FTAE High Energy Theory

ugr Universidad de Granada

Long-term impact of flavor physics in model building

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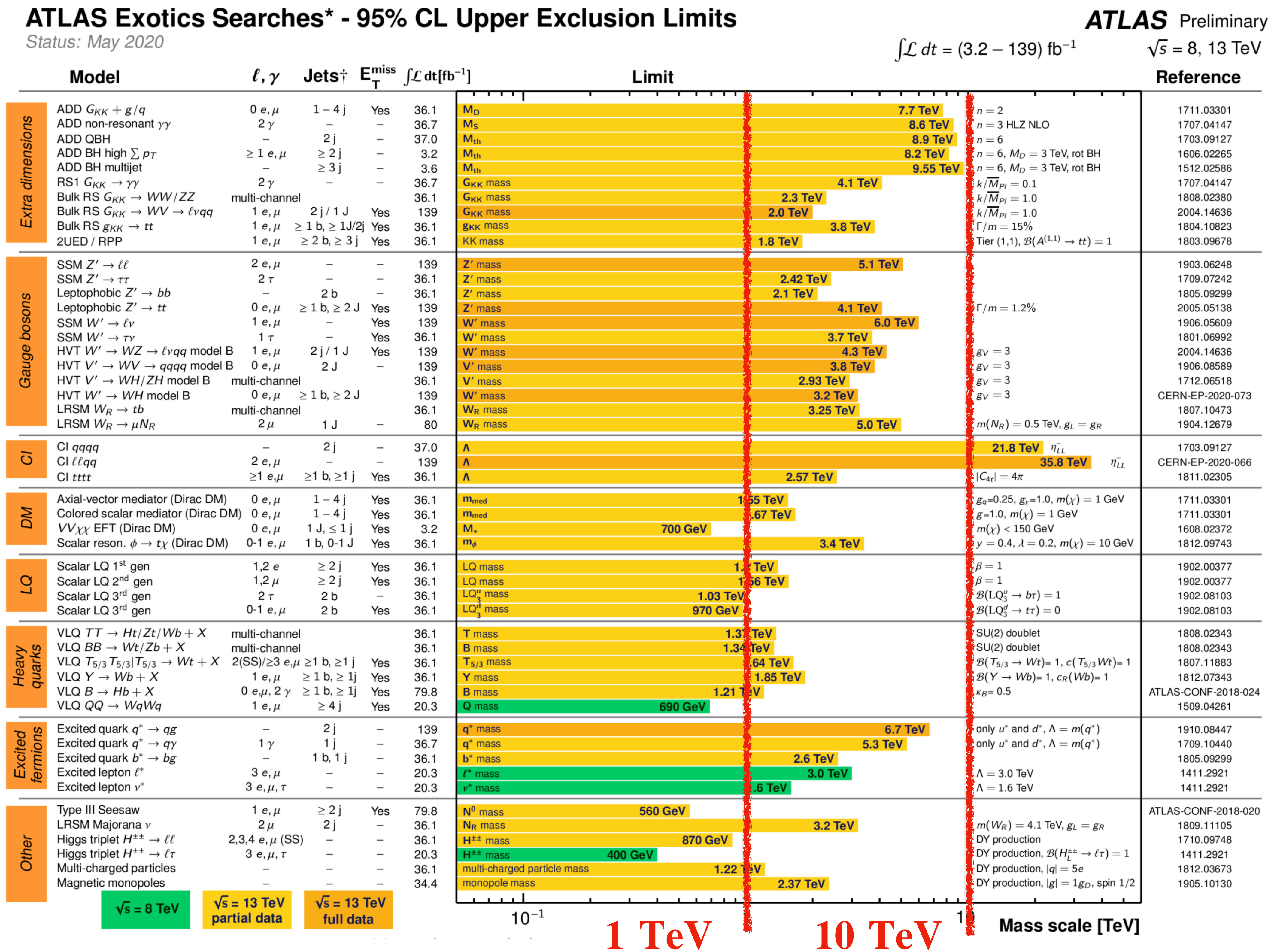
FCC Flavour Physics Programme Workshop

13 September 2022

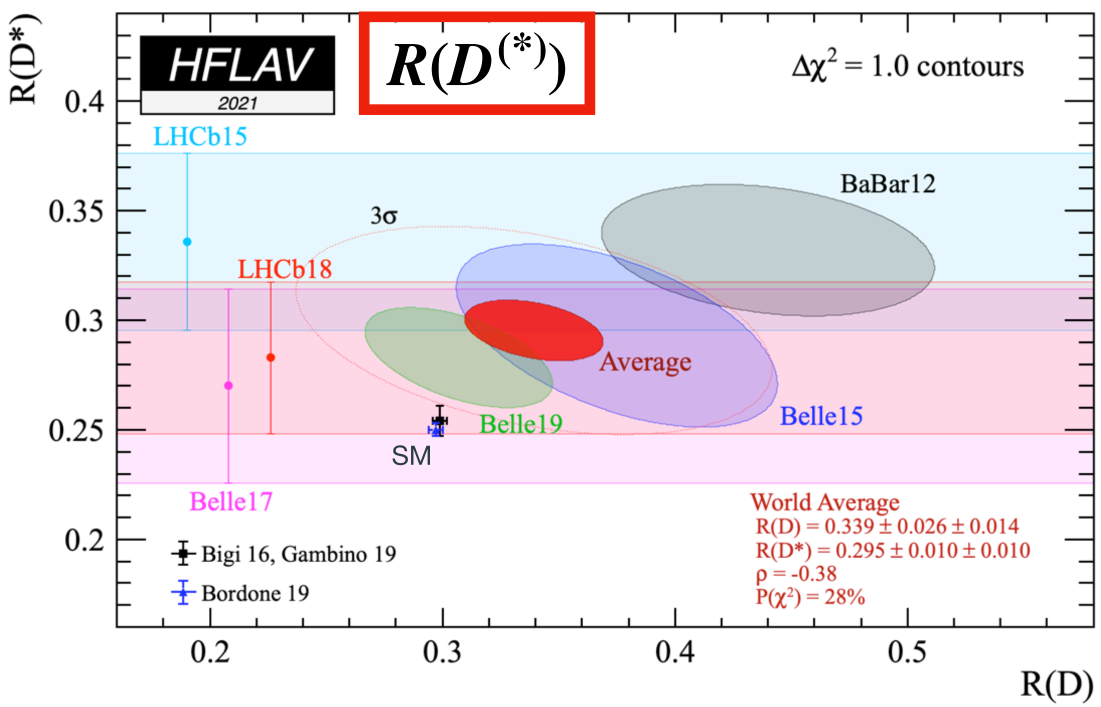
What is experiment telling us?

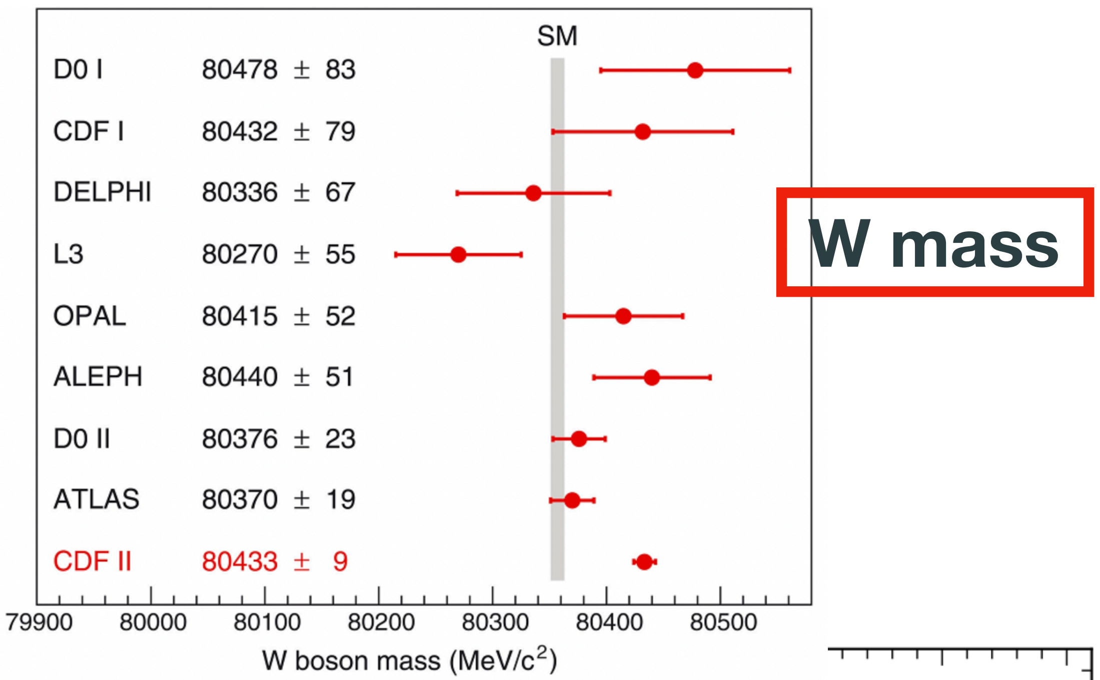
No **direct evidence** for NP despite the many reasons for it [**presence of a mass gap?**]

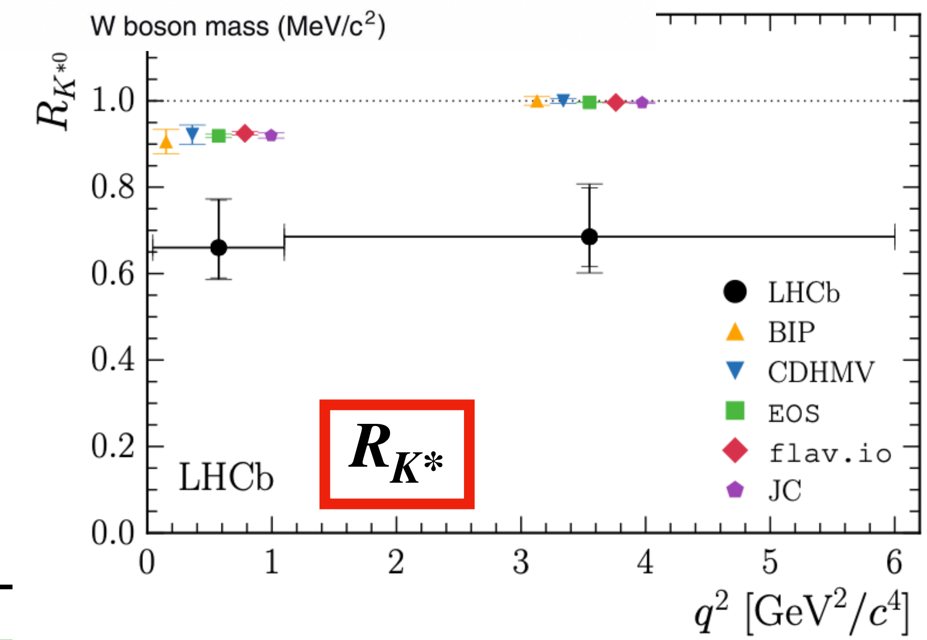


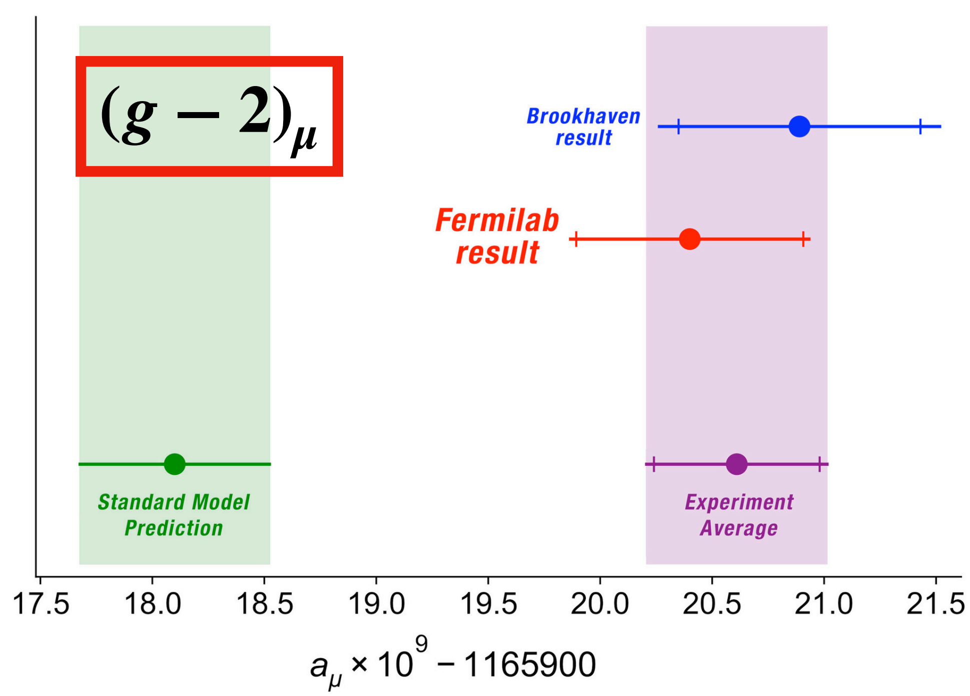
What is experiment telling us?

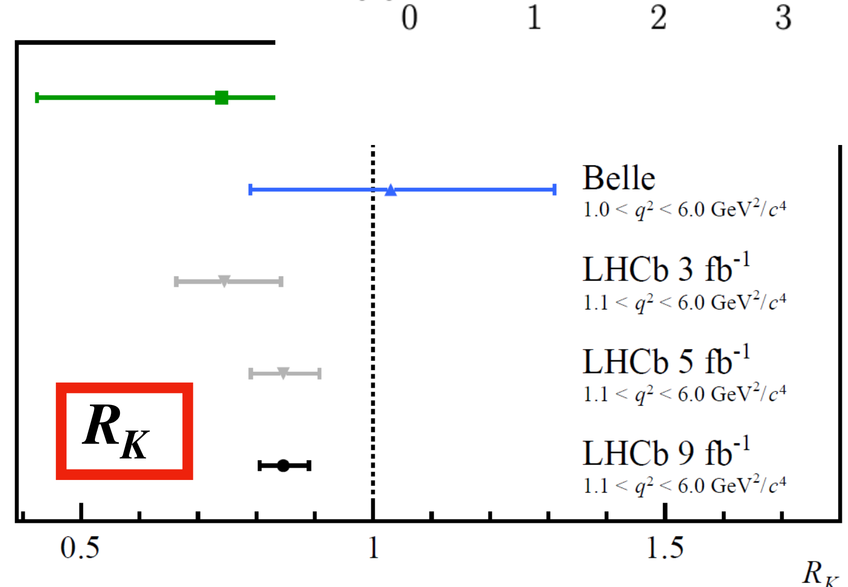
Hints of NP in **low-energy data**?











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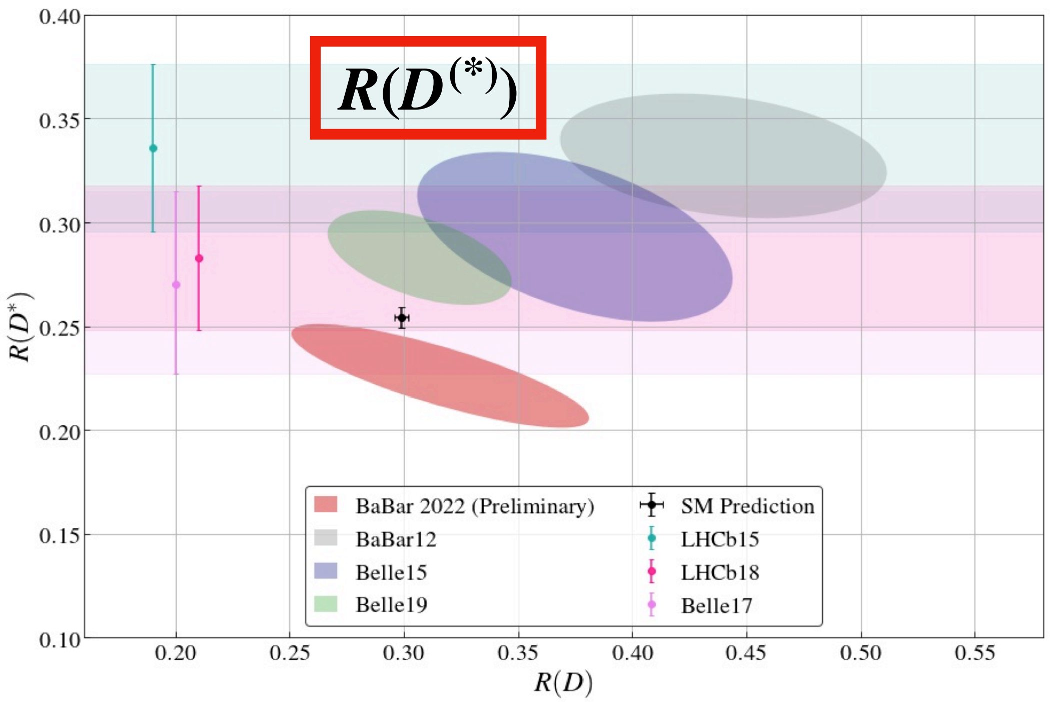
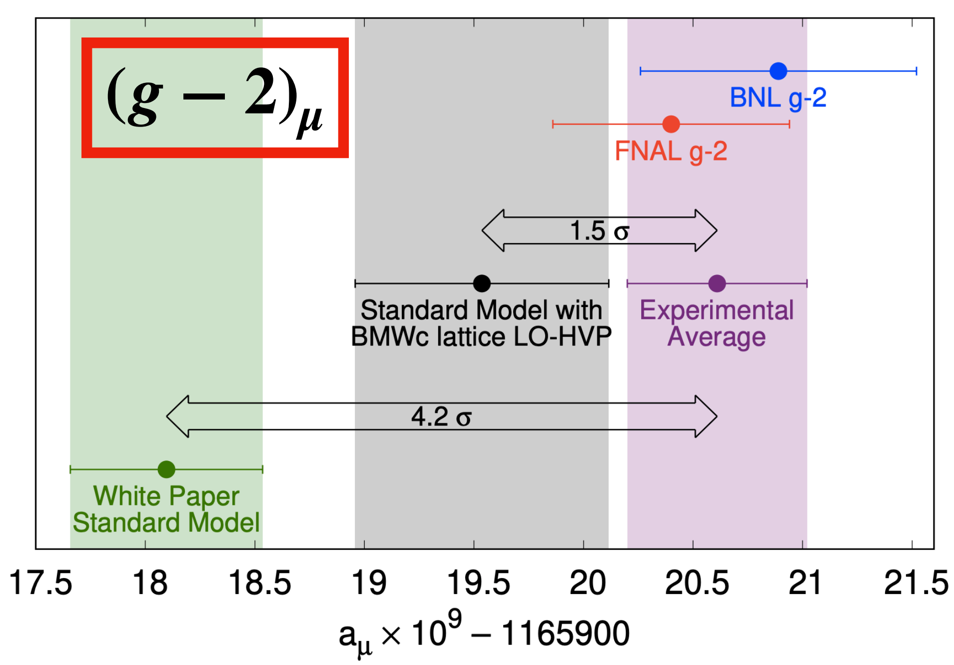
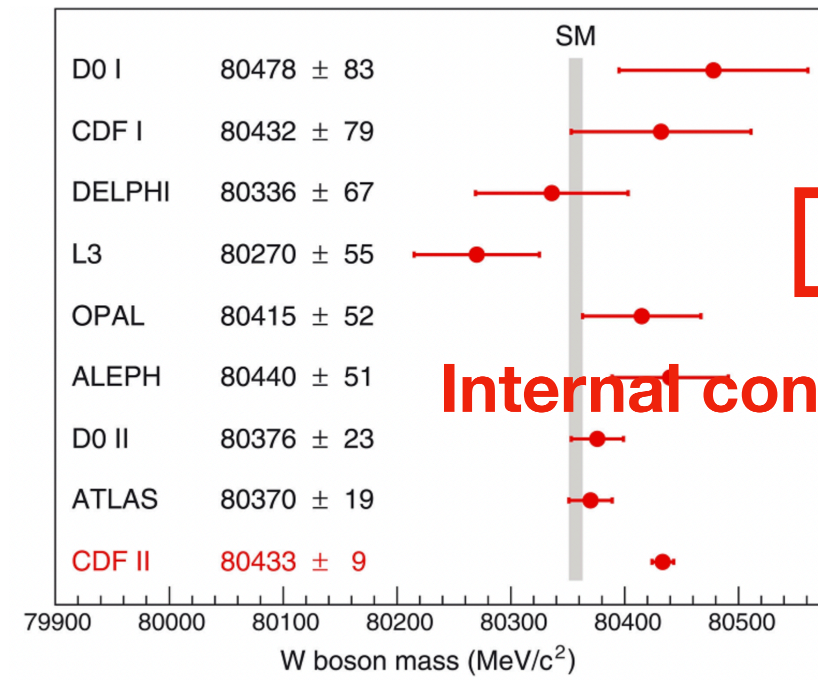
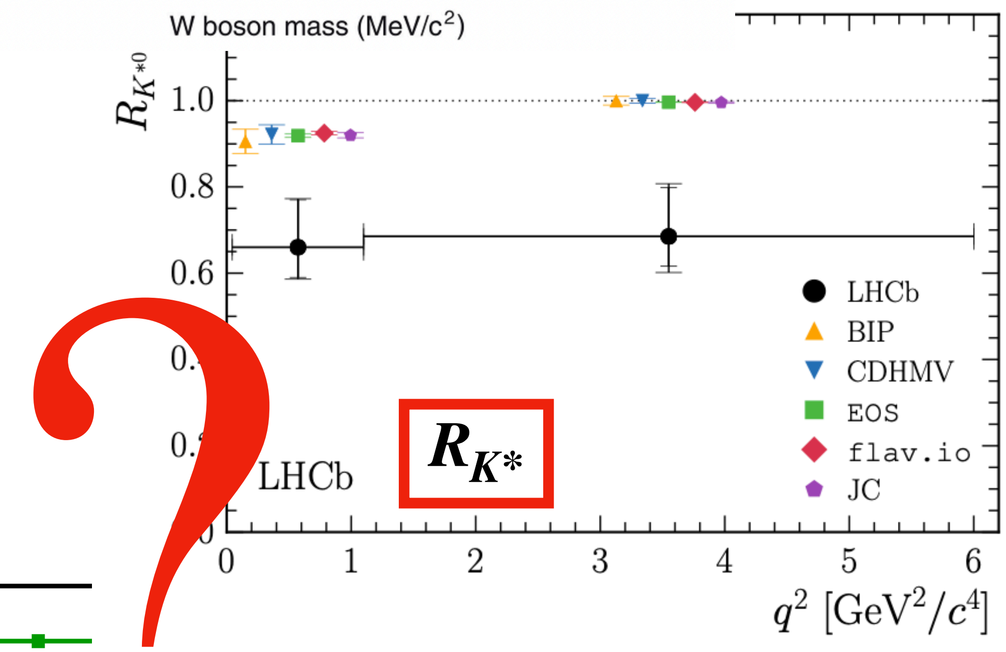


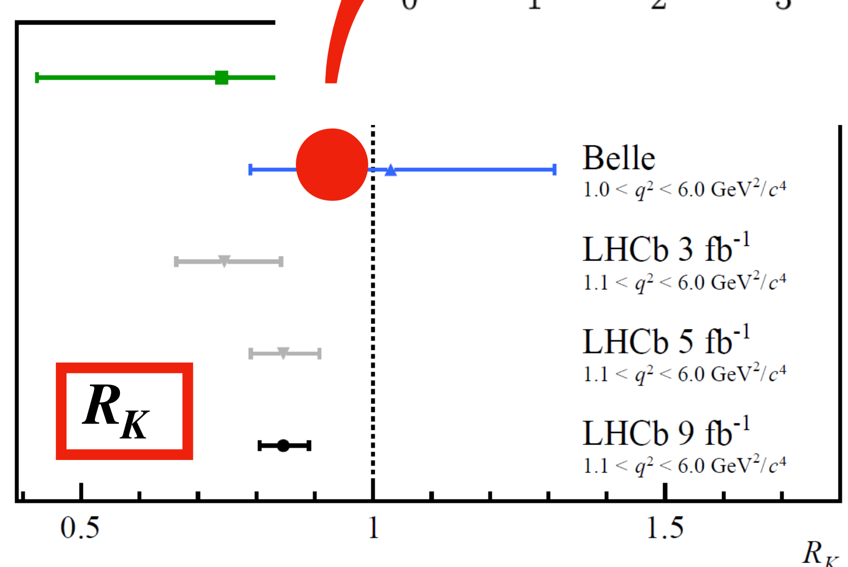




W mass

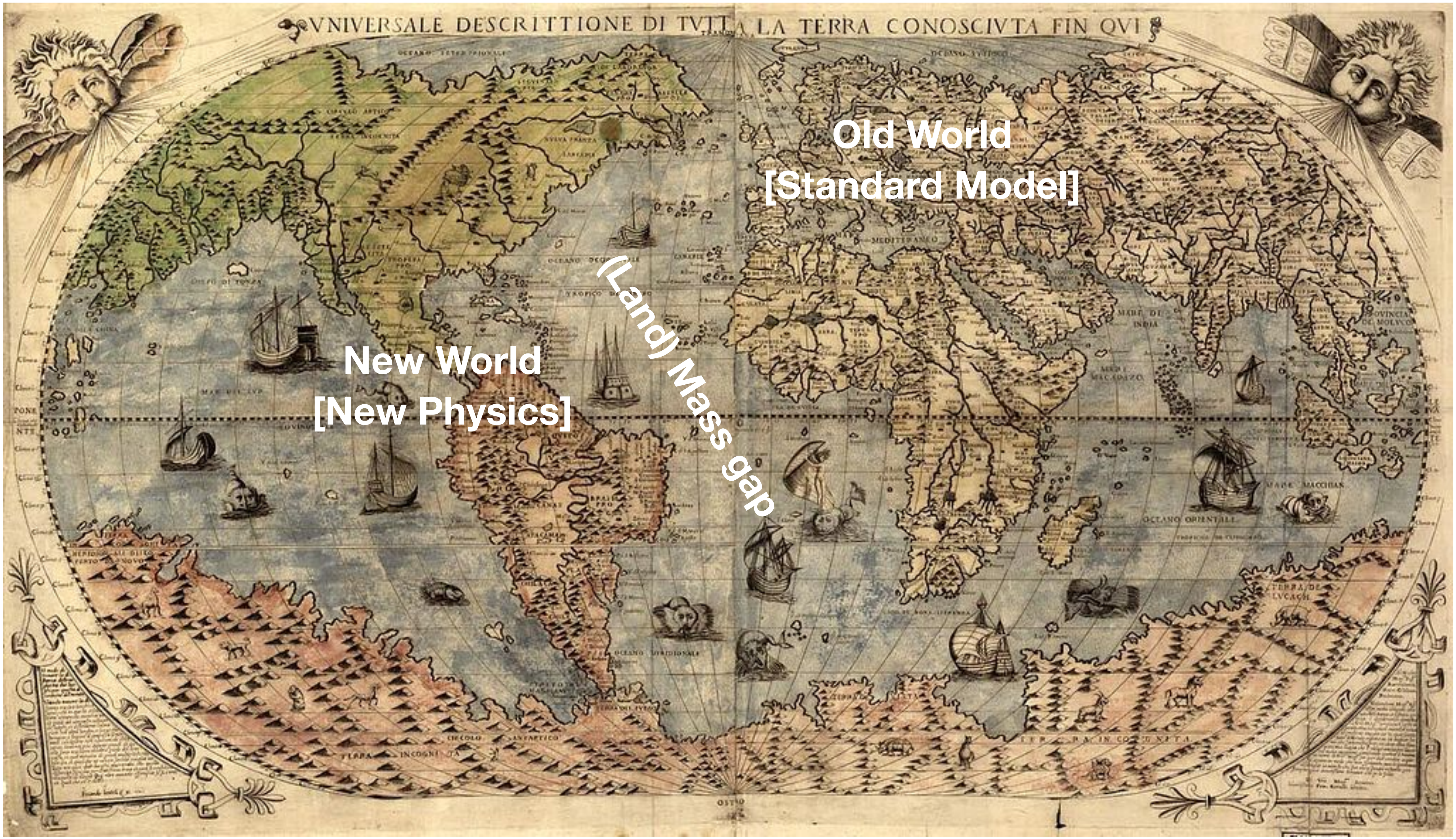
Internal consistency?





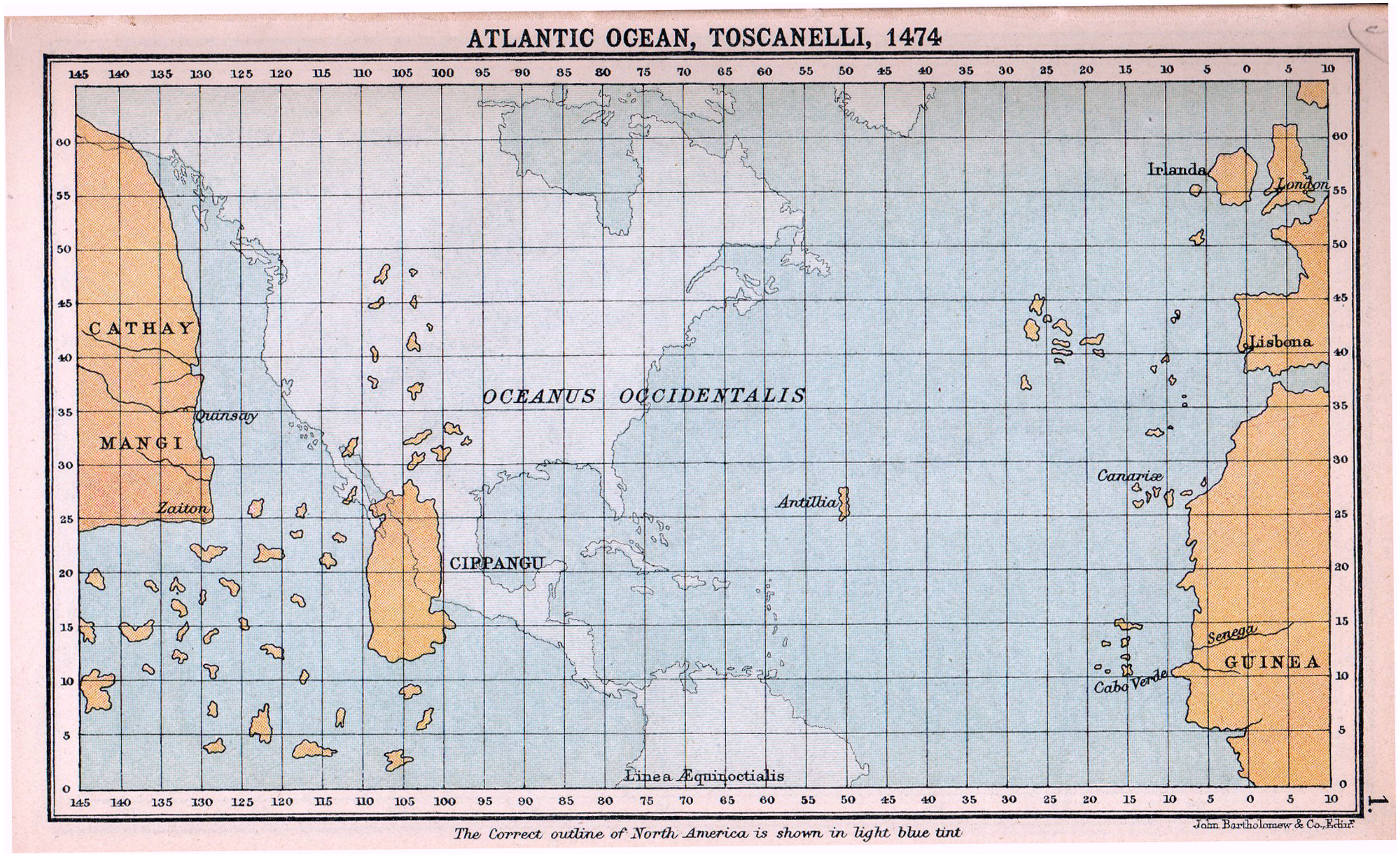
The search for Terra Incognita

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



New Physics Quest: main strategies

N.B.: Cosmological frontier not discussed here



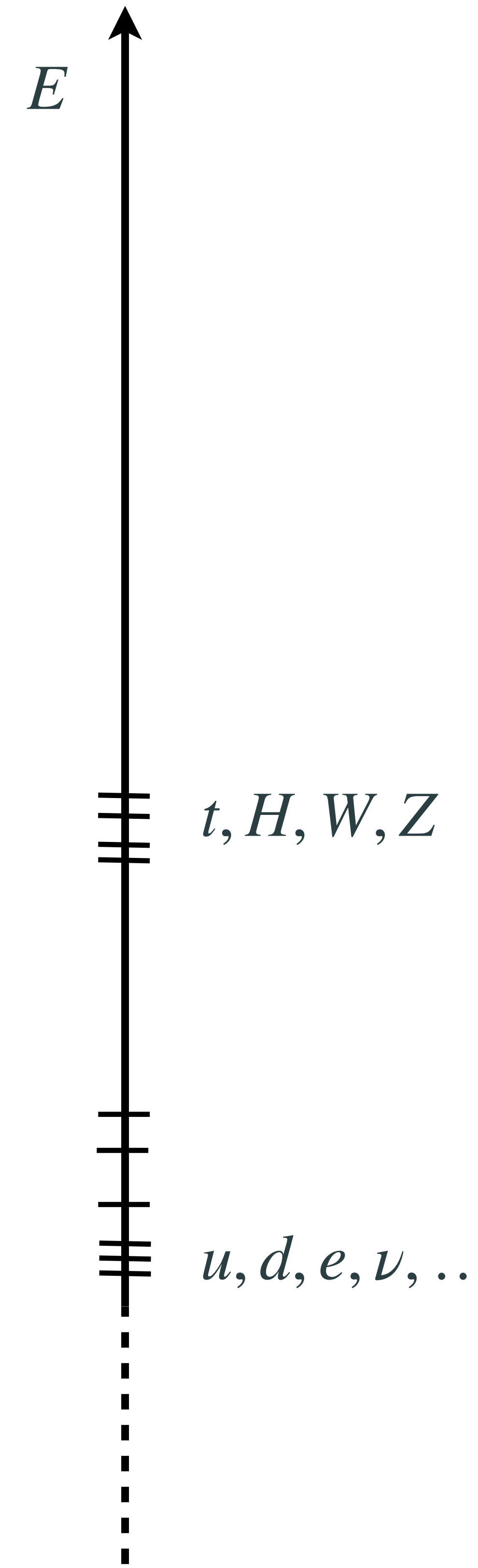
Direct high-energy measurements (ATLAS, CMS, FCC-hh, Muon Collider…):

Simpler interpretation if NP is discovered… but limited reach (the mass gap should not be too large)

Low-energy probes (LHCb, Belle II, FCC-ee…):

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

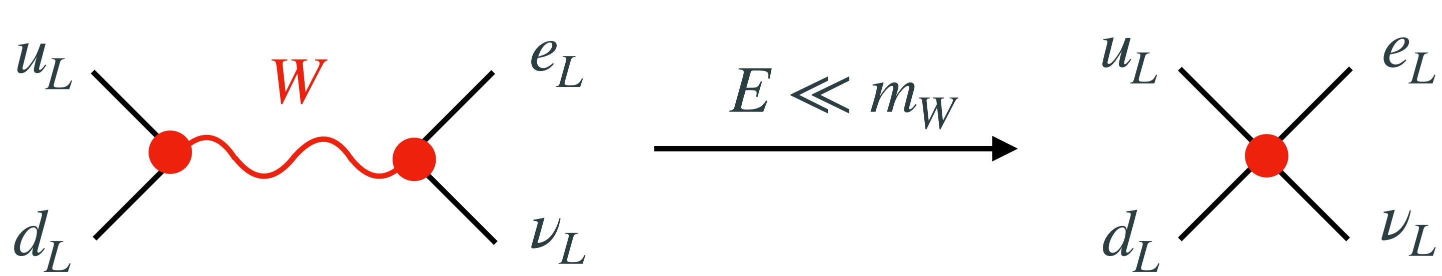
The Fermi theory



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)

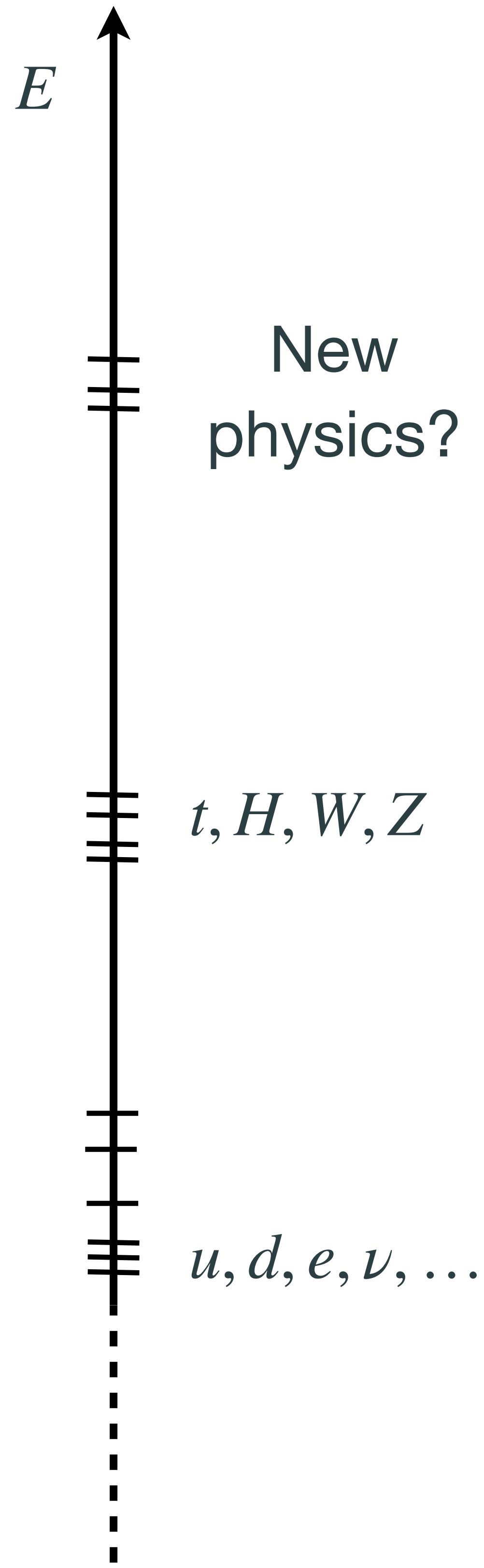
If New Physics (NP) is heavy (mass gap), the SMEFT provides the analog of the Fermi theory for the SM

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

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

- ★ 59 new possible interactions (2499 new flavorful couplings) at $\mathscr{O}(\Lambda^{-2})$
- ★ NP 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 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]

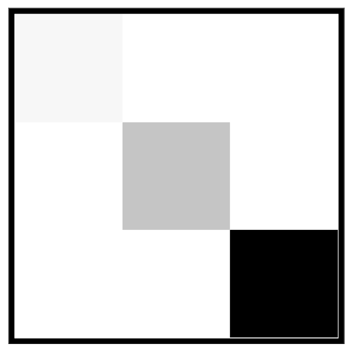
Similar structure also for NP?

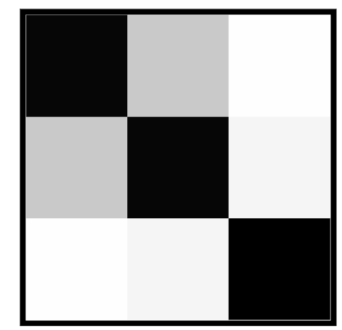
Are these two features correlated?

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

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

$V_{\rm CKM} \sim$ 

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

- 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, minimally broken by 5 (4) *spurions*

$$Y_{u(d)} = y_{t(b)} \begin{pmatrix} \Delta_{u(d)} & x_{t(b)} V_q \\ 0 & 1 \end{pmatrix}$$

$U(2)_q$ (row), $U(2)_{u(d)}$ (column)

$$Y_e = y_\tau \begin{pmatrix} \Delta_e & x_\tau V_\ell \\ 0 & 1 \end{pmatrix}$$

$U(2)_\ell$ (row), $U(2)_e$ (column)

$$|V_q| \sim V_{cb}$$

$$|\Delta_u| \sim y_c$$

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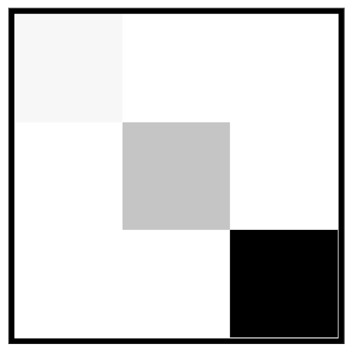
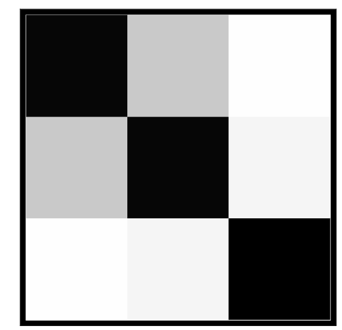
$M_{u,d,e} \sim$ 

$V_{\rm CKM} \sim$ 

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- Lepton Flavor Universality [$U(3)_\ell \times U(3)_e$] is a good *approximate* symmetry ($Y_{e,\mu,\tau} \ll g_{s,L,Y}$)
- Baryon number is *exactly* preserved
- Individual lepton flavor *extremely well* preserved (exact for massless neutrinos)
  $U(1)_e \times U(1)_\mu \times U(1)_\tau$

LFV $\Longrightarrow$ / $\not\Longleftarrow$ ~~LFU~~

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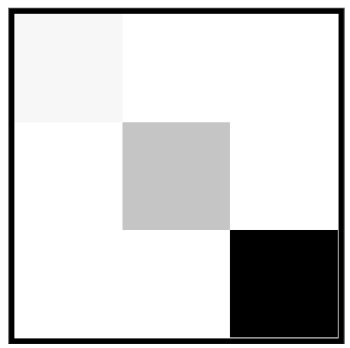
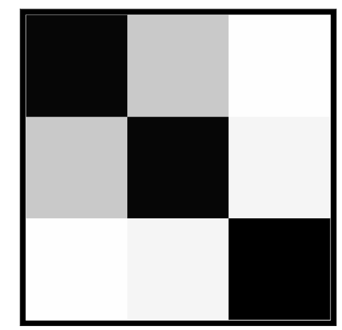
$M_{u,d,e} \sim$ 

$V_{\rm CKM} \sim$ 

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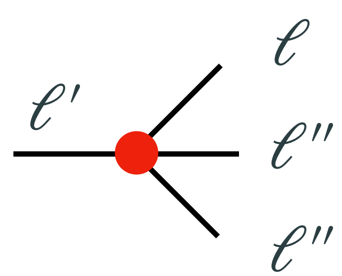
What is the origin of these symmetries? Will new physics respect any of them?

The new physics flavor problem

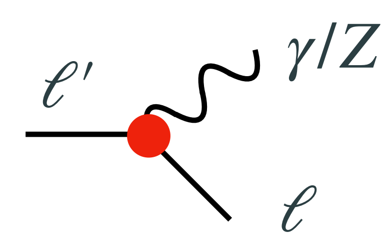
$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{Gauge}} + \mathscr{L}_{\text{Higgs}} + \mathscr{L}_{\text{Yukawa}} + \sum_{i,d} \frac{1}{\Lambda_i^{d-4}} C_i \mathcal{O}_i^d$$

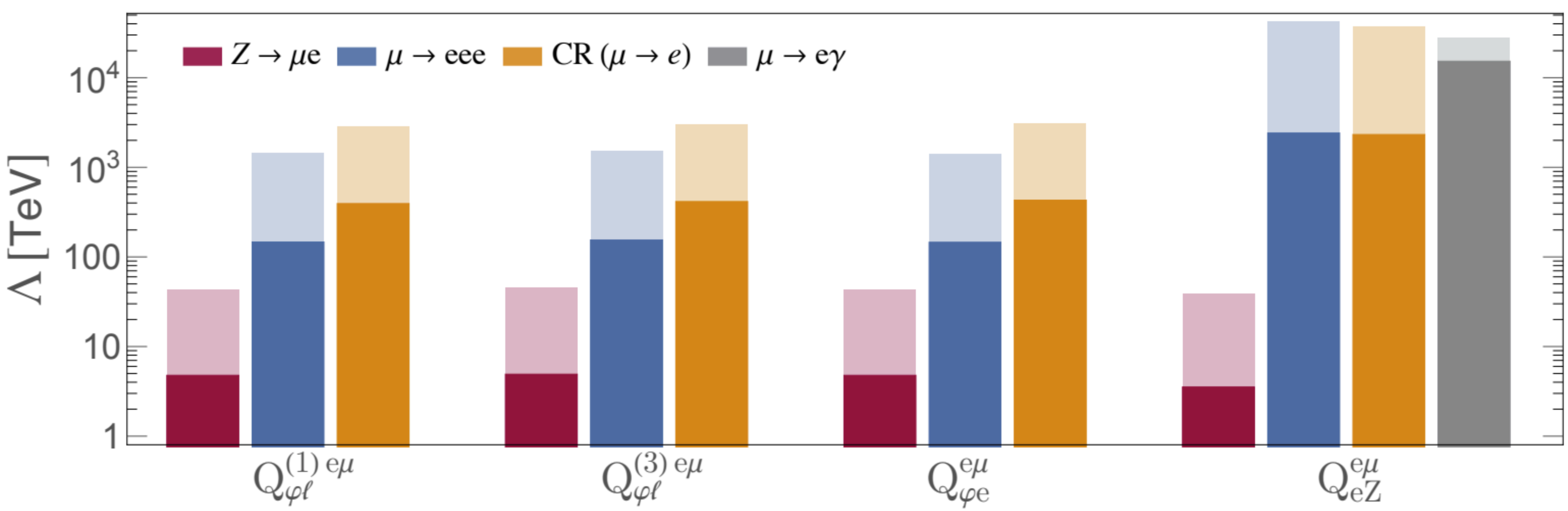
Very stringent bounds on the new physics scale if it has a generic flavor structure (far too heavy to be directly probed or to stabilize the Higgs)

$$\frac{1}{\Lambda^2}(\bar{\ell}_i \ell_j)^2$$



$$\frac{1}{\Lambda^2} F_{\mu\nu}(\bar{\ell}_i \sigma^{\mu\nu} H \ell_j)$$





[Calibbi, Marcano, Roy, 2107.10273]

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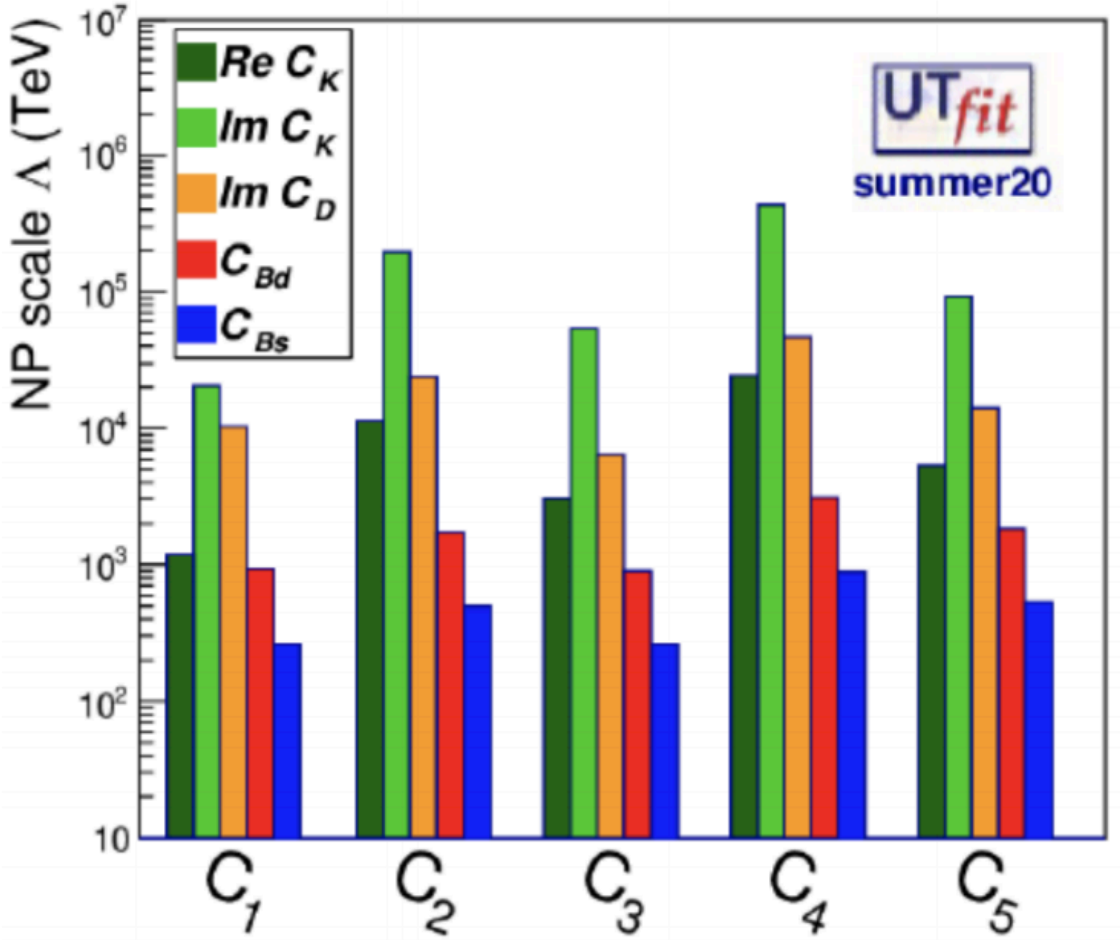
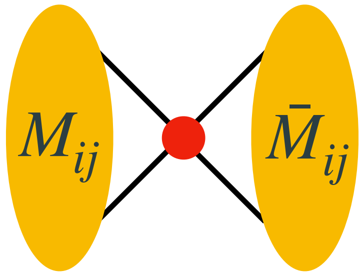


$$\frac{1}{\Lambda^2} (\bar{q}_i \, q_j)^2$$



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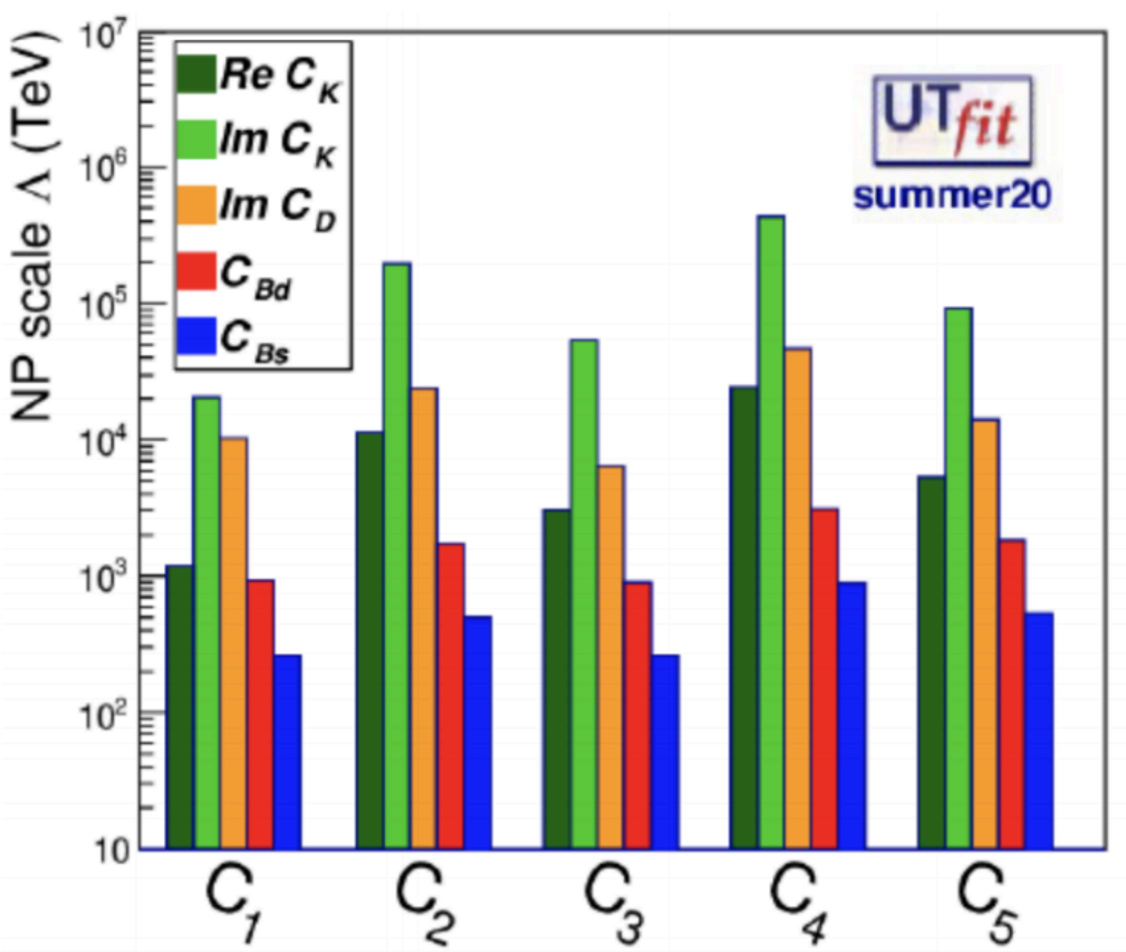
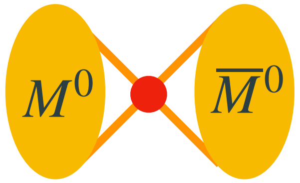
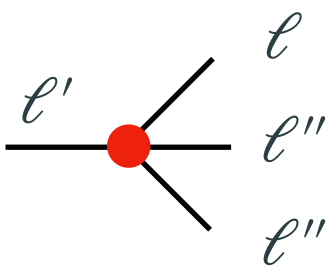


$$\frac{1}{\Lambda^2}(\psi_i\psi_j)^2$$





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 specific** and possibly connected to the origin of the Yukawa hierarchies [perhaps $U(2)$-like ?]

Flavor model building

Explain (some of) the peculiar flavor patterns with/without the light Higgs mass

- Froggatt-Nielsen

  Froggatt:1978nt, hep-ph/9212278, hep-ph/9310320, 1909.05336, 1907.10063, 2009.05587, 2002.04623, 2010.03297...

- (Gauged) flavor symmetries

  hep-ph/9512388, hep-ph/9507462, 1009.2049, 1105.2296, 1505.03862, 1609.05902, 1611.02703, 1807.03285, 1805.07341, 2201.07245...

- Radiative masses

  Weinberg:1972ws, hep-ph/9601262, 1409.2522, 2001.06582, 2012.10458...

- Clockwork flavor

  1610.07962, 1711.05393, 1807.09792, 2106.09869...

- Warped extra dimensions

  hep-ph/9905221, hep-ph/9903417, hep-ph/0003129, hep-ph/ 9912408, hep-ph/0408134, 0903.2415, 1004.2037, 1509.02539, 2203.01952...

- Partial compositeness

  hep-ph/030625, 0804.1954, 1404.7137, 1506.01961, 1506.00623, 1607.01659, 1908.09312, 1911.05454...

- Multi-scale flavor

  1603.06609, 1712.01368, 2011.01946, 2203.01952...

- …

Multi-scale solution of the flavor problem/puzzle

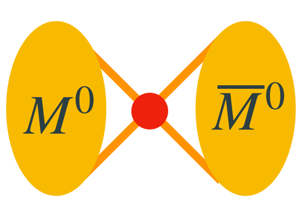
$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{Gauge}} + \mathscr{L}_{\mathrm{Higgs}} + \mathscr{L}_{\mathrm{Yukawa}} + \sum_{i,d} \frac{1}{\Lambda_i^{d-4}} C_i\, \mathcal{O}_i^d$$

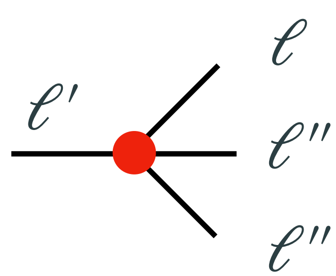
Non-trivial UV imprints

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

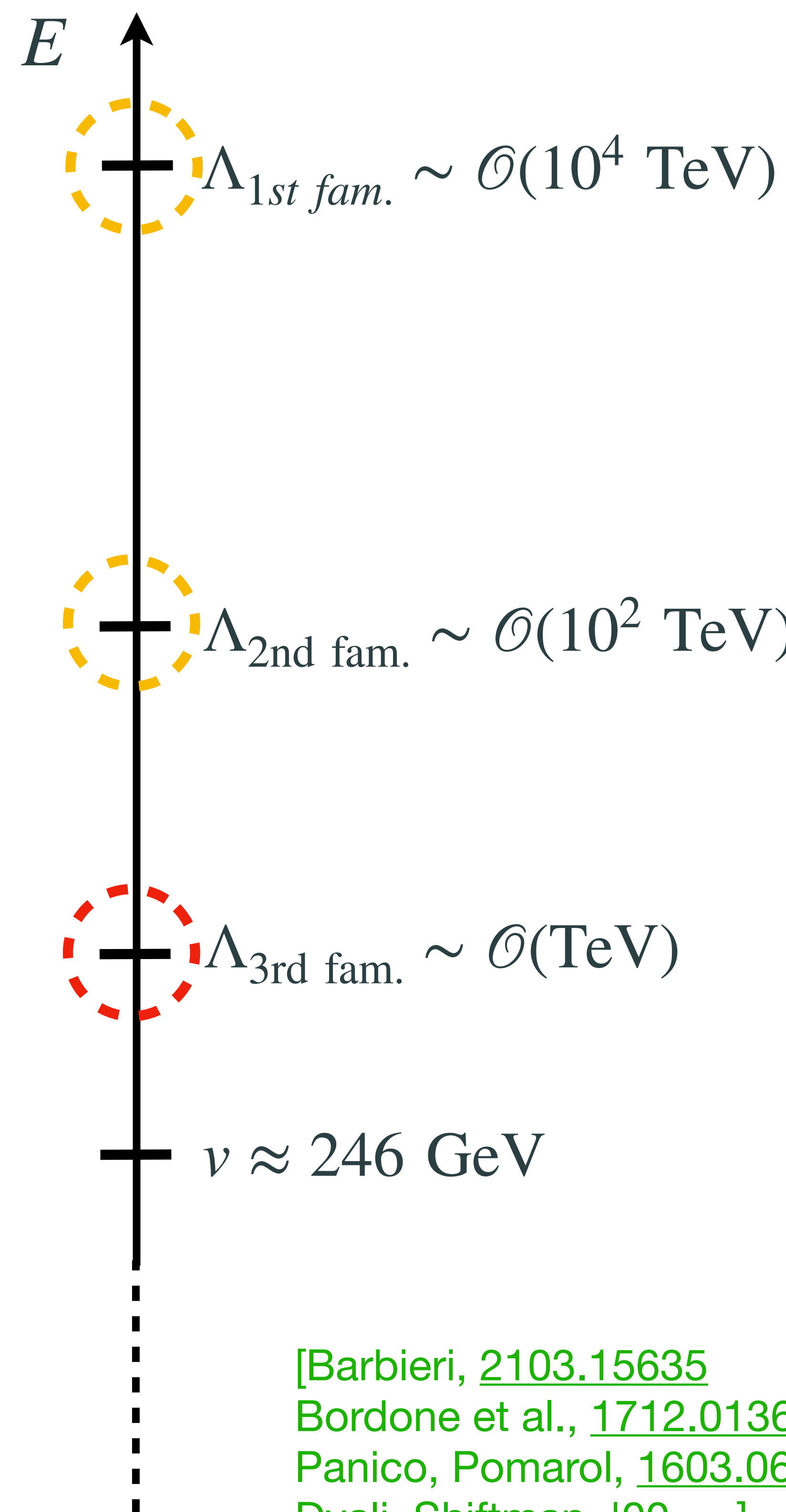
★ TeV-scale NP dominantly coupled to third family [protection from flavor constraints]

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 et al., 1712.01368
Panico, Pomarol, 1603.06609
Dvali, Shiftman, '00, …]

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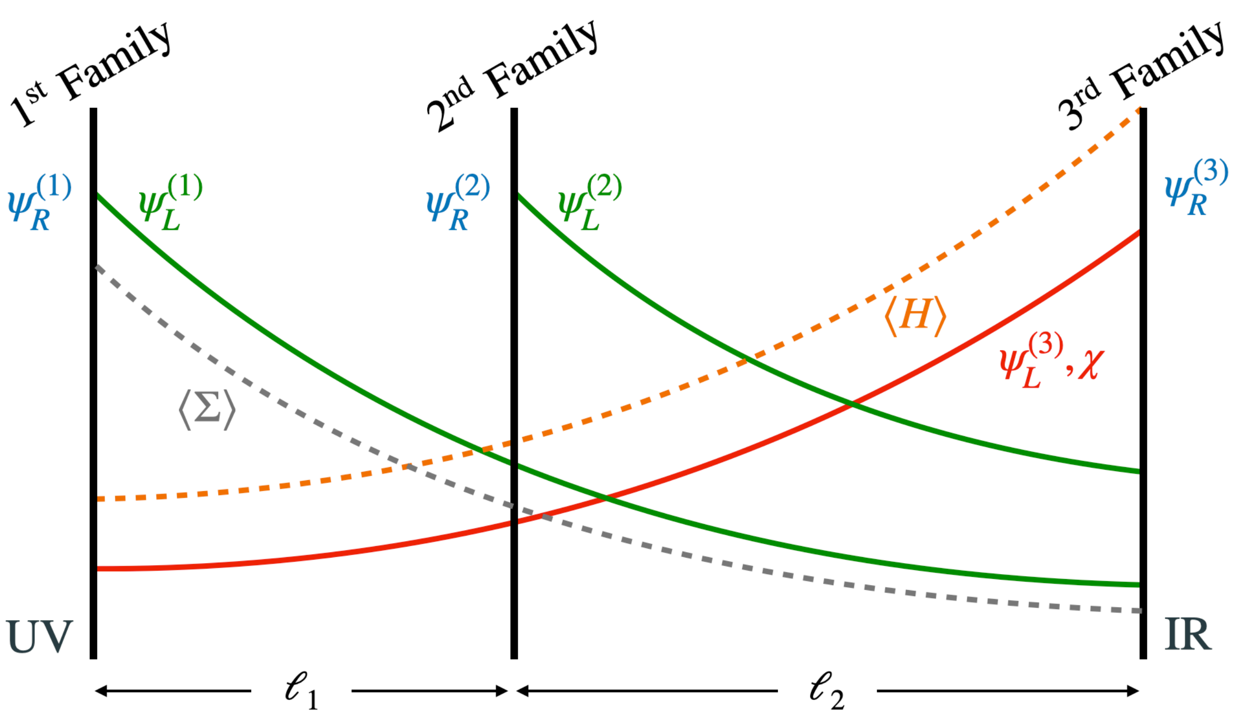
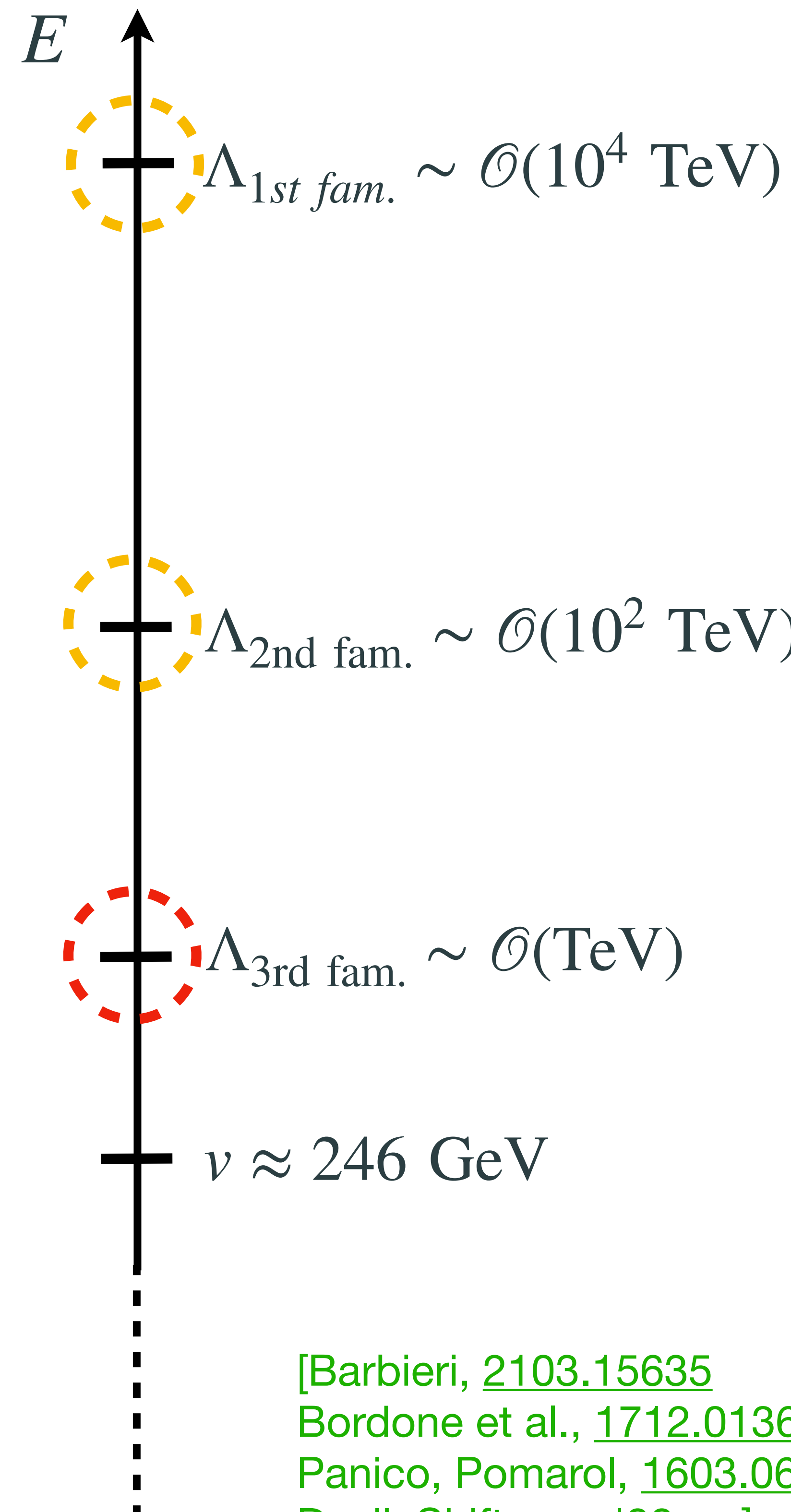


$\Longleftrightarrow$



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, …]

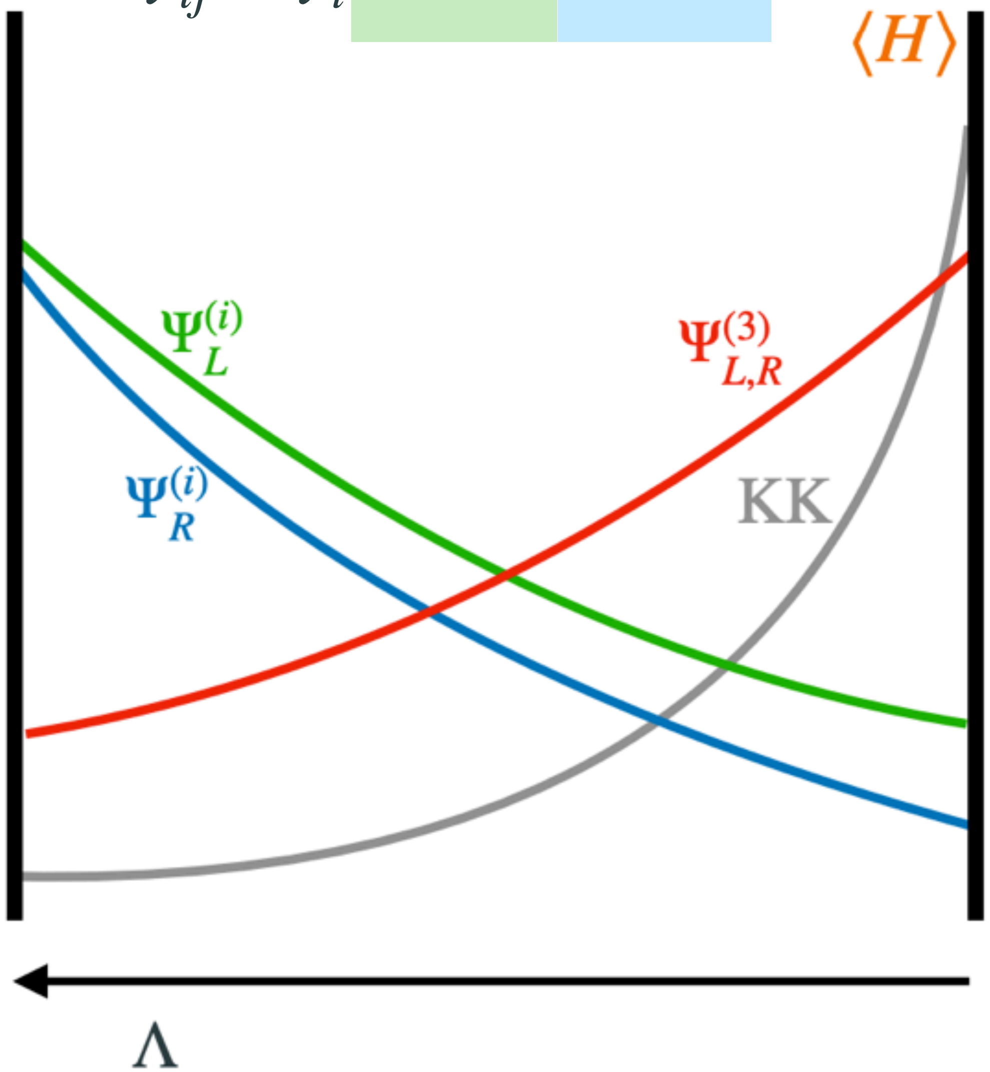
Flavor in Randall-Sundrum

Curvature of the AdS slice

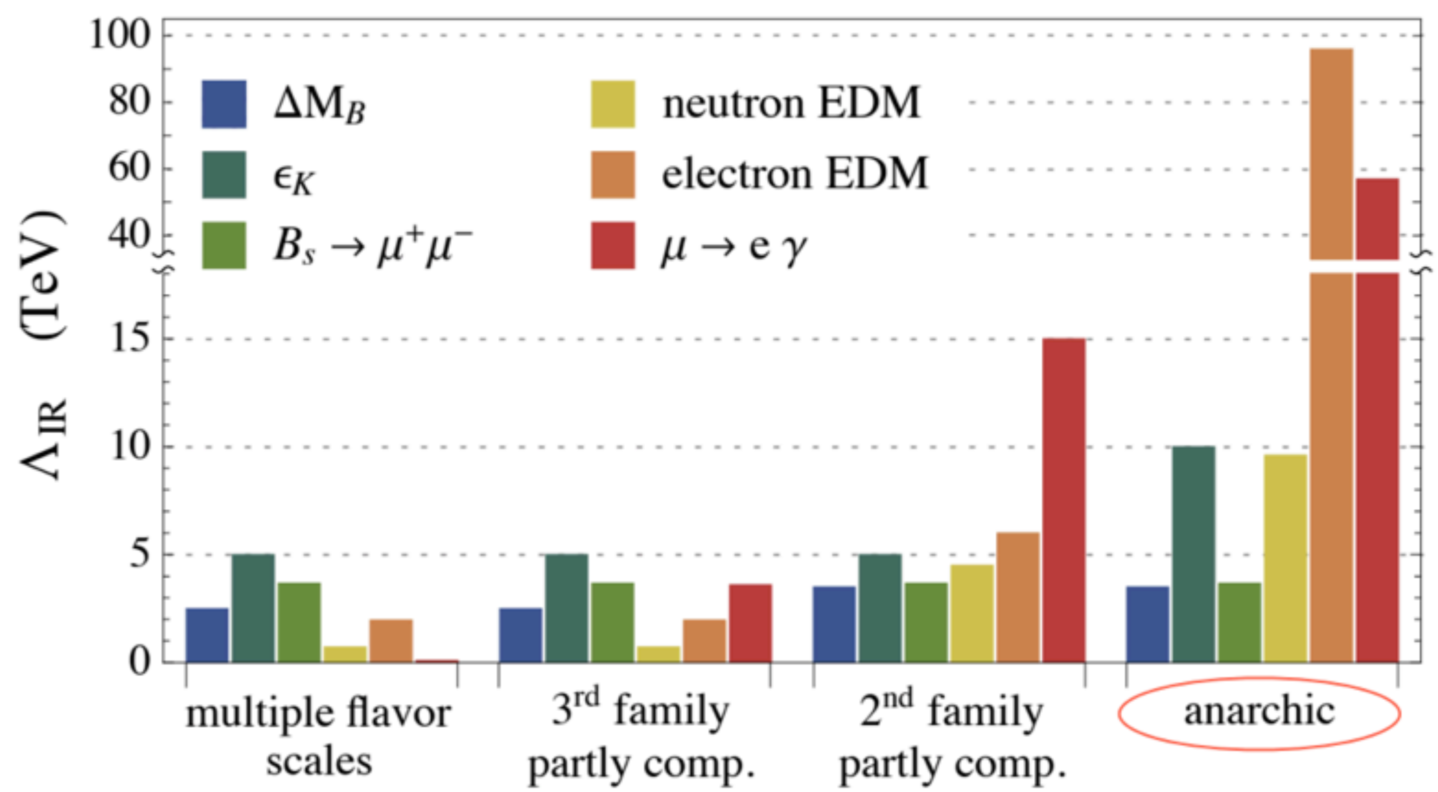
Warped 5D geometry (RS): $ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$

- 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]

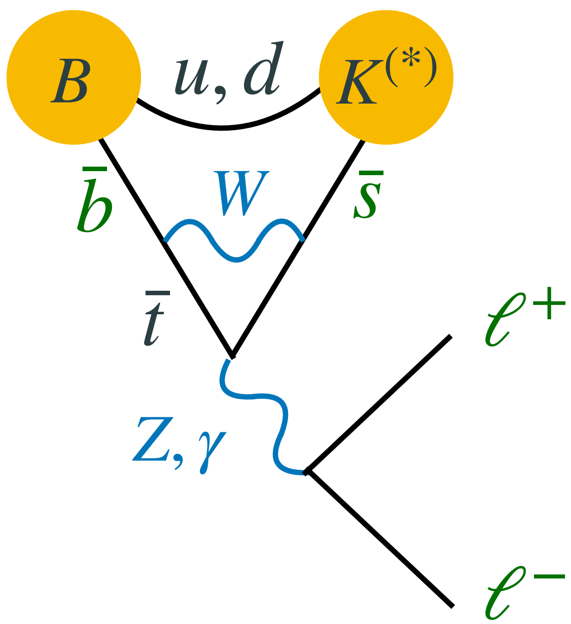
A model builder's look into the current experimental situation

The B anomalies

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

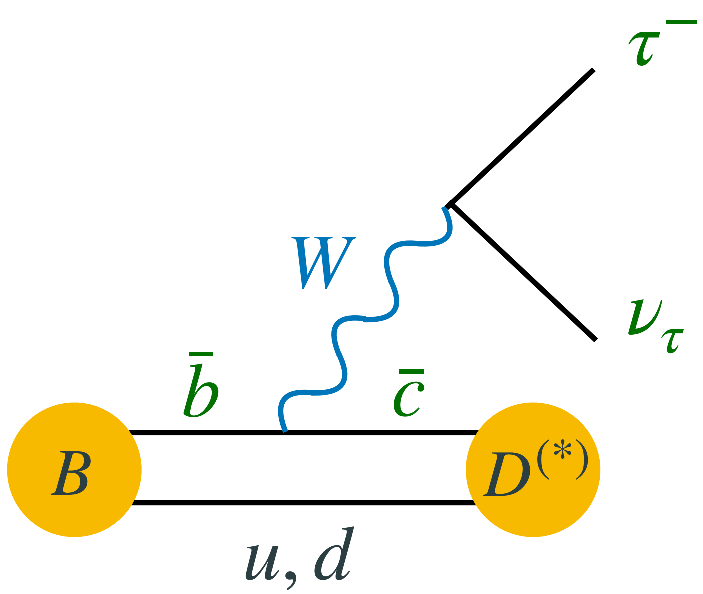
$b \to s\ell^+\ell^-$

μ/e ~~universality~~



$b \to c\tau\nu$

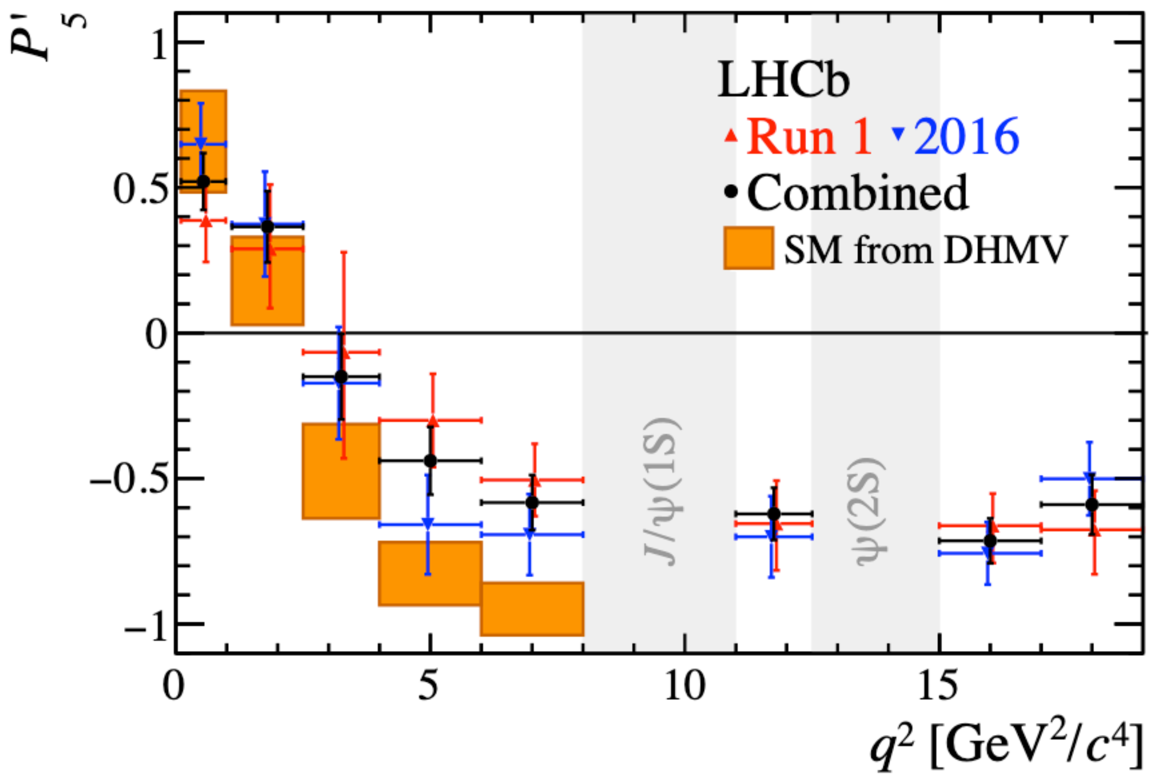
$\tau/\mu\,,e$ ~~universality~~

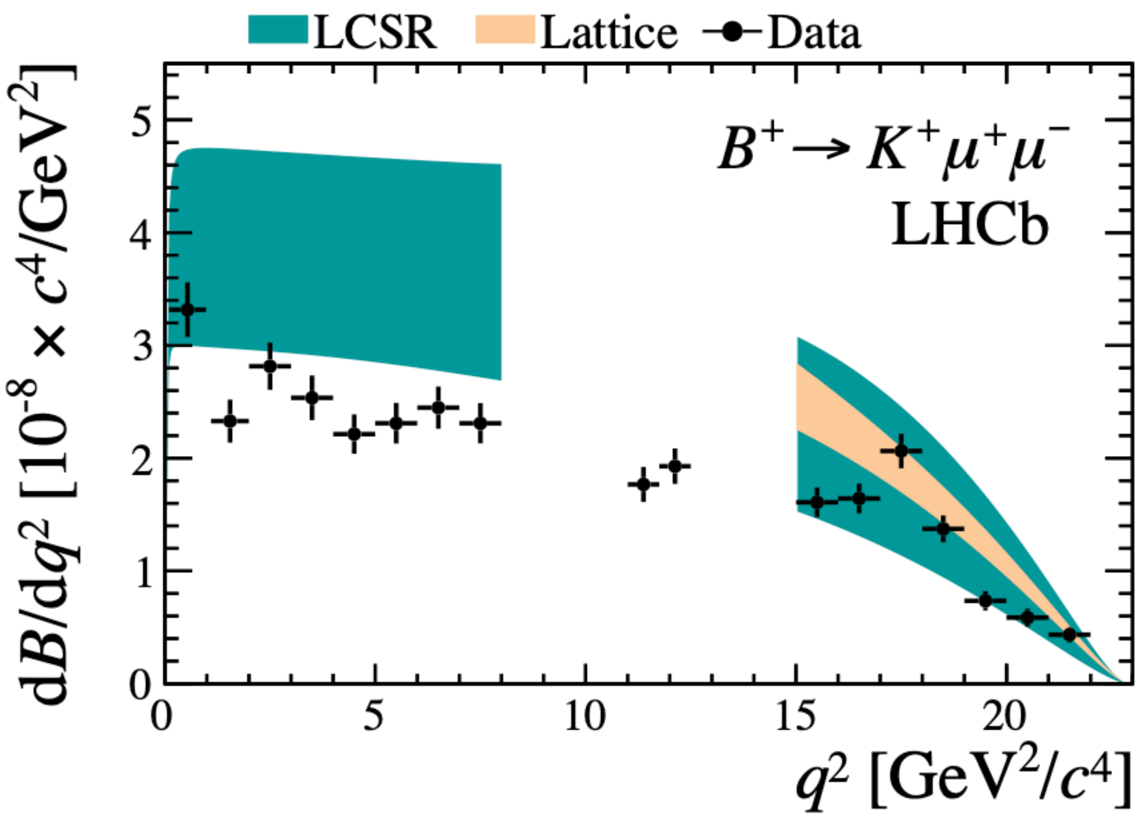


The $b \to s\mu^+\mu^-$ anomalies

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

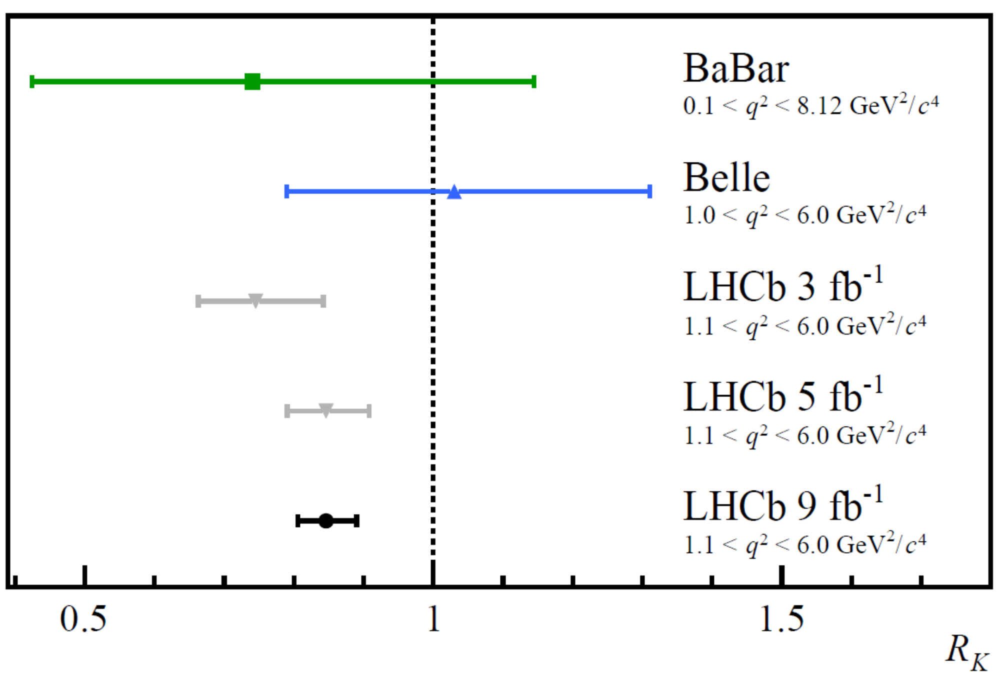
Lepton flavor universality ratios also show deviations from SM prediction

[Theoretically "very clean": $1\,\%$ theory error (QED and lepton mass effects)] [See Gino's talk]

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

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

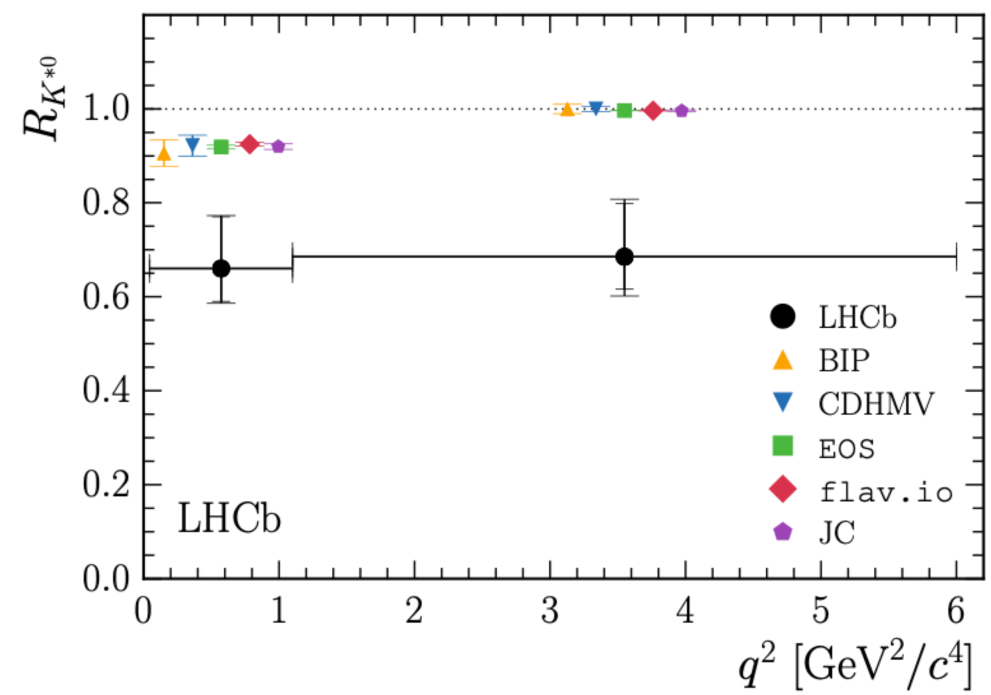
[Isidori, Bordone, Pattori, 1605.07633]



2014

2019

2021



2017

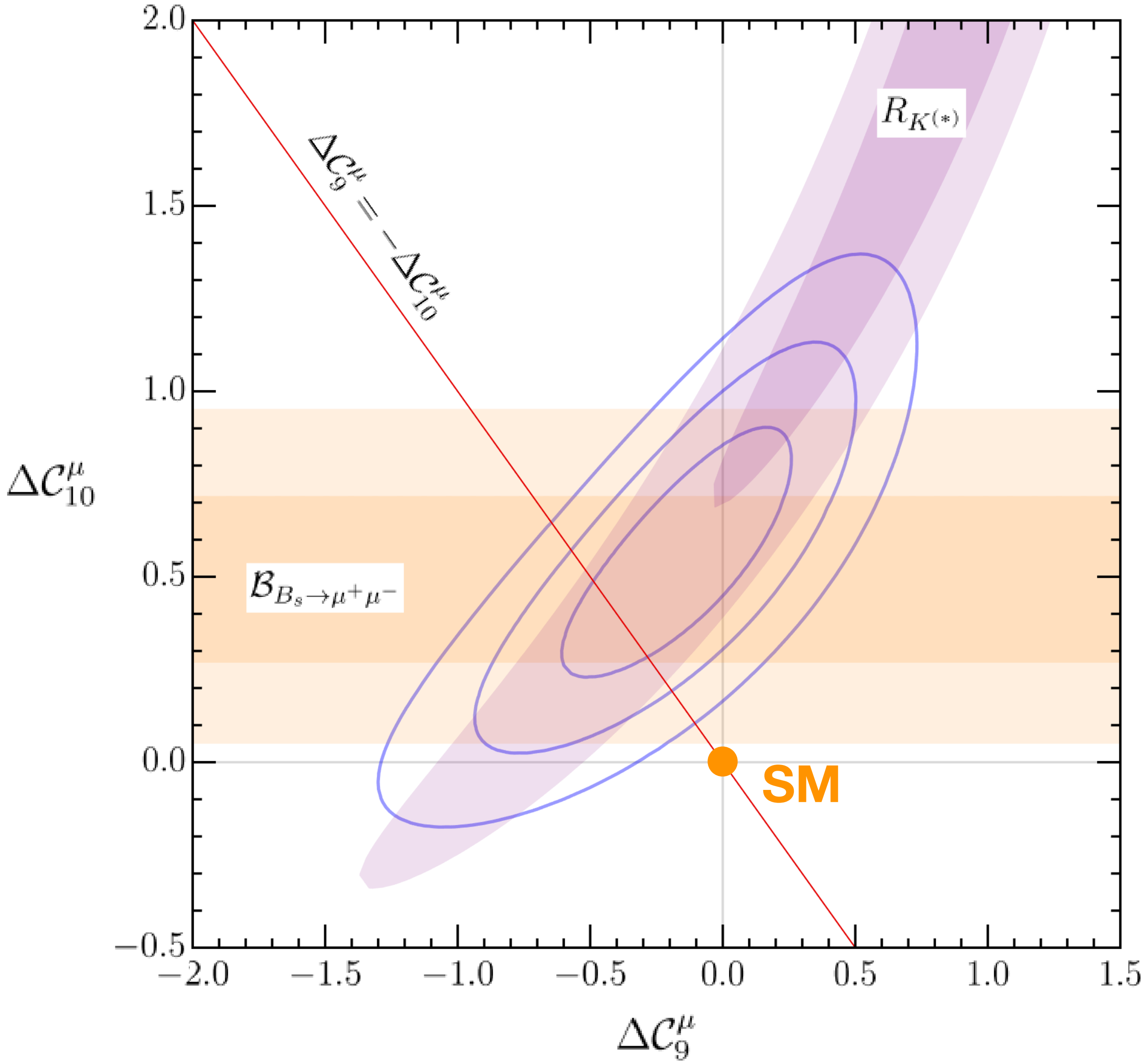
[LHCb, 2103.11769]

[LHCb, 1705.05802]

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

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

Conservative fit using "th clean observables" only
$[\ \Delta C_i^\mu = C_i^\mu - C_i^e\ ]$



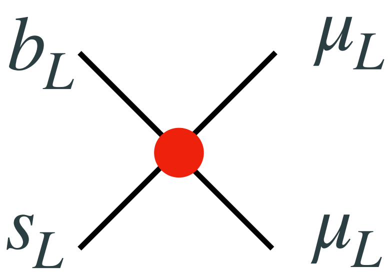
[Cornella, JFM et al., 2103.16558]

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

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

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

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



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

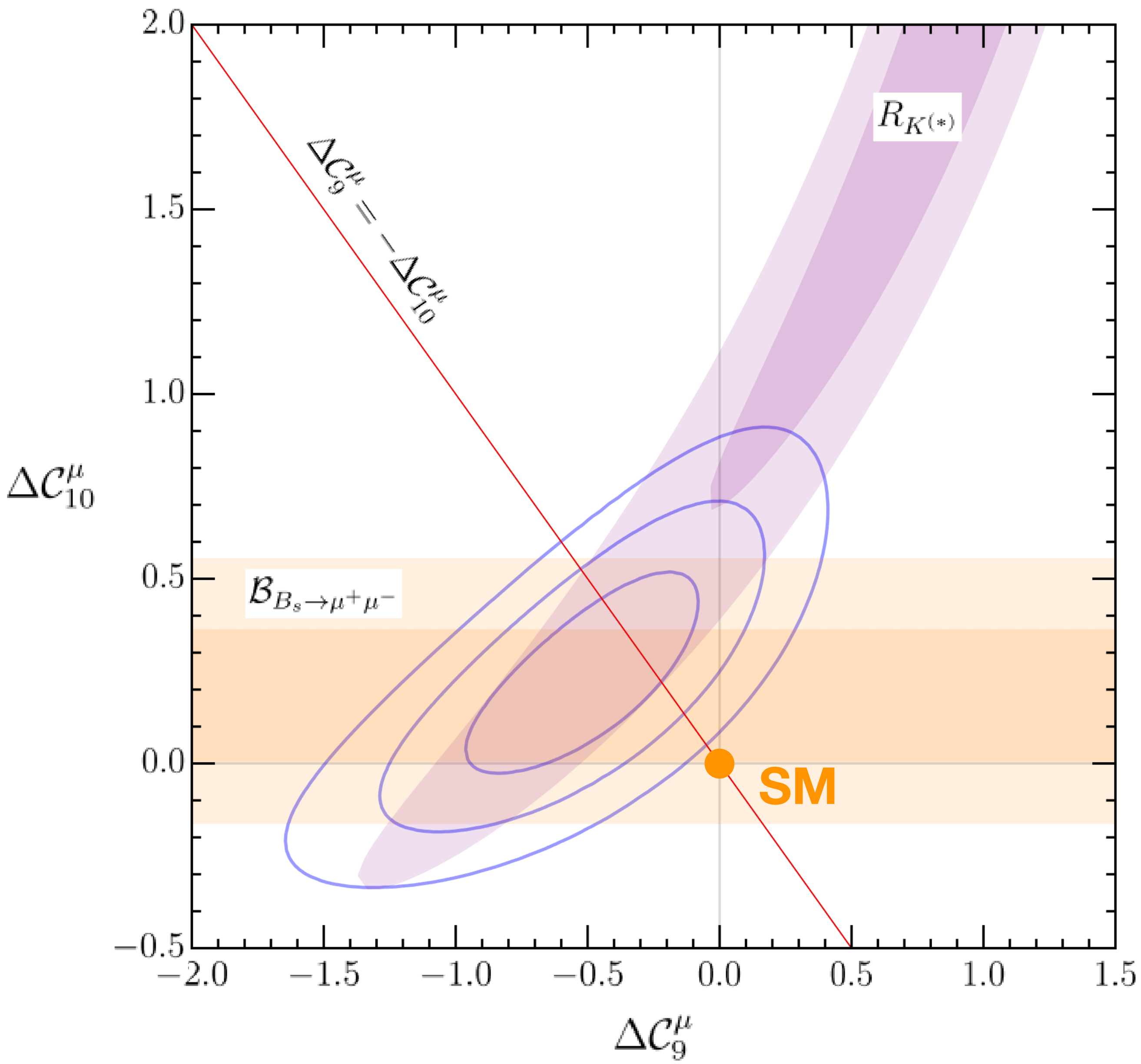
$$\Longrightarrow \frac{g_{\rm NP}^2}{M_{\rm NP}^2} \sim \frac{1}{(40\ {\rm TeV})^2}$$

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

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

Conservative fit using "th clean observables" only *

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



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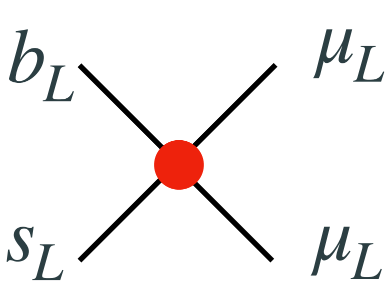
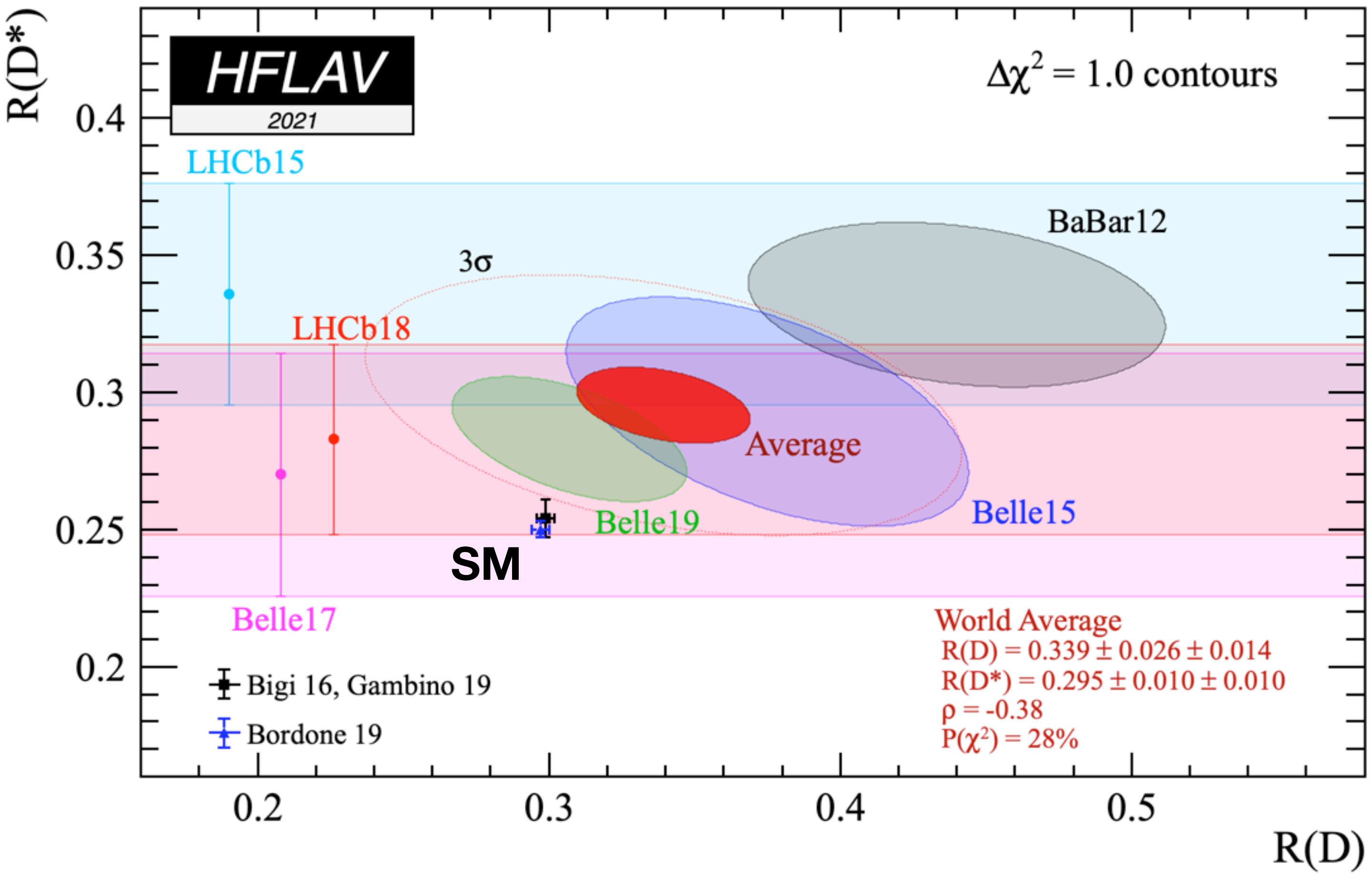
Left-handed new physics [$\Delta C_9^\mu = -\Delta C_{10}^\mu$] preferred over the SM by 3.9σ

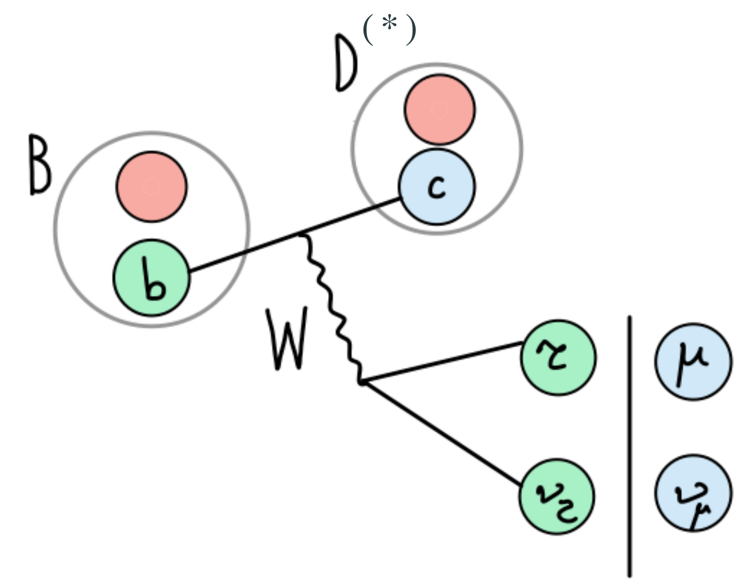


$$\sim 3\times 10^{-5}\, G_F$$

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

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

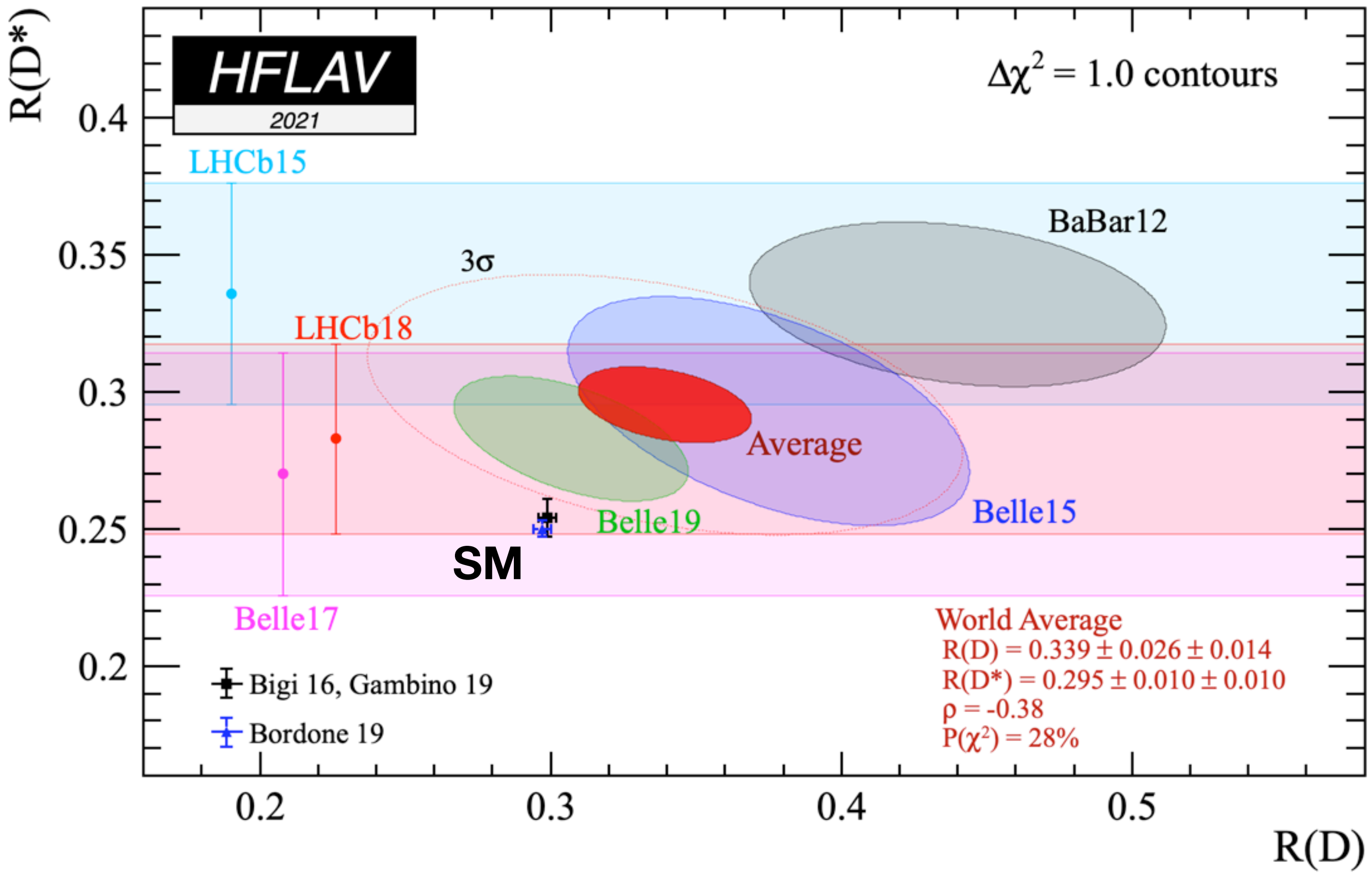




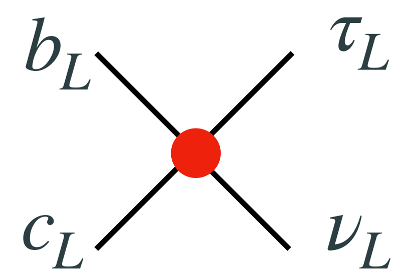
$$R_{D^{(*)}} \equiv \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})} \qquad [\ell = e, \mu]$$

- $\sim 15\,\%$ enhancement due to excess in tau mode
- Theoretically clean: QCD uncertainties cancel (to a large extent) in the ratios
- Measurements by Babar, Belle, LHCb (so far $R(D^*)$ only) in reasonable agreement
- 3.4σ tension (R_D and R_{D^*} comb.)
- Recent measurement of $R(\Lambda_c)$ [$\Lambda_b \to \Lambda_c \ell\nu$] reduces the tension slightly [LHCb, 2201.03497]

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



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



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

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

- $\sim 15\,\%$ enhancement due to excess in tau mode
- Theoretically clean: QCD uncertainties cancel (to a large extent) in the ratios
- Measurements by Babar, Belle, LHCb (so far $R(D^*)$ only) in reasonable agreement
- 3.4σ tension (R_D and R_{D*} comb.)
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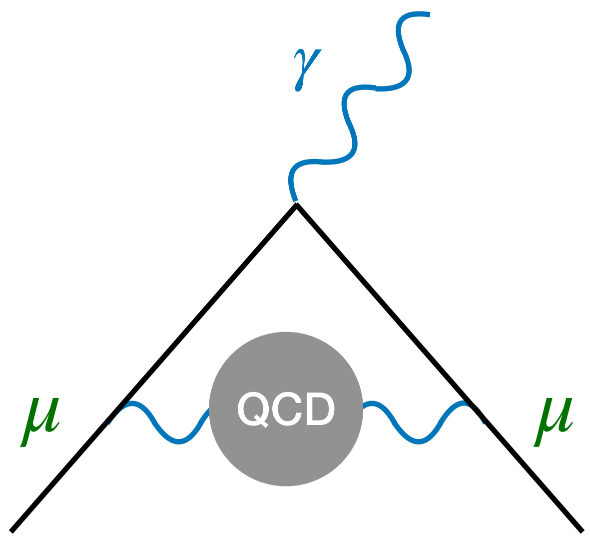
The $(g-2)_\mu$ anomaly



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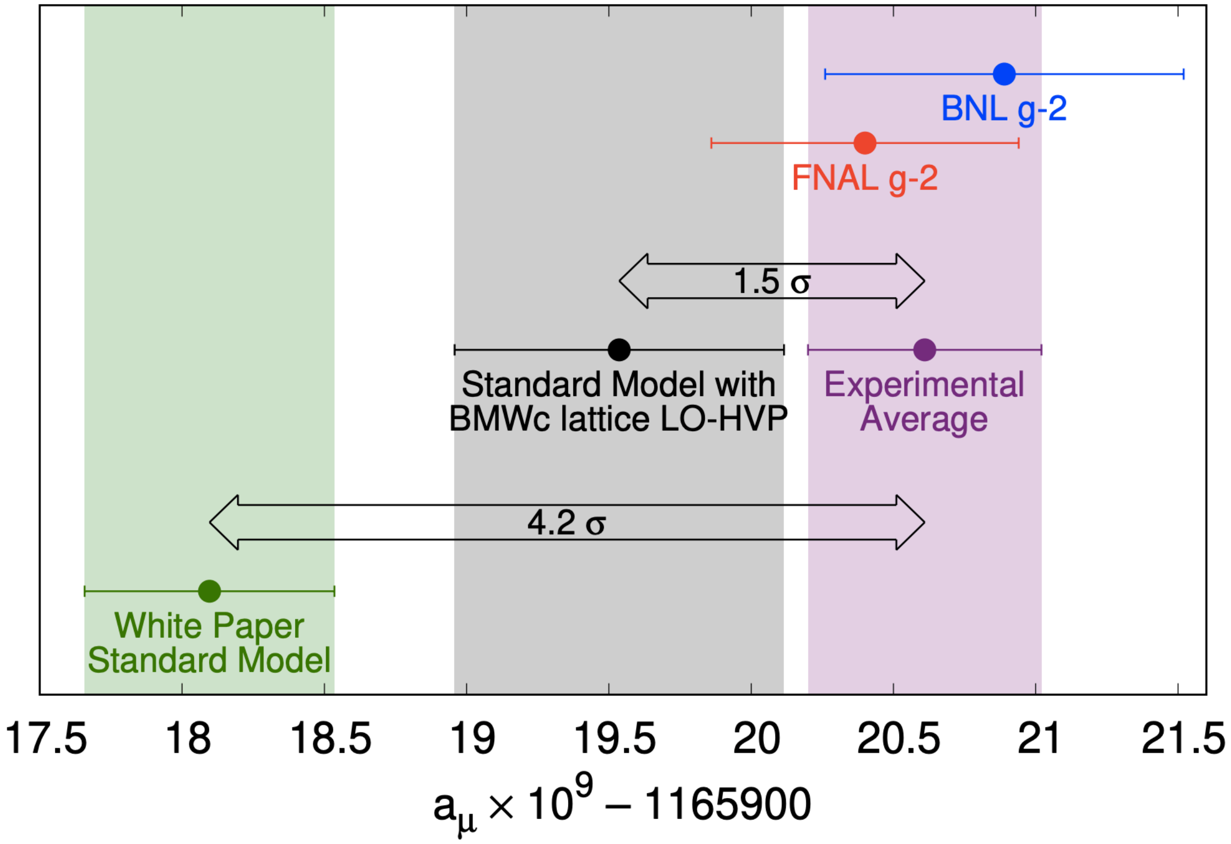
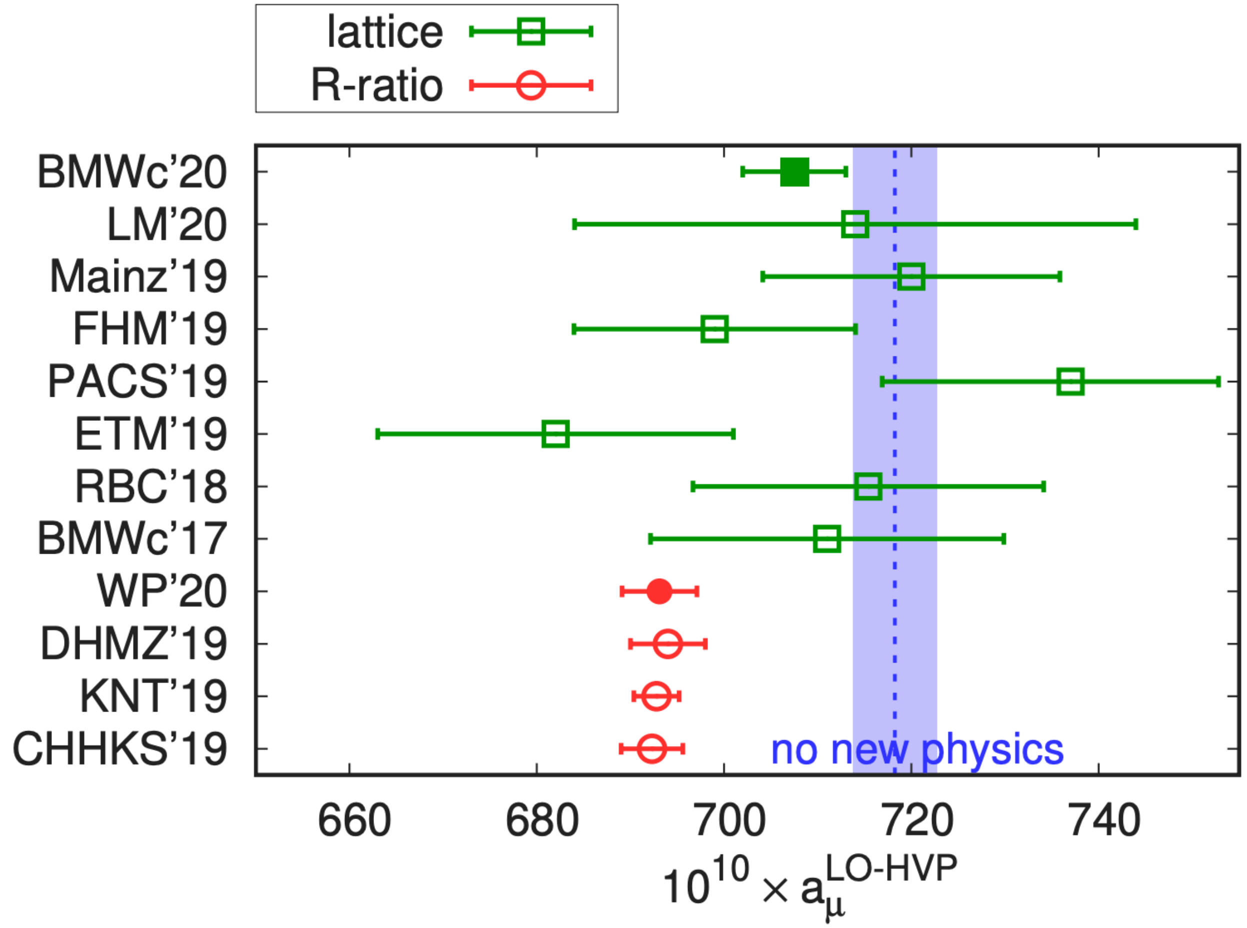


[Figure from BMWc lattice collaboration]



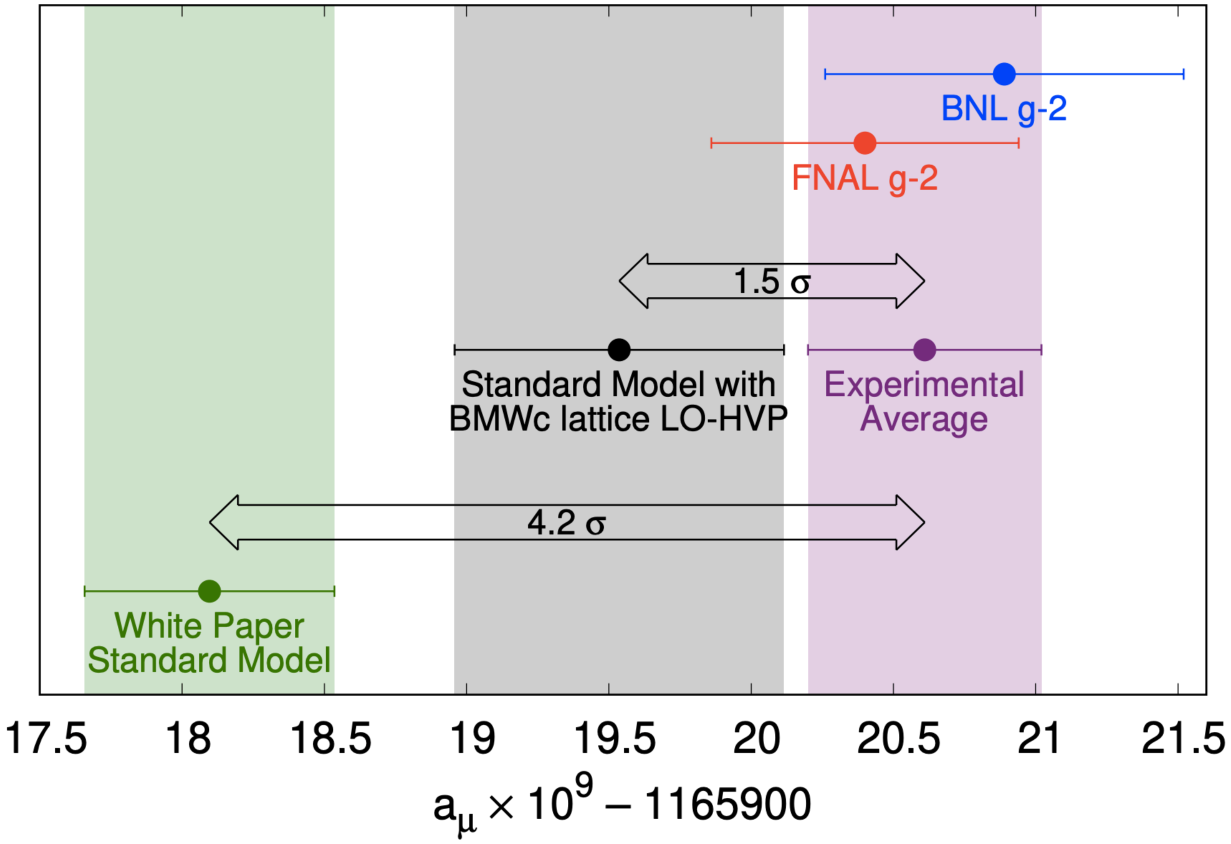
[Borsanyi et al., 2002.12347;
See also Cè et al., 2206.06582]

Recent confirmation by Fermilab of the Brookhaven experimental result
[strong evidence of new physics 4.2σ (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]

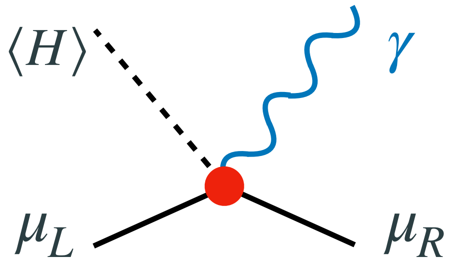
The $(g-2)_\mu$ anomaly



[Figure from BMWc lattice collaboration]

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

→ NP is either light or not chirally suppressed



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

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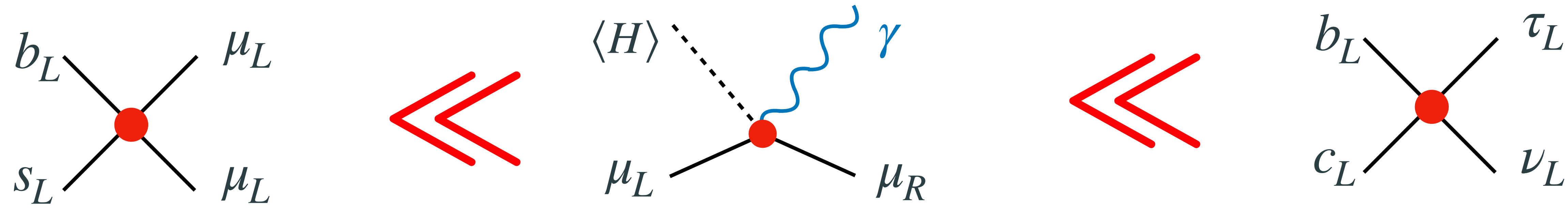
Consistency with a multi-scale picture?



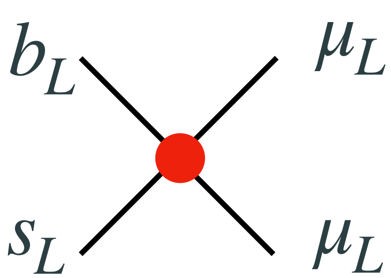
$\sim \frac{1}{(40\ \text{TeV})^2}$ $\quad$ $\sim \frac{e}{16\pi^2}\frac{1}{(10\ \text{TeV})^2}$ * $\quad$ $\sim \frac{1}{(3\ \text{TeV})^2}$

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

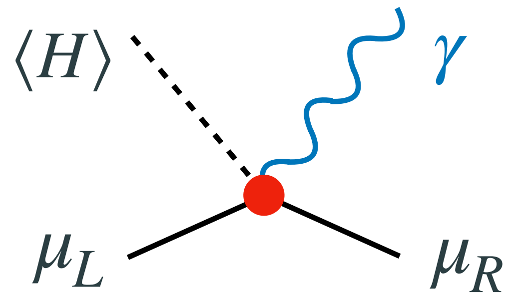
The only source of **lepton flavor universality violation** in the SM (Yukawas) follows a very similar trend: $y_e \ll y_\mu \ll y_\tau$

* N.B.: Assuming no chiral suppression

Consistency with a multi-scale picture?



$\ll$



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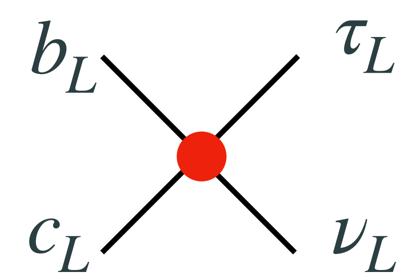


$$\sim \frac{1}{(1\ \text{TeV})^2} |V_q|\,|V_\ell|^2 \qquad \sim \frac{e}{16\pi^2}\frac{1}{(1\ \text{TeV})^2} |V_\ell|\,|V_\mu|^{*} \qquad \sim \frac{1}{(1\ \text{TeV})^2} |V_q|$$

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

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 $|V_q|, |V_\ell|, |V_\mu| \sim 0.1$
[roughly the size inferred from the SM Yukawa $|\boldsymbol{V_q}| \sim V_{cb} \approx 0.04$]

* N.B.: Assuming no chiral suppression

Possible mediators behind the anomalies

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

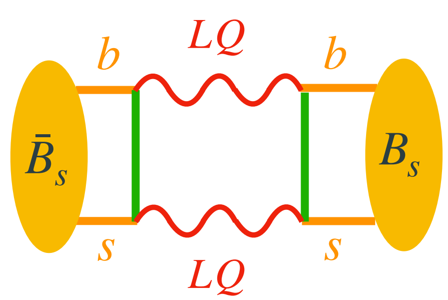
$\boldsymbol{b \to s\ell^+\ell^-}$ **only :** Z', U_1, U_3, S_3

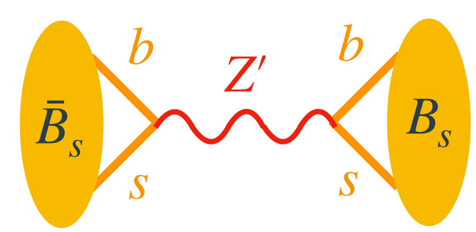
$\boldsymbol{b \to s\ell^+\ell^- + R_{D^{(*)}}}$ **:** $U_1, S_1 + S_3, R_2 + S_3$

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

Leptoquarks (both scalars and vectors) have two important features

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





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

Explanation of both B anomalies: 4321 models

[See also Di Luzio, Greljo, Nardecchia, 1708.08450;
Diaz, Schmaltz, Zhong, 1706.05033; Georgi, Nakai, 1606.05865]

$U(1)_Y$

$$SU(4)_h \times SU(3)_l \times SU(2)_L \times U(1)_{R+l} \xrightarrow{\langle \Omega_{1,3,15} \rangle \sim \mathcal{O}(\mathrm{TeV})} SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$+ U_1, G', Z'$$

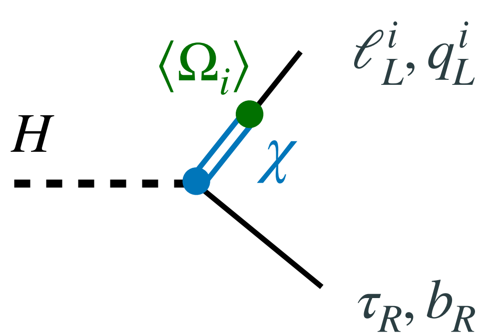
$SU(3)_c$

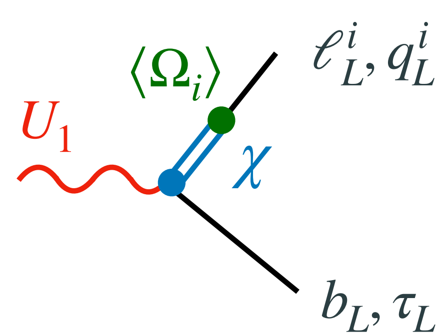
★ Third-family quark-lepton unification at the TeV

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

★ 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





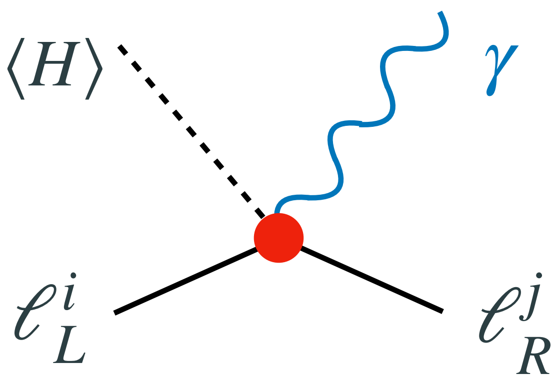
$i = 1,2$

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

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

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



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

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

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 $b \to s\ell^+\ell^-$ and $(g-2)_\mu$

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

[Davighi, Greljo, Thomsen, 2202.05275]

A glimpse into the future

Future prospects for LHCb and Belle II

[Belle II, 1808.10567]

Observables	Expected the. accuracy	Expected exp. uncertainty	Facility (2025)
(Semi-)leptonic			
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	Belle II
$R(B \to D\tau\nu)$	***	3%	Belle II
$R(B \to D^*\tau\nu)$	***	2%	Belle II/LHCb
EW Penguins			
$\mathcal{B}(B \to K^*\nu\bar{\nu})$ $[10^{-6}]$	***	15%	Belle II
$R(B \to K^*\ell\ell)$	***	0.03	Belle II/LHCb
Charm			
$\mathcal{B}(D_s \to \mu\nu)$	***	0.9%	Belle II
$\mathcal{B}(D_s \to \tau\nu)$	***	2%	Belle II
Tau			
$\tau \to \mu\gamma$ $[10^{-10}]$	***	< 50	Belle II
$\tau \to e\gamma$ $[10^{-10}]$	***	< 100	Belle II
$\tau \to \mu\mu\mu$ $[10^{-10}]$	***	< 3	Belle II/LHCb

But...

LHCb is poor on missing-energy modes (virtually all τ decays..)

At Belle II there are no B_s, and b & τ have a very small boost

FCC-ee: an ideal experiment for flavor physics?

$5 \cdot 10^{12}\ Z \qquad Z \to b\bar{b} \sim 15\,\%$

[See Hector Gisbert's talk]

Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\bar{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	300	300	80	80	600	150

$\sim 4 \times 10^9\ B_c^\pm$ for $f_{B_c}/(f_{B_u} + f_{B_d}) \sim 3.7 \cdot 10^{-3}$

[Talk by S. Monteil]

N.B.: Comparison with LHCb depends on trigger efficiency

Large samples for *all species* of b-flavored hadrons

Boost at the Z: topological reconstruction of decays

Clean and hermetic experimental environment

No pile up and no trigger

$\Longrightarrow$ Several unique signatures not accesible to any running or foreseeable experiment

Decay	Current bound	FCC-ee sensitivity
Z -> eμ	0.75 x $^{-6}$	10^{-8}
Z -> μτ	12 x 10^{-6}	10^{-9}
Z -> eτ	9.8 x 10^{-6}	10^{-9}

Decay	Current bound	FCC-ee sensitivity
τ -> μγ	4.4 x 10^{-8}	2 x 10^{-9}
τ -> 3μ	2 x 10^{-8}	10^{-10}

FCC-ee potential to measure B-physics observables

Decay mode/Experiment	Belle II (50/ab)	LHCb Run I	LHCb Upgr. (50/fb)	FCC-*ee*
EW/H penguins				
$B^0 \to K^*(892)e^+e^-$	~ 2000	~ 150	~ 5000	~ 200000
$\mathcal{B}(B^0 \to K^*(892)\tau^+\tau^-)$	~ 10	–	–	~ 1000
$B_s \to \mu^+\mu^-$	n/a	~ 15	~ 500	~ 800
$B^0 \to \mu^+\mu^-$	~ 5	–	~ 50	~ 100
$\mathcal{B}(B_s \to \tau^+\tau^-)$				
Leptonic decays				
$B^+ \to \mu^+\nu$	5%	–	–	3%
$B^+ \to \tau^+\nu$	7%	–	–	2%
$B_c^+ \to \tau^+\nu$	n/a	–	–	5%

[Table from S. Monteil]

The huge sample in a clean environment should also allow to study other $b \to d\ell^+\ell^-$ transitions such as $B^0 \to \rho\ell^+\ell^-$ or $B_s \to K^*\ell^+\ell^-$

Models based on minamilly-broken $U(2)^5$ (Yukawa-like) symmetry predict [Barbieri et al. 1105.2296]

$$\frac{b \to s\ell\ell}{b \to d\ell\ell} = \left.\frac{b \to s\ell\ell}{b \to d\ell\ell}\right|_{\rm SM} \qquad \frac{b \to c\ell\nu}{b \to u\ell\nu} = \left.\frac{b \to c\ell\nu}{b \to u\ell\nu}\right|_{\rm SM}$$

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$B^0 \to \mu^+\mu^-$	~ 5	–	~ 50	~ 100
$\mathcal{B}(B_s \to \tau^+\tau^-)$				
Leptonic decays				
$B^+ \to \mu^+\nu$	5%	–	–	3%
$B^+ \to \tau^+\nu$	7%	–	–	2%
$B_c^+ \to \tau^+\nu$	n/a	–	–	5%

[Table from S. Monteil]

Very relevant observables out of reach for LHCb/Belle II

The huge sample in a clean environment should also allow to study other $b \to d\ell^+\ell^-$ transitions such as $B^0 \to \rho\ell^+\ell^-$ or $B_s \to K^*\ell^+\ell^-$

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Probing new physics with τ/W decays

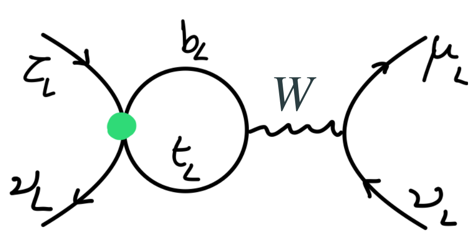
$$\left|g_e^{(\tau)}/g_e^{(\mu)}\right|^2 \equiv \frac{\Gamma(\tau\to e\nu\bar{\nu})}{\Gamma(\mu\to e\nu\bar{\nu})}\left[\frac{\Gamma_{\rm SM}(\tau\to e\nu\bar{\nu})}{\Gamma_{\rm SM}(\mu\to e\nu\bar{\nu})}\right]^{-1}$$

[Pich, 1310.7922]

	$\Gamma_{\tau\to\mu}/\Gamma_{\tau\to e}$	$\Gamma_{\pi\to\mu}/\Gamma_{\pi\to e}$	$\Gamma_{K\to\mu}/\Gamma_{K\to e}$	$\Gamma_{K\to\pi\mu}/\Gamma_{K\to\pi e}$	$\Gamma_{W\to\mu}/\Gamma_{W\to e}$
$\lvert g_\mu/g_e\rvert$	1.0018 (14)	1.0021 (16)	0.9978 (20)	1.0010 (25)	0.996 (10)
	$\Gamma_{\tau\to e}/\Gamma_{\mu\to e}$	$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	$\Gamma_{W\to\tau}/\Gamma_{W\to\mu}$	
$\lvert g_\tau/g_\mu\rvert$	1.0011 (15)	0.9962 (27)	0.9858 (70)	1.034 (13)	
	$\Gamma_{\tau\to\mu}/\Gamma_{\mu\to e}$	$\Gamma_{W\to\tau}/\Gamma_{W\to e}$			
$\lvert g_\tau/g_e\rvert$	1.0030 (15)	1.031 (13)			

$$\mathcal{L}_{\rm EFT}^{\rm NP} = -\frac{2}{v^2}\,C_{LL}^{ij\alpha\beta}\,(\bar{q}_L^i\gamma^\mu l_L^\alpha)(\bar{l}_L^\beta\gamma_\mu q_L^j)$$

$$\Downarrow$$



$$C_{LL}^{33\tau\tau}\,\frac{\alpha_w}{4\pi}\,\log\left(\frac{\Lambda}{m_t}\right)$$

NP expectation from B anomalies: $(0.2-4.0)\times 10^{-3}$

SM theory precision: $\sim 10^{-5}$

Belle II can (at most) reach: $\sim 0.3\times 10^{-3}$

FCC-ee could go below 10^{-4}!

[See Lukas Allwicher's talk]

Probing new physics with LFV decays

Explaining $b \to s\ell^+\ell^-$ and $b \to c\tau\nu$ anomalies requires LQ couplings to both μ and τ

$\Longrightarrow$ Lepton Flavor Violation!

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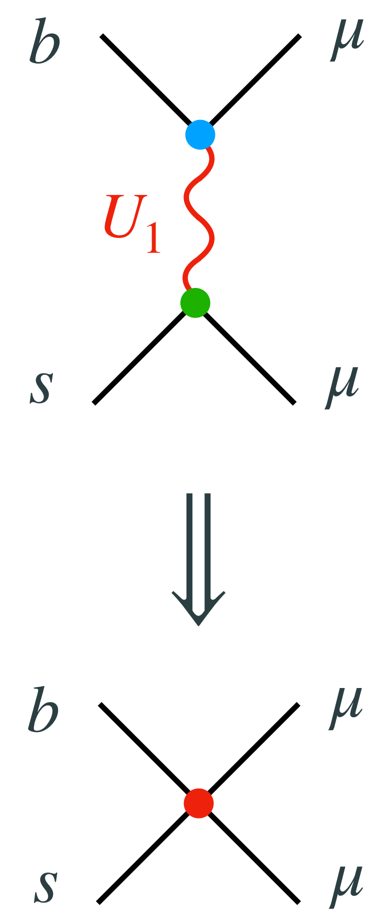
E.g. U_1 vector LQ

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



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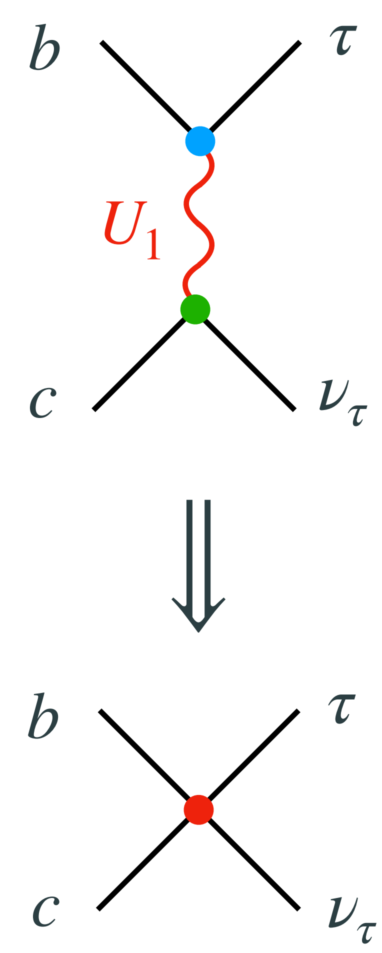

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Explaining $b \to s\ell^+\ell^-$ and $b \to c\tau\nu$ anomalies requires LQ couplings to both μ and τ

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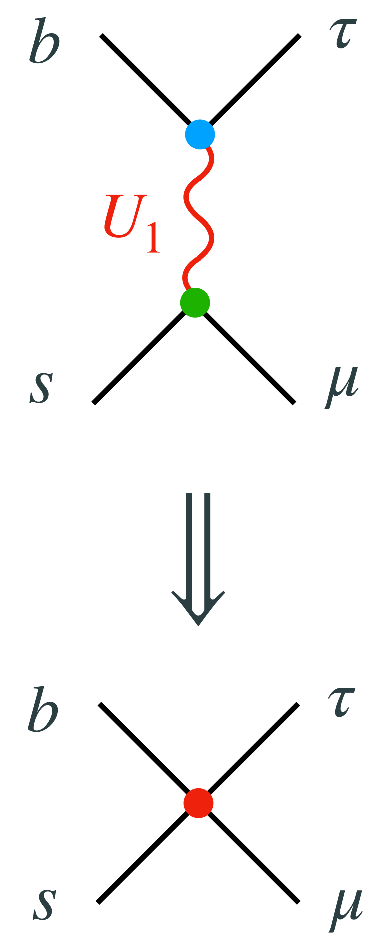
$\boldsymbol{b \to s\tau^-\mu^+}$	$b \to s\mu^+\mu^-$	$b \to c\tau\nu$
	g_{lq}^{23}	$\boldsymbol{g_{lq}^{33}}$
	$\boldsymbol{g_{lq}^{22}}$	g_{lq}^{33}



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Explaining $b \to s\ell^+\ell^-$ and $b \to c\tau\nu$ anomalies requires LQ couplings to both μ and τ
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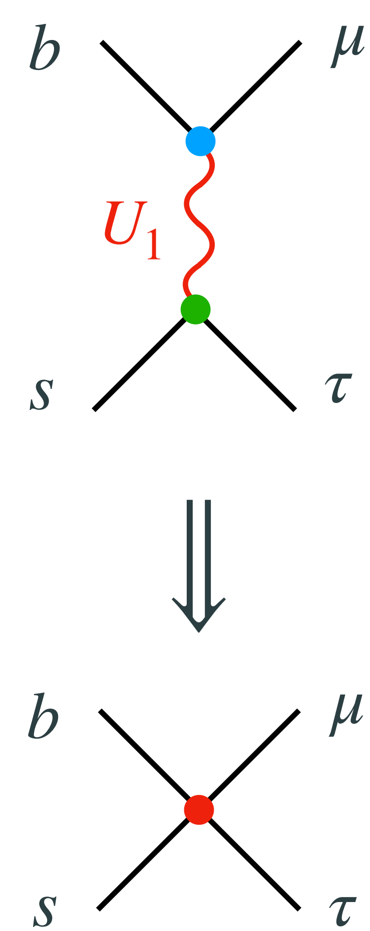
$b \to s\tau^-\mu^+$

$\boldsymbol{b \to s\tau^+\mu^-}$

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



Probing new physics with LFV decays

Explaining $b \to s\ell^+\ell^-$ and $b \to c\tau\nu$ anomalies requires LQ couplings to both μ and τ

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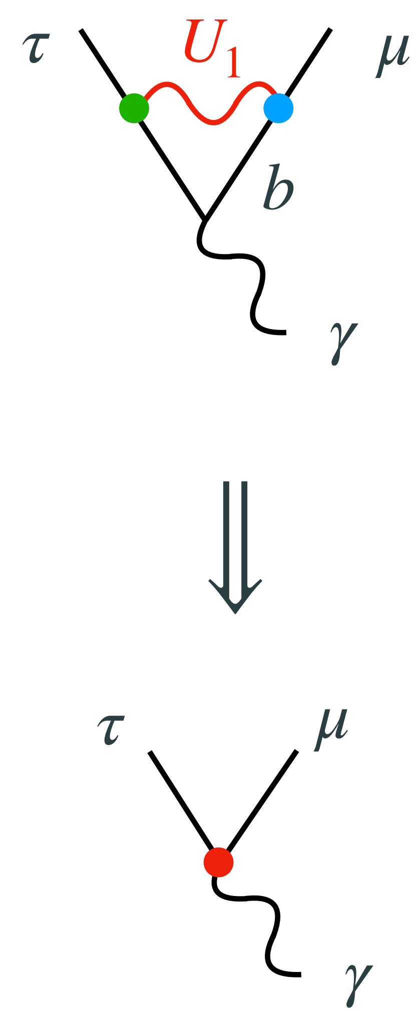
$b \to s\tau^-\mu^+$

$b \to s\tau^+\mu^-$

$\boldsymbol{\tau \to \mu\gamma}$

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

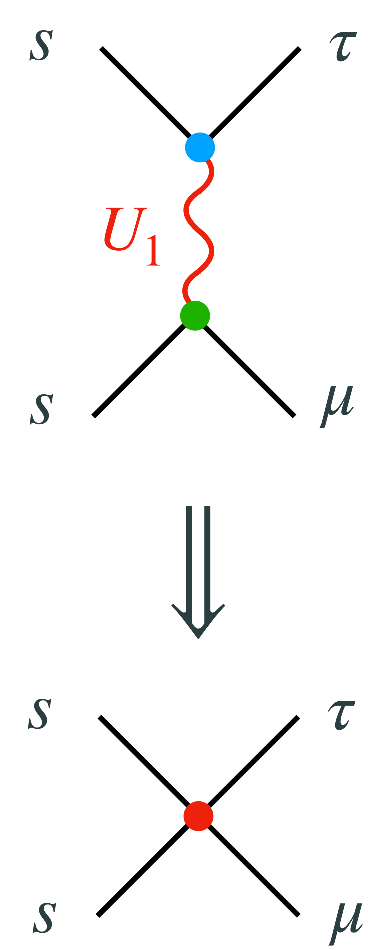


Probing new physics with LFV decays

Explaining $b \to s\ell^+\ell^-$ and $b \to c\tau\nu$ anomalies requires LQ couplings to both μ and τ

$\Longrightarrow$ Lepton Flavor Violation!

$b \to s\tau^-\mu^+$	$b \to s\mu^+\mu^-$	$b \to c\tau\nu$
$b \to s\tau^+\mu^-$		
$\tau \to \mu\gamma$	g_{lq}^{23}	g_{lq}^{33}
$\boldsymbol{\tau \to \mu s\bar{s}}$	$\boldsymbol{g_{lq}^{22}}$	$\boldsymbol{g_{lq}^{32}}$



Probing new physics with LFV decays

Explaining $b \to s\ell^+\ell^-$ and $b \to c\tau\nu$ anomalies requires LQ couplings to both μ and τ
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$b \to s\tau^-\mu^+$

$b \to s\tau^+\mu^-$

$\tau \to \mu\gamma$

$\boldsymbol{\tau \to \mu s\bar{s}}$

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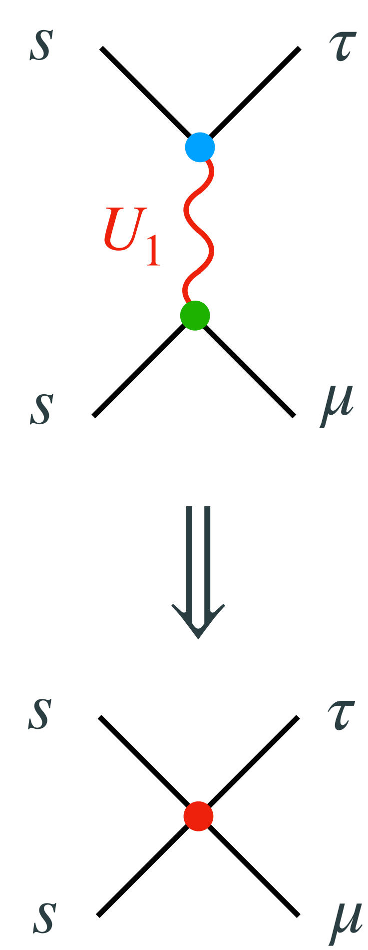
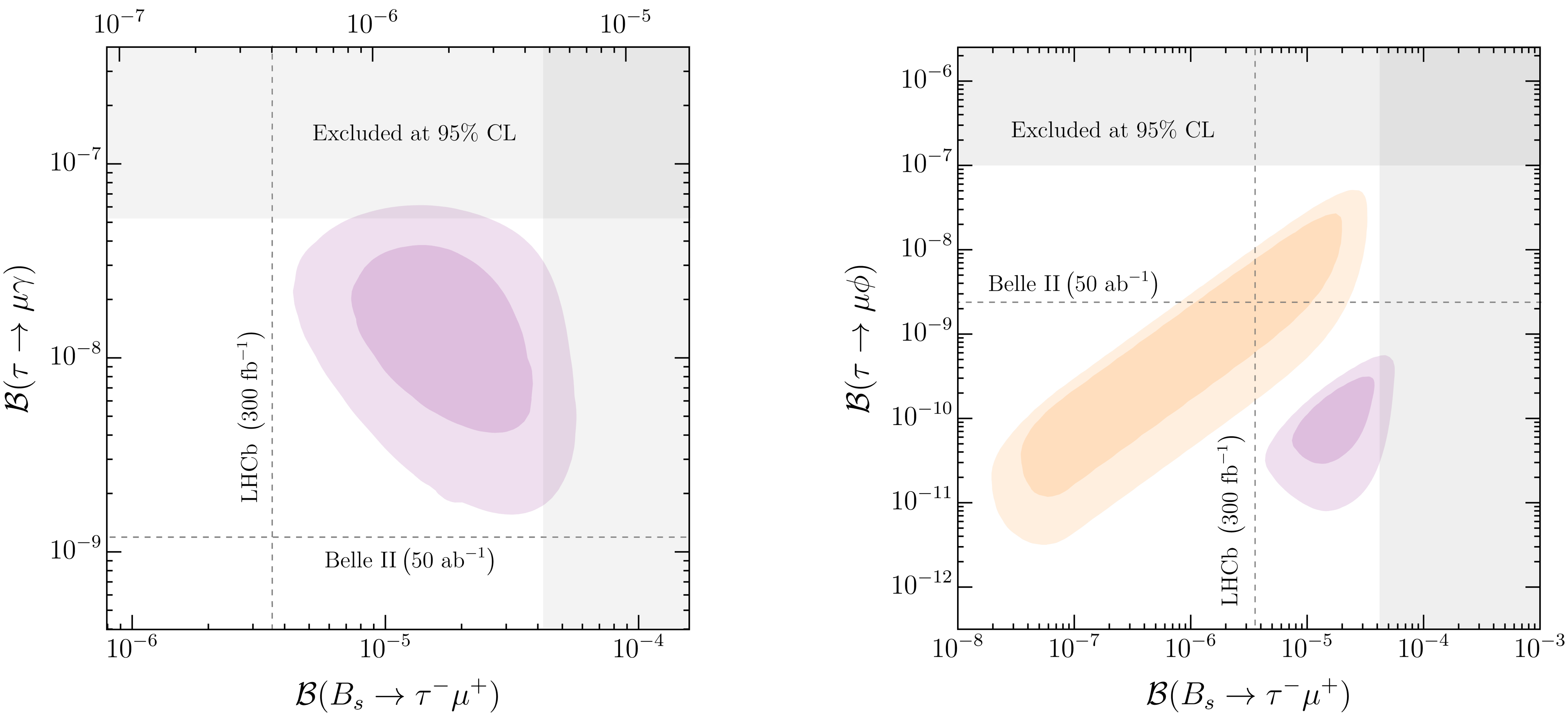


N.B.: In a theory of flavor (or a more complete model) $\mu \to e$ LFV would also be expected!

LFV predictions in U_1 leptoquark model

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

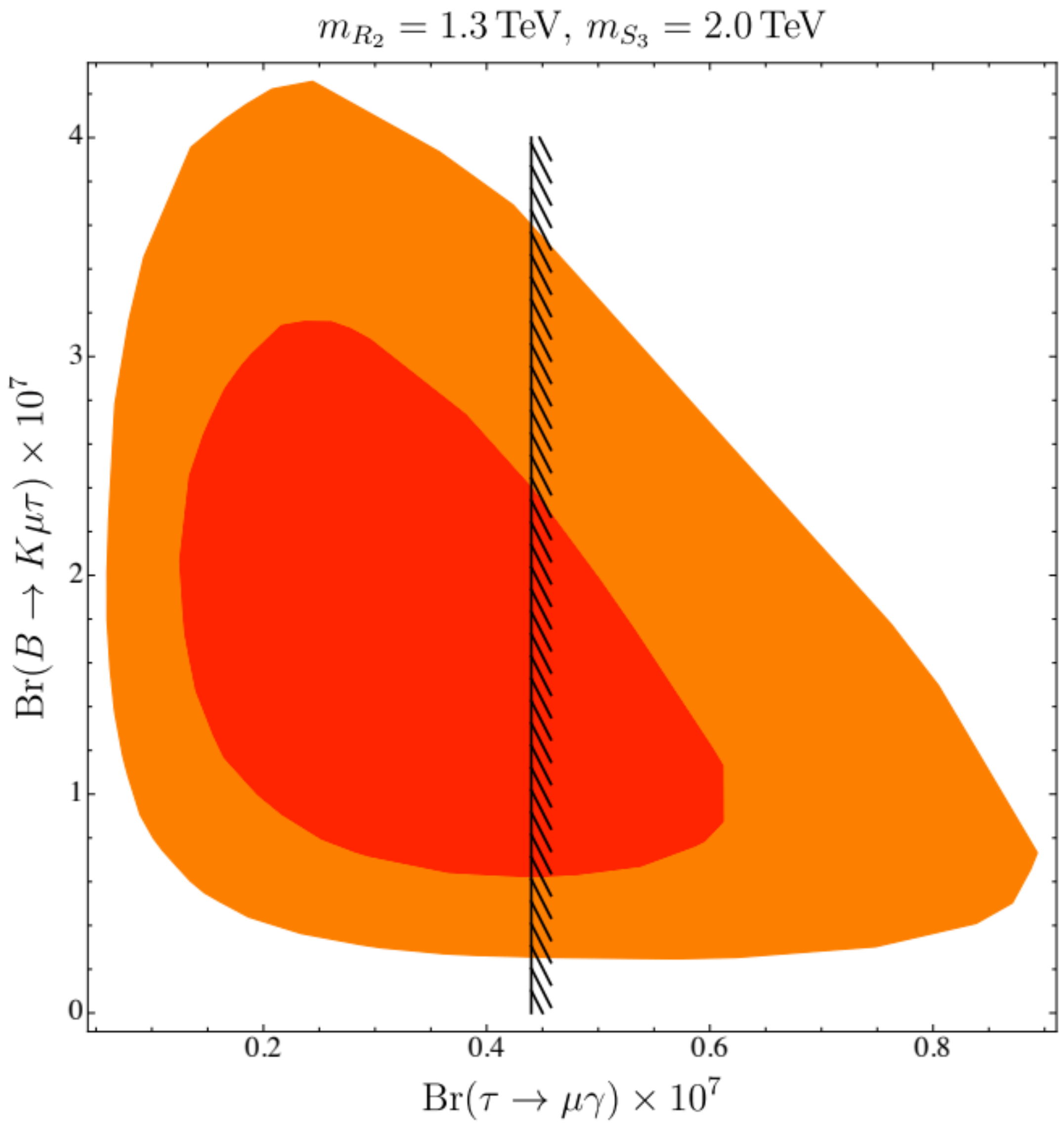
- only left-handed leptoquark couplings
- including a right-handed leptoquark coupling



[Cornella, JFM et al., 2103.16558]

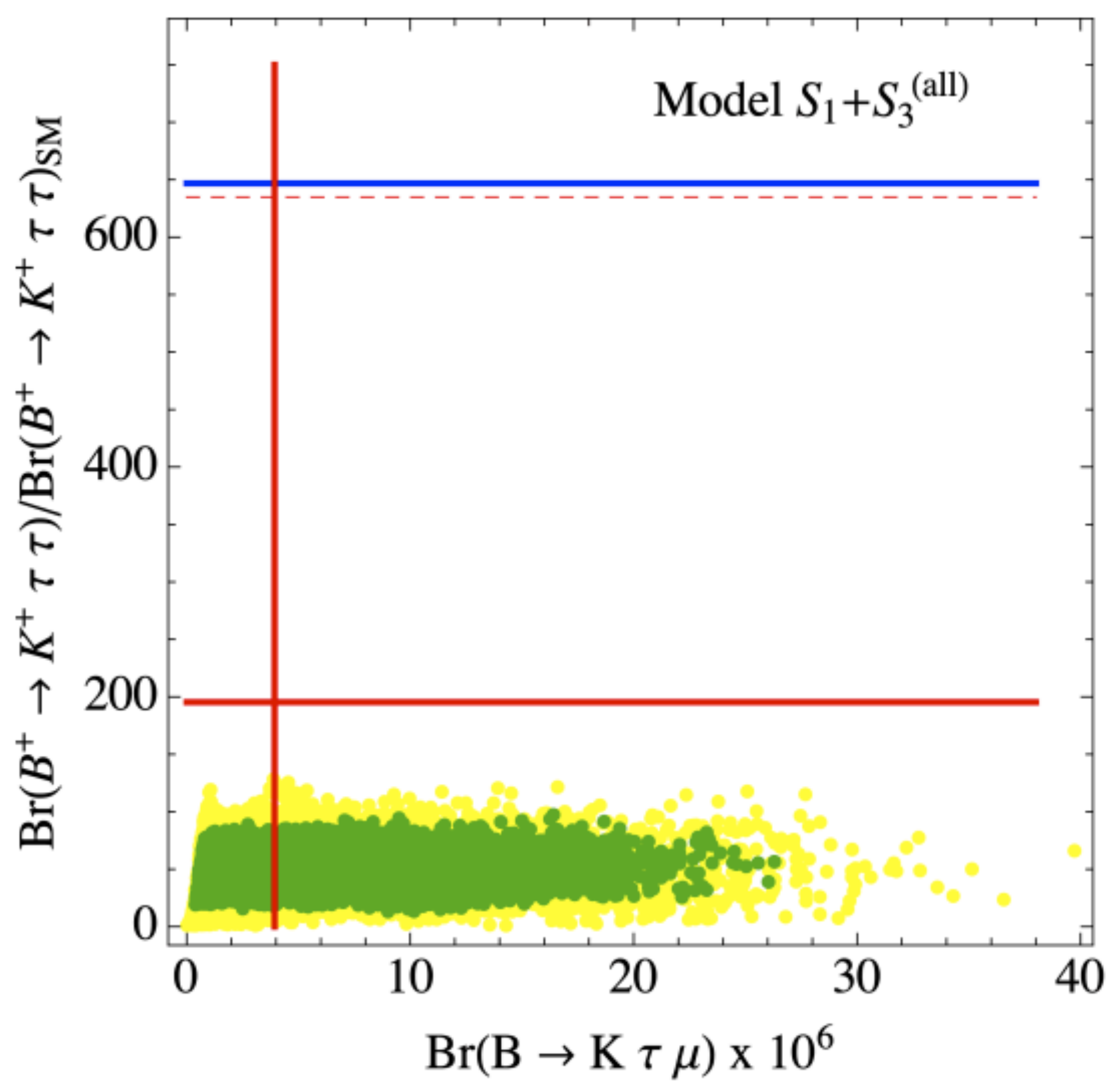
LFV predictions in other leptoquark models

$R_2 + S_3$



[Bečirević et al., 2206.09717]

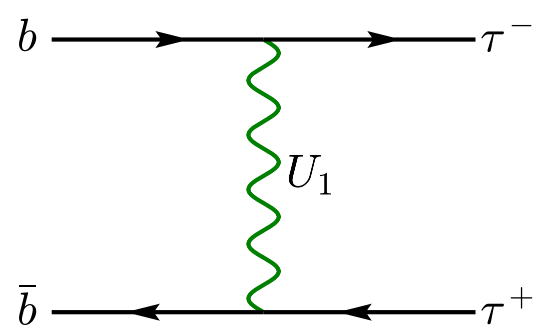
$S_1 + S_3$



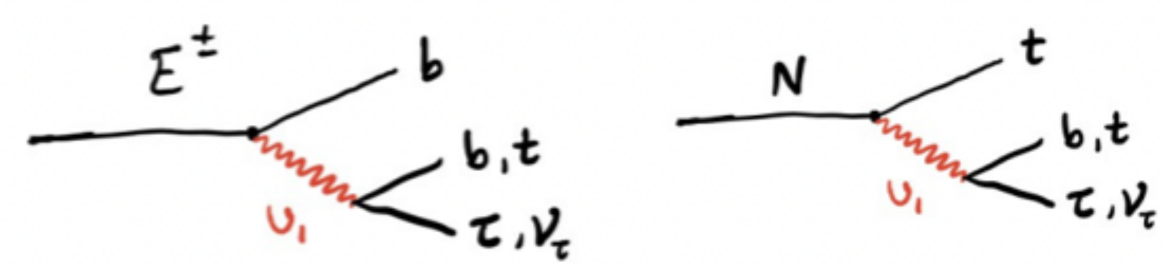
[Gherardi, Marzocca, Venturini, 2008.09548]

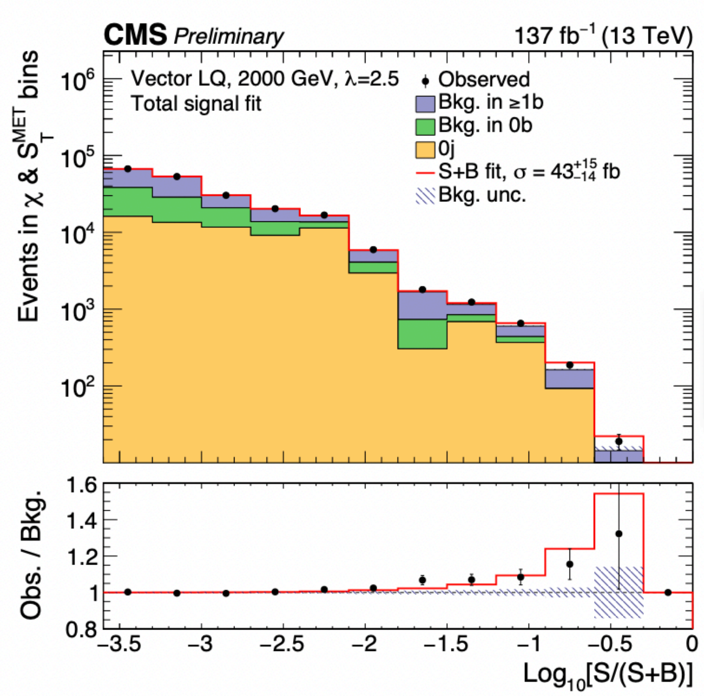
Exciting results for 4321 models from direct searches

[Faroughy, Greljo, Kamenik, 1609.07138]



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

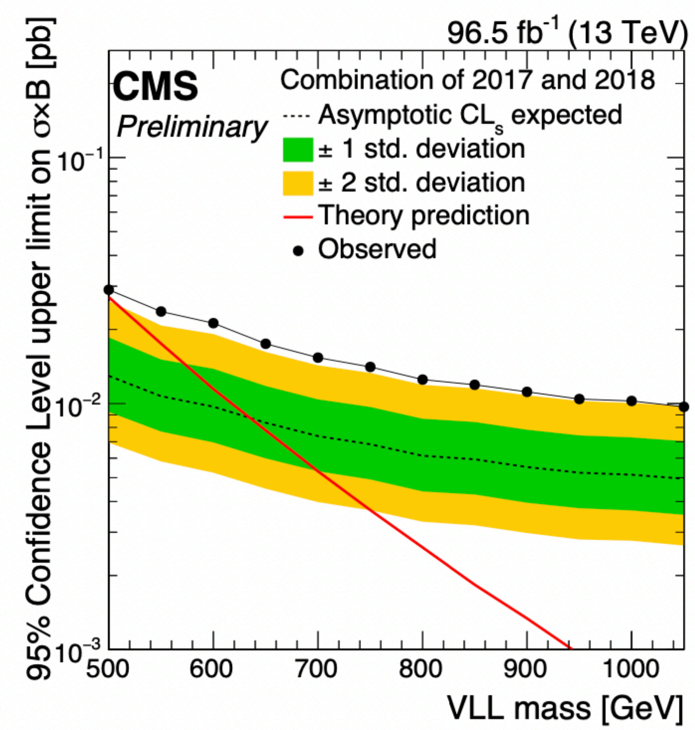




3.4σ

[CMS PAS EXO-19-016](#)

ICHEP 2022

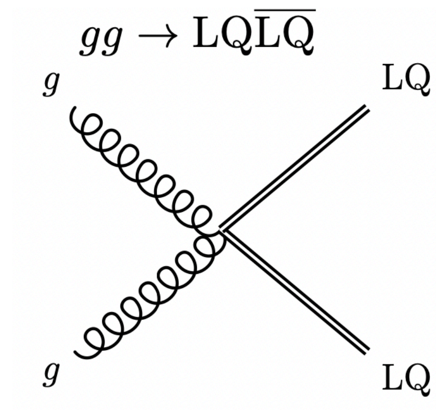


2.8σ

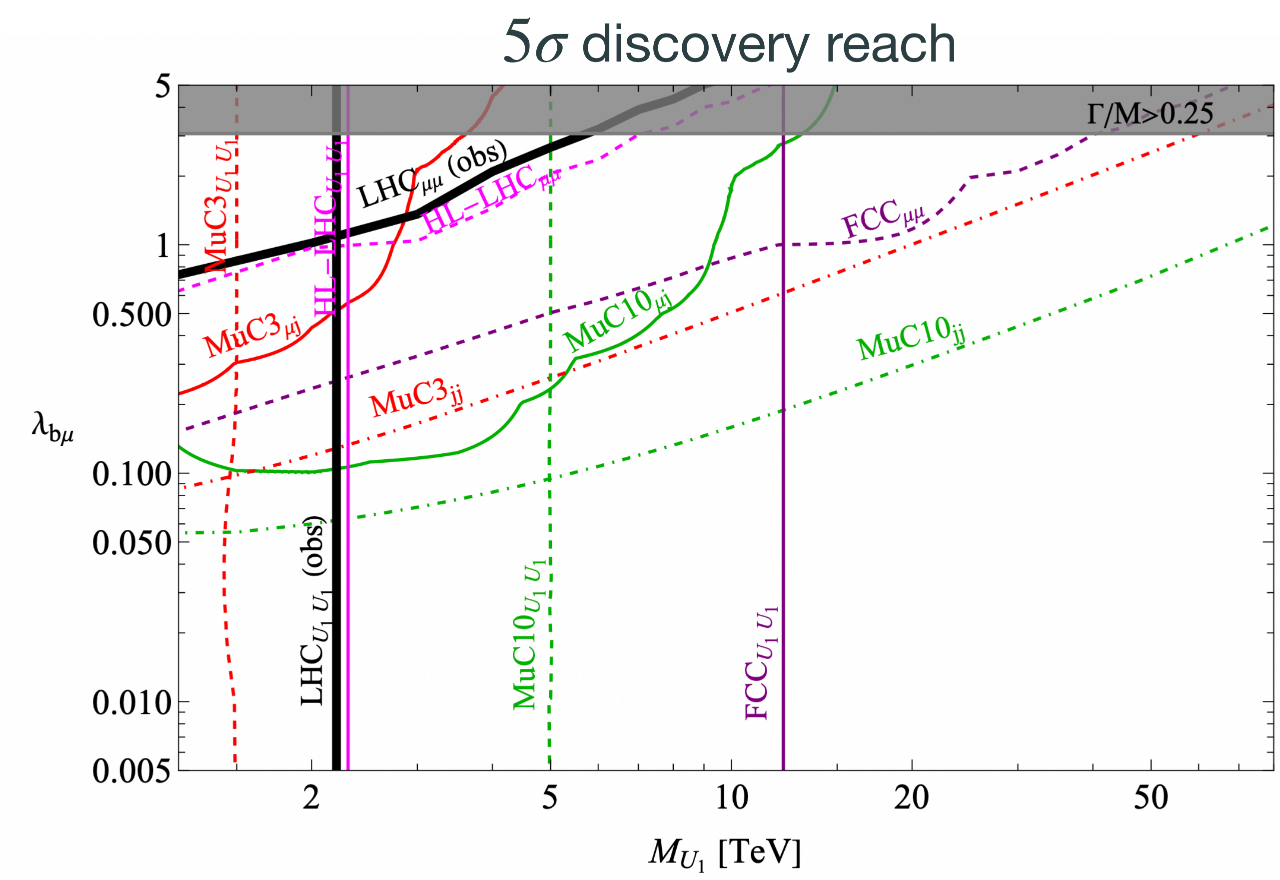
[CMS PAS B2G-21-004](#)

Moriond 2022

FCC-hh discovery reach for pair-produced leptoquarks

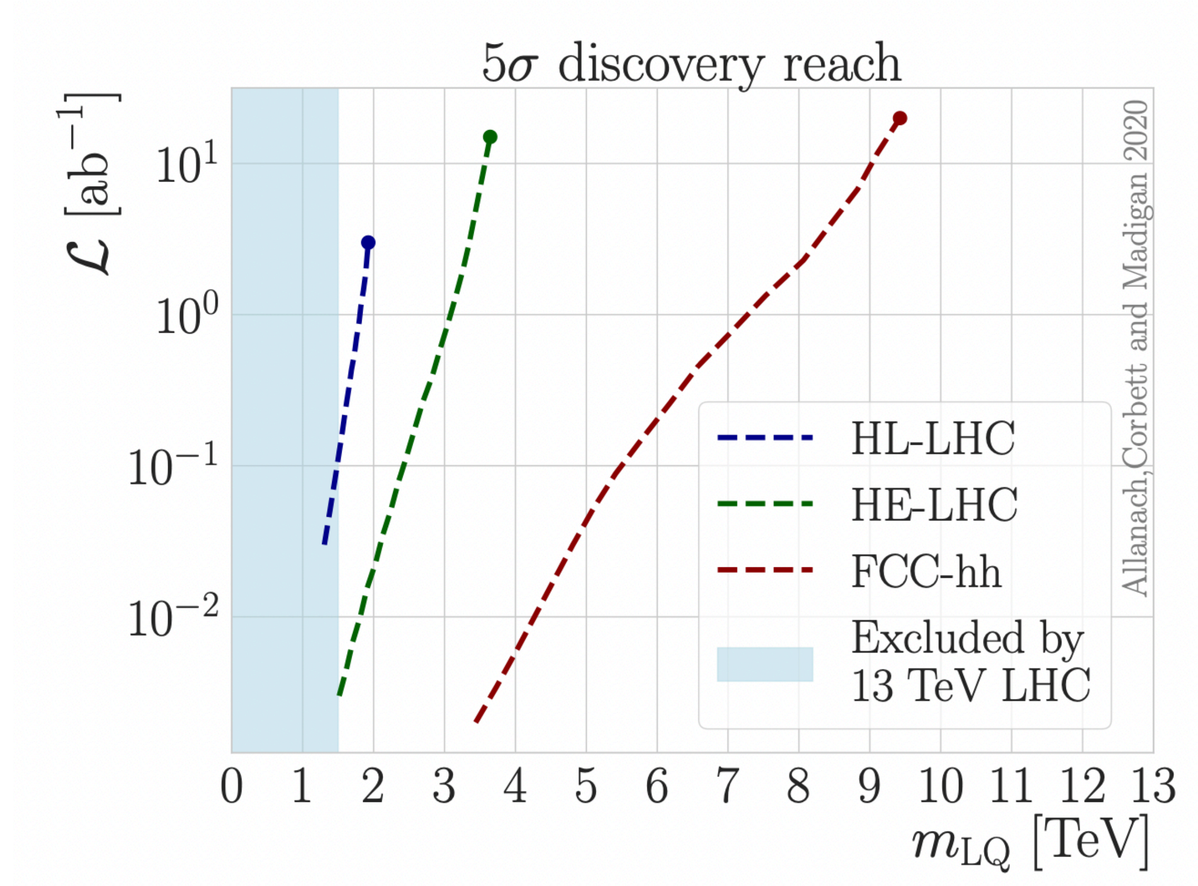


U_1



[Azatov et al., 2205.13552]

S_3



[Allanach, Corbett, Madigan, 1911.04455]

Conclusions

> "There is a theory which states that if ever anyone discovers exactly what the Universe is for and why it is here, it will instantly disappear and be replaced by something even more bizarre and inexplicable. There is another theory which states that this has already happened."
>
> —Douglas Adams, The Hitchhiker's Guide to the Galaxy

I honestly have no idea how the future of flavor physics model building will look like…

The fact that we have not seen any *clear* indications of new physics (either direct or indirect) is disappointing but several interesting ideas remain feasible (e.g. multi-scale flavor picture)

A huge amount of (flavor) data by running experiments is expected, with the potential to define/reshape the model building landscape in flavor physics

FCC-ee would offer crucial information in this regard:

- Outstanding performance on EPWO @ Z-pole with no competition (same for Higgs physics)
- Key advantages in b and tau physics (boosted b's & tau's + clean), providing unique information in several important channels

Thank you!