Recent results in Flavour Physics
- Theory (BSM) -

David Marzocca
INFN Trieste

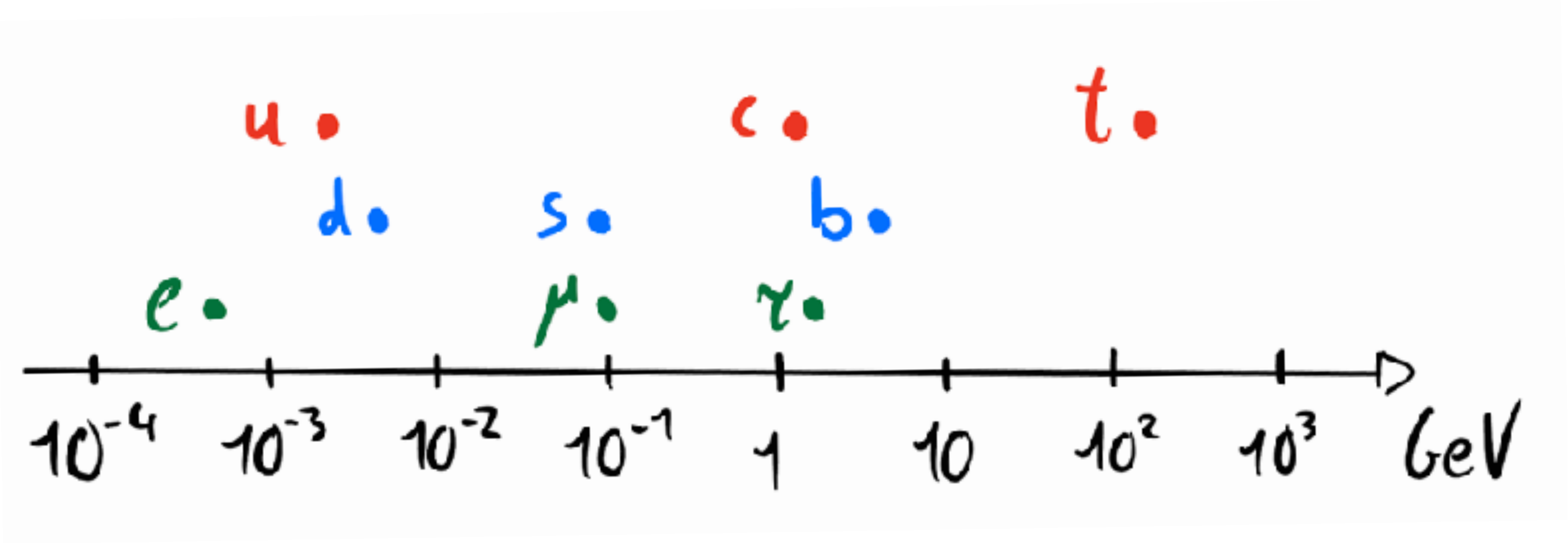
Workshop on Flavour Changing and Conserving Processes (FCCP2025) - Anacapri - 29/09/2025

SM Flavour Puzzle

Most of the **richness and complexity** of the Standard Model is in the **Yukawa sector**, which presents a **very peculiar structure**:

- **hierarchical fermion masses**

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



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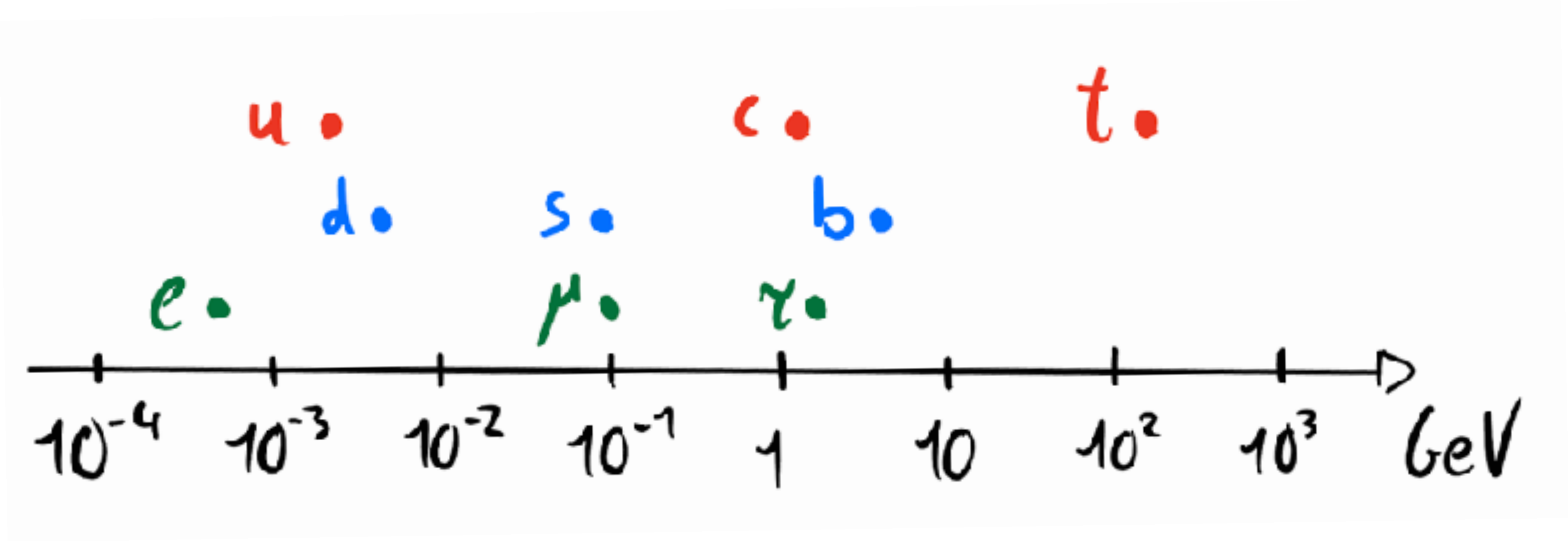

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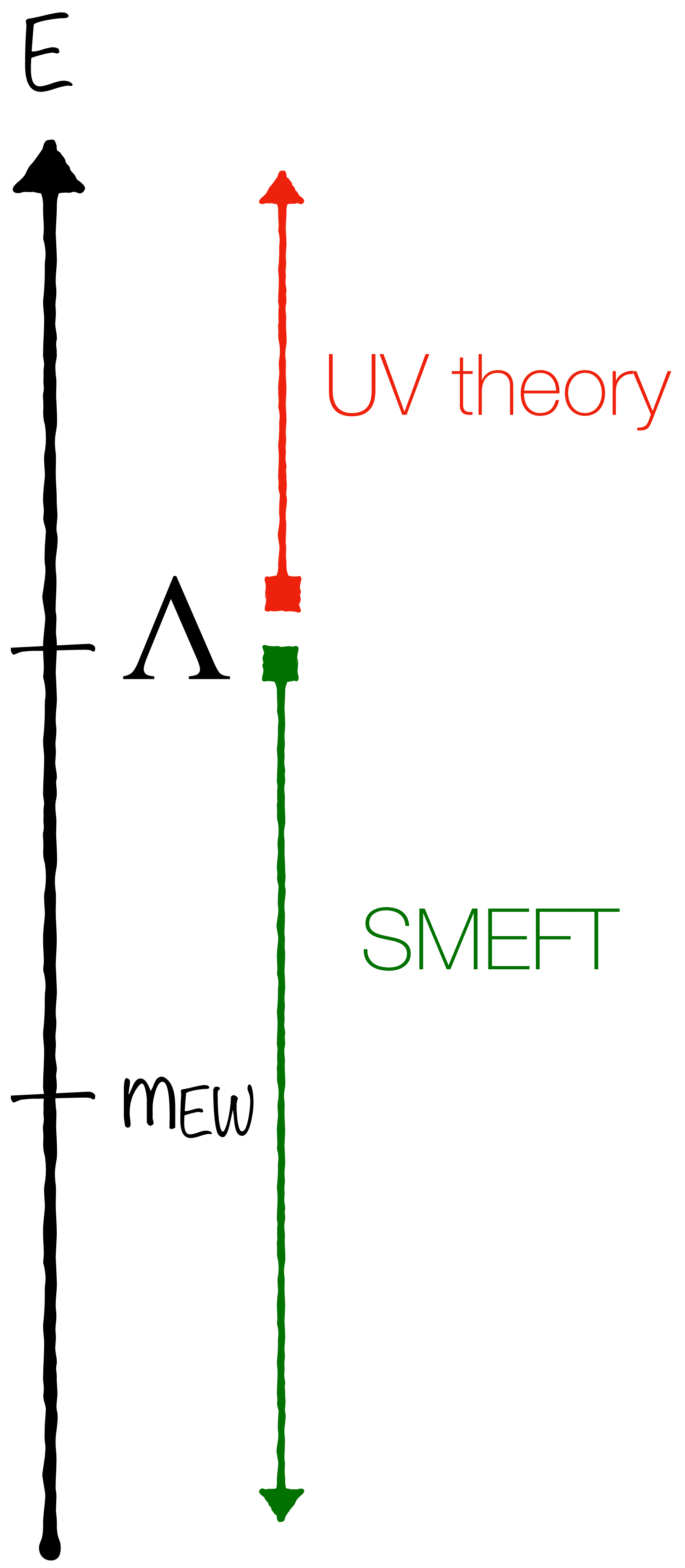
This puzzle in general **doesn't point to a specific New Physics scale for its solutions**. They could be anywhere from **near the TeV** till up to **GUT/Planck**.

However, since it must generate this non-trivial flavour structure, **it is some Flavourful New Physics**:
- **non universal**
- **flavour changing**

The Standard Model as an EFT



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**.

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM}^{(d\le 4)} + \frac{c^{(5)}}{\Lambda_L}\mathcal{O}_W + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)}[\varphi_{SM}] + \mathcal{O}(\Lambda^{-4})$$

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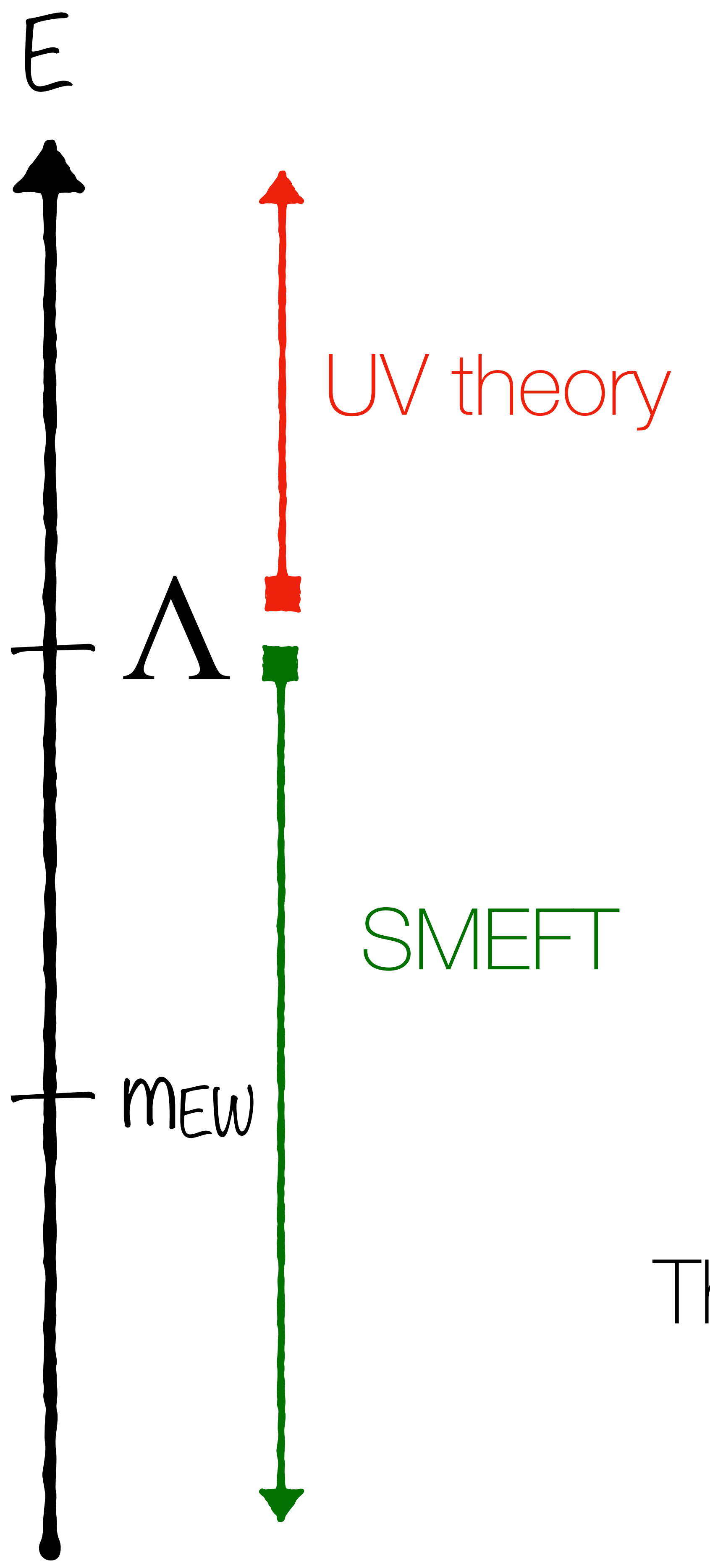

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At **low energies**, the effects from higher-dimension operators are **suppressed** by powers of $\left(\frac{E}{\Lambda}\right)^{d-4} \ll 1$

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

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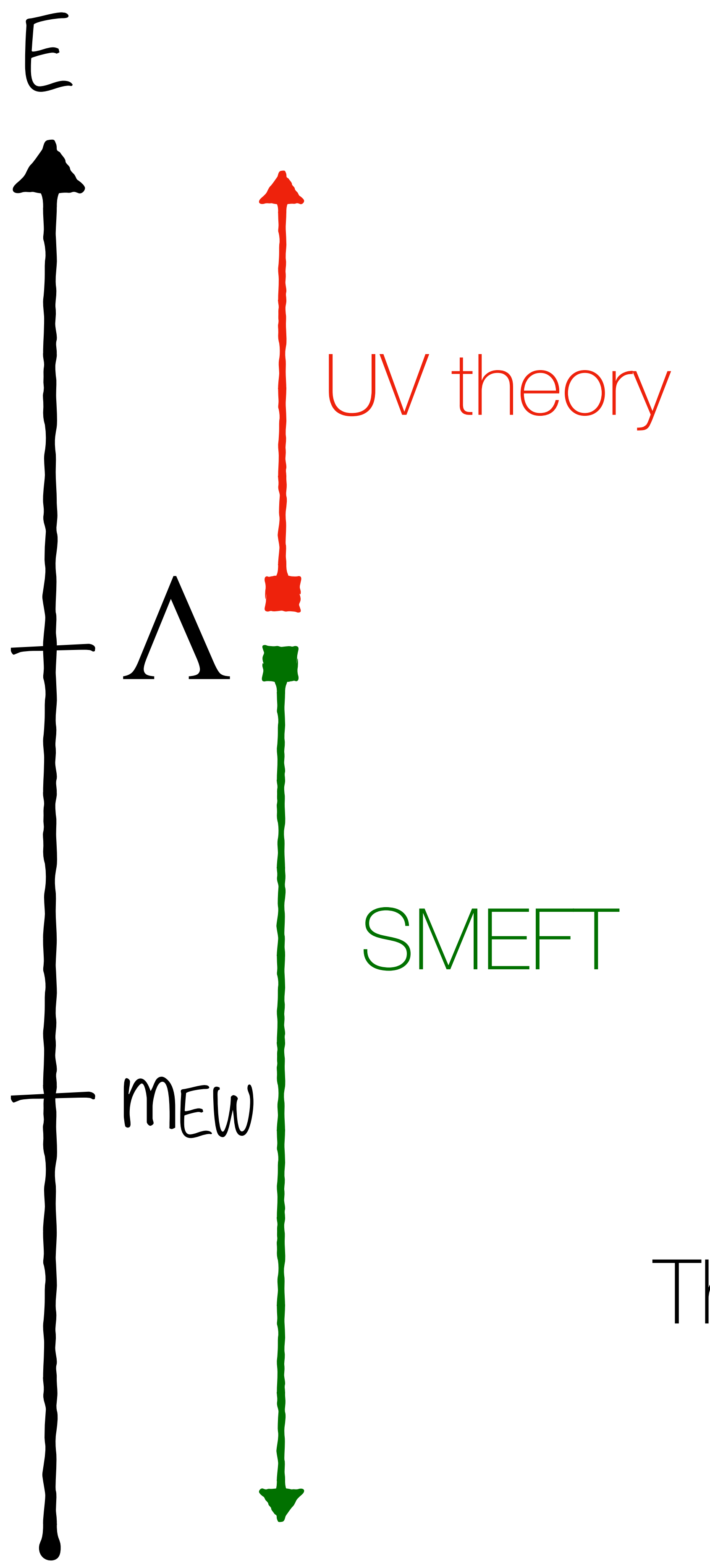

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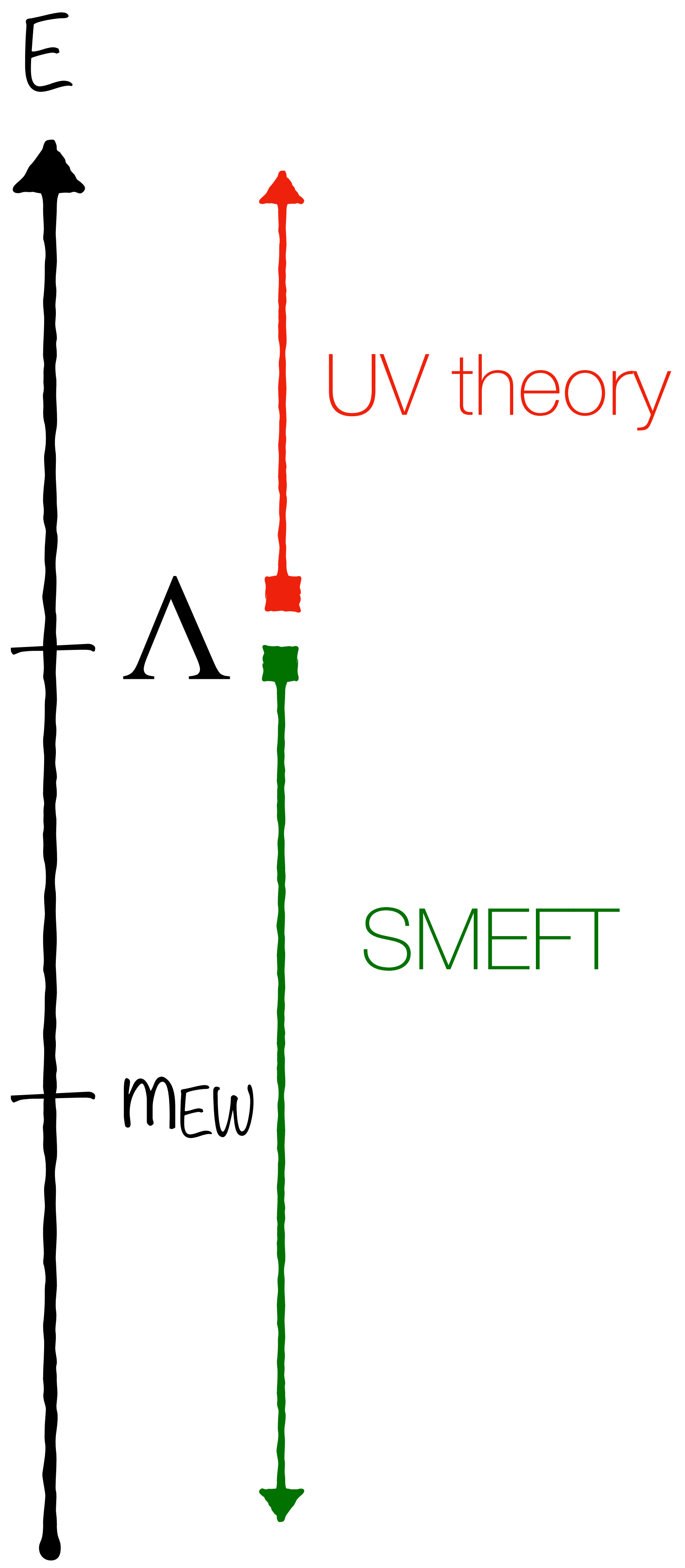
The limited set of operators allowed at $d \leq 4$ automatically endows the **SM** with **accidental features & symmetries**

(absence of tree-level FCNC and CP-violation, LFU, custodial symmetry, B & L_i conservation, massless neutrinos, etc..)

The Standard Model as an EFT



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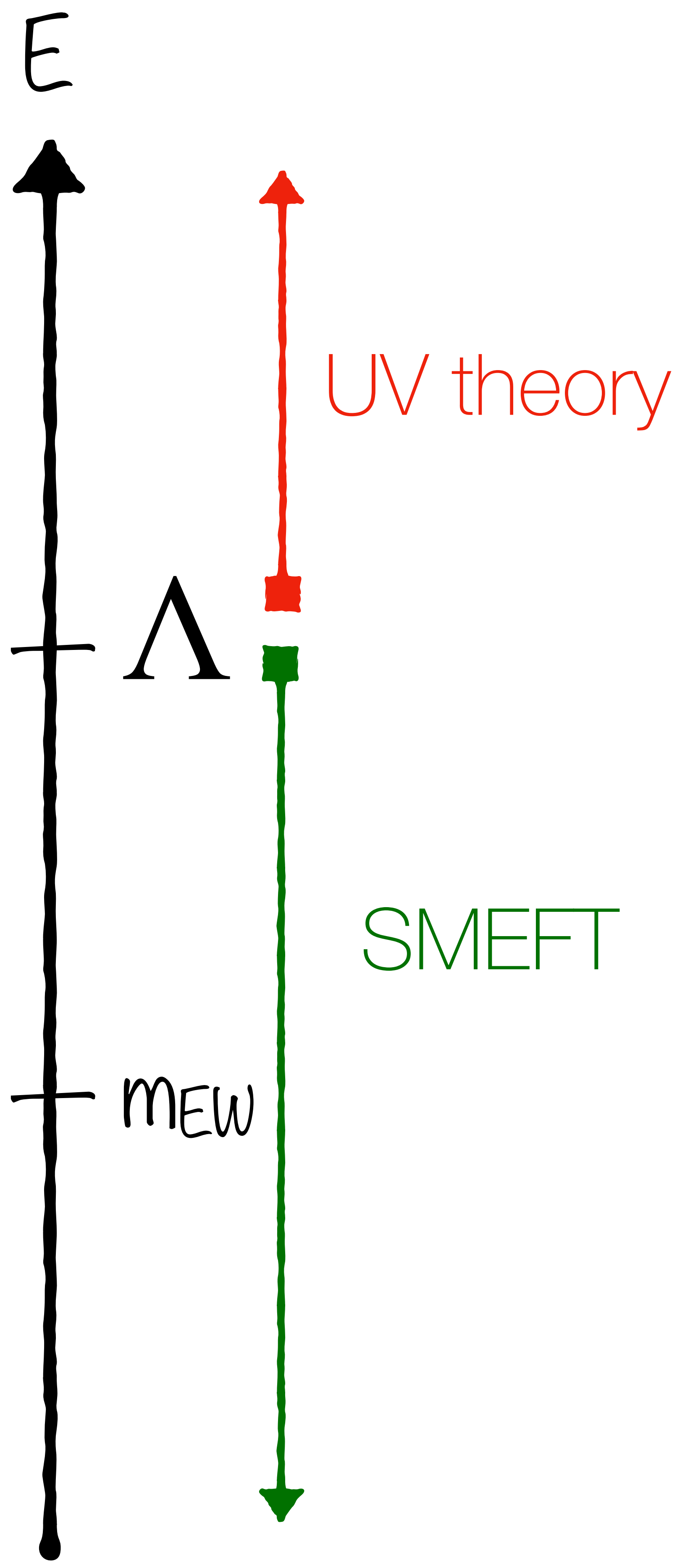

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We can expect large effects in rare or forbidden processes!

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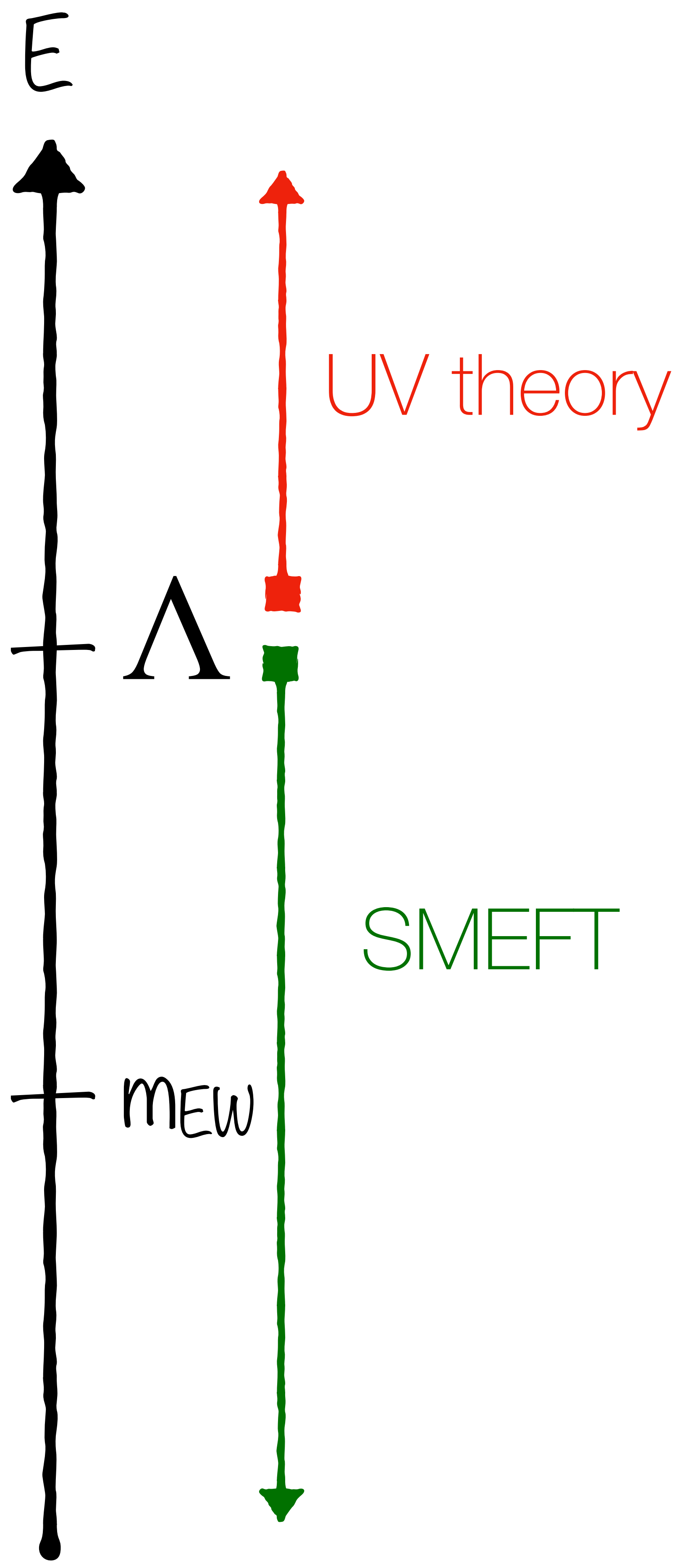

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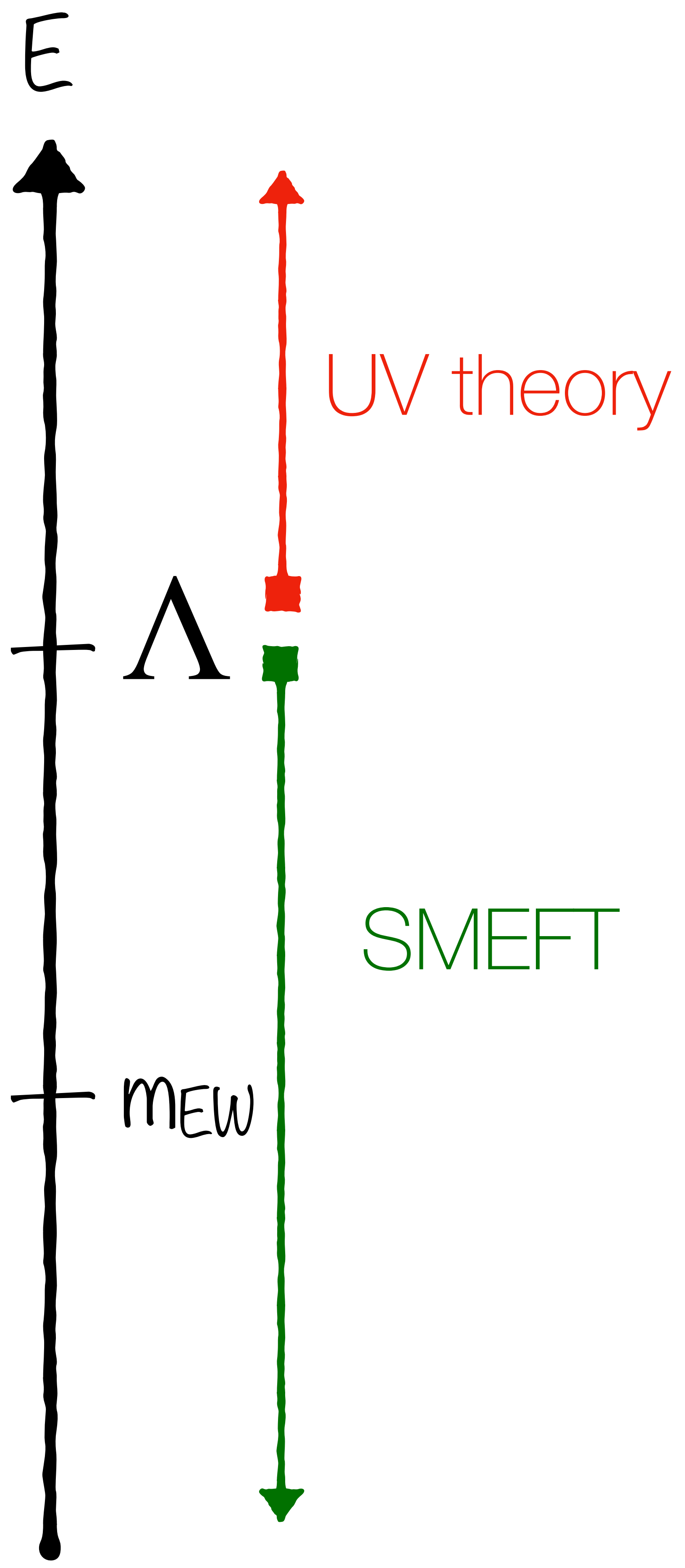

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How **BIG** or **small** should Λ be?

Motivated Reasons for a **"low"** Λ:

Hierarchy problem of the EW scale,

$\Lambda \sim$ TeV

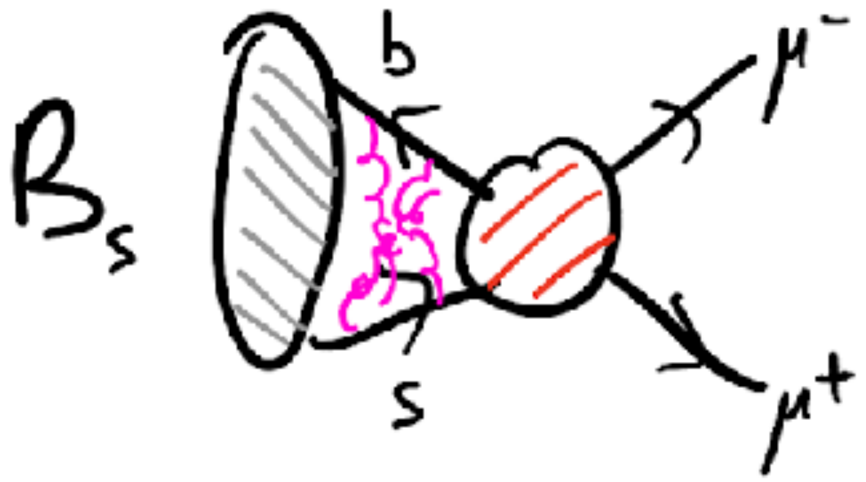
Experimental signatures of BSM physics (***anomalies***)

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

WIMP miracle for Dark Matter

$\Lambda \sim 0.1$ - O(10) TeV

The BSM Flavour Problem



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

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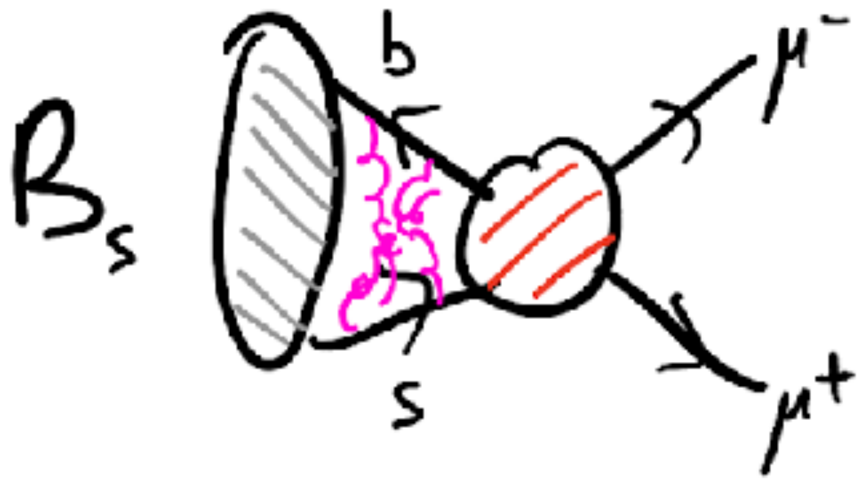

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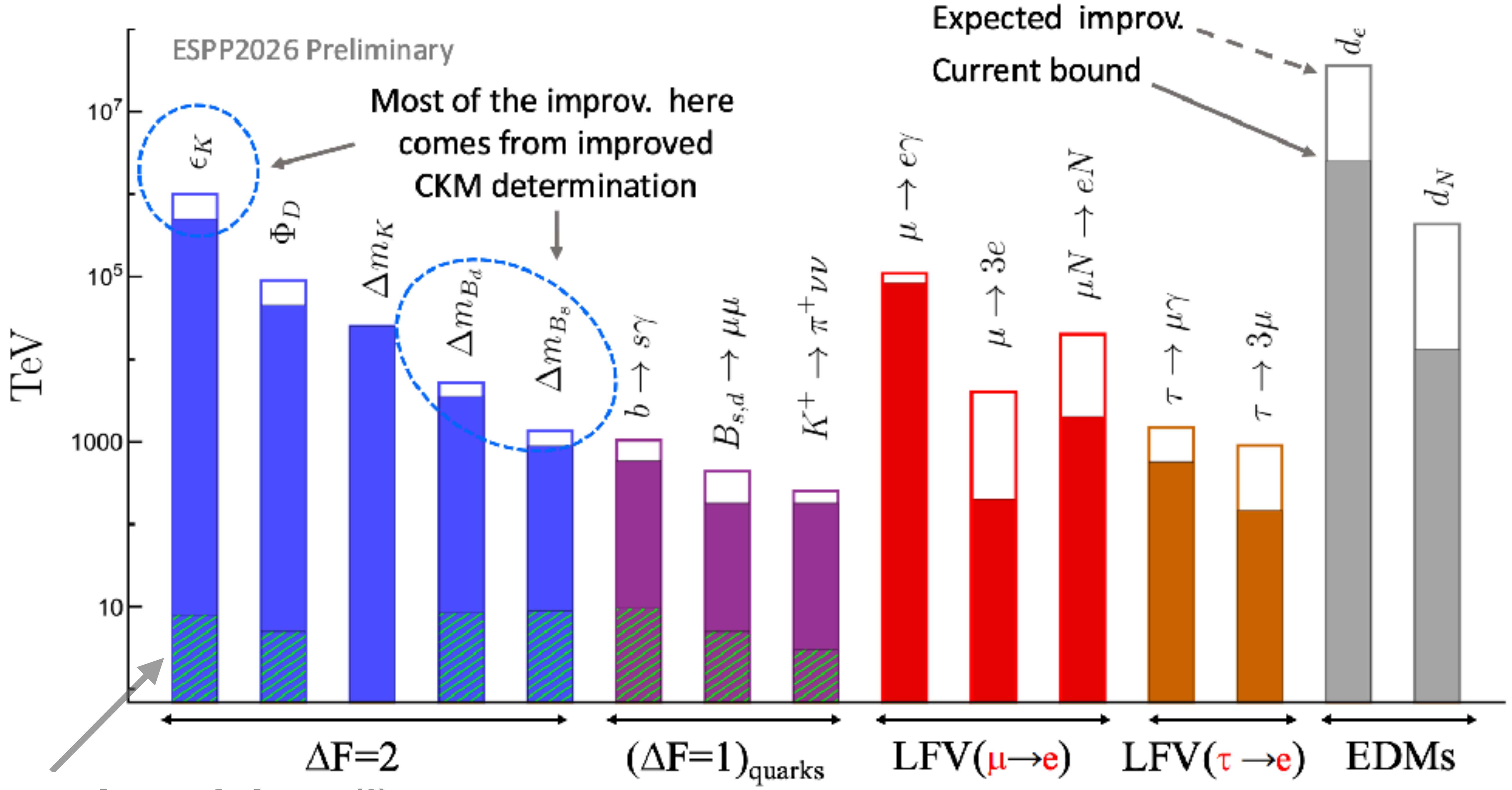
Bounds on Λ (taking $c_i^{(6)} = 1$) from various processes:



CKM-like suppression of the $c_i^{(6)}$

[G. Isidori's talk @ OpenSymposium ESPPU2026]

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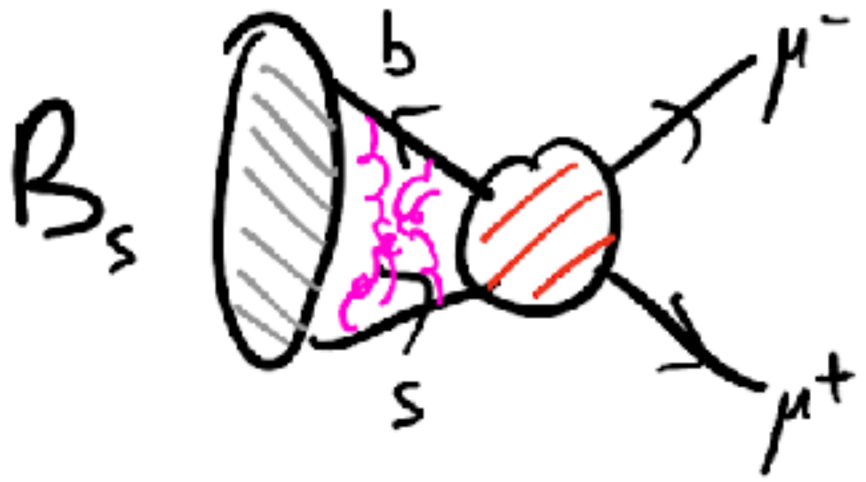

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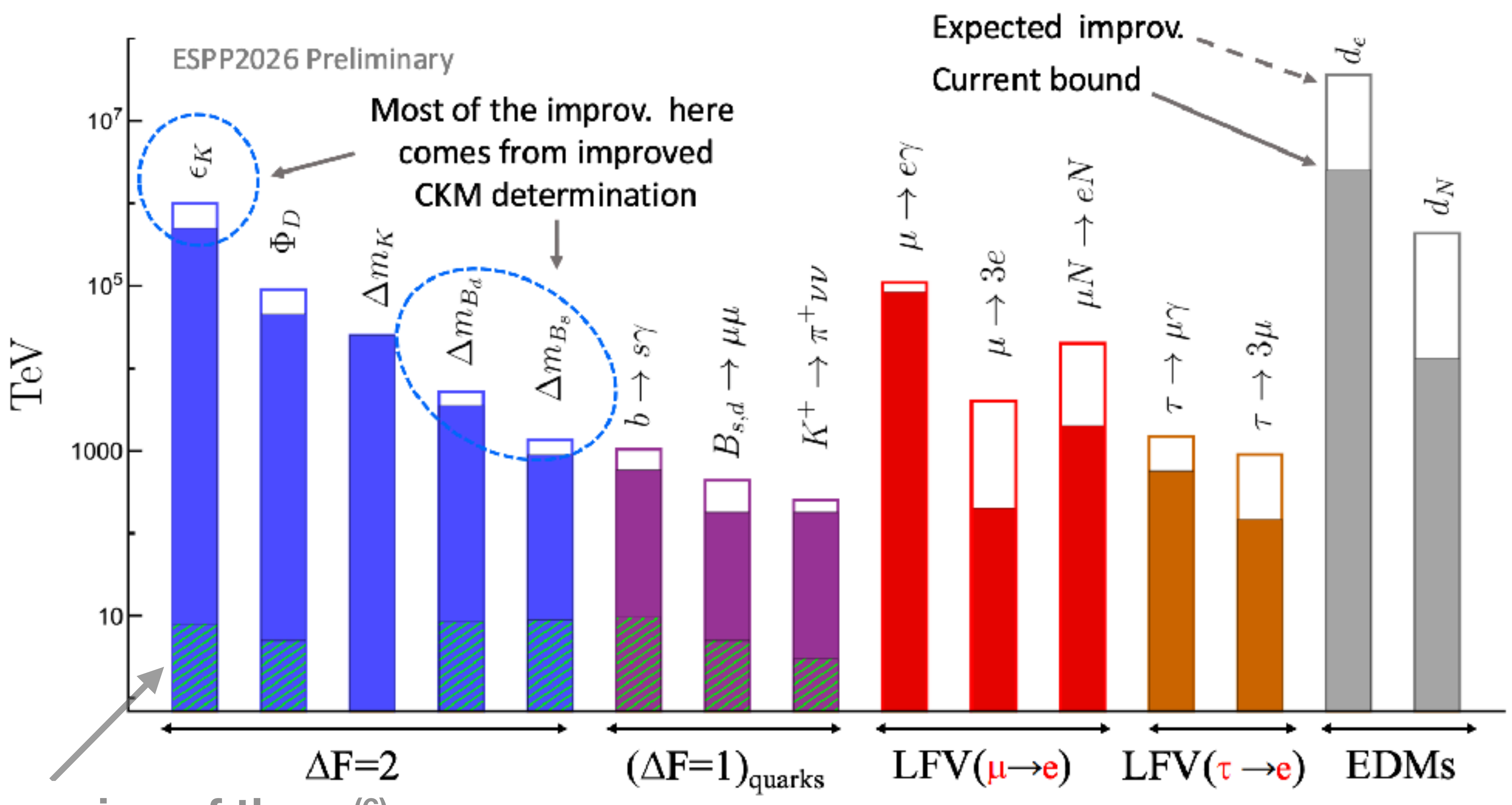
Bounds on Λ (taking $c_i^{(6)} = 1$) from various processes:

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**.

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

Need: **$c^{(6)}$(Flav. Violating) ≪ 1 !!**



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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:

"CKM-like"

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

$\lambda \sim \sin\vartheta_c$

Cabibbo angle

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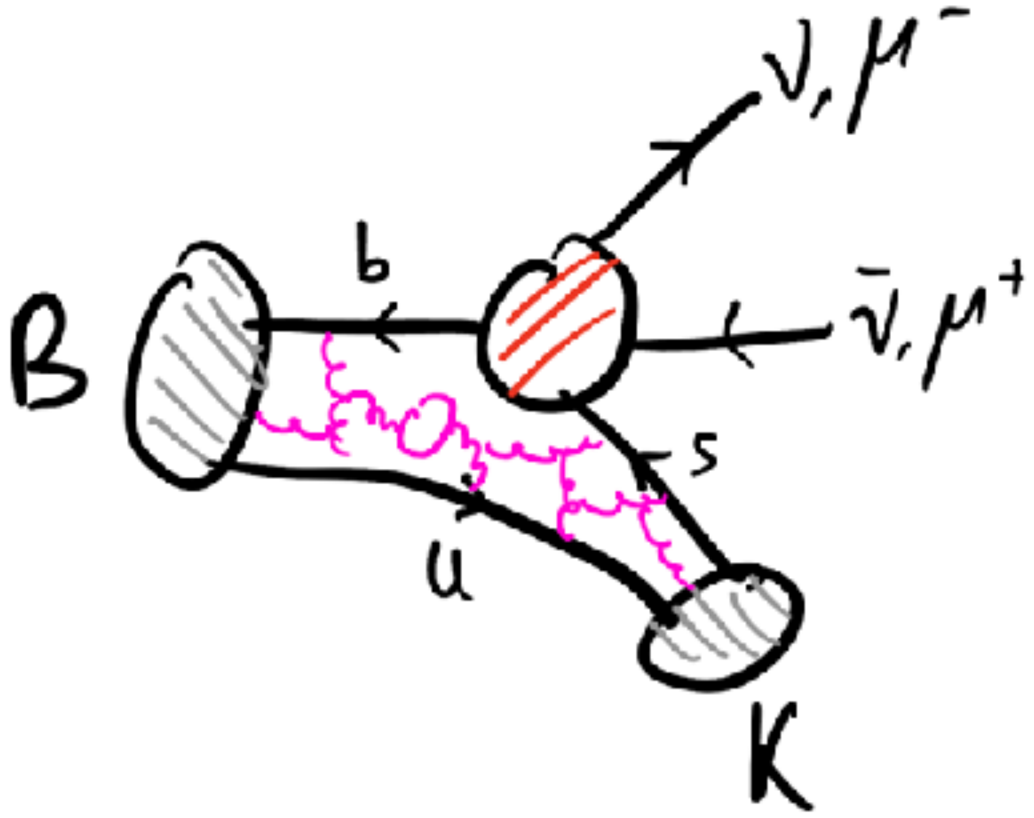
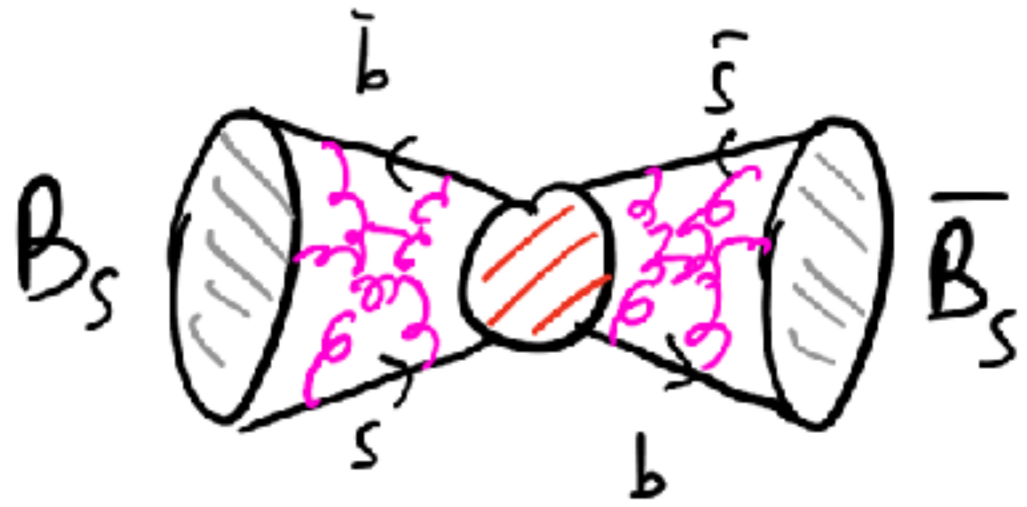
$\varepsilon_{1,2}$:

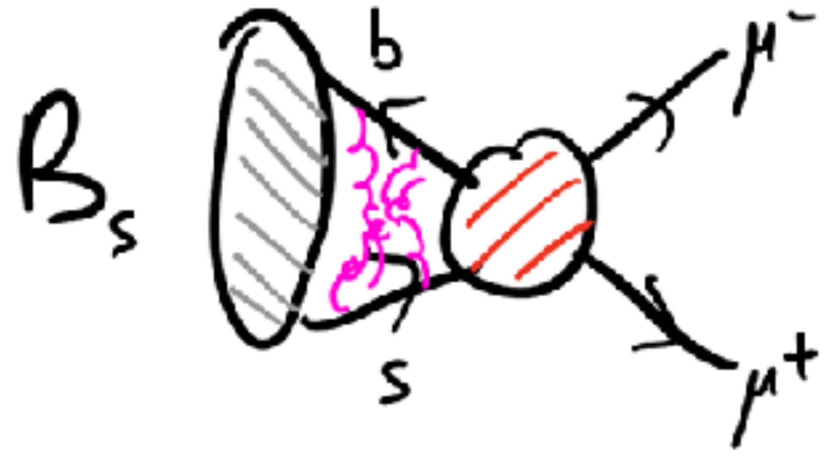
U(2)-like: $\varepsilon_{1,2} \ll 1$
Barbieri et al. '11,'12

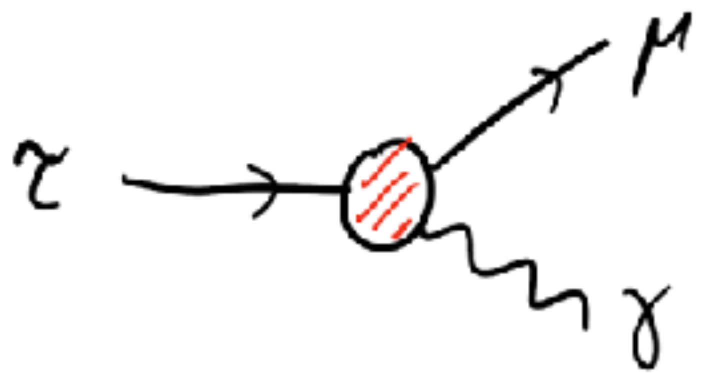
MFV-like: $\varepsilon_{1,2} \sim 1$
D'Ambrosio et al. '02

Probing New Physics with Rare or Forbidden Processes









Consider a **rare low-energy FCNC process in the SM**

Short-distance low-energy EFT coefficient

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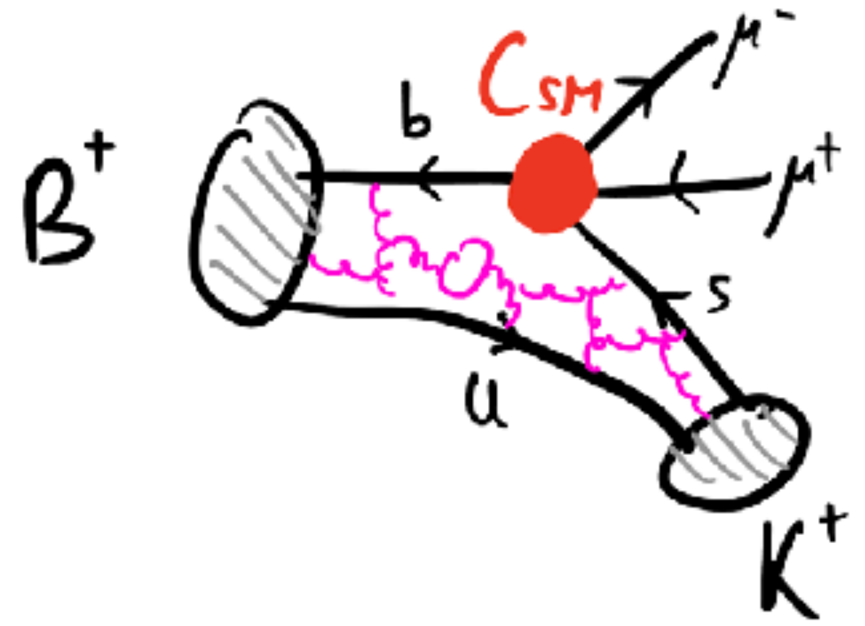

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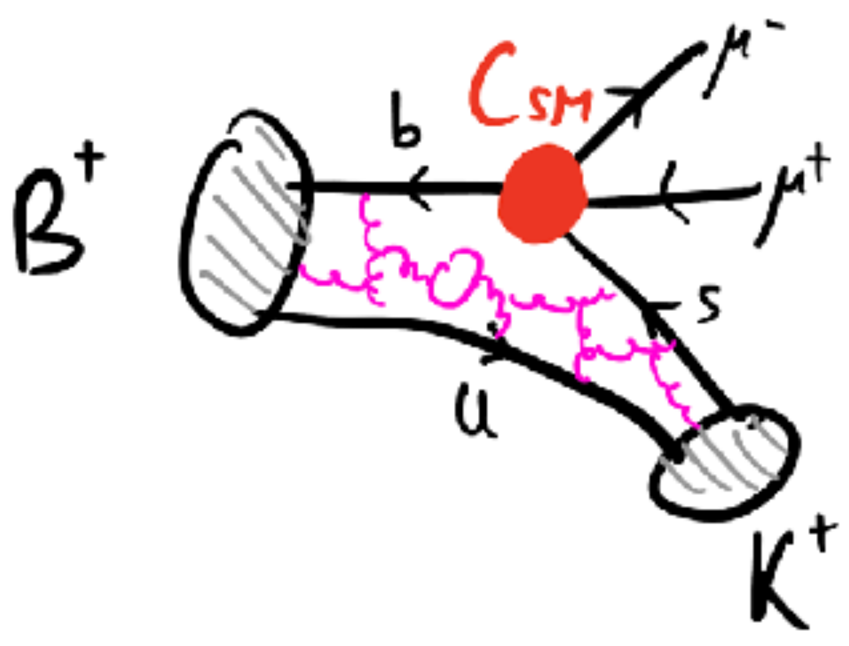

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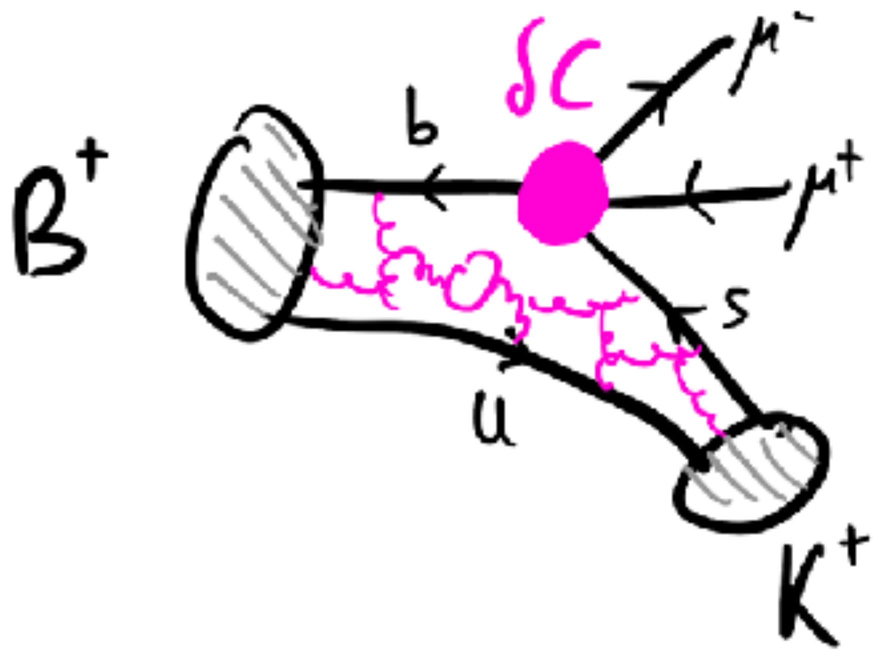

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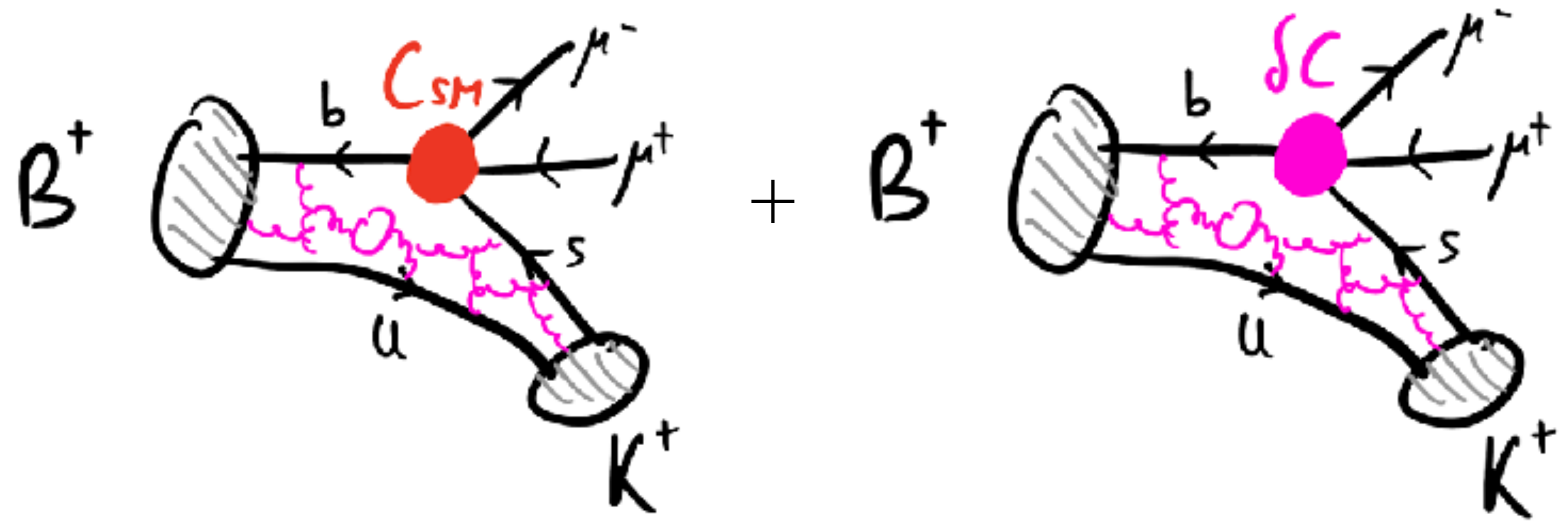

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$$\frac{\delta C}{C_{SM}} \sim \frac{c}{\lambda_{SM}} \frac{v^2}{\Lambda^2}$$

Relative **deviation in the short-distance coefficient**
> i.e. size of the deviation compared to the SM <

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

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

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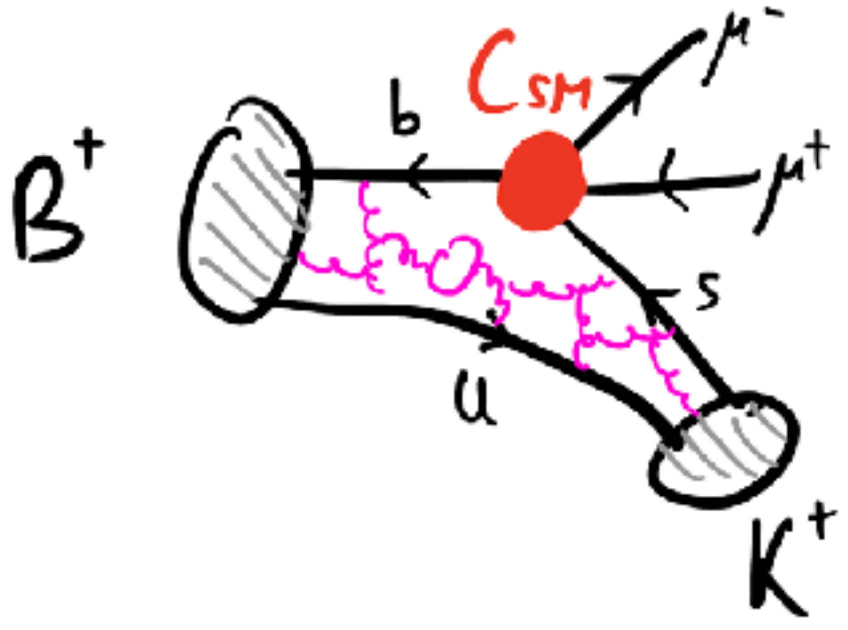


For this goal it is crucial to have the **smallest possible uncertainty on the short-distance contributions**:

Exp

- Very **large statistics**
- Small **backgrounds and systematics**

TH

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

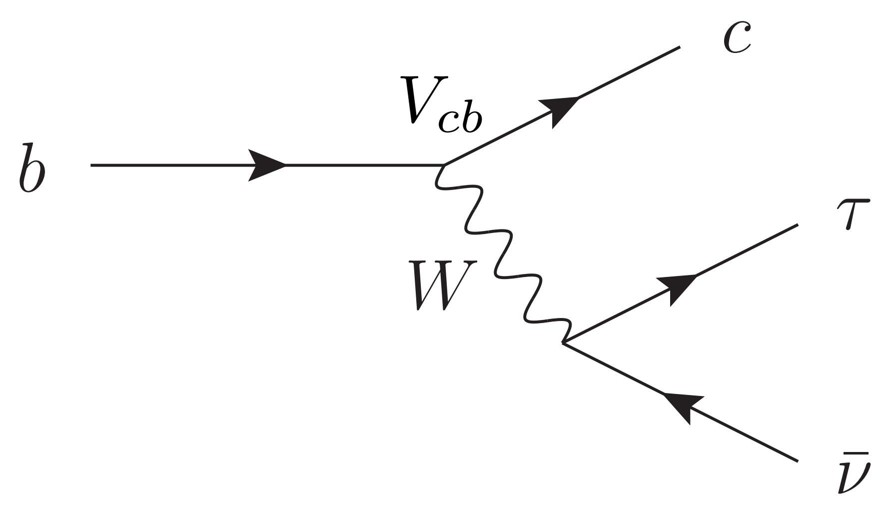
B-anomalies in charged current $b \to c\, \tau\, \bar{\nu}_\tau$

Lepton Flavour Universality

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

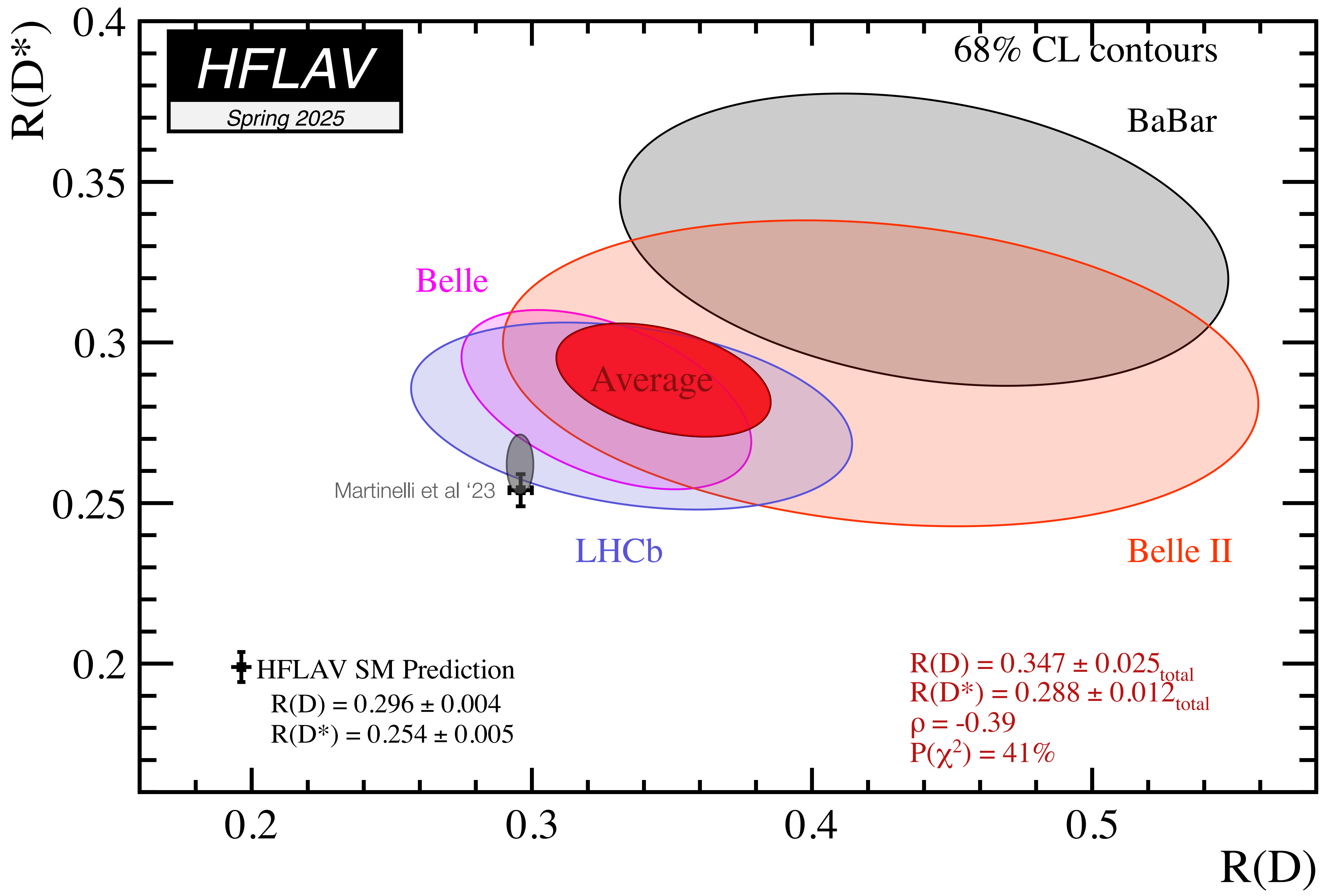
$$\ell = \mu, e$$

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



SM prediction under control for R(D), less so for R(D*), related to Vcb incl/excl tension.

Martinelli et al. '23, '24



Most recent measurement by Belle-II confirmed the **tension: 3 - 4σ**.

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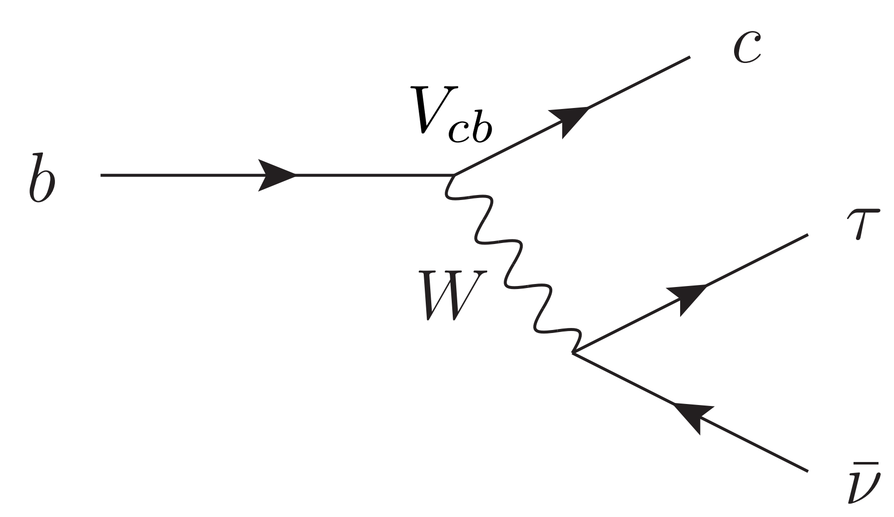

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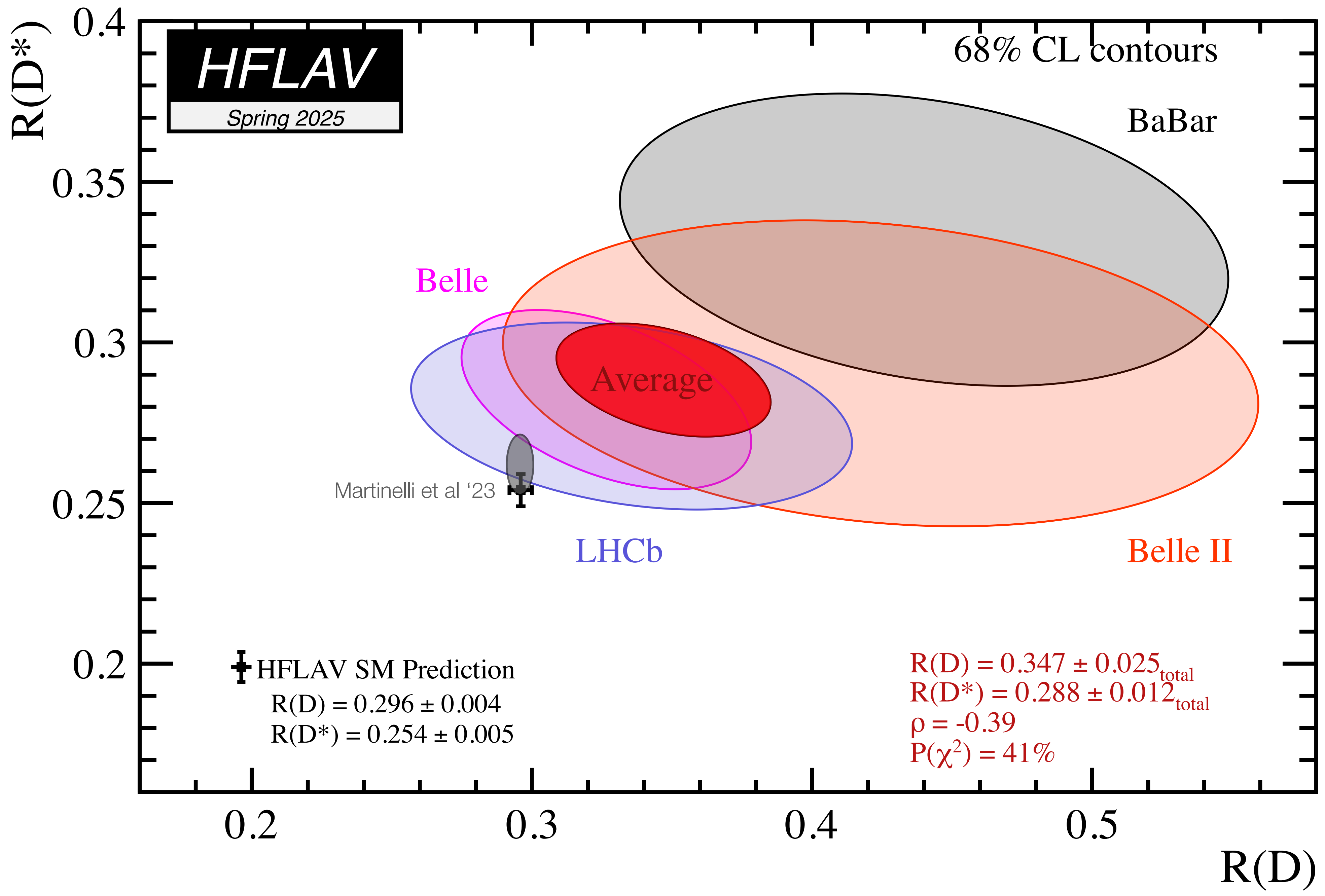


$$\mathcal{L}_{EFT} \supset C^{du\nu\tau}_{ij\tau\tau} \left(\bar{d}_{iL} \gamma_\mu u_{jL}\right)\left(\bar{\nu}_\tau \gamma^\mu \tau_L\right)$$

Corresponds to a **New Physics scale** of

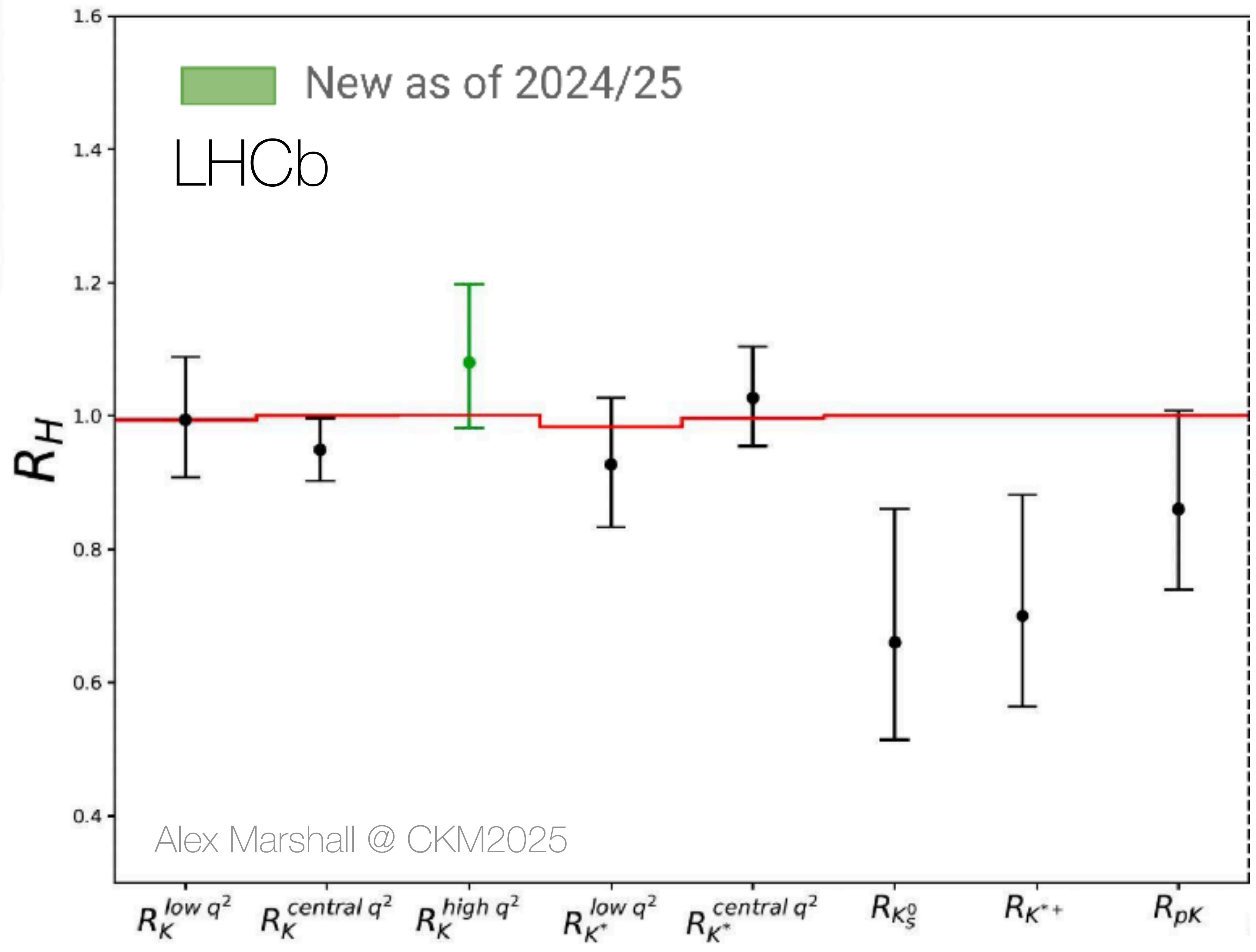
$$\Lambda_{bc\tau\nu} \sim 4\ \text{TeV}$$

Most recent measurement by Belle-II confirmed the **tension: 3 - 4σ**.

We eagerly wait for more data by Belle-II and LHCb.
SM predictions will take advantage of larger and more precise datasets!

Neutral-current semileptonic B decays

$b \to s\, \mu^+ \mu^- / b \to s\, e^+ e^-$: $R(K^{(*)})$



Clean SM prediction ($R_X = 1$), test of LFU between μ and e.

***μ* vs. *e* LFU established at ~5% level.**

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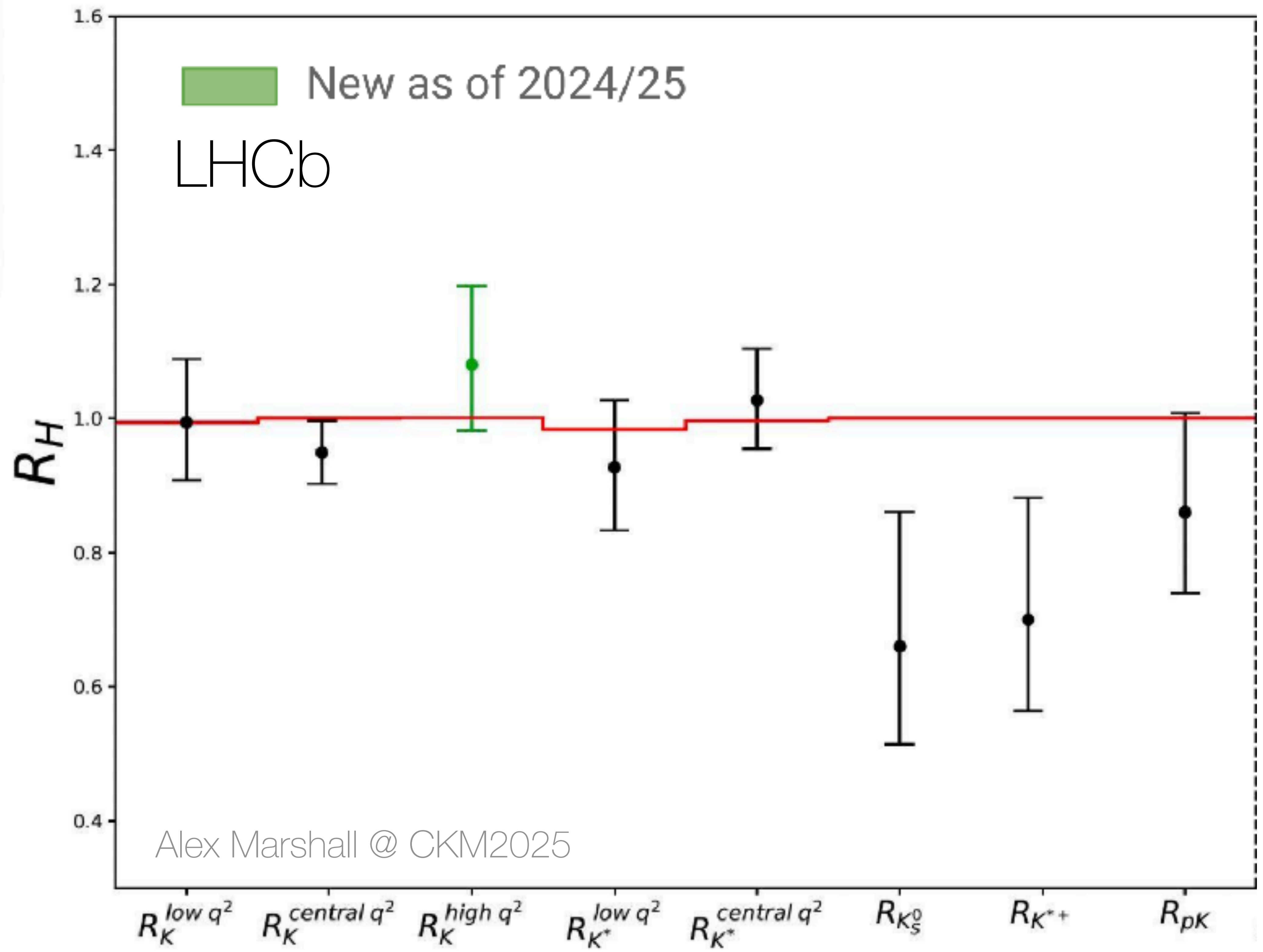

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To **which NP scale Λ** are these measurements **sensitive** to?

Take this *current* x *current* LFUV operator as example

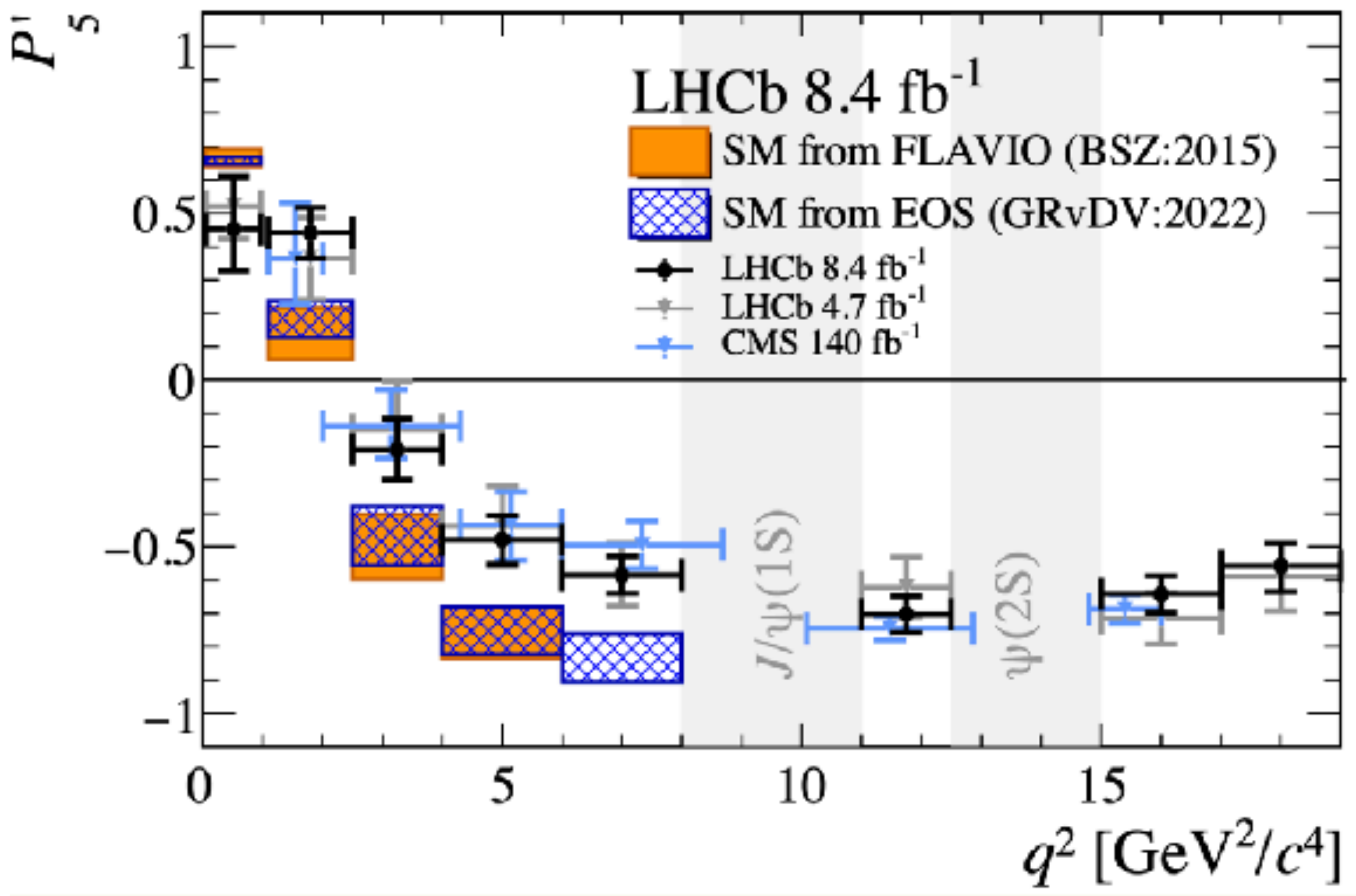
$$\mathcal{L}_{EFT} \supset \frac{c}{\Lambda^2} (\bar{b}_L \gamma_\alpha s_L)(\bar{\mu}_L \gamma^\alpha \mu_L)$$

if c = 1: $\Lambda_{bs\mu\mu} \gtrsim$ **56 TeV**

Lower scales require same couplings to electrons and muons.

Neutral-current semileptonic B decays

LHCb Run1 + Run2



$b \to s\,\mu^+\mu^-$: P_5' and $Br's$

Very significant tension (>4σ) between data and SM prediction in angular observables and Br's of $b \to s\mu^+\mu^-$ transitions.

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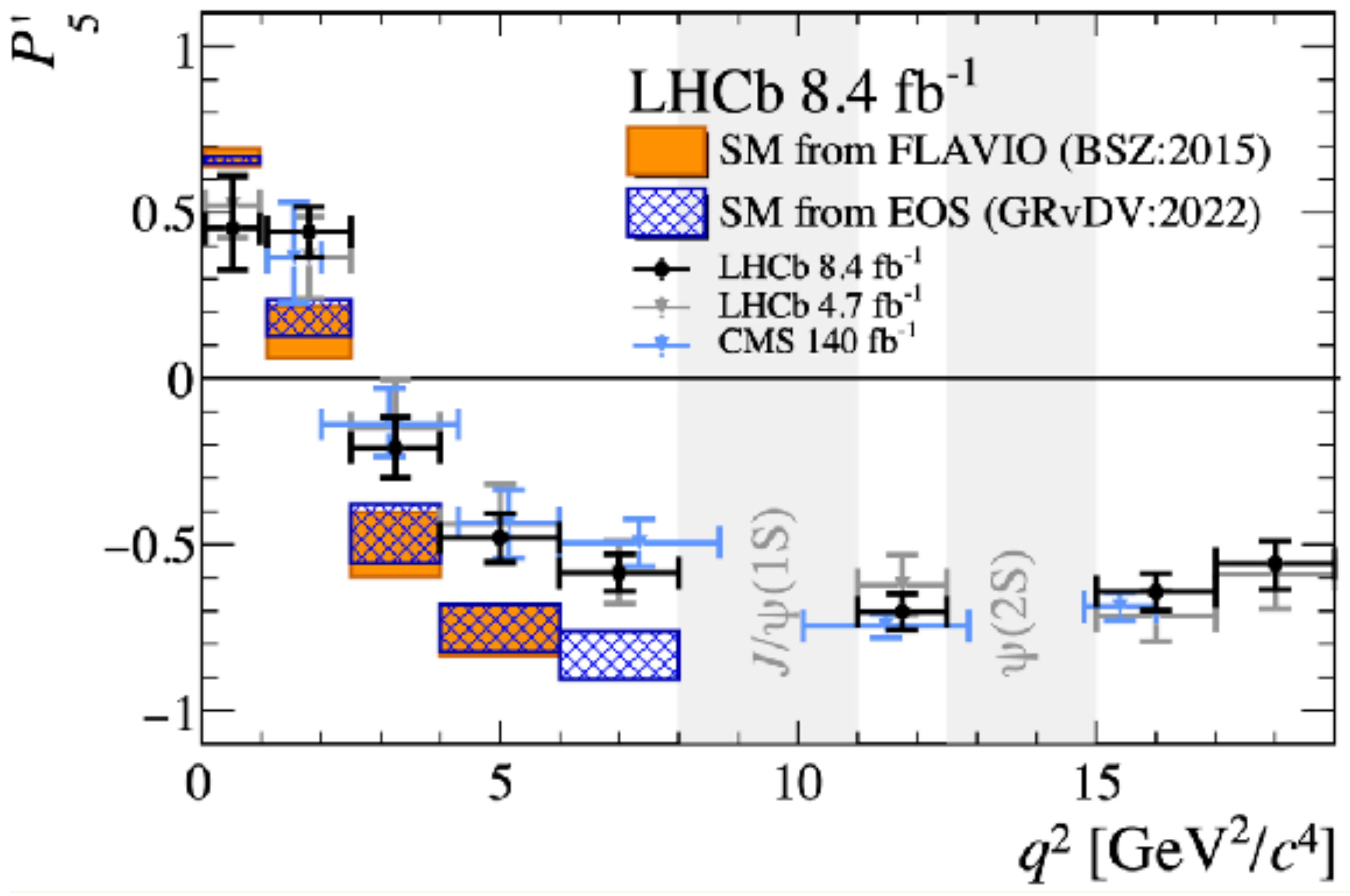

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if c = 1:

$\Lambda_{bs\ell\ell} \sim 40$ TeV

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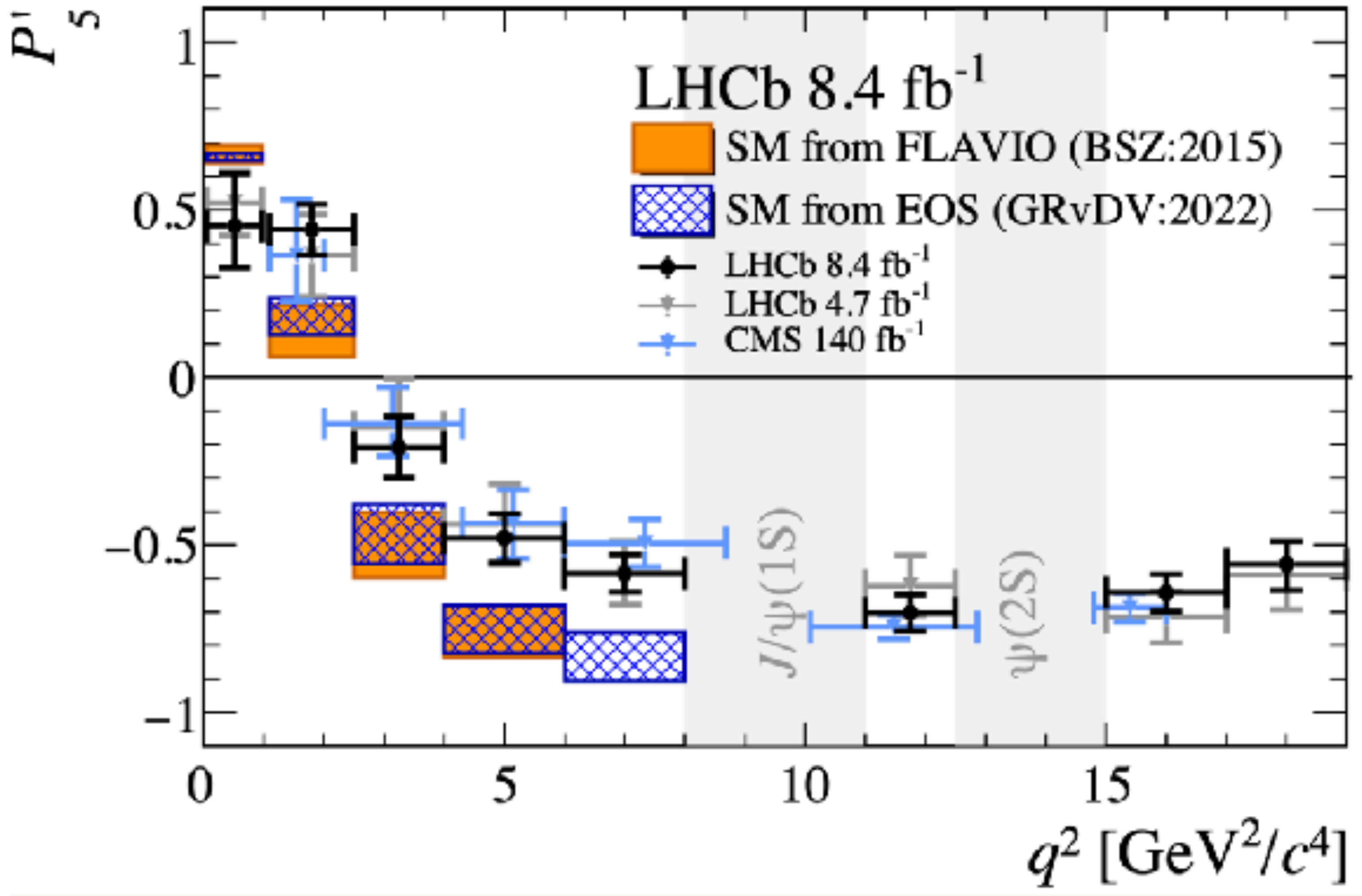

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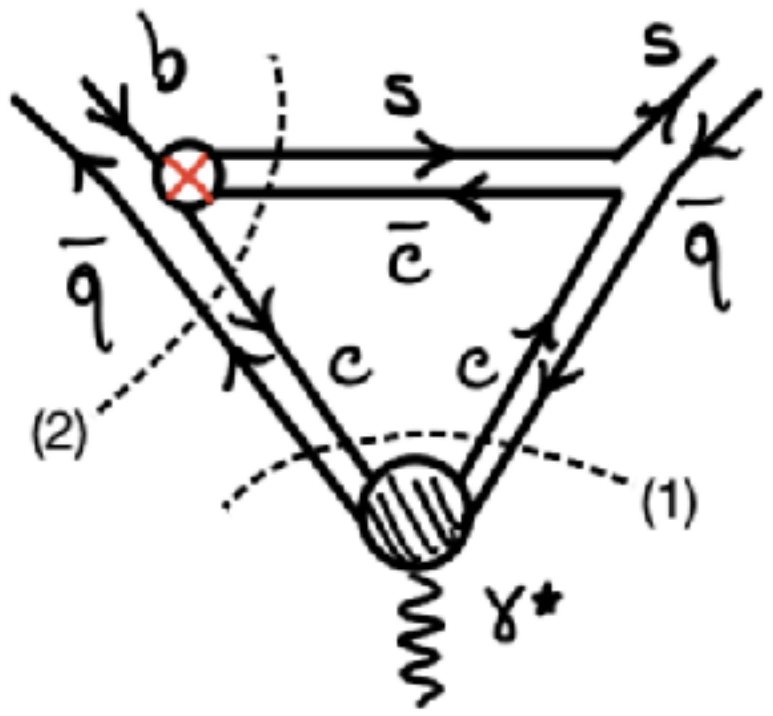
However, **non-perturbative long-distance QCD** dynamics could reproduce the same effect.



Q^2

Charm-rescattering: effects not accounted for in the SM predictions above.

Ciuchini et al. 2212.10516

Model estimates based on HHChPT estimate impact at 5% to 20% of short-distance.

Isidori et al. 2405.1755, 2507.17824

Recent progress towards a lattice calculation! Rome group 2508.03655

More data will help in clarifying: allows for check of Q^2 dependence of the result and more detailed studies.

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$$\mathcal{L}_{EFT} \supset \frac{c}{\Lambda^2}\,(\bar{b}_L \gamma_\alpha s_L)\left[(\bar{\mu}_L \gamma^\alpha \mu_L) + (\bar{e}_L \gamma^\alpha e_L)\right]$$

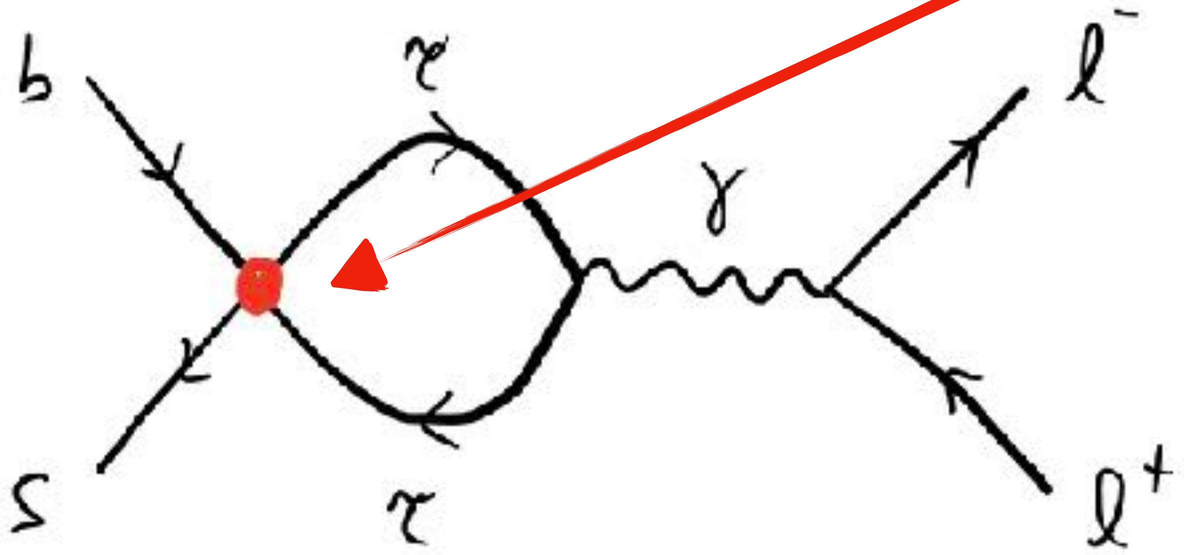
if $c = 1$:

$\Lambda_{bs\ell\ell} \sim 40$ TeV

An interesting New Physics contribution

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,

$$(\bar{b}_L \gamma^\mu c_L)(\bar{\nu}_L \gamma^\mu \tau_L) \overset{SU(2)_L}{\longleftrightarrow} (\bar{b}_L \gamma^\mu s_L)(\bar{\tau}_L \gamma^\mu \tau_L)$$



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

→ Related to $R(D^{(*)})$

→ Induce C_9^U, $R(K)=1$

$\Lambda_{bs\tau\tau} \sim O(4)$ TeV

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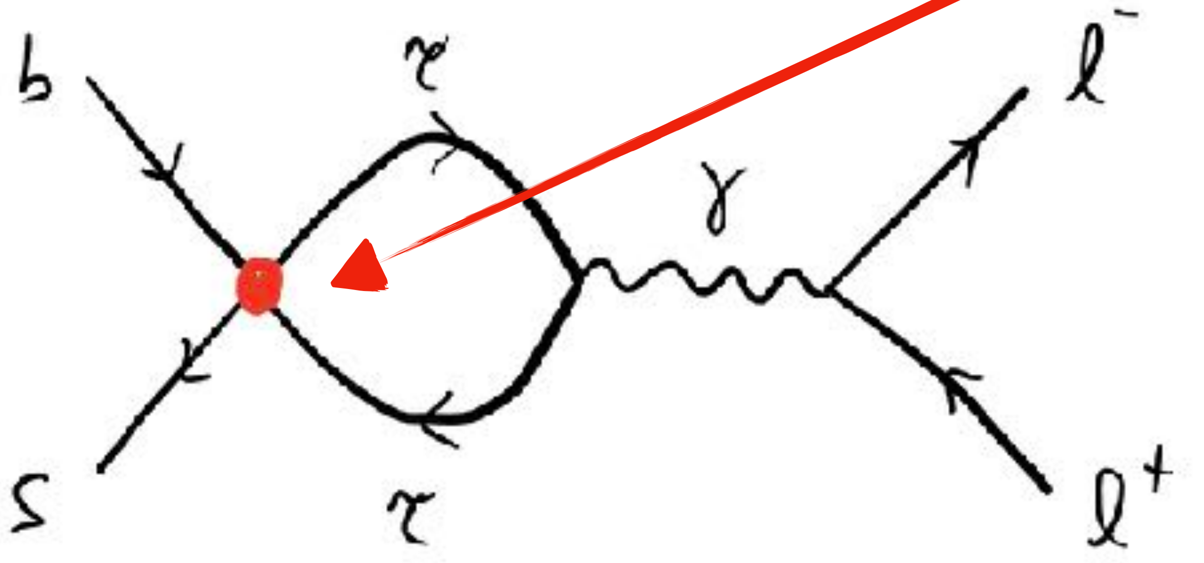

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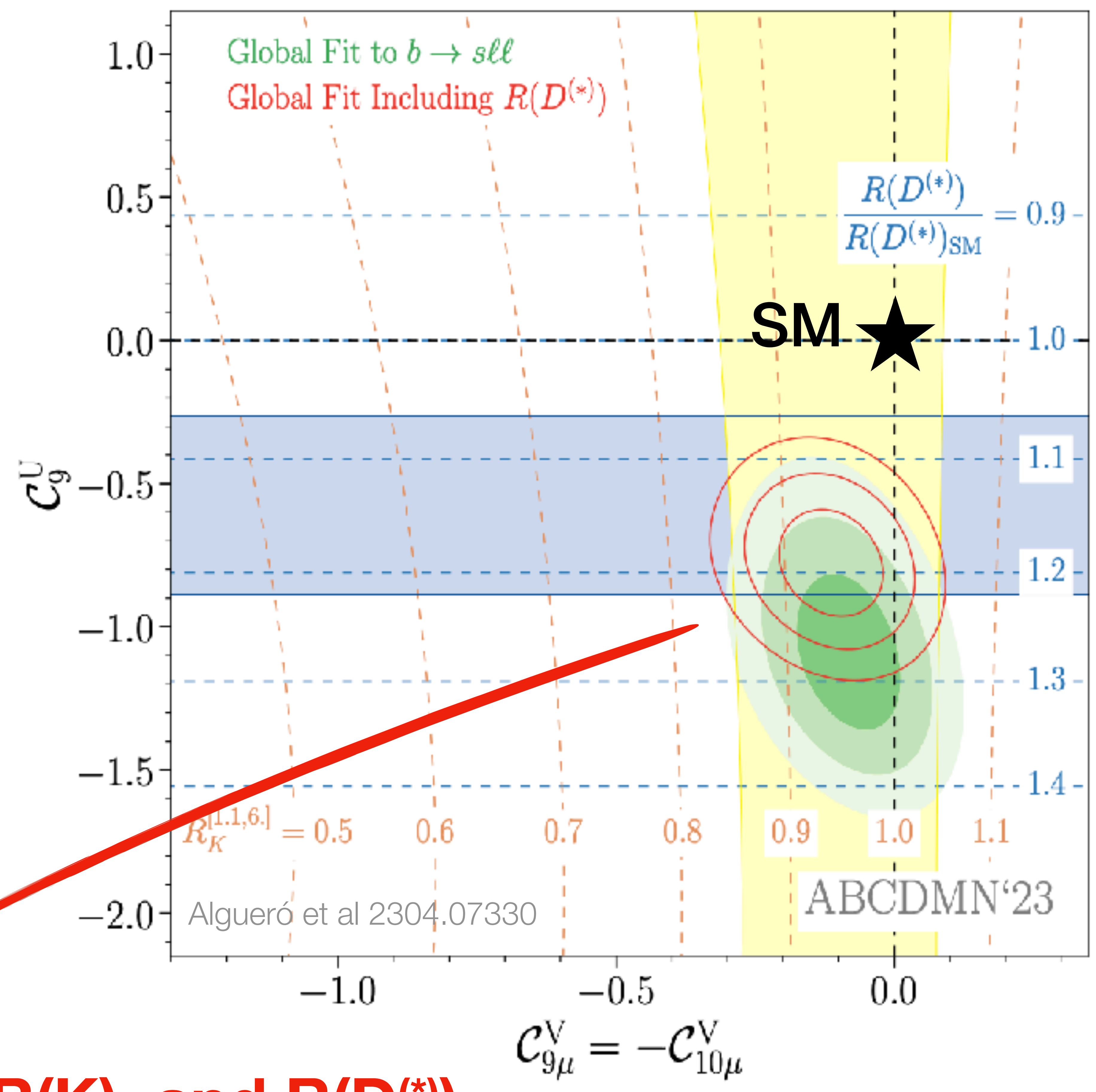

Compatible fit between b→sℓℓ, R(K), and R(D(*)).

Rare Semileptonic and Leptonic decays

Let us look at the **flavour structure**: other **rare decays into muons**

$$\mathcal{L}_{EFT} \supset \frac{c_{ij}}{\Lambda^2} \left(\bar{q}_L^i \gamma_\alpha q_L^j\right)\left(\bar{\mu}_L \gamma^\alpha \mu_L\right)$$

2σ bound on Λ	LHCb '23 R(K)	2210.07221 $B_s \to \mu\mu$	PDG 2024 $B_d \to \mu\mu$	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	18 TeV	74 TeV	$c = i$ 10.7 TeV	6.9 TeV

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Anarchic flavour	$c = 1$	56 TeV	33 TeV	18 TeV	74 TeV	$c = i$ 10.7 TeV	6.9 TeV
CKM-like (MFV, U(2),..)	$c = c_{CKM}$	$c_{CKM} = \|V_{ts}\|$ **11 TeV**	$c_{CKM} = \|V_{ts}\|$ **6.6 TeV**	$c_{CKM} = \|V_{td}\|$ **1.6 TeV**	$c_{CKM} = \|V_{td} V_{ts}\|$ **1.4 TeV**	$c_{CKM} = i\|V_{td} V_{ts}\|$ **0.2 TeV**	$c_{CKM} = \|V_{cb} V_{ub}\|$ **0.086 TeV**

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

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

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

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

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

BaBar, Belle, Belle II (JPARC)

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

NA62 (CERN)

KOTO (JPARC)

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NA62 (CERN)

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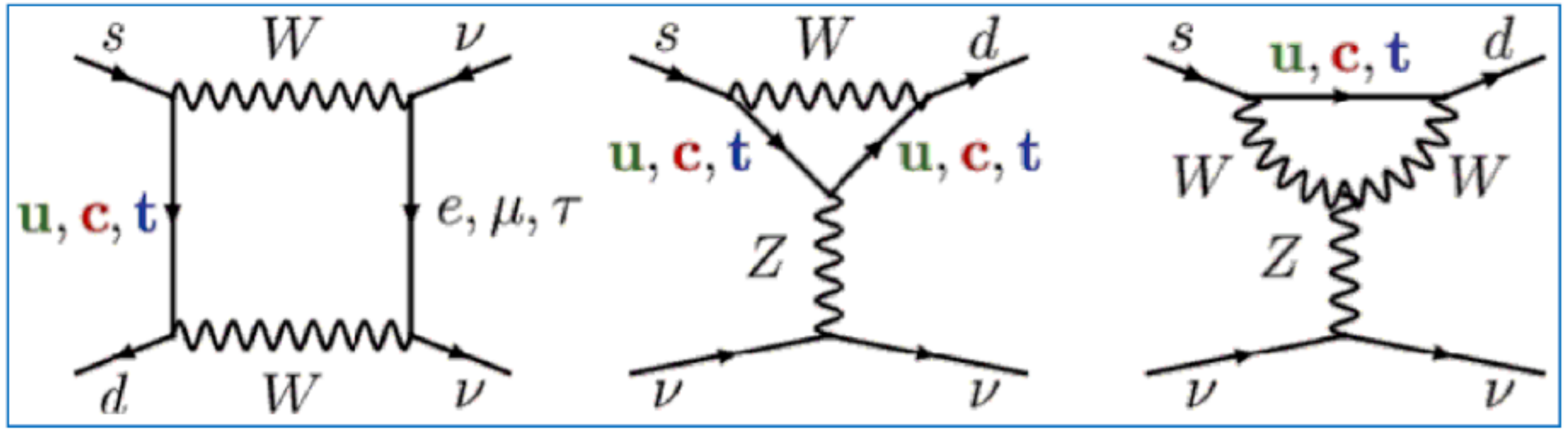
KOTO (JPARC)

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**.

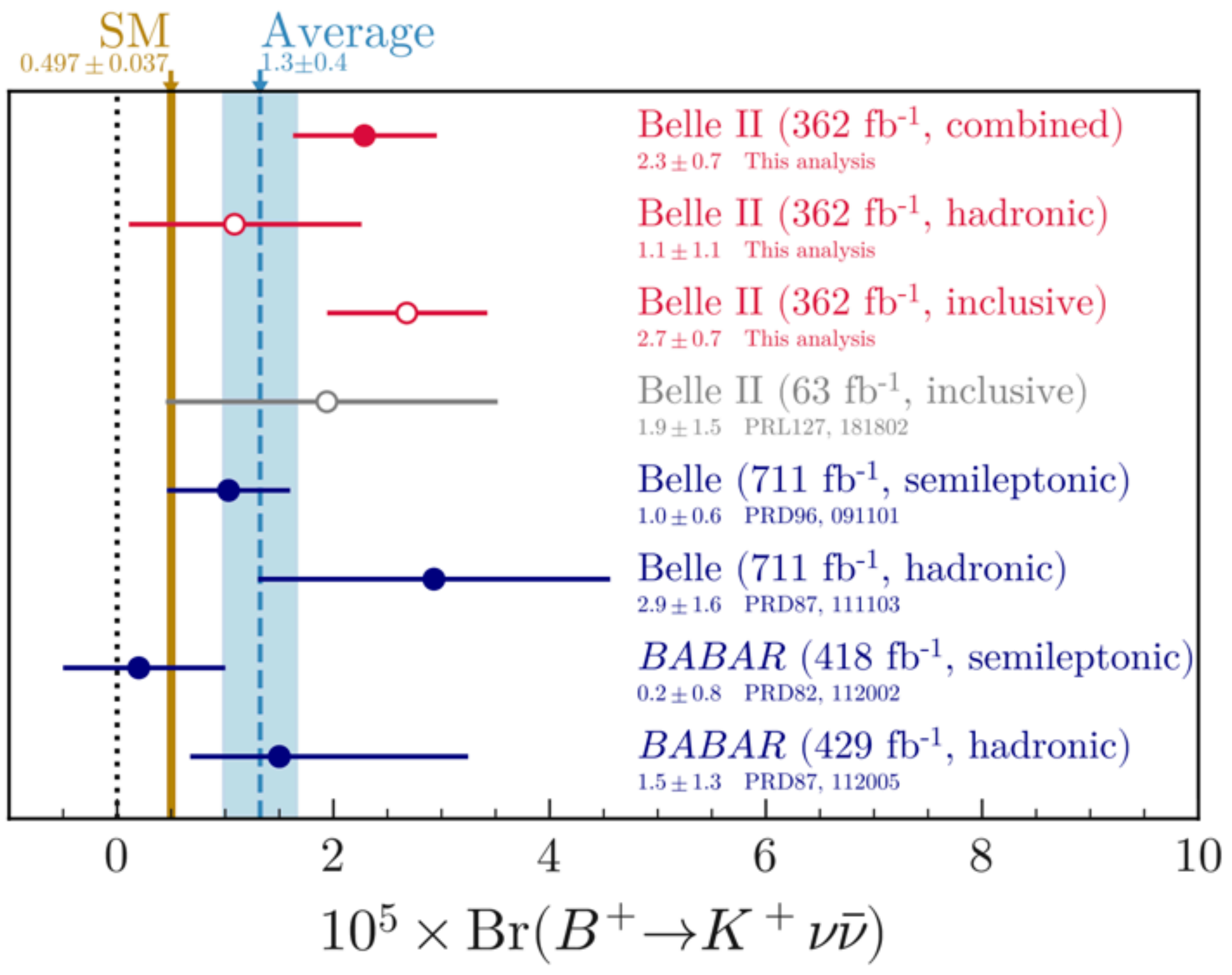
$B \to K^{(*)} \nu \bar{\nu}$

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

Becirevic et al. 2301.06990

Belle-II2023: $\mathrm{BR}(B^+ \to K^+ \nu \bar{\nu}) = (2.3 \pm 0.6) \times 10^{-5}$

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



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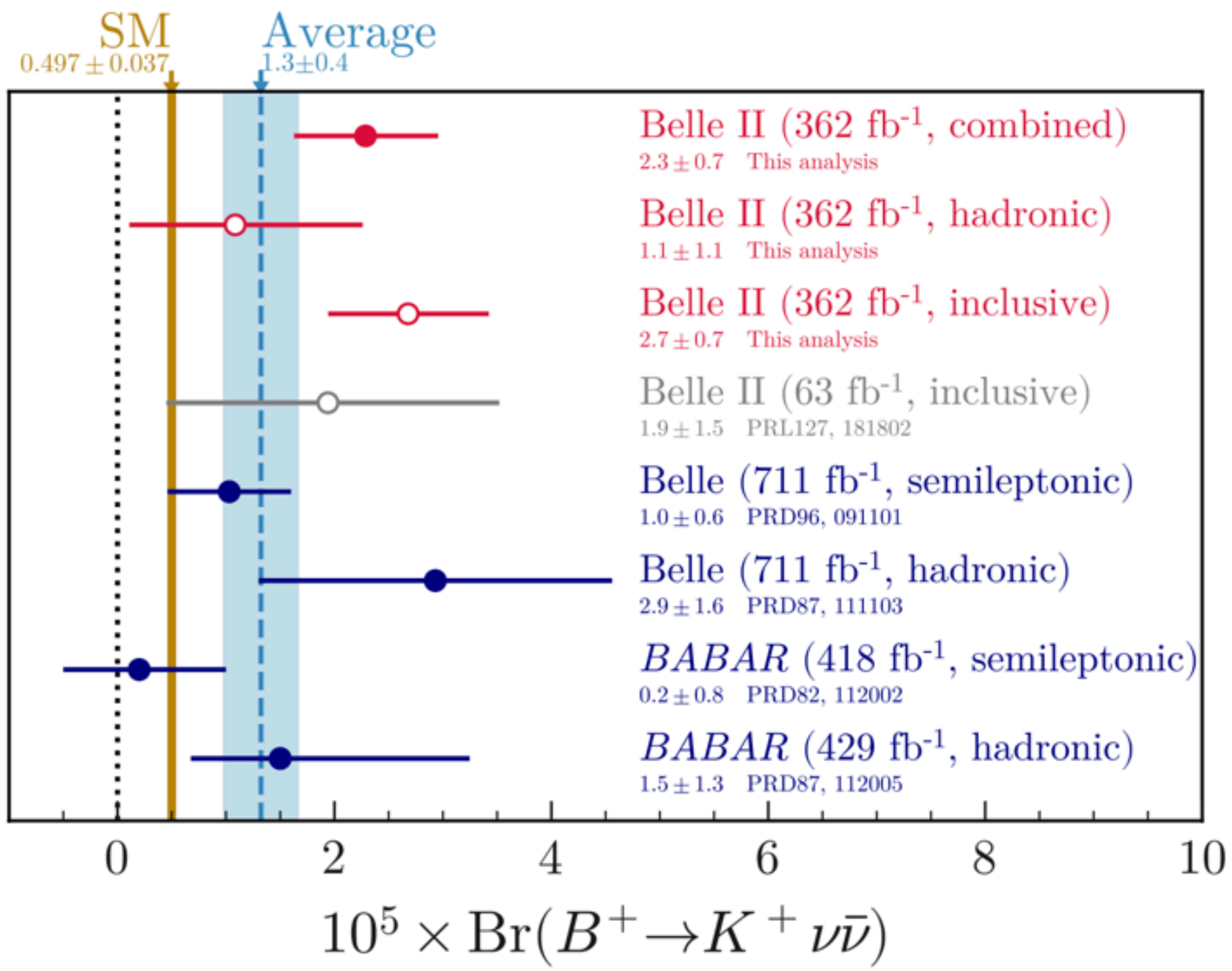

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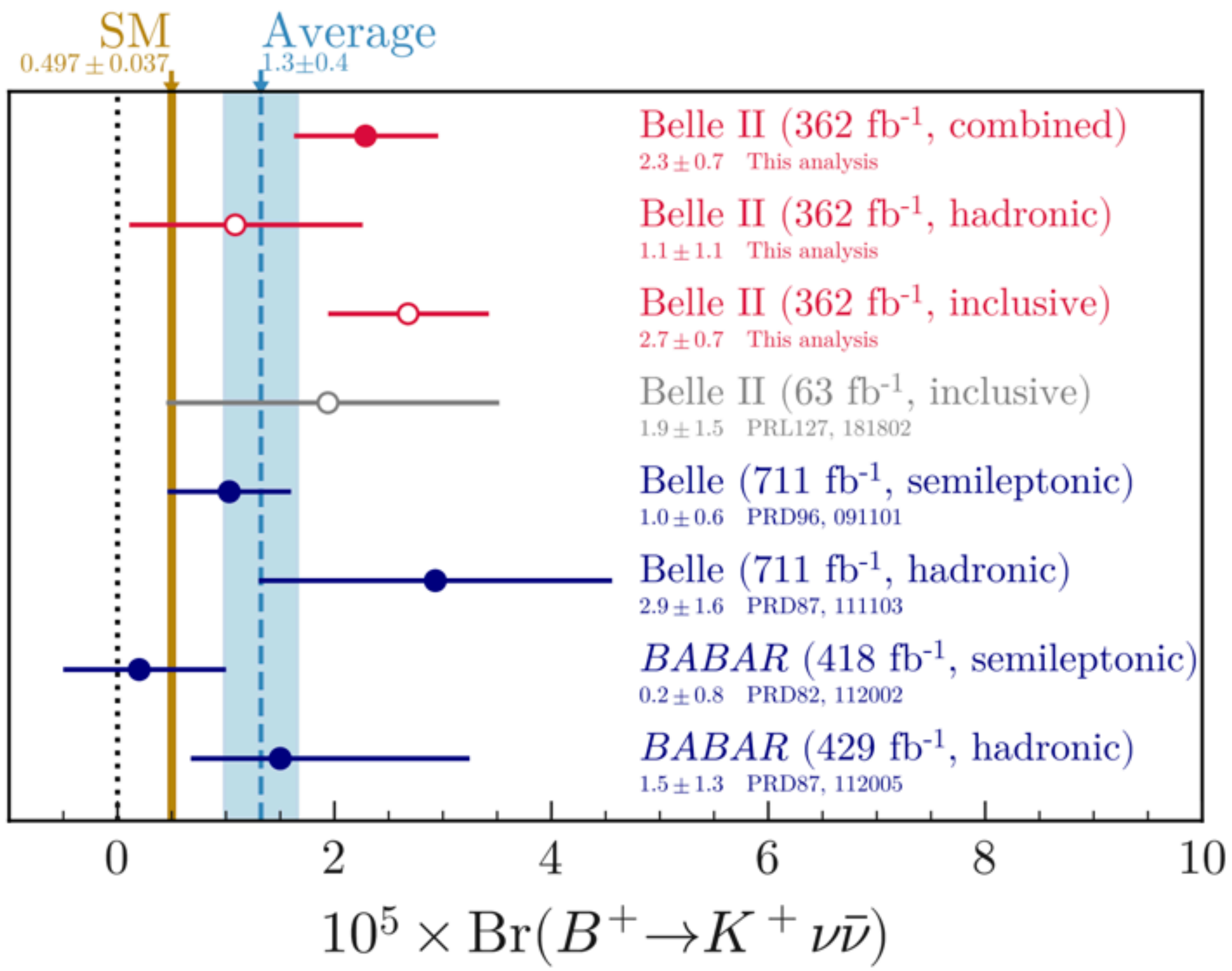

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Belle2017: $BR(B \to K^* \nu \bar{\nu}) < 2.7 \times 10^{-5}$ @ 90%CL

$$R_K^\nu = \frac{BR(B \to K\nu\nu)}{BR(B \to K\nu\nu)^{SM}} = 2{,}93 \pm 0{,}90 \quad 2.10$$

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

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

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

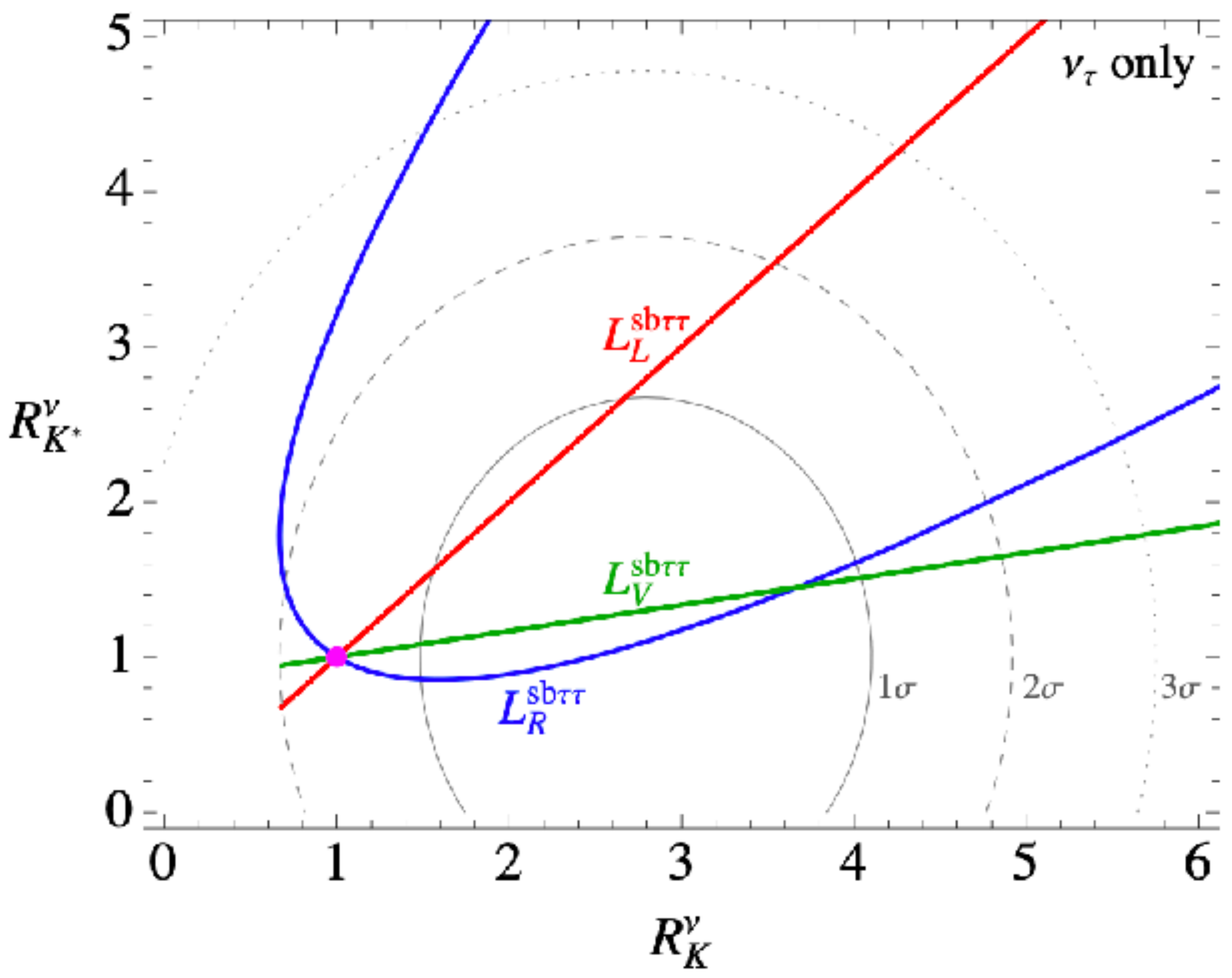
Assuming **only NP in tau**

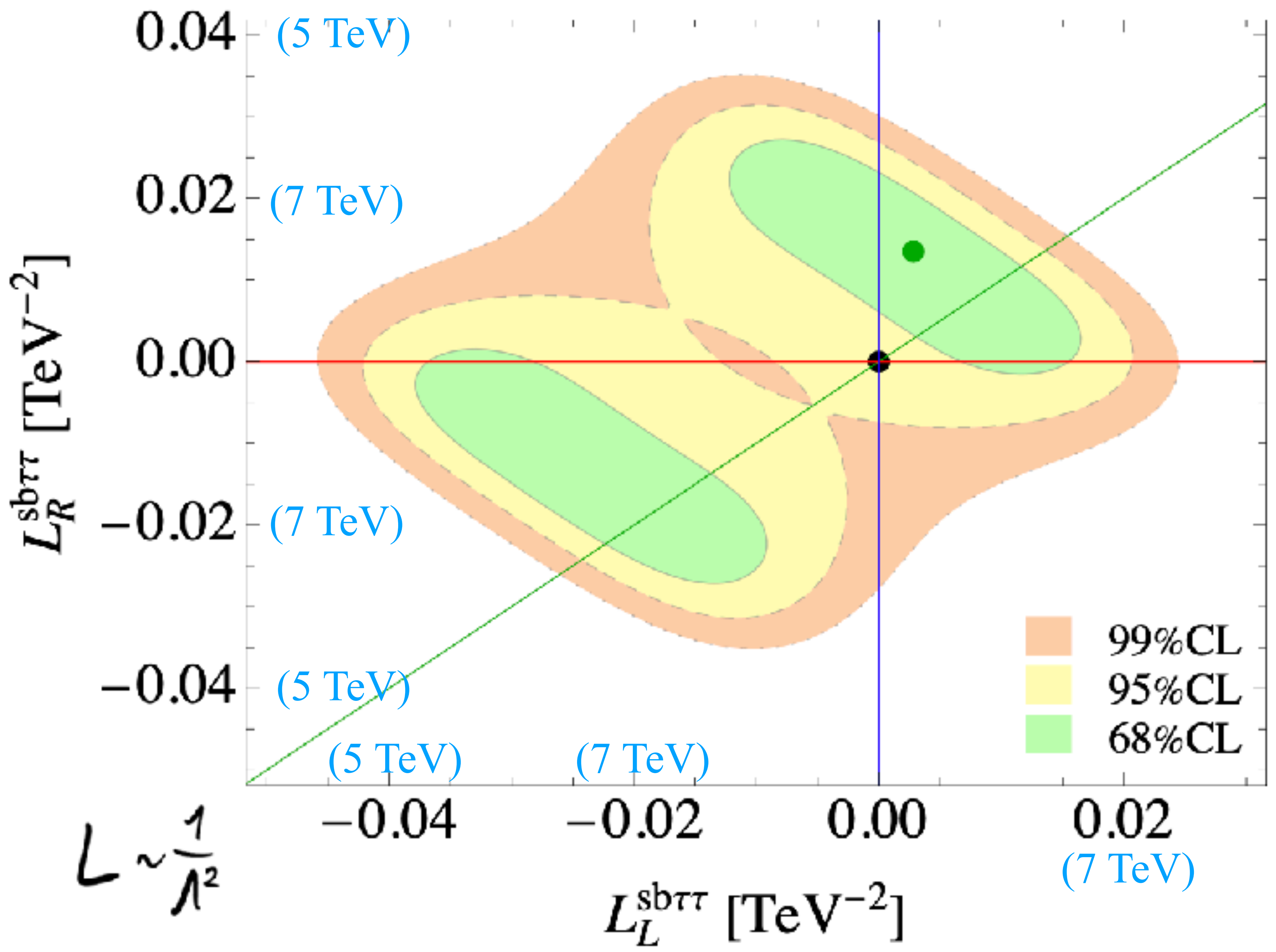
$$\mathcal{L}_{EFT} \supset L^{ij\tau\tau}_{L,R} \left(\bar{d}_{i_{L,R}} \gamma_\mu d_{j_{L,R}}\right)\left(\bar{\nu}_\tau \gamma^\mu \nu_\tau\right)$$

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

The limits from R(K) and $B_s \to \mu\mu$ disfavour interpretations with electron or muon neutrinos

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





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

$\Lambda_{bs\nu\nu} \sim 7$ TeV

Future Belle II results (in particular from the K* mode) will help to clarify the preferred chiral structure.

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

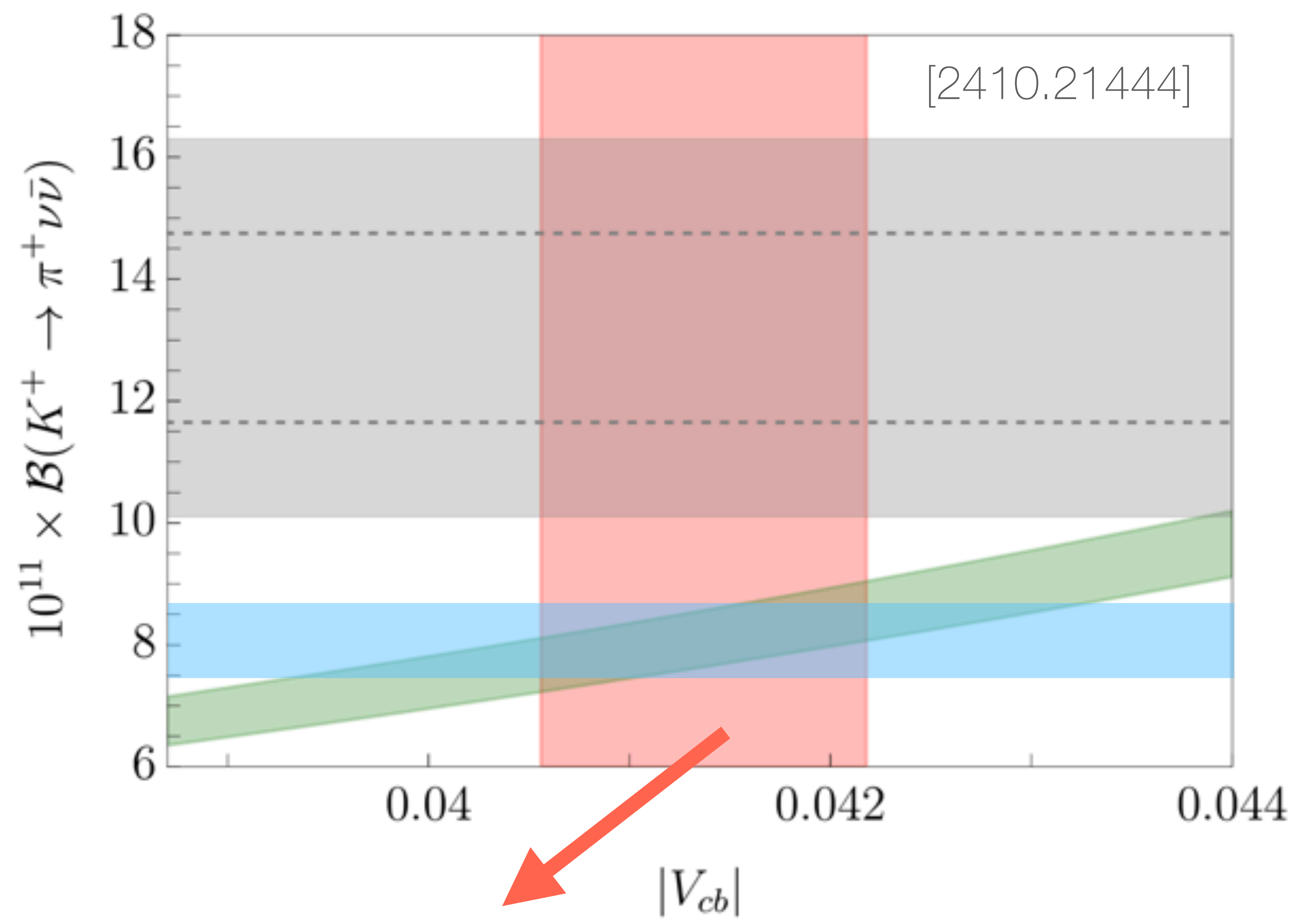
NA62 (CERN)

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

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

NA62$_{2024}$:

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



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

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

KOTO (JPARC)

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

Allwicher et al. [2410.21444]

KOTO$_{2021}$:

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

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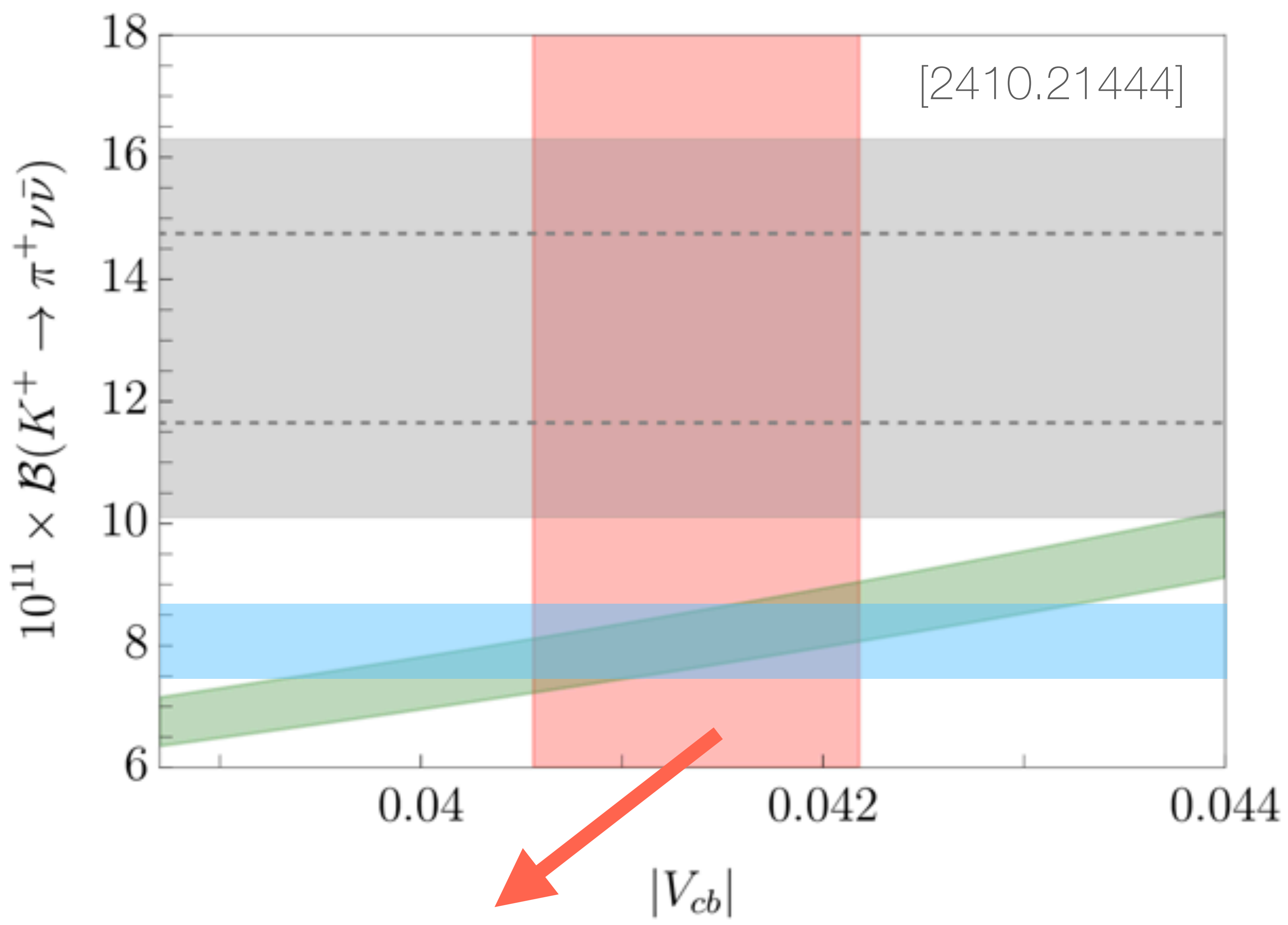

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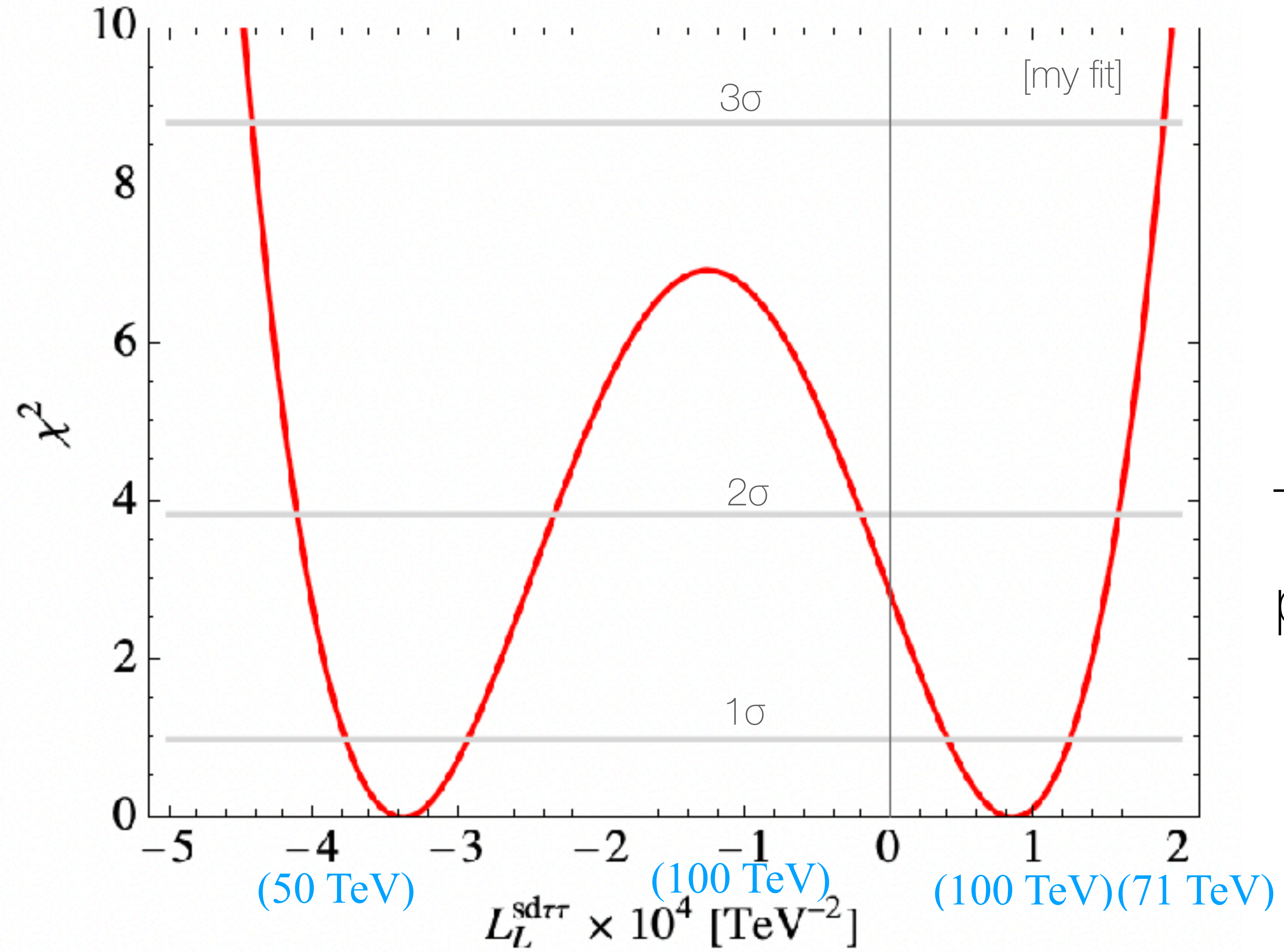


$L \sim \frac{1}{\Lambda^2}$

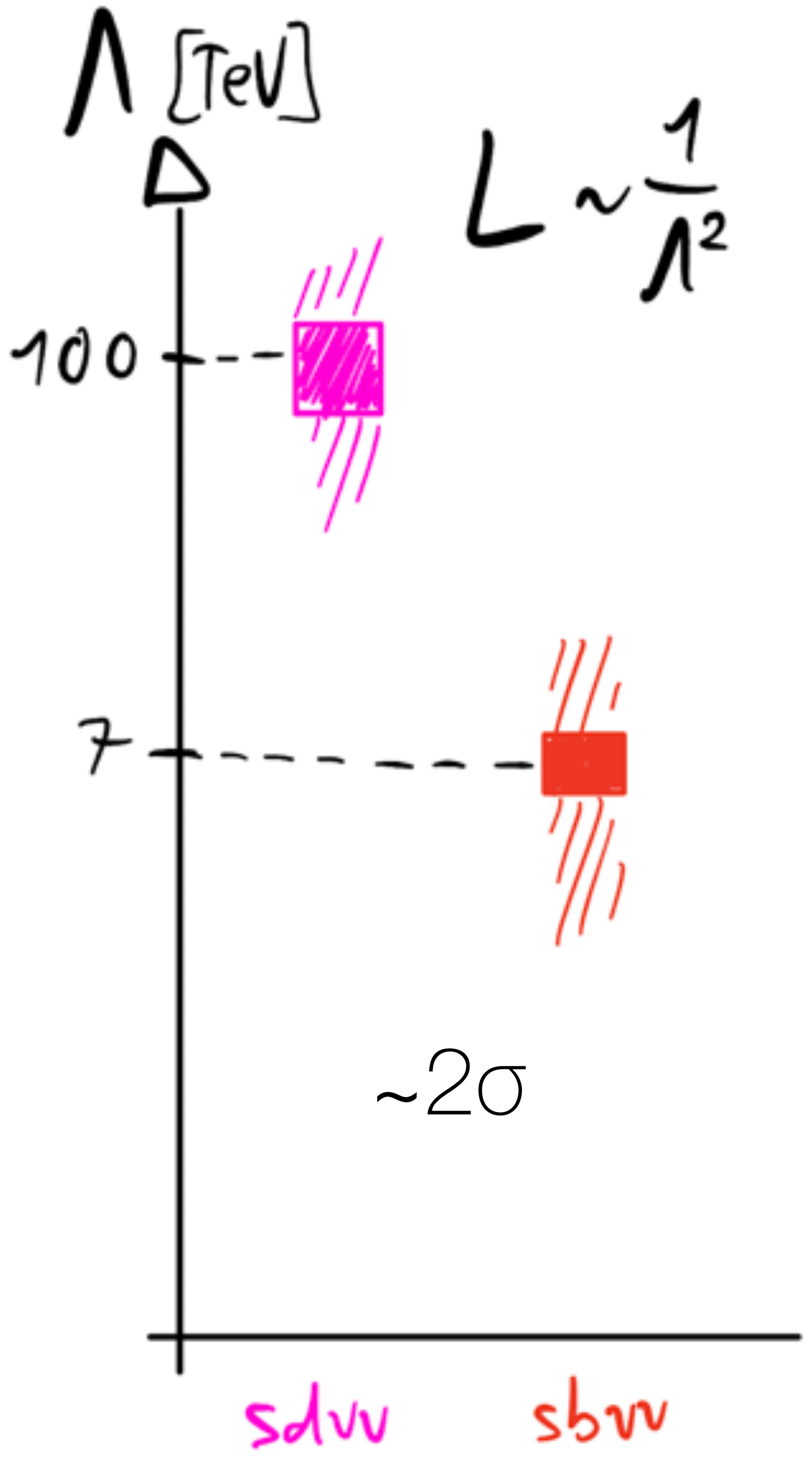
The slight **~1.7σ excess** points to new physics scales

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

Is a picture emerging from data?

Neutral-current

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



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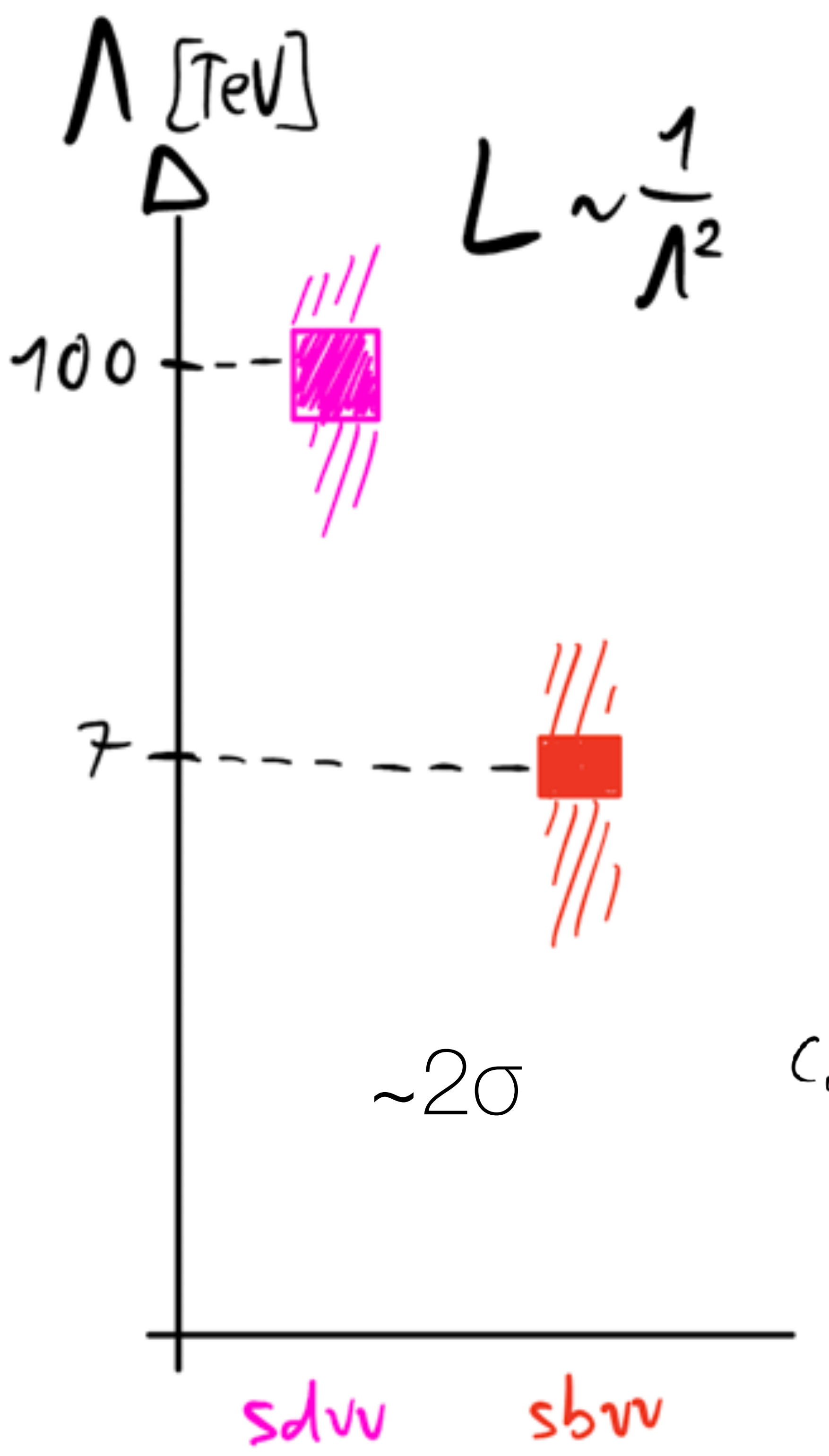
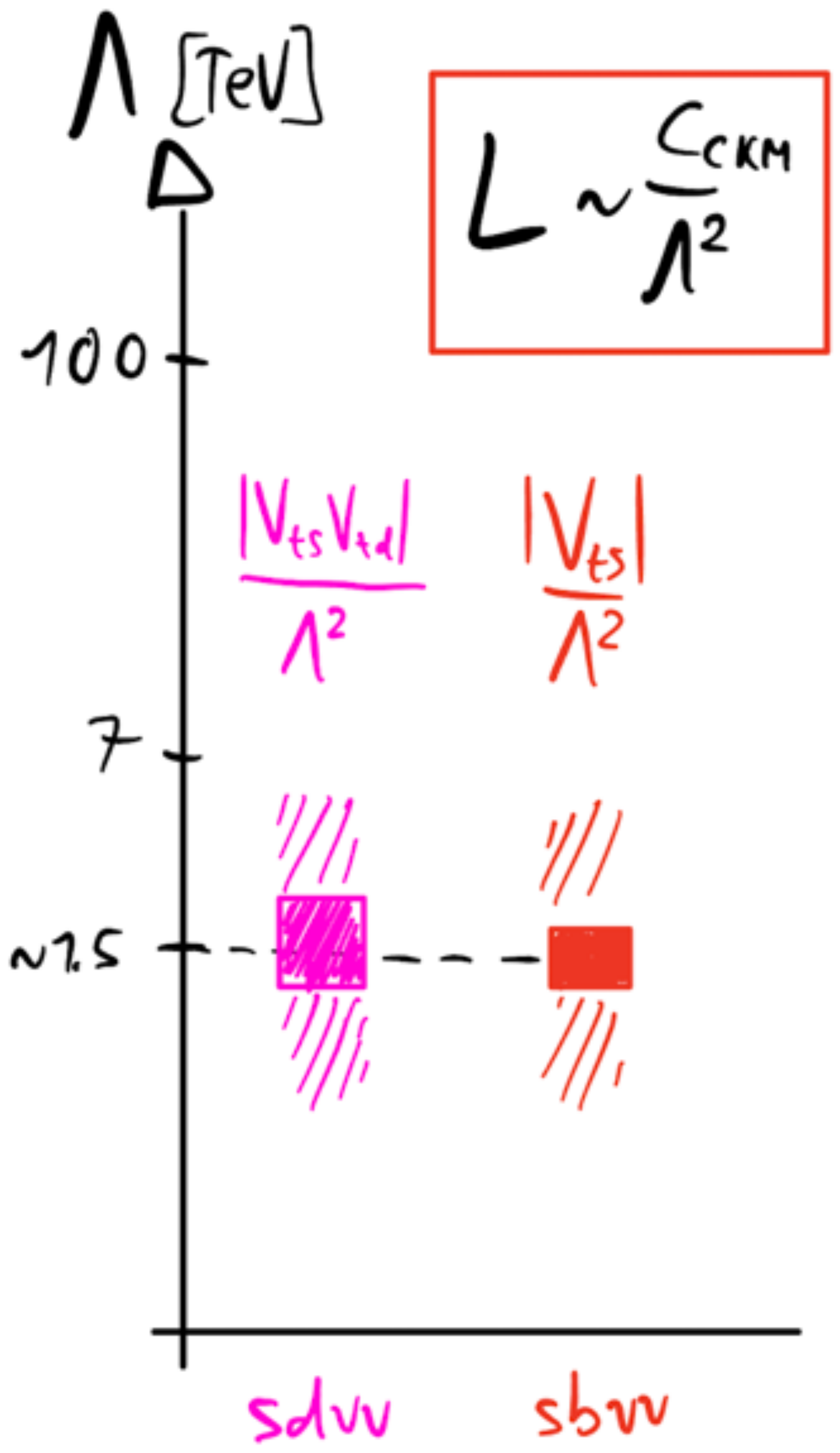


Assuming a CKM-like structure

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



The physics scales become compatible!

Is a picture emerging from data?

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$\xleftrightarrow{SU(2)_L}$

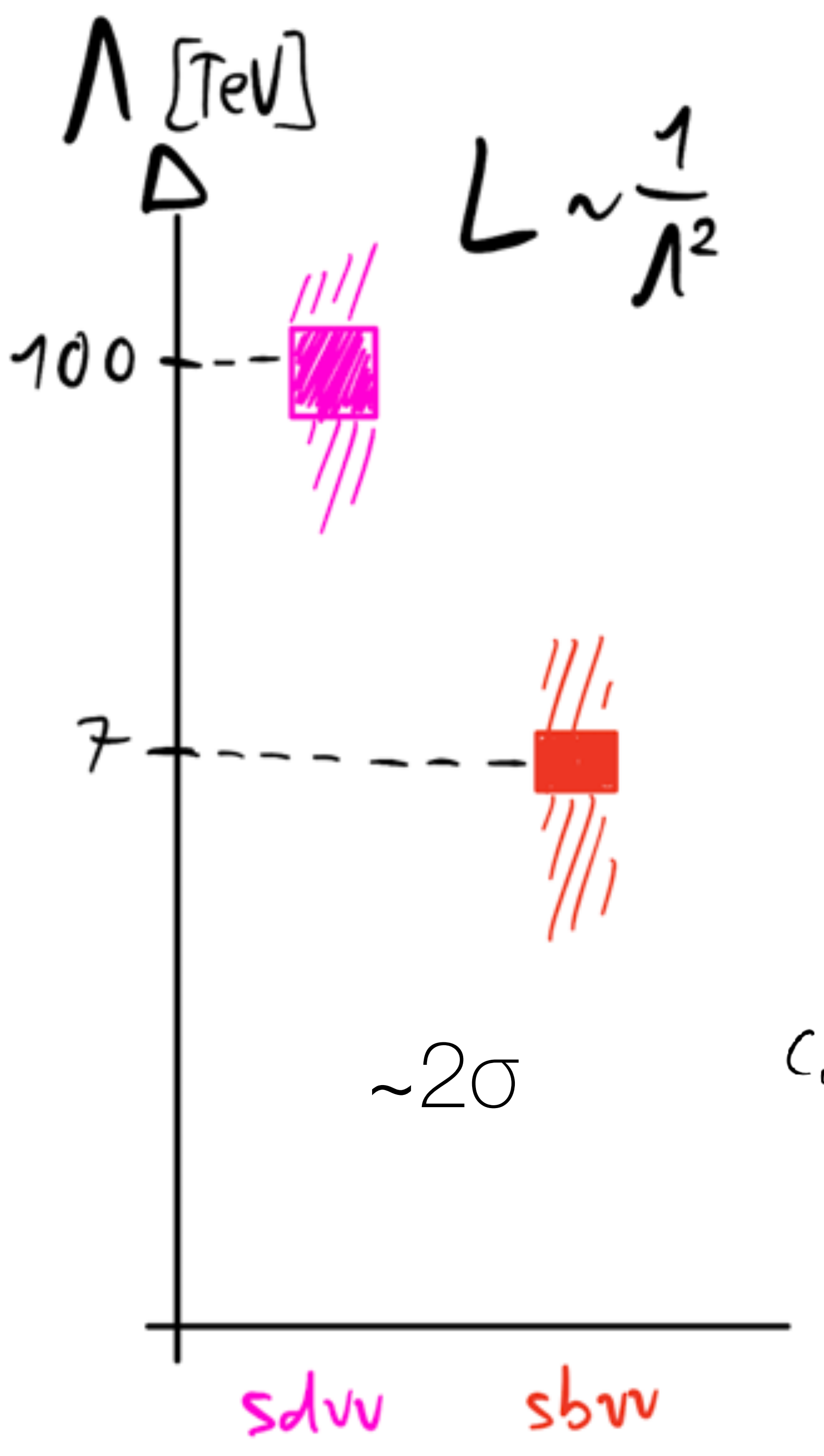
$(\bar{Q}_L \gamma_\mu \sigma^a Q_L)(\bar{L}_L \gamma^\mu \sigma^a L_L)$

The precise correlation is model-dependent

Charged-current

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

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



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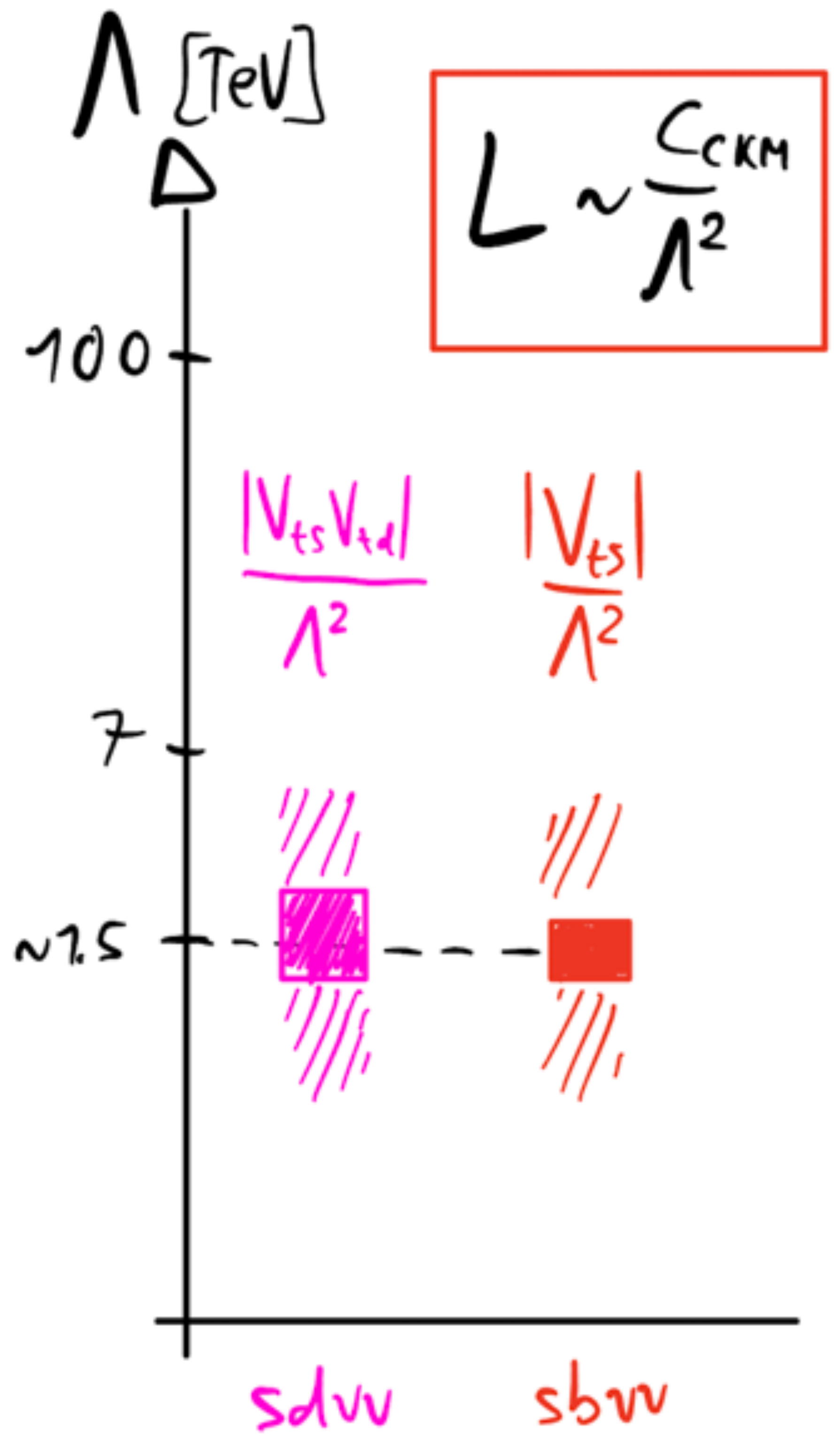

The physics scales become compatible!

Is a picture emerging from data?

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Charged-current

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

$SU(2)_L$

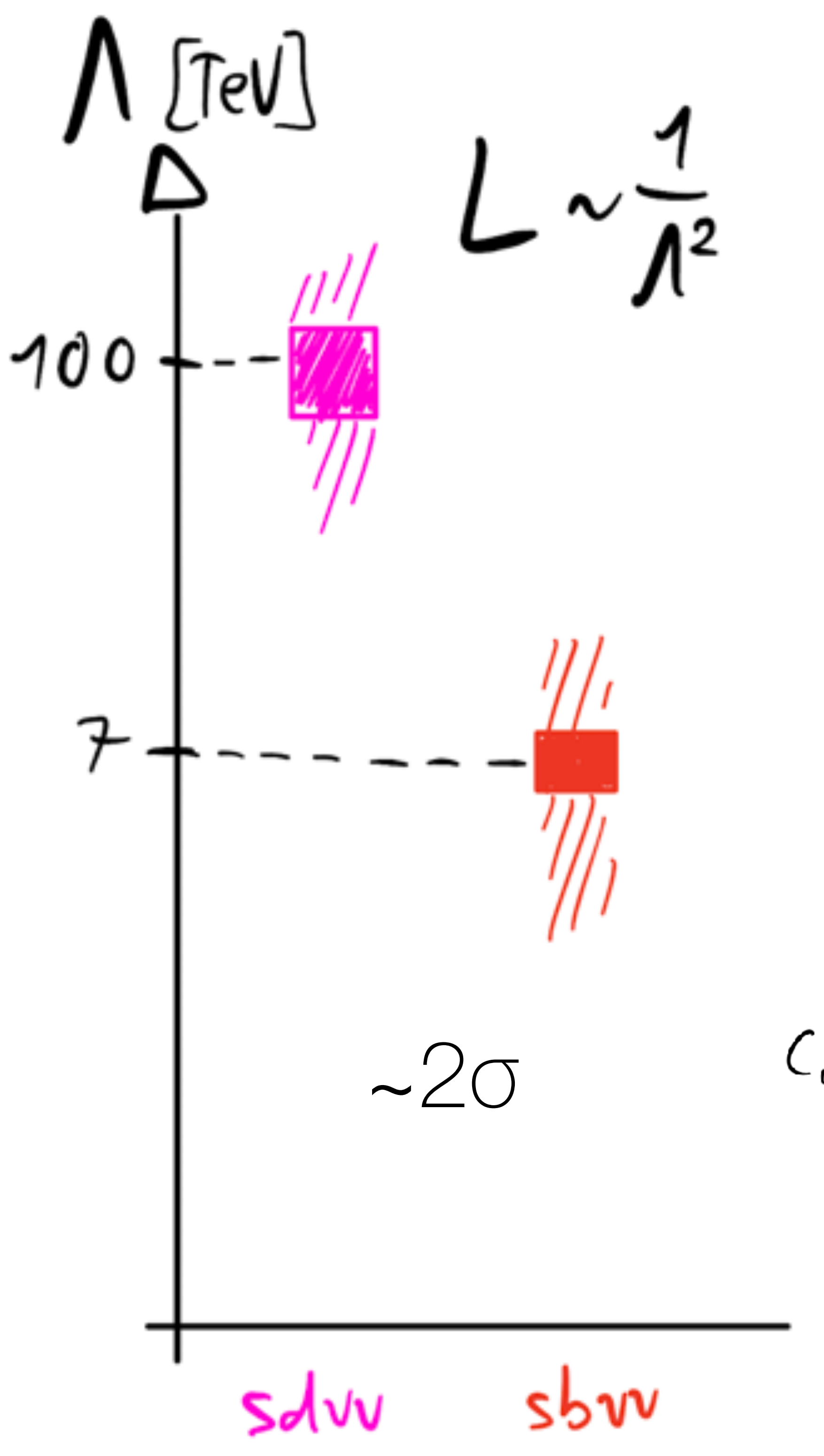
$$\left(\bar Q_L \gamma_\mu \sigma^a Q_L\right)\left(\bar L_L \gamma^\mu \sigma^a L_L\right)$$

The precise correlation is model-dependent

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

$(c \sim 3\, V_{cb})$

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



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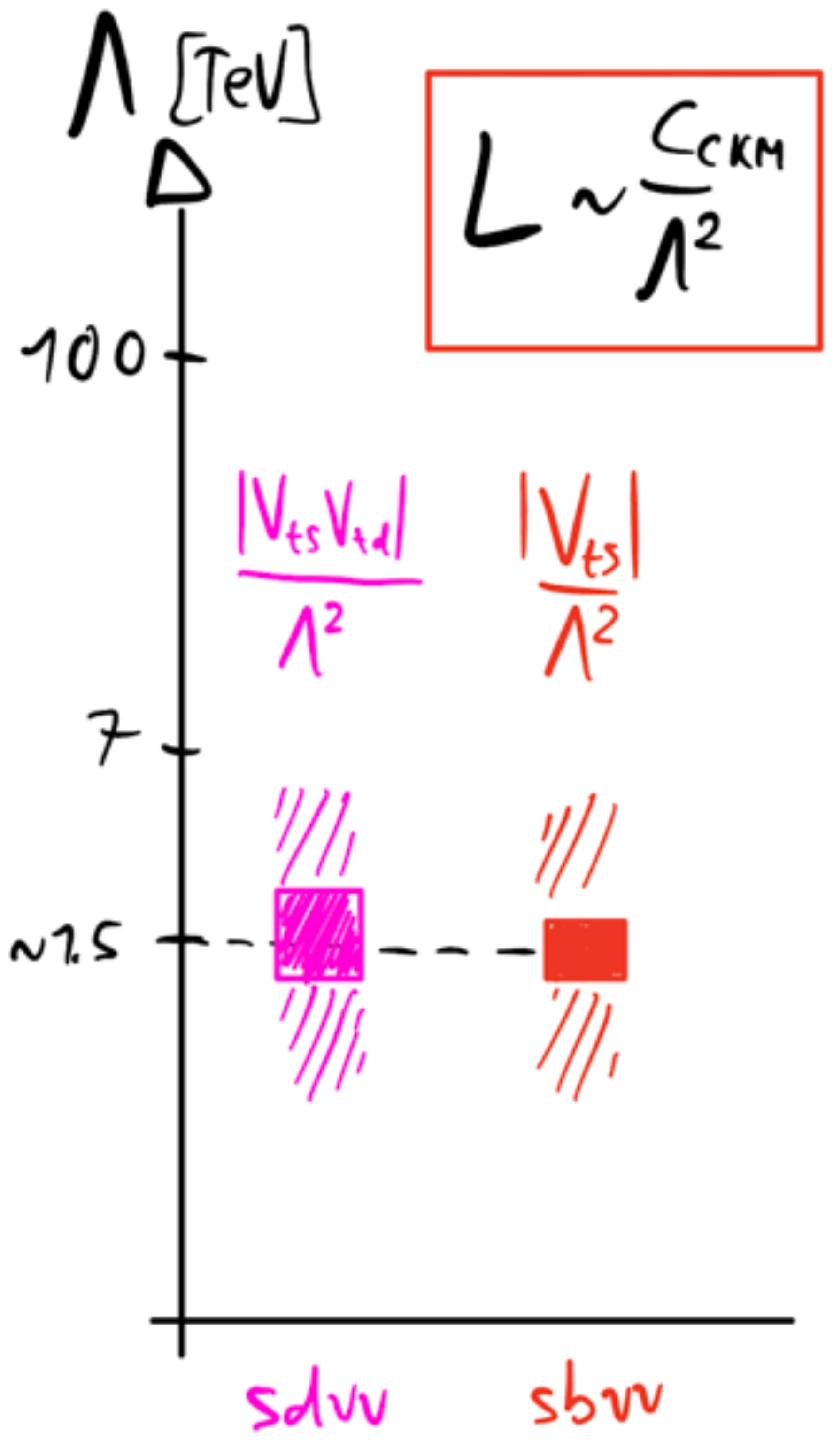
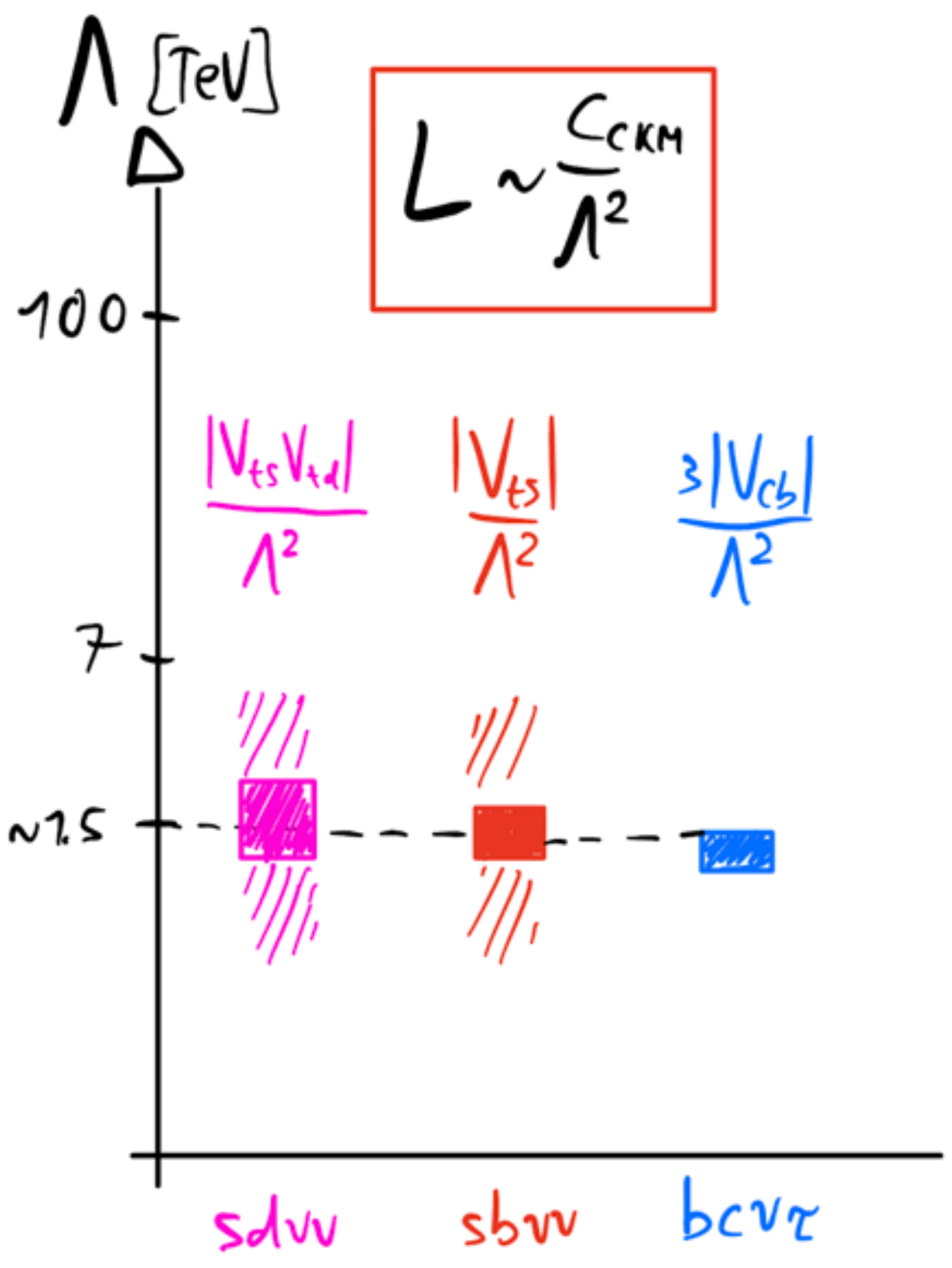




All the deviations are compatible with a U(2)-like flavour structure.

See Allwicher et al. [2410.21444]

The physics scales become compatible!

Is a picture emerging from data?

Conclusions

Many of the peculiar aspects of the **Standard Model** are **tested in Flavour Physics**: conservation rules, forbidden processes, suppressed rates, etc.
This provides a large number of very **powerful probes of New Physics**.

New Physics scales of **O(100) TeV** are tested in rare decays.

This scale goes down to **~O(TeV) if a CKM-like flavour structure** (MFV, U(2), ..) is assumed.

A **number of interesting (but mild) deviations** from the SM point to a **similar NP scale Λ ~ 1.5 TeV**, for a **CKM-like quark flavour structure** and coupling **mainly to 3rd gen. quarks and leptons**.

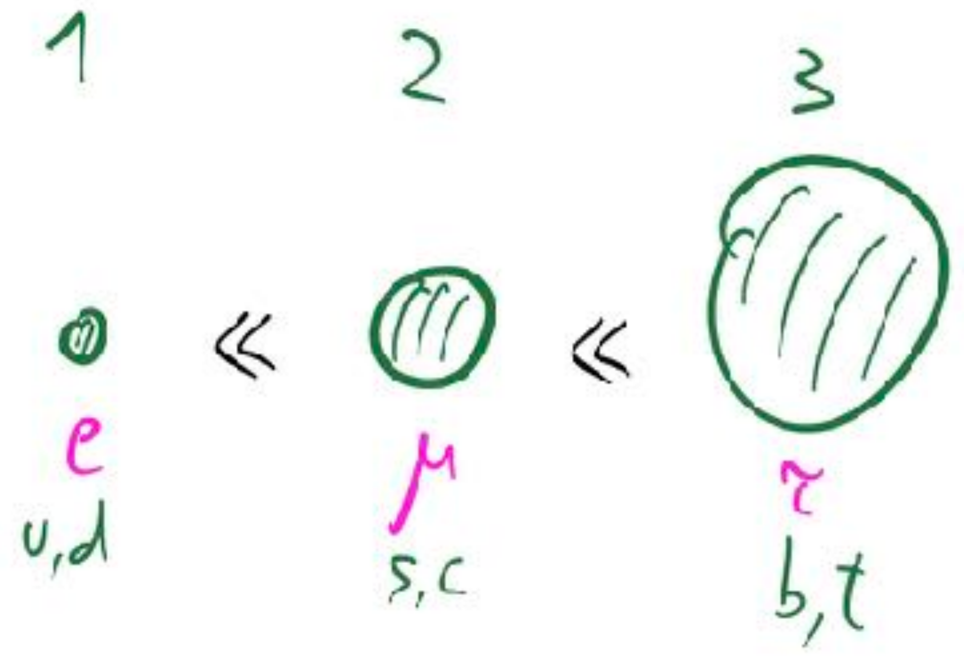
While all these results are still very fluid and could change in the future, this compatibility is interesting.

UV models explaining these anomalies could be related to the **SM flavor puzzle** and the **EW hierarchy problem**.

Looking forward to future results!

Backup

U(2)⁵ flavour symmetry



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

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

In this case the SM 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]

$\kappa_q \sim O(1)$

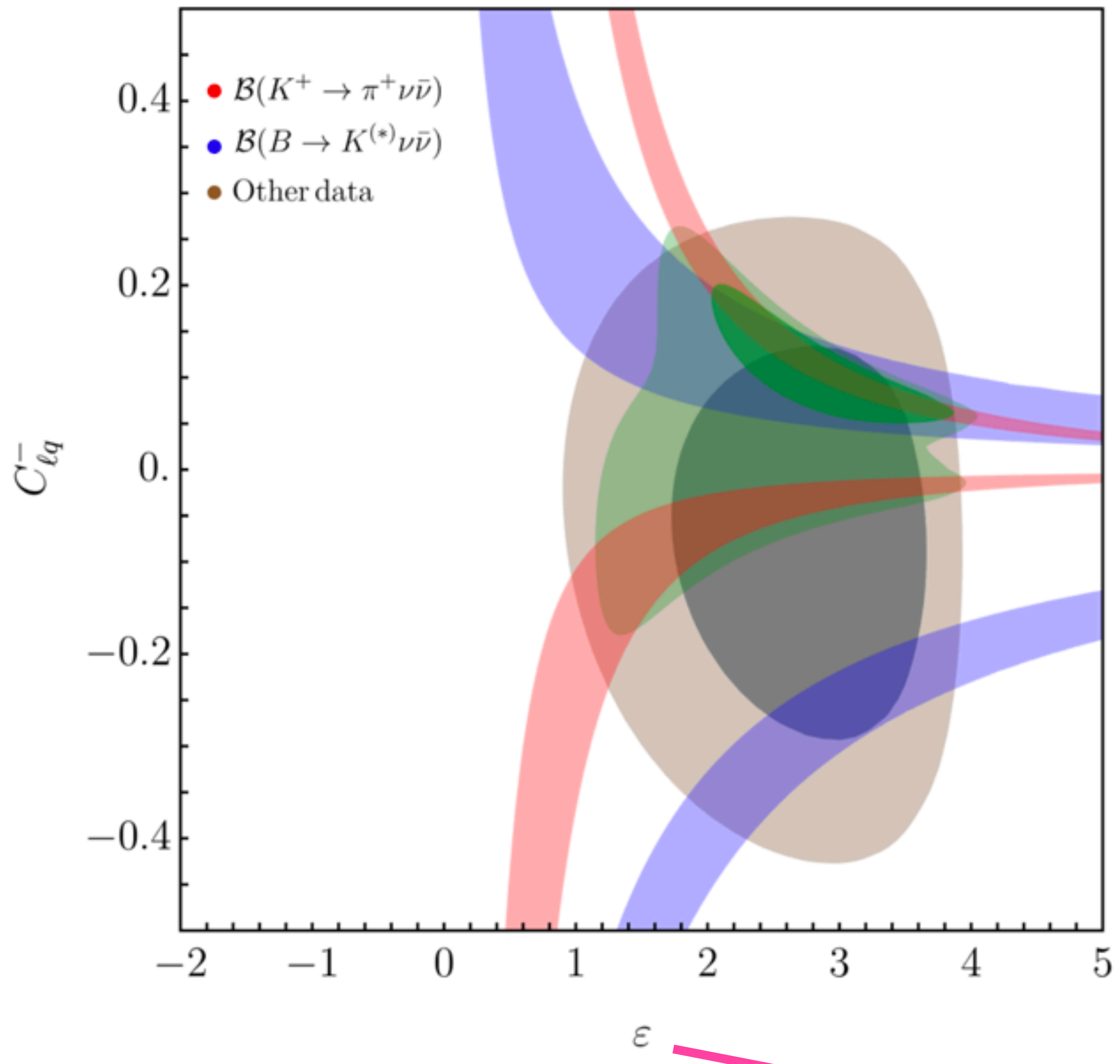
U(2)^5 flavour symmetry and data

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

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

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

Allwicher et al. [2410.21444]



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