# Reading the footprints of the flavor anomalies

**Javier Fuentes-Martín**
Mainz Institute for Theoretical Physics,
Johannes Gutenberg University

Theory Seminar Zeuthen

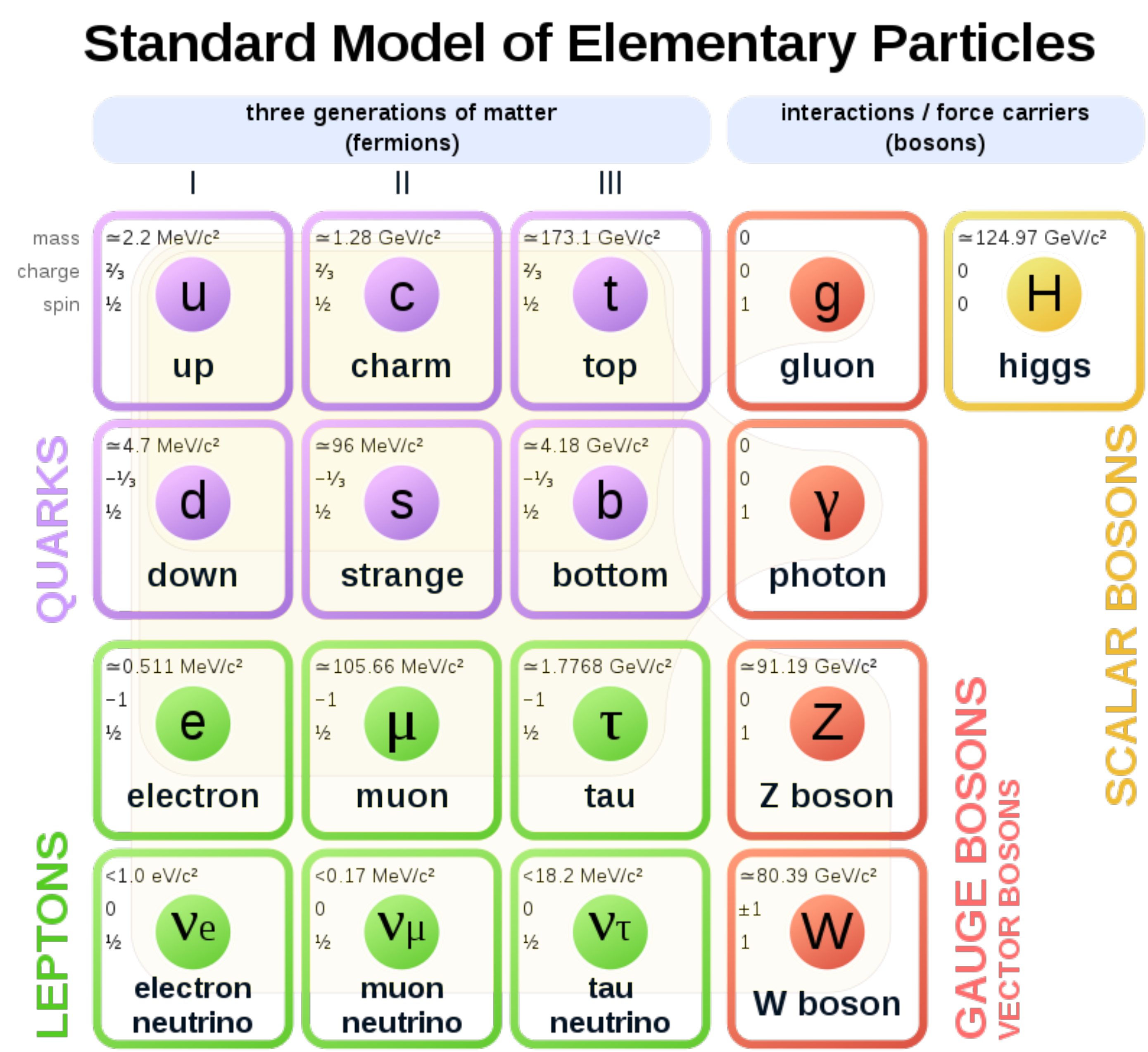
# The Standard Model (SM)

Extremely successful description of Nature…

… yet many unanswered questions

- Neutrino masses
- Dark matter
- Naturalness problems
- …

$$\mathcal{G}_{\rm SM} \equiv SU(3)_c \times SU(2)_L \times U(1)_Y$$



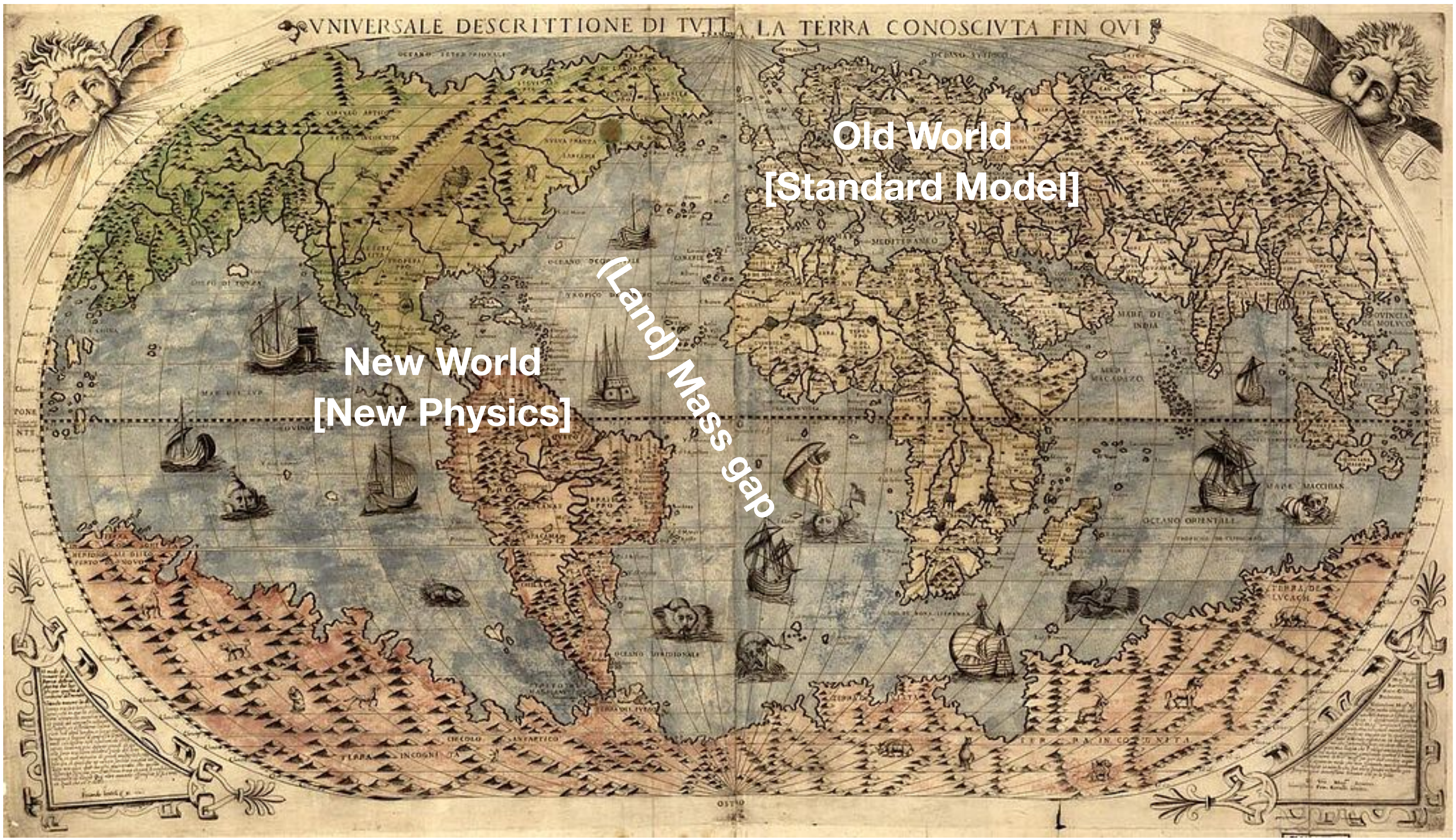

What we know after LHC runs I & II:

★ The Higgs boson is SM-like and relatively light [**SM is complete!**]

★ No direct evidence for new particles [**presence of a mass gap?**]

# The search for Terra Incognita

Much like late Middle Age Europe, particle physics has entered an age of exploration

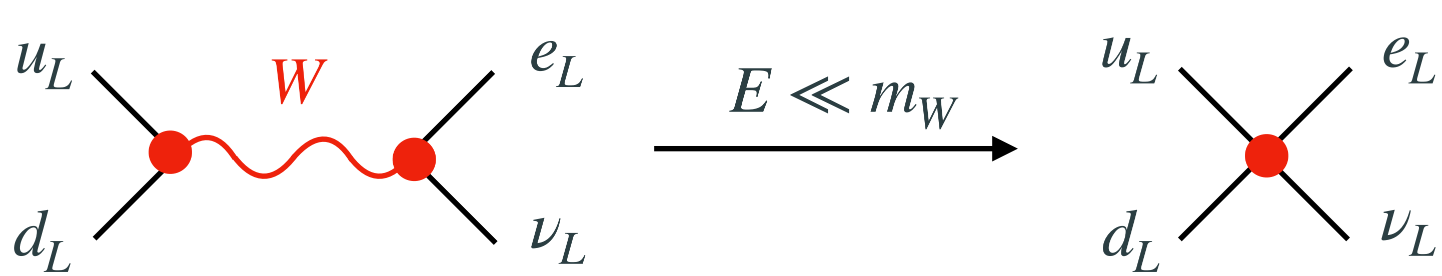


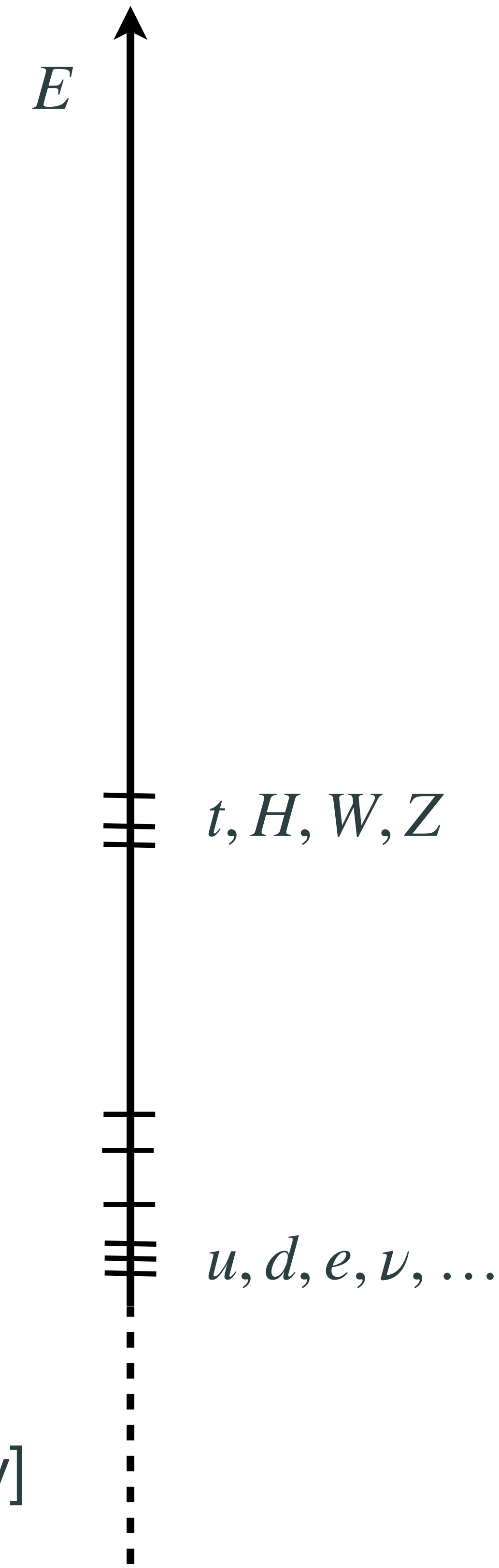
# The Fermi theory

Not the first time we have faced a mass gap in particle physics

**Fermi Theory [$E \ll m_W$]**

$$\mathscr{L}_{WET} = \mathscr{L}_{\rm QED} + \mathscr{L}_{\rm QCD} - \frac{4G_F}{\sqrt{2}}(\bar{u}_L\gamma_\mu d_L)(\bar{e}_L\gamma^\mu \nu_L) + \ldots \qquad [G_F \sim g_W^2/M_W^2]$$

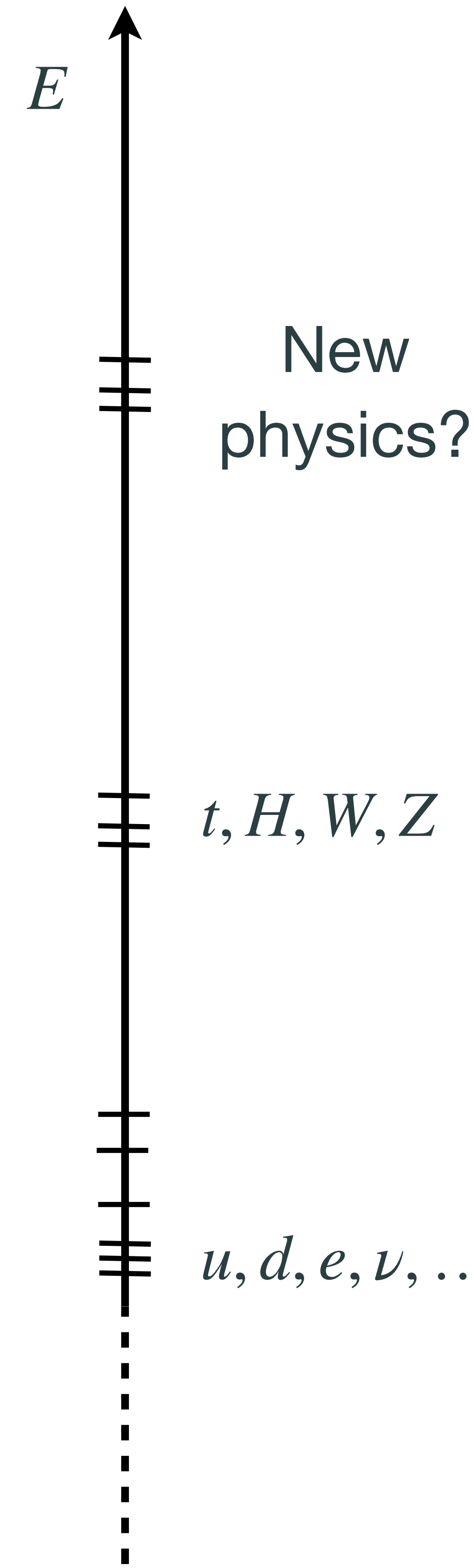



Reconstructing a UV theory from its low-energy imprints is a **very difficult task** (no unique solution due to limited information)

[It took **more than 30 years** to arrive to the SM from the Fermi theory]

# The SM effective theory (SMEFT)




If New Physics is heavy (mass gap), we can write the analog of the Fermi theory for the SM

**SMEFT [$E \ll M_{\rm NP}$]**

$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + C_{\ell q}^{\alpha\beta ij}\,(\ell_L^\alpha \gamma_\mu \ell_L^\beta)(q_L^i \gamma^\mu q_L^j) + \dots \qquad [C_{\ell q} \sim \Lambda^{-2} \sim g_{\rm NP}^2/m_{\rm NP}^2]$$


★ 59 new possible interactions (2499 new couplings) at $\mathcal{O}(\Lambda^{-2})$

★ New physics is unlikely to produce them all with the same strength

Can we infer anything about them from the SM couplings?

# The SM Lagrangian: Naturalness problems

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + |D_\mu \phi|^2 - V(\phi) + \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

The SM Lagrangian contain two **unnatural features** pointing towards new physics

**Higgs hierarchy problem**

[Instability of the Higgs mass under quantum corrections]

TeV-scale new physics?

**SM flavor puzzle**

[Very hierarchical structure in the Yukawa couplings]

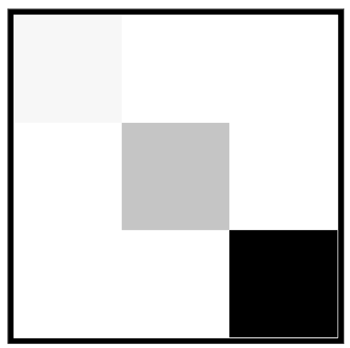
Similar structure also for new physics?

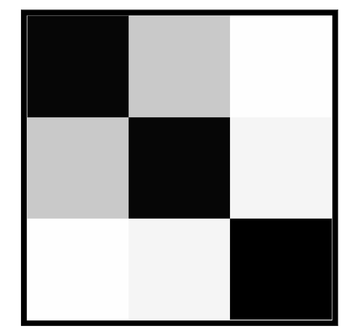
Are these two features correlated?

# The SM flavor puzzle

The SM Yukawa sector is characterized by 13 parameters (for massless neutrinos)
[3 lepton masses + 6 quark masses + 3+1 CKM parameters]

… whose values span 5 orders of magnitude and do not look at all accidental

$M_{u,d,e} \sim$ 

$V_{\rm CKM} \sim$ 

Possible explanations/approaches to the observed hierarchies:

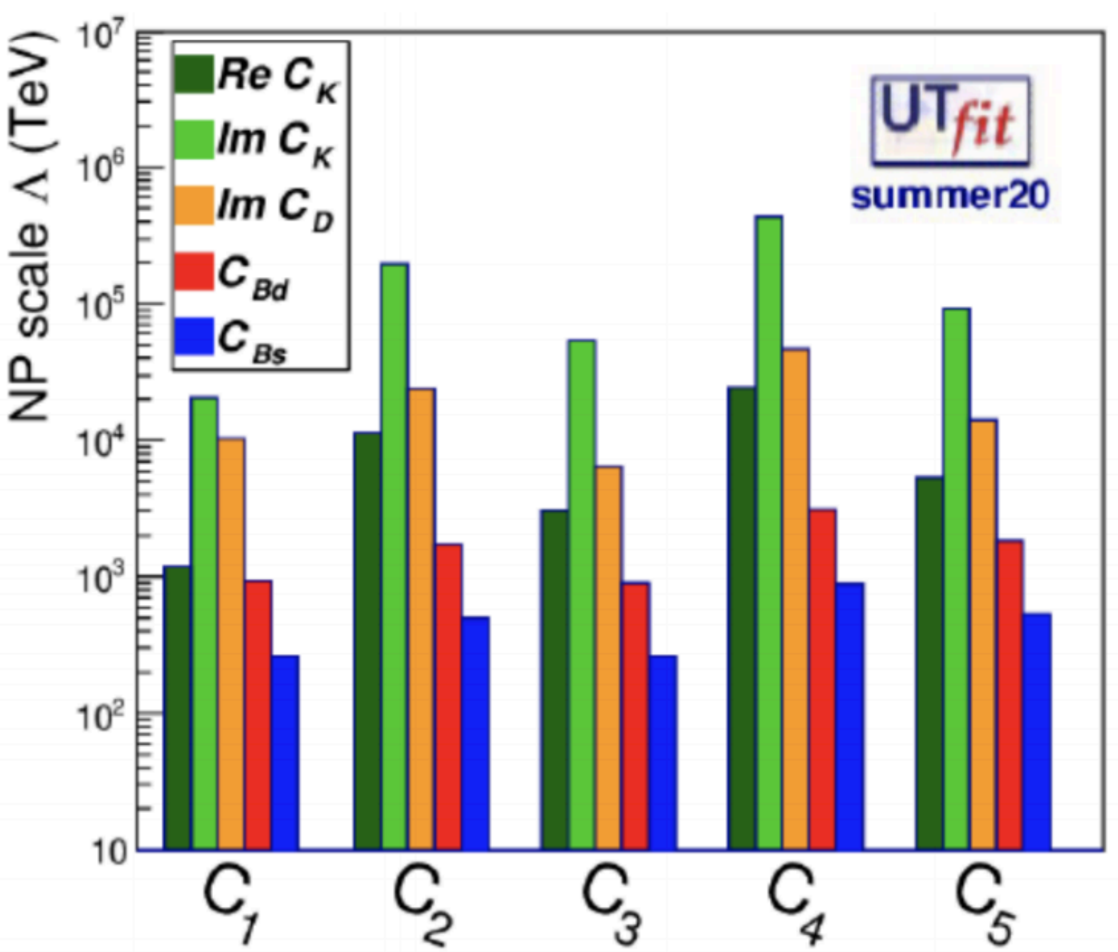
1. They are accidental and/or arise from very high-scale new physics out of our current reach

2. They are low-energy imprints of new symmetries/dynamics deeply connected to the next layer of new physics (possibly related to the Higgs hierarchy problem)

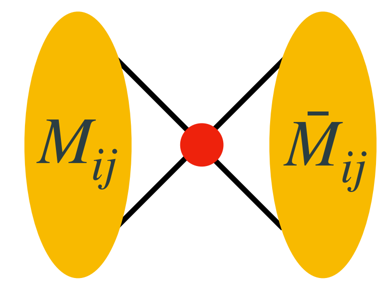
# The new physics flavor problem

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{Gauge}} + \mathscr{L}_{\text{Higgs}} + \mathscr{L}_{\text{Yukawa}} + \sum_{i,d} \frac{1}{\Lambda_i^{d-4}} C_i \mathscr{O}_i^d$$

Very stringent bounds on the new physics scale if it has a generic flavor structure (far too heavy to be directly probed or to stabilize the Higgs)




$$\frac{1}{\Lambda^2} (\bar{\psi}_i \psi_j)^2$$



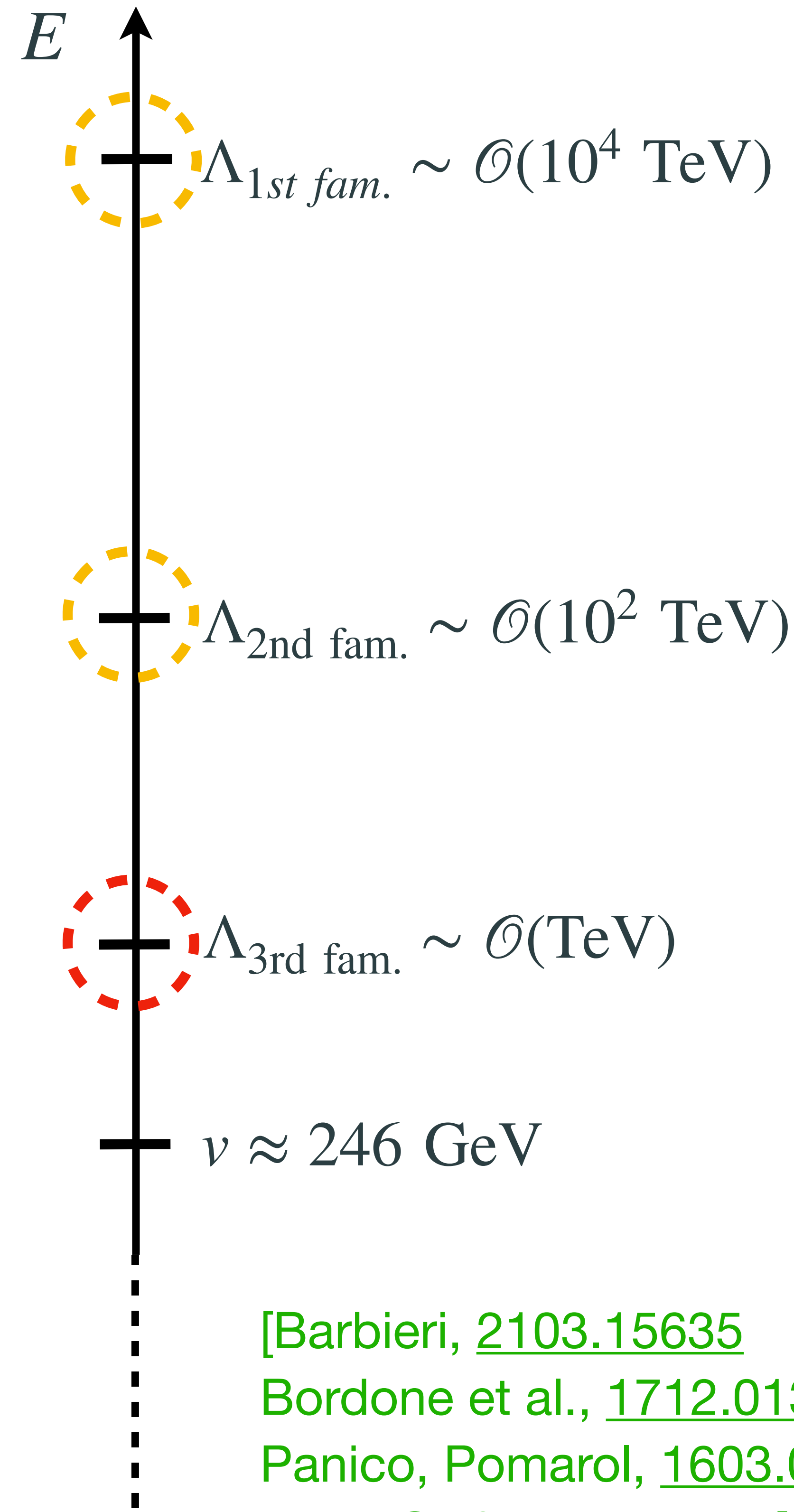

1. **Minimal flavor violation:** SM Yukawas are the only source of flavor violation [new physics is flavor blind/universal]
[D'Ambrosio, Giudice, Isidori, Strumia, '02]

2. **New physics is flavor non-universal** and possibly connected to the origin of the Yukawa hierarchies

# Multi-scale solution of the flavor problem/puzzle

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{Gauge}} + \mathscr{L}_{\text{Higgs}} + \mathscr{L}_{\text{Yukawa}} + \sum_{i,d} \frac{1}{\Lambda_i^{d-4}} C_i \mathcal{O}_i^d$$

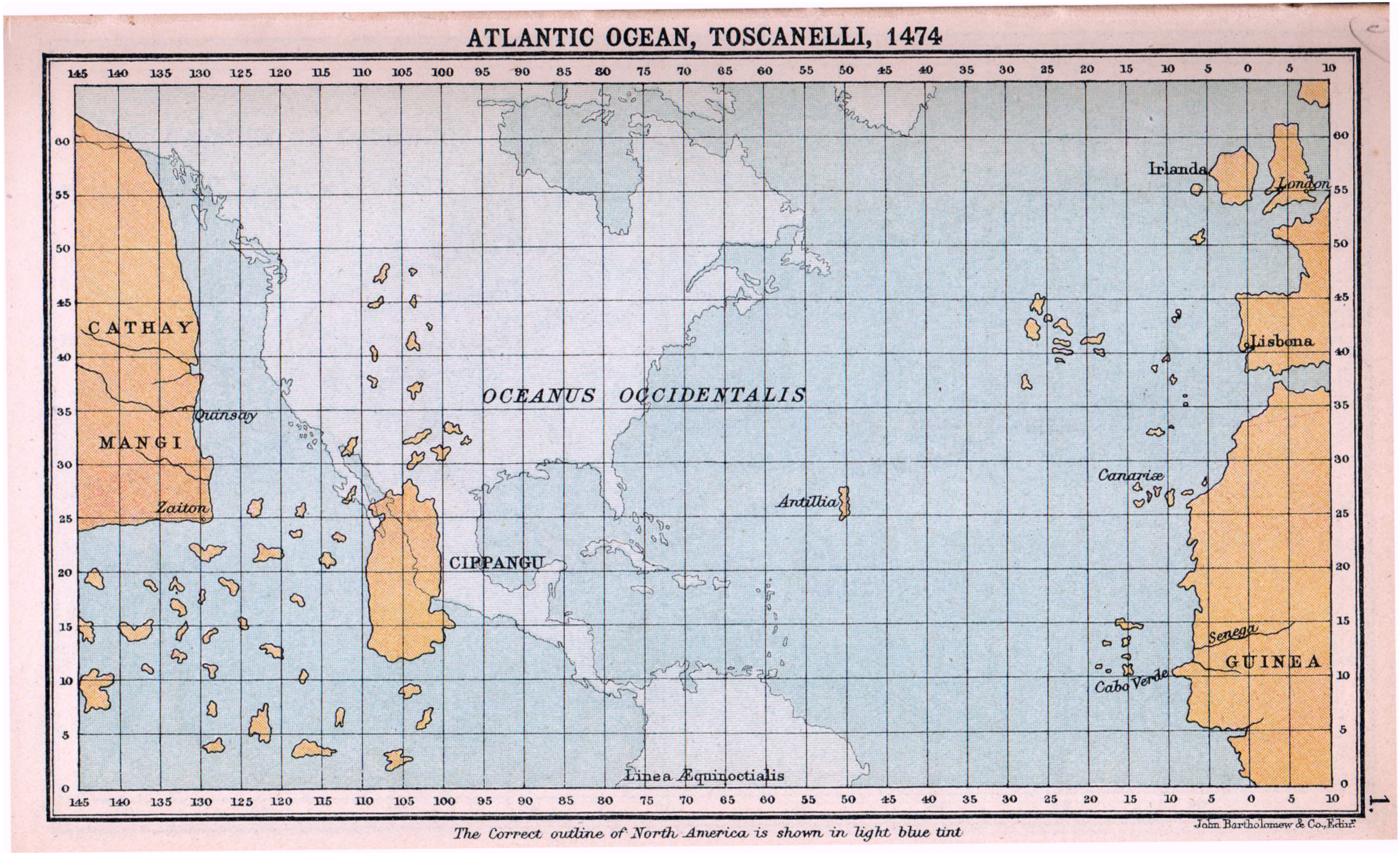
Non-trivial UV imprints




- ★ The SM Yukawas are very different because they originate at separate scales!
- ★ TeV-scale new physics dominantly coupled to the third and (to a lesser extent) second families
- ★ Direct production of new physics states at the LHC is naturally more suppressed [ new physics scale can be lower ]

[Barbieri, 2103.15635
Bordone et al., 1712.01368
Panico, Pomarol, 1603.06609
Dvali, Shiftman, '00, …]

# A closer look to the data and EFT analysis

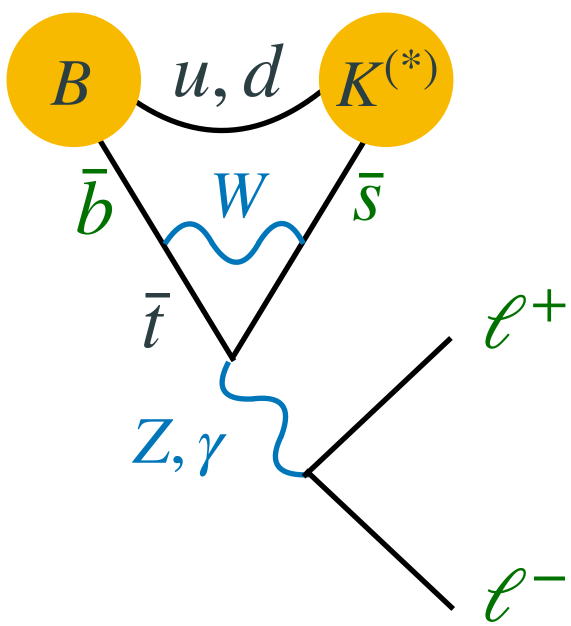


# The B anomalies

Hints of Lepton Flavour Universality Violation (LFUV) in semileptonic B decays

**$b \to s\ell^+\ell^-$**

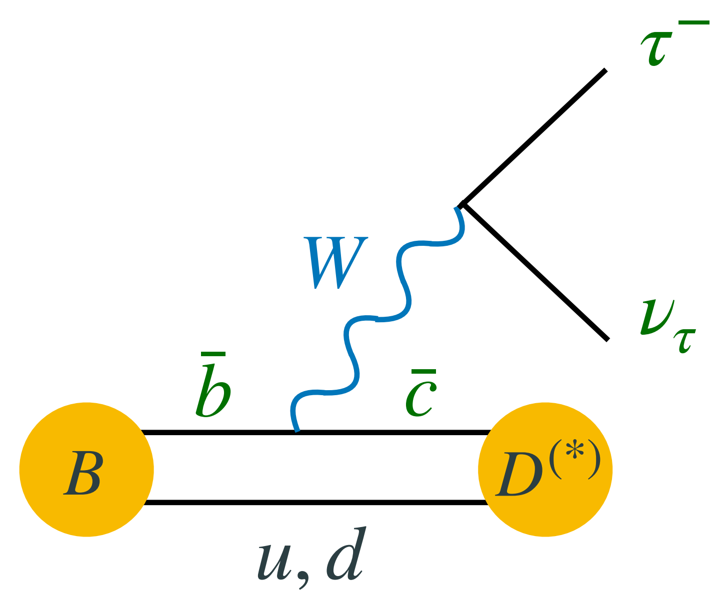
$\mu/e$ ~~universality~~




$> 4.5\,\sigma$

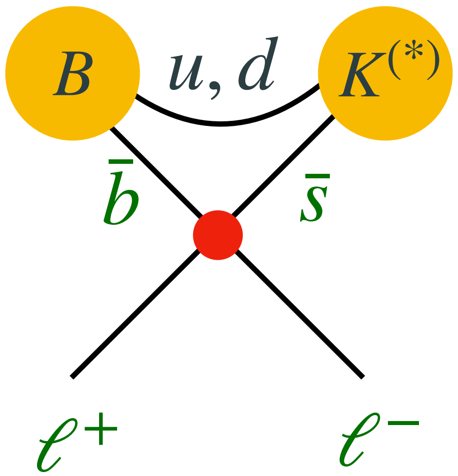
**$b \to c\tau\nu$**

$\tau/\mu\,,e$ ~~universality~~



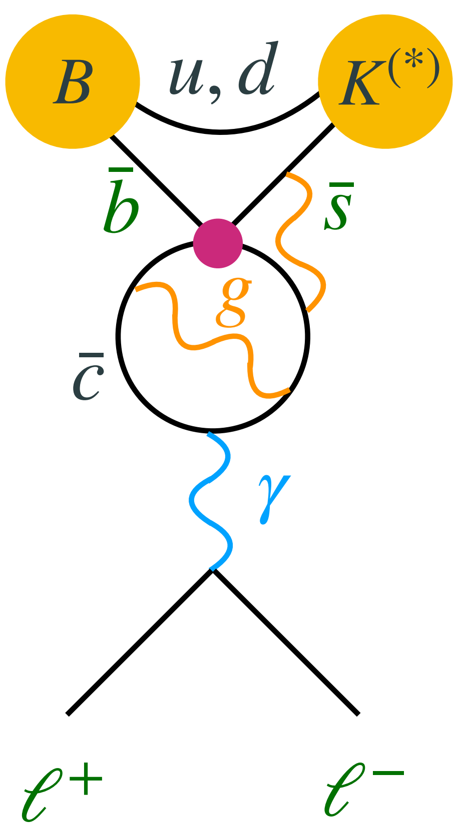

$\sim 3\,\sigma$

# Anatomy of $b \to s\ell^+\ell^-$ decays




**Short-distance**
(semileptonic int.)

"Easy" to compute



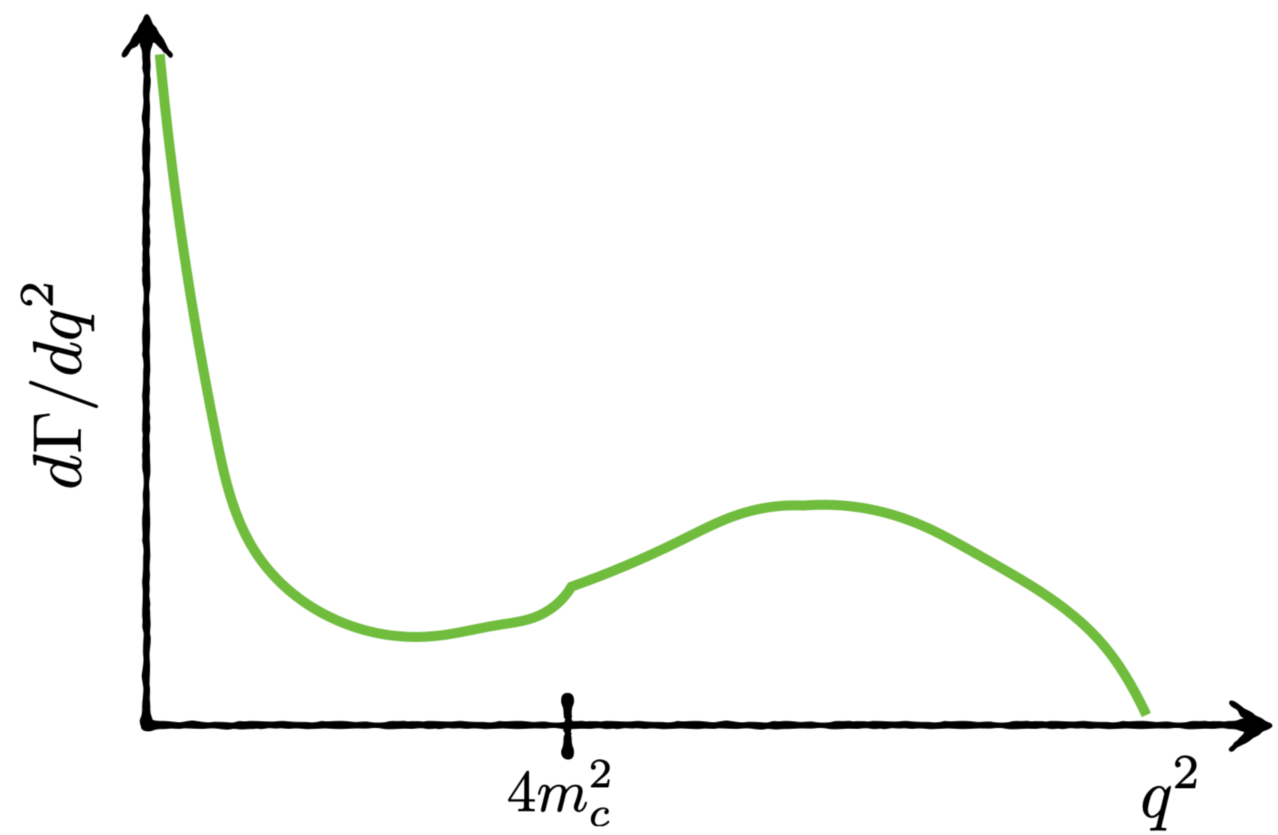

**Long-distance**
(four-quark int.)

Difficult to estimate

Induces a vectorial and lepton-universal contribution

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

In an ideal world

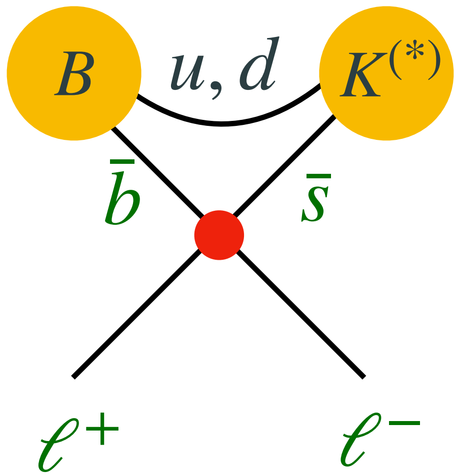



[Figure from Uli Haisch]

★ Long-distance effects cannot induce:

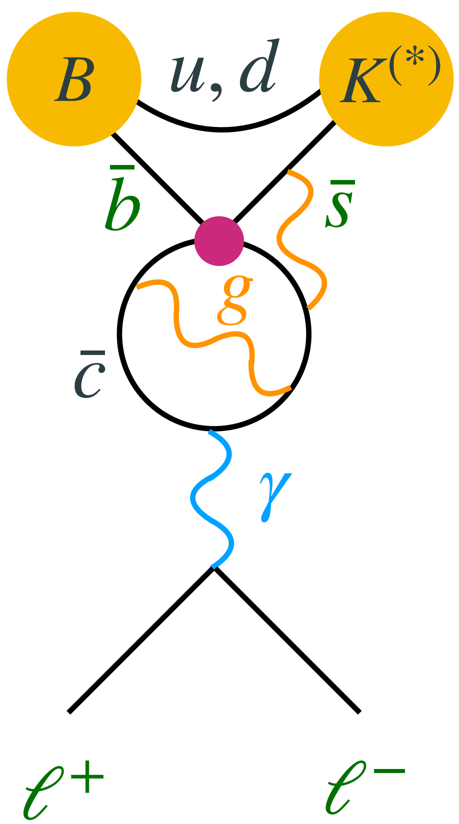
- Breakings of lepton universality
- Axial-current contributions ( no effect in $B_s \to \mu^+\mu^-$ )

# Anatomy of $b \to s\ell^+\ell^-$ decays




**Short-distance**
(semileptonic int.)

"Easy" to compute



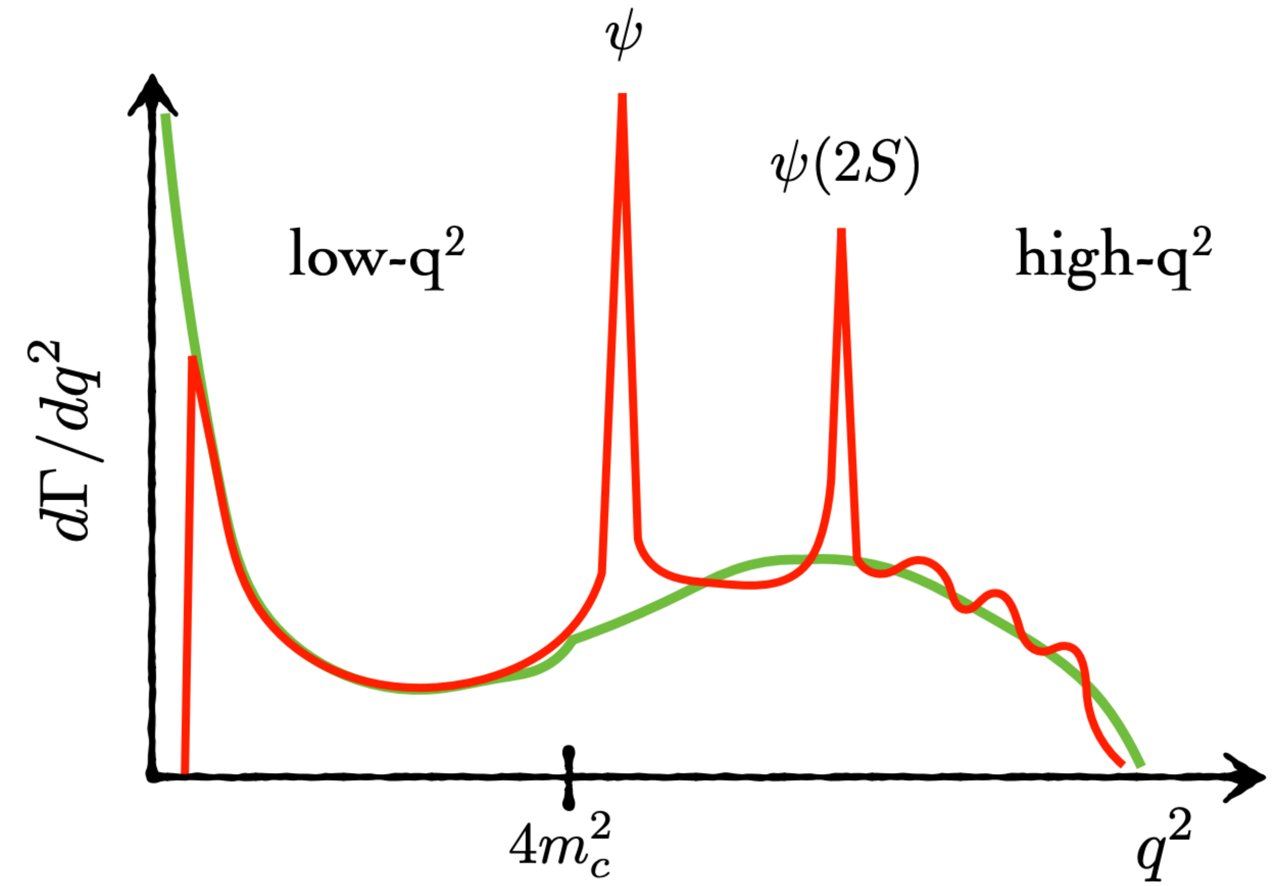

**Long-distance**
(four-quark int.)

Difficult to estimate

Induces a vectorial and lepton-universal contribution

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

… but in reality




[Figure from Uli Haisch]

★ Long-distance effects cannot induce:

- Breakings of lepton universality
- Axial-current contributions ( no effect in $B_s \to \mu^+\mu^-$ )

# The $b \to s\ell^+\ell^-$ anomalies

Since 2013, several "anomalies" started to appear in $B$-meson decays involving the $b \to s\ell^+\ell^-$ $[\ell = e, \mu]$ semileptonic transition [ **plenty of updates this year!** ]

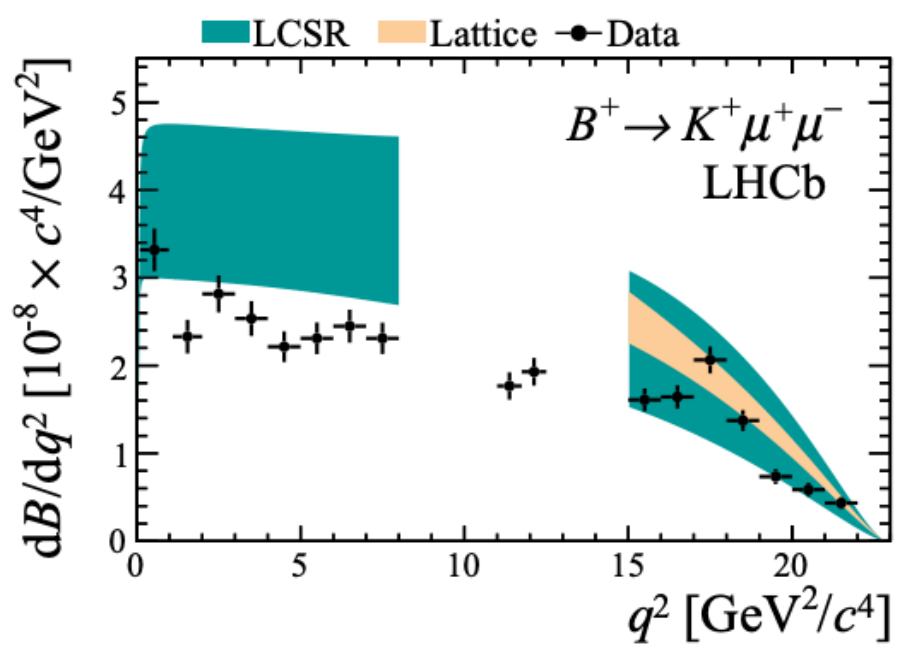
- ★ Deficit in the exclusive $B \to K^{(*)}\mu^+\mu^-$ and $B_s \to \phi\mu^+\mu^-$ decay rates [sizable QCD uncertainties (form factors and long-distance contributions)]
- ★ Deviations in optimized angular observables in $B \to K^*\mu^+\mu^-$ ($P_5'$ anomaly) [reduced theory errors but still sizable QCD uncertainties]
- ★ Deficit in the leptonic $B_s \to \mu^+\mu^-$ decay rate [**theoretically "clean":** theory error below $5\,\%$ (no charm loop)]
- ★ Departures from unity in lepton flavor universality ratios with $B \to K^{(*)}\ell^+\ell^-$ [**theoretically very "clean":** $1\,\%$ theory error (QED and lepton mass effects)]

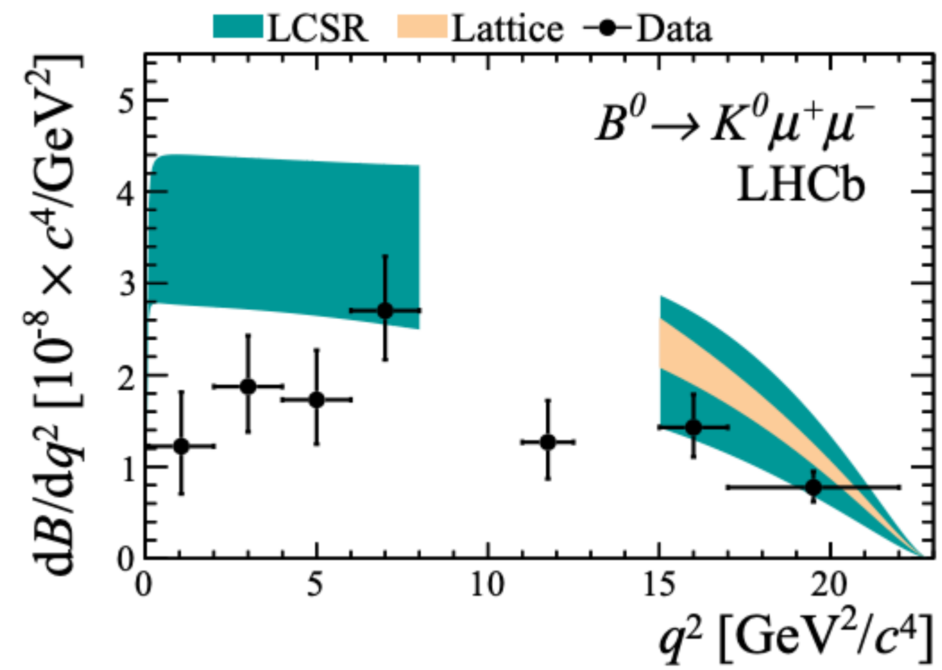
Theoretical robustness ↓

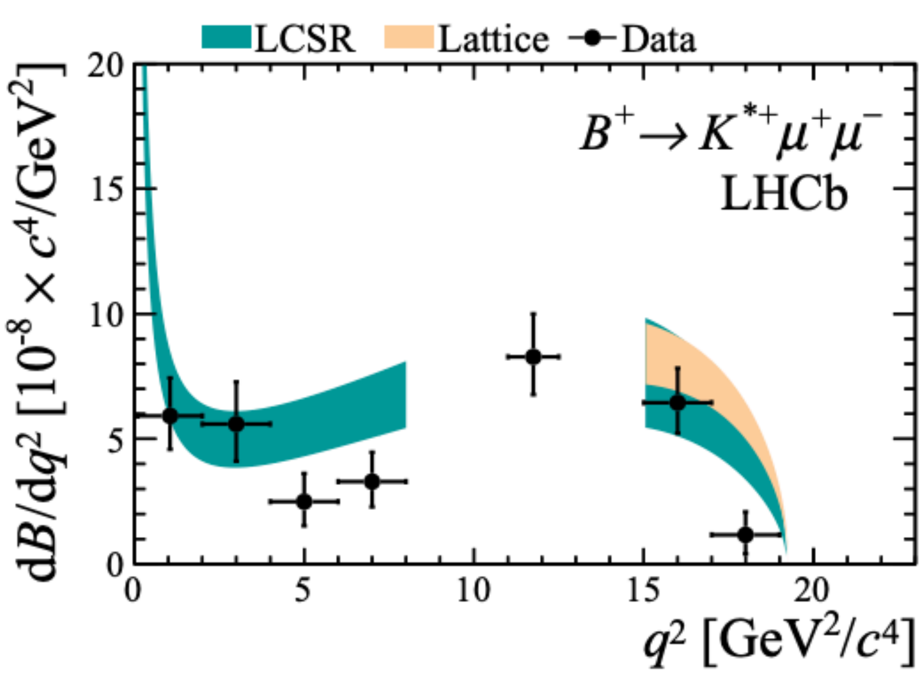
Remarkably, all this data point to **coherent NP effects**

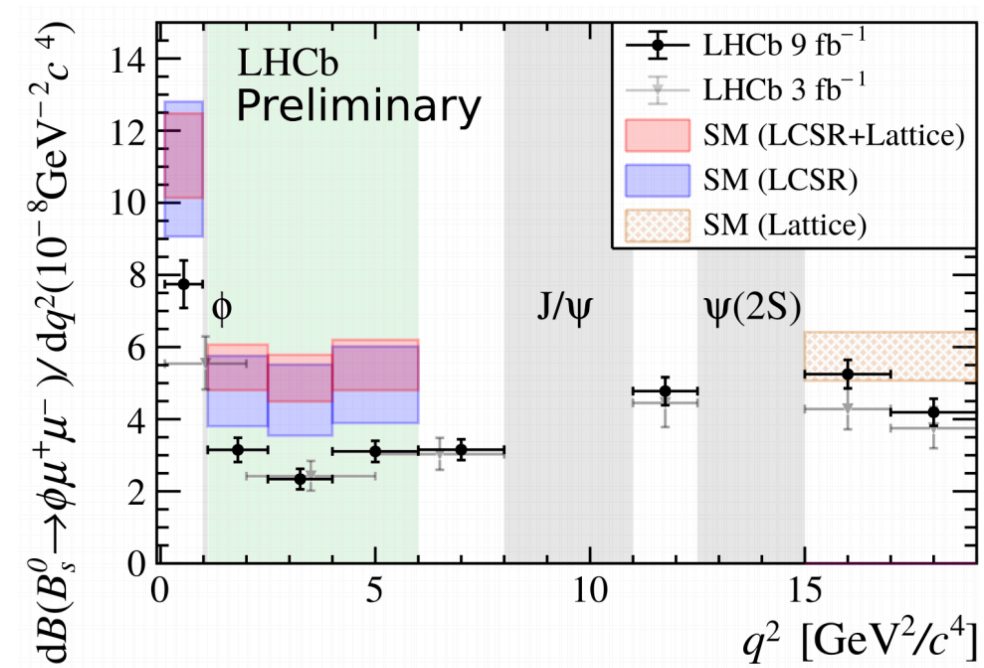
# The $b \to s\ell^+\ell^-$ anomalies

★ Deficit in the exclusive $B \to K^{(*)}\mu^+\mu^-$ and $B_s \to \phi\mu^+\mu^-$ decay rates [sizable QCD uncertainties form factors and long-distance contributions]



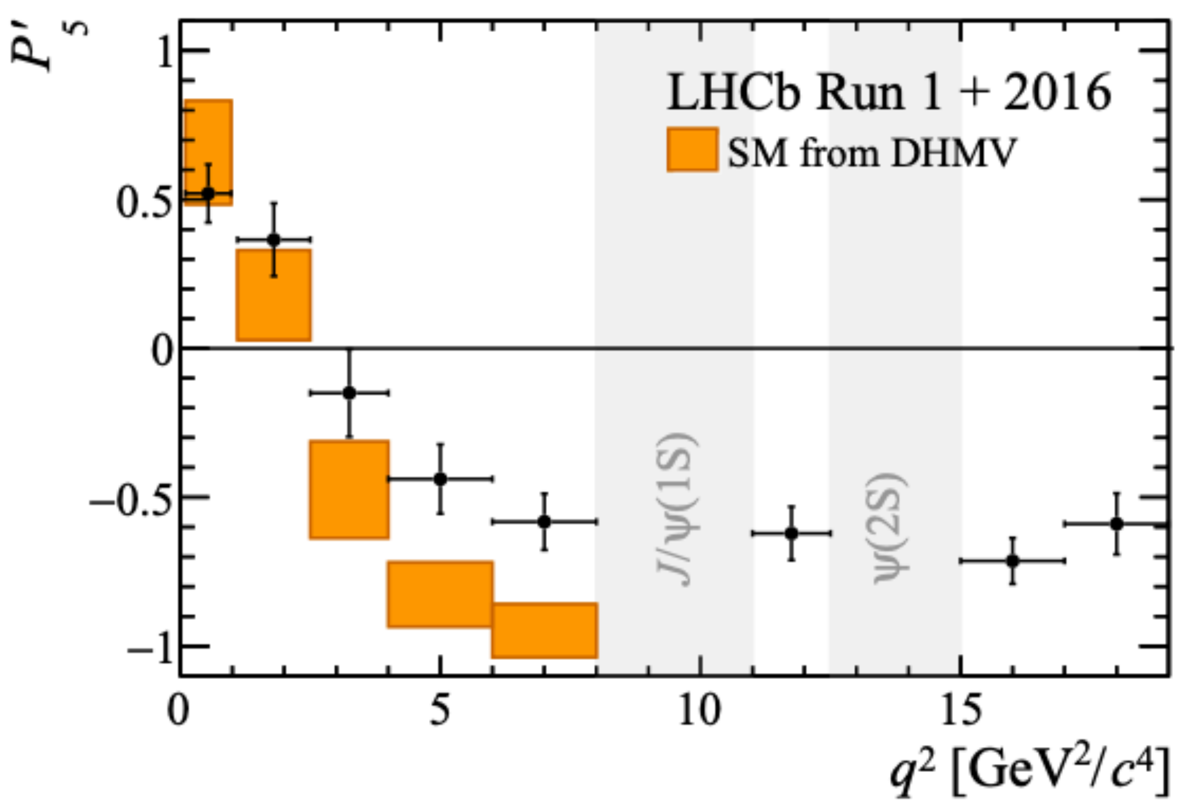



[LHCb, 1403.8044, 1506.08777, LHCB-PAPER-2021-014]

# The $b \to s\ell^+\ell^-$ anomalies

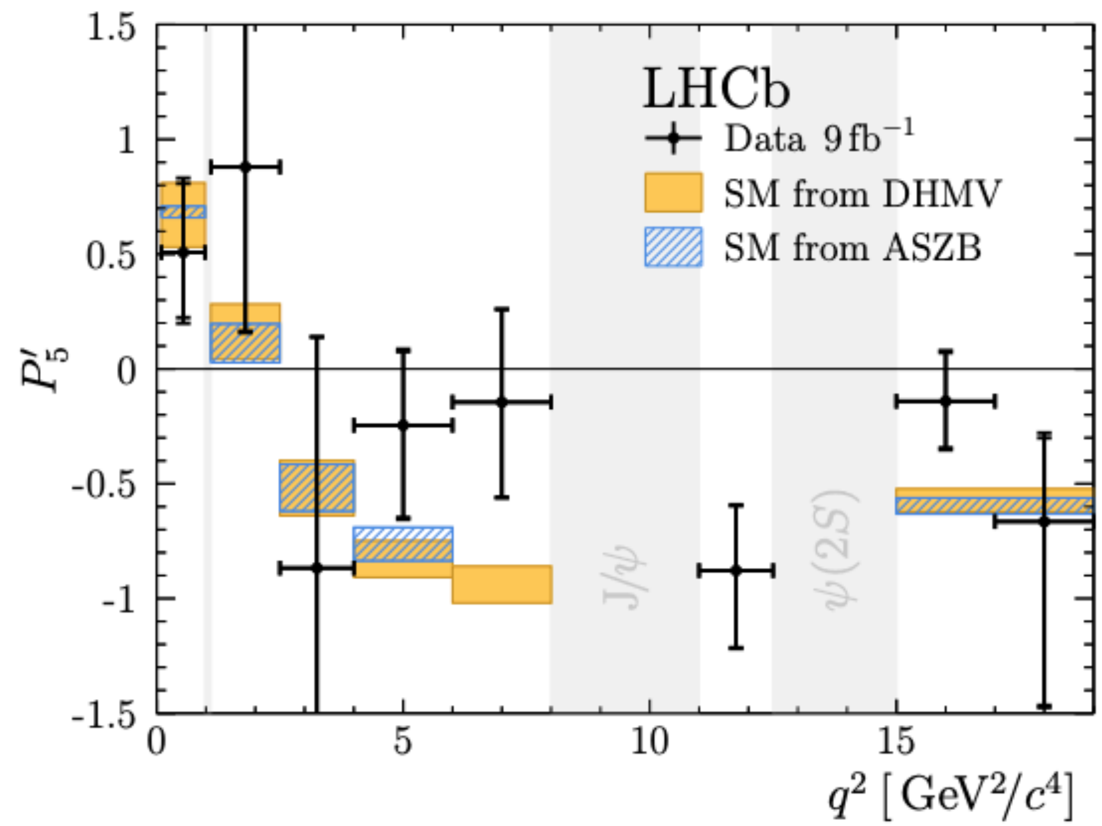
- ★ Deviations in optimized angular observables in $B \to K^*\mu^+\mu^-$ ($P_5'$ anomaly) [reduced theory errors but still sizable QCD uncertainties]

$B^0 \to K^{*0}\mu^+\mu^-$




[LHCb, 2003.04831]

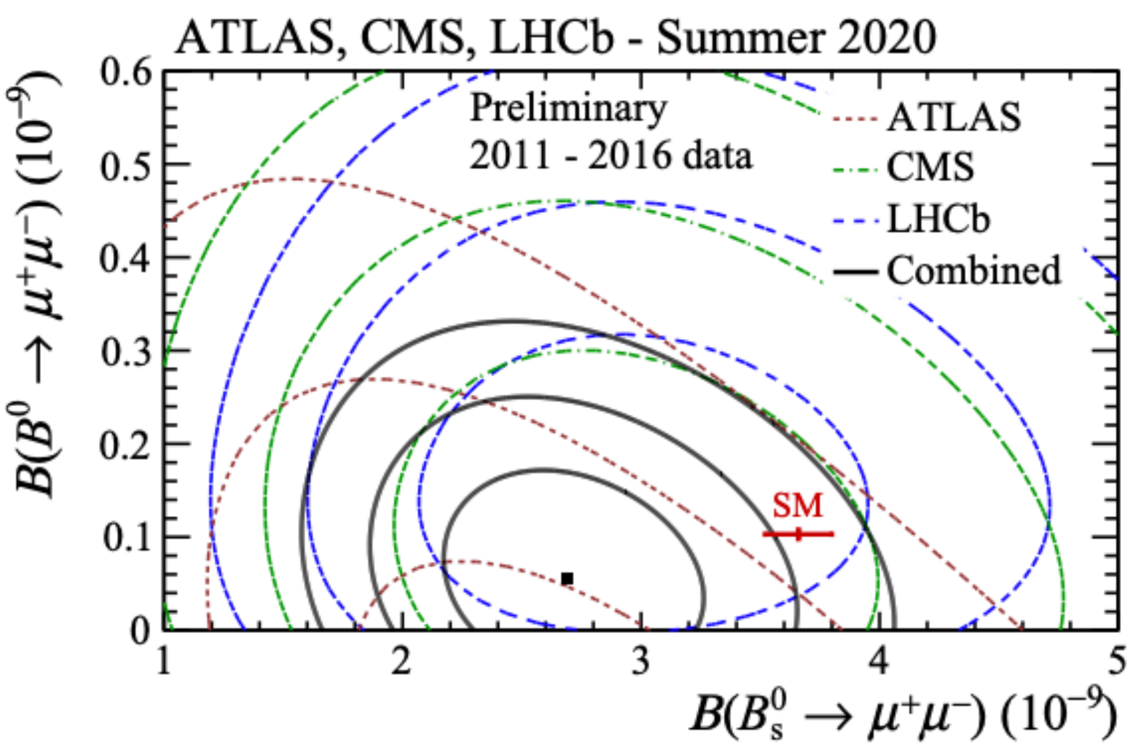
$B^+ \to K^{*+}\mu^+\mu^-$



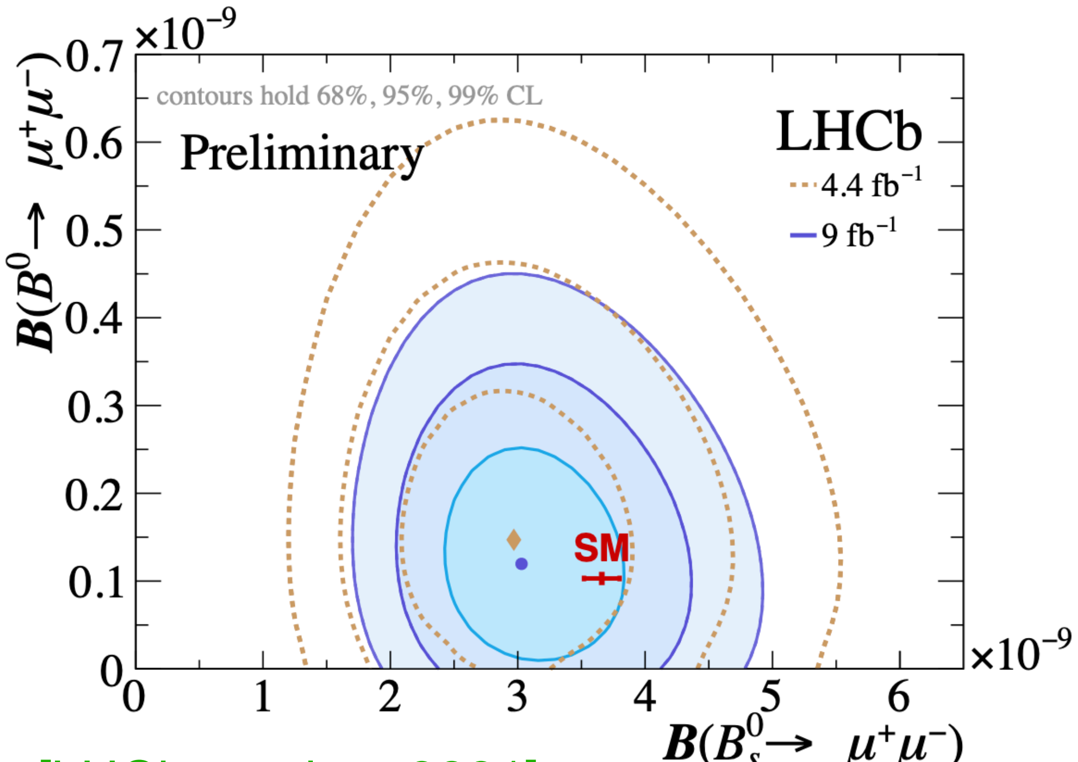

[LHCb, 2012.13241]

# The $b \to s\ell^+\ell^-$ anomalies

★ Deficit in the leptonic $B_s \to \mu^+\mu^-$ decay rate
[**theoretically "clean":** theory error below $5\,\%$ (no charm loop)]




[ATLAS-CONF-2020-049]




[LHCb seminar 2021]

$$\mathscr{B}(B_s \to \mu^+\mu^-)_{\rm exp} = (2.85^{+0.32}_{-0.31}) \times 10^{-9}$$

$$\mathscr{B}(B_s \to \mu^+\mu^-)_{\rm SM} = (3.66 \pm 0.14) \times 10^{-9}$$

$2.3\sigma$ deviation from the SM prediction

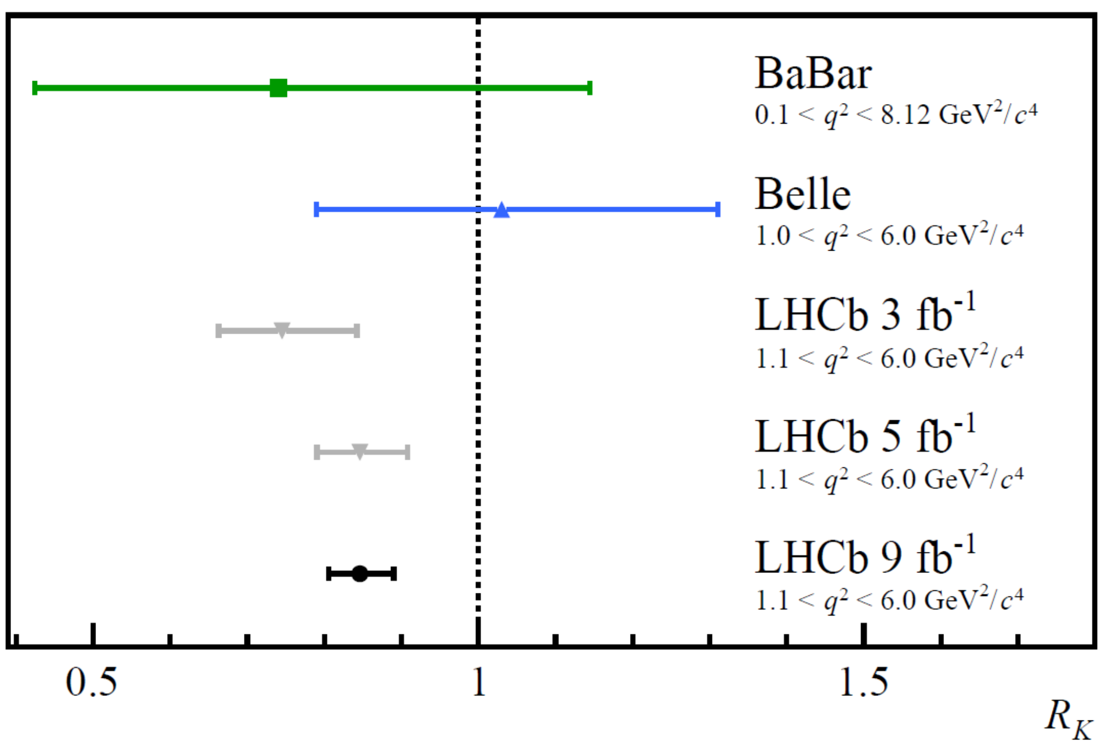
# The $b \to s\ell^+\ell^-$ anomalies

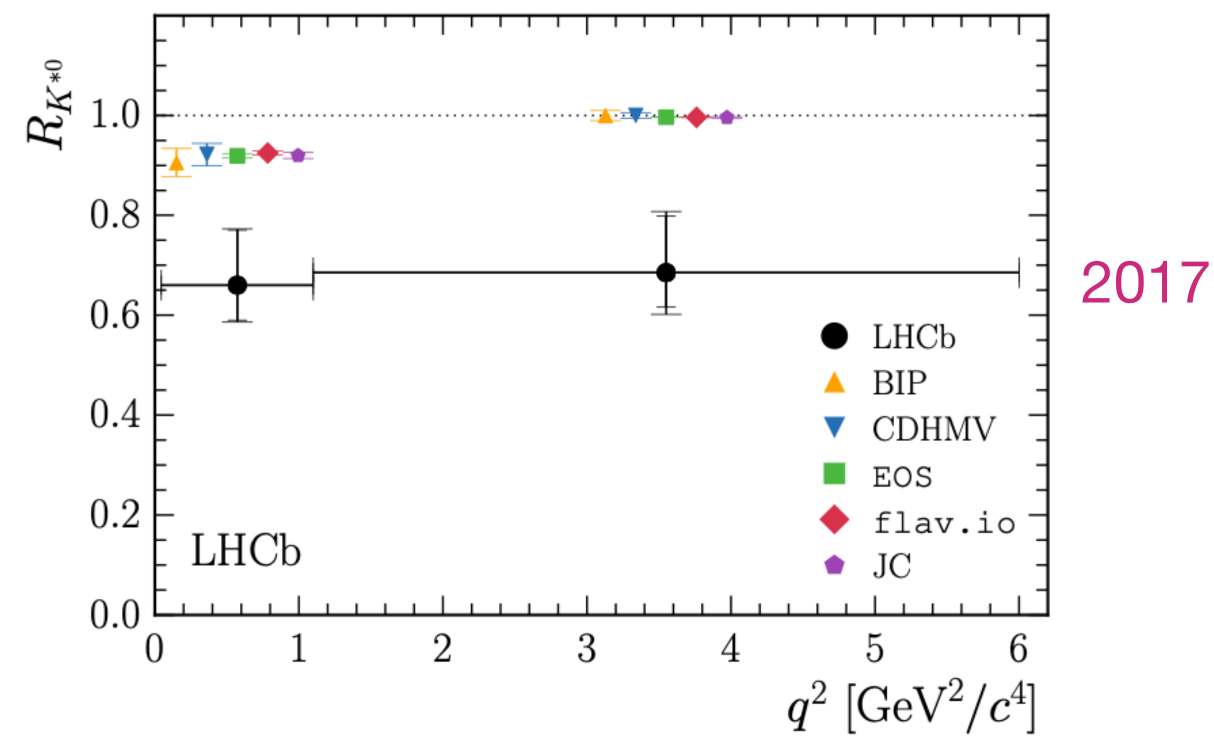
★ Departures from unity in lepton flavor universality ratios with $B \to K^{(*)}\ell^+\ell^-$ [**theoretically very "clean":** $1\,\%$ theory error (QED and lepton mass effects)]

$$R_{K^{(*)}}^{[q^2_{\min},q^2_{\max}]} \equiv \frac{\int_{q^2_{\min}}^{q^2_{\max}} d\Gamma(B \to K^{(*)}\mu^+\mu^-)}{\int_{q^2_{\min}}^{q^2_{\max}} d\Gamma(B \to K^{(*)}e^+e^-)}$$

$$R_{K^{(*)}}^{[1.1,6]\ \mathrm{GeV}^2} = 1.00 \pm 0.01$$

[Isidori, Bordone, Pattori, 1605.07633]




Evidence for LFUV in $R_K$ [ $3.1\sigma$ ]

[LHCb, 2103.11769]

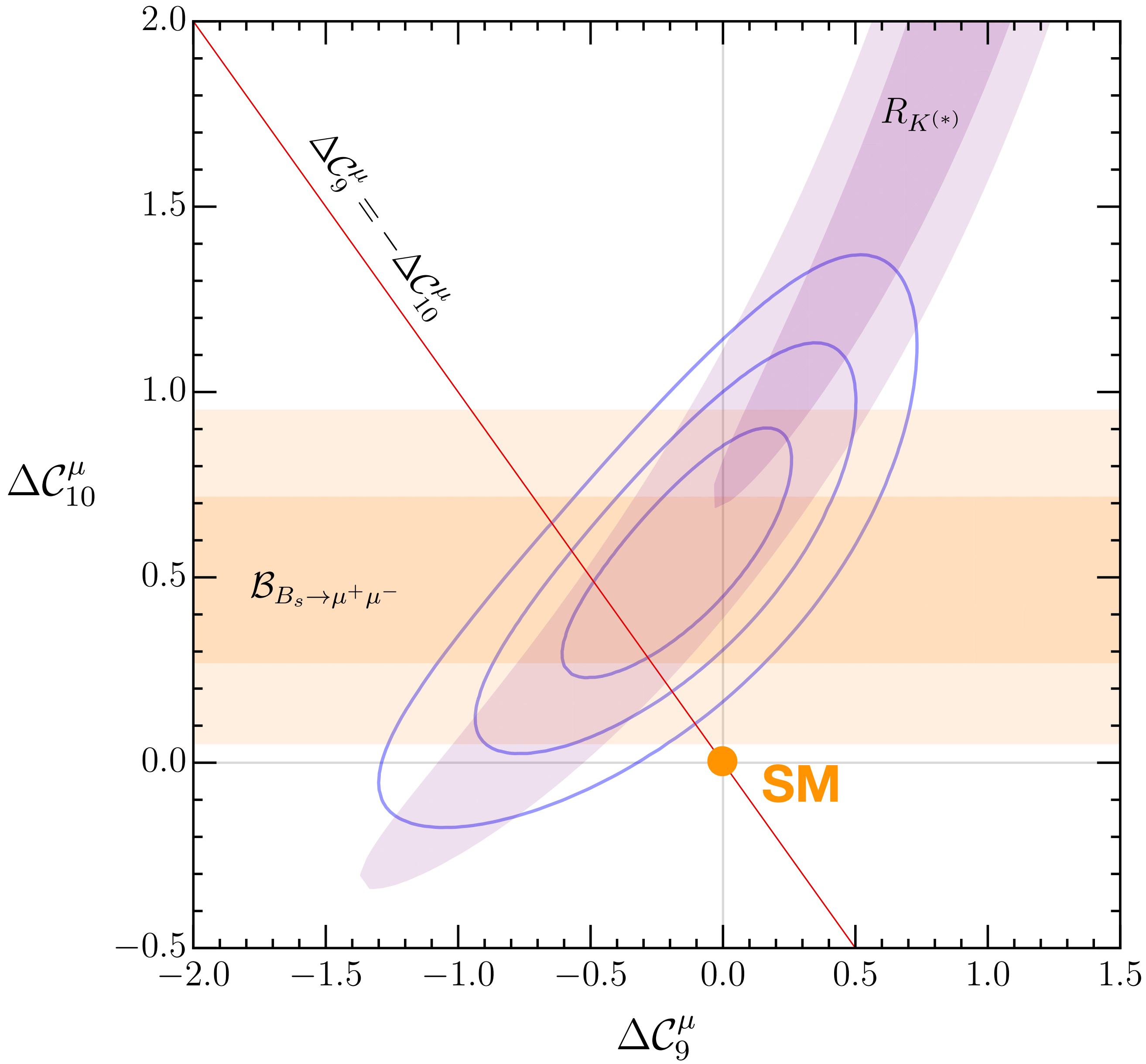
$2\sigma - 2.5\sigma$ deviations in $R_{K*}$

[LHCb, 1705.05802]

# The $b \to s\ell^+\ell^-$ anomalies

**Conservative fit** using "clean observables" only

$[C_i^\mu = C_i^{SM} + \Delta C_i^\mu + \Delta C_9^U,\ C_i^e = C_i^{SM} + \Delta C_9^U]$



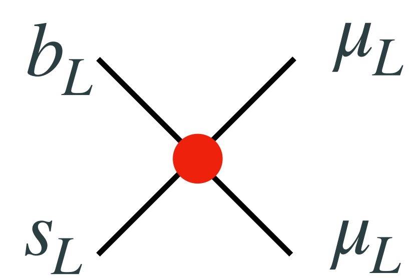

[Cornella et al., 2103.16558]

$$\mathscr{L}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \frac{\alpha}{4\pi} \sum_i C_i \mathcal{O}_i$$

$$\mathcal{O}_9^\mu = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}\gamma^\mu \mu) \qquad C_9^{SM} \approx 4.1$$

$$\mathcal{O}_{10}^\mu = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}\gamma^\mu \gamma_5 \mu) \qquad C_{10}^{SM} \approx -4.2$$

Left-handed new physics hypothesis ($\Delta C_9^\mu = -\Delta C_{10}^\mu$) preferred over the SM by $4.6\sigma$



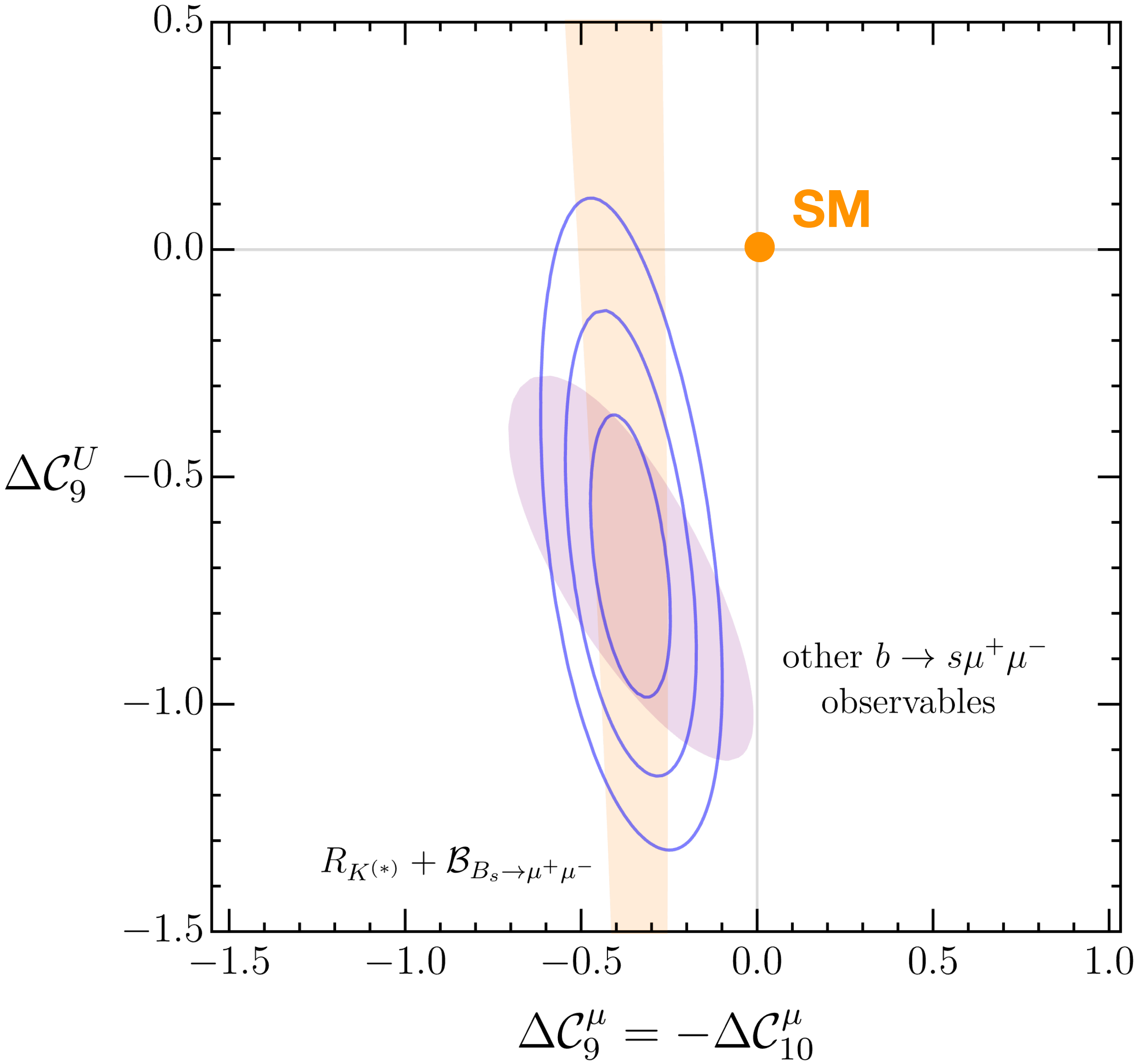

$\sim 3 \times 10^{-5}\, G_F$

$$\Longrightarrow \frac{g_{\rm NP}^2}{M_{\rm NP}^2} \sim \frac{1}{(40\ {\rm TeV})^2}$$

# The $b \to s\ell^+\ell^-$ anomalies

Fit using all observables

$[C_i^\mu = C_i^{\rm SM} + \Delta C_i^\mu + \Delta C_9^U,\ C_i^e = C_i^{\rm SM} + \Delta C_9^U]$

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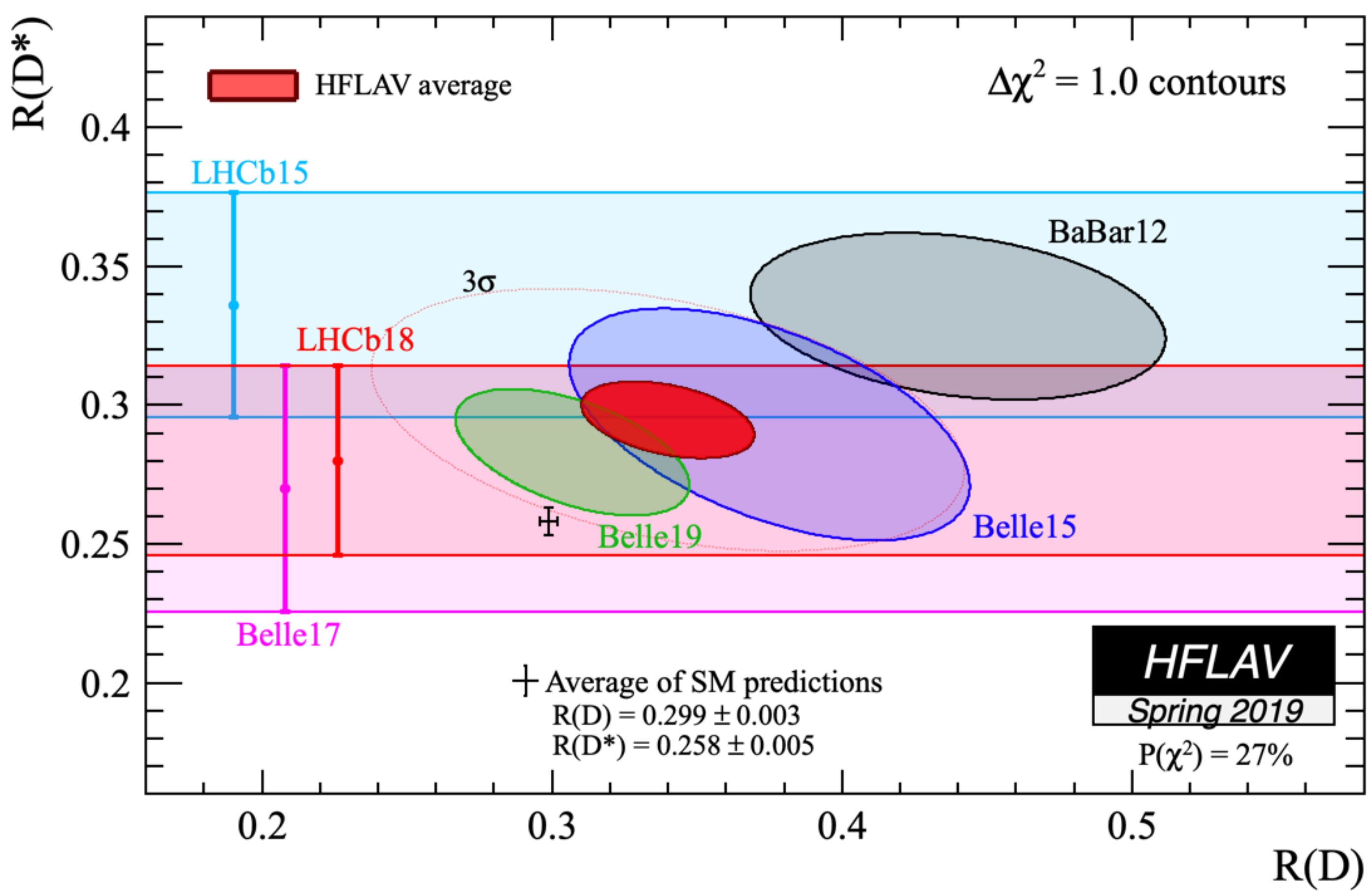
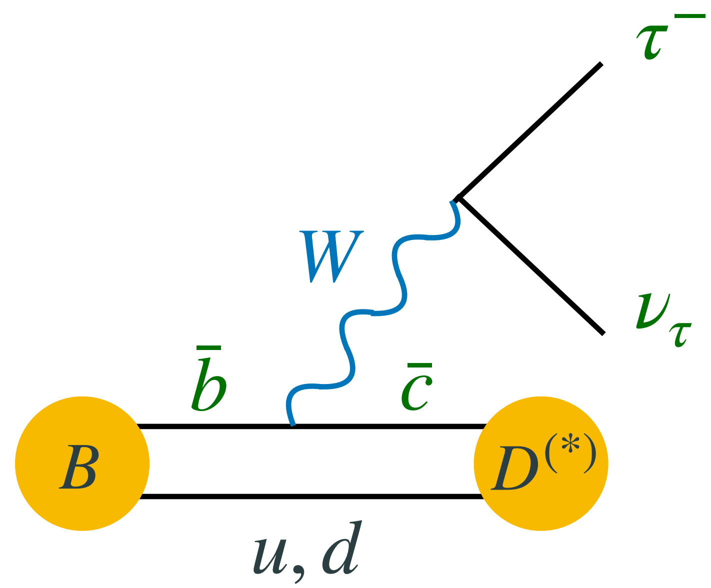
$$\mathcal{O}_{10}^\mu = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu} \gamma^\mu \gamma_5 \mu) \qquad C_{10}^{\rm SM} \approx -4.2$$

Adding all $b \to s\ell\ell$ measurements [ $\mathcal{O}(100)$ observables ] with the current best estimate of the QCD contributions, the significance of the new physics hypothesis grows to well over $5\sigma$

[Altmannshofer, Stangl, 2103.13370;
Algueró et al, 2104.08921;
Hurth et al. 2104.10058...]

# The $b \to c\tau\bar{\nu}$ anomalies




**Clean observable:** QCD uncertainties cancel (to a large extent) in the ratios

$$R_{D^{(*)}} \equiv \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})} \qquad [\ell = e, \mu]$$

Consistent result by three experiments (BaBar, Belle and LHCb) show a $3.1\sigma$ deviation ($R_D$ and $R_{D^*}$ comb.)

$$R_{D^*}/R_{D^*}^{\rm SM} = 1.14 \pm 0.05$$

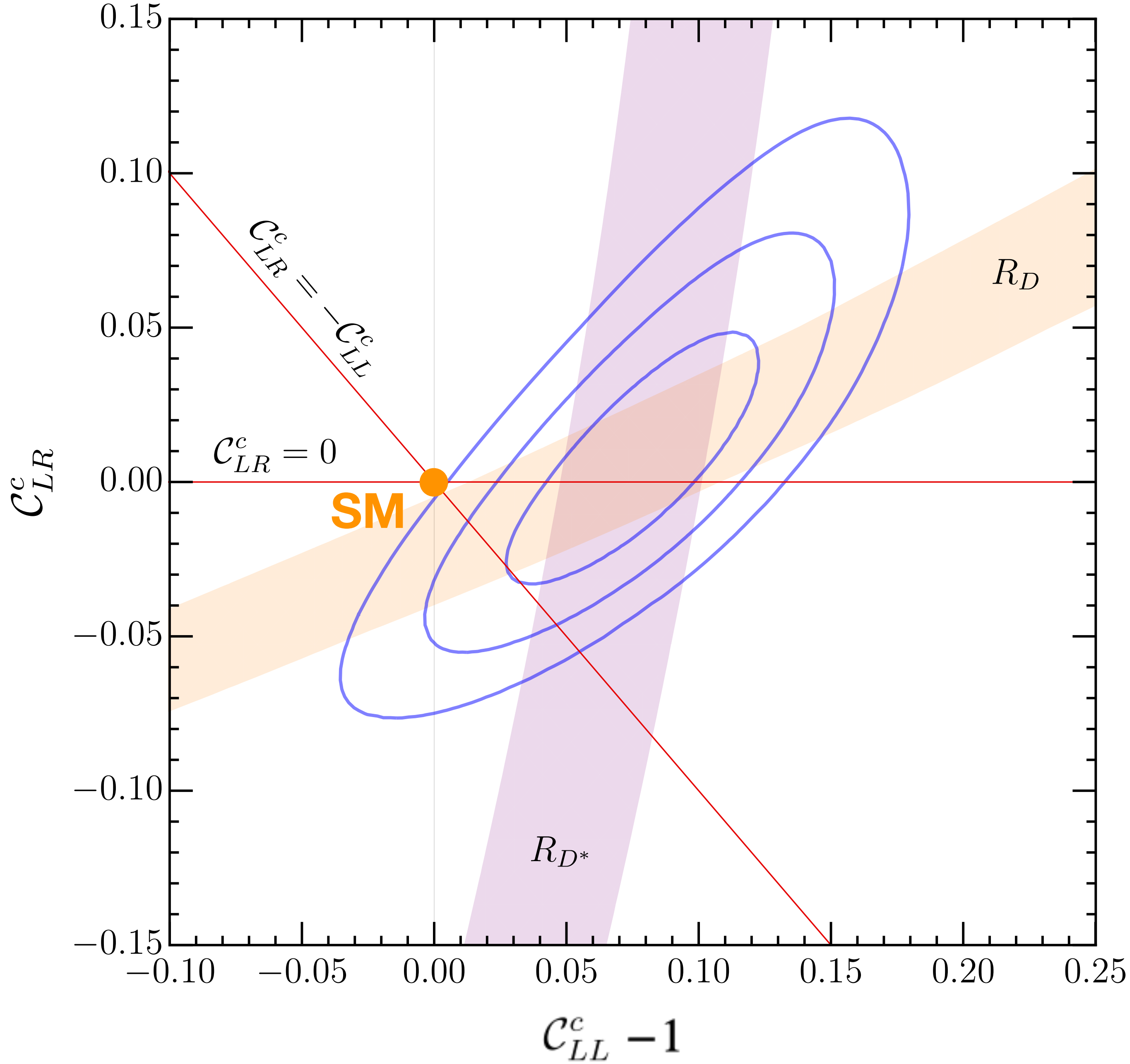
$$\rho = -0.38$$

$$R_D/R_D^{\rm SM} = 1.14 \pm 0.10$$

N.B.: SM different from unity due to $\tau$ mass effects (phase space)

# The $b \to c\tau\bar{\nu}$ anomalies

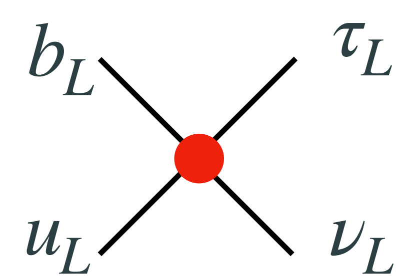
$$\mathscr{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{cb} \sum_i C_i \mathscr{O}_i$$




$$\mathscr{O}^i_{LL} = (\bar{u}^i_L \gamma_\mu \nu_L)(\bar{\tau}_L \gamma^\mu b_L) \qquad C^{\text{SM}}_{LL} = 1$$

$$\mathscr{O}^i_{LR} = (\bar{u}^i_L \gamma_\mu \nu_L)(\bar{\tau}_R \gamma^\mu b_R) \qquad C^{\text{SM}}_{LR} = 0$$

Preference for left-handed type new physics [ analogous to the SM ]



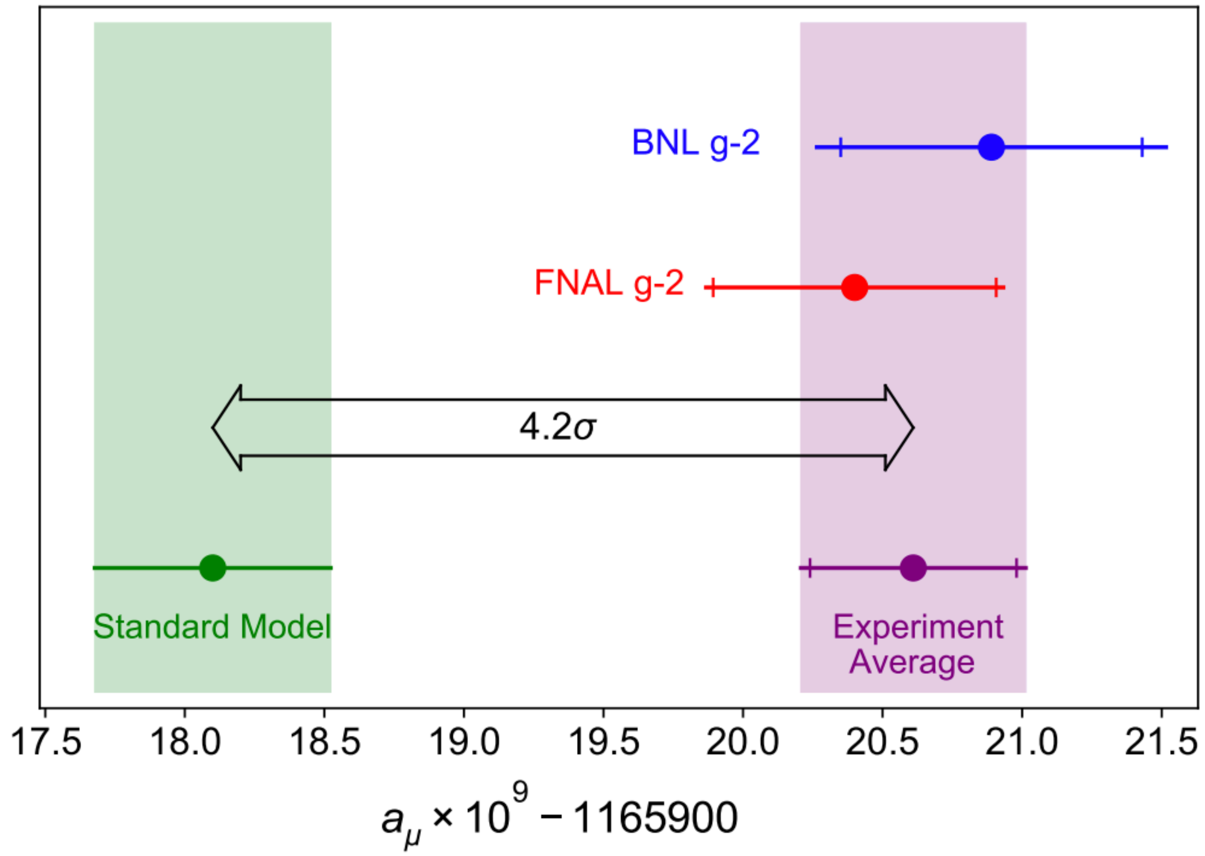

$$\sim 10^{-2}\, G_F$$

$$\Longrightarrow \frac{g^2_{\text{NP}}}{M^2_{\text{NP}}} \sim \frac{1}{(2\ \text{TeV})^2}$$

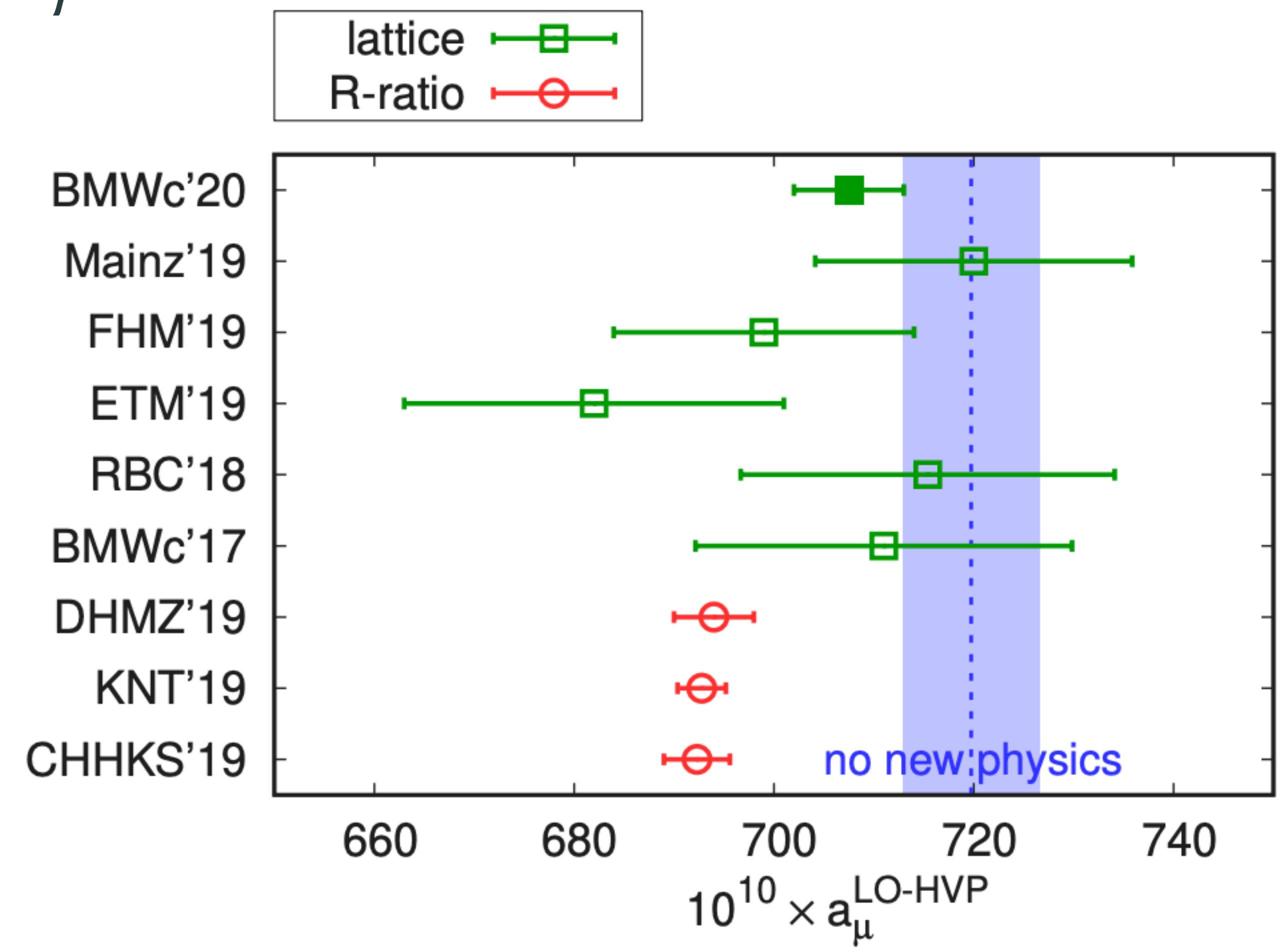
Although other new physics structures are also possible

[Cornella et al., 2103.16558]

# A brief comment on $(g-2)_\mu$




[Muon g-2 collaboration, 2104.03281]




[Borsanyi et al., 2002.12347]

Recent confirmation by Fermilab of the Brookhaven experimental result [strong evidence of new physics $4.2\sigma$ (Fermilab + Brookhaven comb.)]

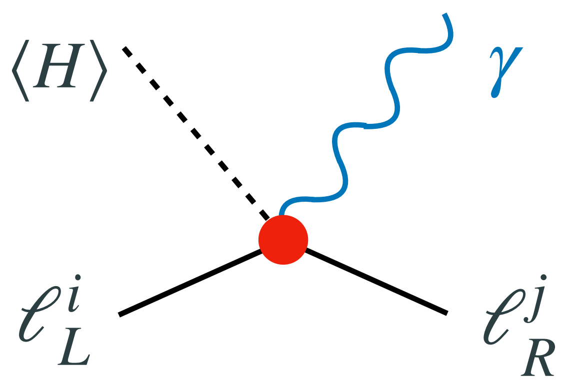
While the SM prediction is dominated by QED, the SM error is dominated by QCD [current evaluation uses data-driven methods ($R$-ratio)… in tension with BMW lattice]

# A brief comment on $(g-2)_\mu$

The discrepancy is roughly the same size as the SM electroweak contribution

$$\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}} \approx (a_\mu^{\text{SM}})_{\text{EW}} \approx \frac{m_\mu^2}{16\pi^2} \times \frac{4\,G_F}{\sqrt{2}} \approx 3\times 10^{-9} \qquad a_\mu \equiv \frac{g_\mu - 2}{2}$$

⟶ NP is either light or is **not chirally suppressed**




$$\frac{\mathcal{B}(\mu\to e\gamma)}{3\times 10^{-13}} \approx \left(\frac{\Delta a_\mu}{3\times 10^{-9}}\right)^2 \left(\frac{\theta_{12}}{10^{-5}}\right)^2$$

$$\frac{\mathcal{B}(\tau\to \mu\gamma)}{4\times 10^{-8}} \approx \left(\frac{\Delta a_\mu}{3\times 10^{-9}}\right)^2 \left(\frac{\theta_{23}}{10^{-2}}\right)^2$$

Naive expectation:

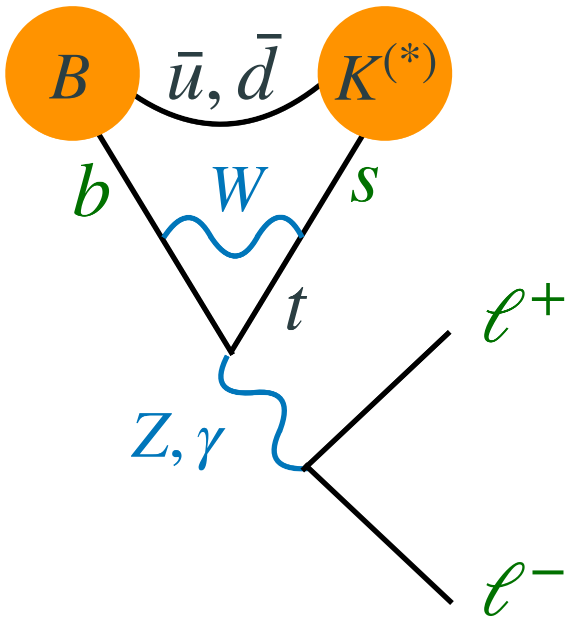
$\theta_{12}^2 \sim m_e/m_\mu \approx 5\times 10^{-3}$

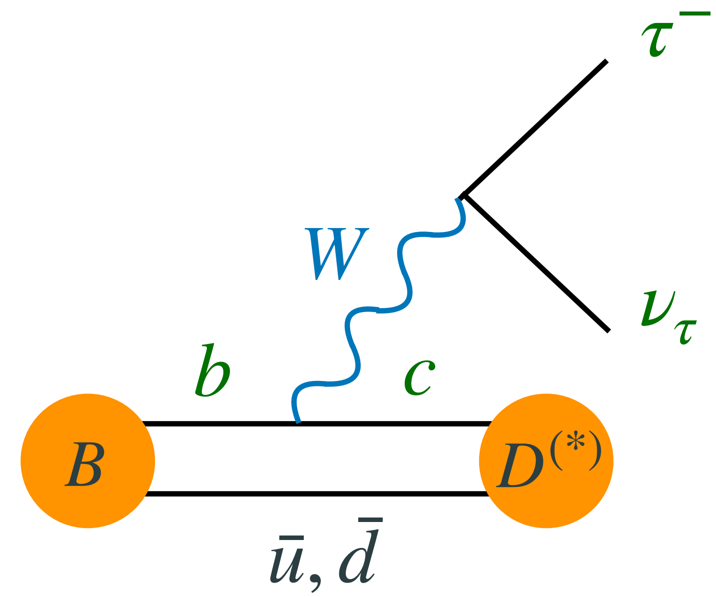
$\theta_{23}^2 \sim m_\mu/m_\tau \approx 6\times 10^{-2}$

⟶ NP should be **nearly lepton flavor conserving**

Not easy to reconcile $(g-2)_\mu$ with both $B$ anomalies and, more generally, with models with a “natural” flavor structure ( i.e. similar to that of the SM Yukawa )

# Combined explanation of B anomalies: Theoretical hint




$3_Q \to 2_Q 2_L 2_L$ $\ll$ $3_Q \to 2_Q 3_L 3_L$

~10% of a SM loop effect

~10% of a SM tree-level effect

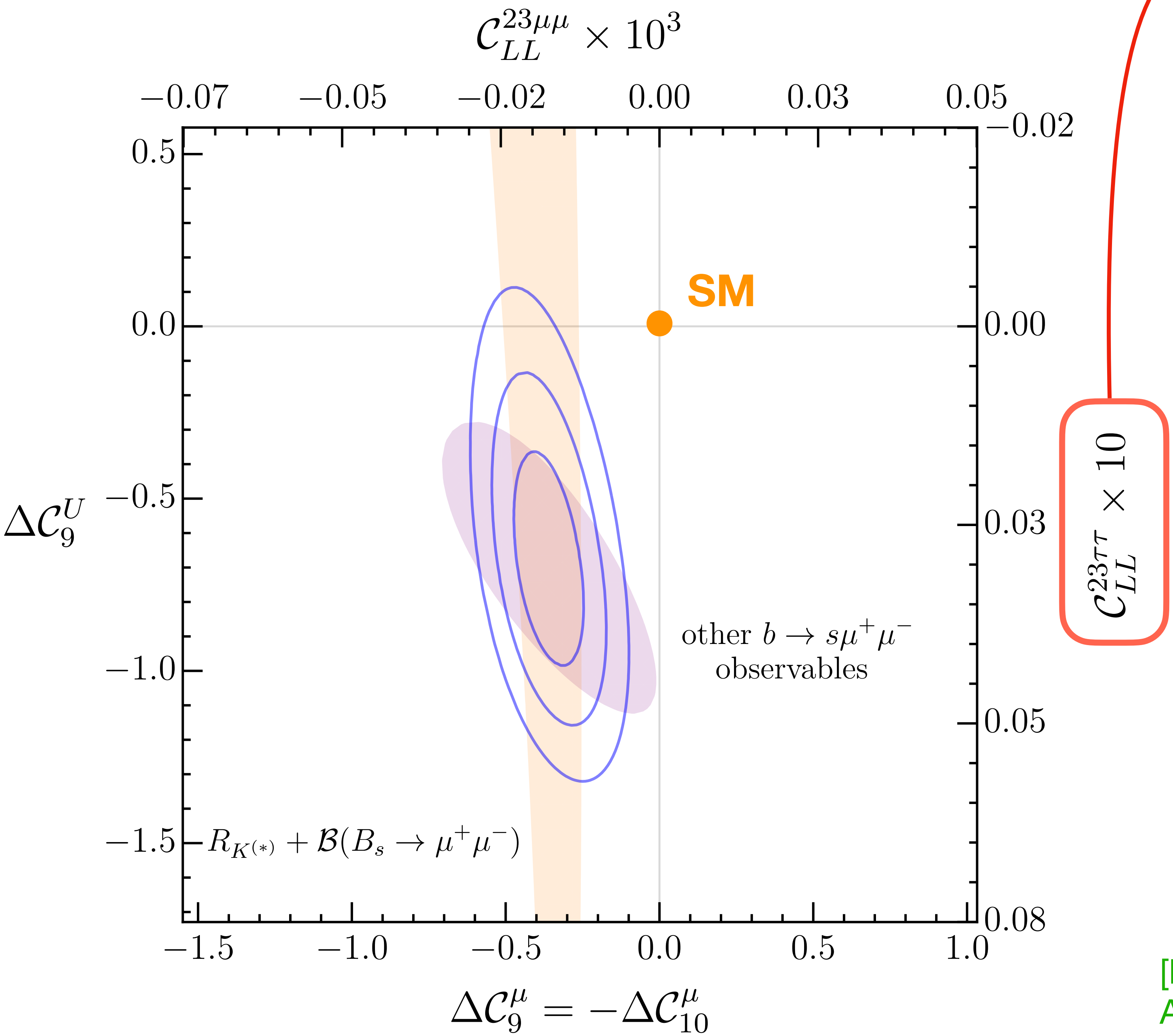
The only source of lepton flavor universality violation in the SM (Yukawas) follows a very similar trend: $y_e \ll y_\mu \ll y_\tau$

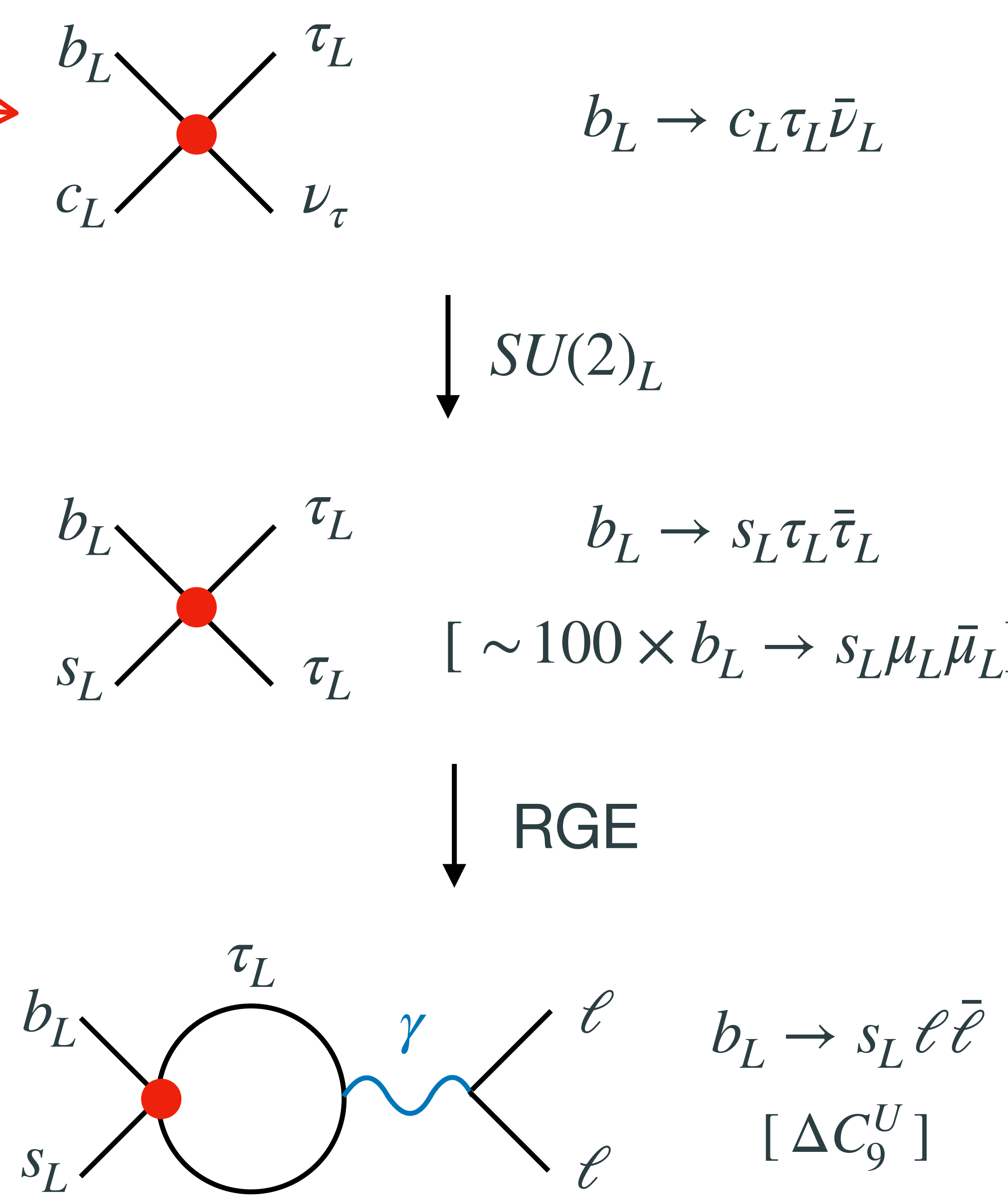
Combined explanation with TeV-scale new physics dominantly coupled to 3rd family with $\mathcal{O}(0.1)$ suppressed couplings to 2nd family

[ Hints of underlying (flavor) symmetries and/or solutions to the SM flavor puzzle? ]

# Combined explanation of B anomalies: Pheno hint

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




[Bobeth, Haisch, 1109.1826; Crivellin et al., 1807.02068; Algueró et al., 1809.08447]

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

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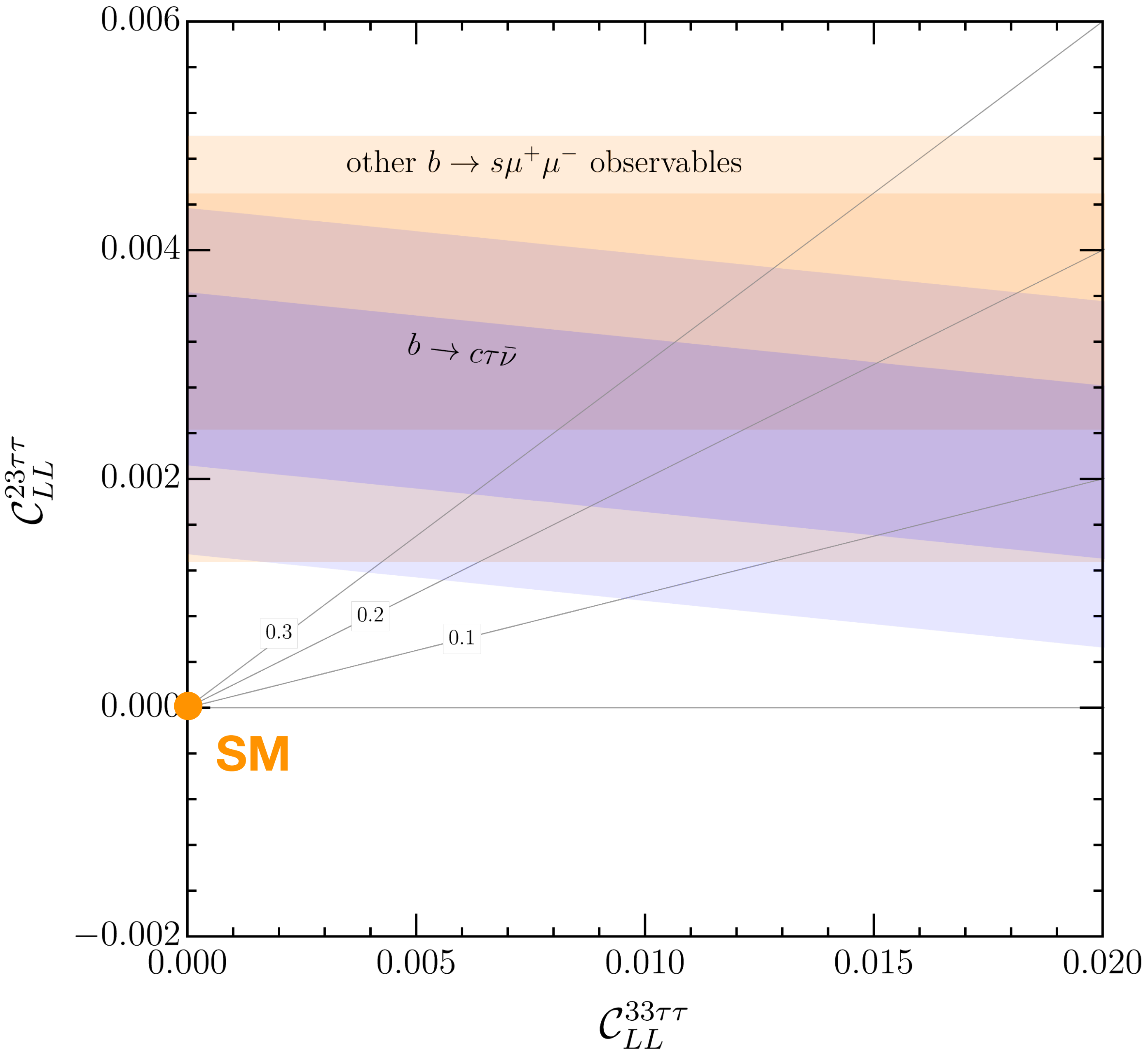
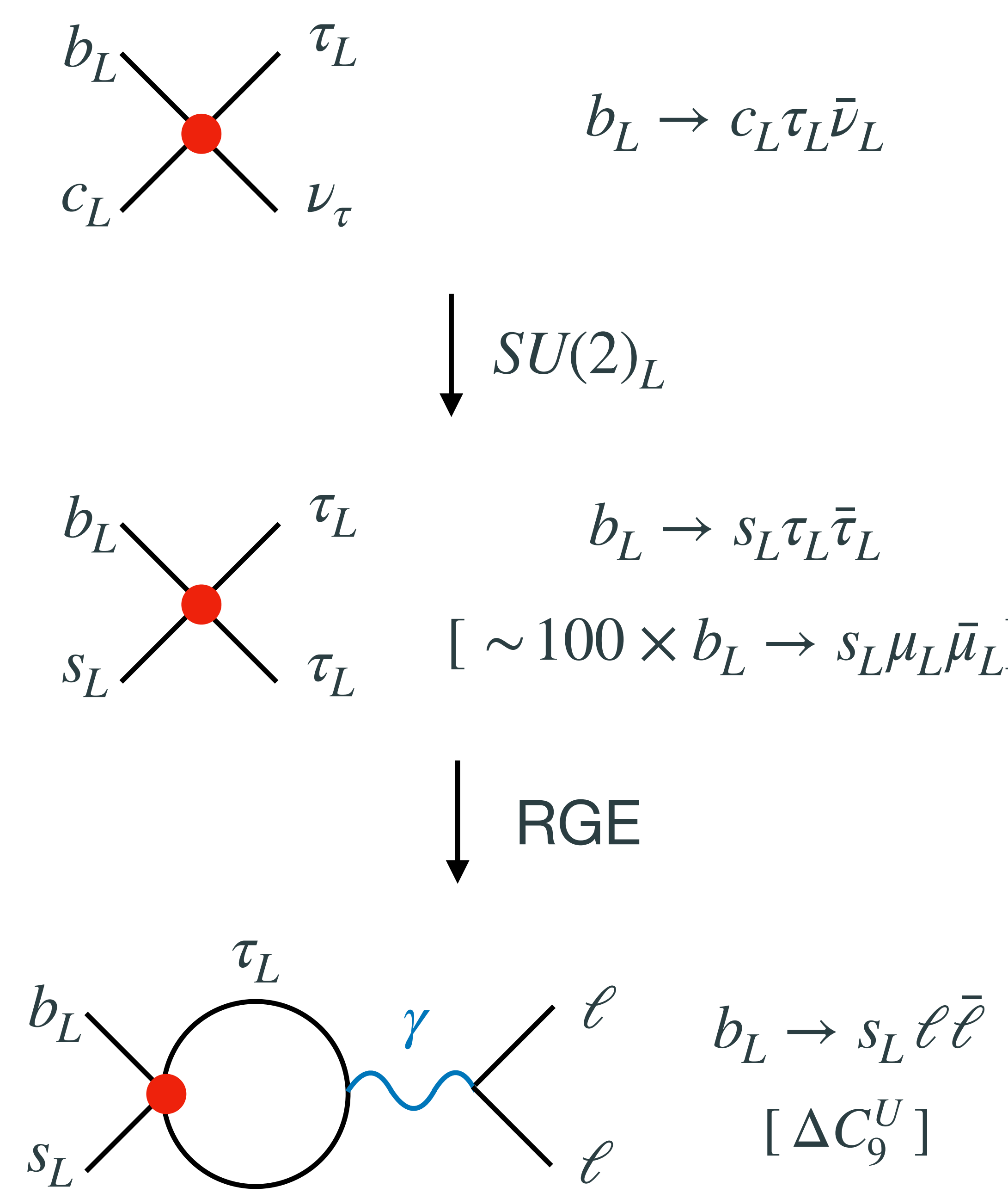
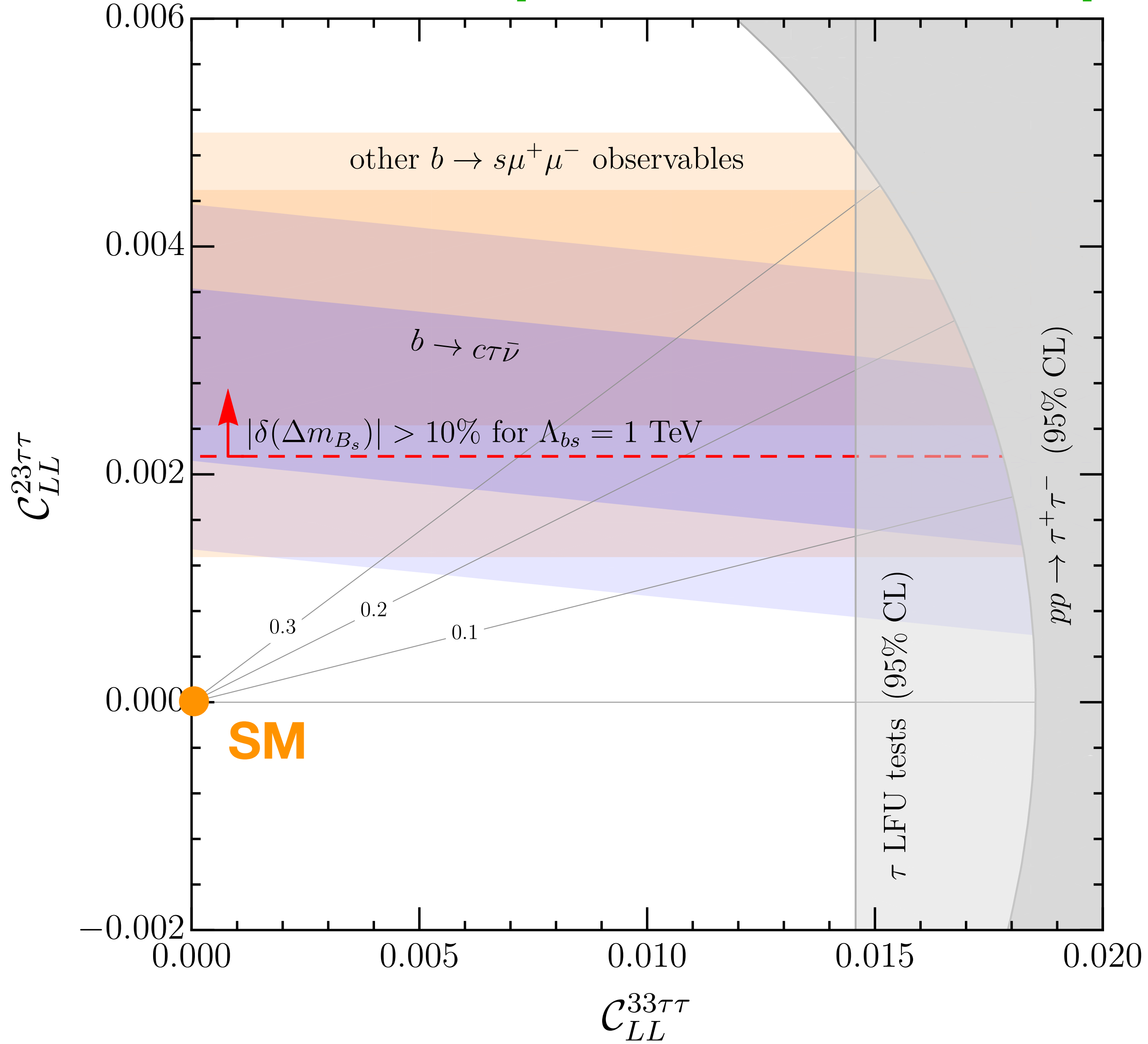



[Bobeth, Haisch, 1109.1826; Crivellin et al., 1807.02068; Algueró et al., 1809.08447]

# Additional constraints

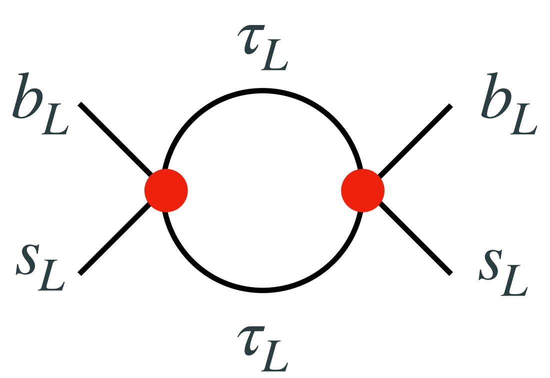
[Cornella et al., 2103.16558]



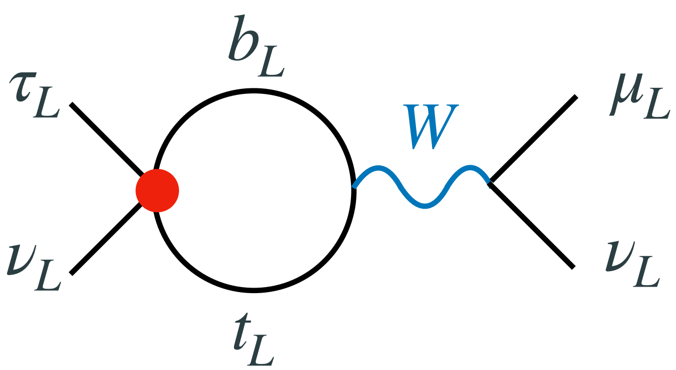

$$\mathcal{O}_{LL}^{ij\alpha\beta} = (\bar{q}_L^i \gamma_\mu \ell_L^\alpha)(\bar{\ell}_L^\beta \gamma^\mu q_L^j) = \frac{1}{2}\left[\mathcal{O}_{\ell q}^{(1)} + \mathcal{O}_{\ell q}^{(3)}\right]^{ij\alpha\beta}$$

There is a long list of constraints:

- No observation of $B \to K^{(*)}\nu\bar{\nu}$
- High-$p_T$ searches at LHC [ $pp \to \tau^+\tau^-$ ]
- Lepton universality tests in $\tau$ decays [ e.g. $\tau \to \mu\nu\bar{\nu}$ vs $\tau \to e\nu\bar{\nu}$]
- Meson-antimeson mixing ($B_s - \bar{B}_s$)




$\sim \left(C_{LL}^{23\tau\tau}\right)^2 \Lambda^2$

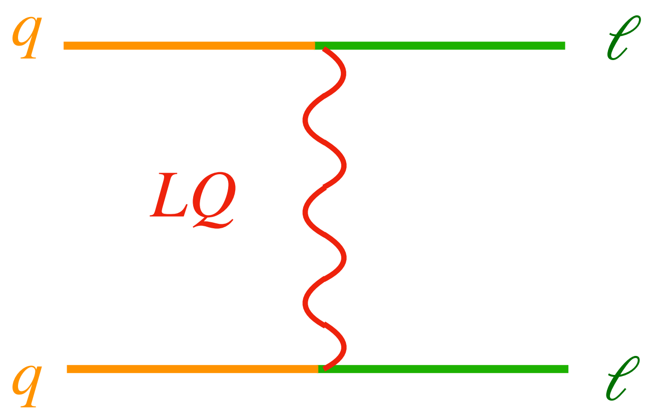


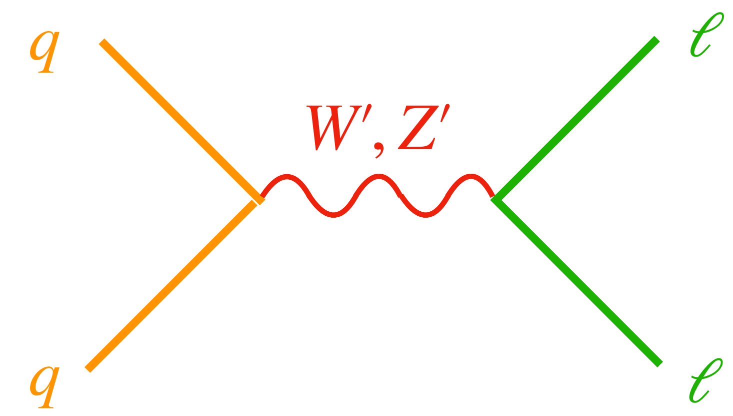

$\sim \left(C_{LL}^{33\tau\tau}\right)^2 \log\left(\Lambda/m_t\right)$

# From EFT analyses to simplified models

# Which mediator?

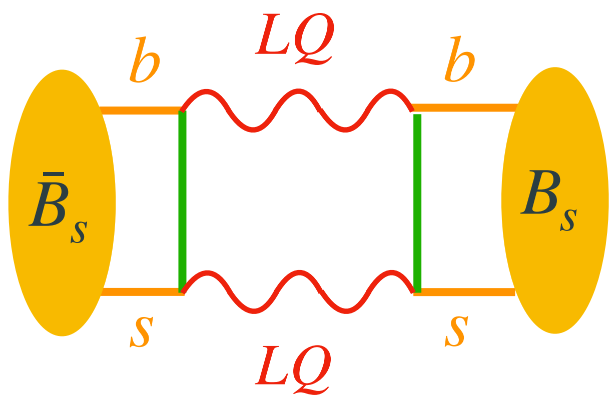
If we consider only tree-level mediators [ $R_{D^{(*)}}$ point to a low new physics scale ]

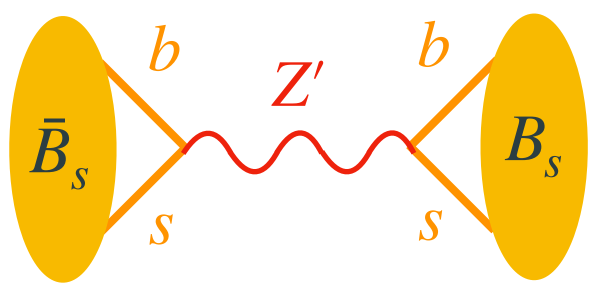



Leptoquarks (both scalars and vectors) have two important advantages

1. $\Delta F = 2$ & $\tau \to \mu\nu\bar{\nu}$




2. Direct searches: t-channel versus resonant s-channel production

# Which leptoquark?

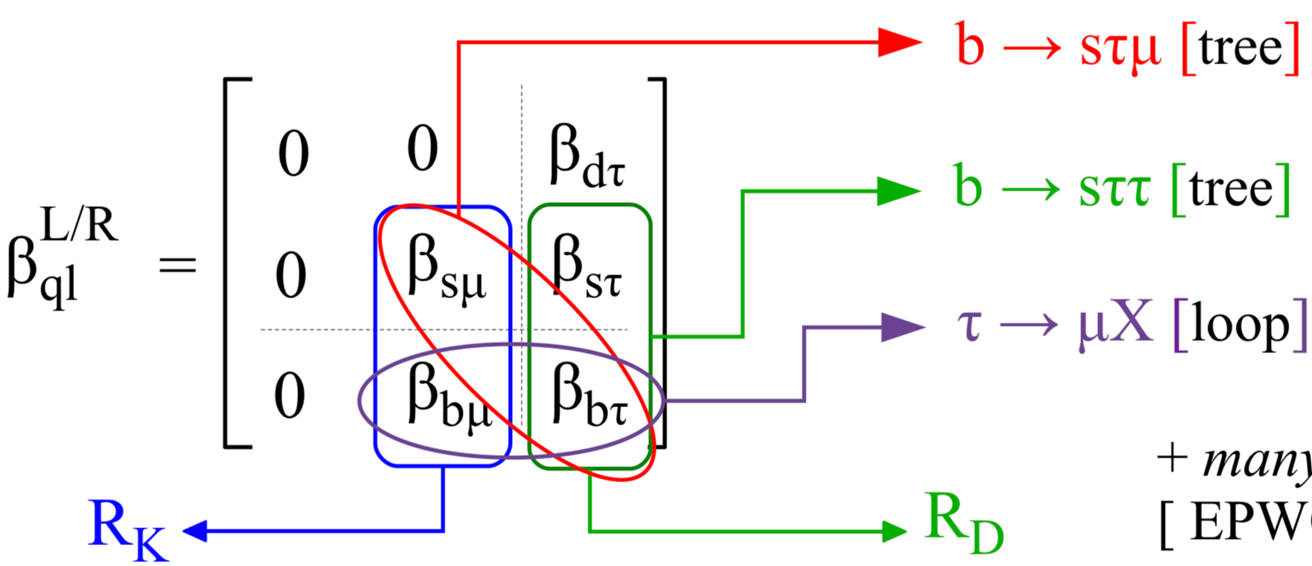
The $U_1$ vector leptoquark is (one of) the most promising mediator(s) to explain the $B$ anomalies

$$\mathscr{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[\beta_L^{i\alpha} (\bar{q}_L^i \gamma_\mu \ell_L^\alpha) + \beta_R^{i\alpha} (\bar{d}_R^i \gamma_\mu e_R^\alpha)\right] + \mathrm{h.c.} \qquad U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$$

It has two important advantages with respect to other leptoquarks:

1. No tree-level contribution to $b \to s\nu\bar{\nu}$
2. Automatic protection from proton decay

It provides a good description of all low-energy data with a “natural” flavor structure




+ *many other effects*
[ EPWO, LFU in τ's...]

$\beta_{b\tau}^L = 1$

$\beta_{b\tau}^R \sim \mathcal{O}(1)$

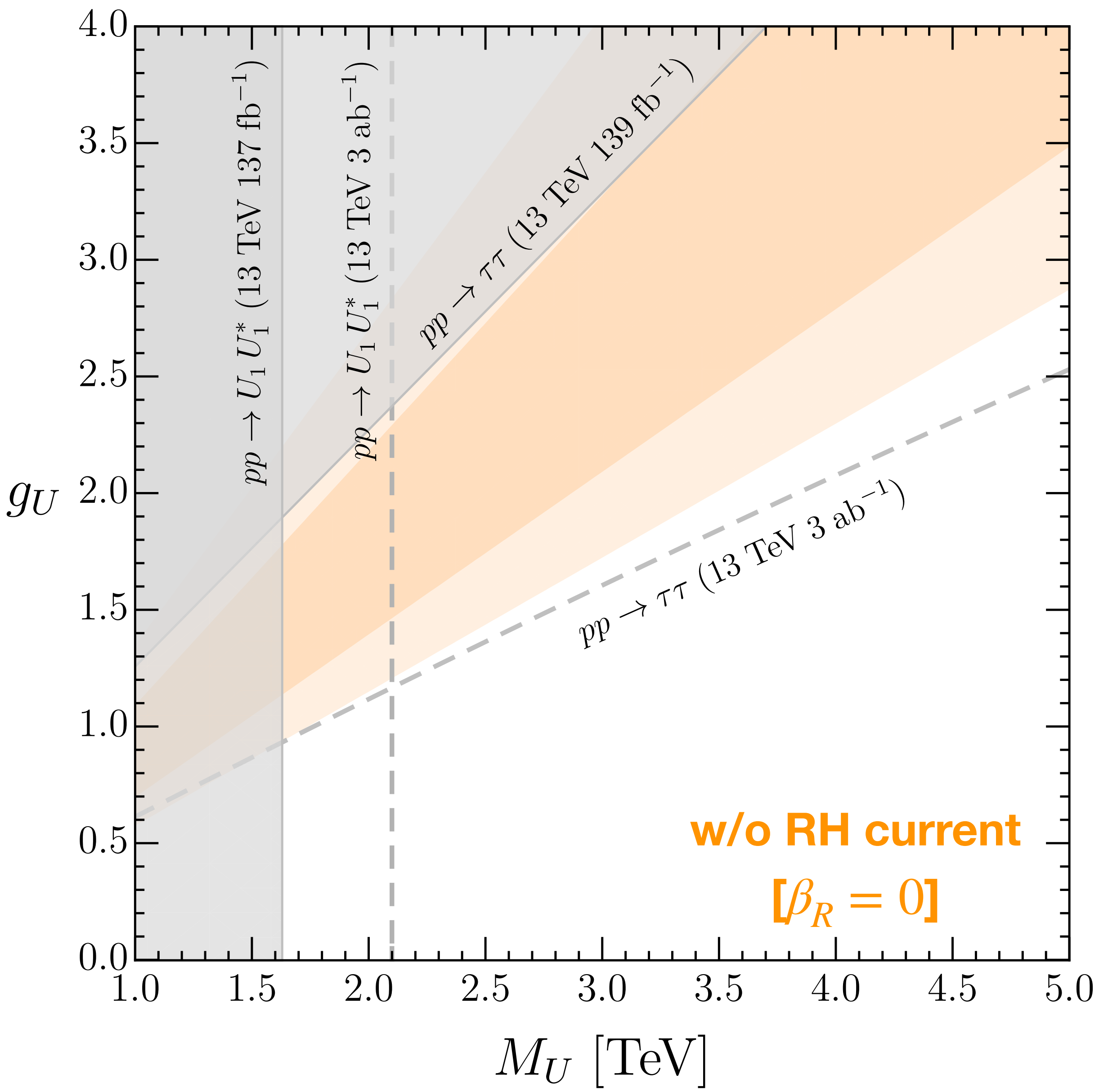
$\beta_{s\tau}^L, \beta_{b\mu}^L \sim \mathcal{O}(0.1)$

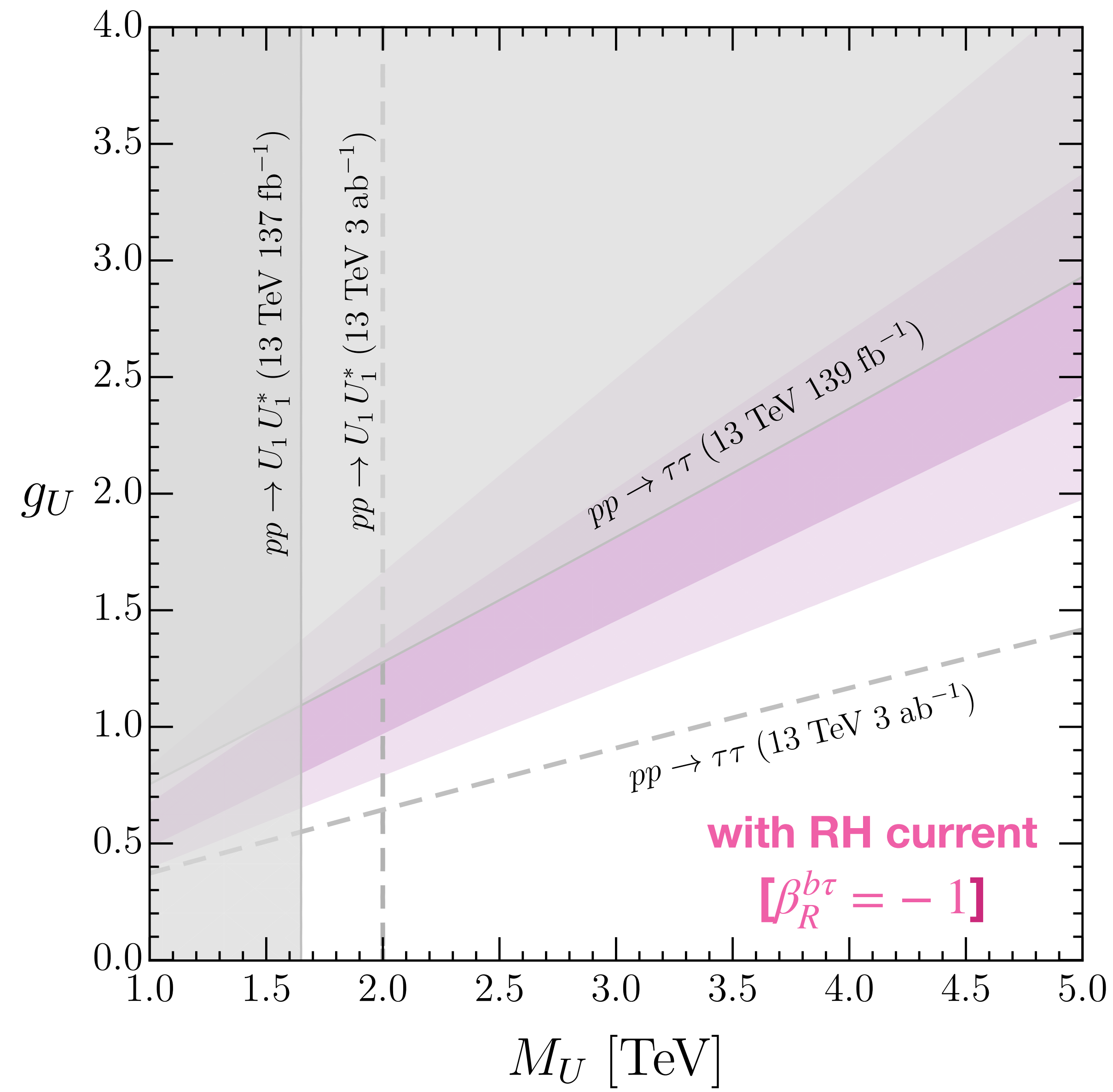
$\beta_{s\mu}^L, \beta_{d\tau}^L \sim \mathcal{O}(0.01)$

# Corroborating the $U_1$ hypothesis: High-$p_T$ searches

$U_1$ leptoquark solution also consistent with high-$p_T$ data and within the HL-LHC reach!

[Expected enhancement of high-$p_T$ $\tau^+\tau^-$ pairs in Drell-Yan data]



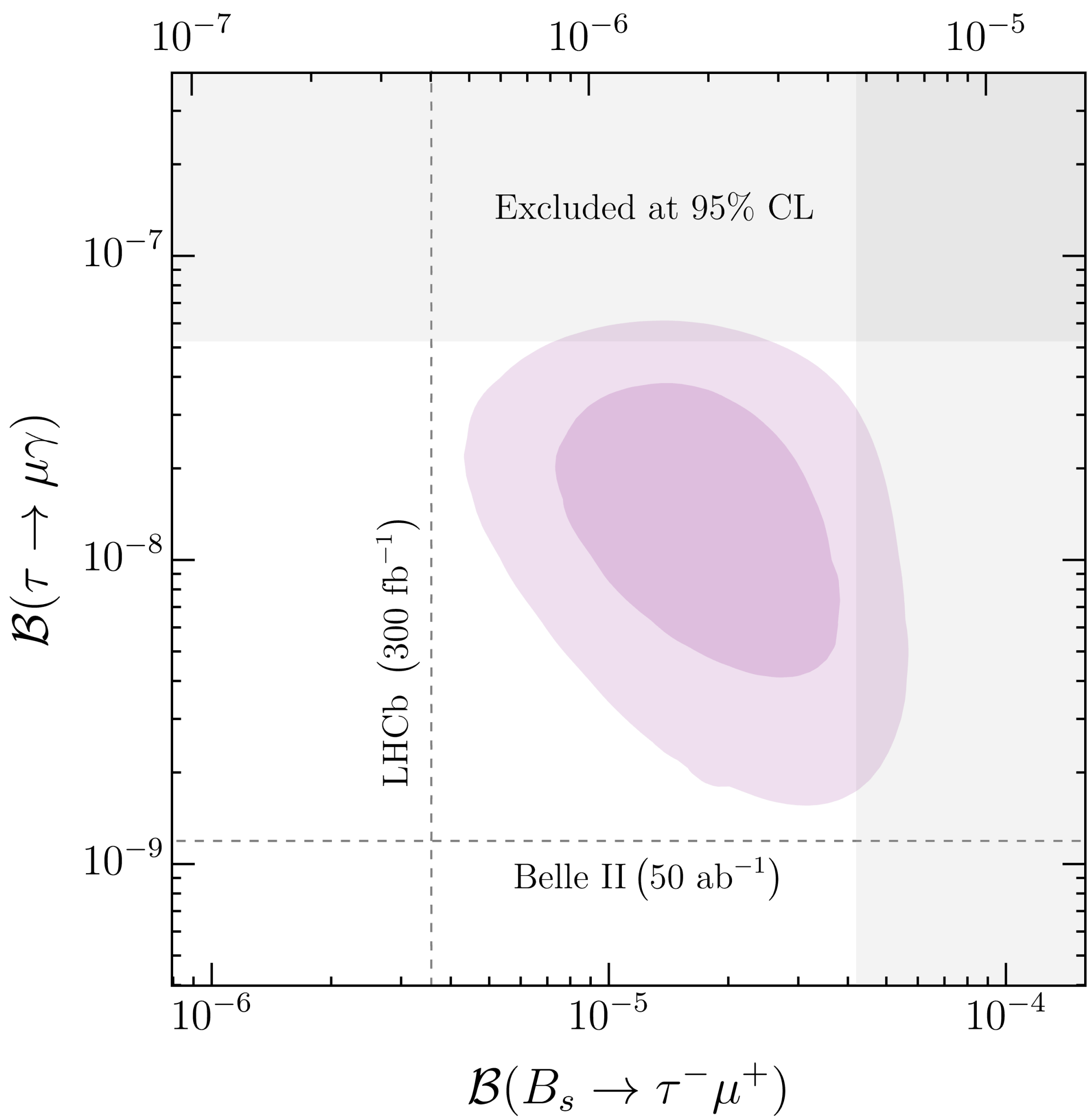

[Cornella et al., 2103.16558]

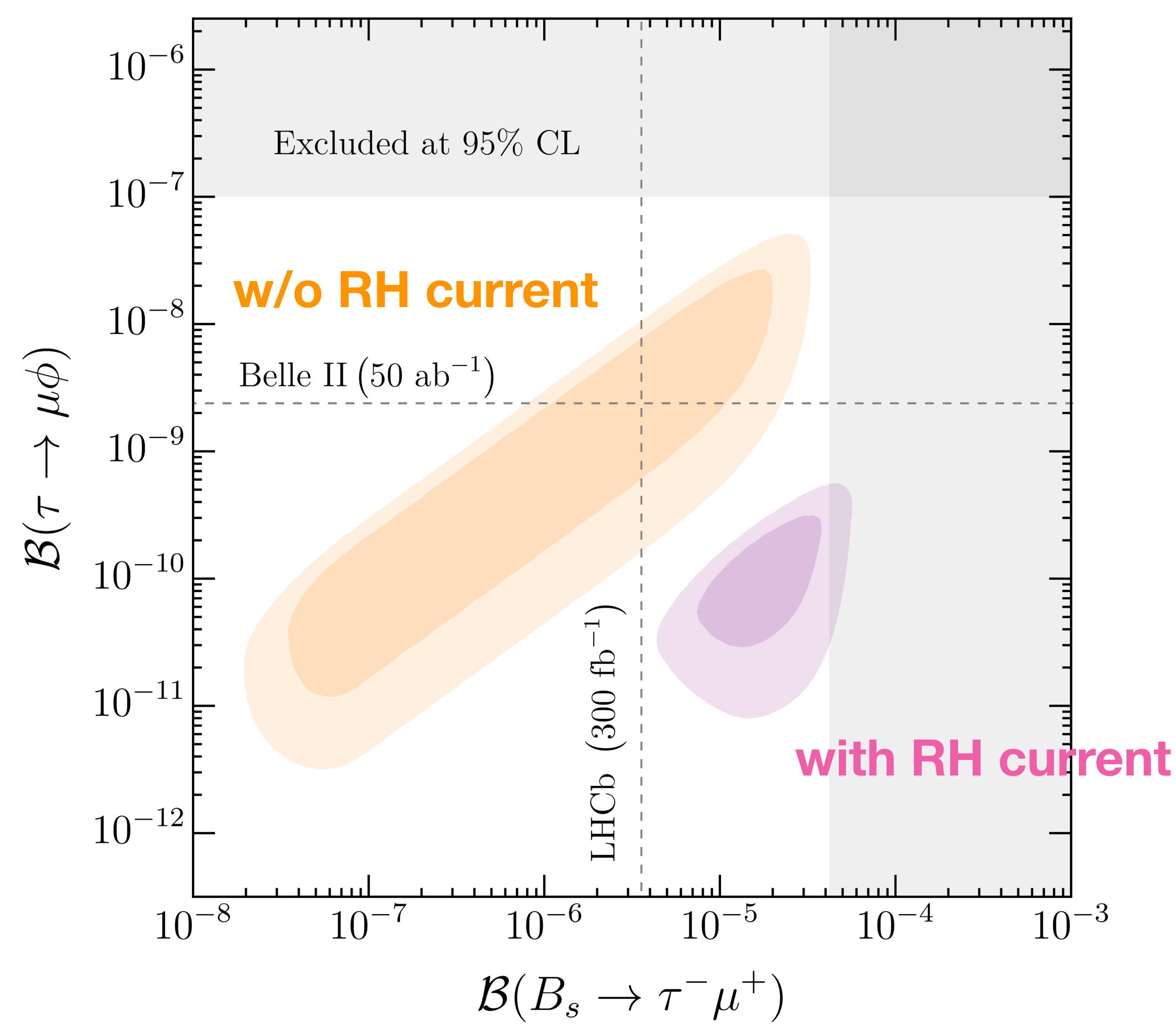
[$pp \to \tau\tau$ for $U_1$ originally proposed in Faroughy, Greljo, Kamenik, 1609.07138]

# Corroborating the $U_1$ hypothesis: other B and $\tau$ decays

LHCb & Belle II essential to confirm/exclude this solution in a large class of correlated observables and, if confirmed, to determine its coupling & flavor structure

## I. LFV in B and $\tau$ decays



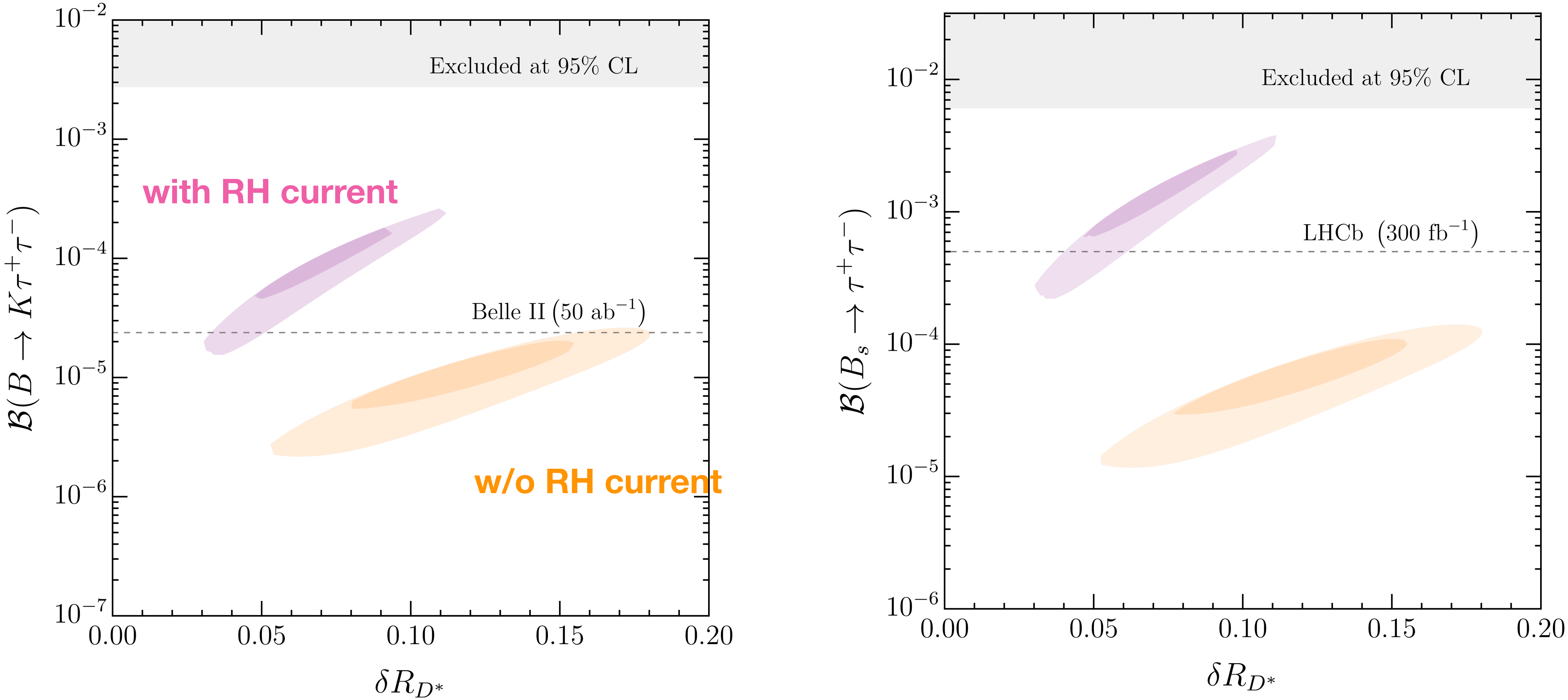

[Cornella et al., 2103.16558]

# Corroborating the $U_1$ hypothesis: other B and $\tau$ decays

LHCb & Belle II essential to confirm/exclude this solution in a large class of correlated observables and, if confirmed, to determine its coupling & flavor structure

### II. $b \to s\tau^+\tau^-$ decays

N.B: $\delta R_{D^*} = \dfrac{R_{D^*} - R_{D^*}^{SM}}{R_{D^*}^{SM}}$




[Cornella et al., 2103.16558]

# Speculations about a UV complete description

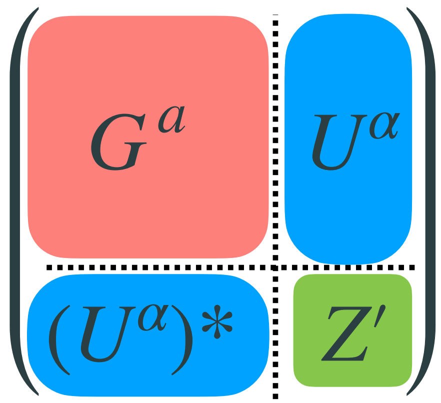
# Gauge UV completion for the $U_1$ leptoquark

The $U_1$ solution points to Pati-Salam unification

[Pati, Salam, Phys. Rev. D10 (1974) 275]
(7 years after the SM was proposed)

$$\boldsymbol{SU(4) \times SU(2)_L \times SU(2)_R}$$

$SU(4) \sim$




$$\Psi_{L,R} = \begin{pmatrix} Q^1_{L,R} \\ Q^2_{L,R} \\ Q^3_{L,R} \\ L_{L,R} \end{pmatrix}$$

Leptons as the fourth "color"

- ✔ $\mathrm{SU}(4)$ is the smallest group containing the $U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$
- ✔ No proton decay (protected by symmetry)
- ✘ The (flavor universal) Pati-Salam model cannot work
  - ⟶ The bounds from $K_L \to \mu e$ lift the LQ mass to 100 TeV
- ✘ The associated $Z'$ would be excessively produced at LHC
  - ⟶ $M_U \sim M_{Z'} \sim \mathcal{O}(\mathrm{TeV})$ & $\mathcal{O}(g_s)$ $Z'$ couplings to valence quarks

# 4321 model(s)

[Georgi and Y. Nakai, 1606.05865; Diaz, Schmaltz, Zhong, 1706.05033; Di Luzio, Greljo, Nardecchia, 1708.08450]

We can “protect” the light families by decorrelating $SU(4)$ from the SM color group

**PS group:** $\mathcal{G}_{\rm PS} \supset SU(4) \times SU(2)_L \times U(1)_R$ [ Flavor universal ]

**4321 group:** $\mathcal{G}_{4321} \equiv SU(4) \times SU(3)' \times SU(2)_L \times U(1)_X$ [ Flavor non-universal ]

$U(1)_Y$

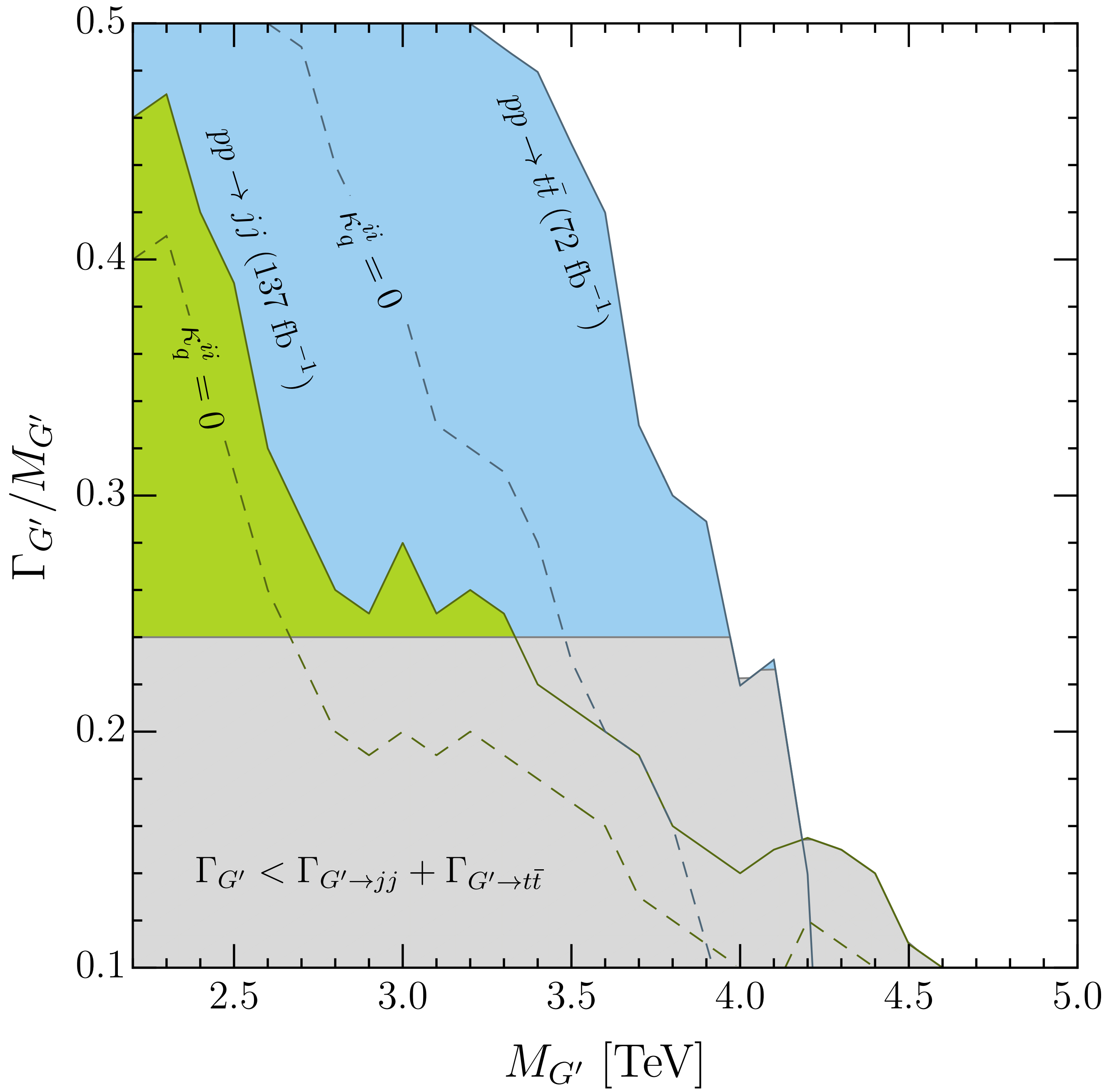
$$SU(4) \times SU(3)' \times SU(2)_L \times U(1)_X \xrightarrow{SSB} SU(3)_c \times SU(2)_L \times U(1)_Y$$

$SU(3)_c$

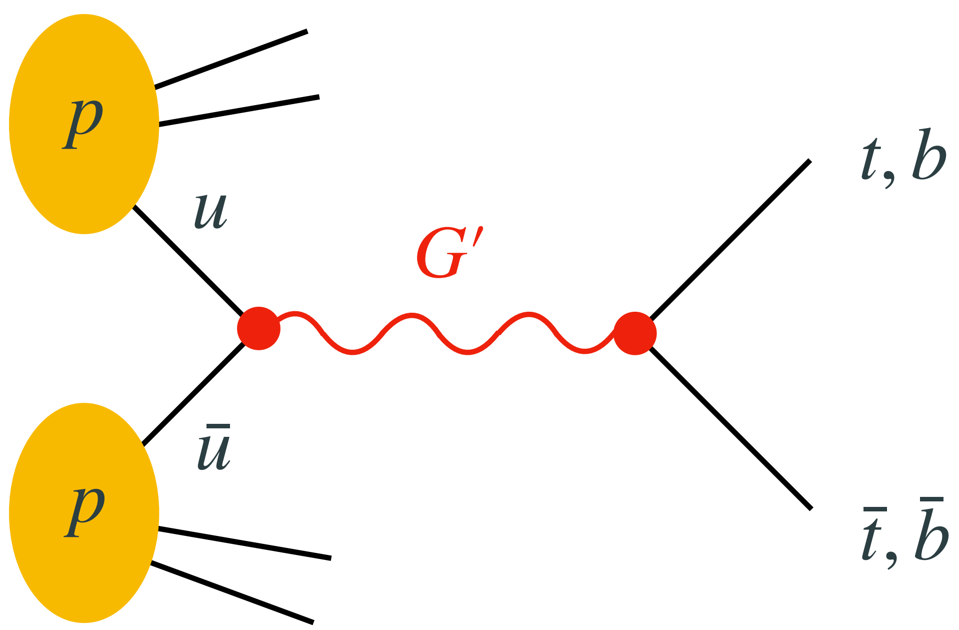
$+U_1, Z', G'$

[ Flavor non-universal ]

# Coloron direct searches at the LHC




Relevant collider signatures for $G'$ ("coloron" = heavy color-octet vector)




Strongest constraint on the model scale from $pp \to \bar{t}t$

[Cornella et al., 2103.16558]

# Third-family quark-lepton unification at the TeV scale

$U(1)_Y$

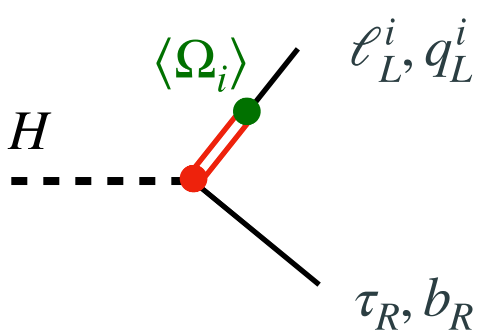
$$SU(4)_3 \times SU(3)_{1+2} \times SU(2)_L \times U(1)_X \xrightarrow{\langle \Omega_{1,3,15} \rangle \sim \mathcal{O}(\text{TeV})} SU(3)_c \times SU(2)_L \times U(1)_Y + U_1, G', Z'$$

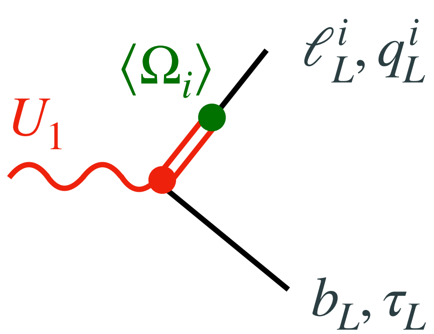
$SU(3)_c$

$$\psi = ((\psi_1 \; \psi_2)(\psi_3))$$

★ Direct new physics couplings to 3rd family only

★ CKM mixing and new physics couplings to lighter families via (small) mixing with $\chi$ fermions




| Field | $SU(4)$ | $SU(3)'$ | $SU(2)_L$ | $U(1)_X$ | |
|---|---|---|---|---|---|
| $q_L^i$ | **1** | **3** | **2** | $1/6$ | 1st & 2nd families |
| $u_R^i$ | **1** | **3** | **1** | $2/3$ | |
| $d_R^i$ | **1** | **3** | **1** | $-1/3$ | |
| $\ell_L^i$ | **1** | **1** | **2** | $-1/2$ | |
| $e_R^i$ | **1** | **1** | **1** | $-1$ | |
| $\psi_L$ | **4** | **1** | **2** | $0$ | 3rd family |
| $\psi_R^\pm$ | **4** | **1** | **1** | $\pm 1/2$ | |
| $\chi_L^i$ | **4** | **1** | **2** | $0$ | $n_\chi = 2$ |
| $\chi_R^i$ | **4** | **1** | **2** | $0$ | |
| $H$ | **1** | **1** | **2** | $1/2$ | |
| $\Omega_1$ | $\bar{\mathbf{4}}$ | **1** | **1** | $-1/2$ | |
| $\Omega_3$ | $\bar{\mathbf{4}}$ | **3** | **1** | $1/6$ | |
| $\Omega_{15}$ | **15** | **1** | **1** | $0$ | |

[Bordone, Cornella, JFM, Isidori 1712.01368, 1805.09328; Greljo, Stefanek, 1802.04274; Cornella, JFM, Isidori 1903.11517]

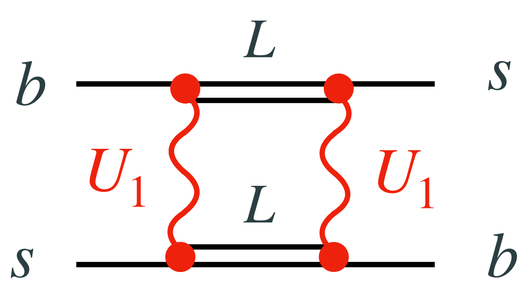
★ Fully calculable loop contributions

[JFM, Isidori, König, Selimovic, 1910.13474, 2006.16250, 2009.11296]

# Importance of loop effects: $U_1$ is the new $W$

Some (important) effects appear only at one loop

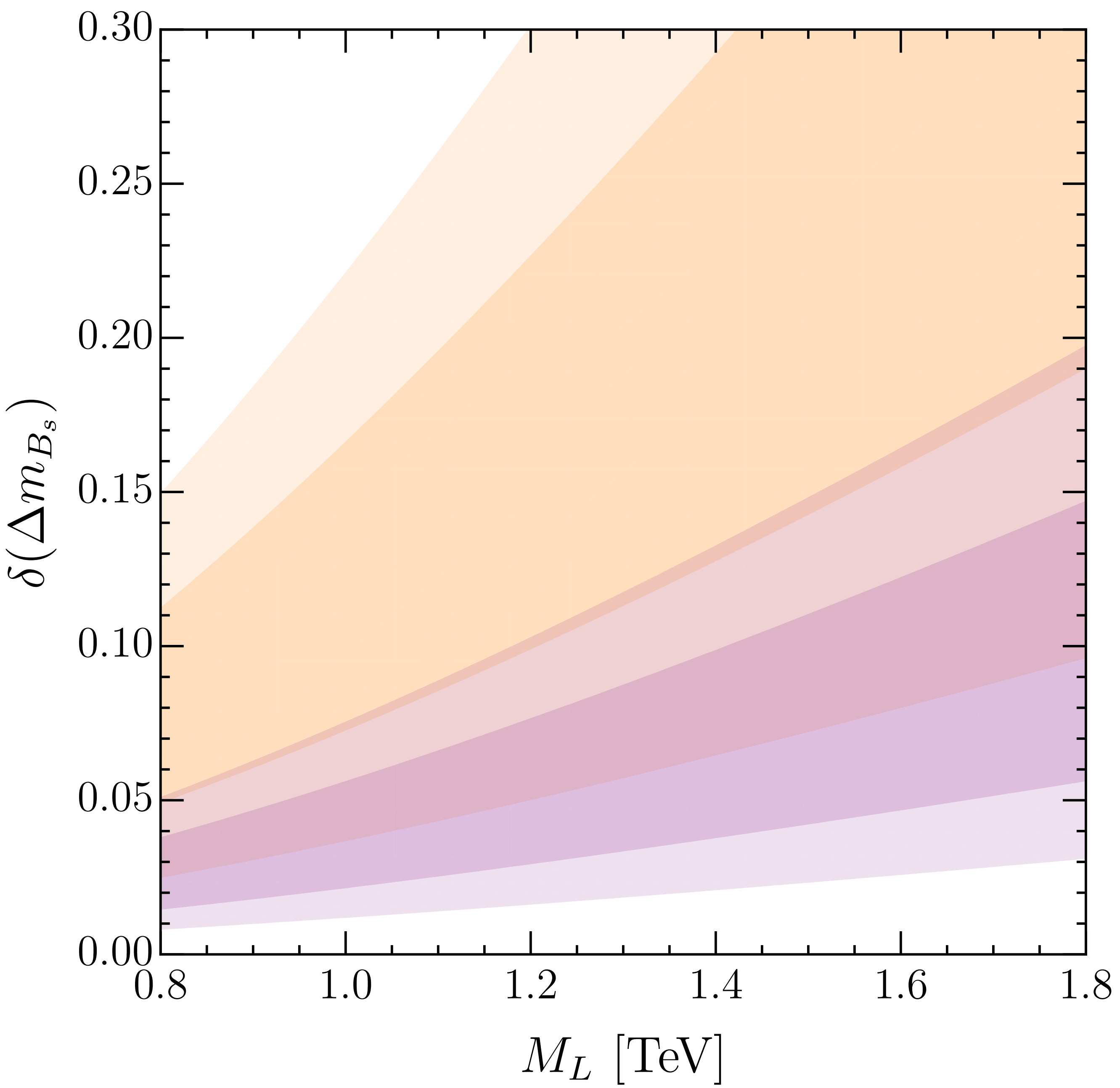
**I.** bound on $M_L$ from $\Delta F = 2$
(similar to SM with charm quark)




$$\chi = \begin{pmatrix} Q \\ L \end{pmatrix}$$

$$\sim \Delta R_{D^*}^2 M_L^2 \Longrightarrow M_L \sim \text{TeV}$$

[ Within the LHC reach! ]




GIM-like suppression of FCNC loops

[di Luzio, JFM, Greljo, Nardecchia, Renner 1808.00942;
Cornella, JFM, Isidori 1903.11517;
JFM, Isidori, König, Selimovic, 2009.11296]

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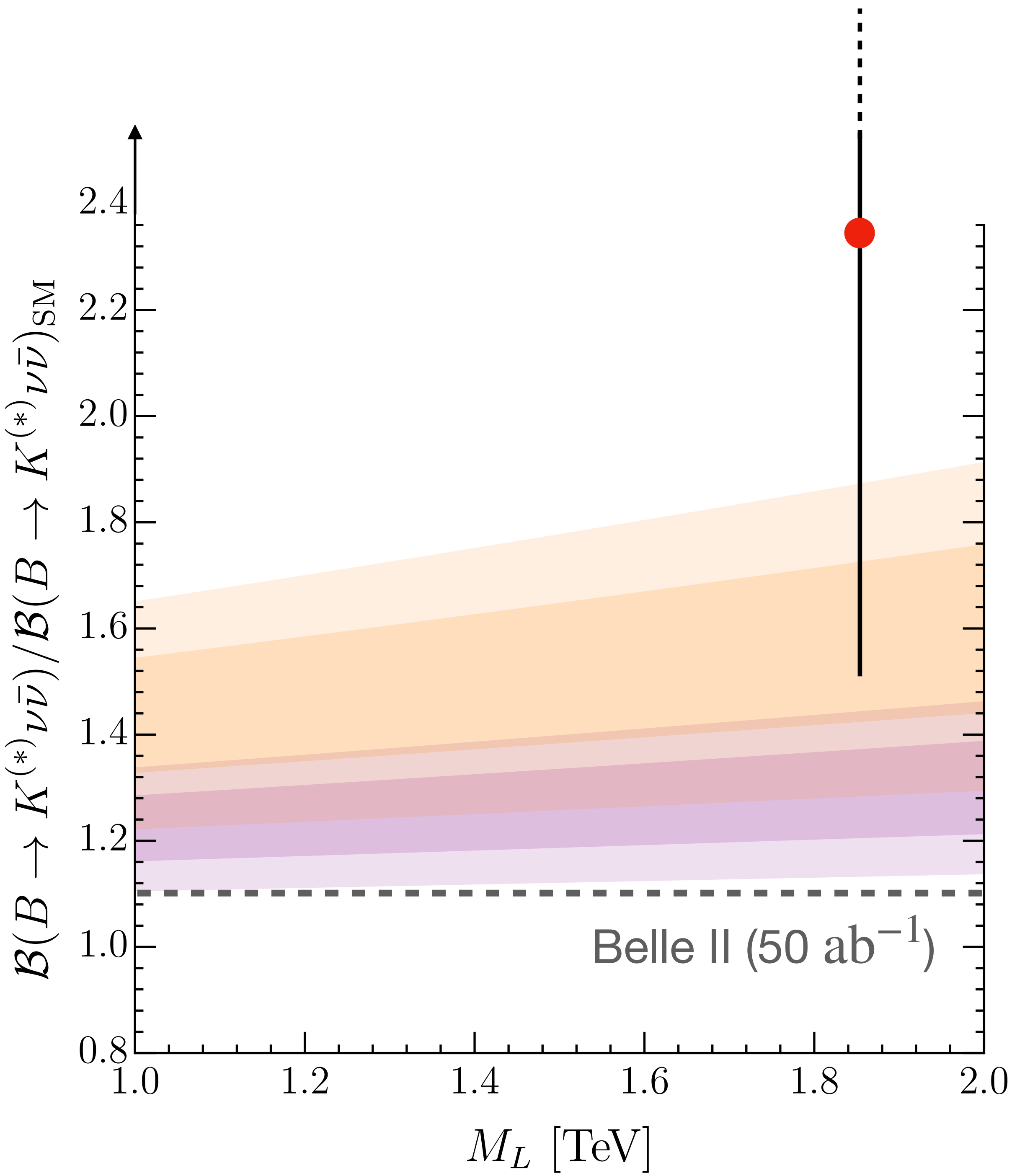
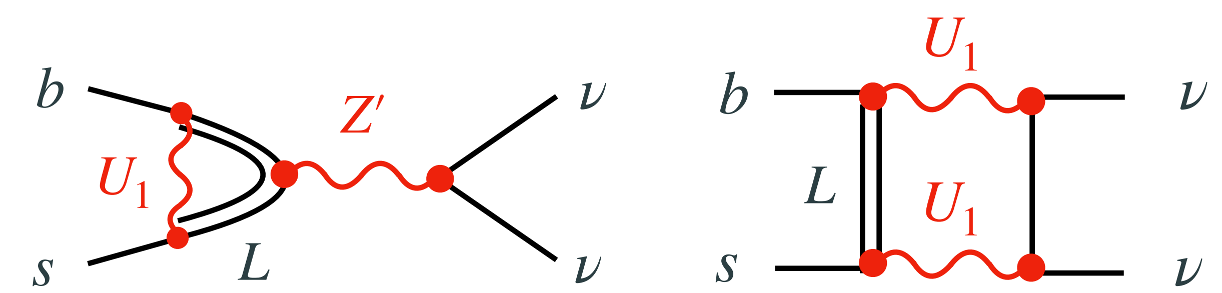
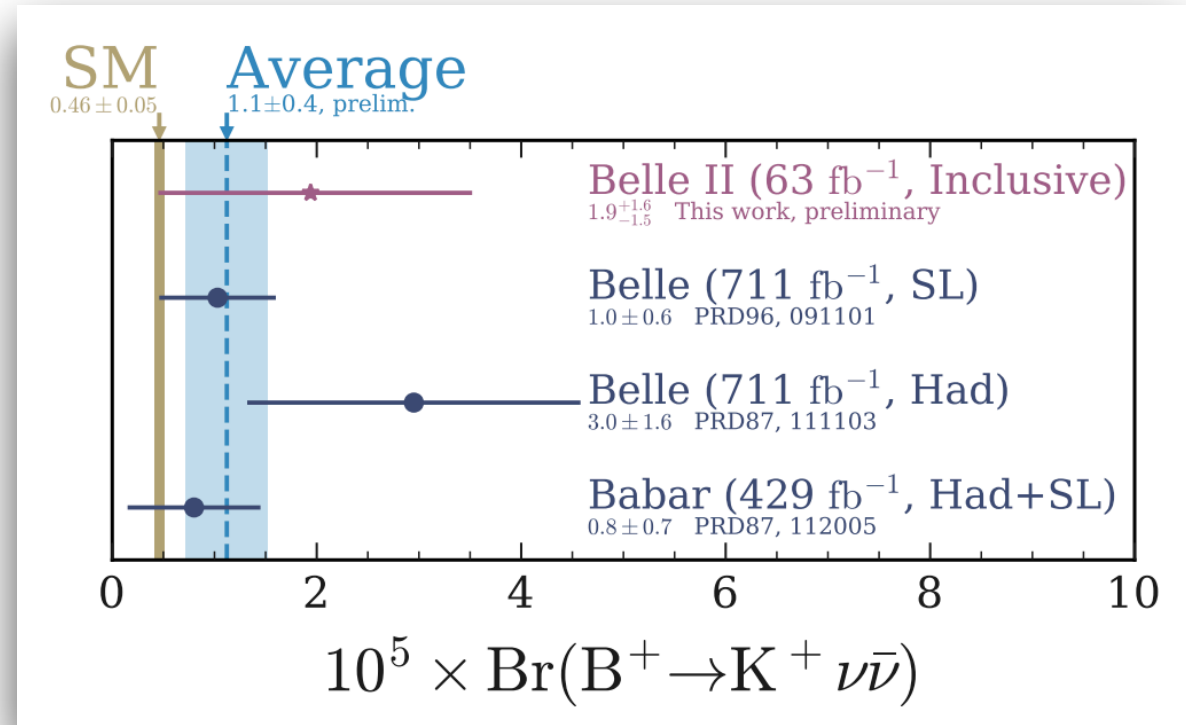



**II.** $B \to K^{(*)}\nu\nu$ [JFM, Isidori, König, Selimovic, 2009.11296]




Filippo Dattola (Belle II) @ Moriond EW

# Back to Pati-Salam… but in five dimensions!

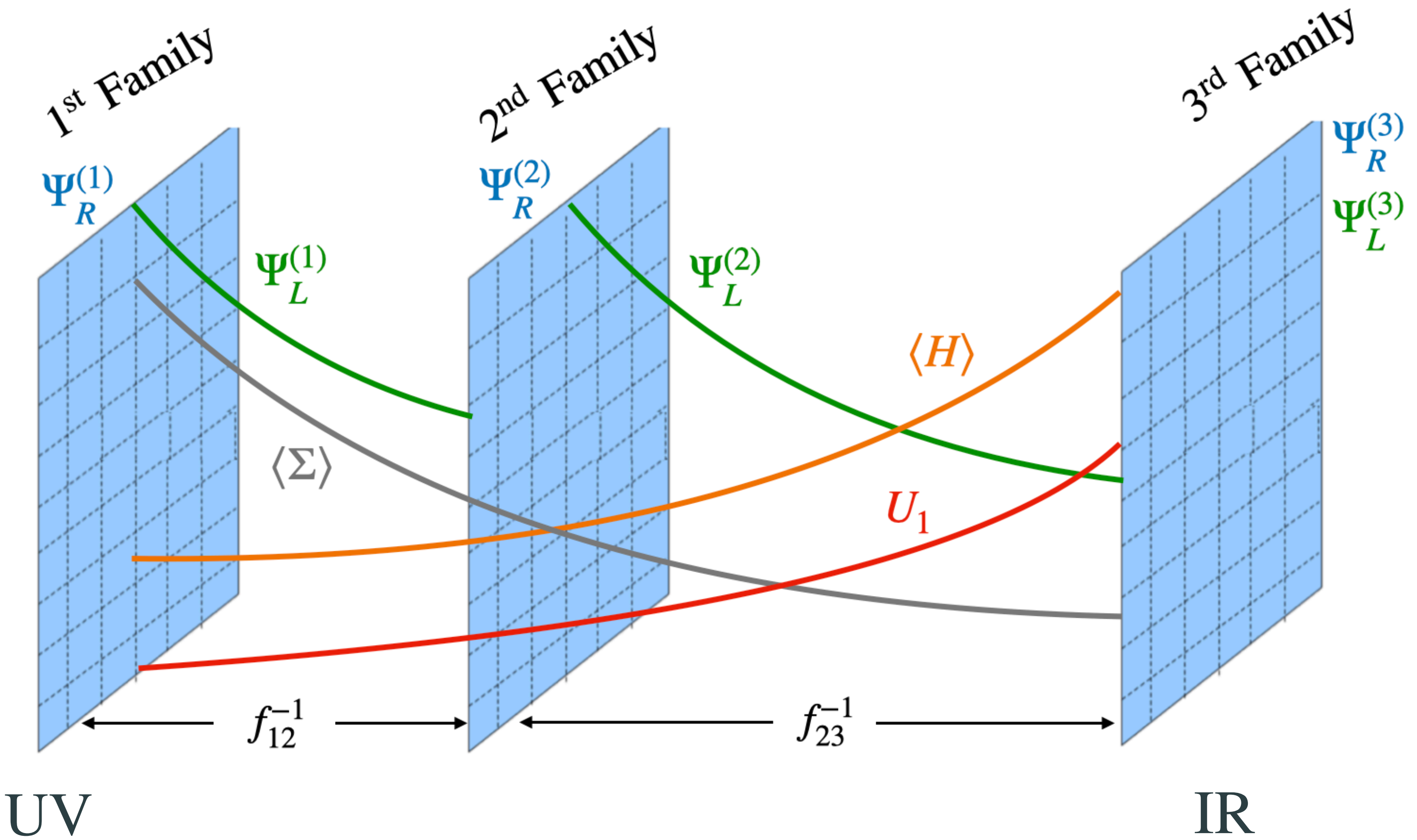
Warped compact extra dimension ( $\mathrm{AdS}_5$ ) with multiple four-dimensional branes

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$

$$\mathrm{PS}_{5D} \equiv SU(4) \times SU(2)_L \times SU(2)_R$$

Flavor $\longleftrightarrow$ fermion (quasi-)localization in each of the branes (fermion mixing from nearest neighbor interactions) [Dvali, Shifman, '00]

$$f_L^i(y) \sim e^{-c_i y}$$




Higgs IR (quasi-)localization $\longleftrightarrow$ stabilization of the mass hierarchies (as in the Randall-Sundrum model)

[Randall, Sundrum '99]

$SU(4)$ symmetry broken in the UV $\longleftrightarrow$ $U_1$ LQ as $SU(4)$ KK mode(s) (dominantly coupled to 3rd family)

[JFM, Isidori, Pagès, Stefanek, 2012.10492
JFM, Isidori, Lizana, Selimovic, Stefanek, w.i.p]

# Conclusions

The statistical significance of the **LFU anomalies in $b \to s\ell\ell$** data is growing and amounts to $4.6\sigma$ when considering only observables with a very robust theory prediction [ Recent evidence of LFUV in $R_K$ alone ( $3.1\sigma$ ) ]

**LFU anomalies in $b \to c\tau\bar{\nu}$** data are also seen. Although statistically less significant, in combination with $b \to s\ell\ell$ data, they point to TeV-scale new physics with a similar flavor structure to that of the SM Yukawas

⟶ Possible connection to the **origin of SM flavor hierarchies** from a multi-scale picture

New physics picture consistent with low- & high-energy data, but **new physics effects should emerge soon in other observables** ( closing in on the mass gap? )

[ **Caveat:** Many of the predictions rely on the present value of $R_{D^{(*)}}$ ]

**Plenty of upcoming measurements** from both the energy and intensity frontiers

[e.g. part of LHC run II data still to be analyzed and Belle II data coming]

# Thank you!