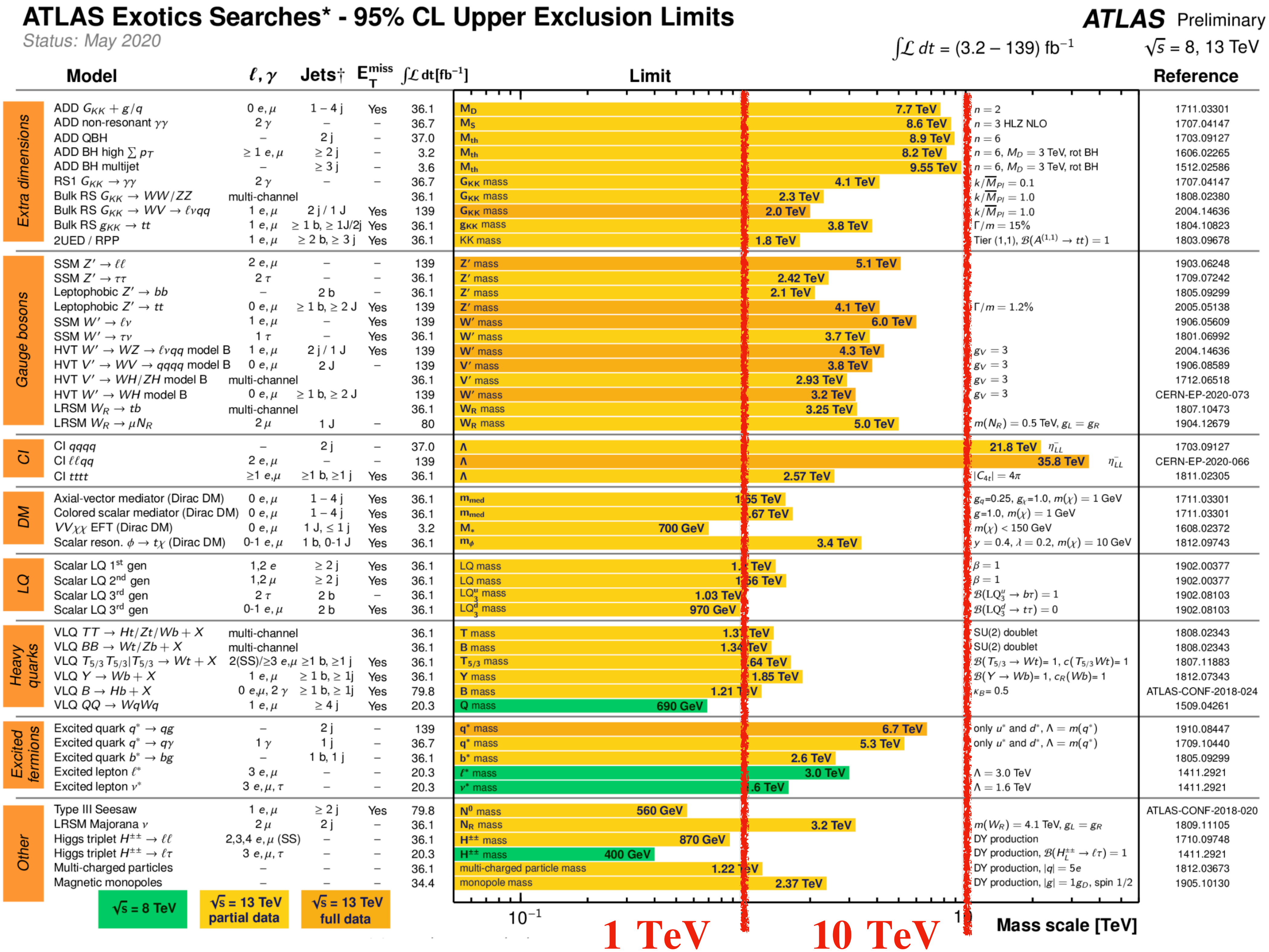
New Physics from B Decays

Javier Fuentes-Martín
University of Granada

4th World Summit on Exploring the Dark Side of the Universe, November 8, 2022

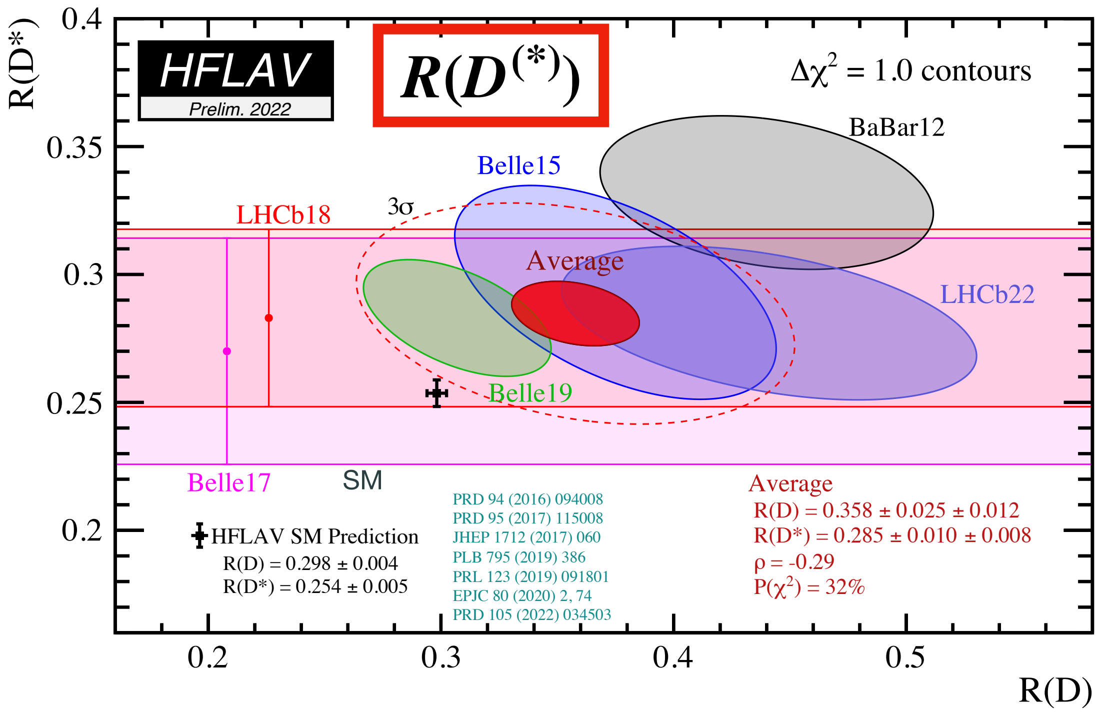
What is experiment telling us?

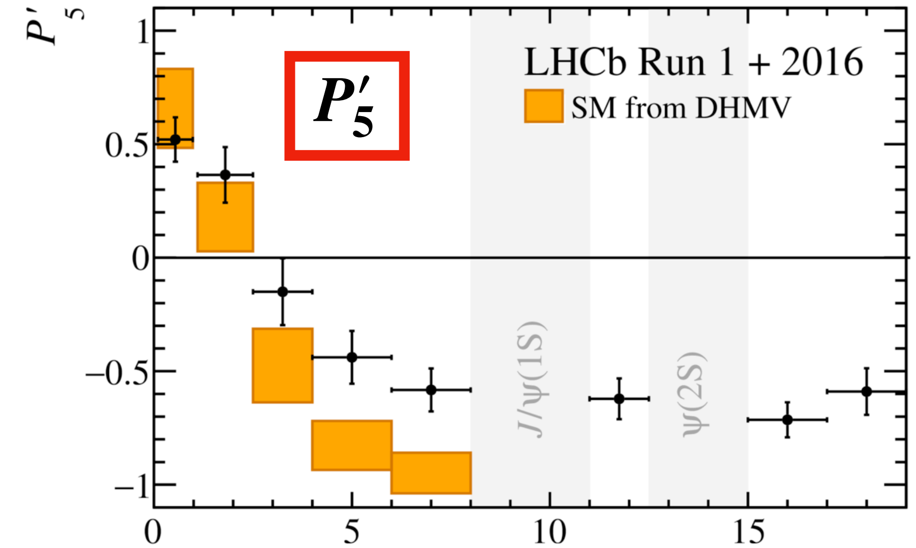
No **direct evidence** for NP, yet many reasons to expect it [**presence of a mass gap?**]

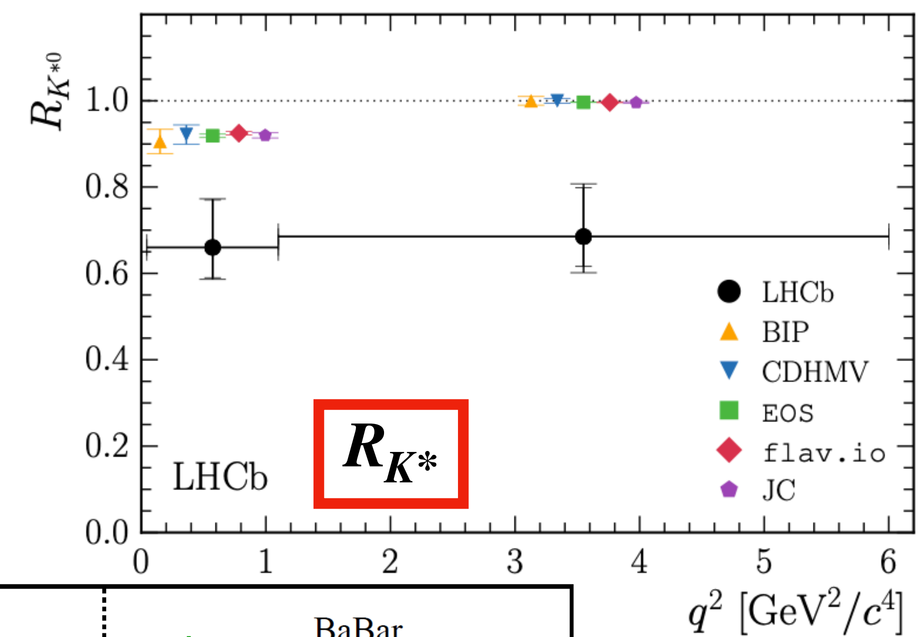


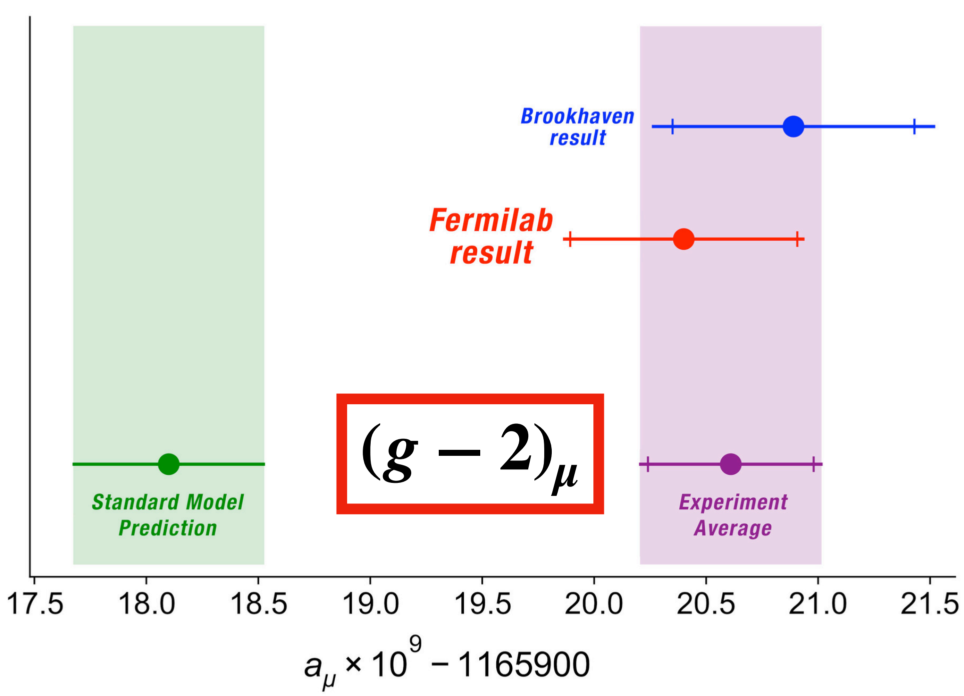
What is experiment telling us?

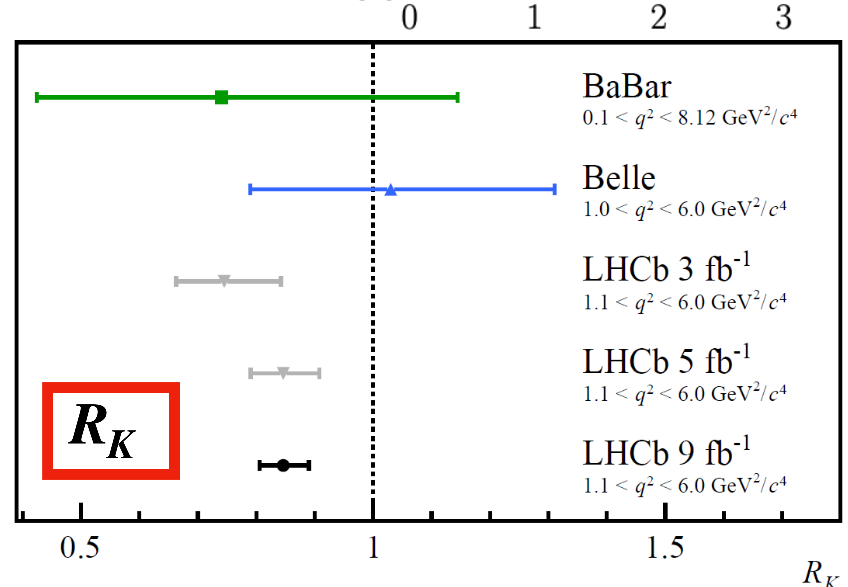
Footprints of NP in **low-energy data**?





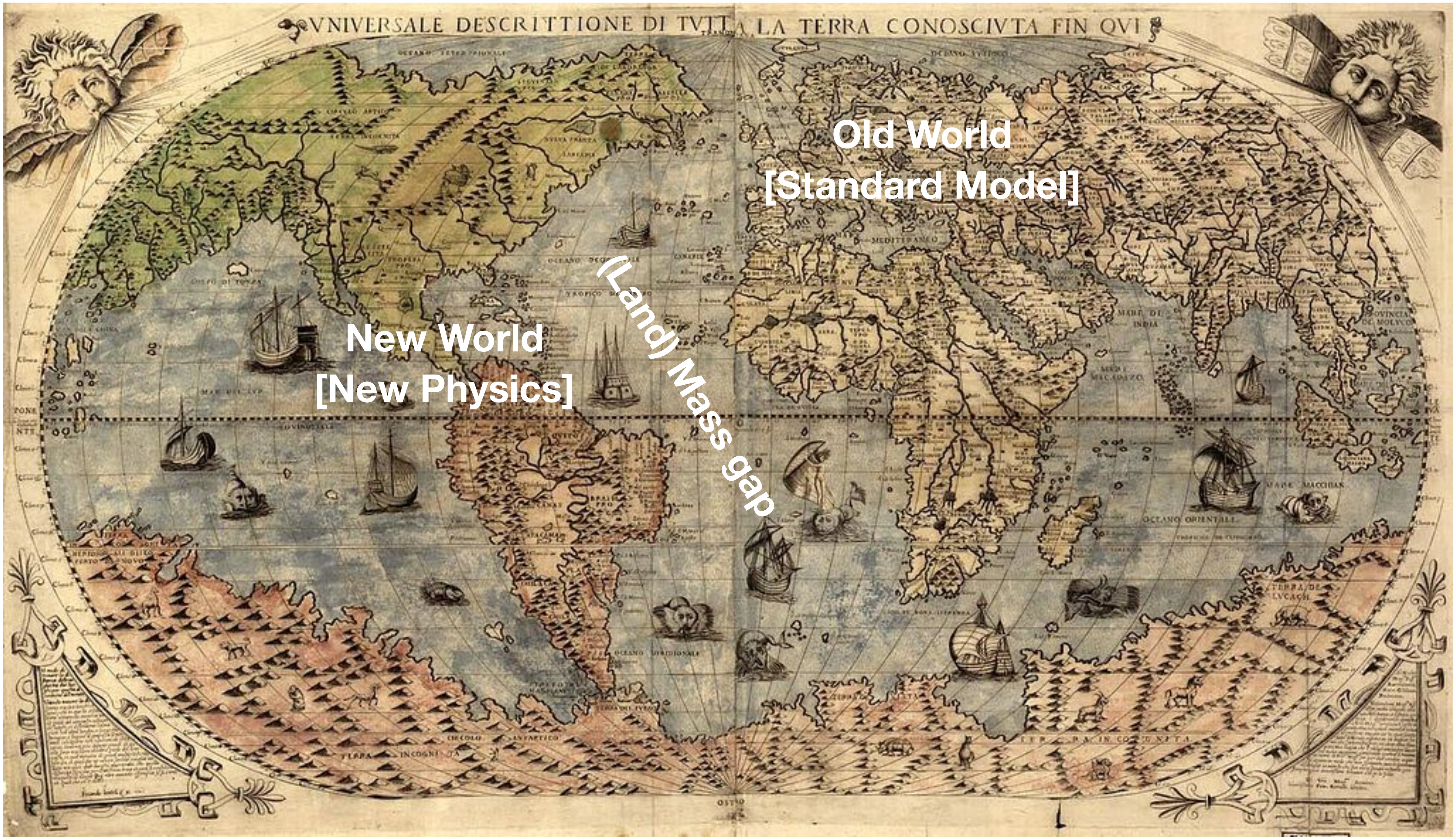






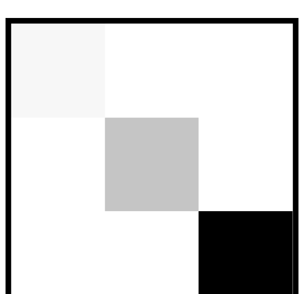
The search for Terra Incognita

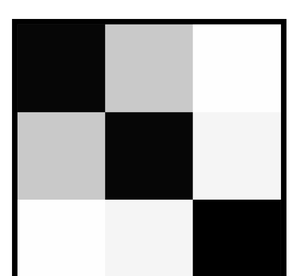
Particle Physics has entered an age of exploration



The SM Lagrangian: Naturalness problems

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

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

$V_{\mathrm{CKM}} \sim$ 

The SM Lagrangian contain a few unnatural features pointing towards NP

Higgs hierarchy problem

[Instability of the Higgs mass under quantum corrections]

TeV-scale NP?

SM flavor puzzle

[Very hierarchical structure in the Yukawa couplings]

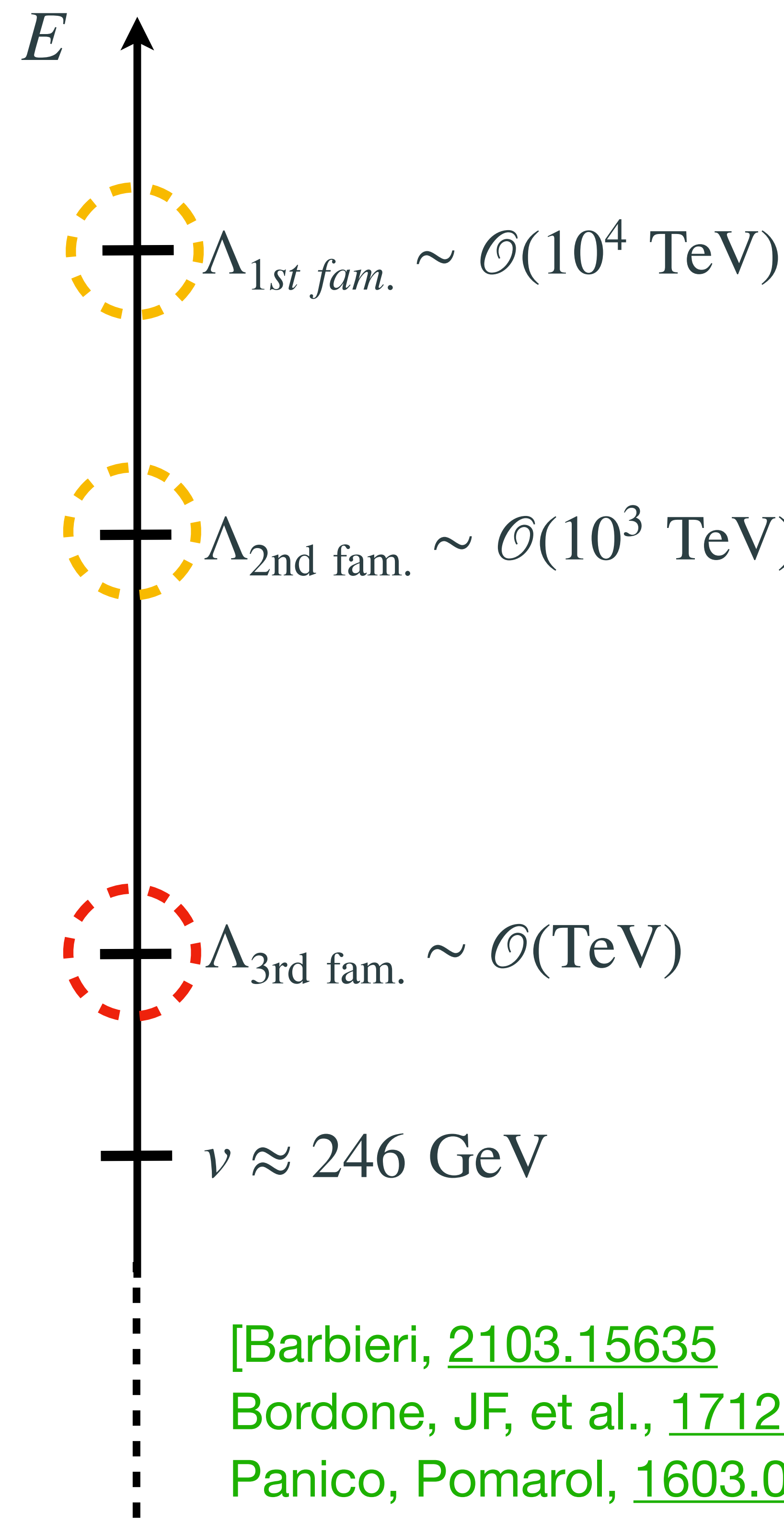
Similar structure also for NP?

Are these two features correlated?

Multi-scale solution of the flavor puzzle/problem

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

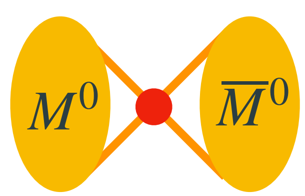
Non-trivial UV imprints



★ The SM Yukawas are very different because they originate at very separate scales!

★ TeV-scale NP dominantly coupled to third and (to a lesser extent) second families
[protection from flavor constraints]

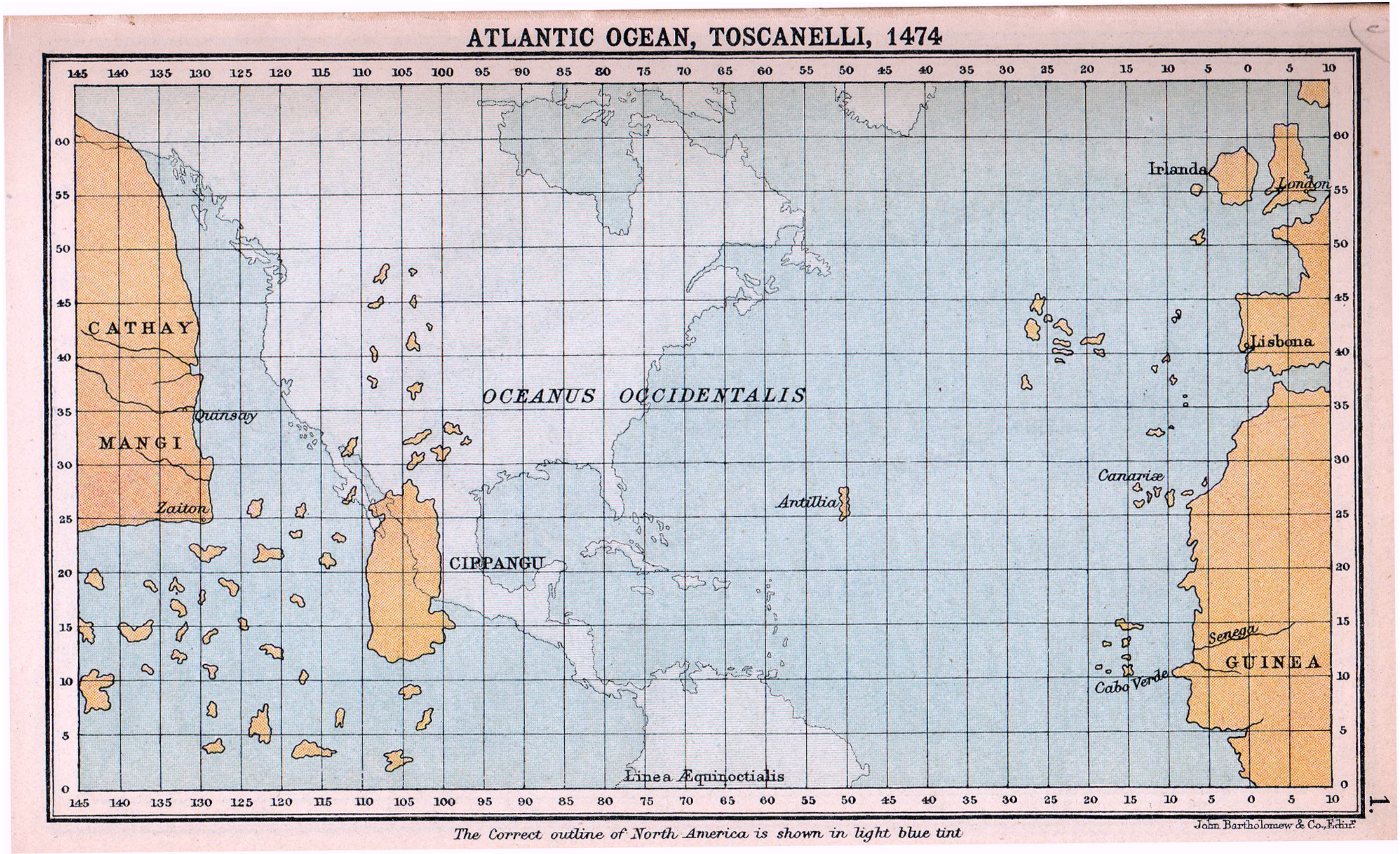
e.g. from $\frac{1}{\Lambda^2}(\psi_i \psi_j)^2$



★ Direct production of new states at the LHC is naturally more suppressed
[NP scale can be lower]

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

A closer look to the data and EFT analysis

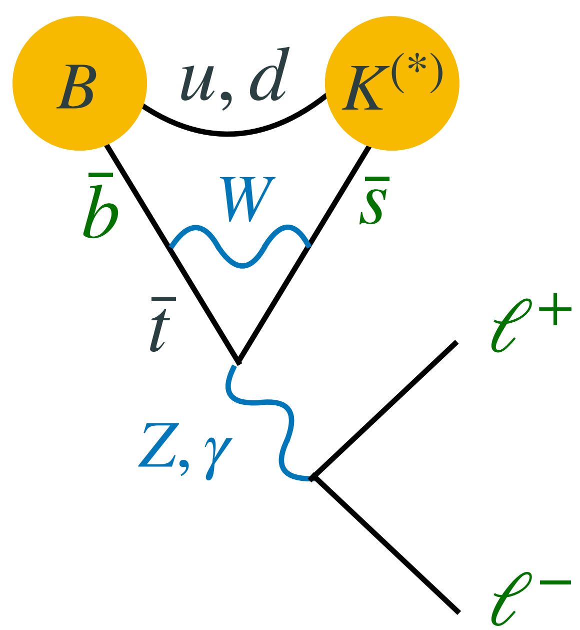


The B anomalies

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

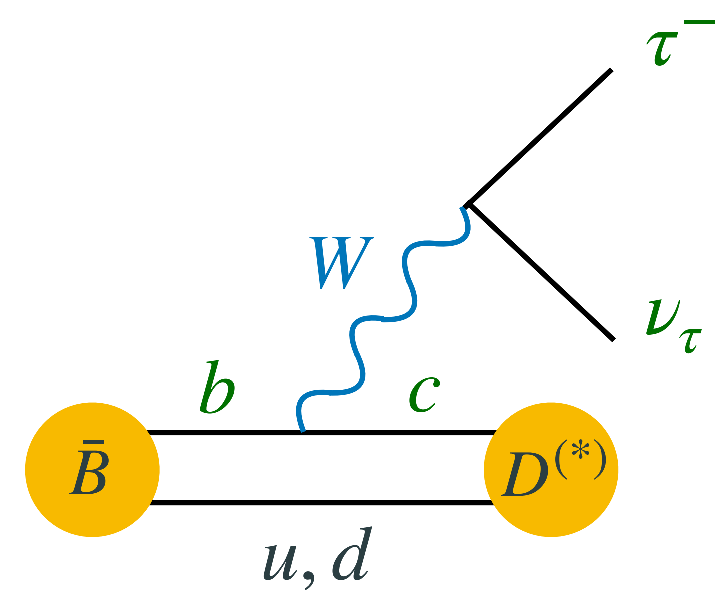
$b \to s\ell^+\ell^-$

μ/e ~~universality~~



$b \to c\tau\nu$

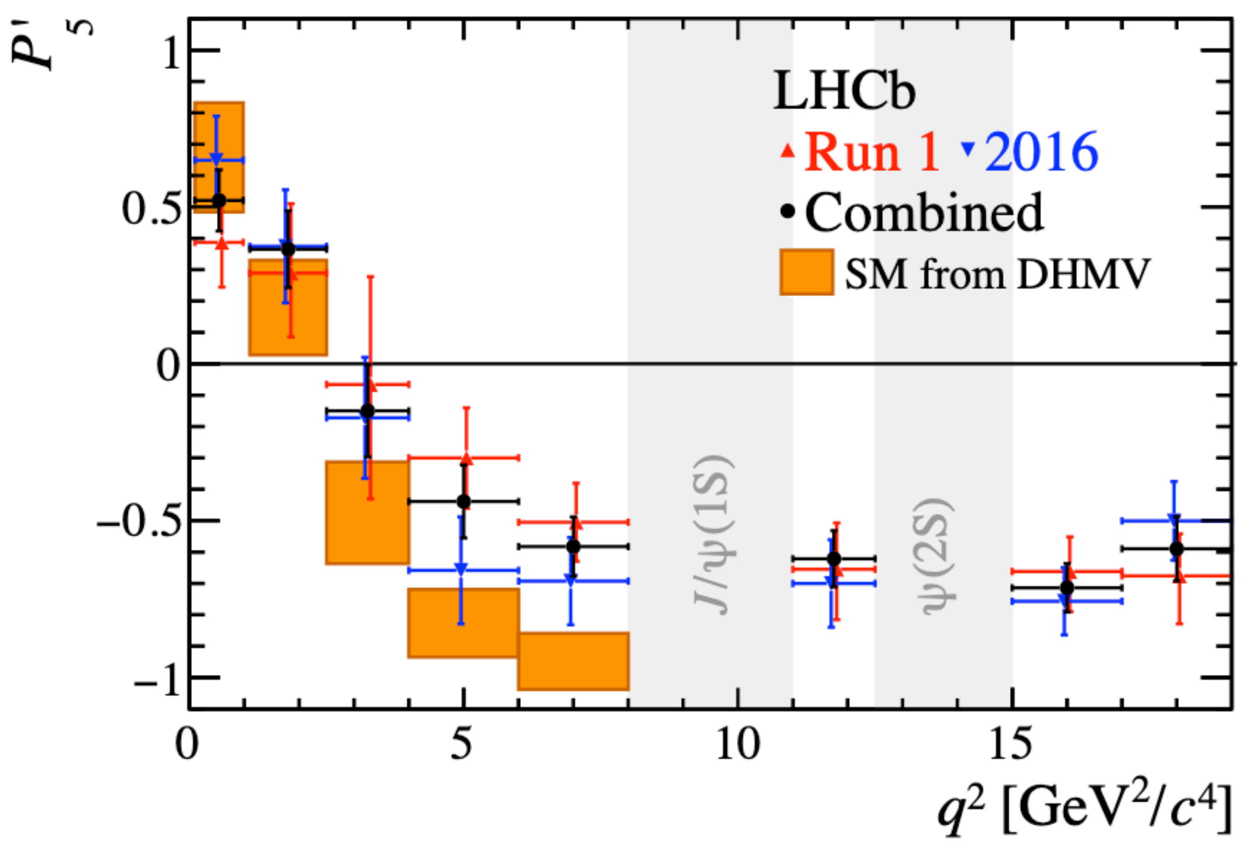
$\tau/\mu, e$ ~~universality~~

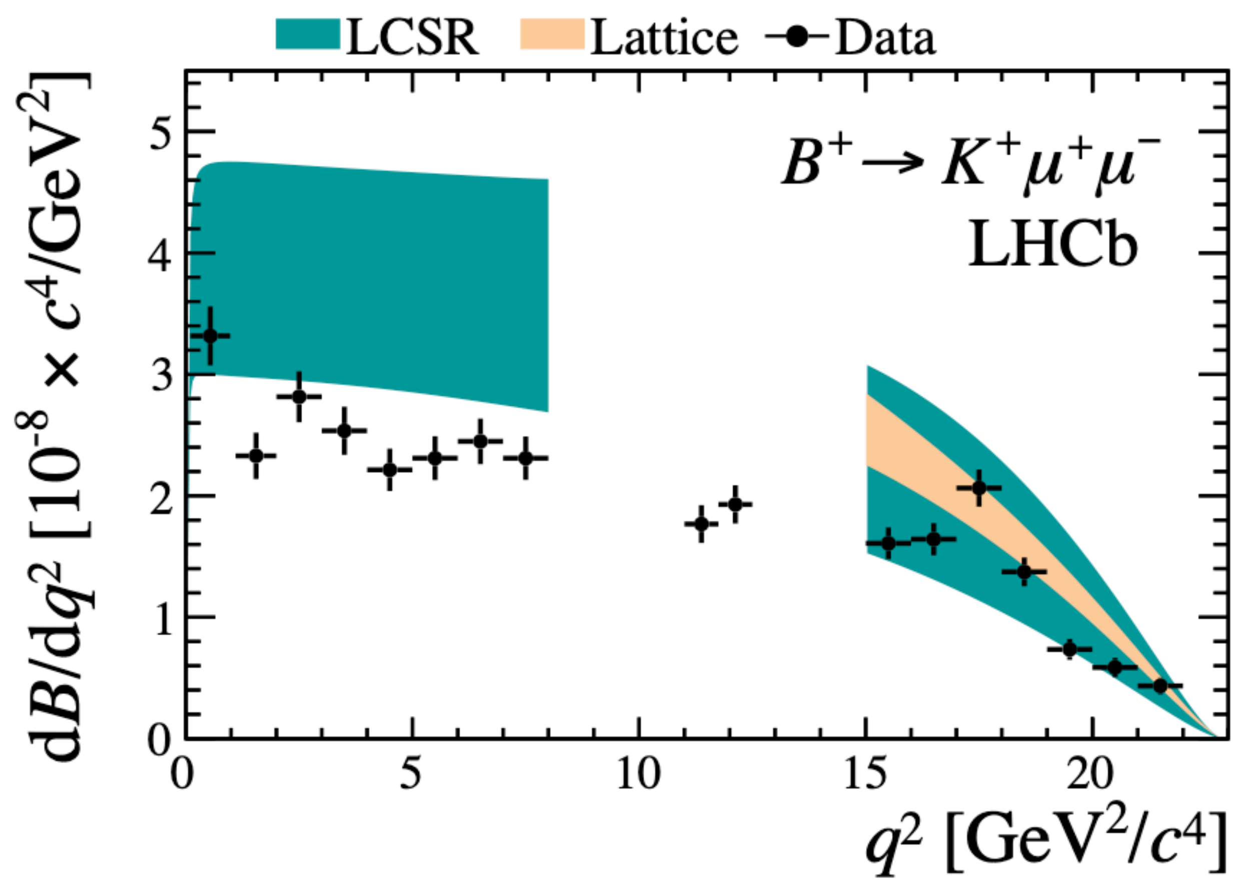


The $b \to s\mu^+\mu^-$ anomalies

Several LHCb measurements deviate from SM predictions* by 2-3σ:

- Angular observables in $B \to K^*\mu^+\mu^-$ [LHCb, 2003.04831, 2012.13241]
- Branching ratios $B \to K^{(*)}\mu^+\mu^-$ and $B_s \to \phi\mu^+\mu^-$ [LHCb, 1403.8044, 1506.08777, 2105.14007]





*: based on hadronic assumptions on which there is no theory consensus

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

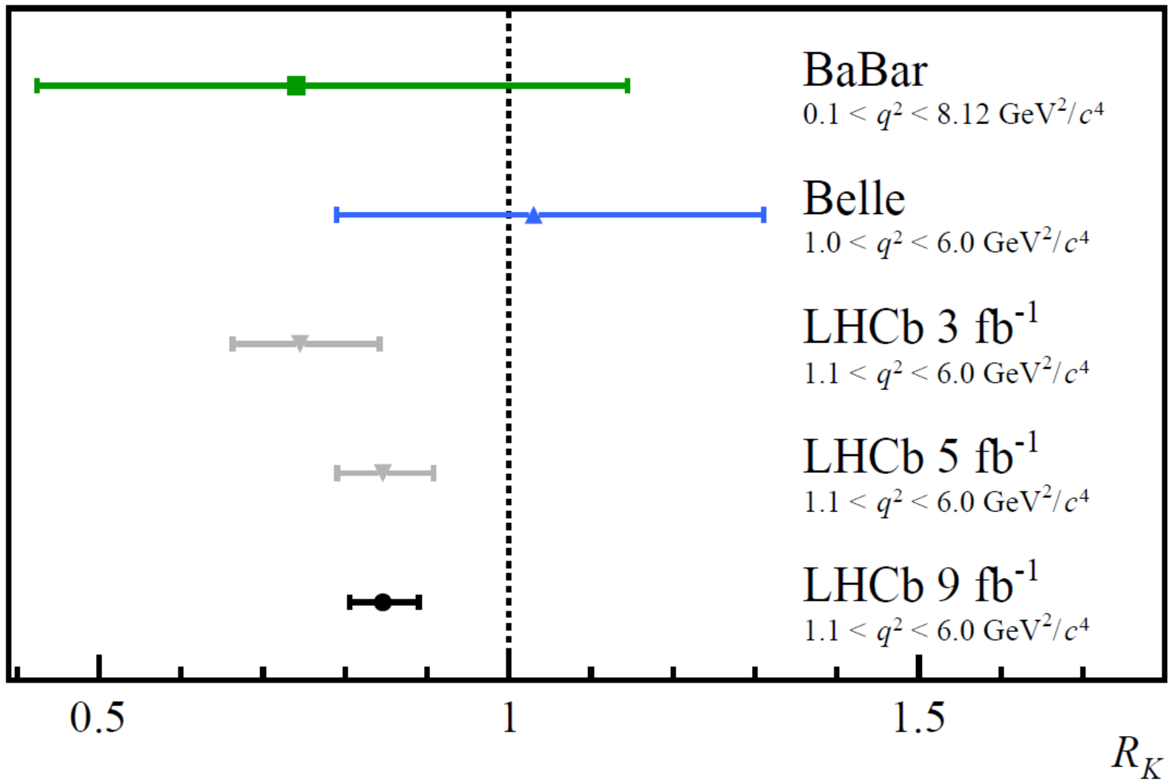
Lepton flavor universality ratios also show deviations from SM prediction

[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]

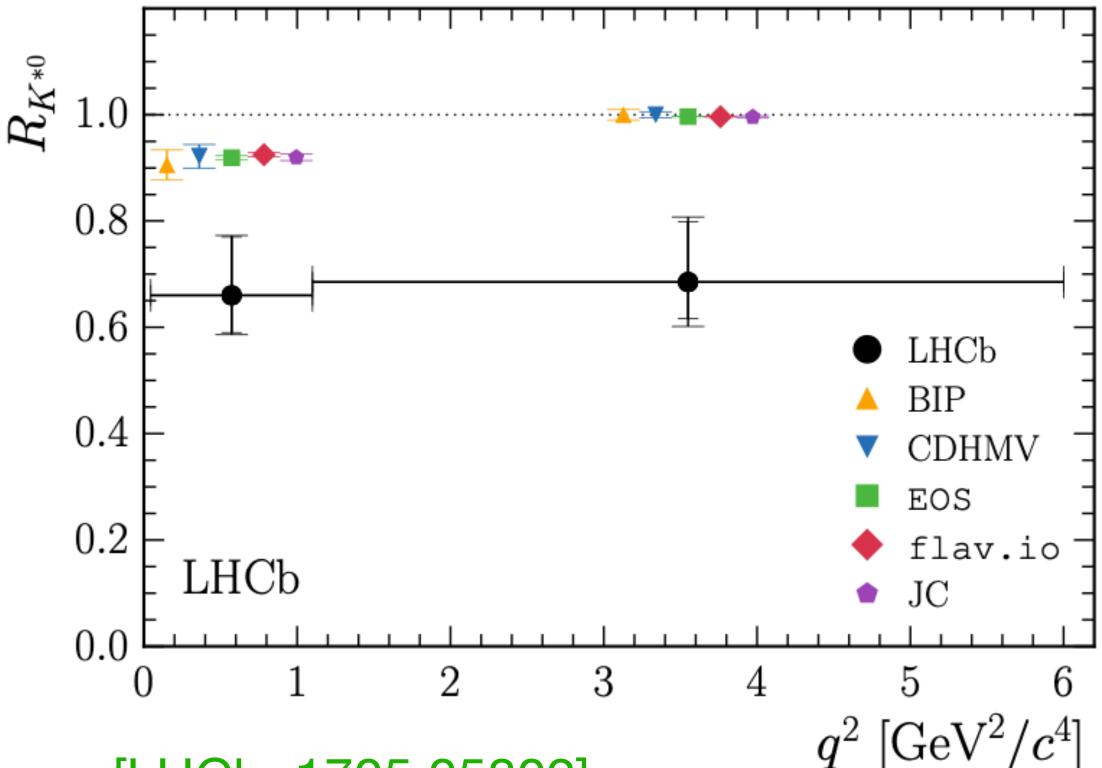


2014

2019

2021

[LHCb, 2103.11769]



2017

[LHCb, 1705.05802]

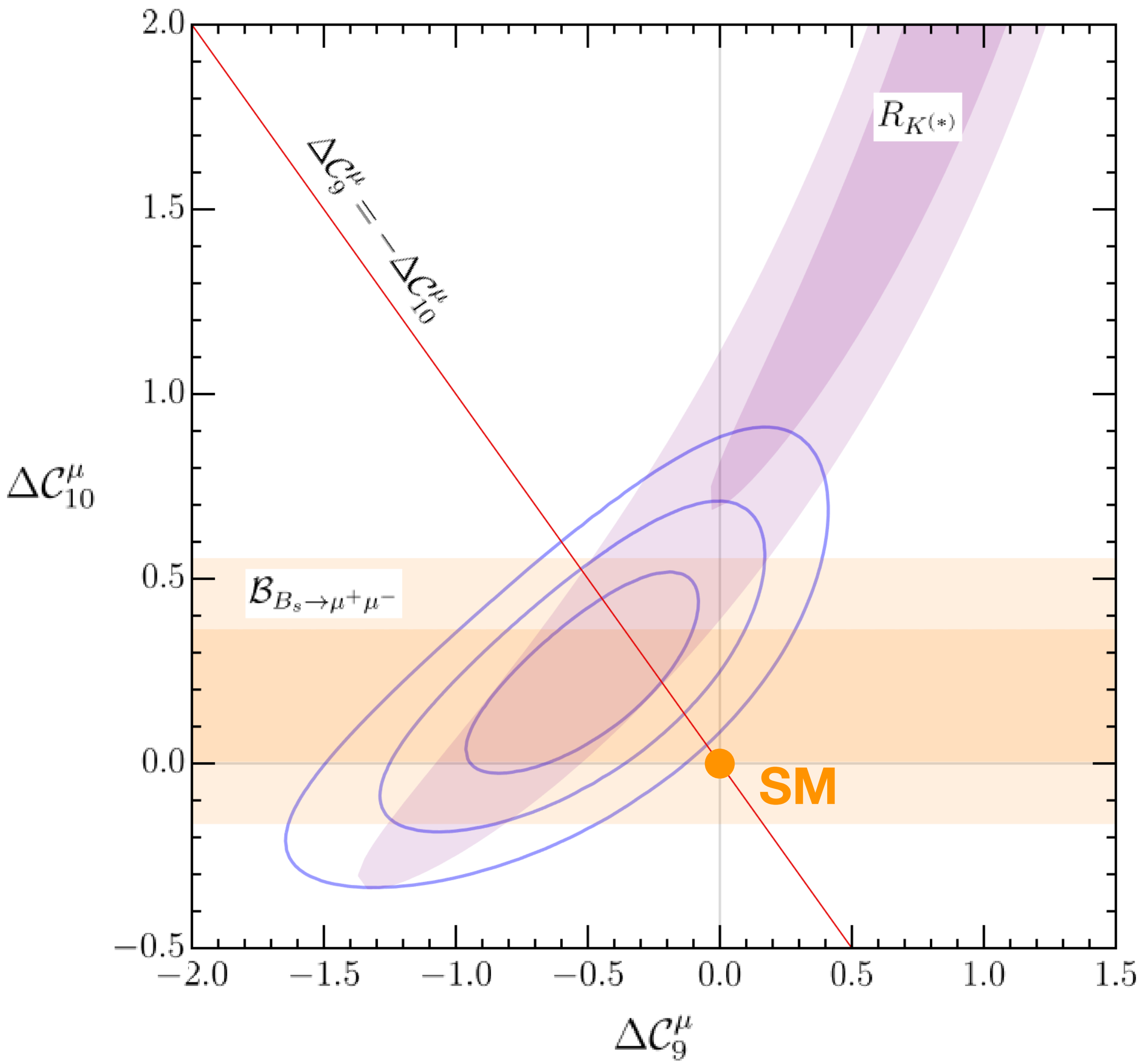
Deviations in other LFUV ratios (R_{pK}, $R_{K^{*+}}$, R_{K^0}) (with larger errors) [LHCb, 2110.09501,1912.08139]

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

*: with *new* $\mathscr{B}_{B_s\to\mu^+\mu^-}$ from [CMS PAS BPH-21-006]

Conservative fit using "th clean observables" only *

$$[\ \Delta C_i^\mu = C_i^\mu - C_i^e\ ]$$



[Update from Cornella, JF et al., 2103.16558]

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

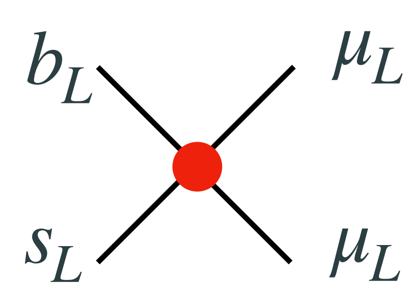
$$\mathcal{O}_9^\mu = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}\gamma^\mu \mu) \qquad C_9^{\rm SM} \approx 4.1$$

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

Left-handed new physics [$\Delta C_9^\mu = -\Delta C_{10}^\mu$]
preferred over the SM by 3.9σ

[Consistent with $b \to s\mu^+\mu^-$ deviations
…considerably increasing NP significancy]

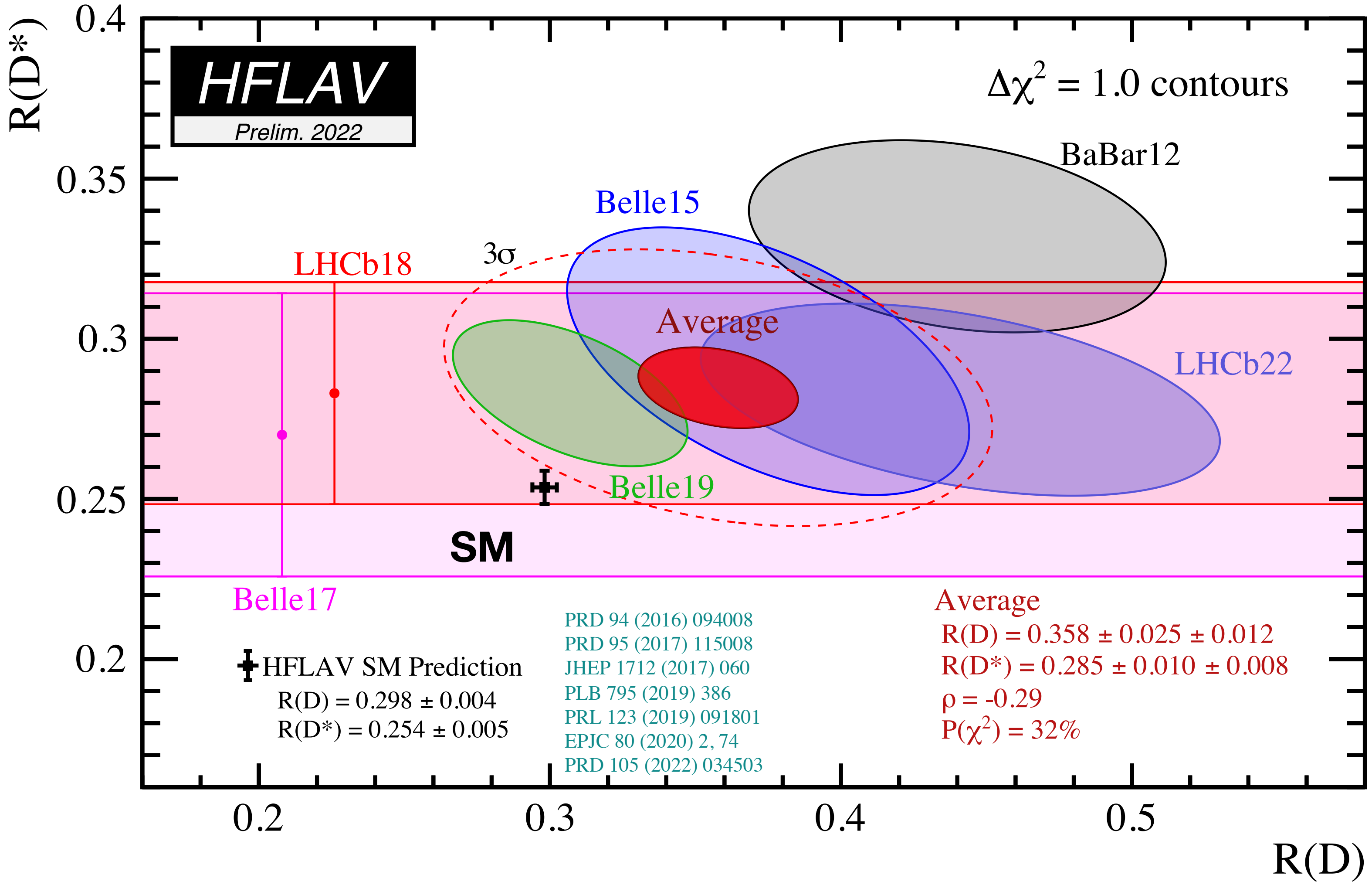
[See e.g. Algueró et al., 1903.09578]

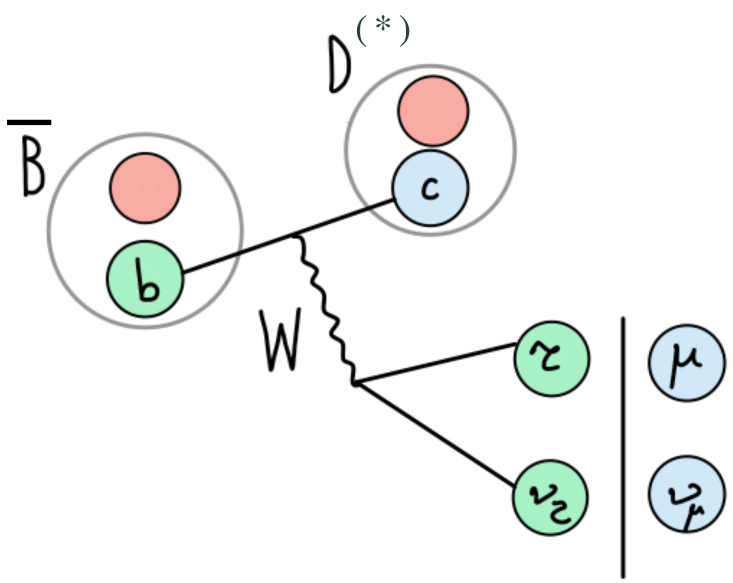


$$\sim 3\times 10^{-5}\, G_F$$

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

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

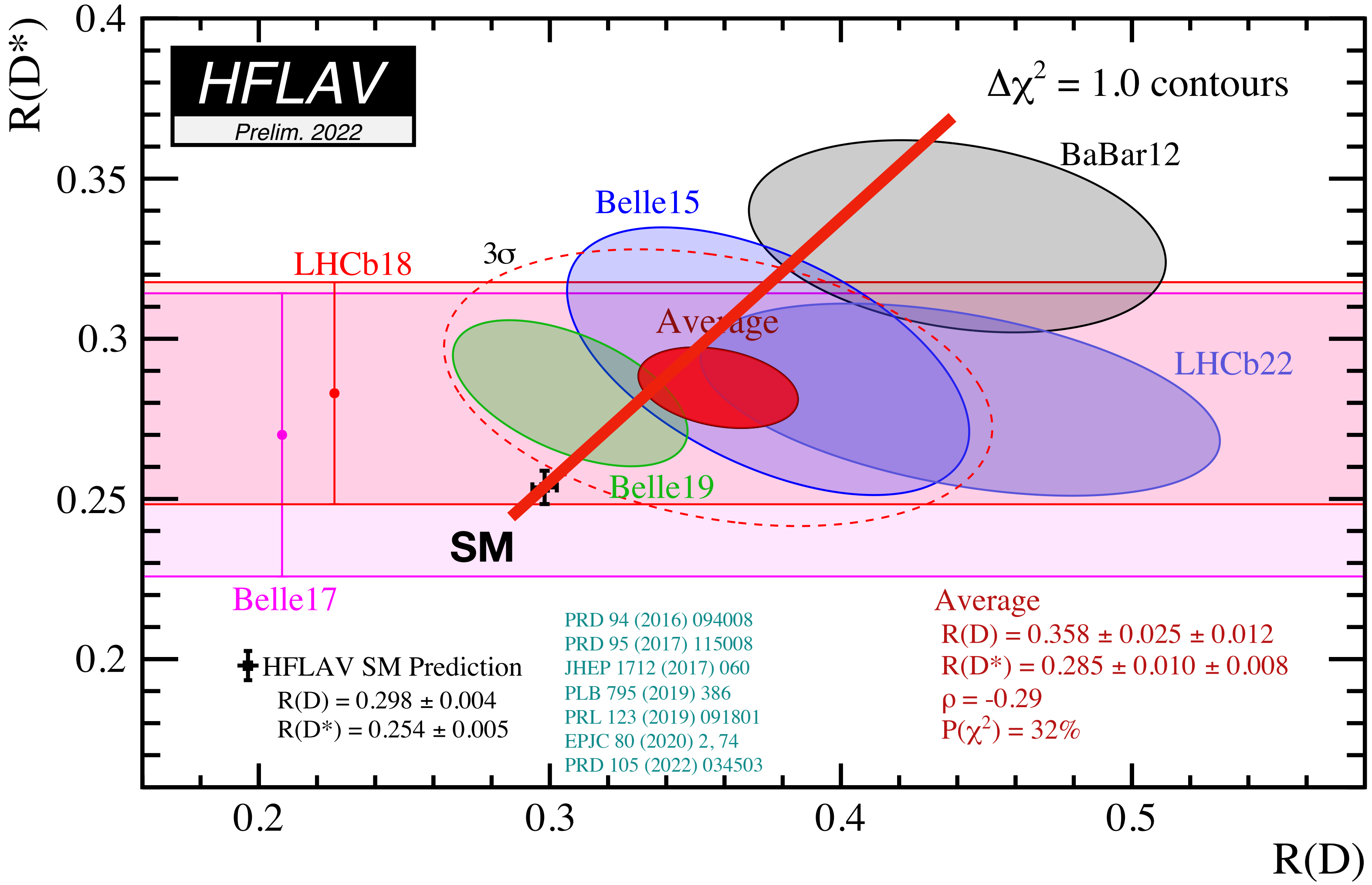




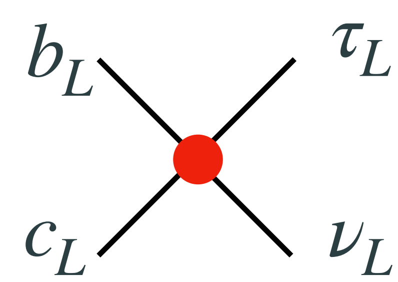
$[\ell = e, \mu]$

- $\sim 15\,\%$ enhancement due to excess in tau mode
- Theoretically clean: QCD uncertainties cancel (to a large extent) in the ratios
- Measurements by Babar, Belle, LHCb in reasonable agreement
- 3.2σ tension (R_D and R_{D*} combined)

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



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



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

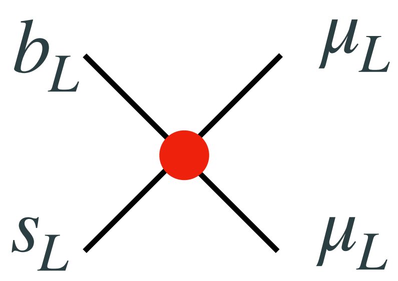
$$\Longrightarrow \frac{g_{\rm NP}^2}{M_{\rm NP}^2} \sim \frac{1}{(3\ \text{TeV})^2}$$

… with room for other NP structures

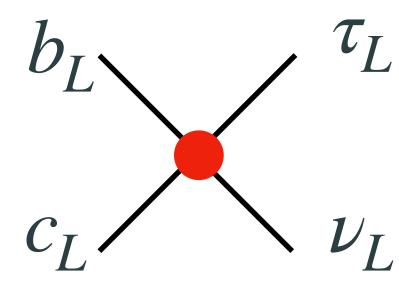
- $\sim 15\,\%$ enhancement due to excess in tau mode
- Theoretically clean: QCD uncertainties cancel (to a large extent) in the ratios
- Measurements by Babar, Belle, LHCb in reasonable agreement
- 3.2σ tension (R_D and R_{D*} combined)
- Recent measurement of $R(\Lambda_c)$ [$\Lambda_b \to \Lambda_c \ell \nu$] reduces the tension slightly [LHCb, 2201.03497]

Consistency with a multi-scale picture?

$$C_{LL}^{ij\alpha\beta}\left(\bar{q}_L^i\gamma^\mu l_L^\alpha\right)\left(\bar{l}_L^\beta\gamma_\mu q_L^j\right)$$



$\ll$



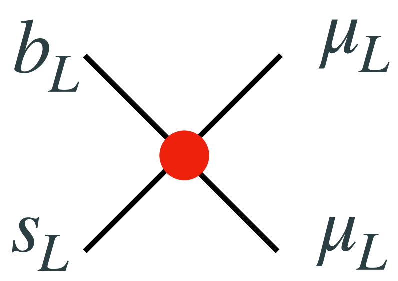
$$C_{LL}^{2322} \sim \frac{1}{(40\ \text{TeV})^2} \qquad C_{LL}^{2333} \sim \frac{1}{(3\ \text{TeV})^2}$$

$$3_q \to 2_q 2_\ell 2_\ell \qquad 3_q \to 2_q 3_\ell 3_\ell$$

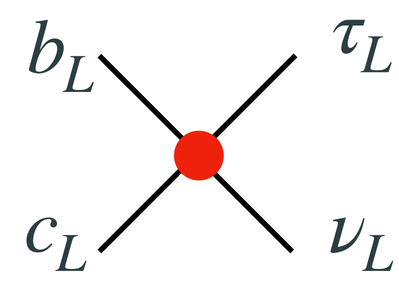
The only source of **lepton flavor universality violation** in the SM (Yukawas) follows a very similar trend: $y_e \ll y_\mu \ll y_\tau$

Consistency with a multi-scale picture?

$$C_{LL}^{ij\alpha\beta}\,(\bar{q}_L^i\gamma^\mu l_L^\alpha)(\bar{l}_L^\beta\gamma_\mu q_L^j)$$



$\ll$



$$C_{LL}^{2322} \sim \frac{1}{(1\ \text{TeV})^2}\,|V_q|\,|V_\ell|^2 \qquad C_{LL}^{2333} \sim \frac{1}{(1\ \text{TeV})^2}\,|V_q|$$

$$3_q \to 2_q 2_\ell 2_\ell \qquad 3_q \to 2_q 3_\ell 3_\ell$$

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

Data consistent with **TeV-scale NP** with a Yukawa-like scaling with $|V_q|, |V_\ell| \sim 0.1$
[roughly the size inferred from the SM Yukawa $|V_q| \sim V_{cb} \approx 0.04$]

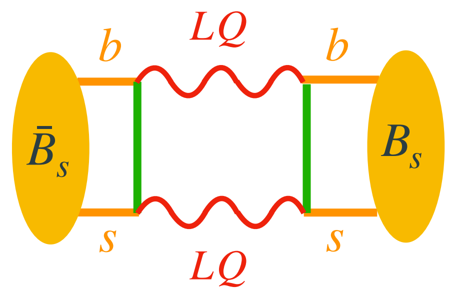
[JF, Isidori, Pagès, Yamamoto, 1909.02519]

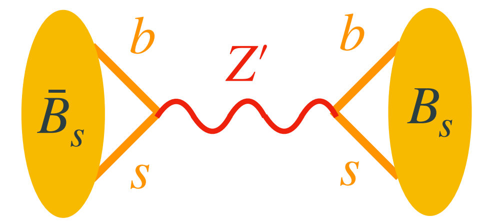
From EFT solutions to simplified BSM models

The main suspects

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

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

[Angelescu, Bečirević, Faroughy, Sumensary, 1808.08179]

Three viable options in the market:

★ U_1 + UV completion

[di Luzio, Greljo, Nardecchia 1708.08450;
Calibbi, Crivellin, Li 1709.00692;
Bordone, Cornella, JF, Isidori 1712.01368;
Barbieri, Tesi, 1712.06844…]

★ $S_1 + S_3$

[Crivellin, Muller, Ota 1703.09226;
Buttazzo et al. 1706.07808;
Marzocca 1803.10972,…]

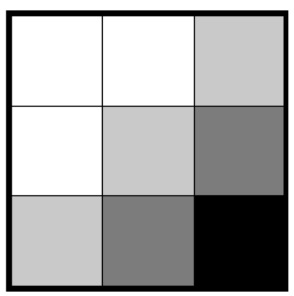
★ $S_3 + R_2$

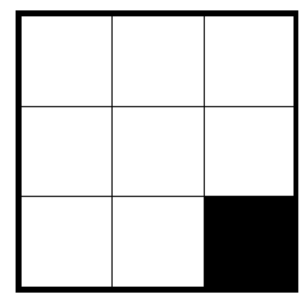
[Bečirević et al., 1806.05689]

The U_1 vector leptoquark

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

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

$\beta_L^{ql} \sim$ 

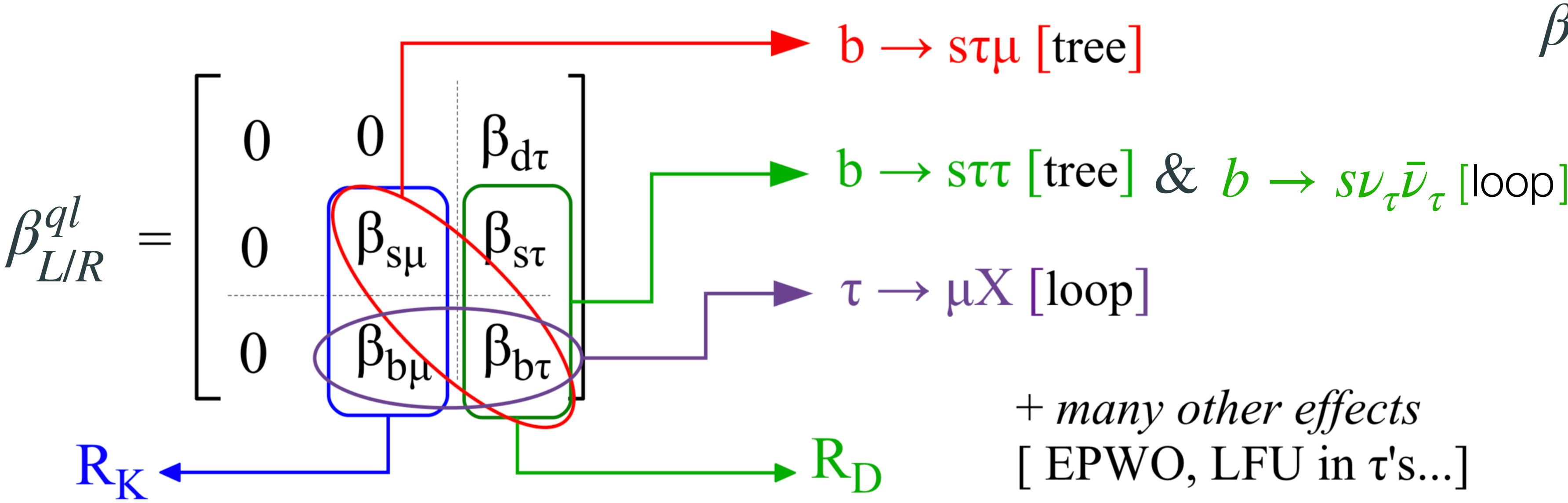
$\beta_R^{ql} \sim$ 

Yukawa-like scaling:

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

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

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

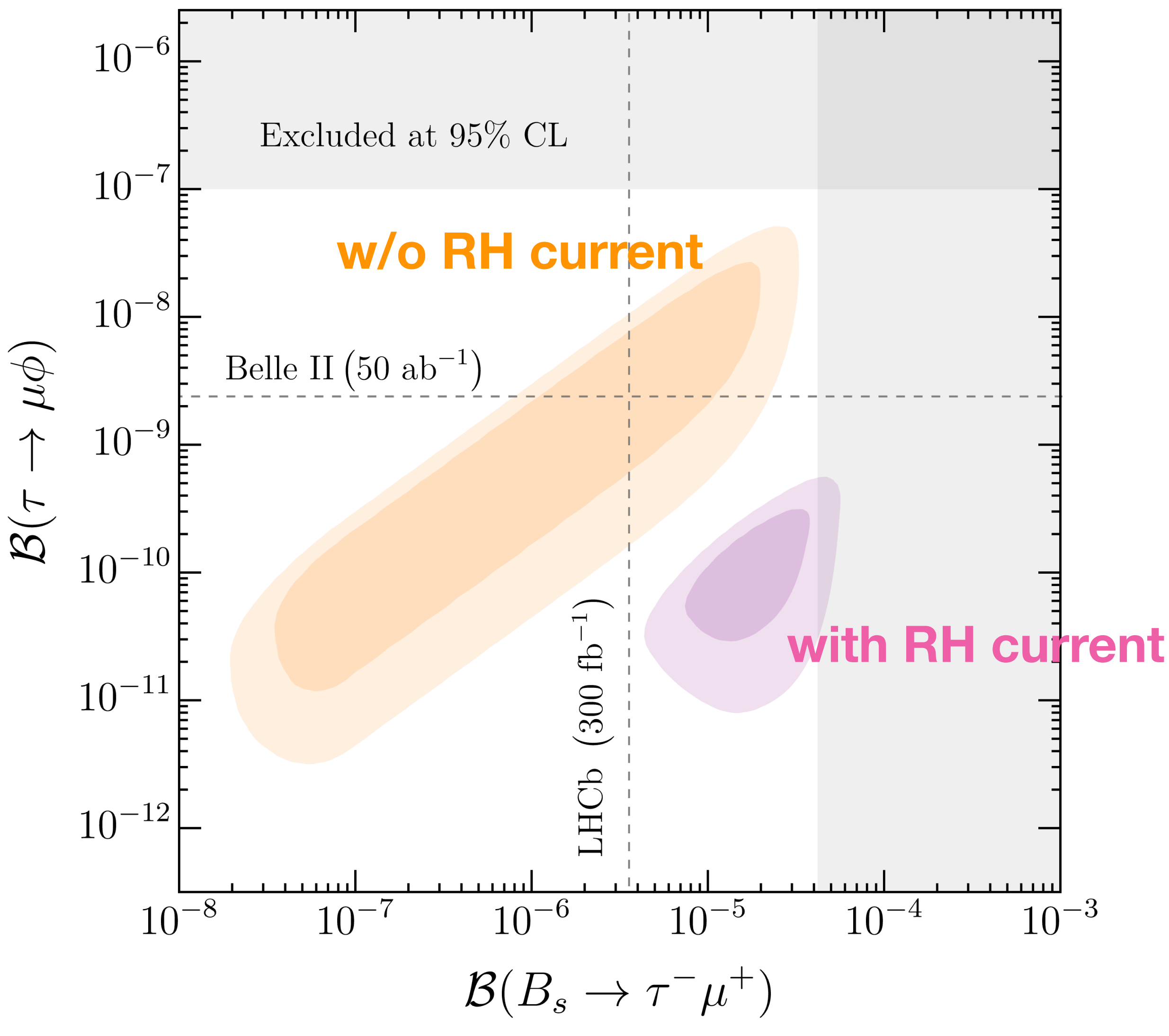


Some (key) low-energy predictions

[Cornella, JF et al., 2103.16558]

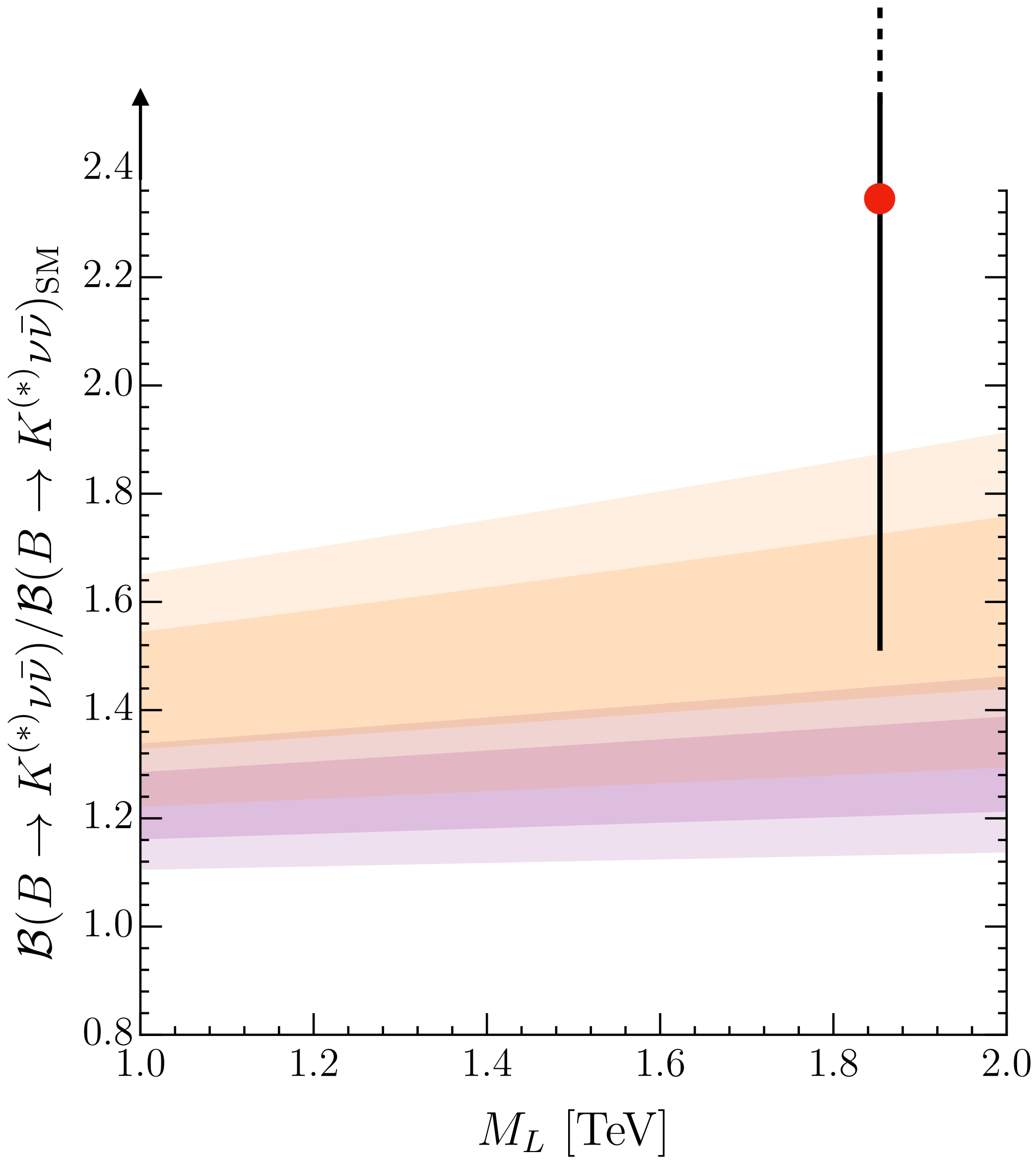
LHCb & Belle II essential to confirm/exclude the new physics solution in a large class of correlated observables

$\tau - \mu$ Lepton Flavor Violation



$b \to s\nu_{(\tau)}\bar{\nu}_{(\tau)}$ (loop-level for U_1 model)

[$b \to s\tau^+\tau^-$ also key (see backup)]

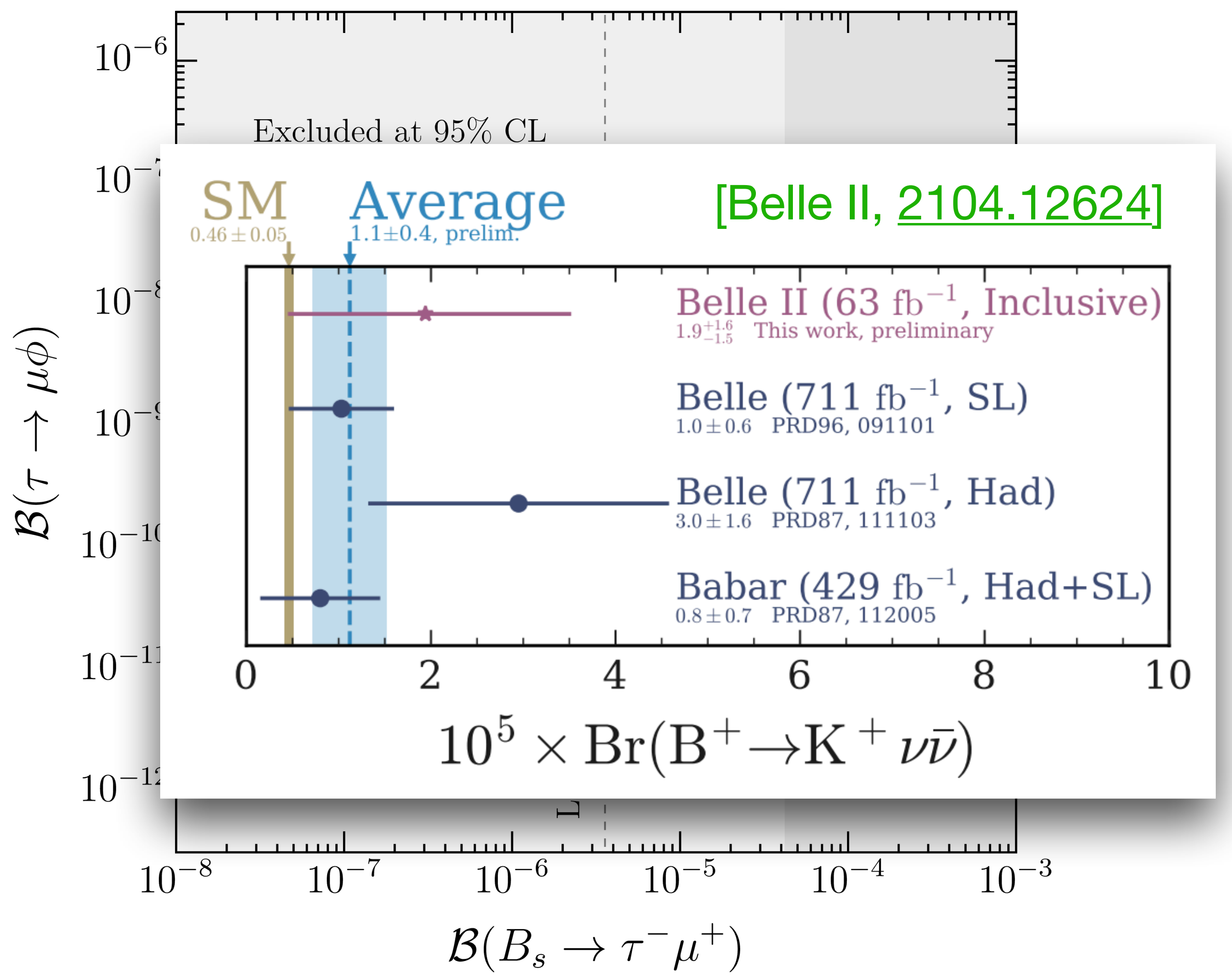


Some (key) low-energy predictions

[Cornella, JF et al., 2103.16558]

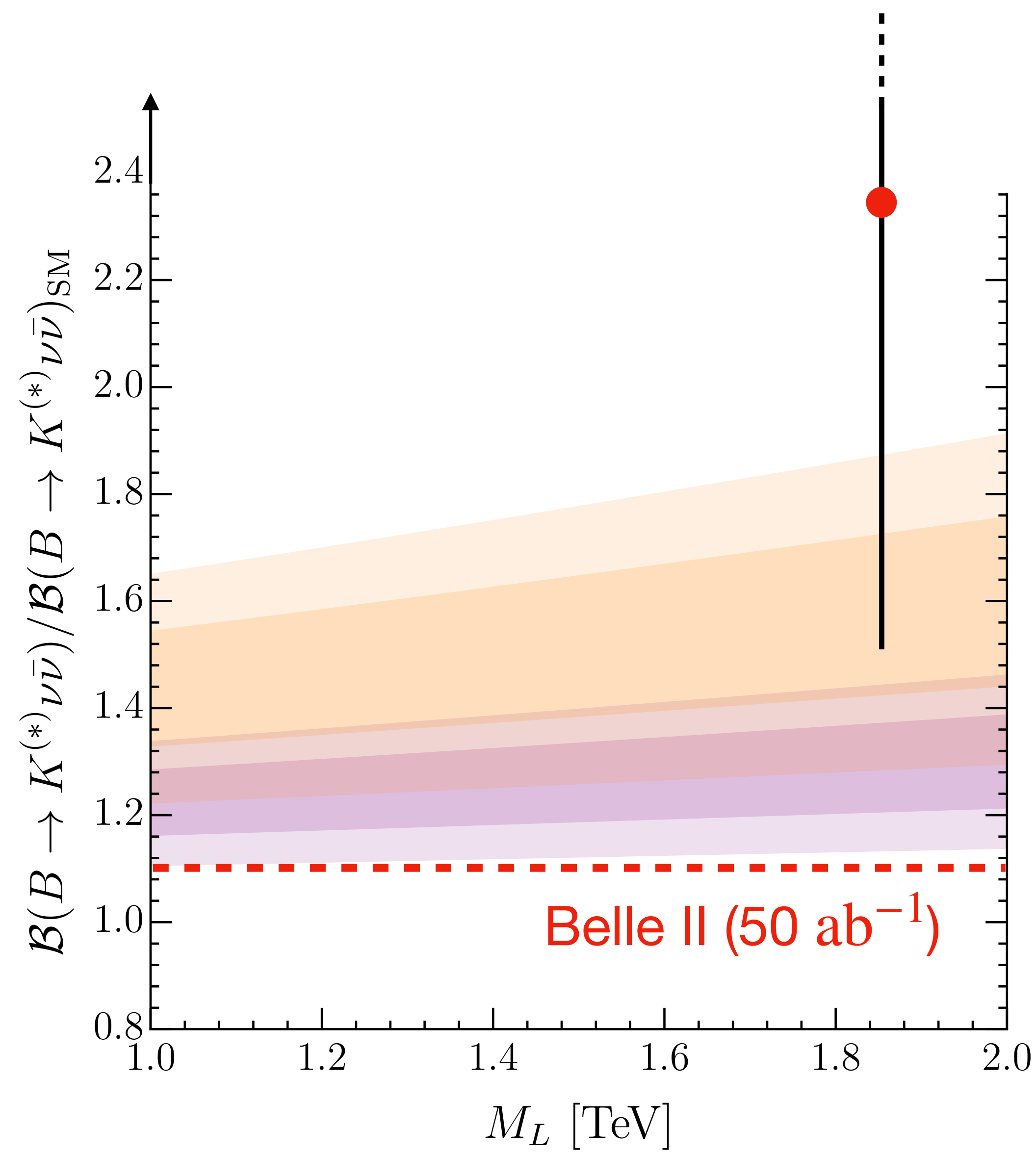
LHCb & Belle II essential to confirm/exclude the new physics solution in a large class of correlated observables

$\tau - \mu$ Lepton Flavor Violation



$b \to s\nu_{(\tau)}\bar{\nu}_{(\tau)}$ (loop-level for U_1 model)

[$b \to s\tau^+\tau^-$ also key (see backup)]



A glimpse into possible UV completions

Gauge UV completion for the U_1 leptoquark

$$U_1 \sim (3,1,2/3) \dashrightarrow SU(4) \dashrightarrow \mathrm{PS} = SU(4) \times SU(2)_L \times SU(2)_R$$

$$SU(4) \sim \begin{pmatrix} G^a & U^\alpha \\ (U^\alpha)^* & Z' \end{pmatrix} \qquad \psi_{L,R} = \begin{bmatrix} q^1_{L,R} \\ q^2_{L,R} \\ q^3_{L,R} \\ l_{L,R} \end{bmatrix}$$

Leptons as the fourth "color"

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

- ✓ $SU(4)$ is the smallest group containing the $U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$
- ✓ No proton decay (accidental baryon number symmetry like in the SM)
- ✘ Flavor-blind U_1 mediates $K_L \to \mu e \;\Rightarrow\; m_{U_1} \gtrsim 100\,\mathrm{TeV}$
- ✘ Extra fermions can make the U_1 non-universal, but not the Z'
- ✘ Strongly coupled, universal Z' would be excessively produced at the LHC

4321 model(s)

[Georgi and Y. Nakai, 1606.05865; Diaz, Schmaltz, Zhong, 1706.05033; Di Luzio, Greljo, Nardecchia, 1708.08450; Bordone, Cornella, JF, Isidori 1712.01368]

We can "protect" the light families by de-correlating $SU(4)$ from the SM color group $(g_4 \gg g_3)$

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

$\Psi^{1,2,3}_{L,R}$

$\downarrow$

4321 group: $\mathcal{G}_{4321} \equiv SU(4)_h \times SU(3)_l \times SU(2)_L \times U(1)_{R+l}$ [Flavor non-universal]

$\Psi^{3}_{L,R}$ $\qquad$ $\Psi^{1,2}_{L,R}$

$U(1)_Y$

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

$SU(3)_c$

$+U_1, Z', G'$

[Flavor non-universal]

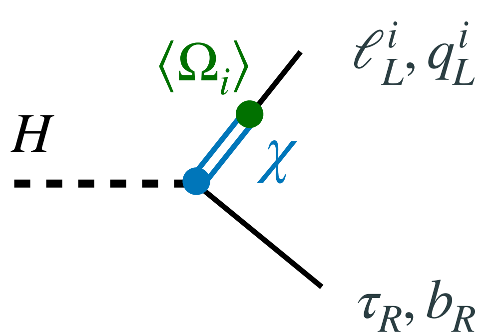
Third-family quark lepton unification at the TeV scale

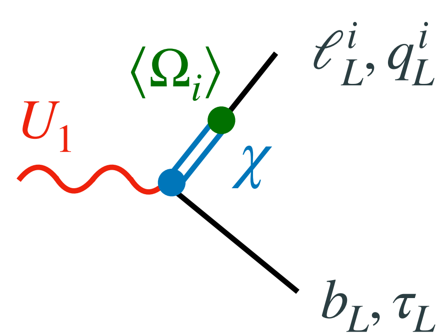
$$\underbrace{\overbrace{SU(4)_h \times SU(3)_l \times SU(2)_L \times U(1)_{R+l}}^{U(1)_Y}}_{SU(3)_c} \xrightarrow{\langle \Omega_{1,3,15} \rangle \sim \mathcal{O}(\text{TeV})} SU(3)_c \times SU(2)_L \times U(1)_Y + U_1, G', Z'$$

- ★ Third-family quark-lepton unification at the TeV

$$\psi_{L,R} = \left[q^1_{L,R} \quad q^2_{L,R} \quad q^3_{L,R} \quad l_{L,R} \right]$$

- ★ Direct new physics couplings to 3rd family only [as in the multi-scale picture]
- ★ CKM mixing and NP couplings to light families via (small) mixing with vectorlike fermions χ





$i = 1,2$

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)_X$	
q^i_L	**1**	**3**	**2**	1/6	1st & 2nd families
u^i_R	**1**	**3**	**1**	2/3	
d^i_R	**1**	**3**	**1**	−1/3	
ℓ^i_L	**1**	**1**	**2**	−1/2	
e^i_R	**1**	**1**	**1**	−1	
ψ_L	**4**	**1**	**2**	0	3rd family
$\psi^\pm_R$	**4**	**1**	**1**	±1/2	
χ^i_L	**4**	**1**	**2**	0	vectorlike fermions
χ^i_R	**4**	**1**	**2**	0	
H	**1**	**1**	**2**	1/2	
Ω_1	$\bar{\mathbf{4}}$	**1**	**1**	−1/2	4321 breaking scalars
Ω_3	$\bar{\mathbf{4}}$	**3**	**1**	1/6	
Ω_{15}	**15**	**1**	**1**	0	

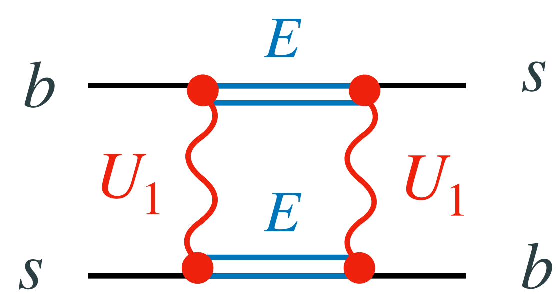
[Bordone, Cornella, JF, Isidori 1712.01368, 1805.09328;
Greljo, Stefanek, 1802.04274;
Cornella, JF, Isidori 1903.11517]

High-p_T predictions: vector-like leptons at high-p_T

Some (important) effects appear only at one loop $\chi_{L,R} = (Q\ L)^T$

$Q \sim (\mathbf{3}, \mathbf{2}, 1/6)$ $Q = \begin{pmatrix} U \\ D \end{pmatrix}$

$L \sim (\mathbf{1}, \mathbf{2}, -1/2)$ $L = \begin{pmatrix} N \\ E \end{pmatrix}$



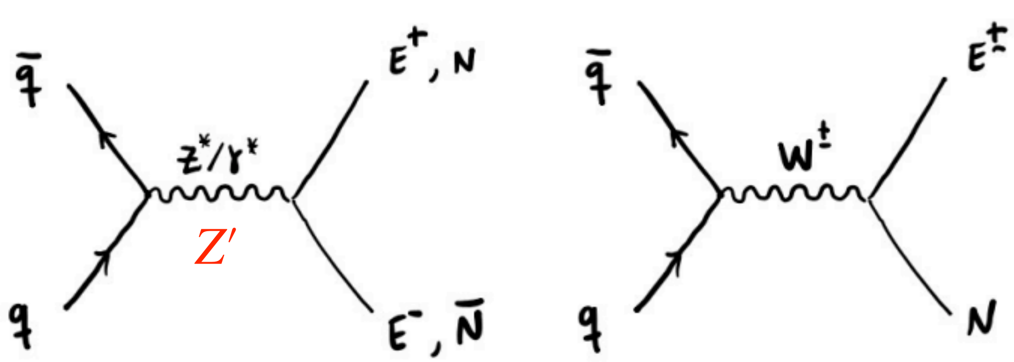
$\sim \Delta R_{D^*}^2 M_L^2 \Longrightarrow M_L \lesssim \text{TeV}$

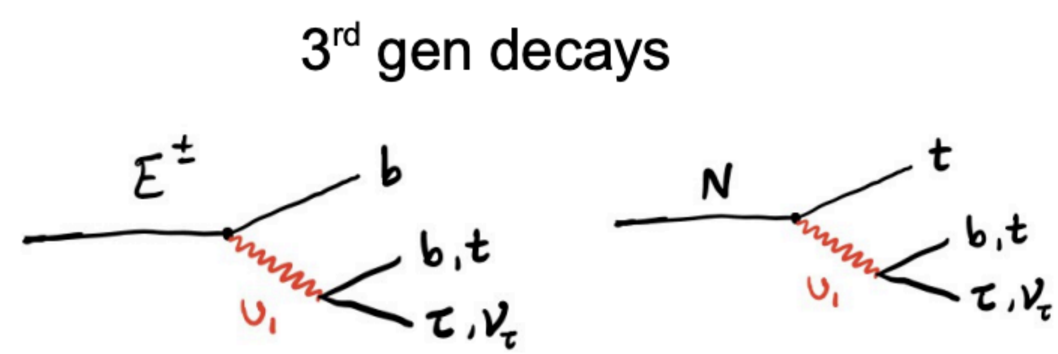
Analogously to the charm quark in the SM

[vectorlike leptons within the LHC reach!]

[di Luzio, JF, et al 1808.00942; Cornella, JF, Isidori 1903.11517; JF et al., 2009.11296]

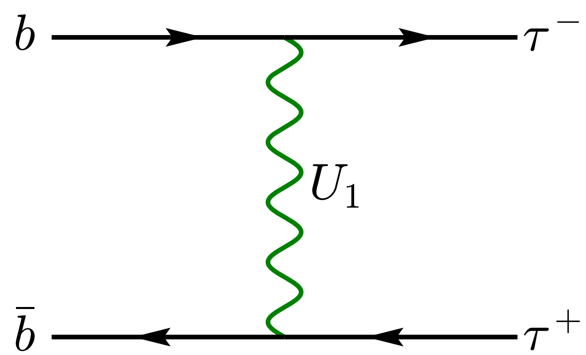
Electroweak (or Z') produced. Dominant **decay to three 3rd generation** SM fermions!

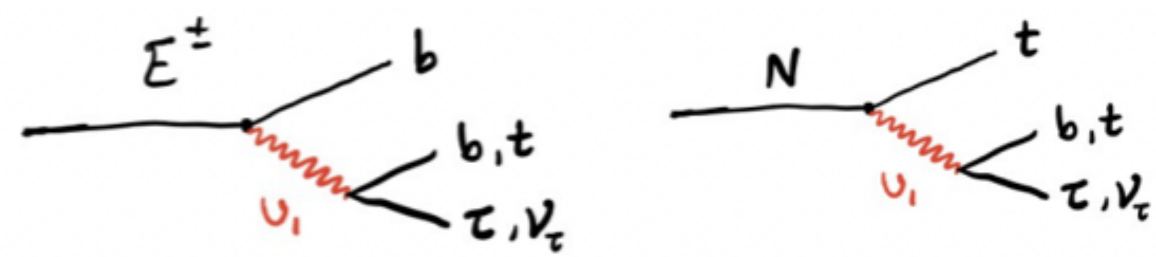




Exciting results for 4321 models from CMS

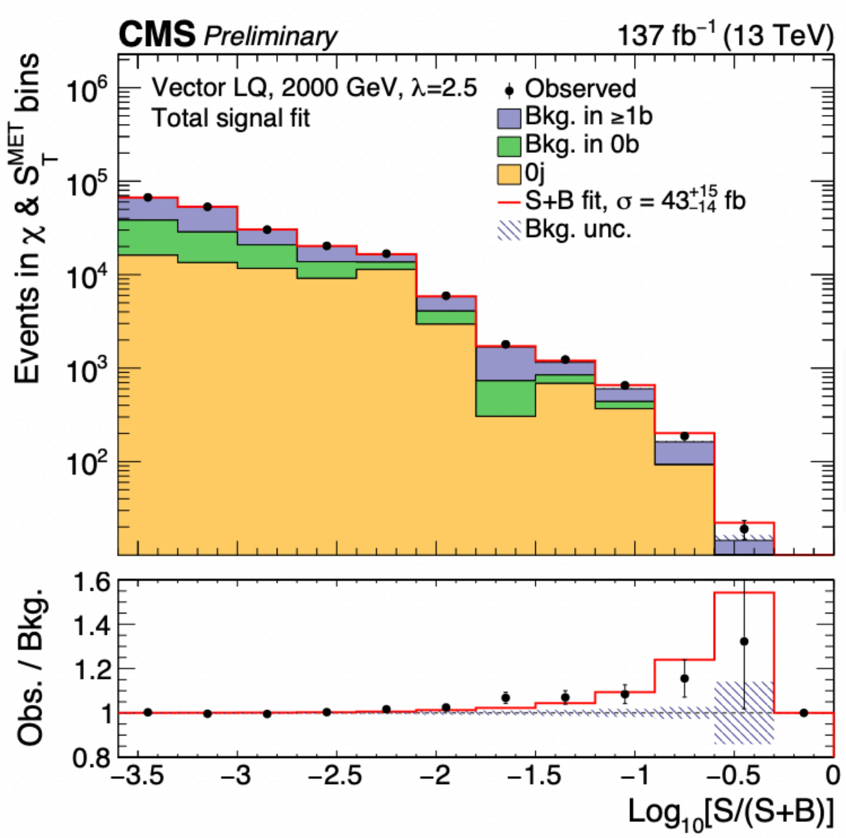
[See talk by Sabino Meola]





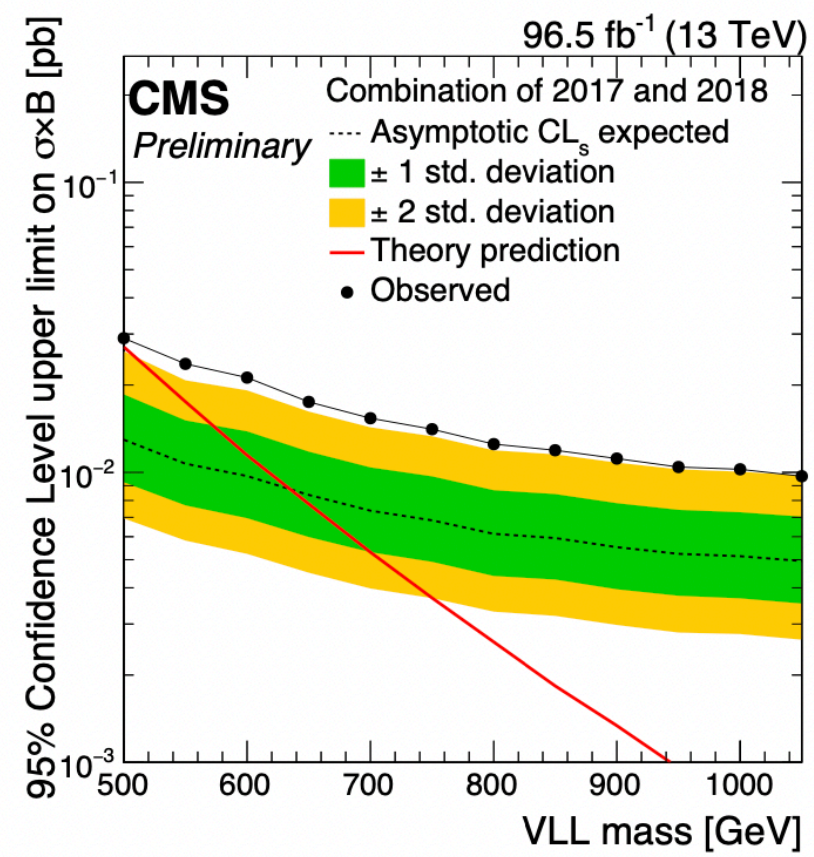
[Faroughy, Greljo, Kamenik, 1609.07138]

[Di Luzio, JF, Greljo, Nardecchia, Renner, 1708.08450]



3.4σ

CMS PAS EXO-19-016



2.8σ

CMS-B2G-21-004

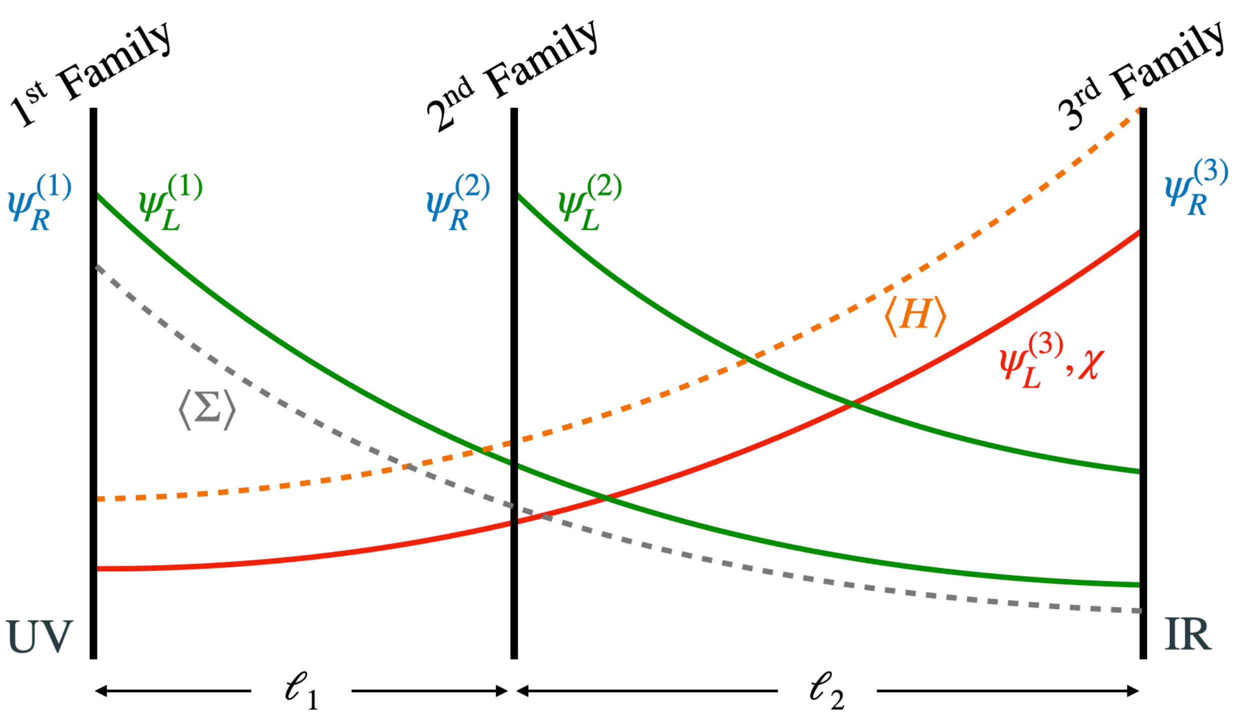
[No excess in ATLAS data (no dedicated search)]

[ATLAS search currently ongoing]

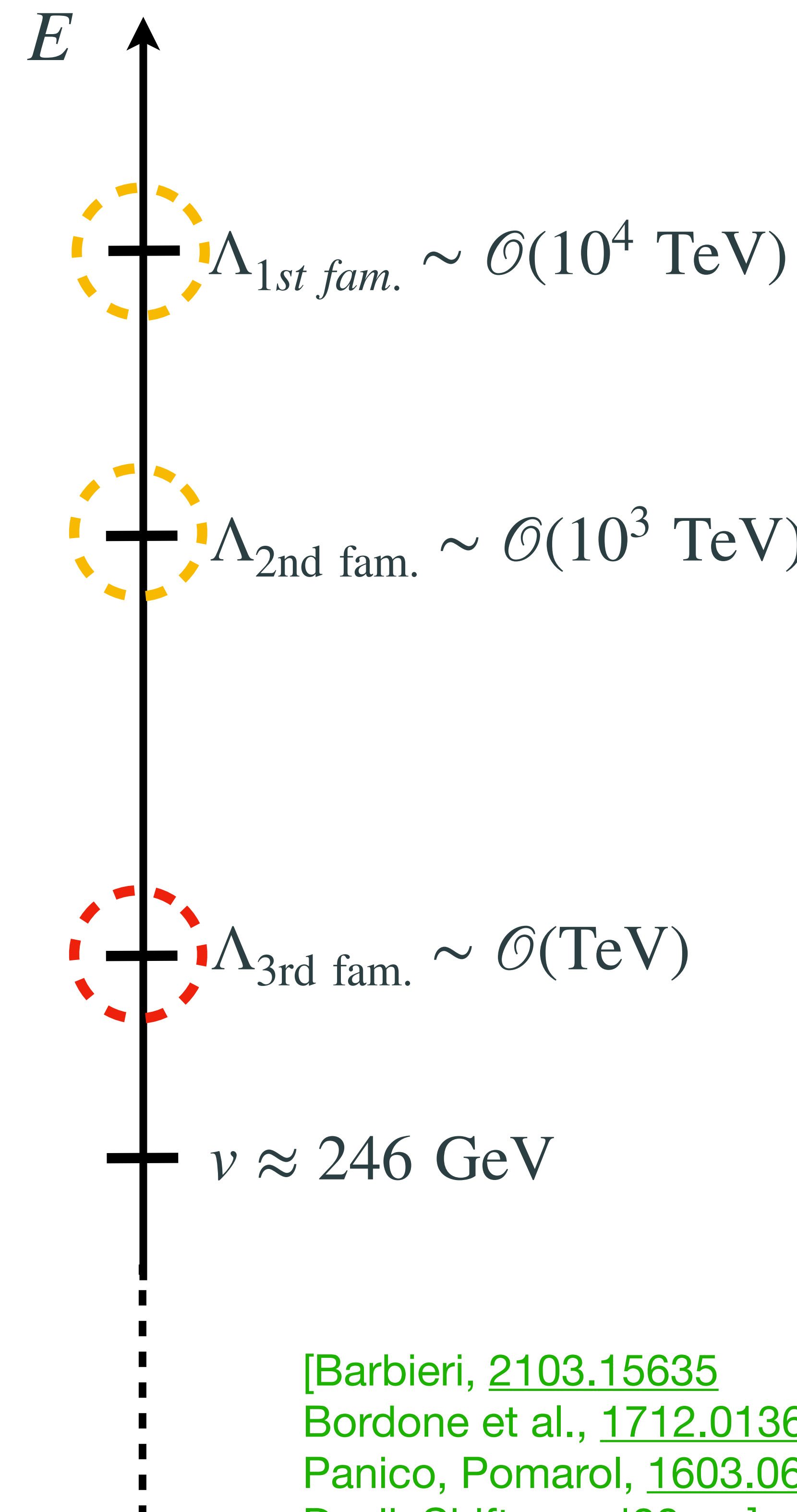
Back to the multi-scale picture

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

Non-trivial UV imprints



$\Longleftrightarrow$

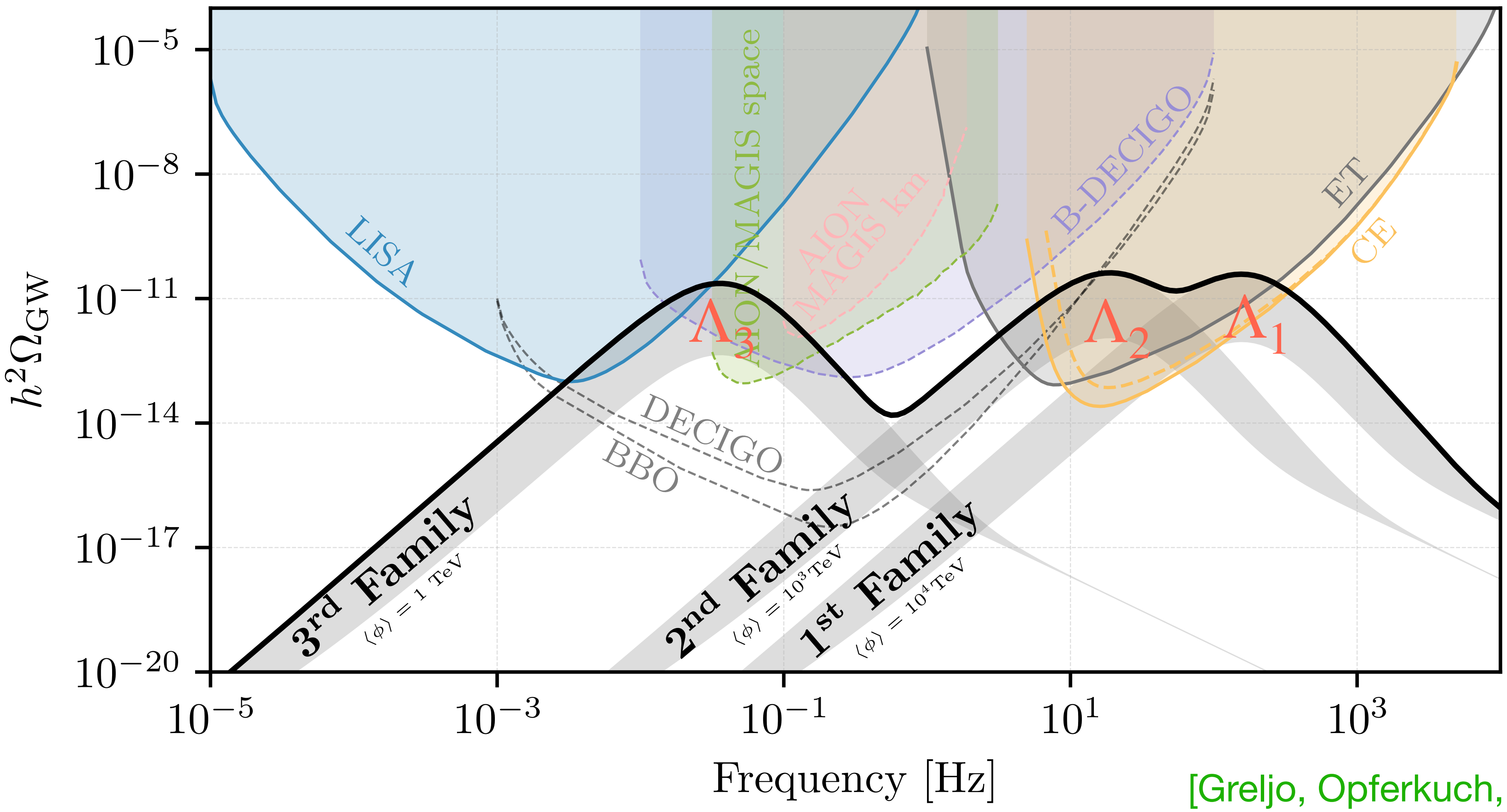


Flavor ⟷ fermion (quasi-)localization along a warped extra dimension

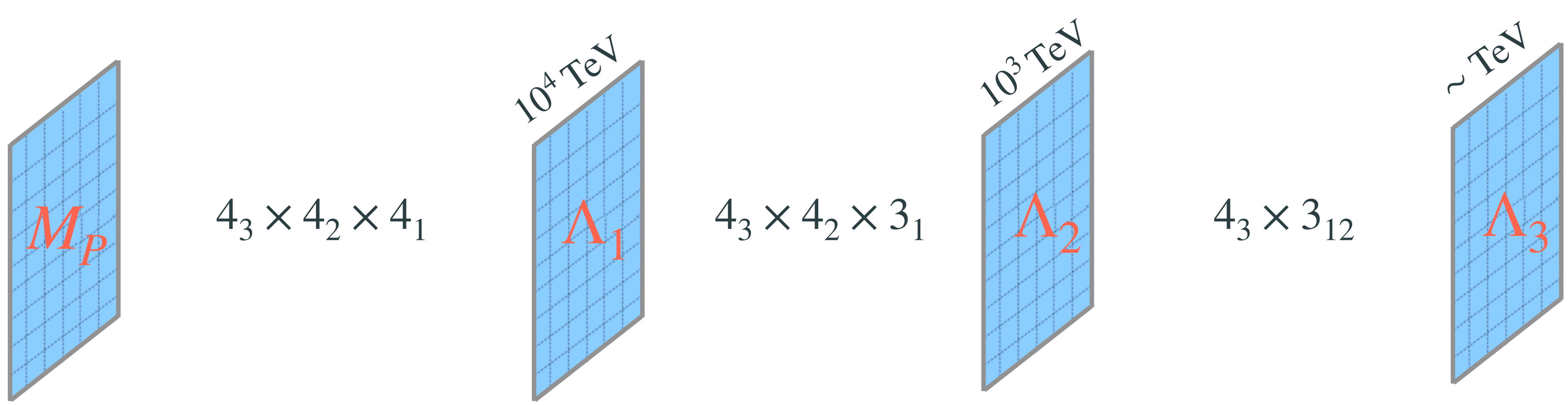
[JF, Isidori, Pagès, Stefanek, 2012.10492
JF, Isidori, Lizana, Selimovic, Stefanek, 2203.01952]

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

Cosmological signatures in multi-scale picture



[Greljo, Opferkuch, Stefanek, 1910.02014]



Conclusions

In combination, $b \to s\ell^+\ell^-$ and $b \to c\tau^-\bar{\nu}$ anomalies point to TeV-scale new physics with a flavor structure similar to that of the SM Yukawas

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

New physics solution consistent with low- & high-energy data, but new physics effects should emerge soon in multiple observables

⟶ Closing in the mass gap or new physics mirage ?

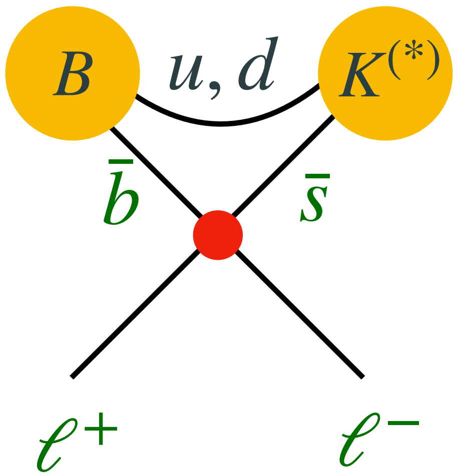
Plenty of upcoming measurements from both the energy and intensity frontiers

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

Thank you!

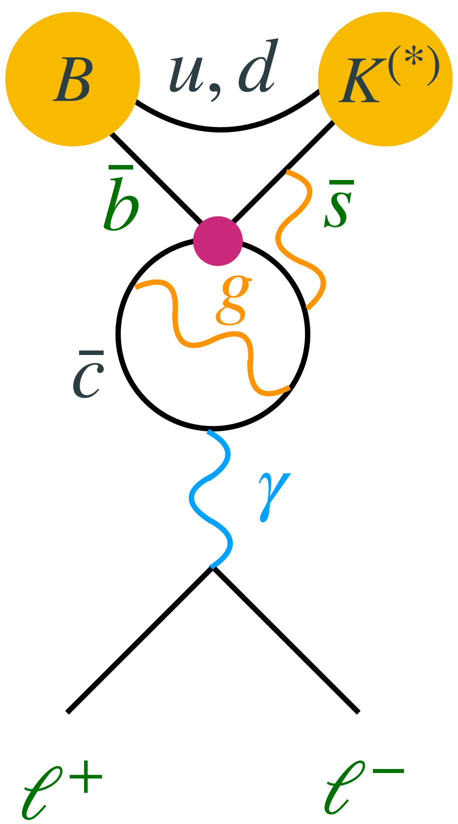
Backup

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



Short-distance
(semileptonic int.)

"Easy" to compute



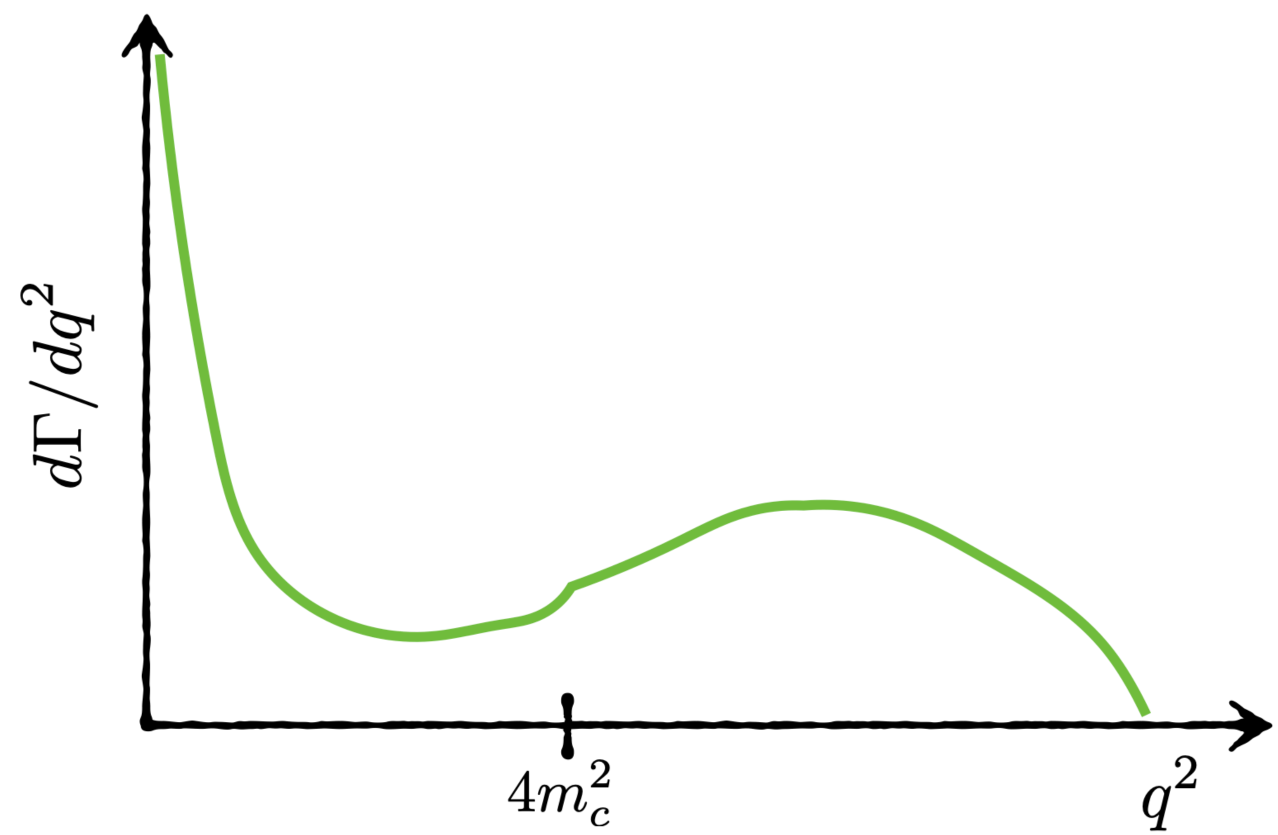
Long-distance
(four-quark int.)

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

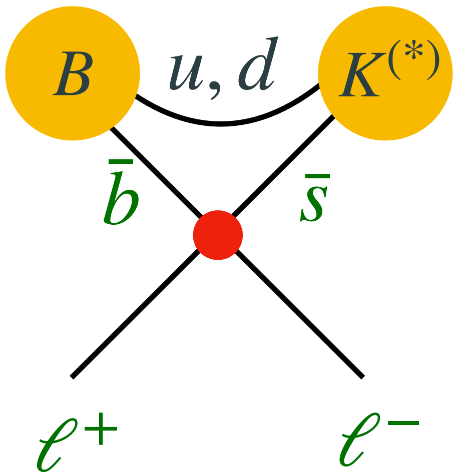


[Figure from Uli Haisch]

★ Long-distance effects cannot induce:

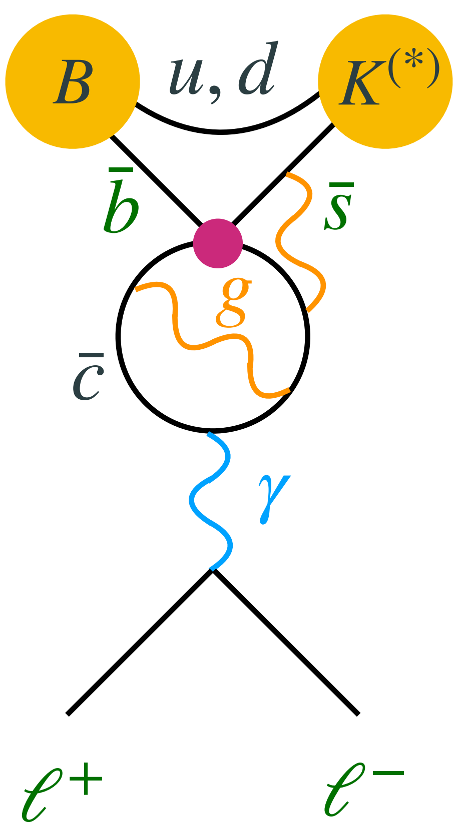
- Breaking of lepton universality
- Axial-current contributions
  (no effect in $B_s \to \mu^+\mu^-$)

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



Short-distance
(semileptonic int.)

"Easy" to compute



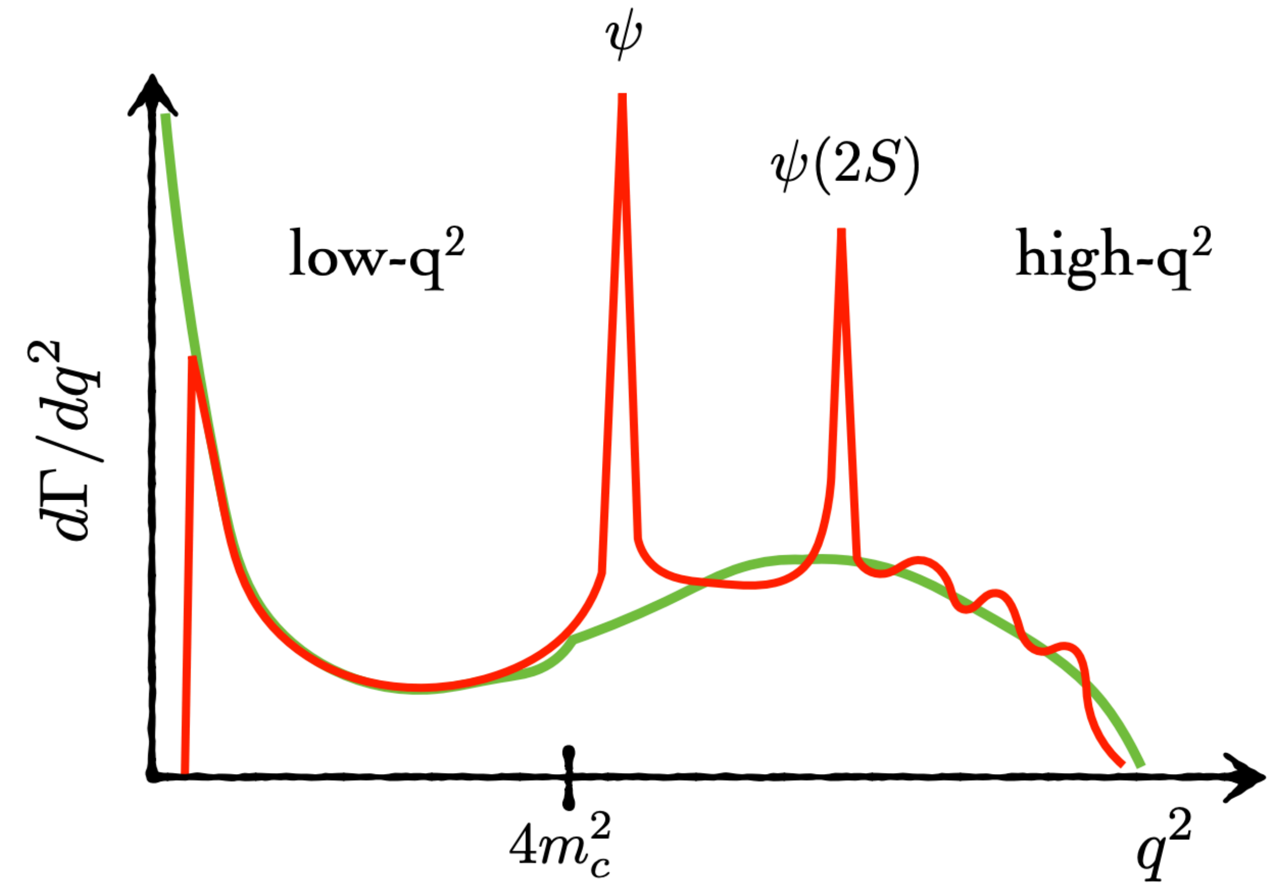
Long-distance
(four-quark int.)

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



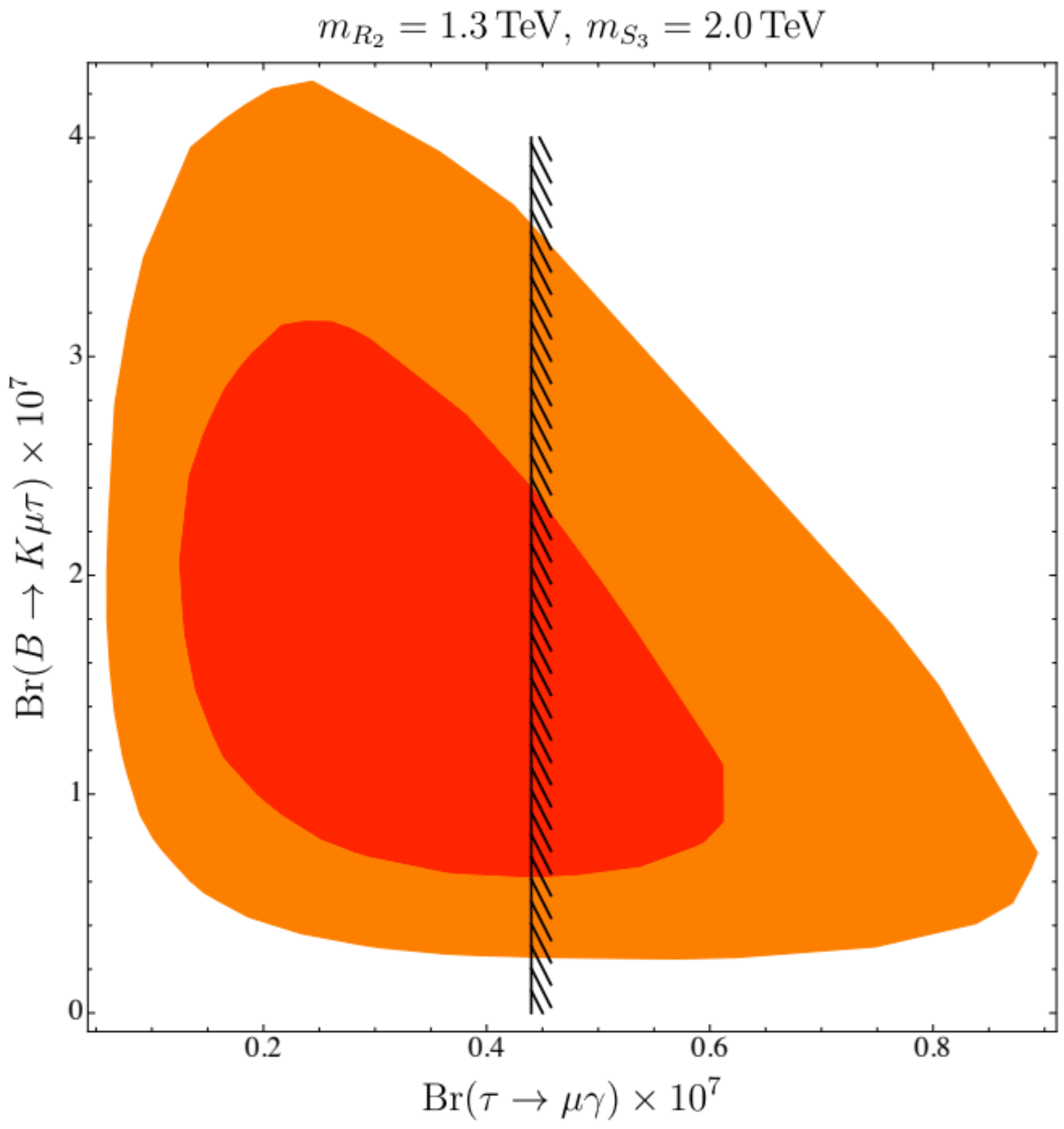
[Figure from Uli Haisch]

★ Long-distance effects cannot induce:

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

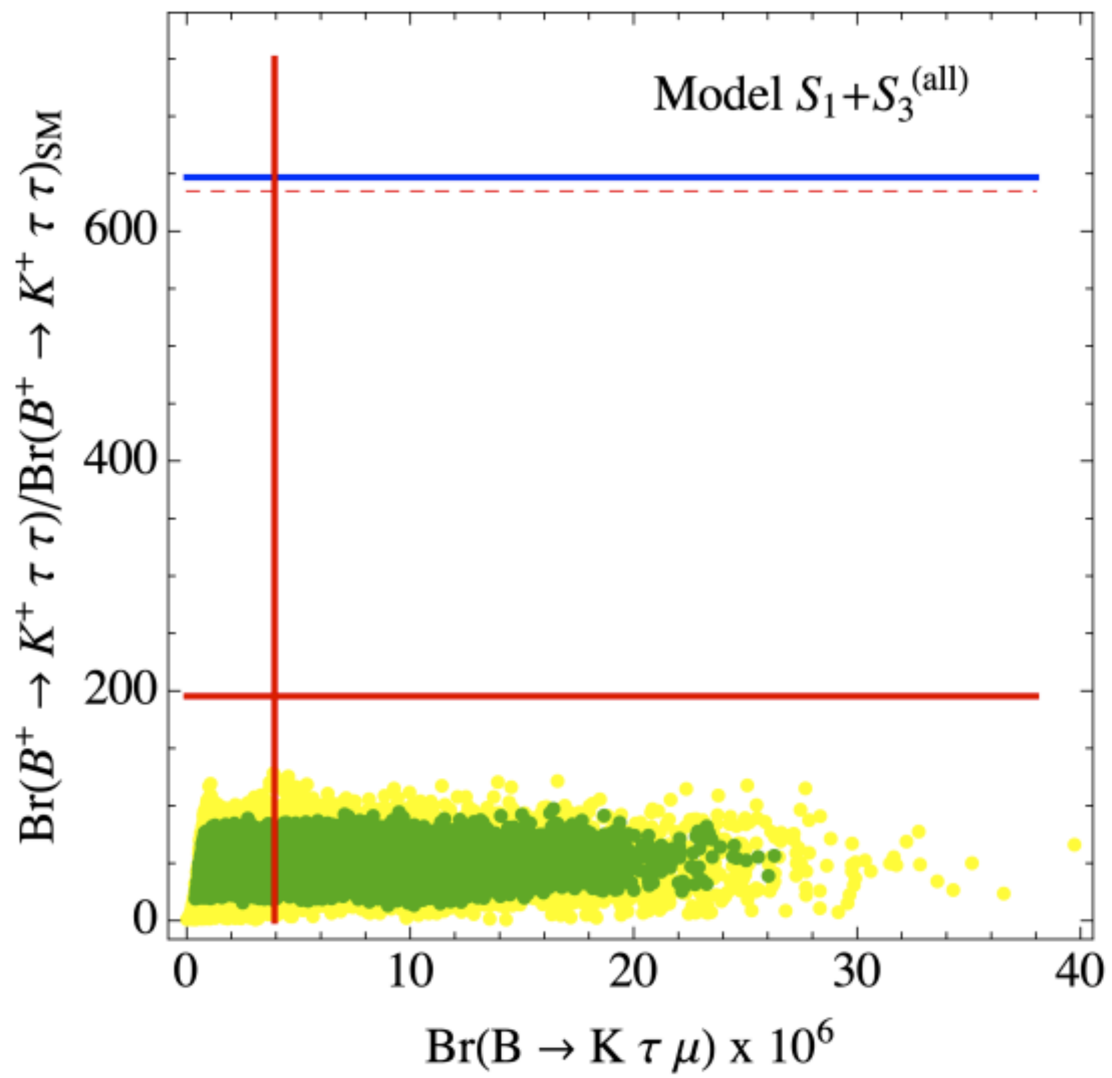
LFV predictions in other leptoquark models

$R_2 + S_3$



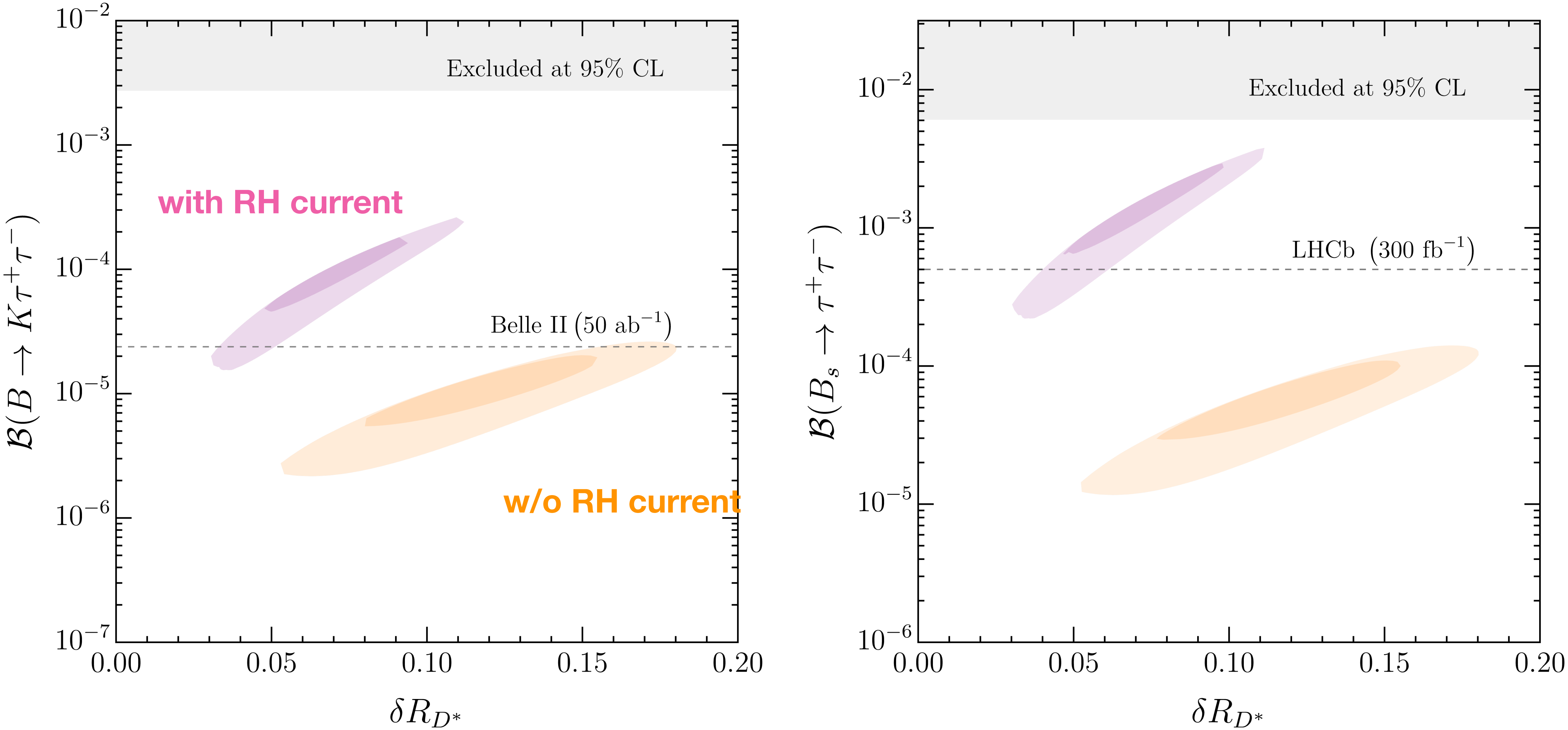
[Bečirević et al., 2206.09717]

$S_1 + S_3$



[Gherardi, Marzocca, Venturini, 2008.09548]

Corroborating the U_1 hypothesis: $b \to s\tau^+\tau^-$

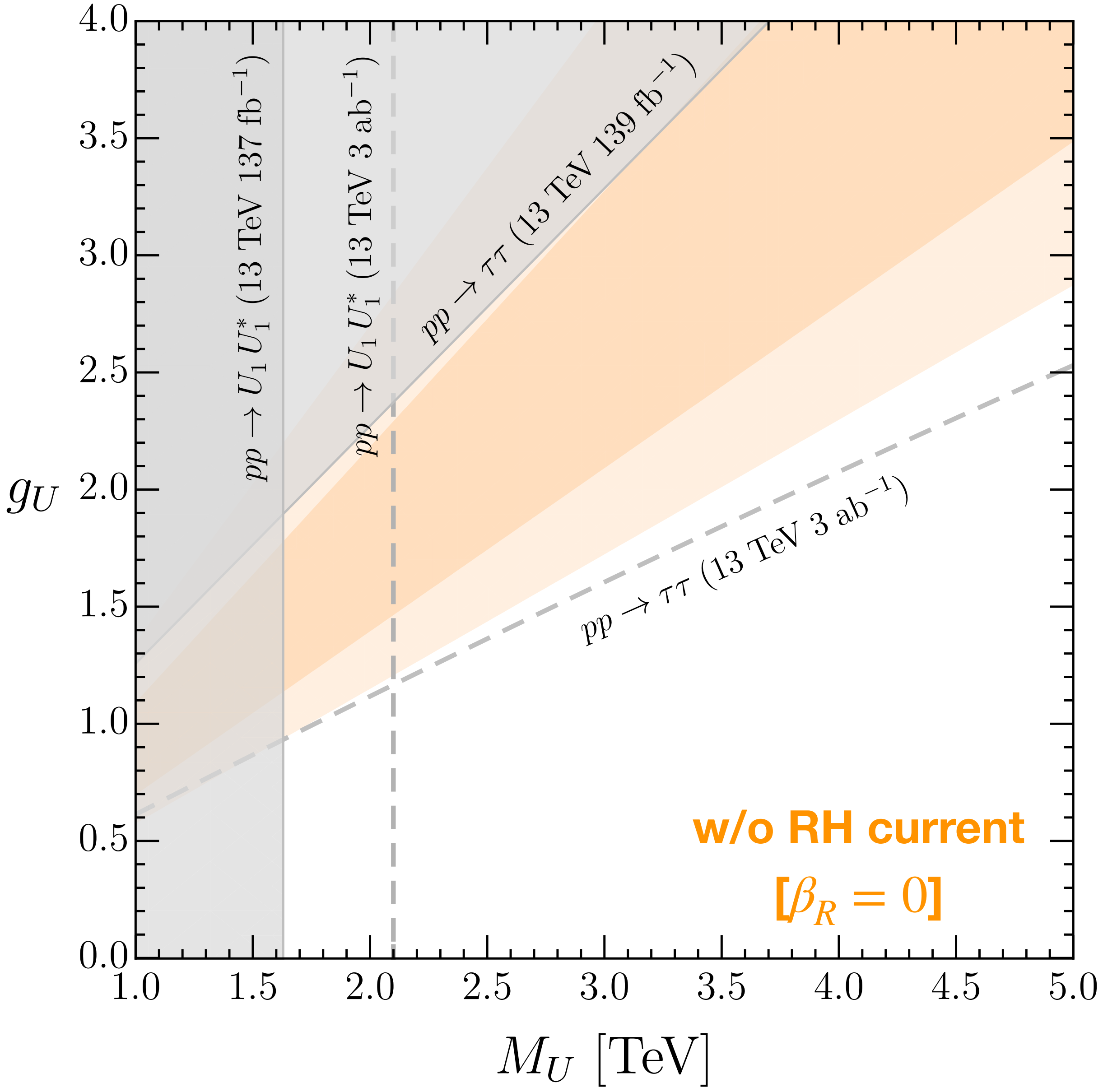


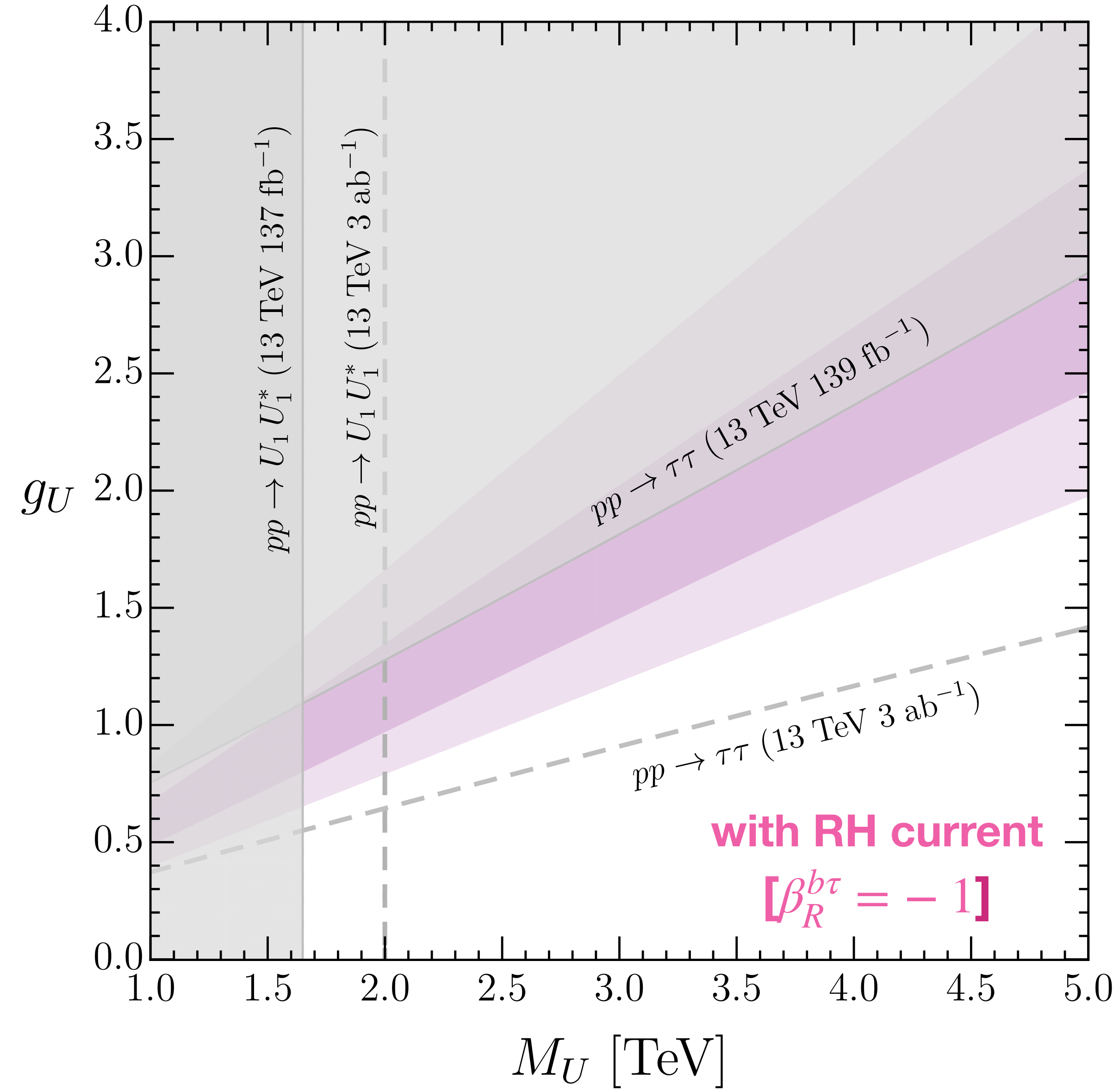
[Cornella, JF et al., 2103.16558]

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

U_1 searches at LHC

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]

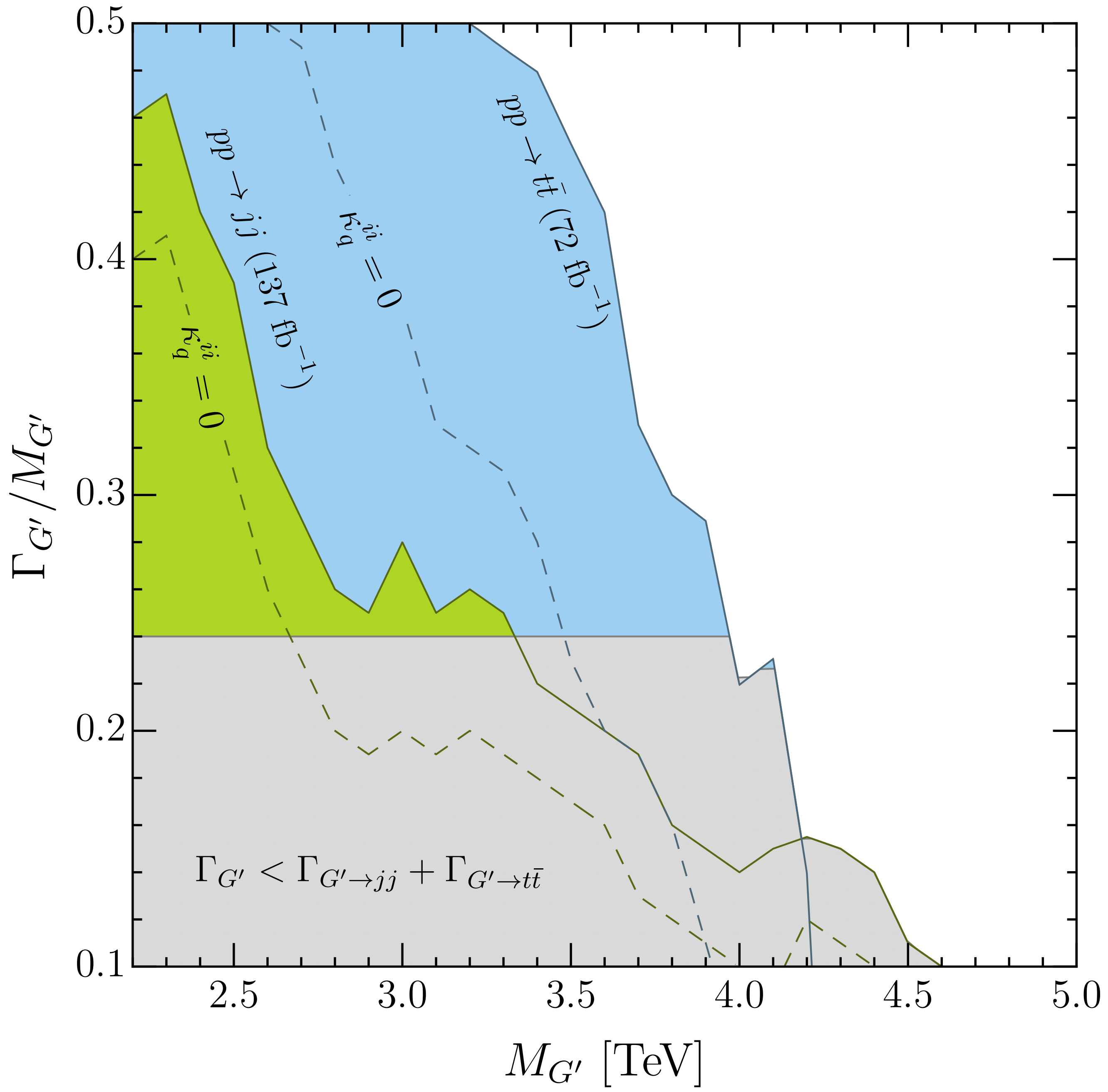




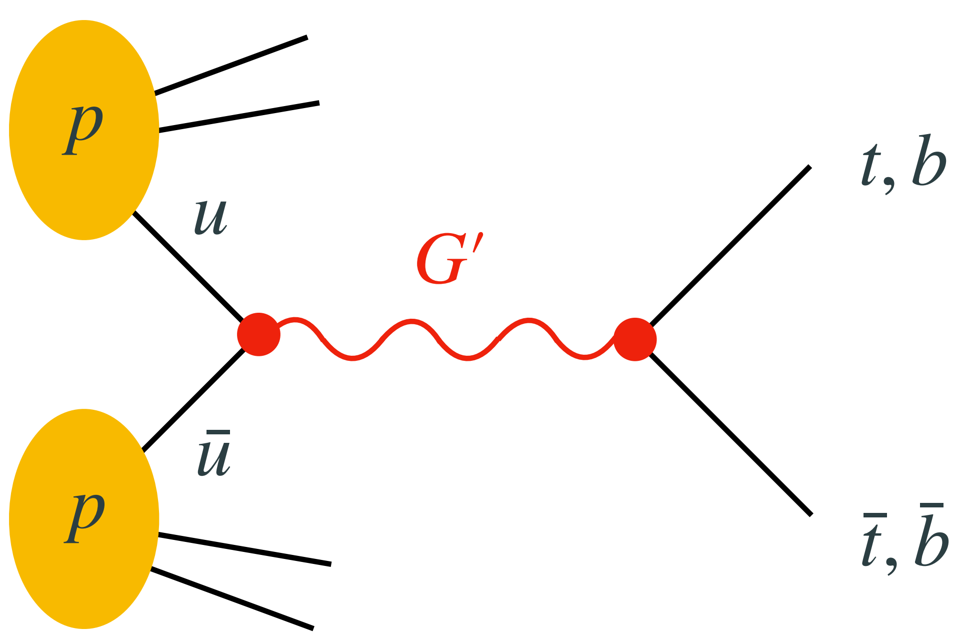
[Cornella, JF et al., 2103.16558]

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

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, JF et al., 2103.16558]

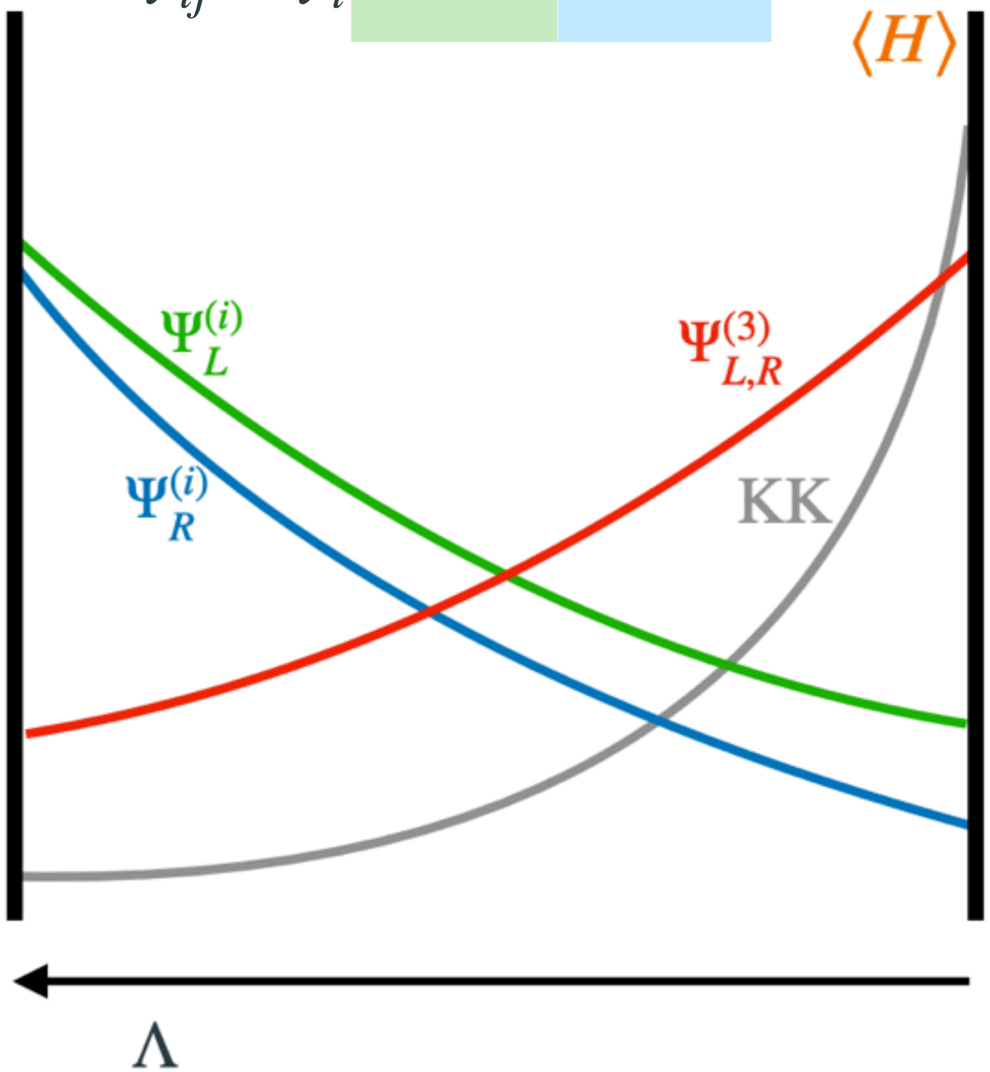
Flavor in Randall-Sundrum

Curvature of the AdS slice

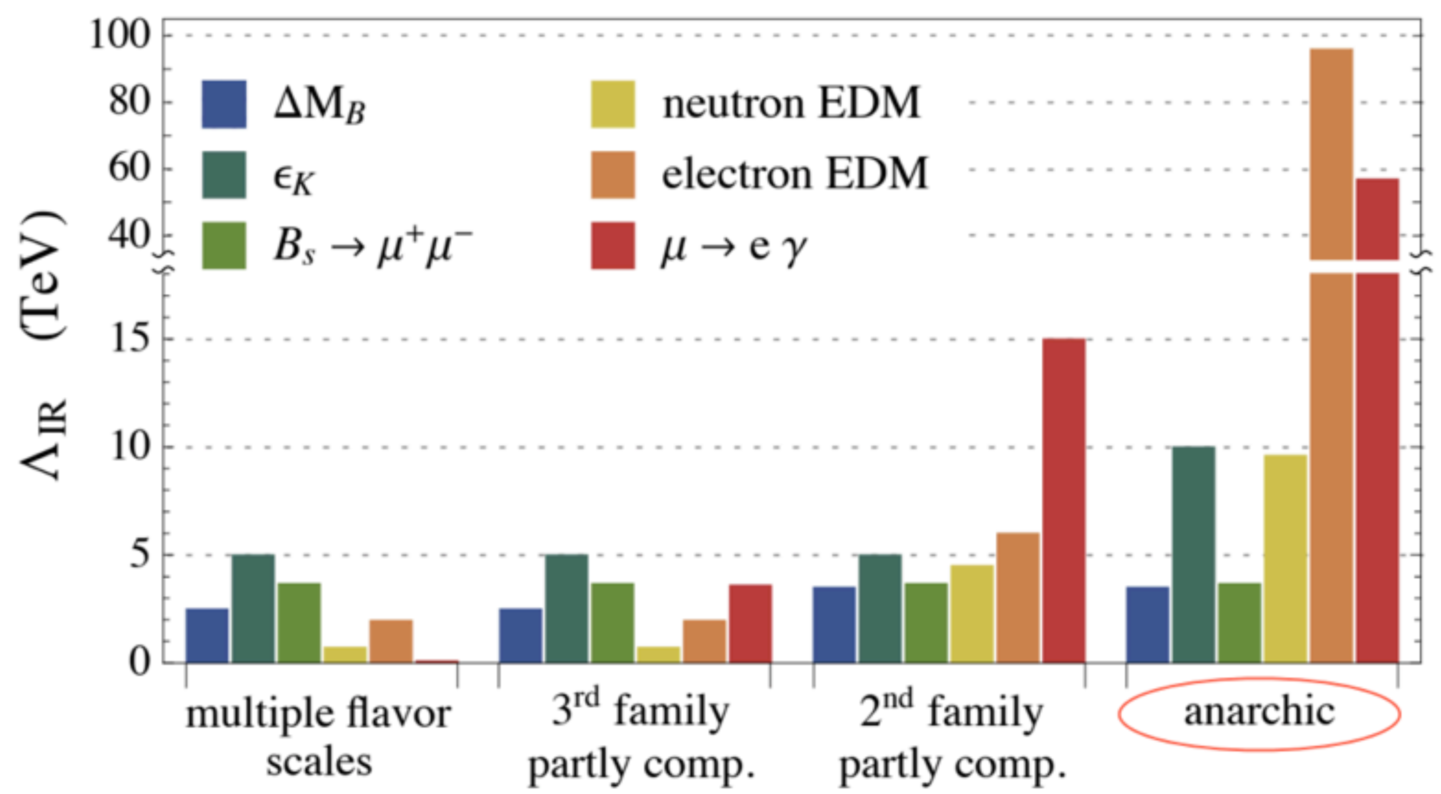
Warped 5D geometry (RS): $ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$

- Justification of the Yukawa hierarchies through exponentiation + flavor anarchy
- Analogous to anarchic partial compositeness in composite models

$y_{ij} \approx y_t e^{-k c_L L} e^{-k c_R L}$



Dangerous dipoles (among others) generated at the IR scale $\sim \frac{g_*^2}{16\pi^2}\frac{m_e}{\Lambda_{\rm IR}^2}\bar{e}_L\sigma_{\mu\nu}e_R F^{\mu\nu}$

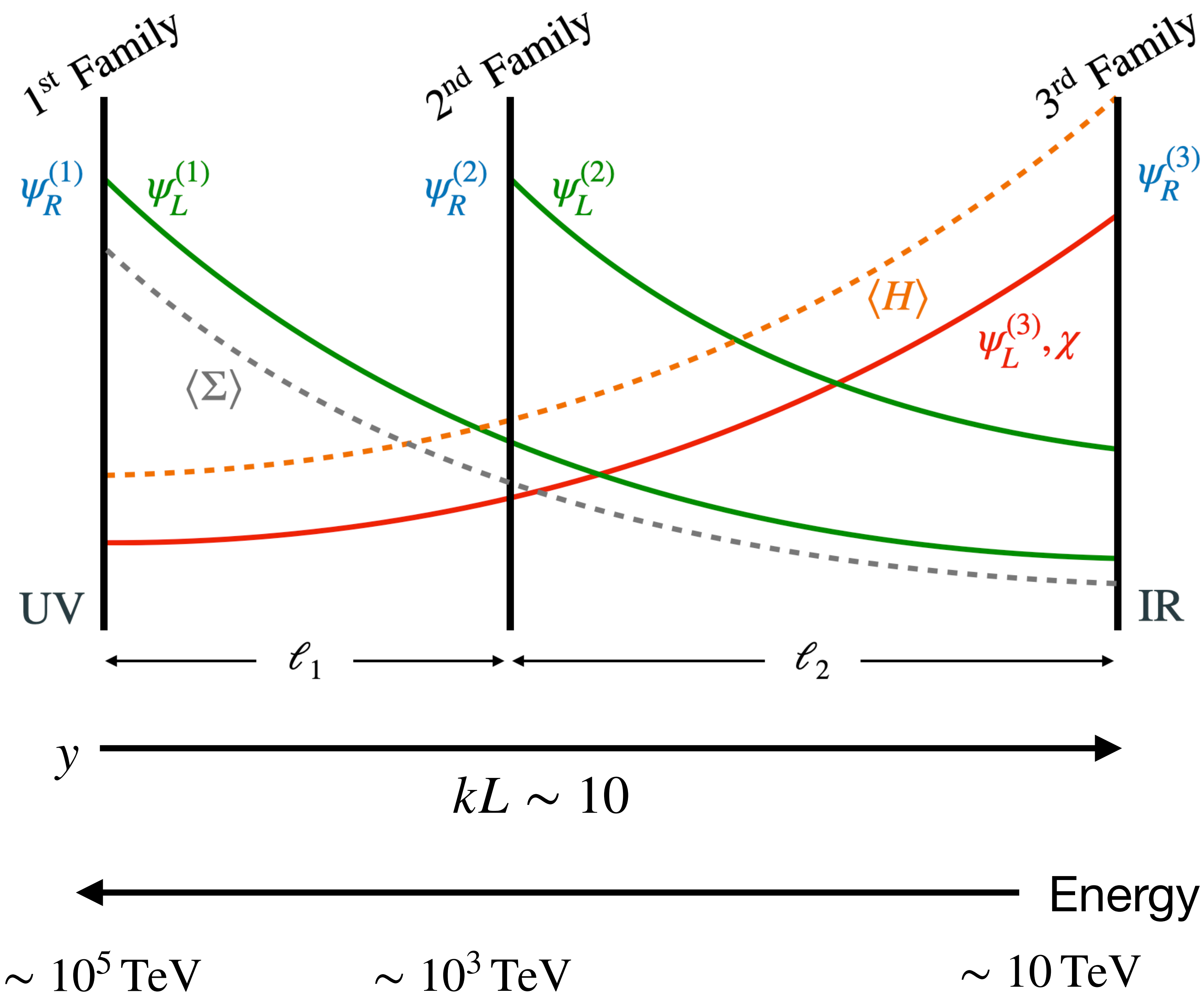


[Panico, Pomarol, 1603.06609]

A 5D UV completion of 4321

[JF, Isidori, Pagès, Stefanek, 2012.10492
JF, Isidori, Lizana, Selimovic, Stefanek, 2203.01952]

Attempt to construct a full theory of flavor by embedding the 4321 group in a compact warped extra dimension (AdS_5) with multiple four-dimensional branes



Flavor $\longleftrightarrow$ fermion (quasi-)localization in each of the branes

[Dvali, Shifman, '00; Panico, Pomarol, 1603.06609]

$$y_{ij} \approx y_t \, e^{-k(L-\ell_j)} \, e^{-k(c_i-1/2)(y_i-\ell_j)}$$

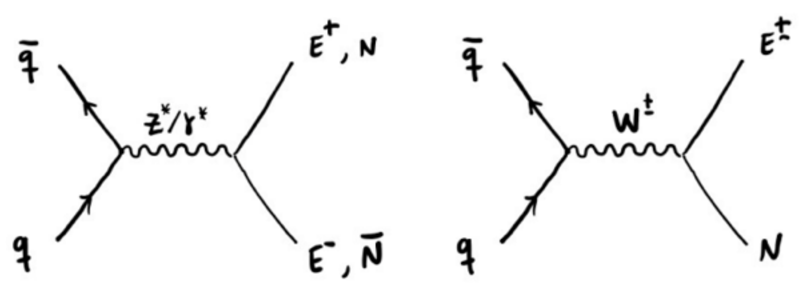
Same dynamics that breaks 4321 also generates a pNGB Higgs $\longleftrightarrow$ stabilization of the EW hierarchy with an $\mathcal{O}(0.1\%)$ tuning (little hierarchy)

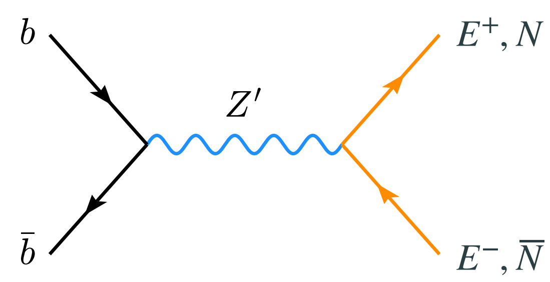
Anarchic neutrino masses via inverse see-saw mechanism

Hunting 4321 vectorlike fermions at high-p_T

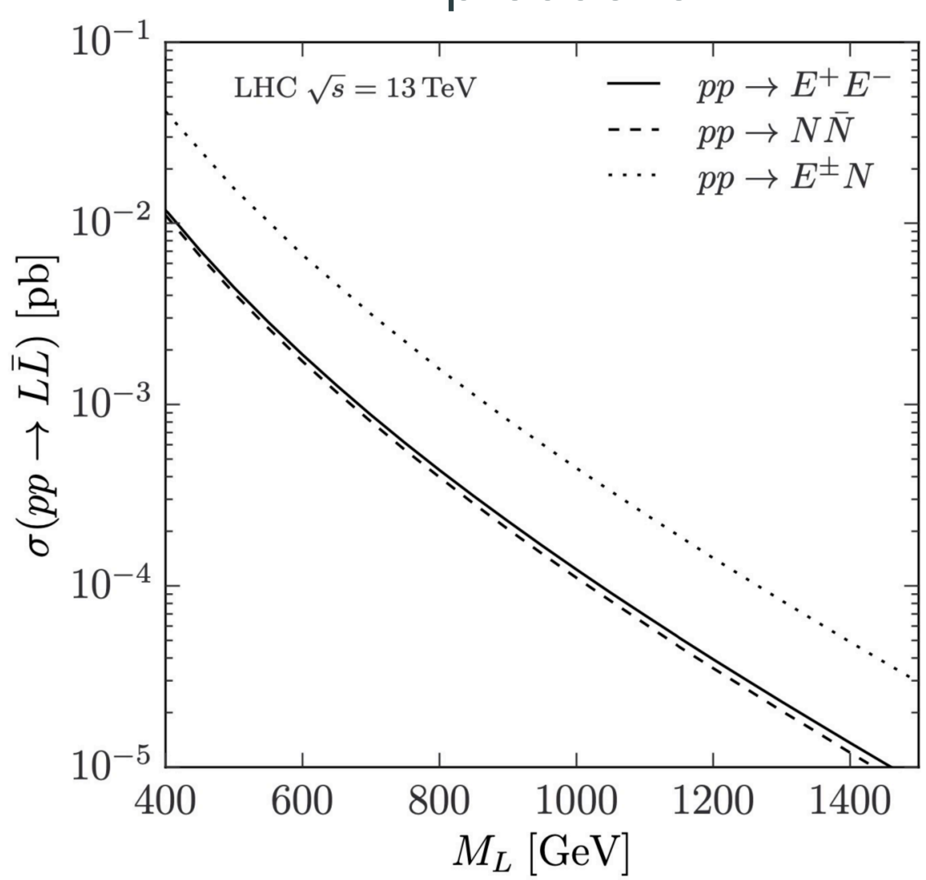
New search for pair produced heavy lepton doublet decaying into 3rd generation fermions

[K. Cormier, Darius Faroughy, JFM, V. Mikuni, w.i.p]

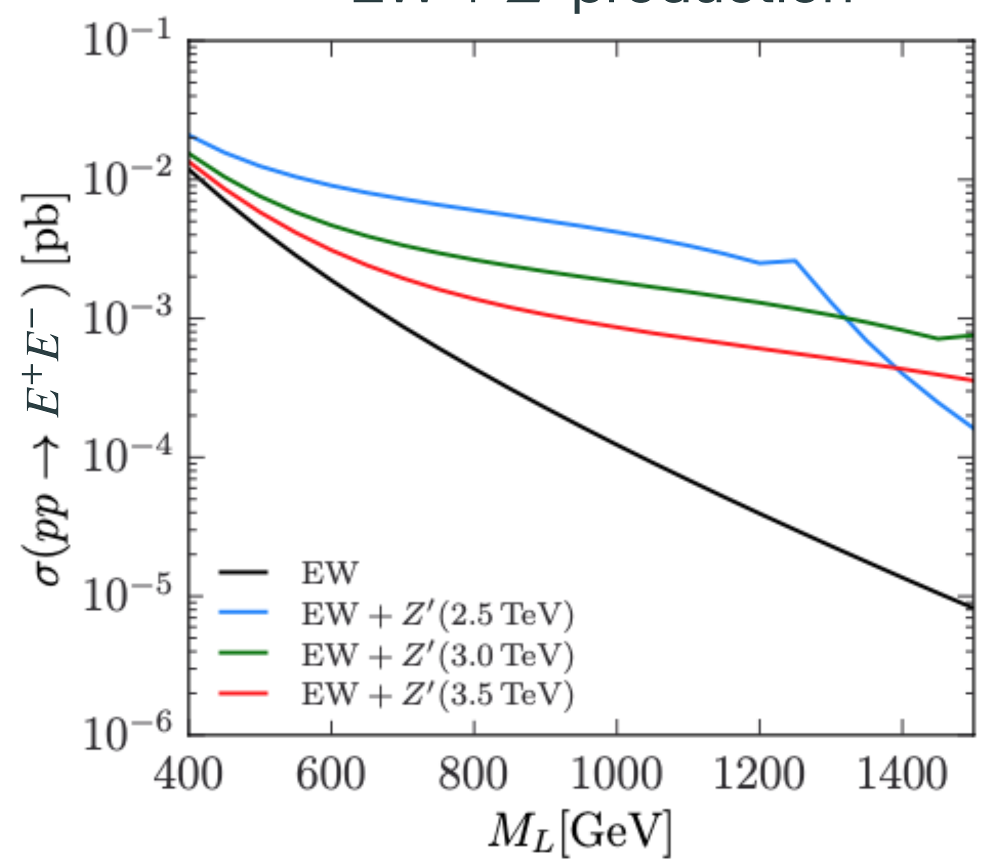




EW production



EW + Z' production



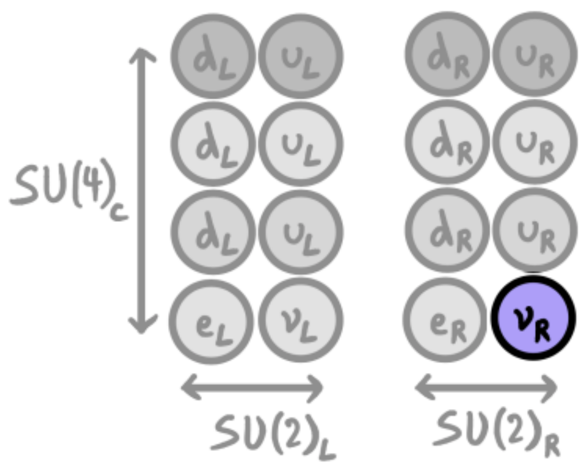
Third-family quark-lepton unification at the TeV scale

In first approximation, third-family quark-lepton unification implies

$$y_\tau = y_b \quad \checkmark \qquad\qquad y_{\nu_\tau} = y_t$$

[$y_\tau = 0.8\, y_b$ at 2 TeV]

PS multiplets



TeV-scale unification limits Majorana mass for ν_R to $m_{\nu_R} \lesssim \mathrm{TeV}$

Type-I see-saw: $m_\nu \approx \dfrac{m_D^2}{m_{\nu_R}} \sim 10\ \mathrm{GeV}$ ✘ $\qquad m_D \equiv y_\nu v/\sqrt{2}$

Solution: Inverse seesaw via new fermion singlets S_L^i with hierarchical Majorana masses μ^i

[Greljo, Stefanek, 1802.04274
Fileviez, Wise, 1307.6213]

$$m_\nu \approx m_D\, m_R^{-1}\, \mu\, (m_R^{-1})^\intercal m_D^\intercal$$

$$m_D^i \approx m_u^i \sim (10^{-2}, 1, 10^2)\ \mathrm{GeV} \quad \Longrightarrow \quad \mu^i \sim (10^7, 10^{-1}, 10^{-9})\ \mathrm{GeV}$$

Third-family quark-lepton unification at the TeV scale

Model prediction: mixing between active neutrino and pseudo-Dirac heavy neutral leptons yields

PMNS unitarity violation

with the expected pattern: $$\eta \equiv |1 - NN^\dagger| \sim \left|\frac{m_D^3}{m_R^3}\right|^2 \begin{pmatrix} \epsilon_L^4 & \epsilon_L^3 & \epsilon_L^2 \\ \epsilon_L^3 & \epsilon_L^2 & \epsilon_L \\ \epsilon_L^2 & \epsilon_L & 1 \end{pmatrix} \qquad \epsilon_L \approx 0.1$$

First sign of violation in 33 entry: $$\eta_{33} \approx \left|\frac{m_D^3}{m_R^3}\right|^2 \sim \left|\frac{100\ \text{GeV}}{2\ \text{TeV}}\right|^2 = 2.5 \times 10^{-3}$$

$$\eta_{33}^{\text{exp}} < 5.3 \times 10^{-3} \quad (90\ \%\ \text{C.L.})$$

[Antusch, Fischer, 1407.6607]