.5$ TeV

NP stabilizing the Higgs sector

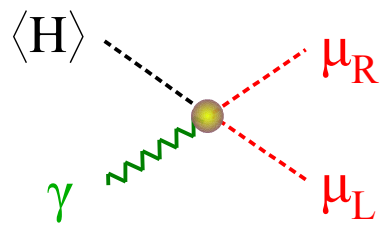
Higgs = pNGB of the new dynamics ($\leftrightarrow$ LQ mass)

General EFT considerations

A possible alternative story...

$|V_{ts}| \frac{1}{\Lambda^2}$ 

→ ~~LFU~~ in $b \to s\, l^+ l^-$ [R_K, ...] **> 4 σ**

$\frac{e}{16\pi^2} \frac{1}{\Lambda^2}$ 

→ $\Delta a_\mu = (a_\mu^{exp} - a_\mu^{SM})$ **~ 4 σ**

(*more controversial...*)

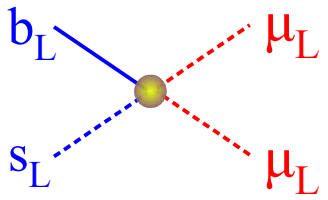
Ignoring the (less convincing) CC anomaly other paths are certainly possible...

$\Lambda \approx 10$ TeV

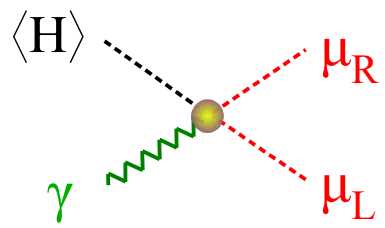
General EFT considerations

A possible alternative story...

$|V_{ts}| \frac{1}{\Lambda^2}$ $(\bar{b}_L \gamma_\mu s_L)(\bar{\mu}_L \gamma^\mu \mu_L)$



$\frac{e}{16\pi^2} \frac{1}{\Lambda^2}$ $\langle H \rangle (\bar{\mu}_R \sigma_{\mu\nu} \mu_L) F^{\mu\nu}$



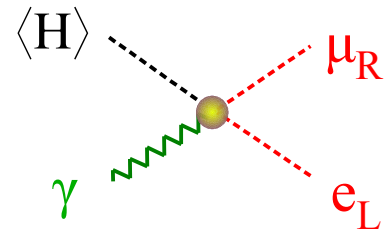
Possible unified description by means of a new interaction with special role for muons (and maybe tau's)

Greljo, Stangl, Thomsen '21
Baum *et al.* '21
Davighi, '21
Altmannshofer *et al.* '21
+ many others…

→ talk by Crivellin & Zupan

However...

$\frac{e}{16\pi^2} \frac{\Theta_{\mu e}}{\Lambda^2}$ $\langle H \rangle (\bar{\mu}_R \sigma_{\mu\nu} e_L) F^{\mu\nu}$



$|\Theta_{\mu e}| < 2\times10^{-5}$

Tight constraint involving several ops. → Exact flavor symm. @ work in the lepton sector → *different behavior of quarks & leptons*

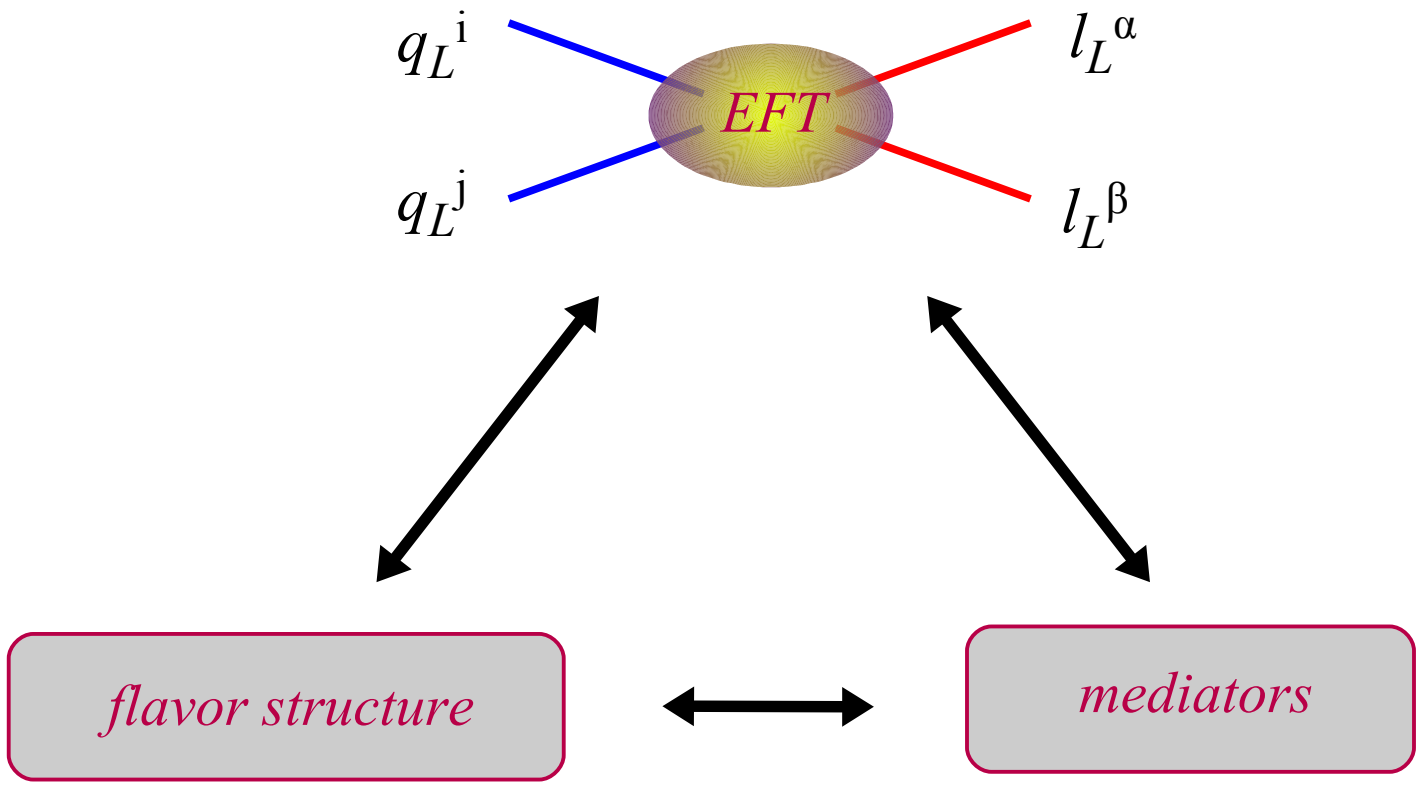
GI, Pages, Wilsch '21

$\Lambda \approx 10$ TeV

General model-building considerations

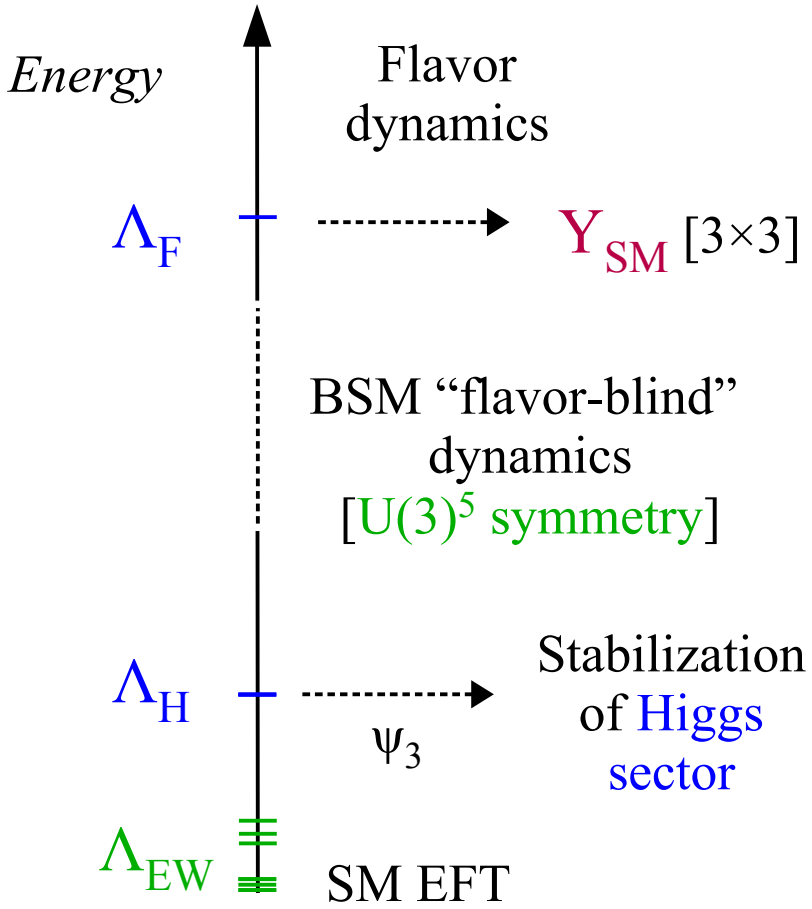
General odel-building considerations

To move from the EFT toward more complete/ambitious models, we need to address two general aspects: the *flavor structure* of the underlying theory, and the nature of the possible *mediators*



General odel-building considerations

The old (Minimal Flavor Violation) paradigm:



Main idea:

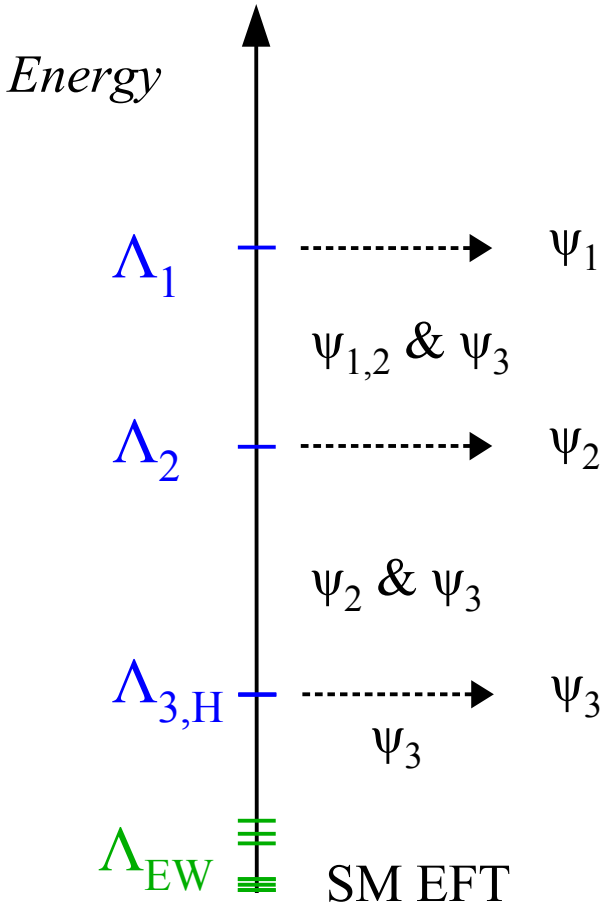
- Concentrate on the Higgs hierarchy problem
- Postpone (*ignore*) the flavor problem

⬇

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

General odel-building considerations

~~The old (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:
- 1st & 2nd gen. have small masses because they are coupled to NP at heavier scales

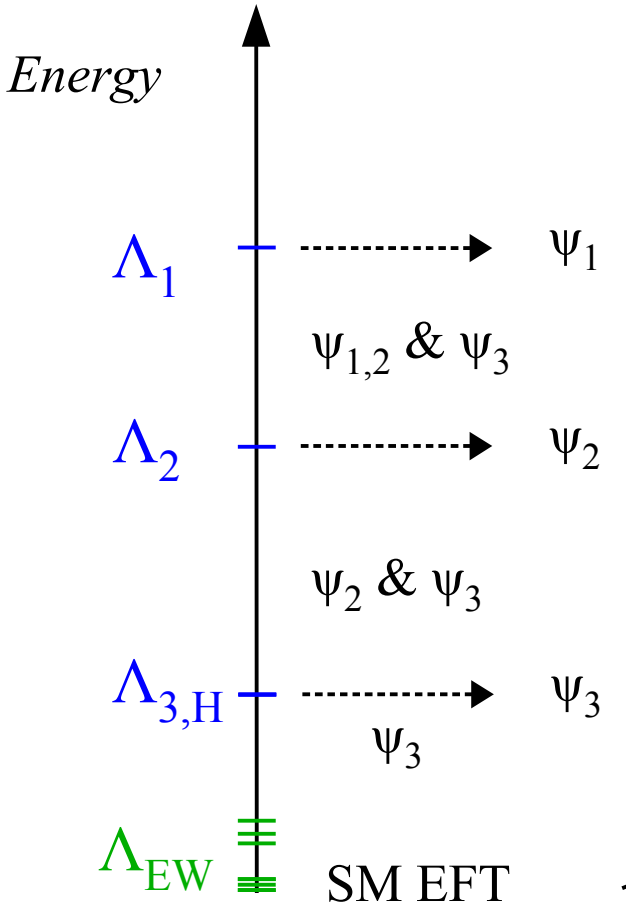
⬇

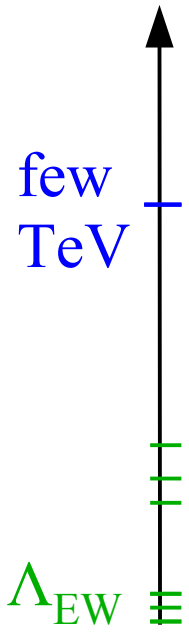
~~3 gen. = "identical copies" up to high energies~~

General odel-building considerations

~~The old (MFV) paradigm~~

Multi-scale picture @ origin of flavor:





NP coupled mainly to ψ_3

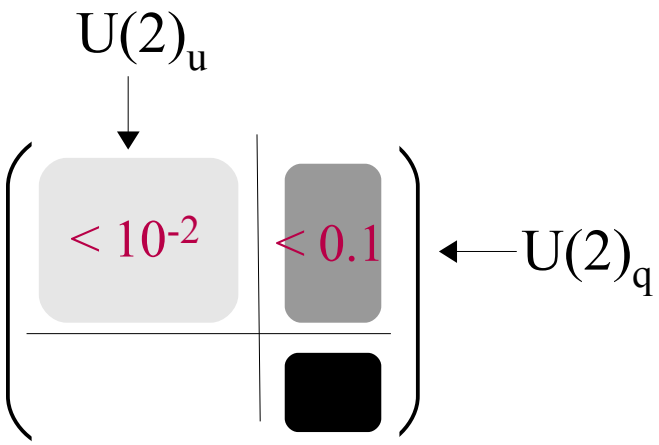
$\psi_{1,2}$ ~ massless [$U(2)^n$ symm.]

Barbieri *et al.* '11

→ talk by Marzocca

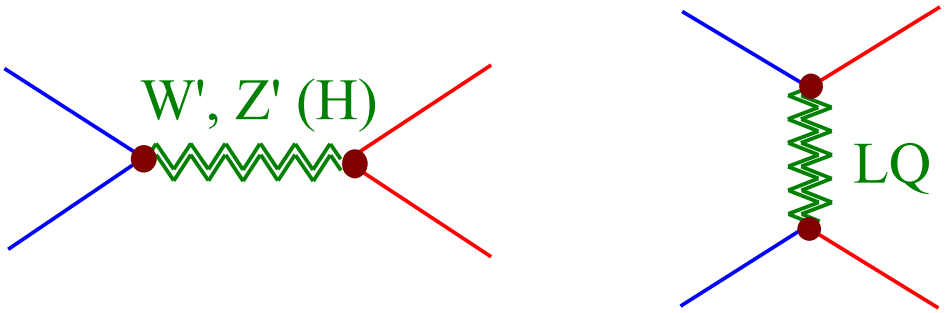
"UV imprint" in the Yukawa couplings:

$Y_U \sim$



General odel-building considerations

Which mediators can generate the effective operators required for by the EFT fit?
If we restrict the attention to tree-level mediators, not many possibilities...



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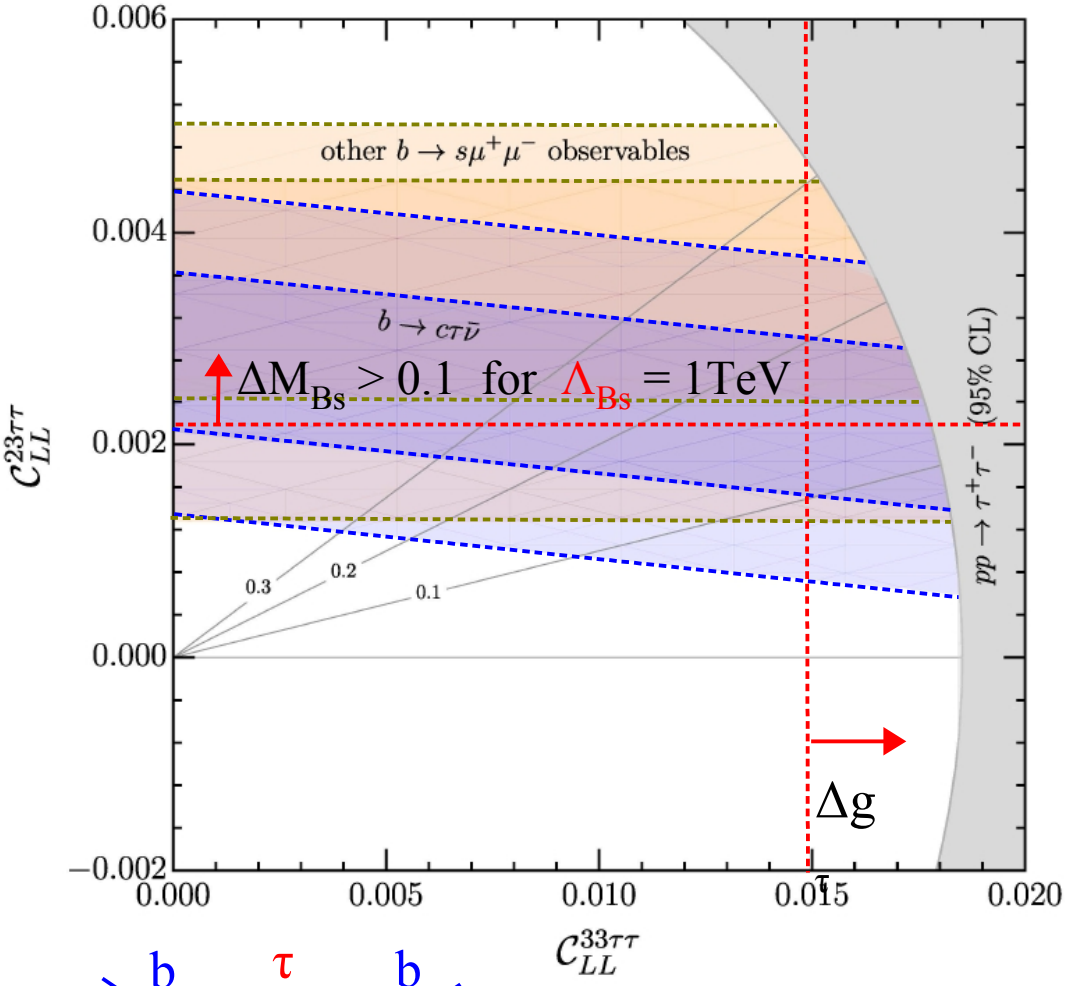
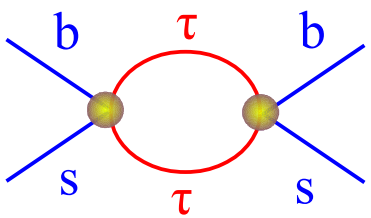


Pattern emerging from data:

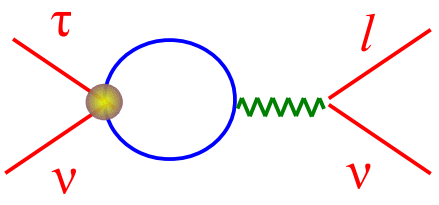
- ✔ O(10^{-1}) for each 2nd gen. q_L or l_L
- ✔ Nice consistency among the two sets of anomalies

What we do not see (*seem to call for an additional loop suppression*):

- ✖ Four-quarks (ΔF=2)
- ✖ Four-leptons (τ→μνν)
- ✖ Semi-leptonic $O^{(1-3)}$ (b→sνν)



$\Delta M_{Bs} \sim (C^{23\tau\tau})^2 \Lambda_{Bs}^2$



$\Delta g_\tau \sim (C^{33\tau\tau})\log(\Lambda/m_t)$

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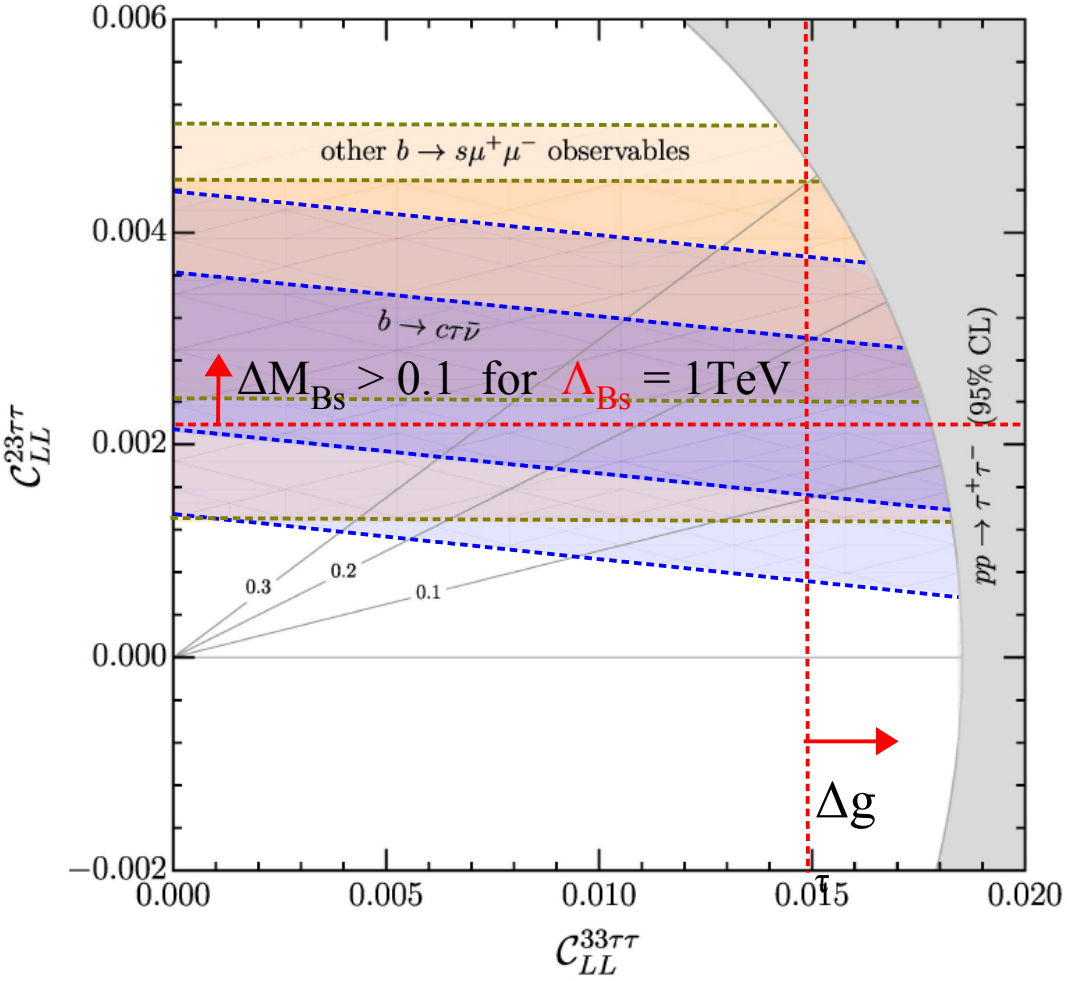

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⬇

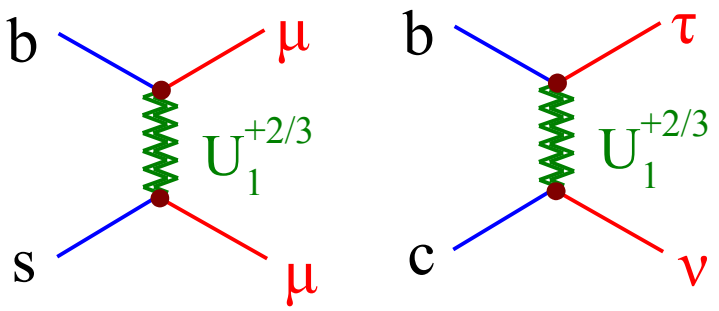
Leptoquarks

General odel-building considerations

Which LQ explains which anomaly?

	Model	$R_{K(*)}$	$R_{D(*)}$	$R_{K(*)}$ & $R_{D(*)}$
Scalars	$S_1 = (\mathbf{3},\mathbf{1})_{-1/3}$	✗	✓	✗
	$R_2 = (\mathbf{3},\mathbf{2})_{7/6}$	✗	✓	✗
	$\tilde{R}_2 = (\mathbf{3},\mathbf{2})_{1/6}$	✗	✗	✗
	$S_3 = (\mathbf{3},\mathbf{3})_{-1/3}$	✓	✗	✗
Vector	$U_1 = (\mathbf{3},\mathbf{1})_{2/3}$	✓	✓	✓
	$U_3 = (\mathbf{3},\mathbf{3})_{2/3}$	✓	✗	✗

Angelescu, Becirevic, DAF, Sumensari [1808.08179]



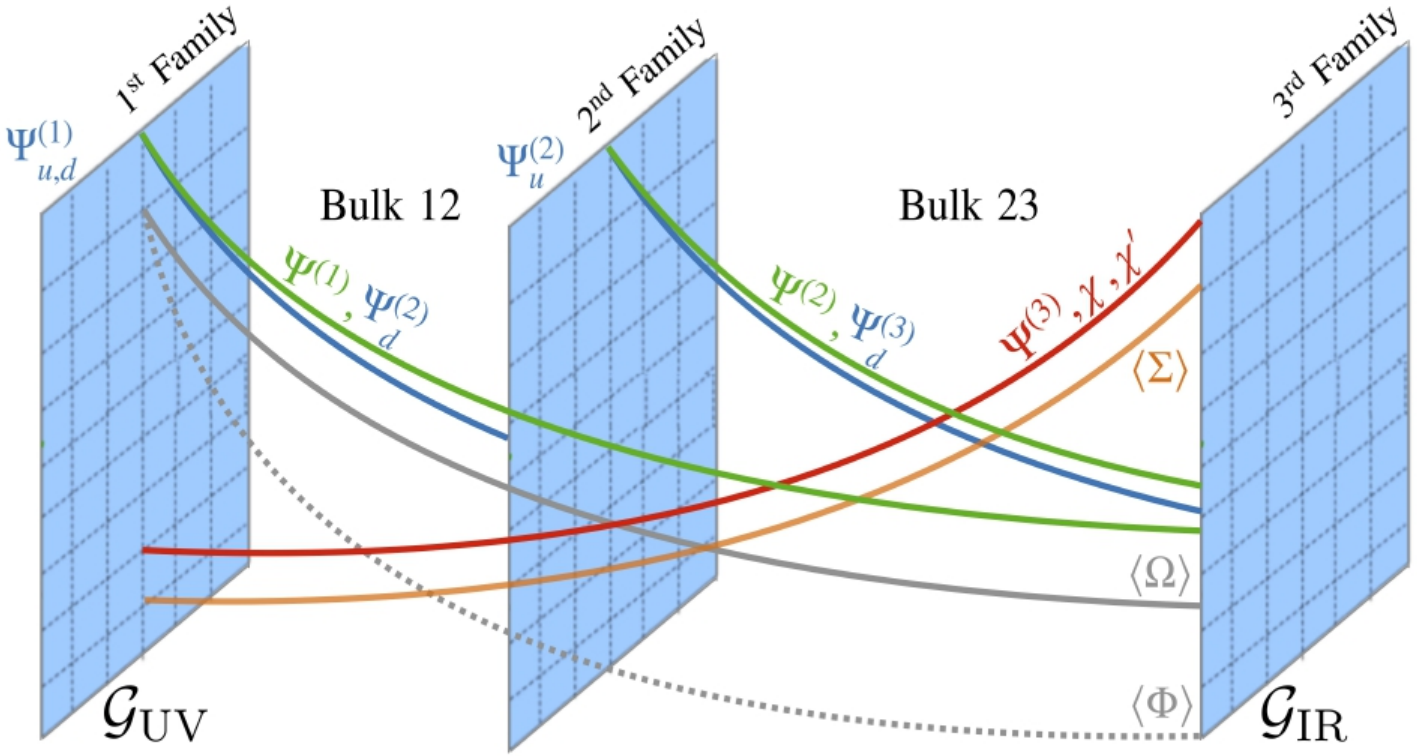
Barbieri, GI, Pattori, Senia '15

- mediator: U_1
- flavor structure: $U(2)^n$
- UV completion: SU(4) [→ quark-lepton unification]

We identifid this path back in 2015, as a motivated simplfied 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 $SU(4) \to SU(3)_C\times U(1)_{B-L}$

$$SU(4) \sim \left[\begin{array}{c|c} SU(3)_C & 0 \\ \hline 0 & 0 \end{array}\right] \quad \left[\begin{array}{c|c} 0 & LQ \\ \hline LQ & \end{array}\right] \quad \left[\begin{array}{c|c} \frac{1}{3} & 0 \\ \hline 0 & -1 \end{array}\right]$$

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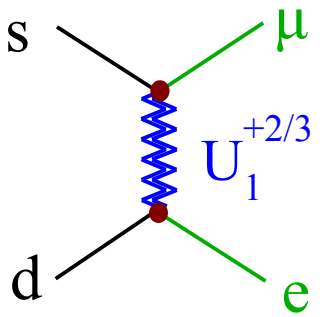
The problem of the "original PS model" are the strong bounds on the LQ couplings to 1st & 2nd generations [e.g. $M > 200$ TeV from $K_L \to \mu e$]

Attempts to solve this problem simply adding extra fermions or scalars

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

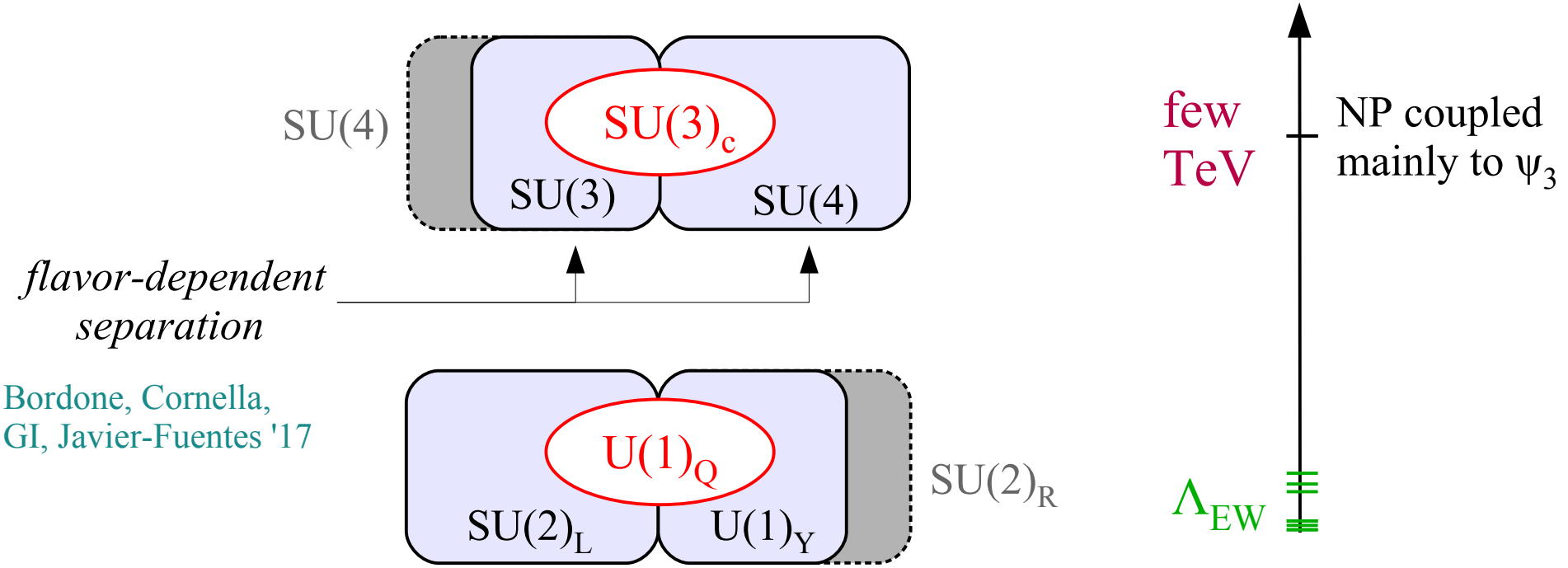


UV completions: 4321 & beyond

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



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- *Non-universality via mixing*

$SU(4)\times SU(3)$ $\quad$ $SU(4)_3 \times SU(3)_{1,2}$

- *Accidental* $U(2)^5$ *flavor symm. in the gauge sect.*

$SU(3)\times G_{EW}\times G_{HC}$
Barbieri, Tesi '17

$SU(4)\times SU(3)\times G_{EW}$
Di Luzio, Greljo, Nardecchia, '17

UV completions

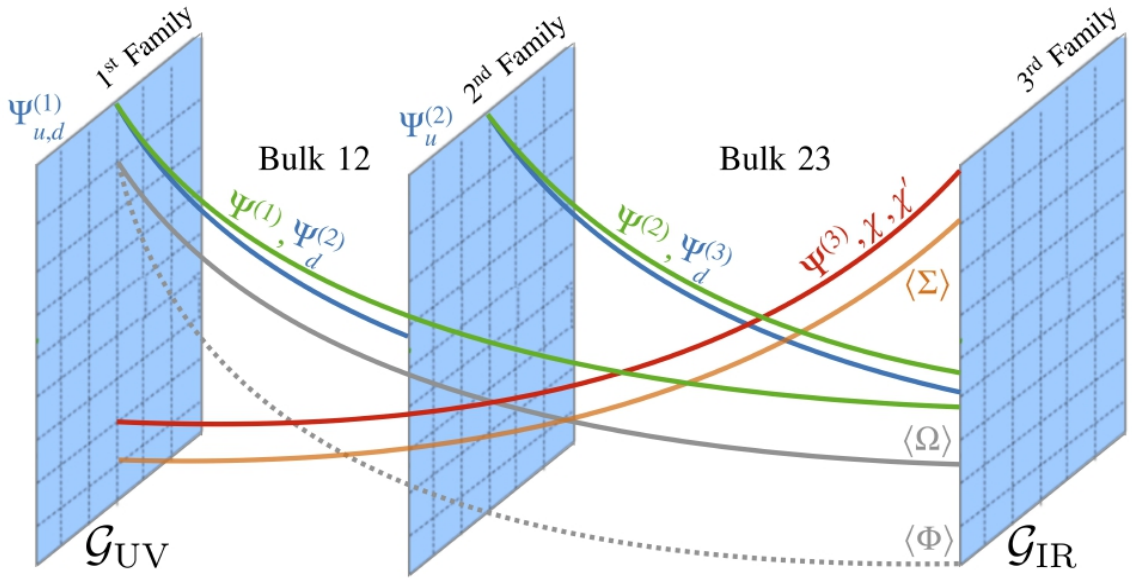
$SU(4)_h \times SU(4)_l \times G_{EW} \times G_{HC}$
Fuentes-Martin & Stangl '20

$[PS]^3 = [SU(4)\times G_{EW}]^3$
Bordone *et al.* '17

$[\, SU(4)_h \times SU(4)_l \,]_{\text{warped-5D, 3-branes}}$
Fuentes-Martin, GI, Lizana, Selimovic, Stefanek '22

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

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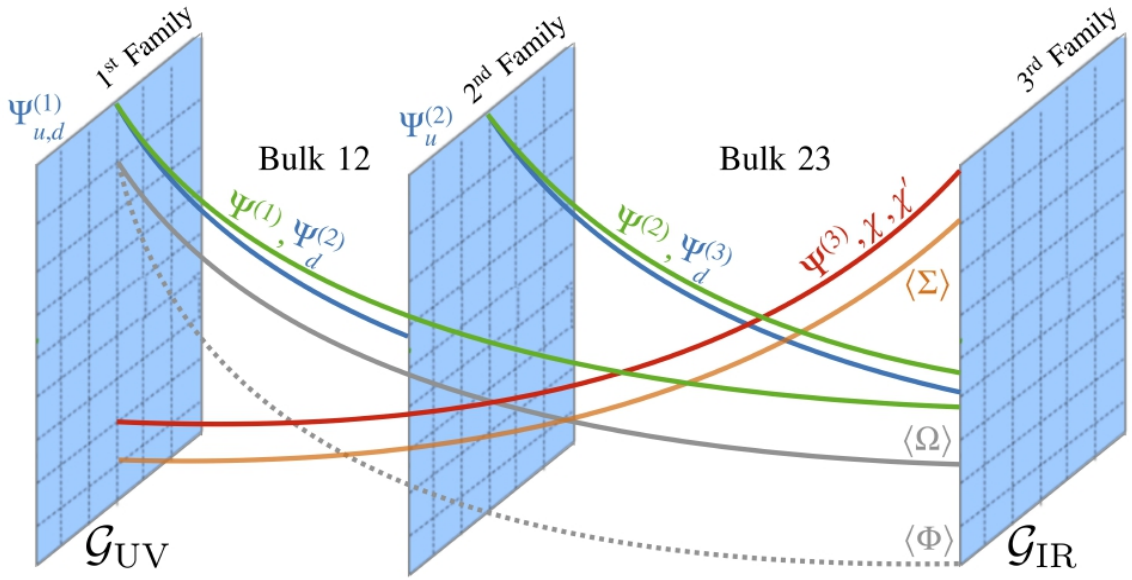

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Bordone, Cornella, GI, Javier-Fuentes '17

* Anarchic neutrino masses via inverse see-saw mechanism — Fuentes-Martin, GI, Pages, Stefanek '22

* "Holographic" Higgs from appropriate choice of bulk/brane gauge symm.
  [$G_{\text{bulk-23}} = SU(4)_3 \times SU(3)_{1,2} \times U(1) \times SO(5)$ $G_{IR} = SU(3)_c \times U(1)_{B-L} \times SO(4)$]

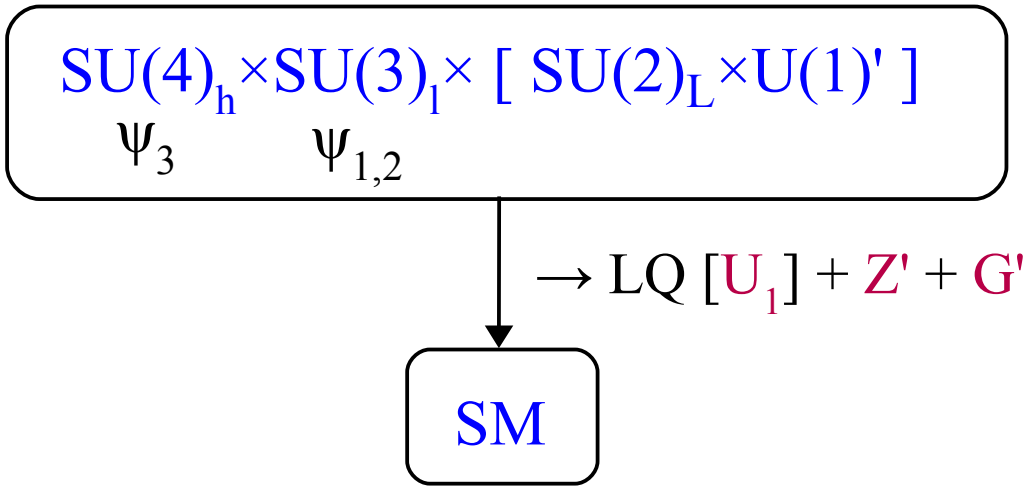
→ Light Higgs as pseudo Goldstone

Agashe, Contino, Pomarol '05

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

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']



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$$SU(4)_h \times SU(3)_l \times [\, SU(2)_L \times U(1)' \,]$$
$$\psi_3 \qquad \psi_{1,2}$$

→ LQ [U_1] + Z' + G'

SM

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 familes of chiral fermions

$SU(4)_h \times SU(3)_l$

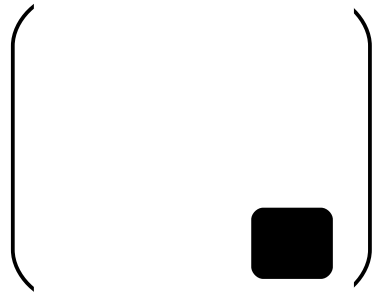
ψ_{1L}

ψ_{2L}

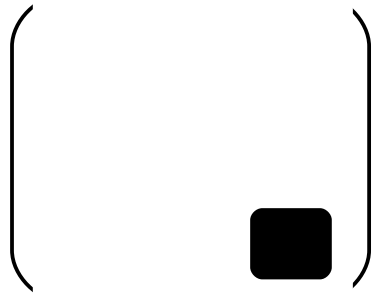
χ (VL fermions)

ψ_{3L}

SM Yukawa coupling → $Y \sim$



LQ eff. coupling → $\beta_L \sim$



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

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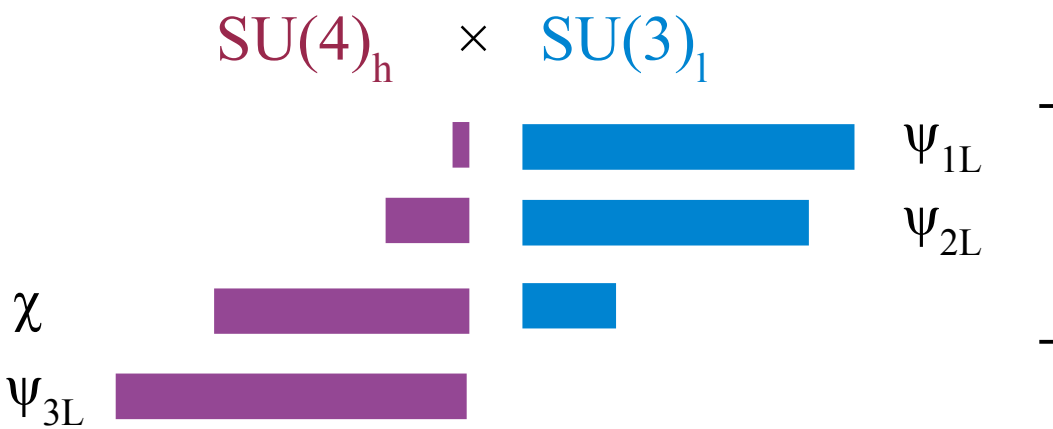

$$Y \sim \begin{pmatrix} & & \\ & \blacksquare & \blacksquare \\ & \blacksquare & \blacksquare \end{pmatrix}$$

$$\beta_L \sim \begin{pmatrix} & & \\ & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \end{pmatrix}$$

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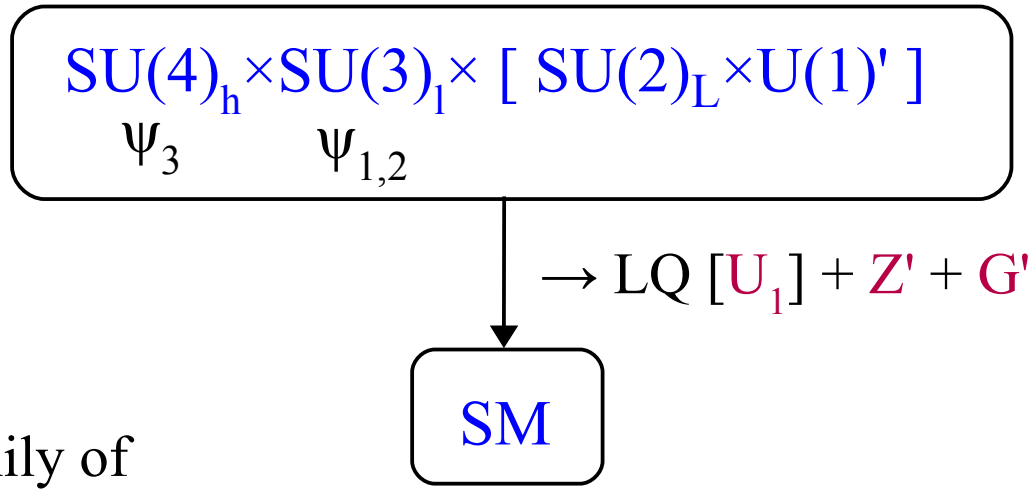

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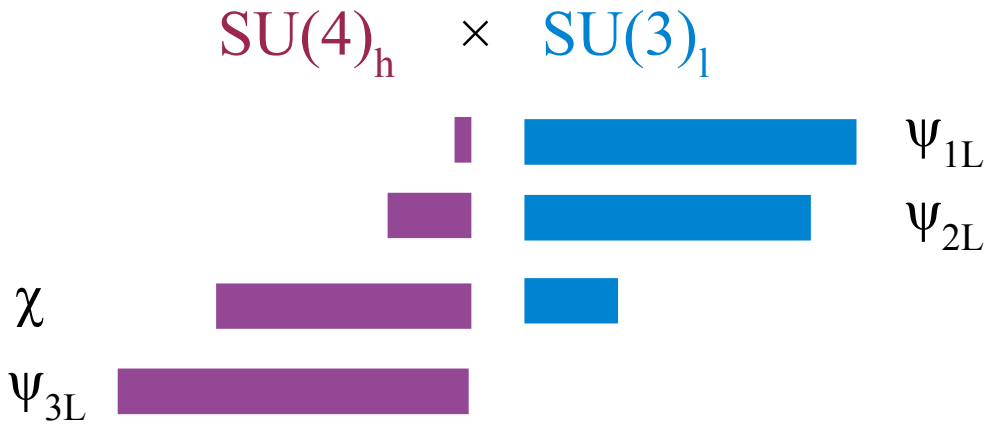
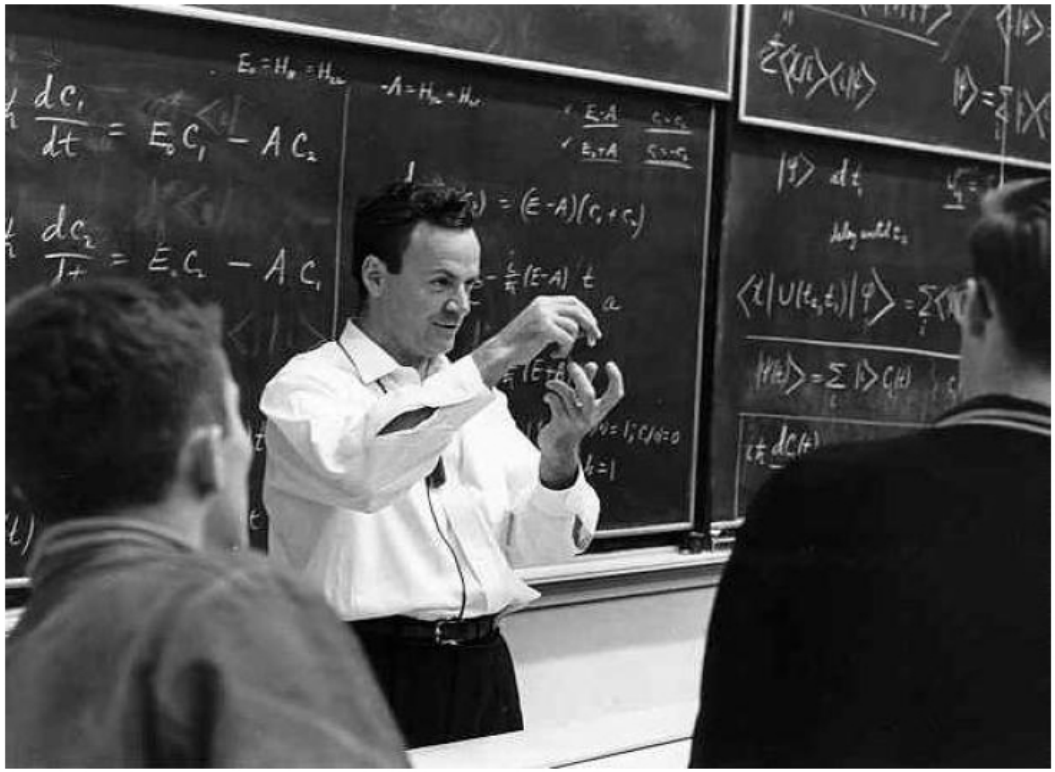


- Positive features the EFT reproduced
- Calculability of ΔF=2 processes
- Precise predictions for high-pT data

} *consistent with present data*

Predictions @ 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]

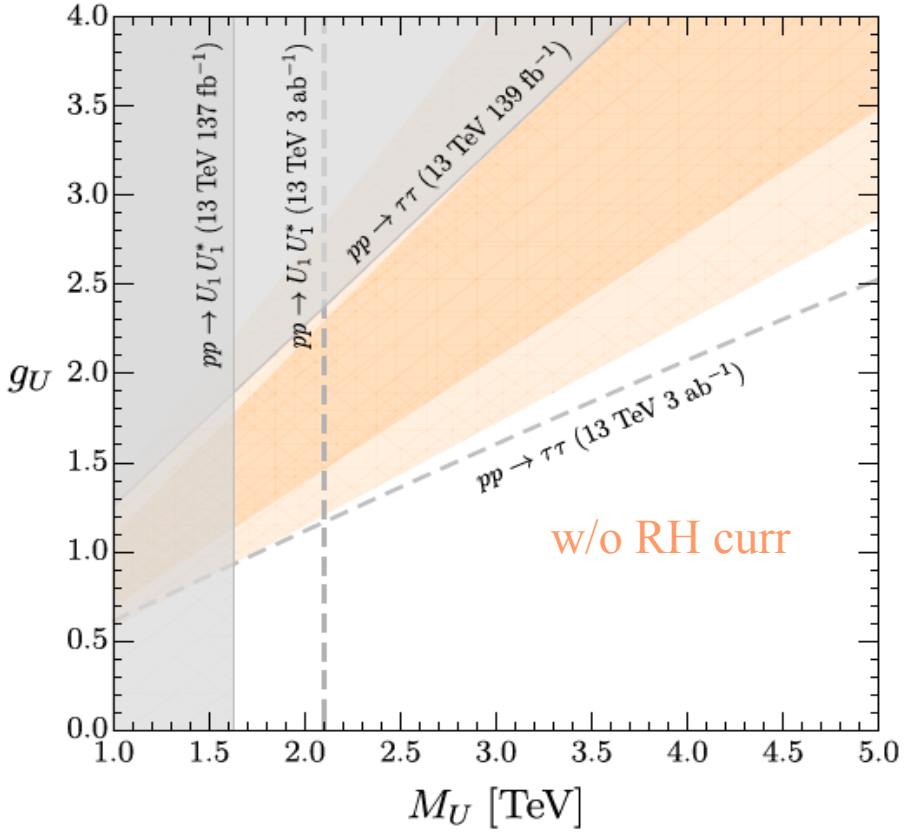
Predictions @ low- & high energies

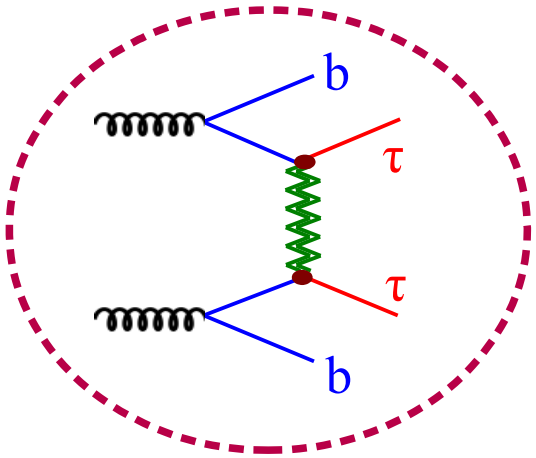
I General predcitons of U_1 exchange @ high-energies

[Very general, directly connected to the EFT analysis]

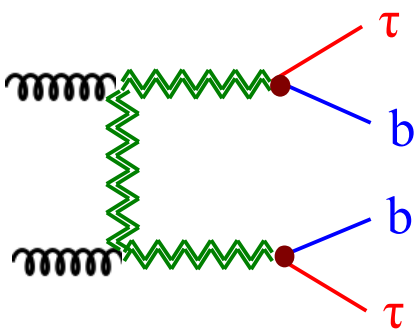
$pp \to \tau\tau$

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





Faroughi, Greljo, Kamenik '16



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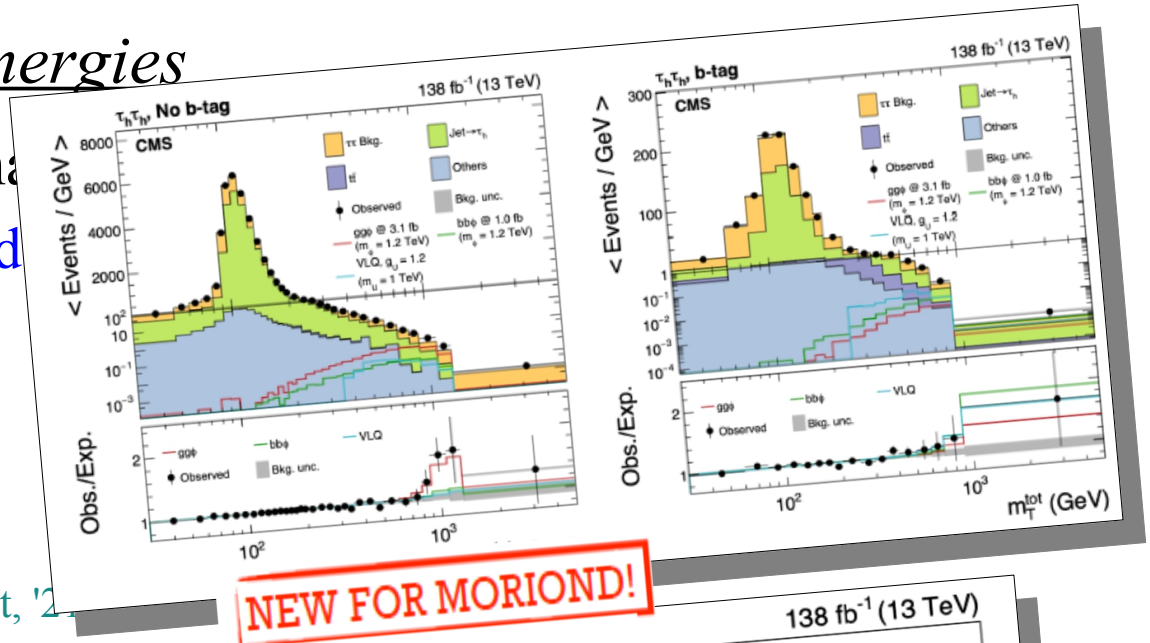
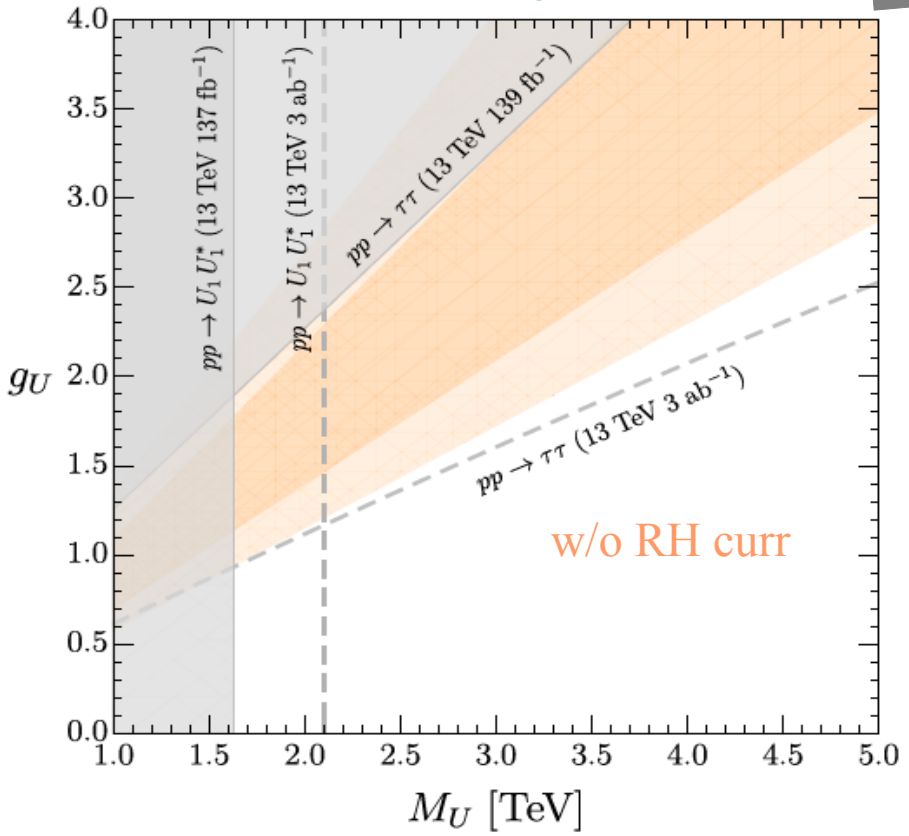
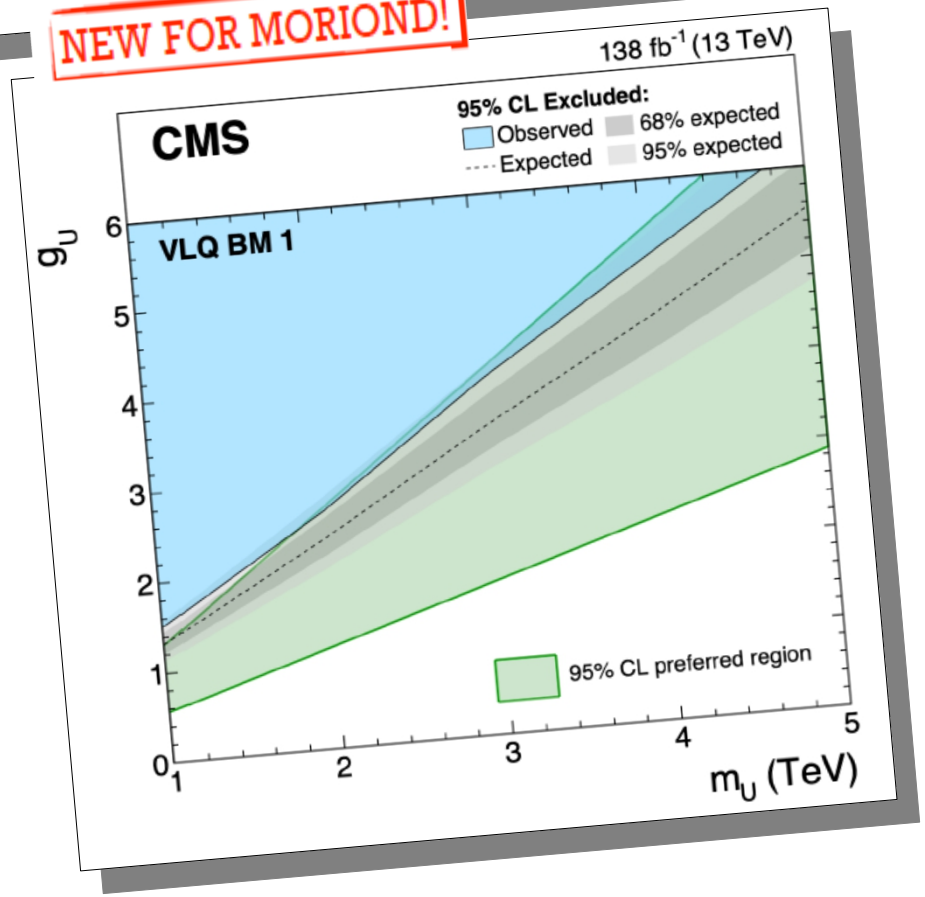


Cornella, Fuentes-Martin, Faroughi, GI, Neubert, '2



NEW FOR MORIOND!



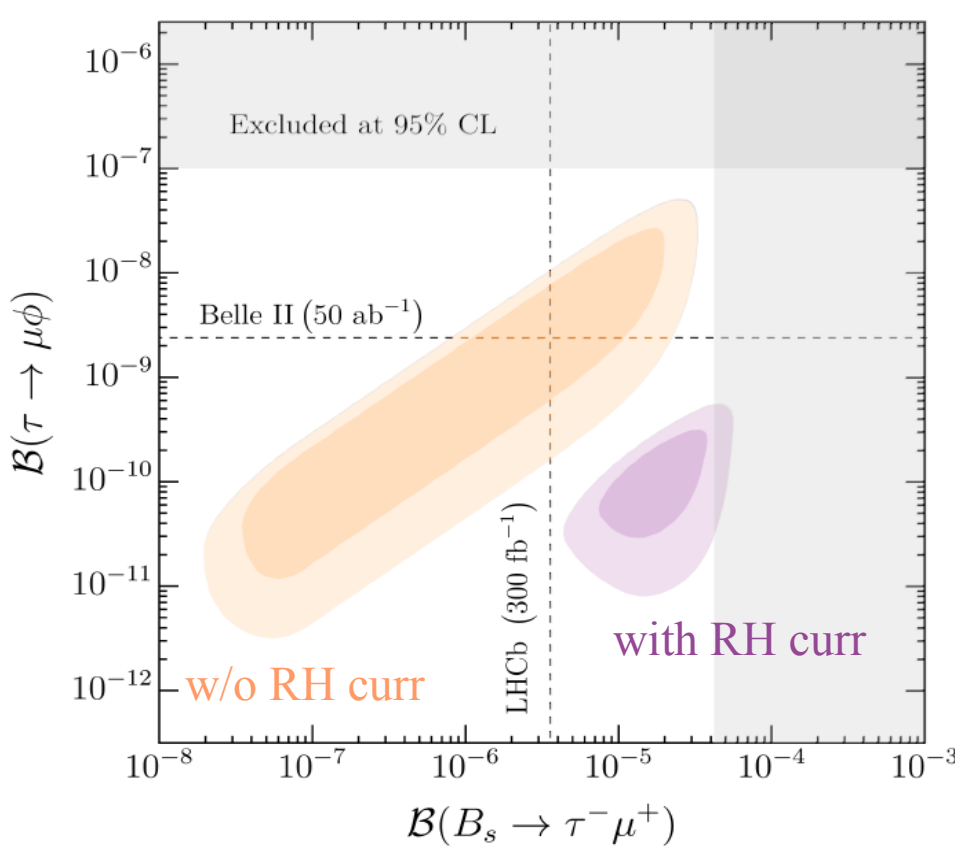
Predictions @ low- & high energies

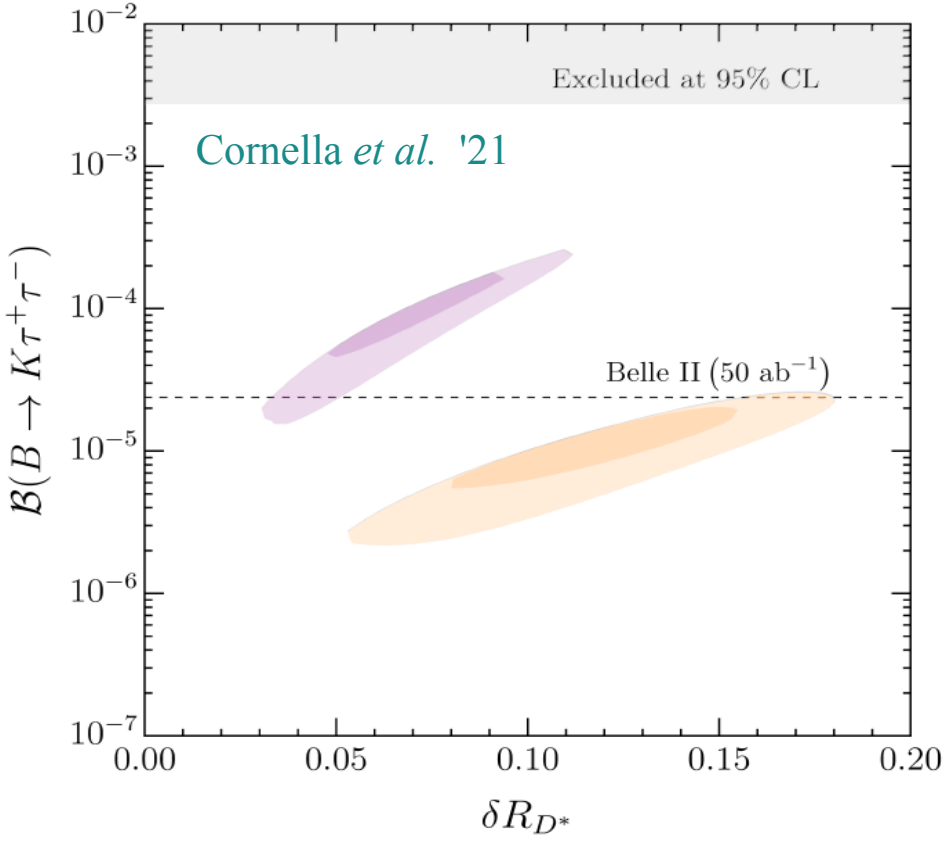
II General predcitons of U_1 exchange @ low-energies

[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 channles)





Predictions @ low- & high energies

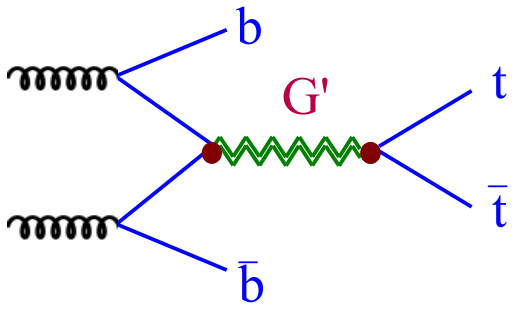
III General predcitons of 4321 models @ high-energies

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

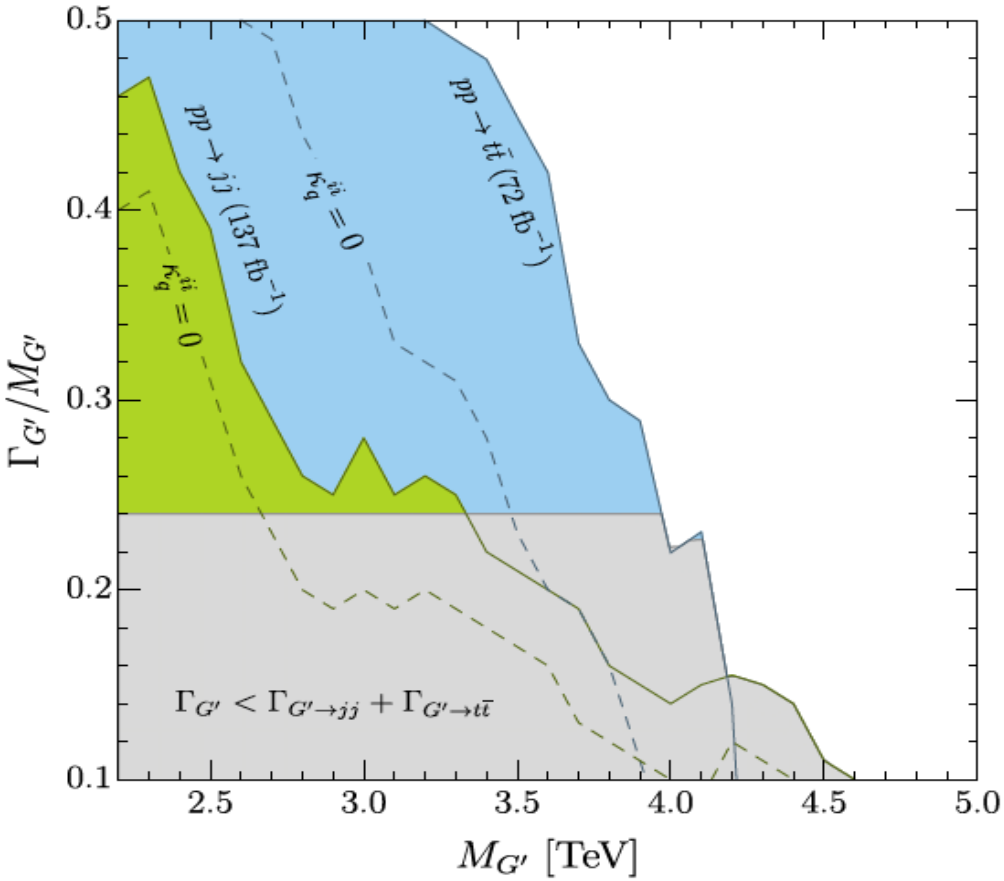
$SU(4)_h \times SU(3)_l \times [\, SU(2)_L \times U(1)' \,]$ → SM

→ $U_1 + Z' + G'$

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

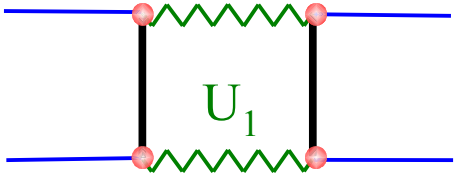


→ strongest constraint on the scale of the model from pp → $t\,\bar{t}$

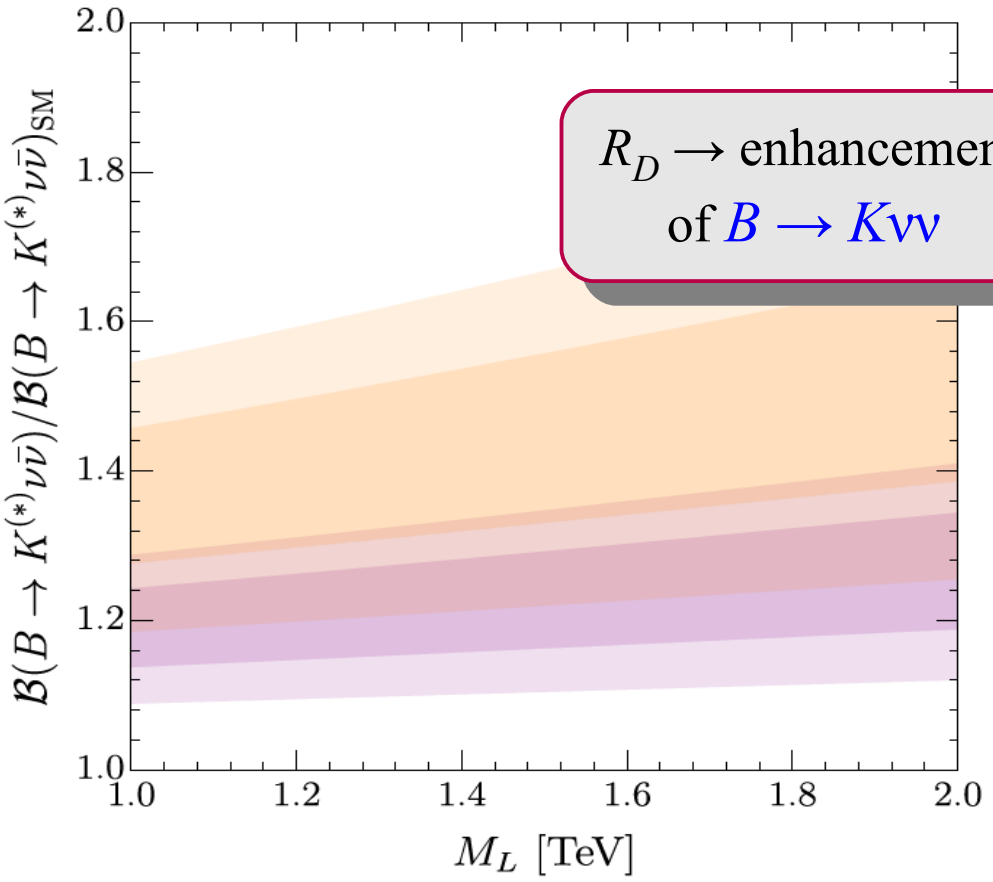


Predictions @ low- & high energies

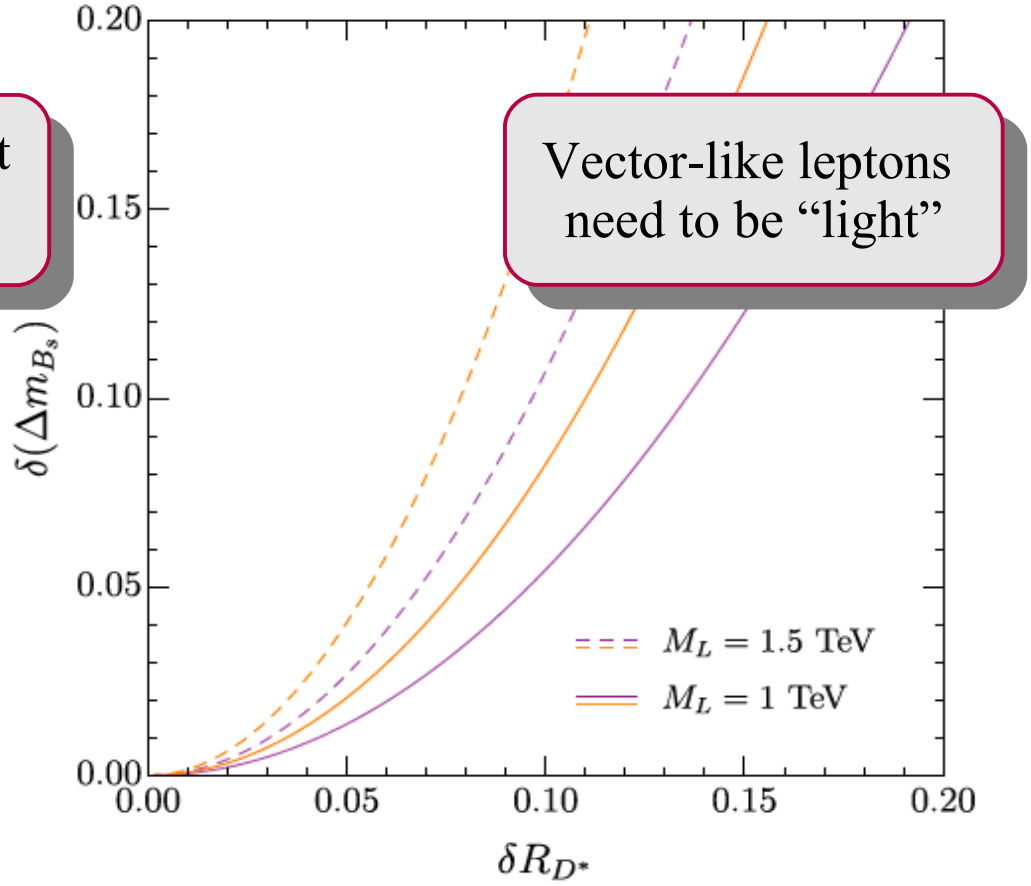
IV Specific predcitons of 4321 @ low-energies
[UV sensitive low-energy observables]



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



B) B_s mixing [ΔF=2]



Cornella, Fuentes-Martin, Faroughi, GI, Neubert, '21
Fuentes-Martin, GI, Konig, Selimovic, '20

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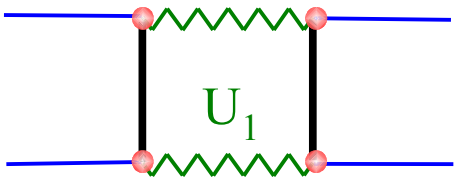
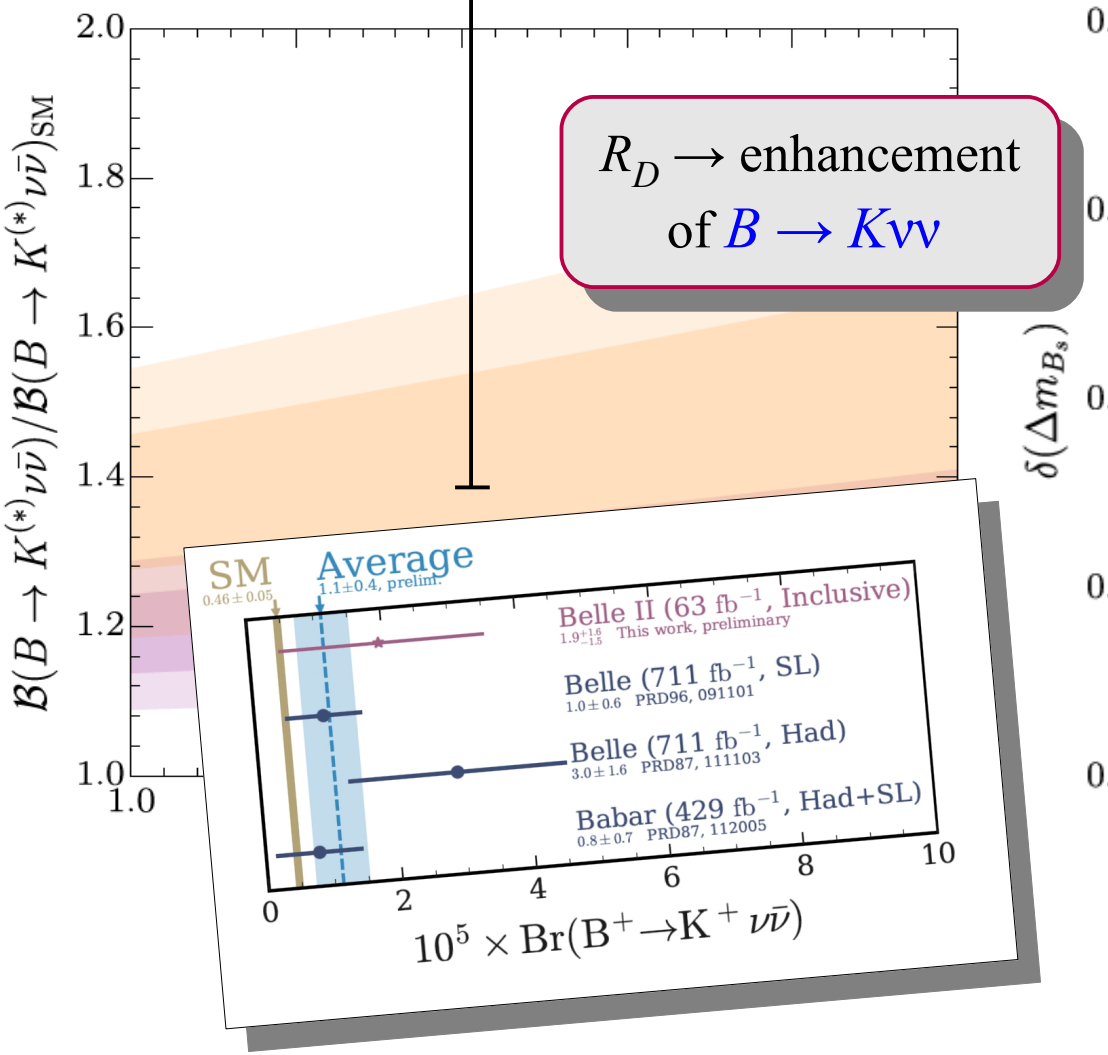


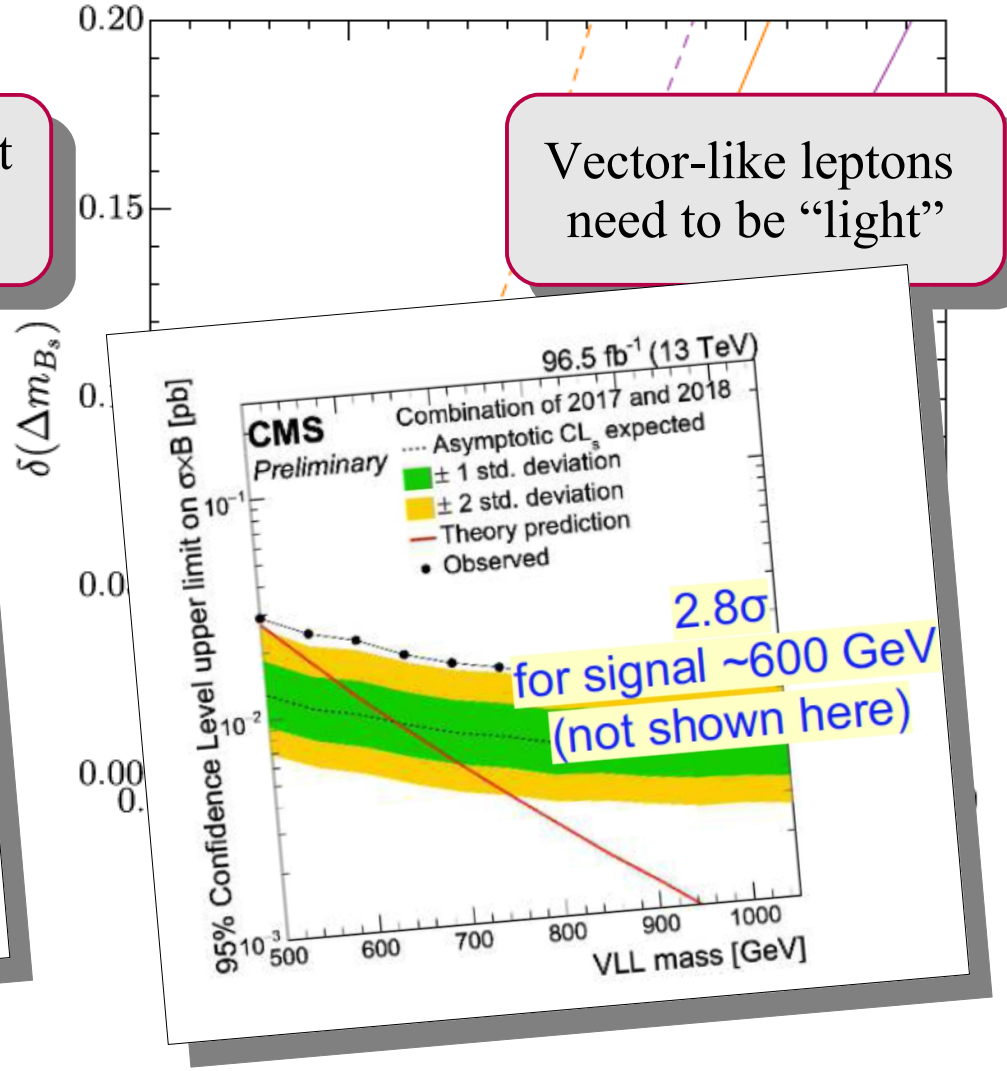
A) $B \to K\nu\nu$

$R_D \to$ enhancement of $B \to K\nu\nu$



B) B_s mixing [ΔF=2]

Vector-like leptons need to be "light"



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) ingreideint that emerged in the last few years is the possibilty 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

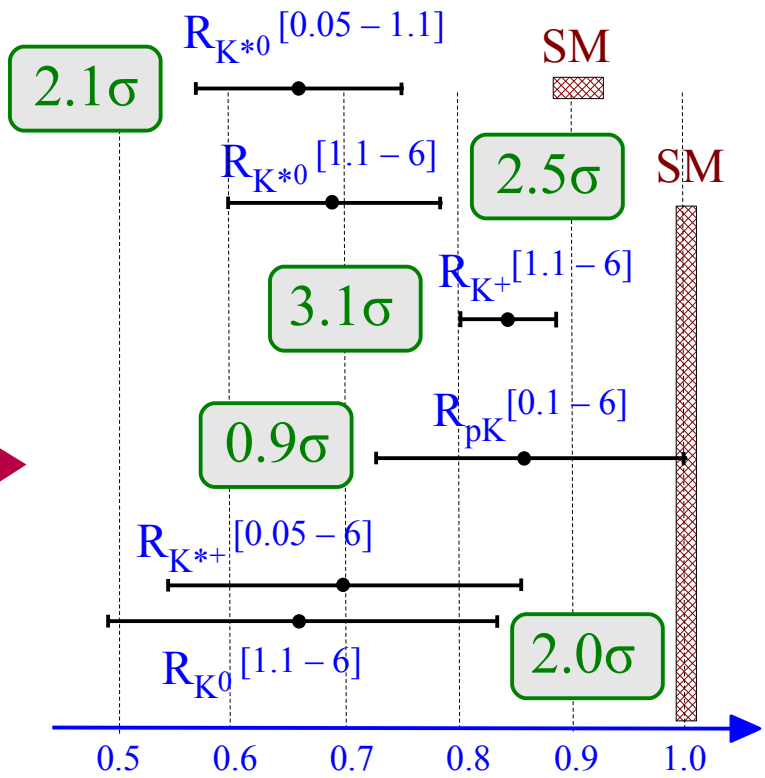
- No contradiction with existing low- & high-energy data, but new non-standard effects should emerge soon in both these areas

The LFU anomalies

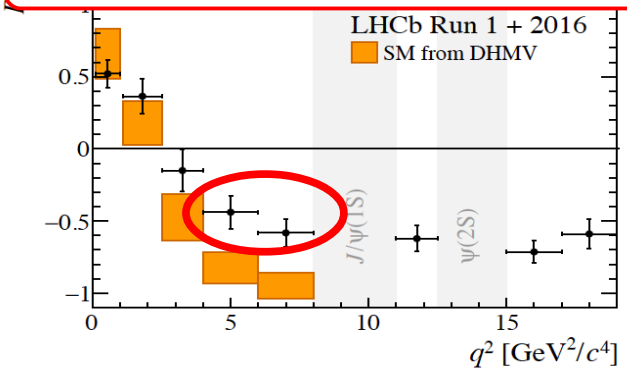
- $b \to s\, l^+ l^-$ (neutral currents): μ vs. e

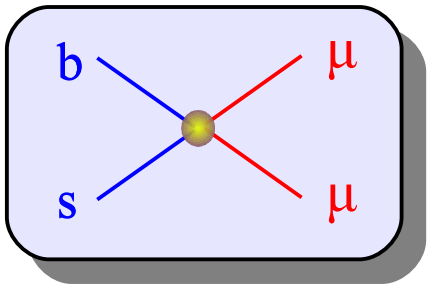
High significance: several observables pointing to the same coherent picture [several new results in 2021]

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

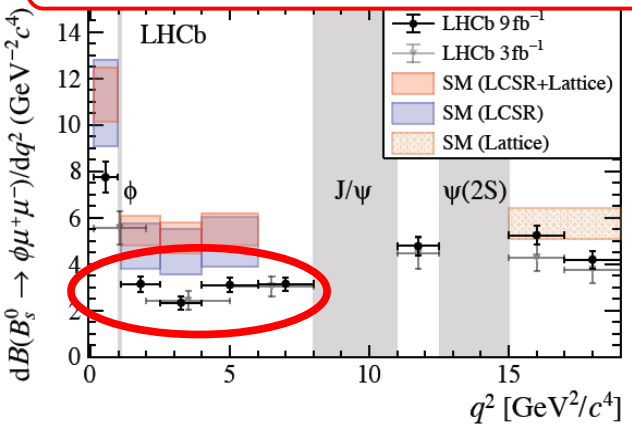


$B \to K^* \mu\mu$ angular distribution





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



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

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

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

2.3σ

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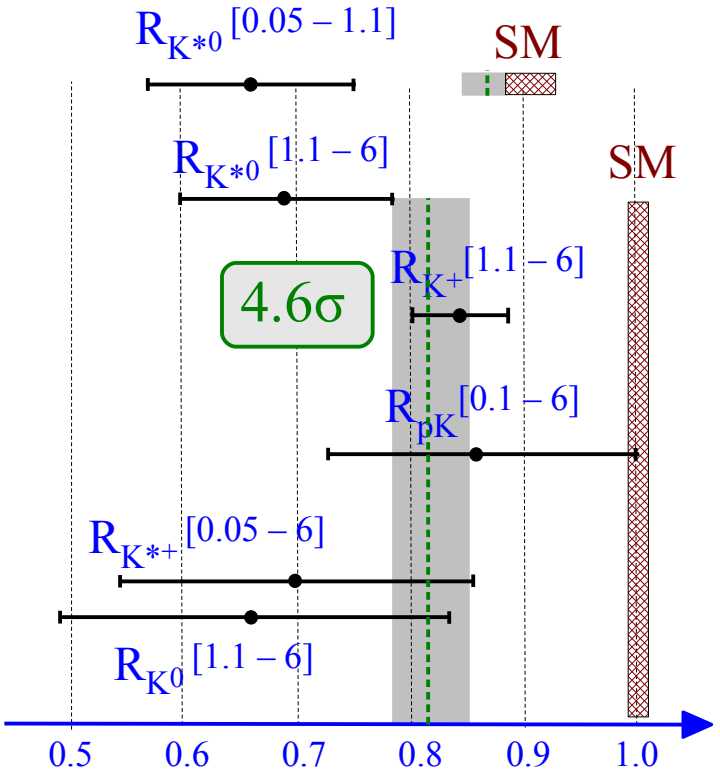

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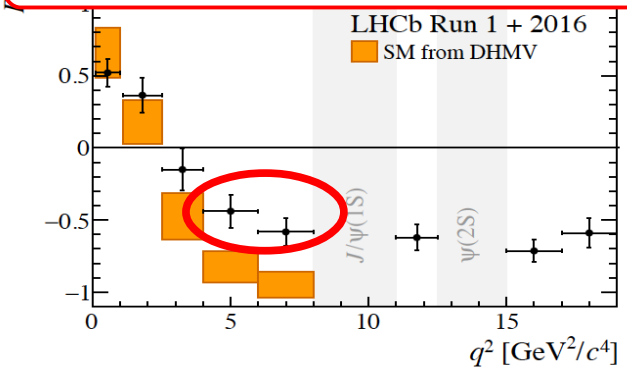

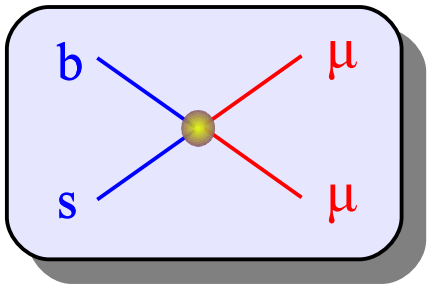

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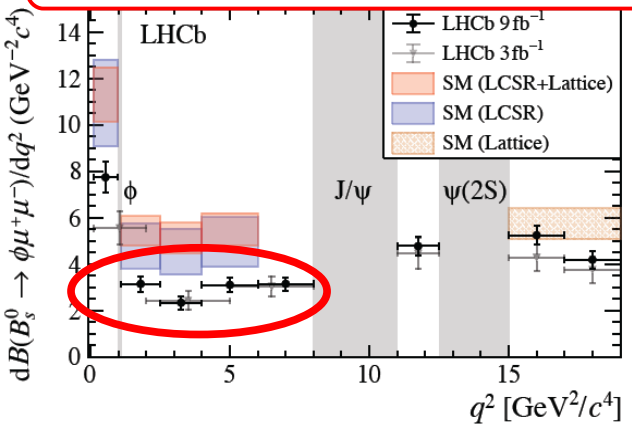

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