Probing New Physics with Rare Decays

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INFN Trieste

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The Flavour of the Standard Model

Most of the **richness and complexity** of the Standard Model comes from the **Yukawa sector:**

$$\mathcal{L}_{SM}^{Yuk} = - y_e^{ij} \bar{L}'_i e'_j H - y_d^{ij} \bar{Q}'_i d'_j H - y_u^{ij} \bar{Q}'_i u'_j \tilde{H} + h.c.$$

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the **QCD mass gap** (pion mass), **$0 < m_e \ll m_{p,n}$** , **CKM** mixing, …

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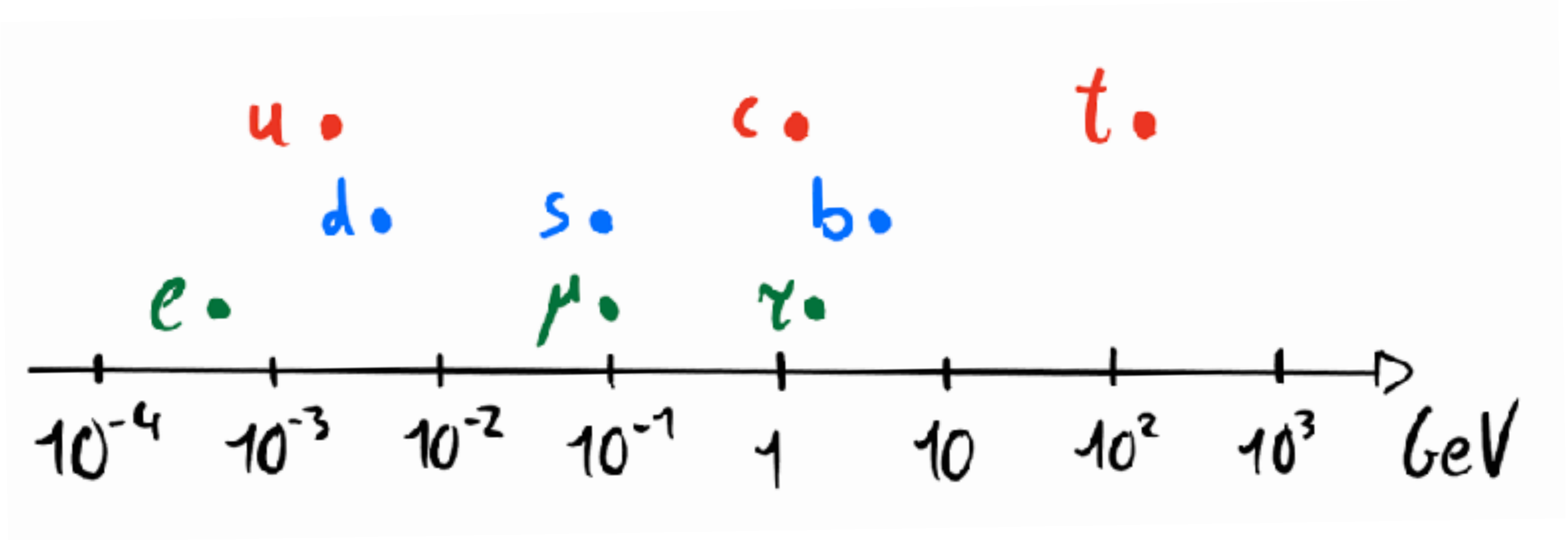
($m_\nu \sim 10^{-11}$ GeV)



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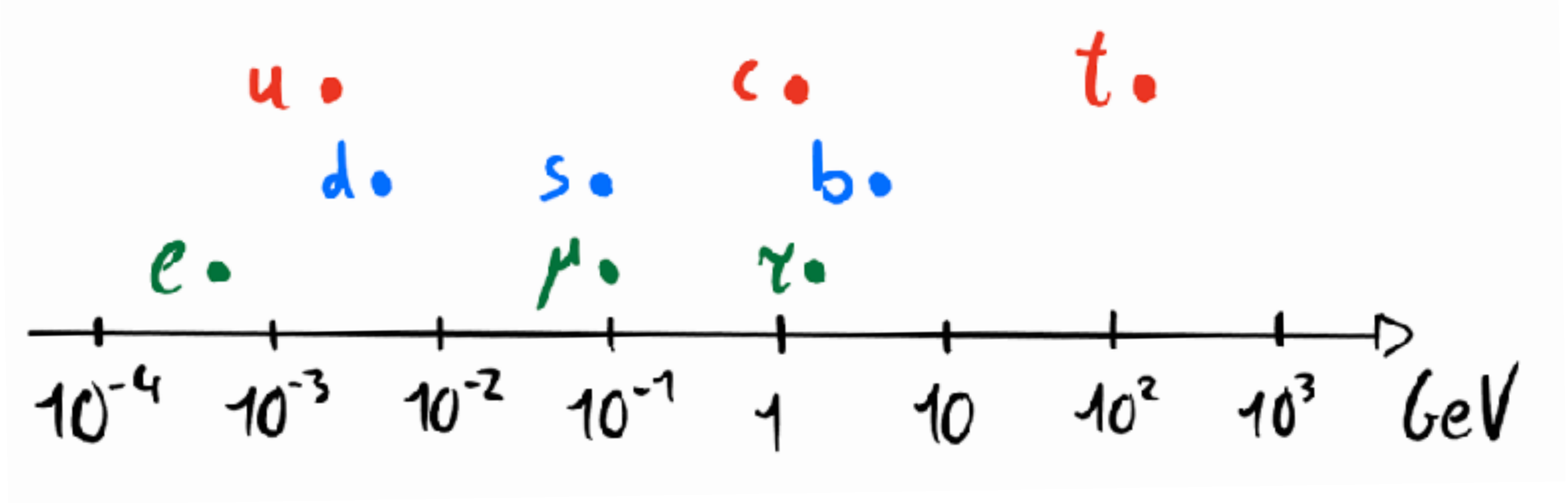

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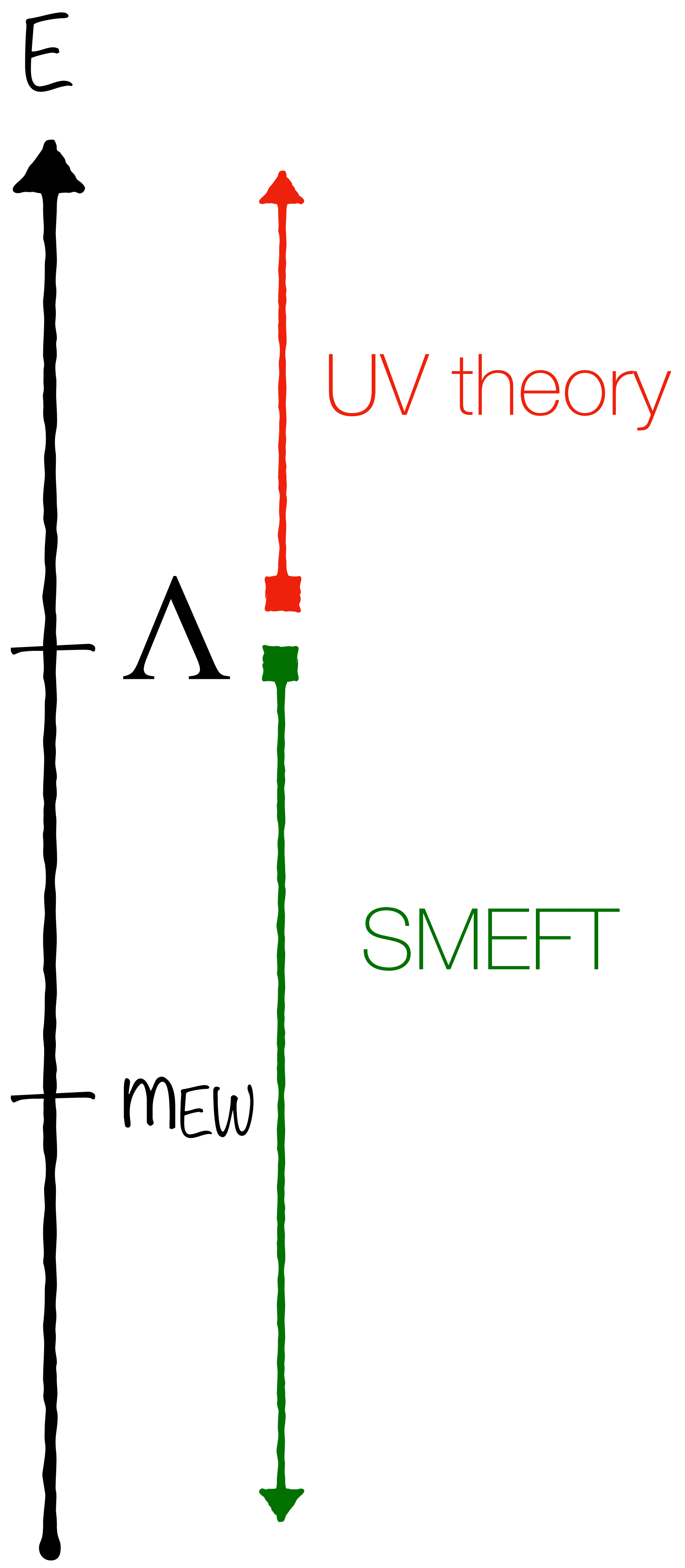
However, **the theory gives no explanation** for these hierarchies.
Is there a more fundamental underlying theory which does?

“SM Flavour Puzzle”

The Standard Model as an EFT

We know that **the Standard Model must be extended at some high energy scale Λ**.



If we are interested in physics at energies $\mathbf{E} \ll \mathbf{\Lambda}$ we can write the low-energy Lagrangian as a series **expanded in powers of $1/\Lambda$**: the **Standard Model Effective Field Theory**.

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM}^{(d\leq 4)} + \frac{C^{(5)}}{\Lambda_{\not L}}\mathcal{O}_{W} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)}[\varphi_{SM}] + \mathcal{O}(\Lambda^{-4})$$

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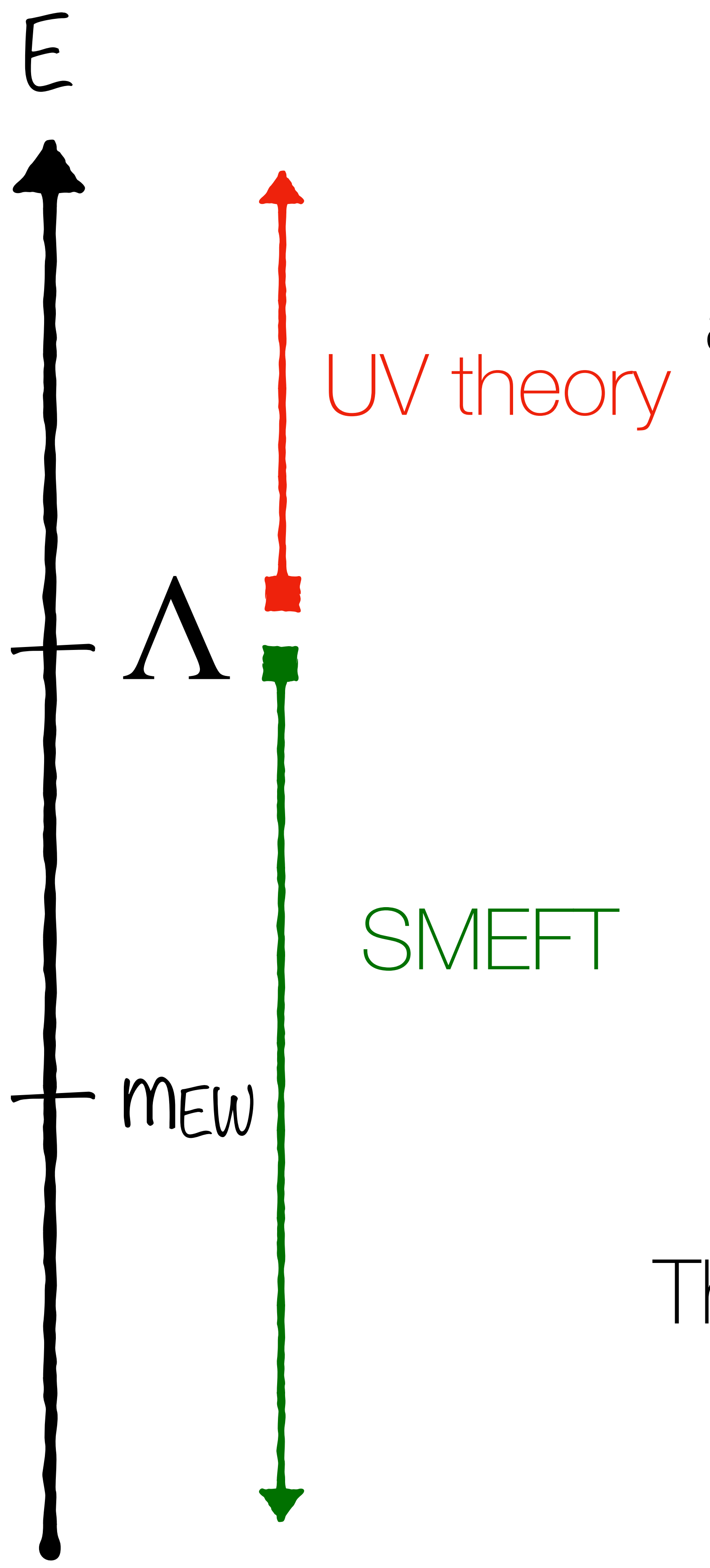

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$$\left(\frac{E}{\Lambda}\right)^{d-4} \ll 1$$

The **SM** is just the **renormalisable IR remnant of the more fundamental UV theory**.

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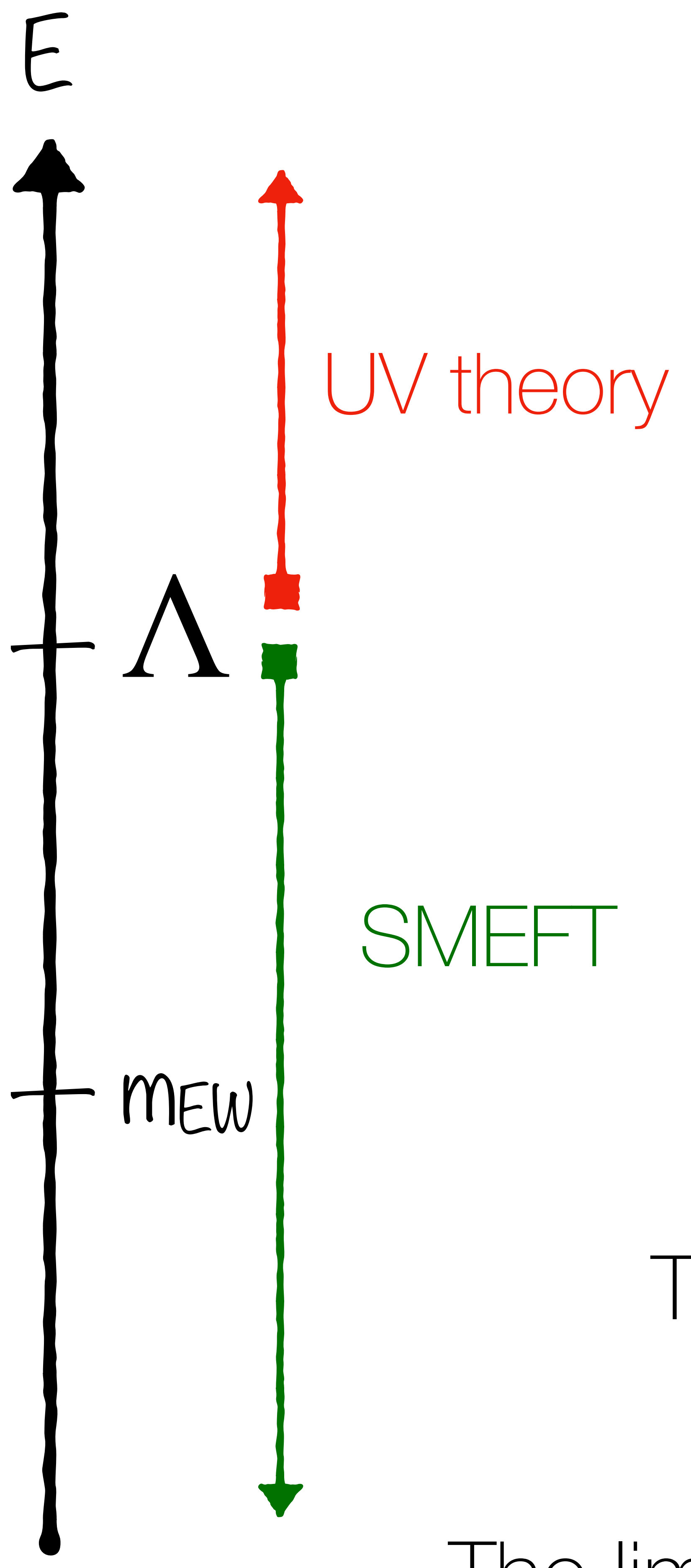

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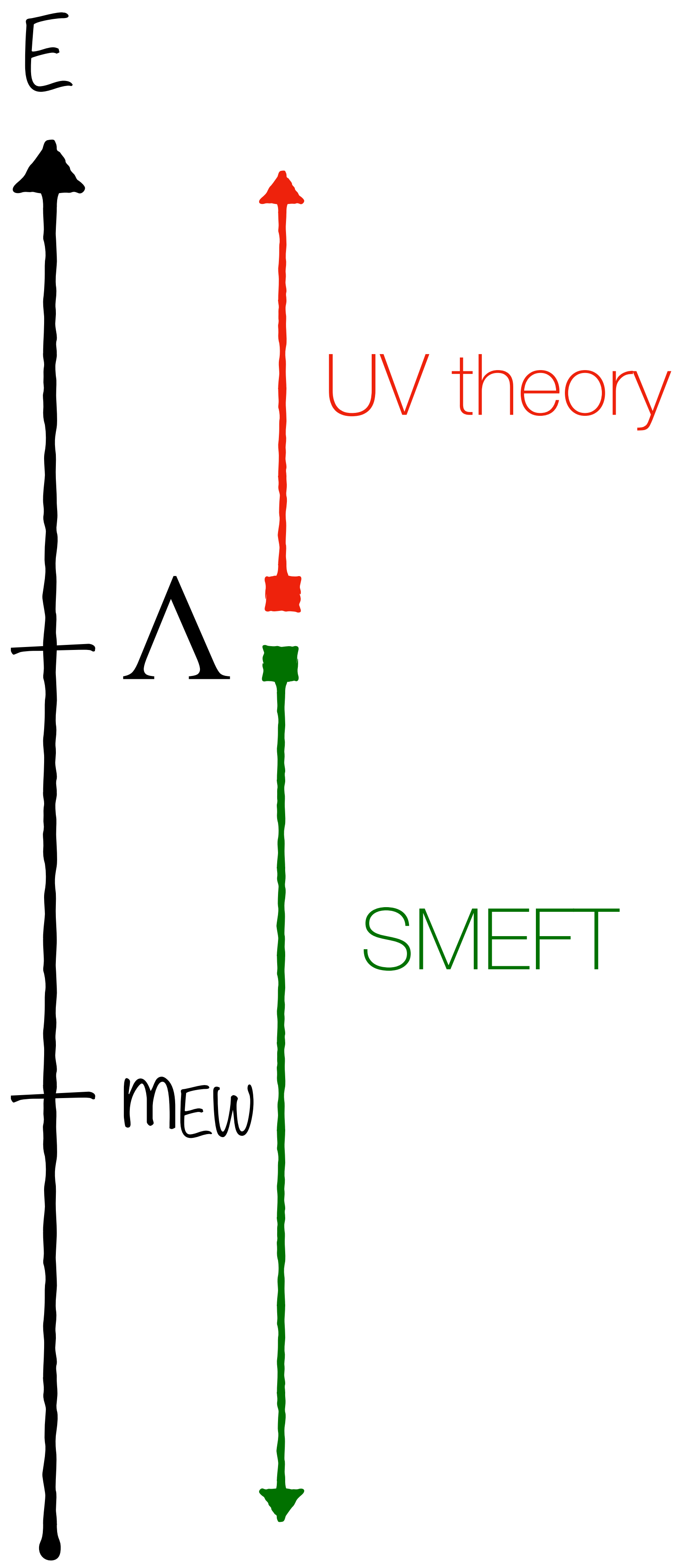
The **SM** is just the **renormalisable IR remnant of the more fundamental UV theory**.

The limited set of operators allowed at $d \leq 4$ automatically endows the **SM** with **accidental features & symmetries:**

- **suppression of FCNC** and CP-violation
- **Lepton Flavour Universality**
- conservation of B, L_e, L_μ, L_τ
- custodial symmetry
- very small neutrino masses

The Standard Model as an EFT



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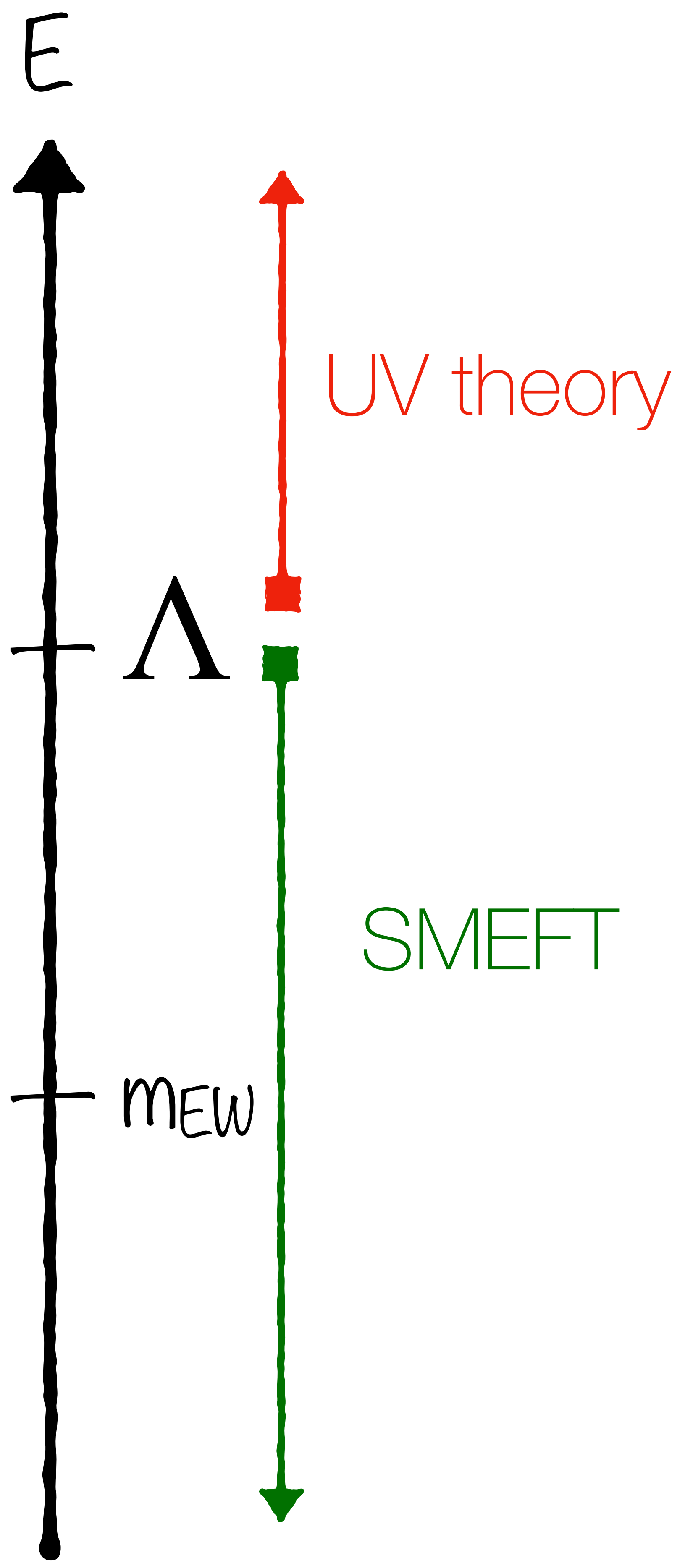

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We can expect large effects in rare or forbidden processes!

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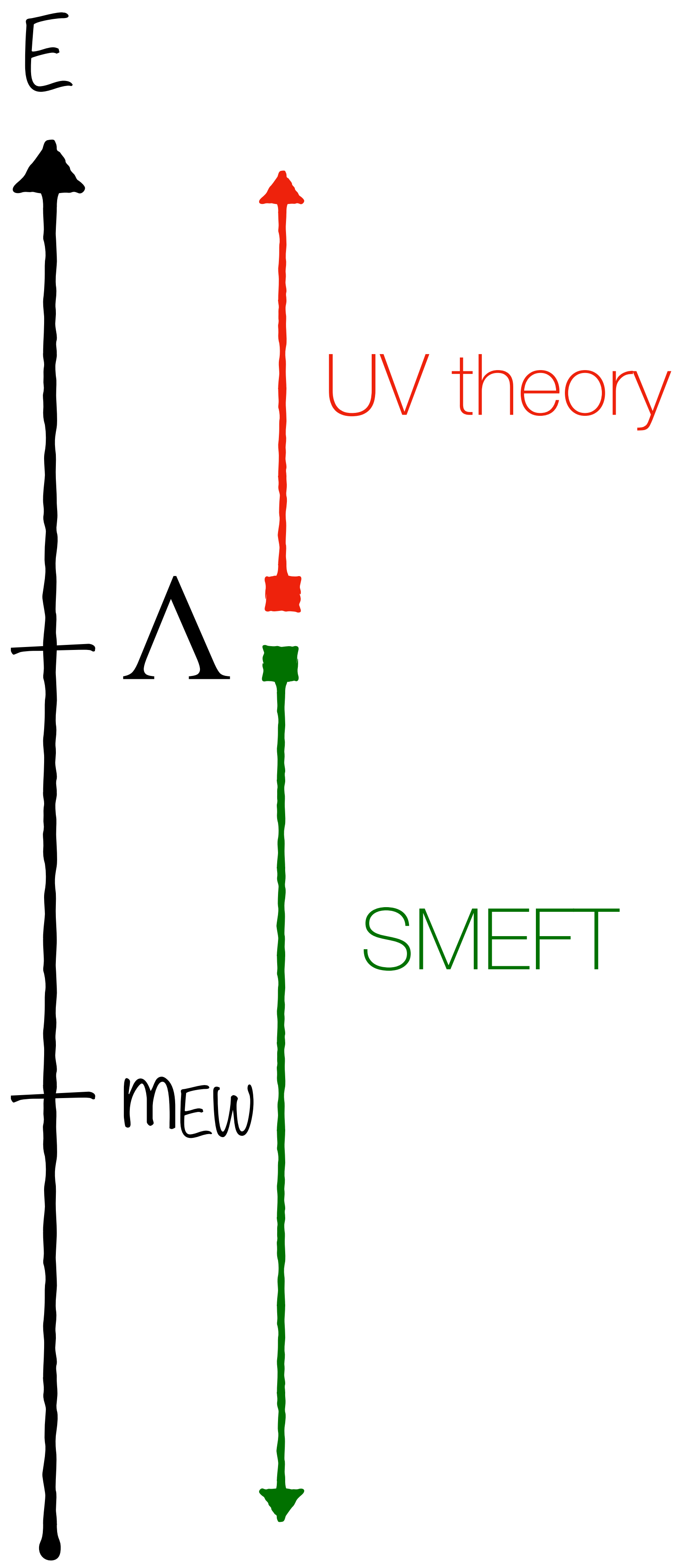

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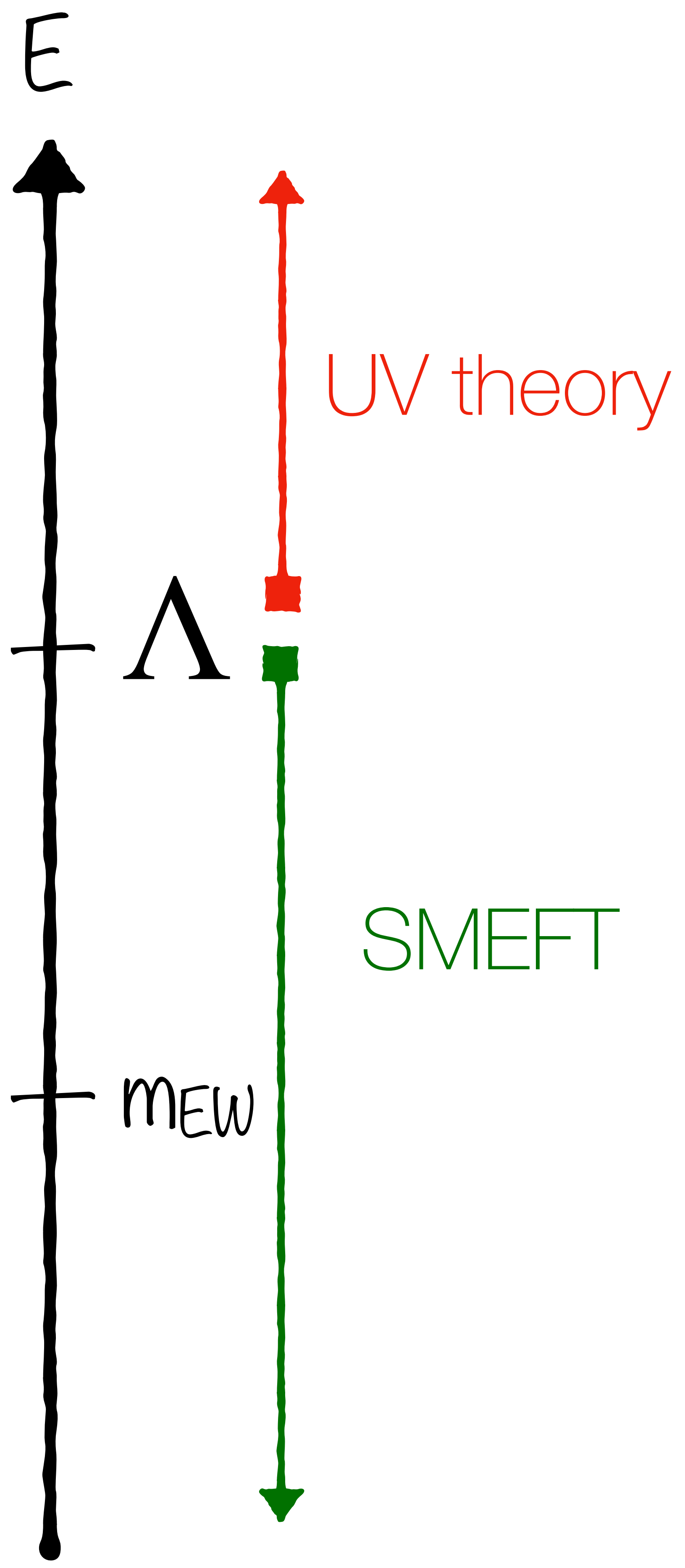

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Remember:

There can be **different scales Λ associated to the violation of different SM properties**:
quark flavour, lepton flavour, L and B violation, etc..

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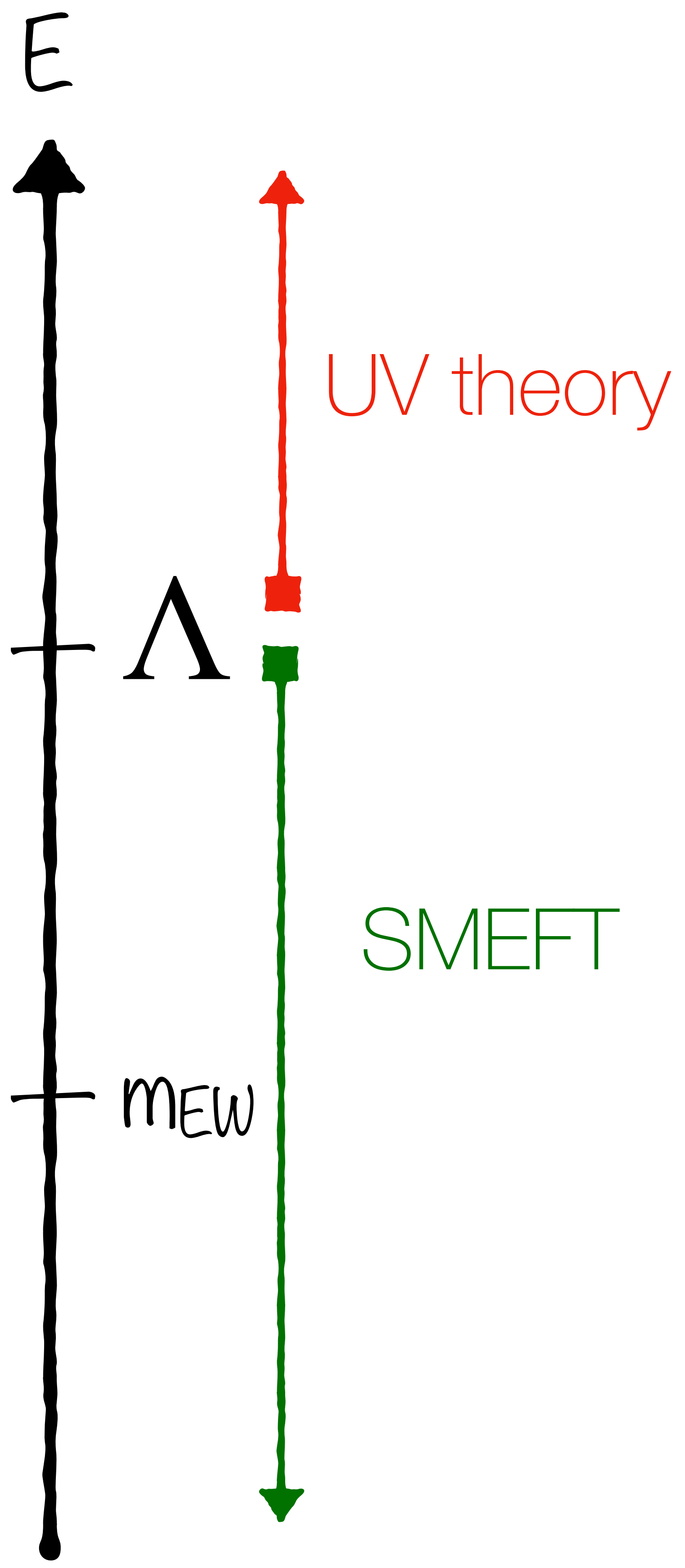

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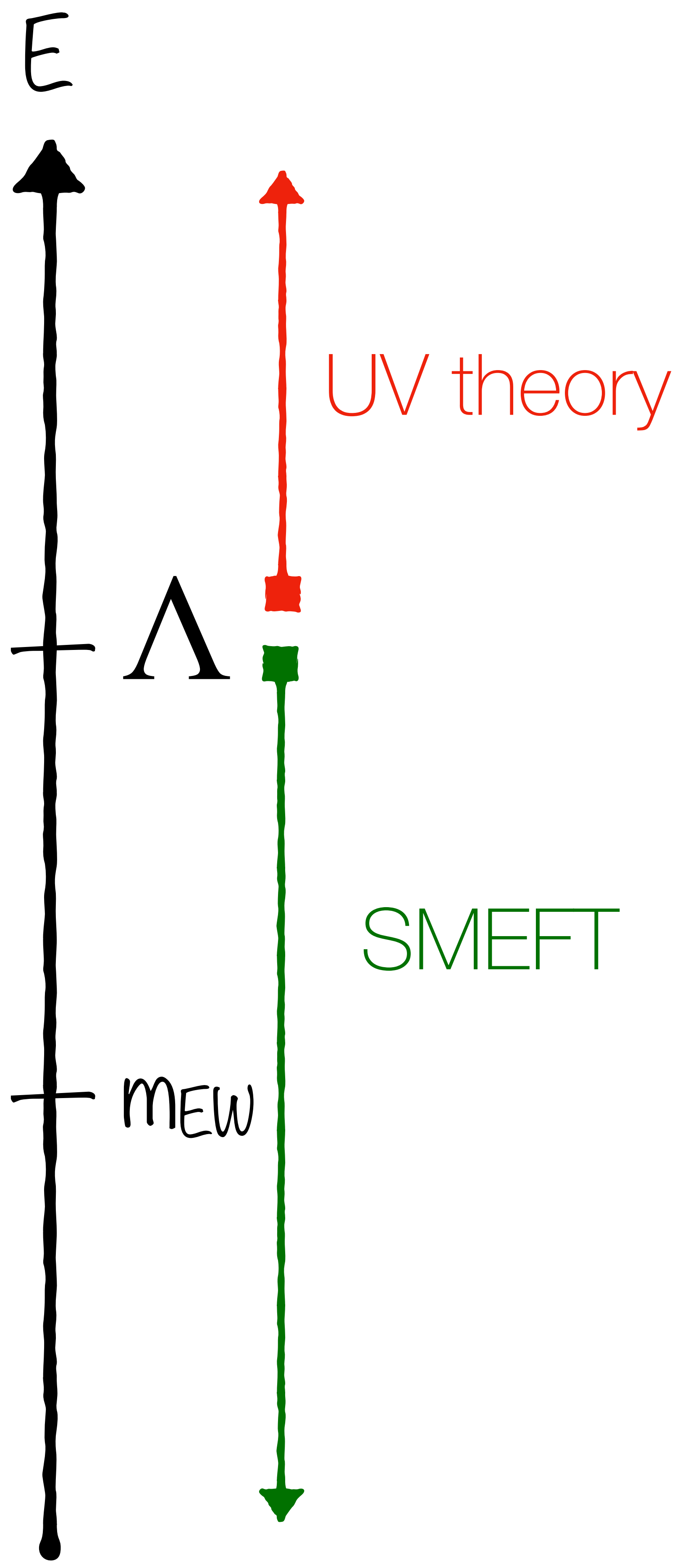

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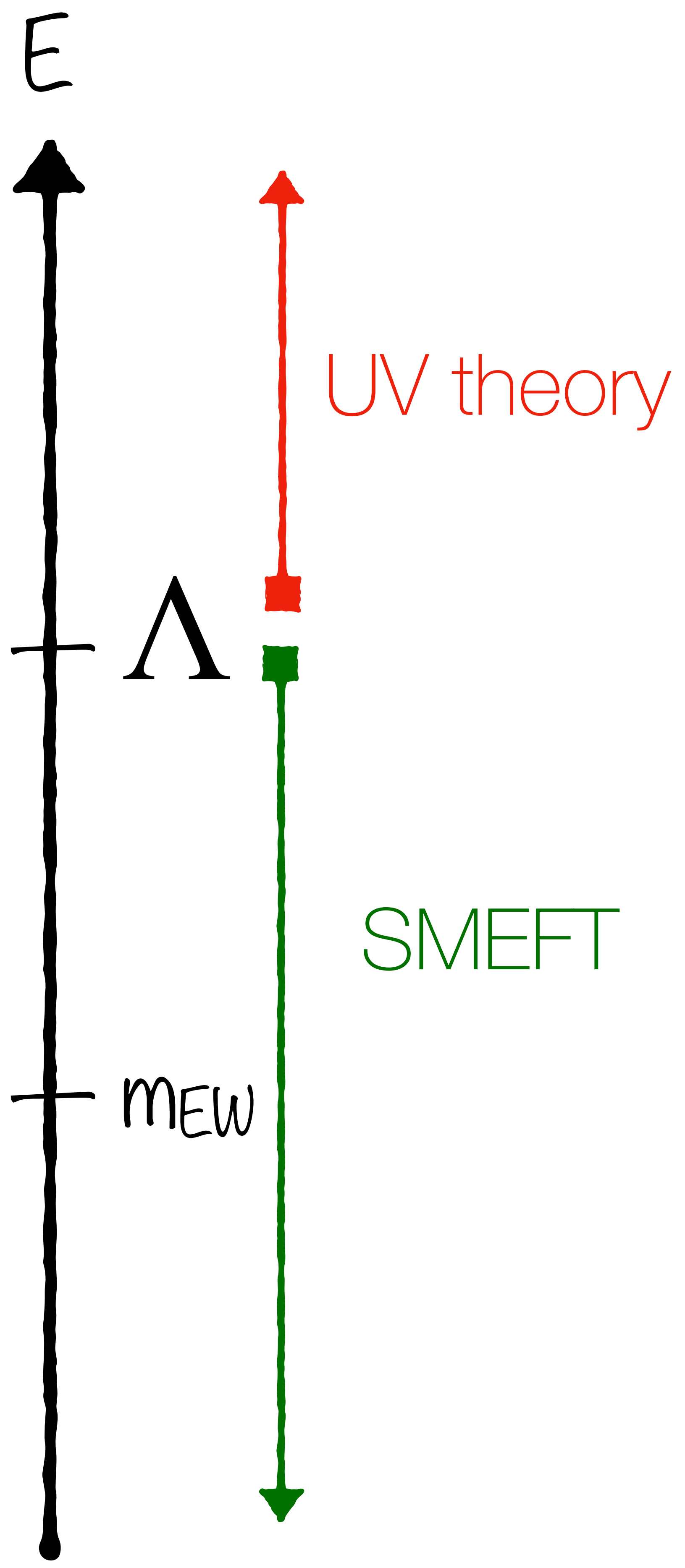

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Motivated Reasons for a **"low"** Λ:

Hierarchy problem
of the EW scale,

$\Lambda \sim \text{TeV}$

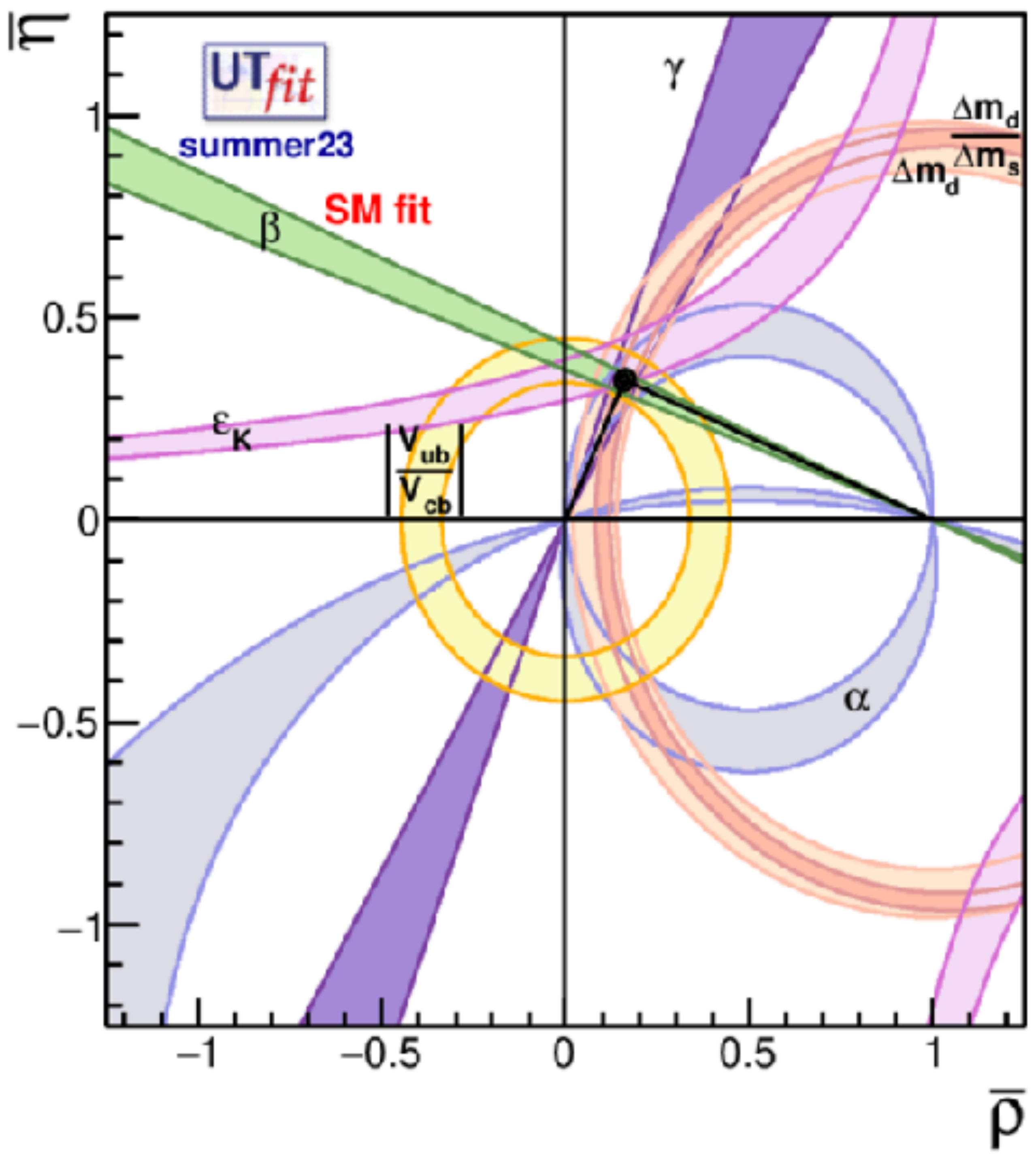
Experimental signatures
of BSM physics (***anomalies***)

$\Lambda \sim ?$ (it depends on the measurement)

WIMP miracle
for Dark Matter

$\Lambda \sim 0.1 - O(10)\ \text{TeV}$

The BSM Flavour Problem



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Measuring flavour transitions puts strong constraints on New Physics with generic flavour structure.

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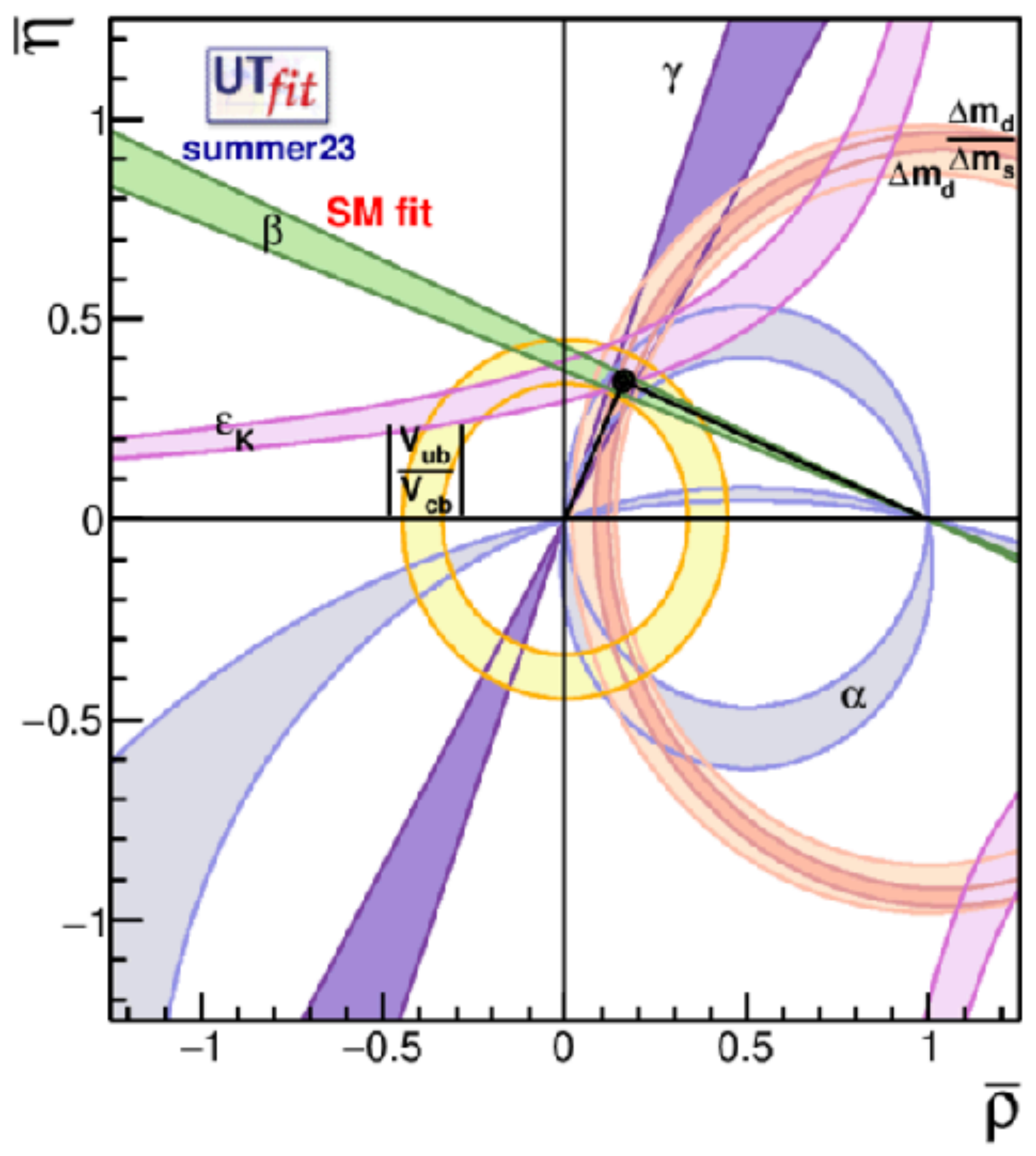

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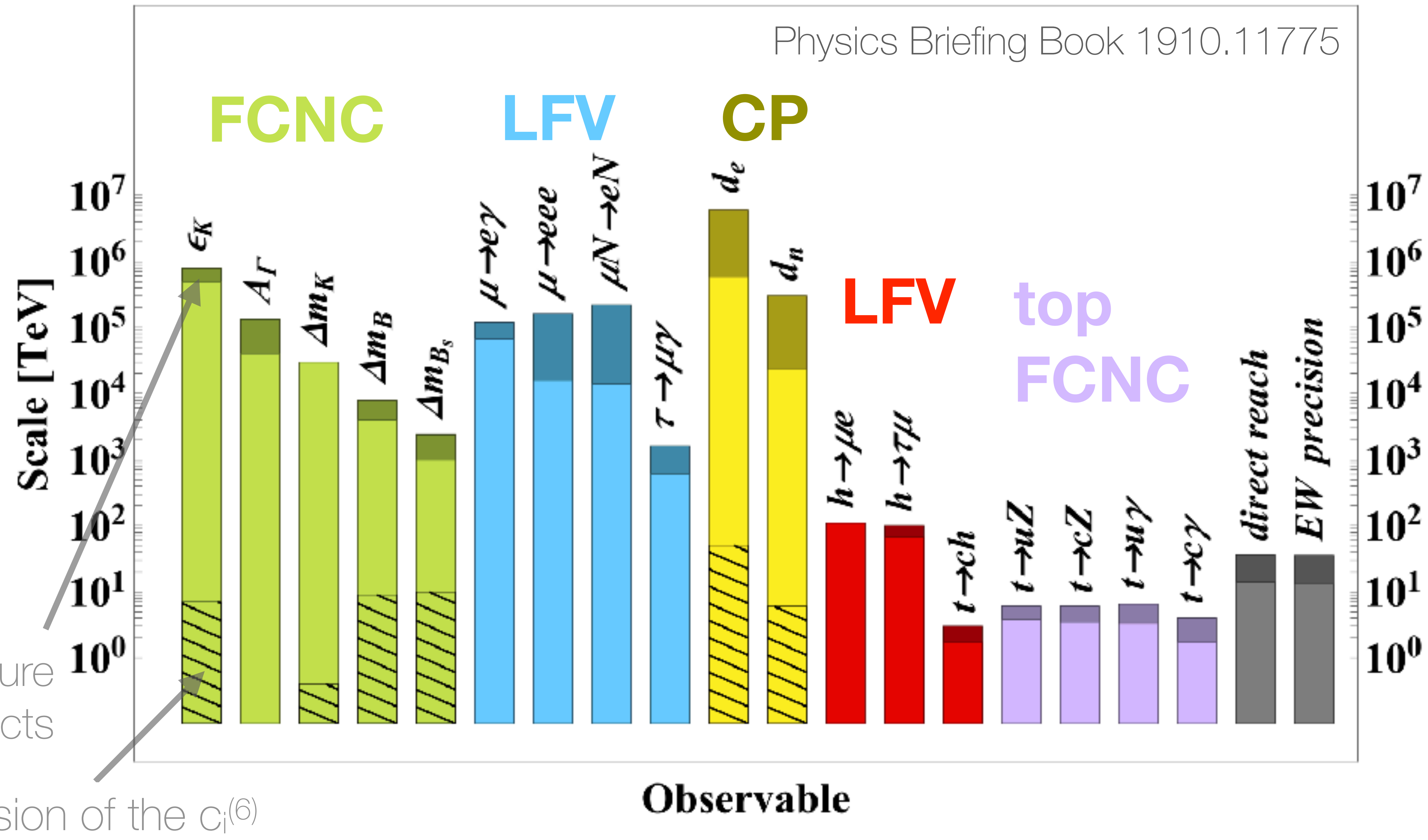
Bounds on Λ (taking $c_i^{(6)} = 1$) from various processes



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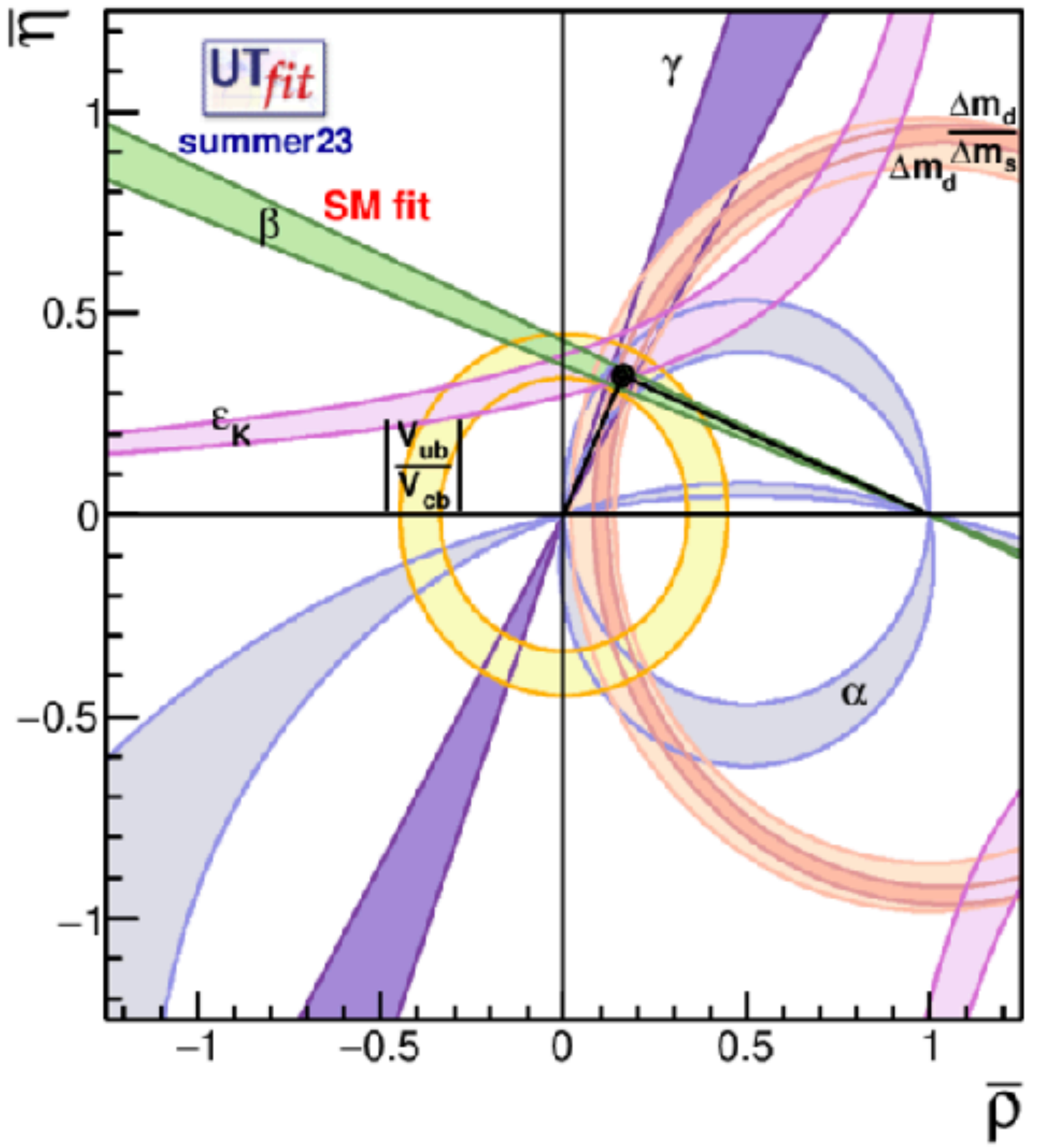

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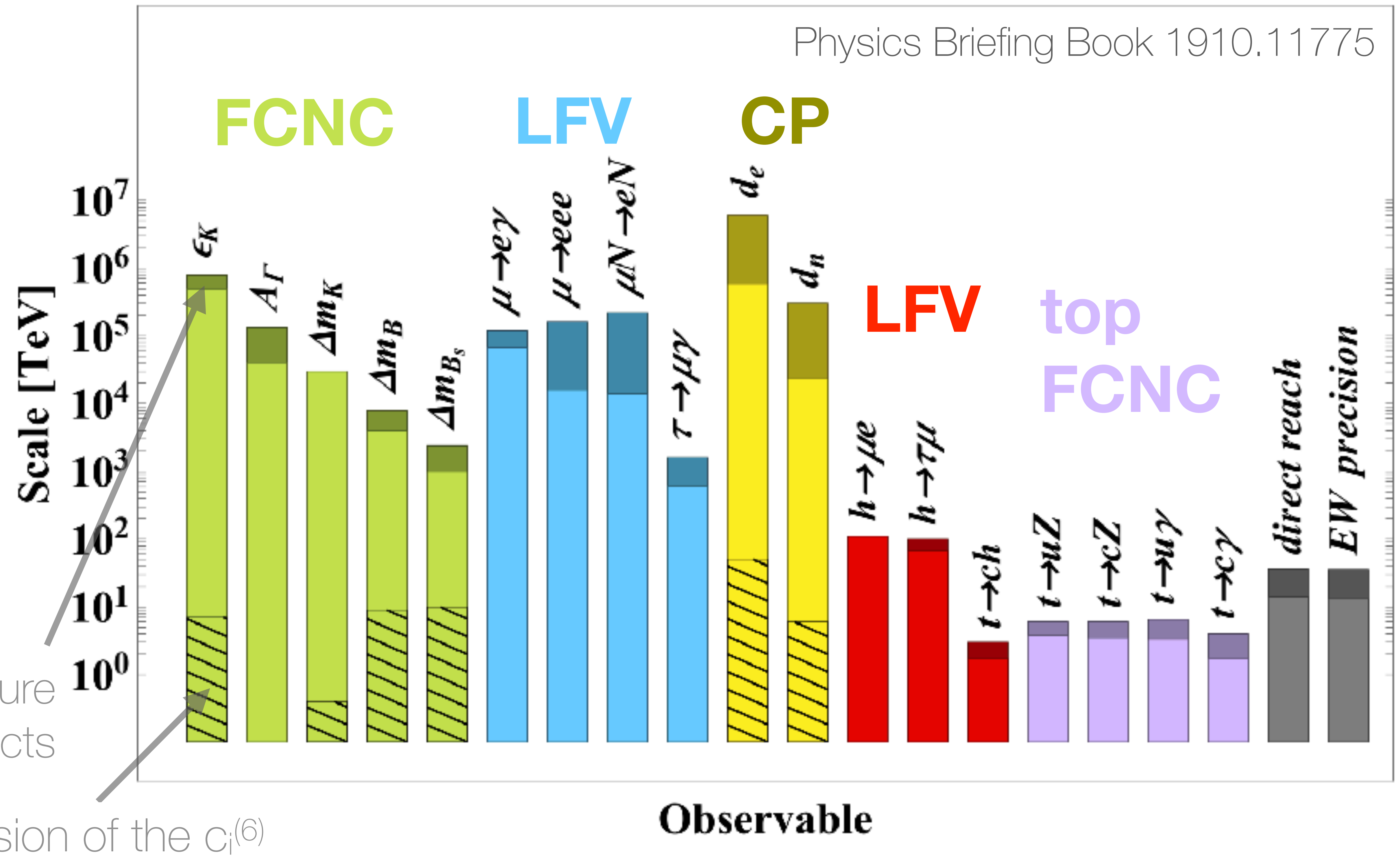

If New Physics is present **at the TeV scale**,
its flavour structure should be constrained
by some “protecting” principle (symmetry or dynamics):
the BSM Flavour Problem.
→ the $c^{(6)}$ coefficients should be suppressed.

$$\mathcal{L}_{SMEFT}^{(d=6)} = \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)}[\varphi_{SM}]$$

The BSM Flavour Problem

Let us consider the hypothetical case $\Lambda \sim 1 - 10$ TeV

- Solutions to the Hierarchy Problem
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Typically, a good **flavour structure for a quark-current operator** $\mathcal{O}_{ij} \propto (\bar{d}_i \gamma_\mu d_j) \ldots$ is:

$$C_{ij} \sim \begin{pmatrix} \varepsilon_1 & \lambda^5 & \lambda^3 \\ \lambda^5 & \varepsilon_2 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \qquad \lambda \sim \sin\vartheta_c$$

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$\varepsilon_{1,2}$:

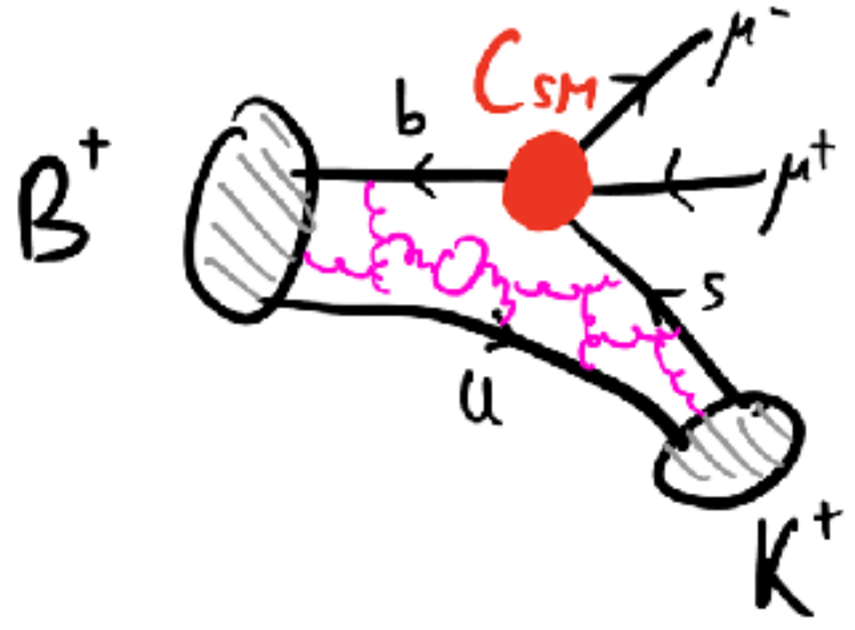
- **U(2)**-like: $\varepsilon_{1,2} \ll 1$
- **MFV**-like: $\varepsilon_{1,2} \sim 1$

Probing New Physics with Rare Decays

Consider a **rare low-energy process in the SM**
Short-distance low-energy EFT coefficient

$$C_{SM} \sim \frac{\lambda_{SM}}{v^2} \qquad \lambda_{SM} \ll 1$$

Example: $$C^{sb}_{SM} \sim \frac{\alpha}{4\pi} \frac{V_{ts}V_{tb}}{v^2}$$



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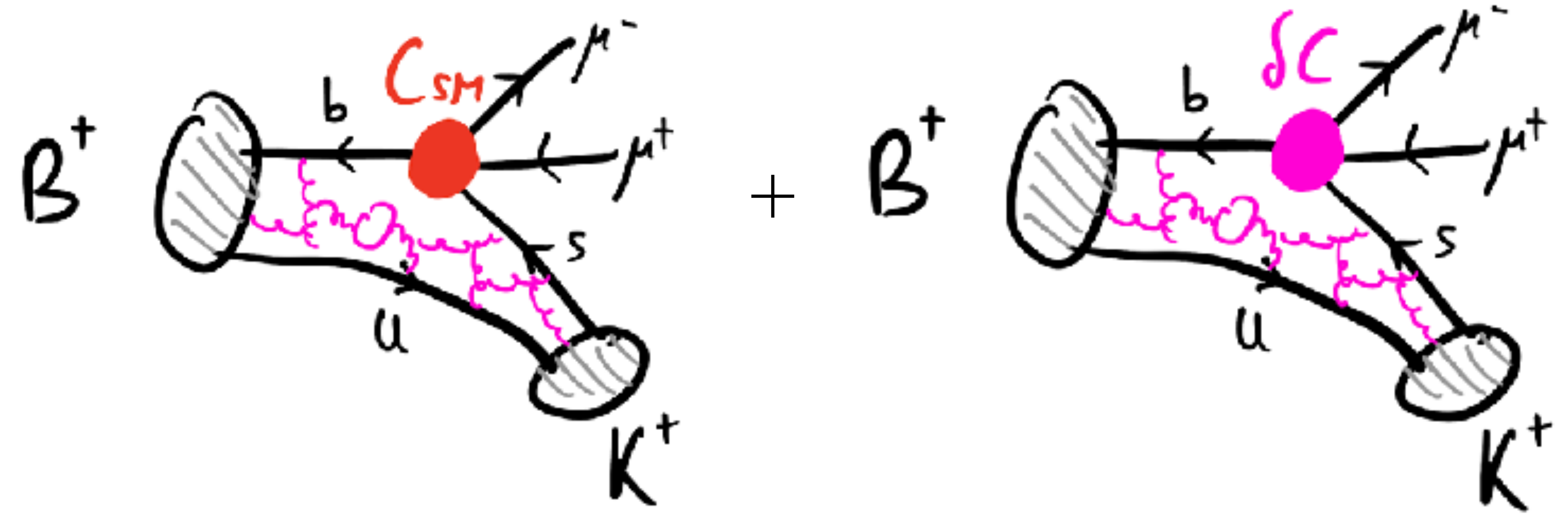

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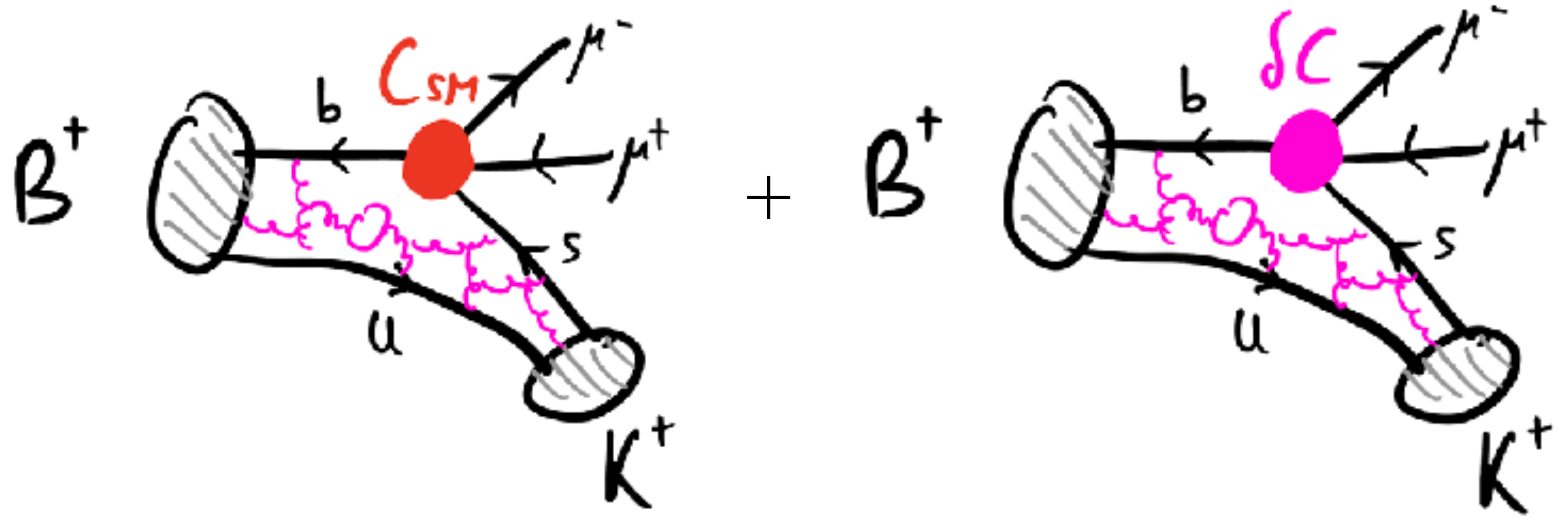

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$$\frac{\delta C}{C_{SM}} \sim \frac{c}{\lambda_{SM}} \frac{v^2}{\Lambda^2}$$

Relative **deviation in the short-distance coefficient**

Measuring this precisely puts strong constraints on the **EFT combination c/Λ^2**,
the **better the smallest λ_{SM}** is.

Probing New Physics with Rare Decays

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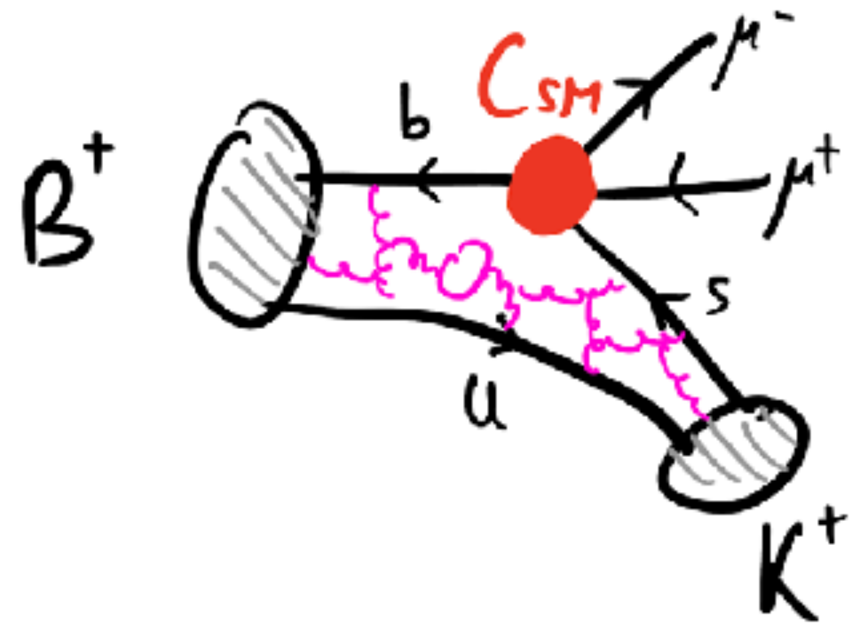

For this goal it is crucial to have the **smallest possible uncertainty on the short-distance contributions**:

Exp

- Very **large statistics** to probe the rare decays with sufficient precision
- Good control over **backgrounds and systematics** (experimental environment and detector performance)

TH

- Good control over the SM prediction:
  - **SM inputs** (CKM matrix elements)
  - **QCD matrix elements** (form factors)
  - control over the possible **long-distance contributions**

Neutral-current semileptonic B decays

$b \rightarrow s\, \mu^+ \mu^-$

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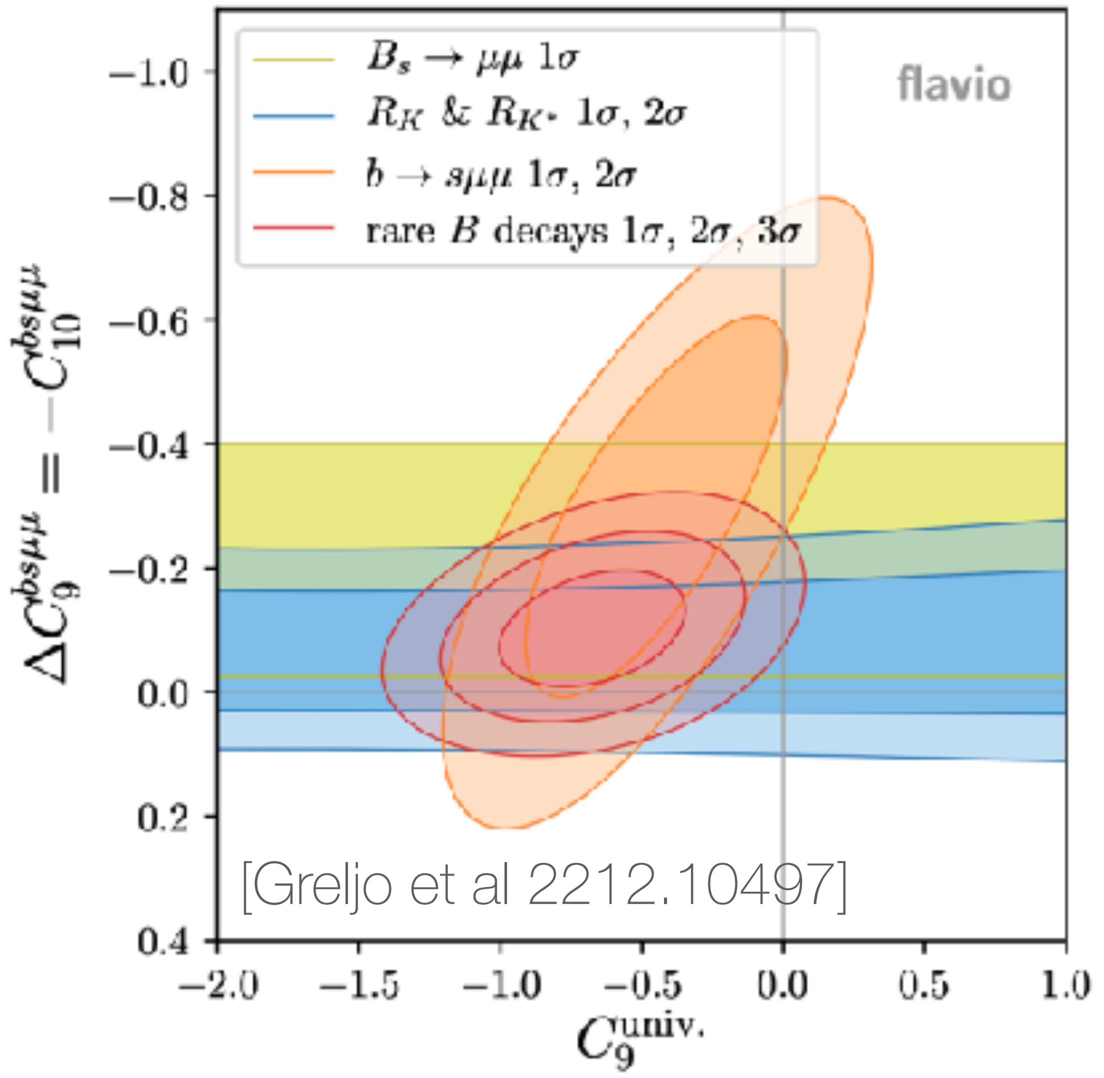

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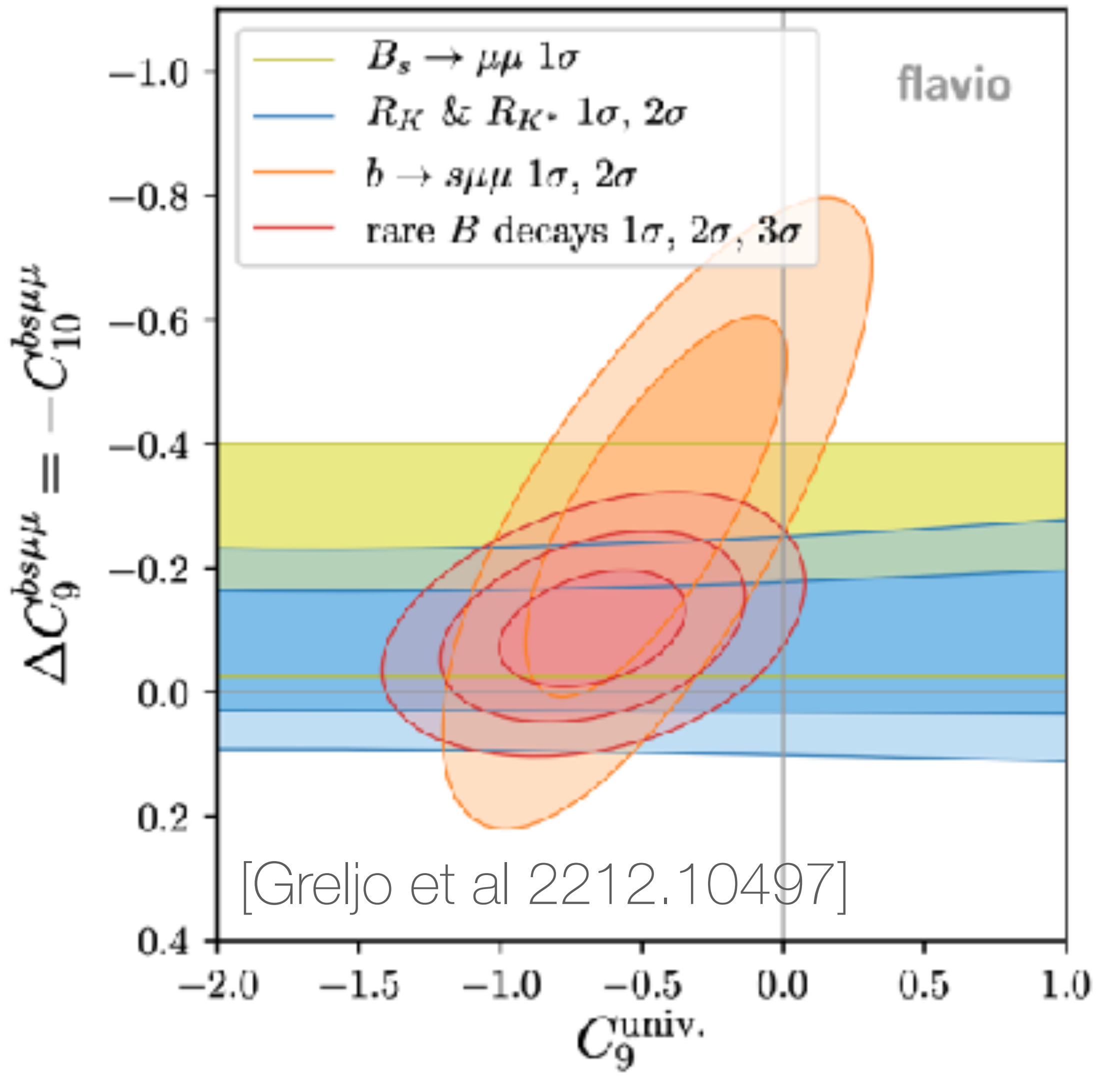

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Brief Overview New Physics solutions: [Greljo et al 2212.10497, Ciuchini et al 2212.10516]

- $\mathbf{R_K = 1}$ → coupling to electrons = coupling to muons
- **Z' models** now challenged by $e^+e^- \to \mu^+ \mu^-$ @ **LEP-II** [see however 2306.08669, 2409.06804]
- **LQ models** now disfavored by $B_s \to \mu e$ & $\mu \to e$ LFV.
  More involved model building required (e.g. two LQ in $SU(2)_F$ symm.)

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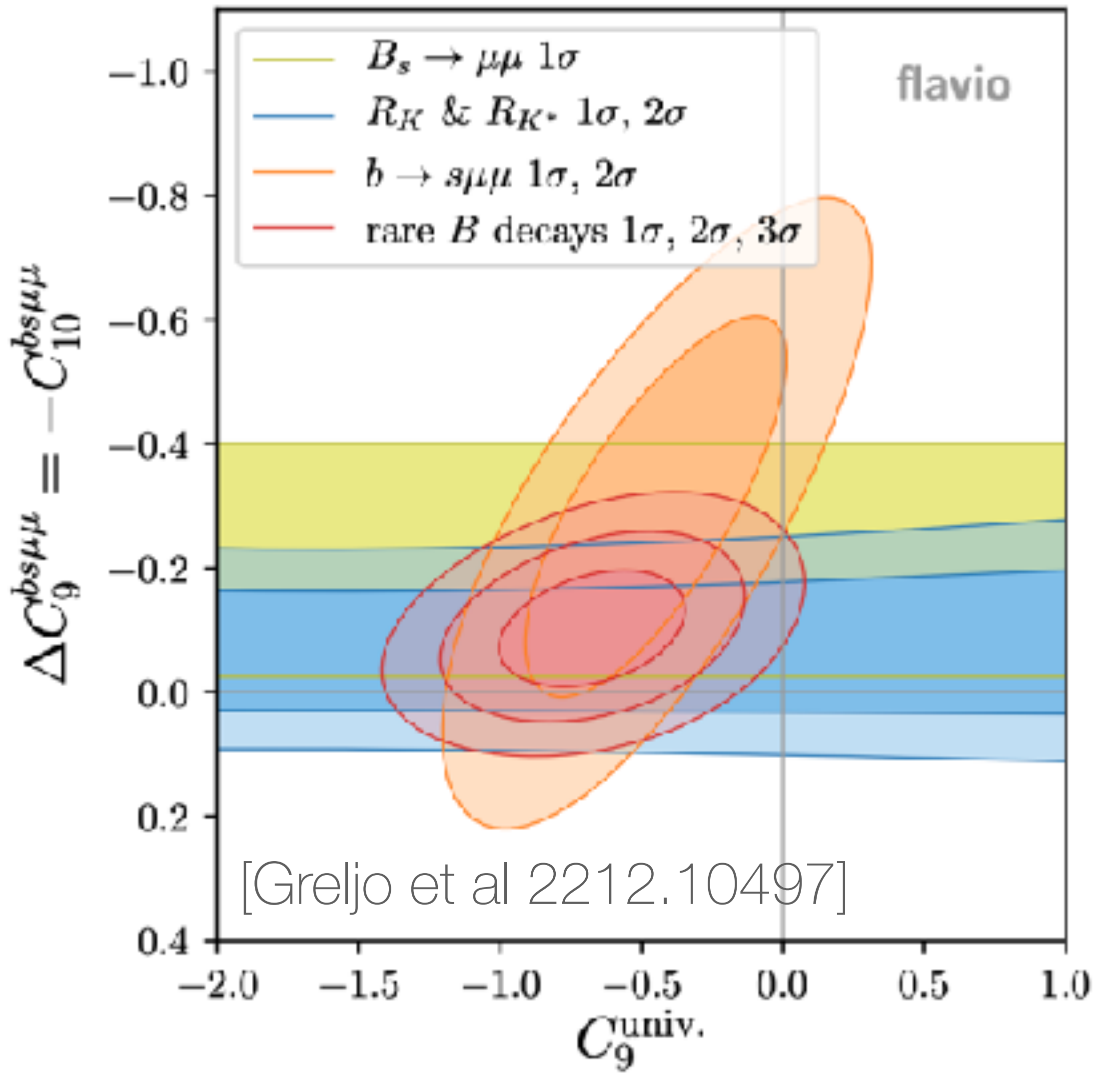

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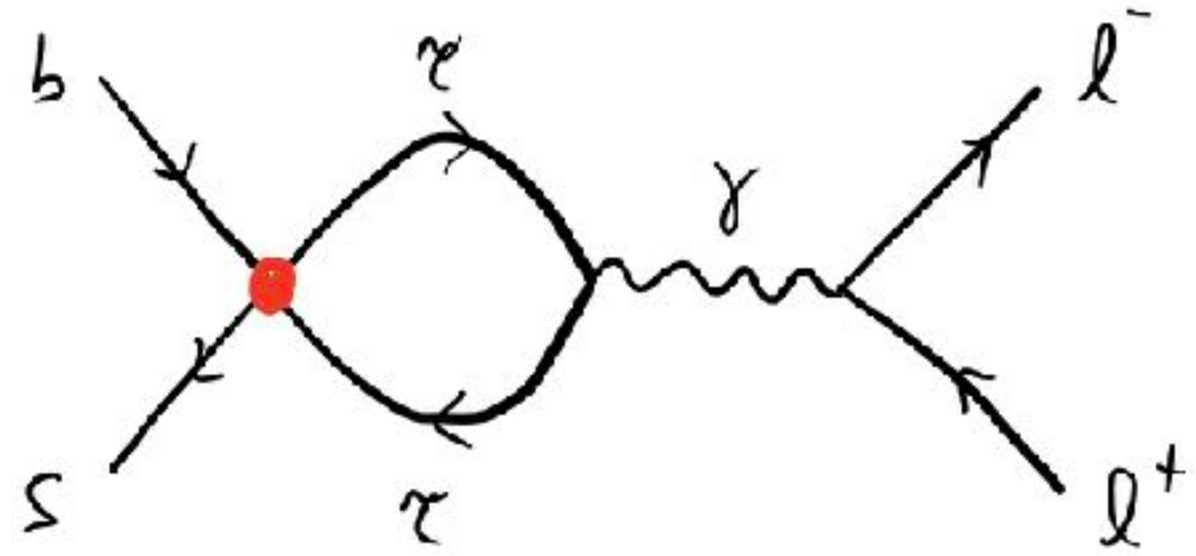
A motivated New Physics contribution to C_9^U

Bobeth et al. 1109.1826, Capdevila et al. 1712.01919, Crivellin et al. 1807.02068, Alguerò et al. 1903.09578, Cornella et al. 2001.04470, Aebischer, Isidori, et al. 2210.13422,



→ **Induce C_9^U**

→ **Related to R(D(*))**

$$C_9^{\rm U} \approx 7.5 \left(1 - \sqrt{\frac{R_{D^{(*)}}}{R_{D^{(*)}\rm SM}}}\right)\left(1 + \frac{\log(\Lambda^2/(1\text{TeV}^2))}{10.5}\right)$$

Rare Semileptonic and Leptonic decays

To **which NP scale Λ** are these measurements **sensitive** to?

Take this current x current operator just as example

$$\mathcal{L}_{EFT} \supset \frac{c}{\Lambda^2} (\bar{q}^i_L \gamma_\alpha q^j_L)(\bar{\mu}_L \gamma^\alpha \mu_L)$$

	bound on Λ	LHCb '23 R(K)
Anarchic flavour	$c = 1$	**56 TeV**
CKM-like (MFV, U(2),..)	$c = c_{CKM}$	$c_{CKM} = \lvert V_{ts} \rvert$ 11 TeV

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	bound on Λ	LHCb '23 R(K)	2210.07221 $B_s \to \mu\mu$	hep-ph/0311084 $K_L \to \mu\mu$	LHCb '20 $K_S \to \mu\mu$	2011.09478 $D^0 \to \mu\mu$
Anarchic flavour	$c = 1$	**56 TeV**	**33 TeV**	**74 TeV**	$c = i$ **10.7 TeV**	**5.2 TeV**
CKM-like (MFV, U(2),..)	$c = c_{CKM}$	$c_{CKM} = \|V_{ts}\|$ 11 TeV	$c_{CKM} = \|V_{ts}\|$ 6.7 TeV	$c_{CKM} = \|V_{td} V_{ts}\|$ 1.4 TeV	$c_{CKM} = i\|V_{td} V_{ts}\|$ 0.2 TeV	$c_{CKM} = \|V_{cb} V_{ub}\|$ 0.065 TeV

In new physics scenarios with **CKM-like flavour structure**,
the **strongest constraints in the quark-muon couplings come from bsμμ observables**.

Golden-channels of rare decays

$b \to s\, \nu\, \bar{\nu}$

$B \to K^{(*)}\, \nu\, \bar{\nu}$

BaBar, Belle, Belle II (JPARC)

$s \to d\, \nu\, \bar{\nu}$

$K^+ \to \pi^+\, \nu\, \bar{\nu}$, $K_L \to \pi^0\, \nu\, \bar{\nu}$

NA62 (CERN) KOTO (JPARC)

Golden-channels of rare decays

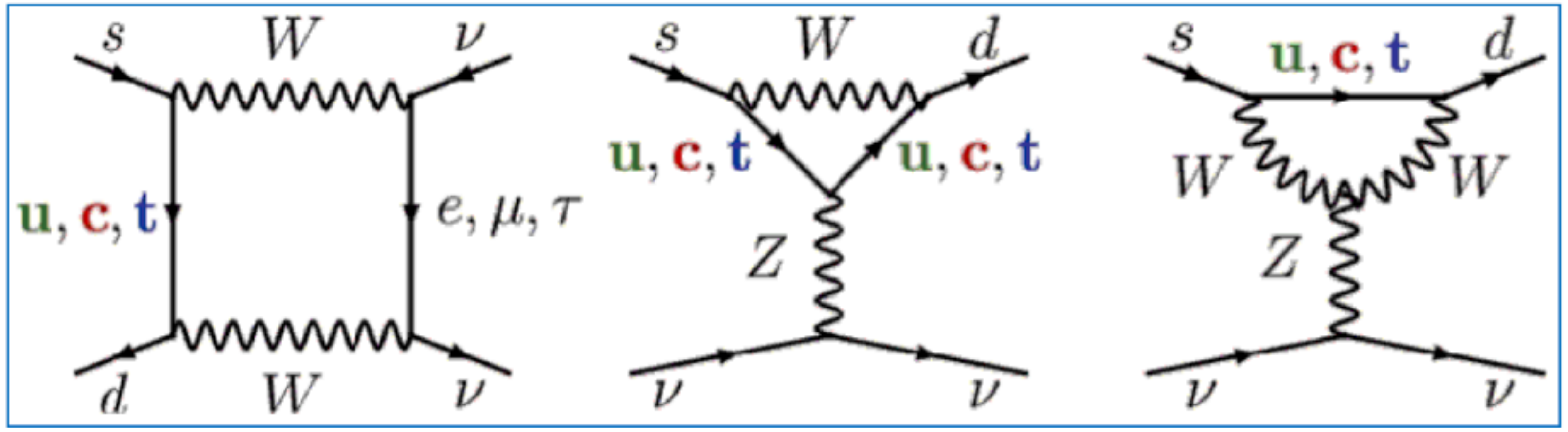
$b \to s\, \nu\, \bar{\nu}$ $\quad$ $s \to d\, \nu\, \bar{\nu}$

$B \to K^{(*)}\, \nu\, \bar{\nu}$ $\quad$ $K^+ \to \pi^+\, \nu\, \bar{\nu}$, $\quad$ $K_L \to \pi^0\, \nu\, \bar{\nu}$

BaBar, Belle, Belle II (JPARC) $\quad$ NA62 (CERN) $\quad$ KOTO (JPARC)

Precise SM predictions possible due to absence of long-distance QCD effects: neutrinos do not couple to the electromagnetic current.

see 1409.4557, 1503.02693, 2109.11032, 2301.06990, …



Main th. uncertainties due to:

- Hadronic form factors (Lattice QCD)
- CKM matrix elements

$B^+ \to K^+ \nu\bar{\nu}$	$(5.06 \pm 0.14 \pm 0.28) \times 10^{-6}$
$B^0 \to K_S \nu\bar{\nu}$	$(2.05 \pm 0.07 \pm 0.12) \times 10^{-6}$
$B^+ \to K^{*+} \nu\bar{\nu}$	$(10.86 \pm 1.30 \pm 0.59) \times 10^{-6}$
$B^0 \to K^{*0} \nu\bar{\nu}$	$(9.05 \pm 1.25 \pm 0.55) \times 10^{-6}$

Becirevic et al. 2301.06990

The **SM rate is suppressed** by loop and small CKM factors: **high sensitivity to New Physics**.

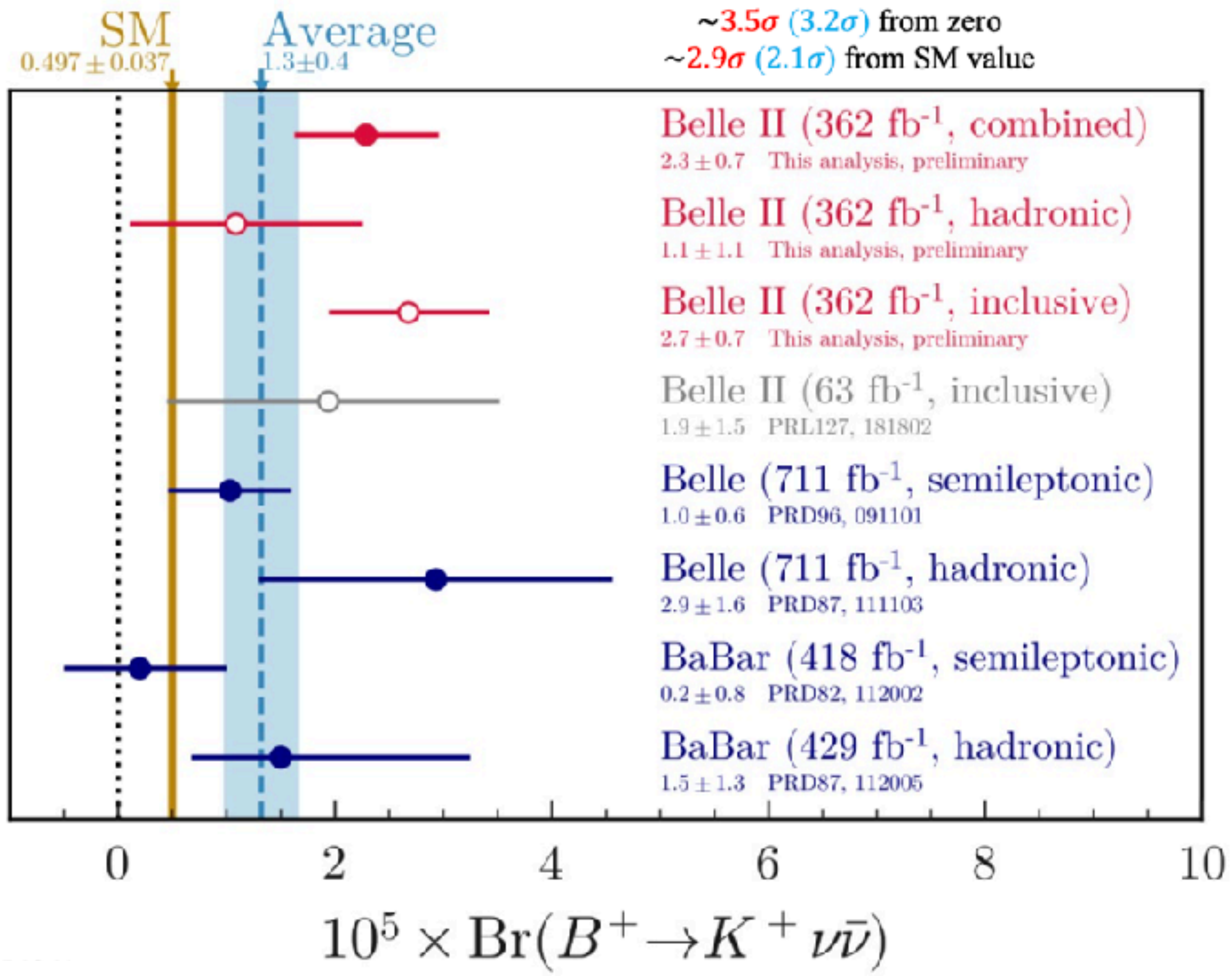
$B \to K^{(*)} \nu \bar{\nu}$

$\mathrm{BR}(B^+ \to K^+ \nu \bar{\nu})_{\mathrm{SM}} = (0.444 \pm 0.030) \times 10^{-5}$

Becirevic et al. 2301.06990

Belle-II$_{2023}$: $\mathrm{BR}(B^+ \to K^+ \nu \bar{\nu}) = (2.3 \pm 0.6) \times 10^{-5}$

Combination: $\mathrm{BR}(B^+ \to K^+ \nu \bar{\nu}) = (1.3 \pm 0.4) \times 10^{-5}$



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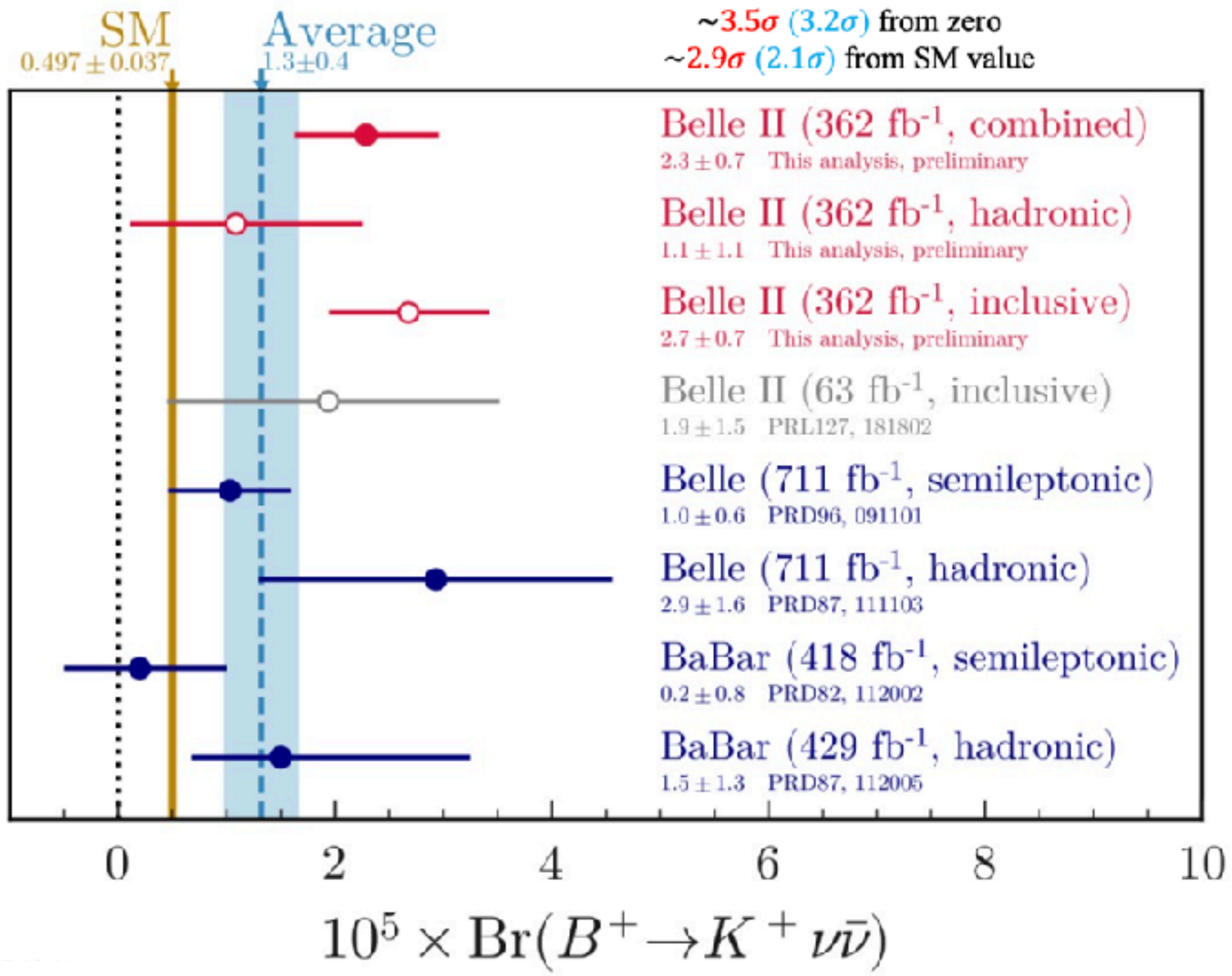
Becirevic et al. 2301.06990

Belle$_{2017}$: $\mathbf{BR}(B \to K^* \nu \bar{\nu}) < 2.7 \times 10^{-5}$ @ 90%CL



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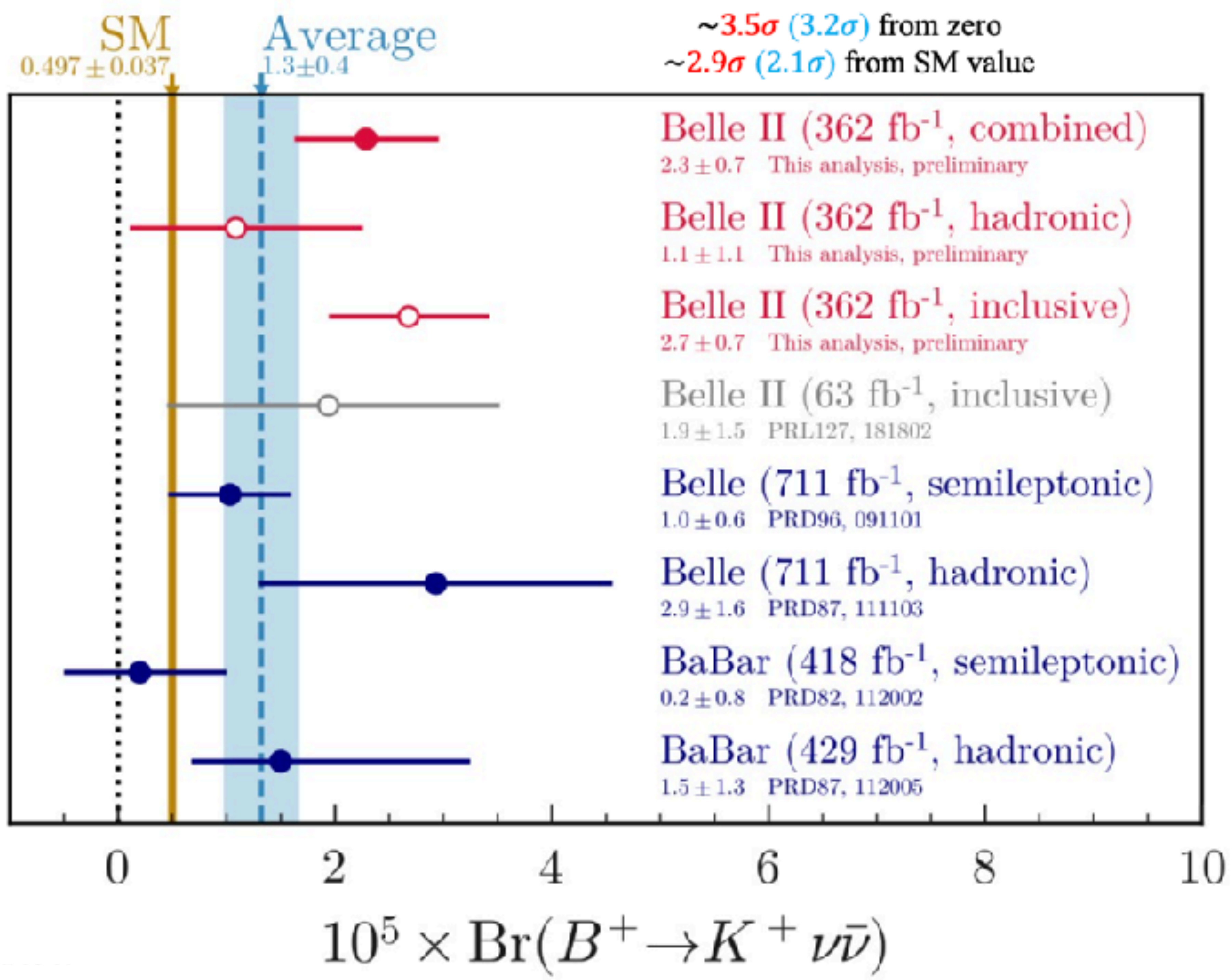


$$R_K^\nu = \frac{BR(B \to K \nu\nu)}{BR(B \to K \nu\nu)^{SM}} = 2{,}93 \pm 0{,}90 \quad 2.1\sigma$$

$$R_{K^*}^\nu = \frac{BR(B \to K^* \nu\nu)}{BR(B \to K^* \nu\nu)^{SM}} = 1.0 \pm 1.1^{*}$$

* Assuming SM to be the central value, also motivated by a small 2σ excess in the K*+ channel.

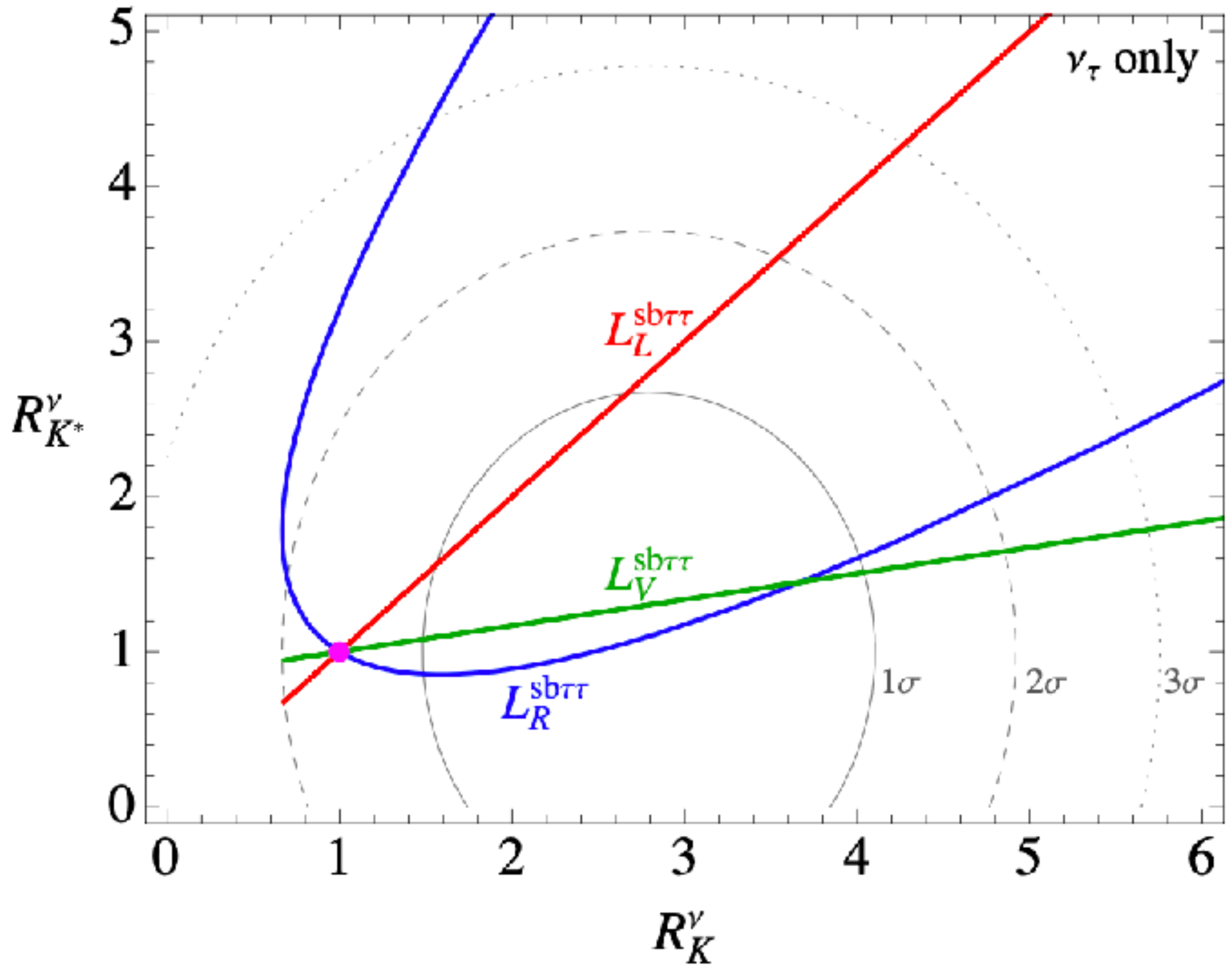
$B \to K^{(*)} \nu \bar{\nu}$

Assuming **only NP in tau**
(see paper for other cases)

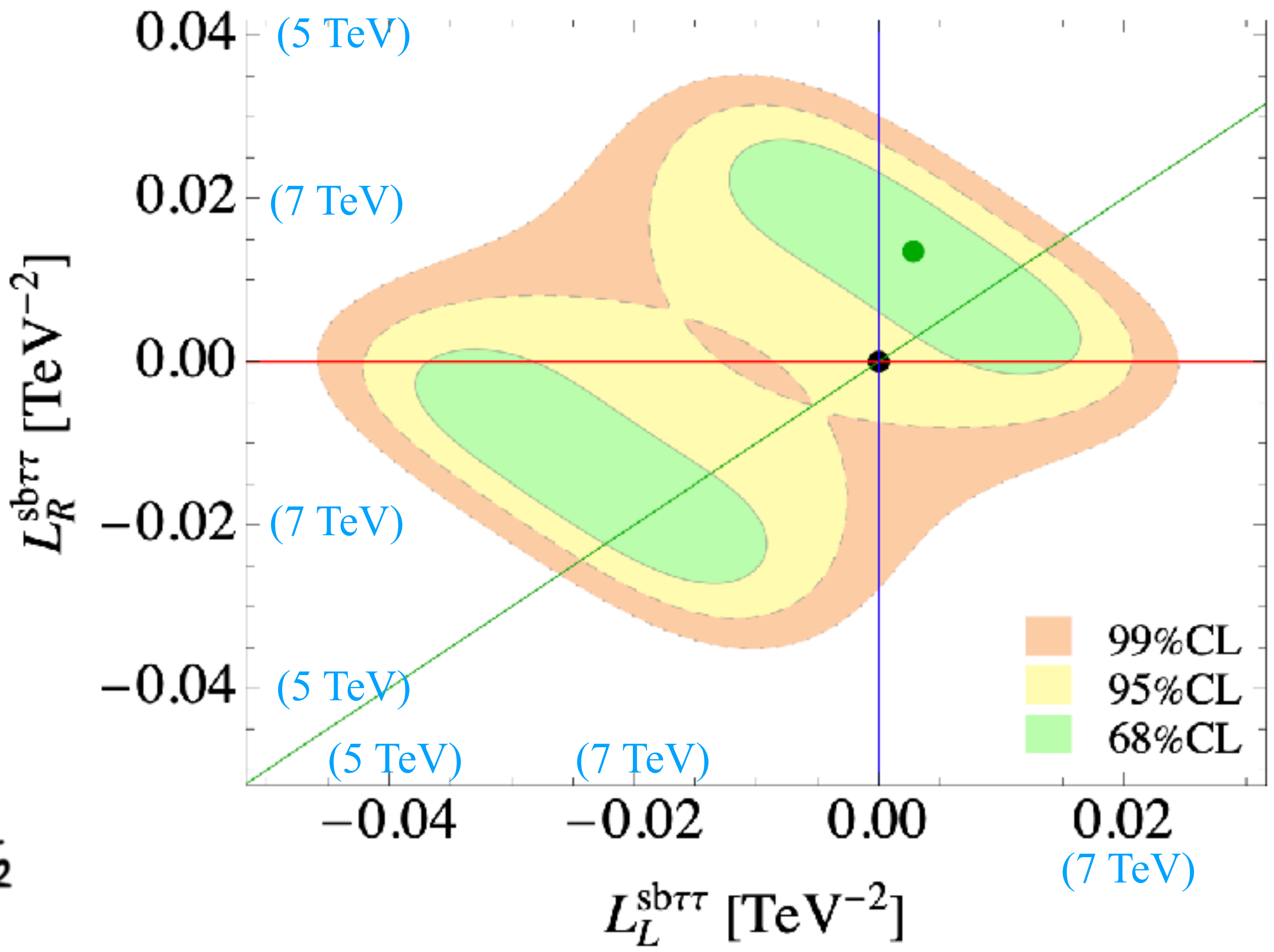
$$\mathcal{L}_{EFT} \supset L^{ij\tau\tau}_{L,R} \left(\bar{d}_{i_{L,R}} \gamma_\mu d_{j_{L,R}}\right)\left(\bar{\nu}_\tau \gamma^\mu \nu_\tau\right)$$

DM, M. Nardecchia, A. Stanzione, C. Toni [2404.06533]

$L^{sb\alpha\beta}_{V,A} \equiv L^{sb\alpha\beta}_R \pm L^{sb\alpha\beta}_L$



$$L \sim \frac{1}{\Lambda^2}$$



They probe scales of about 5-7 TeV,
with a slight excess from the SM preferring either a RH or vector-like quark current.
Future Belle II results (in particular from the K* mode) will help to clarify the situation.

$K^+ \to \pi^+ \nu \bar{\nu}$, $K_L \to \pi^0 \nu \bar{\nu}$

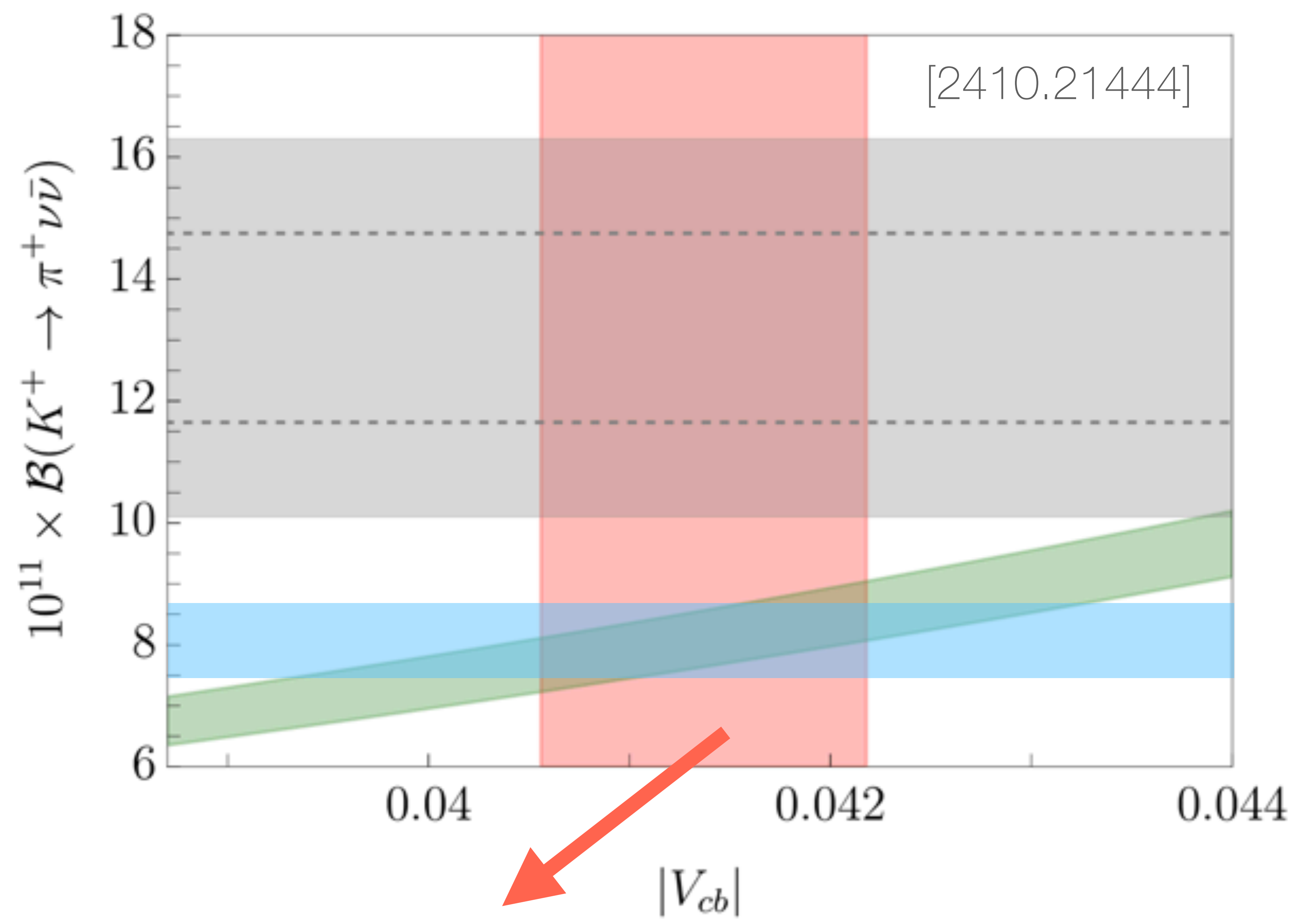
NA62 (CERN)

$\mathrm{BR}(K^+ \to \pi^+ \nu \bar{\nu})_{\mathrm{SM}} = (8.09 \pm 0.63) \times 10^{-11}$

Allwicher et al. [2410.21444] (see also Buras et al. 1503.02693, 2109.11032, etc..)

$\mathrm{NA62}_{2024}$:

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = \left(13.6\,\left({}^{+3.0}_{-2.7}\right)_{\mathrm{stat}}\left({}^{+1.3}_{-1.2}\right)_{\mathrm{syst}}\right) \times 10^{-11}$$



$|V_{cb}| = (41.37 \pm 0.81) \times 10^{-3}$

Derived by combining exclusive and inclusive determinations. [2310.20324, 2406.10074]

KOTO (JPARC)

$\mathrm{BR}(K_L \to \pi^0 \nu \bar{\nu})_{\mathrm{SM}} = (2.58 \pm 0.30) \times 10^{-11}$

Allwicher et al. [2410.21444]

KOTO_{2021}:

$\mathrm{BR}(K_L \to \pi^0 \nu \bar{\nu}) < 4.9 \times 10^{-9}$ @ 90%CL

$K^+ \to \pi^+ \nu \bar{\nu}$, $K_L \to \pi^0 \nu \bar{\nu}$

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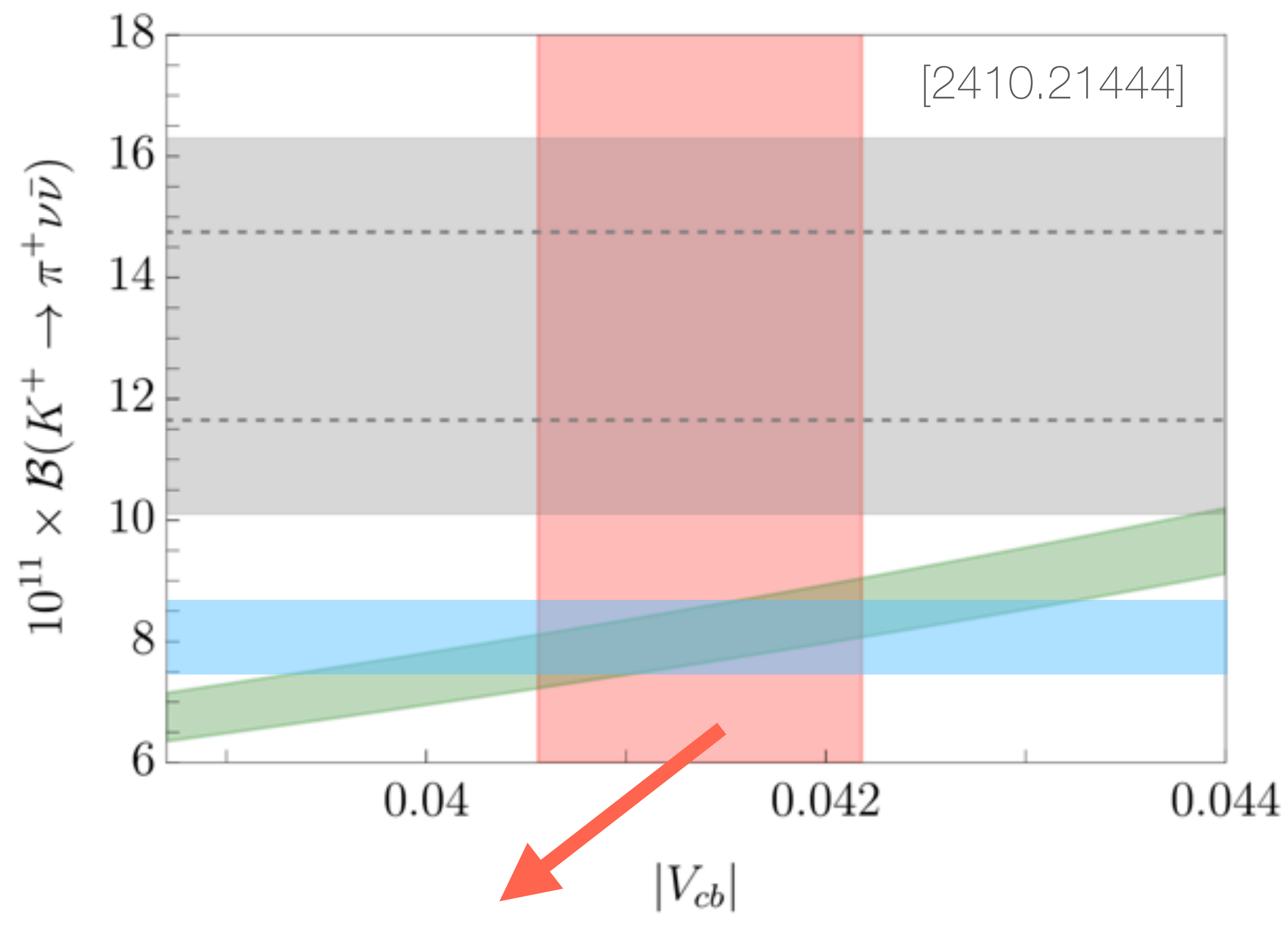

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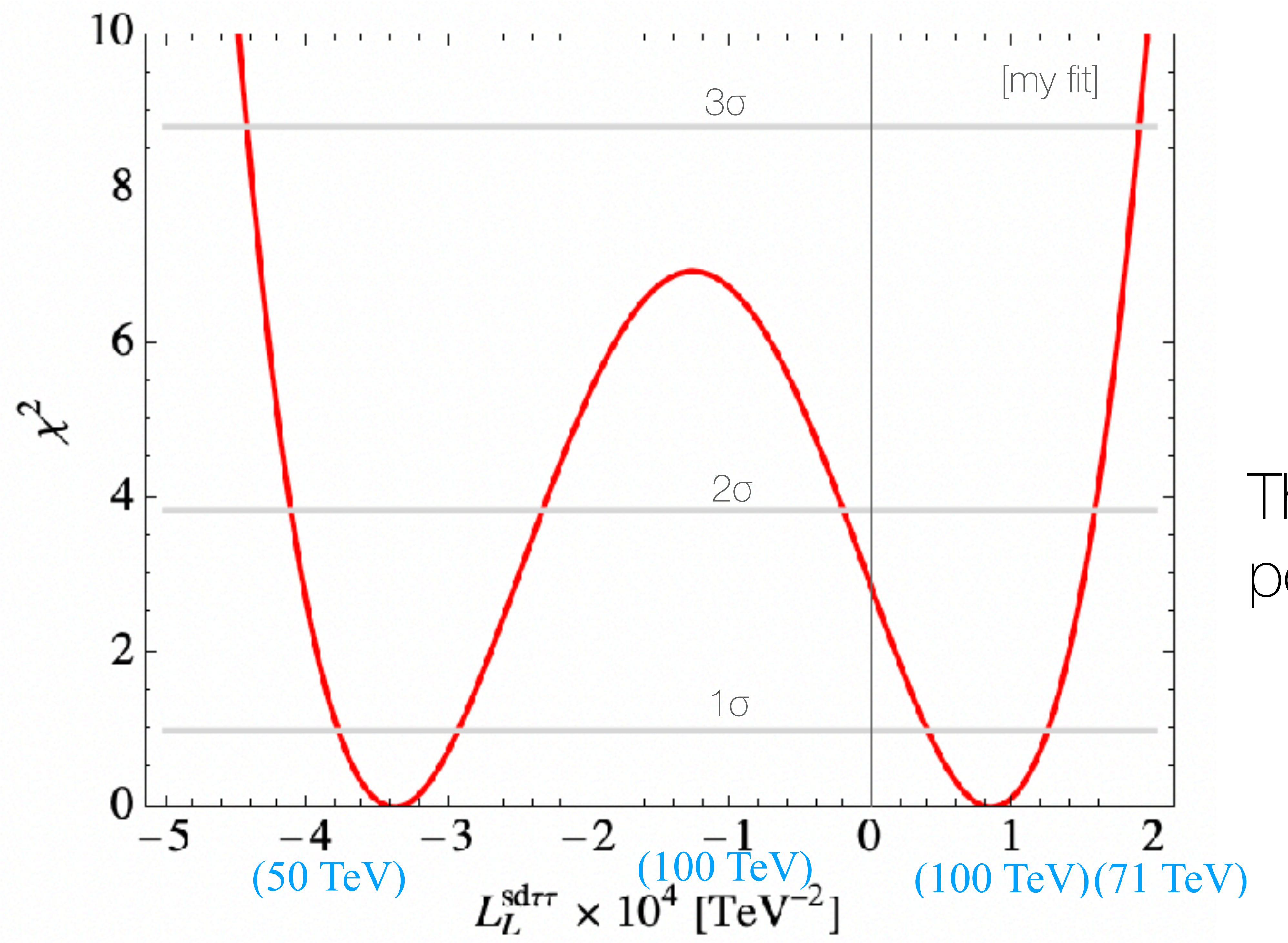


$L \sim \frac{1}{\Lambda^2}$

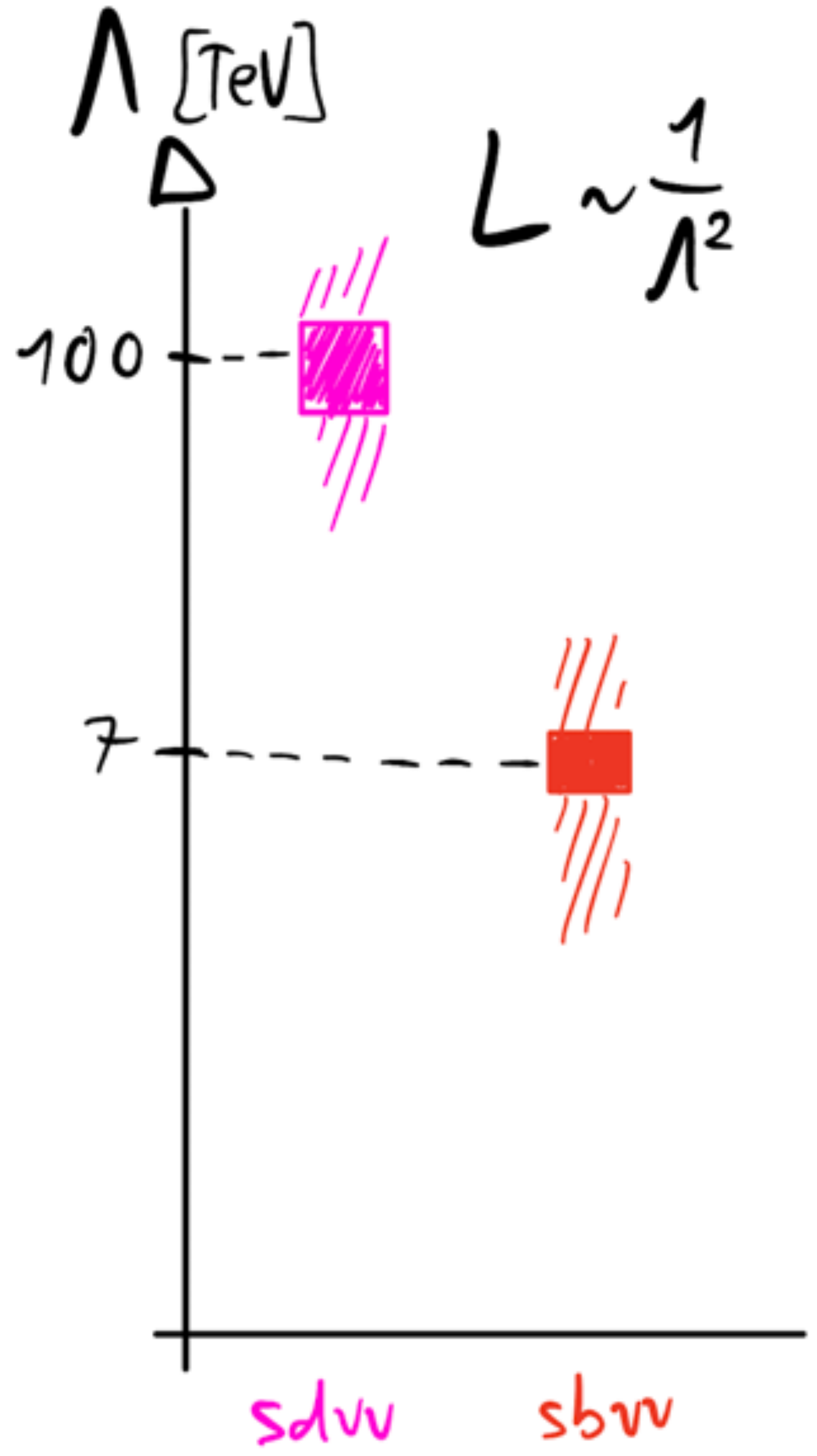
The **slight <2σ excess** points to new physics scales

$\Lambda_{sd\nu\nu} \sim 100\,\mathrm{TeV}$

A clue for a flavor struture

Neutral-current

$$\mathcal{L}_{EFT} \supset L^{ij\tau\tau}_{L,R} \left(\bar{d}_{i L,R}\gamma_\mu d_{j L,R}\right)\left(\bar{\nu}_\tau \gamma^\mu \nu_\tau\right)$$



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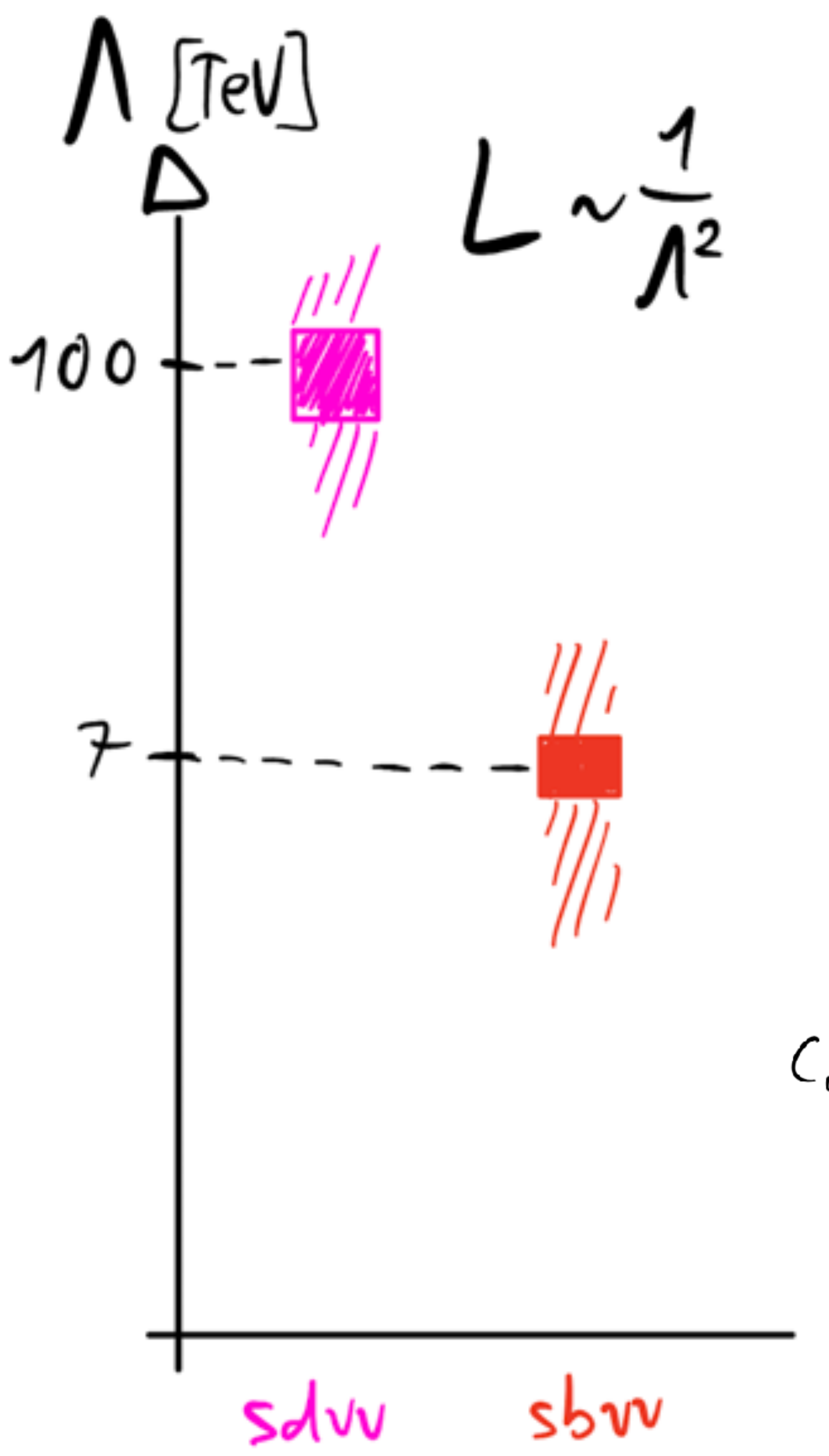
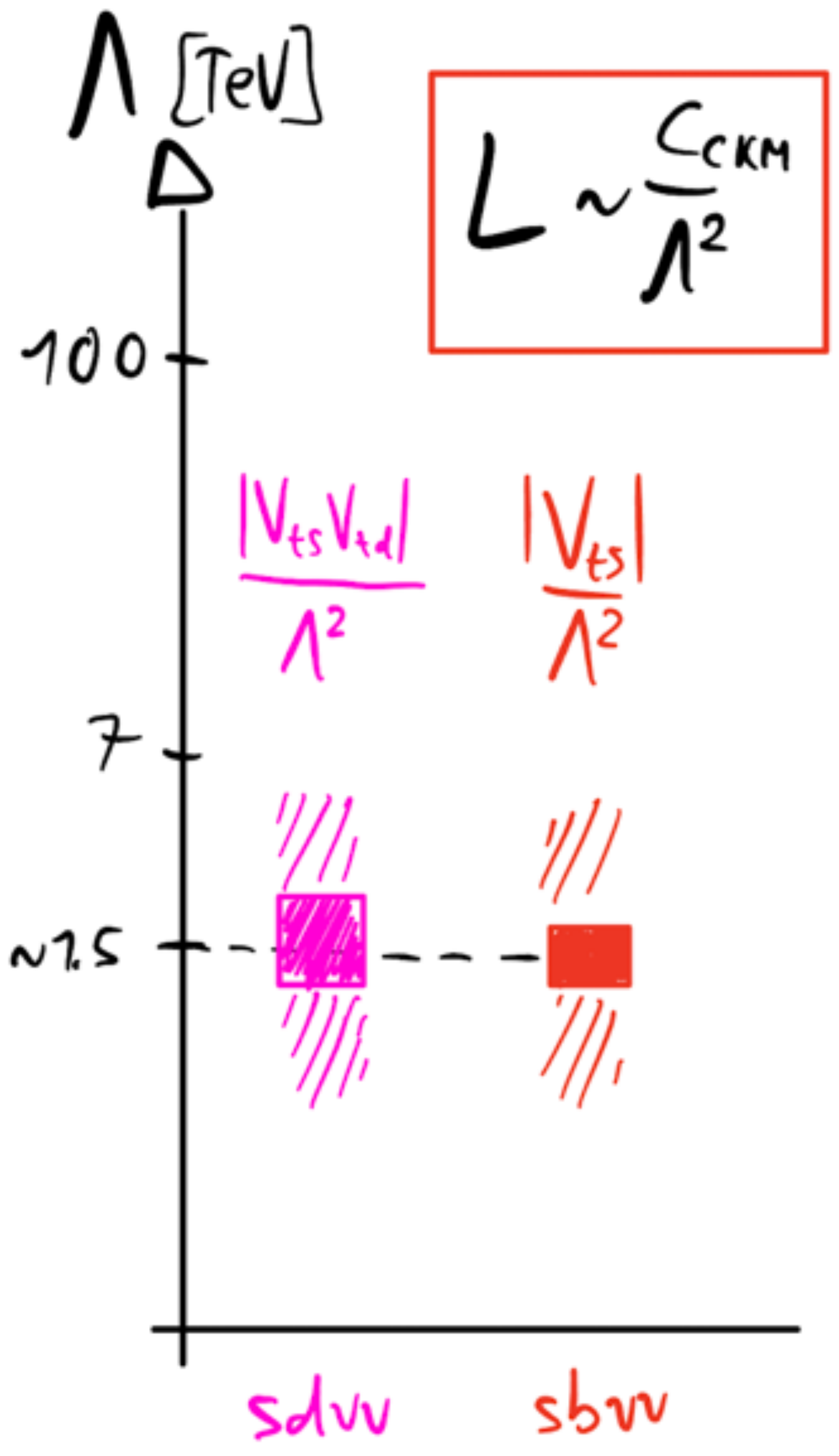


Assuming a CKM-like structure

$$C_{ij} \sim \begin{pmatrix} \varepsilon_1 & \lambda^5 & \lambda^3 \\ \lambda^5 & \varepsilon_2 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$



The physics scales become compatible!

A clue for a flavor struture

Neutral-current

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Charged-current

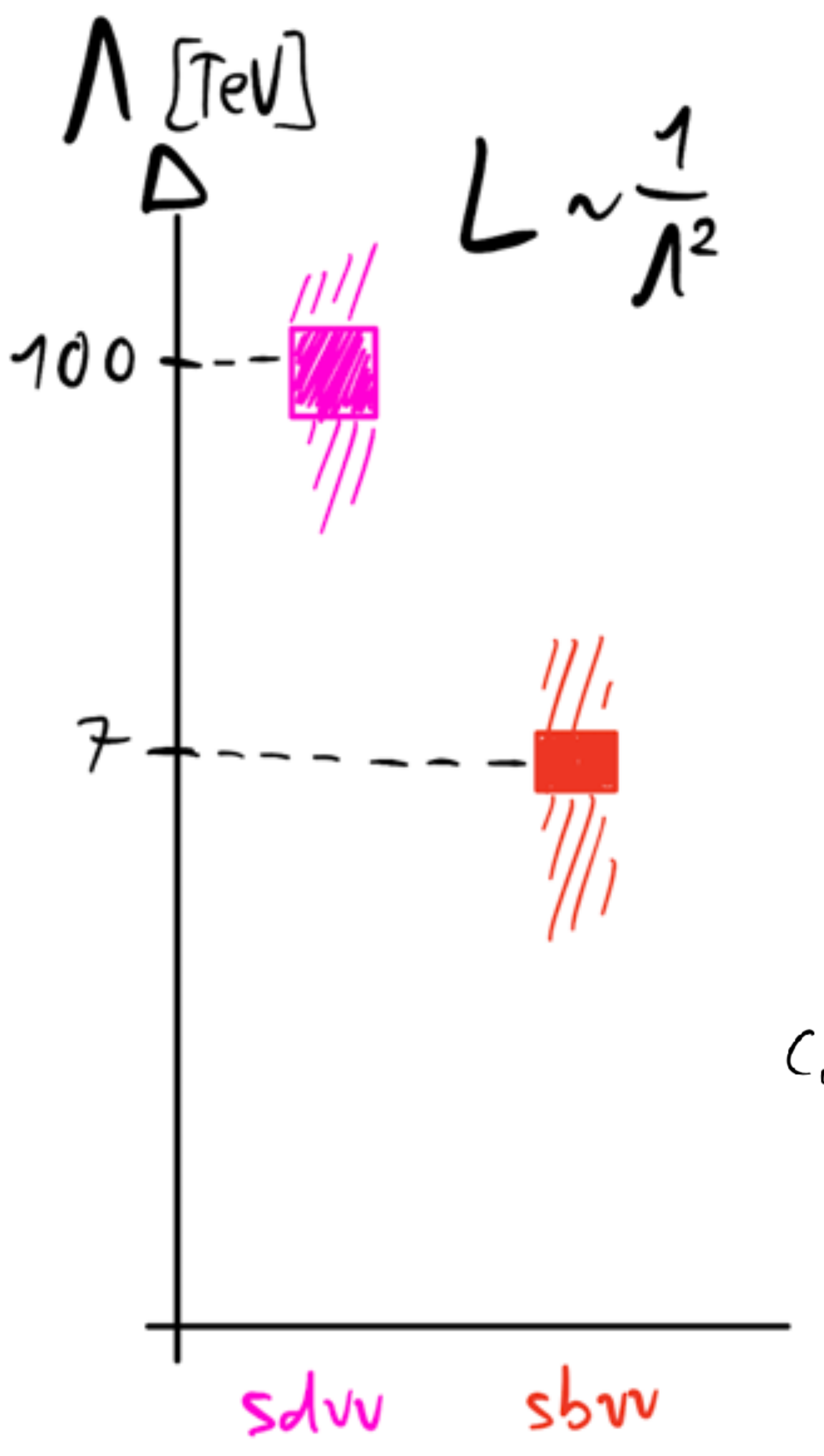
$$\mathcal{L}_{EFT} \supset L^{cc}_{ij\tau\tau} \left(\bar{d}_{iL}\gamma_\mu u_{jL}\right)\left(\bar{\nu}_\tau \gamma^\mu \tau_L\right)$$

$SU(2)_L$ ⟷

$$\left(\bar{Q}_L\gamma_\mu \sigma^a Q_L\right)\left(\bar{L}_L\gamma^\mu \sigma^a L_L\right)$$

The precise correlation is model-dependent

$$R(D^{(*)}) \rightarrow L^{cc}_{bc\nu\tau} \sim \frac{1}{(4\,\mathrm{TeV})^2}$$



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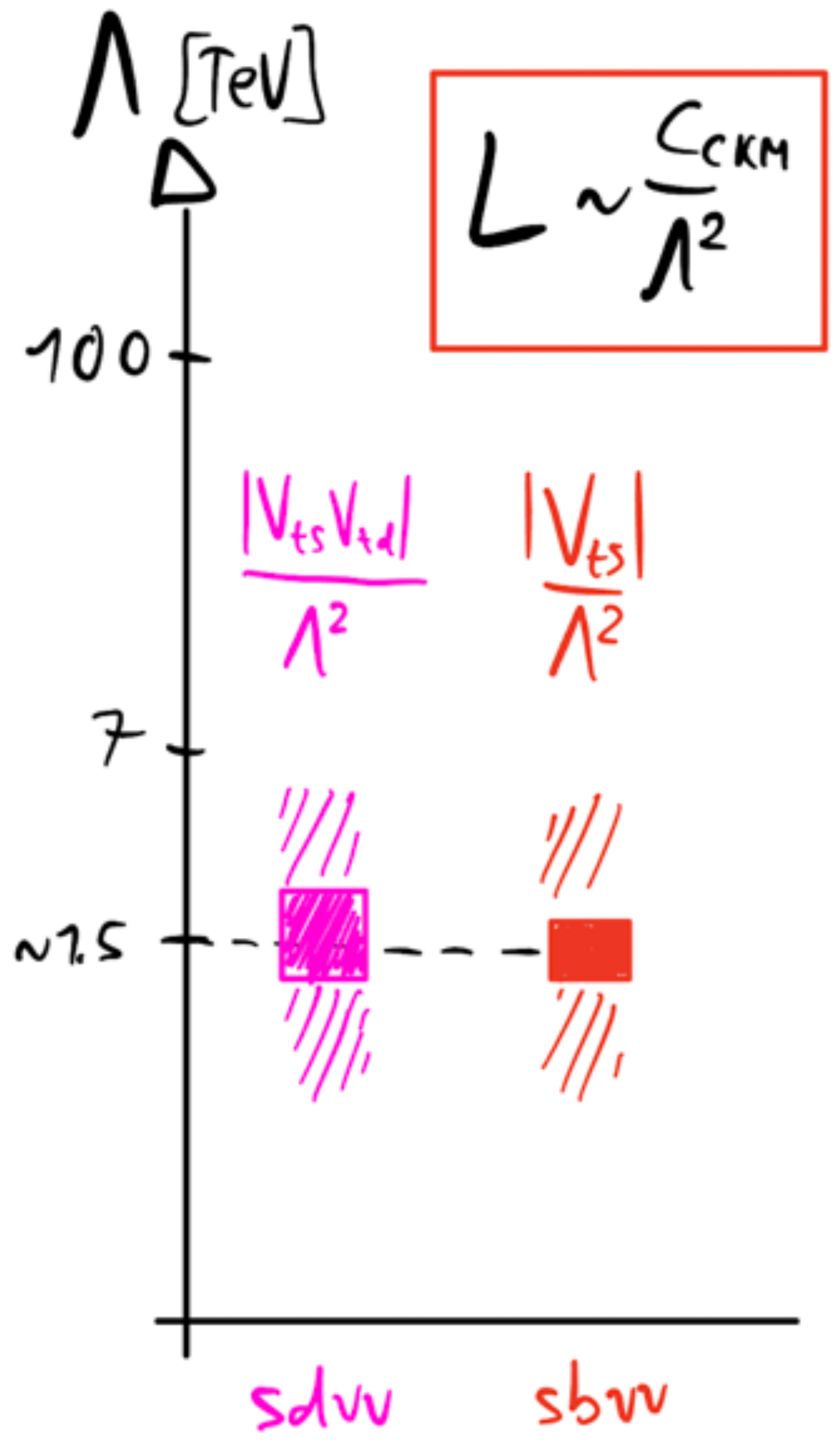

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SU(2)L

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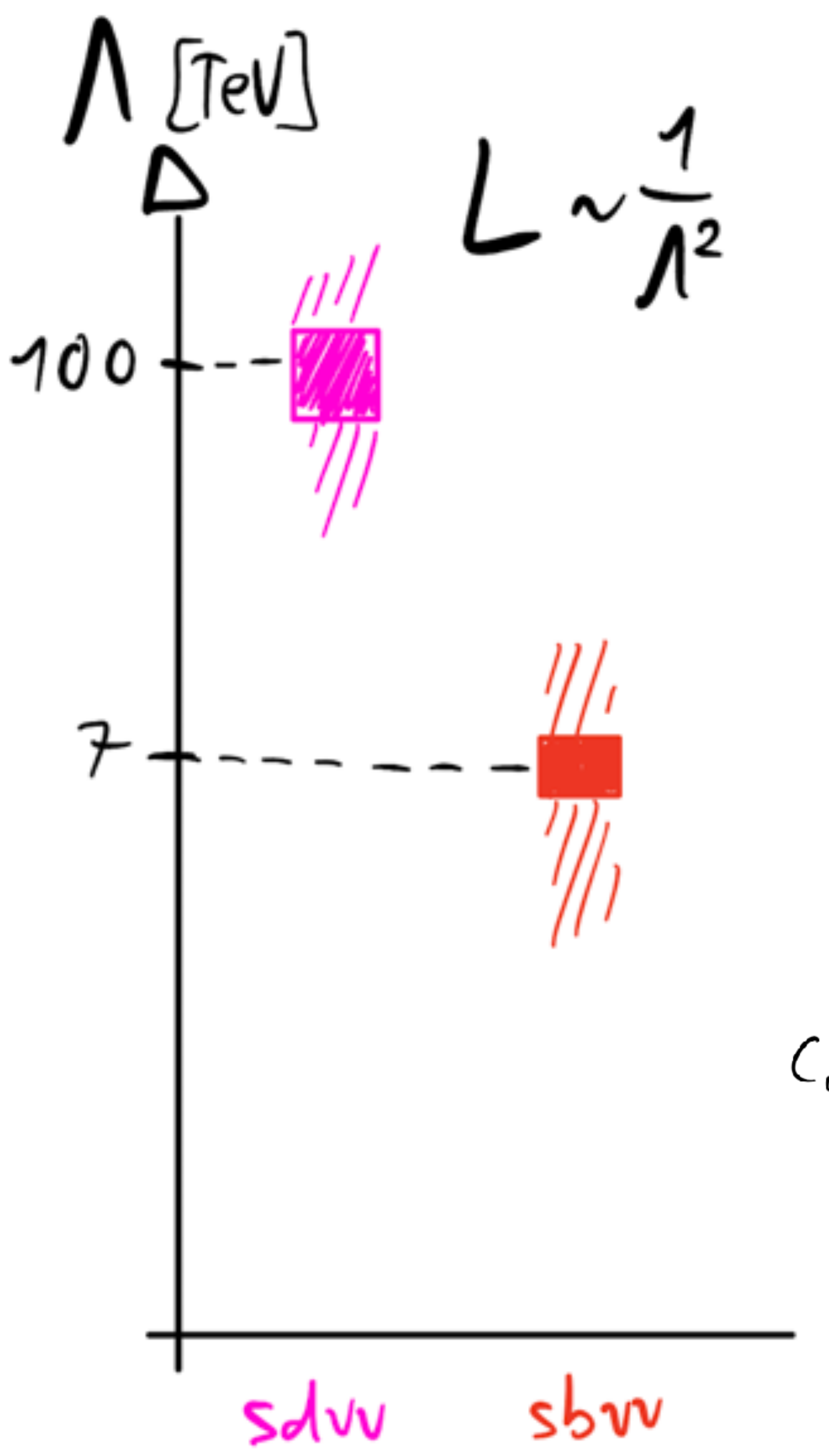

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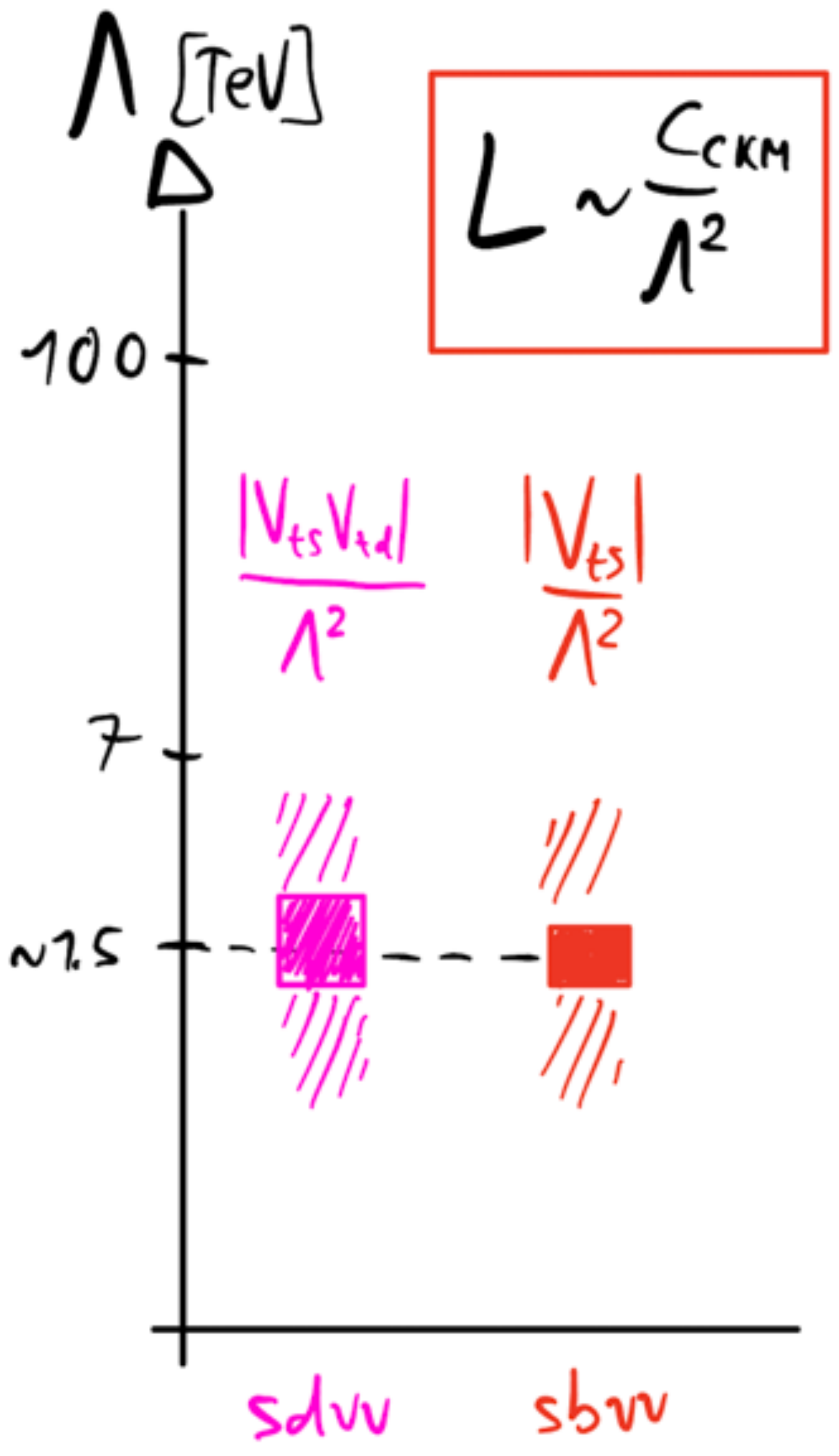
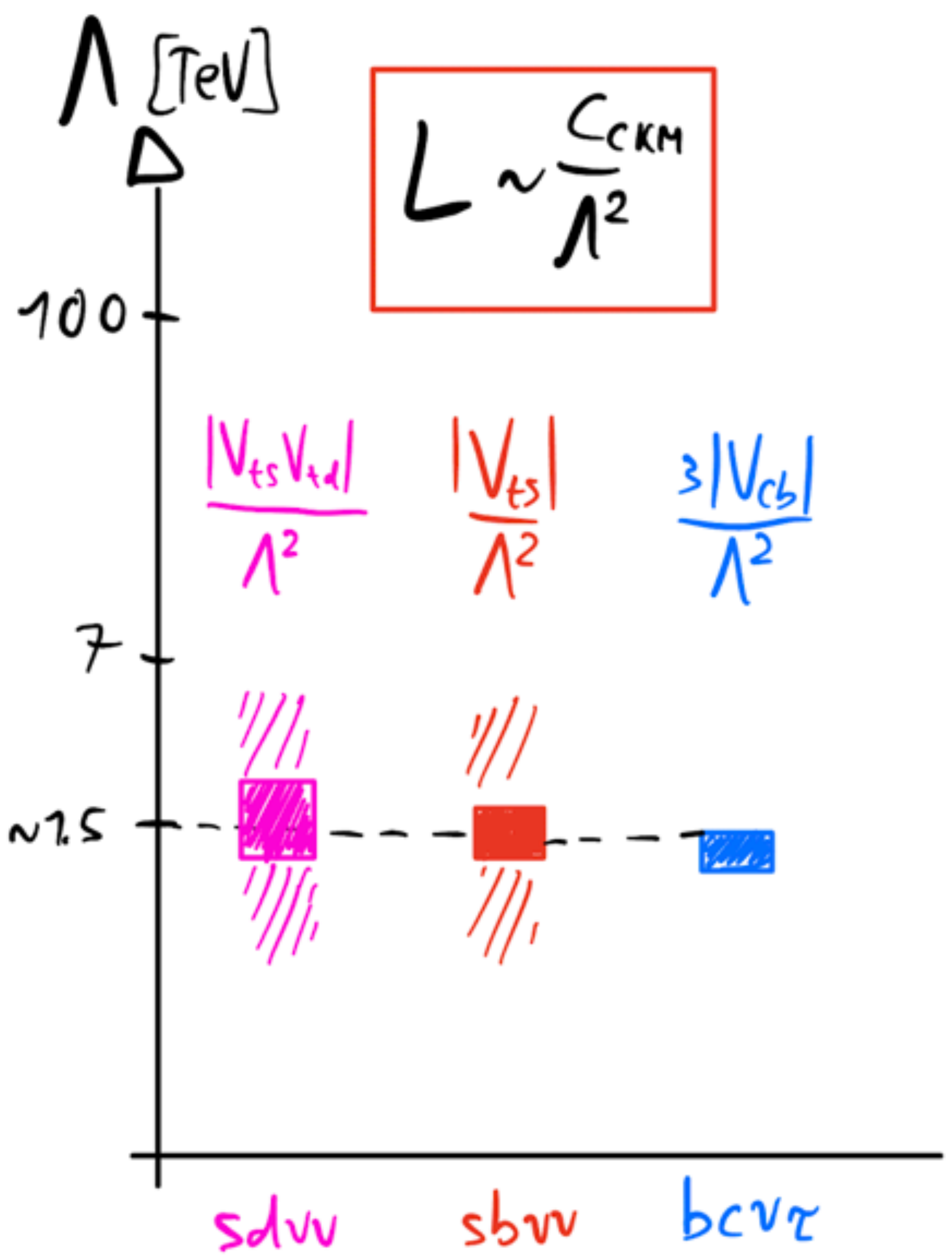




$$L^{cc}_{bc\nu\tau} \sim \frac{3|V_{cb}|}{(1.4\,\text{TeV})^2}$$

The three "excesses" are compatible with a U(2)-like flavour structure.

See Allwicher et al. [2410.21444]

The physics scales become compatible!

Conclusions

Many of the peculiar aspects of the **Standard Model** are **tested in Flavour Physics**:
conservation rules, forbidden processes, suppressed rates, etc.

Rare decays provide a large number of very **powerful probes of New Physics**.

Effective Field Theories are the natural playing ground for **new interpretation**.

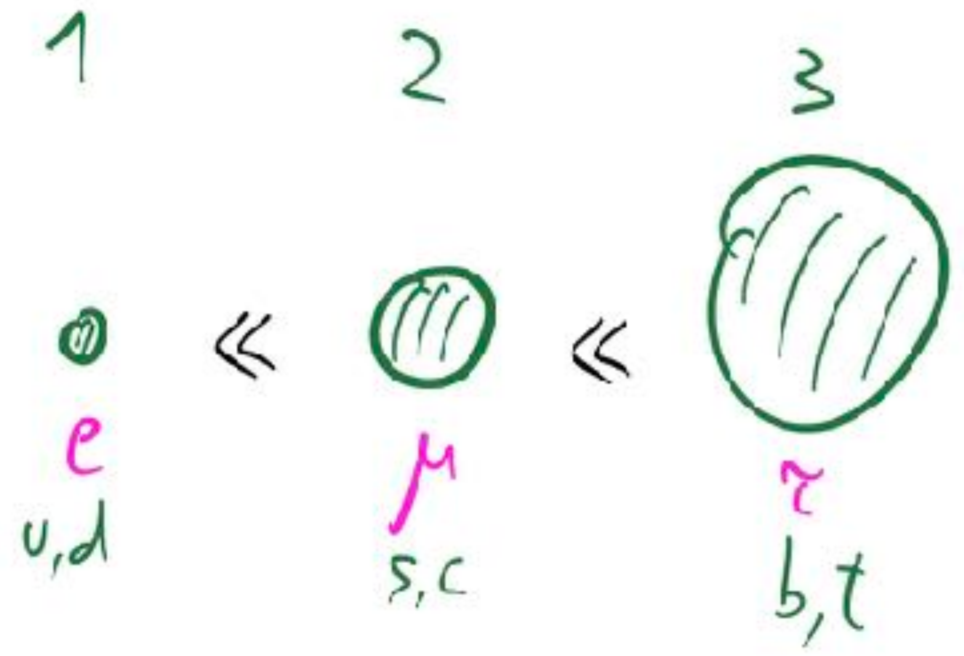
The **effective scales** probed in rare decays **reach O(100) TeV**.

This scale goes down to **~few TeV if a CKM-like flavour structure** (MFV, U(2), ..) of new physics couplings is assumed.
Under this assumptions, the new physics scale probed in golden channel decays is compatible with the mass scale required to address $R(D^{(*)})$ anomalies.

Grazie!

Backup

A clue for a flavor struture



In first approximation only the 3rd generation couples to the Higgs

$$Y_t \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_{33} \end{pmatrix}$$

In this case the theory enjoys a $U(2)^5$ global symmetry

$$G_F = U(2)_q \times U(2)_\ell \times U(2)_u \times U(2)_d \times U(2)_e$$

Barbieri et al. [1105.2296, 1203.4218, 1211.5085]

The **minimal breaking** of this symmetry to reproduce the SM Yukawas is:

$$Y_{u(d)} = y_{t(b)} \begin{pmatrix} \mathbf{\Delta}_{u(d)} & x_{t(b)} \mathbf{V}_q \\ 0 & 1 \end{pmatrix} , \qquad Y_e = y_\tau \begin{pmatrix} \mathbf{\Delta}_e & x_\tau \mathbf{V}_\ell \\ 0 & 1 \end{pmatrix}$$

$x_{t,b,\tau}$ are $\mathcal{O}(1)$, $\mathrm{V}_\ell \ll 1$

This is a very good approximate symmetry: the largest breaking has size $\epsilon \approx y_t |V_{ts}| \approx 0.04$

Diagonalizing quark masses, the **V_q doublet spurion is fixed** to be $\mathbf{V}_q = \kappa_q (V_{td}^*, V_{ts}^*)^T$

See also Fuentes-Martin, Isidori, Pagès, Yamamoto [1909.02519]

$\kappa_q \sim O(1)$

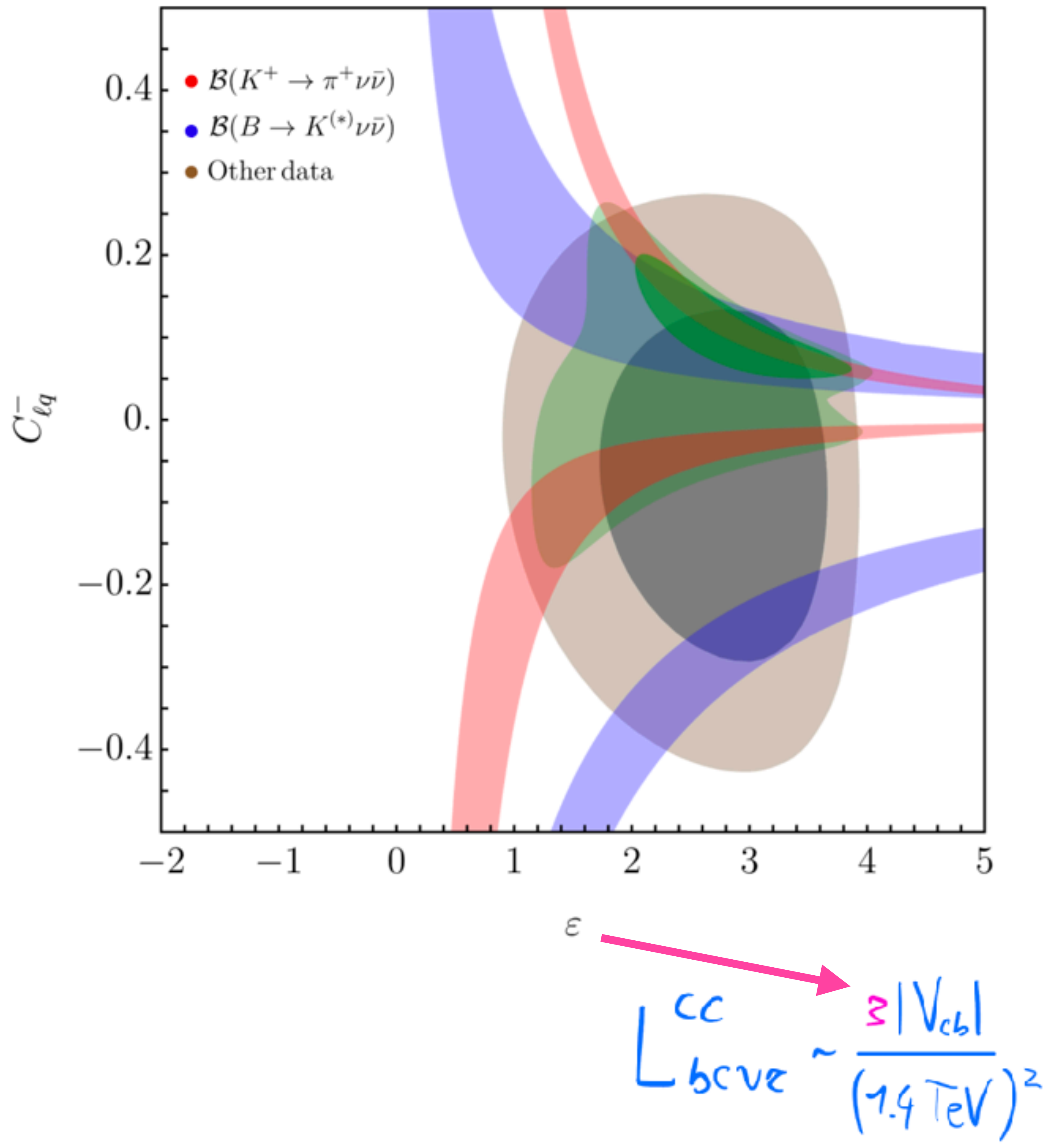
A clue for a flavor struture

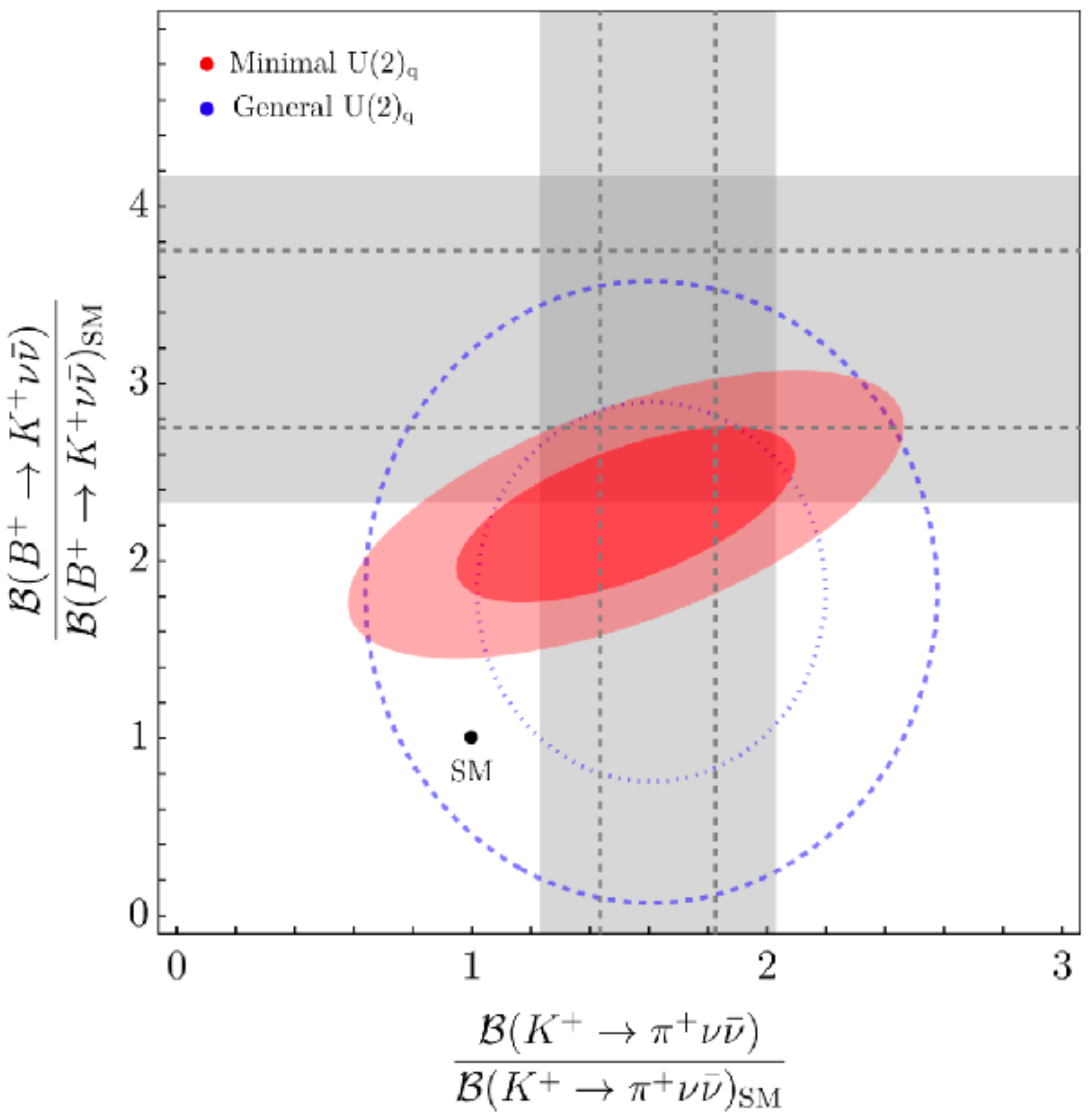
$$Q^{\pm}_{\ell q} = (\bar{q}^3_L \gamma^\mu q^3_L)(\bar{\ell}^3_L \gamma_\mu \ell^3_L) \pm (\bar{q}^3_L \gamma^\mu \sigma^a q^3_L)(\bar{\ell}^3_L \gamma_\mu \sigma^a \ell^3_L)$$

$$\tilde{V} = -\varepsilon V_{ts} \begin{pmatrix} \kappa V_{td}/V_{ts} \\ 1 \end{pmatrix}$$

Minimal $U(2)_q$: $\kappa = 1$.

Allwicher et al. [2410.21444]





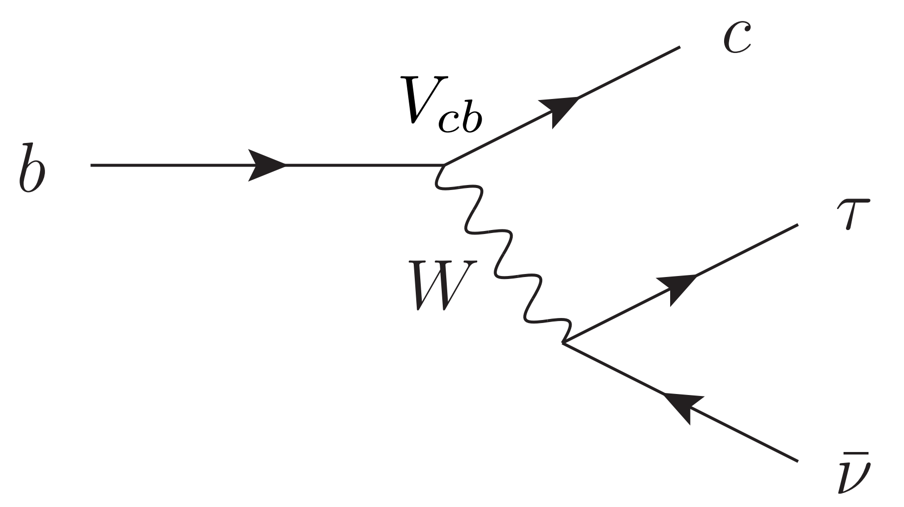
B-anomalies in charged current $b \to c\,\tau\,\bar{\nu}_\tau$

Lepton Flavour Universality

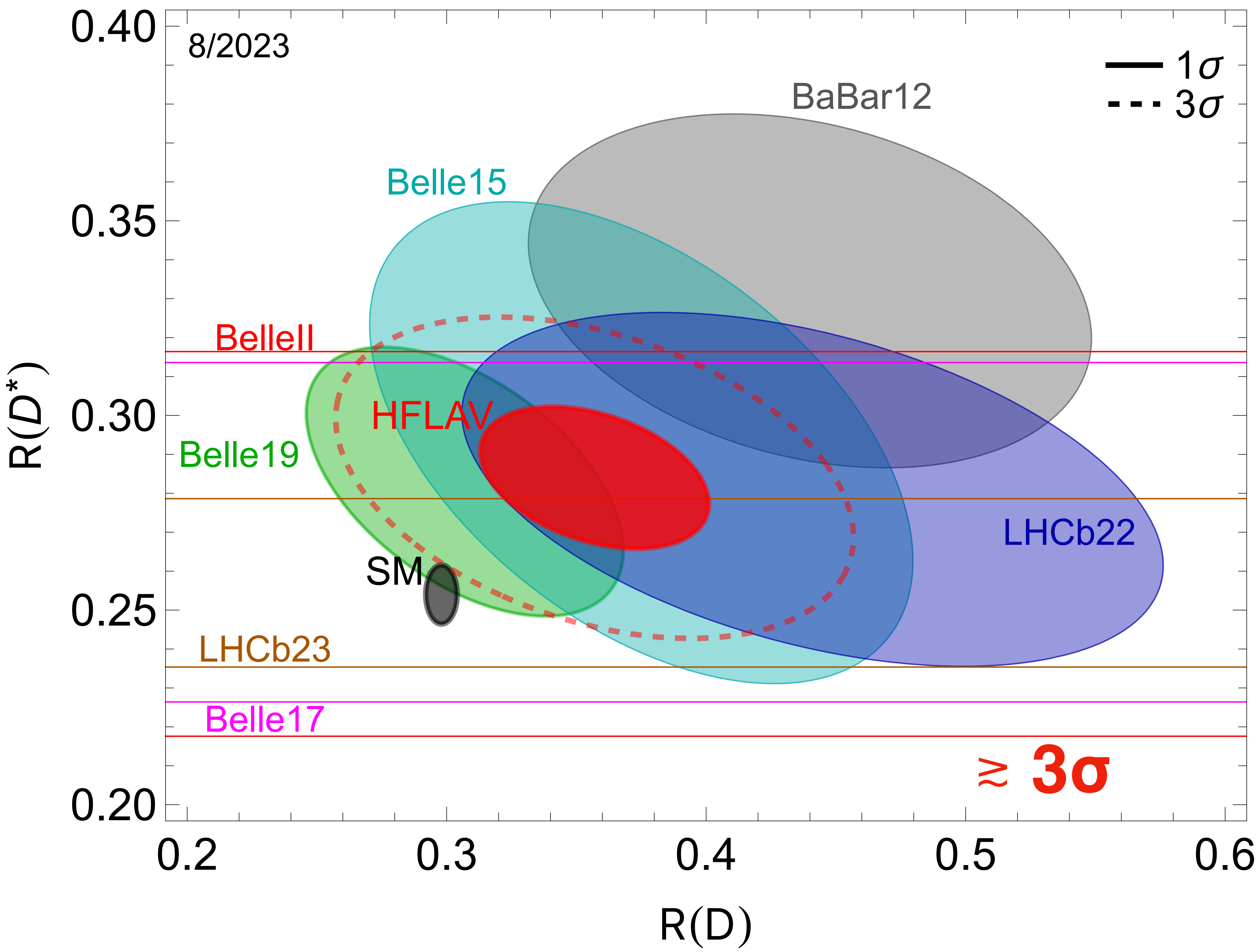
$$R(D^{(*)}) \equiv \frac{\mathcal{B}(B^0 \to D^{(*)+}\tau\nu)}{\mathcal{B}(B^0 \to D^{(*)+}\ell\nu)}, \quad R(X) = \frac{\mathcal{B}(B \to X\tau\nu_\tau)}{\mathcal{B}(B \to X\ell\nu_\ell)}$$

$$\ell = \mu, e$$

Tree-level SM process with V_{cb} suppression.



SM prediction under control.



$$R^\tau_{cc} \equiv \frac{R(D)}{R(D)_{SM}} = \frac{R(D^*)}{R(D^*)_{SM}} = \frac{R(X)}{R(X)_{SM}}$$

$$R^\tau_{cc} = 1{,}135 \pm 0{,}034$$

$$\mathcal{L}_{EFT} \supset C^{du\nu\tau}_{ij\tau\tau} \left(\bar{d}_{iL}\gamma_\mu u_{jL}\right)\left(\bar{\nu}_\tau \gamma^\mu \tau_L\right)$$

Corresponds to a **New Physics scale** of

$$C^{R(D^{(*)})}_{cb\tau\nu} \sim (4\,\text{TeV})^{-2}$$