

# Lepton Number/Flavour violation: Introduction

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University of Granada

# Lepton Number/Flavour violation session

<i>Lepton Flavor Violating <math>B \rightarrow K_2^* \ell_1 \ell_2</math> Decay</i>	Juhi Vardani	
<i>COMET: Search for mu-e Conversion at J-PARC</i>	Satoshi Mihara	COMET
<i>Searching for Charged Lepton Flavour Violation with the Mu3e Experiment</i>	Ben Gayther	Mu3E
<i>Lepton universality tests with semileptonic b decays with taus performed by LHCb</i>	Luke Scantlebury-Smead	LHCb
<i>Dark Sector and Tau Physics at Belle and Belle II</i>	Léonard Polat	Belle & Belle II
<i>Search for new physics in <math>b \rightarrow s \ell \ell</math> transitions at LHCb</i>	Stefania Ricciardi	LHCb
<i>New physics in <math>b \rightarrow s \mu^+ \mu^-</math>: FCC-hh or a Muon Collider?</i>	Sokratis Trifinopoulos	
<i>Fragmentation fractions and <math>b \rightarrow s \ell \ell</math> transitions</i>	Greg Landsberg	
<i>QED in <math>B \rightarrow K \ell \ell</math> and LFU</i>	Roman Zwicky	
<i>Status of the KOTO Experiment: The Search for <math>K_L \rightarrow \pi^0 \nu \bar{\nu}</math></i>	Joseph Redeker	KOTO
<i>Status and Results from the NA62 Experiment at CERN</i>	Jacopo Pinzino	NA62

— Lepton Flavor Violation ( $\mu \rightarrow e$  and  $b \rightarrow s \ell \ell'$ )

—  $b \rightarrow c \tau \nu$  and  $\tau$  physics

—  $b \rightarrow s \ell^+ \ell^-$

—  $K \rightarrow \pi \nu \nu$

# Outline

“Begin at the beginning,” the King said gravely, “and go on till you come to the end: then stop.”  
— Lewis Carroll, Alice in Wonderland

## 1. General introduction/motivation

[ Flavor symmetries of the Standard Model and possible interpretations ]

## 2. A closer look to the experimental anomalies

[ Hints of Lepton Flavor Universality Violation and  $(g - 2)_\mu$  ]

—  $b \rightarrow s\ell^+\ell^-$

—  $b \rightarrow c\tau\nu$

## 3. A selection of experimental predictions

[ Lepton Flavor Violation and semi-invisible rare decays ]

— LFV  $\mu \rightarrow e$

—  $K \rightarrow \pi\nu\nu$

## 4. Conclusions

# What is experiment telling us?

No **direct evidence** for NP despite the many reasons for it [**presence of a mass gap?**]

## ATLAS Exotics Searches\* - 95% CL Upper Exclusion Limits

Status: May 2020

ATLAS Preliminary

$\int \mathcal{L} dt = (3.2 - 139) \text{ fb}^{-1}$

$\sqrt{s} = 8, 13 \text{ TeV}$

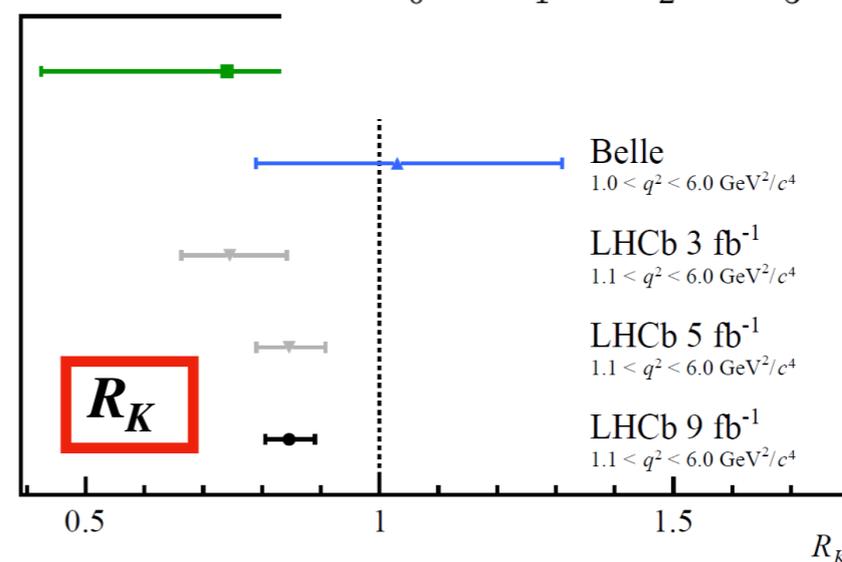
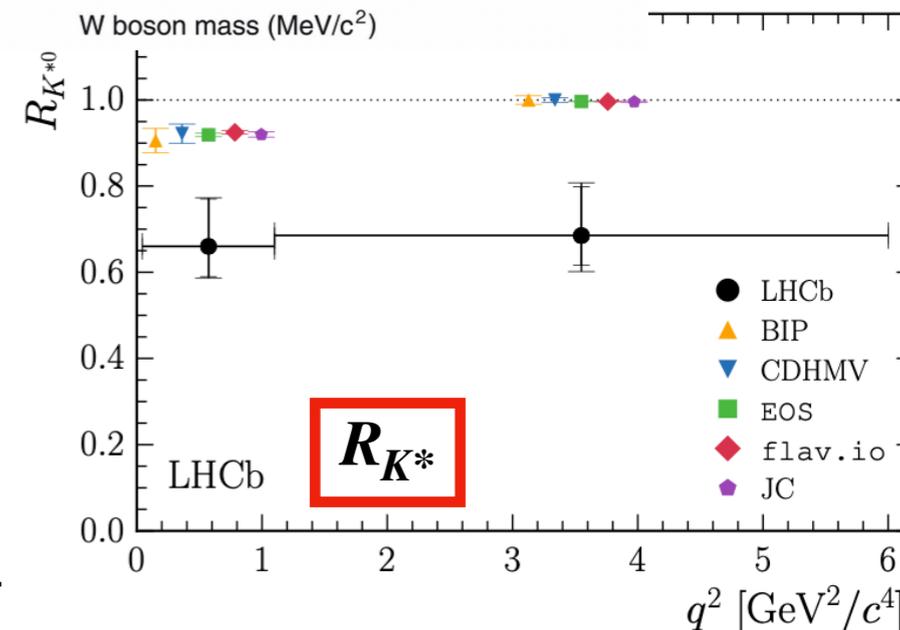
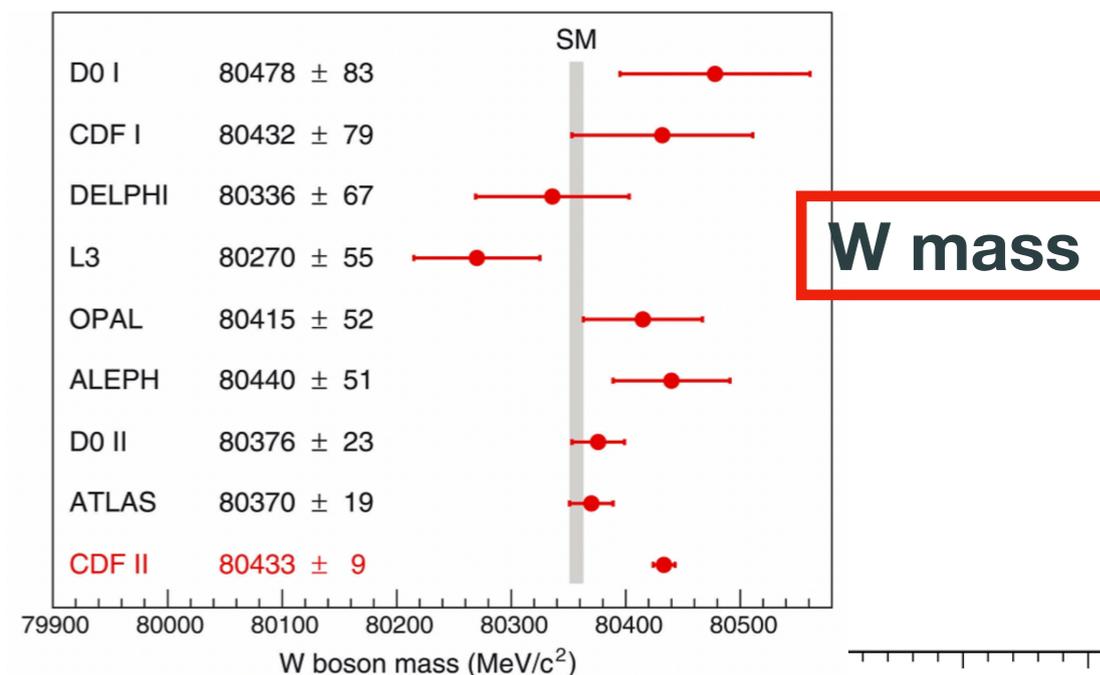
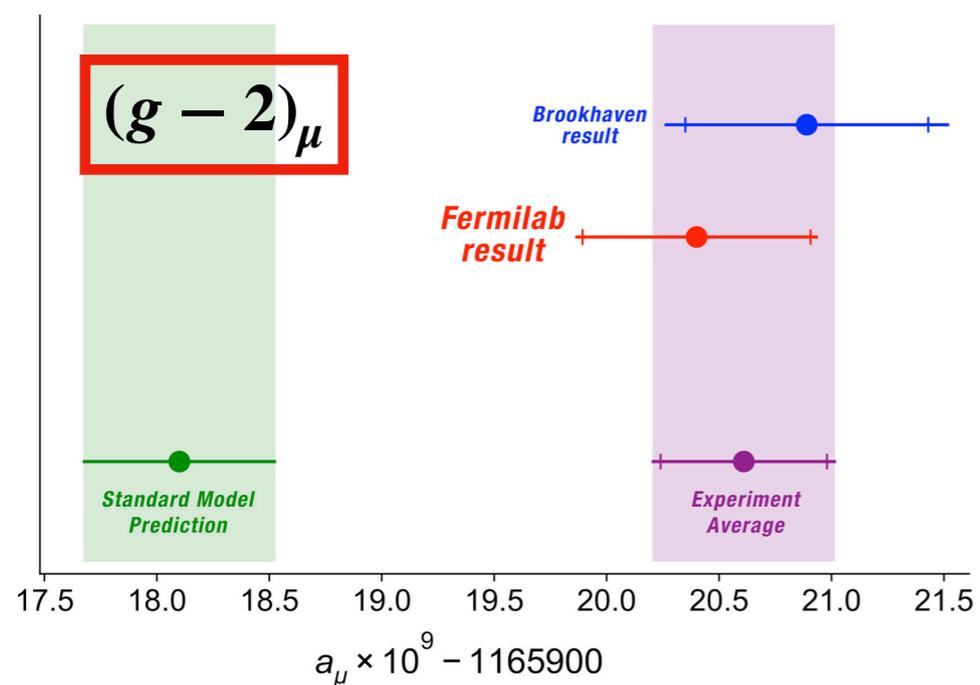
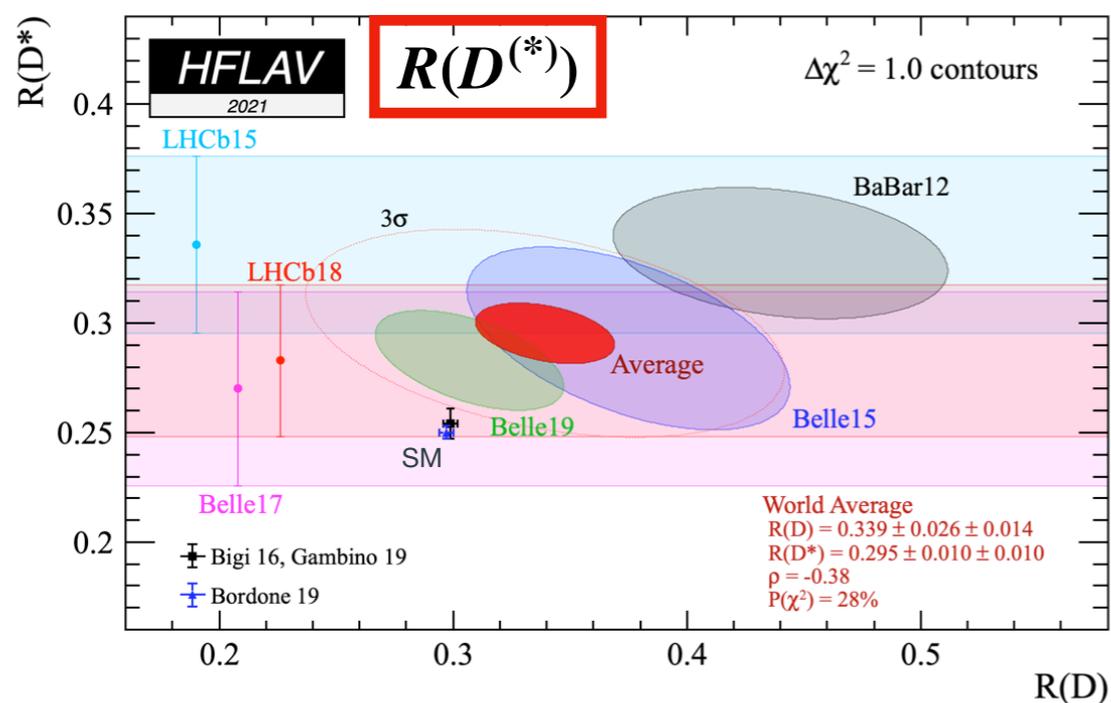
Model	$\ell, \gamma$	Jets†	$E_T^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference	
Extra dimensions	ADD $G_{KK} + g/q$	0 $e, \mu$	1-4 j	Yes	36.1	$M_D$ 7.7 TeV	$n=2$ 1711.03301
	ADD non-resonant $\gamma\gamma$	2 $\gamma$	-	-	36.7	$M_S$ 8.6 TeV	$n=3$ HLZ NLO 1707.04147
	ADD QBH	-	2 j	-	37.0	$M_{\text{th}}$ 8.9 TeV	$n=6$ 1703.09127
	ADD BH high $\sum p_T$	$\geq 1 e, \mu$	$\geq 2 j$	-	3.2	$M_{\text{th}}$ 8.2 TeV	$n=6, M_D = 3 \text{ TeV}$ , rot BH 1606.02265
	ADD BH multijet	-	$\geq 3 j$	-	3.6	$M_{\text{th}}$ 9.55 TeV	$n=6, M_D = 3 \text{ TeV}$ , rot BH 1512.02586
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2 $\gamma$	-	-	36.7	$G_{KK}$ mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$ 1707.04147
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	$G_{KK}$ mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$ 1808.02380
	Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell\nu qq$	1 $e, \mu$	2 j / 1 J	Yes	139	$G_{KK}$ mass 2.0 TeV	$k/\overline{M}_{Pl} = 1.0$ 2004.14636
	Bulk RS $g_{KK} \rightarrow tt$	1 $e, \mu$	$\geq 1 b, \geq 1J/2j$	Yes	36.1	$g_{KK}$ mass 3.8 TeV	$\Gamma/m = 15\%$ 1804.10823
	2UED / RPP	1 $e, \mu$	$\geq 2 b, \geq 3 j$	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$ 1803.09678
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	2 $e, \mu$	-	-	139	$Z'$ mass 5.1 TeV	1903.06248
	SSM $Z' \rightarrow \tau\tau$	2 $\tau$	-	-	36.1	$Z'$ mass 2.42 TeV	1709.07242
	Leptophobic $Z' \rightarrow bb$	-	2 b	-	36.1	$Z'$ mass 2.1 TeV	1805.09299
	Leptophobic $Z' \rightarrow tt$	0 $e, \mu$	$\geq 1 b, \geq 2 J$	Yes	139	$Z'$ mass 4.1 TeV	$\Gamma/m = 1.2\%$ 2005.05138
	SSM $W' \rightarrow \ell\nu$	1 $e, \mu$	-	Yes	139	$W'$ mass 6.0 TeV	1906.05609
	SSM $W' \rightarrow \tau\nu$	1 $\tau$	-	Yes	36.1	$W'$ mass 3.7 TeV	1801.06992
	HVT $W' \rightarrow WZ \rightarrow \ell\nu qq$ model B	1 $e, \mu$	2 j / 1 J	Yes	139	$W'$ mass 4.3 TeV	$g_V = 3$ 2004.14636
	HVT $V' \rightarrow WV \rightarrow qq qq$ model B	0 $e, \mu$	2 J	-	139	$V'$ mass 3.8 TeV	$g_V = 3$ 1906.08589
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	-	36.1	$V'$ mass 2.93 TeV	$g_V = 3$ 1712.06518
	HVT $W' \rightarrow WH$ model B	0 $e, \mu$	$\geq 1 b, \geq 2 J$	-	139	$W'$ mass 3.2 TeV	$g_V = 3$ CERN-EP-2020-073
LRSM $W_R \rightarrow tb$	multi-channel	-	-	36.1	$W_R$ mass 3.25 TeV	1807.10473	
LRSM $W_R \rightarrow \mu N_R$	2 $\mu$	1 J	-	80	$W_R$ mass 5.0 TeV	$m(N_R) = 0.5 \text{ TeV}, g_L = g_R$ 1904.12679	
CI	CI $qqqq$	-	2 j	-	37.0	$\Lambda$ 21.8 TeV	$\eta_{LL}$ 1703.09127
	CI $\ell\ell qq$	2 $e, \mu$	-	-	139	$\Lambda$ 35.8 TeV	$\eta_{LL}$ CERN-EP-2020-066
	CI $tttt$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$\Lambda$ 2.57 TeV	$ C_{4t}  = 4\pi$ 1811.02305
DM	Axial-vector mediator (Dirac DM)	0 $e, \mu$	1-4 j	Yes	36.1	$m_{\text{med}}$ 1.55 TeV	$g_q=0.25, g_\gamma=1.0, m(\chi) = 1 \text{ GeV}$ 1711.03301
	Colored scalar mediator (Dirac DM)	0 $e, \mu$	1-4 j	Yes	36.1	$m_{\text{med}}$ 1.67 TeV	$g=1.0, m(\chi) = 1 \text{ GeV}$ 1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 $e, \mu$	1 J, $\leq 1 j$	Yes	3.2	$M_*$ 700 GeV	$m(\chi) < 150 \text{ GeV}$ 1608.02372
	Scalar reson. $\phi \rightarrow t\chi$ (Dirac DM)	0-1 $e, \mu$	1 b, 0-1 J	Yes	36.1	$m_\phi$ 3.4 TeV	$y = 0.4, \lambda = 0.2, m(\chi) = 10 \text{ GeV}$ 1812.09743
LQ	Scalar LQ 1 <sup>st</sup> gen	1,2 $e$	$\geq 2 j$	Yes	36.1	LQ mass 1.1 TeV	$\beta = 1$ 1902.00377
	Scalar LQ 2 <sup>nd</sup> gen	1,2 $\mu$	$\geq 2 j$	Yes	36.1	LQ mass 1.56 TeV	$\beta = 1$ 1902.00377
	Scalar LQ 3 <sup>rd</sup> gen	2 $\tau$	2 b	-	36.1	$LQ_3^u$ mass 1.03 TeV	$\mathcal{B}(LQ_3^u \rightarrow b\tau) = 1$ 1902.08103
	Scalar LQ 3 <sup>rd</sup> gen	0-1 $e, \mu$	2 b	Yes	36.1	$LQ_3^d$ mass 970 GeV	$\mathcal{B}(LQ_3^d \rightarrow t\tau) = 0$ 1902.08103
	Heavy quarks	VLQ $TT \rightarrow Ht/Zt/Wb + X$	multi-channel	-	-	36.1	T mass 1.31 TeV
VLQ $BB \rightarrow Wt/Zb + X$		multi-channel	-	-	36.1	B mass 1.34 TeV	SU(2) doublet 1808.02343
VLQ $T_{5/3} T_{5/3}   T_{5/3} \rightarrow Wt + X$		2(SS) $\geq 3 e, \mu \geq 1 b, \geq 1 j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3} Wt) = 1$ 1807.11883	
VLQ $Y \rightarrow Wb + X$		1 $e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \rightarrow Wb) = 1, c_R(Wb) = 1$ 1812.07343
VLQ $B \rightarrow Hb + X$		0 $e, \mu, 2 \gamma$	$\geq 1 b, \geq 1 j$	Yes	79.8	B mass 1.21 TeV	$\kappa_B = 0.5$ ATLAS-CONF-2018-024
VLQ $QQ \rightarrow WqWq$	1 $e, \mu$	$\geq 4 j$	Yes	20.3	Q mass 690 GeV	1509.04261	
Excited fermions	Excited quark $q^* \rightarrow qg$	-	2 j	-	139	$q^*$ mass 6.7 TeV	only $u^*$ and $d^*$ , $\Lambda = m(q^*)$ 1910.08447
	Excited quark $q^* \rightarrow q\gamma$	1 $\gamma$	1 j	-	36.7	$q^*$ mass 5.3 TeV	only $u^*$ and $d^*$ , $\Lambda = m(q^*)$ 1709.10440
	Excited quark $b^* \rightarrow bg$	-	1 b, 1 j	-	36.1	$b^*$ mass 2.6 TeV	1805.09299
	Excited lepton $\ell^*$	3 $e, \mu$	-	-	20.3	$\ell^*$ mass 3.0 TeV	$\Lambda = 3.0 \text{ TeV}$ 1411.2921
	Excited lepton $\nu^*$	3 $e, \mu, \tau$	-	-	20.3	$\nu^*$ mass 1.6 TeV	$\Lambda = 1.6 \text{ TeV}$ 1411.2921
Other	Type III Seesaw	1 $e, \mu$	$\geq 2 j$	Yes	79.8	$N^0$ mass 560 GeV	ATLAS-CONF-2018-020
	LRSM Majorana $\nu$	2 $\mu$	2 j	-	36.1	$N_R$ mass 3.2 TeV	$m(W_R) = 4.1 \text{ TeV}, g_L = g_R$ 1809.11105
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2,3,4 $e, \mu$ (SS)	-	-	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production 1710.09748
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	3 $e, \mu, \tau$	-	-	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \rightarrow \ell\tau) = 1$ 1411.2921
	Multi-charged particles	-	-	-	36.1	multi-charged particle mass 1.22 TeV	DY production, $ q  = 5e$ 1812.03673
	Magnetic monopoles	-	-	-	34.4	monopole mass 2.37 TeV	DY production, $ g  = 1g_D$ , spin 1/2 1905.10130

$\sqrt{s} = 8 \text{ TeV}$   $\sqrt{s} = 13 \text{ TeV}$  partial data  $\sqrt{s} = 13 \text{ TeV}$  full data

10<sup>-1</sup> 1 TeV 10 TeV 1 Mass scale [TeV]

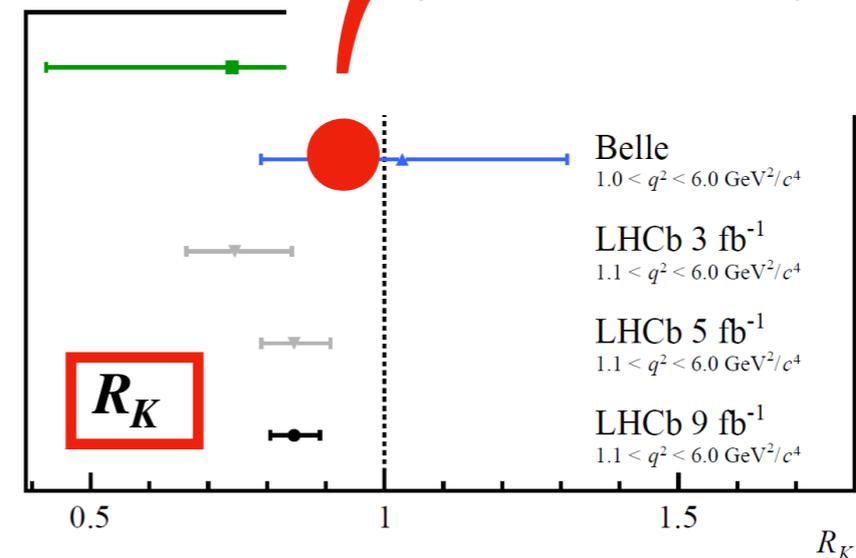
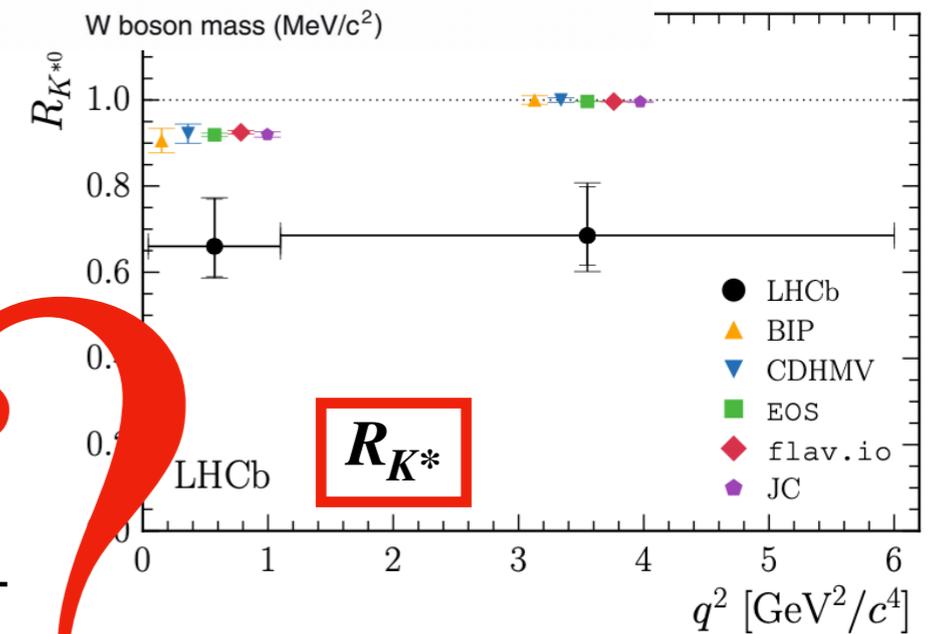
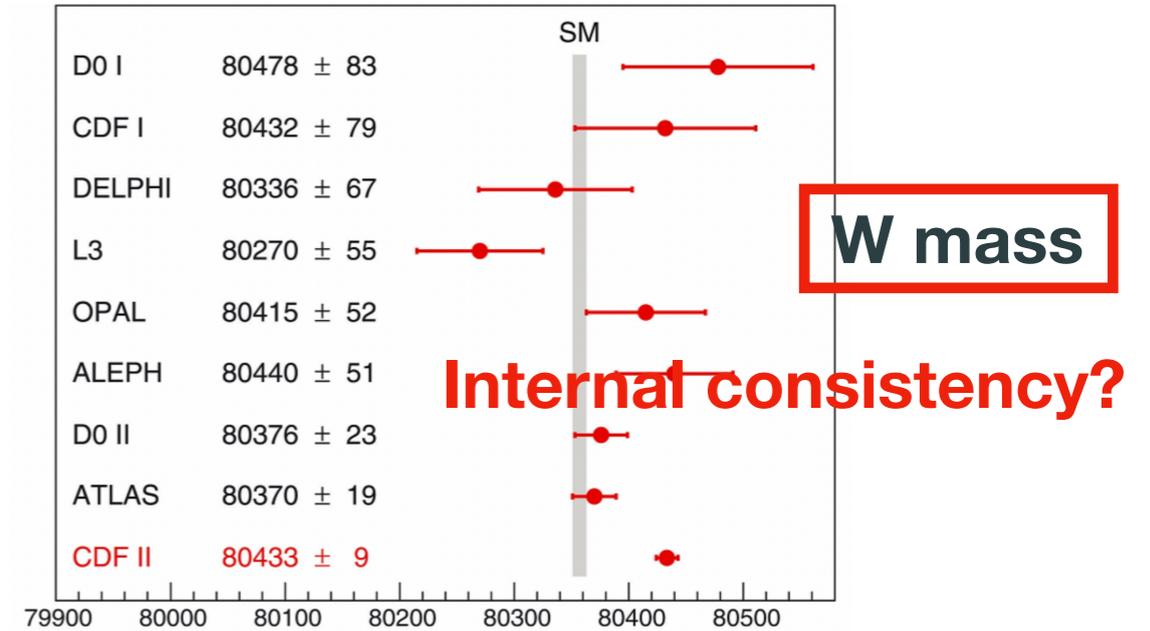
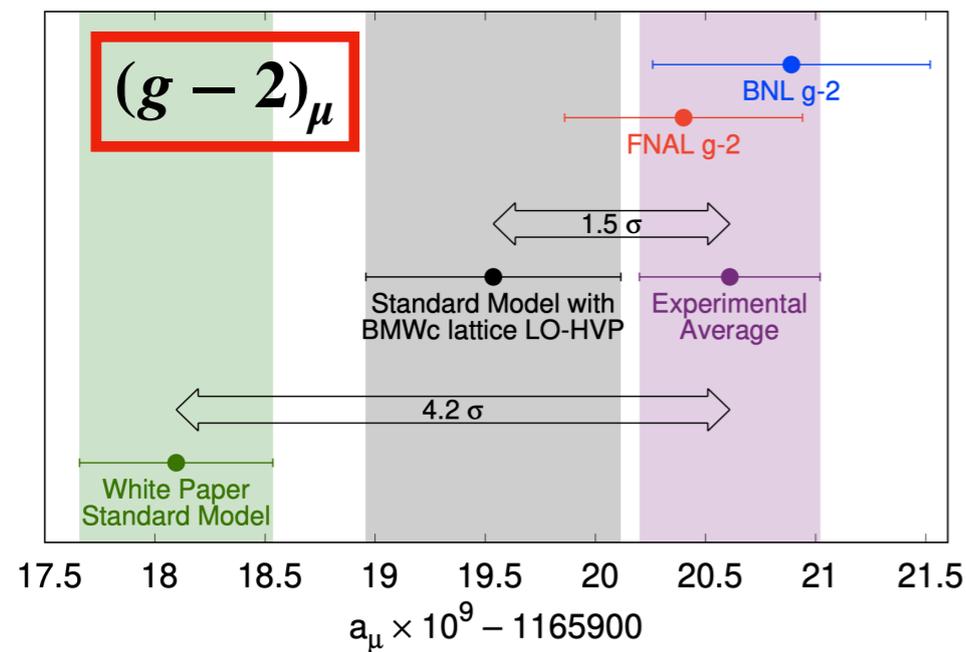
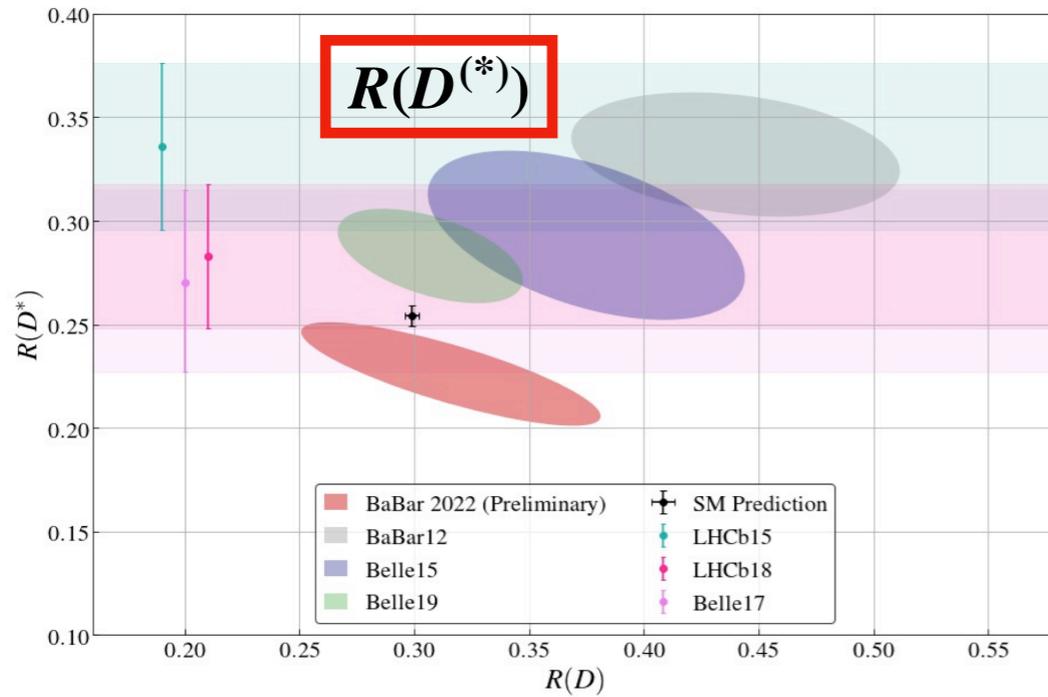
# What is experiment telling us?

Hints of NP in low-energy data?



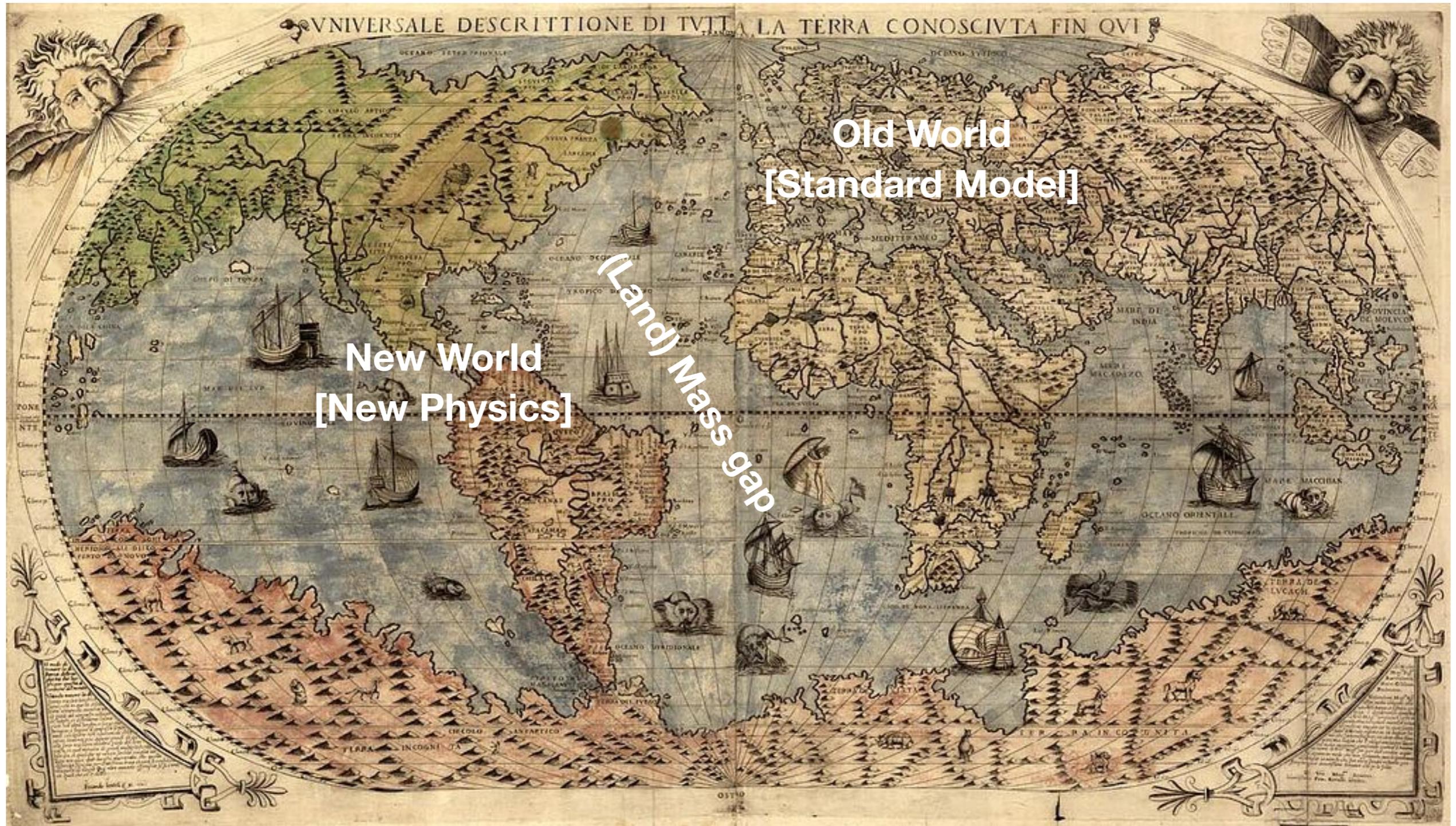
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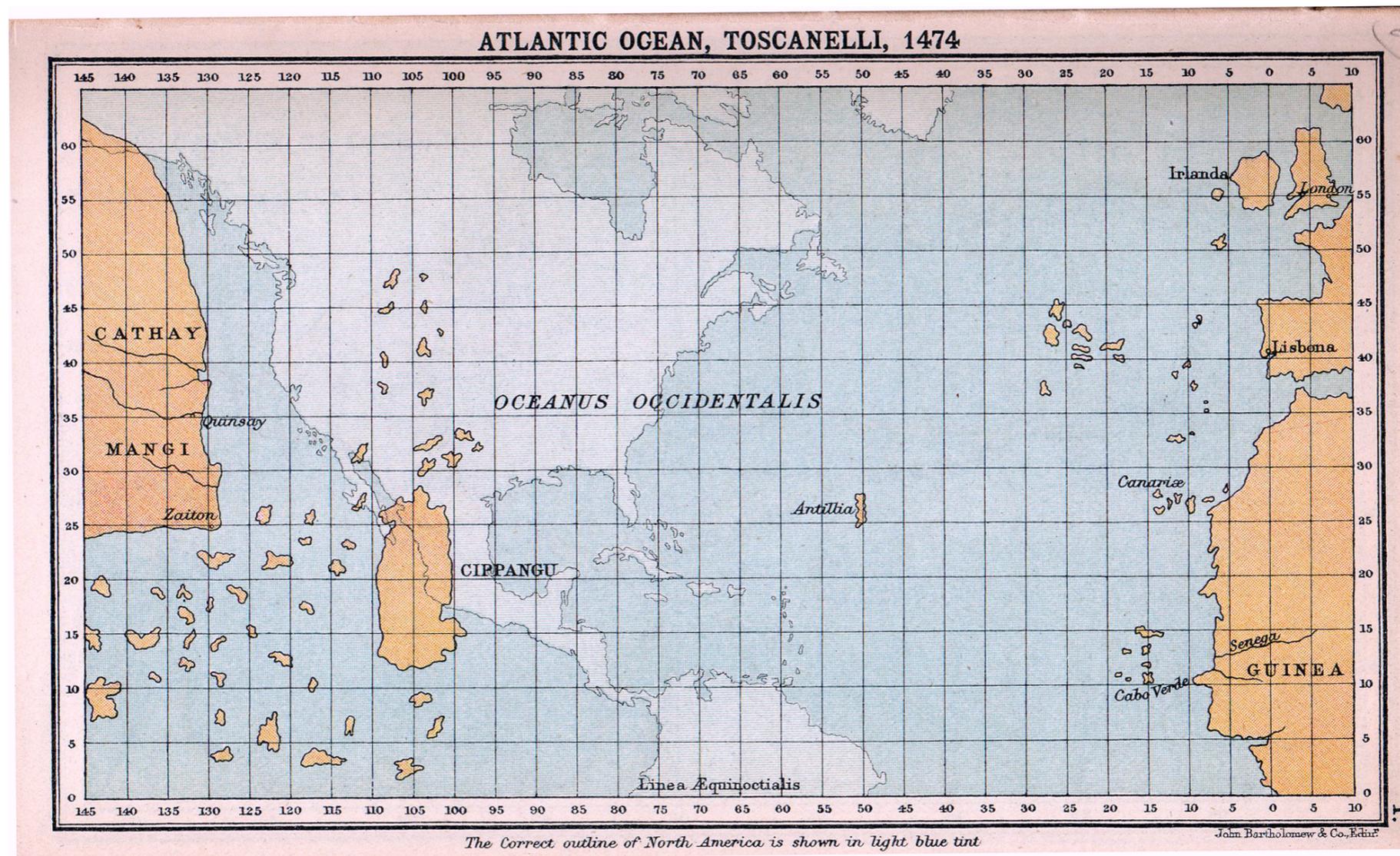


# The search for Terra Incognita

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



# New Physics Quest: main strategies



## Direct high-energy measurements (ATLAS, CMS, FCC, Muon Collider...):

Simpler interpretation if NP is discovered...  
but the mass gap should not be large

## Low-energy probes (COMET, $\mu 3e$ , LHCb, Belle II...):

(Very) precise measurements of low-energy observables and/or **breakings** of (approximate) SM symmetries

# The SM Lagrangian: Naturalness problems

$$\begin{aligned} \mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i \bar{\Psi} \not{\partial} \Psi \\ & + |\mathcal{D}_\mu \phi|^2 - V(\phi) \\ & + \bar{\Psi}_i y_{ij} \Psi_j \phi + \text{h.c.} \end{aligned}$$

The SM Lagrangian contains two **unnatural features** pointing towards NP

## Higgs hierarchy problem

[ Instability of the Higgs mass under quantum corrections ]

TeV-scale NP?

## SM flavor puzzle

[ Accidental symmetries in the SM Yukawas ]

Similar structure also for NP?

Are these two features correlated?

# The SM flavor puzzle

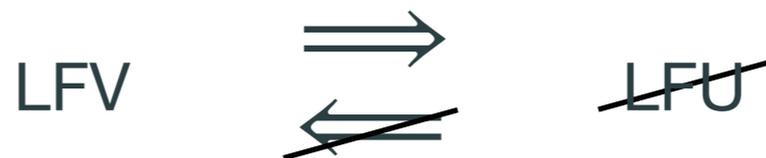
The SM Yukawa sector is characterized by 13 parameters (for massless neutrinos)  
 [3 lepton masses + 6 quark masses + 3+1 CKM parameters]

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

$$M_{u,d,e} \sim \begin{array}{|c|c|c|} \hline \text{light} & \text{light} & \text{light} \\ \hline \text{light} & \text{medium} & \text{medium} \\ \hline \text{light} & \text{medium} & \text{dark} \\ \hline \end{array}$$

$$V_{\text{CKM}} \sim \begin{array}{|c|c|c|} \hline \text{dark} & \text{medium} & \text{light} \\ \hline \text{medium} & \text{dark} & \text{light} \\ \hline \text{light} & \text{light} & \text{dark} \\ \hline \end{array}$$

- ▶ Baryon number is *exactly* preserved  $\psi = (\psi_1 \psi_2 \psi_3)$
- ▶ They respect an *approximate*  $U(2)^5 \equiv U(2)_q \times U(2)_u \times U(2)_d \times U(2)_\ell \times U(2)_e$  symmetry
- ▶ Lepton Flavor Universality [  $U(3)_\ell \times U(3)_e$  ] is a good *approximate* symmetry (  $Y_{e,\mu,\tau} \ll g_{s,L,Y}$  )
- ▶ Individual lepton flavor *extremely well* preserved (exact for massless neutrinos)  
 $U(1)_e \times U(1)_\mu \times U(1)_\tau$



# 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

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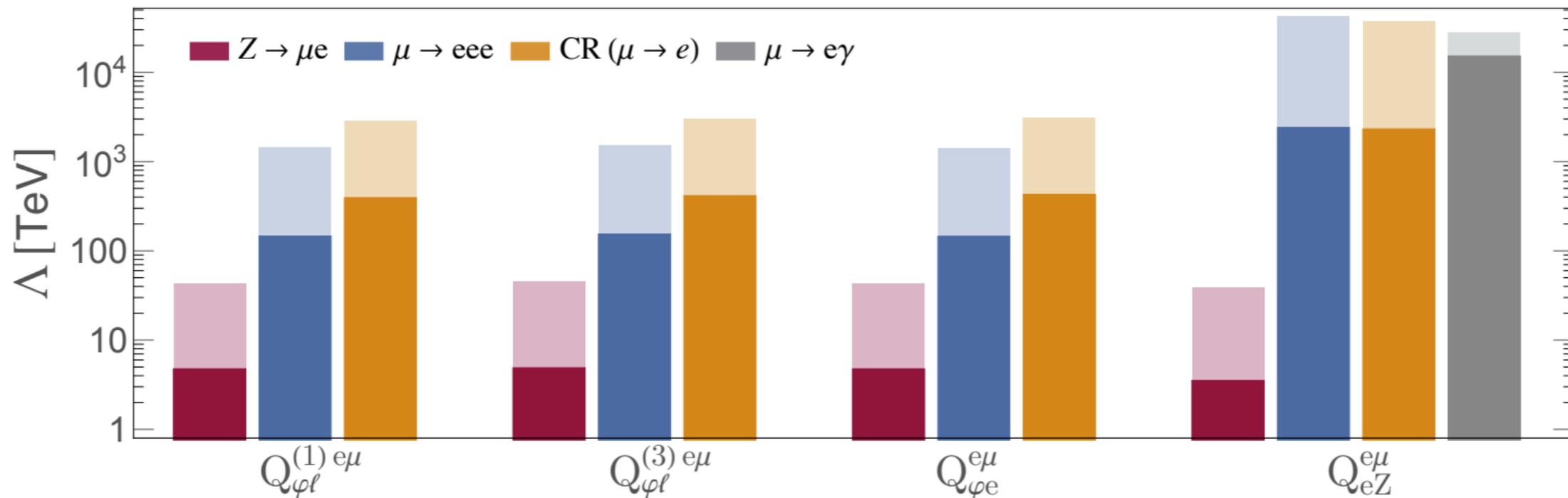
What is the origin of these symmetries? Will new physics respect any of them?

# The new physics flavor problem

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

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)

$$\frac{1}{\Lambda^2} (\bar{\ell}_i \ell_j)^2 \quad \begin{array}{c} \ell \\ \ell'' \\ \ell' \end{array} \quad \frac{1}{\Lambda^2} F_{\mu\nu} (\bar{\ell}_i \sigma^{\mu\nu} H \ell_j) \quad \begin{array}{c} \gamma/Z \\ \ell \\ \ell' \end{array}$$

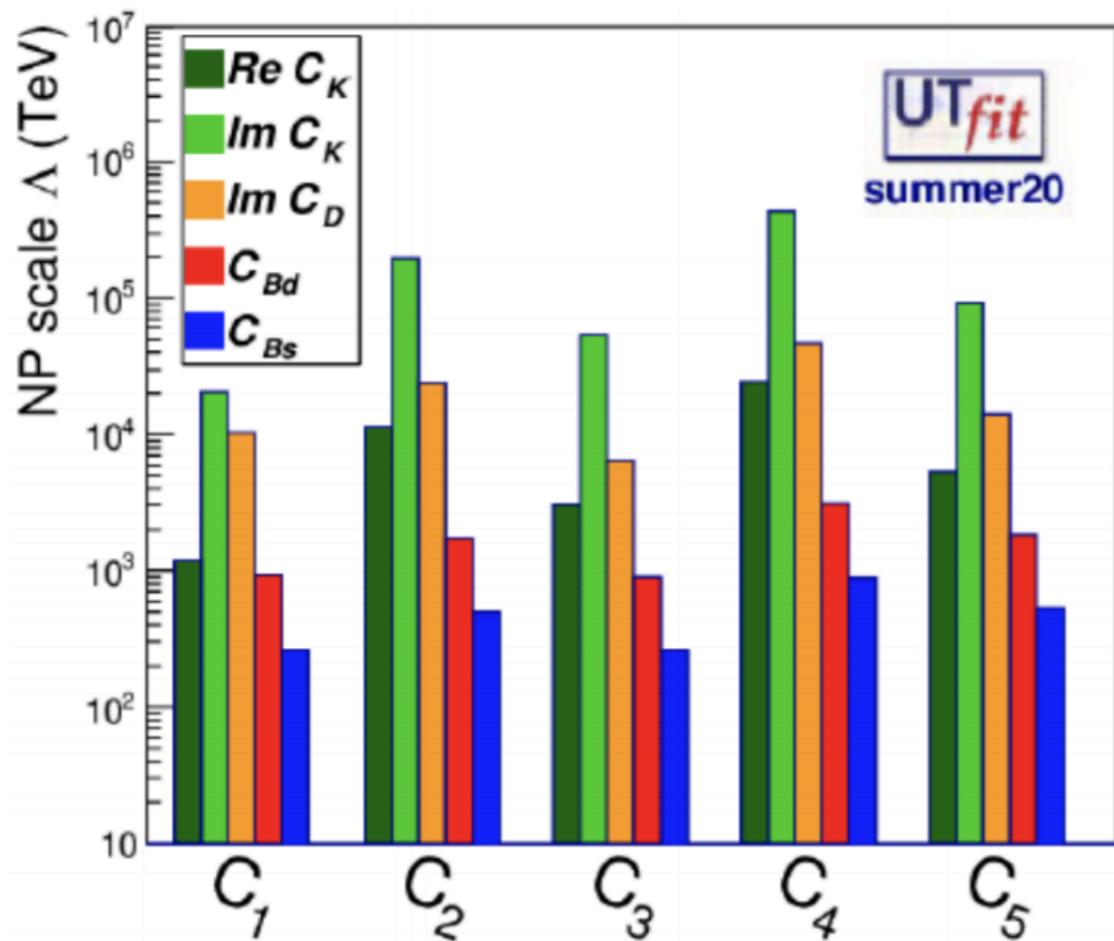


[Calibbi, Marciano, Roy, [2107.10273](https://arxiv.org/abs/2107.10273)]

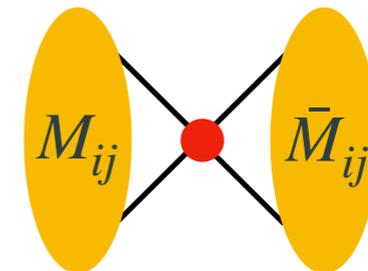
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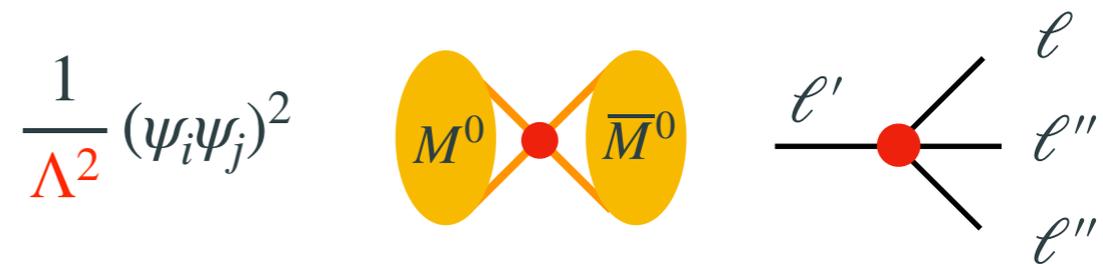
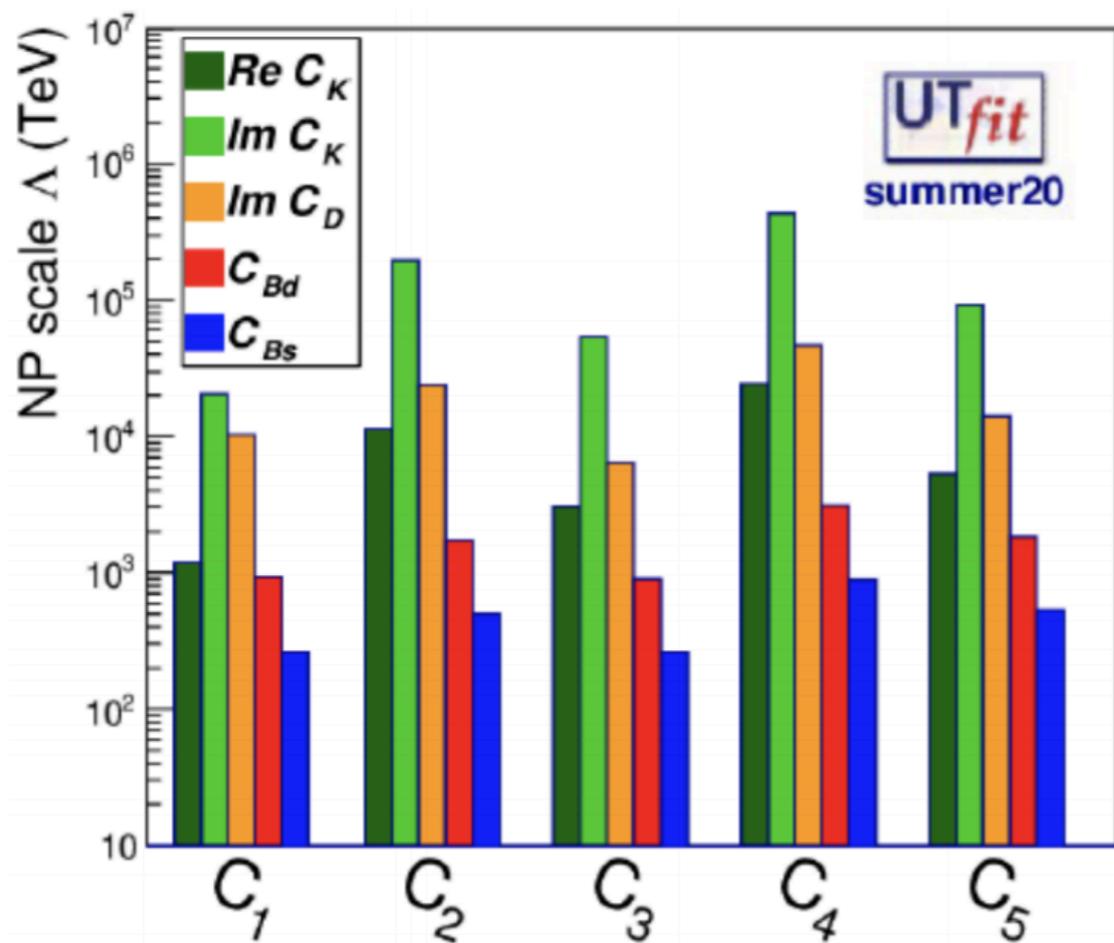
$$\frac{1}{\Lambda^2} (\bar{q}_i q_j)^2$$



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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 specific** and possibly connected to the origin of the Yukawa hierarchies

# Multi-scale solution of the flavor problem/puzzle

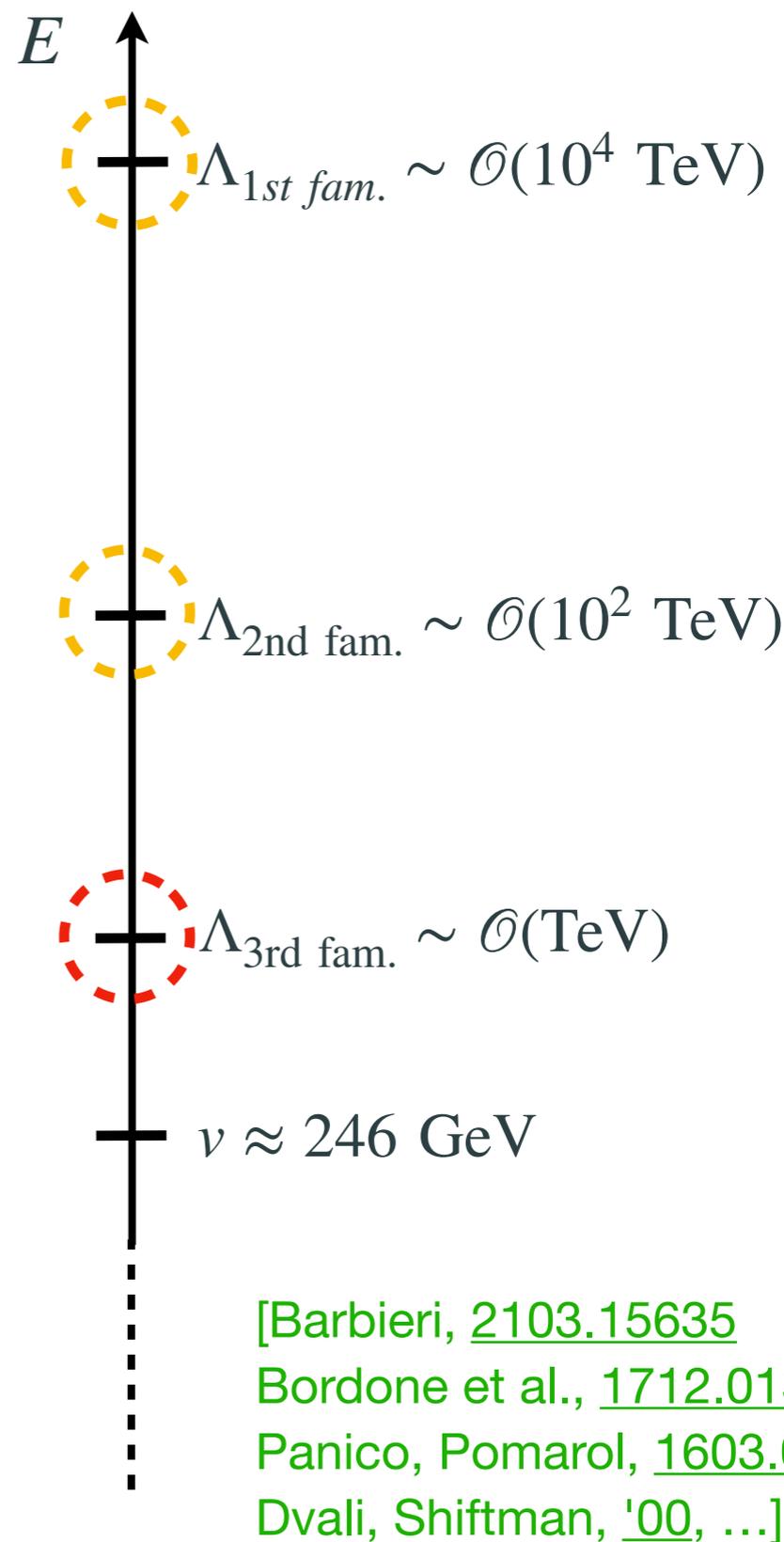
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{Gauge}} + \underbrace{\mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}} + \sum_{i,d} \frac{1}{\Lambda_i^{d-4}} C_i \mathcal{O}_i^d}_{\text{Non-trivial UV imprints}}$$

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

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



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



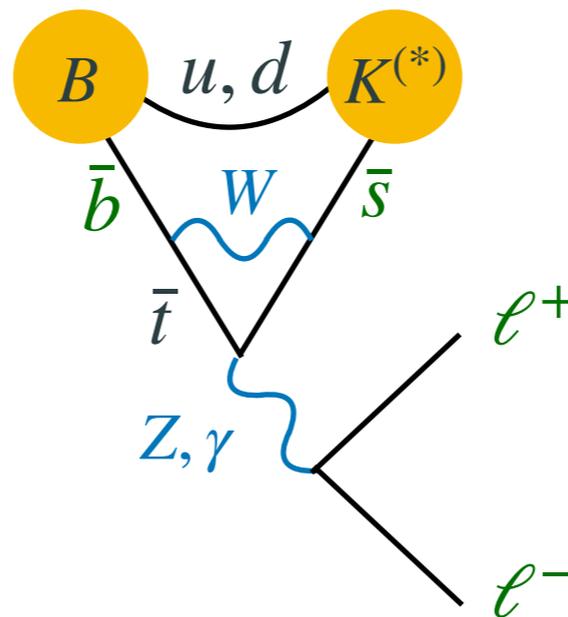
[Barbieri, [2103.15635](#)  
 Bordone et al., [1712.01368](#)  
 Panico, Pomarol, [1603.06609](#)  
 Dvali, Shifman, '00, ...]

# A closer look to the experimental anomalies



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

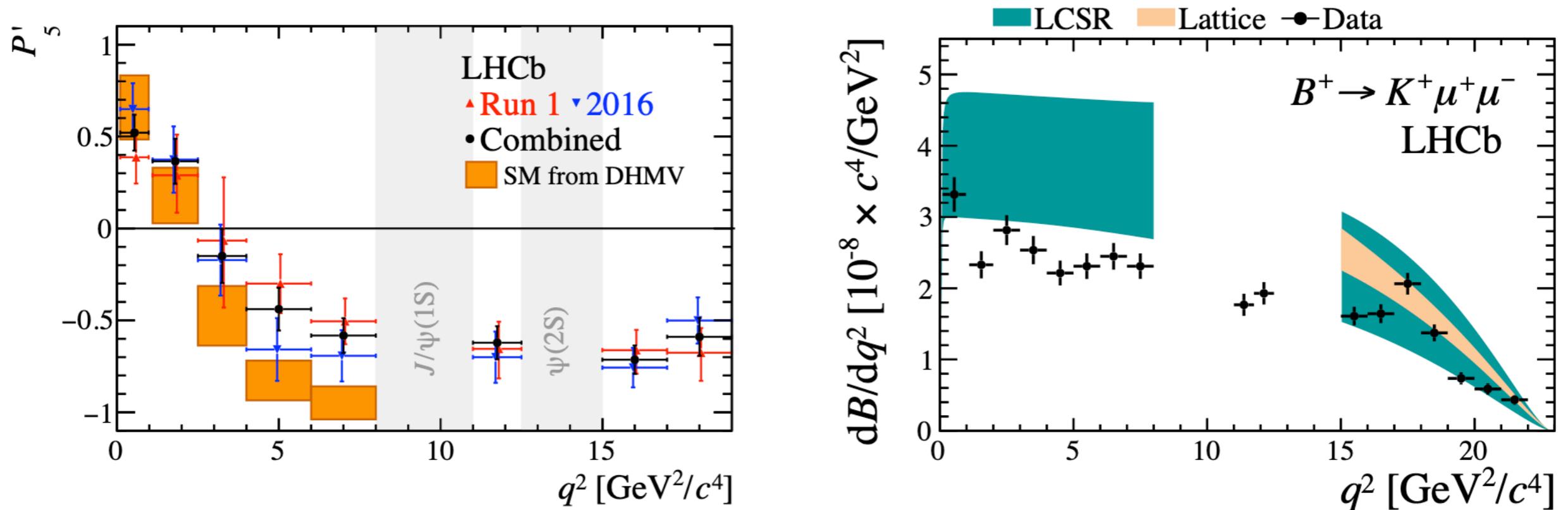
$\mu/e$  universality



# The $b \rightarrow s\mu^+\mu^-$ anomalies [ See Stefania's talk ]

Several LHCb measurements deviate from SM predictions\* by 2-3 $\sigma$ :

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



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

# The $b \rightarrow s \ell^+ \ell^-$ anomalies [ See Stefania's talk ]

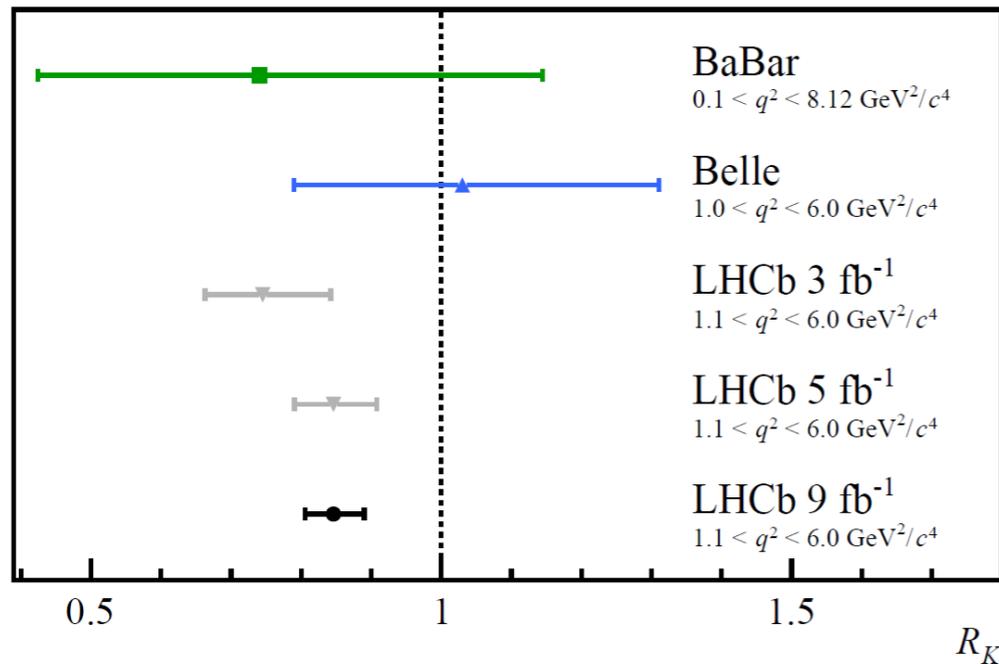
Lepton flavor universality ratios  $R_K^{[1.1,6]}$ ,  $R_{K^*}^{[0.045,1.1]}$ ,  $R_{K^*}^{[1.1,6]}$  deviate from SM pred. by  $3.1, 2.3, 2.5\sigma$

[Theoretically “very clean”: 1 % theory error (QED and lepton mass effects)] [ See Roman's talk ]

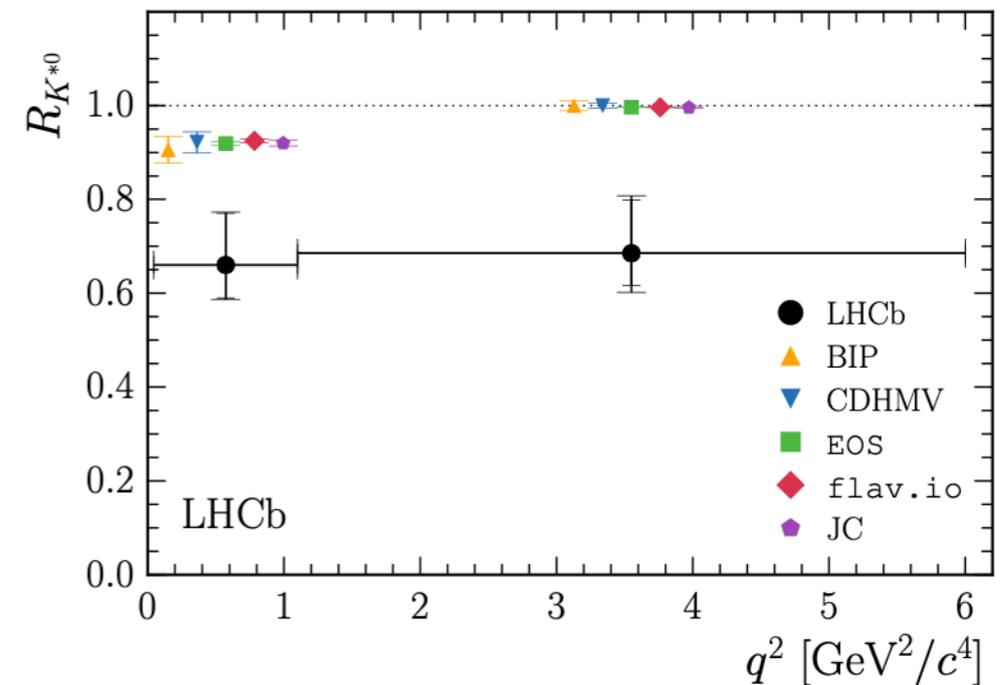
$$R_{K^{(*)}}^{[q_{\min}^2, q_{\max}^2]} \equiv \frac{\int_{q_{\min}^2}^{q_{\max}^2} d\Gamma(B \rightarrow K^{(*)} \mu^+ \mu^-)}{\int_{q_{\min}^2}^{q_{\max}^2} d\Gamma(B \rightarrow K^{(*)} e^+ e^-)}$$

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

[Isidori, Bordone, Pattori, [1605.07633](#)]



[LHCb, [2103.11769](#)]



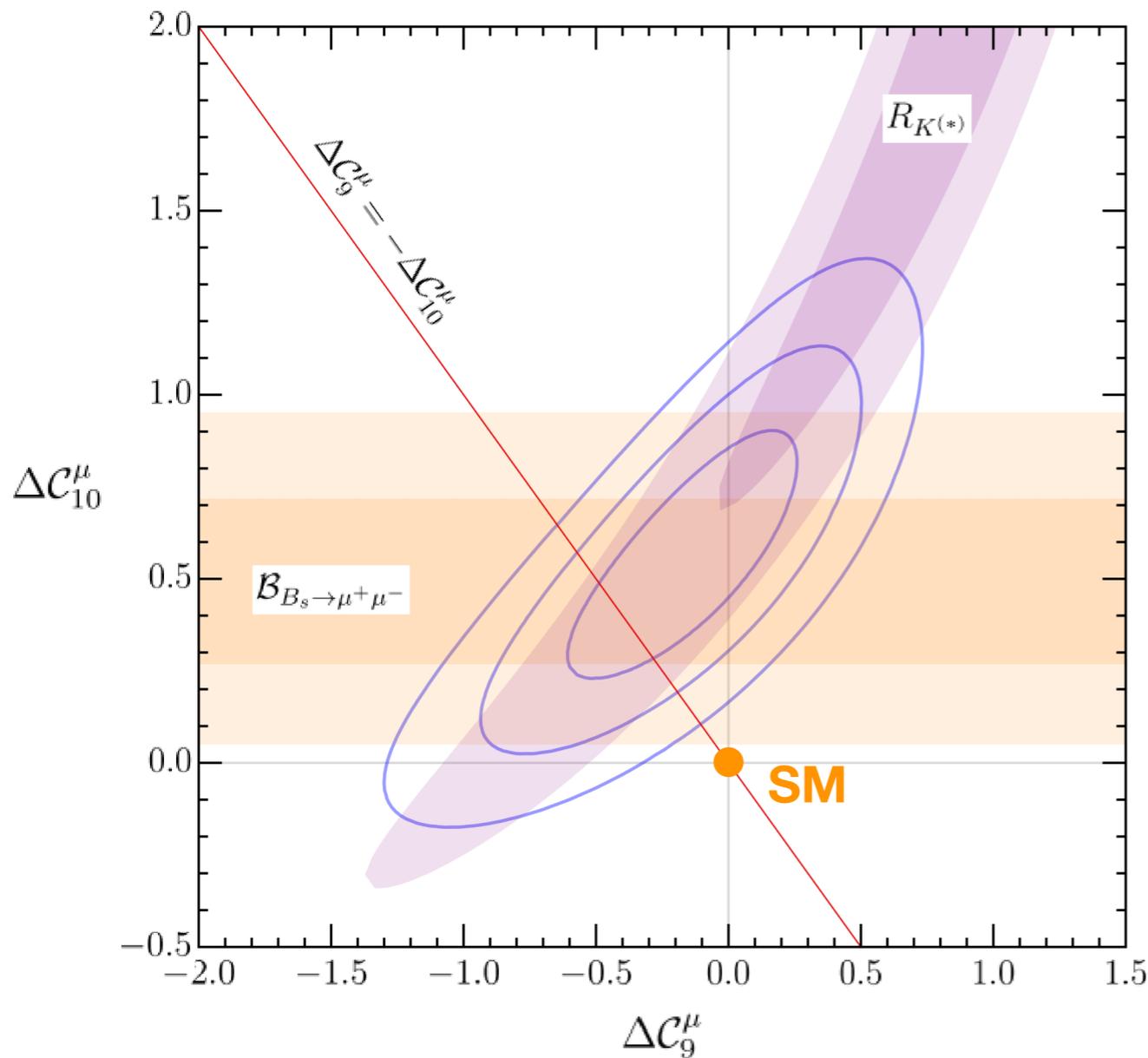
[LHCb, [1705.05802](#)]

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

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

Conservative fit using “th clean observables” only

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



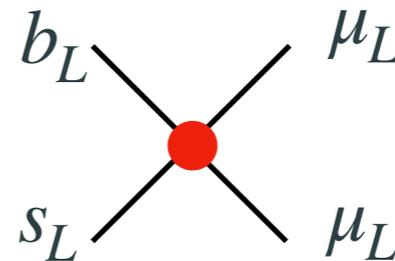
[Cornella, JFM et al., [2103.16558](https://arxiv.org/abs/2103.16558)]

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

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

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

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



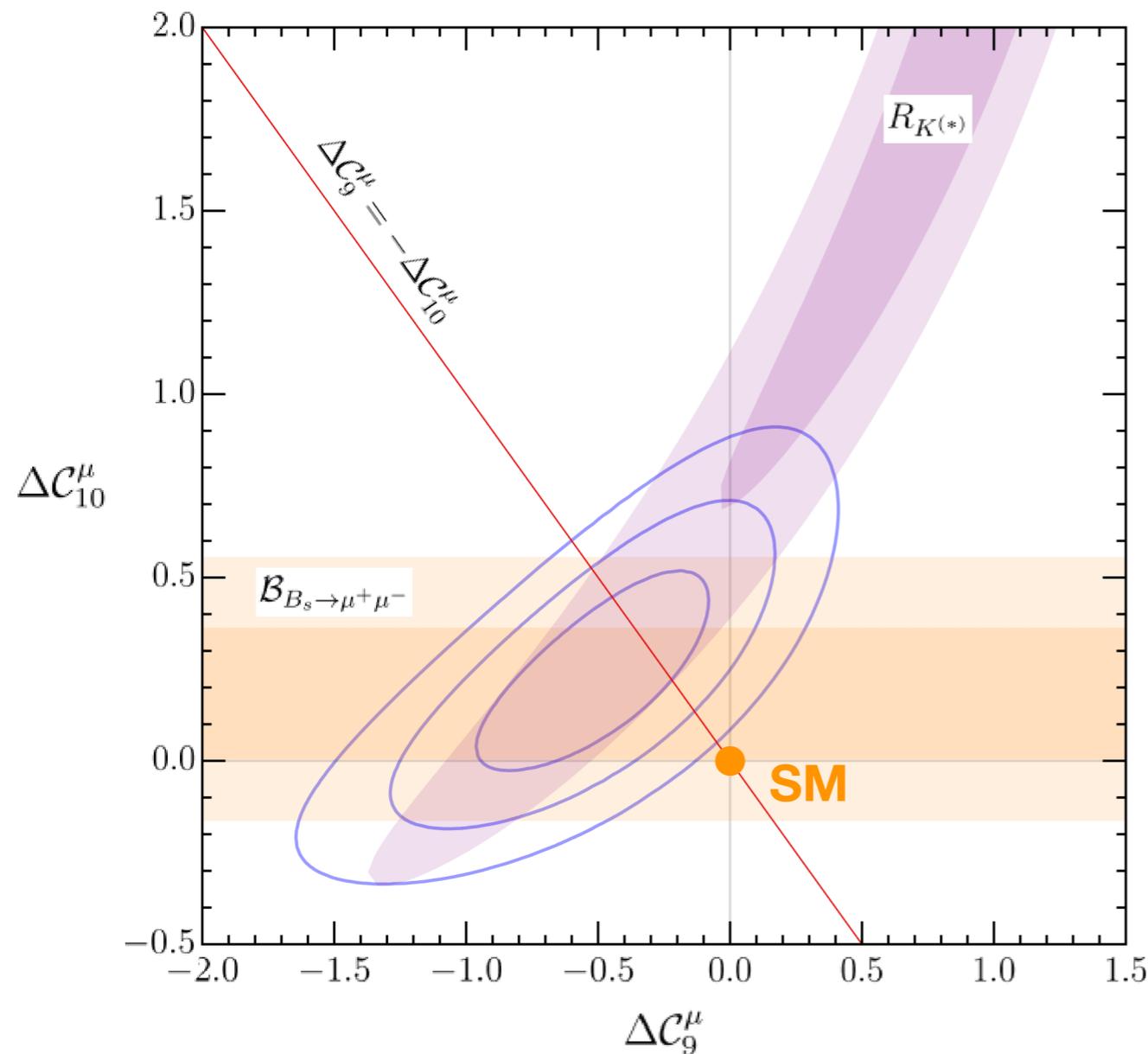
$$\sim 3 \times 10^{-5} G_F$$

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

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

Conservative fit using “th clean observables” only \*

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



\*: with *new*  $\mathcal{B}_{B_s \rightarrow \mu^+ \mu^-}$  from [\[CMS PAS BPH-21-006\]](#)

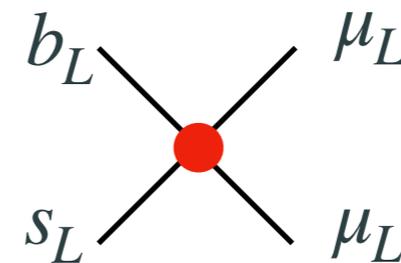
[ Sizable syst. from  $f_s/f_d$ , See Greg's talk ]

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

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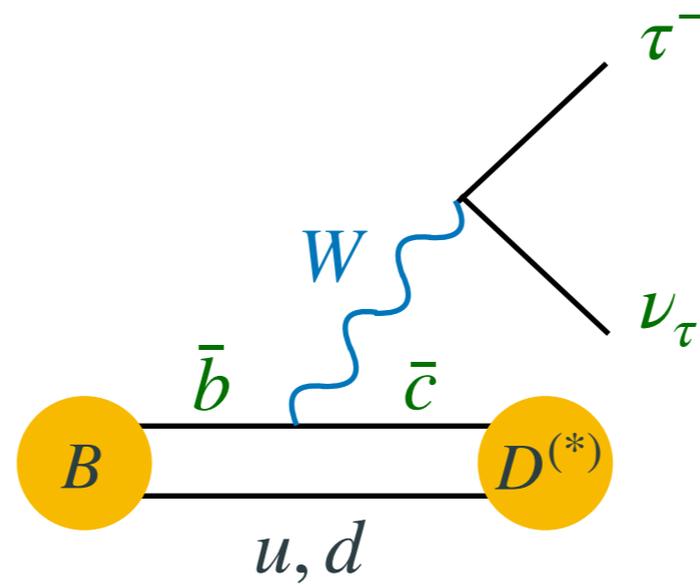
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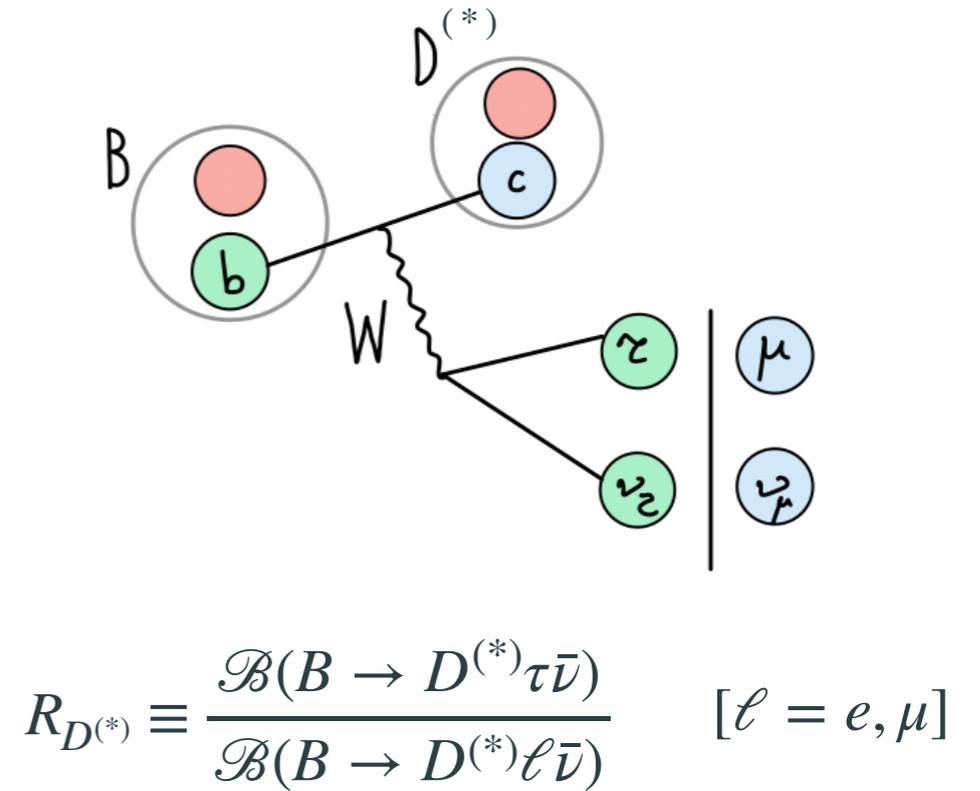
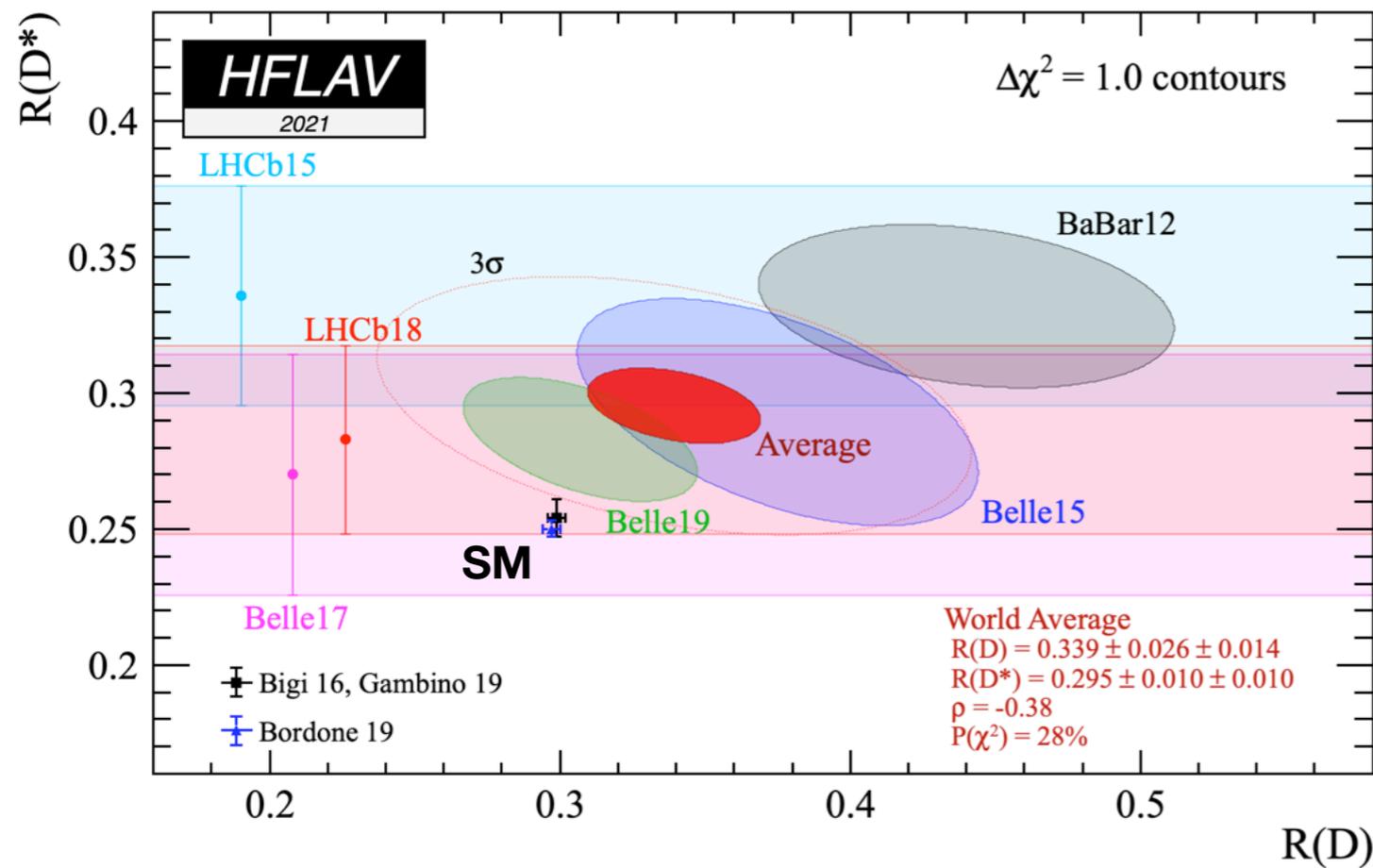
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# The $b \rightarrow c\tau\nu$ anomalies



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

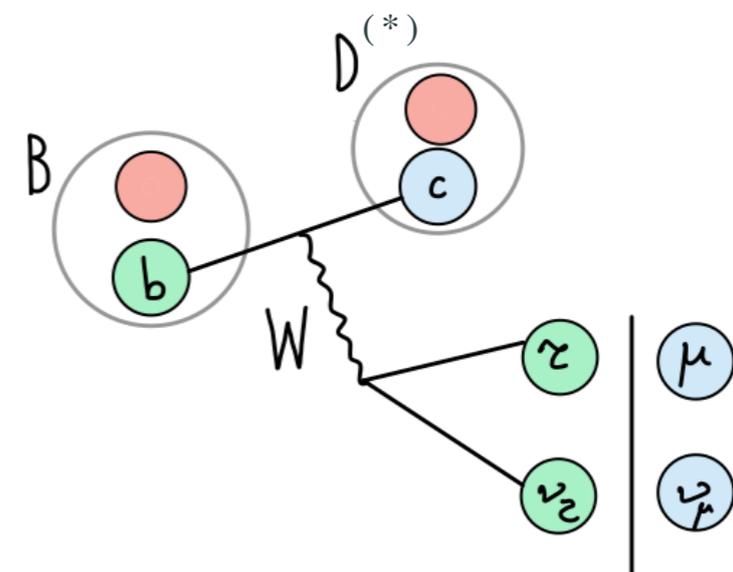
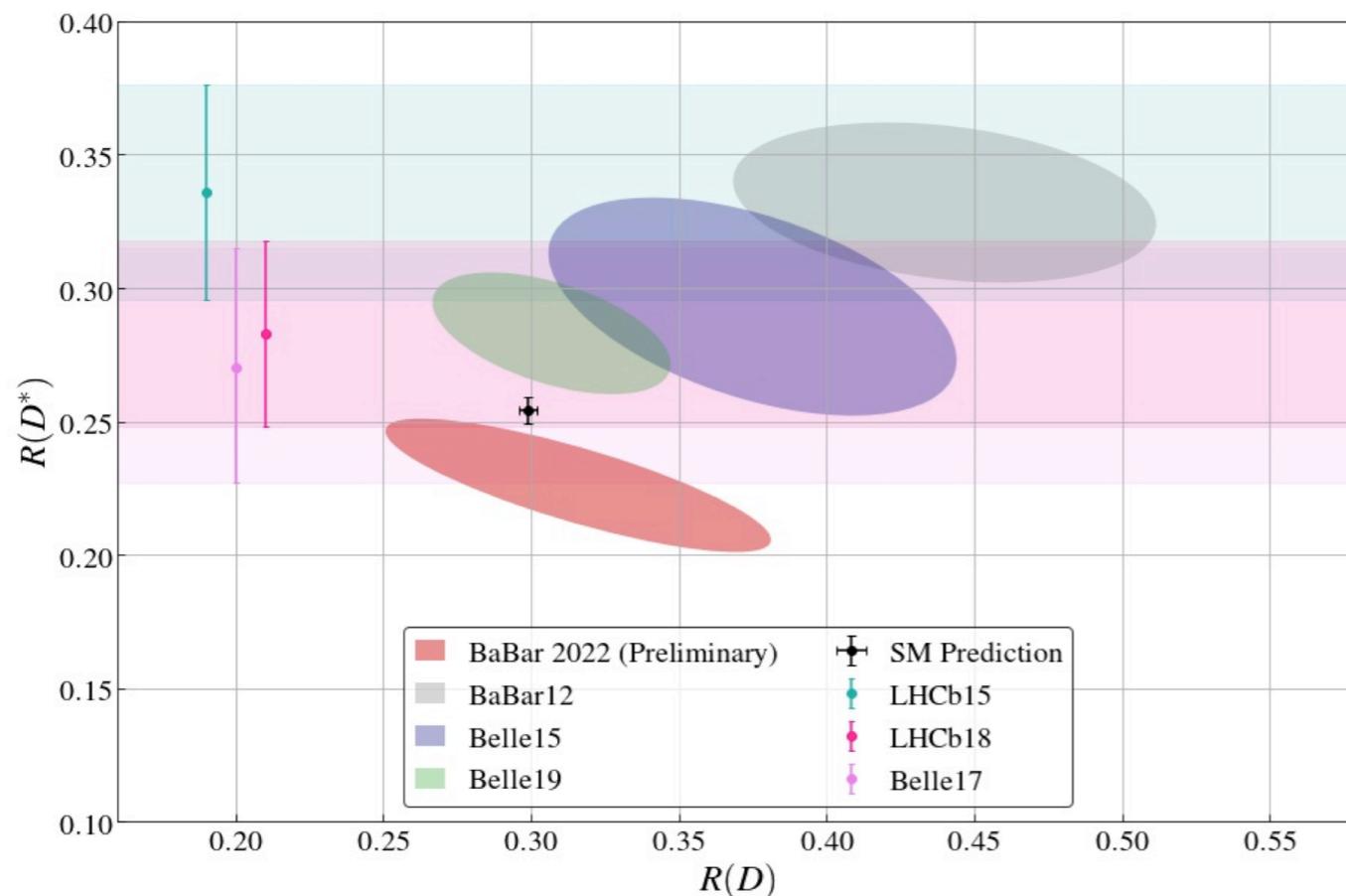
[ See Luke's talk ]



- ▶  $\sim 15\%$  enhancement due to excess in tau mode:  $3.4\sigma$  tension ( $R_D$  and  $R_{D^*}$  comb.)
- ▶ **Theoretically clean:** QCD uncertainties cancel (to a large extent) in the ratios
- ▶ Caveats:
  - New measurement of  $R(\Lambda_c)$  [ $\Lambda_b \rightarrow \Lambda_c \ell \nu$ ] reduces the tension slightly [LHCb, [2201.03497](#)]

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

[ See Luke's talk ]



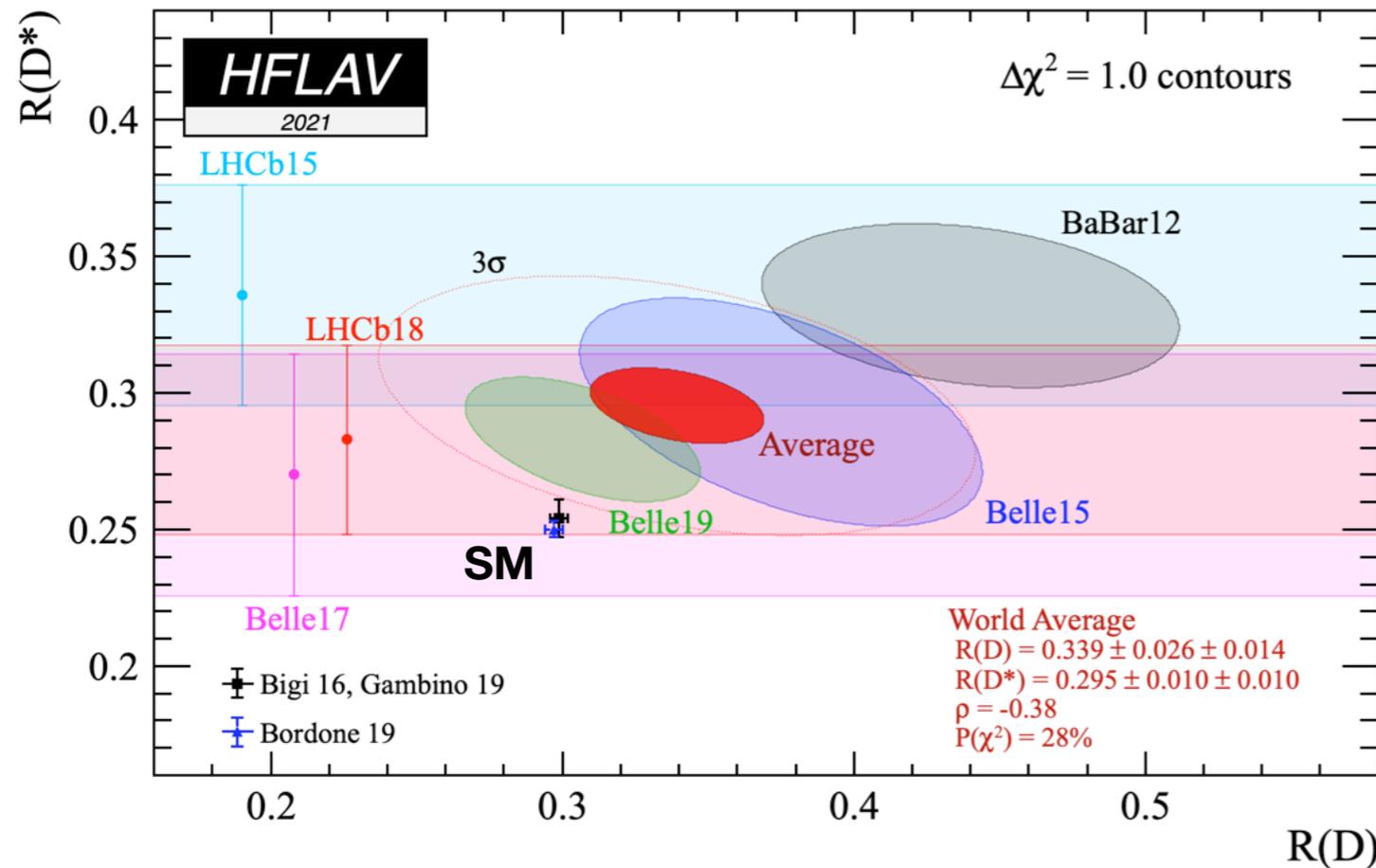
$$R_{D^{(*)}} \equiv \frac{\mathcal{B}(B \rightarrow D^{(*)} \tau \bar{\nu})}{\mathcal{B}(B \rightarrow D^{(*)} \ell \bar{\nu})} \quad [\ell = e, \mu]$$

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  - New preliminary analysis of BaBar data shows a completely different result!

[Yunxuan Li, [PhD thesis at Caltech](#)]

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

[ See Luke's talk ]



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

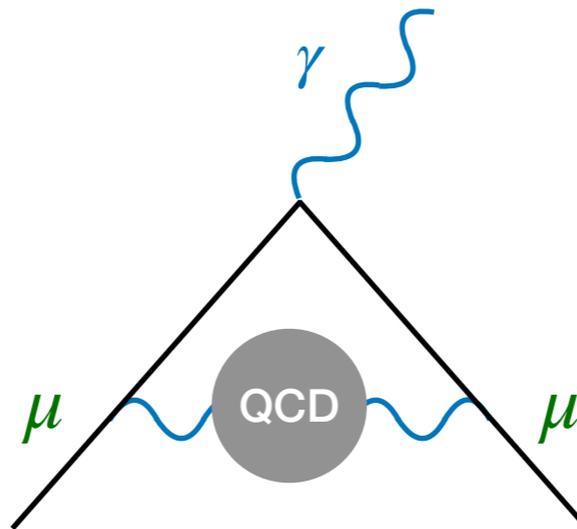
$$\begin{array}{ccc}
 b_L & & \tau_L \\
 & \diagdown & / \\
 & \bullet & \\
 & / & \diagdown \\
 c_L & & \nu_L
 \end{array}
 \sim 10^{-2} G_F$$

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

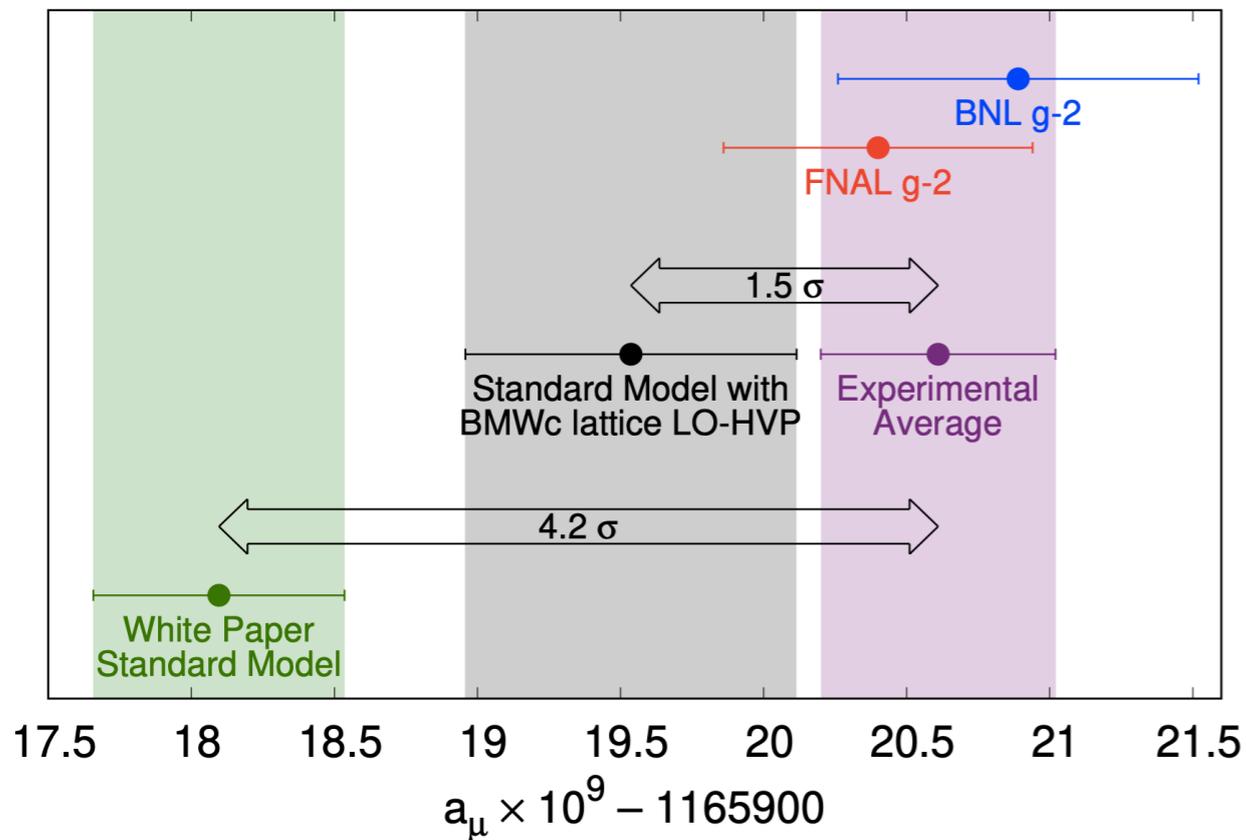
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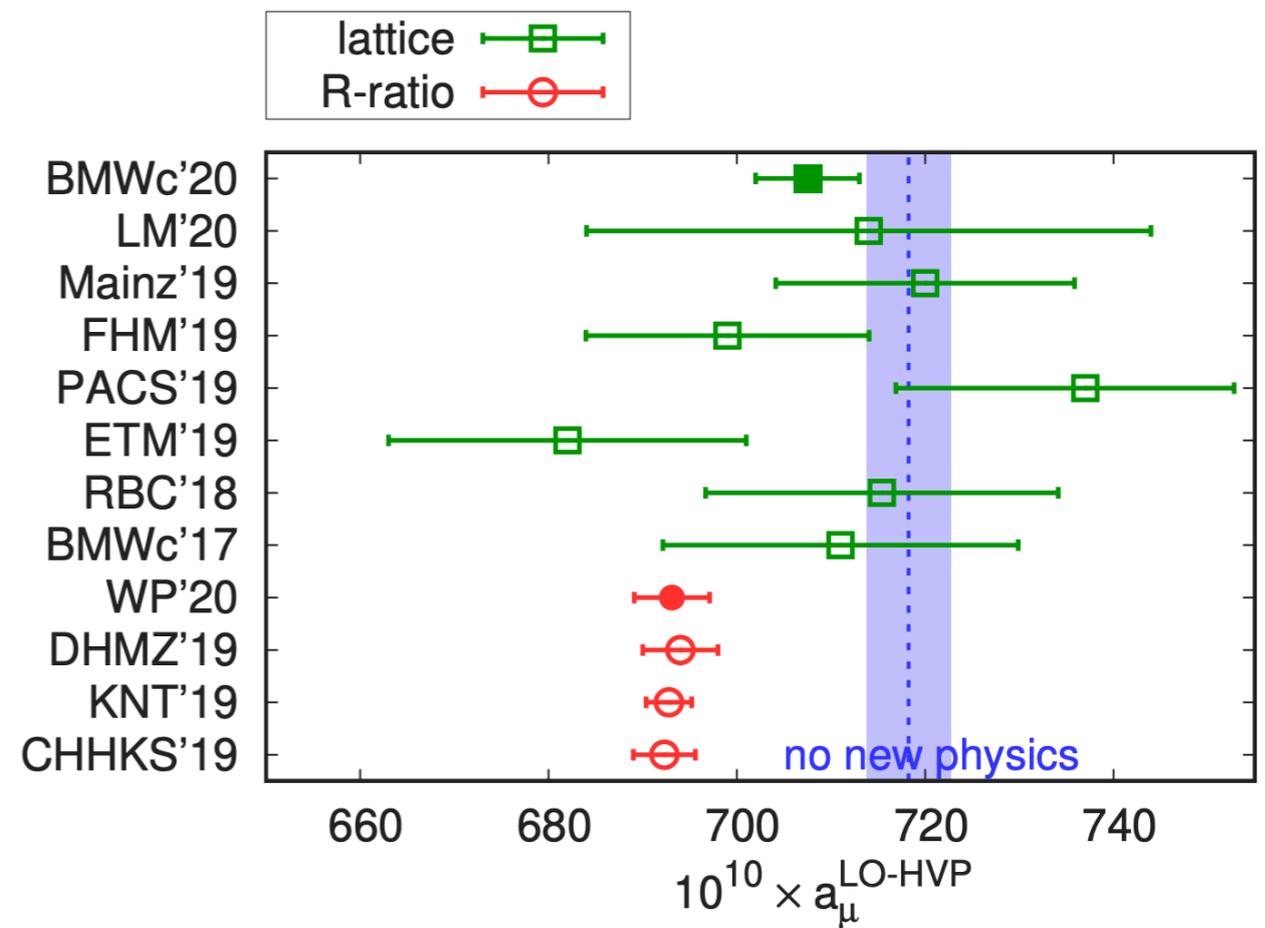
# The $(g - 2)_\mu$ anomaly



# The $(g - 2)_\mu$ anomaly



[Figure from BMWc lattice collaboration]



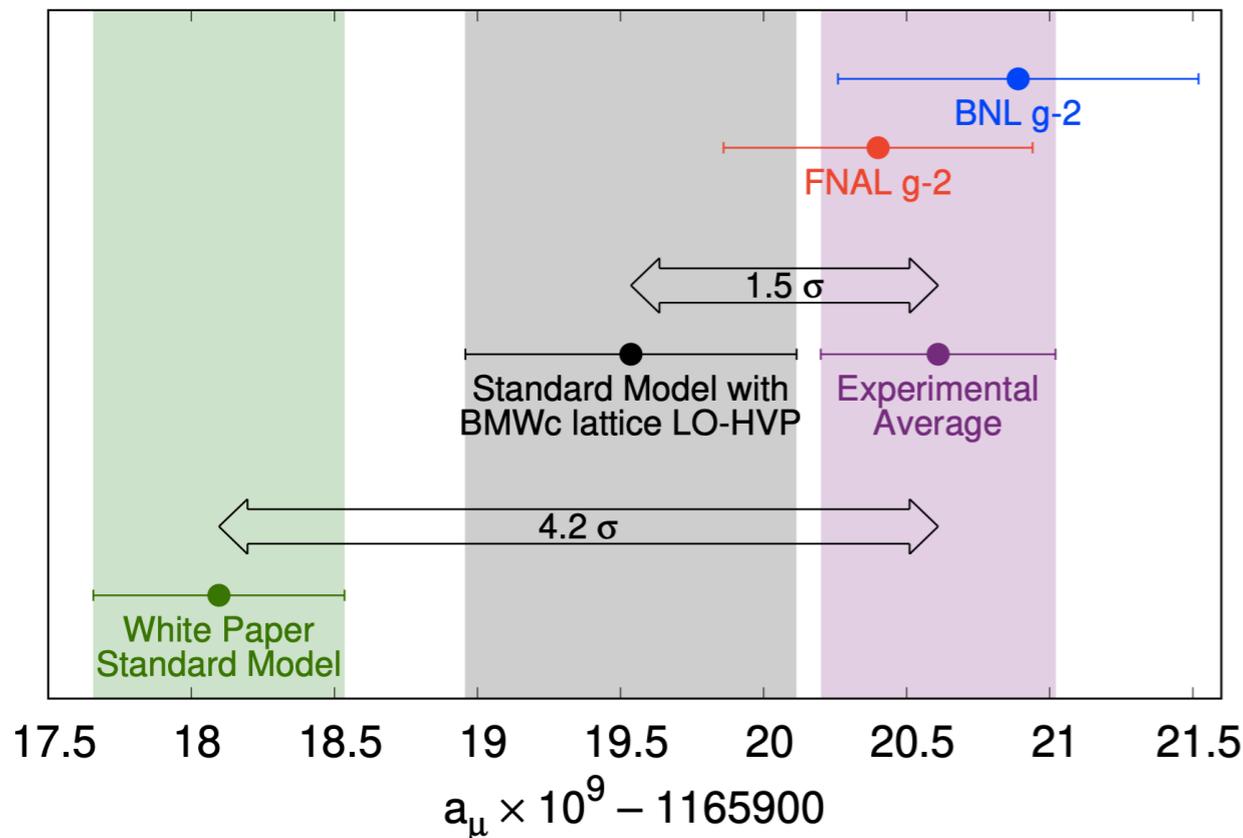
[Borsanyi et al., 2002.12347]

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

[Muon g-2 collaboration, 2104.03281]

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 lattice ]

# The $(g - 2)_\mu$ anomaly



[Figure from BMWc lattice collaboration]

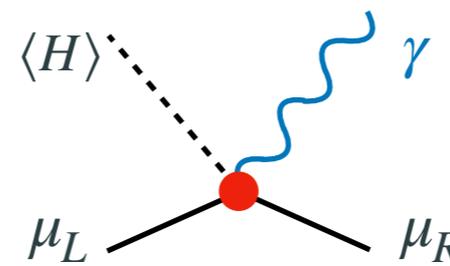
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[Muon g-2 collaboration, [2104.03281](#)]

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 lattice]

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

→ NP is either light or not chirally suppressed



$$\frac{g_{\text{NP}}^2}{M_{\text{NP}}^2} \sim \frac{e}{16\pi^2} \frac{1}{(10 \text{ TeV})^2}$$

# Possible mediators behind the anomalies

	Model	$R_{K^*}$	$R_{D^{(*)}}$	$(g-2)_\mu$
Vectors	$Z' \sim (1, 1)_0$	✓*	✗	✓*
	$U_1 \sim (3, 1)_{2/3}$	✓	✓	✗
	$U_3 \sim (3, 3)_{2/3}$	✓	✗	✗
Scalars	$S_1 \sim (3, 1)_{-1/3}$	✗	✓	✓
	$R_2 \sim (3, 2)_{7/6}$	✗	✓*	✓*
	$\tilde{R}_2 \sim (3, 2)_{1/6}$	✗	✗	✗
	$S_3 \sim (3, 3)_{-1/3}$	✓	✗	✗

$b \rightarrow s\ell^+\ell^-$  only:  $Z', U_1, U_3, S_3$

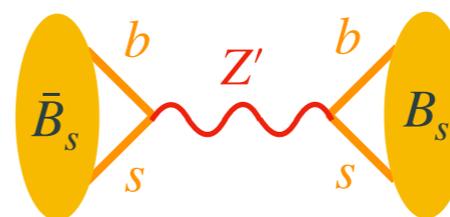
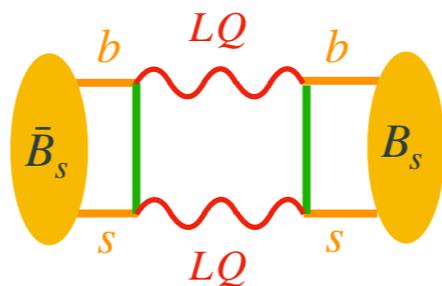
[ For searches @ future colliders, see Sokratis' talk ]

$b \rightarrow s\ell^+\ell^- + R_{D^{(*)}}$ :  $U_1, S_1 + S_3, R_2 + S_3$

$b \rightarrow s\ell^+\ell^- + R_{D^{(*)}} + (g-2)_\mu$ :  $S_1 + S_3$

Leptoquarks (both scalars and vectors) have two important features

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

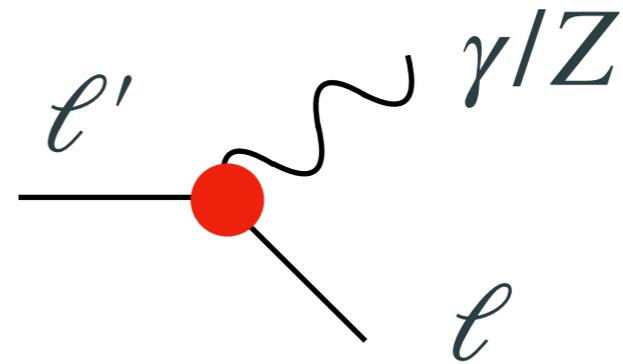
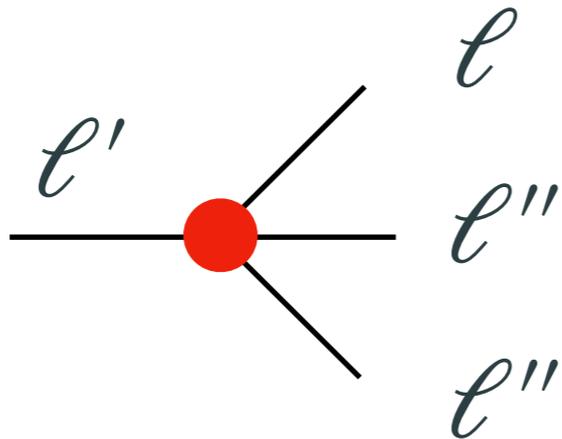


2. Direct searches: t-channel versus resonant s-channel production

# A selection of experimental predictions



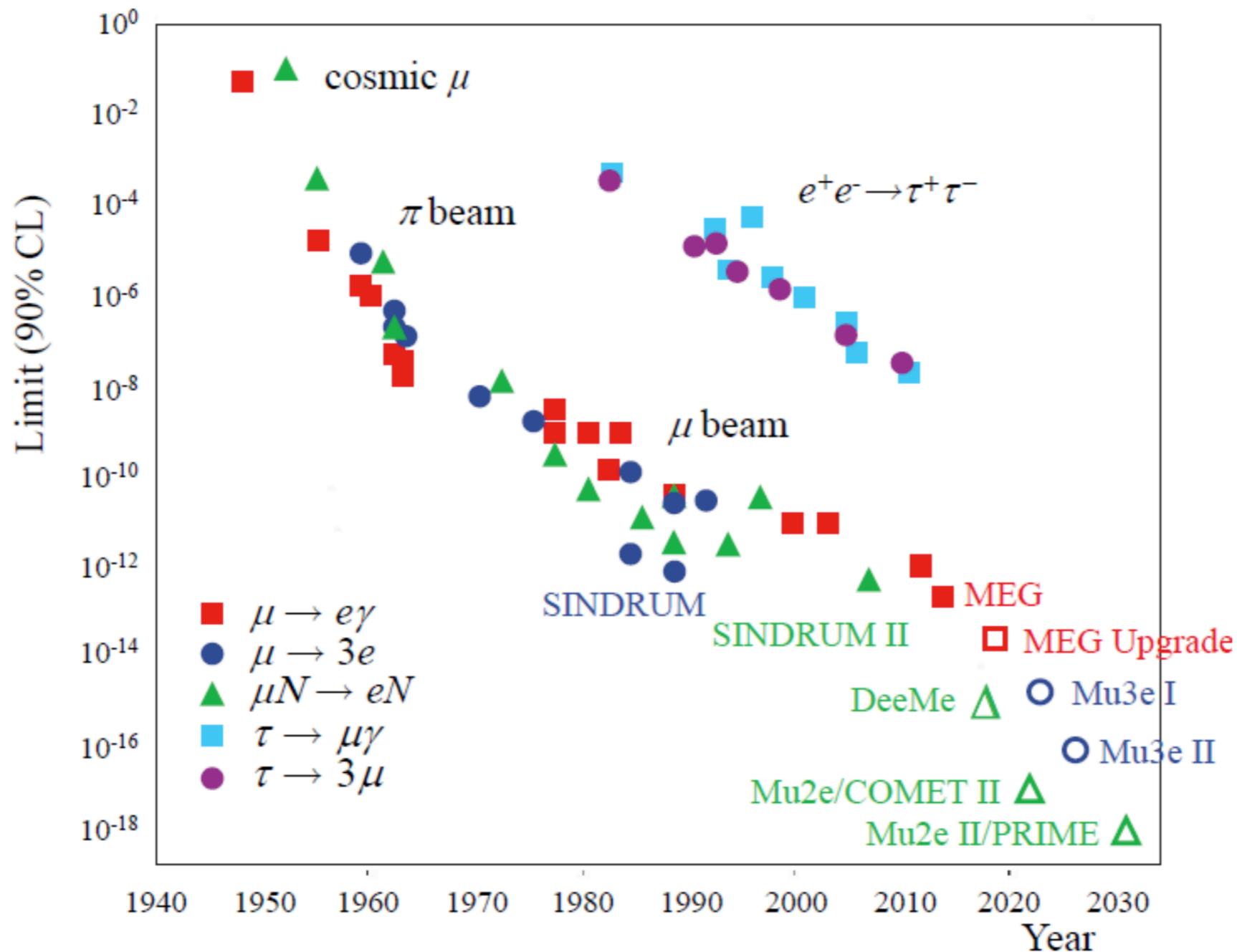
# Lepton Flavor Violation



# Future prospects for Lepton Flavor Violation ( $\mu \rightarrow e$ )

[F. Cei, [KAON19 proceedings](#)]

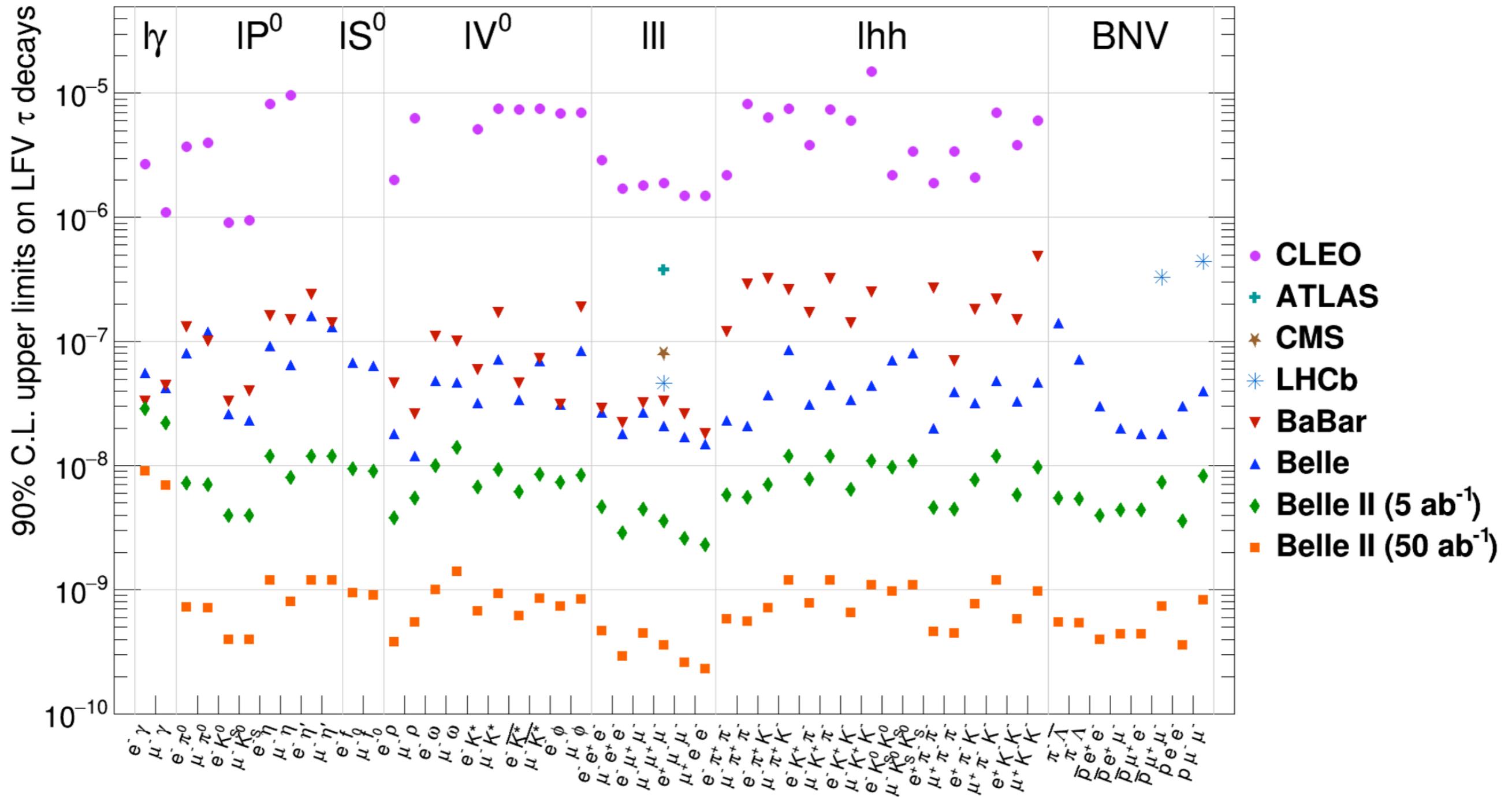
[ See Satoshi's and Ben's talks ]



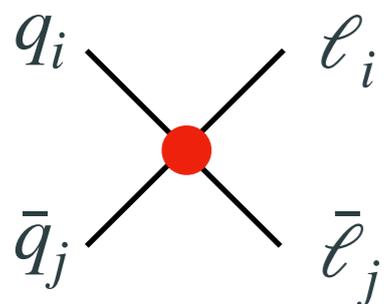
# Future prospects for Lepton Flavor Violation ( $\tau$ decays)

[Belle II, 2207.06307]

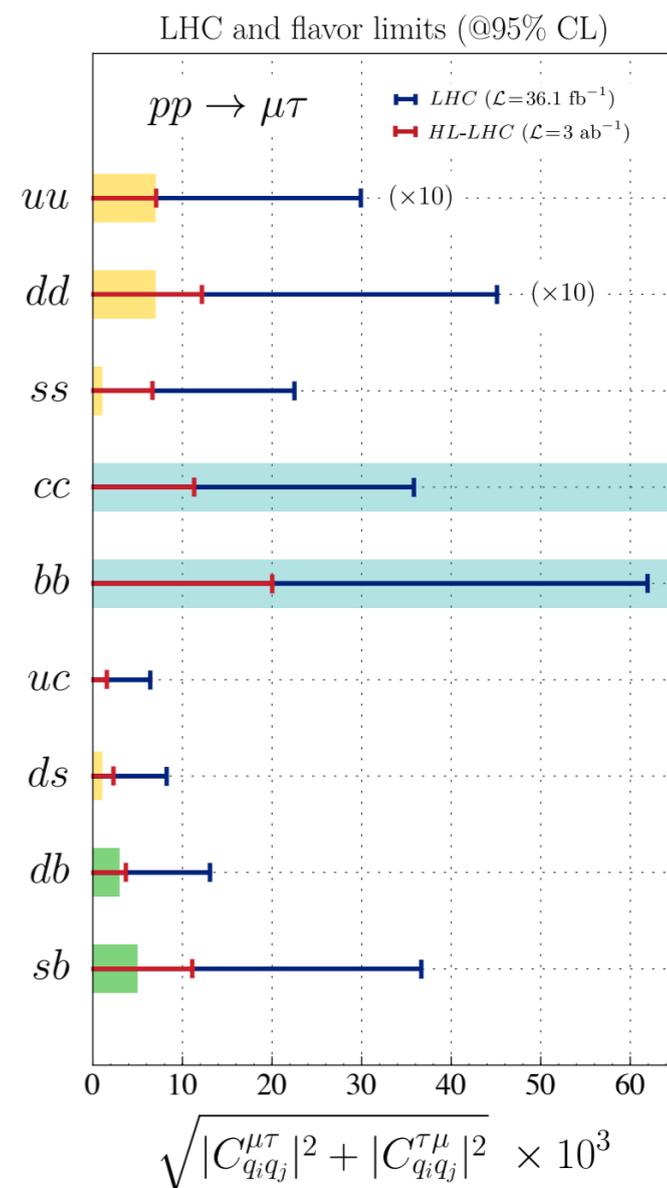
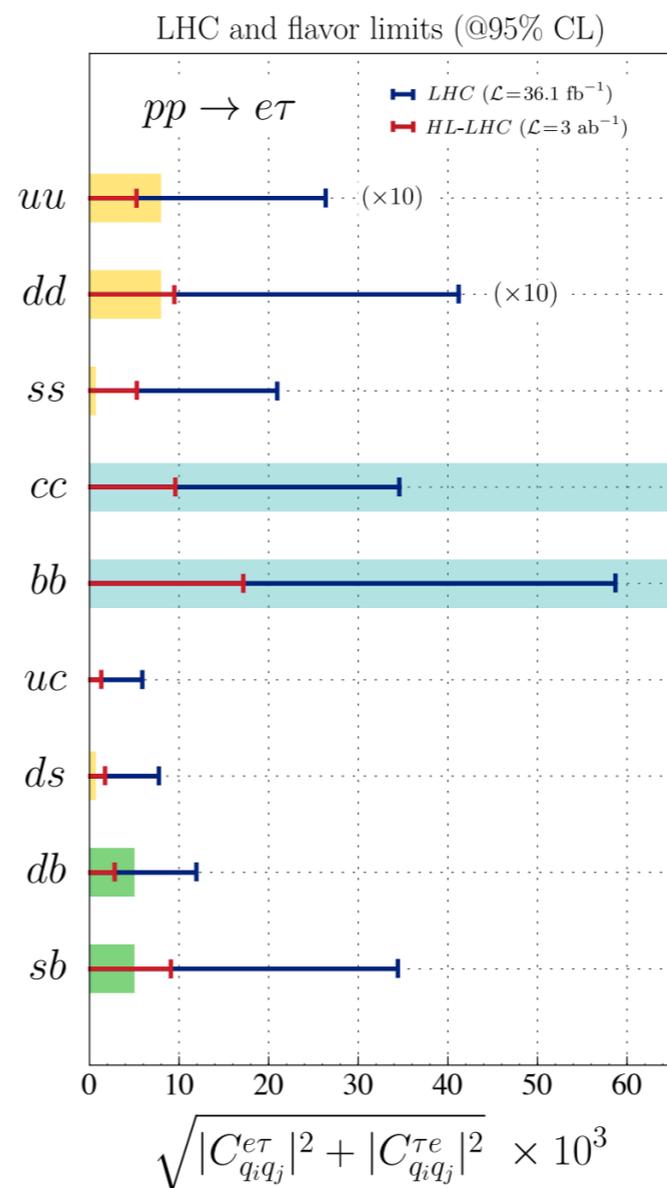
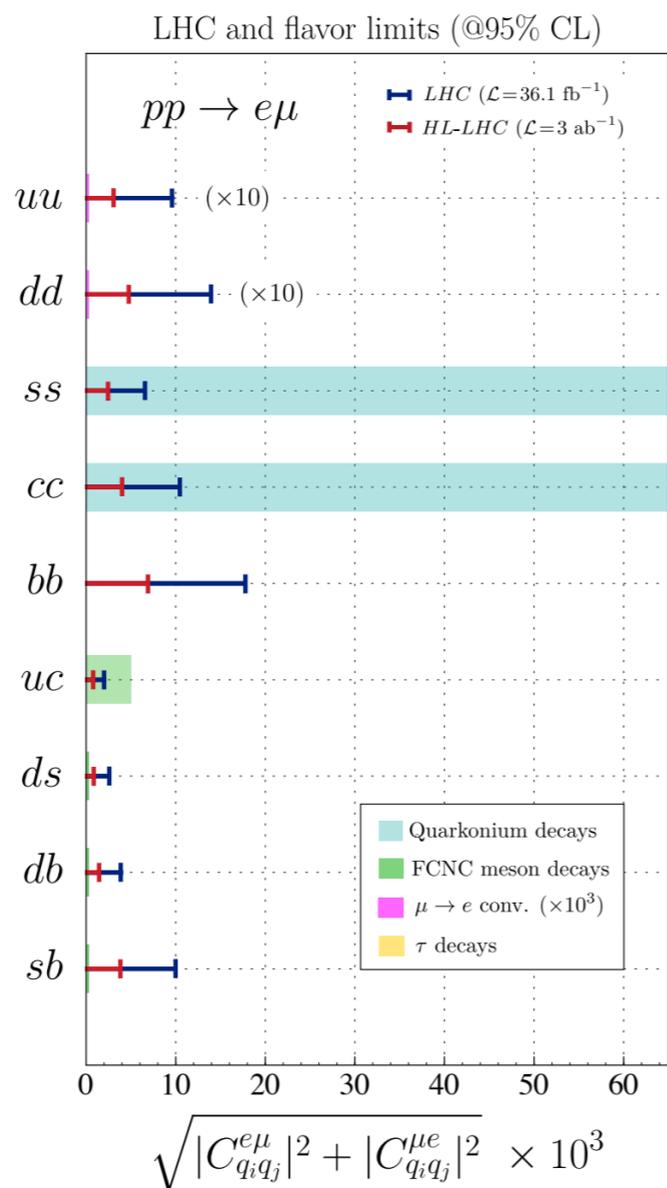
[ See Léonard's talk ]



# Lepton Flavor Violation in high- $p_T$ tails



@ ATLAS & CMS

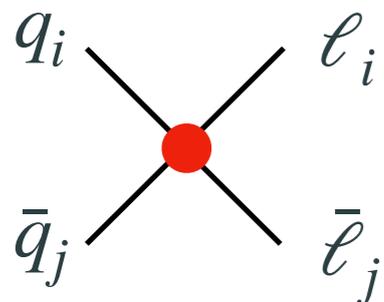


[ For  $b \rightarrow s\ell\ell'$ , see Juhi's talk ]

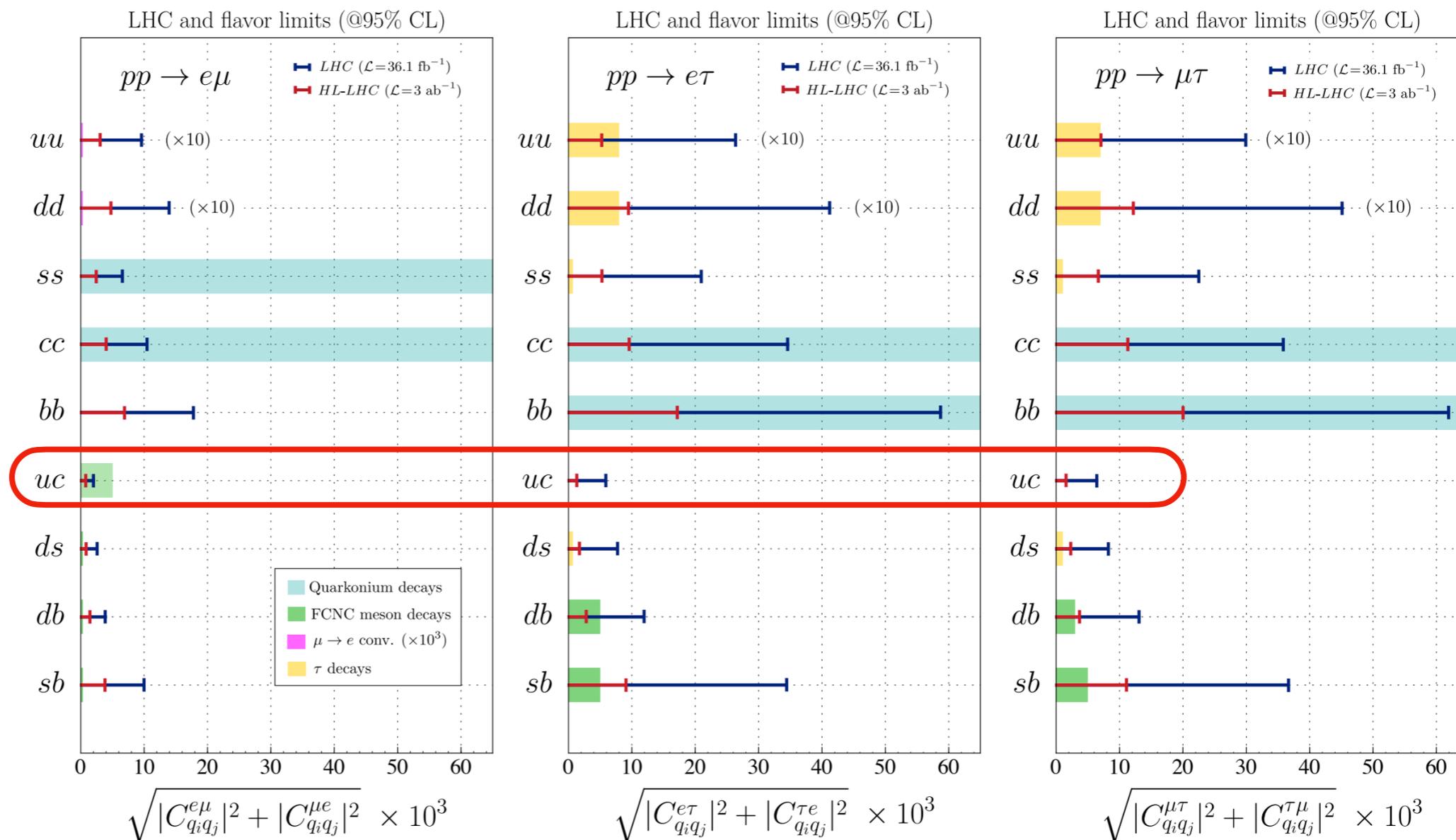
[Angelescu, Faroughy, Sumensari, [2002.05684](#)]

[See also JFM, Greljo, Camalich, Ruiz-Alvarez, [2003.12421](#)]

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@ ATLAS & CMS



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# Both $B$ anomalies imply Lepton Flavor Violation

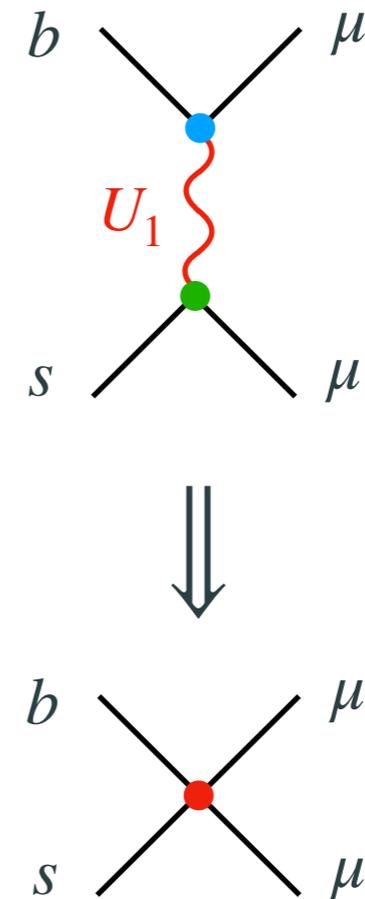
Explaining  $b \rightarrow s\ell^+\ell^-$  and  $b \rightarrow c\tau\nu$  anomalies requires LQ couplings to both  $\mu$  and  $\tau$   
 $\implies$  Lepton Flavor Violation!

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E.g.  $U_1$  vector LQ

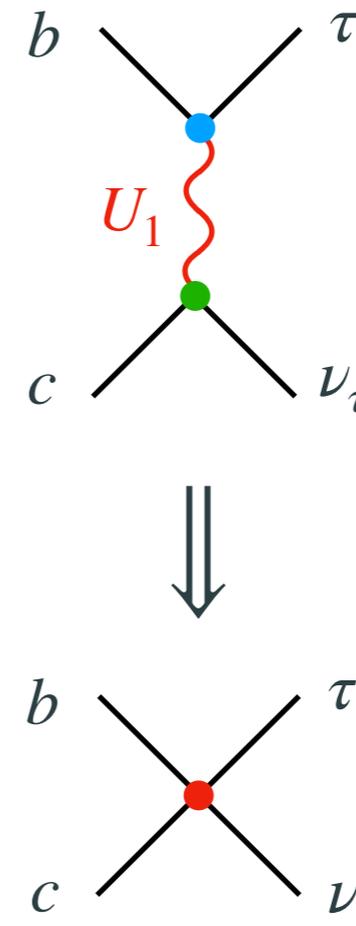
$b \rightarrow s\mu^+\mu^-$	$b \rightarrow c\tau\nu$
$g_{lq}^{23}$	$g_{lq}^{33}$
$g_{lq}^{22}$	$g_{lq}^{32}$



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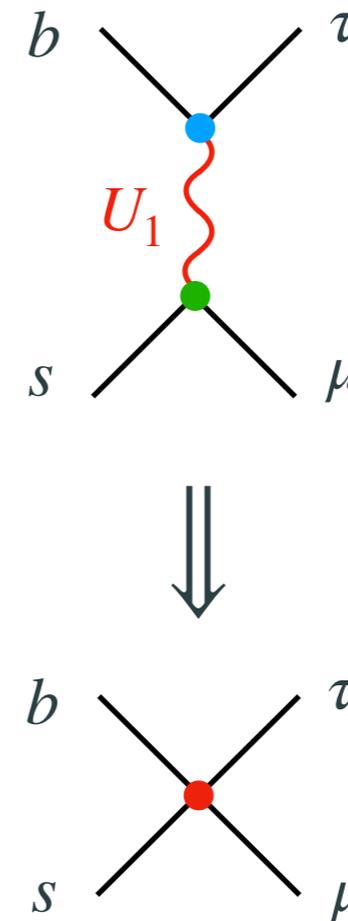
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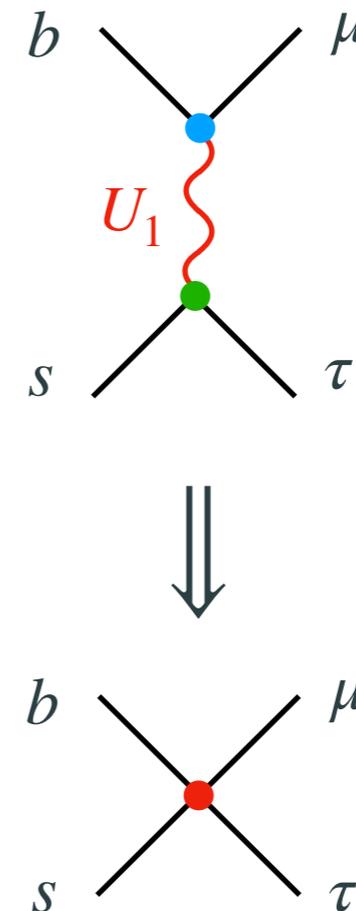
$b \rightarrow s\tau^-\mu^+$	$b \rightarrow s\mu^+\mu^-$	$b \rightarrow c\tau\nu$
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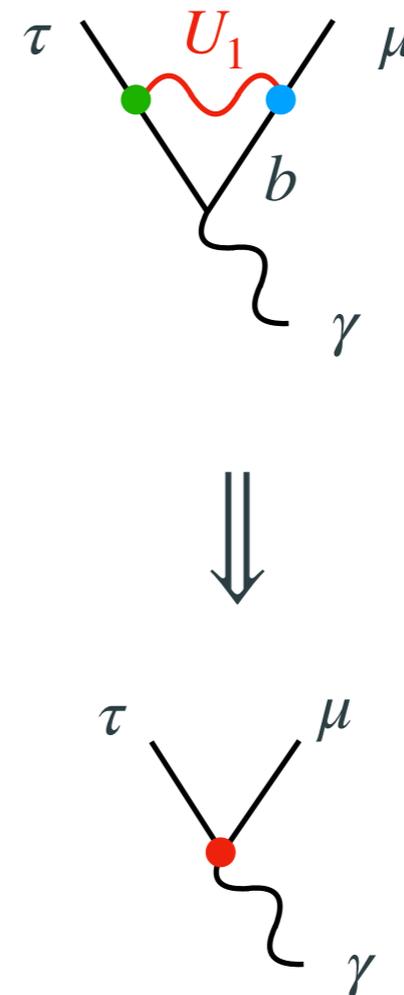
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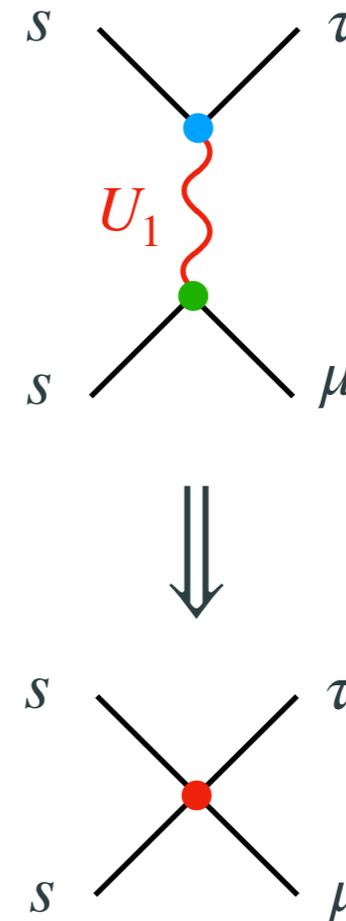
$b \rightarrow s\tau^-\mu^+$	$b \rightarrow s\mu^+\mu^-$	$b \rightarrow c\tau\nu$
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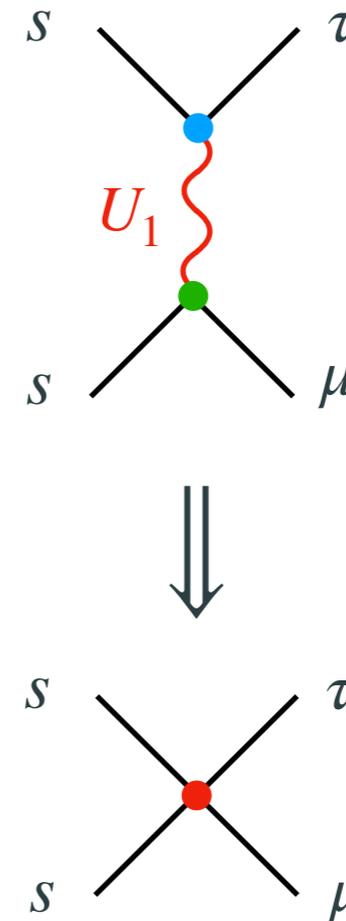
$b \rightarrow s\tau^-\mu^+$	$b \rightarrow s\mu^+\mu^-$	$b \rightarrow c\tau\nu$
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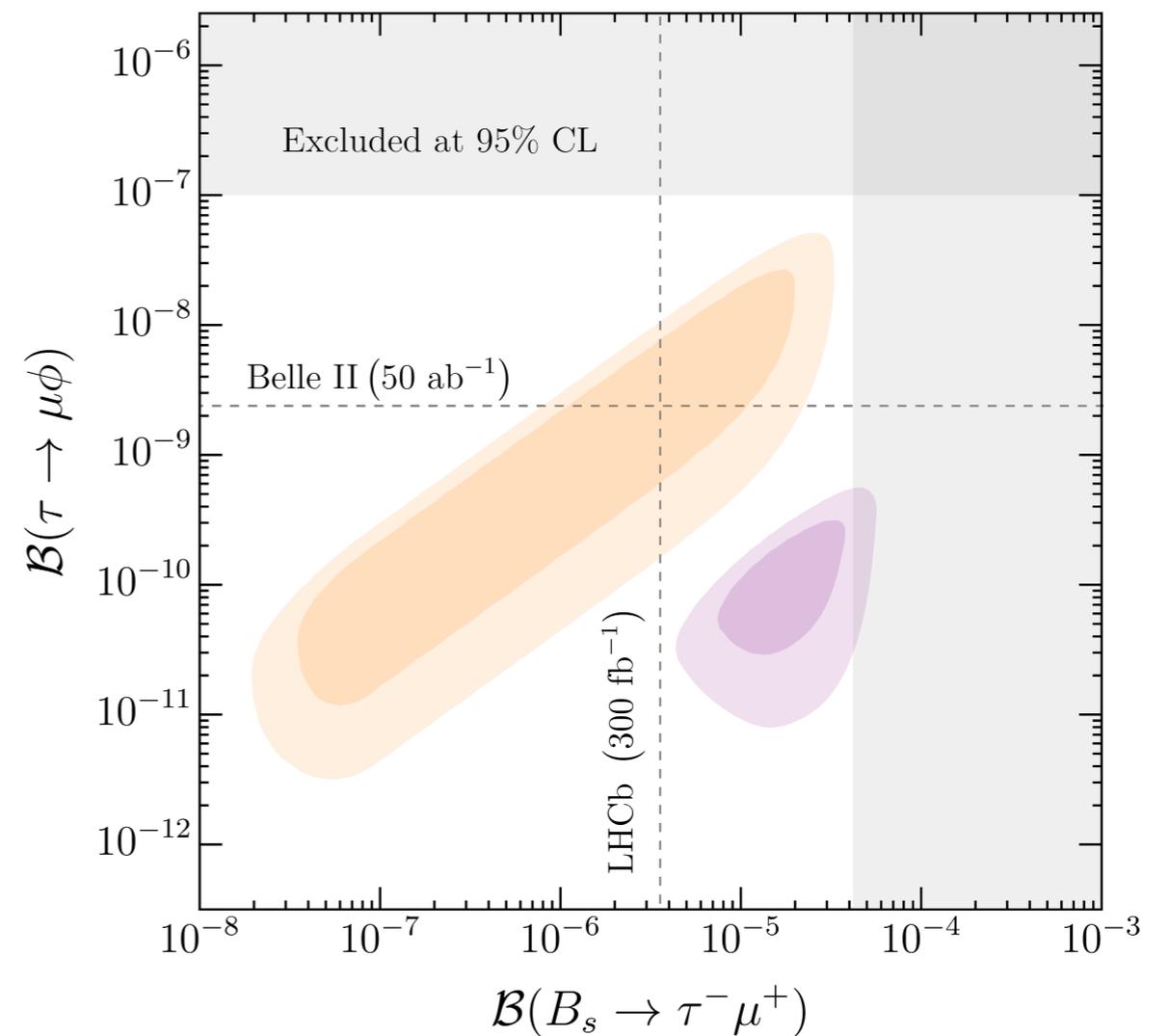
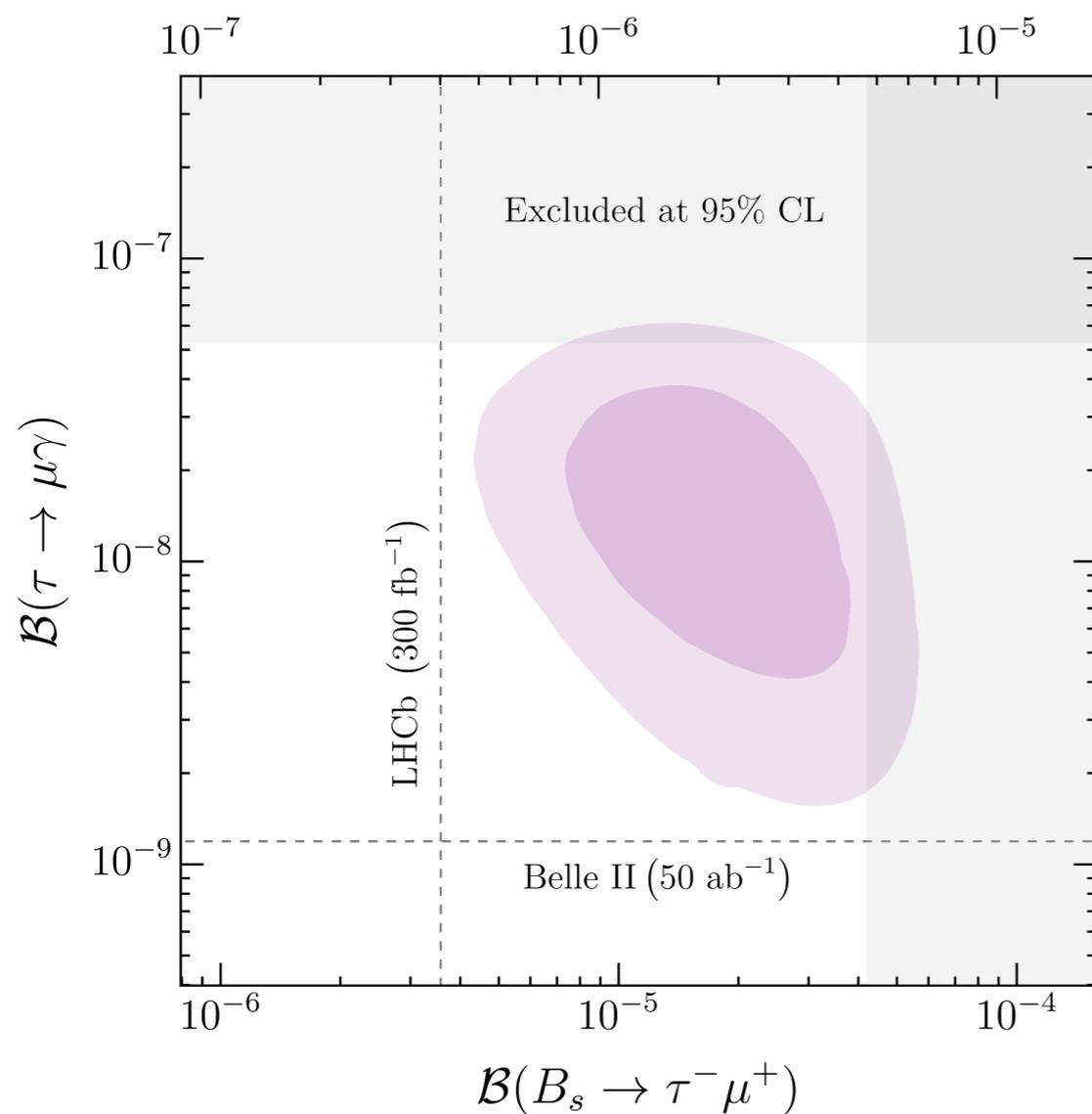


N.B.: In a theory of flavor ( or a more complete model )  $\mu \rightarrow e$  LFV would also be expected!

# LFV predictions in $U_1$ leptoquark model

Comparison of LFV predictions in two versions of the  $U_1$  model:

- ▶ only left-handed leptoquark couplings
- ▶ including a right-handed leptoquark coupling

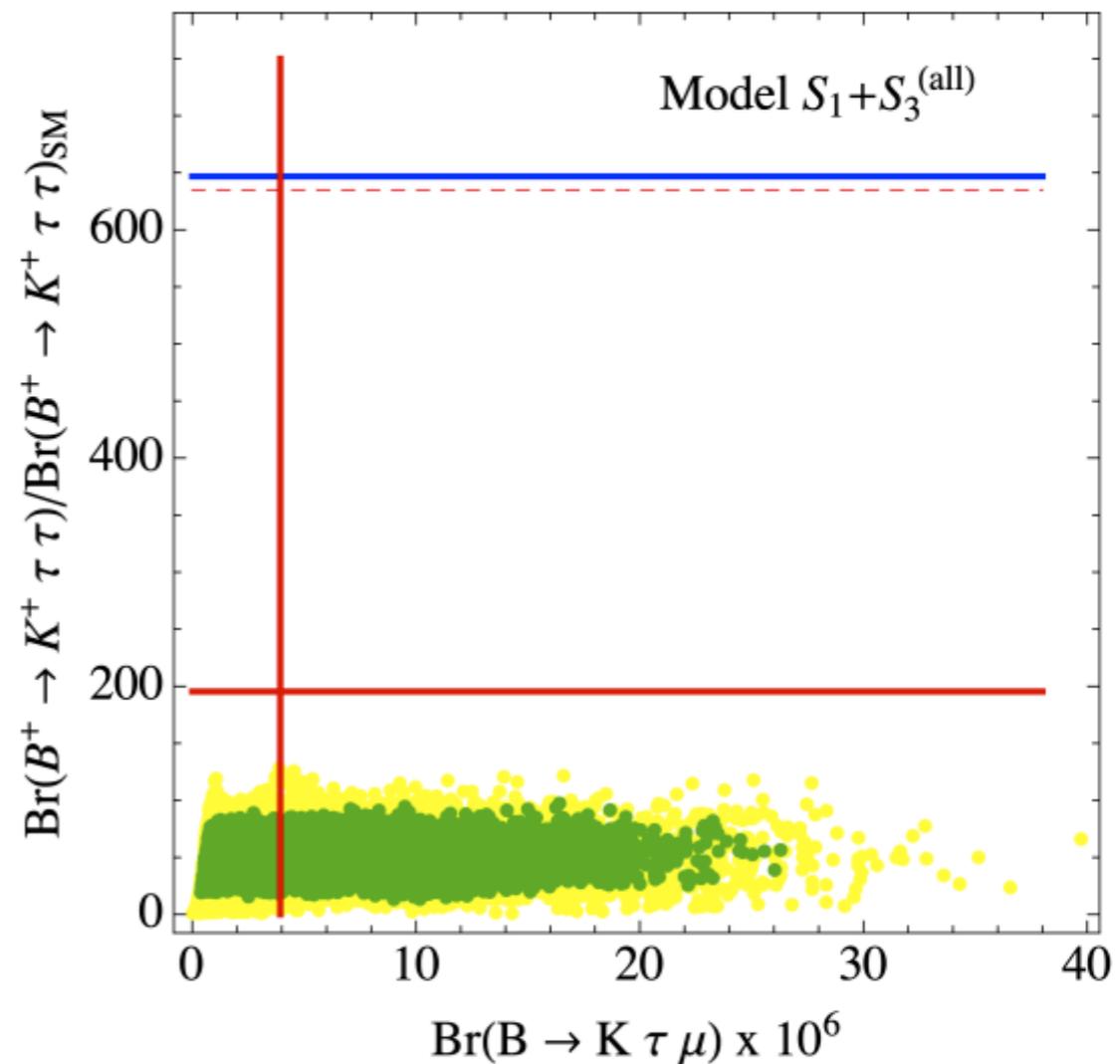
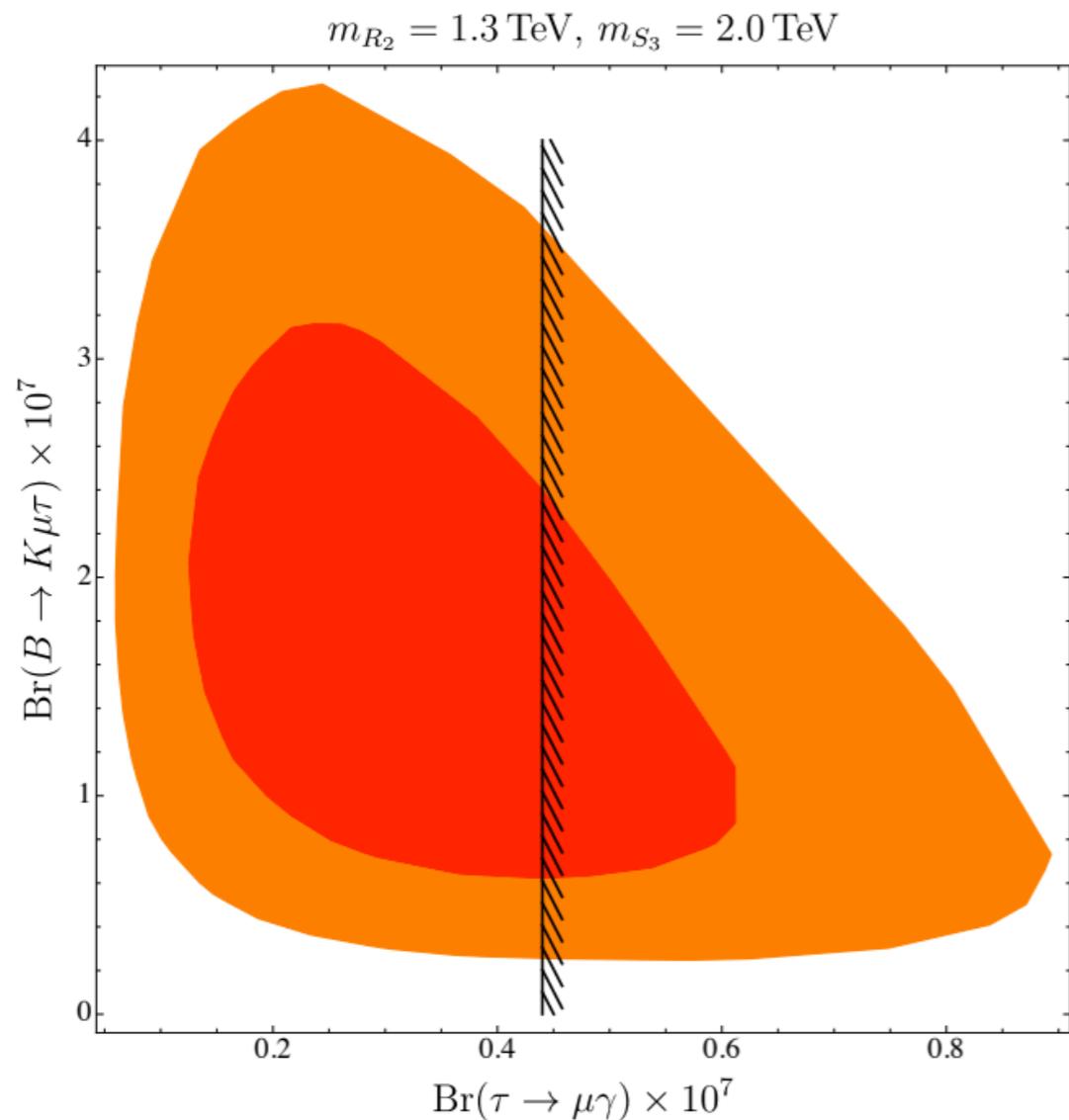


[Cornella, JFM et al., [2103.16558](#)]

# LFV predictions in other leptoquark models

$R_2 + S_3$

$S_1 + S_3$



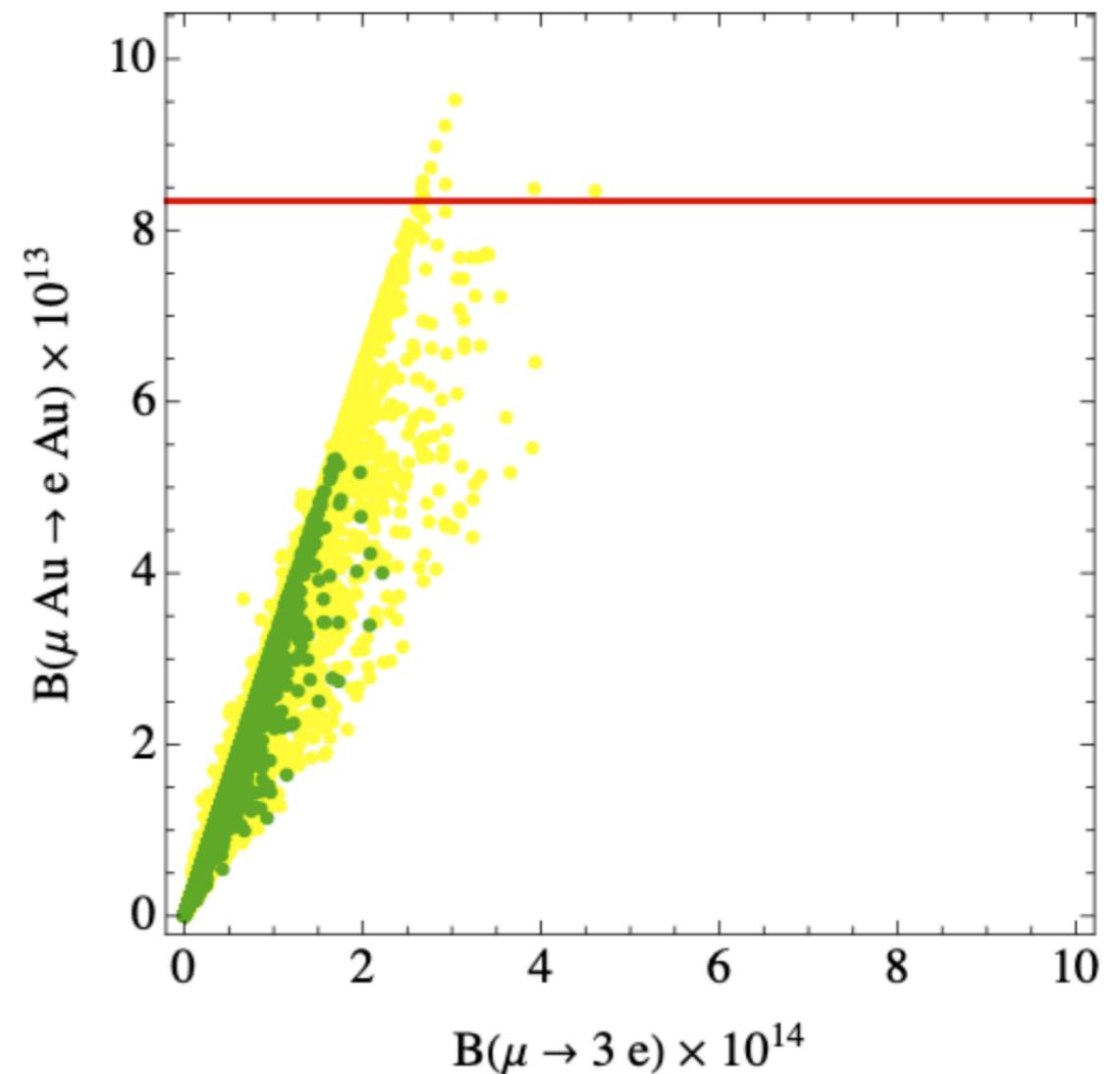
[Bečirević et al., [2206.09717](#)]

[Gherardi, Marzocca, Venturini, [2008.09548](#)]

# LFV predictions in other leptoquark models

Assuming a specific well-motivated flavor structure:  
minimally-broken  $U(2)^5$  symmetry

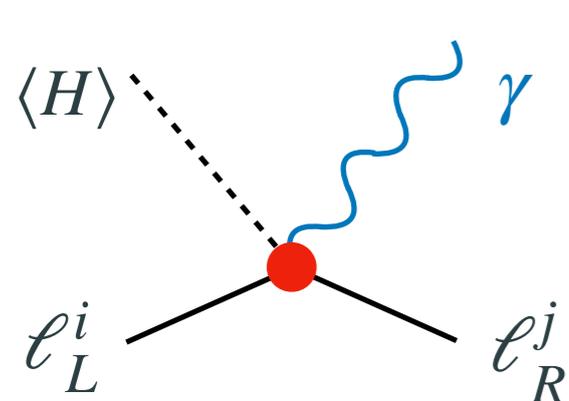
$$S_1 + S_3$$



[Marzocca, Trifinopoulos, Venturini, [2106.15630](#)]

# Explanations of $(g - 2)_\mu$ and Lepton Flavor Violation

New physics (NP) explaining  $(g - 2)_\mu$  should be **nearly lepton flavor conserving**



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

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

Naive expectation:

$$\theta_{23} \sim \sqrt{m_\mu/m_\tau} \approx 2 \times 10^{-1}$$

$$\theta_{12} \sim \sqrt{m_e/m_\mu} \approx 7 \times 10^{-2}$$

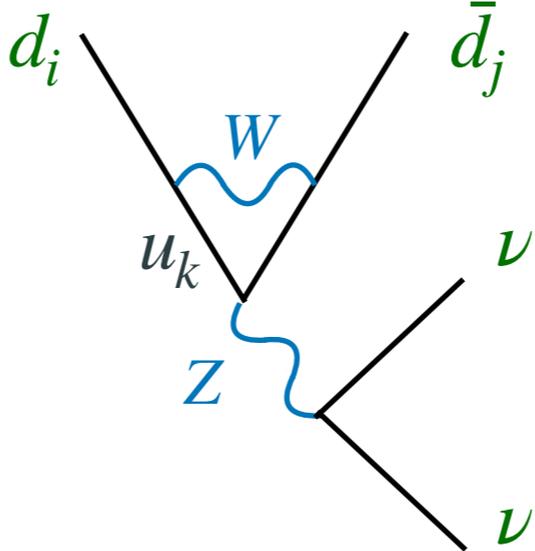
Possible explanation/interpretation: new  $U(1)$  gauge symmetry *forcing* muon-specific NP interactions

[ Greljo, Stangl, Thomsen, [2103.13991](#)]

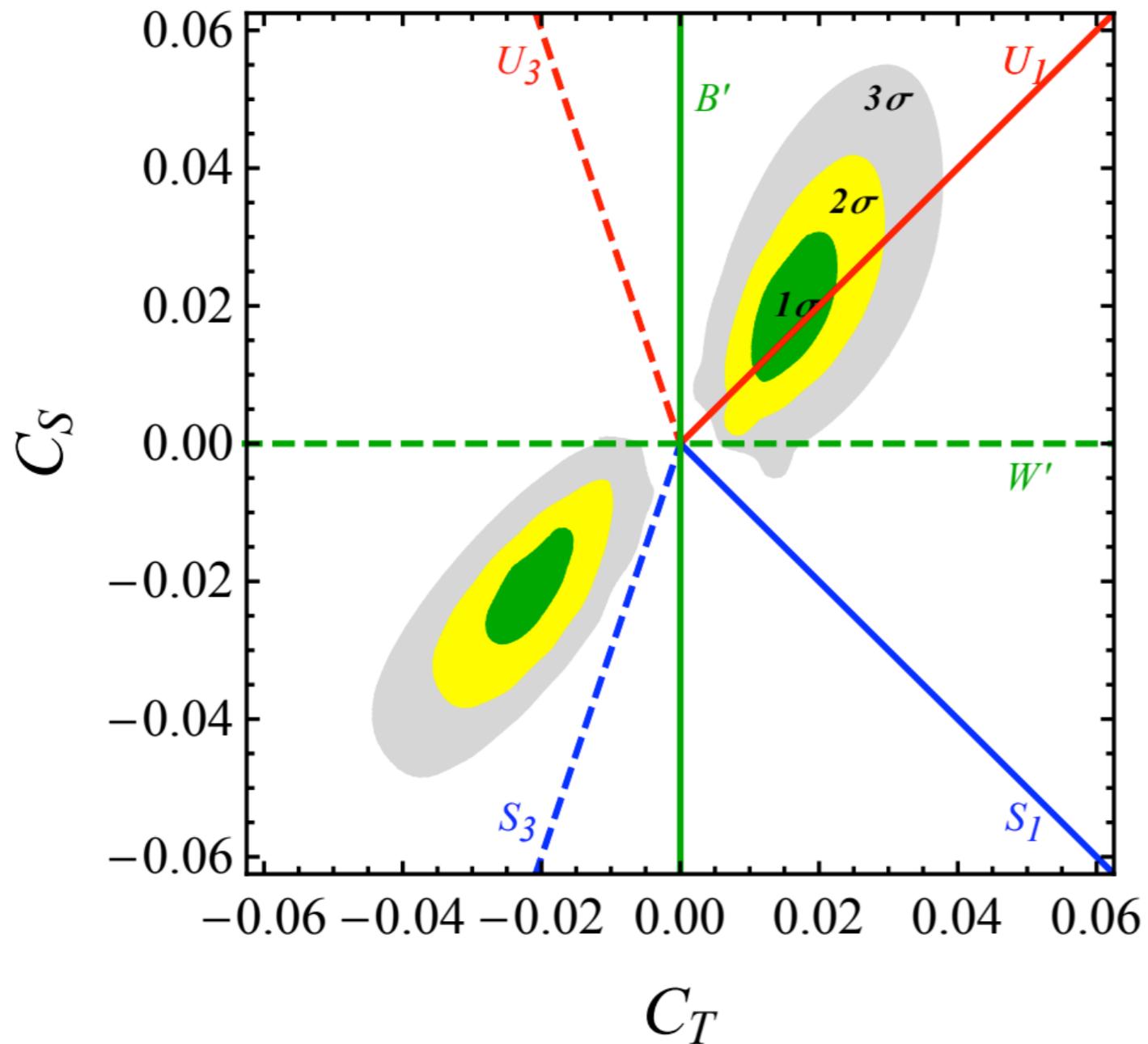
E.g.  $S_1 + S_3$  “muoquarks” can simultaneously explain  $b \rightarrow s\ell^+\ell^-$  and  $(g - 2)_\mu$

$\implies$  Same symmetry that protects LFV forbids also proton decay

$d_i \rightarrow d_j \nu \bar{\nu}$  decays

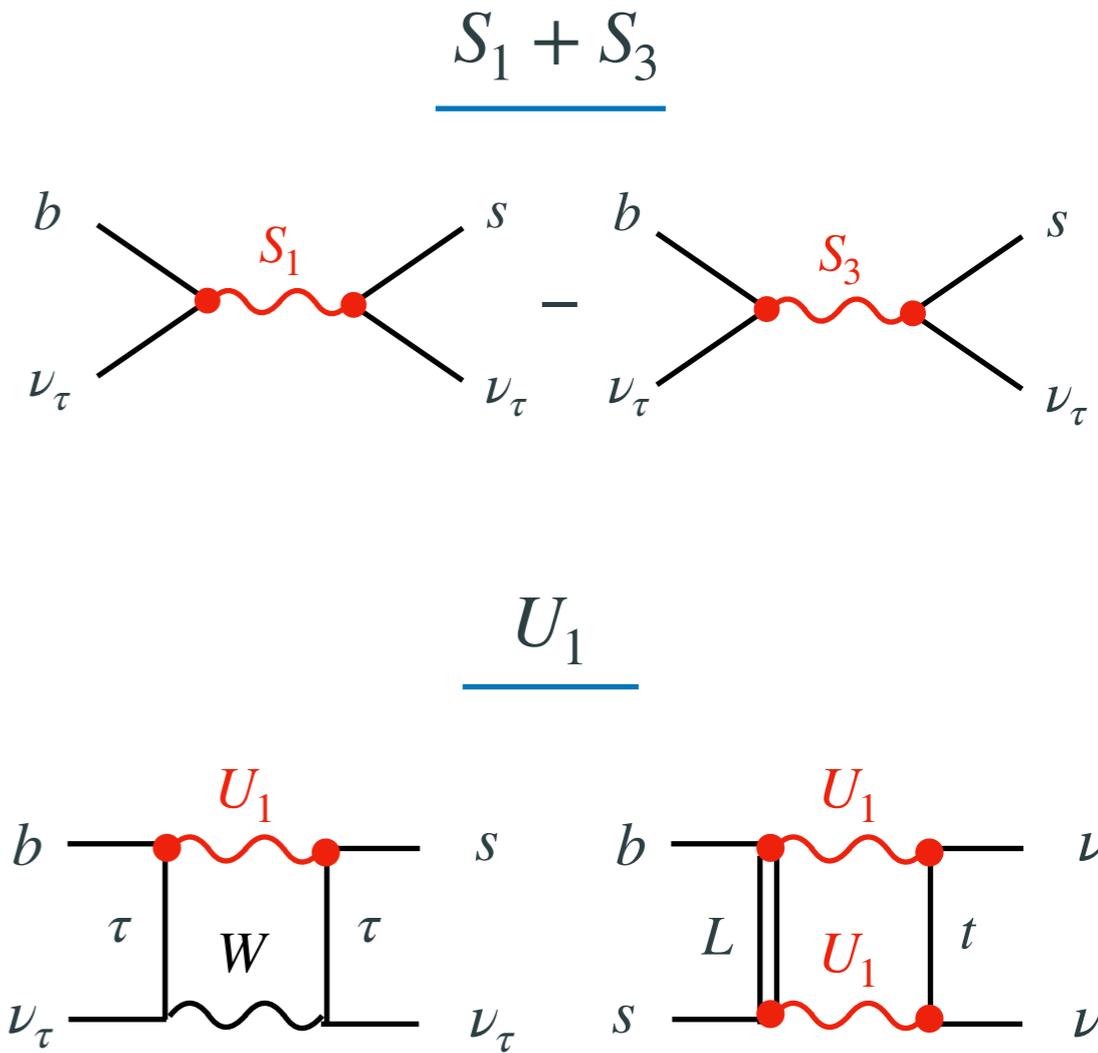


# On the importance of $d_i \rightarrow d_j \nu \bar{\nu}$ observables

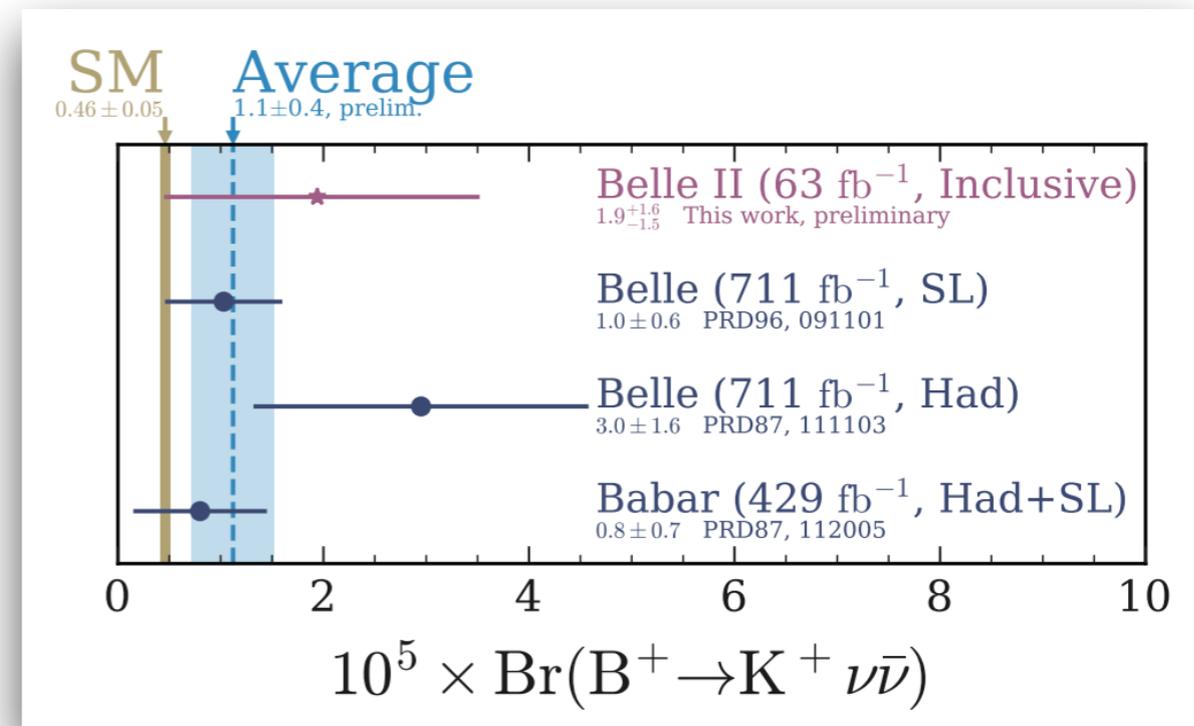
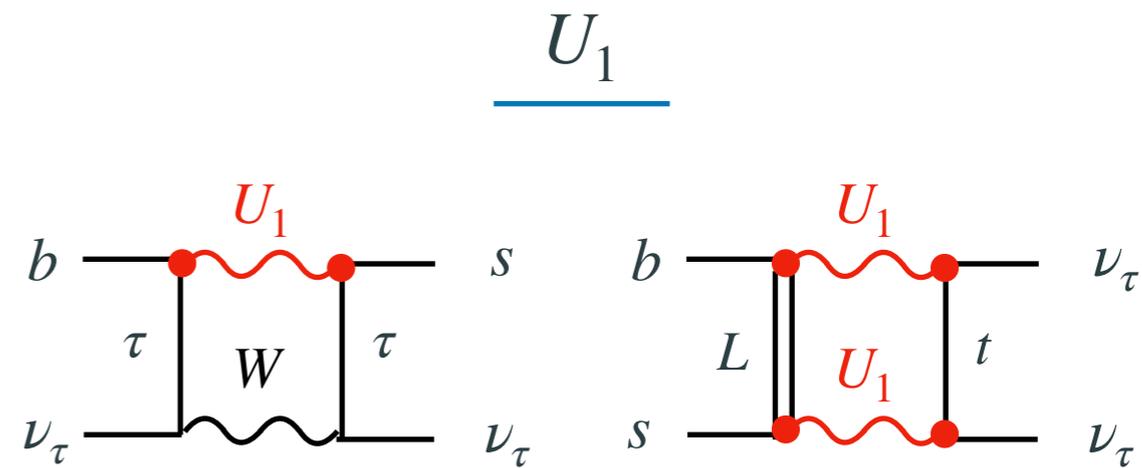
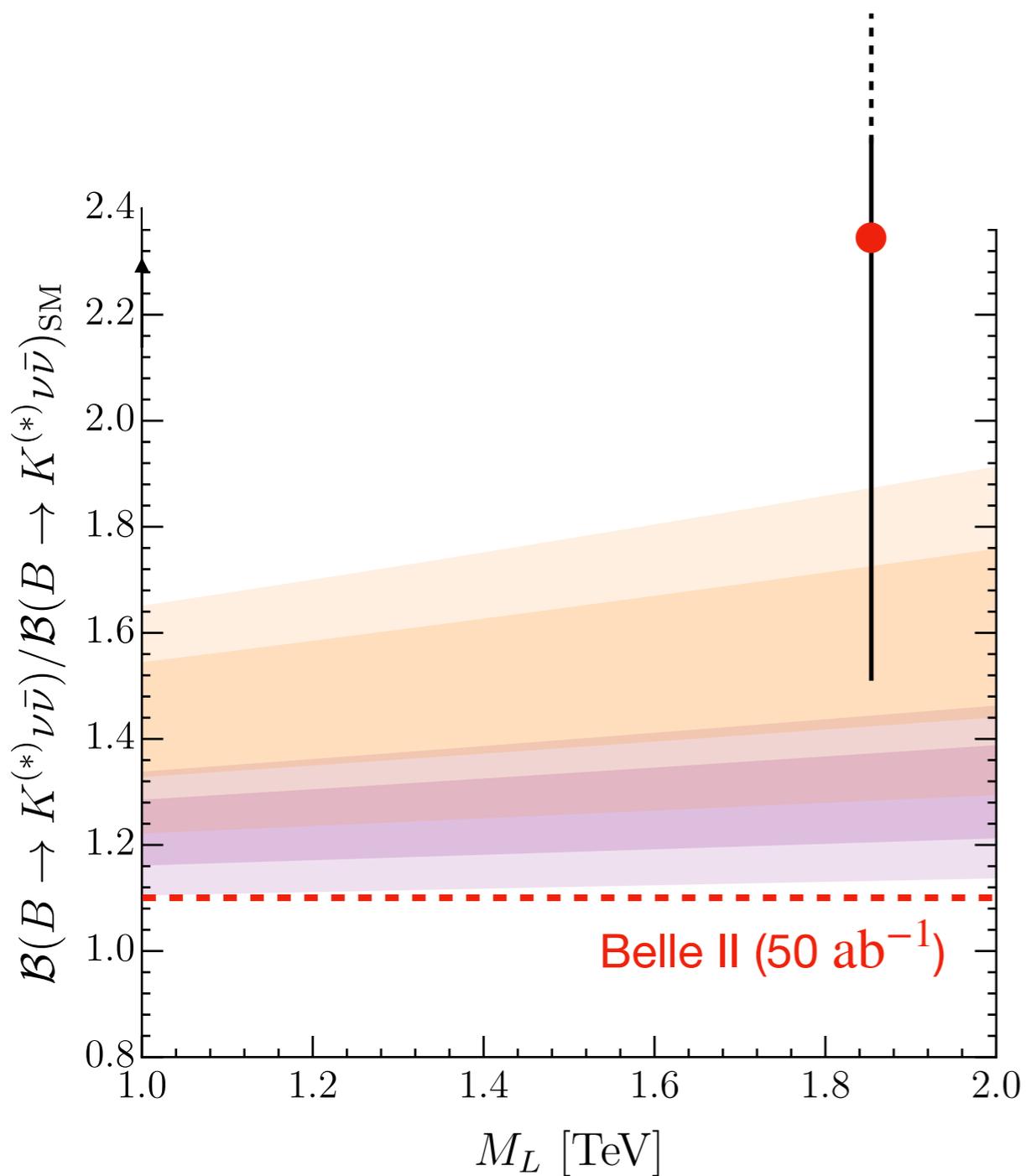


[JFM, Isidori, König, Selimovic, [2009.11296](#)]

$$B \rightarrow K^{(*)} \nu \nu$$



# On the importance of $d_i \rightarrow d_j \nu \bar{\nu}$ observables



[JFM, Isidori, König, Selimovic, [2009.11296](#)]

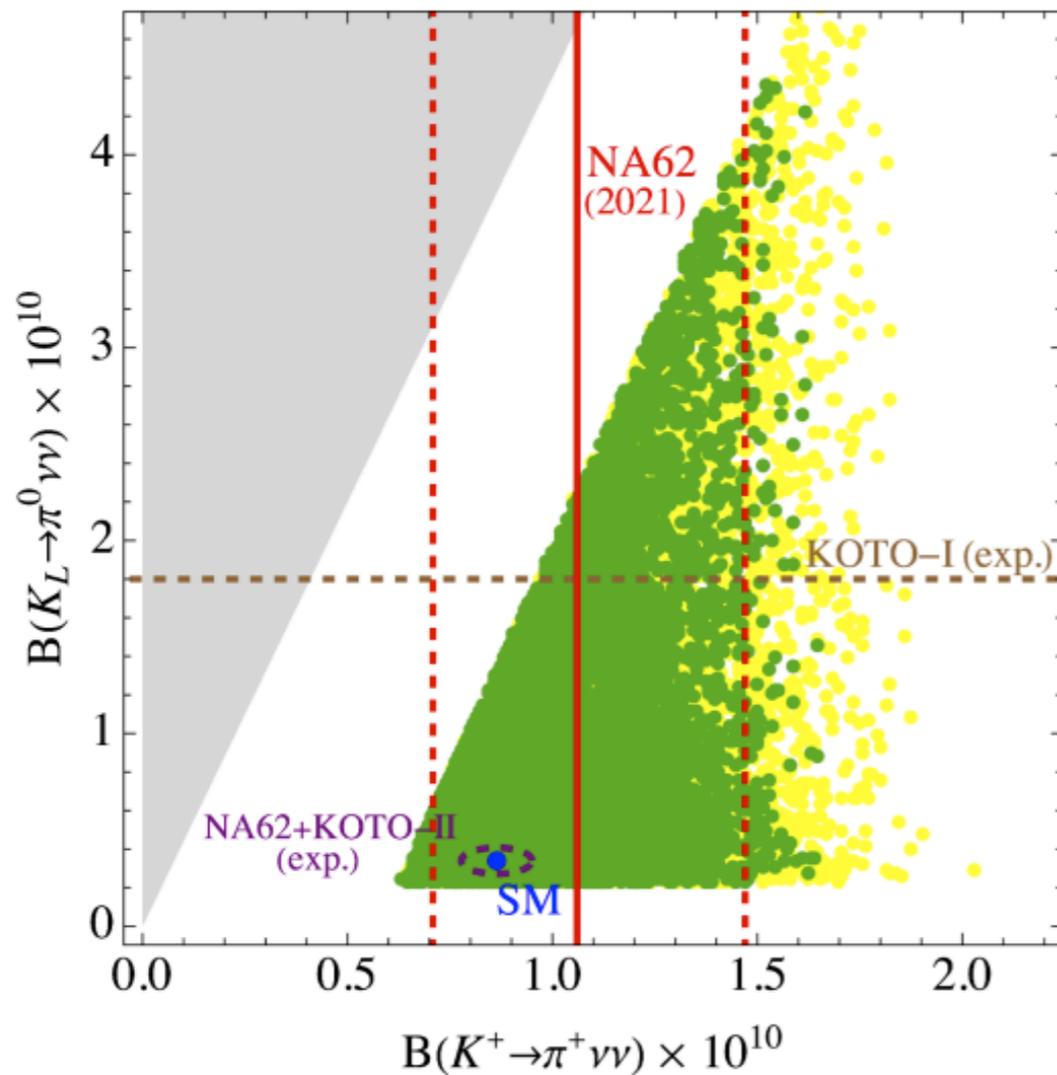
Filippo Dattola (Belle II) @ Moriond EW21

# Predictions for $K \rightarrow \pi \nu \bar{\nu}$

[ See Joseph's and Jacopo's talk ]

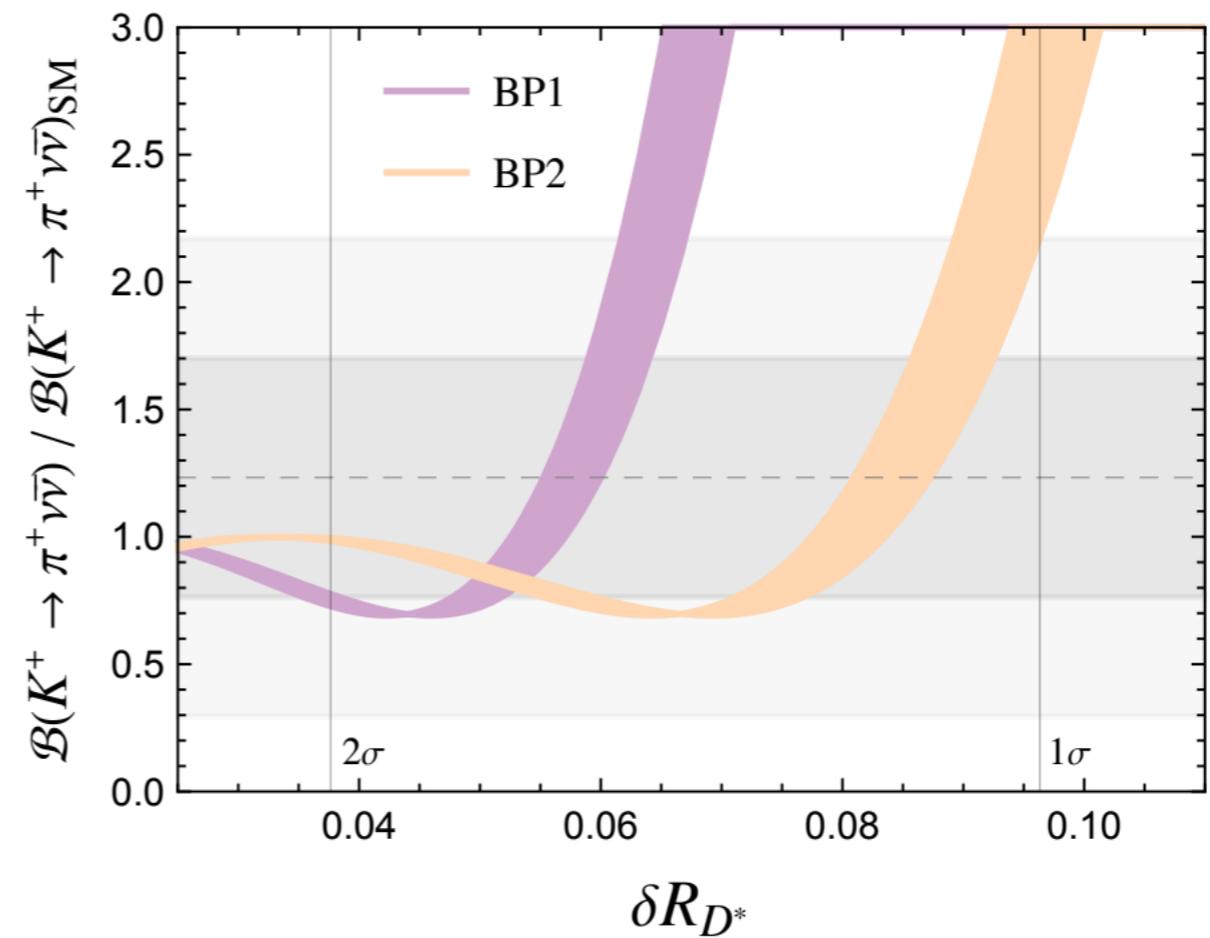
Assuming an specific well-motivated flavor structure: minimally-broken  $U(2)^5$  symmetry

$S_1 + S_3$



[Marzocca, Trifinopoulos, Venturini, [2106.15630](#)]

$U_1$



[Crosas et al, [2207.00018](#)]

# Conclusions

Looking for **violations of SM (approximate) symmetries** can yield crucial information in the quest for new physics

Discrepancies in **B-meson decays** point to **Lepton Flavor Universality Violation (LFUV)**

No experimental indication for **Lepton Flavor Violation (LFV)** so far. However, searches for **LFV** are extremely useful to test different new physics models and flavor structures:

- ▶ In models with flavor misalignment, **LFUV** and **LFV** generically appear together and are related to each other
- ▶ In leptoquark models explaining  $b \rightarrow s\ell\ell$  and  $b \rightarrow c\tau\nu$  anomalies, **LFV** is unavoidable

Experimental studies of  $d_i \rightarrow d_j\nu\bar{\nu}$  decays provide crucial information about the possible underlying new physics and its flavor structure

# Thank you!