Opportunities for flavor physics at future e+ e- EW/Higgs/Top factories

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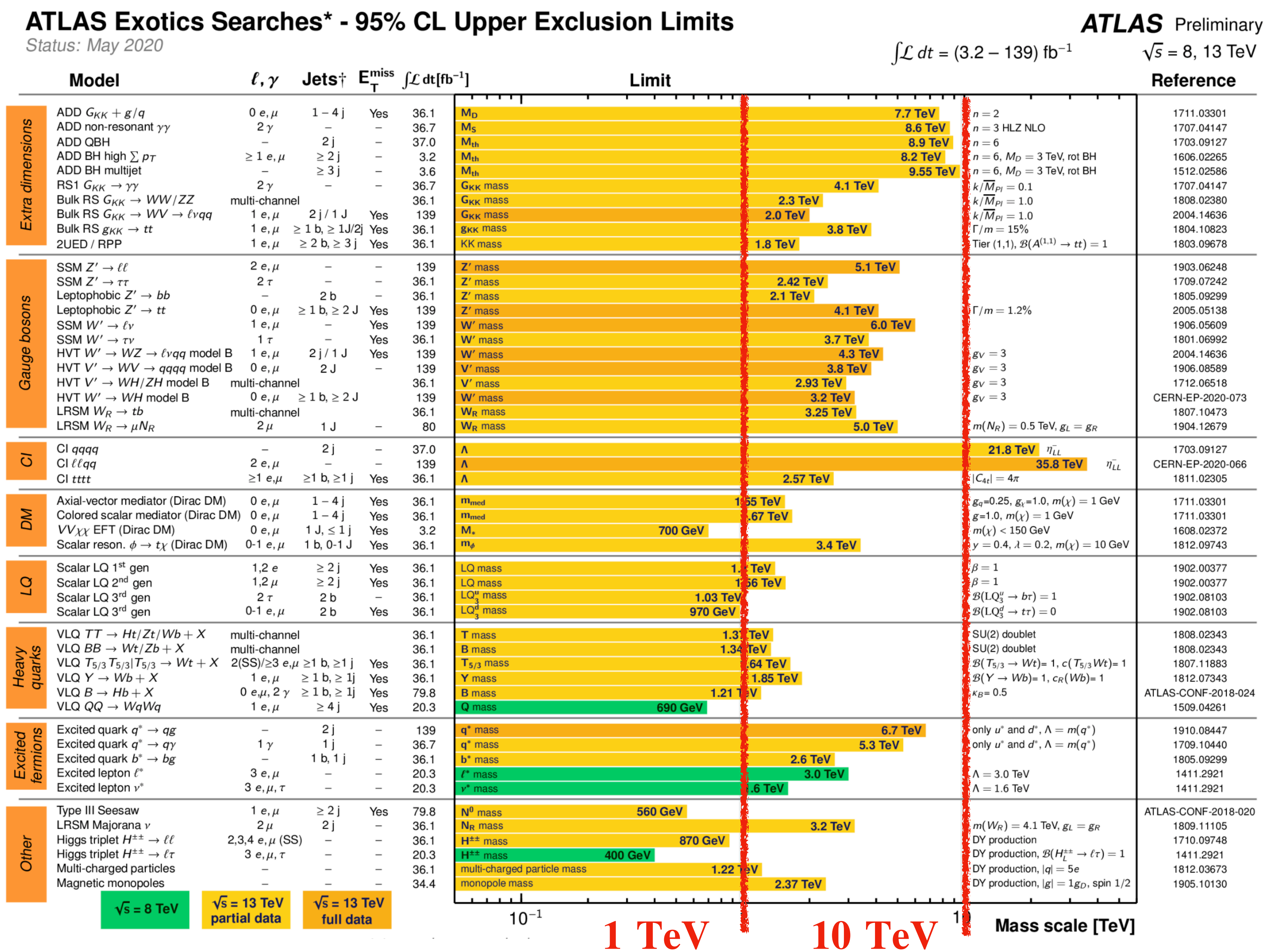
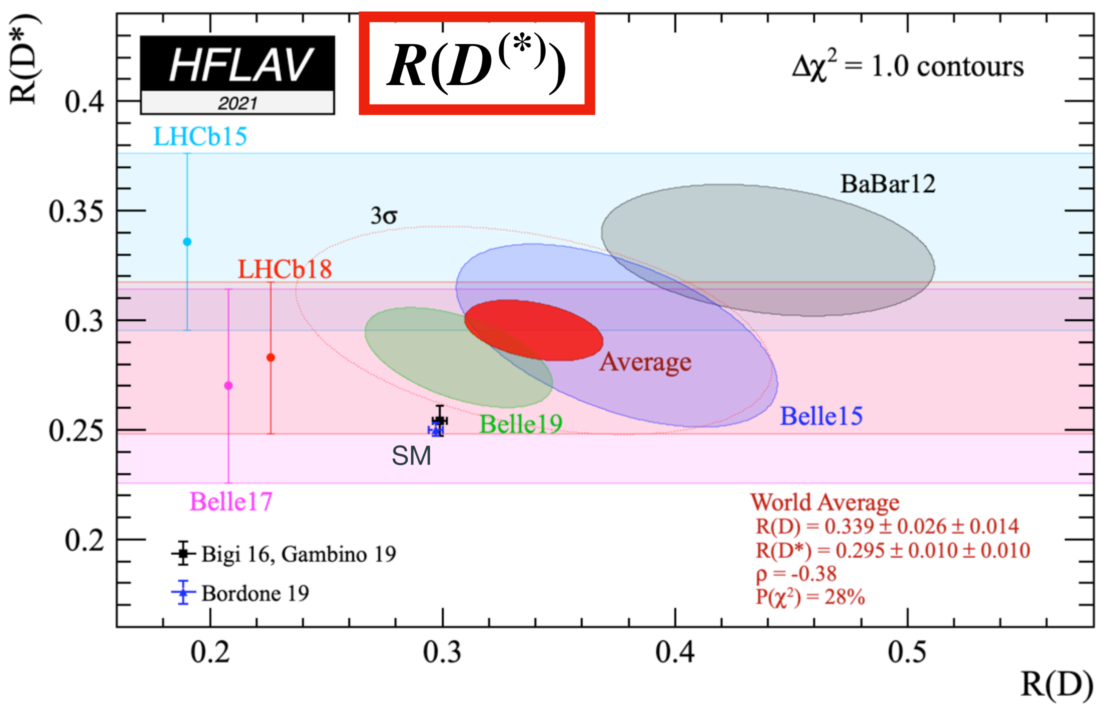
What is experiment telling us?

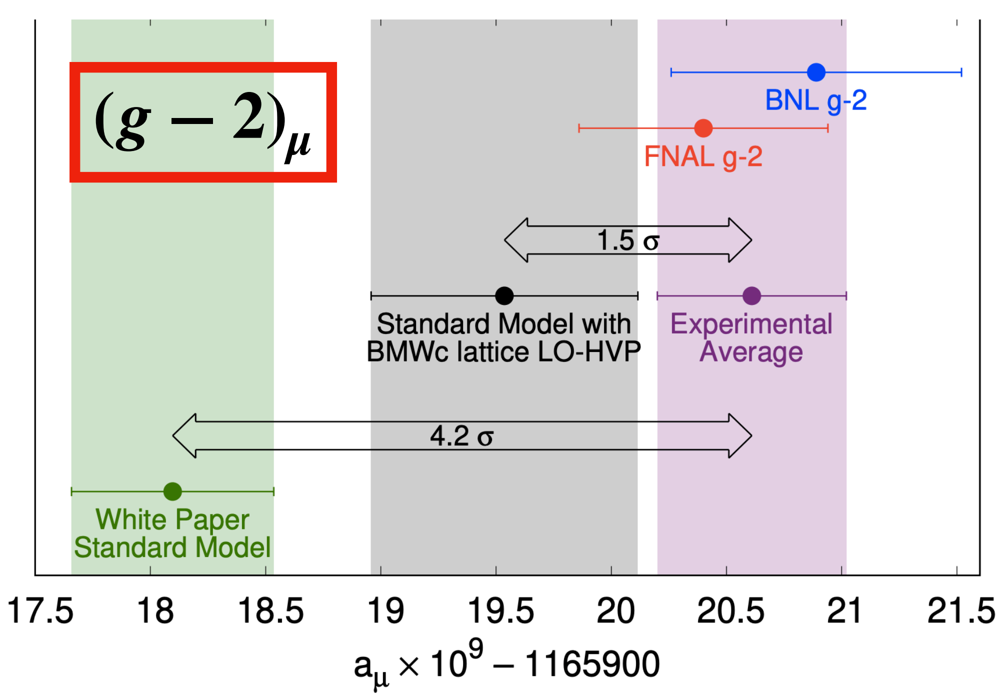
No **direct evidence** for NP despite the many reasons for it [**presence of a mass gap?**]

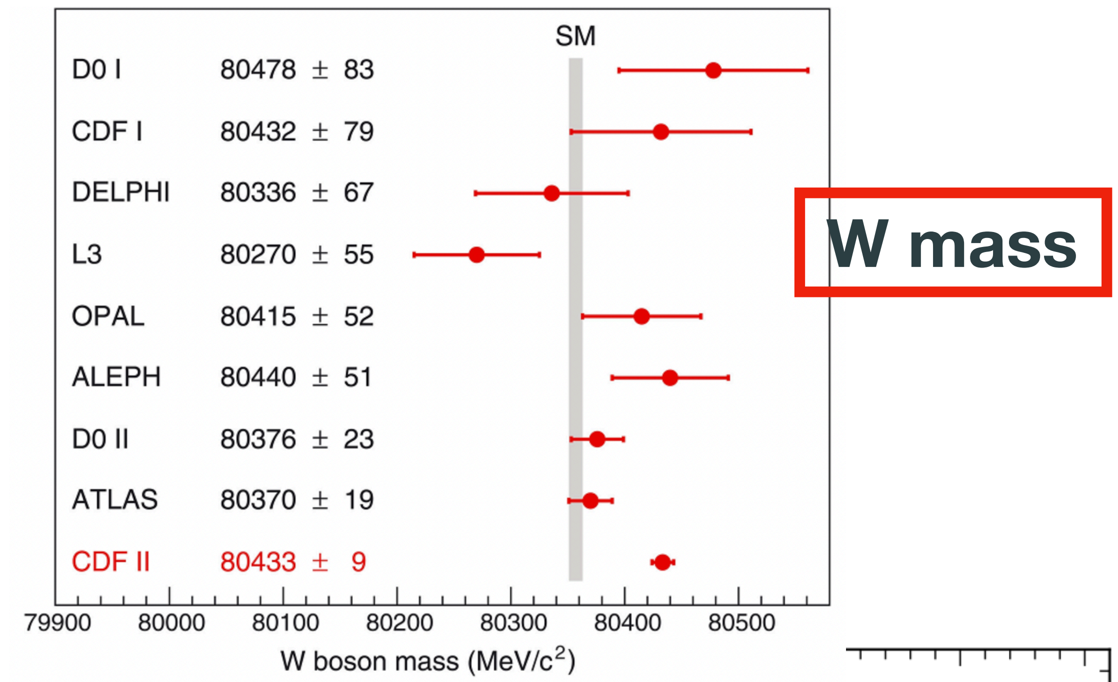


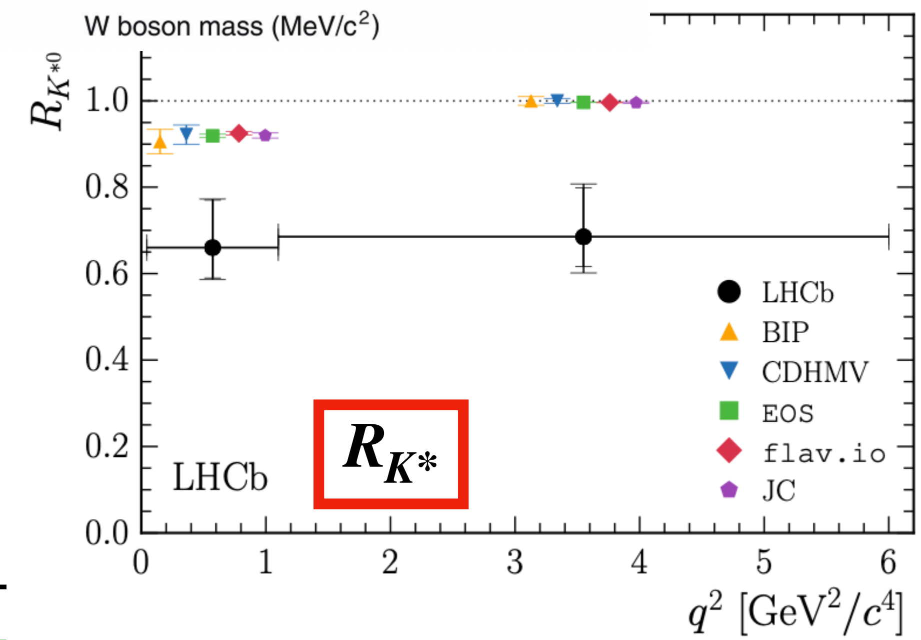
What is experiment telling us?

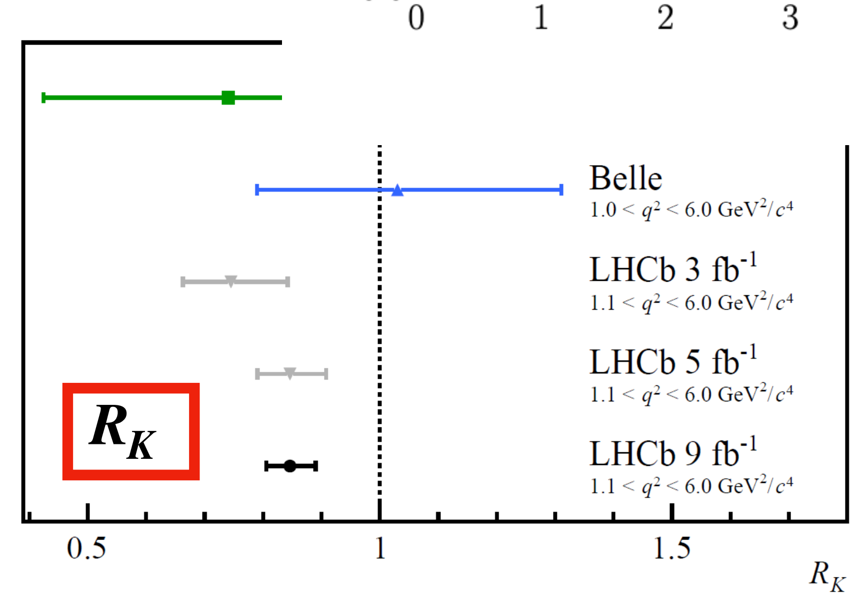
Hints of NP in **low-energy data**?





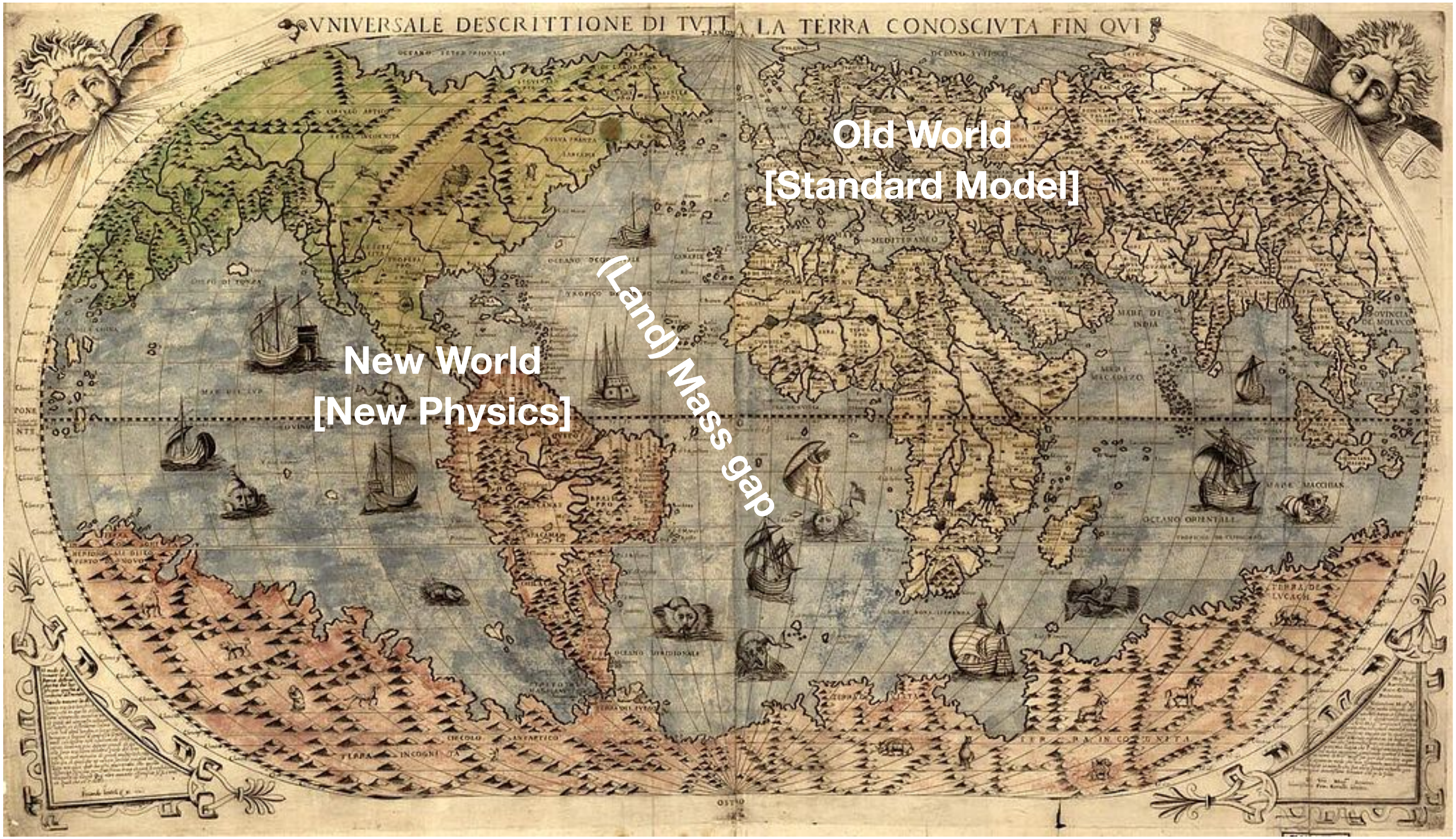






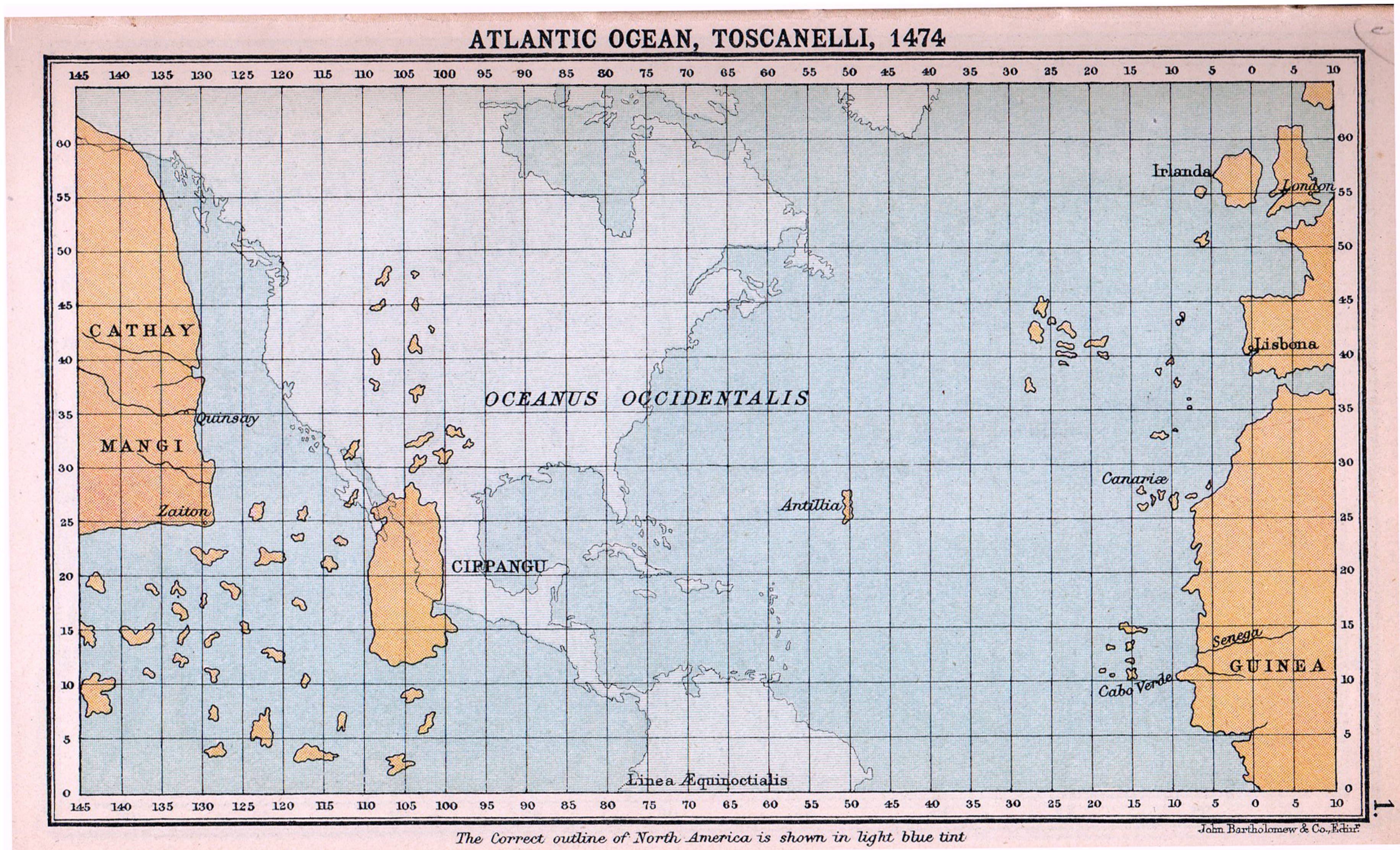
The search for Terra Incognita

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…):

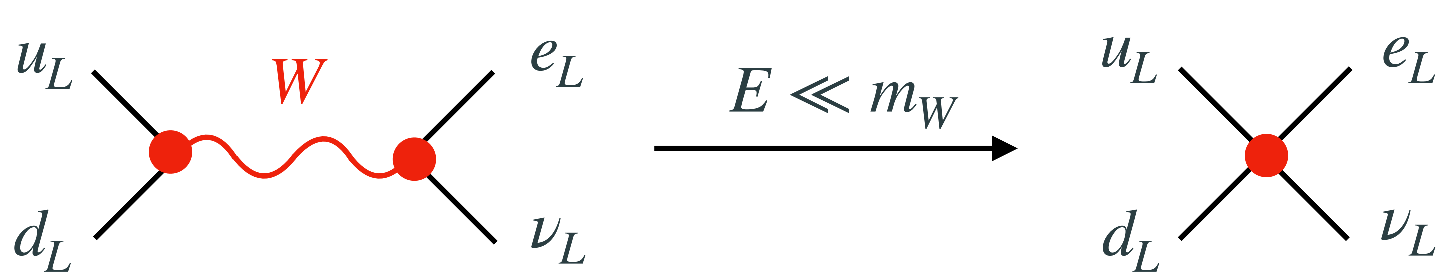
(Very) precise measurements of low-energy observables and/or possible breaking of (approximate) SM symmetries

The Fermi theory

Not the first time we have faced a mass gap in Particle Physics

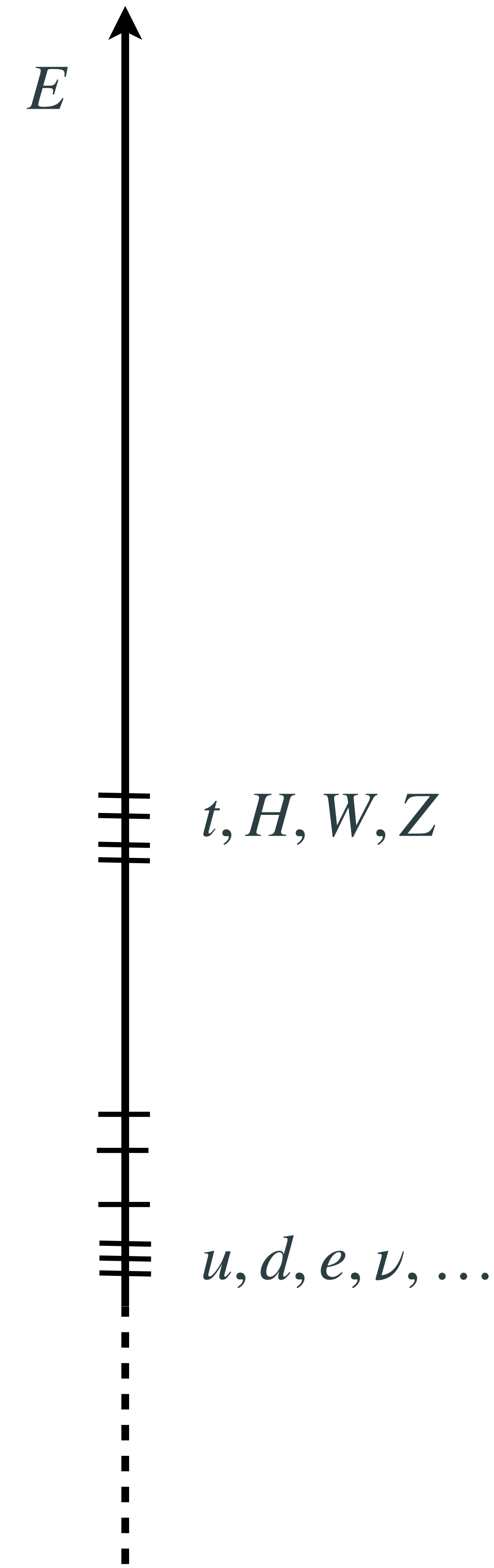
Fermi Theory [$E \ll m_W$]

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

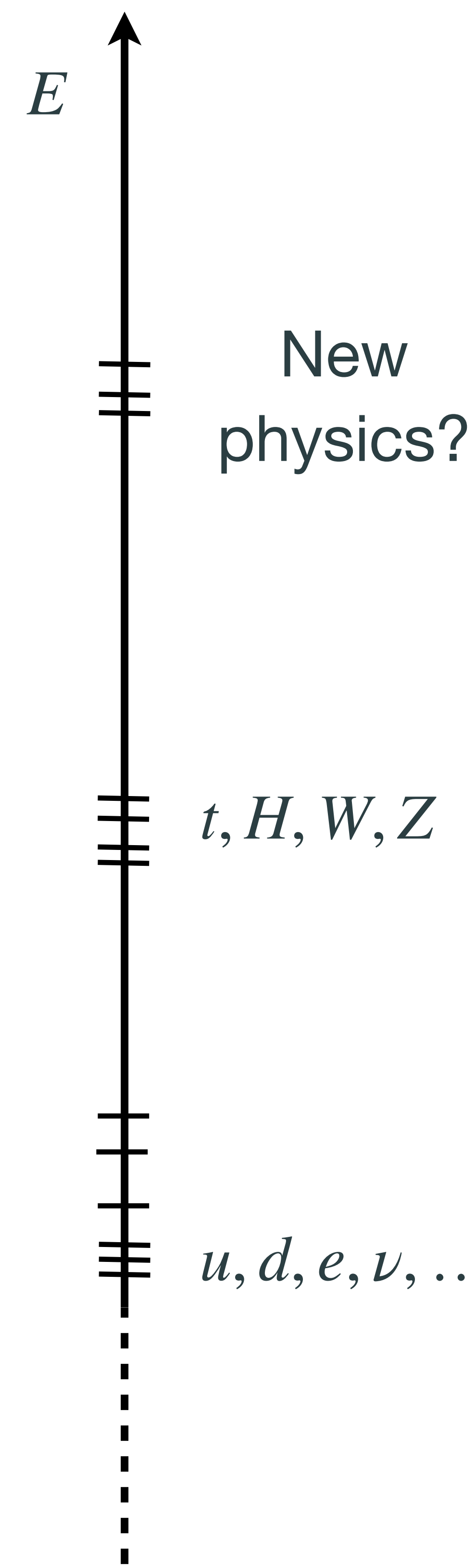


Reconstructing a UV theory from its low-energy imprints is a very difficult task (no unique solution due to limited information)

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



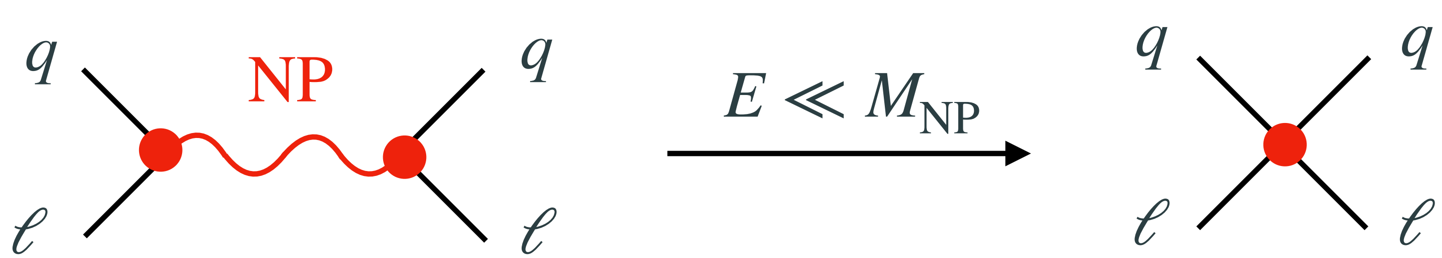
The SM effective theory (SMEFT)



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 $\mathcal{O}(\Lambda^{-2})$
- ★ 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]

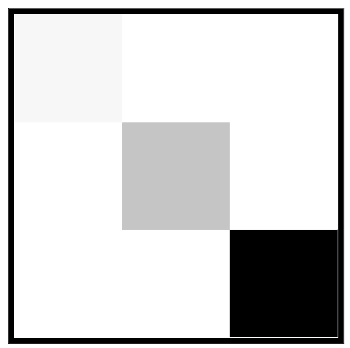
Similar structure also for NP?

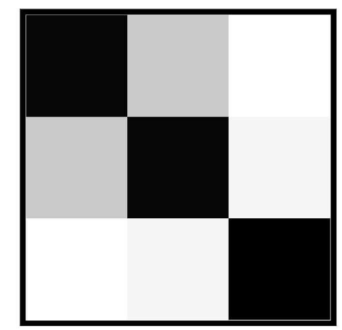
Are these two features correlated?

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

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

$V_{\rm CKM} \sim$ 

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

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

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

$U(2)_q$ $U(2)_{u(d)}$

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

$U(2)_\ell$ $U(2)_e$

$|V_q| \sim V_{cb}$

$|\Delta_u| \sim y_c$

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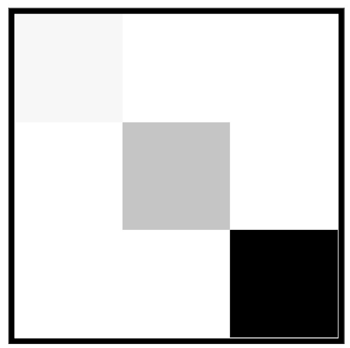
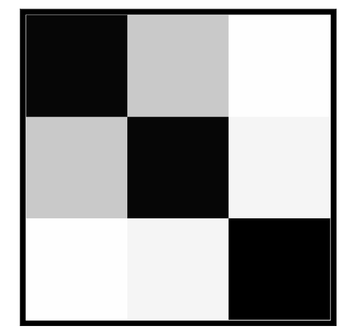
$M_{u,d,e} \sim$ 

$V_{\rm CKM} \sim$ 

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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)
  $U(1)_e \times U(1)_\mu \times U(1)_\tau$

$$\text{LFV} \ \overset{\Longrightarrow}{\not\Longleftarrow}\ \not{\text{LFU}}$$

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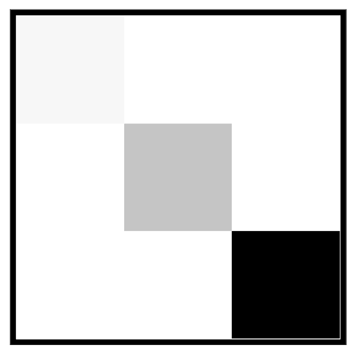
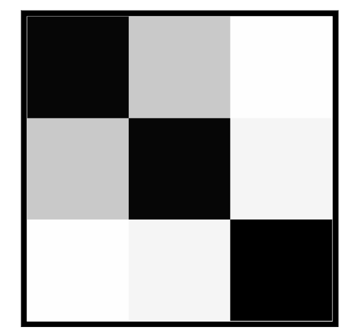
$M_{u,d,e} \sim$ 

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

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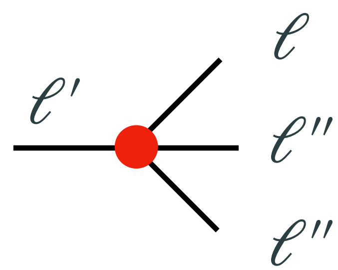
What is the origin of these symmetries? Will new physics respect any of them?

The new physics flavor problem

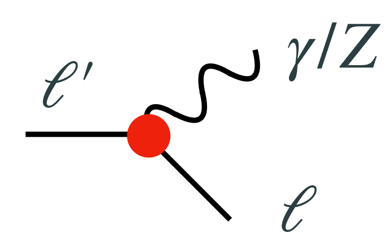
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{Gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}} + \sum_{i,d} \frac{1}{\Lambda_i^{d-4}} C_i \mathcal{O}_i^d$$

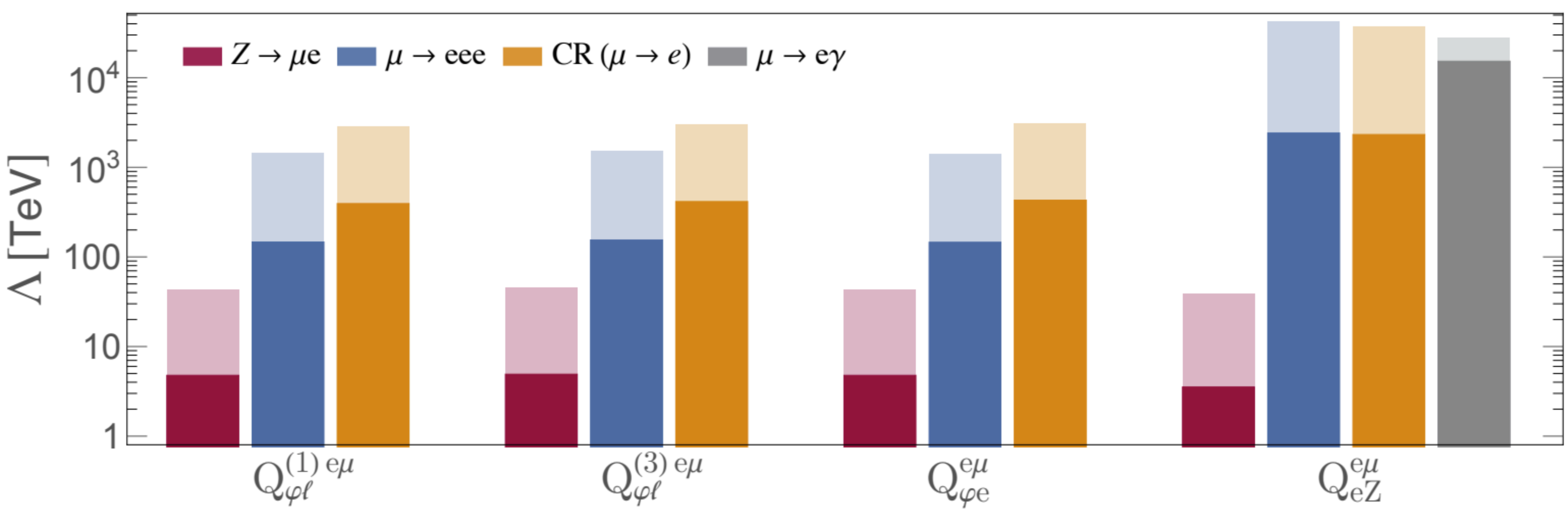
Very stringent bounds on the new physics scale if it has a generic flavor structure (far too heavy to be directly probed or to stabilize the Higgs)

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



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





[Calibbi, Marcano, Roy, 2107.10273]

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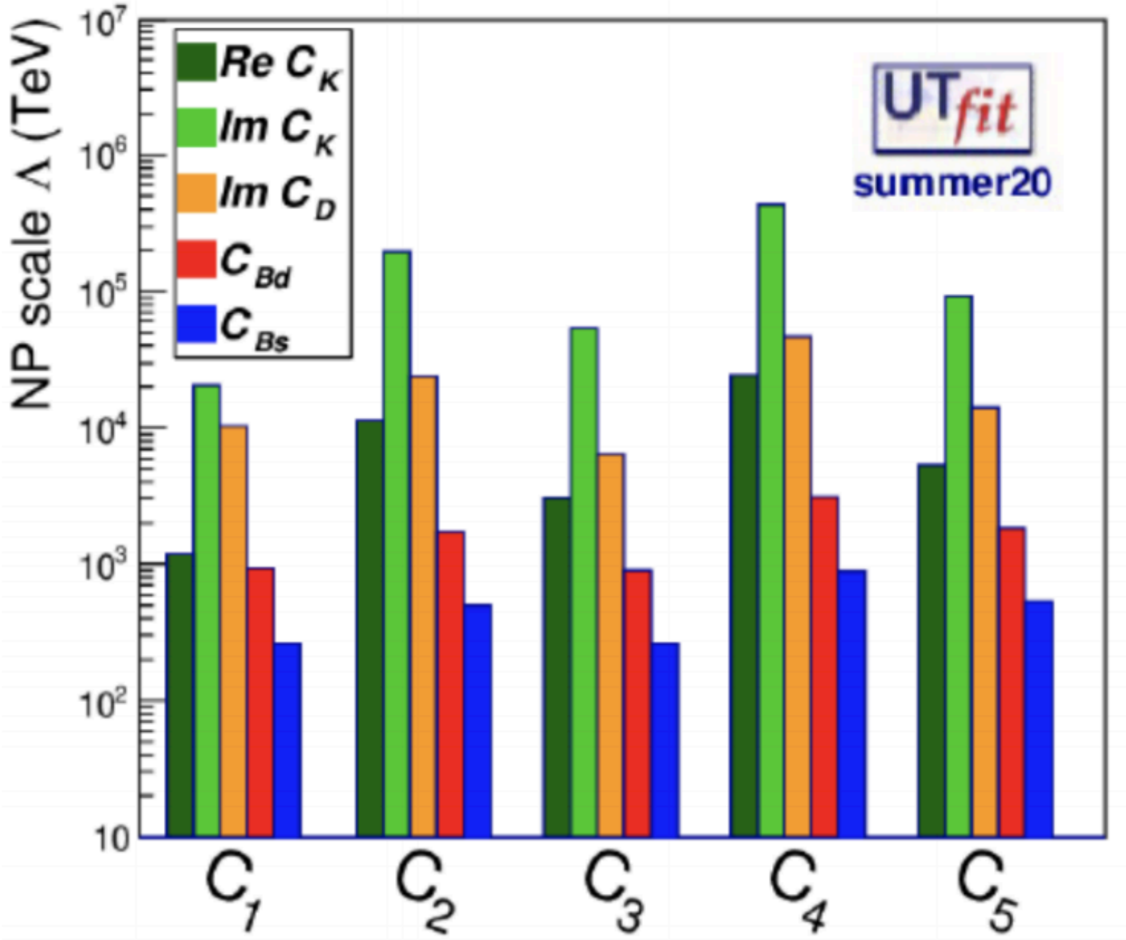
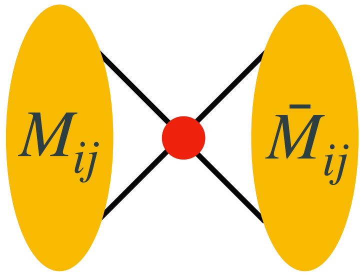


$$\frac{1}{\Lambda^2}(\bar{q}_i\, q_j)^2$$



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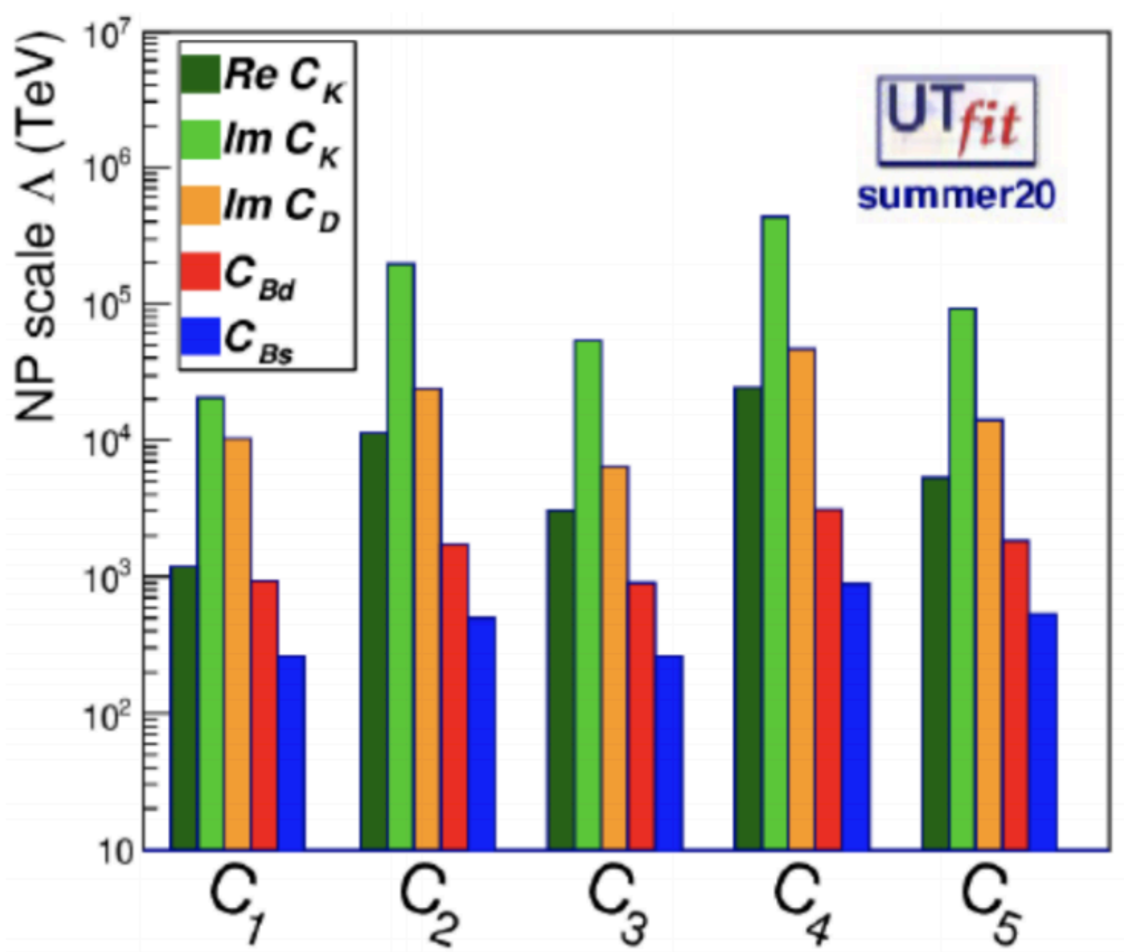
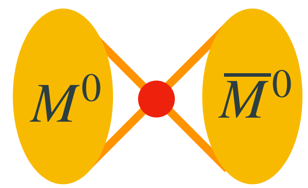
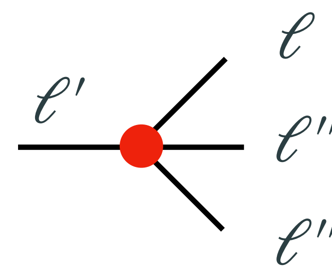


$$\frac{1}{\Lambda^2}(\psi_i\psi_j)^2$$





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

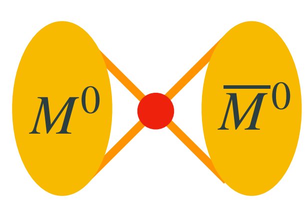
$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm Gauge} + \mathscr{L}_{\rm Higgs} + \mathscr{L}_{\rm Yukawa} + \sum_{i,d} \frac{1}{\Lambda_i^{d-4}} C_i\, \mathcal{O}_i^d$$

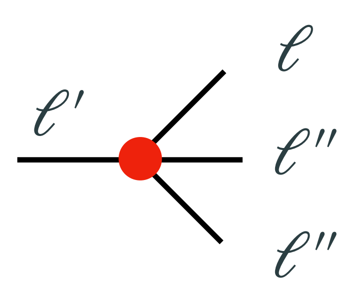
Non-trivial UV imprints

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

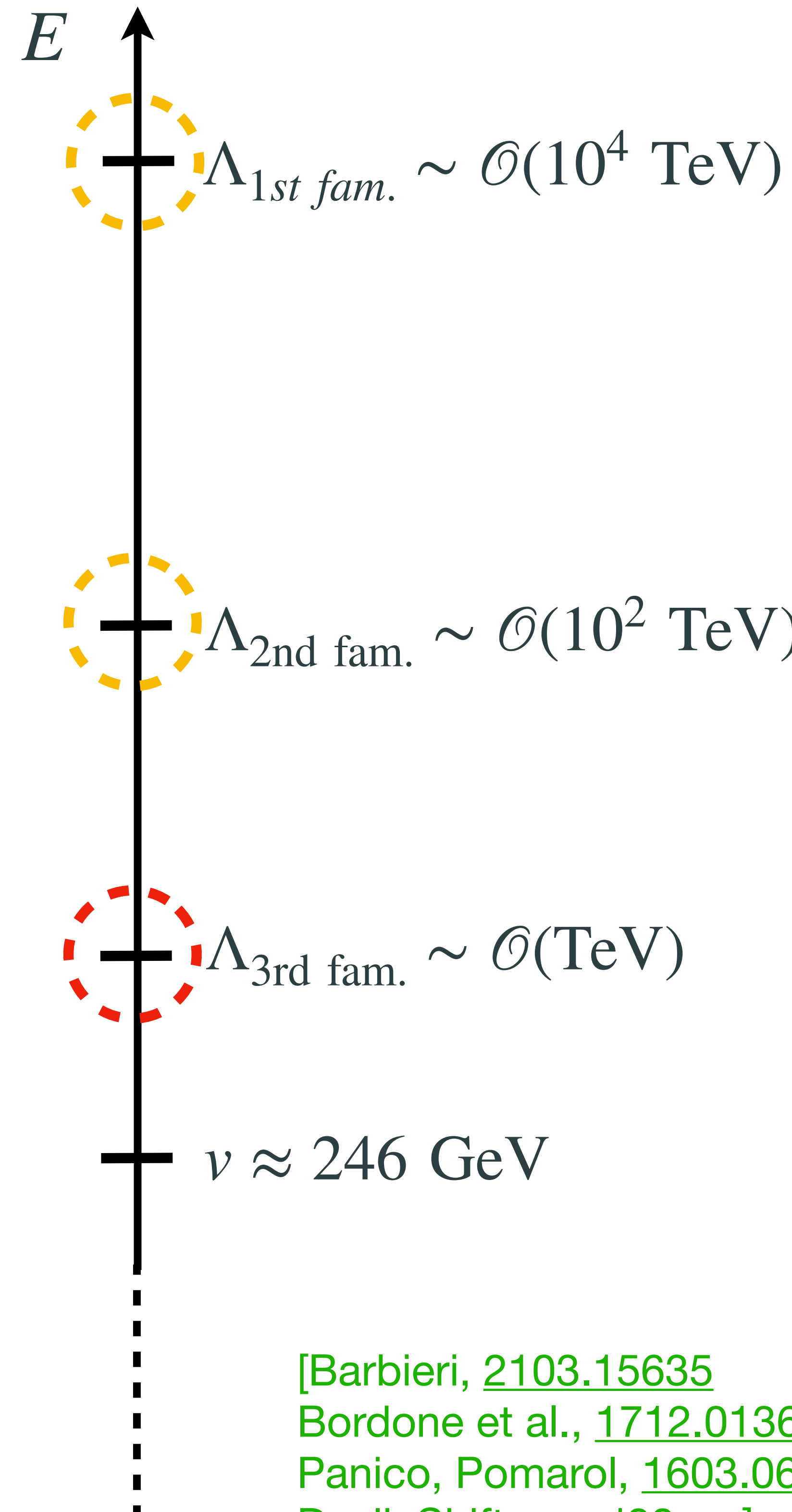
★ TeV-scale NP dominantly coupled to third family [protection from flavor constraints]

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, …]

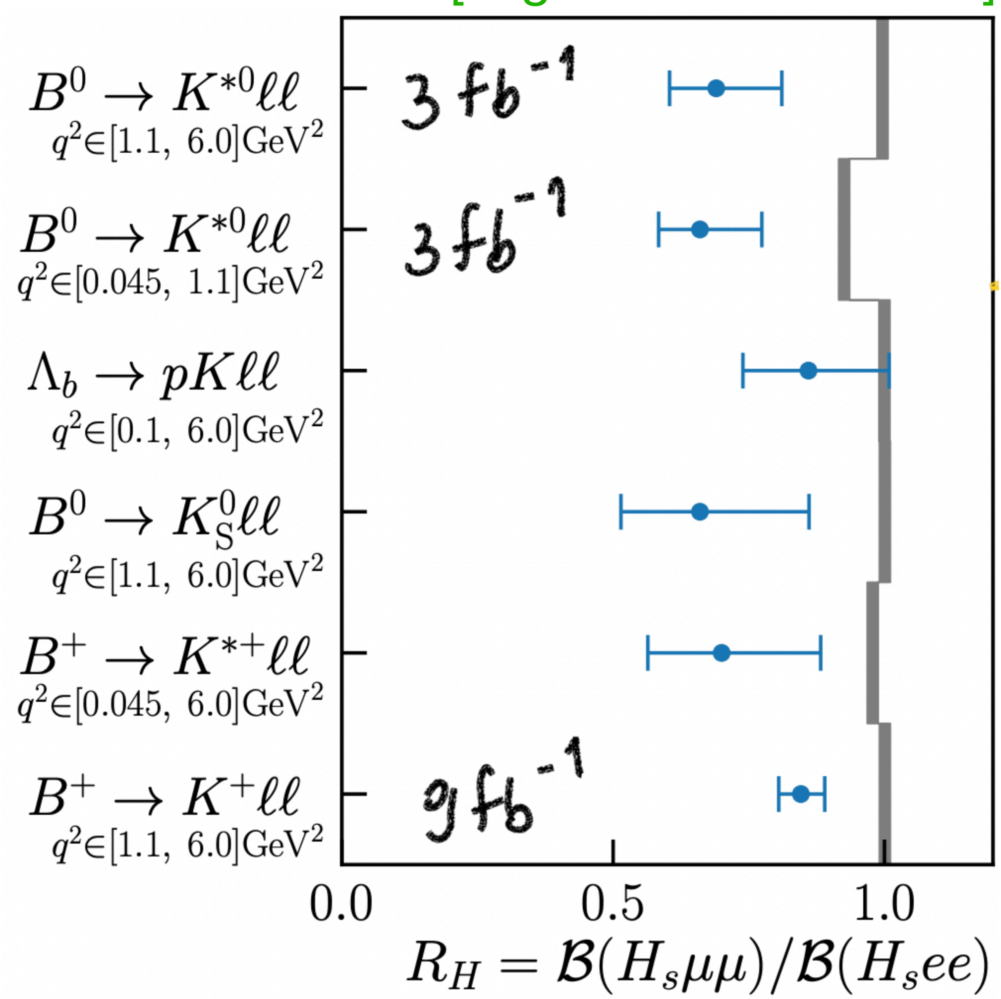
B-physics anomalies

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

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

μ/e ~~universality~~

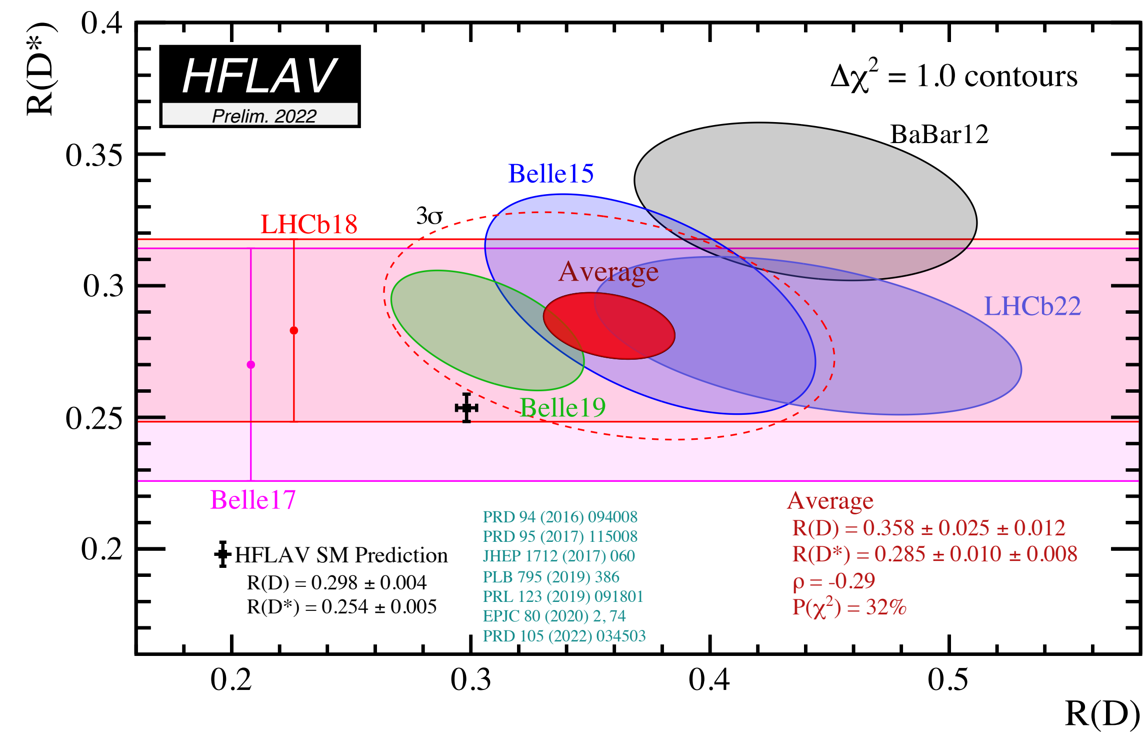
[Fig. from M. Borsato]



LHCb

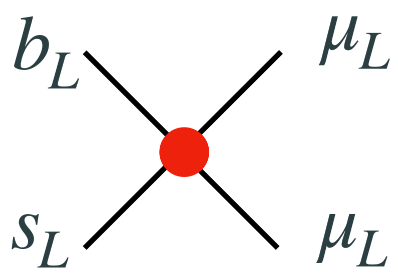
$b \to c\tau\nu$

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



BaBar + Belle + LHCb

Consistency of B anomalies with multi-scale picture



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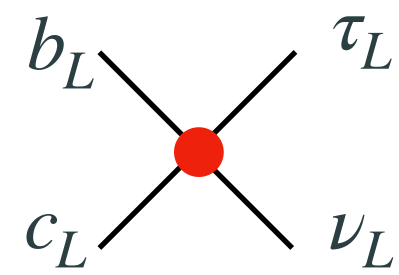

$$\sim \frac{1}{(1\ \mathrm{TeV})^2} |V_q|\,|V_\ell|^2 \qquad\qquad \sim \frac{1}{(1\ \mathrm{TeV})^2} |V_q|$$

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

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 $|V_q| \sim V_{cb} \approx 0.04$]

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 (plus almost 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?

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

Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B_s^0 / $\overline{B}_s^0$	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 $f_{B_c}/(f_{B_u} + f_{B_d}) \sim 3.7 \cdot 10^{-3}$

[Table from 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 experiments

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

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

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$B^0 \to \mu^+\mu^-$	~ 5	–	~ 50	~ 100
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$B^+ \to \tau^+\nu$	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 $B_s \to K^*\ell^+\ell^-$

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

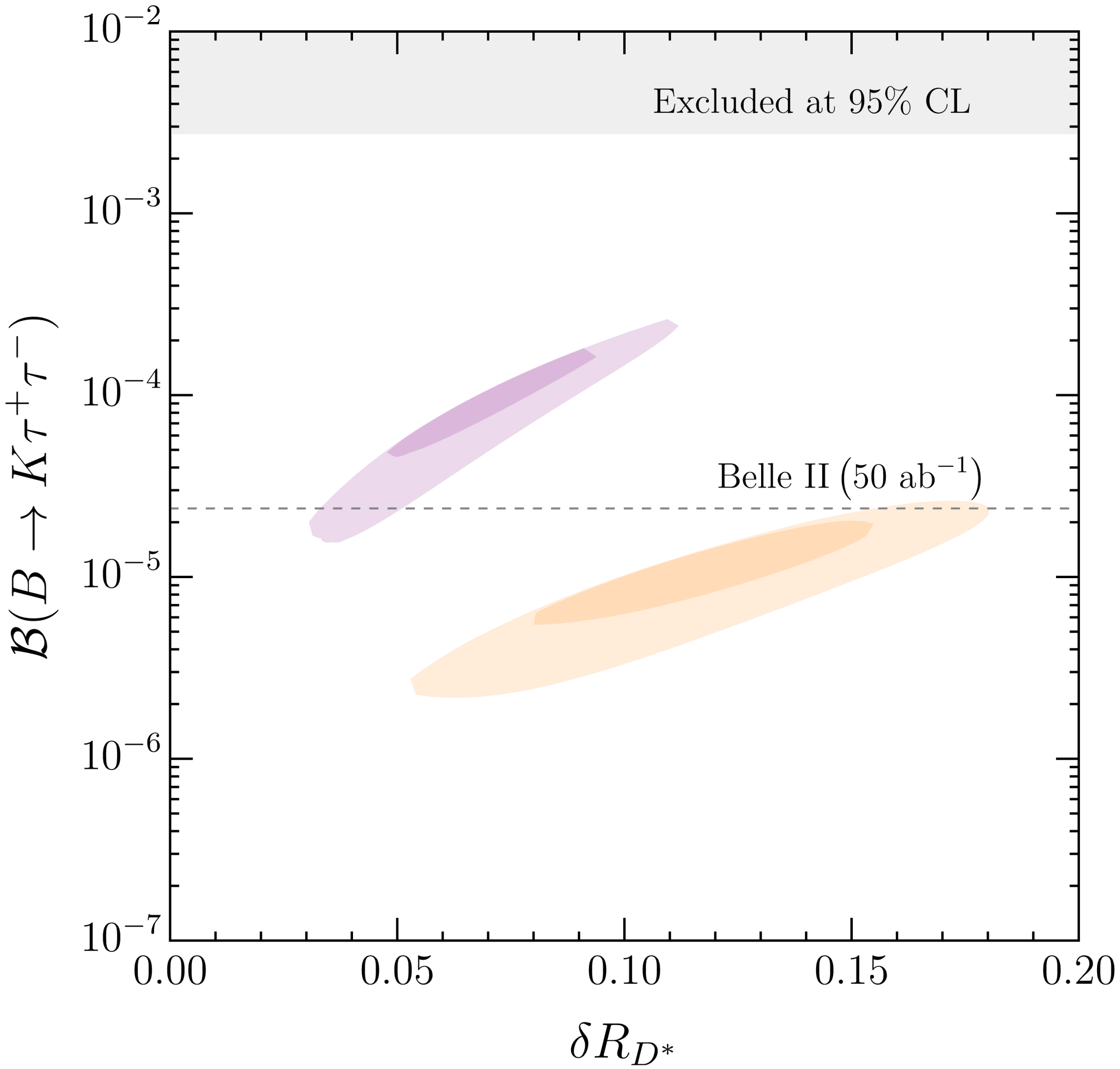
$$\frac{b \to s\ell\ell}{b \to d\ell\ell} = \left.\frac{b \to s\ell\ell}{b \to d\ell\ell}\right|_{\mathrm{SM}} \qquad \frac{b \to c\ell\nu}{b \to u\ell\nu} = \left.\frac{b \to c\ell\nu}{b \to u\ell\nu}\right|_{\mathrm{SM}}$$

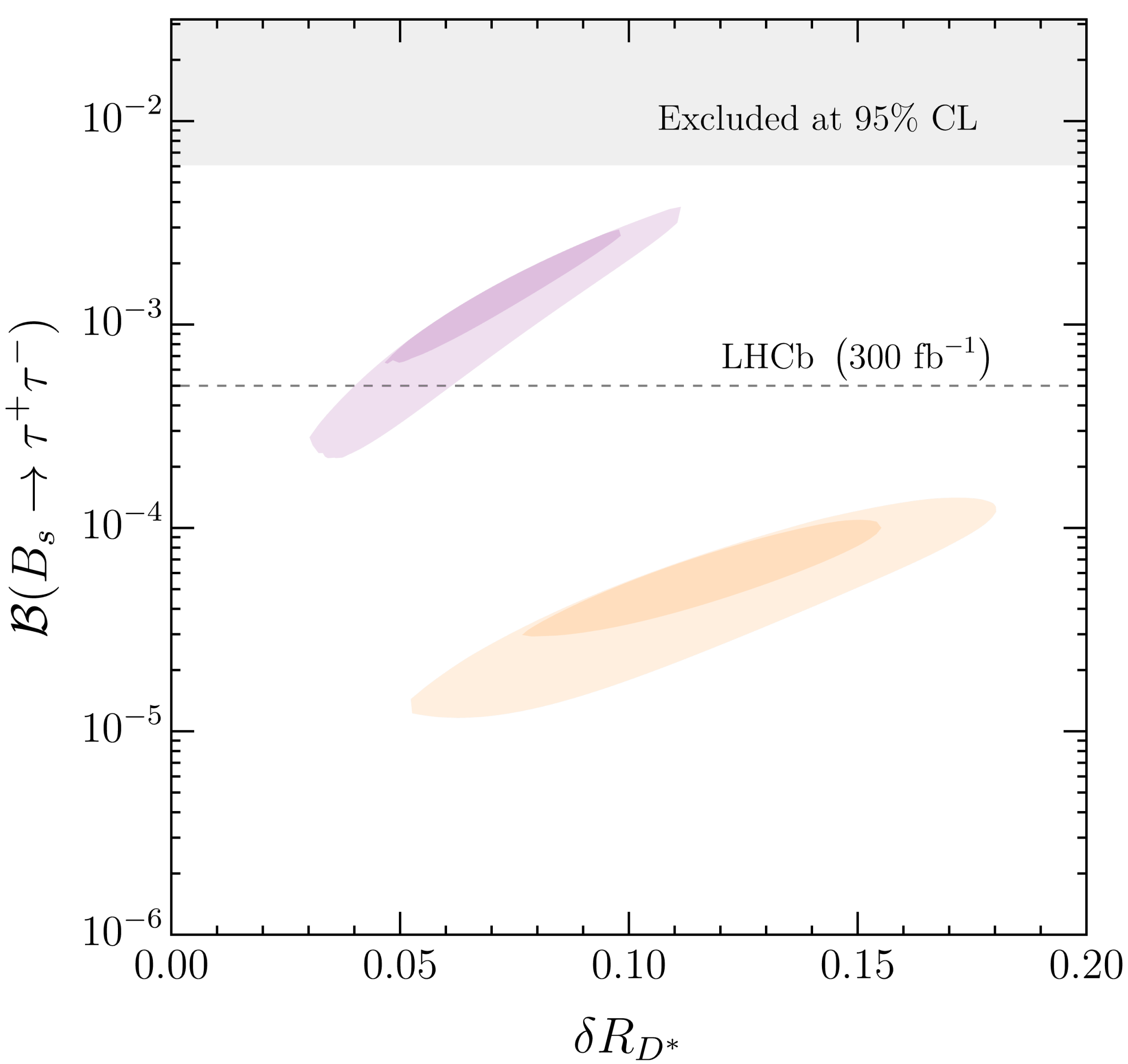
$b \to s\tau^+\tau^-$ predictions in U_1 leptoquark model

Comparison of $b \to s\tau^+\tau^-$ 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]





Relevant parameter space would be fully probed at FCC-ee!

Probing new physics with τ/W decays

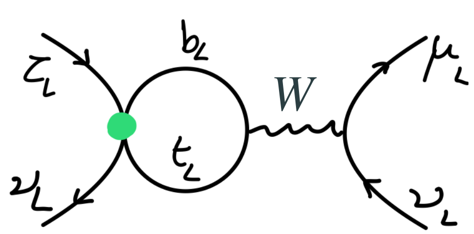
$$\left|g_e^{(\tau)}/g_e^{(\mu)}\right|^2 \equiv \frac{\Gamma(\tau\to e\nu\bar{\nu})}{\Gamma(\mu\to e\nu\bar{\nu})}\left[\frac{\Gamma_{\rm SM}(\tau\to e\nu\bar{\nu})}{\Gamma_{\rm SM}(\mu\to e\nu\bar{\nu})}\right]^{-1}$$

[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)			

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

$$\Downarrow$$



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

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

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

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

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

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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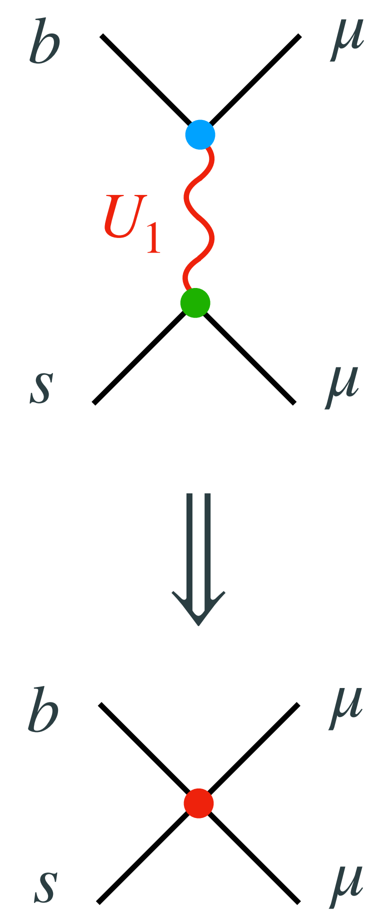
E.g. U_1 vector LQ

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



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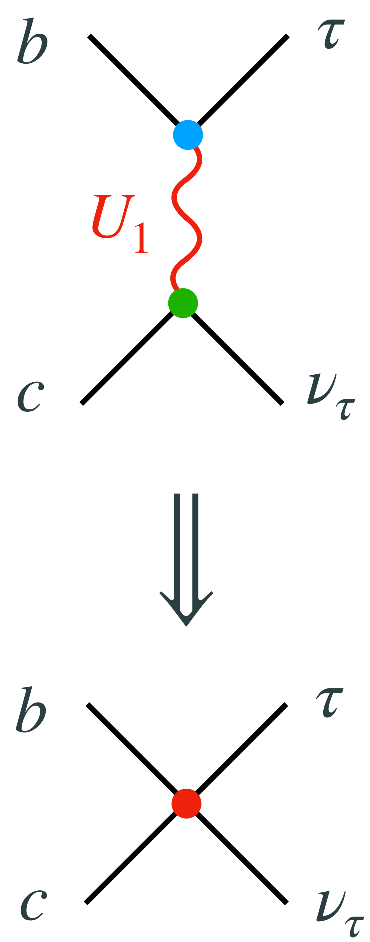
g_{lq}^{22}	$\boldsymbol{g_{lq}^{32}}$



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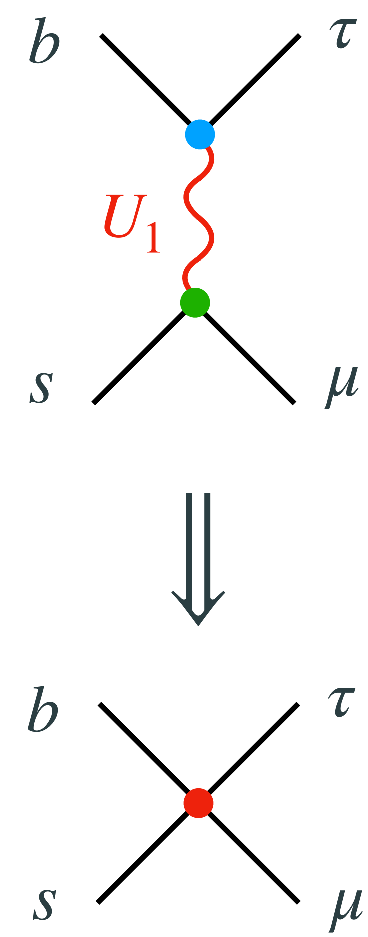
$b \to s\tau^-\mu^+$	$b \to s\mu^+\mu^-$	$b \to c\tau\nu$
	g_{lq}^{23}	g_{lq}^{33}
	g_{lq}^{22}	g_{lq}^{33}



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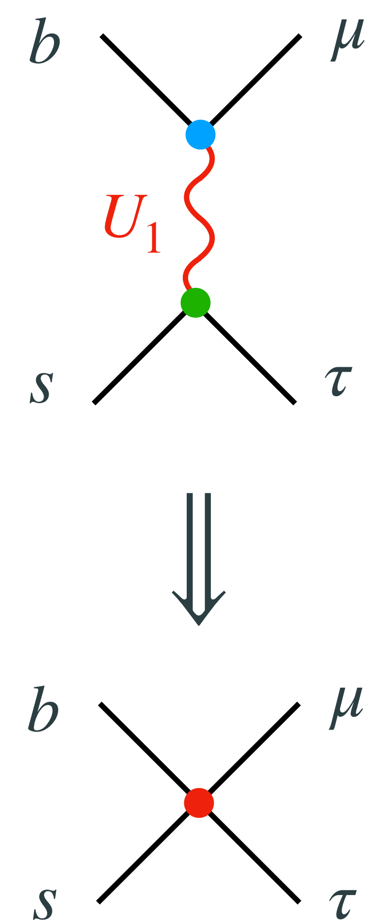
$b \to s\tau^-\mu^+$

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

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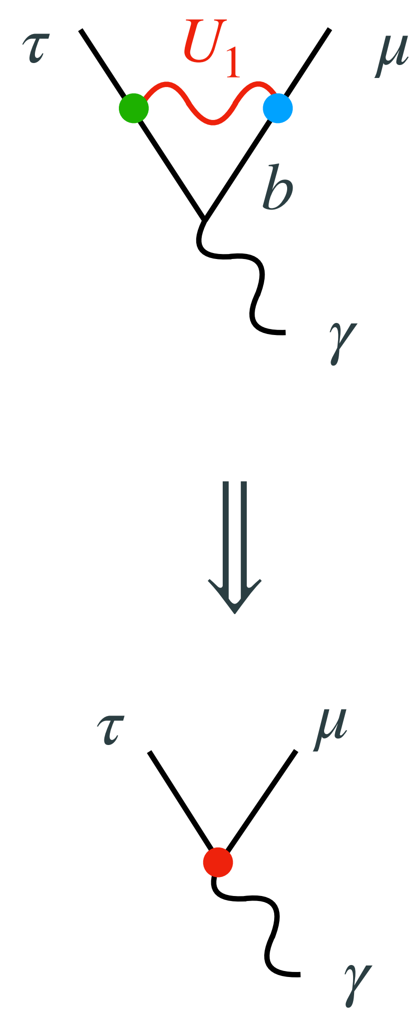
	$b \to s\mu^+\mu^-$	$b \to c\tau\nu$
$b \to s\tau^-\mu^+$		
$b \to s\tau^+\mu^-$		
$\boldsymbol{\tau \to \mu\gamma}$	$\boldsymbol{g_{lq}^{23}}$	$\boldsymbol{g_{lq}^{33}}$
	g_{lq}^{22}	g_{lq}^{32}



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

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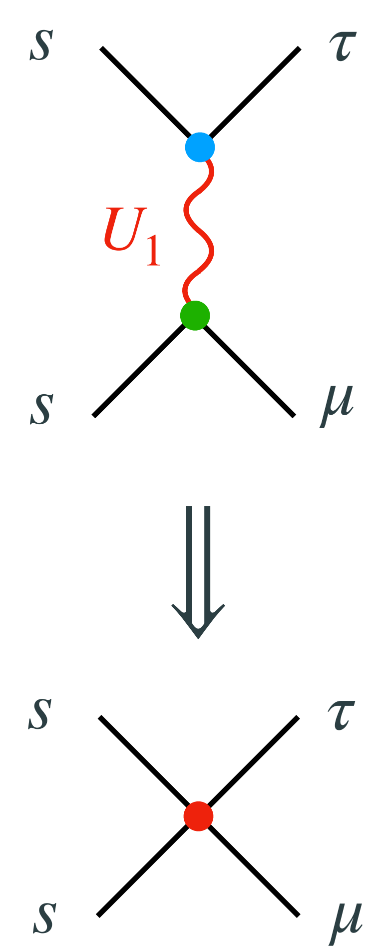
$b \to s\tau^-\mu^+$

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

$\tau \to \mu\gamma$

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

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



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
$\Longrightarrow$ Lepton Flavor Violation!

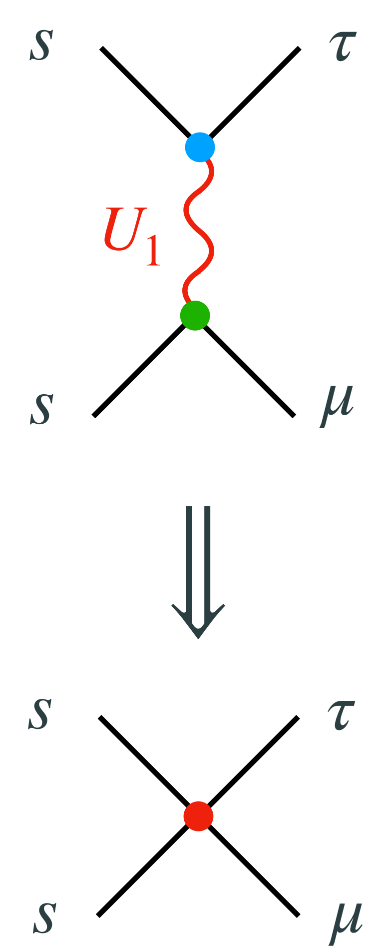
$b \to s\tau^-\mu^+$

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

$\tau \to \mu\gamma$

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

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

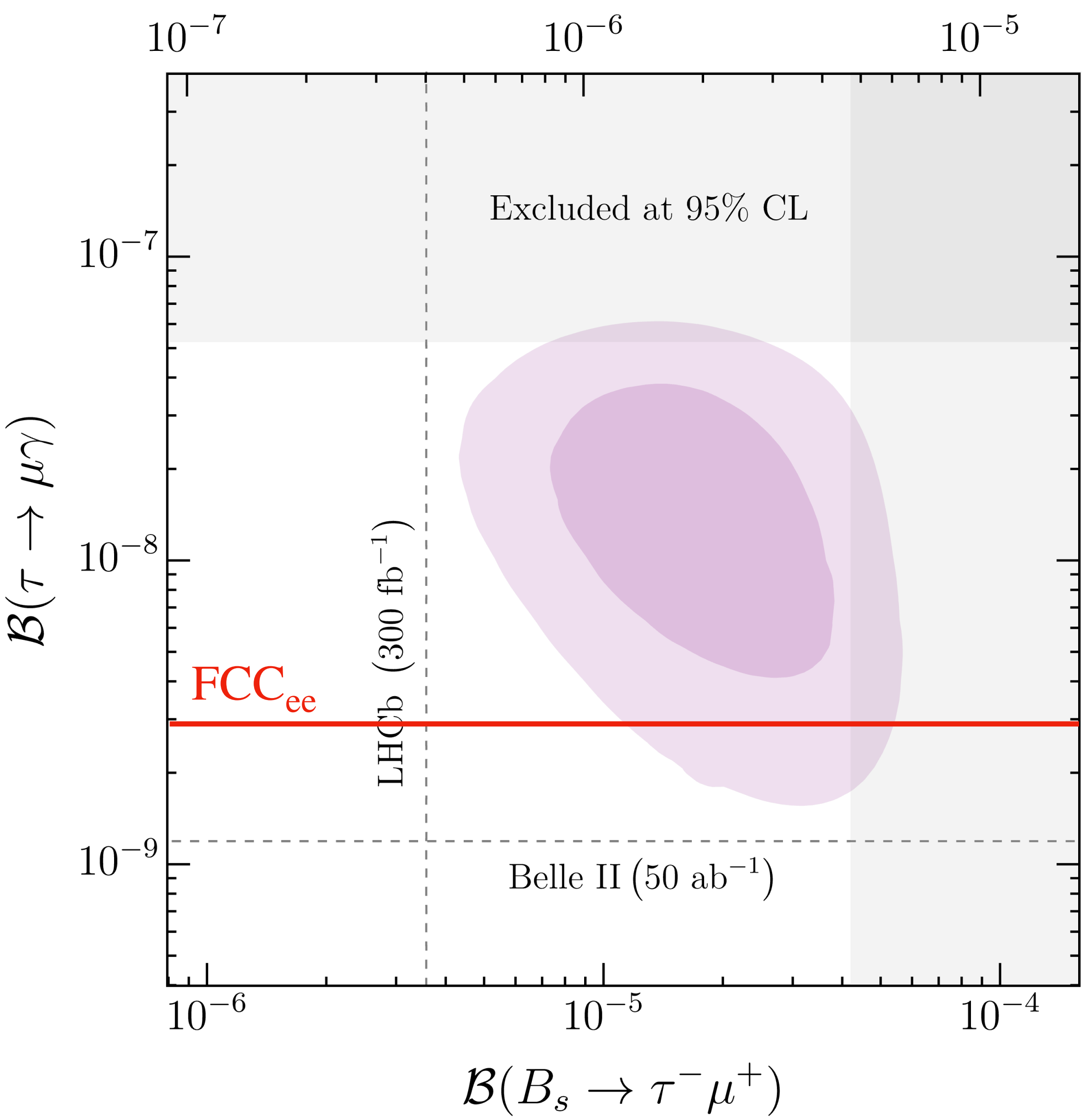


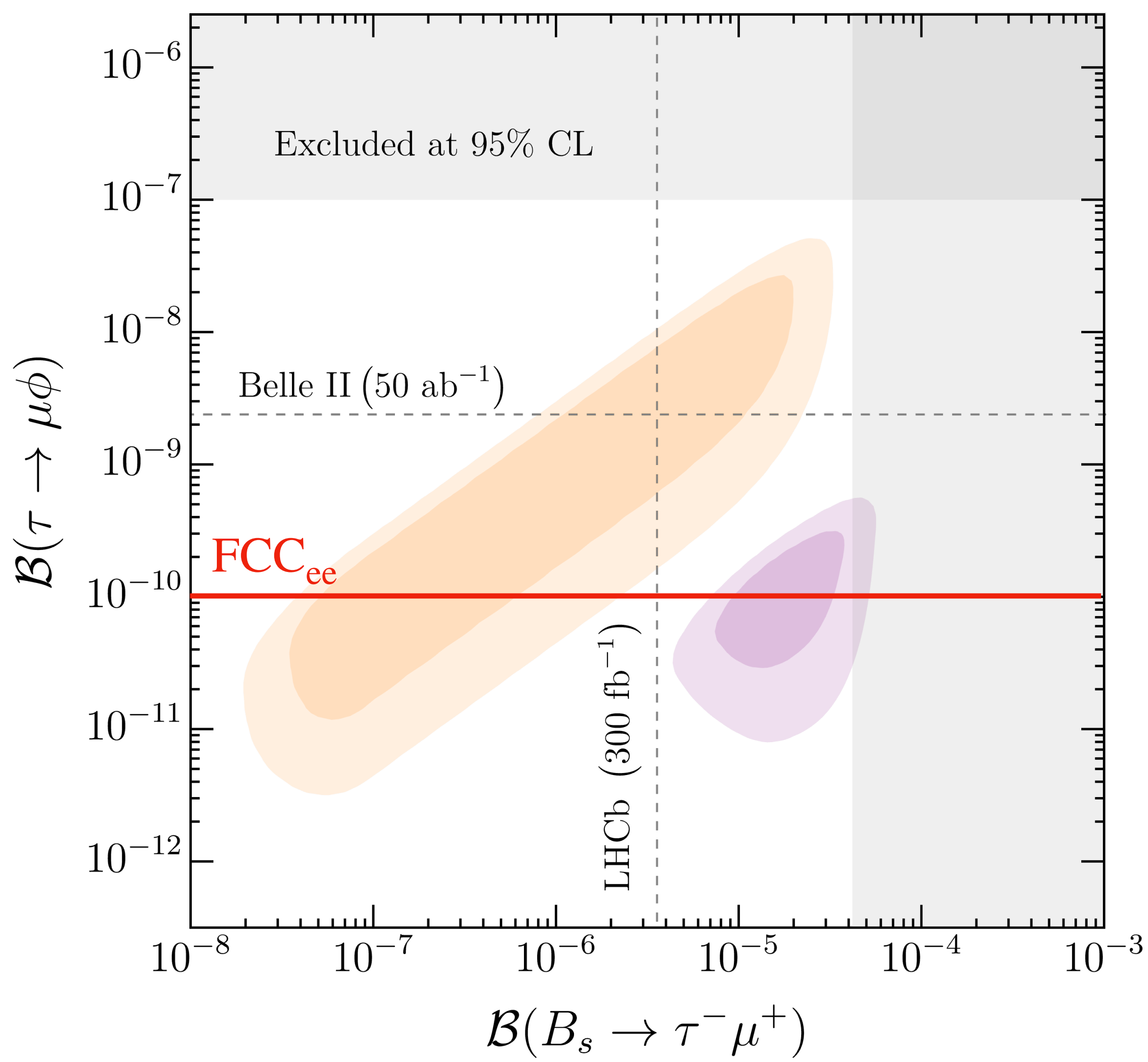
N.B.: In a theory of flavor (or a more complete model) $\mu \to e$ LFV would also be expected!

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

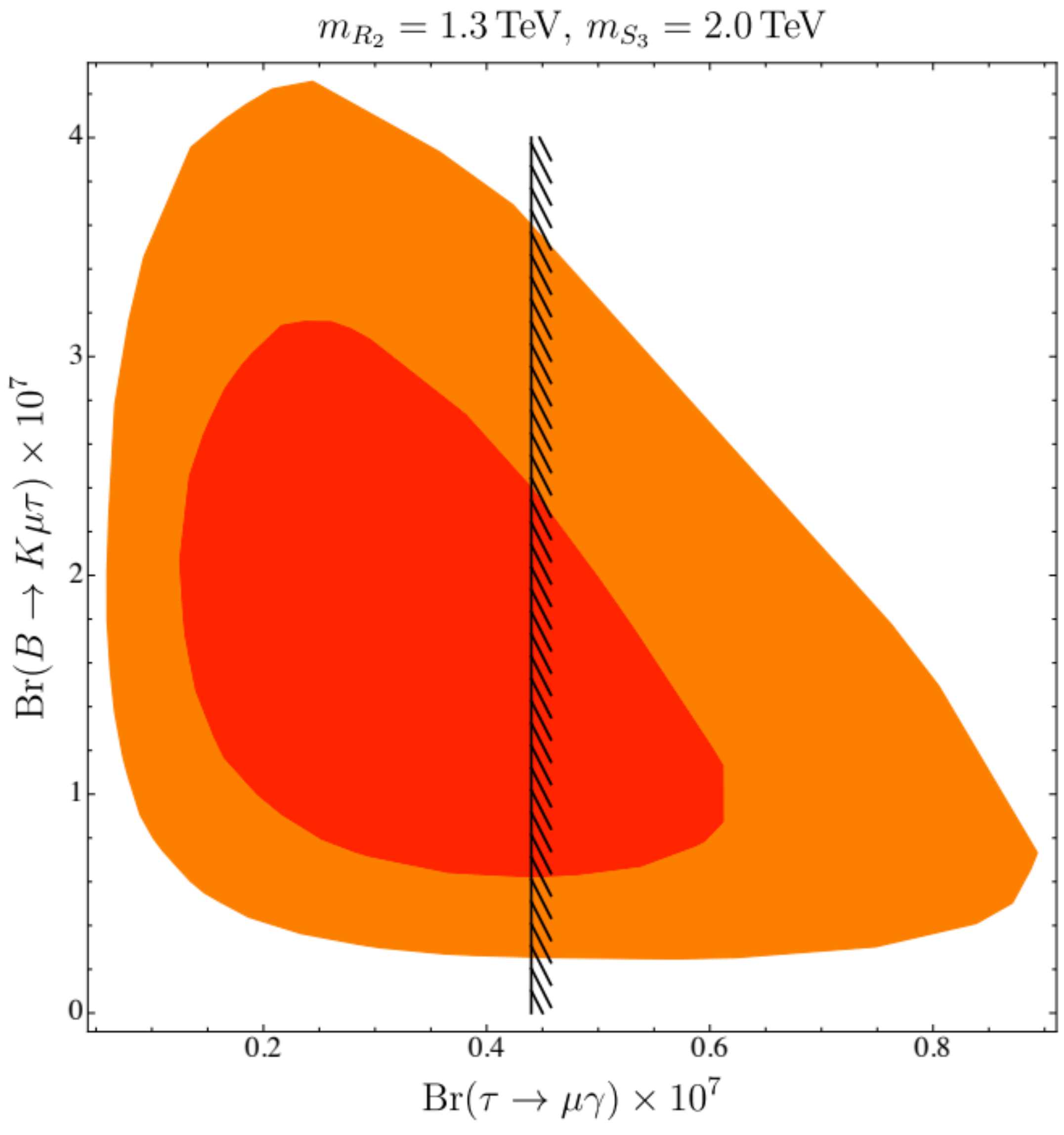




[Cornella, JFM et al., 2103.16558]

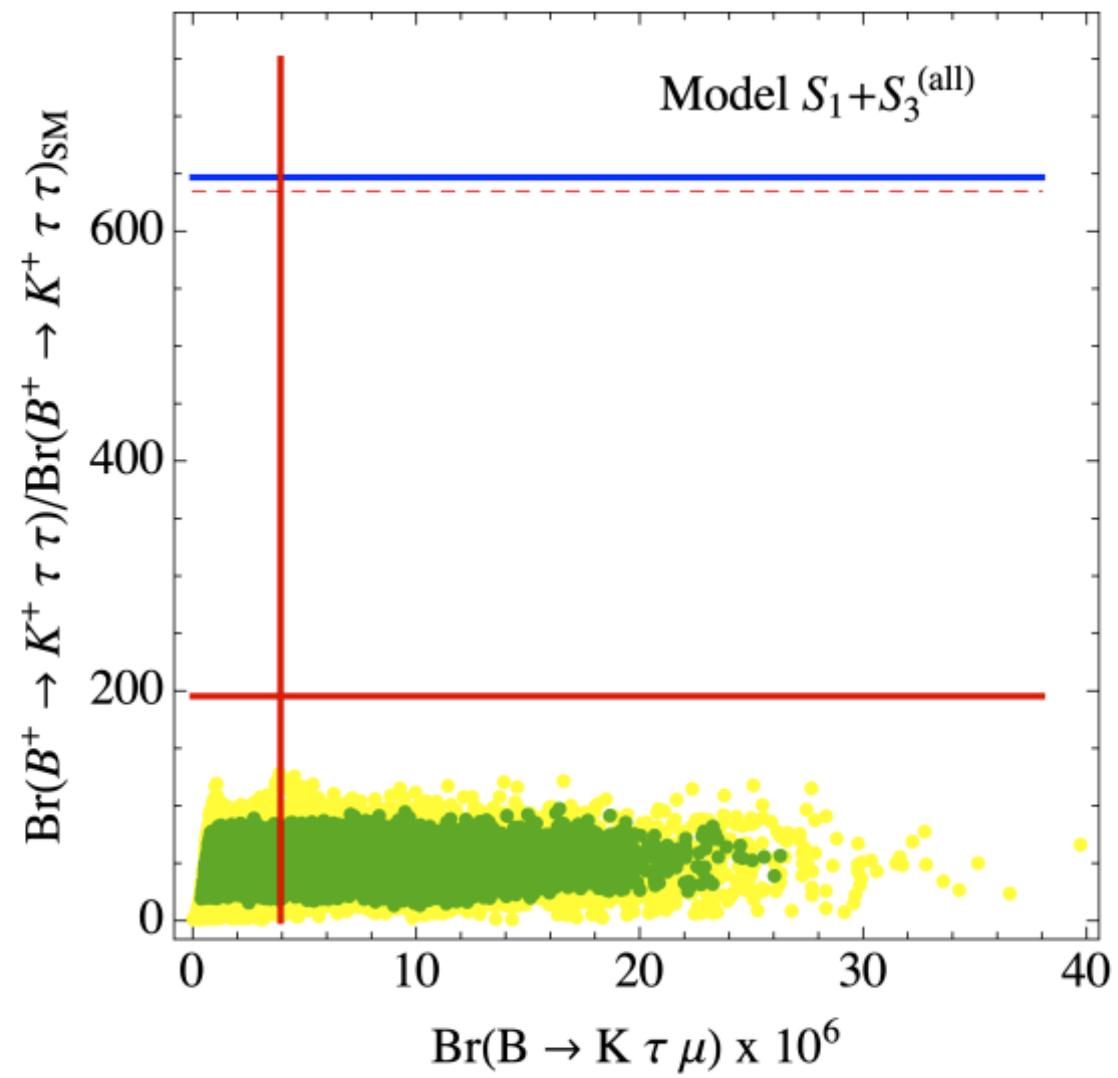
LFV predictions in other leptoquark models

$R_2 + S_3$



[Bečirević et al., 2206.09717]

$S_1 + S_3$



[Gherardi, Marzocca, Venturini, 2008.09548]

Conclusions

Although we have not yet seen any *clear* indications of new physics (either direct or indirect), several interesting ideas remain feasible and promising (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!