New Physics in EWP B decays with missing E

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INFN Trieste

Belle II Physics Week 2025 - 6/10/2025

Outline

Part I

Flavour in the **Standard Model** and beyond.

Effective Field Theory approach to New Physics (NP).

The **New Physics Flavour Problem** and the need for a **flavour structure**.

Part II

Rare decays as probes of heavy New Physics: focus on **golden-channel** decays.

What is the **preferred flavour alignment** of NP?

Hints for a **consistent picture** emerging from data.

Part III

Beyond the leading SMEFT.

L-violating operators in $B \to K\nu\nu$.

Light New Physics in **$B \to KX$**: q^2 spectrum shape and ALPs.

Part I

The success of symmetries and power counting

The Flavour of the Standard Model

Most of the **richness and complexity** of the Standard Model is in the **Yukawa sector:**

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

→ All **lepton masses**, **proton-neutron mass difference**,
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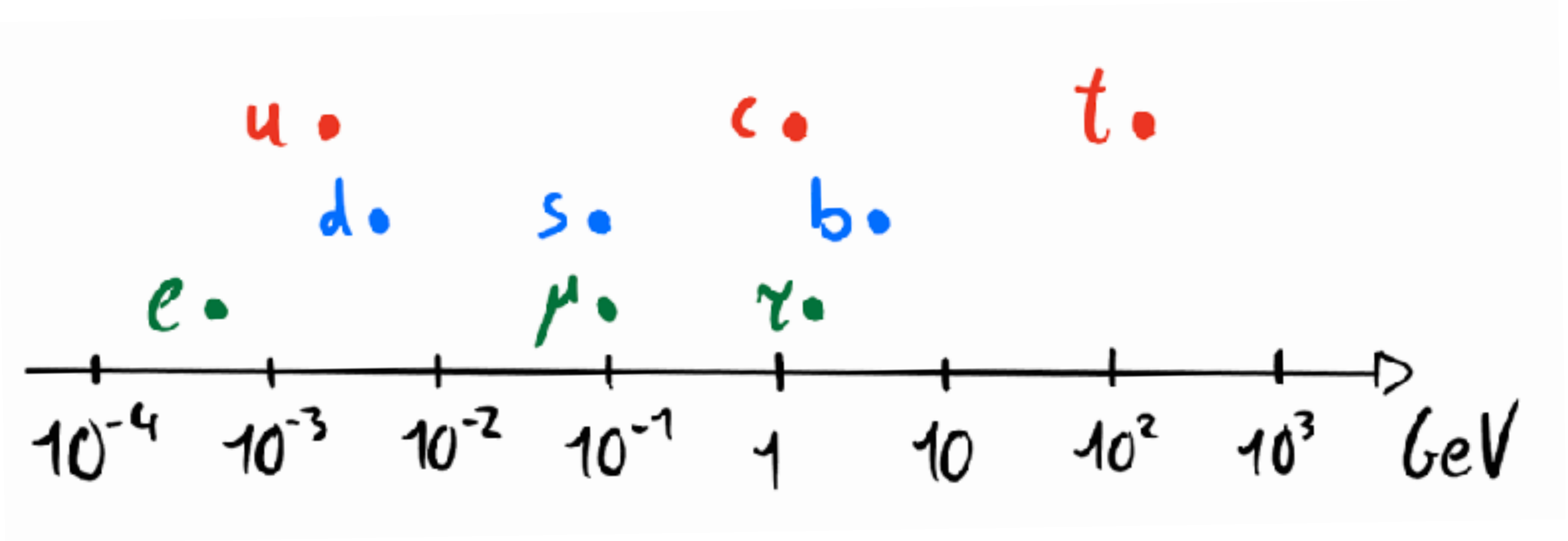
- hierarchical fermion masses

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



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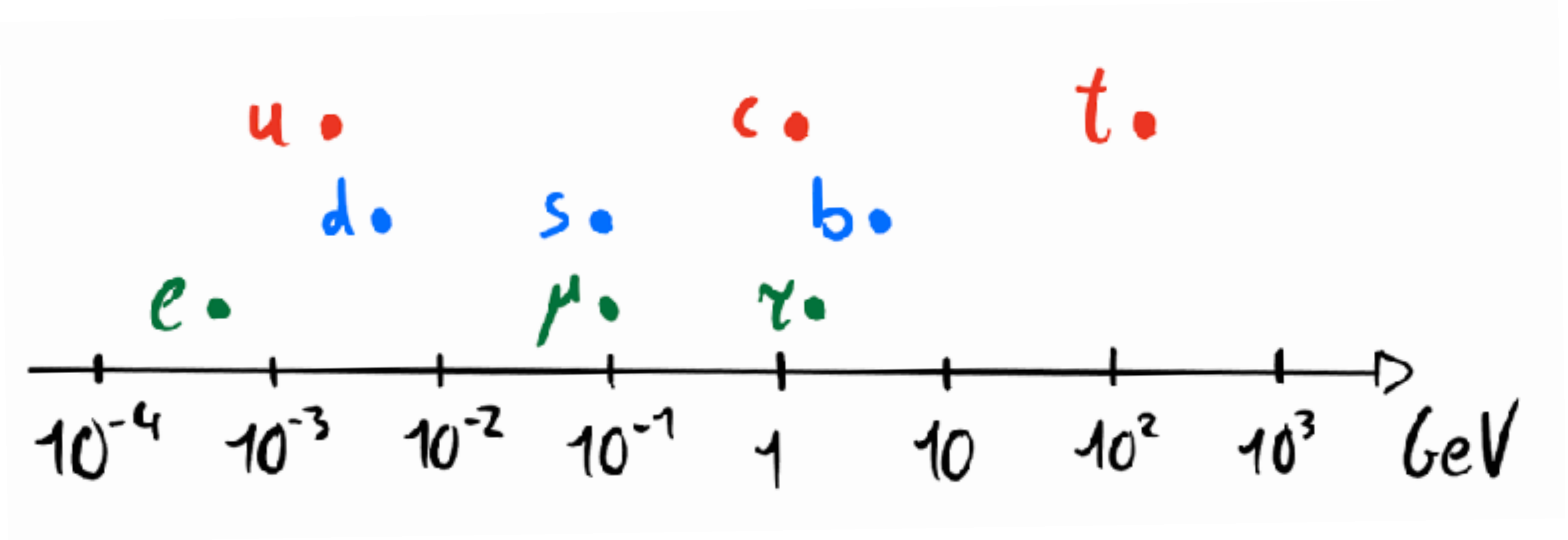

- **hierarchical quark mixing matrix**

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

SM Flavour Puzzle

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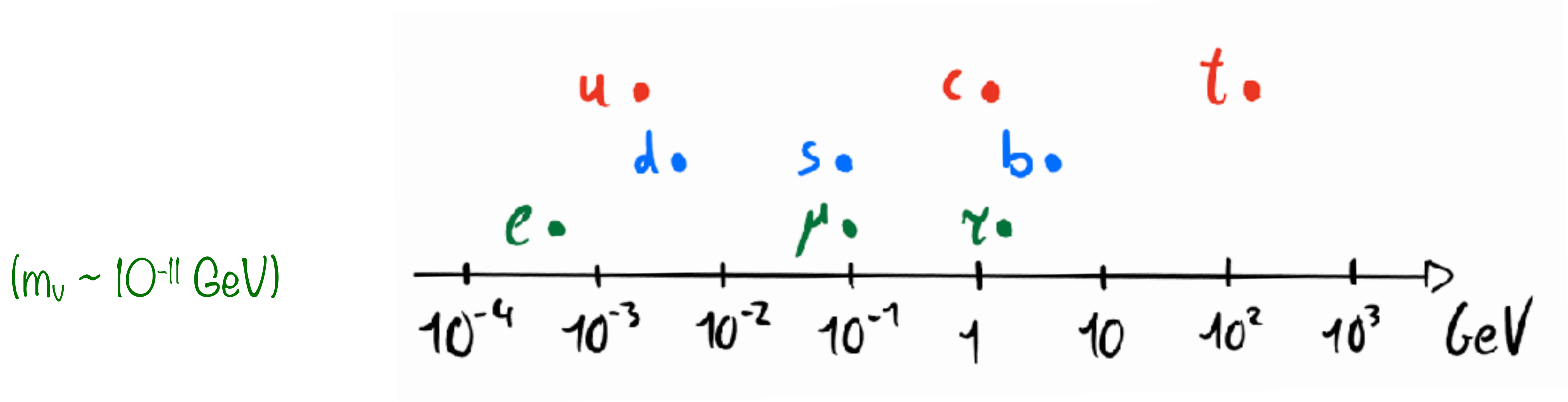

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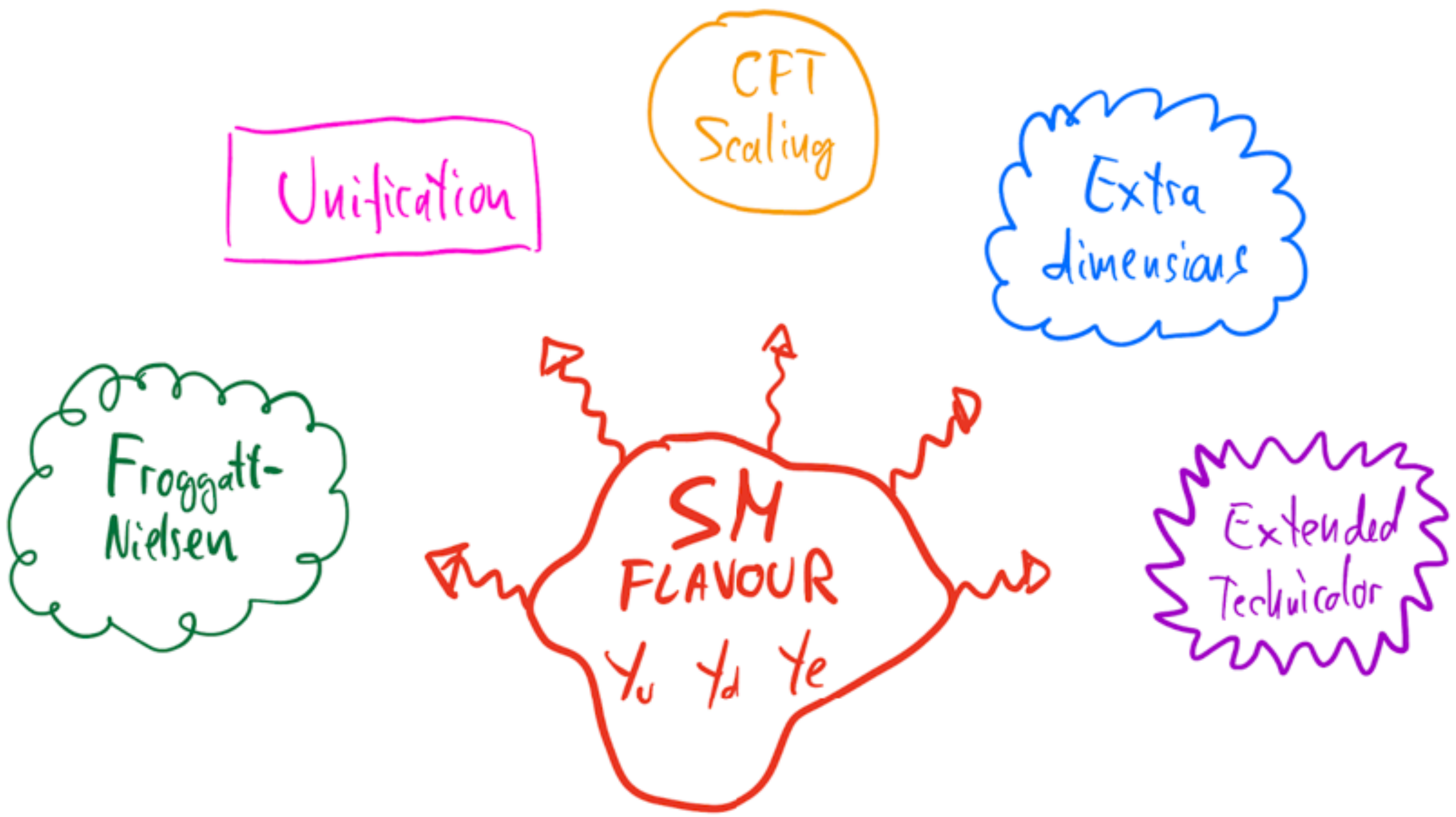
This puzzle in general **doesn't point to a specific New Physics scale for its solutions**.
They could be anywhere from **near the TeV** till up to **GUT/Planck**.

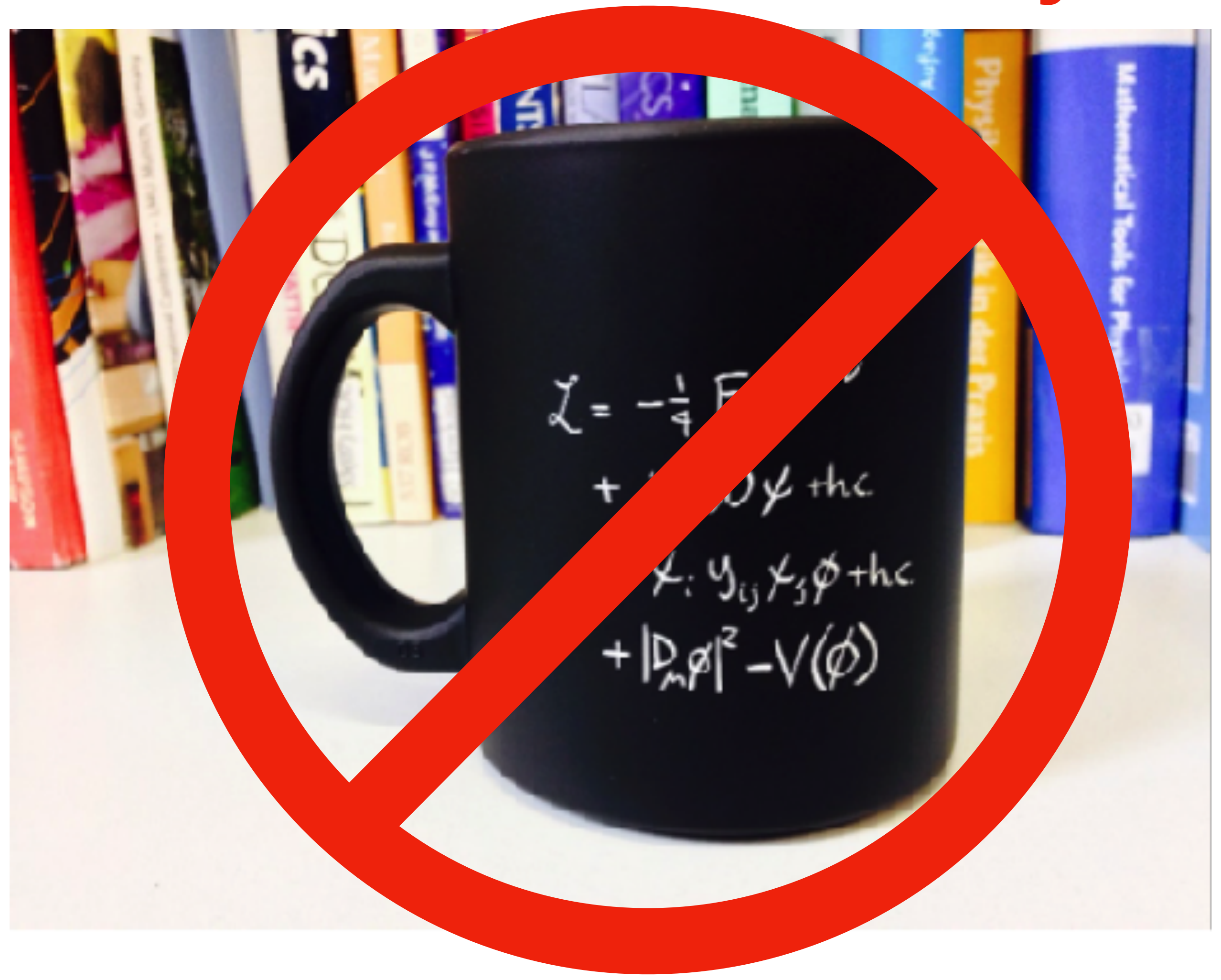


Necessarily Flavourful New Physics:
- **non universal**
- **flavour changing**

New Physics is somewhere out there…

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

not the whole story



- What is the nature of **dark matter**?
- What is the origin of **neutrino masses**?
- Why does **QCD conserve CP**?
- What is the **origin of fermion masses** and mixings?
- Why the specific assignment of **charges** in the SM?
- Why is the **electroweak scale** smaller than the Planck scale? How is it **stable**?
- What is the origin of the **baryon asymmetry of the Universe**?
- What induces the **accellerated expansion** of the Universe?
- What was the mechanism underlying **inflation**?
- How does **gravity behave at the quantum level**?

However, **we don't know what Λ** is, or **what New Physics looks like**.
So, how can we parametrise New Physics effects in our experiments?

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then we can only look at **its effects on processes involving SM particles**.

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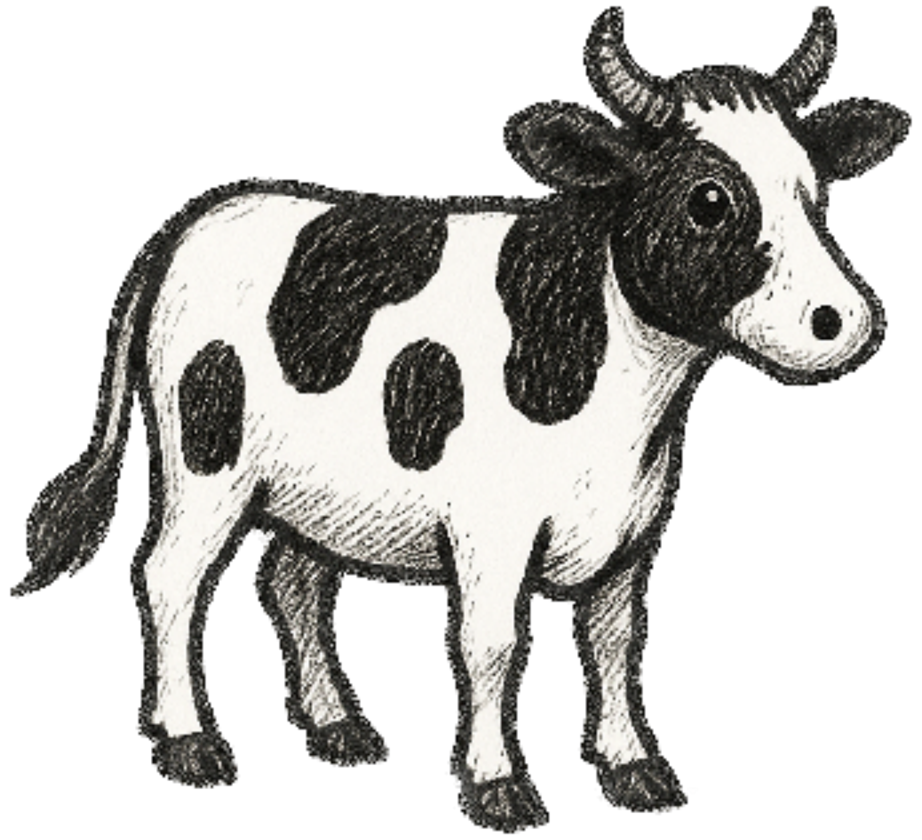

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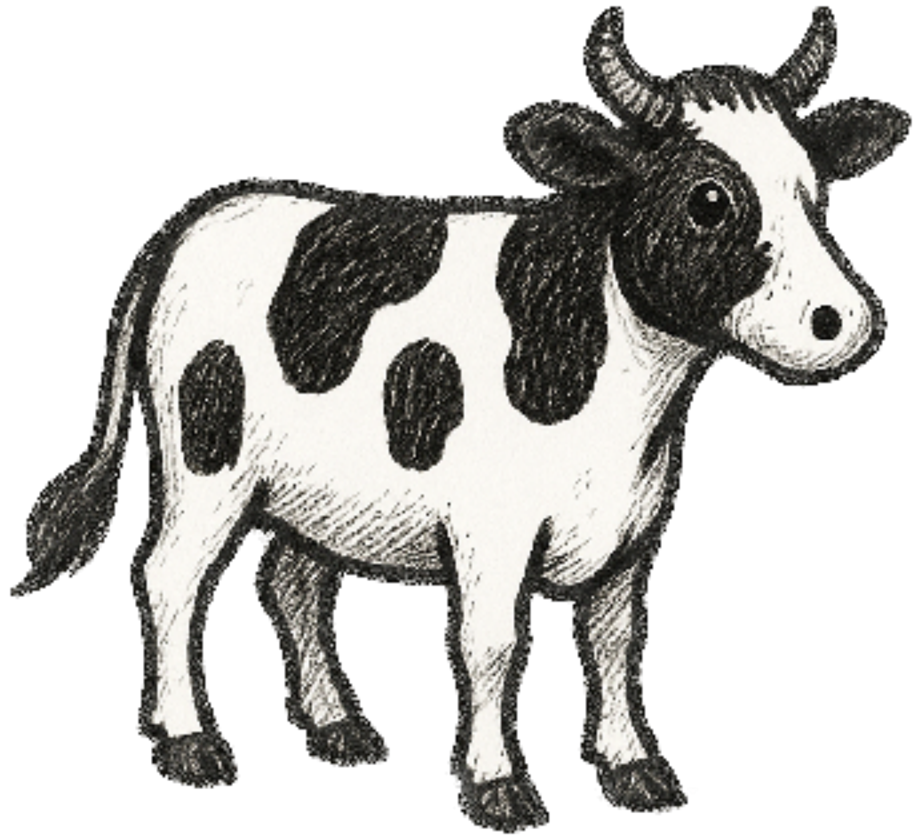
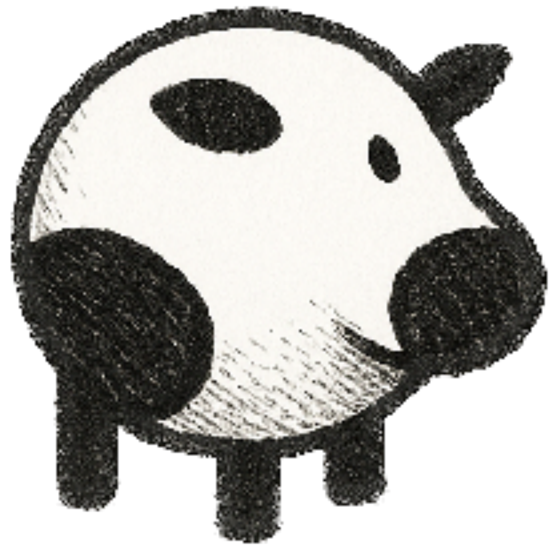


Complete New Physics Model

… we look at deformations of the SM



The same model seen from a distance
(from low energy)

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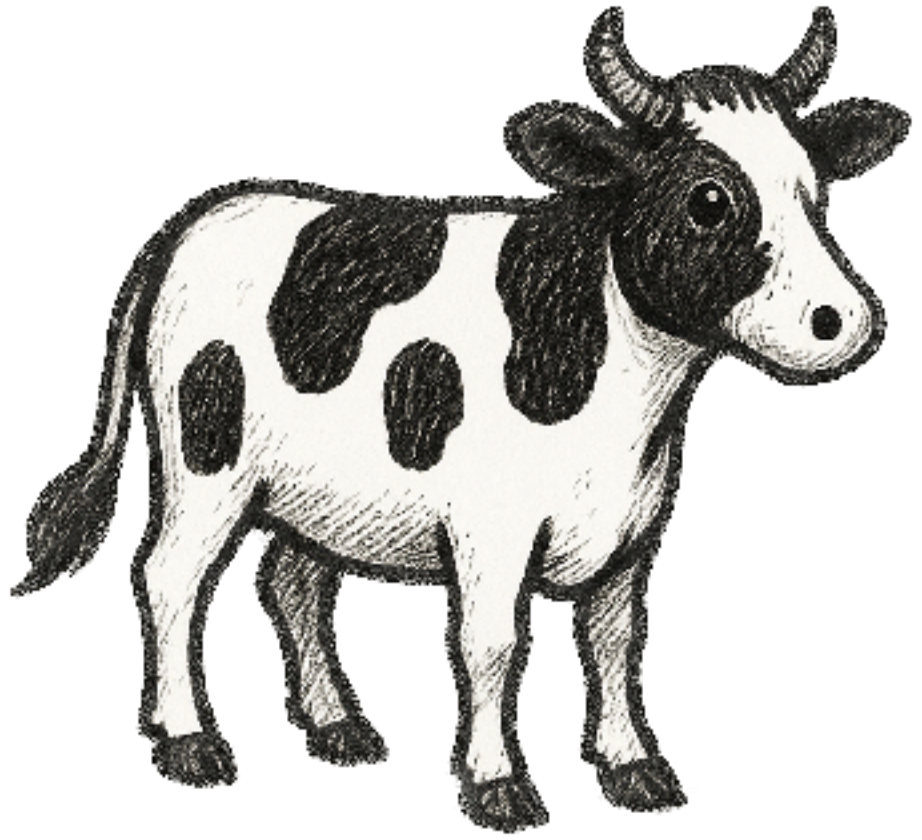

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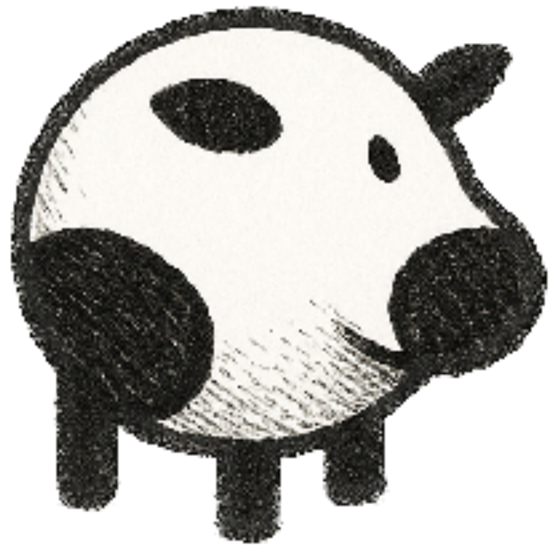

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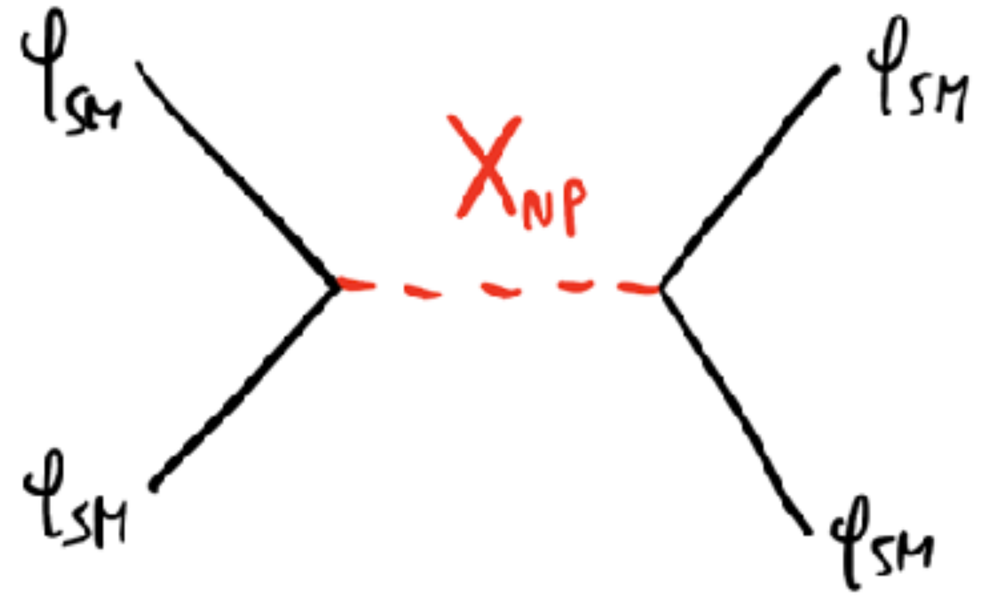
"new interaction among SM fields"



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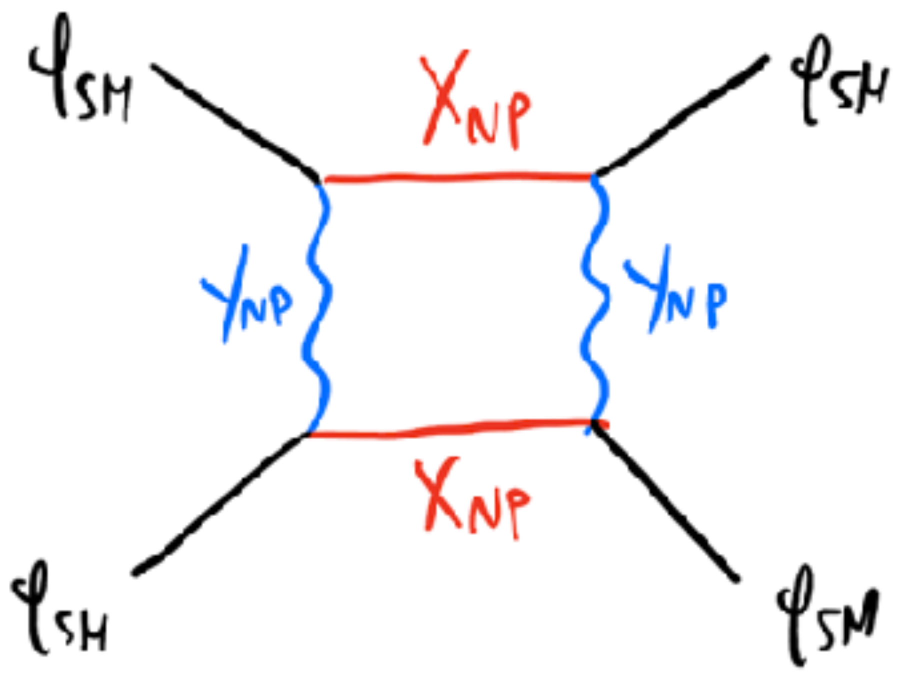

Complete New Physics Model

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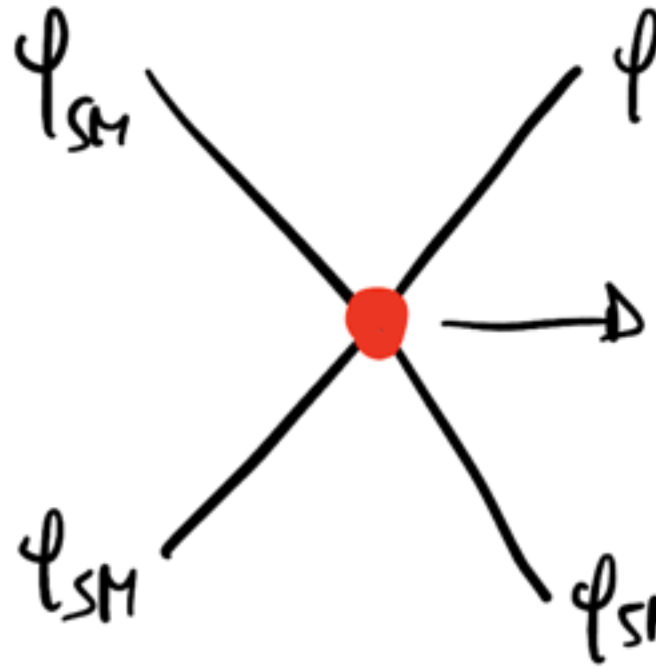

$\frac{C_{NP}}{\Lambda^2}\,\mathcal{O}(\varphi_{SM})$

Local effective operator

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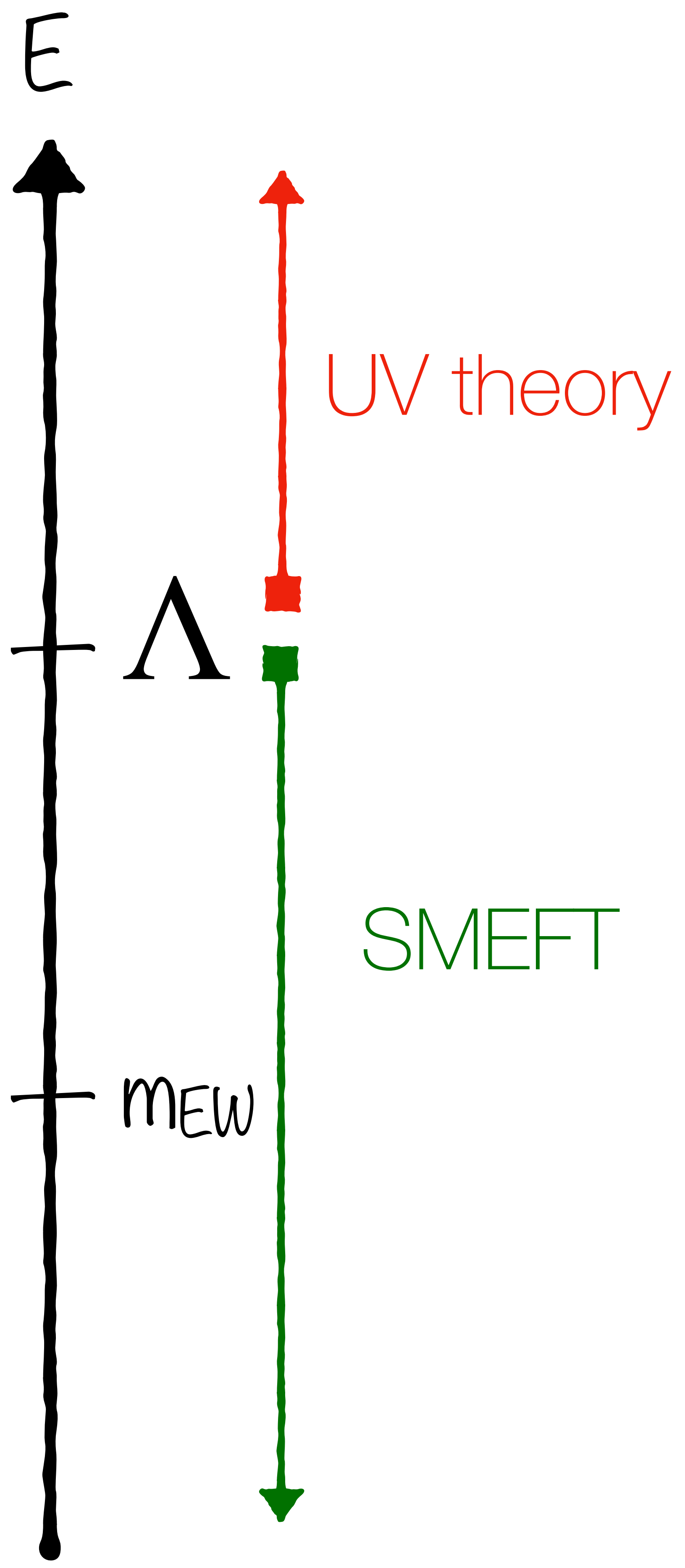
The Standard Model as an EFT



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$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM}^{(d\leq 4)} + \frac{C^{(5)}}{\Lambda_{L}} \mathcal{O}_{W} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)}[\varphi_{SM}] + \mathcal{O}(\Lambda^{-4})$$

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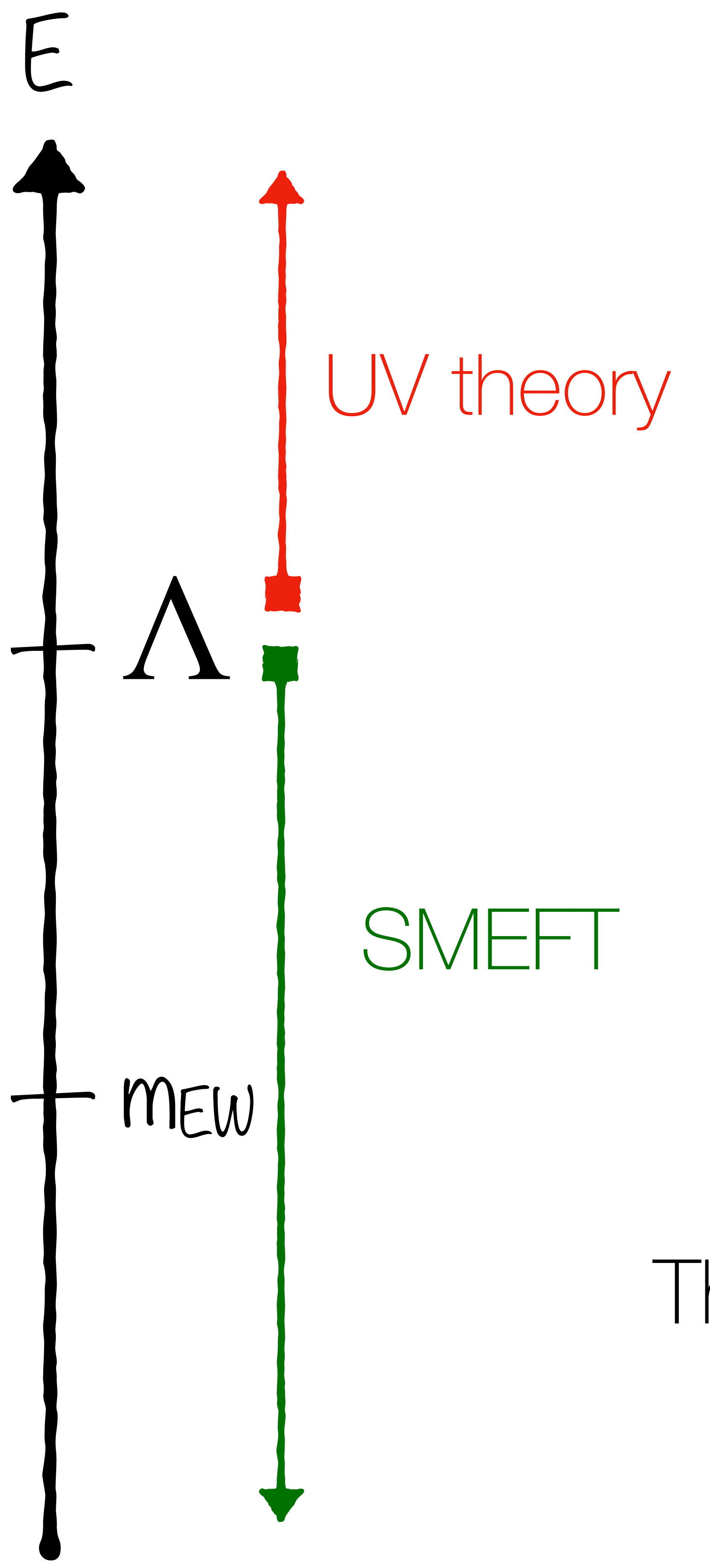

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At **low energies**, the effects from higher-dimension operators are **suppressed** by powers of

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

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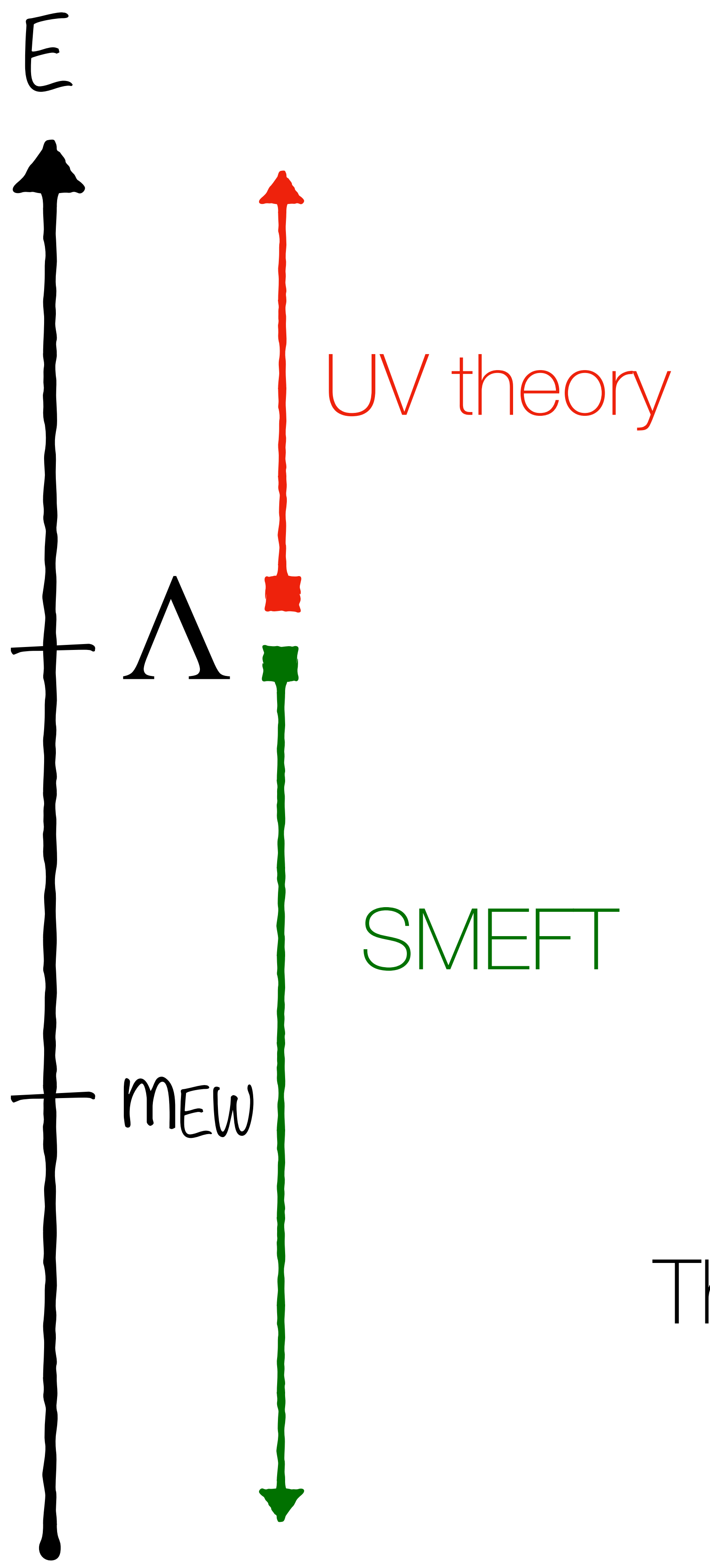

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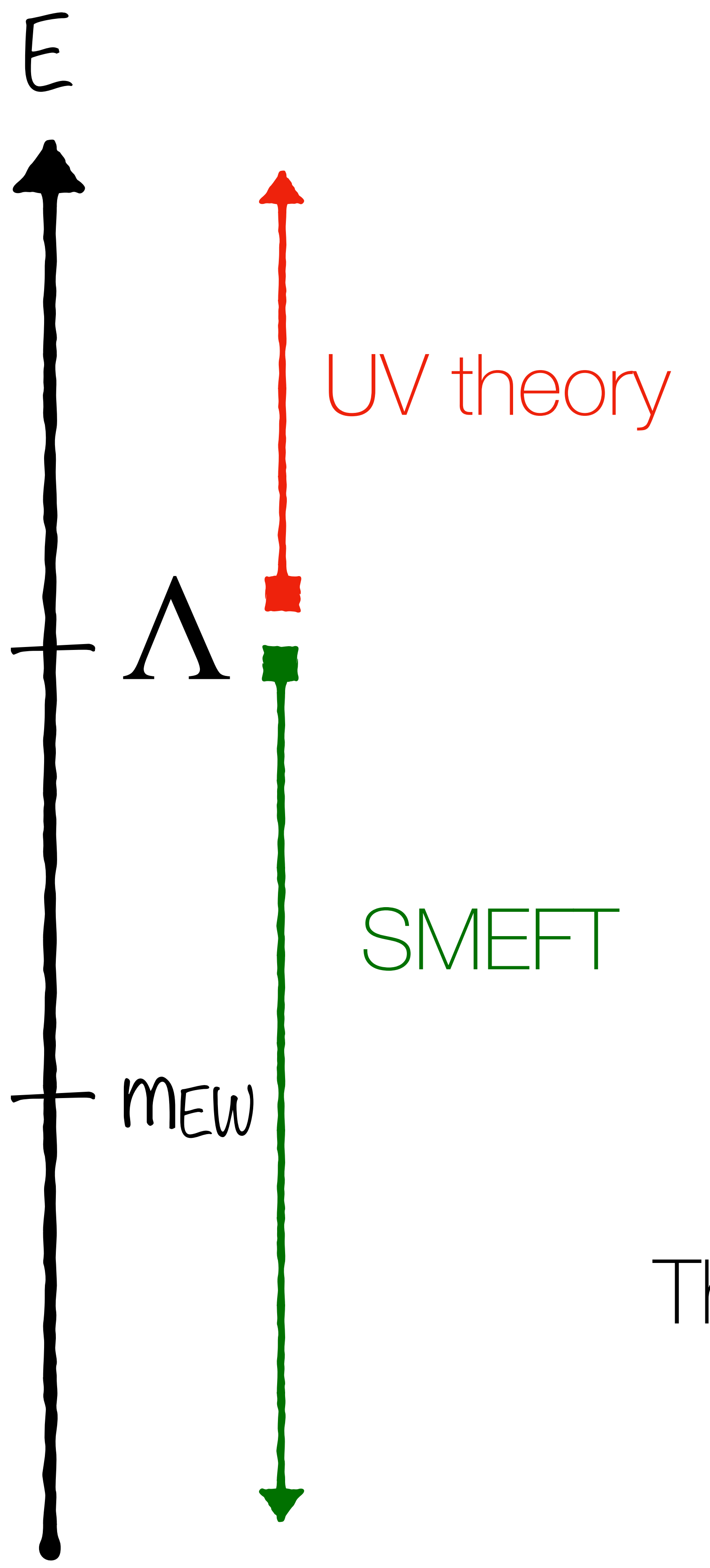

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Symmetries and power counting: There can be **different scales** $\mathbf{\Lambda}$ **associated to the violation of different SM properties**: quark flavour, lepton flavour, L and B violation, etc..

SM: Accidental Features

The structure of the Standard Model implies several **accidental features**,
i.e. properties that arise automatically, not imposed by hand.

Symmetries & conservation laws: conservation of ***B***, ***L_e***, ***L_μ***, ***L_τ***

Custodial symmetry: An approximate global $SU(2)_C$ symmetry in the Higgs sector.
Protects the ratio $m_W / (\cos\theta_W \, m_Z) \approx 1$.

Approximate U(3)[5] Flavour Symmetry: Broken only by Yukawa interactions

Absence of FCNC at tree-level: Z boson, photon and gluon couple in a flavour-conserving way +
Higgs Yukawa couplings are small.

Small CP-violation effects, even though the CP-phase is large: small quark masses and mixing angles.

Lepton-Flavour Universality: SM gauge couplings are generation-independent +
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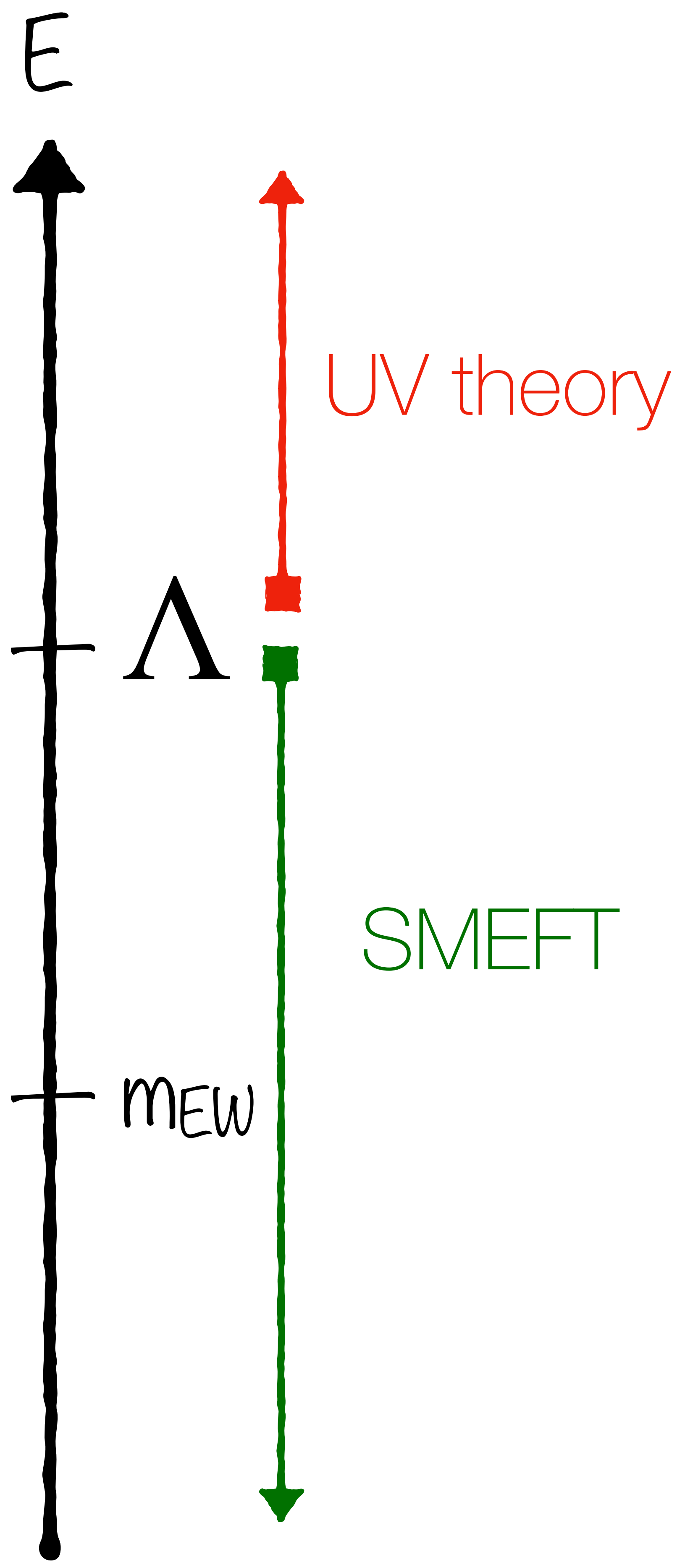

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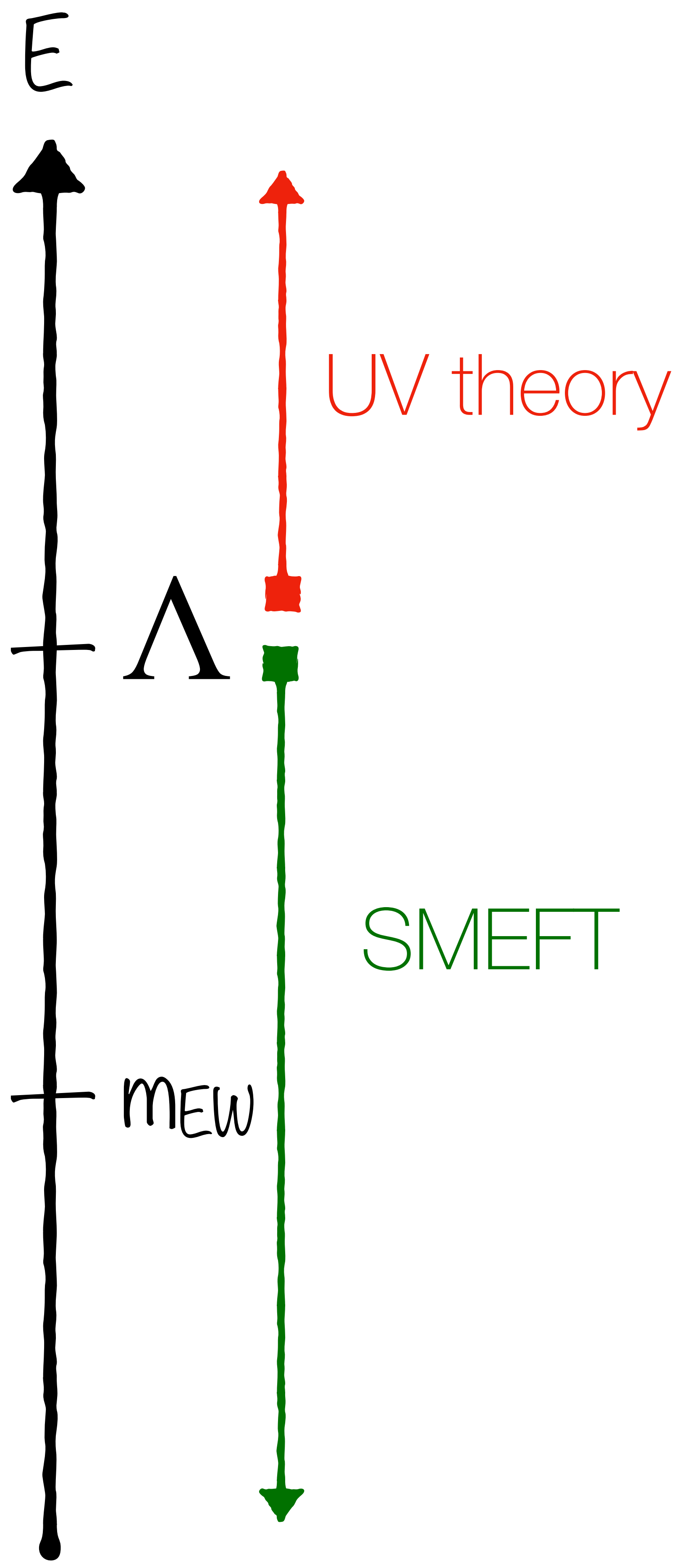

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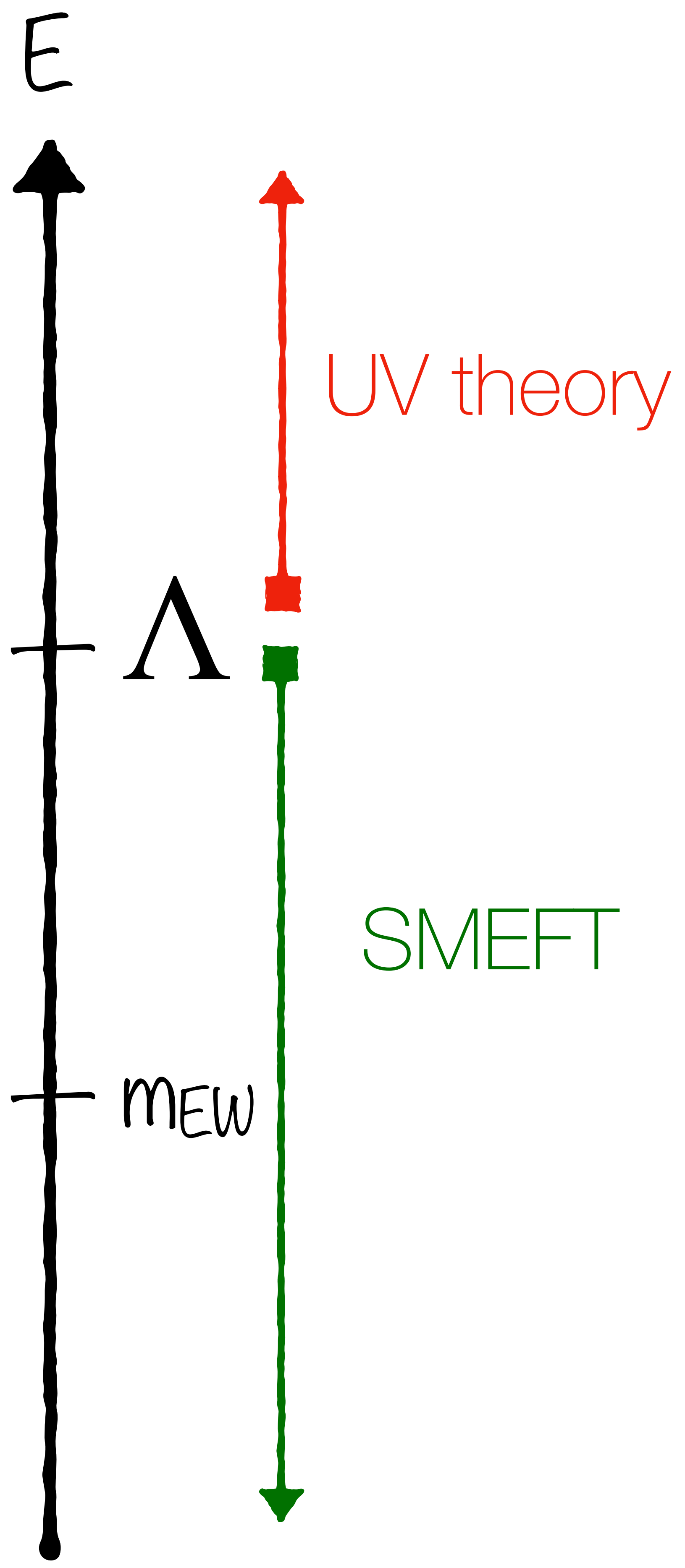

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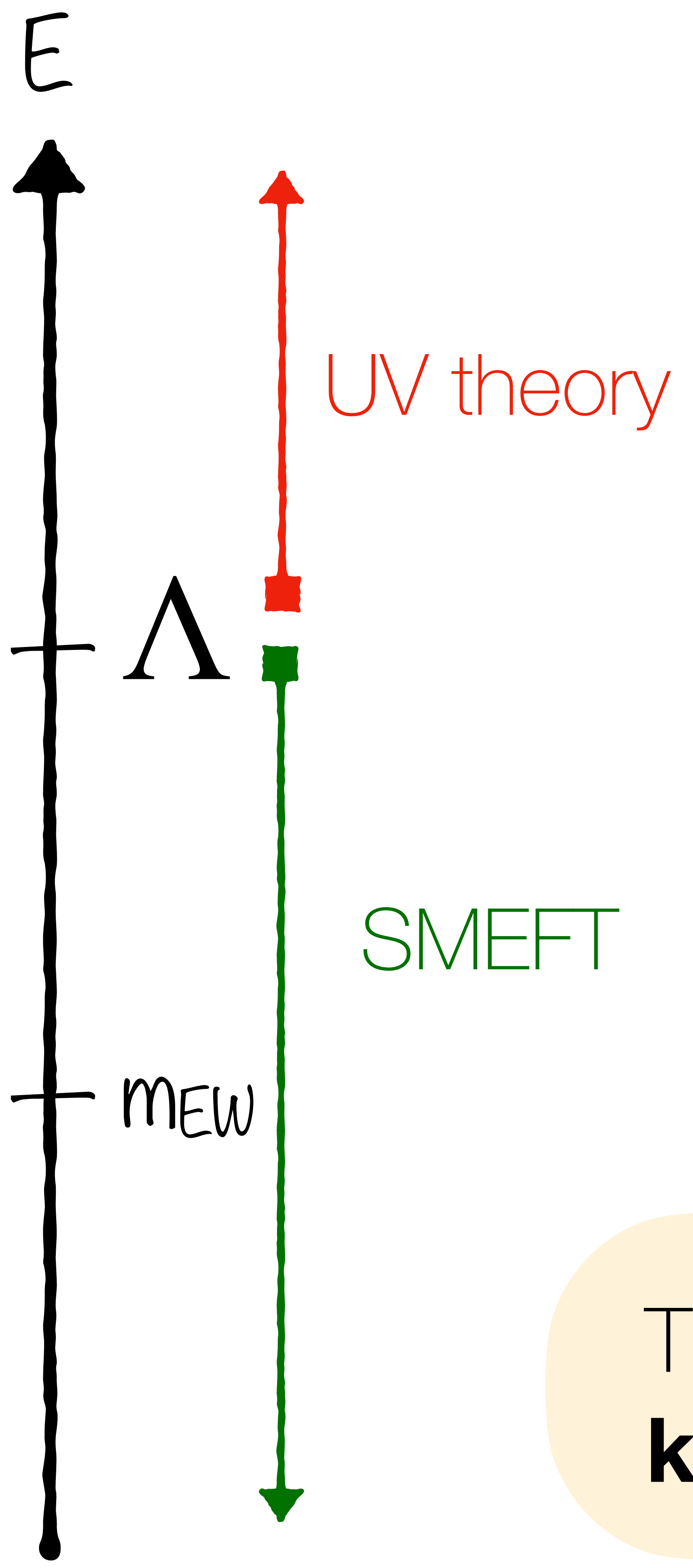

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The **SMEFT** is a consistent **framework to systematically parametrise our knowledge of fundamental interactions** between the known particles.

Every little improvement in any direction in the (big) EFT parameter space means that we learn something more of how particles behave at microscopic scales.

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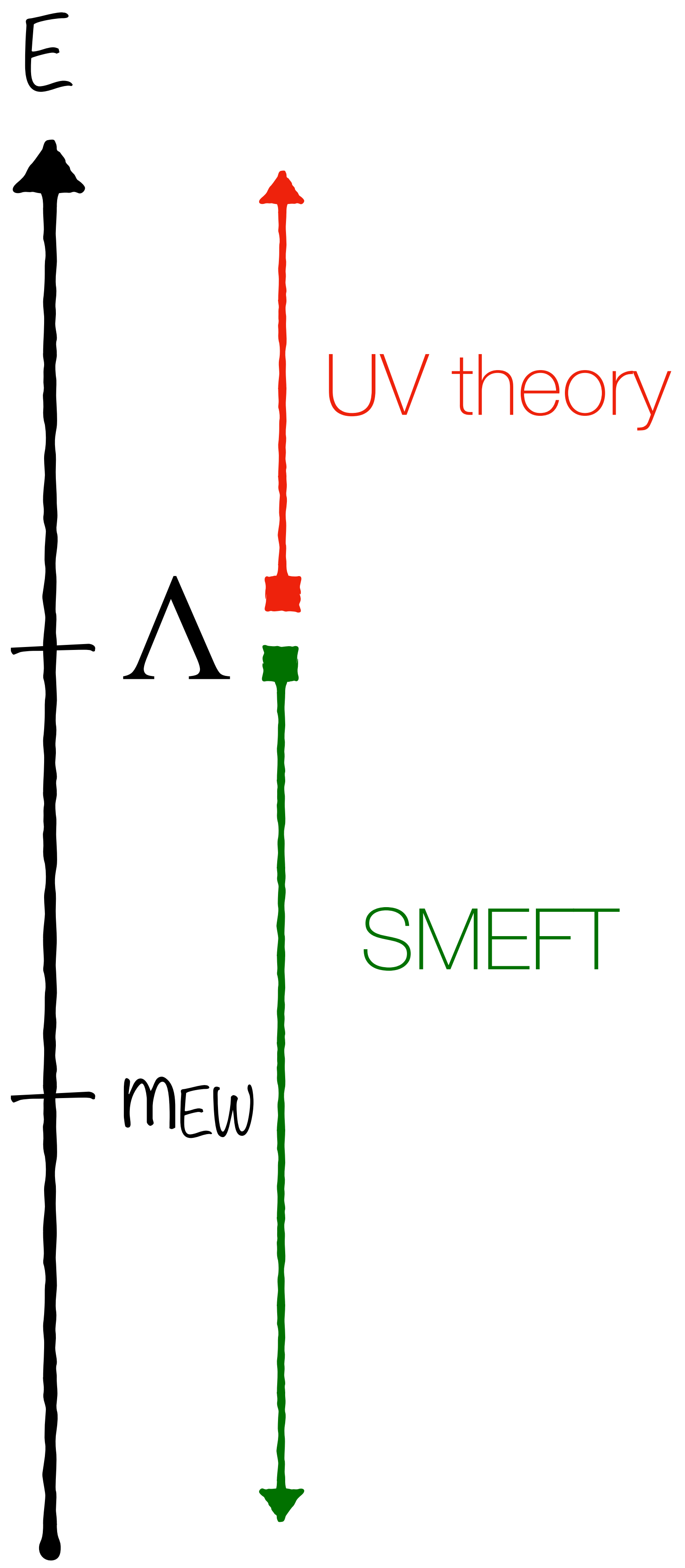

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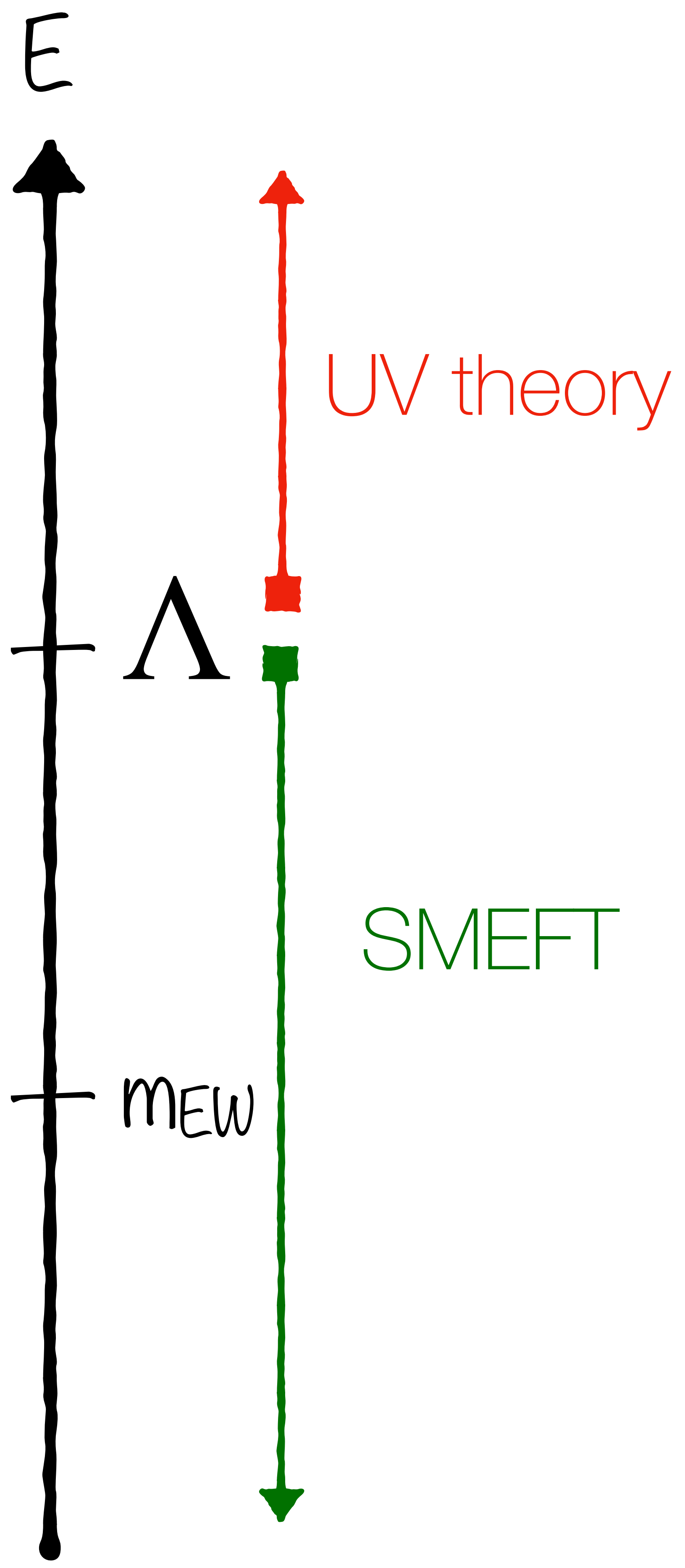

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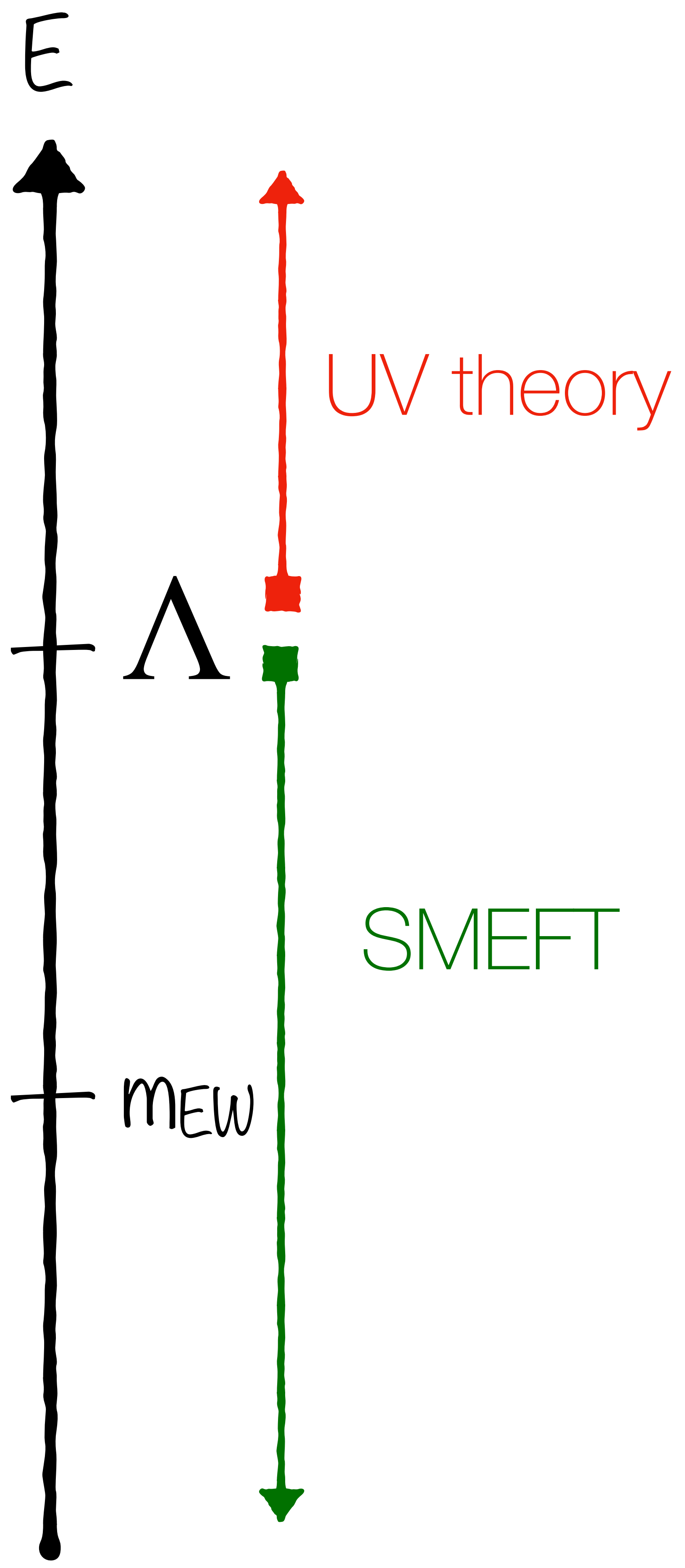

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Motivated Reasons for a **"low"** $\boldsymbol{\Lambda}$:

Hierarchy problem
of the EW scale,

$\boldsymbol{\Lambda \sim \text{TeV}}$

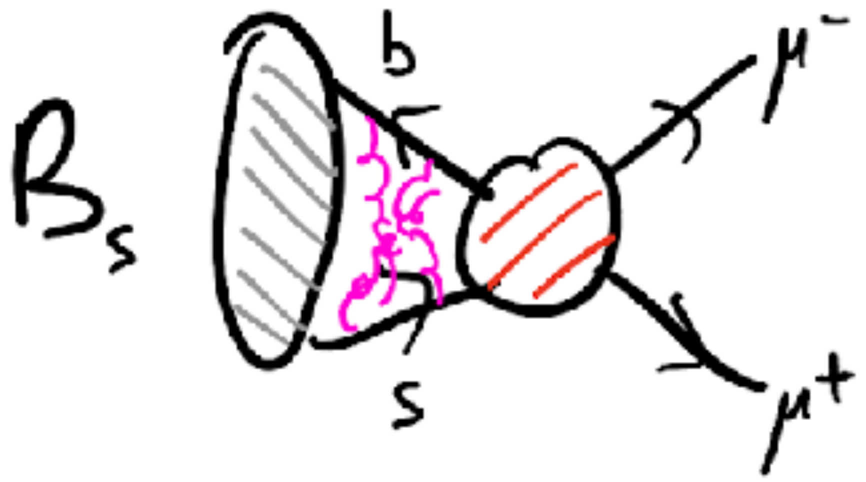
Experimental signatures
of BSM physics (***anomalies***)

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

WIMP miracle
for Dark Matter

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

The BSM Flavour Problem



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

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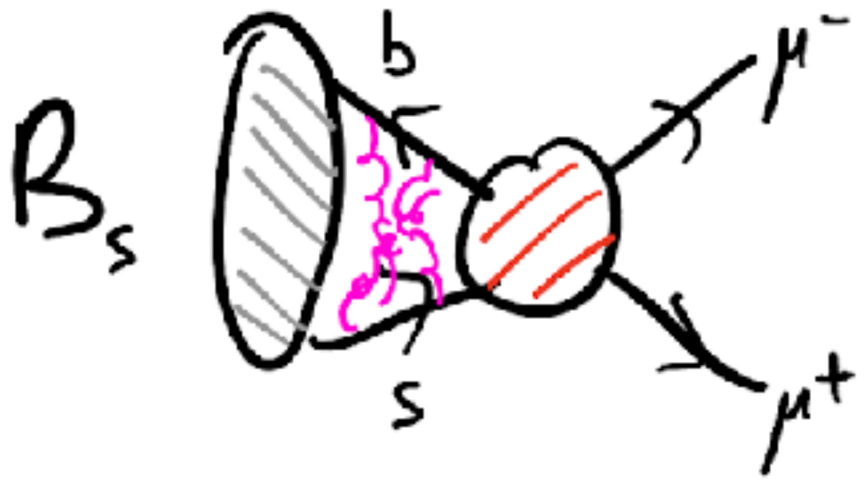

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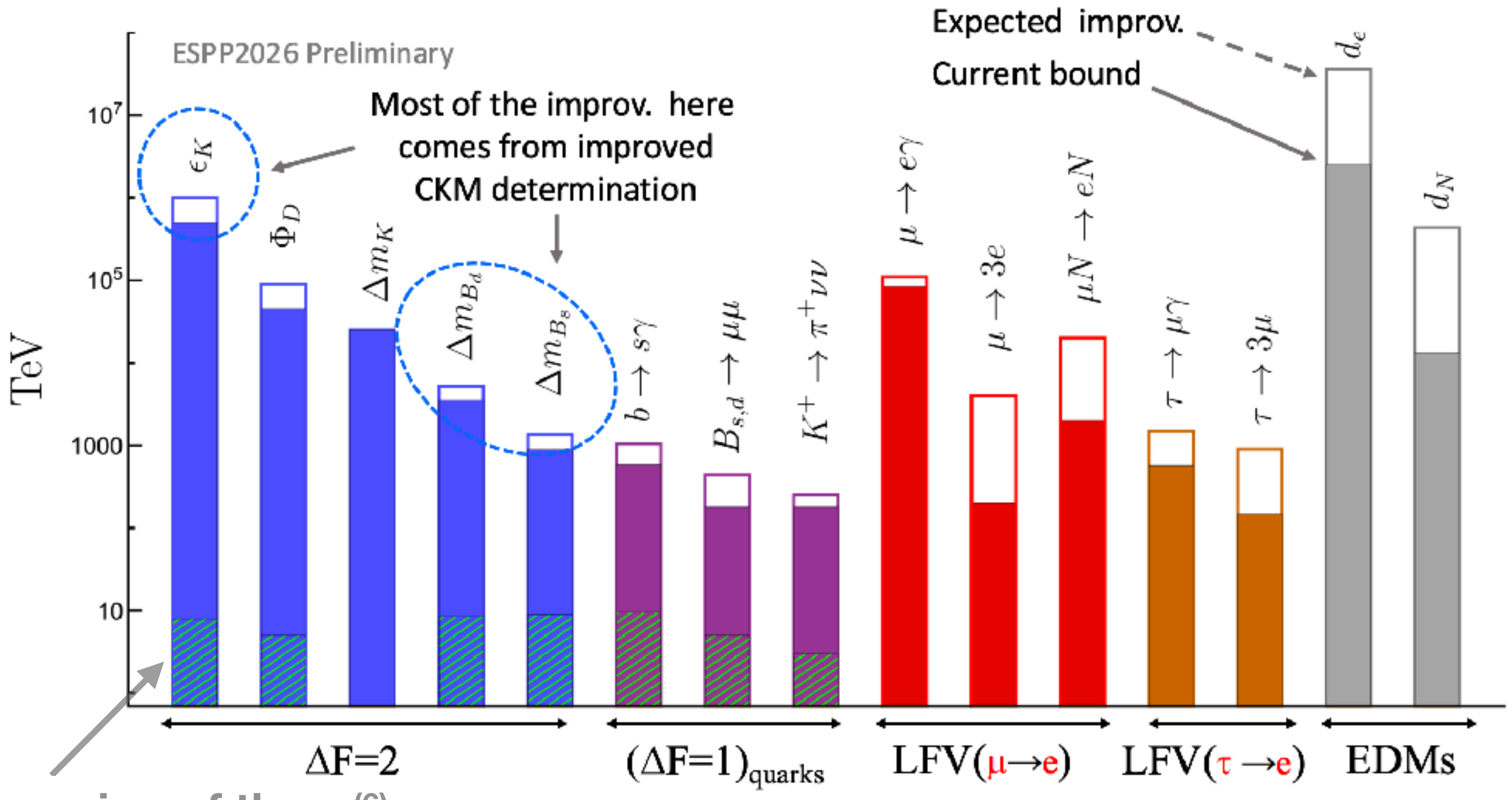
Bounds on Λ (taking $c_i^{(6)} = 1$) from various processes:



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

[G. Isidori's talk @ OpenSymposium ESPPU2026]

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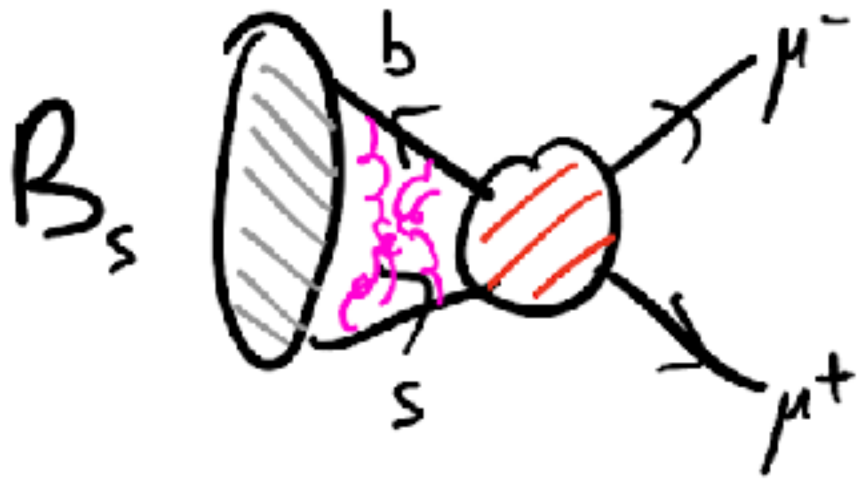

Measuring rare flavour transitions puts strong constraints on New Physics with generic flavour structure.

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**.

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

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

Precision tests push Λ to be very high

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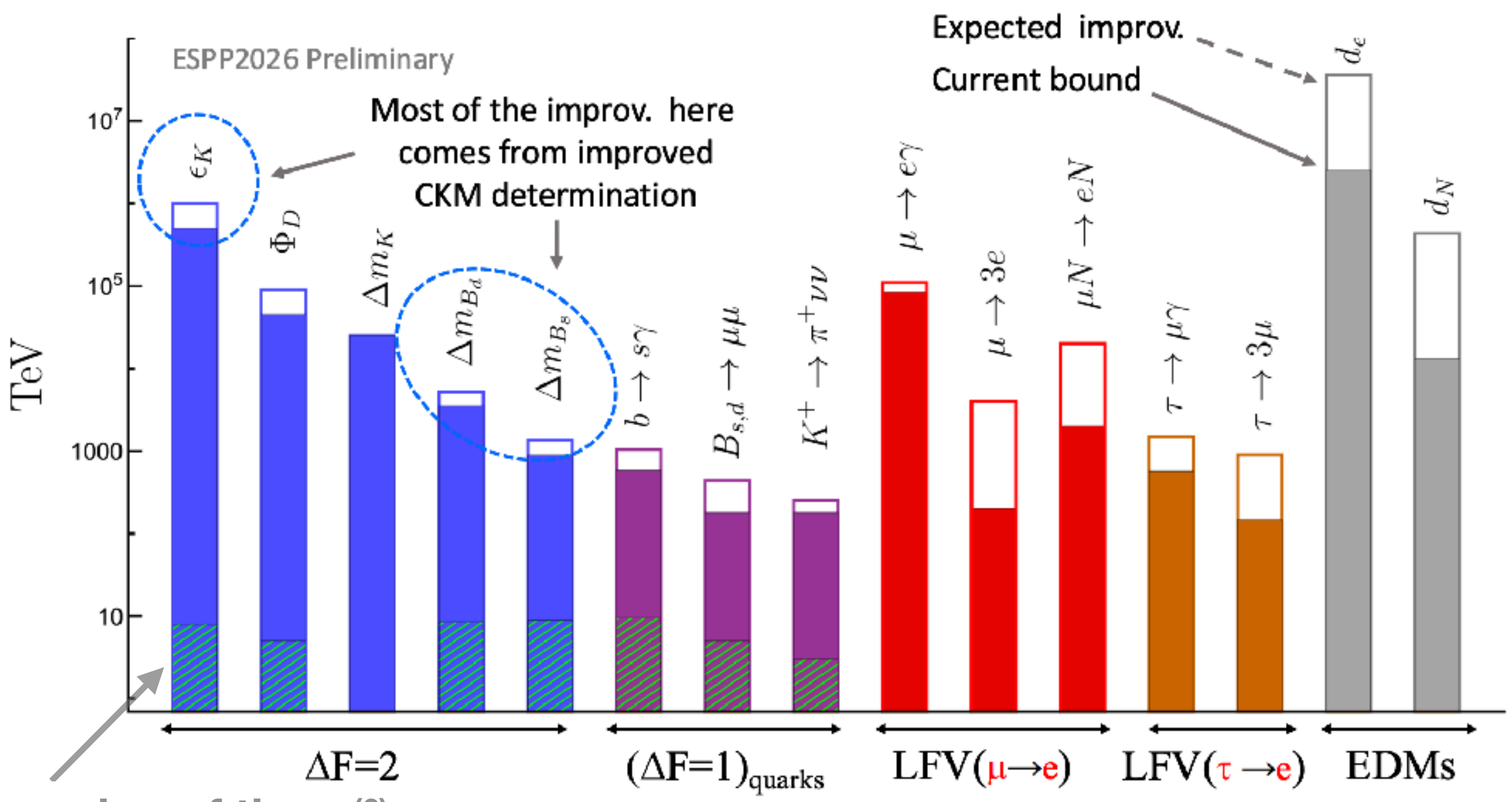

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Let us consider the hypothetical case $\Lambda \sim 1 - 10$ TeV

- Solutions to the Hierarchy Problem
- Reach of present/future colliders
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"CKM-like"

$$C_{ij} \sim \begin{pmatrix} \epsilon_1 & \lambda^5 & \lambda^3 \\ \lambda^5 & \epsilon_2 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$\lambda \sim \sin\theta_c$

Cabibbo angle

Can be protected by **symmetries** or dynamics:

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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

New physics likes the Top

(1)

Bounds from direct searches @ LHC are **stronger for light fermions than for third generation** ones.

E.g. squark: $M_{\tilde{q}_{(1,2)}} \gtrsim 2$ TeV $M_{\tilde{t},\tilde{b}} \gtrsim 1.4$ TeV

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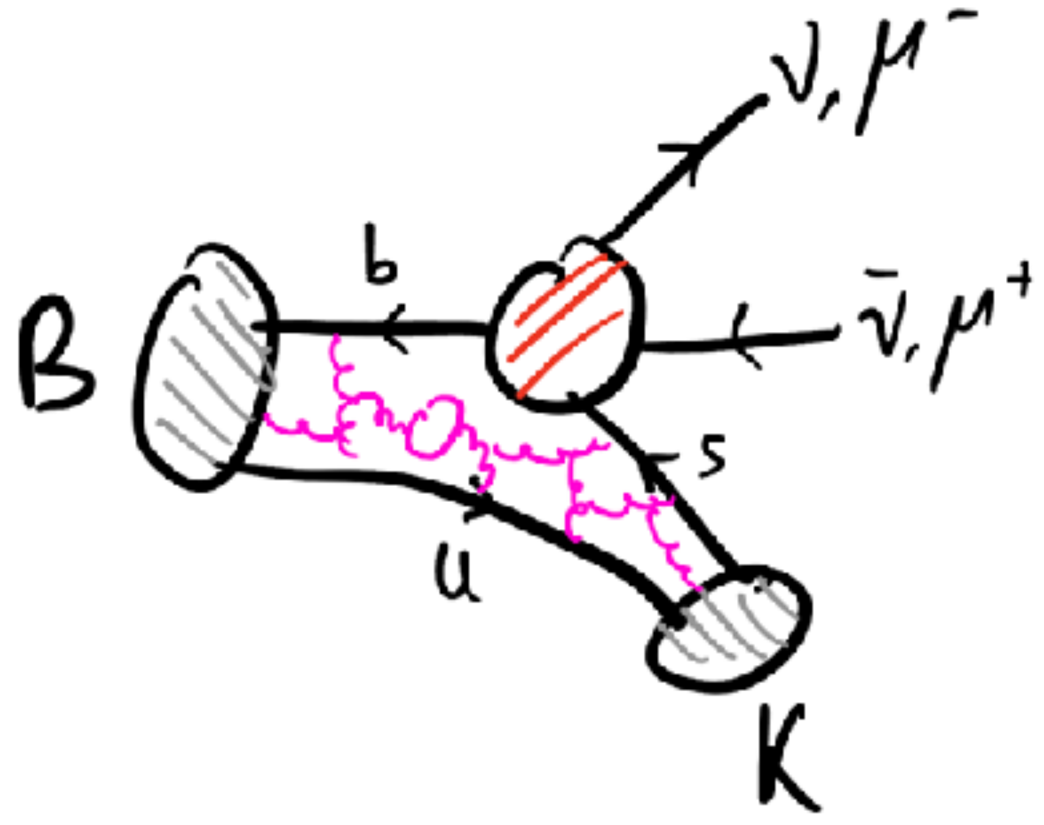
★ **Non-universal couplings preferred**

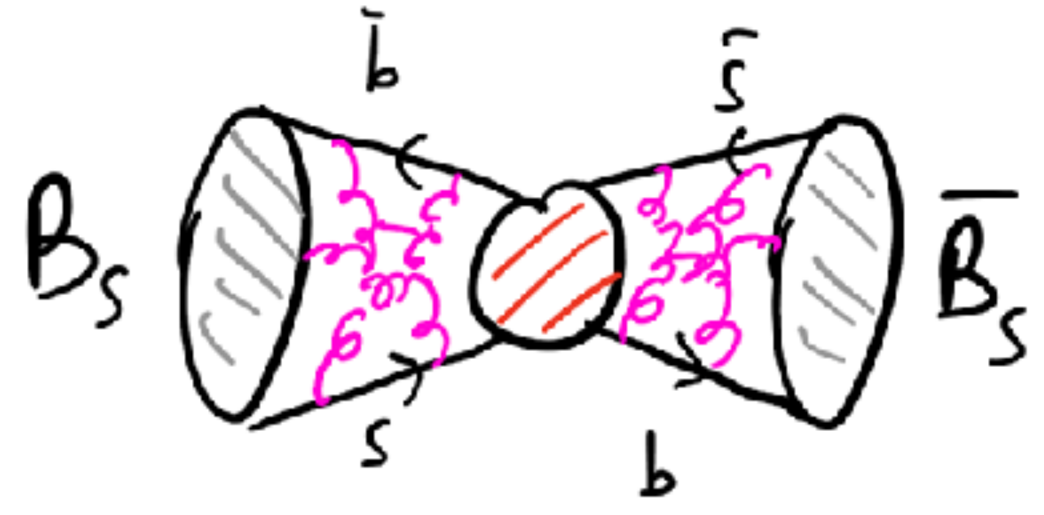
U(2)-like: $\varepsilon_{1,2} \ll 1$

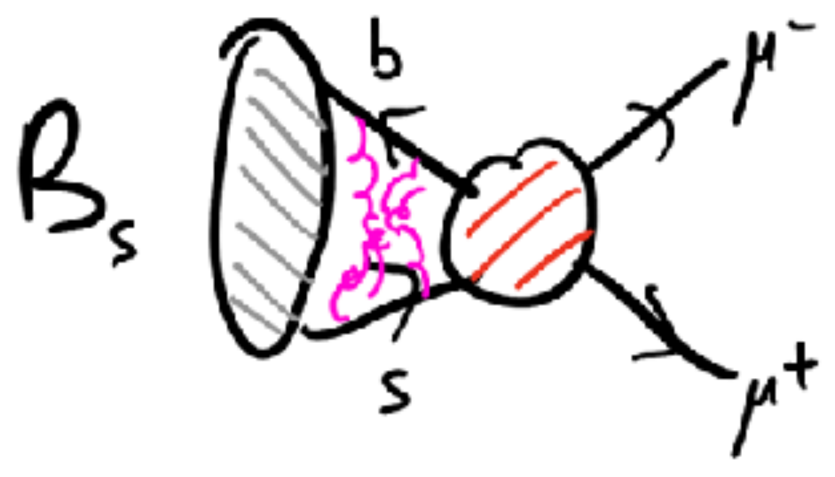
Part II

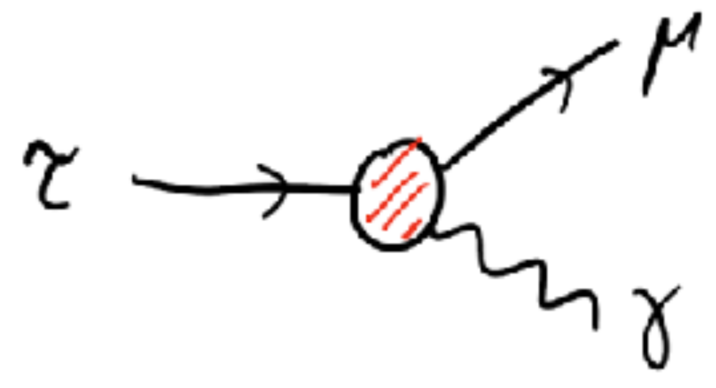
In rarity lies power

Probing New Physics with Rare or Forbidden Processes









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

Short-distance low-energy EFT coefficient

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

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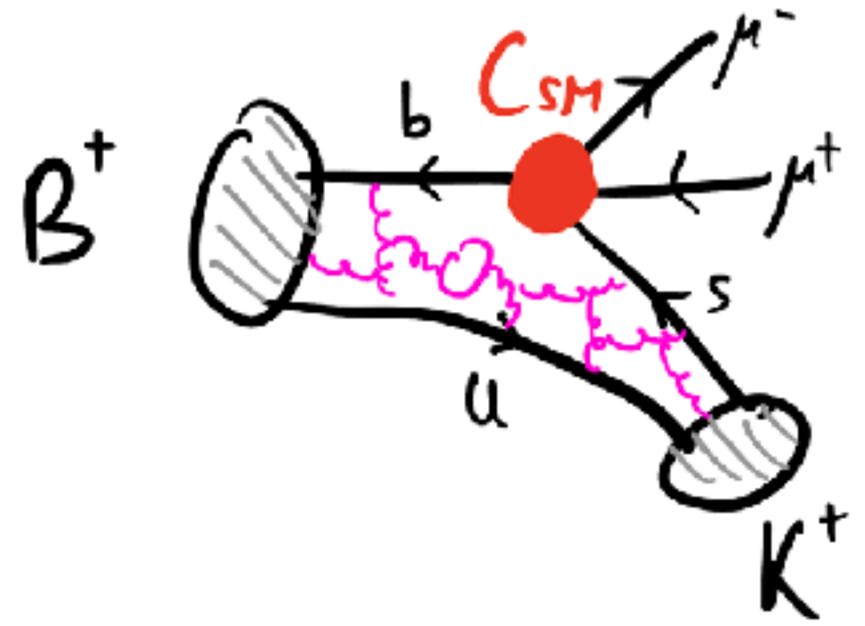

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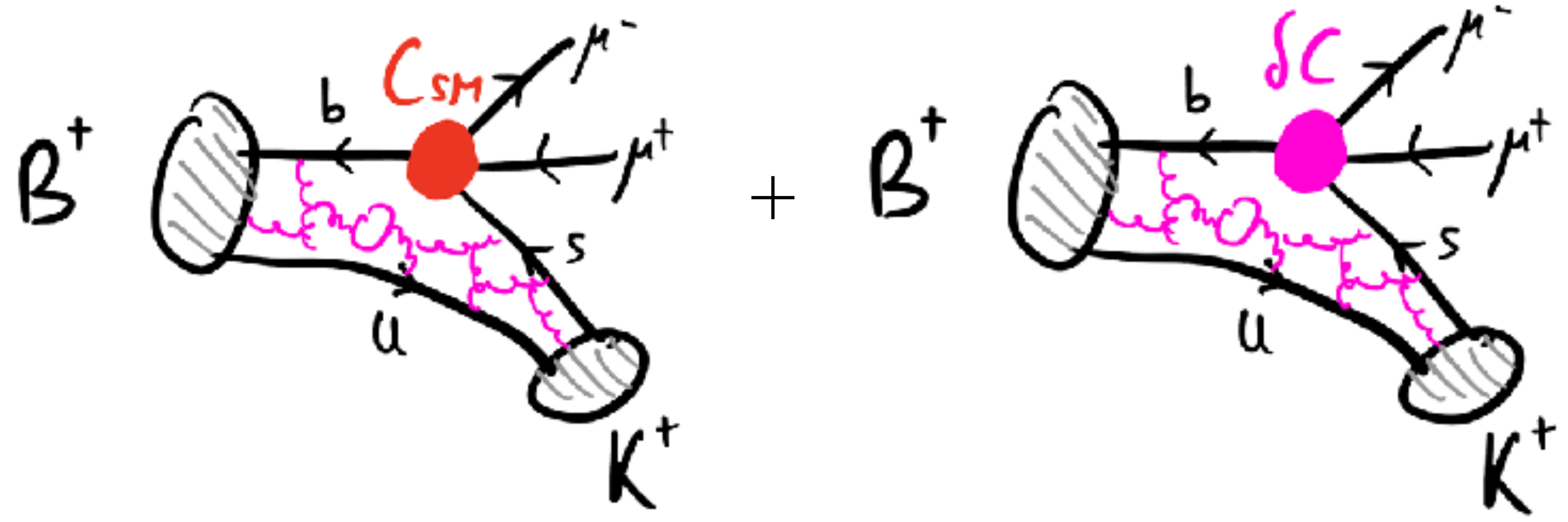

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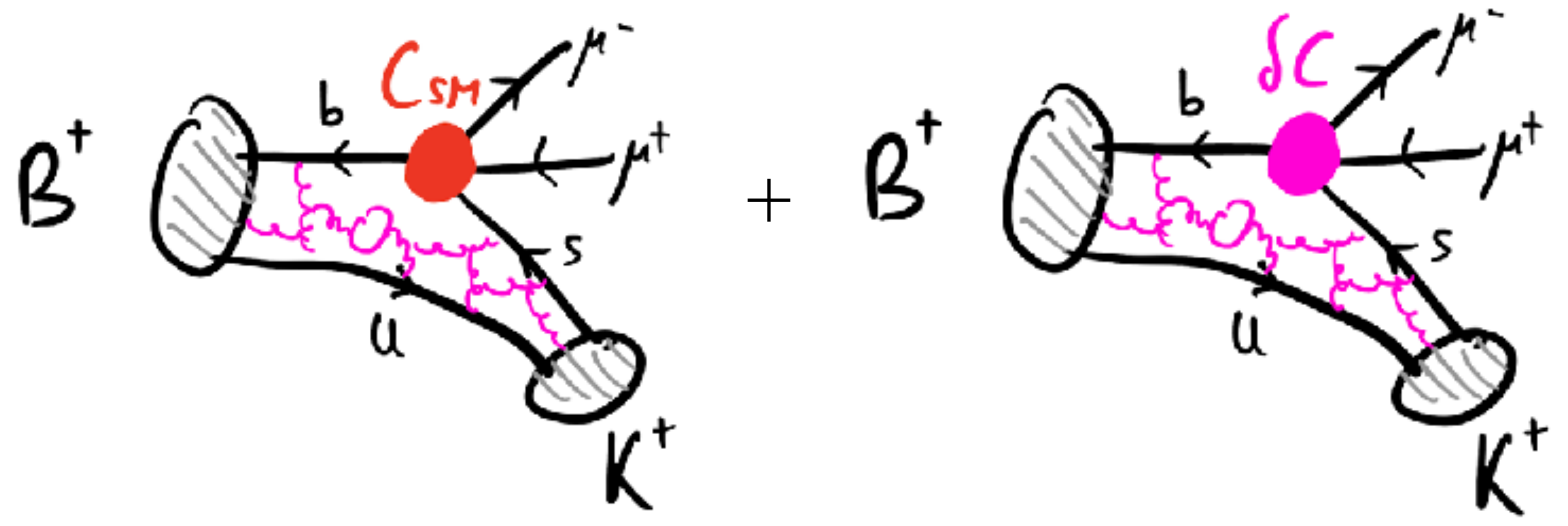

Let us add a **SMEFT contribution**: $$\delta C_{EFT} \sim \frac{c}{\Lambda^2}$$

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

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

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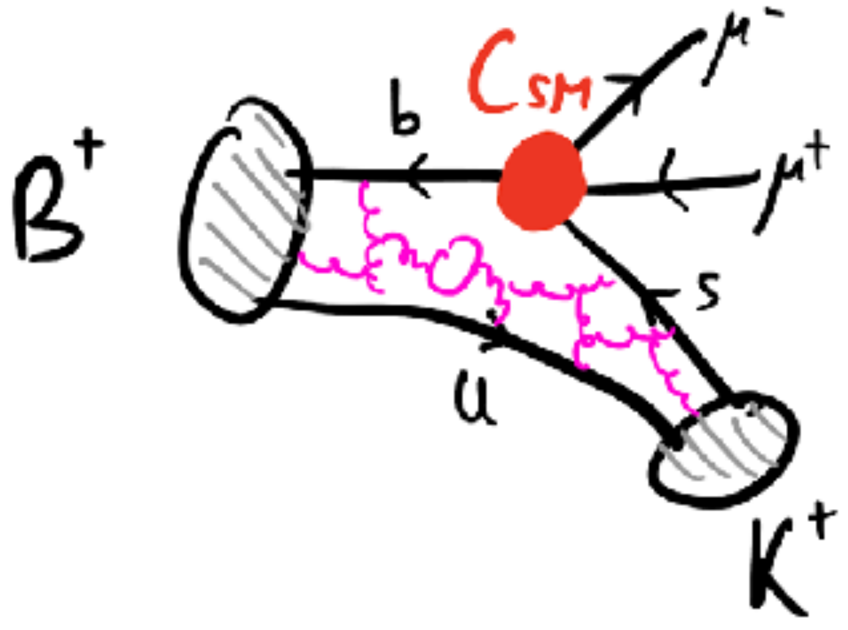

Example

Say we measure the short-distance contribution C_{SM} with 10% precision.

$$C = C_{SM}(1 \pm 10\%)$$

$$\updownarrow$$

$$\delta C < C_{SM} \cdot 10\%$$

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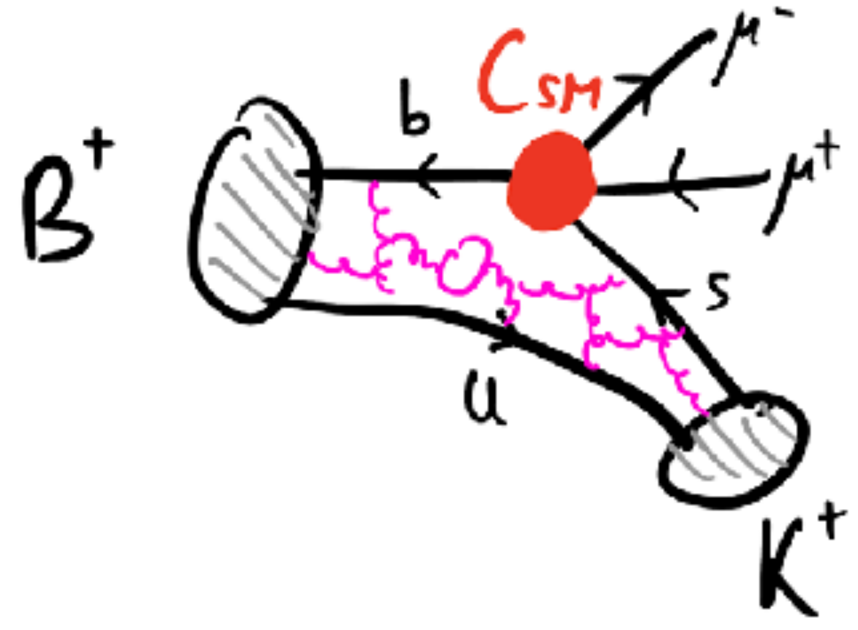

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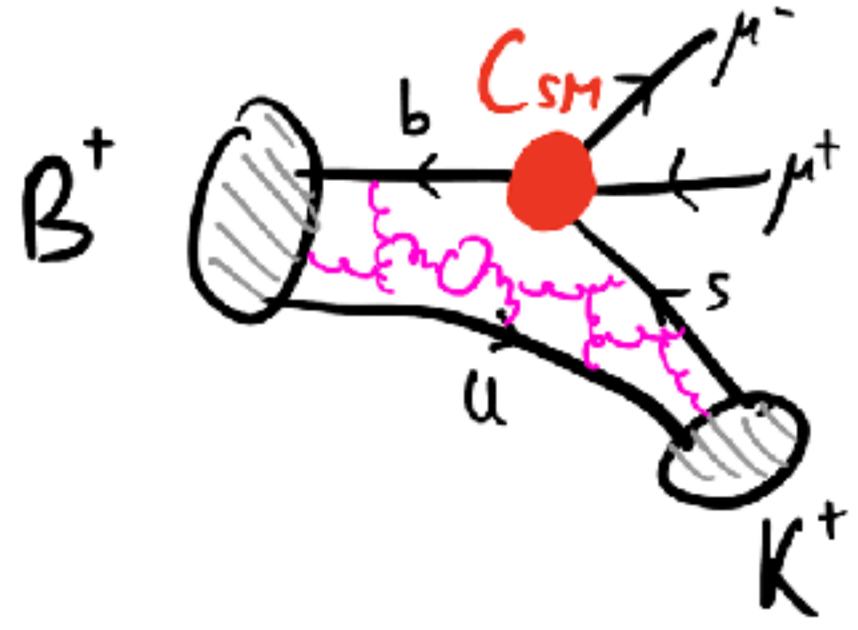

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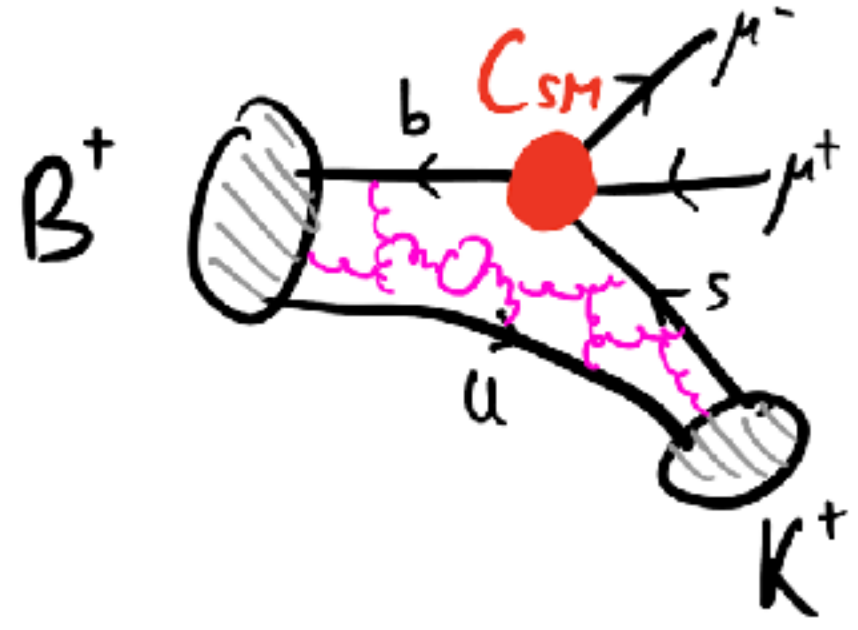

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Measuring this precisely puts strong constraints on the **EFT combination c/Λ²**, the **better the smallest λ_{SM}** is.

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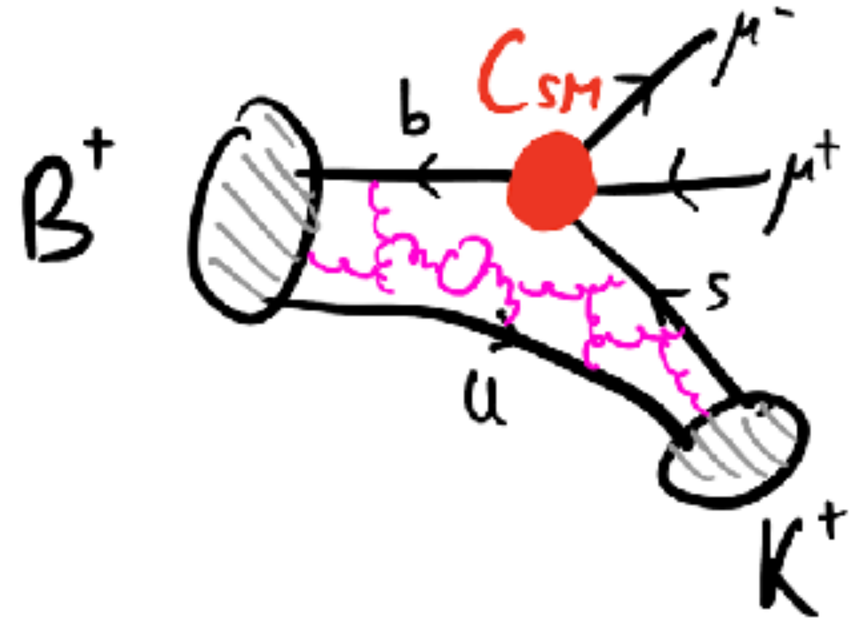

$$\Lambda > \frac{v}{\sqrt{\lambda_{SM}}\sqrt{10\%}} \sim \frac{0{,}8}{\sqrt{\lambda_{SM}}}\ \text{TeV}$$

For this goal it is also 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**

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)

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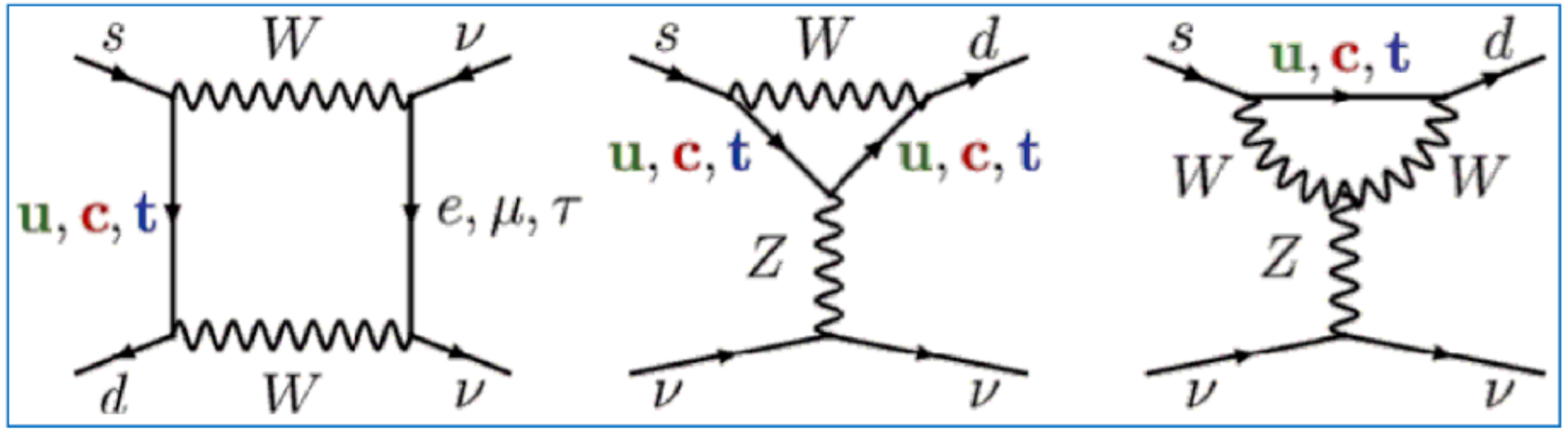
NA62 (CERN) KOTO (JPARC)

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

[see previous lecture by Wolfgang]

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

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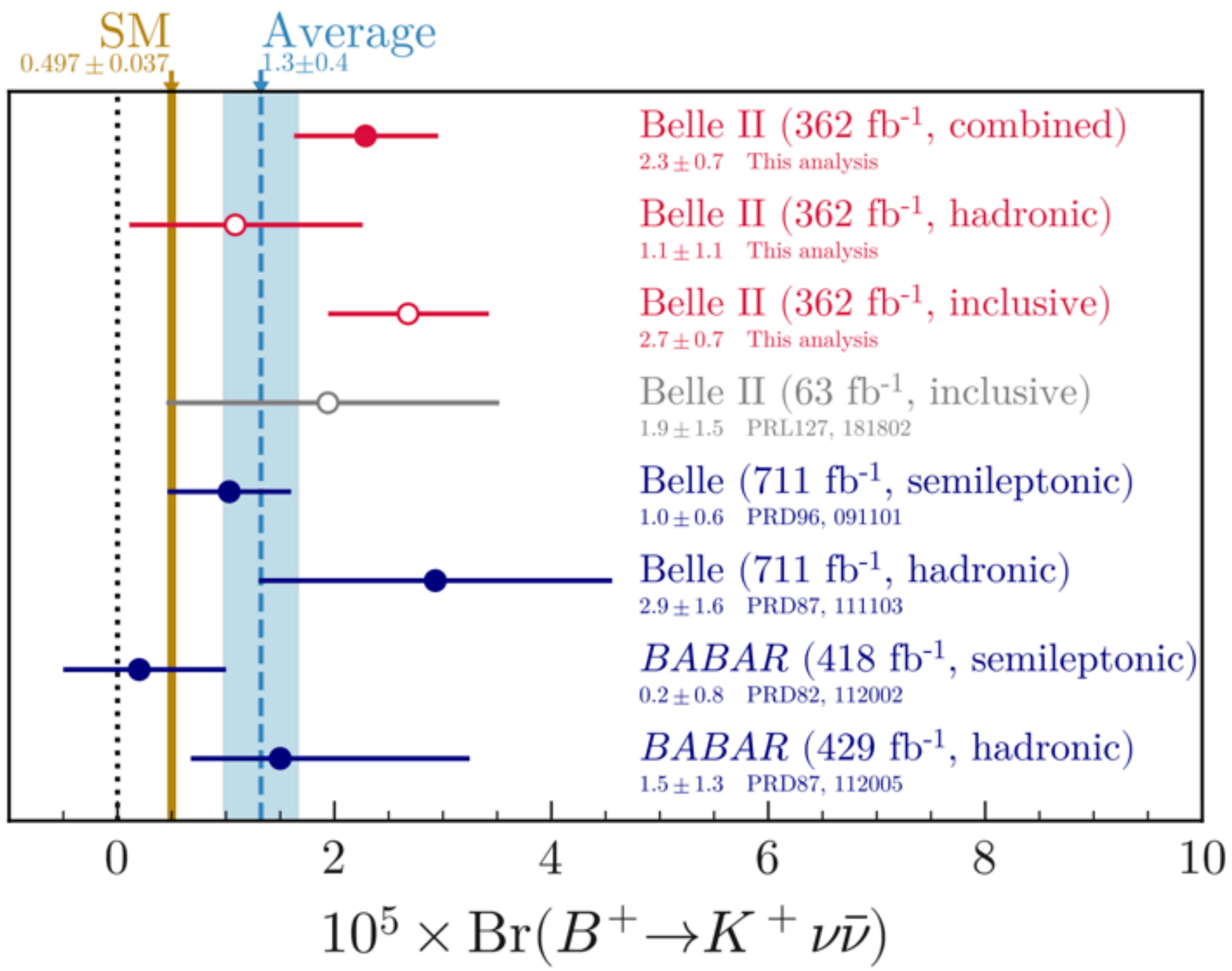

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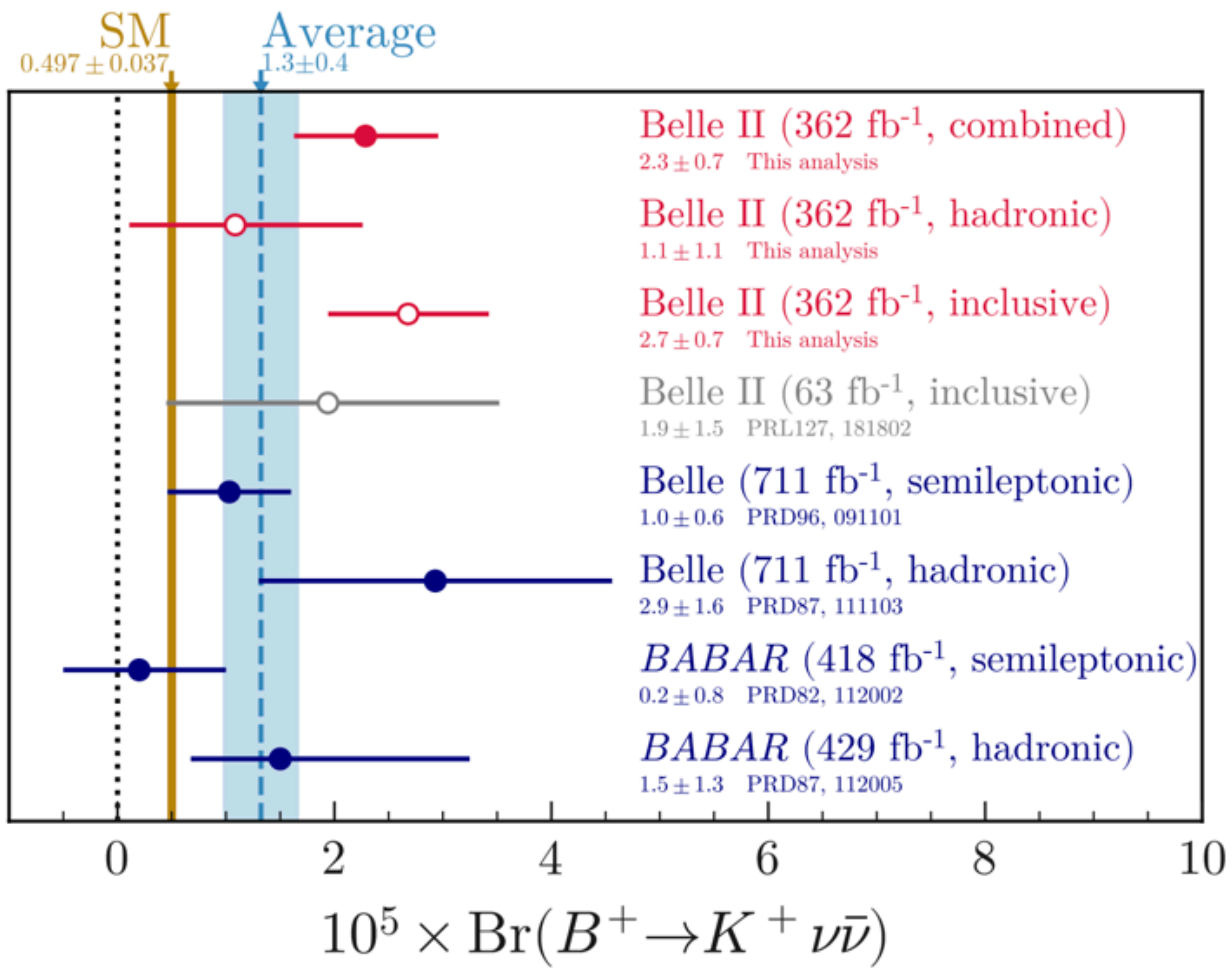

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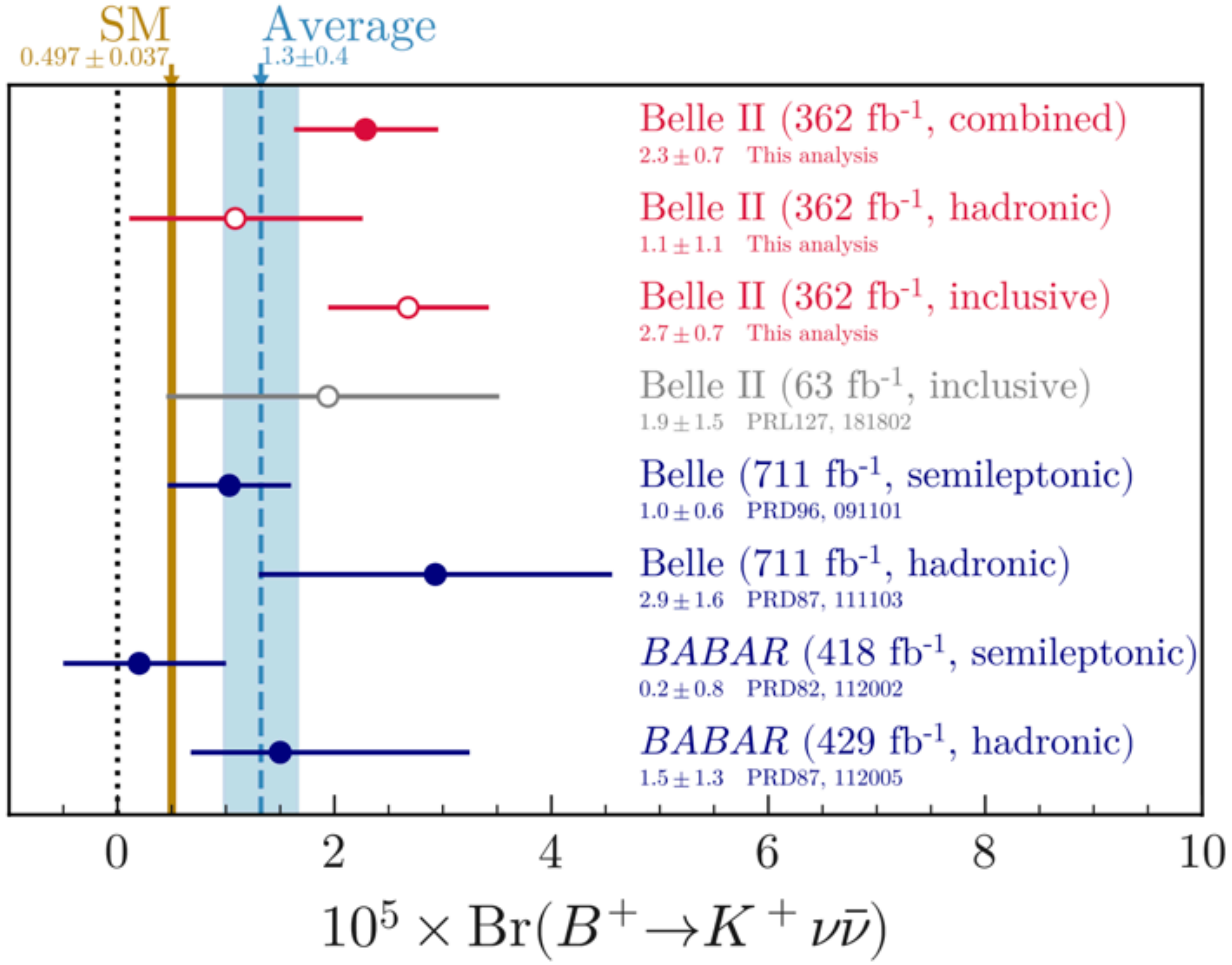

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$$R_K^\nu = \frac{BR(B \to K\nu\nu)}{BR(B \to K\nu\nu)^{SM}} = 2{,}93 \pm 0{,}90 \quad 2.1\sigma \qquad R_{K^*}^\nu = \frac{BR(B \to K^*\nu\nu)}{BR(B \to K^*\nu\nu)^{SM}} = 1.0 \pm 1.1\,^*$$

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

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

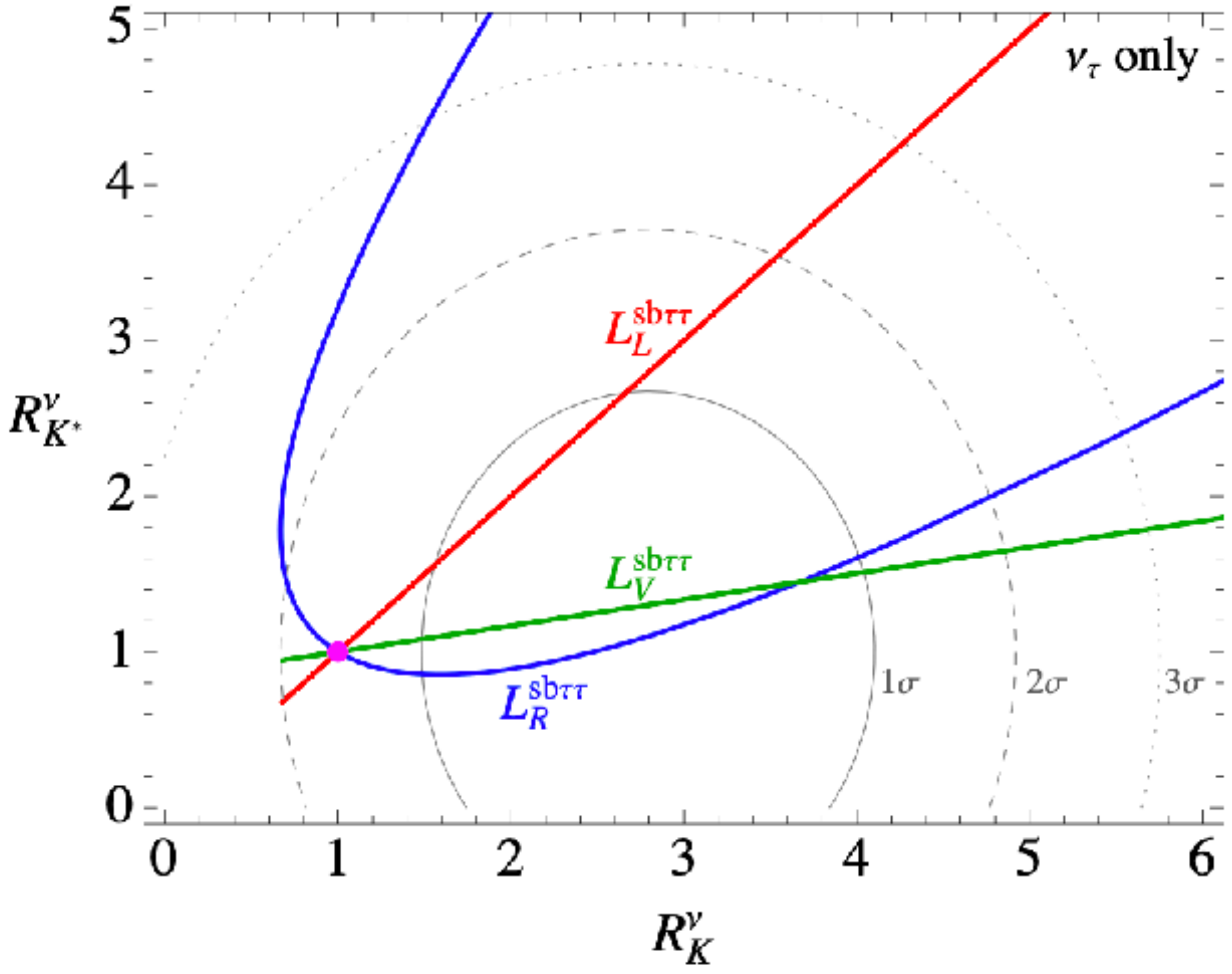
Assuming **only NP in tau**

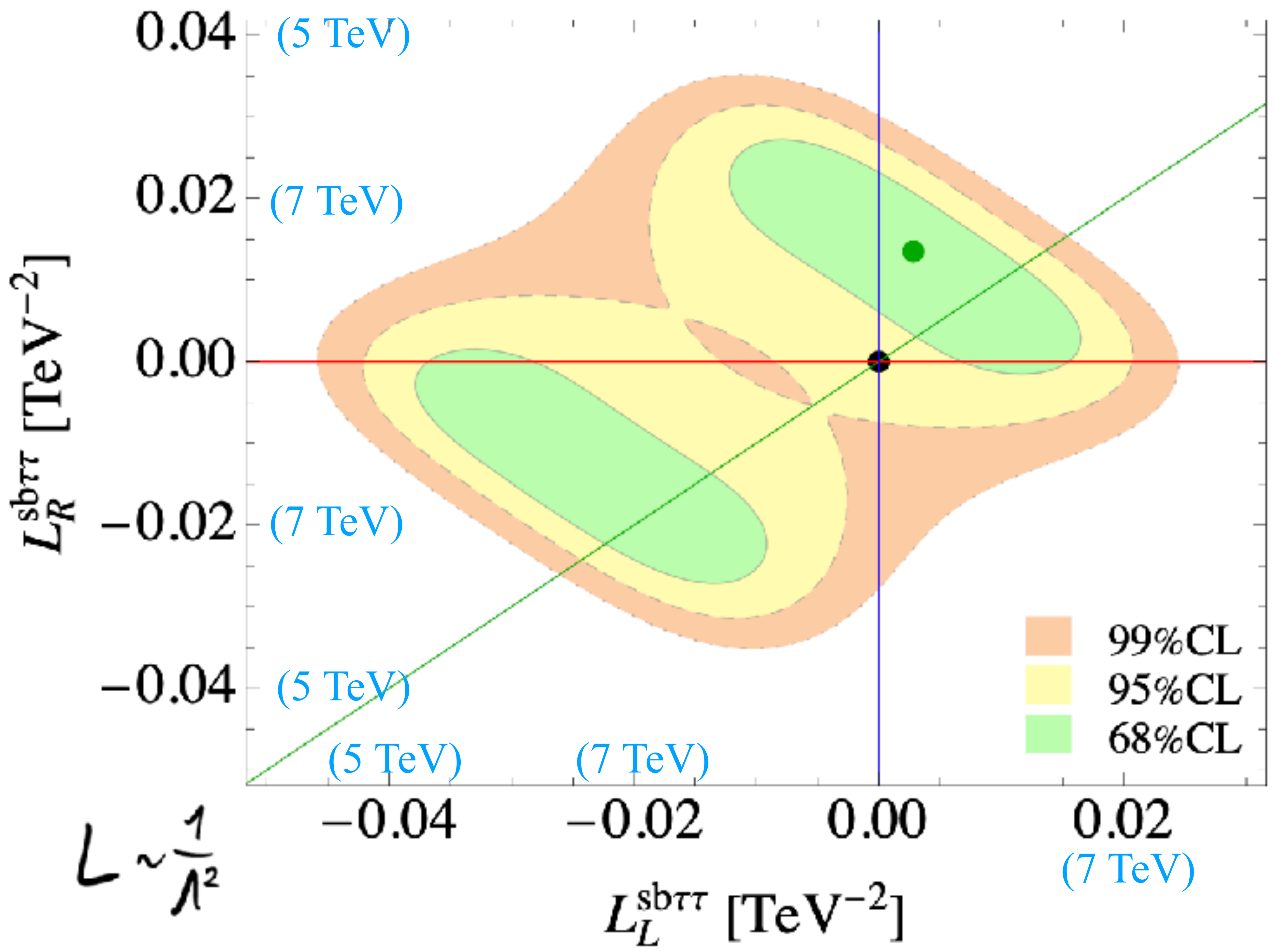
$$\mathcal{L}_{EFT} \supset L^{ij\tau\tau}_{L,R} \left(\bar{d}_{i_{L,R}} \gamma_\mu d_{j_{L,R}}\right) \left(\bar{\nu}_\tau \gamma^\mu \nu_\tau\right)$$

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)

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

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

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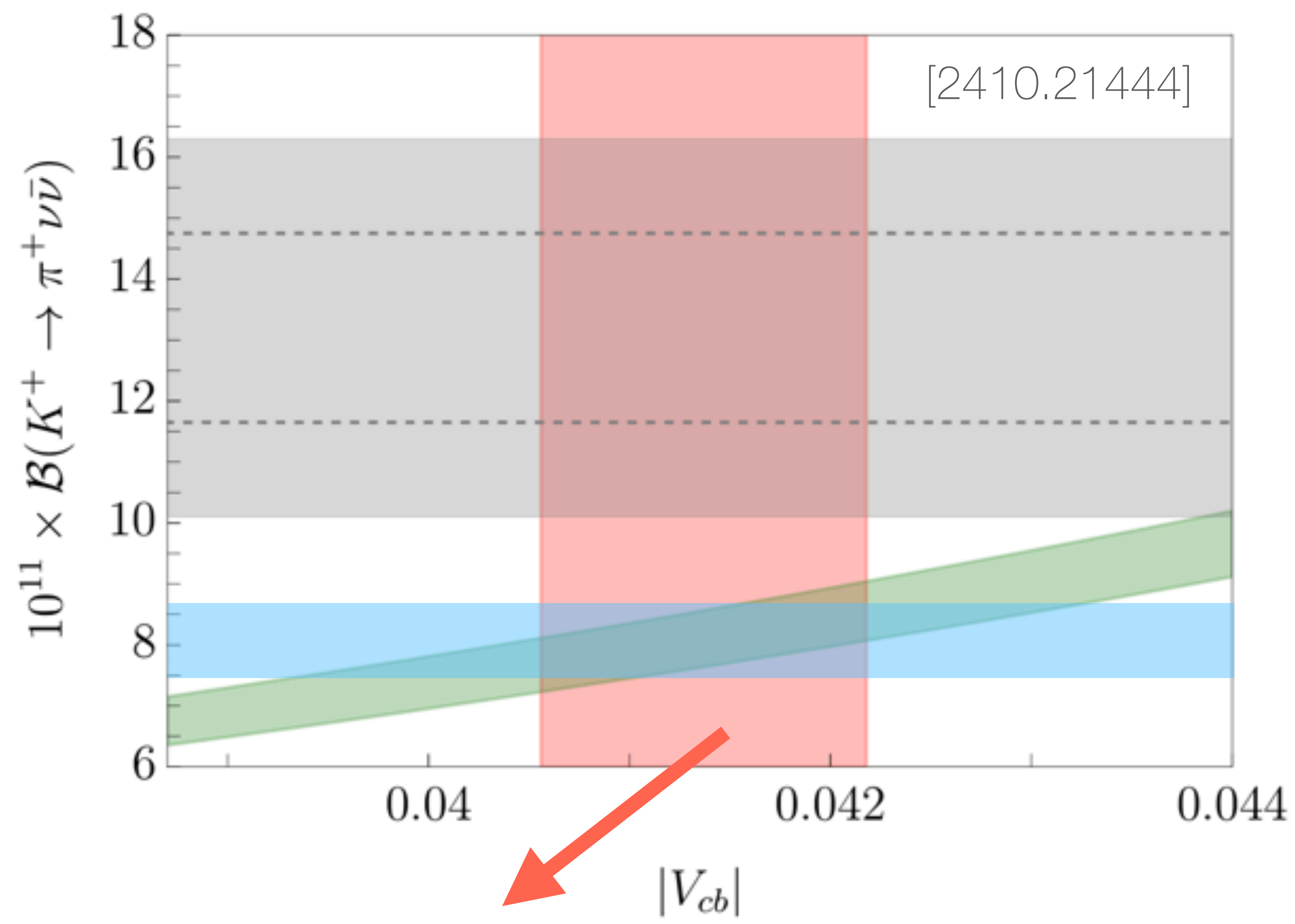
$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = \left(13.6 \left({}^{+3.0}_{-2.7}\right)_{\mathrm{stat}} \left({}^{+1.3}_{-1.2}\right)_{\mathrm{syst}}\right) \times 10^{-11}$$



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

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

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

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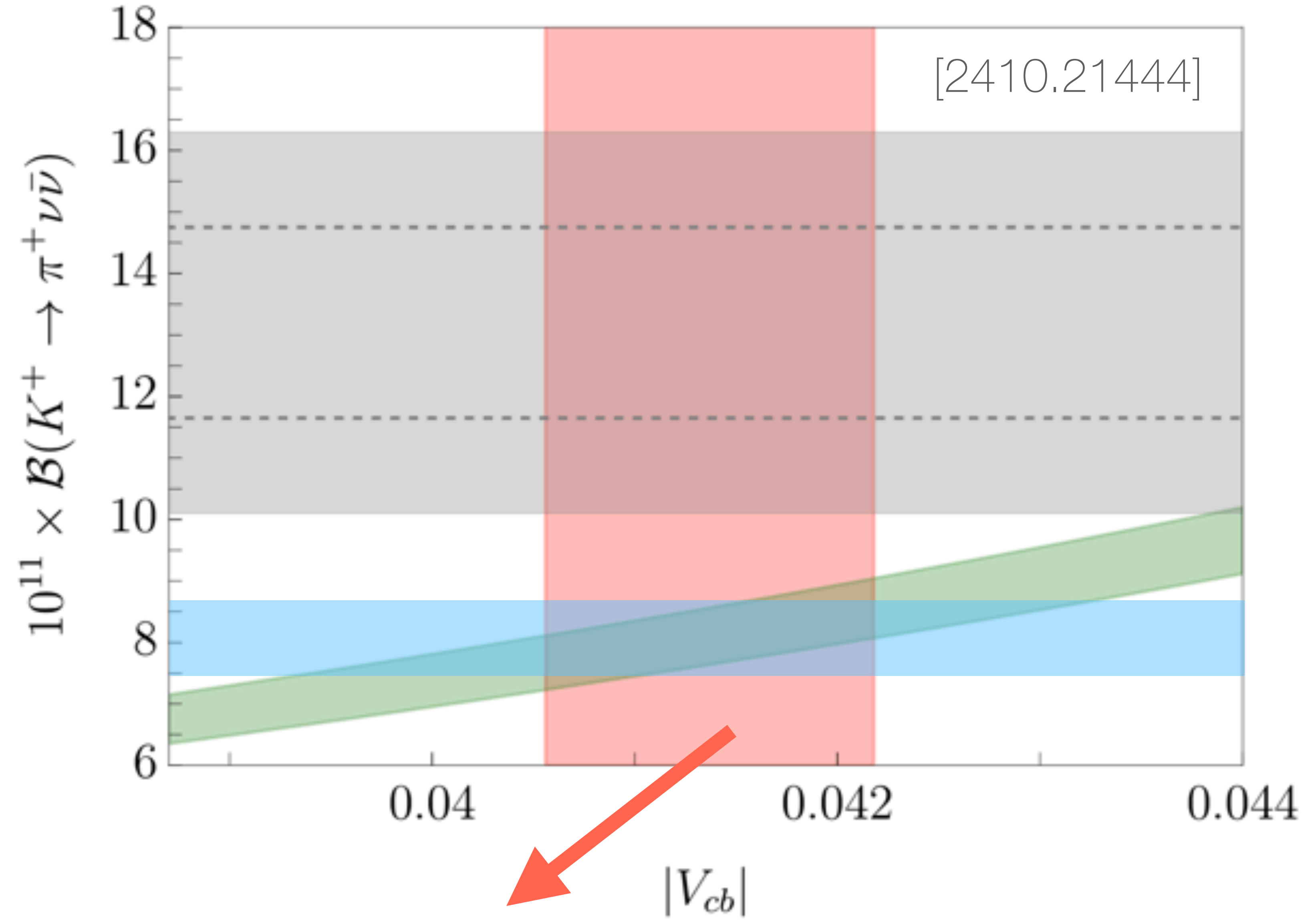

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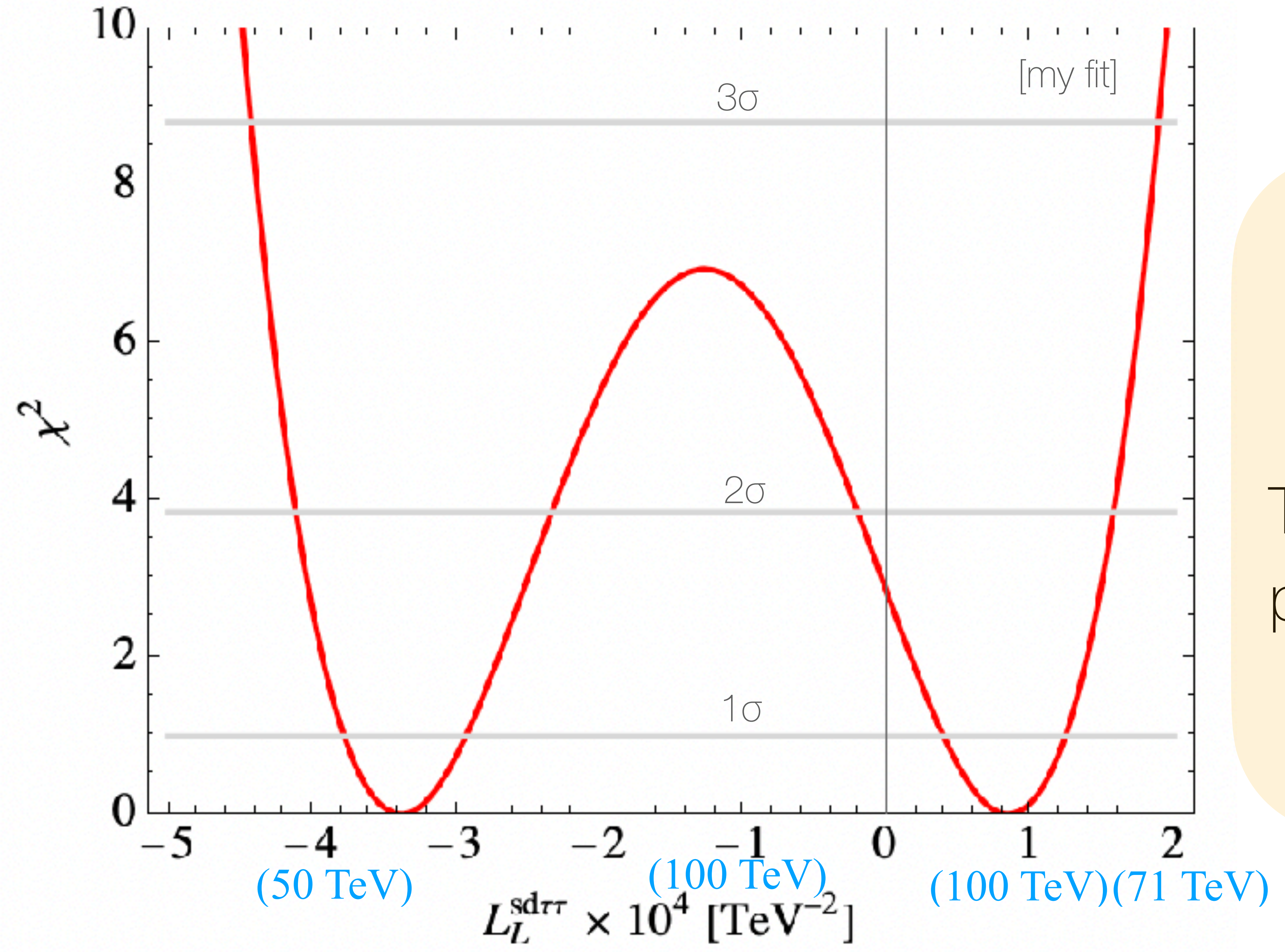
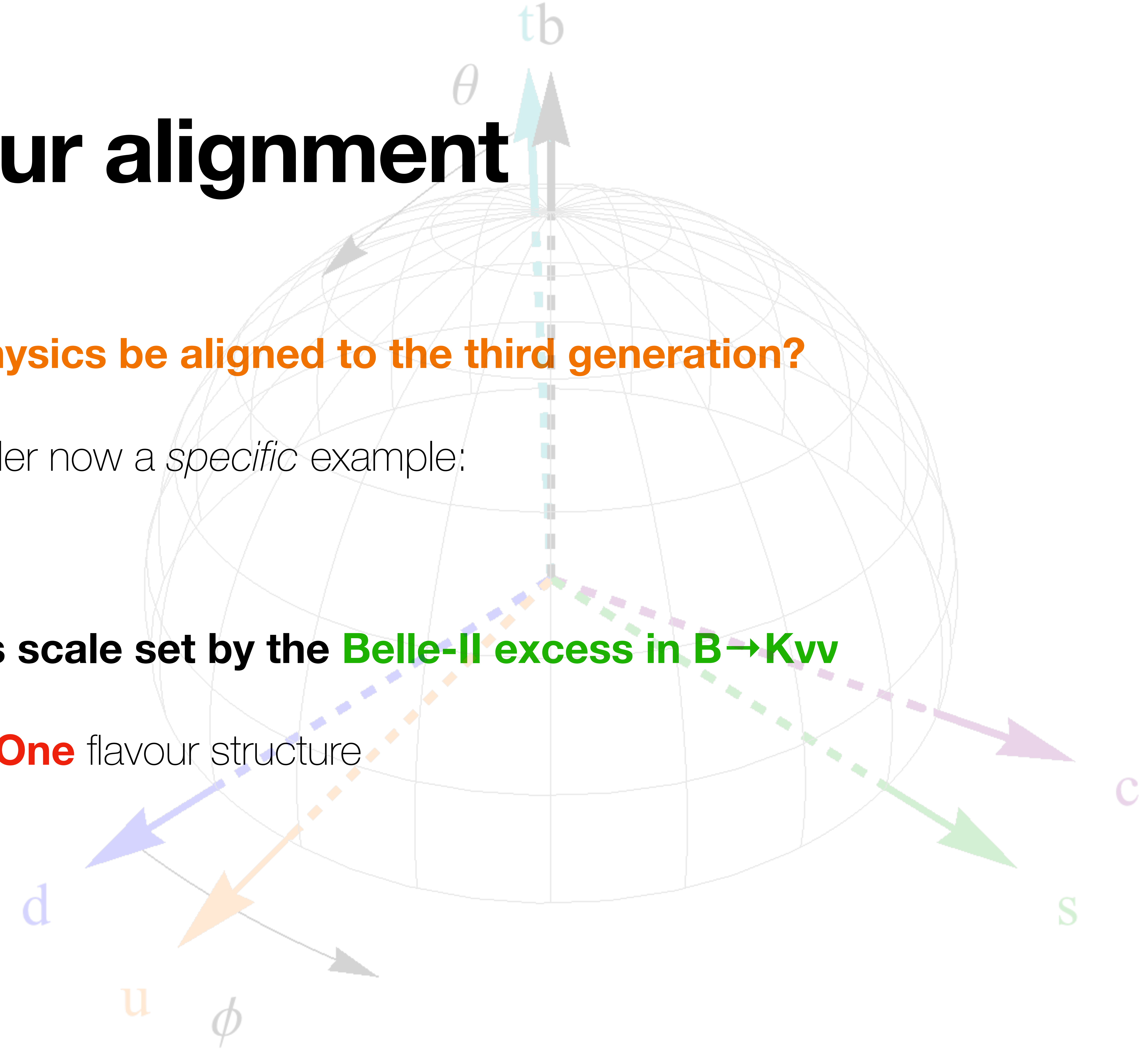


$L \sim \frac{1}{\Lambda^2}$

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

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

Flavour alignment



How much should New Physics be aligned to the third generation?

We consider now a *specific* example:

- Overall **New Physics scale set by the Belle-II excess in B→Kνν**
- We assume a **Rank-One** flavour structure

Directions in Flavour Space

Gherardi, DM, Nardecchia, Romanino 1903.10954
DM, Nardecchia, Stanzione, Toni 2404.06533

Consider the vector space spanned by the
3 generations of down quarks, $SU(3)_q$:

$$\hat{d} \sim \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \quad \hat{s} \sim \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \quad \hat{b} \sim \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

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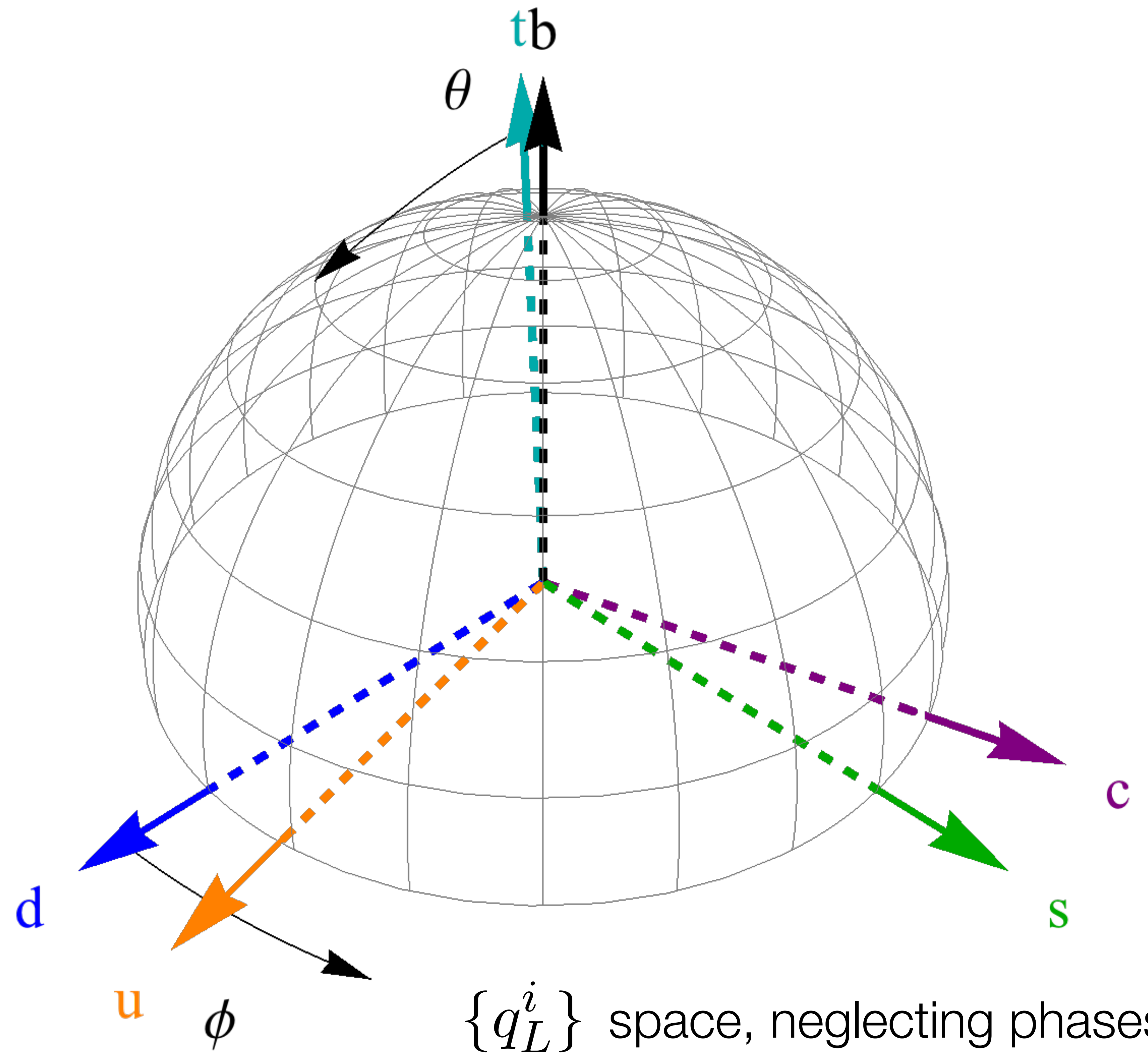
$$\hat{n} = \begin{pmatrix} \sin\theta\cos\phi e^{i\alpha_{bd}} \\ \sin\theta\sin\phi e^{i\alpha_{bs}} \\ \cos\theta \end{pmatrix}$$

neglecting phases, it is a unit-vector on a semi-sphere

$$\theta \in \left[0, \frac{\pi}{2}\right] \; , \quad \phi \in [0, 2\pi) \; , \quad \alpha_{bd} \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right] \; , \quad \alpha_{bs} \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$$

The overall phase is unphysical: U(1)$_B$



$\{q_L^i\}$ space, neglecting phases

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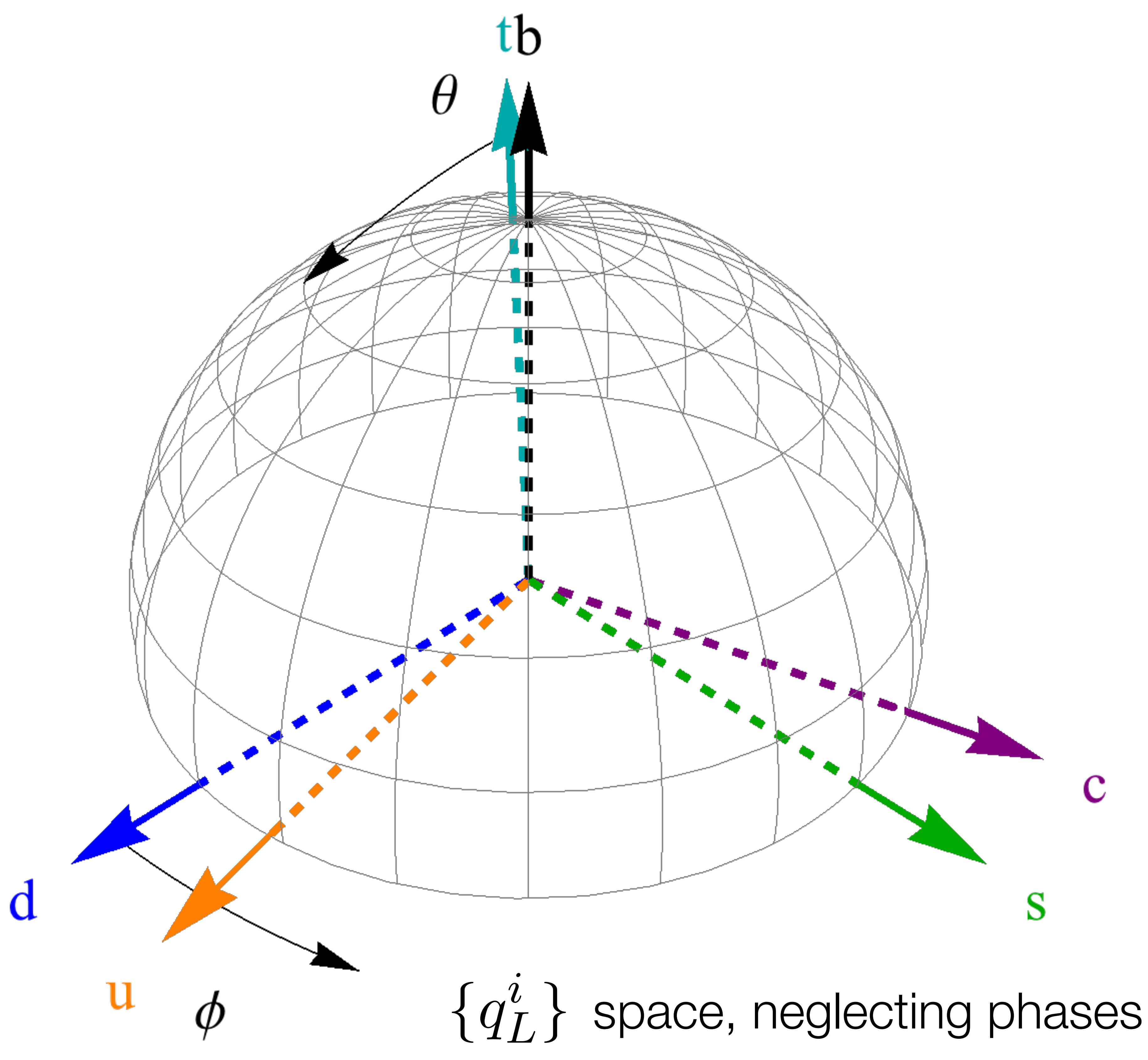

$\{q_L^i\}$ space, neglecting phases

We show also up quarks using:

$$q_L^i = \begin{pmatrix} V_{ji}^* u_L^i \\ d_L^i \end{pmatrix}$$

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DM, Nardecchia, Stanzione, Toni 2404.06533

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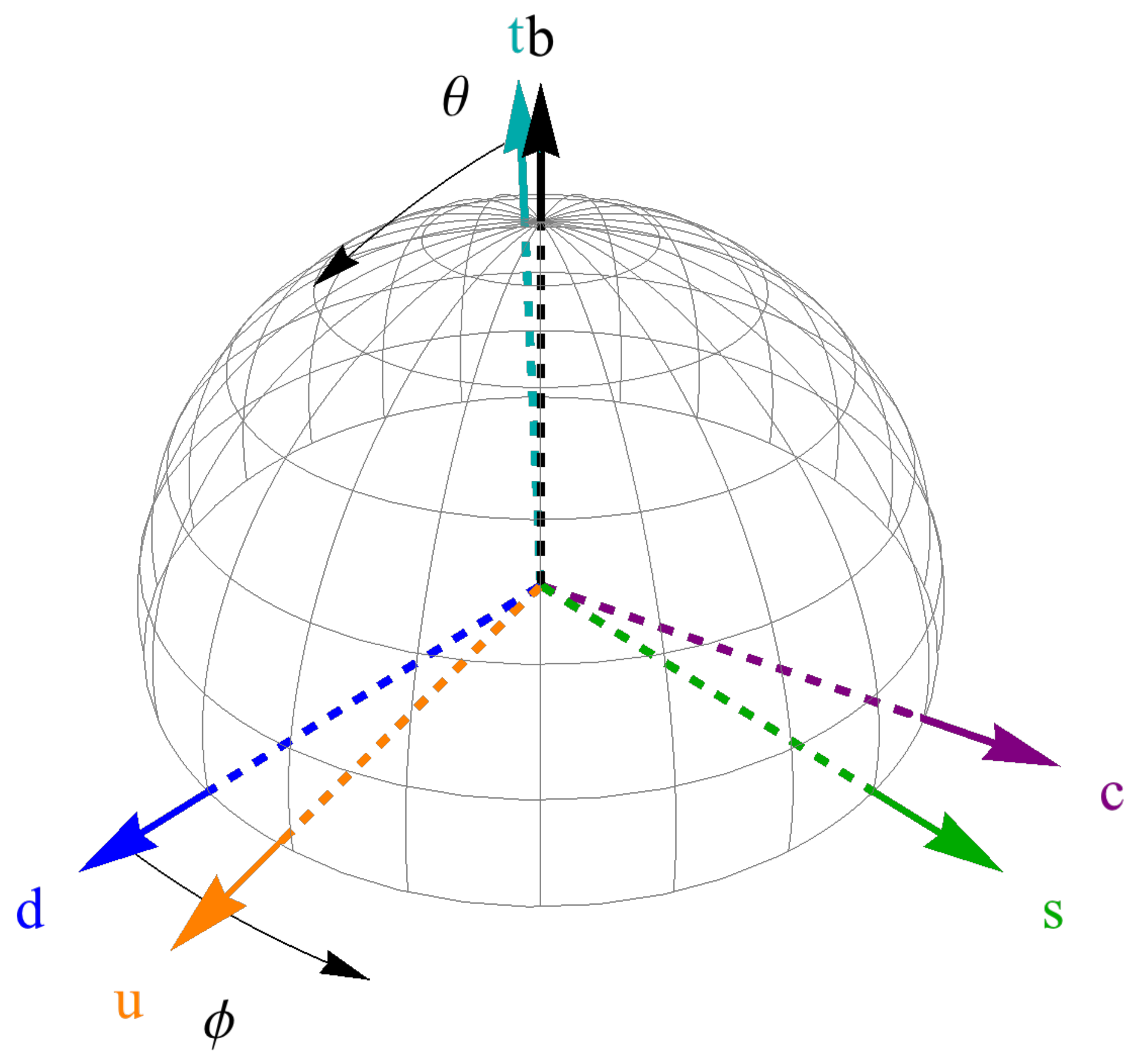
$$q_L^i = \begin{pmatrix} V_{ji}^* u_L^i \\ d_L^i \end{pmatrix}$$



$\{q_L^i\}$ space, neglecting phases

quark	$\hat{n}$	ϕ	θ	α_{bd}	α_{bs}
down	$(1,0,0)$	0	$\pi/2$	0	0
strange	$(0,1,0)$	$\pi/2$	$\pi/2$	0	0
bottom	$(0,0,1)$	0	0	0	0
up	$e^{i\arg(V_{ub})}(V_{ud}^*, V_{us}^*, V_{ub}^*)$	0.23	1.57	-1.17	-1.17
charm	$e^{i\arg(V_{cb})}(V_{cd}^*, V_{cs}^*, V_{cb}^*)$	1.80	1.53	-6.2×10^{-4}	-3.3×10^{-5}
top	$e^{i\arg(V_{tb})}(V_{td}^*, V_{ts}^*, V_{tb}^*)$	4.92	0.042	-0.018	0.39

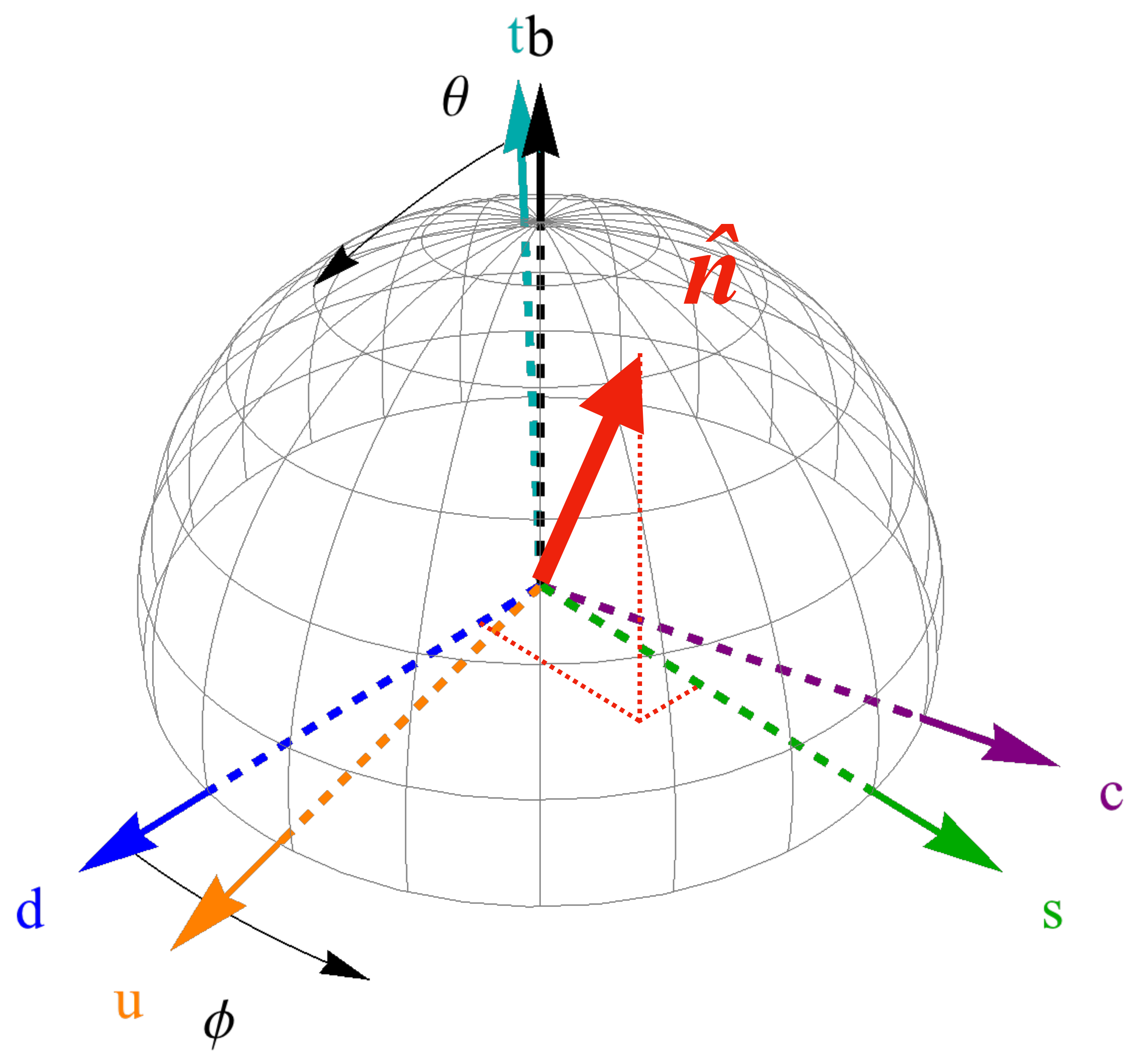
The misalignment between down- and up-quarks is described by the CKM matrix.

Rank-One Flavour Violation

Gherardi, DM, Nardecchia, Romanino 1903.10954

DM, Nardecchia, Stanzione, Toni 2404.06533

$$\mathcal{L}^{\rm NP}_{\rm LEFT} = \sum_{ij\alpha\beta} \left[L_L^{ij\alpha\beta} (\bar{d}_L^i \gamma_\mu d_L^j)(\bar{\nu}_L^\alpha \gamma^\mu \nu_L^\beta) + L_R^{ij\alpha\beta} (\bar{d}_R^i \gamma_\mu d_R^j)(\bar{\nu}_L^\alpha \gamma^\mu \nu_L^\beta) \right]$$



$\{q_L^i\}$ space, neglecting phases

We assume that **New Physics is aligned to a specific direction $\hat{n}$**.

> the **EFT coefficients** are given by an overall scale times the **projection of $\hat{n}$ on the specific flavour direction**

$$L^{ij\nu\nu} = C\, \hat{n}_i \hat{n}_j^*$$

$$\hat{n} = \begin{pmatrix} \sin\theta\cos\phi e^{i\alpha_{bd}} \\ \sin\theta\sin\phi e^{i\alpha_{bs}} \\ \cos\theta \end{pmatrix}$$

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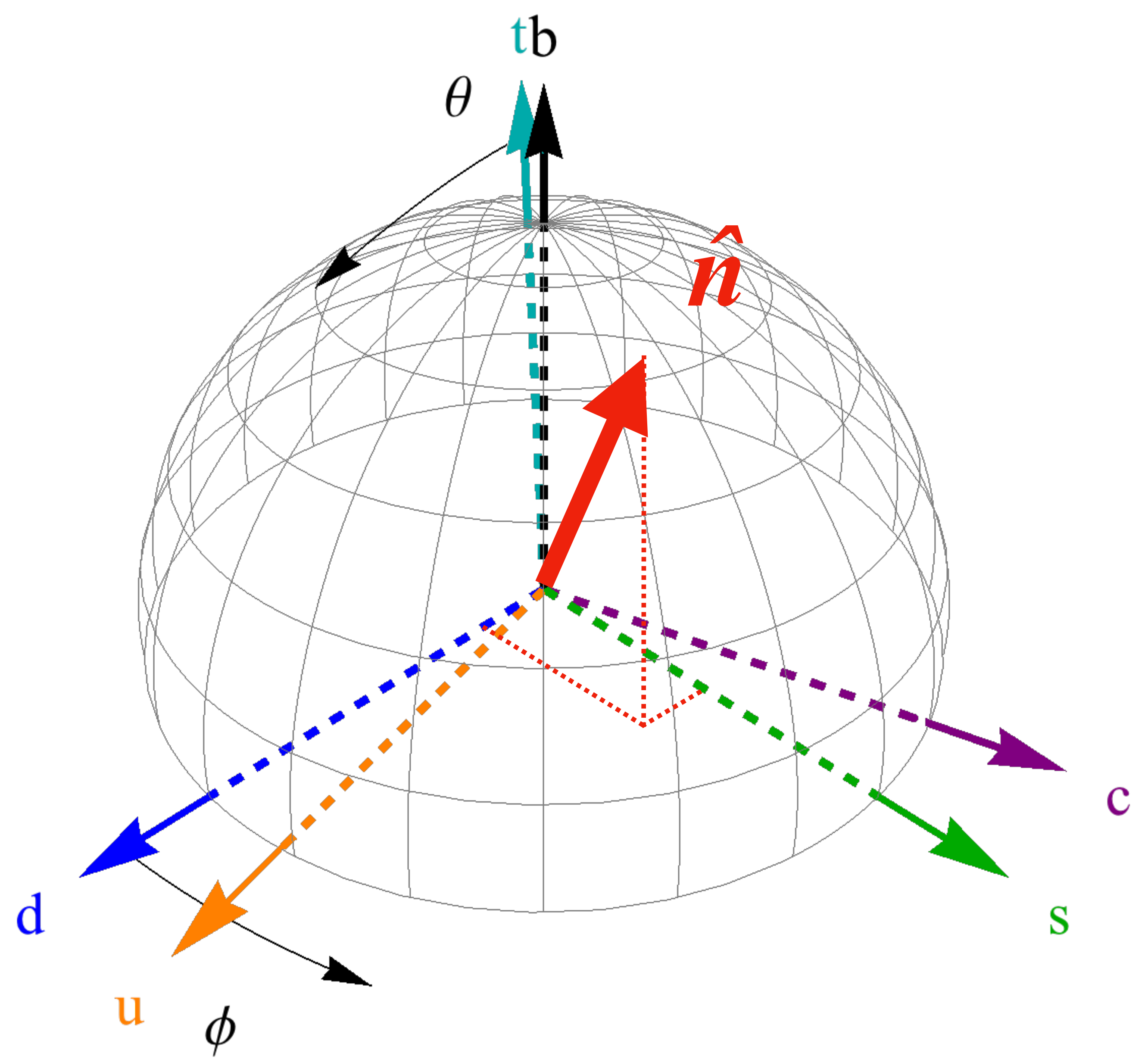

$\{q^i_L\}$ space, neglecting phases

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> the **EFT coefficients** are given by an overall scale times the **projection of $\hat{n}$ on the specific flavour direction**

$$L^{ij\nu\nu} = C\, \hat{n}_i \hat{n}^*_j$$

$$\hat{n} = \begin{pmatrix} \sin\theta\cos\phi e^{i\alpha_{bd}} \\ \sin\theta\sin\phi e^{i\alpha_{bs}} \\ \cos\theta \end{pmatrix}$$

This structure is automatic if New Physics couples linearly to a single combination of quarks:

$$\mathcal{L} \supset \lambda_i \bar{q}^i \mathcal{O}_{\rm NP} + \text{h.c.}$$

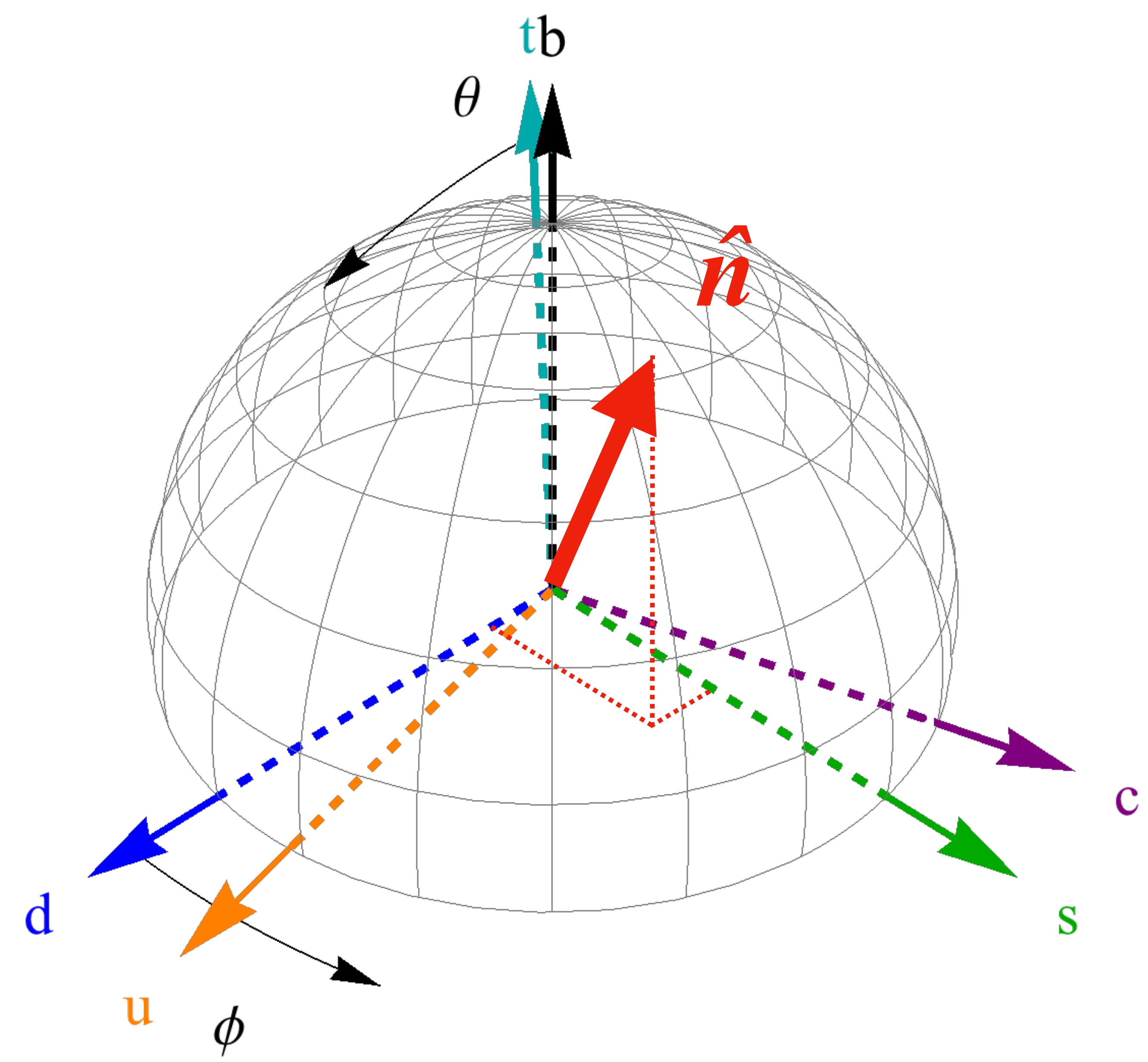
e.g.

- leptoquarks coupled mainly to 1 lepton family
- Vector coupled via the mixing of a single vector-like quark

Rank-One Flavour Violation

Gherardi, DM, Nardecchia, Romanino 1903.10954
DM, Nardecchia, Stanzione, Toni 2404.06533

$$\mathcal{L}_{\rm LEFT}^{\rm NP} = \sum_{ij\alpha\beta} \left[L_L^{ij\alpha\beta} (\bar{d}_L^i \gamma_\mu d_L^j)(\bar{\nu}_L^\alpha \gamma^\mu \nu_L^\beta) + L_R^{ij\alpha\beta} (\bar{d}_R^i \gamma_\mu d_R^j)(\bar{\nu}_L^\alpha \gamma^\mu \nu_L^\beta) \right]$$



$\{q_L^i\}$ space, neglecting phases

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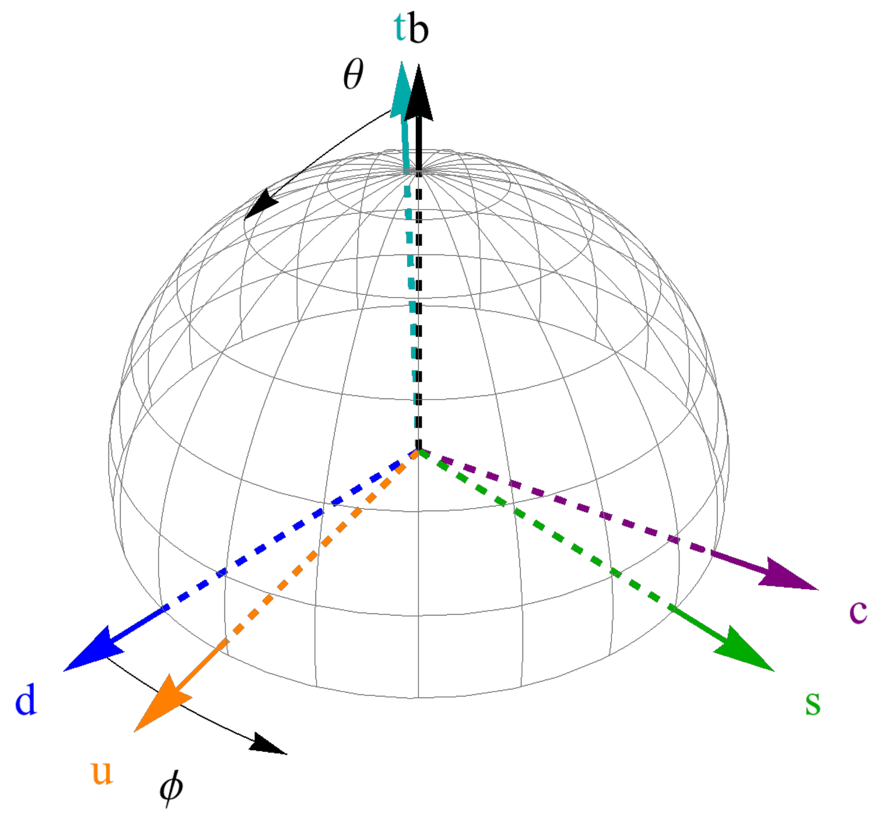
$$\hat{n} = \begin{pmatrix} \sin\theta\cos\phi e^{i\alpha_{bd}} \\ \sin\theta\sin\phi e^{i\alpha_{bs}} \\ \cos\theta \end{pmatrix}$$

At any value of (φ,θ) we can fix the overall scale C by imposing the **best-fit of $B \to K^{(*)} \nu\nu$**.

$$L^{sb\nu\nu} = C \cos\vartheta \sin\vartheta \sin\varphi \equiv (8\,\text{TeV})^{-2}$$

For the best-fit of R^ν_K and for simplicity we fix: $\alpha_{bs} = \alpha_{bd} = 0$ (fit in backup slides)

Rank-One Flavour Violation



$$L^{ij\nu\nu} = C\, \hat{n}_i \hat{n}^*_j$$

$$L^{sb\nu\nu} = C \cos\vartheta \sin\vartheta \sin\varphi \equiv (8\,\mathrm{TeV})^{-2}$$

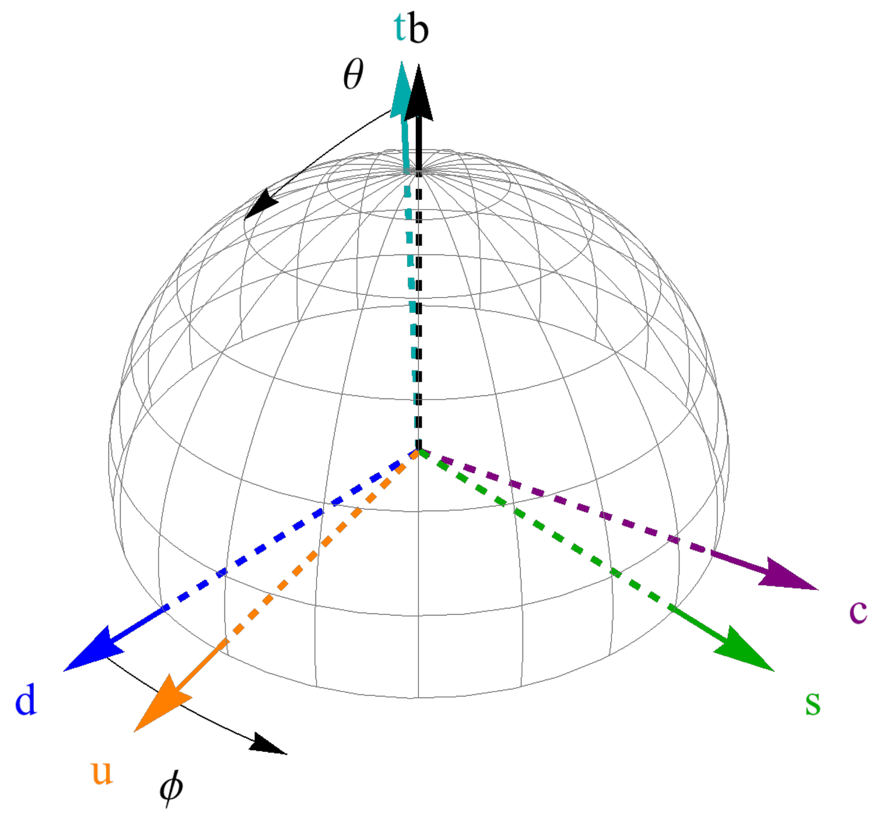
Once **C is fixed as function of (θ, ϕ)**, all parameters are set and we can check the **constraints from other observables**

2404.06533

Rank-One Flavour Violation

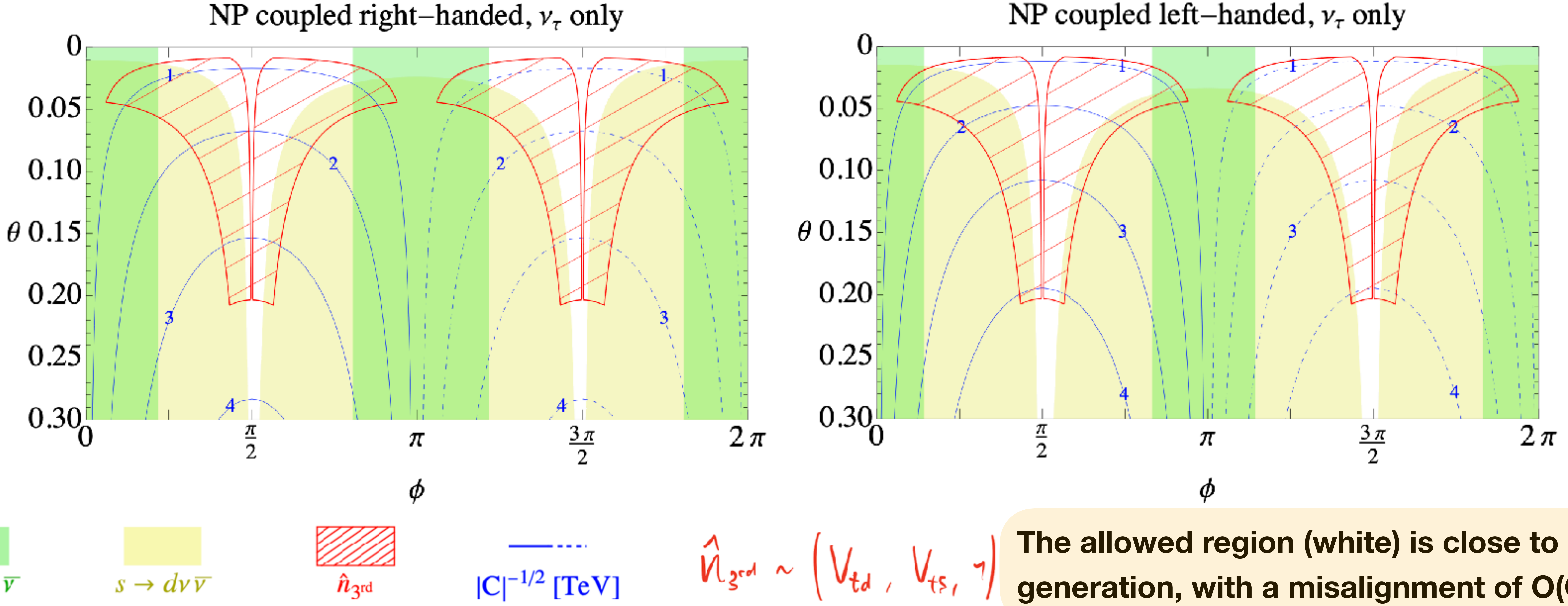
$$L^{ij\nu\nu} = C\, \hat{n}_i \hat{n}_j^*$$

$$L^{sb\nu\nu} = C \cos\theta \sin\theta \sin\phi = (8\,\text{TeV})^{-2}$$



Once ***C*** **is fixed as function of (θ, ϕ)**, all parameters are set and we can check the **constraints from other observables**

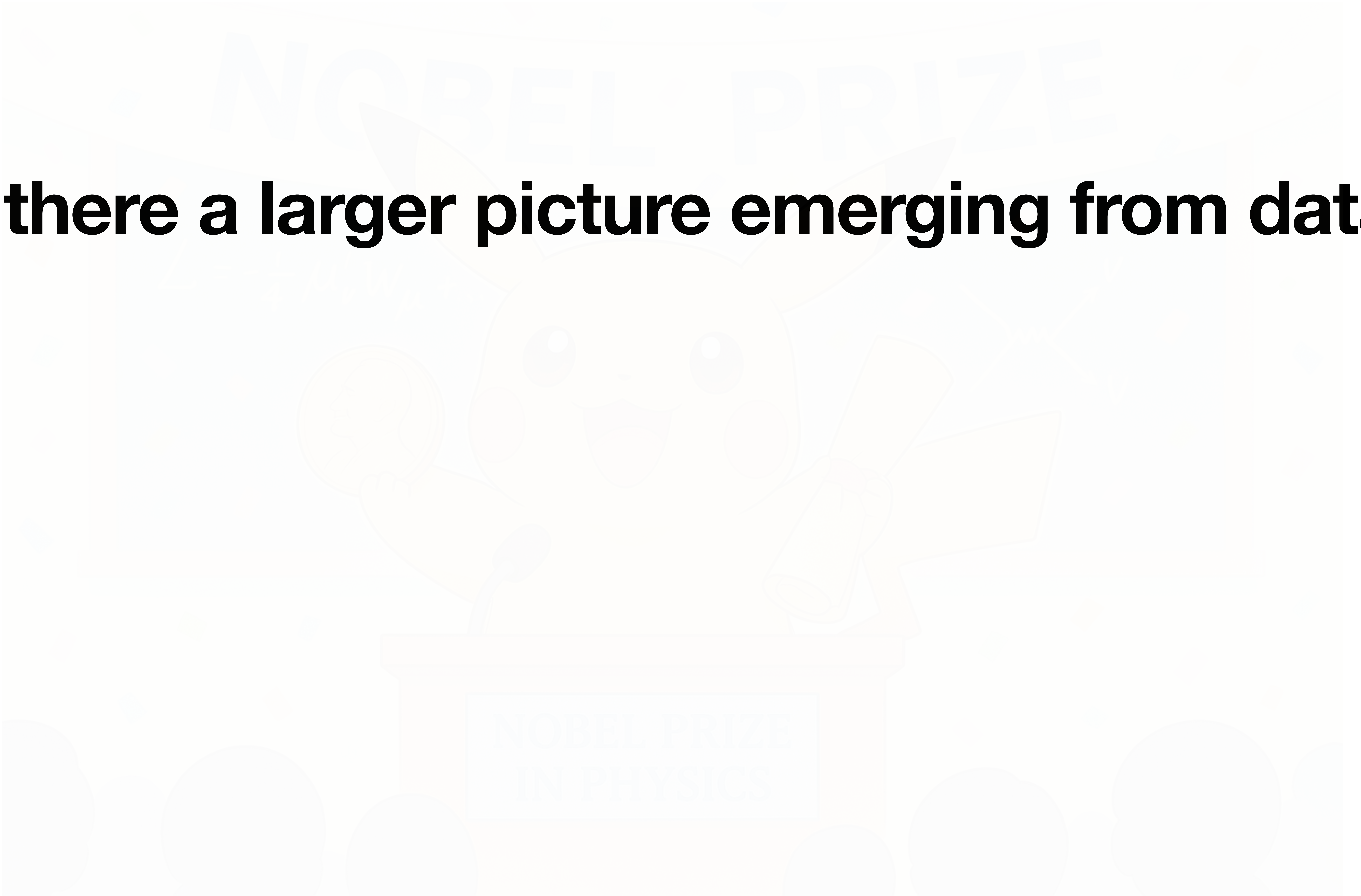
2404.06533



$$\hat{n}_{3^{rd}} \sim (V_{td}, V_{ts}, 1)$$

The allowed region (white) is close to the third generation, with a misalignment of O(CKM).

Is there a larger picture emerging from data?



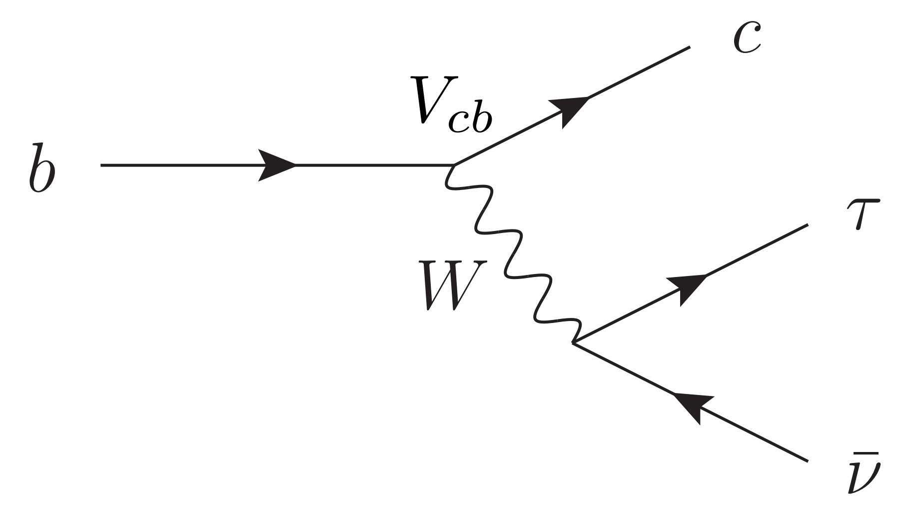
B-anomalies in charged current $b \to c\,\tau\,\bar{\nu}_\tau$

Lepton Flavour Universality

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

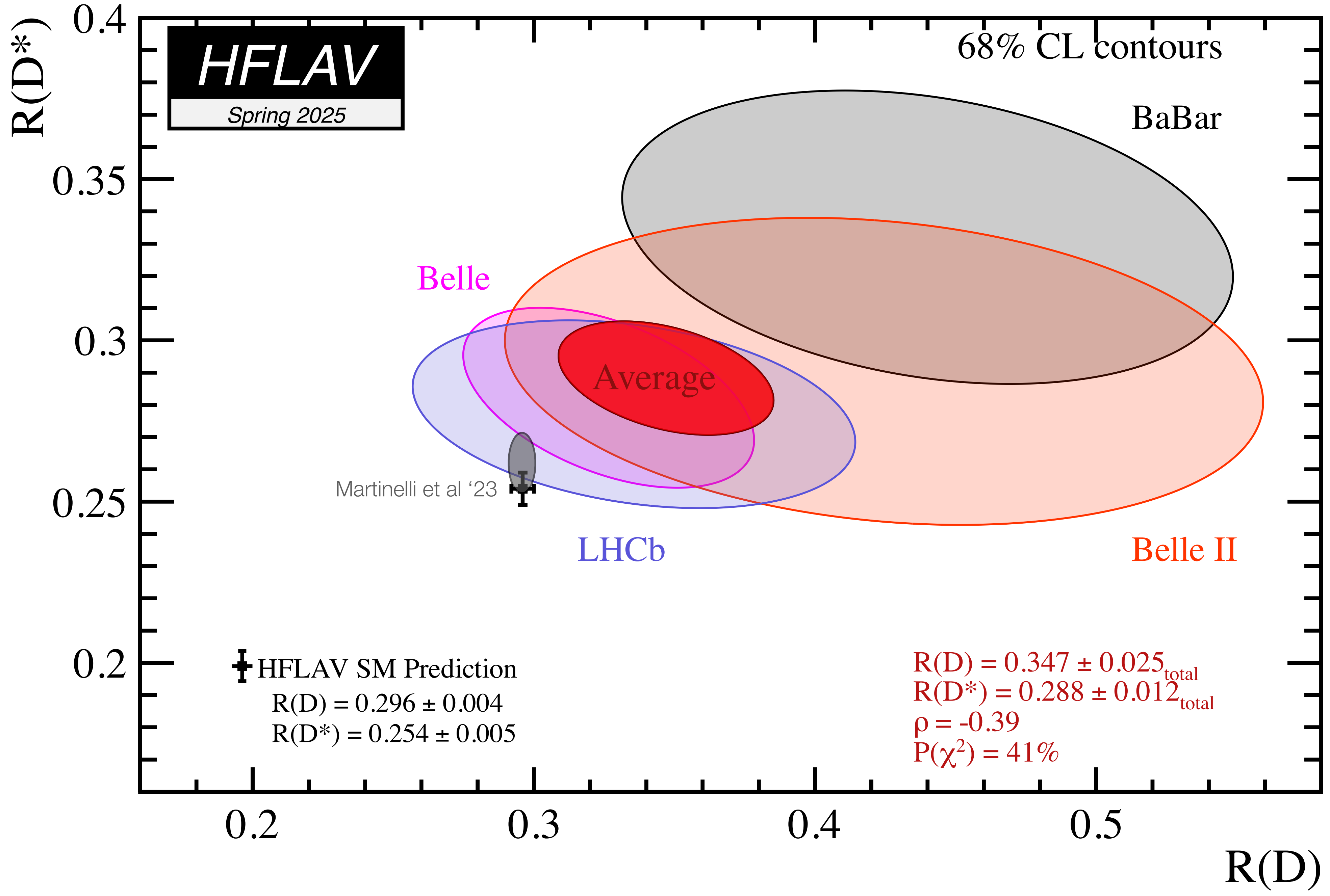
$$\ell = \mu, e$$

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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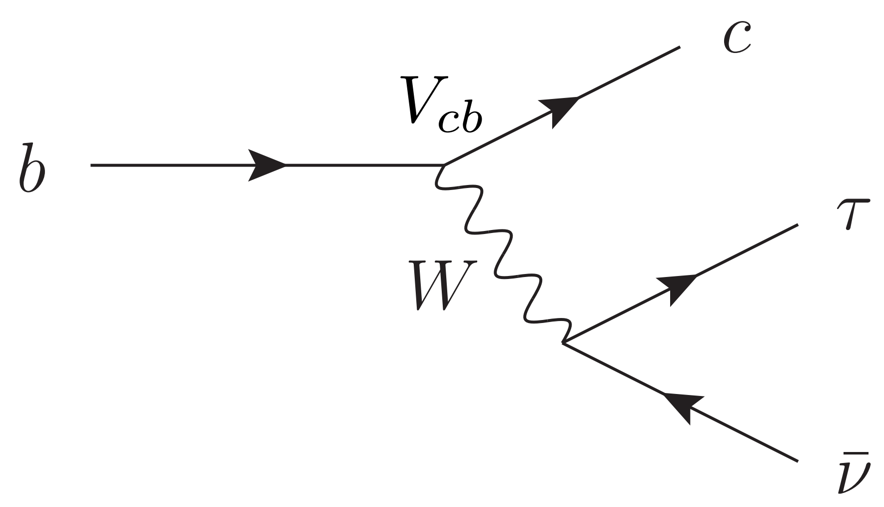

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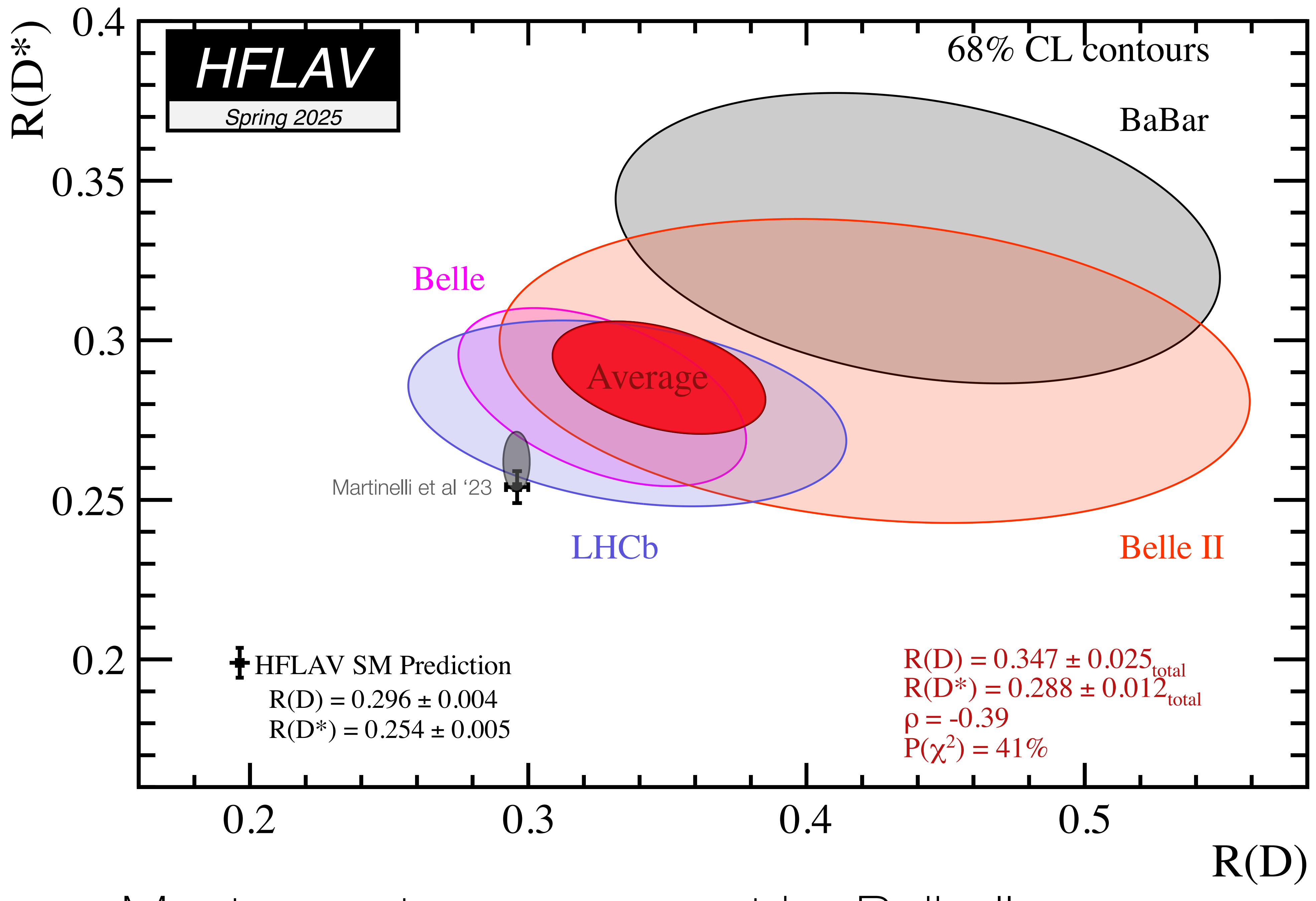


Most recent measurement by Belle-II confirmed the **tension: 3 - 4σ**.

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

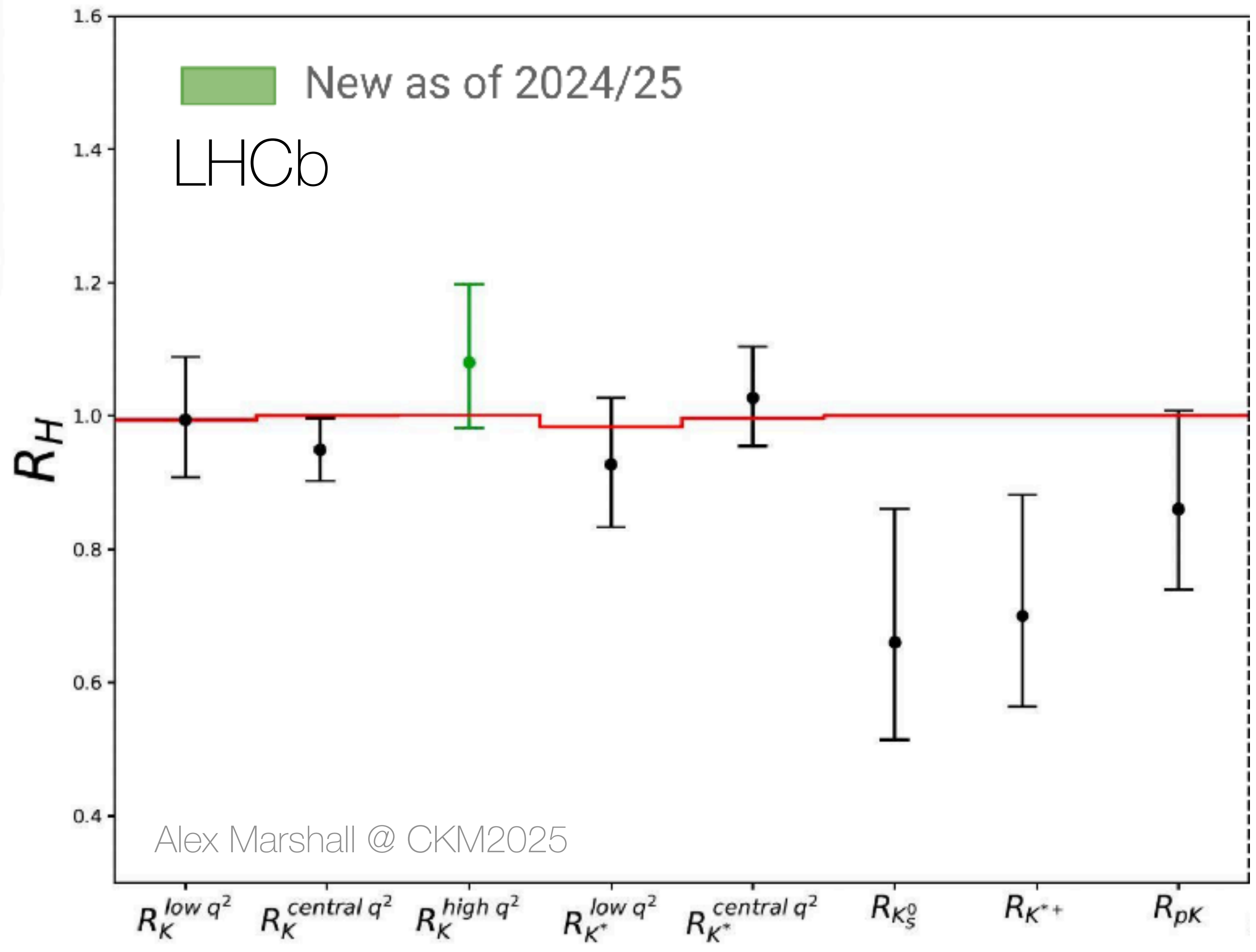
Corresponds to a **New Physics scale** of

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

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

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

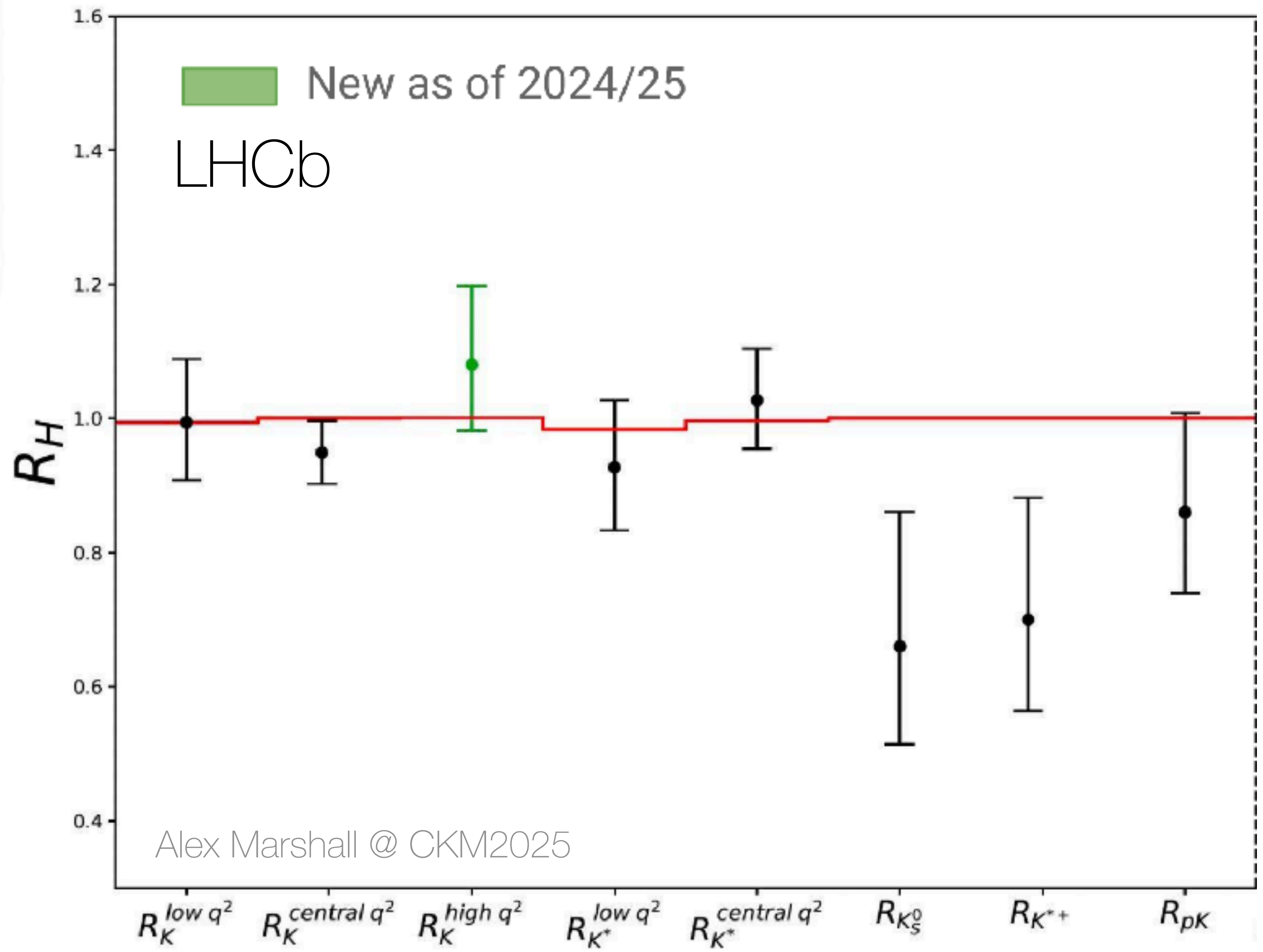


Clean SM prediction ($R_X = 1$), test of LFU between μ and e.

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

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.

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

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

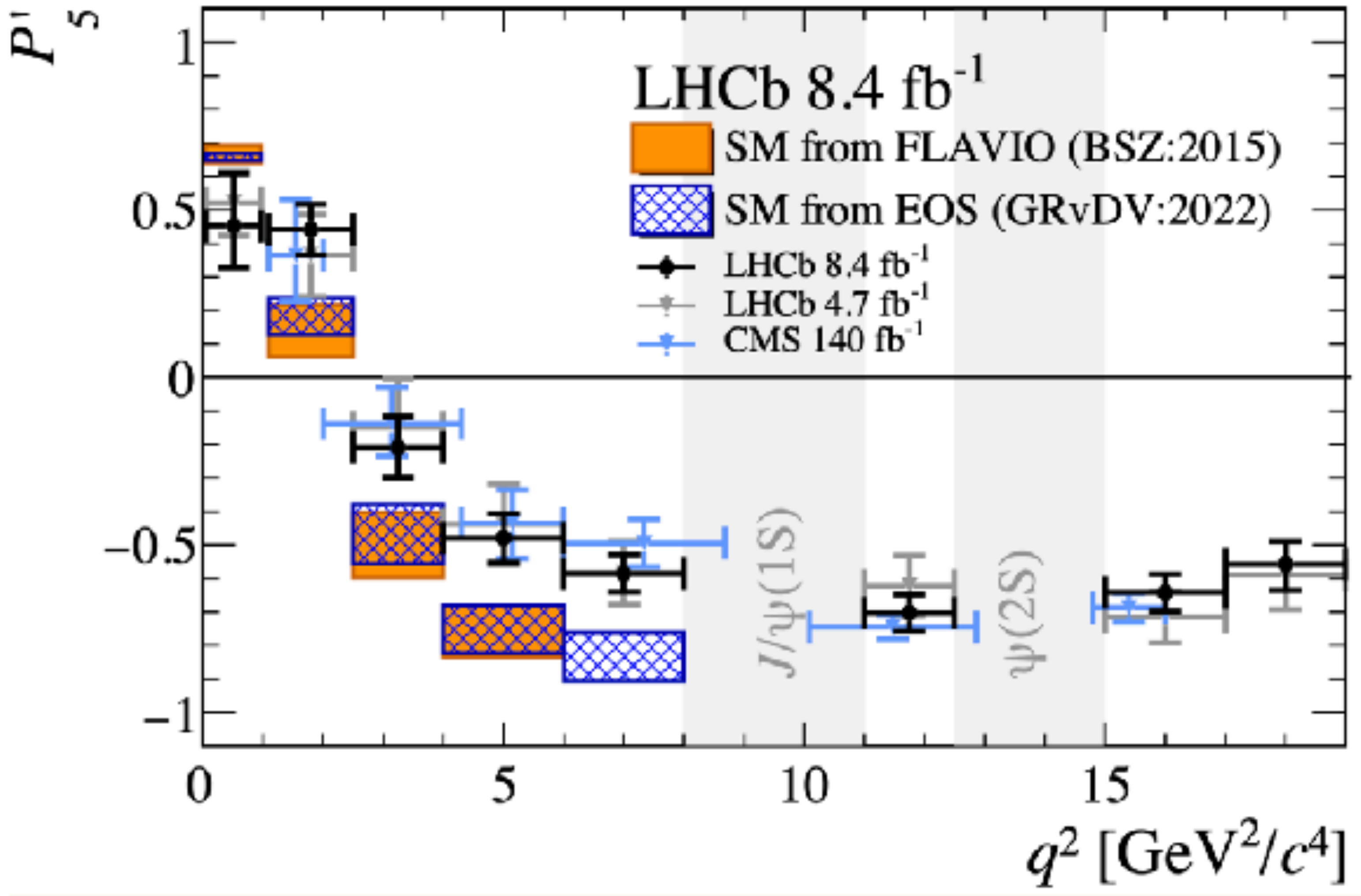
$$\mathcal{L}_{EFT} \supset \frac{c}{\Lambda^2} \left(\bar{b}_L \gamma_\alpha s_L\right)\left(\bar{\mu}_L \gamma^\alpha \mu_L\right)$$

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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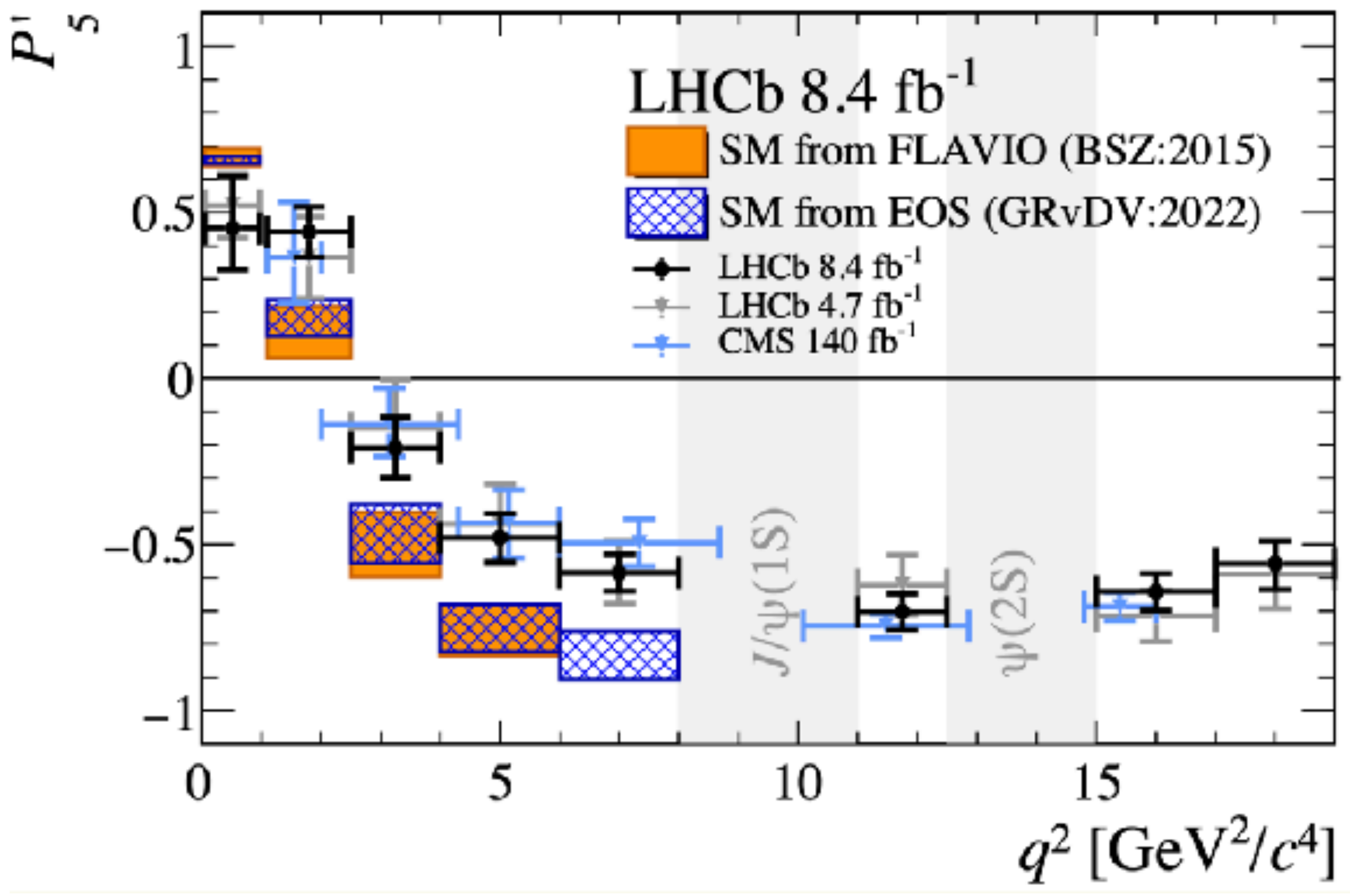

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If it is due to New Physics, it must respect **LFU** (to give R(K)=1)

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

if $c = 1$:

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

Neutral-current semileptonic B decays

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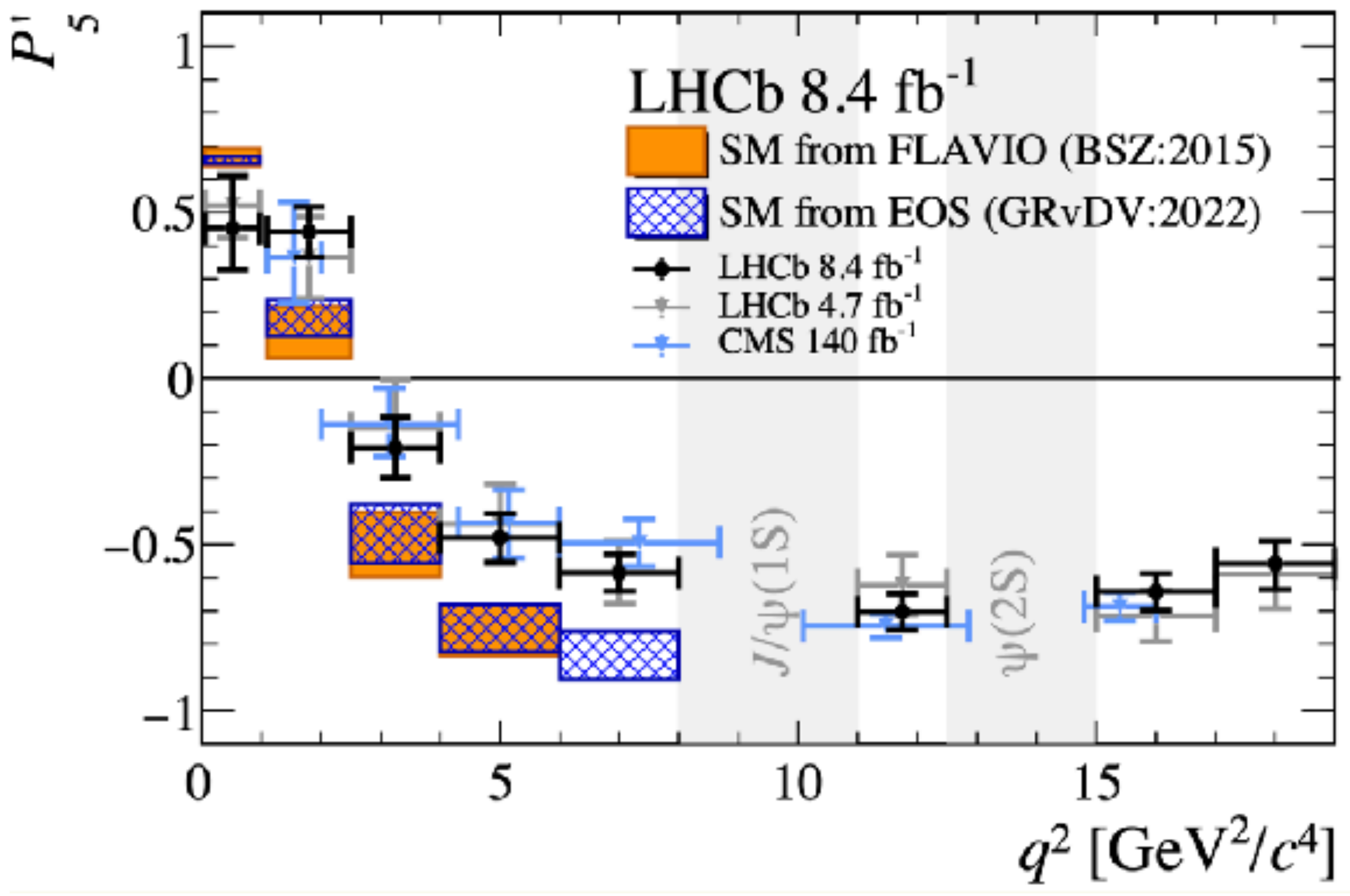

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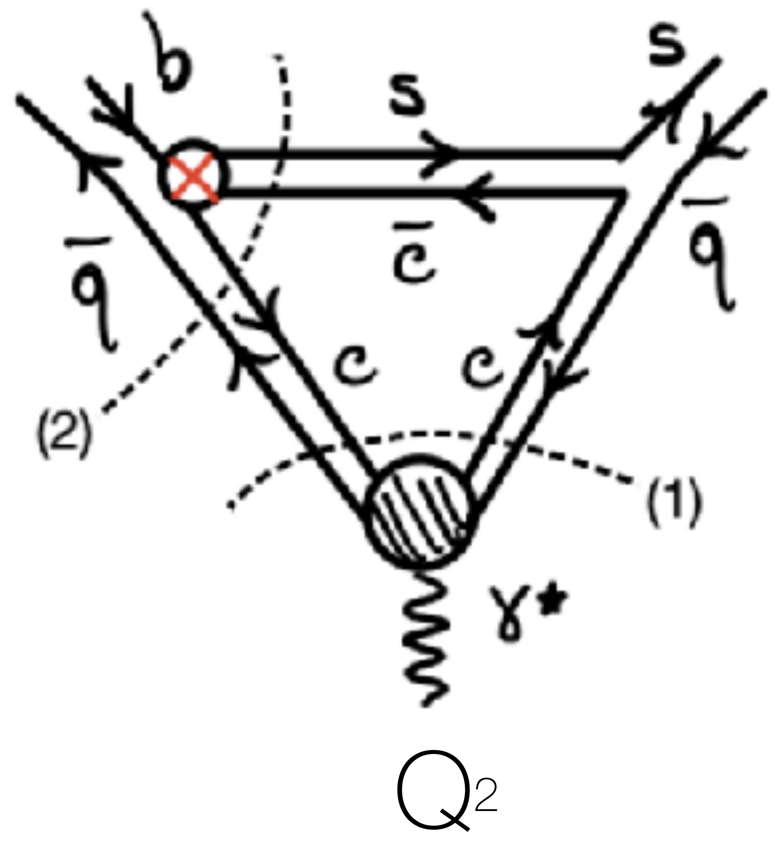
$\Lambda_{bs\ell\ell} \sim 40$ TeV

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



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.

Neutral-current semileptonic B decays

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

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

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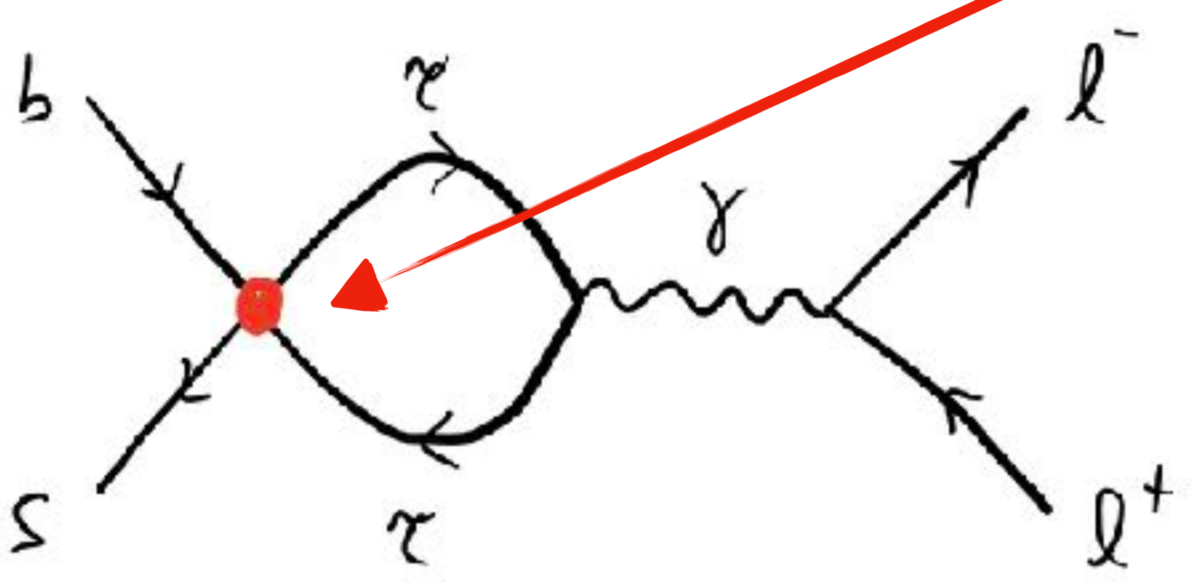
An interesting New Physics contribution

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

Neutral-current semileptonic B decays

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

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

if c = 1:

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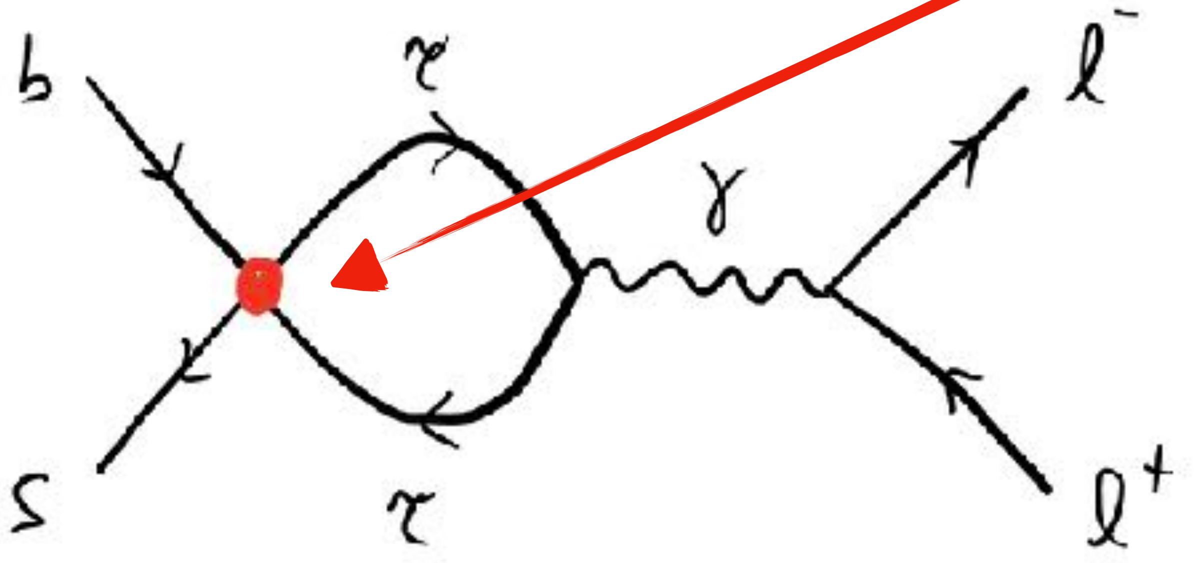

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→ Induce C_9^U, R(K)=1

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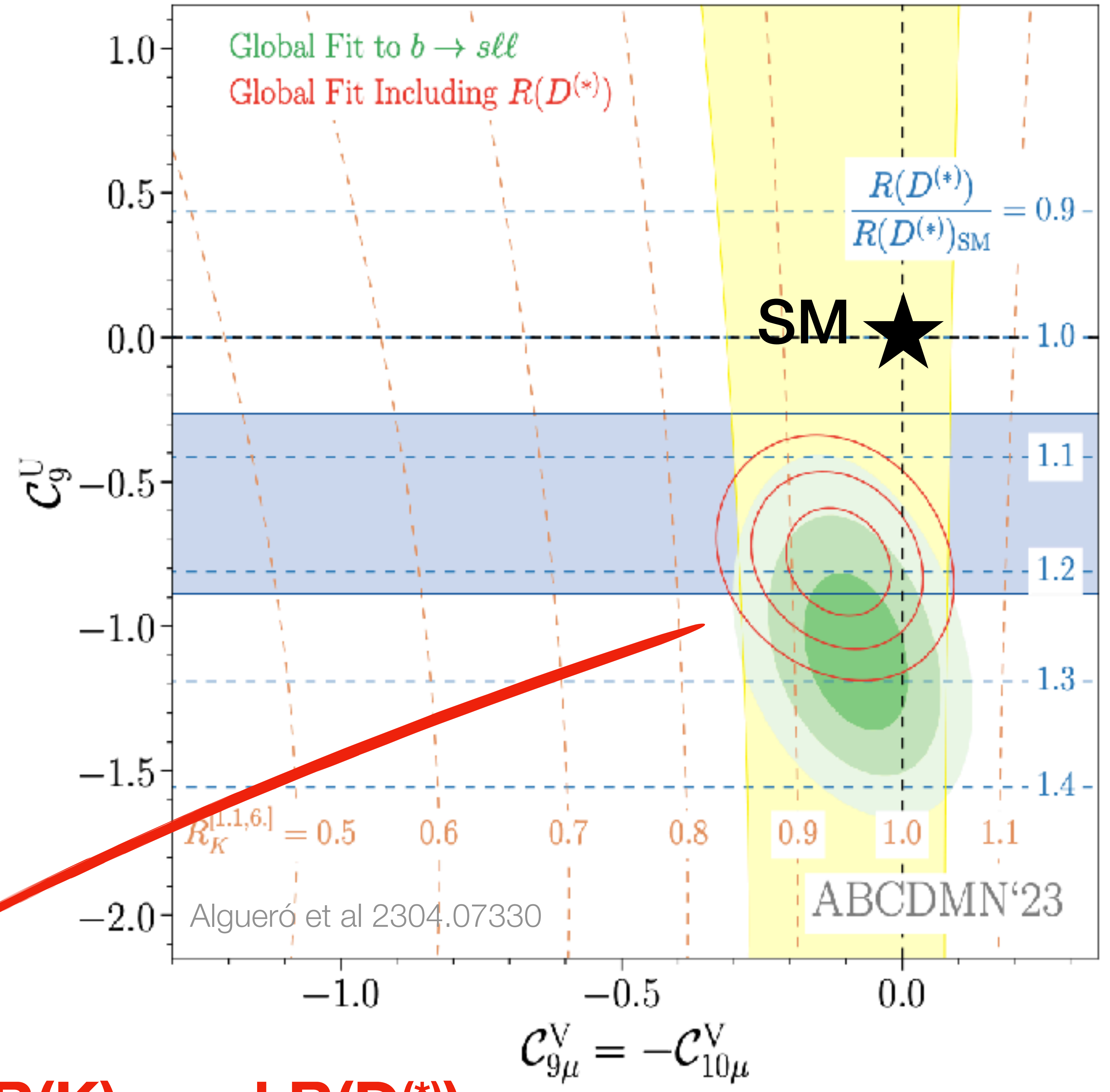
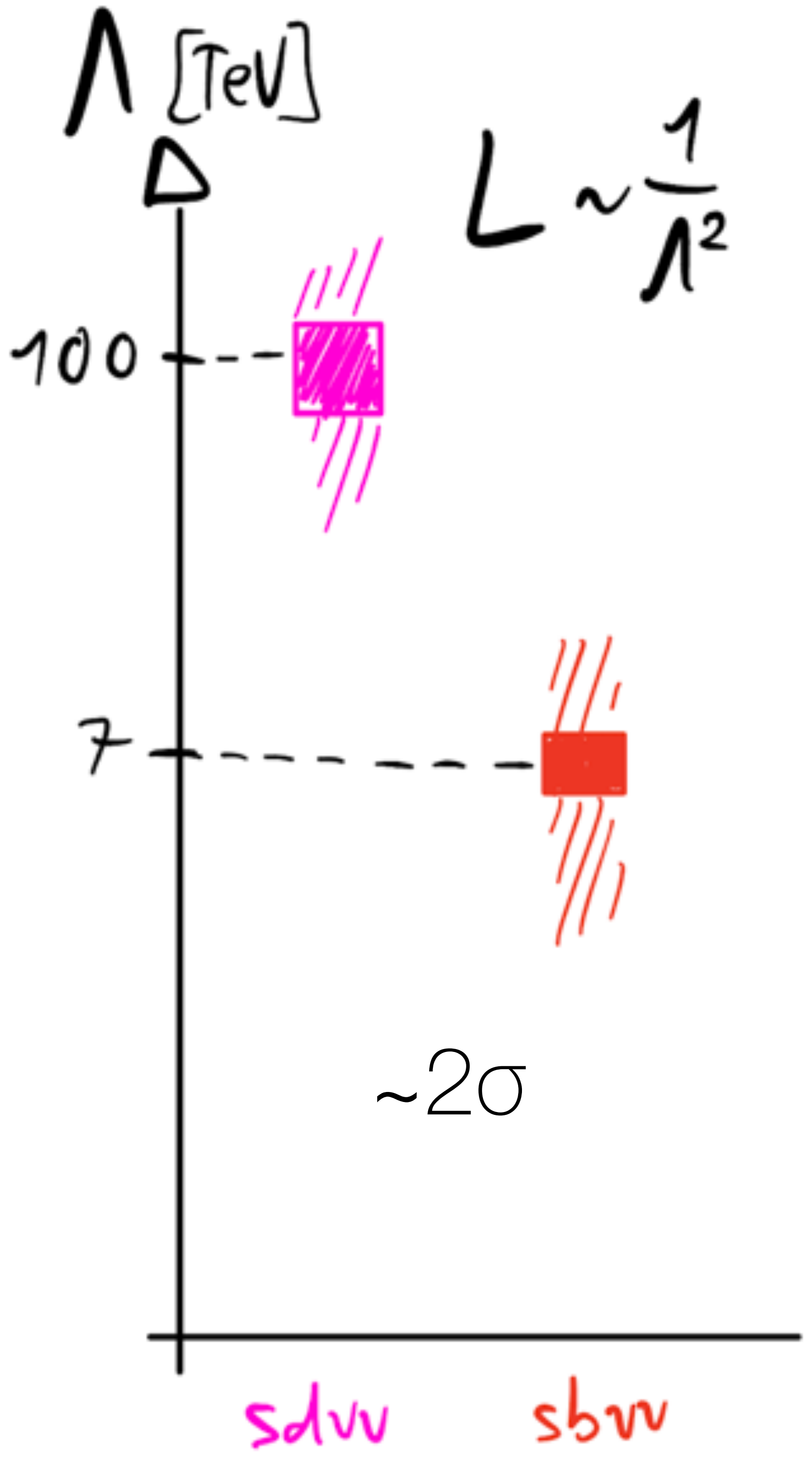


Compatible fit between $b \to s\ell\ell$, R(K), and $R(D^{(*)})$.

Is a picture emerging from data?

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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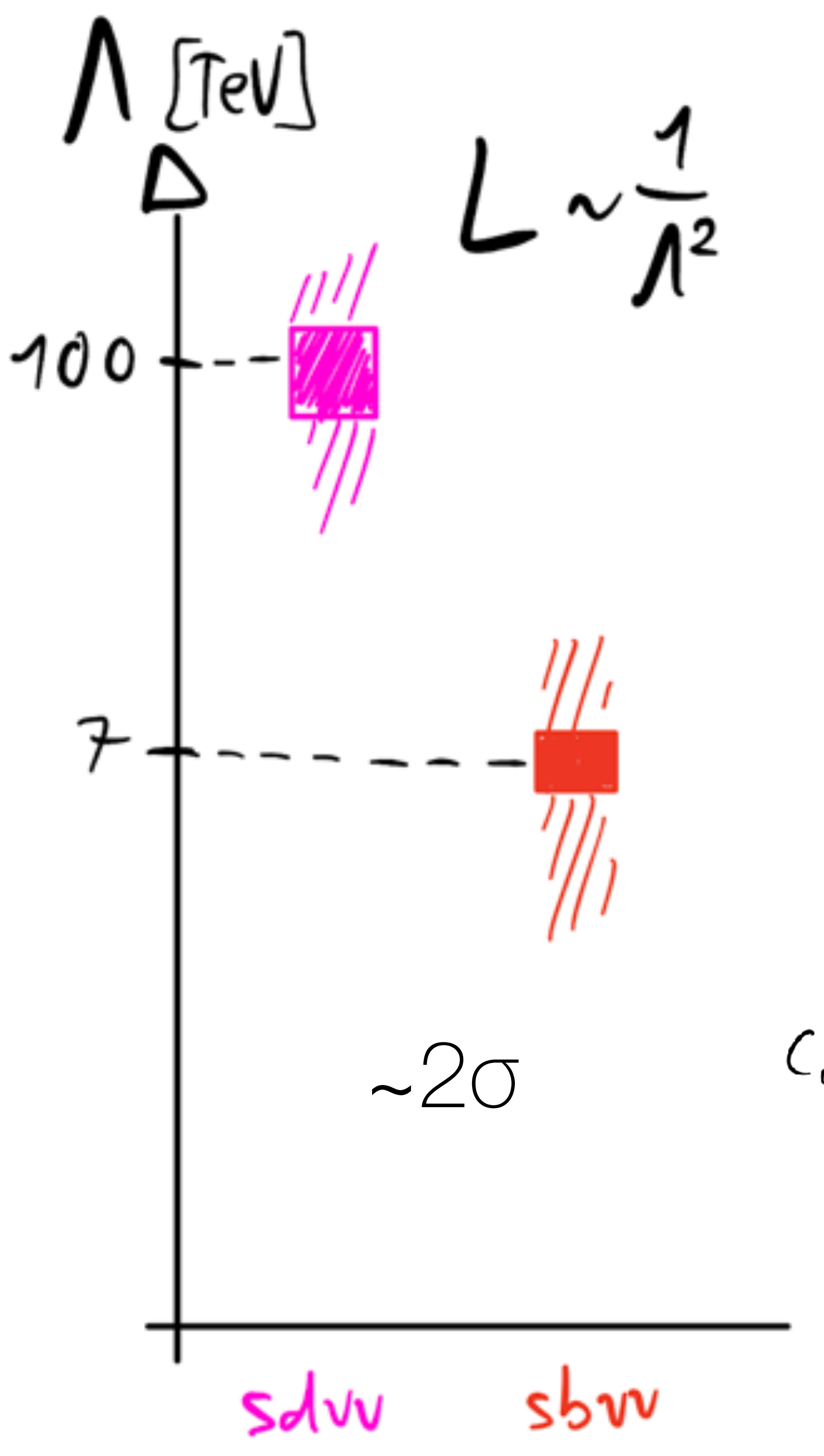
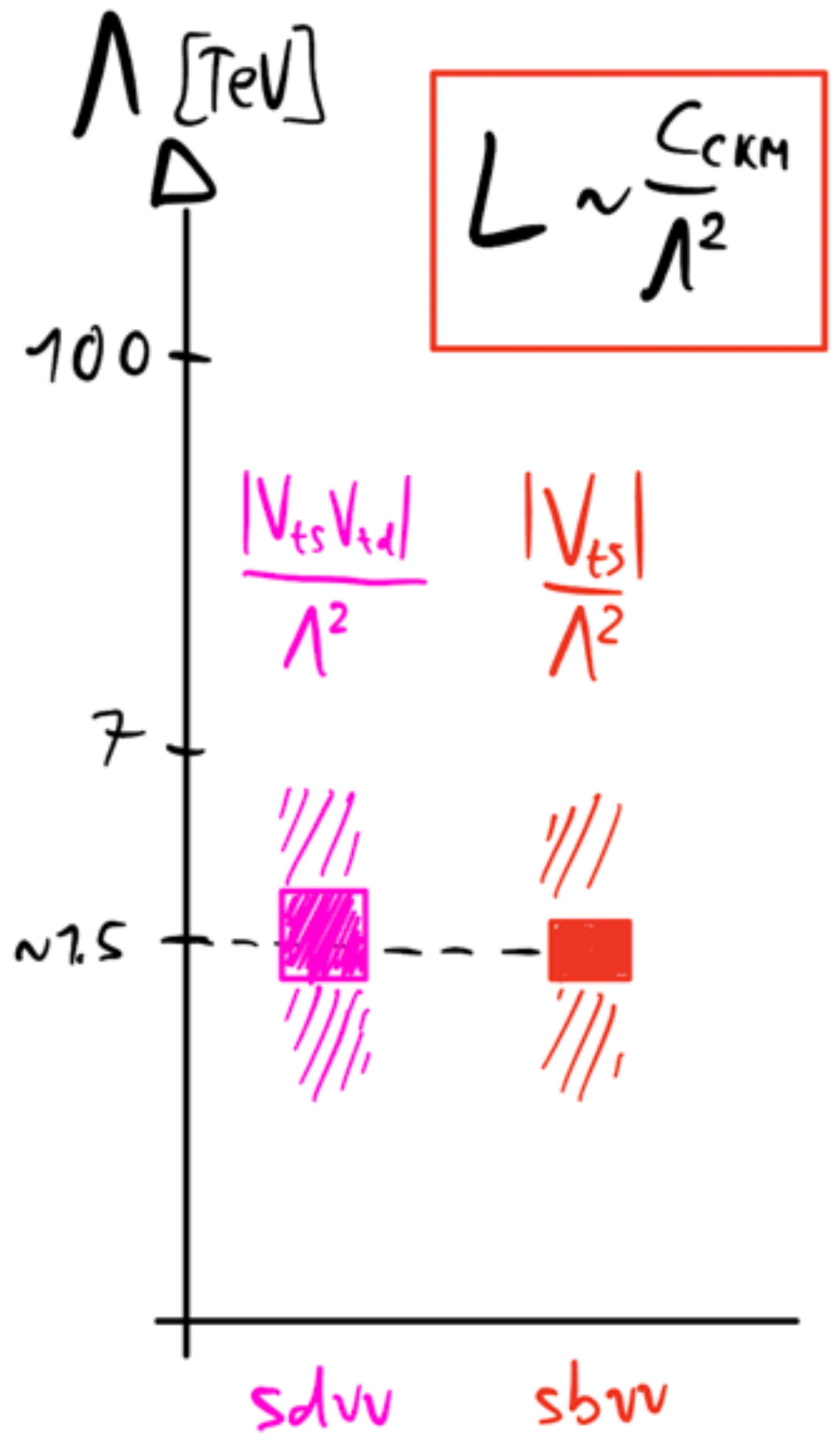


Assuming a CKM-like structure

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



The physics scales become compatible!

Is a picture emerging from data?

Neutral-current

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

SU(2)L

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

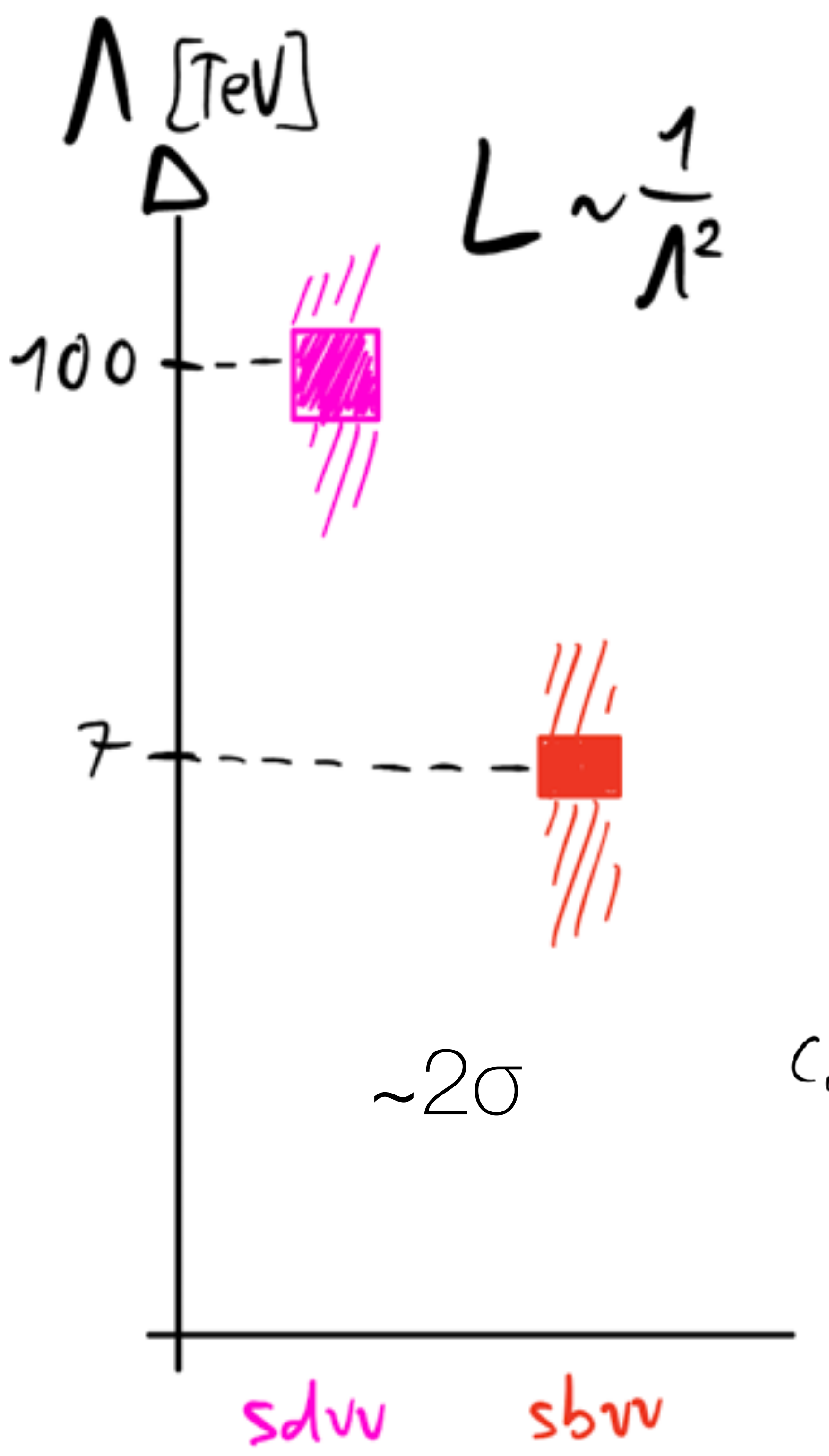
The precise correlation is model-dependent

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→sℓℓ

$$\rightarrow \quad L^{cc}_{bc\nu\tau} \sim \frac{1}{(4\,\text{TeV})^2}$$



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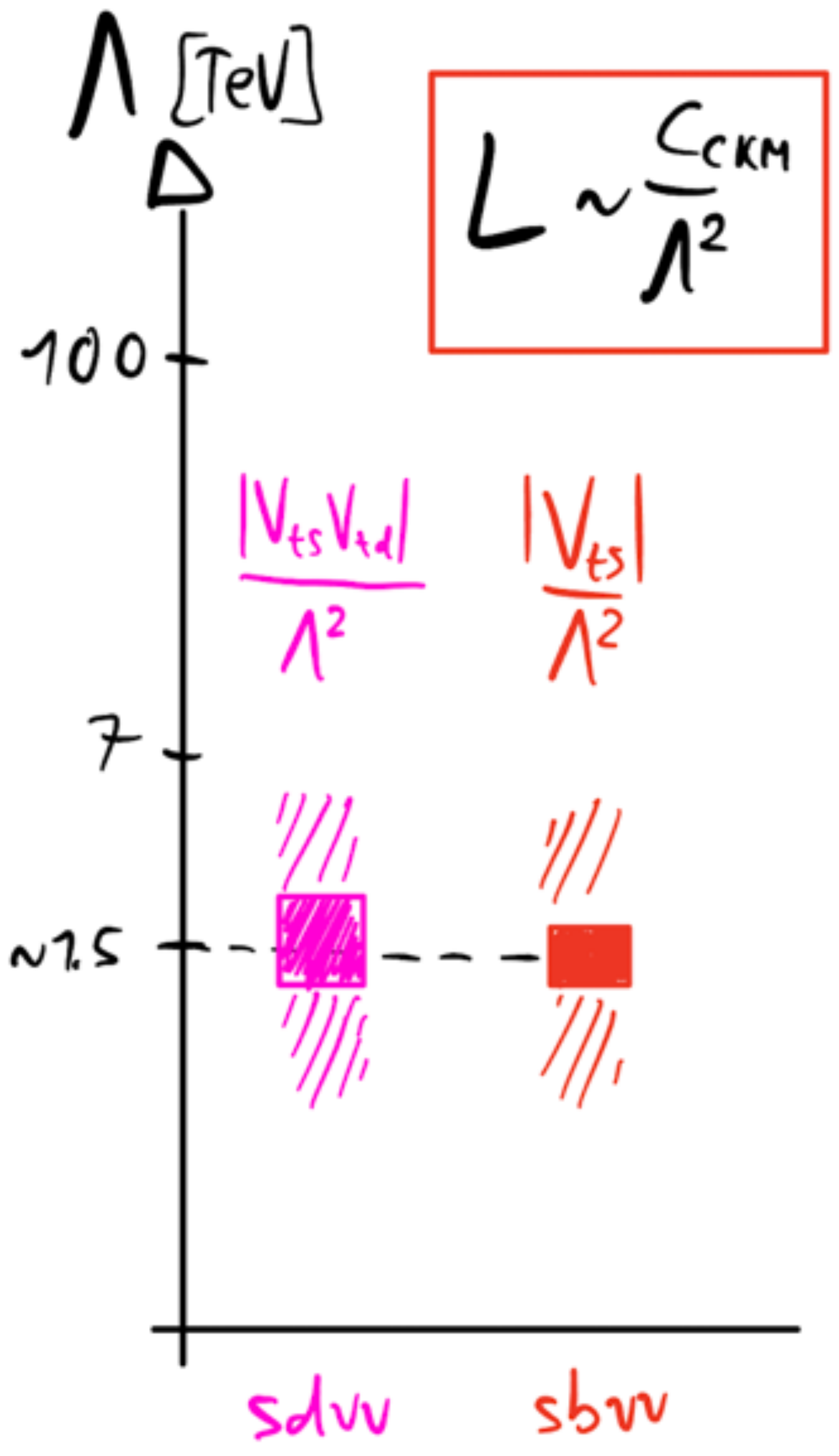

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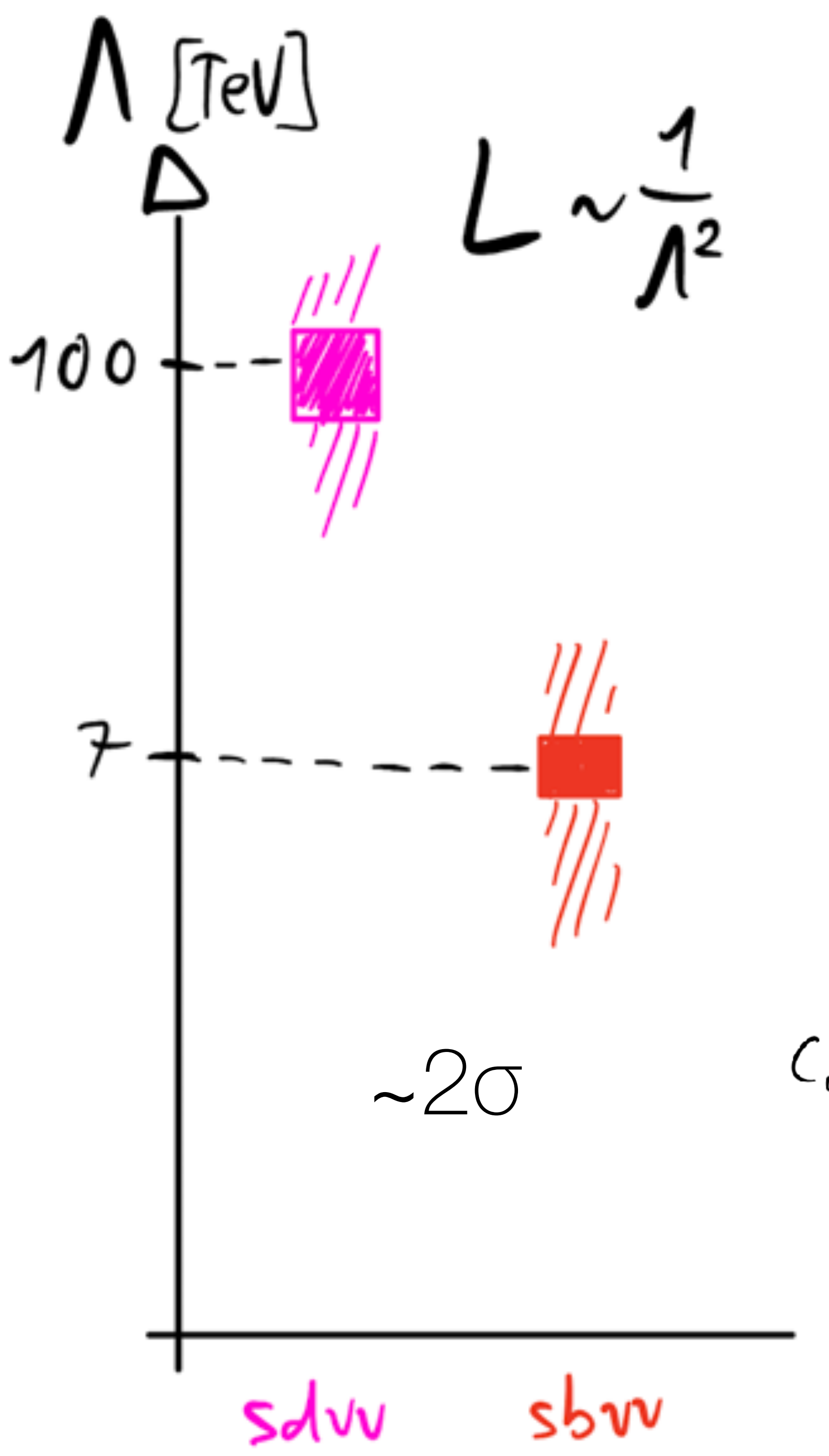
$R(D^{(*)})$, $b \to s\ell\ell$ → $L^{cc}_{bc\nu\tau} \sim \frac{1}{(4\,\text{TeV})^2}$



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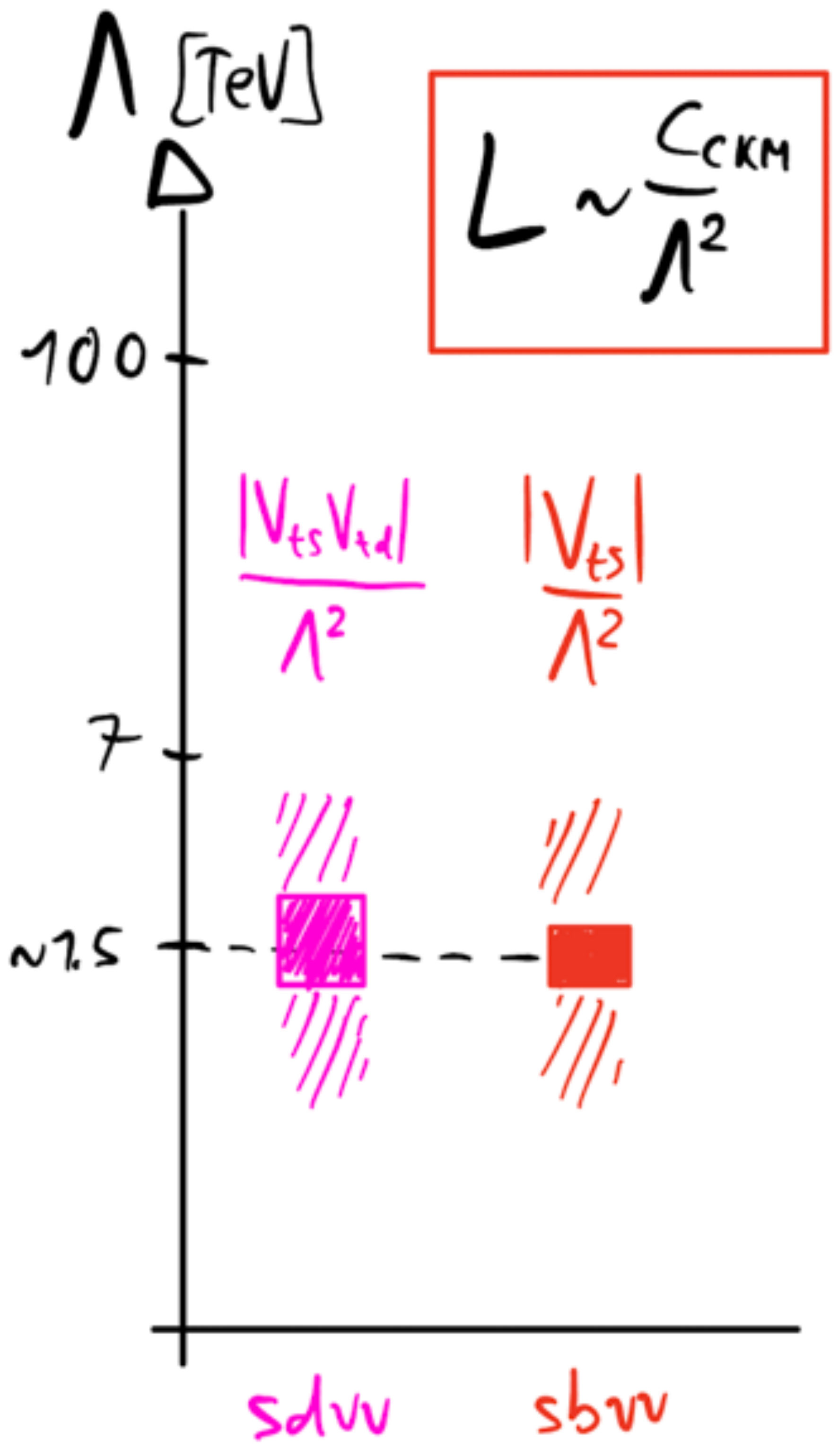
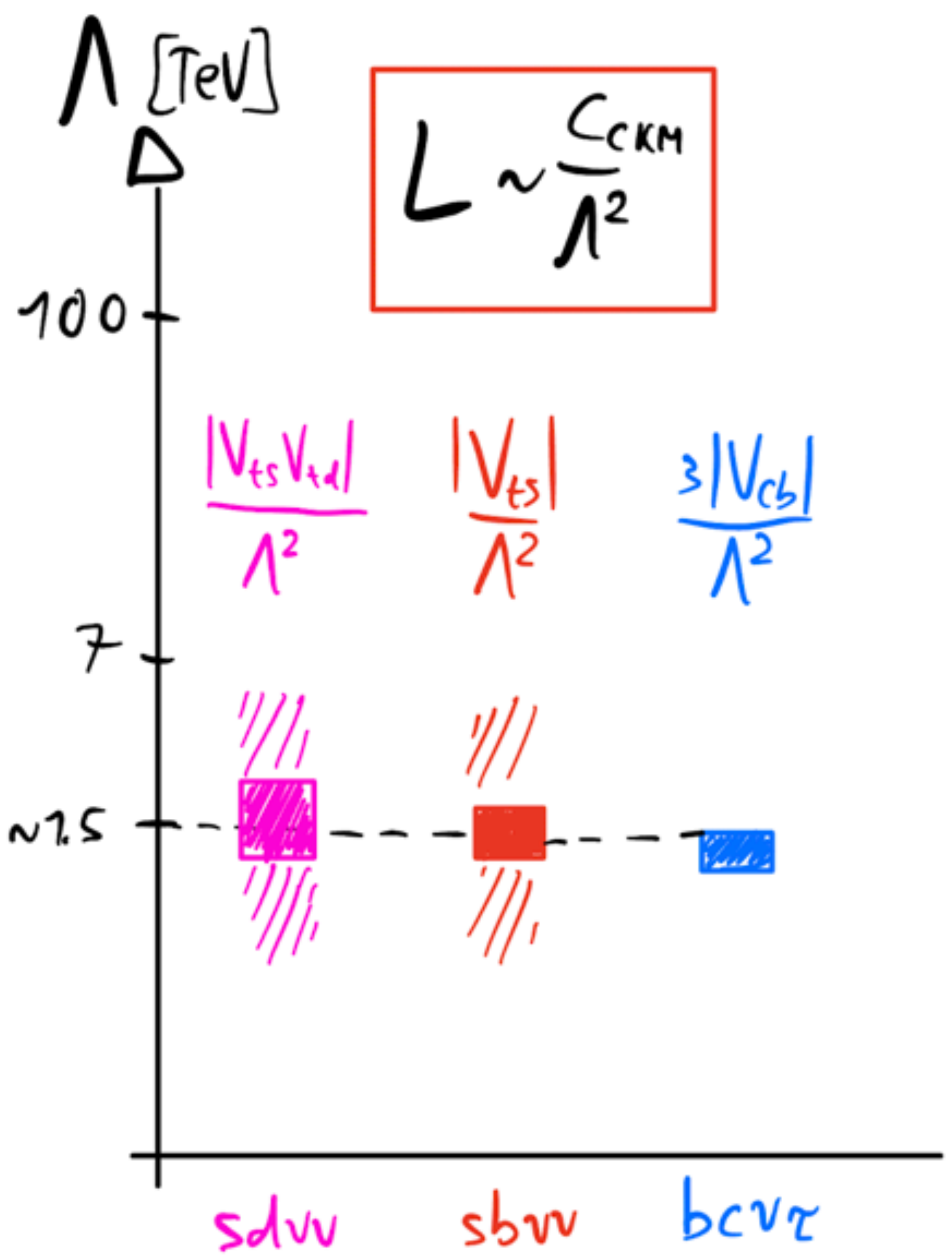




(c ~ 3 V_{cb})

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

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?

$$\frac{C_{ij}}{\Lambda^2}\left(\bar{Q}^i_L \gamma_\alpha T Q^j_L\right)\left(\bar{L}^3_L \gamma_\alpha T L^3_L\right)$$

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

$$\Lambda \sim 1.5\,\text{TeV} \sim \frac{M_{UV}}{g_{UV}}$$

Leptoquark?

$R(D^{(*)})$

LHCb, Belle-II

3-4 σ

$B_s \to \tau\tau,\ B \to K^{(*)}\tau\tau$

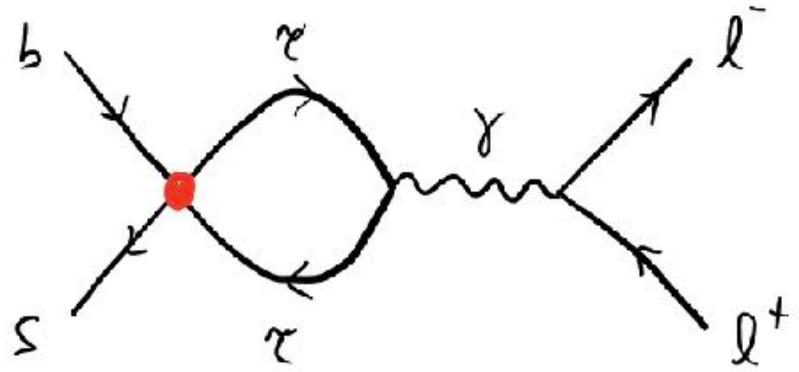
LHCb, Belle-II, FCCee

See talk by
C. Cornella

P_5'

LHCb

>4 σ
SM?



$B \to K\nu\nu$

Belle-II

2 σ

$K \to \pi\nu\nu$

NA62, KOTO-II

<2 σ

$pp \to \tau\tau,\ \tau\nu$

ATLAS, CMS

$Z \to \tau\tau,\ \nu\nu$

LEP (FCCee)

Part III

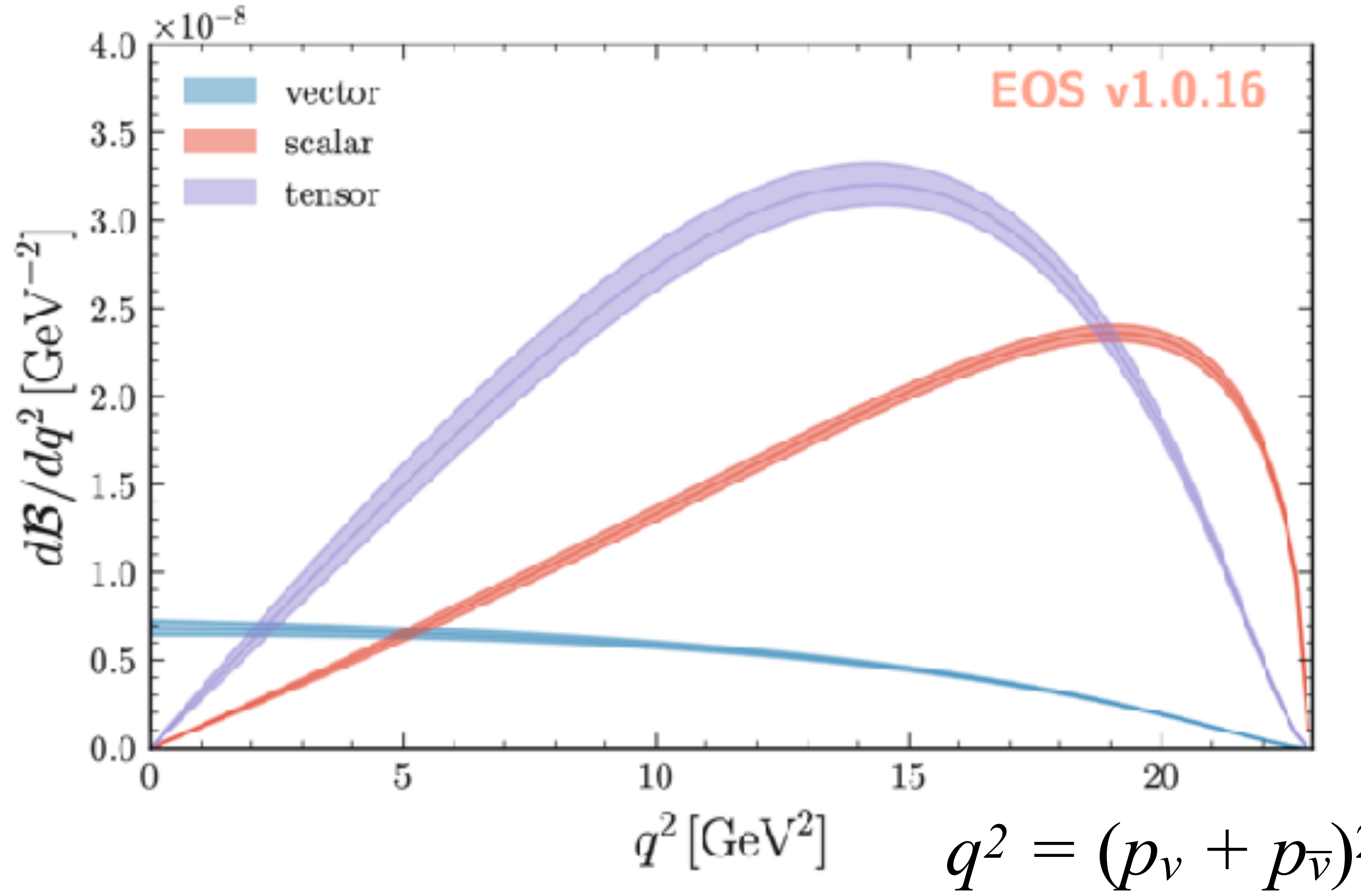
Exploring the exotic frontiers

(but not all theories are created equal)

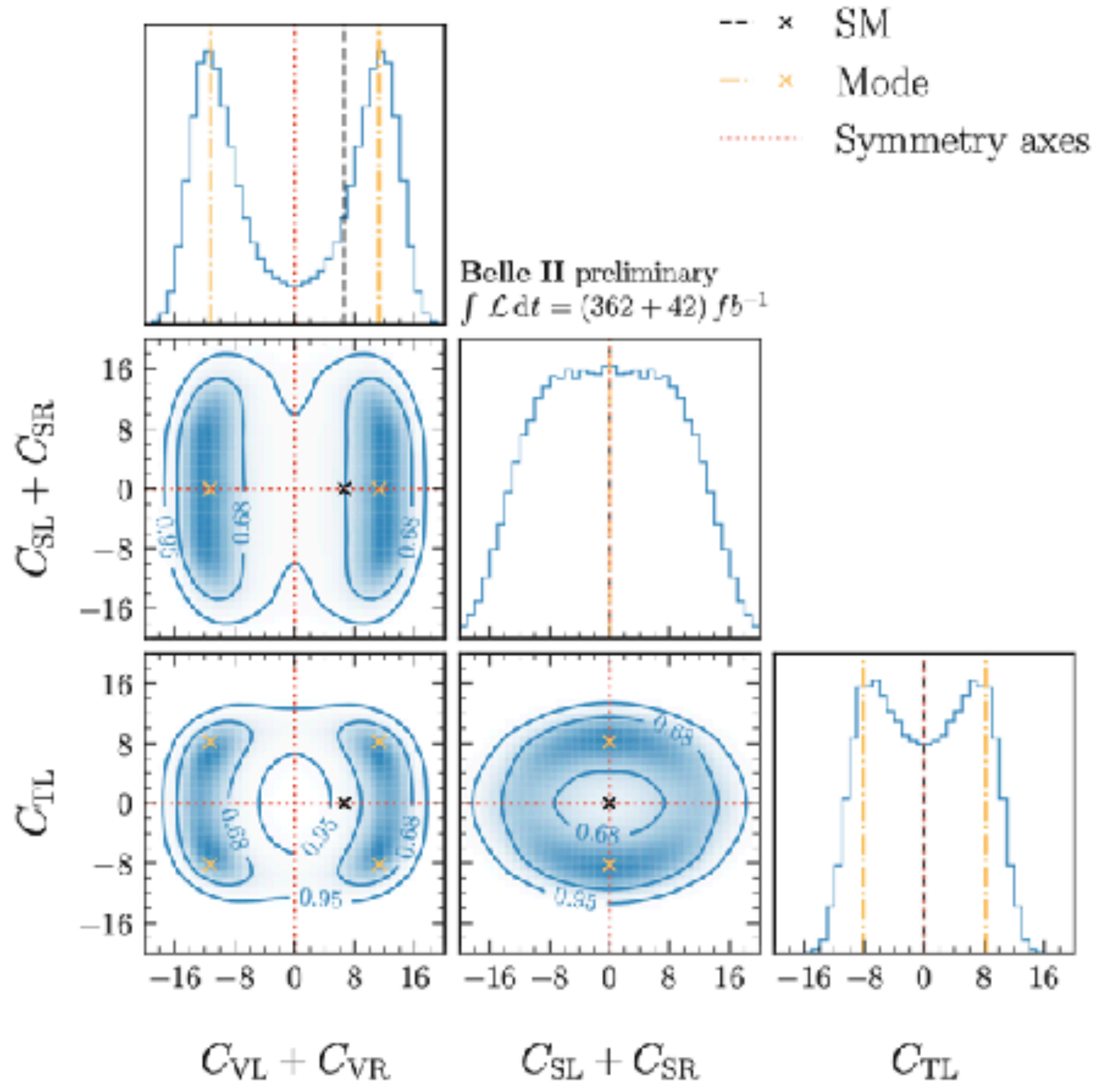
$B^+ \to K^+ \nu\nu$ with L-violating operators

Reinterpretation framework of $B \to K^+ \nu\nu$, **generalising the EFT beyond the d=6 SMEFT**:

Gartner at al. 2402.08417, Belle-II 2507.12393



$q^2 = (p_\nu + p_{\bar{\nu}})^2$



$$\mathcal{L}^{\rm WET} = -\frac{4G_F}{\sqrt{2}}\frac{\alpha}{2\pi} V_{ts}^* V_{tb} \sum_i C_i(\mu_b) O_i + \text{h.c.}$$

$$\mathcal{O}_{\rm VL} = (\overline{\nu_L}\gamma_\mu \nu_L)(\overline{s_L}\gamma^\mu b_L)$$

$$\mathcal{O}_{\rm VR} = (\overline{\nu_L}\gamma_\mu \nu_L)(\overline{s_R}\gamma^\mu b_R)$$

d=6: $O_{lq}^{(1,3)}$, O_{ld}

$$\mathcal{O}_{\rm SL} = (\overline{\nu_L^c}\nu_L)(\overline{s_R} b_L)$$

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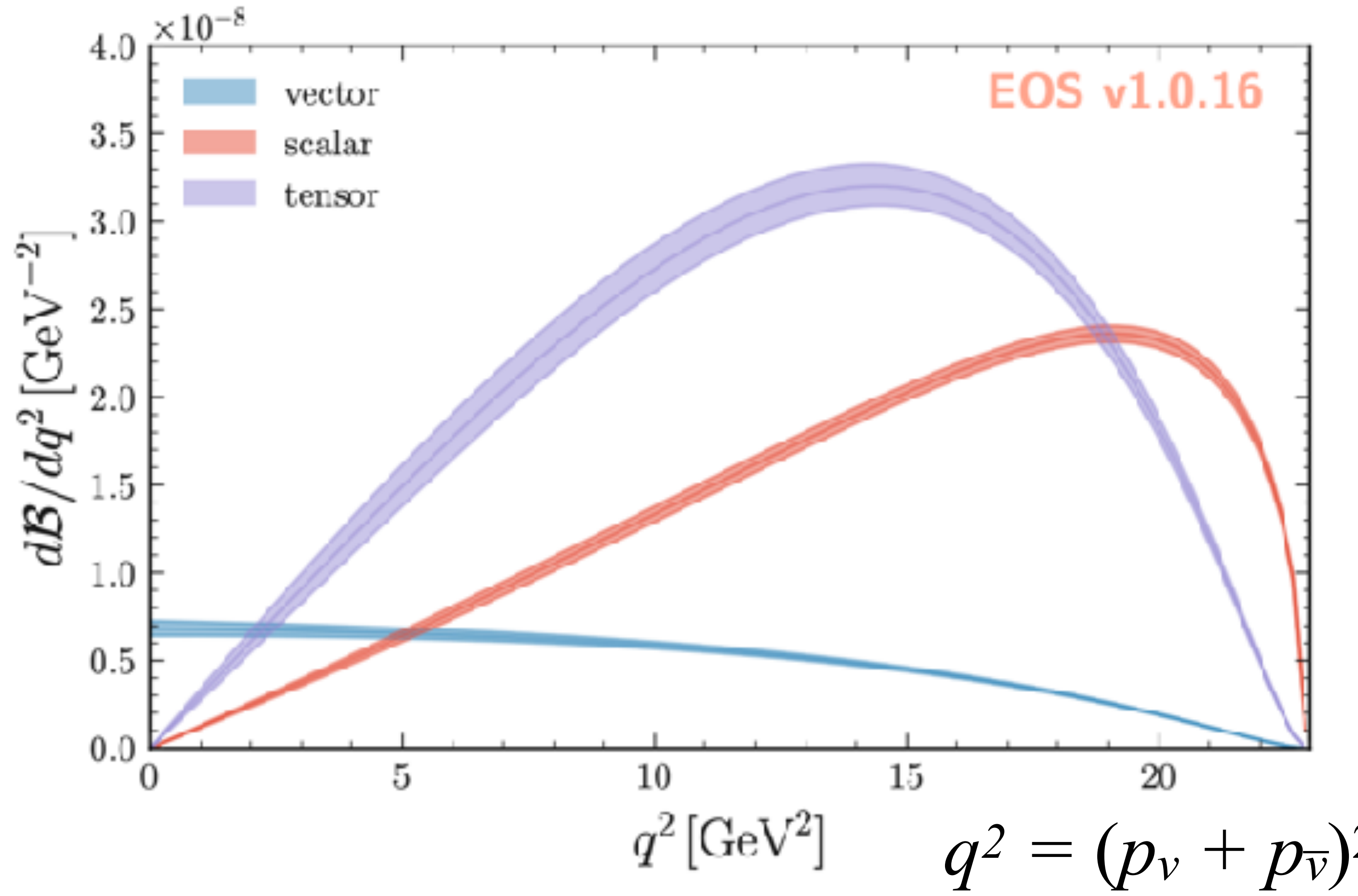

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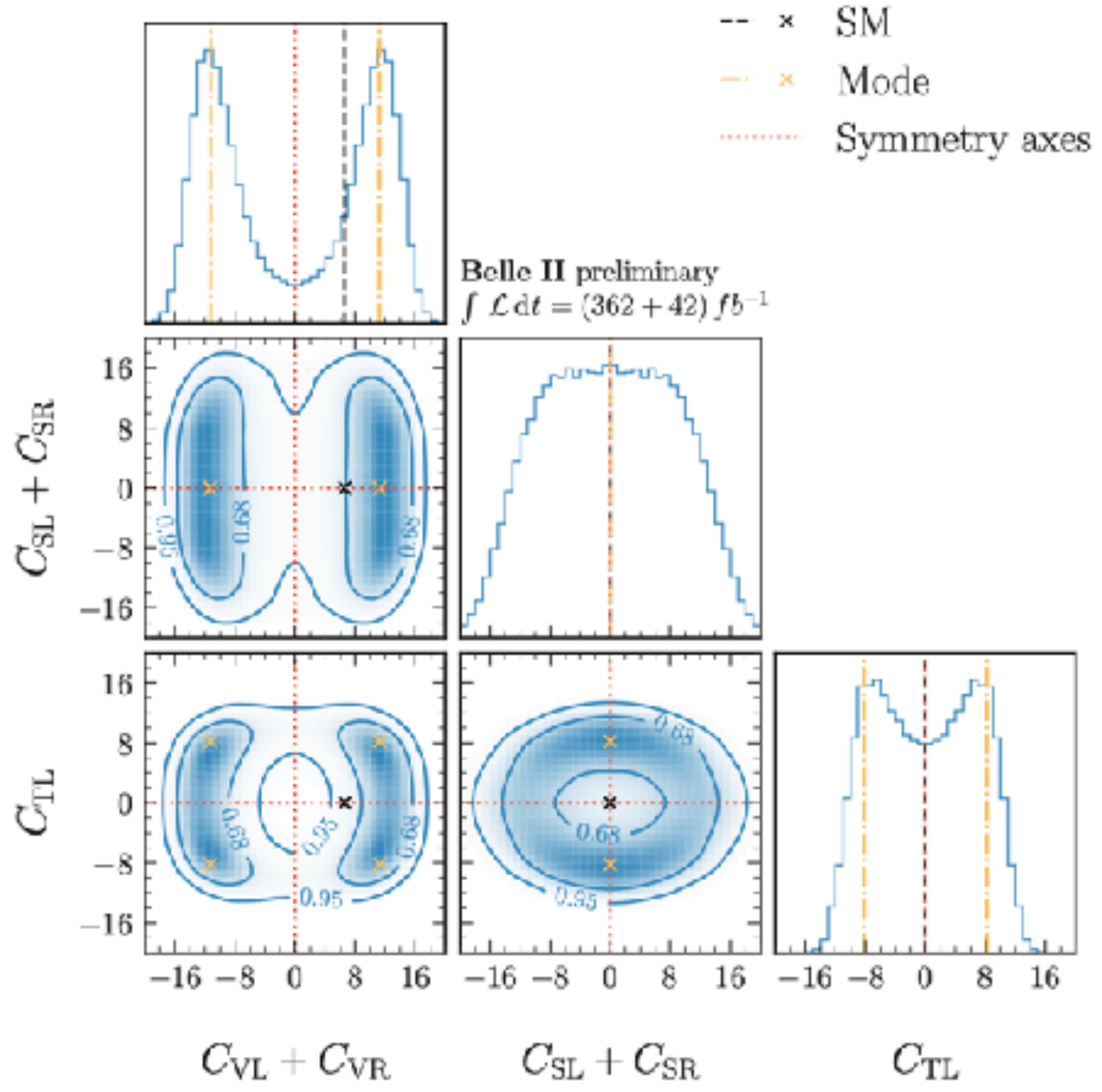

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ΔL = 2

Lepton number-violating operators

Generated at d=7 in SMEFT

Fridell et al. 2306.08709

$$\frac{C^{(7)}}{\Lambda^3}(\bar{d}_R L_L)(\bar{Q}^c_L L_L)H$$

If at d=6 the EFT scale required was $\Lambda^{(6)} \sim 7$ TeV,
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B⁺ → K⁺ νν with L-violating operators

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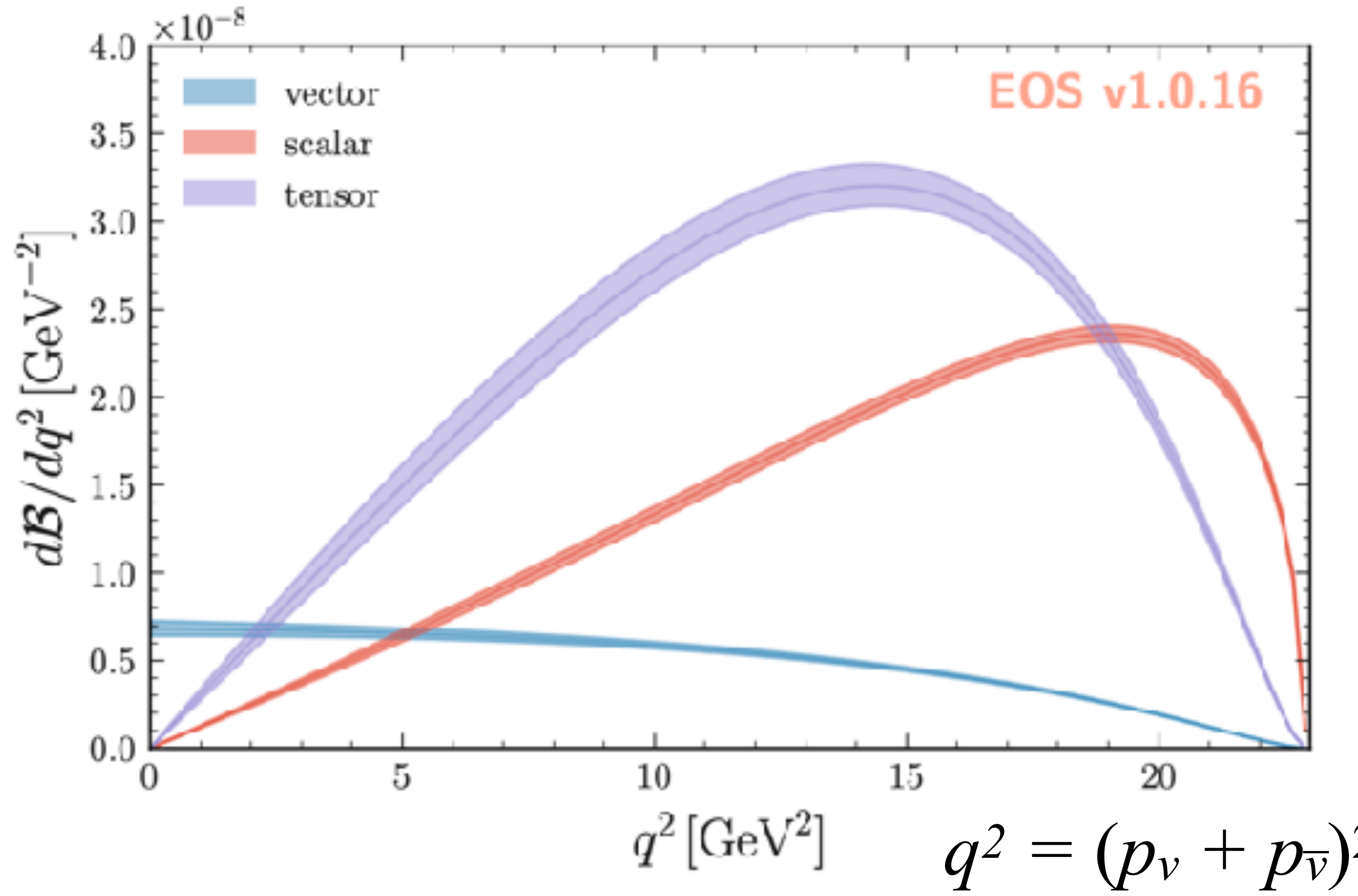

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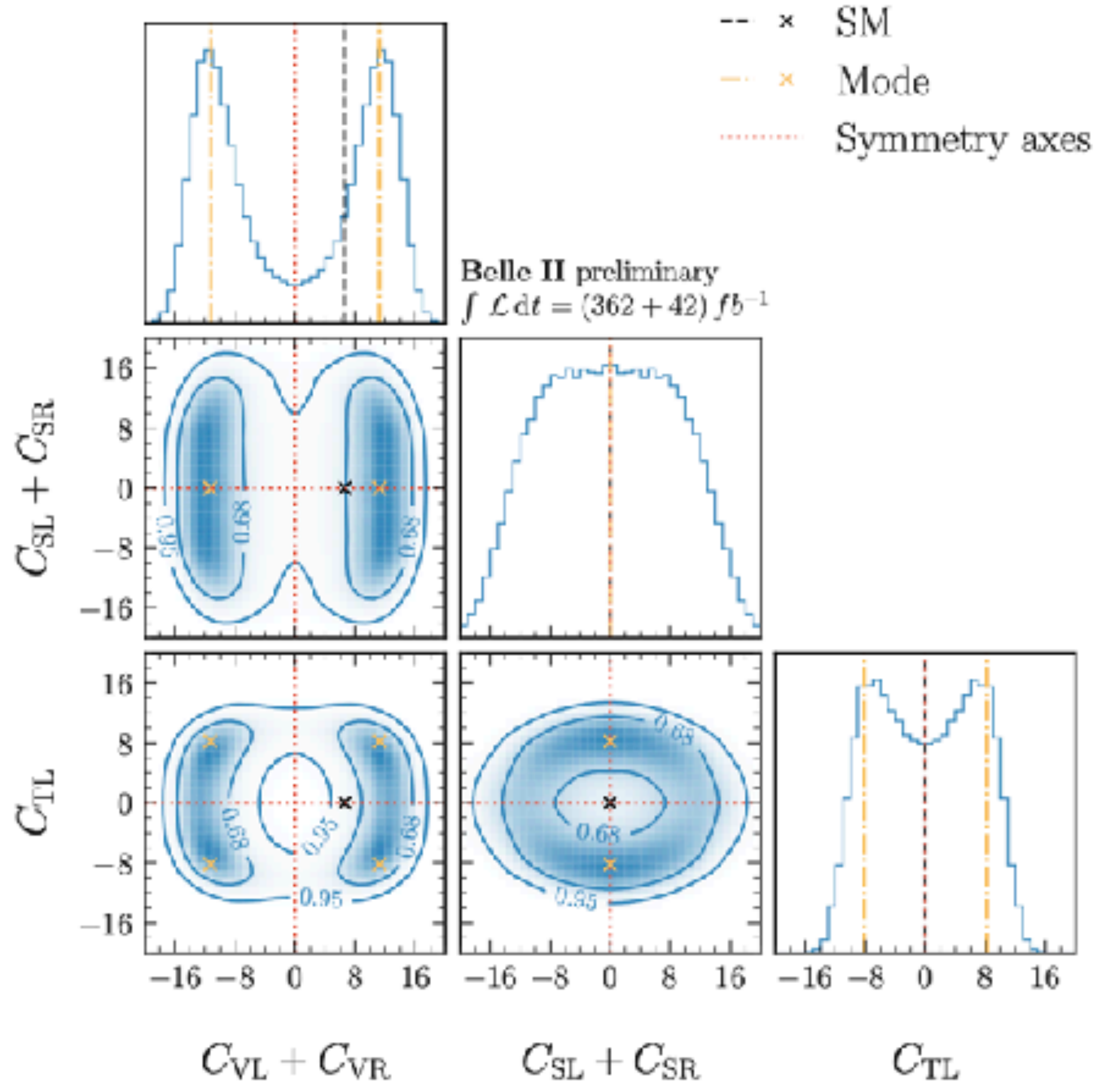

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Bounds from $0\nu\beta\beta$ decay ~ **100 TeV** (for down quarks). 2306.08709
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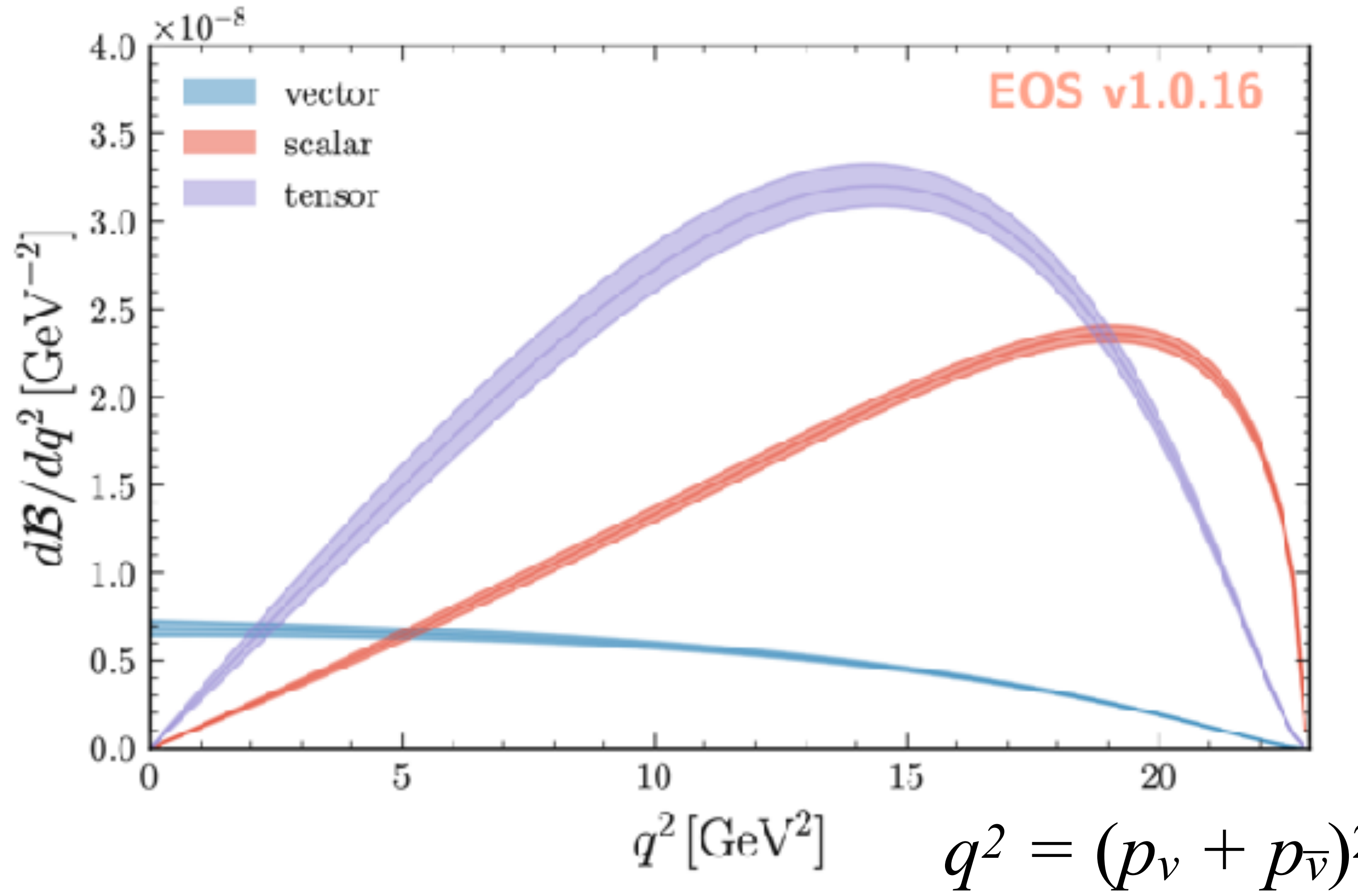

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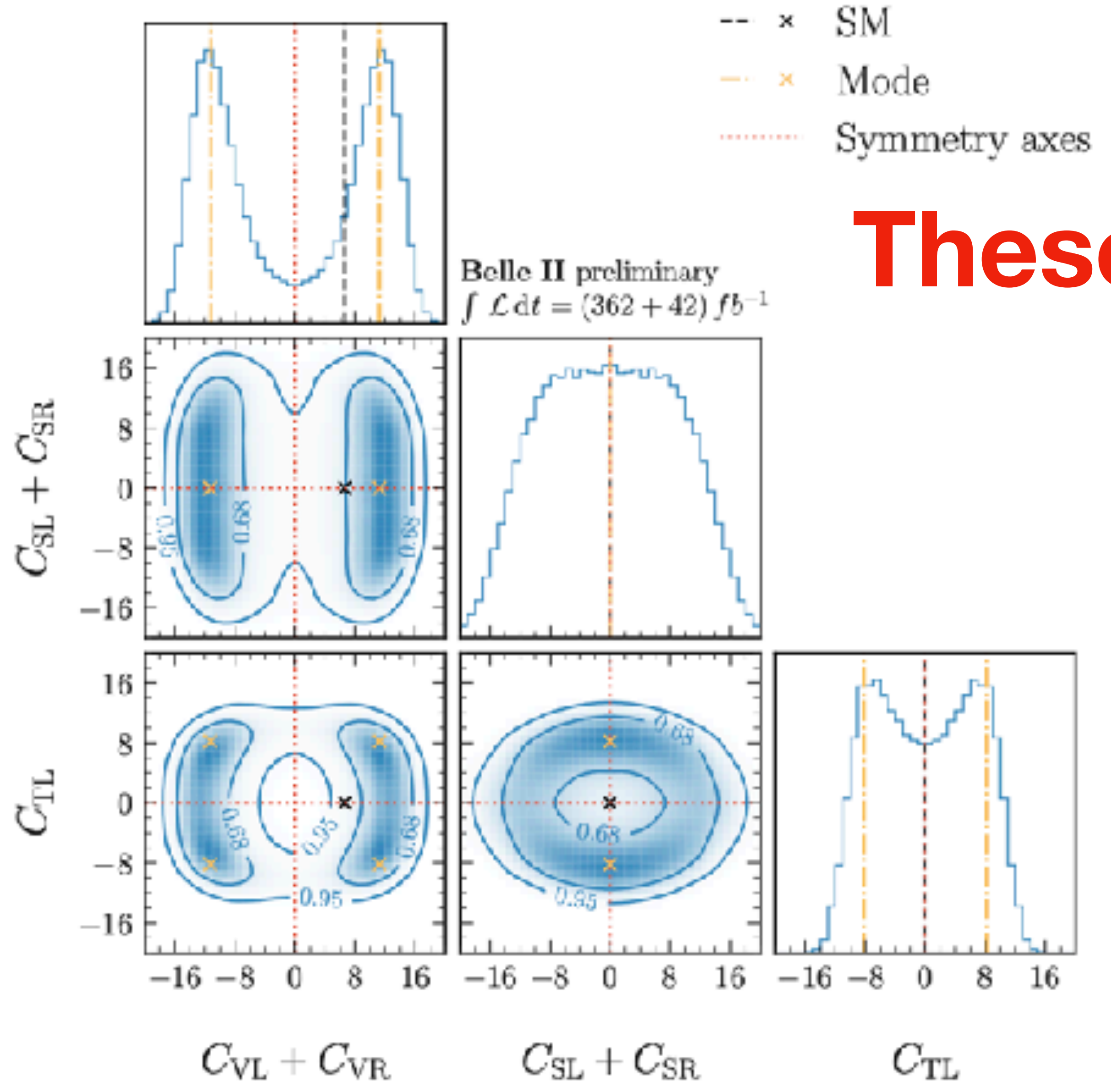

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Generated at d=7 in SMEFT

Fridell et al. 2306.08709

$$\frac{C^{(7)}}{\Lambda^3}(\bar{d}_R L_L)(\bar{Q}_L^c L_L)H$$

These operators are on all the same footing!

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Why should flavour-conserving couplings be more suppressed than violating ones?

$B^+ \to K^+ \nu\nu$ with L-violating operators

Neutrino masses in the SM EFT are generated at dim=5 by the Weinberg operator

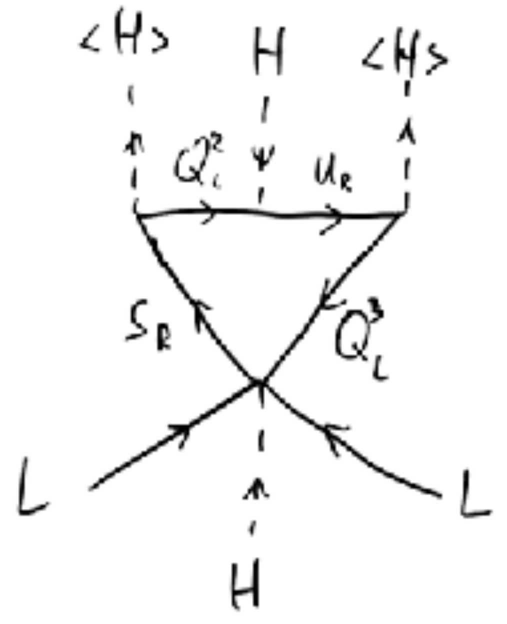
ΔL = 2: $$\frac{c_W}{\Lambda_L}(L\tilde{H})(L\tilde{H})$$

$$\Lambda_L / c_W \sim 10^{14}\ \text{GeV}$$

This is the **scale of breaking of lepton number L**.

ΔL = 2: $$\frac{C^{(7)}}{\Lambda^3}(\bar{d}_R L_L)(\bar{Q}^c_L L_L)H \;\to\; \Lambda^{(7)}_{BK\nu\nu} \sim 2\ \text{TeV}$$

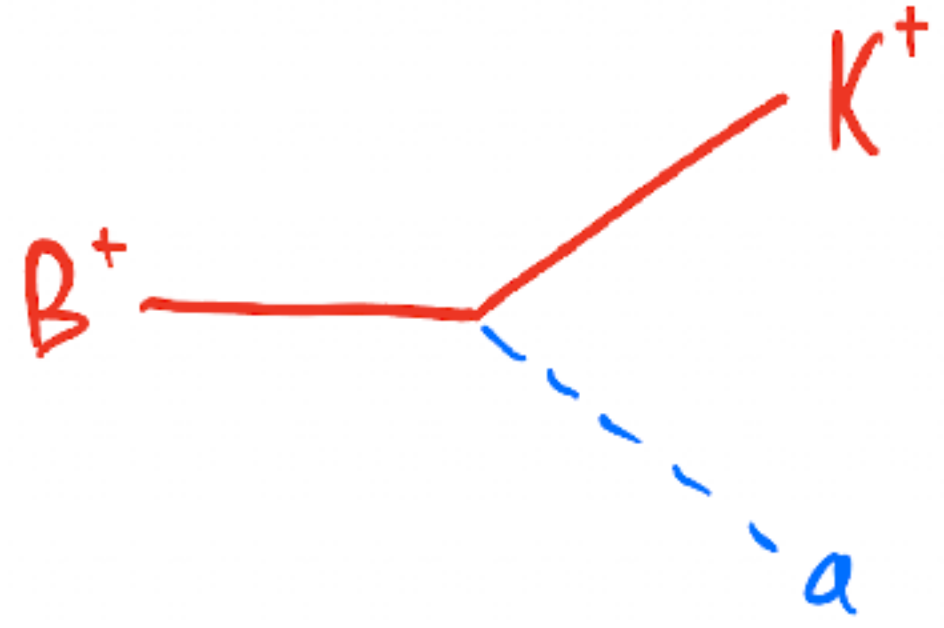
If this operator is present, with a much lower scale, there is **no symmetry argument that prevents the generation of the Weinberg operator with a too large coefficient** (too low scale).
Indeed, it is induced radiatively.



"Everything which is not forbidden is allowed"

Similar conclusions can be obtained if HNL are used instead of L-violating operators: that operator will generically induce at the radiative level too large neutrino masses.

$B^+ \rightarrow K^+ X$



A **2-body decay** is only allowed into a neutral scalar (or pseudo-scalar): **ALPs**.
In this case, the q^2 dependence is **peaked** at $q^2 = m_a^2$.

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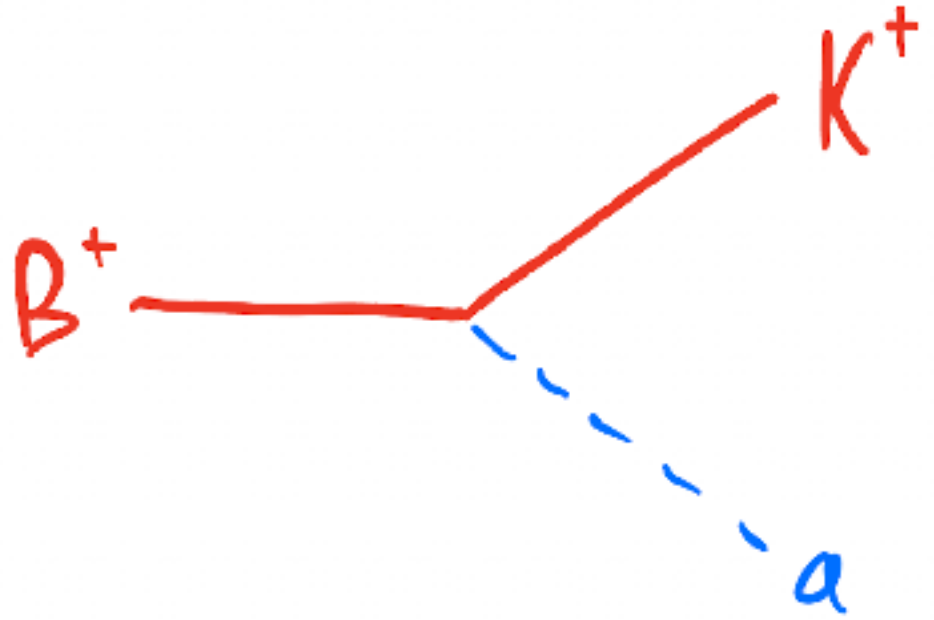
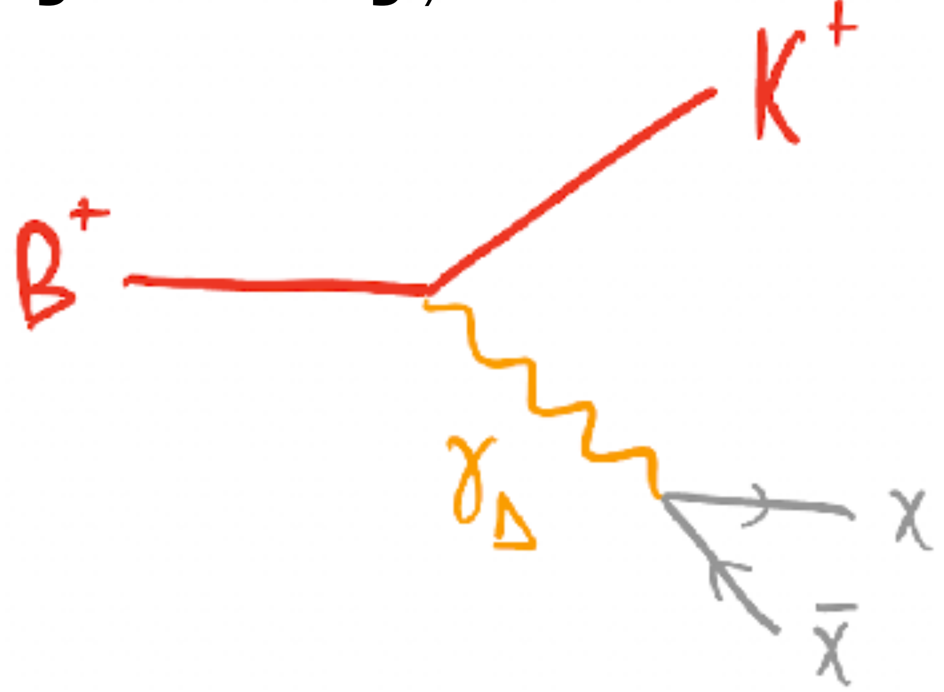
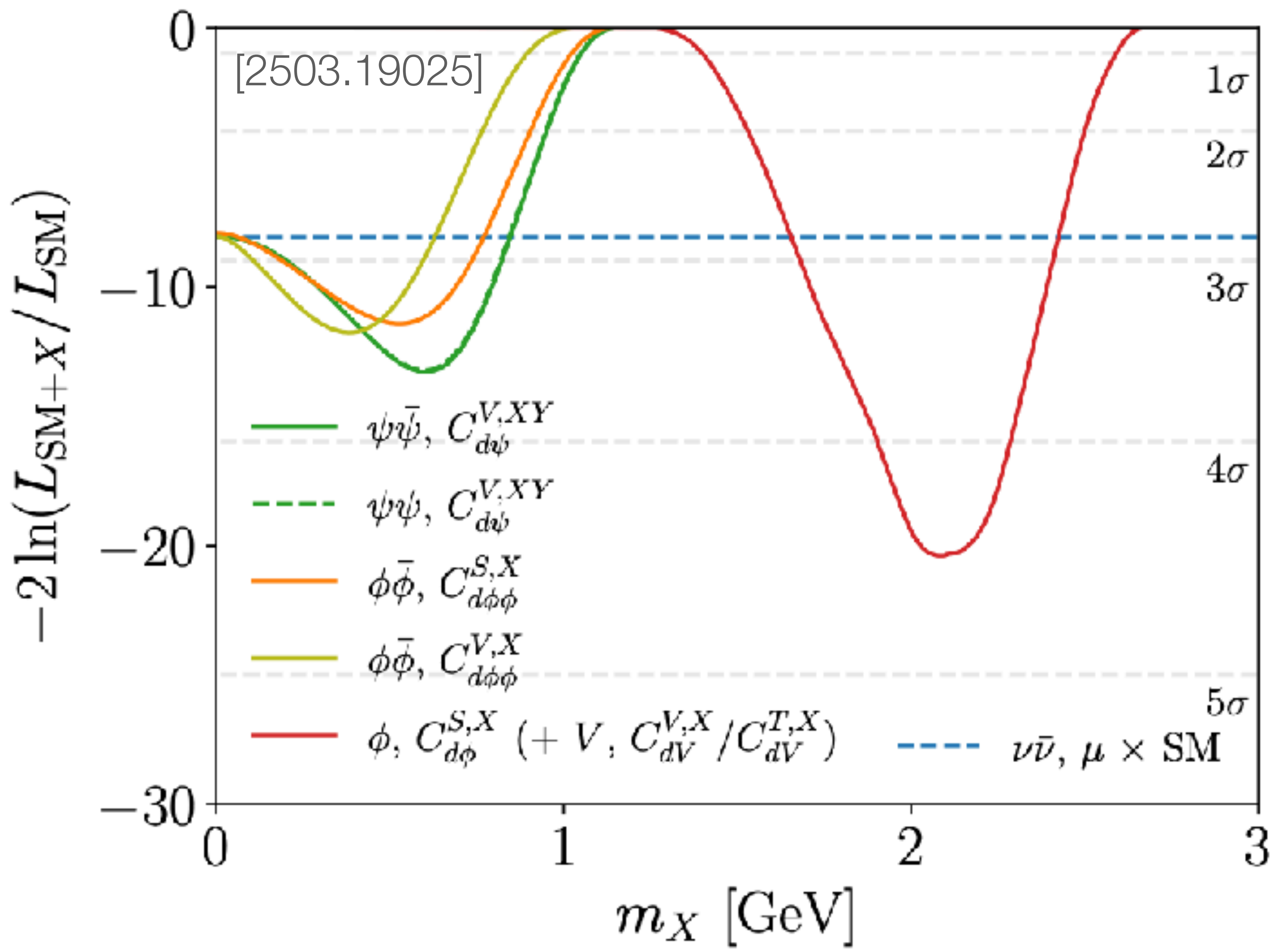


Vectors can contribute only as mediators, going then into **2 dark fermions** (**3-body decay**).
(perhaps these could then be **DM candidates**?) e.g. Gabrielli et al. 2402.05901



Data can differentiate between these scenarios

See e.g. Bolton et al. 2403.13887, 2503.19025



Axions … and ALPs

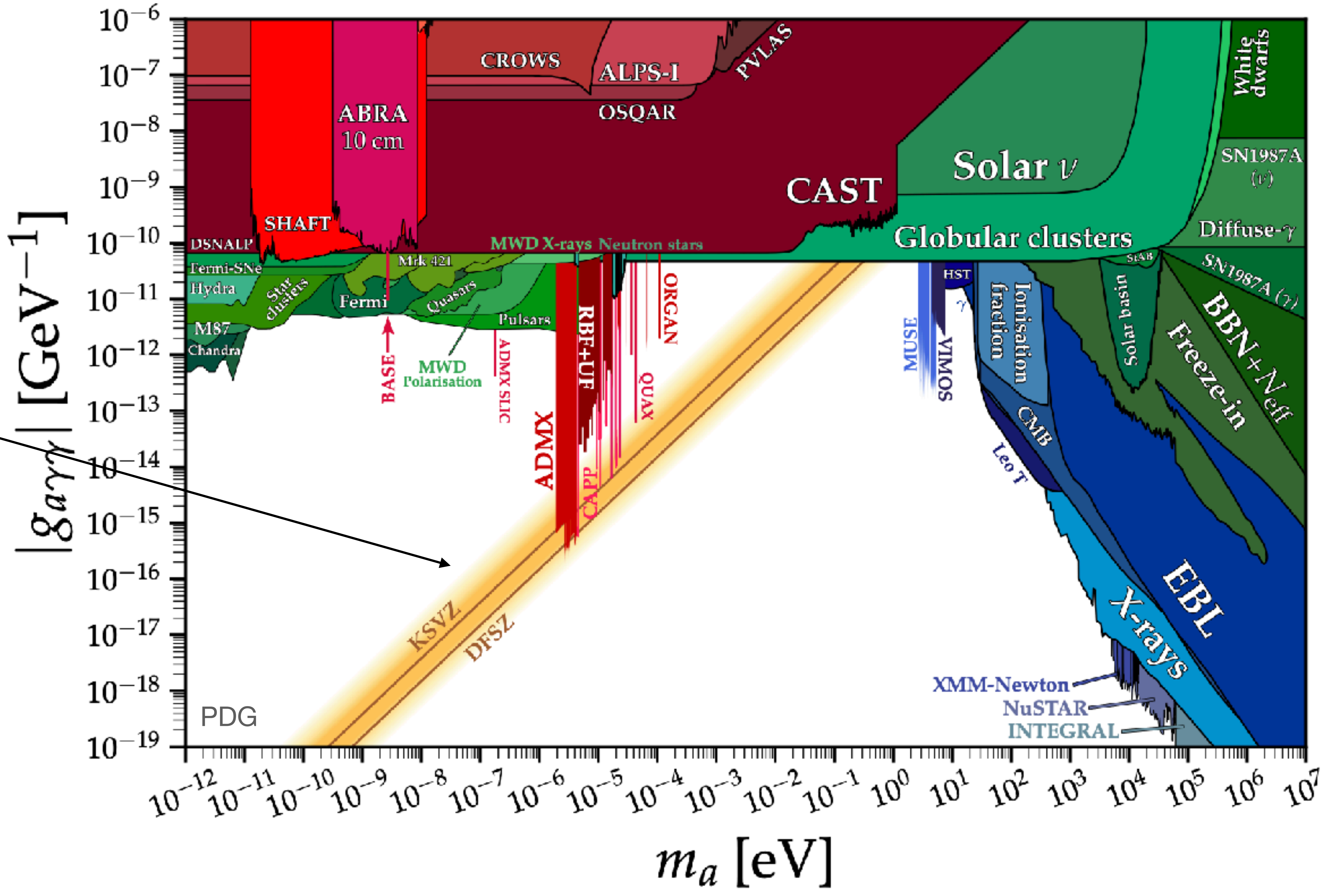
The **QCD axion** is the main prediction of the solution of the **QCD θ-problem** via a spontaneously broken **$U(1)_{PQ}$ symmetry**,

$$m_a = 5.691(51) \left(\frac{10^9\ \mathrm{GeV}}{f_a}\right) \mathrm{meV}$$

$$g_{a\gamma\gamma} \sim \frac{\alpha}{4\pi f}$$

The coupling to photons depends on the other states in the model.

$$g_{a\gamma\gamma} = \left(0.203(3)\frac{E}{N} - 0.39(1)\right) \frac{m_a}{\mathrm{GeV}^2}$$



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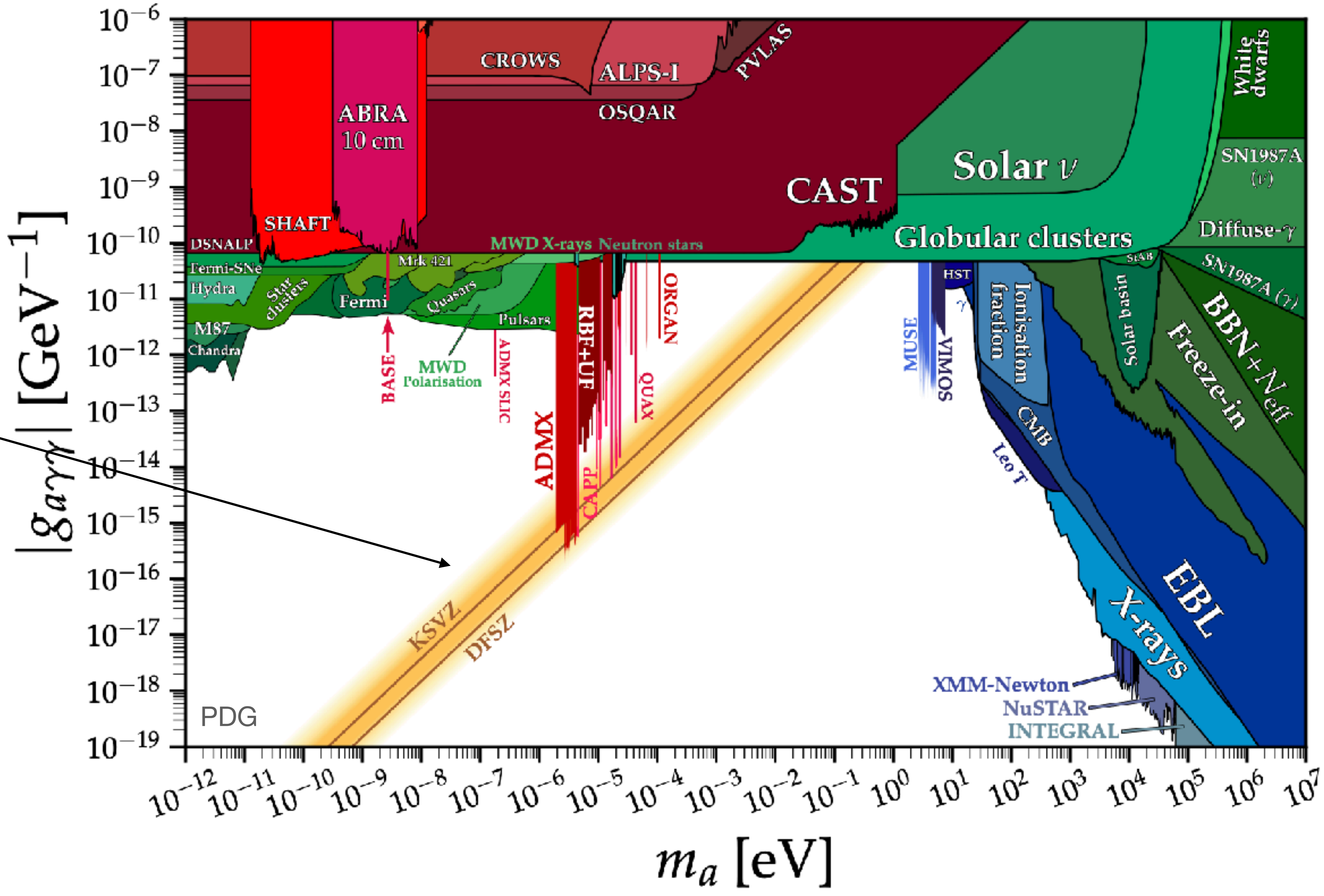


Other regions in *m-g* plane are not motivated by the θ-problem, they represent possible generic extensions of the SM.

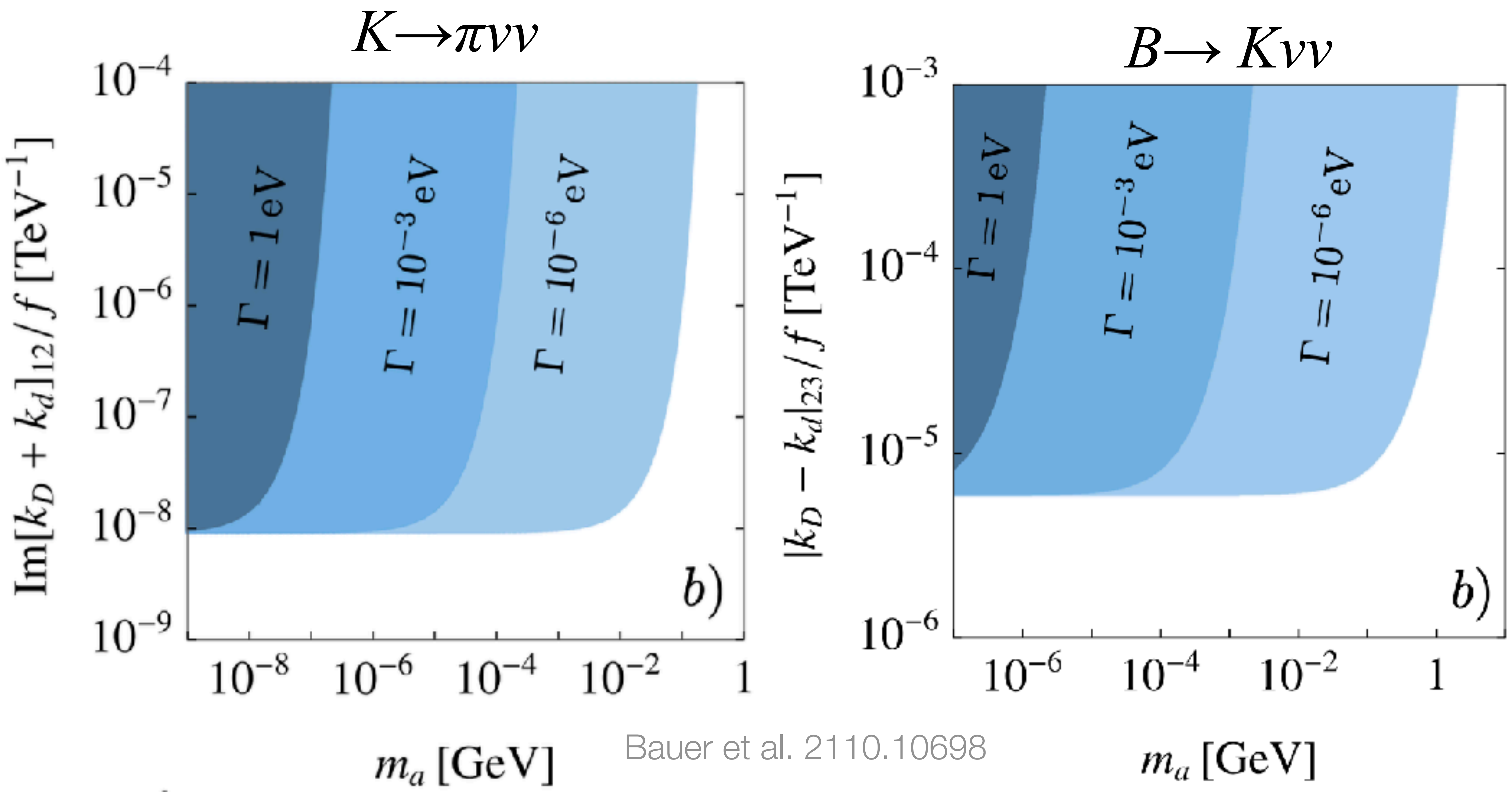
The whole log-log plane can be populated by BSM theories.

Axions … and ALPs

The QCD axion **couplings to fermions** can be **flavour-violating**, if the **PQ charges are family-dependent**.
This is well motivated in models where the PQ symmetry is connected with the explanation of SM Yukawa's.

e.g. 1806.00660, 1905.01084, 1911.02591, Axion review 2003.01100

$$\mathscr{L}_{\text{fermion}} = \frac{\partial^\mu a}{f} \bar{\psi}\, \mathbf{k}_\psi \gamma_\mu \psi$$



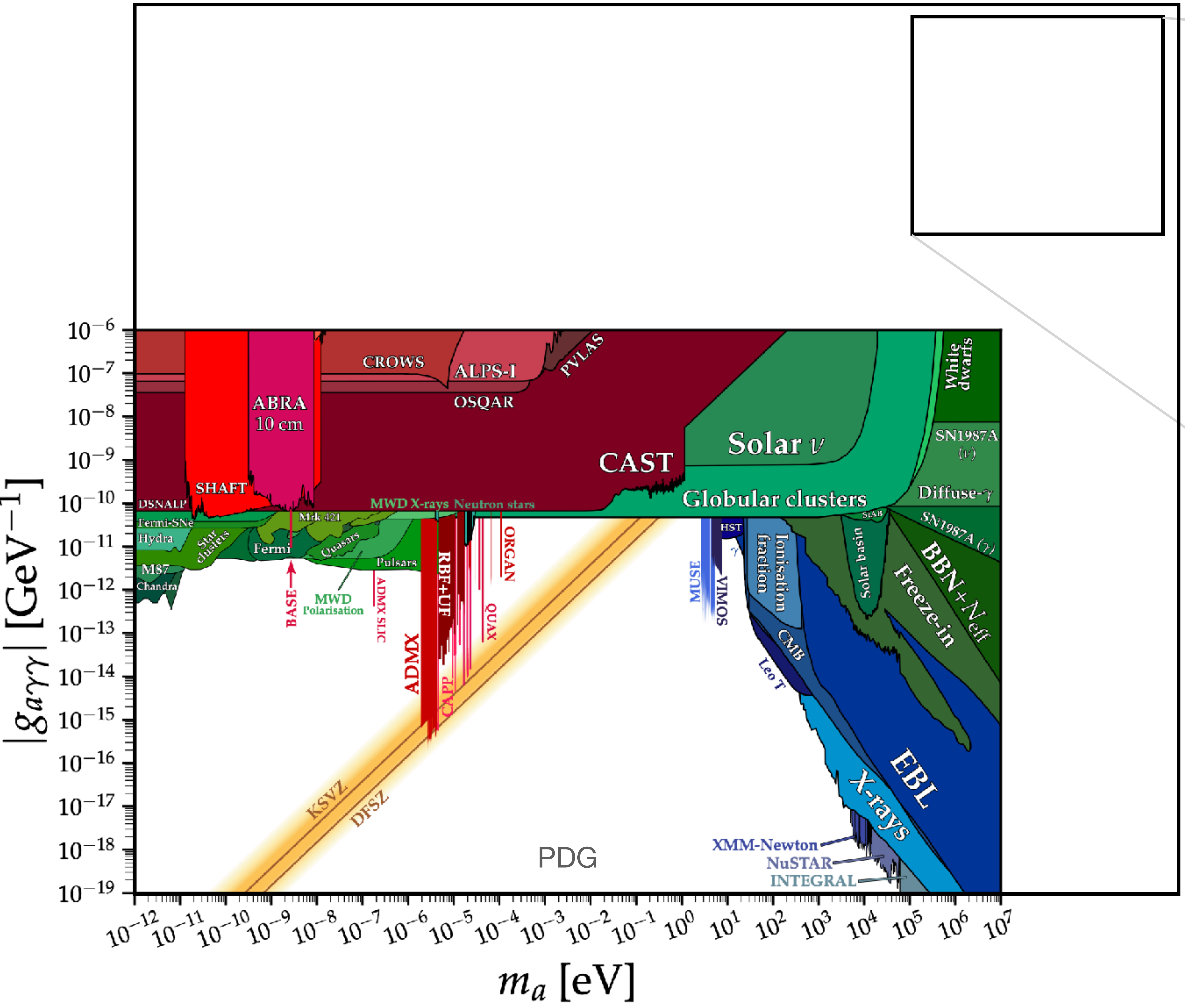
Bauer et al. 2110.10698

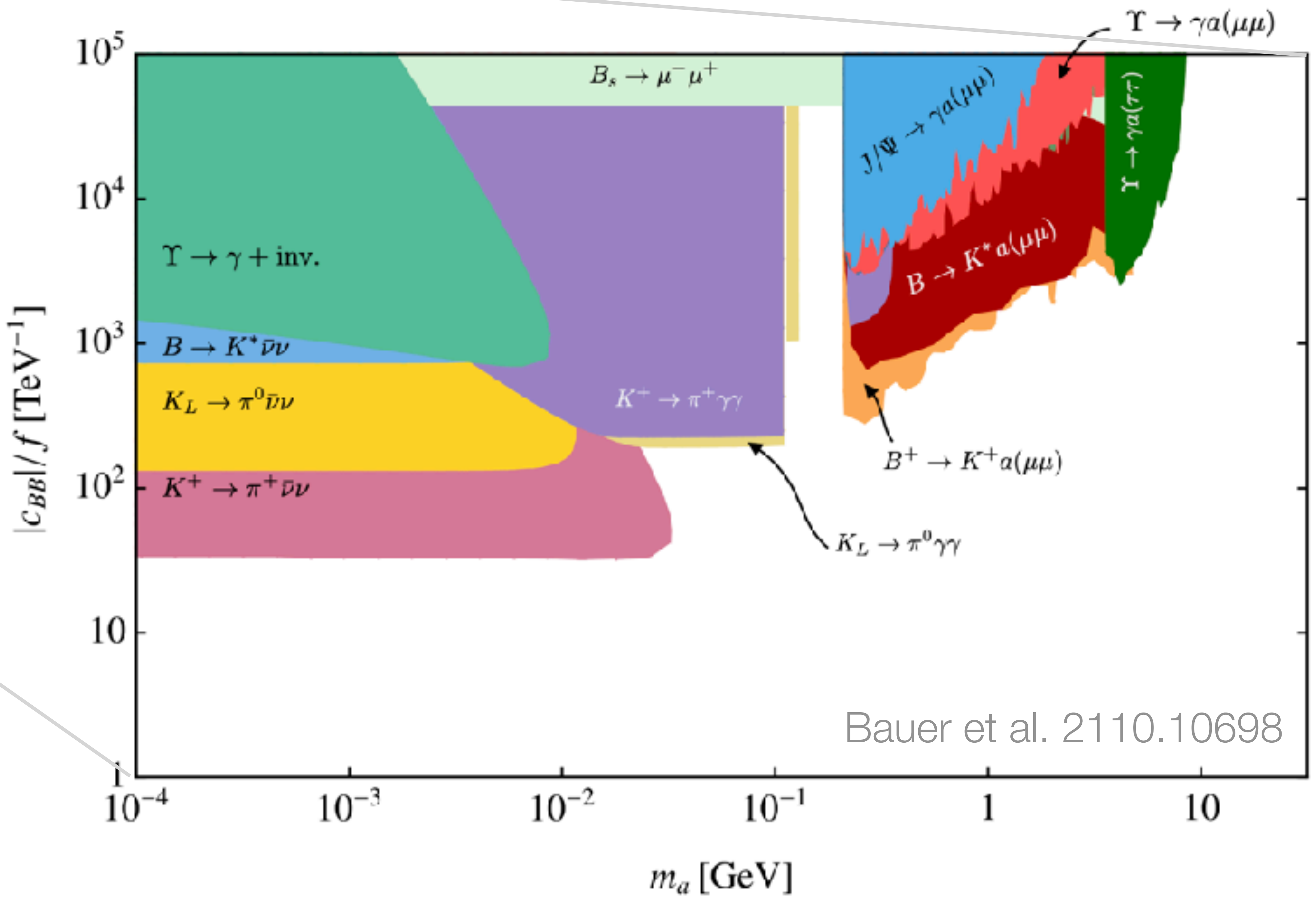
$f \gtrsim 10^{11}\, k_{12}\, \text{GeV}$ $\qquad$ $f \gtrsim 10^{8}\, k_{23}\, \text{GeV}$

For large flavour-mixings, k_{ij}~O(1), these bounds are very strong, also surpassing astrophysical ones!

Axions … and ALPs

Also **flavour-universal couplings to EW bosons** induce FCNC (via SM-like penguin diagrams)





However, in this case the region of mass and couplings probed by flavour experiments is not the one of the QCD axion:

$$f \gtrsim 10^2\, c_{BB}\, \text{GeV}$$

Axions … and ALPs

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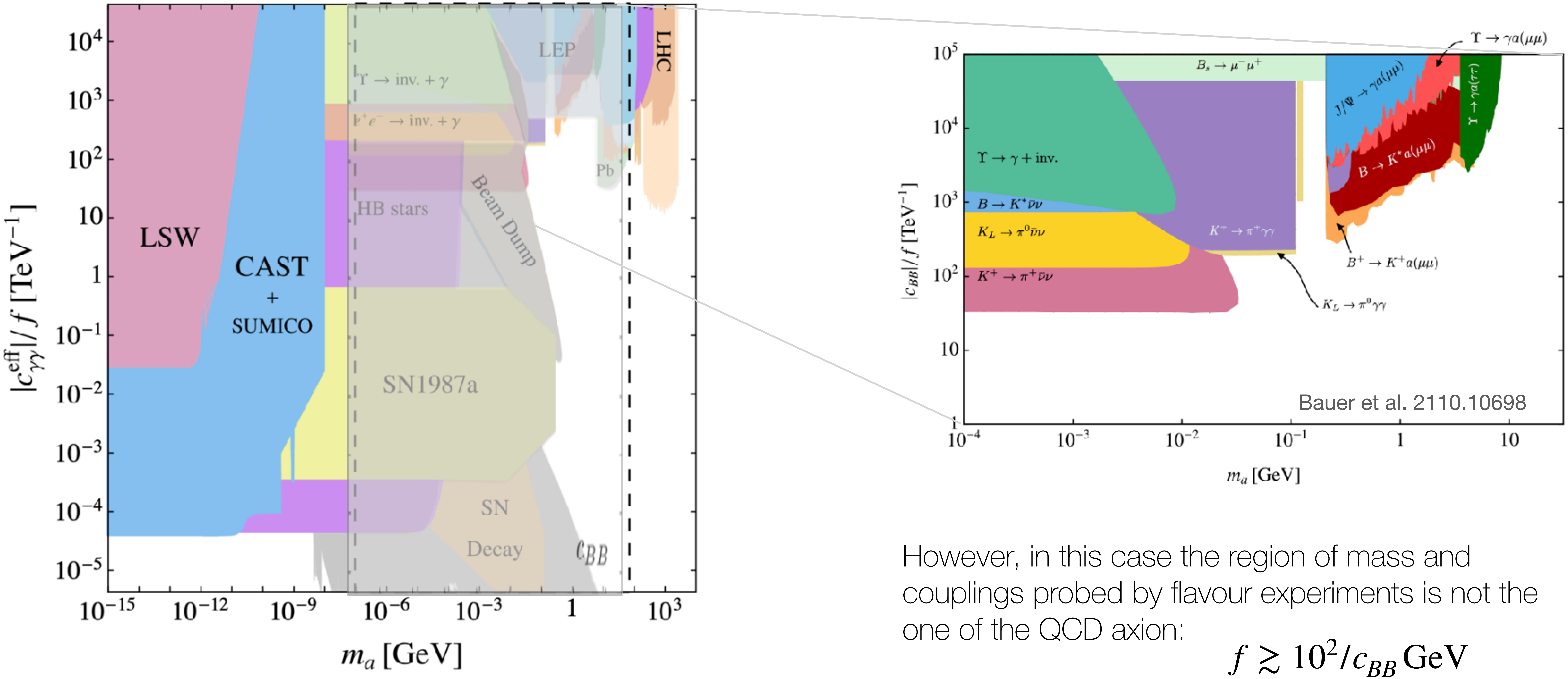

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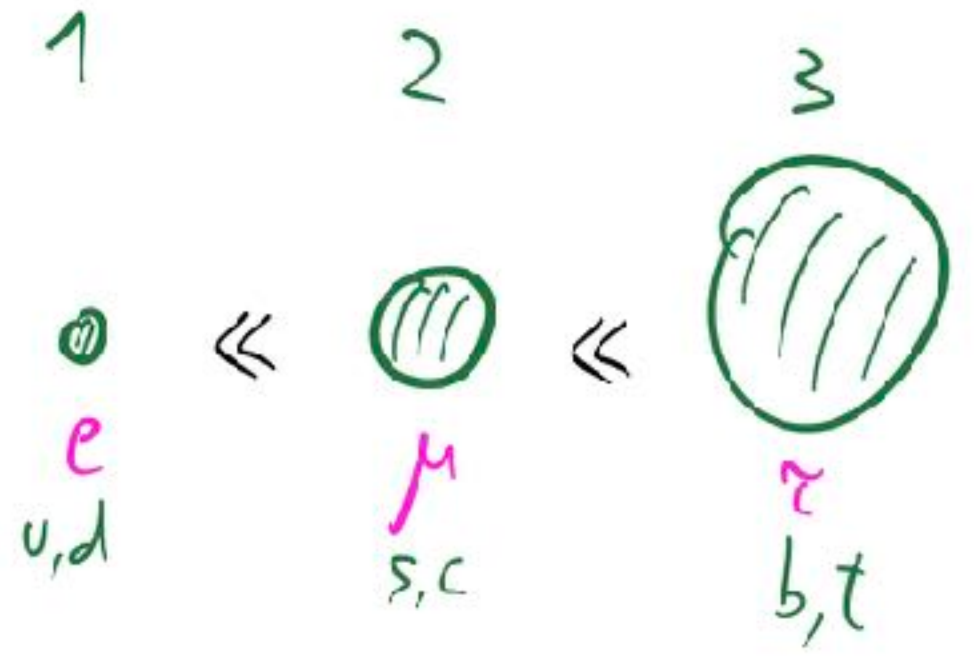
Backup

U(2)⁵ flavour symmetry



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

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

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:

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

$x_{t,b,\tau}$ 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]

$\kappa_q \sim O(1)$

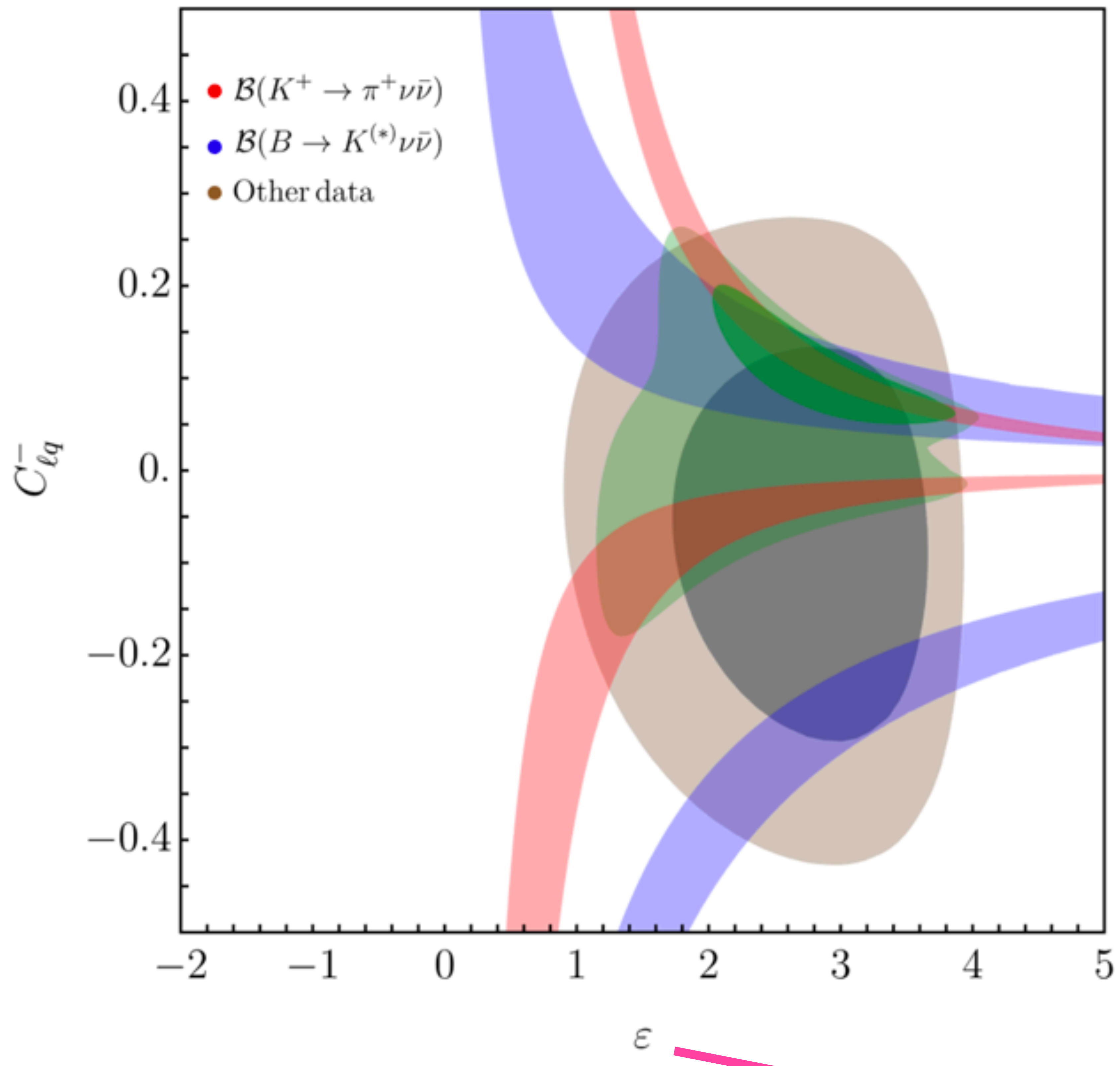
U(2)⁵ flavour symmetry and data

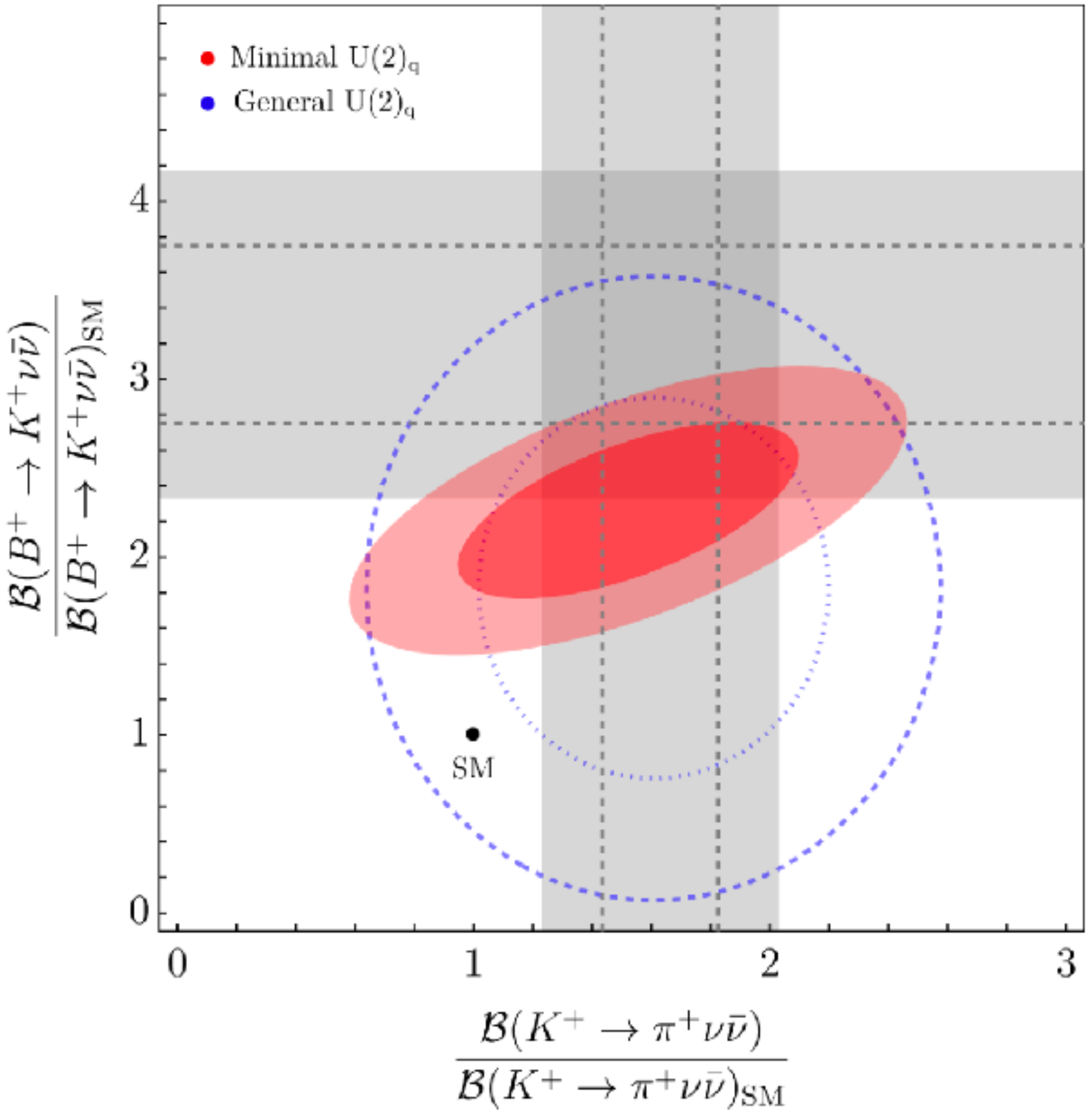
$$Q^{\pm}_{\ell q} = (\bar{q}^3_L \gamma^\mu q^3_L)(\bar{\ell}^3_L \gamma_\mu \ell^3_L) \pm (\bar{q}^3_L \gamma^\mu \sigma^a q^3_L)(\bar{\ell}^3_L \gamma_\mu \sigma^a \ell^3_L)$$

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

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

Allwicher et al. [2410.21444]





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

Rare Semileptonic and Leptonic decays

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

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

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
CKM-like (MFV, U(2),..)	$c = c_{CKM}$	$c_{CKM} = \lvert V_{ts}\rvert$ **11 TeV**	$c_{CKM} = \lvert V_{ts}\rvert$ **6.6 TeV**	$c_{CKM} = \lvert V_{td}\rvert$ **1.6 TeV**	$c_{CKM} = \lvert V_{td} V_{ts}\rvert$ **1.4 TeV**	$c_{CKM} = i\lvert V_{td} V_{ts}\rvert$ **0.2 TeV**	$c_{CKM} = \lvert V_{cb} V_{ub}\rvert$ **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**.