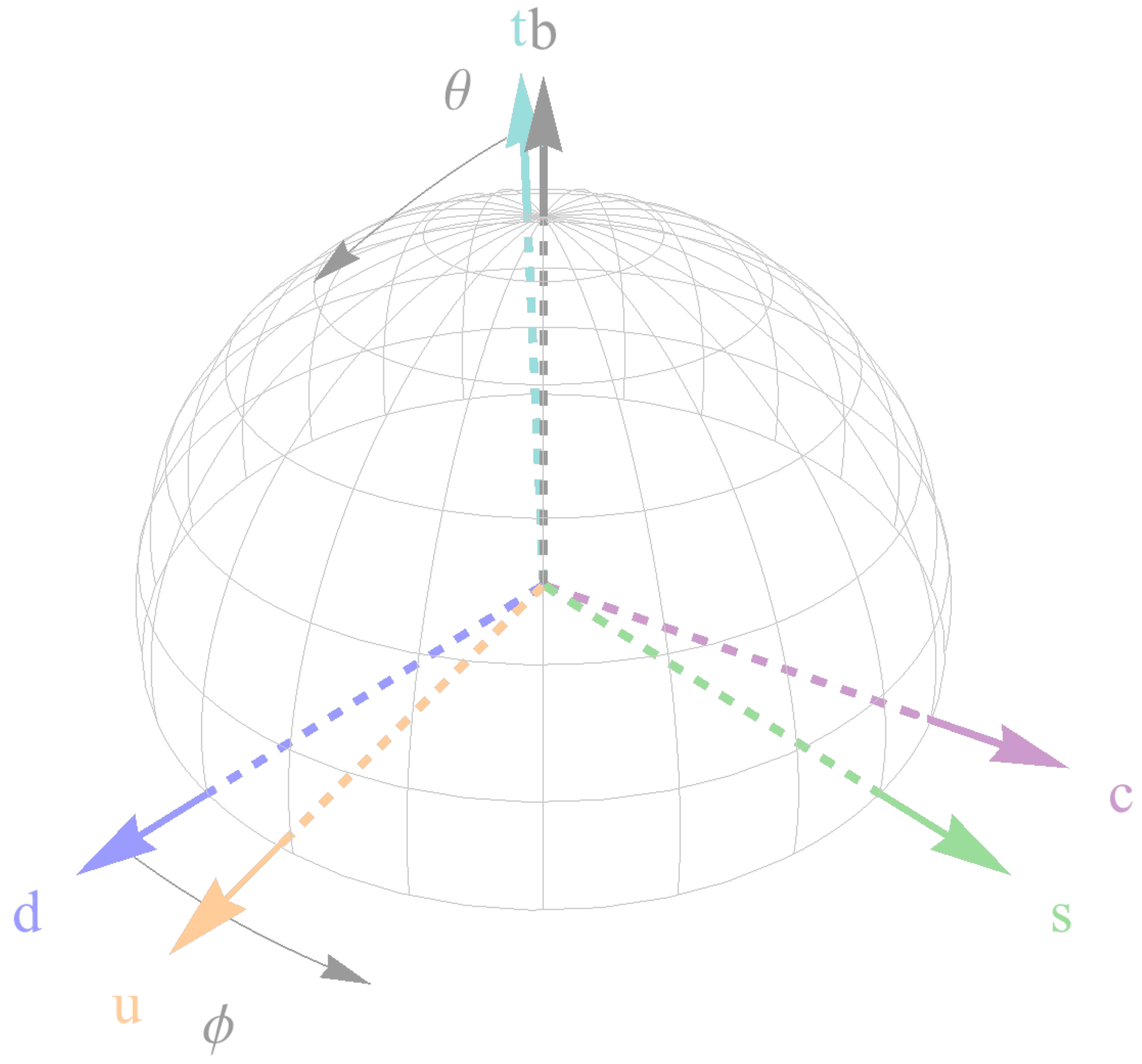
New Physics in Top Operators

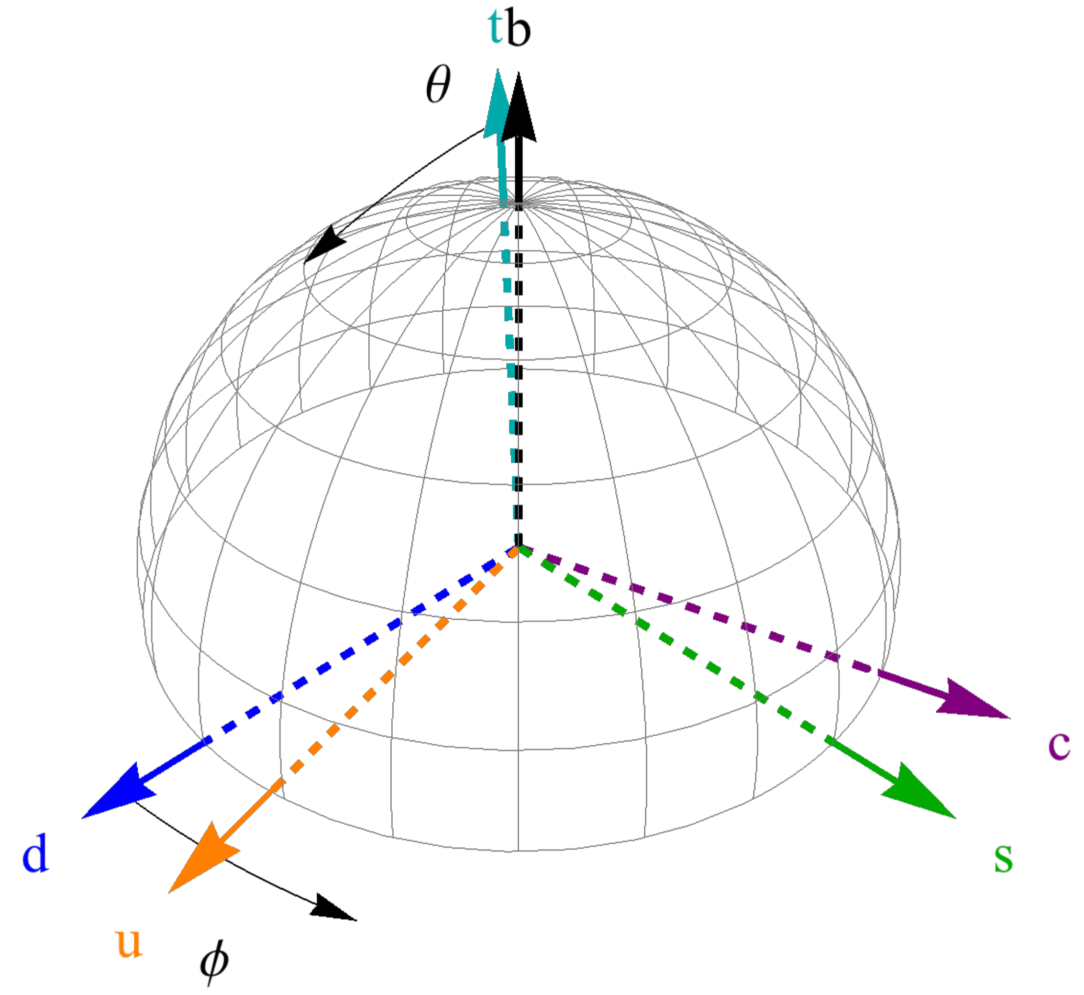


David Marzocca

INFN Trieste

DISCRETE 2024 - 02/12/2024

Outline



1) Introduction: the New Physics flavour problem & EFT approach

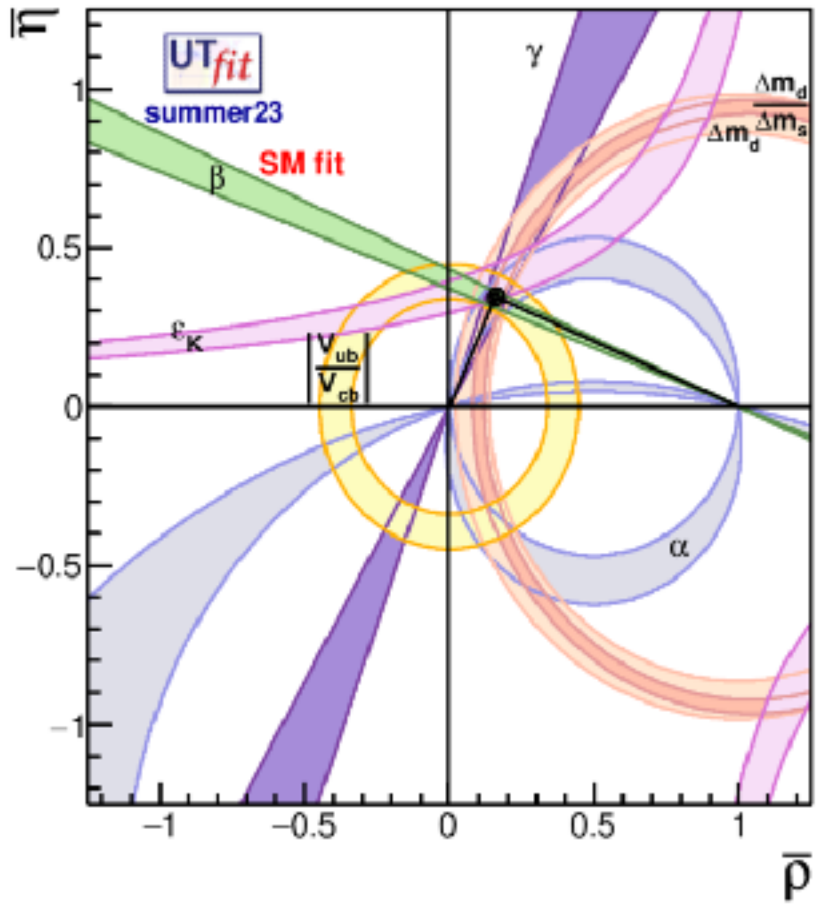
2) How much aligned to the third generation should New Physics couplings be?

- Take the $B \to K\nu\nu$ **excess** as a guide to set an overall scale of New Physics
- Consider a **specific flavour structure** that allows to deviate arbitrarily from the third generation, while keeping only a few parameters (unlike a general SMEFT approach).
- Evaluate **quantitatively** the **allowed misalignment** from third generation.

3) What are the constraints on heavy New Physics coupled to the top quark?

Indirect (Flavour + EW) vs. ***Direct*** (LHC)

The BSM Flavour Problem



Flavour in the **SM has a rigid structure**: accidental symmetries and suppression (**FCNC**, **CP violation**, **LFV**, etc).

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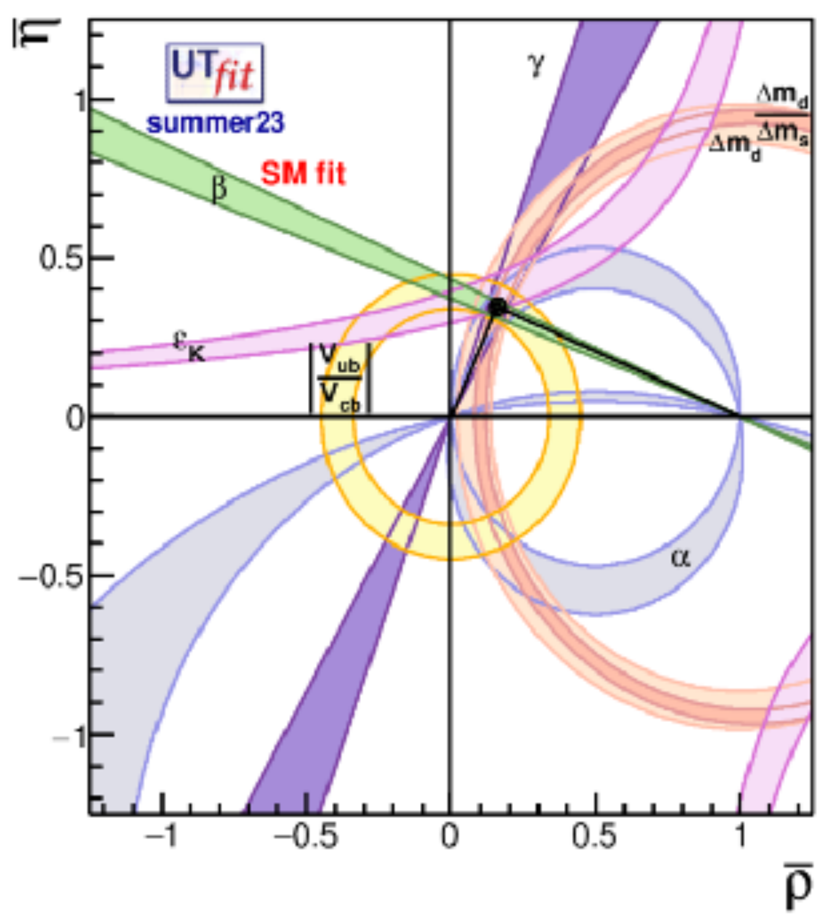

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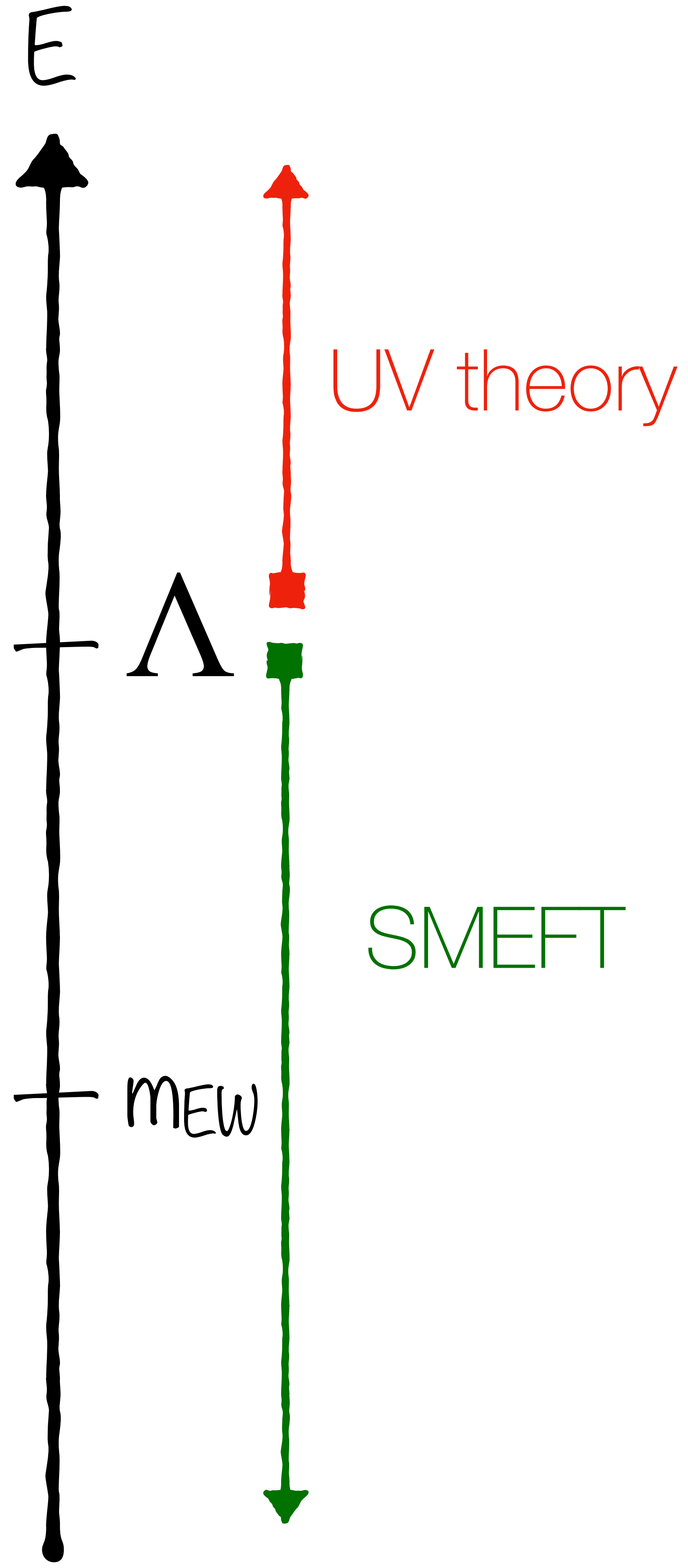

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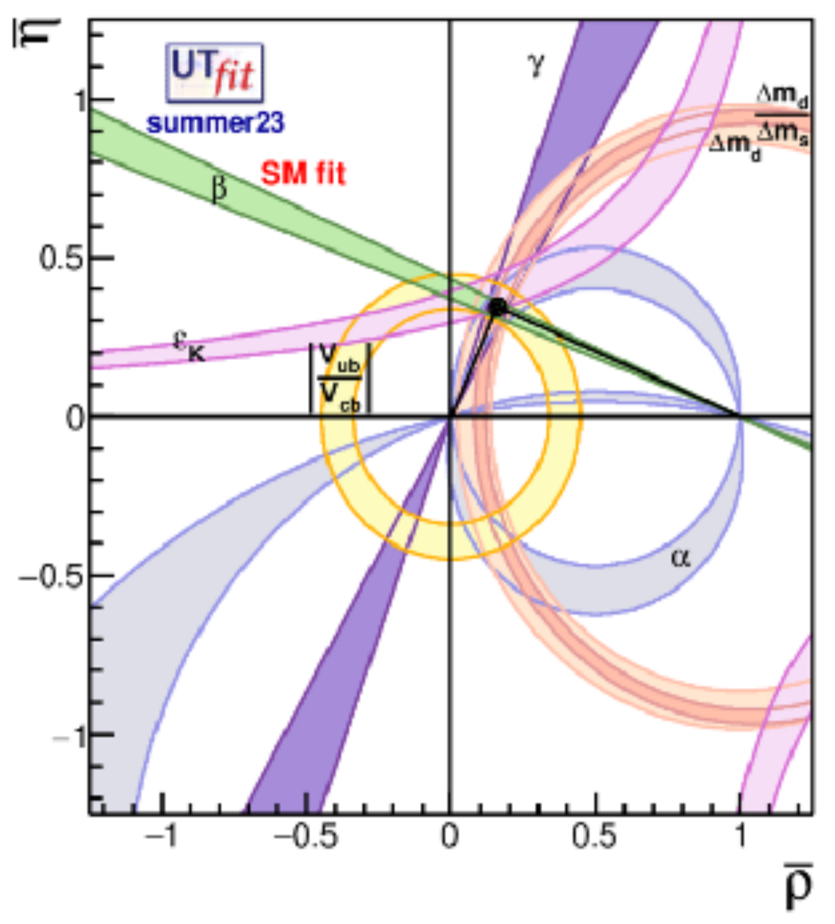

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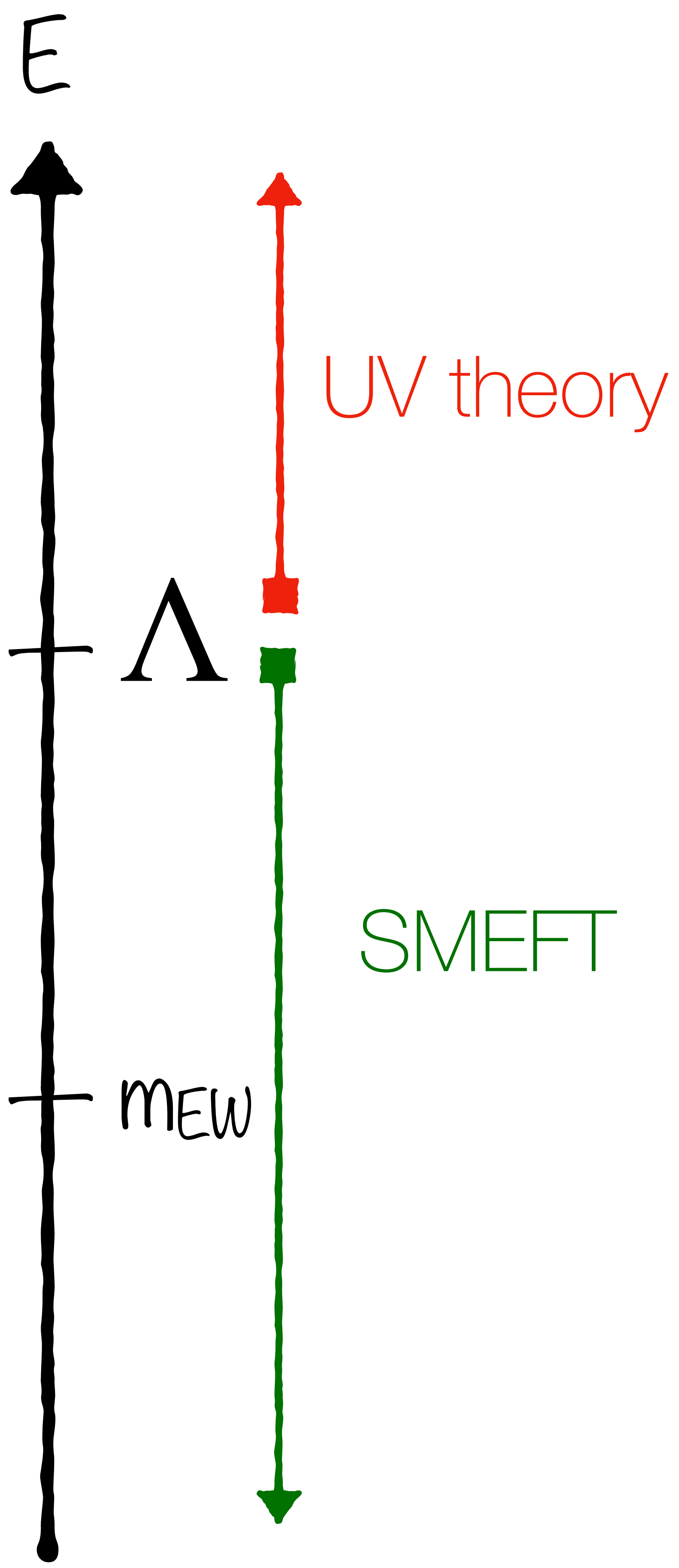

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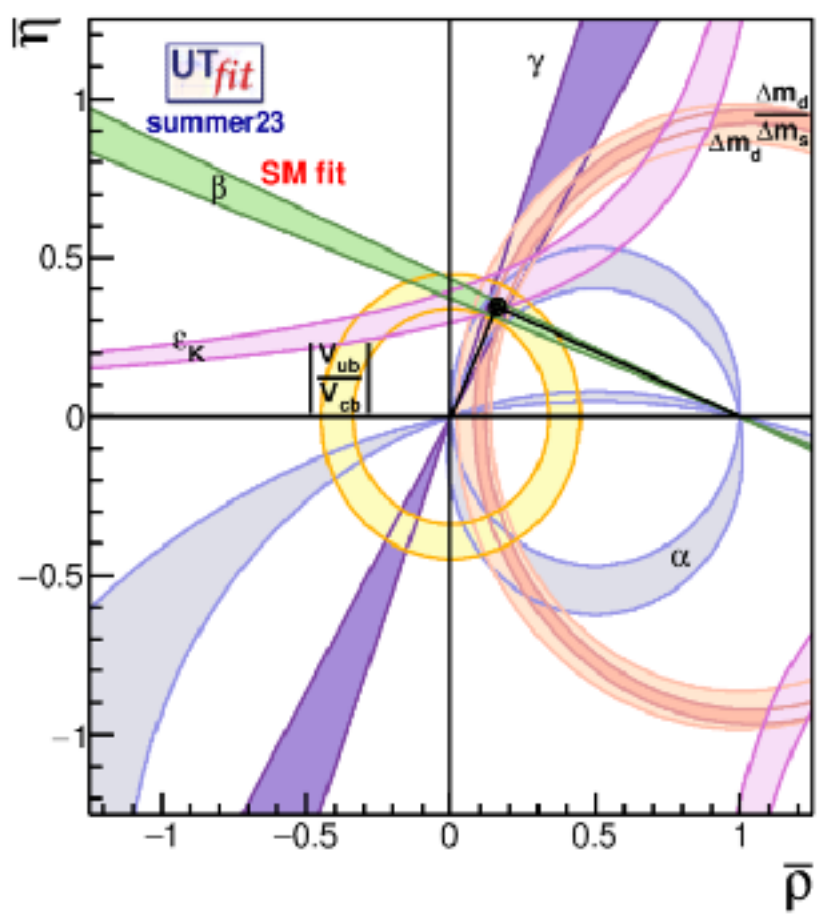
$$\mathcal{L}_{SMEFT}^{(d=6)} = \sum_i \frac{C_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)}[\varphi_{SH}]$$

→ ***in general violate all the accidental symmetries and properties of the SM***

We can expect large effects in rare or forbidden processes!

The BSM Flavour Problem



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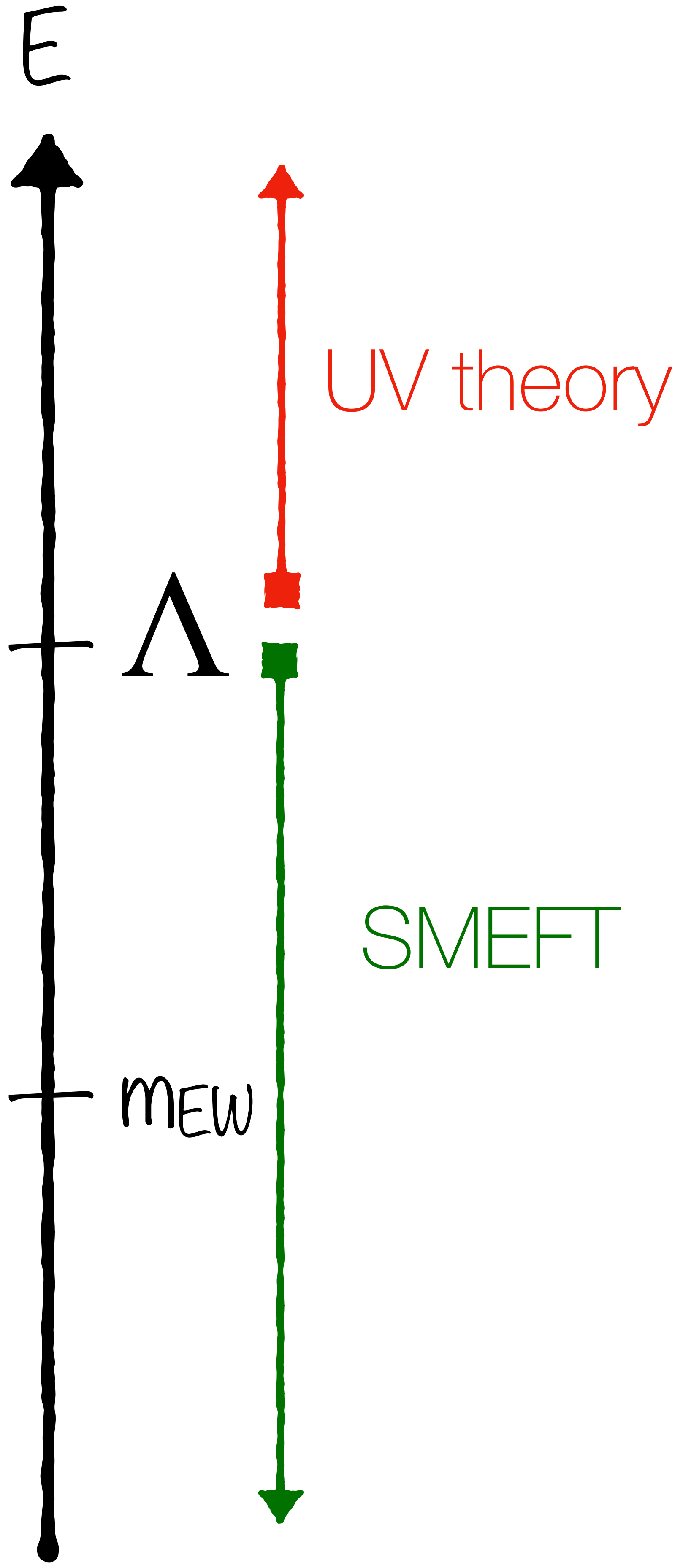

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We can expect large effects in rare or forbidden processes!

Precision tests of forbidden or suppressed processes in the SM **are powerful probes of physics Beyond the Standard Model.**

>> Flavour Physics ! <<

The BSM Flavour Problem

Precision tests push Λ to be very high

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

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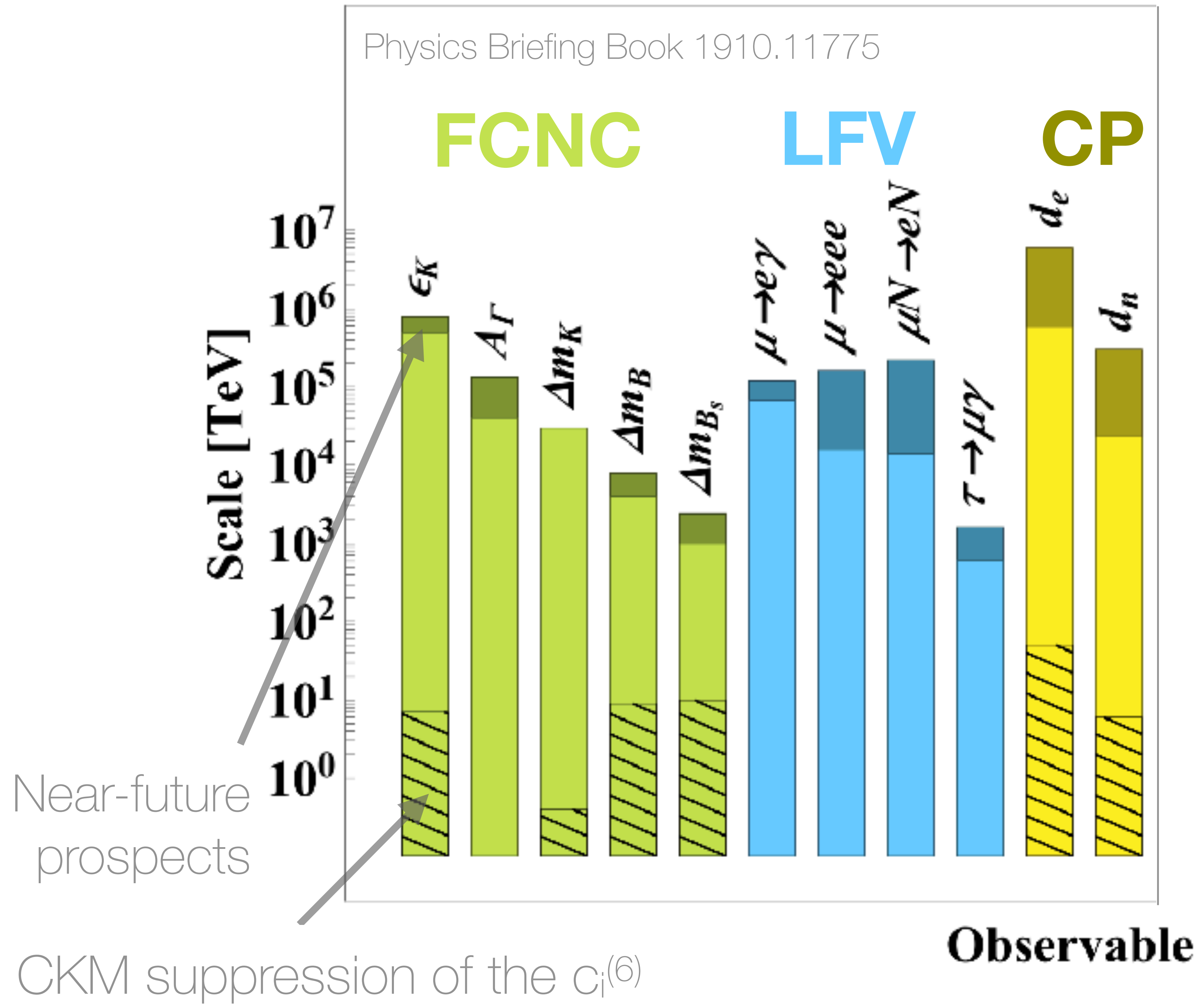

If $c_{FV}^{(6)} = 1$: $\Lambda_{FV} \gtrsim 10^6$ TeV

The BSM Flavour Problem

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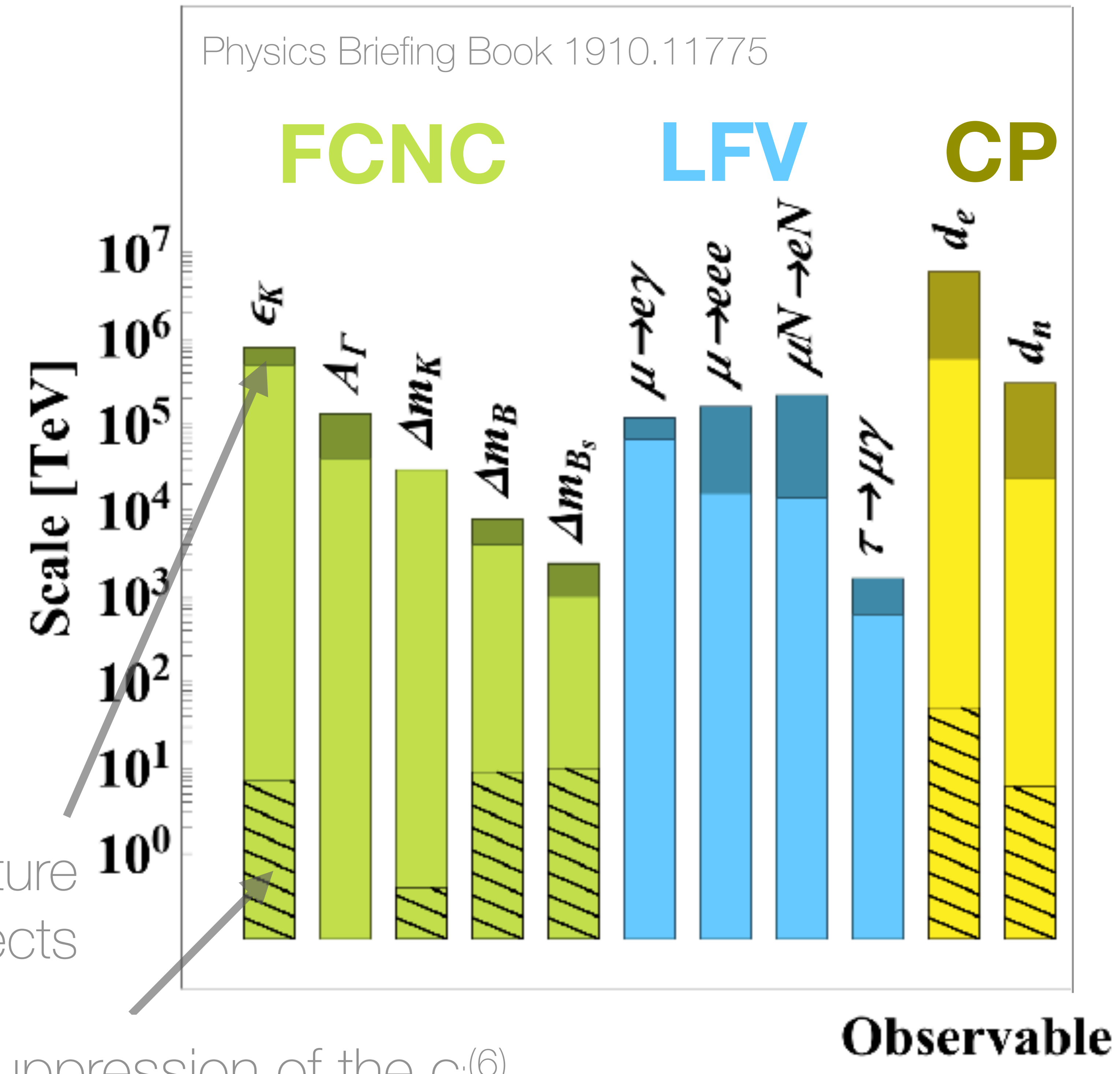

Near-future prospects

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

If $c_{FV}^{(6)} = 1$: $\Lambda_{FV} \gtrsim 10^6$ TeV

Smaller values of the NP scale are instead **motivated**

$\Lambda_{NP} \sim 1$ - 10 TeV

- Solutions to the Hierarchy Problem
- Reach of present/future colliders
- Experimental anomalies

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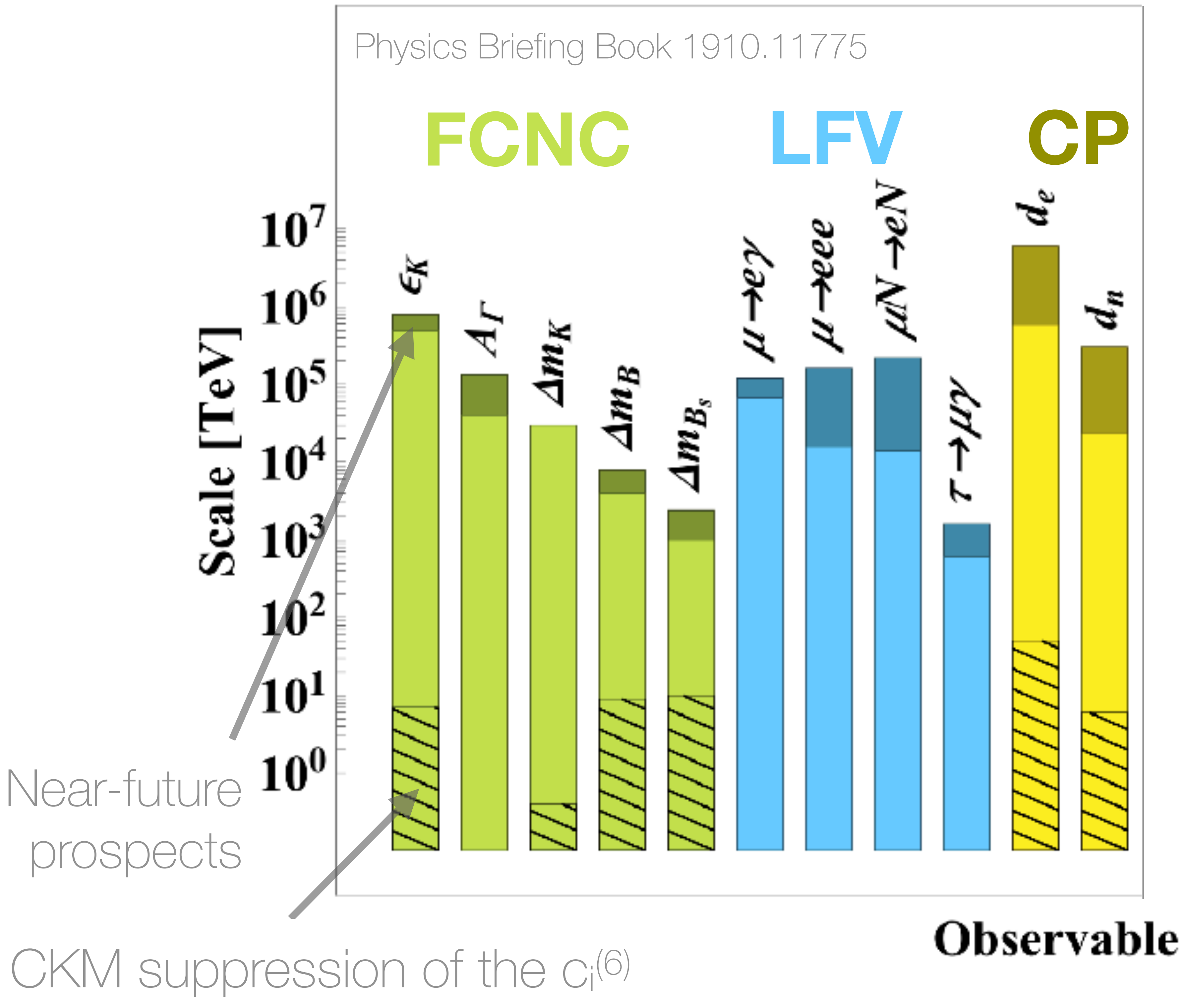

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★ Need some Flavour Protection

E.g. CKM-like suppression of FCNC

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

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

MFV-like: $\varepsilon_{1,2} \sim 1$

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

E.g. Scalar LQ: $M_{LQ(\mu,e)} \gtrsim 1.8$ TeV $M_{LQ(\tau)} \gtrsim 1.1$ TeV

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New Physics coupled to the top should be **lighter** in order to address the **Higgs hierarchy problem**, could also be related to the SM flavour puzzle (lighter NP gives larger Yukawas in some models).

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★ **Non-universal couplings preferred**

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

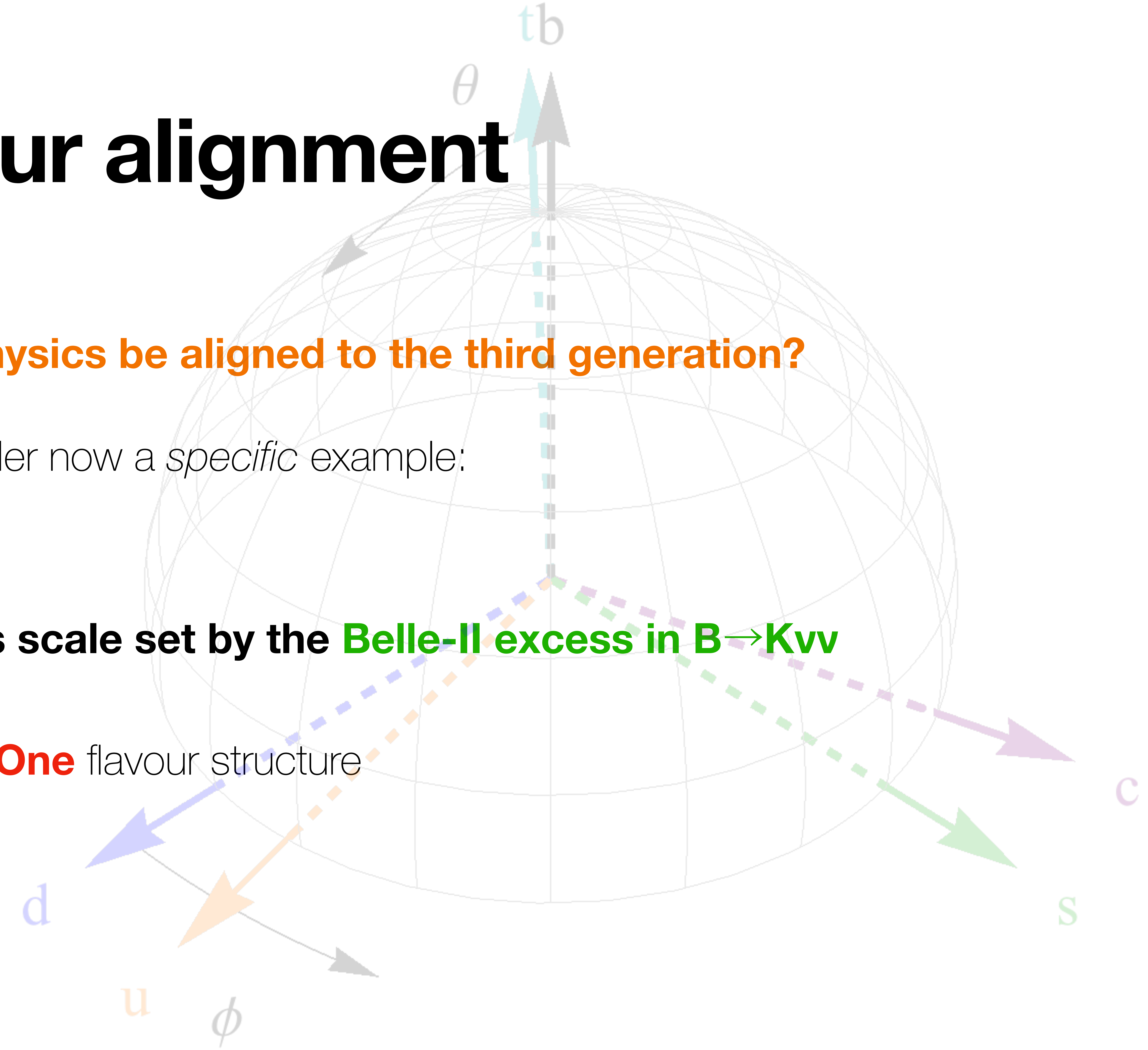
Flavour alignment

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**

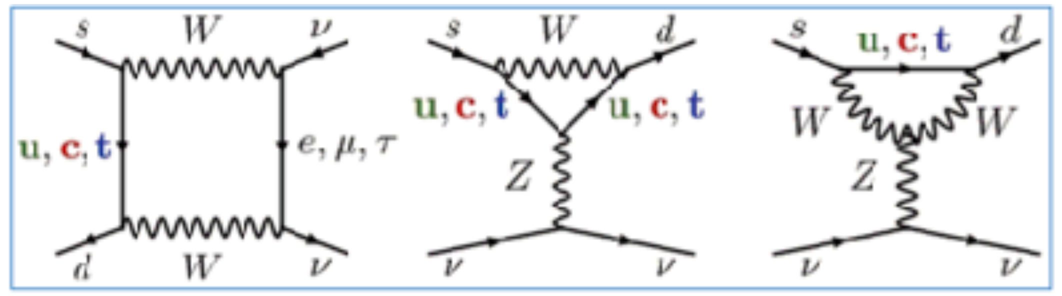
- We assume a **Rank-One** flavour structure



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

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

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, …

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

Becirevic et al. 2301.06990

$\mathrm{BR}(B^0 \to K^{*0} \nu \bar{\nu})_{\mathrm{SM}} = (9.05 \pm 1.4) \times 10^{-6}$

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

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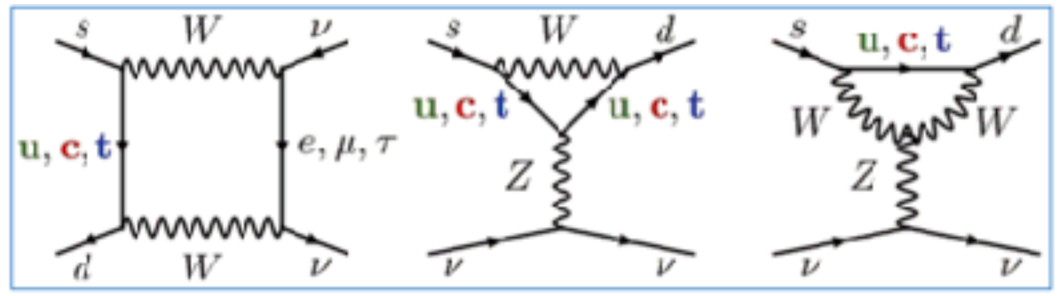

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$$R_K^\nu = \frac{\mathrm{BR}(B \to K \nu \bar{\nu})}{\mathrm{BR}(B \to K \nu \bar{\nu})^{SM}} = 2{,}93 \pm 0{,}90 \quad 2.1\sigma$$

$$R_{K^*}^\nu = \frac{\mathrm{BR}(B \to K^* \nu \bar{\nu})}{\mathrm{BR}(B \to K^* \nu \bar{\nu})^{SM}} < 3.2 \quad @95\%CL$$

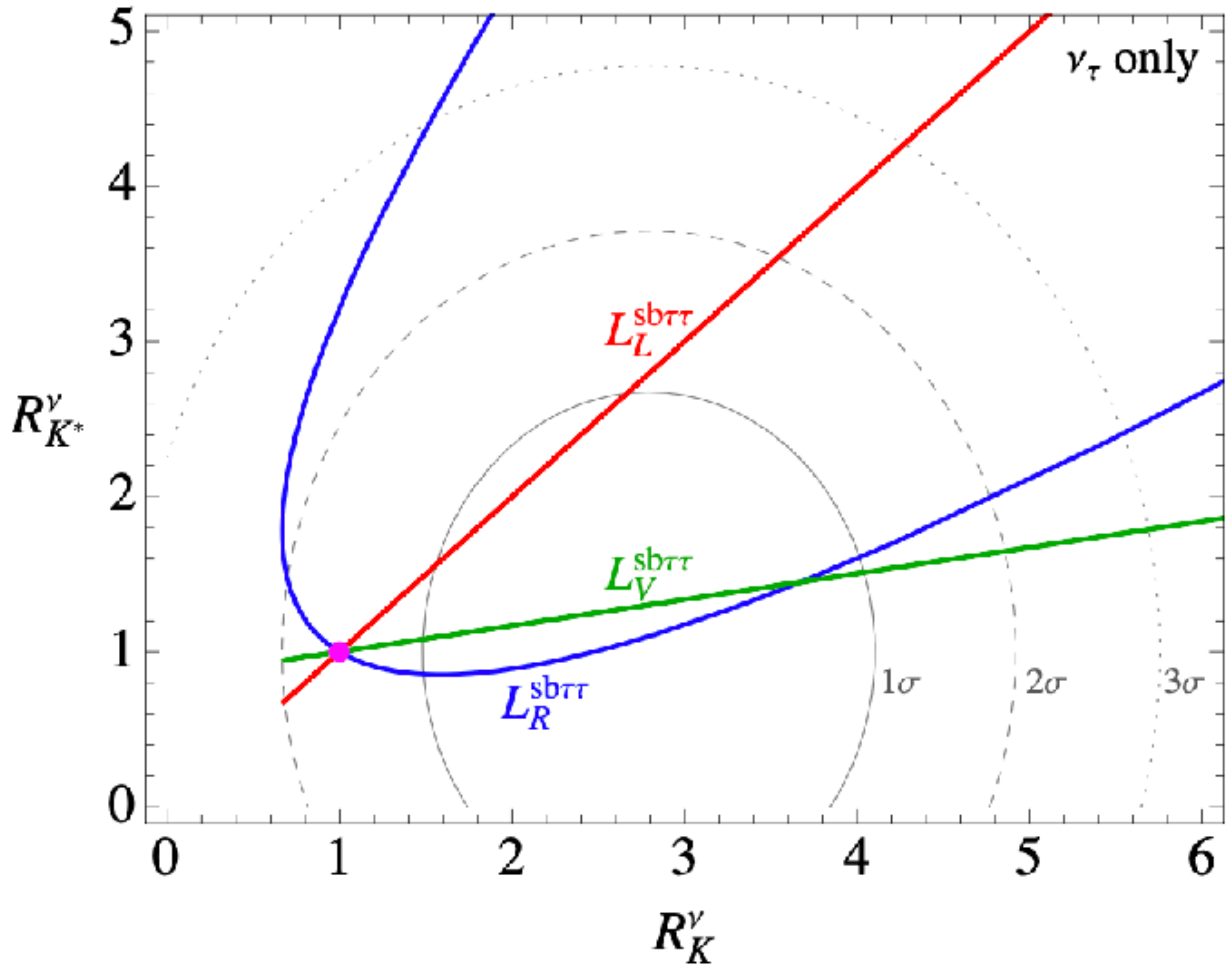
Golden channel decay $B \to K^{(*)} \nu \bar{\nu}$

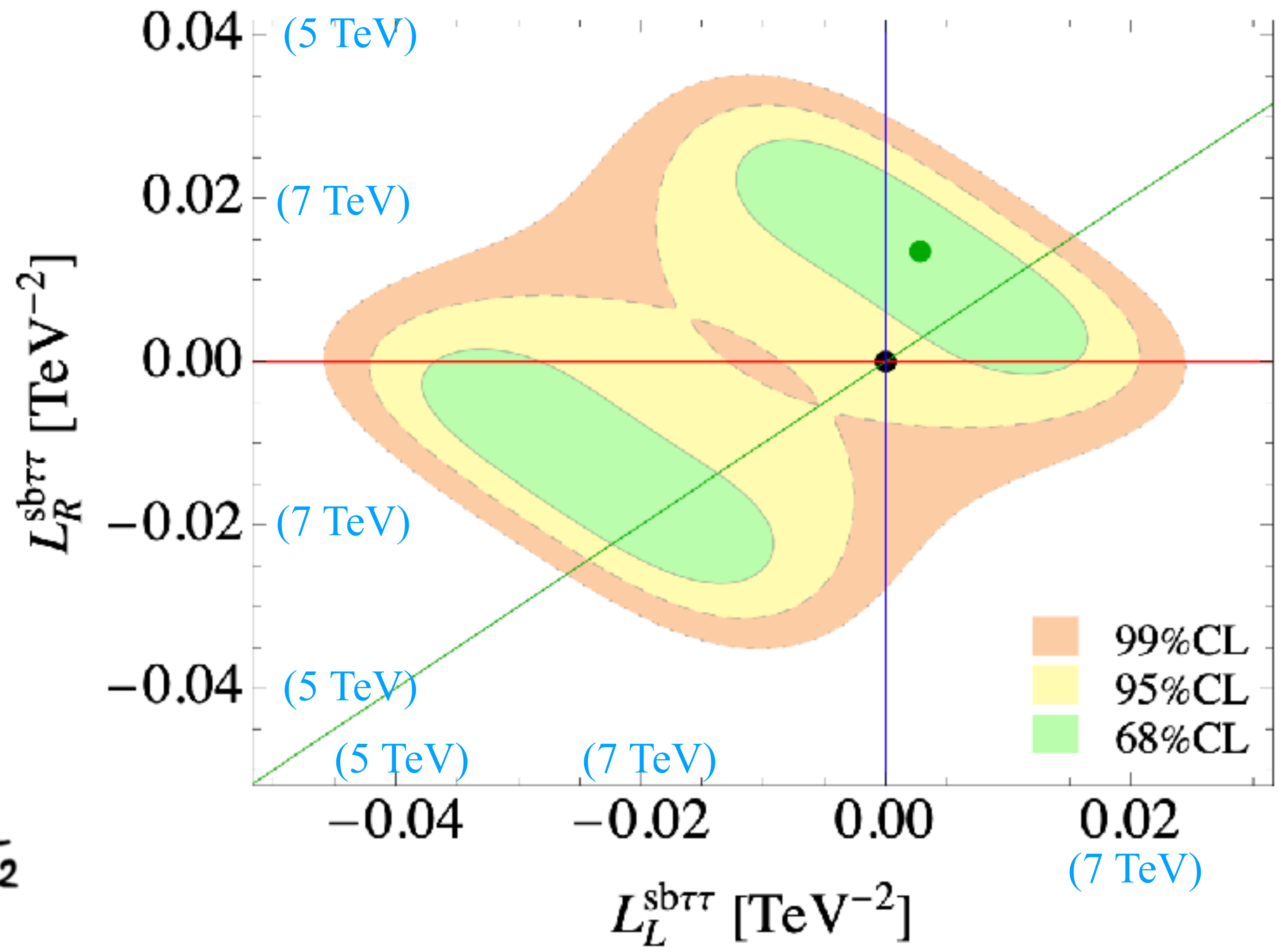
Assuming **only NP in tau**
(see paper for other cases)

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

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

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





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

$$L^{sb\nu\nu} \sim \frac{1}{(8\ \text{TeV})^2}$$

They probe scales of about 8 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.

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

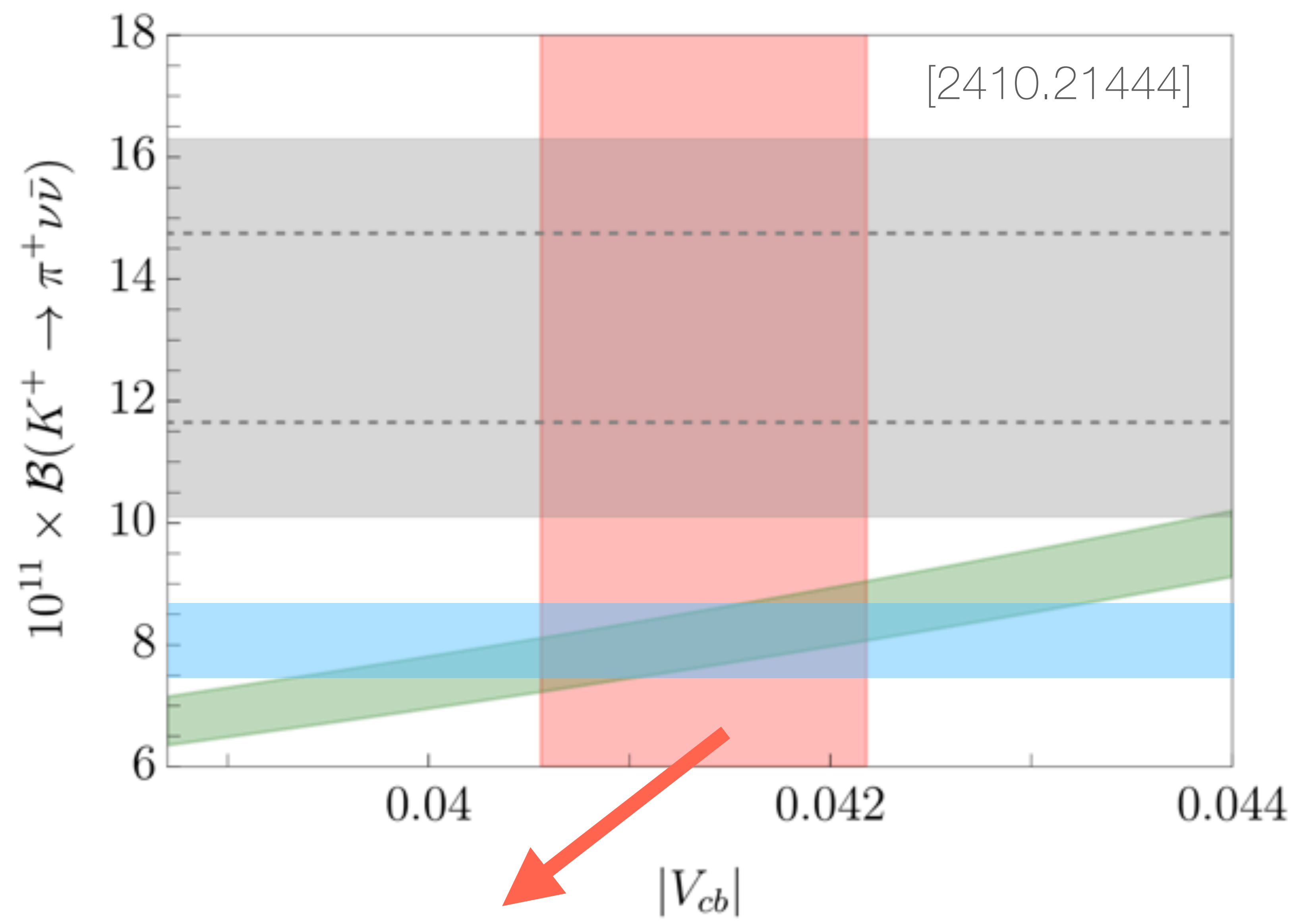
NA62 (CERN)

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

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)

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

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KOTO_{2021}:

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

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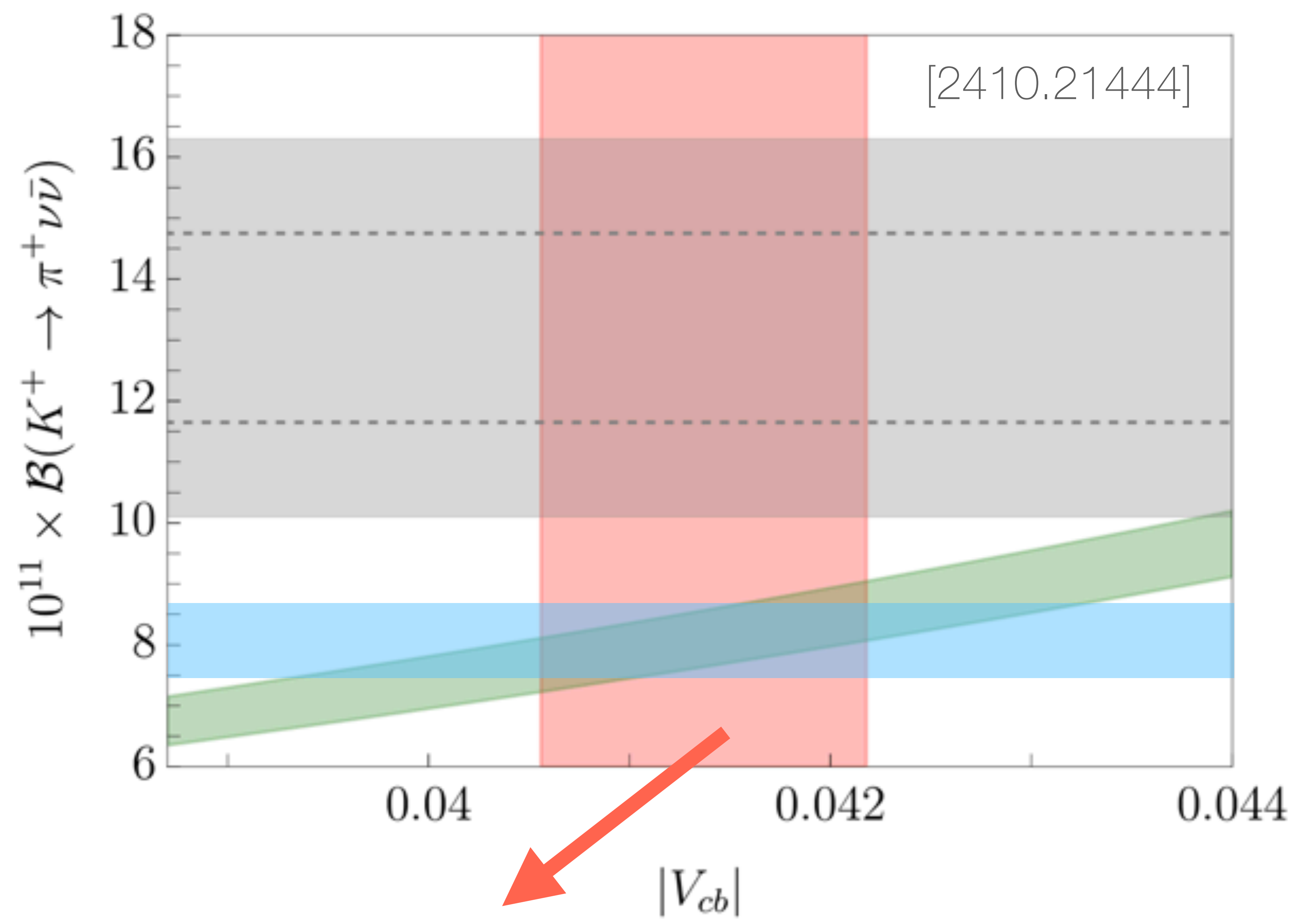

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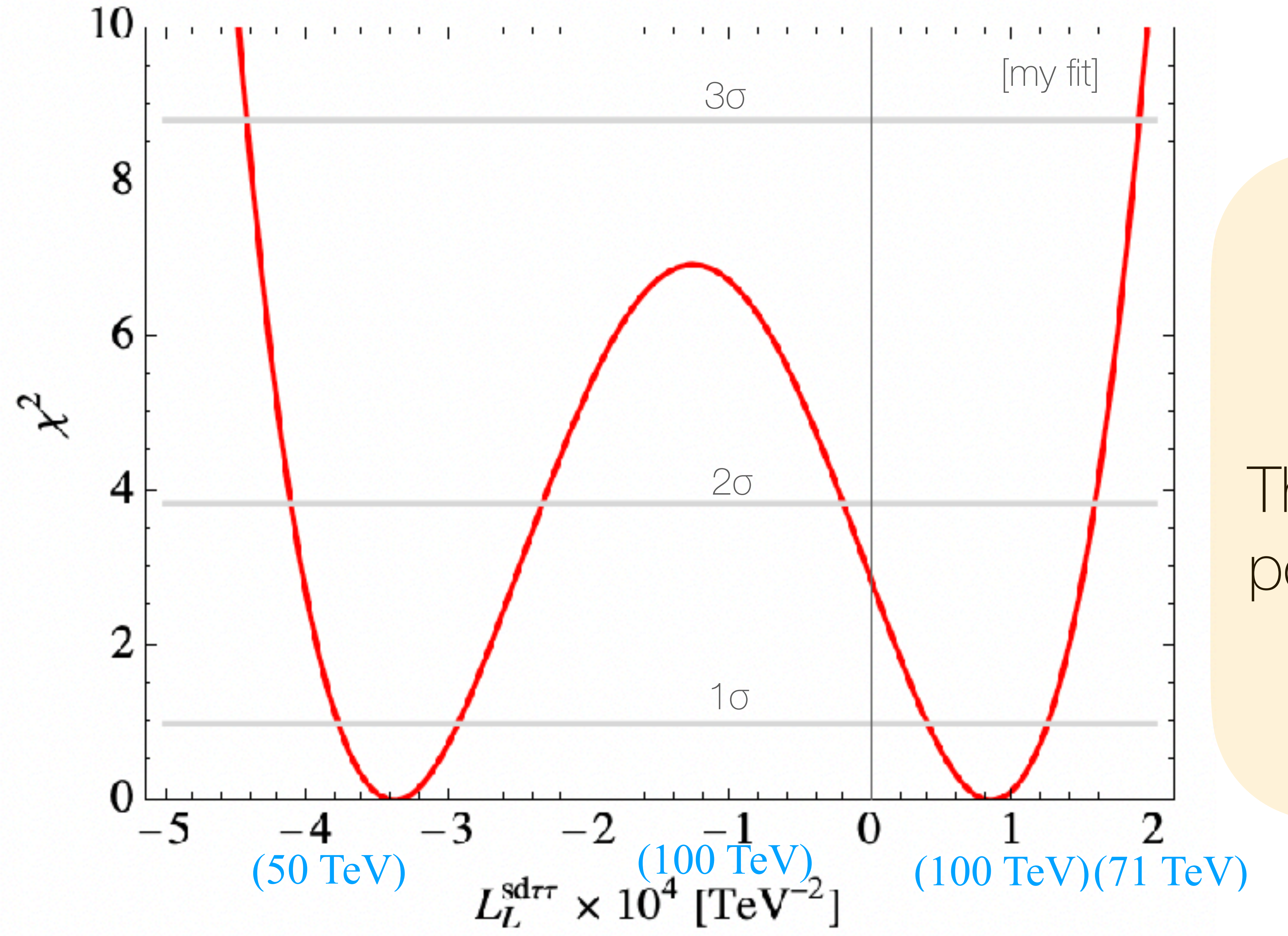

$L \sim \frac{1}{\Lambda^2}$

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

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

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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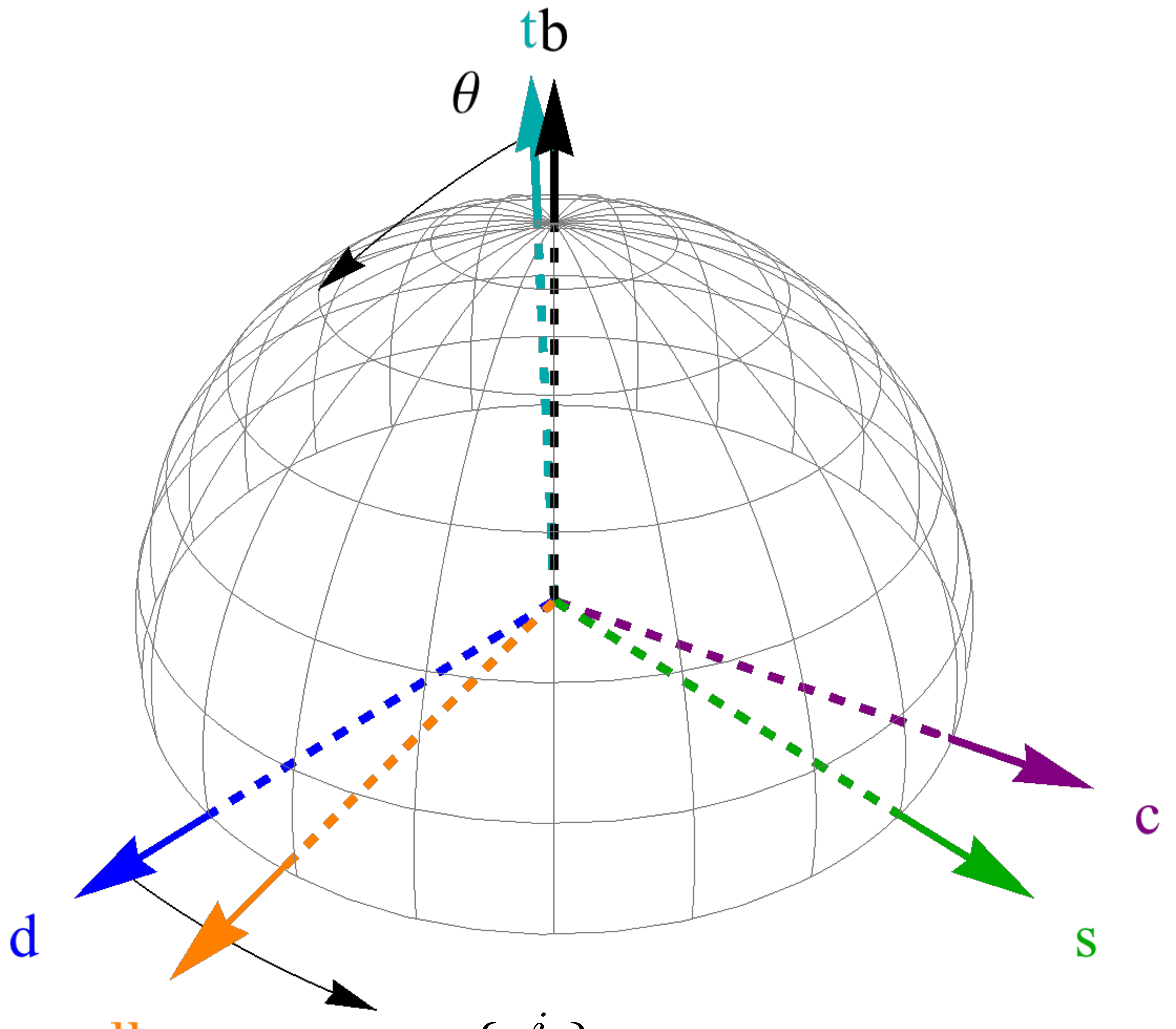
We can parametrise a generic directions as:

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

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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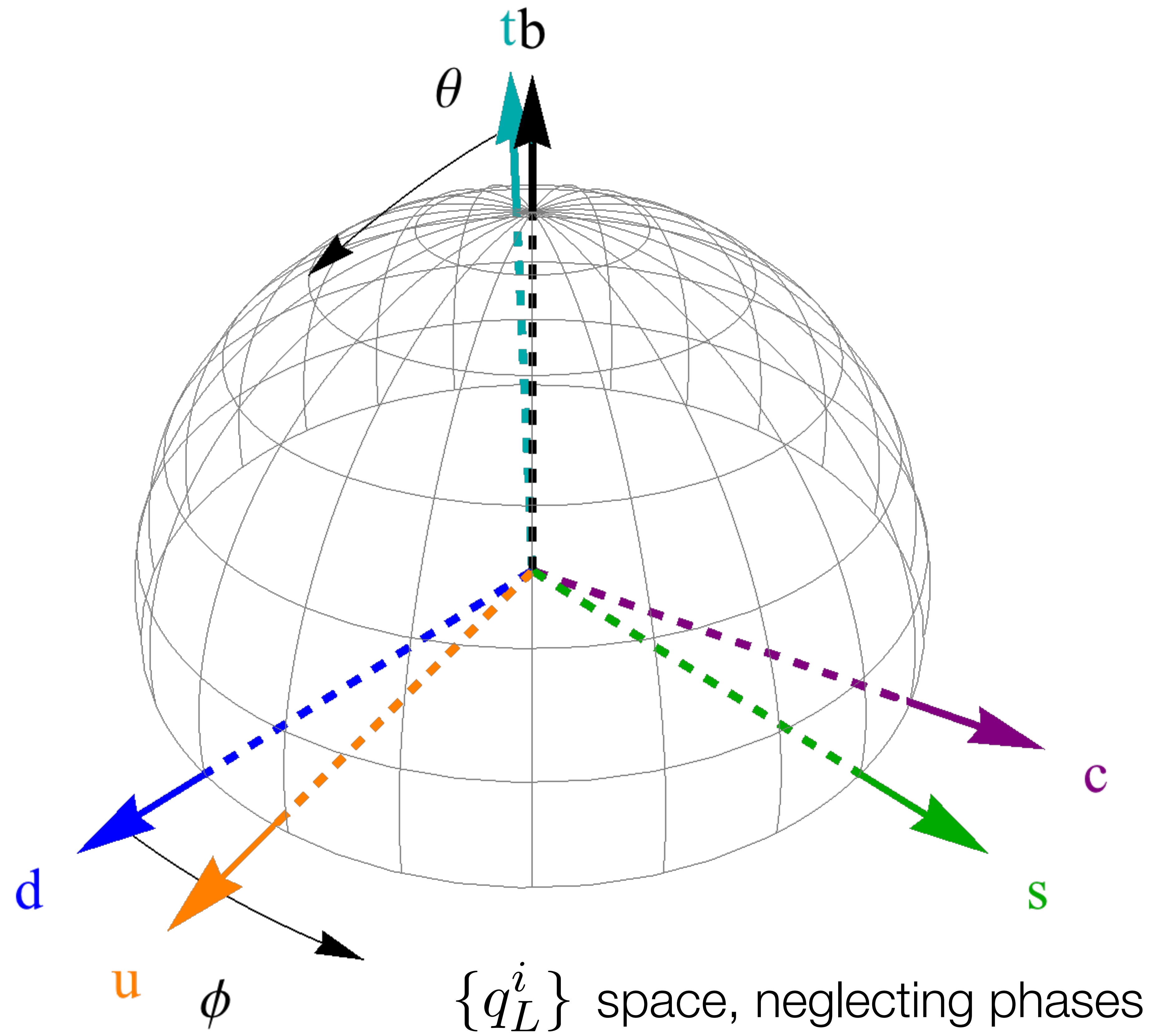


$\{q_L^i\}$ space, neglecting phases

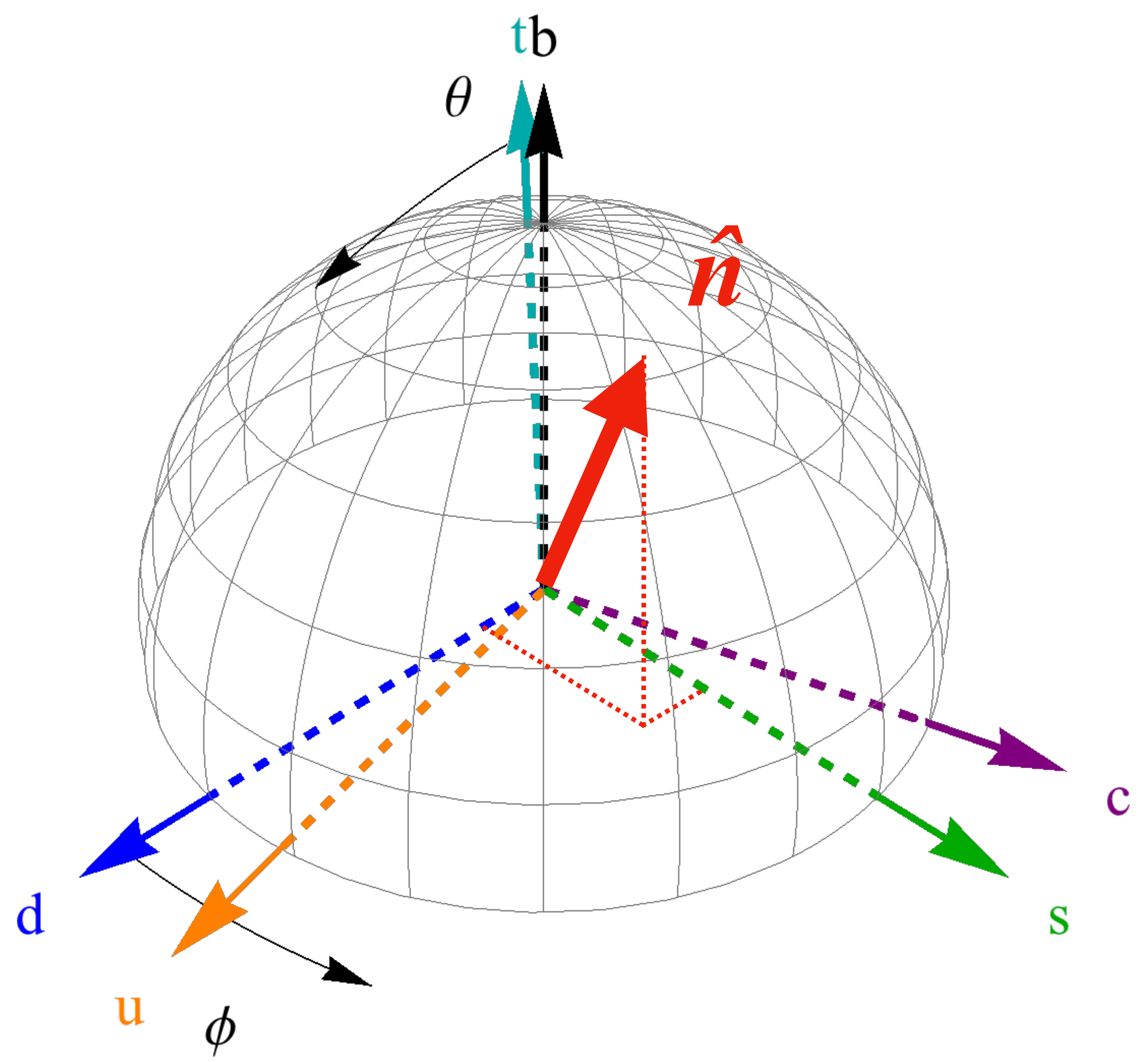
We show also up quarks using:

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

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

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**

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

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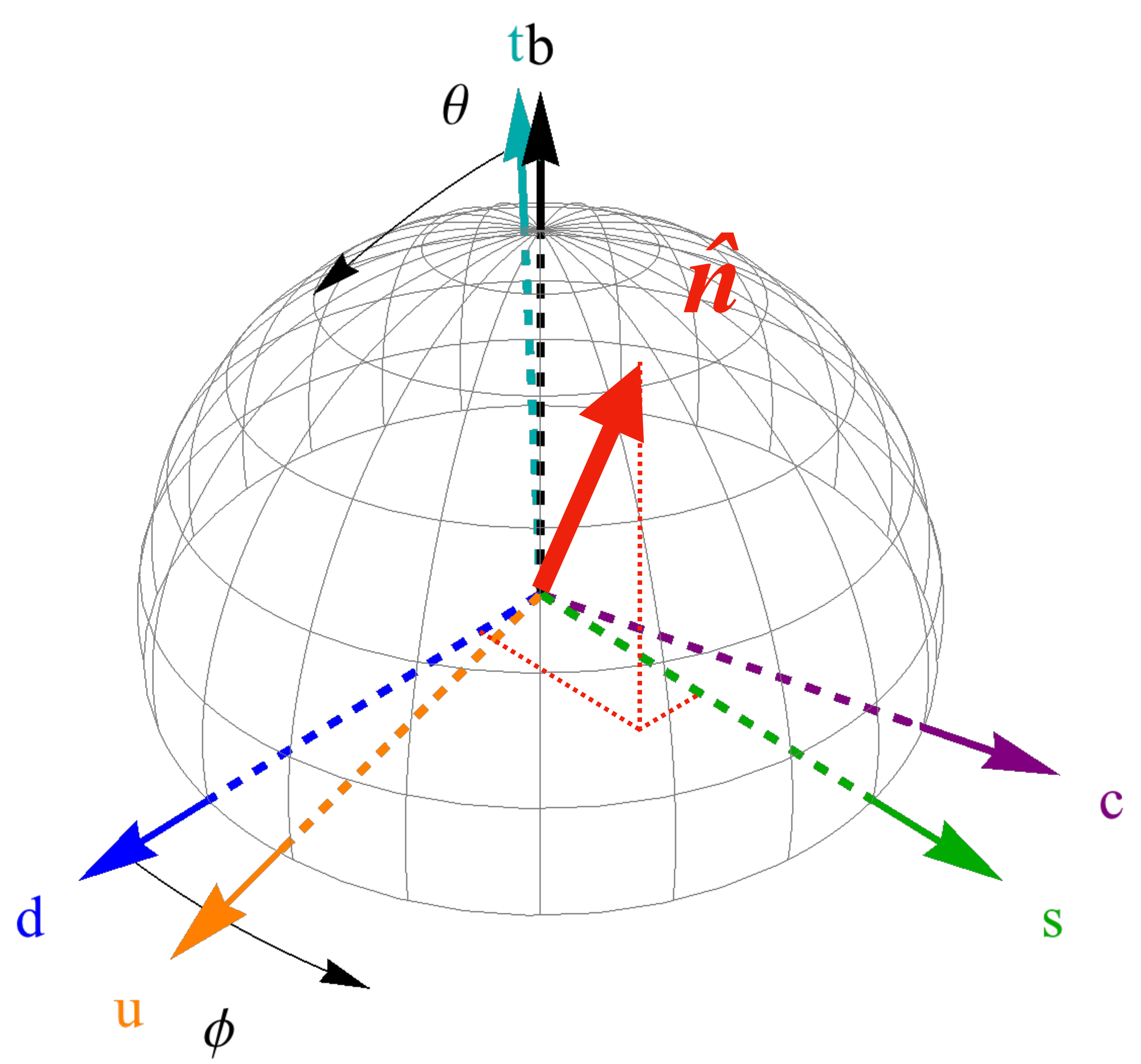

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This structure is automatic if New Physics couples linearly to a single combination of quarks:

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

e.g.

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

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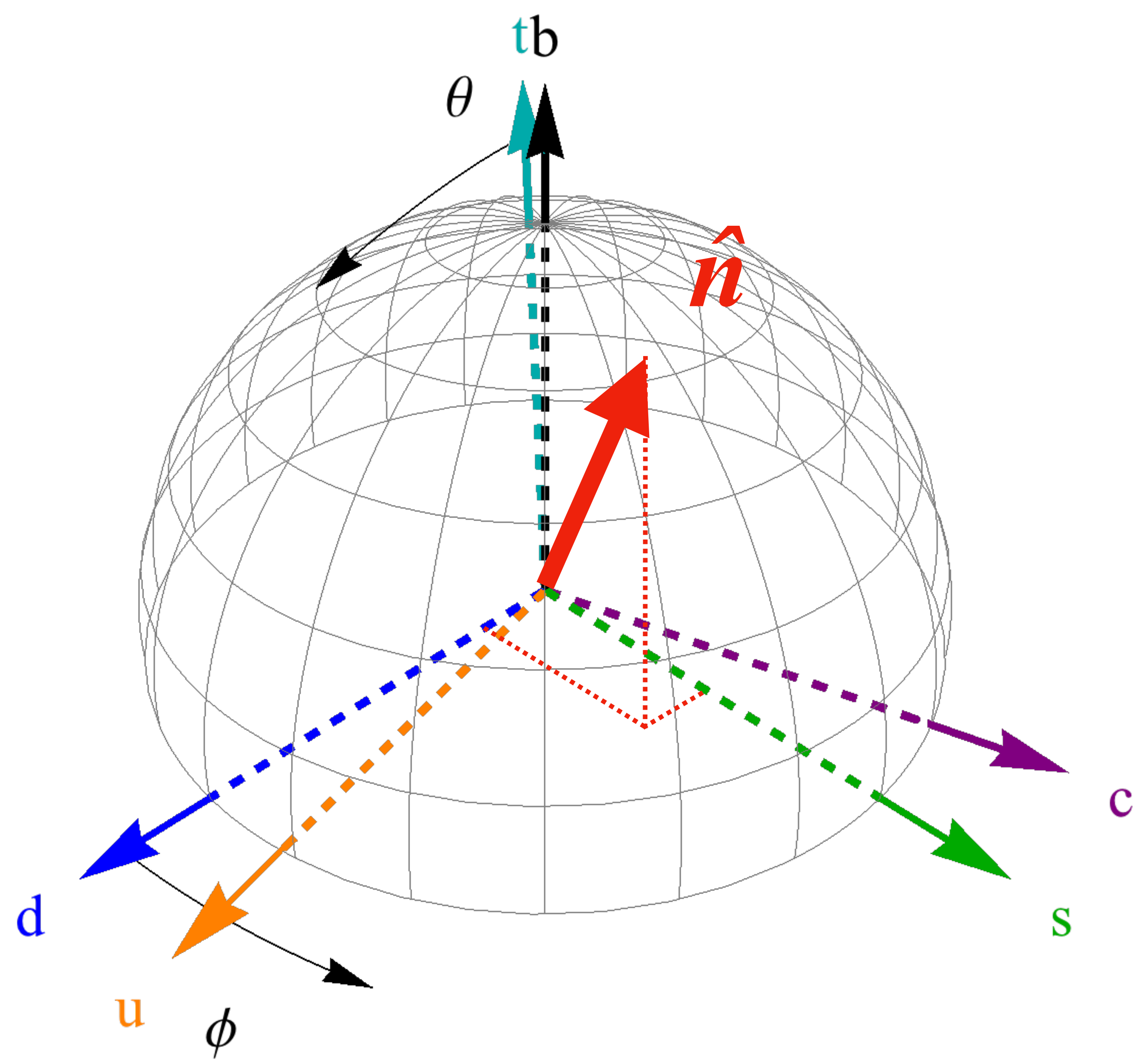

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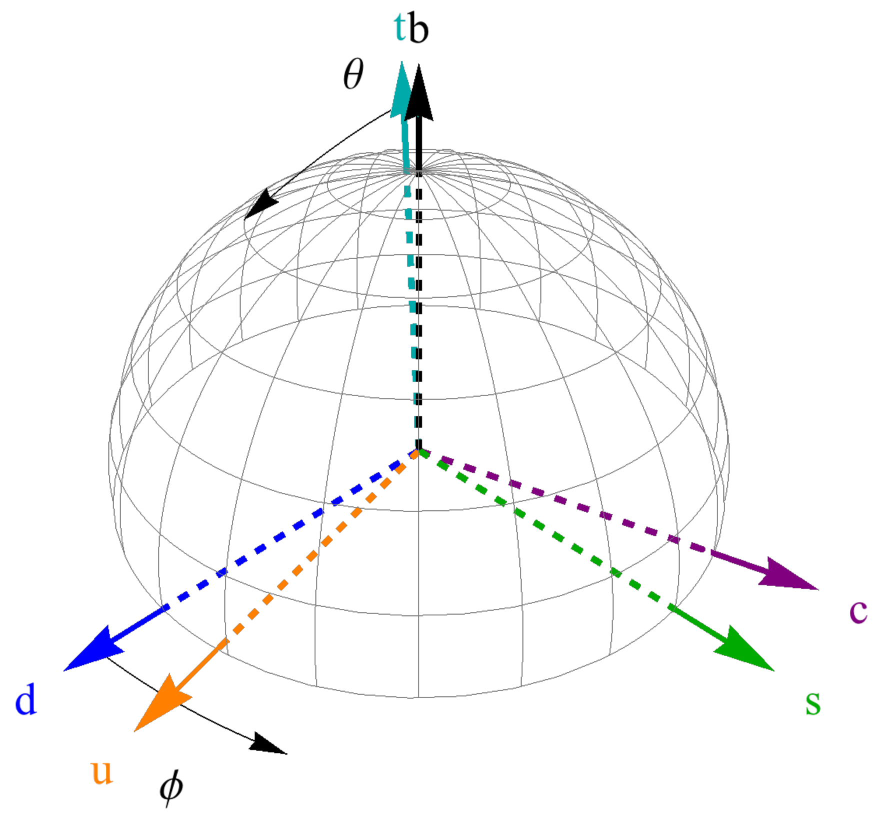
$$\hat{n} = \begin{pmatrix} \sin\theta\cos\phi e^{i\alpha_{bd}} \\ \sin\theta\sin\phi e^{i\alpha_{bs}} \\ \cos\theta \end{pmatrix}$$

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

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

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



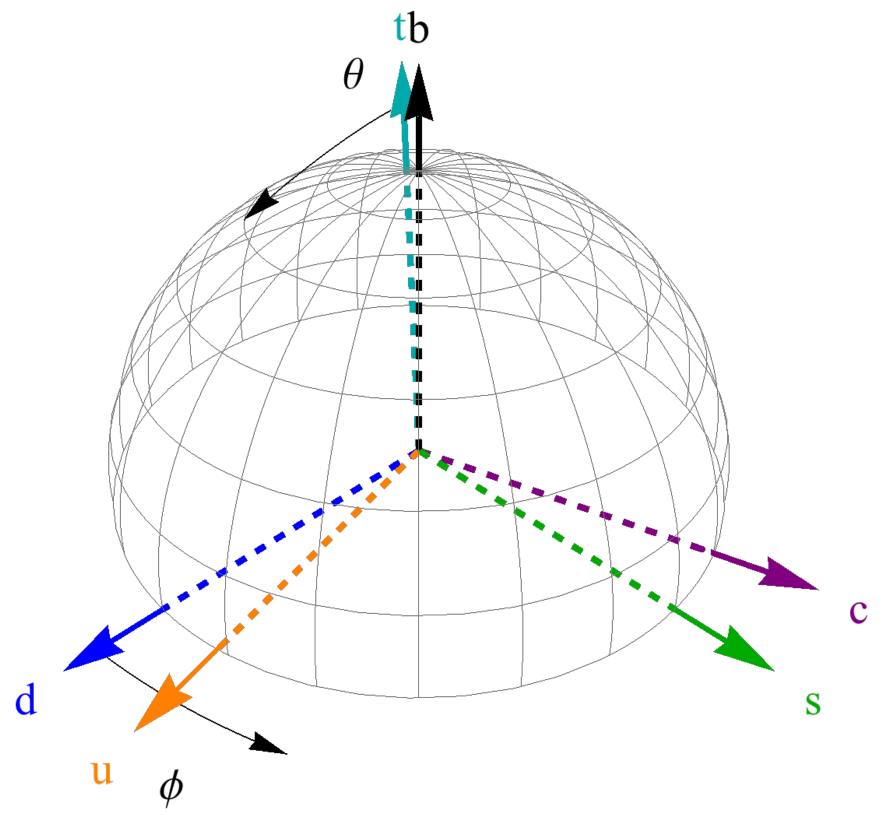
$$L^{ij\nu\nu} = C\,\hat{n}_i \hat{n}^*_j$$

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

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

2404.06533

Rank-One Flavour Violation



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

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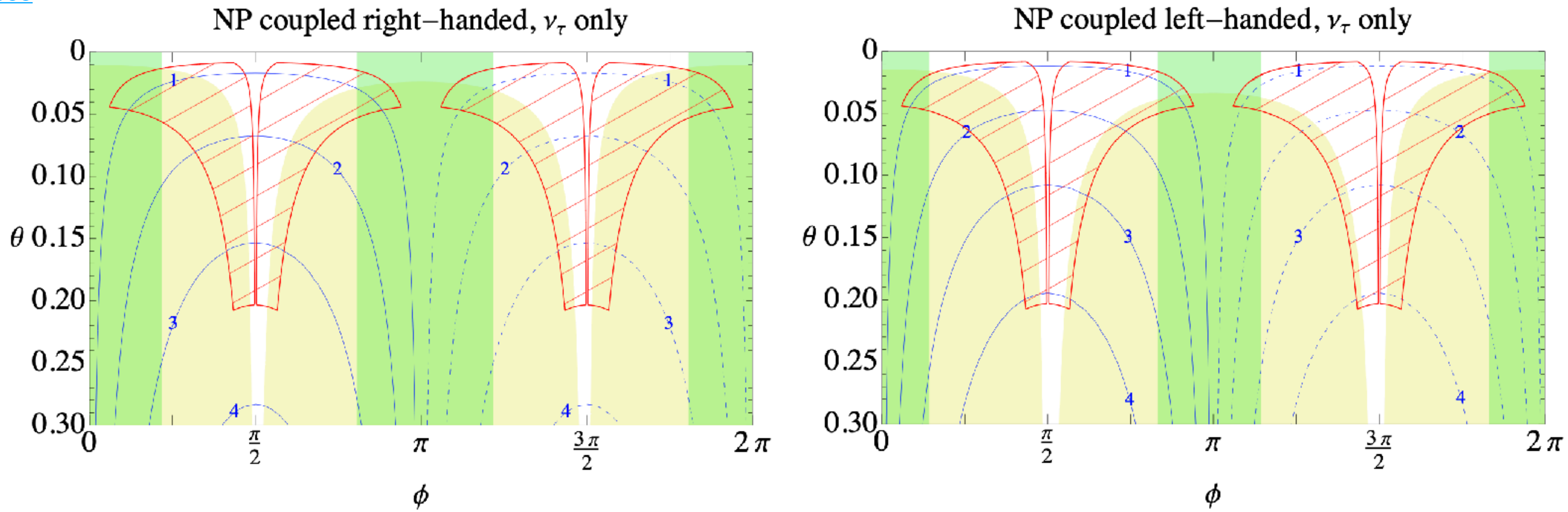
2404.06533



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

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

Top-philic New Physics

We just saw how the **preferred region** to address the Belle-II excess compatibly with other constraints is **close to the third generation quarks** (up to O(CKM) deviations).

This trend is expected and well known, can be generalised:

Both experimental and theory arguments motivate having
TeV-scale New Physics coupled mostly to the top quark.

[e.g. review by Franceschini 2301.04407]

If, in the quark sector, **New Physics couples indeed mostly to the top quark:**

- ★ **What are the strongest constraints** we can put?
- ★ **Where** do they come from?
- ★ **How** do indirect bounds compare with direct ones from LHC?

[Garosi, DM, Rodriguez-Sanchez, Stanzione 2310.00047]

[see also these, on similar spirit: 0704.1482, 0802.1413, 1109.2357, 1408.0792, 1909.13632, 2012.10456]

Top SMEFT

Let us **assume heavy NP couples, among quarks, mostly to the top**.

We leave **arbitrary lepton flavour and gauge structures**

These are the **SMEFT dim-6** operators satisfying these conditions:

Semi-leptonic	
$\mathcal{O}_{lq}^{(1),\alpha\beta}$	$(\bar\ell^\alpha\gamma_\mu\ell^\beta)(\bar q^3\gamma^\mu q^3)$
$\mathcal{O}_{lq}^{(3),\alpha\beta}$	$(\bar\ell^\alpha\gamma_\mu\tau^a\ell^\beta)(\bar q^3\gamma^\mu\tau^a q^3)$
$\mathcal{O}_{lu}^{\alpha\beta}$	$(\bar\ell^\alpha\gamma^\mu\ell^\beta)(\bar u^3\gamma_\mu u^3)$
$\mathcal{O}_{qe}^{\alpha\beta}$	$(\bar q^3\gamma^\mu q^3)(\bar e^\alpha\gamma_\mu e^\beta)$
$\mathcal{O}_{eu}^{\alpha\beta}$	$(\bar e^\alpha\gamma^\mu e^\beta)(\bar u^3\gamma_\mu u^3)$
$\mathcal{O}_{lequ}^{(1),\alpha\beta}$	$(\bar\ell^\alpha e^\beta)\epsilon(\bar q^3 u^3)$
$\mathcal{O}_{lequ}^{(3),\alpha\beta}$	$(\bar\ell^\alpha\sigma_{\mu\nu}e^\beta)\epsilon(\bar q^3\sigma^{\mu\nu}u^3)$

Dipoles	
$\mathcal{O}_{uG}$	$(\bar q^3\sigma^{\mu\nu}T^A u^3)\tilde H G^A_{\mu\nu}$
$\mathcal{O}_{uW}$	$(\bar q^3\sigma^{\mu\nu}u^3)\tau^a\tilde H W^a_{\mu\nu}$
$\mathcal{O}_{uB}$	$(\bar q^3\sigma^{\mu\nu}u^3)\tilde H B_{\mu\nu}$

Four quarks	
$\mathcal{O}_{qq}^{(1)}$	$(\bar q^3\gamma^\mu q^3)(\bar q^3\gamma_\mu q^3)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar q^3\gamma^\mu\tau^a q^3)(\bar q^3\gamma_\mu\tau^a q^3)$
$\mathcal{O}_{uu}$	$(\bar u^3\gamma^\mu u^3)(\bar u^3\gamma_\mu u^3)$
$\mathcal{O}_{qu}^{(1)}$	$(\bar q^3\gamma^\mu q^3)(\bar u^3\gamma_\mu u^3)$
$\mathcal{O}_{qu}^{(8)}$	$(\bar q^3\gamma^\mu T^A q^3)(\bar u^3\gamma_\mu T^A u^3)$

Higgs-Top	
$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q^3\gamma^\mu q^3)$
$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^a_\mu H)(\bar q^3\gamma^\mu\tau^a q^3)$
$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u^3\gamma^\mu u^3)$
$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar q^3 u^3\tilde H)$

[Garosi, DM, Rodriguez-Sanchez, Stanzione 2310.00047]

Since we are assuming that the top quark is somehow "special" from the UV point of view, we work in the **up quark mass basis**:

$$q^i = (u_L^i,\, V_{ij} d_L^j)$$

[see Isidori et al. 2024 for an analysis varying continuously from up to down basis]

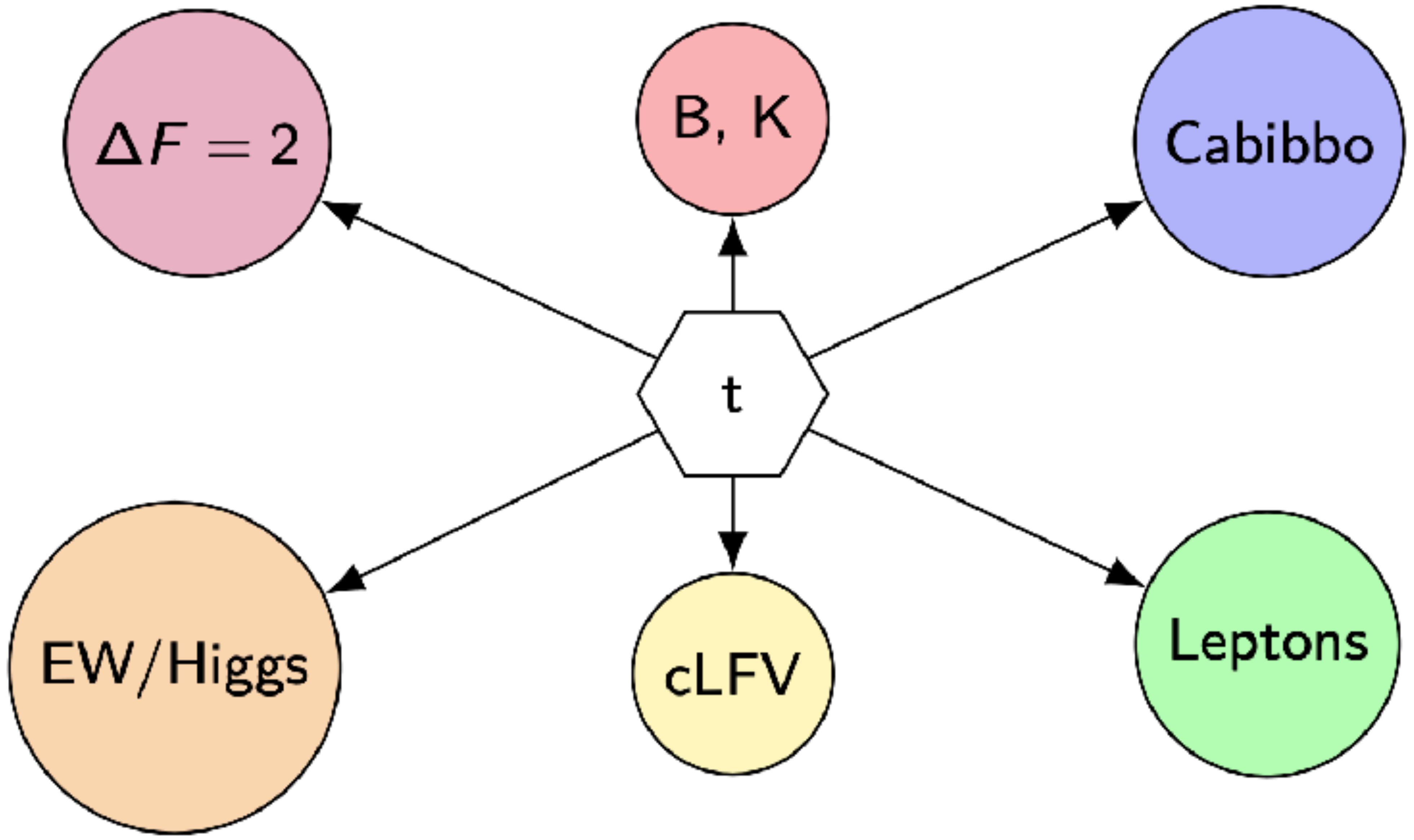
Indirect constraints

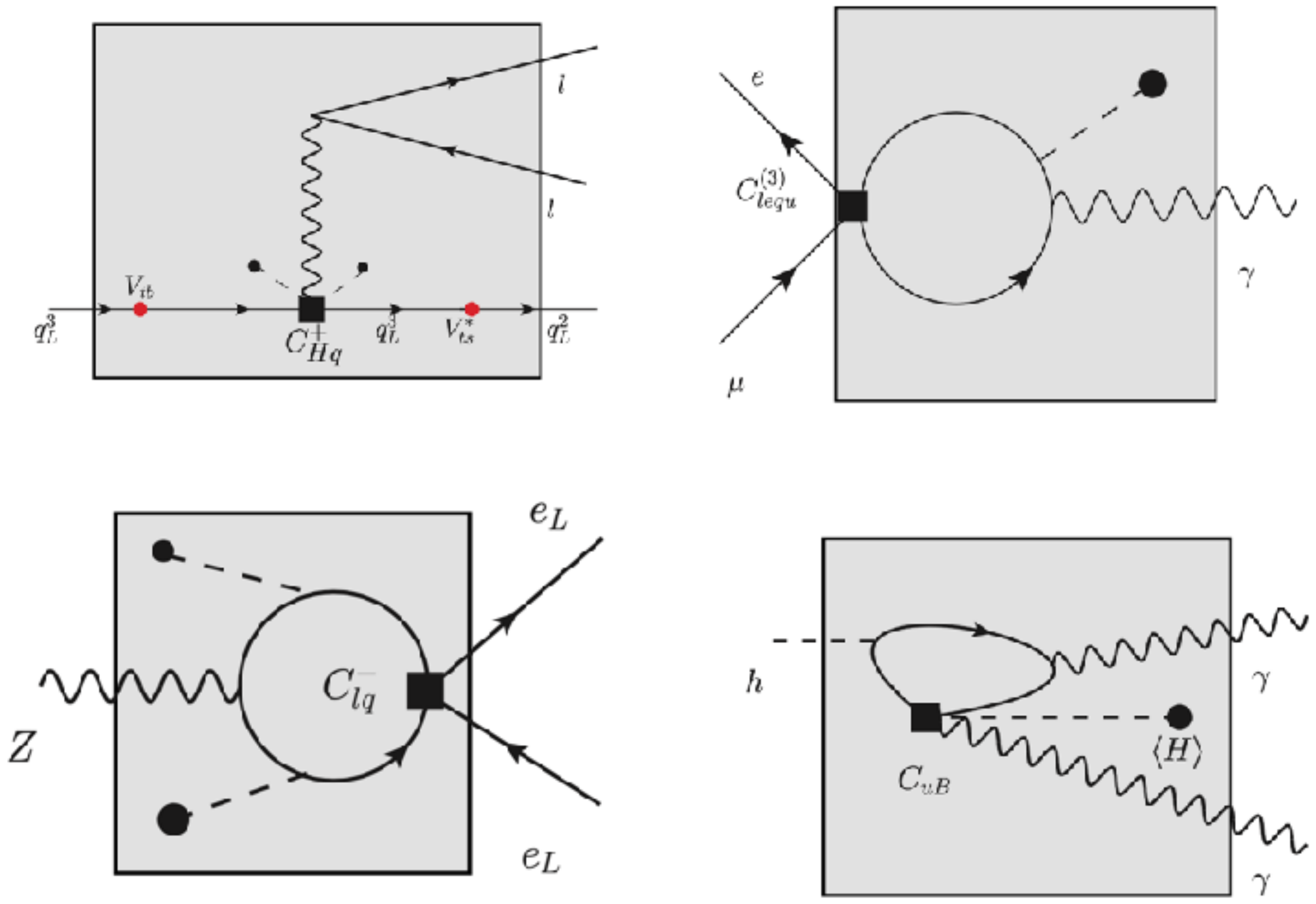
$C_{top}(1\text{TeV})$ —RG: LL→ $C_{SMEFT}(m_{EW})$ —1-loop matching + RG→ $L_{LEFT}(\text{GeV})$

dilepton constraints | EW precision tests | Fit of B → K(*)νν + Flavour bounds

[Jenkins, Manohar and Trott 2013; Dekens and Stoffer [1908.05295]; Jenkins, Manohar and Stoffer [1711.05270], DSixTools ...

RG evolution to low scales induce effects in a wide range of observables





Observables included

B physics

Observable	Experimental value
$B \to X_s \gamma$	$(3.49 \pm 0.19) \times 10^{-4}$ [38]
R_K^{ν}	2.93 ± 0.90 [35, 36]
$R_{K^*}^{\nu}$	< 3.21 [35, 37]
$R_K[1.1, 6]$	0.949 ± 0.047 [34]
$R_{K^*}[1.1, 6]$	1.027 ± 0.077 [34]
$\mathcal{B}(B \to K e\mu)$	$< 4.5 \times 10^{-8}$ [39]
$\mathcal{B}(B \to K e\tau)$	$< 3.6 \times 10^{-5}$ [40]
$\mathcal{B}(B \to K \mu\tau)$	$< 4.5 \times 10^{-5}$ [41]

Observable	Experimental value
$\mathcal{B}(B_s \to ee)$	$< 11.2 \times 10^{-9}$ [42]
$\mathcal{B}(B_s \to \mu\mu)$	$(3.01 \pm 0.35) \times 10^{-9}$ [43]
$\mathcal{B}(B_s \to \tau\tau)$	$< 6.8 \times 10^{-3}$ [44]
$\mathcal{B}(B_s \to e\mu)$	$< 6.3 \times 10^{-9}$ [45]
$\mathcal{B}(B_s \to \mu\tau)$	$< 4.2 \times 10^{-5}$ [46]
$\mathcal{B}(B_d \to ee)$	$< 3.0 \times 10^{-9}$ [42]
$\mathcal{B}(B_d \to \mu\mu)$	$< 2.6 \times 10^{-10}$ [43]
$\mathcal{B}(B_d \to \tau\tau)$	$< 2.1 \times 10^{-3}$ [44]
$\mathcal{B}(B_d \to e\mu)$	$< 1.3 \times 10^{-9}$ [45]
$\mathcal{B}(B_d \to \mu\tau)$	$< 1.4 \times 10^{-5}$ [46]

ΔF = 2

Observable	Experimental value	SM prediction
ϵ_K	$(2.228 \pm 0.011) \times 10^{-3}$	$(2.14 \pm 0.12) \times 10^{-3}$
ΔM_s	$(17.765 \pm 0.006)\,\mathrm{ps}^{-1}$	$(17.35 \pm 0.94)\,\mathrm{ps}^{-1}$
ΔM_d	$(0.5065 \pm 0.0019)\,\mathrm{ps}^{-1}$	$(0.502 \pm 0.031)\,\mathrm{ps}^{-1}$

Leptonic

Observable	Experimental value	
	$\ell = e$	$\ell = \mu$
Δa_ℓ	$(2.8 \pm 7.4) \times 10^{-13}$	$(20.0 \pm 8.4) \times 10^{-10}$
$g_\tau / g_\ell - 1$	$(2.7 \pm 1.4) \times 10^{-3}$	$(0.9 \pm 1.4) \times 10^{-3}$

Kaon physics

Observable	Experimental value
$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$	$(1.14^{+0.4}_{-0.33}) \times 10^{-10}$ [47] [48]
$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$	$< 3.6 \times 10^{-9}$ [49]
$\mathcal{B}(K_S \to \mu^+\mu^-)$	$< 2.5 \times 10^{-10}$ [50]
$\mathcal{B}(K_L \to \mu^+\mu^-)_{SD}$	$< 2.5 \times 10^{-9}$ [51]
$\mathcal{B}(K_L \to \mu^\pm e^\mp)$	$< 5.6 \times 10^{-12}$ [52]
$\mathcal{B}(K_L \to \pi^0 \mu^+\mu^-)$	$< 4.5 \times 10^{-10}$ [53]
$\mathcal{B}(K_L \to \pi^0 e^+ e^-)$	$< 3.3 \times 10^{-10}$ [54]
$\mathcal{B}(K_L \to \pi^0 e^+ \mu^-)$	$< 9.1 \times 10^{-11}$ [55]
$\mathcal{B}(K^+ \to \pi^+ e^+ \mu^-)$	$< 7.9 \times 10^{-11}$ [56]

LFV

Observable	Experimental limit
$\mathcal{B}(\mu \to e\gamma)$	5.0×10^{-13} [102]
$\mathcal{B}(\mu \to 3e)$	1.2×10^{-12} [103]
$\mathcal{B}(\mu\,\mathrm{Au} \to e\,\mathrm{Au})$	8.3×10^{-13} [104]
$\mathcal{B}(\tau \to e\gamma)$	3.9×10^{-8} [105]
$\mathcal{B}(\tau \to 3e)$	3.2×10^{-8} [106]
$\mathcal{B}(\tau \to e\bar{\mu}\mu)$	3.2×10^{-8} [106]
$\mathcal{B}(\tau \to e\pi^0)$	9.5×10^{-8} [107]
$\mathcal{B}(\tau \to e\eta)$	1.1×10^{-7} [107]
$\mathcal{B}(\tau \to e\eta')$	1.9×10^{-7} [107]

Observable	Experimental limit
$\mathcal{B}(\tau \to e\pi^+\pi^-)$	2.7×10^{-8} [108]
$\mathcal{B}(\tau \to eK^+K^-)$	4.1×10^{-8} [108]
$\mathcal{B}(\tau \to \mu\gamma)$	5.0×10^{-8} [109]
$\mathcal{B}(\tau \to 3\mu)$	2.5×10^{-8} [106]
$\mathcal{B}(\tau \to \mu\bar{e}e)$	2.1×10^{-8} [106]
$\mathcal{B}(\tau \to \mu\pi^0)$	1.3×10^{-7} [110]
$\mathcal{B}(\tau \to \mu\eta)$	7.7×10^{-8} [107]
$\mathcal{B}(\tau \to \mu\eta')$	1.5×10^{-7} [107]
$\mathcal{B}(\tau \to \mu\pi^+\pi^-)$	2.5×10^{-8} [108]
$\mathcal{B}(\tau \to \mu K^+K^-)$	5.2×10^{-8} [108]

Cabibbo angle-related

Global analysis of Cabibbo-related observables by [Cirigliano et al. 2112.02087]

EW precision obs. + Higgs

[Falkowski et al. [1503.07872, 1911.07866]

One-parameter fits

What **scale** are we probing with **indirect** probes?

One-parameter fits from our global analysis of indirect constraints on top quark operators.
In the third column we report the observable giving the dominant constraint in each case.

Wilson	Global fit [TeV^{-2}]	Dominant
$C_{qq}^{(+)}$	$(-1.9 \pm 2.3) \times 10^{-3}$	ΔM_s
$C_{qq}^{(-)}$	$(-2.0 \pm 1.0) \times 10^{-1}$	$B_s \to \mu\mu$
$C_{qu}^{(1)}$	$(1.3 \pm 1.0) \times 10^{-1}$	ΔM_s
$C_{qu}^{(8)}$	$(-1.7 \pm 4.4) \times 10^{-1}$	ΔM_s
C_{uu}	$(-3.0 \pm 1.7) \times 10^{-1}$	$\delta g_{L,11}^{Ze}$
$C_{Hq}^{(+)}$	$(18.7 \pm 8.8) \times 10^{-3}$	$B_s \to \mu\mu$
$C_{Hq}^{(-)}$	$(5.8 \pm 4.5) \times 10^{-2}$	$\delta g_{L,11}^{Ze}$
C_{Hu}	$(-4.3 \pm 2.3) \times 10^{-2}$	$\delta g_{L,11}^{Ze}$
C_{uB}	$(-0.6 \pm 2.0) \times 10^{-2}$	$c_{\gamma\gamma}$
C_{uG}	$(-0.1 \pm 2.0) \times 10^{-2}$	c_{gg}
C_{uH}	$(-0.3 \pm 5.2) \times 10^{-1}$	$C_{uH,33}$
C_{uW}	$(-0.1 \pm 3.1) \times 10^{-2}$	$c_{\gamma\gamma}$

Wilson	Global fit [TeV^{-2}]	Dominant
$C_{lq}^{(+),11}$	$(2.4 \pm 3.5) \times 10^{-3}$	R_K
$C_{lq}^{(+),22}$	$(-4.0 \pm 3.4) \times 10^{-3}$	R_K
$C_{lq}^{(+),33}$	$(7.2 \pm 4.4) \times 10^{-1}$	g_τ / g_i
$C_{lq}^{(-),11}$	$(10.9 \pm 7.6) \times 10^{-2}$	$R_{K^{(*)}}^{\nu}$
$C_{lq}^{(-),22}$	$(-6.0 \pm 7.0) \times 10^{-2}$	$R_{K^{(*)}}^{\nu}$
$C_{lq}^{(-),33}$	$(-1.8 \pm 1.0) \times 10^{-1}$	$R_{K^{(*)}}^{\nu}$
C_{lu}^{11}	$(-1.7 \pm 7.0) \times 10^{-2}$	$\delta g_{L,11}^{Ze}$
C_{lu}^{22}	$(-4.3 \pm 1.8) \times 10^{-1}$	$\delta g_{L,22}^{Ze}$, R_K
C_{lu}^{33}	$(0.5 \pm 2.4) \times 10^{-1}$	$\Delta g_{L,33}^{Ze}$
C_{qe}^{11}	$(-0.7 \pm 3.9) \times 10^{-2}$	R_{K^*}
C_{qe}^{22}	$(12.1 \pm 9.2) \times 10^{-3}$	$B_s \to \mu\mu$
C_{qe}^{33}	$(2.2 \pm 2.4) \times 10^{-1}$	$\delta g_{R,33}^{Ze}$

Wilson	Global fit [TeV^{-2}]	Dominant
C_{eu}^{11}	$(5.0 \pm 8.1) \times 10^{-2}$	$\Delta g_R^{Ze}{}_{11}$
C_{eu}^{22}	$(4.8 \pm 2.1) \times 10^{-1}$	$\Delta g_R^{Ze}{}_{22}$
C_{eu}^{33}	$(-2.3 \pm 2.5) \times 10^{-1}$	$\Delta g_R^{Ze}{}_{33}$
$C_{lequ}^{(1),11}$	$(0.4 \pm 1.0) \times 10^{-2}$	$(g-2)_e$
$C_{lequ}^{(1),22}$	$(1.8 \pm 1.6) \times 10^{-2}$	$C_{eH\,22}$
$C_{lequ}^{(1),33}$	$(8.0 \pm 9.1) \times 10^{-2}$	$C_{eH\,33}$
$C_{lequ}^{(3),11}$	$(-0.6 \pm 1.5) \times 10^{-5}$	$(g-2)_e$
$C_{lequ}^{(3),22}$	$(-19.3 \pm 8.1) \times 10^{-5}$	$(g-2)_\mu$
$C_{lequ}^{(3),33}$	$(-7.0 \pm 7.8) \times 10^{-1}$	$C_{eH\,33}$

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$C_{lequ}^{(3),33}$	$(-7.0 \pm 7.8) \times 10^{-1}$	$C_{eH\,33}$

Indirect bounds are in the **few TeV range.**

Exception for tree-level contributions to **Bs-mixing, R_K, Bs→μμ**, and top-loop **from dipoles to $(g-2)_{e,\mu}$**.

Λ ≳ 10 TeV **Λ ≳ 180 - 80 TeV**

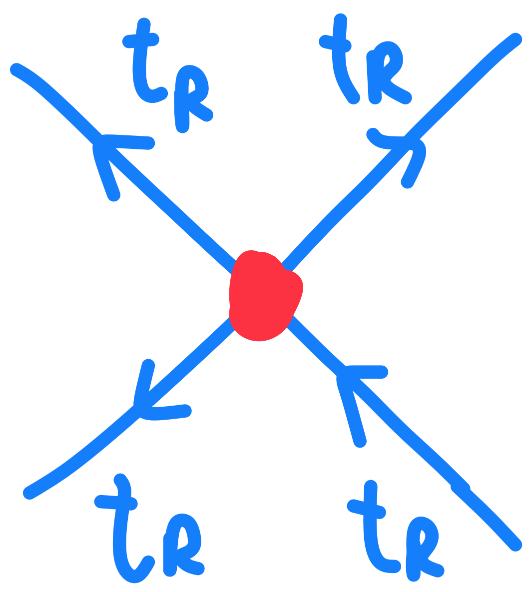
Example

Let us take for example this 4-top operator.
Its strongest bound is from LEP (Z-pole).

$$\mathcal{L}_{SMEFT} = C_{uu} (\bar{t}_R \gamma_\mu t_R)(\bar{t}_R \gamma^\mu t_R)$$

C_{uu}	$(-3.0 \pm 1.7) \times 10^{-1}$	$\delta g^{Ze}_{L,11}$

How does it generate a contribution?



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1-loop ↓

$$C_{uu} \frac{N_c y_t^2}{(4\pi)^2} \log \frac{\Lambda^2}{m_t^2} (\bar{t}_R \gamma_\mu t_R)(H^\dagger \overleftrightarrow{D}^\mu H)$$

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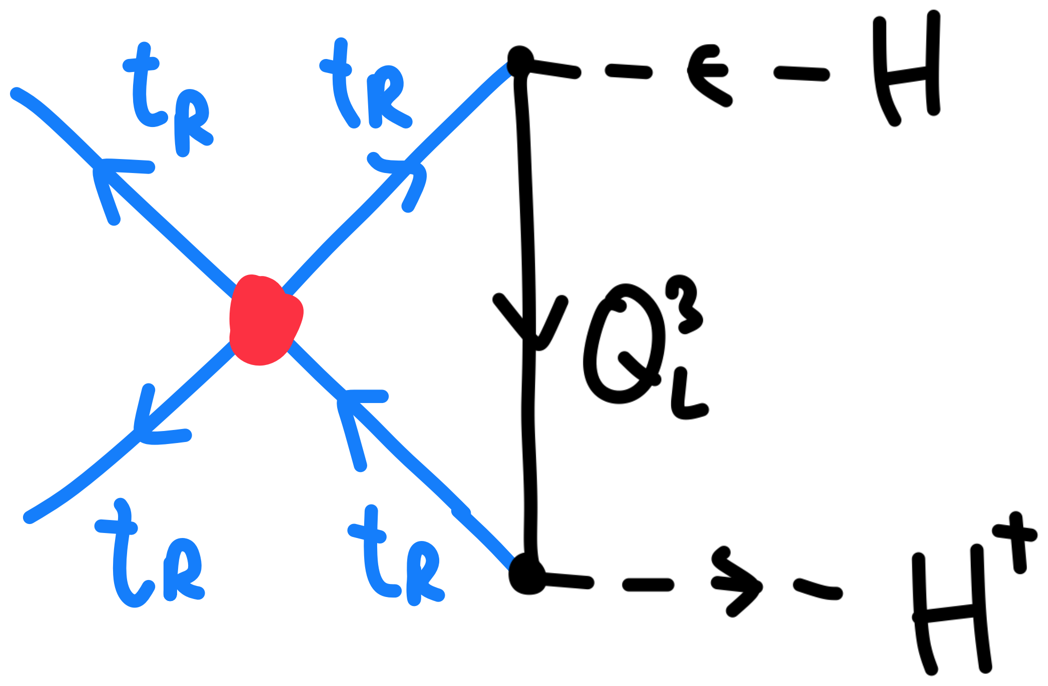

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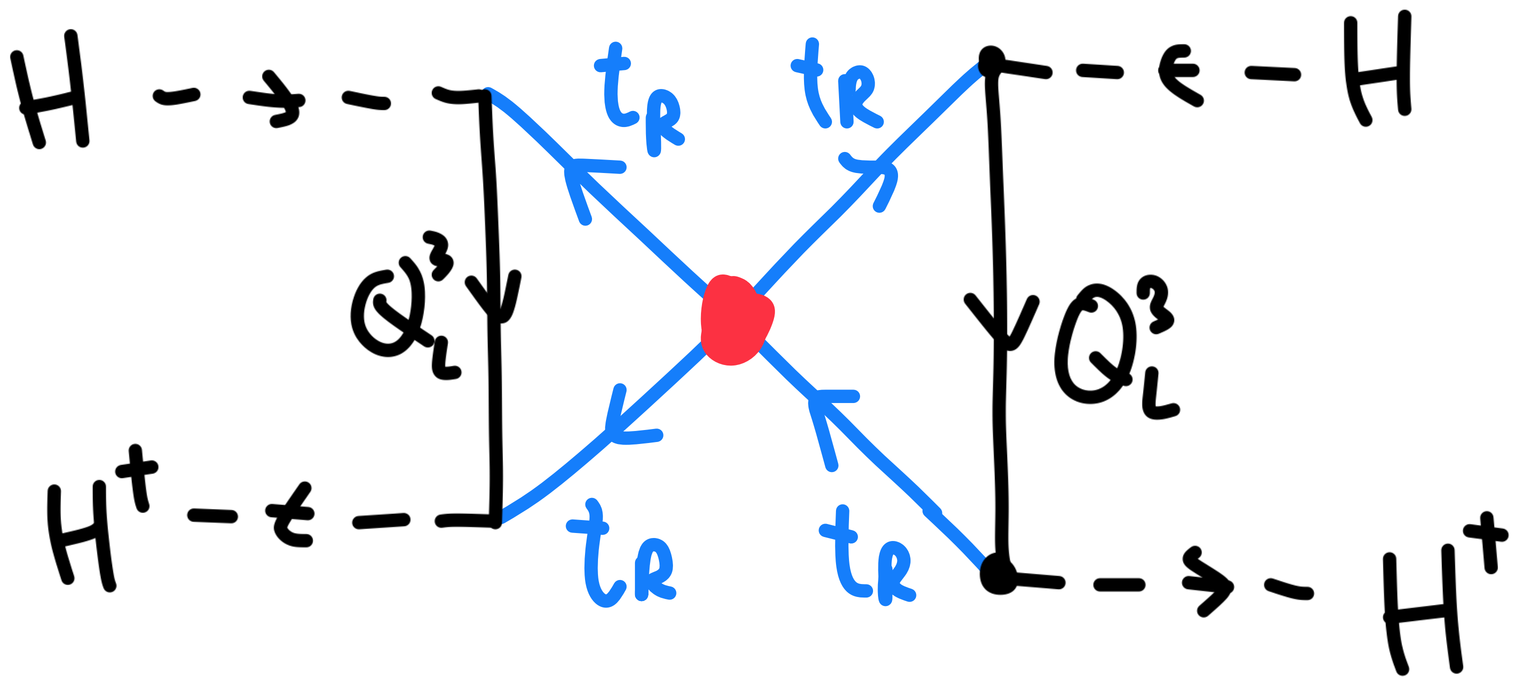

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2-loop (Leading Log) ↓

$$C_{uu} \left(\frac{N_c y_t^2}{(4\pi)^2} \log\frac{\Lambda^2}{m_t^2}\right)^2 (H^\dagger \overleftrightarrow{D}^\mu H)^2$$

This is the operator contributing to the **EW T-parameter** (Z-mass).
In the fit we used it shows up as a Z-coupling contribution.

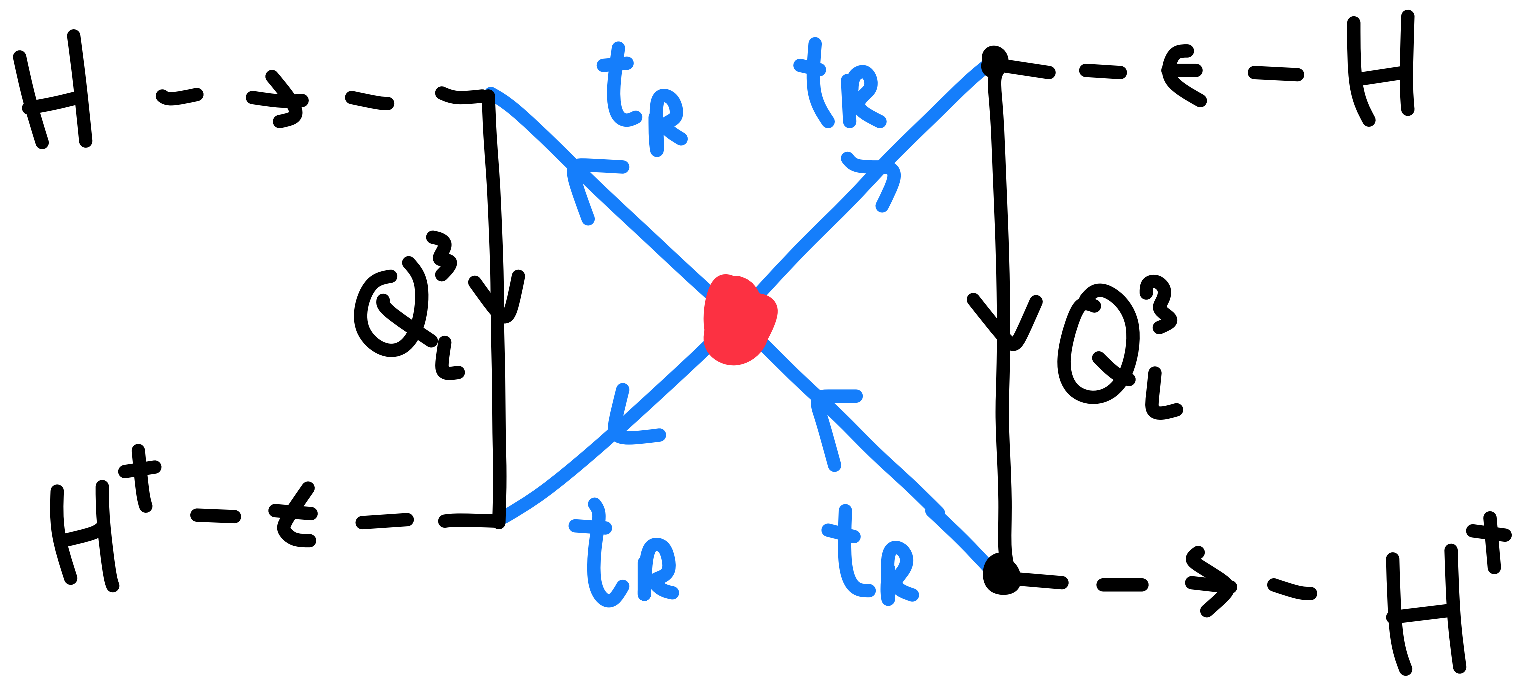
[1911.07866]

Example

Let us take for example this 4-top operator.
Its strongest bound is from LEP (Z-pole).

C_{uu}	$(-3.0 \pm 1.7) \times 10^{-1}$	$\delta g^{Ze}_{L,11}$

How does it generate a contribution?



$$\mathcal{L}_{SMEFT} = C_{uu} \left(\bar{t}_R \gamma_\mu t_R\right)\left(\bar{t}_R \gamma^\mu t_R\right)$$

1-loop ↓

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This is the operator contributing to the **EW T-parameter** (Z-mass).
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[1911.07866]

Direct constraints from LHC

Top operators can be constrained directly from LHC measurements of top quark processes:

SMEFiT 2105.00006

$pp \to t\bar{t}$

$pp \to t\bar{t}t\bar{t}$

$pp \to t\bar{t}b\bar{b}$

$pp \to t\bar{t}Z$

$pp \to t\bar{t}W$

$pp \to t\bar{t}H$

$pp \to t + X$

$pp \to tZ + X$

$pp \to tW + X$

$pp \to tH + X$

Higgs physics

ggF, VBF, Vh, etc..

Indirect vs. Direct

How **direct bounds** compare with **indirect** ones? **Indirect are typically much stronger.**

[Garosi, DM, Rodriguez-Sanchez, Stanzione 2310.00047]

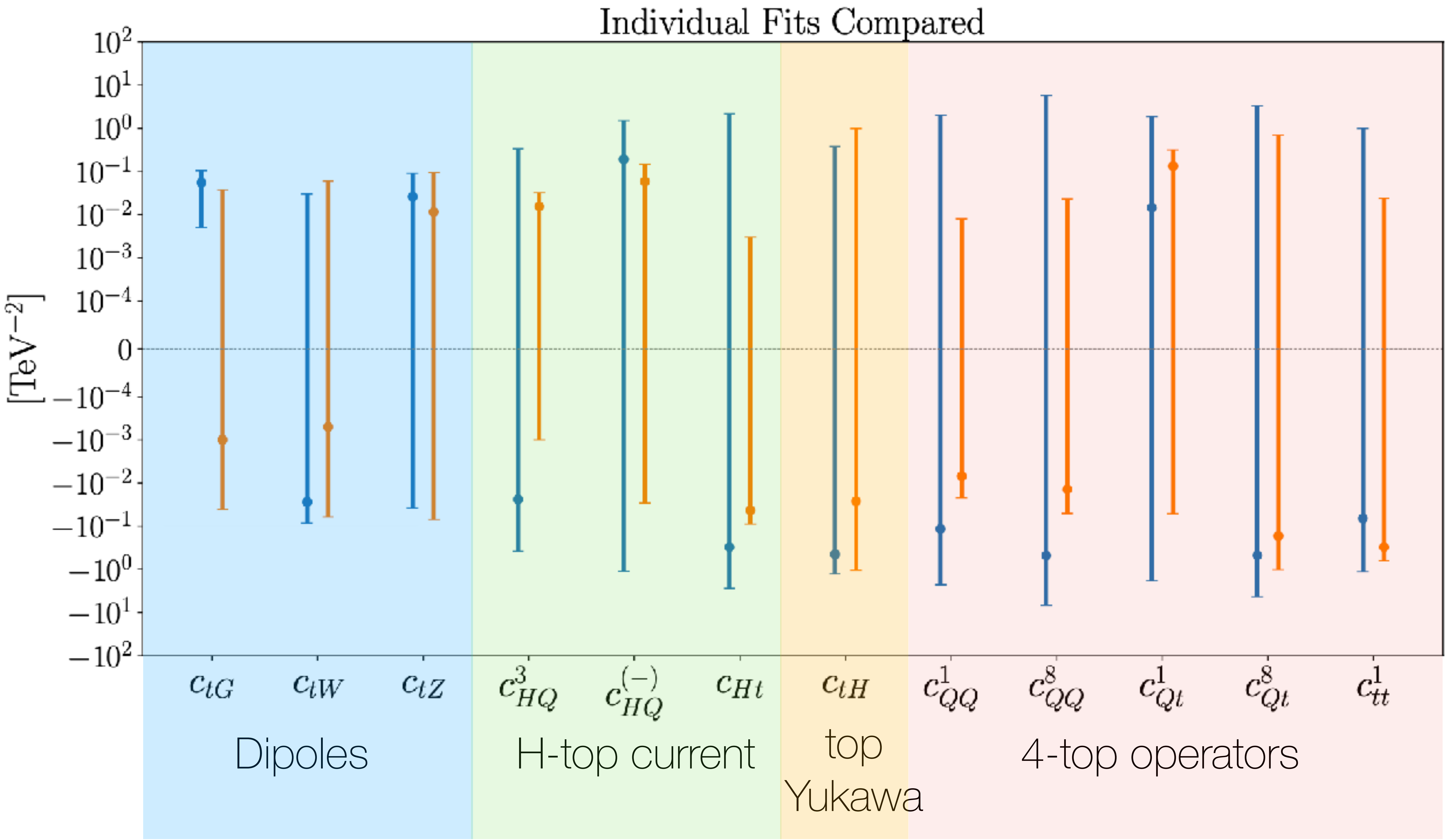
Direct bounds from LHC

top production,
Higgs physics,
diboson production

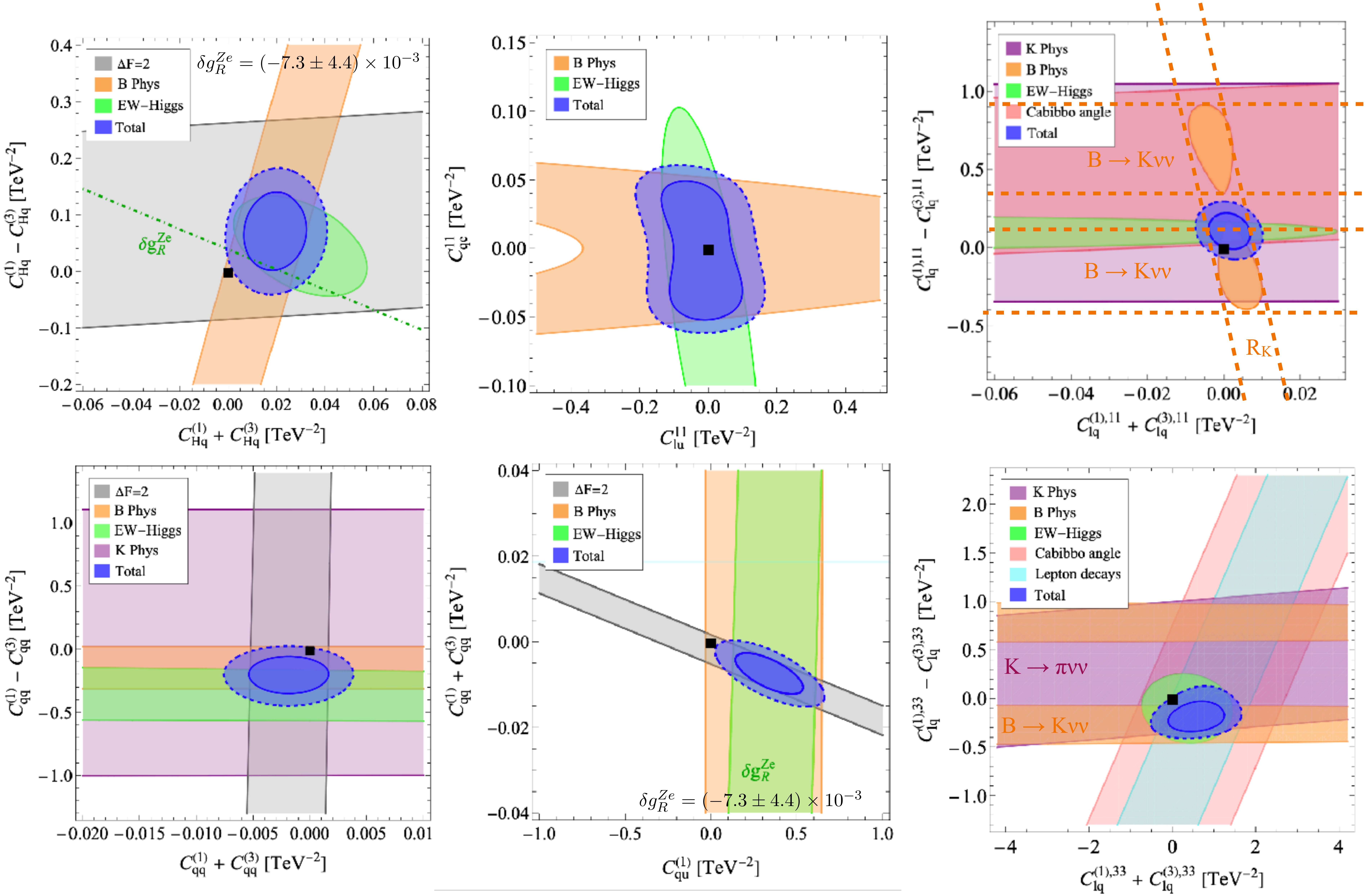
SMEFiT 2105.00006

Indirect bounds from EW+Flavour

2310.00047



2D fits



Combining bounds from different datasets allows to derive **much stronger constraints**.

Conclusions

If **New Physics** is present at a scale reachable by present or (~near) future colliders, then it must enjoy some **non-trivial flavour structure** that suppresses large FCNC effects.

Typically this tends to **align it close it to the 3rd generation**.

With a **Rank-One Flavour Violation** setup we show how close to the top direction this should be, in the case of fitting the $B \to K\nu\nu$ excess: **only deviations of $\lesssim$ O(CKM)** are allowed.

Correlations between different observables are crucial to identify the flavour structure.

Assuming **New Physics couples mostly to the top quark**, we show that **indirect bounds provide almost always stronger constraints than direct bounds** from LHC: also here it is crucial to combine different datasets.

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If **New Physics** is present at a scale reachable by present or (~near) future colliders, then it must enjoy some **non-trivial flavour structure** that suppresses large FCNC effects.

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Thank you!

Backup

ATLAS SUSY Searches* - 95% CL Lower Limits

July 2024

ATLAS Preliminary

$\sqrt{s}$ = 13 TeV

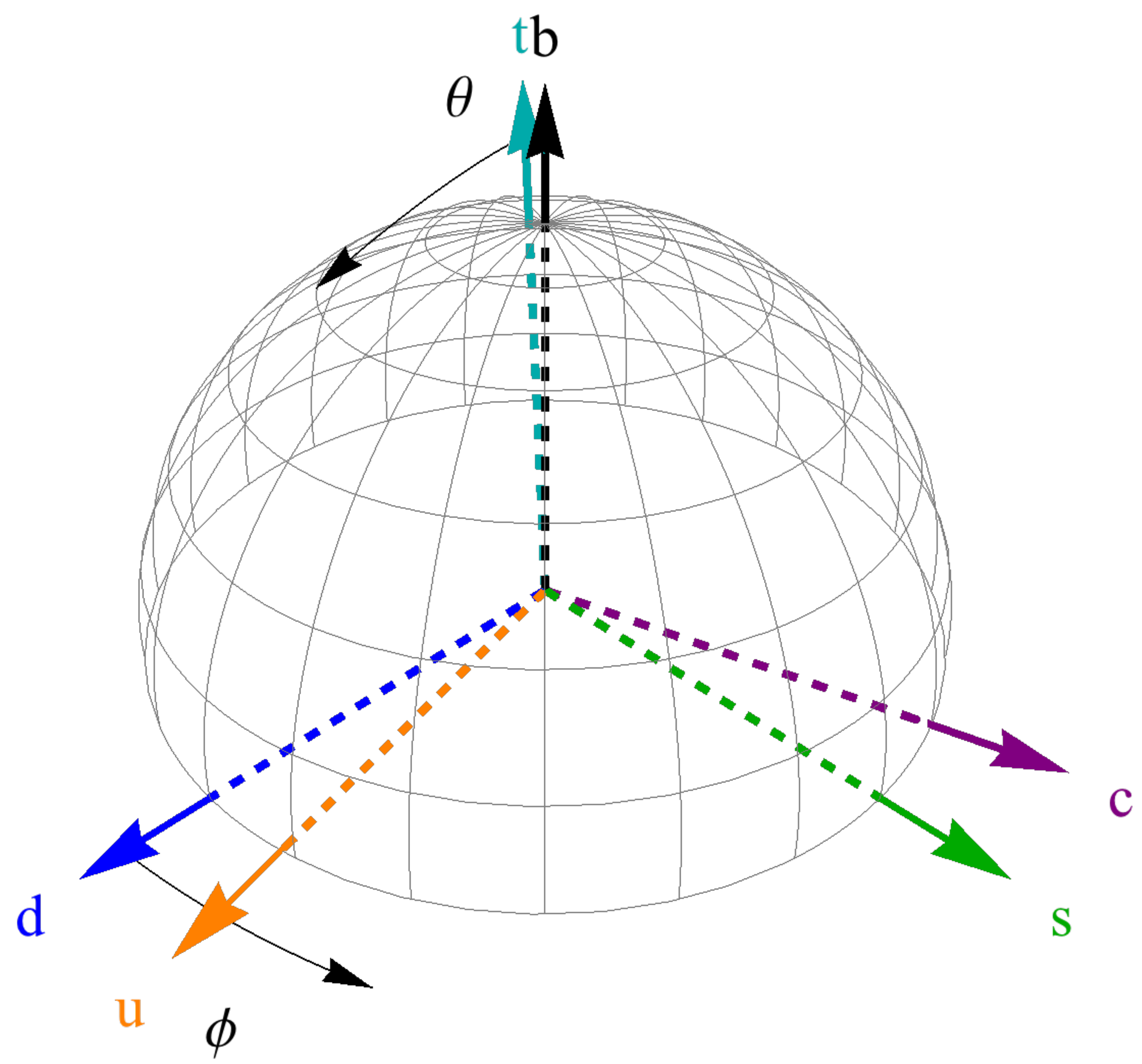
	Model	Signature			$\int \mathcal{L}\, dt$ [fb^{-1}]	Mass limit [TeV]		Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0 e,μ	2-6 jets	E_T^{miss}	140	$\tilde{q}$ [1×, 8× Degen.] 1.0 1.85	$m(\tilde{\chi}^0_1)$<400 GeV	2010.14293
		mono-jet	1-3 jets	E_T^{miss}	140	$\tilde{q}$ [8× Degen.] 0.9	$m(\tilde{q})$-$m(\tilde{\chi}^0_1)$=5 GeV	2102.10874
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0 e,μ	2-6 jets	E_T^{miss}	140	$\tilde{g}$ 2.3	$m(\tilde{\chi}^0_1)$=0 GeV	2010.14293
						$\tilde{g}$ Forbidden 1.15-1.95	$m(\tilde{\chi}^0_1)$=1000 GeV	2010.14293
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}W\tilde{\chi}^0_1$	1 e,μ	2-6 jets		140	$\tilde{g}$ 2.2	$m(\tilde{\chi}^0_1)$<600 GeV	2101.01629
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	$ee,\mu\mu$	2 jets	E_T^{miss}	140	$\tilde{g}$ 2.2	$m(\tilde{\chi}^0_1)$<700 GeV	2204.13072
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}^0_1$	0 e,μ	7-11 jets	E_T^{miss}	140	$\tilde{g}$ 1.97	$m(\tilde{\chi}^0_1)$ <600 GeV	2008.06032
		SS e,μ	6 jets		140	$\tilde{g}$ 1.15	$m(\tilde{g})$-$m(\tilde{\chi}^0_1)$=200 GeV	2307.01094
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	E_T^{miss}	140	$\tilde{g}$ 2.45	$m(\tilde{\chi}^0_1)$<500 GeV	2211.08028
		SS e,μ	6 jets		140	$\tilde{g}$ 1.25	$m(\tilde{g})$-$m(\tilde{\chi}^0_1)$=300 GeV	1909.08457
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e,μ	2 b	E_T^{miss}	140	$\tilde{b}_1$ 1.255	$m(\tilde{\chi}^0_1)$<400 GeV	2101.12527
						$\tilde{b}_1$ 0.68	10 GeV<$\Delta m(\tilde{b}_1,\tilde{\chi}^0_1)$<20 GeV	2101.12527
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_2\to bh\tilde{\chi}^0_1$	0 e,μ	6 b	E_T^{miss}	140	$\tilde{b}_1$ Forbidden 0.23-1.35	$\Delta m(\tilde{\chi}^0_2,\tilde{\chi}^0_1)$=130 GeV, $m(\tilde{\chi}^0_1)$=100 GeV	1908.03122
		2 τ	2 b	E_T^{miss}	140	$\tilde{b}_1$ 0.13-0.85	$\Delta m(\tilde{\chi}^0_2,\tilde{\chi}^0_1)$=130 GeV, $m(\tilde{\chi}^0_1)$=0 GeV	2103.08189
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_1$	0-1 e,μ	$\geq$ 1 jet	E_T^{miss}	140	$\tilde{t}_1$ 1.25	$m(\tilde{\chi}^0_1)$=1 GeV	2004.14060, 2012.03799
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$	1 e,μ	3 jets/1 b	E_T^{miss}	140	$\tilde{t}_1$ Forbidden 1.05	$m(\tilde{\chi}^0_1)$=500 GeV	2012.03799, 2401.13430
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to\tilde{\tau}_1 b\nu$, $\tilde{\tau}_1\to\tau\tilde{G}$	1-2 τ	2 jets/1 b	E_T^{miss}	140	$\tilde{t}_1$ Forbidden 1.4	$m(\tilde{\tau}_1)$=800 GeV	2108.07665
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}^0_1$	0 e,μ	2 c	E_T^{miss}	36.1	$\tilde{c}$ 0.85	$m(\tilde{\chi}^0_1)$=0 GeV	1805.01649
		0 e,μ	mono-jet	E_T^{miss}	140	$\tilde{t}_1$ 0.55	$m(\tilde{t}_1,\tilde{c})$-$m(\tilde{\chi}^0_1)$=5 GeV	2102.10874
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_2$, $\tilde{\chi}^0_2\to Z/h\tilde{\chi}^0_1$	1-2 e,μ	1-4 b	E_T^{miss}	140	$\tilde{t}_1$ 0.067-1.18	$m(\tilde{\chi}^0_2)$=500 GeV	2006.05880
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ	1 b	E_T^{miss}	140	$\tilde{t}_2$ Forbidden 0.86	$m(\tilde{\chi}^0_1)$=360 GeV, $m(\tilde{t}_1)$-$m(\tilde{\chi}^0_1)$= 40 GeV	2006.05880
EW direct	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via WZ	Multiple ℓ/jets		E_T^{miss}	140	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.96	$m(\tilde{\chi}^0_1)$=0, wino-bino	2106.01676, 2108.07586
		$ee,\mu\mu$	$\geq$ 1 jet	E_T^{miss}	140	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.205	$m(\tilde{\chi}^\pm_1)$-$m(\tilde{\chi}^0_1)$=5 GeV, wino-bino	1911.12606
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via WW	2 e,μ		E_T^{miss}	140	$\tilde{\chi}^\pm_1$ 0.42	$m(\tilde{\chi}^0_1)$=0, wino-bino	1908.08215
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via Wh	Multiple ℓ/jets		E_T^{miss}	140	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ Forbidden 1.06	$m(\tilde{\chi}^0_1)$=70 GeV, wino-bino	2004.10894, 2108.07586
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		E_T^{miss}	140	$\tilde{\chi}^\pm_1$ 1.0	$m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}^\pm_1)$+$m(\tilde{\chi}^0_1)$)	1908.08215
	$\tilde{\tau}\tilde{\tau}$, $\tilde{\tau}\to\tau\tilde{\chi}^0_1$	2 τ		E_T^{miss}	140	$\tilde{\tau}$ [$\tilde{\tau}_R\tilde{\tau}_R$] 0.35 0.5	$m(\tilde{\chi}^0_1)$=0	2402.00603
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0 jets	E_T^{miss}	140	$\tilde{\ell}$ 0.7	$m(\tilde{\chi}^0_1)$=0	1908.08215
		$ee,\mu\mu$	$\geq$ 1 jet	E_T^{miss}	140	$\tilde{\ell}$ 0.26	$m(\tilde{\ell})$-$m(\tilde{\chi}^0_1)$=10 GeV	1911.12606
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	$\geq$ 3 b	E_T^{miss}	140	$\tilde{H}$ 0.94	BR($\tilde{\chi}^0_1\to h\tilde{G}$)=1	2401.14922
		4 e,μ	0 jets	E_T^{miss}	140	$\tilde{H}$ 0.55	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	2103.11684
		0 e,μ	$\geq$ 2 large jets	E_T^{miss}	140	$\tilde{H}$ 0.45-0.93	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	2108.07586
		2 e,μ	$\geq$ 2 jets	E_T^{miss}	140	$\tilde{H}$ 0.77	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=BR($\tilde{\chi}^0_1\to h\tilde{G}$)=0.5	2204.13072
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	E_T^{miss}	140	$\tilde{\chi}^\pm_1$ 0.66	Pure Wino	2201.02472
						$\tilde{\chi}^\pm_1$ 0.21	Pure higgsino	2201.02472
	Stable $\tilde{g}$ R-hadron	pixel dE/dx		E_T^{miss}	140	$\tilde{g}$ 2.05		2205.06013
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$	pixel dE/dx		E_T^{miss}	140	$\tilde{g}$ [$\tau(\tilde{g})$ =10 ns] 2.2	$m(\tilde{\chi}^0_1)$=100 GeV	2205.06013
	$\tilde{\ell}\tilde{\ell}$, $\tilde{\ell}\to\ell\tilde{G}$	Displ. lep		E_T^{miss}	140	$\tilde{e},\tilde{\mu}$ 0.74	$\tau(\tilde{\ell})$ = 0.1 ns	ATLAS-CONF-2024-011
						$\tilde{\tau}$ 0.36	$\tau(\tilde{\ell})$ = 0.1 ns	ATLAS-CONF-2024-011
		pixel dE/dx		E_T^{miss}	140	$\tilde{\tau}$ 0.36	$\tau(\tilde{\ell})$ = 10 ns	2205.06013
RPV	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_1$, $\tilde{\chi}^\pm_1\to Z\ell\to\ell\ell\ell$	3 e,μ			140	$\tilde{\chi}^\mp_1/\tilde{\chi}^0_1$ [BR($Z\tau$)=1, BR(Ze)=1] 0.625 1.05	Pure Wino	2011.10543
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	E_T^{miss}	140	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ [$\lambda_{i33}\neq 0,\lambda_{12k}\neq 0$] 0.95 1.55	$m(\tilde{\chi}^0_1)$=200 GeV	2103.11684
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$		$\geq$8 jets		140	$\tilde{g}$ [$m(\tilde{\chi}^0_1)$=50 GeV, 1250 GeV] 1.6 2.34	Large λ''_{112}	2401.16333
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to tbs$		Multiple		36.1	$\tilde{t}$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05	$m(\tilde{\chi}^0_1)$=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to b\tilde{\chi}^\pm_1$, $\tilde{\chi}^\pm_1\to bbs$		$\geq 4b$		140	$\tilde{t}$ Forbidden 0.95	$m(\tilde{\chi}^\pm_1)$=500 GeV	2010.01015
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$ [qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to q\ell$	2 e,μ	2 b		140	$\tilde{t}_1$ 0.4-1.85	BR($\tilde{t}_1\to be/b\mu$)>20%	2406.18367
		1 μ	DV		136	$\tilde{t}_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9] 1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, $\cos\theta_t$=1	2003.11956
	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2/\tilde{\chi}^0_1$, $\tilde{\chi}^0_{1,2}\to tbs$, $\tilde{\chi}^+_1\to bbs$	1-2 e,μ	$\geq$6 jets		140	$\tilde{\chi}^0_1$ 0.2-0.32	Pure higgsino	2106.09609

Mass scale [TeV] (axis: 10^{-1}, 1)

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Directions in Flavour Space

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



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

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

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

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

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.

SMEFT

Since the **scale of New Physics is ~TeV**, the contribution could come from heavy New Physics: **SMEFT**.

Possible tree-level contributions from the following SMEFT dim-6 operators:

$$\mathcal{O}_{lq}^{(1)\alpha\beta ij} = \left(\bar{l}_L^\alpha \gamma_\mu l_L^\beta\right)\left(\bar{q}_L^i \gamma^\mu q_L^j\right), \qquad \mathcal{O}_{Hq}^{(1)ij} = \left(H^\dagger \overleftrightarrow{D}_\mu H\right)\left(\bar{q}_L^i \gamma^\mu q_L^j\right),$$

$$\mathcal{O}_{lq}^{(3)\alpha\beta ij} = \left(\bar{l}_L^\alpha \gamma_\mu \sigma_a l_L^\beta\right)\left(\bar{q}_L^i \gamma^\mu \sigma_a q_L^j\right), \qquad \mathcal{O}_{Hq}^{(3)ij} = \left(H^\dagger \sigma_a \overleftrightarrow{D}_\mu H\right)\left(\bar{q}_L^i \gamma^\mu \sigma_a q_L^j\right),$$

$$\mathcal{O}_{ld}^{\alpha\beta ij} = \left(\bar{l}_L^\alpha \gamma_\mu l_L^\beta\right)\left(\bar{d}_R^i \gamma^\mu d_R^j\right), \qquad \mathcal{O}_{Hd}^{ij} = \left(H^\dagger \overleftrightarrow{D}_\mu H\right)\left(\bar{d}_R^i \gamma^\mu d_R^j\right).$$

$$L_L^{ij\alpha\beta} = C_{lq}^{(1)\alpha\beta ij} - C_{lq}^{(3)\alpha\beta ij} + C_{Hq}^{(1)ij}\delta_{\alpha\beta} + C_{Hq}^{(3)ij}\delta_{\alpha\beta}$$

$$L_R^{ij\alpha\beta} = C_{ld}^{\alpha\beta ij} + C_{Hd}^{ij}\delta_{\alpha\beta}\,.$$

$C_{SMEFT}(1\text{TeV})$ —RG→ $C_{SMEFT}(m_{EW})$ —matching + RG→ $L_{LEFT}(\text{GeV})$

dilepton constraints | EW precision tests | Fit of B → $K^{(*)}\nu\nu$ + Flavour bounds

SMEFT: **which combinations of coefficients** to study?

We assume they are **induce by specific heavy UV states** and study those simplified models instead.

SMEFT

$$\mathcal{O}_{lq}^{(1)\alpha\beta ij} = \left(\bar{l}_L^\alpha \gamma_\mu l_L^\beta\right)\left(\bar{q}_L^i \gamma^\mu q_L^j\right)$$
$$\mathcal{O}_{lq}^{(3)\alpha\beta ij} = \left(\bar{l}_L^\alpha \gamma_\mu \sigma_a l_L^\beta\right)\left(\bar{q}_L^i \gamma^\mu \sigma_a q_L^j\right)$$
$$\mathcal{O}_{ld}^{\alpha\beta ij} = \left(\bar{l}_L^\alpha \gamma_\mu l_L^\beta\right)\left(\bar{d}_R^i \gamma^\mu d_R^j\right)$$

$$\mathcal{O}_{Hq}^{(1)ij} = \left(H^\dagger \overleftrightarrow{D}_\mu H\right)\left(\bar{q}_L^i \gamma^\mu q_L^j\right) ,$$
$$\mathcal{O}_{Hq}^{(3)ij} = \left(H^\dagger \sigma_a \overleftrightarrow{D}_\mu H\right)\left(\bar{q}_L^i \gamma^\mu \sigma_a q_L^j\right) ,$$
$$\mathcal{O}_{Hd}^{ij} = \left(H^\dagger \overleftrightarrow{D}_\mu H\right)\left(\bar{d}_R^i \gamma^\mu d_R^j\right) .$$

Colorless vectors & Leptoquarks

	Spin	G_{SM}	Interaction term	SMEFT coeff.
V'	1	$(\mathbf{1},\mathbf{3},0)$	$\left[g_q^{ij}(\bar{q}_L^i\gamma^\mu\sigma_a q_L^j) + g_\ell^{\alpha\beta}(\bar{l}_L^\alpha\gamma^\mu\sigma_a l_L^\beta)\right] V'_{a\mu}$	$C_{lq}^{(3)}$
Z'_L	1	$(\mathbf{1},\mathbf{1},0)$	$\left[g_q^{ij}(\bar{q}_L^i\gamma^\mu q_L^j) + g_\ell^{\alpha\beta}(\bar{l}_L^\alpha\gamma^\mu\sigma_a l_L^\beta)\right] Z'_{L\mu}$	$C_{lq}^{(1)}$
Z'_R	1	$(\mathbf{1},\mathbf{1},0)$	$\left[g_q^{ij}(\bar{d}_R^i\gamma^\mu d_R^j) + g_\ell^{\alpha\beta}(\bar{l}_L^\alpha\gamma^\mu\sigma_a l_L^\beta)\right] Z'_{R\mu}$	C_{ld}
S_1	0	$(\bar{\mathbf{3}},\mathbf{1},1/3)$	$\lambda_{i\alpha}^*(\overline{q_L^{i,c}}\epsilon l_L^\alpha)S_1$	$C_{lq}^{(1)} = -C_{lq}^{(3)}$
S_3	0	$(\bar{\mathbf{3}},\mathbf{3},1/3)$	$\lambda_{i\alpha}^*(\overline{q_L^{i,c}}\epsilon\sigma_a l_L^\alpha)(S_3)_a$	$C_{lq}^{(1)} = 3C_{lq}^{(3)}$
U_3	1	$(\mathbf{3},\mathbf{3},2/3)$	$\lambda_{i\alpha}(\overline{q_L^i}\gamma_\mu\sigma_a l_L^\alpha)(U_3^\mu)_a$	$C_{lq}^{(1)} = -3C_{lq}^{(3)}$
$\tilde{R}_2$	0	$(\mathbf{3},\mathbf{2},1/6)$	$\lambda_{i\alpha}\overline{d_R^i}(l_L^\alpha\epsilon\tilde{R}_2)$	C_{ld}
V_2	1	$(\bar{\mathbf{3}},\mathbf{2},5/6)$	$\lambda_{i\alpha}^*\overline{d_R^{i,c}}\gamma_\mu(l_L^\alpha\epsilon V_2^\mu)$	C_{ld}

U_1 LQ does not contribute to bsνν: we don't consider it

vectorlike quarks

Simplified model	Spin	SM irrep	SMEFT couplings
D	1/2	$(\mathbf{3},\mathbf{1},-1/3)$	$C_{Hq}^{(1)} = C_{Hq}^{(3)}$
T_1	1/2	$(\mathbf{3},\mathbf{3},-1/3)$	$C_{Hq}^{(1)} = -3C_{Hq}^{(3)}$
T_2	1/2	$(\mathbf{3},\mathbf{3},2/6)$	$C_{Hq}^{(1)} = 3C_{Hq}^{(3)}$
Q_1	1/2	$(\mathbf{3},\mathbf{2},1/6)$	C_{Hd}
Q_5	1/2	$(\mathbf{3},\mathbf{2},-5/6)$	C_{Hd}

These give too large contributions to B_s mixing and $B_s \to \mu\mu$:

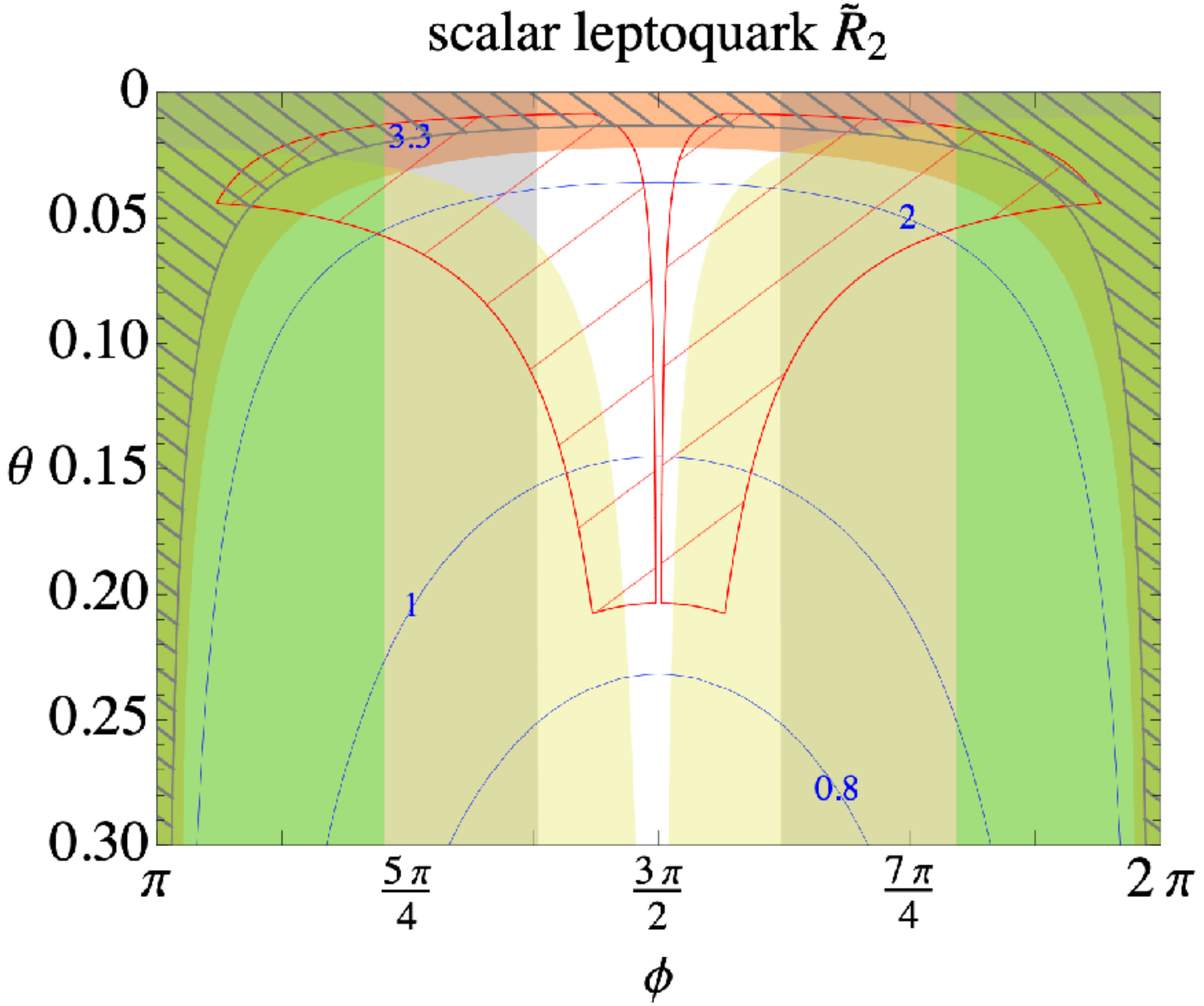
A good fit of the R_K^{ν} excess is never allowed.
(see backup slide)

L. Allwicher, D. Becirevic, G. Piazza, S. Rosauro-Alcaraz and O. Sumensari [2309.02246]

UV mediators - $\tilde{R}_2$ leptoquark

(similar for S_1)

LQ	Spin	G_{SM}	Interaction term	SMEFT coeff.	C
$\tilde{R}_2$	0	$(\mathbf{3}, \mathbf{2}, 1/6)$	$\lambda_{i\tau} \overline{d_R^i}(l_L^\tau \epsilon \tilde{R}_2)$	C_{ld}	$-\frac{1}{2}\frac{\lvert\lambda\rvert^2}{m_{LQ}^2}$

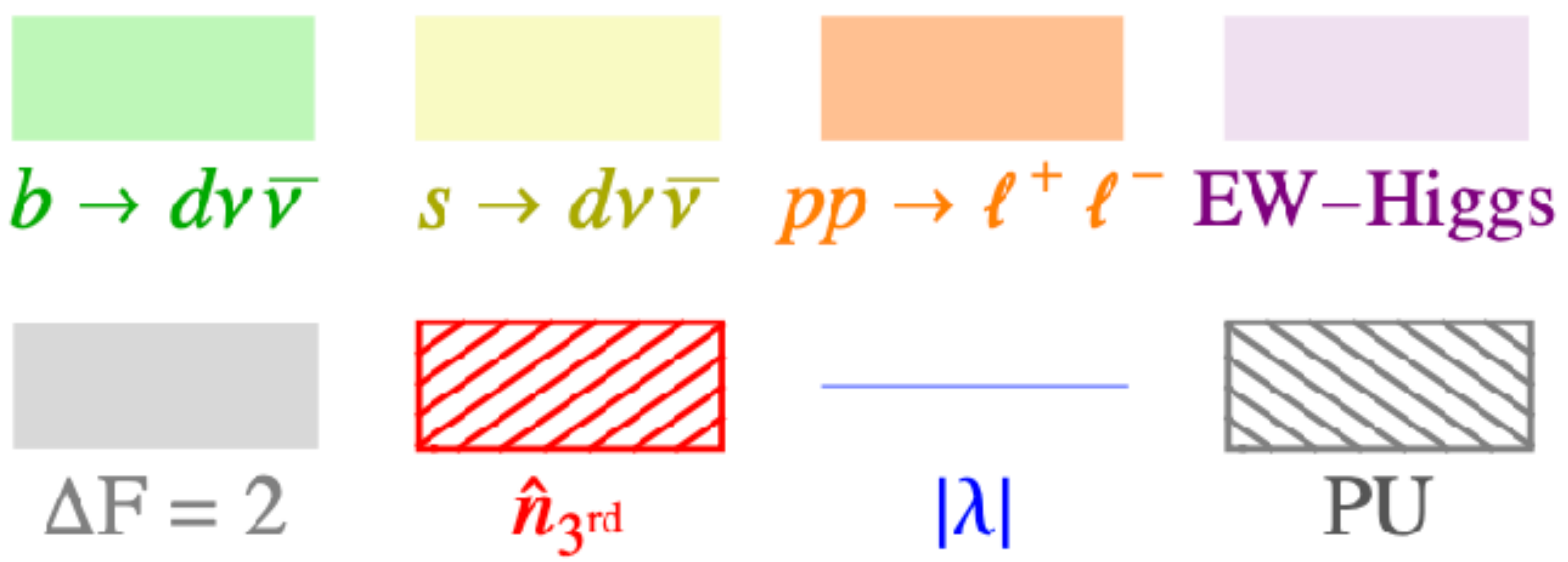


We fix the **LQ mass at 2 TeV** to avoid direct-searches bounds.

At each parameter space point we fix the best-fit:

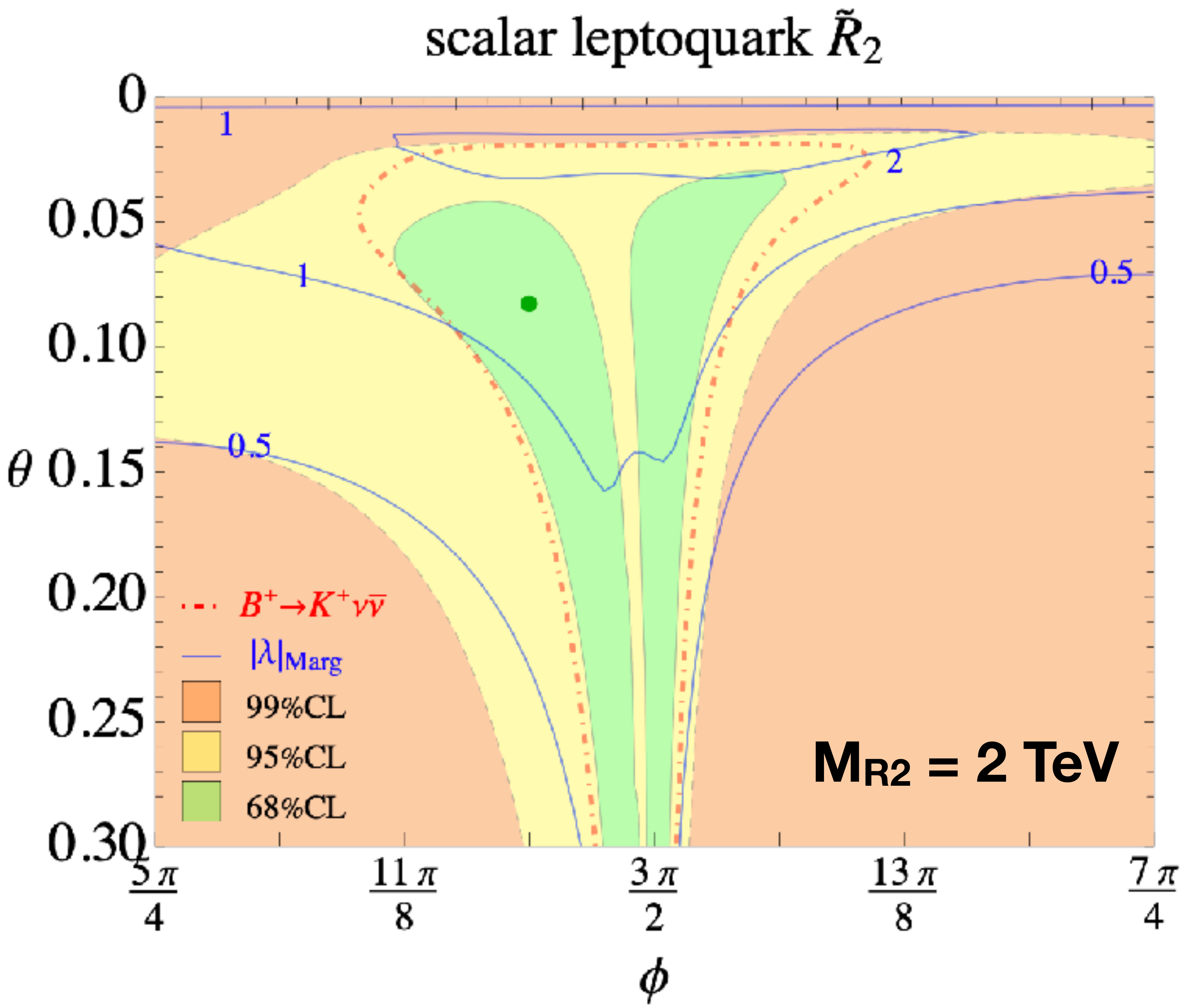
$$C_{ld}^{\tau\tau sb}\Big|_{\tilde{R}_2,\mathrm{best-fit}} \approx (7.5\,\mathrm{TeV})^{-2}$$

Show regions excluded by:

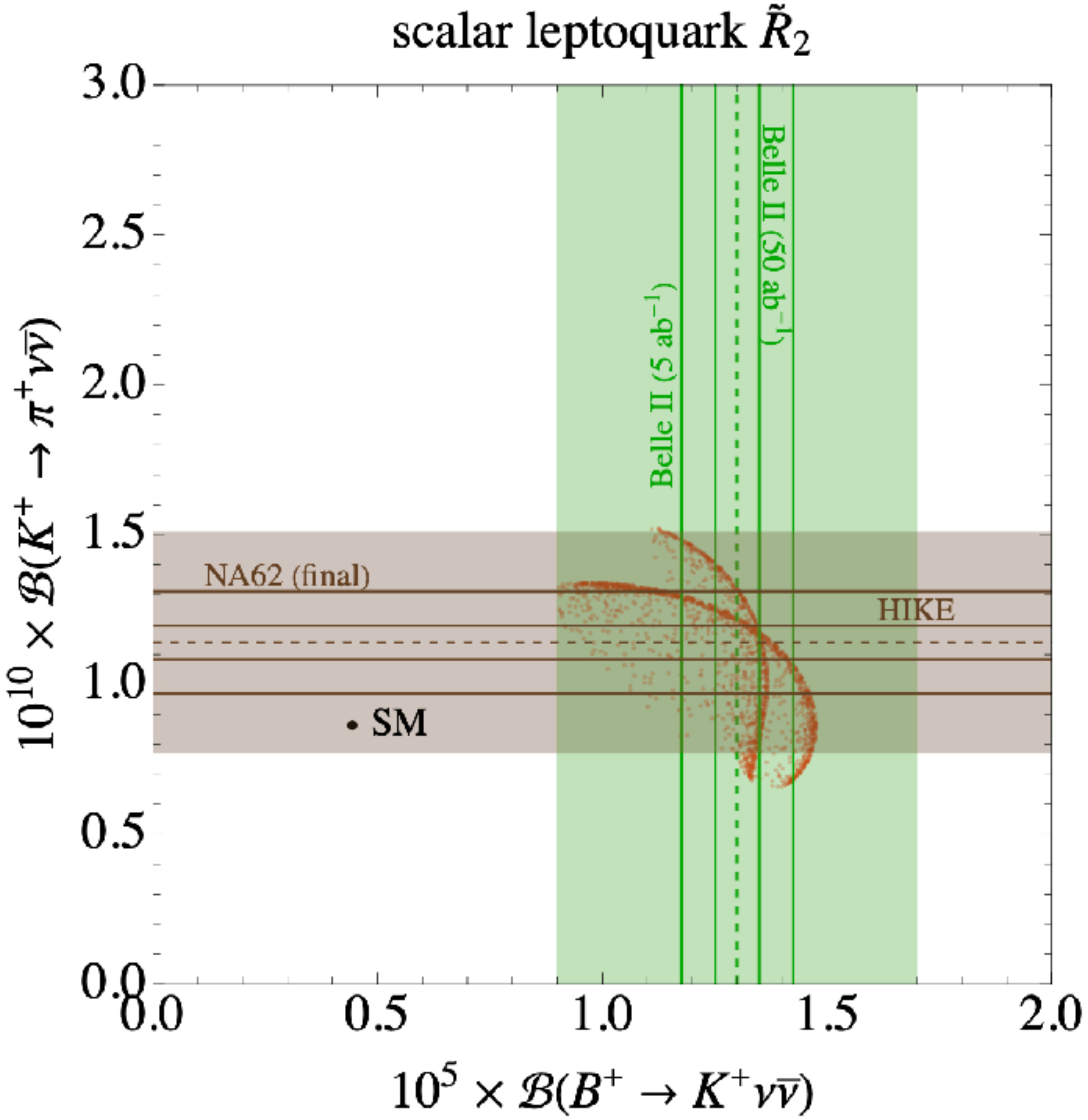


UV mediators - $\tilde{R}_2$ leptoquark (similar for S_1)

Favoured region from the global fit of all observables, marginalising over $|\lambda|$.

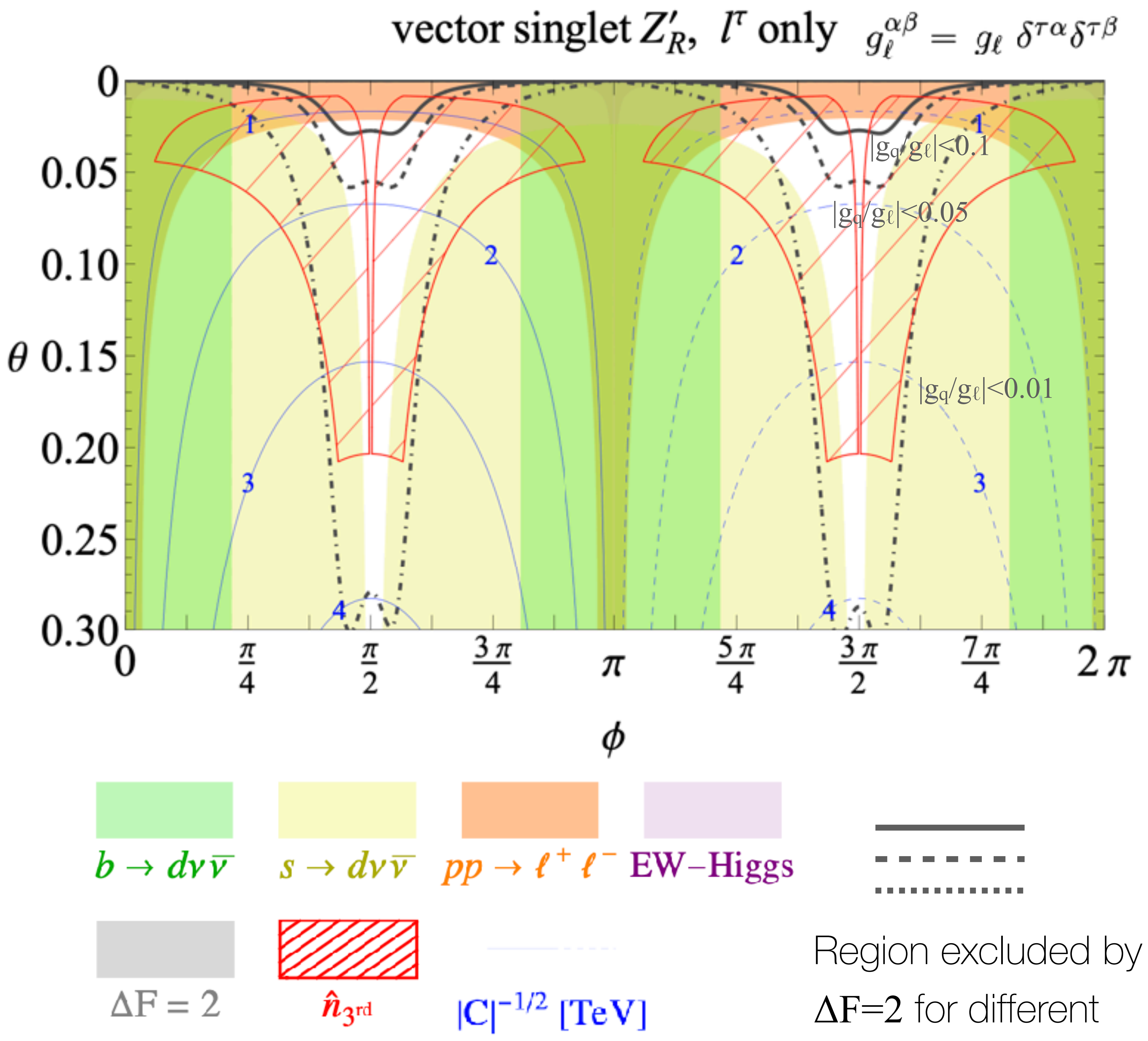


Correlation between ***BKvv*** and ***Kπvv*** for the points within 1σ region.



UV mediators - Z'

$$\mathcal{L} \supset \left[\sum_{ij} g_L^{ij} (\bar{q}_L^i \gamma^\mu q_L^j) + \sum_{ij} g_R^{ij} (\bar{d}_R^i \gamma^\mu d_R^j) + \sum_{\alpha\beta} g_\ell^{\alpha\beta} \bar{l}_L^\alpha \gamma^\mu l_L^\beta \right] Z'_\mu$$



Region excluded by ΔF=2 for different max values of $|g_q/g_\ell|$.

$$C = -g_q g_\ell / M_{Z'}^2$$

(similar for a coupling to LH quarks or for a SU(2) triplet V')

$$C_{ld}^{\tau\tau sb}\Big|_{Z_R,\text{best-fit}} \approx (7.7\,\text{TeV})^{-2}$$

Meson mixing puts an upper bound on $|g_q/g_\ell|$.

Combined with the **perturbative unitarity** constraint $g_\ell < 2.3$ we get an **upper limit on the vector mass** for each point in the plane, when imposing a fit to the anomaly:

$$M_{V'} \lesssim 1391 \text{ GeV} \left(\frac{|g_q/g_\ell|^{\max}}{0.05}\right)^{1/2} |\sin\theta\cos\theta\sin\phi|^{\frac{1}{2}}$$

$$\approx 762 \text{ GeV} \left(\frac{|g_q/g_\ell|^{\max}}{0.05}\right)^{1/2} \left|\frac{\theta}{0.3}\right|^{1/2}, \quad \text{(for } \theta \ll 1 \text{ and } \phi \sim \pi/2)$$

The **vector must be rather light** in the allowed region!

Need to check di-tau bounds without assuming EFT.

UV mediators - Z'

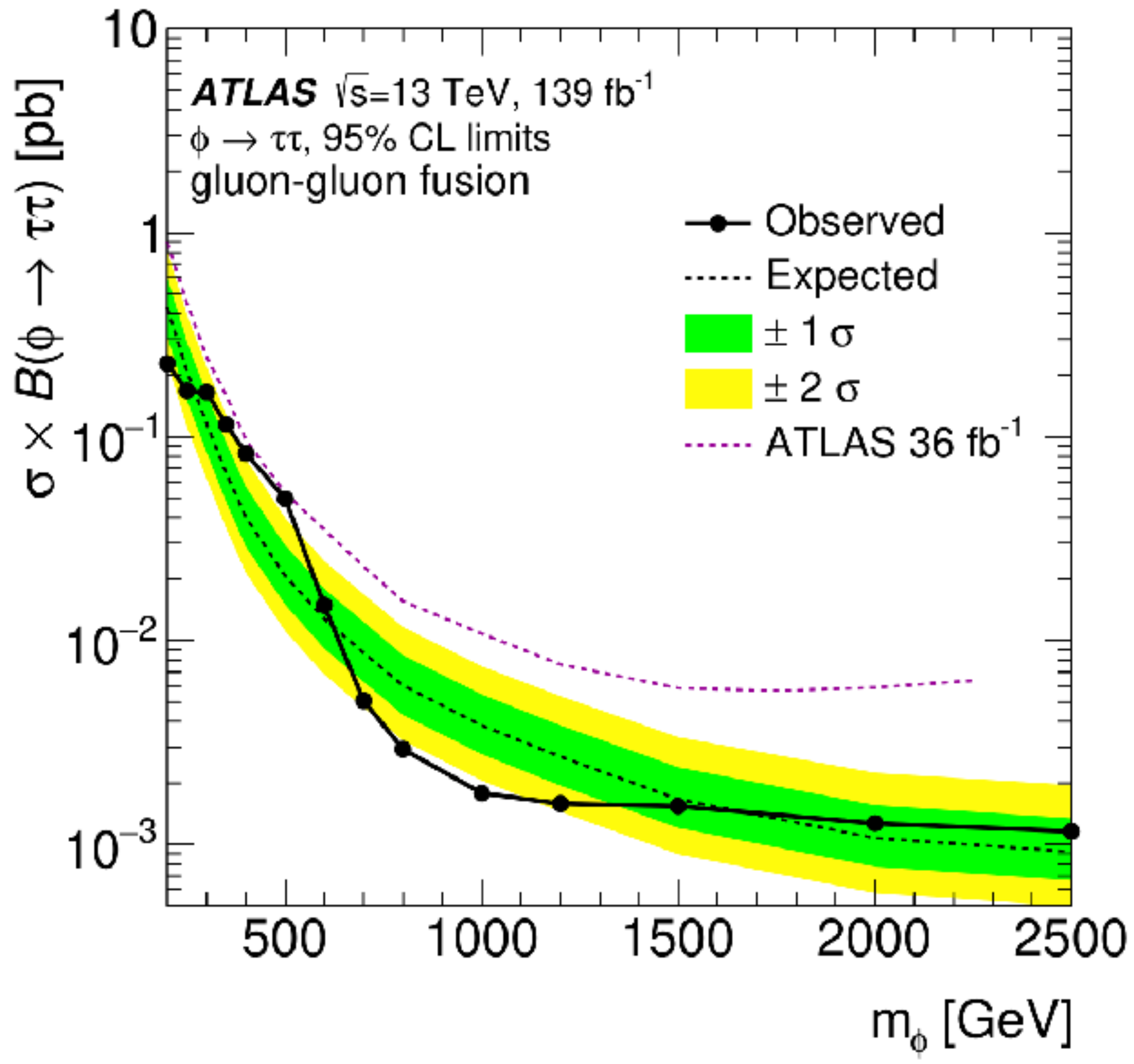
$$\mathcal{L} \supset \left[\sum_{ij} g_L^{ij} (\bar{q}_L^i \gamma^\mu q_L^j) + \sum_{ij} g_R^{ij} (\bar{d}_R^i \gamma^\mu d_R^j) + \sum_{\alpha\beta} g_\ell^{\alpha\beta} \bar{l}_L^\alpha \gamma^\mu l_L^\beta \right] Z'_\mu$$

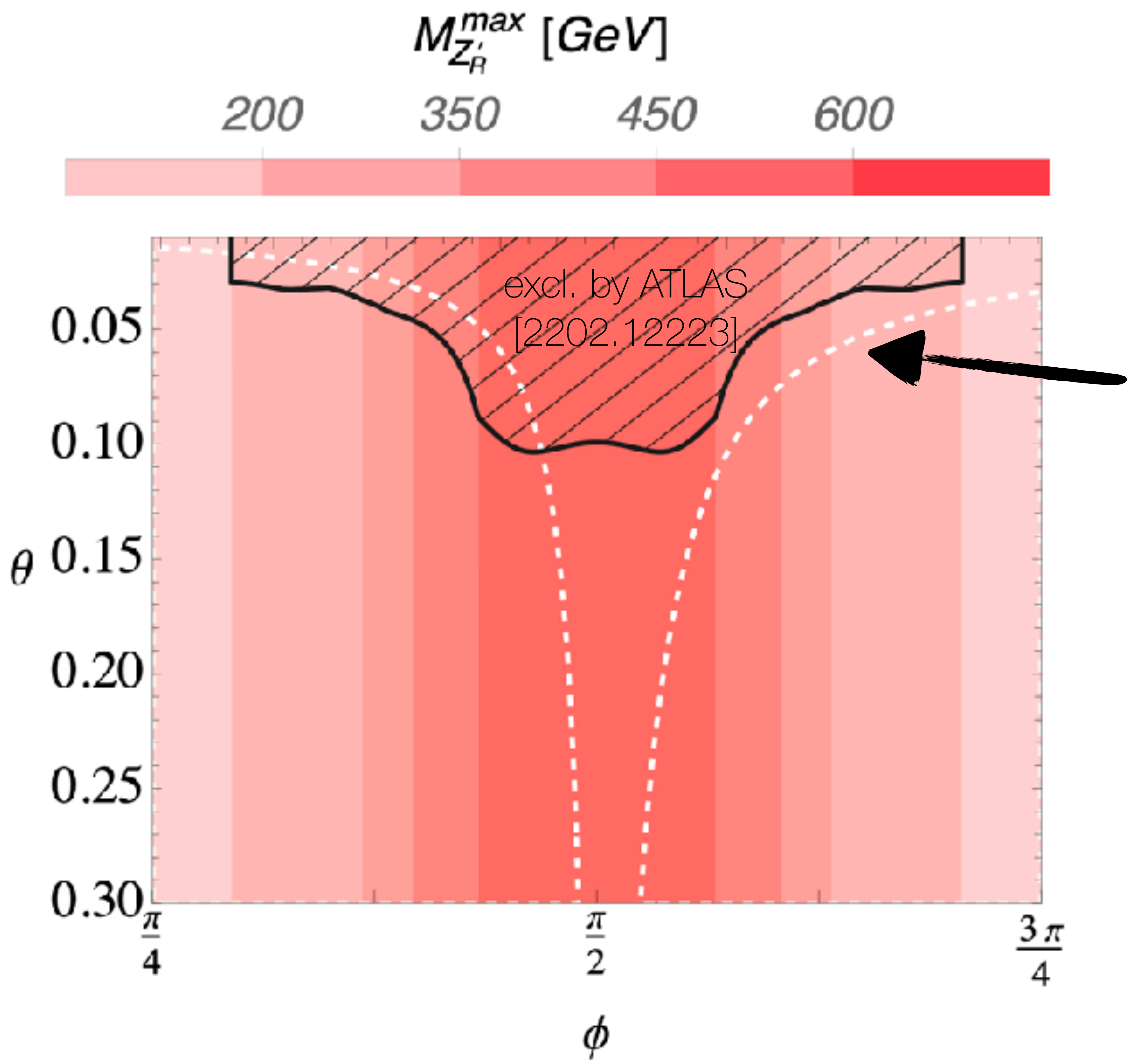
Since g_ℓ is large, the Z' decays mostly to $\tau\tau$ or $\nu\nu$, with $\mathrm{Br} \sim 1/2$.

$$\Gamma_{\rm tot}/M_{V'} \approx 14\%$$

$$\sigma(pp \to V'^0 \to \tau^+\tau^-) \approx \frac{4\pi^2}{3}\mathcal{B}(V'^0 \to \tau^+\tau^-) \sum_{i,j=u,d,s,c,b} \frac{\Gamma(V'^0 \to q^i\bar{q}^j)}{M_{V'}} \frac{2}{s_0}\mathcal{L}_{q^i\bar{q}^j}(M_{V'})$$

$$\Gamma(V'^0 \to q^i\bar{q}^j) = \frac{M_{V'}N_c}{24\pi}|g_q^{ij}|^2$$

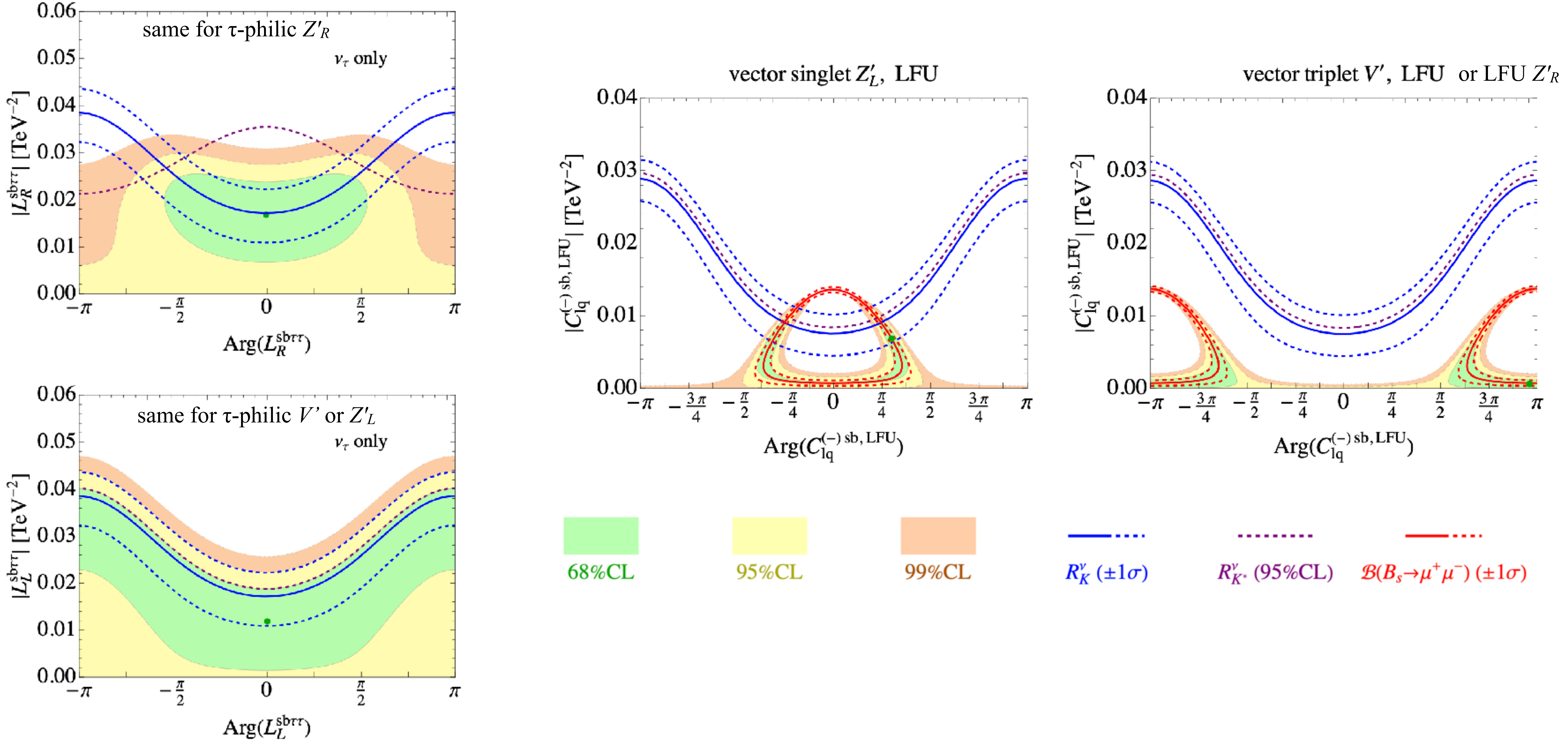




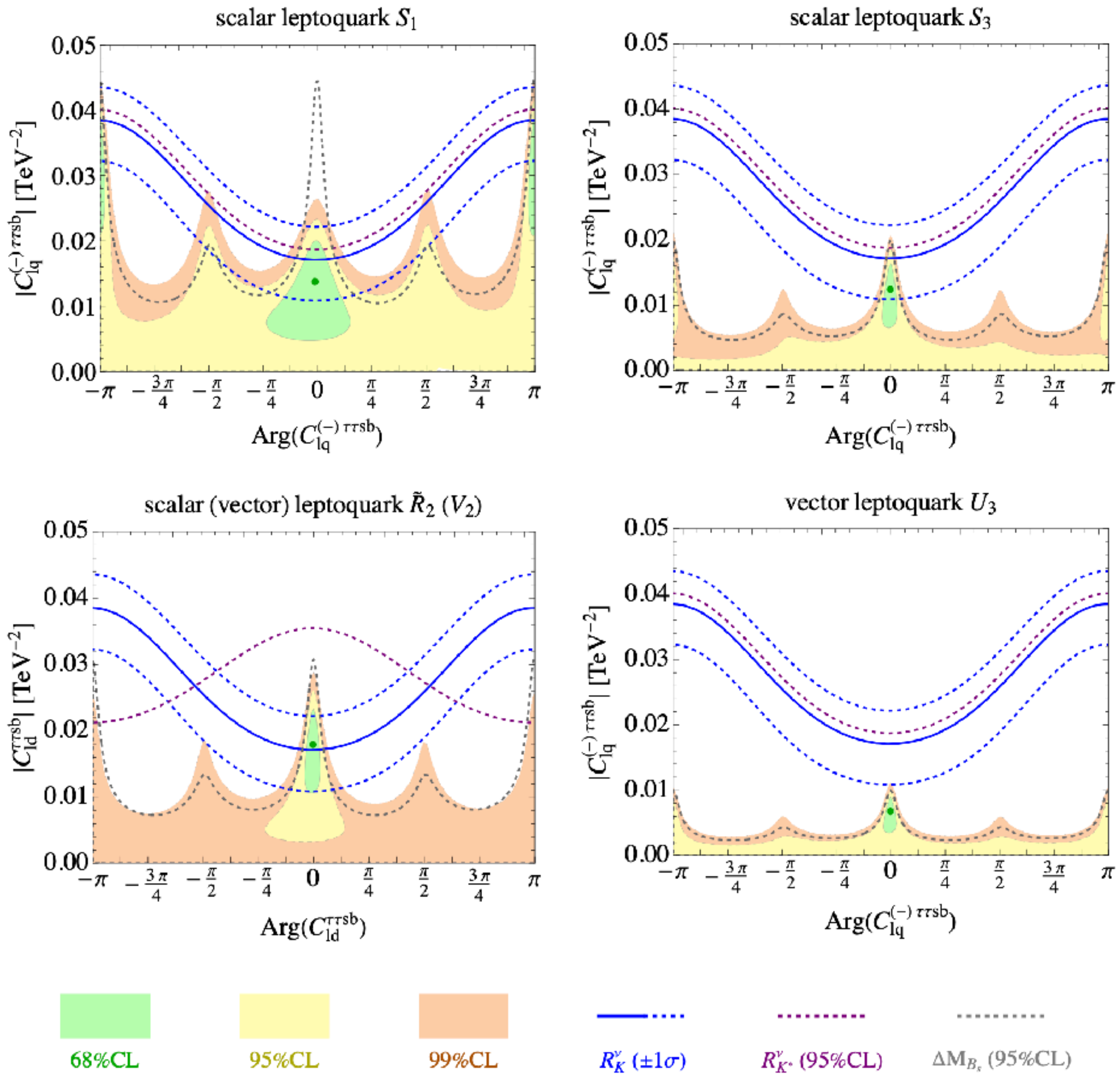
Outside the white dashed line is excluded by Flavour + EW

(this is a rough constraint, we neglect effect of different acceptances between scalar and vector resonances)

Fits of the s-b couplings - LEFT & vectors



Fits of the s-b couplings - LQ

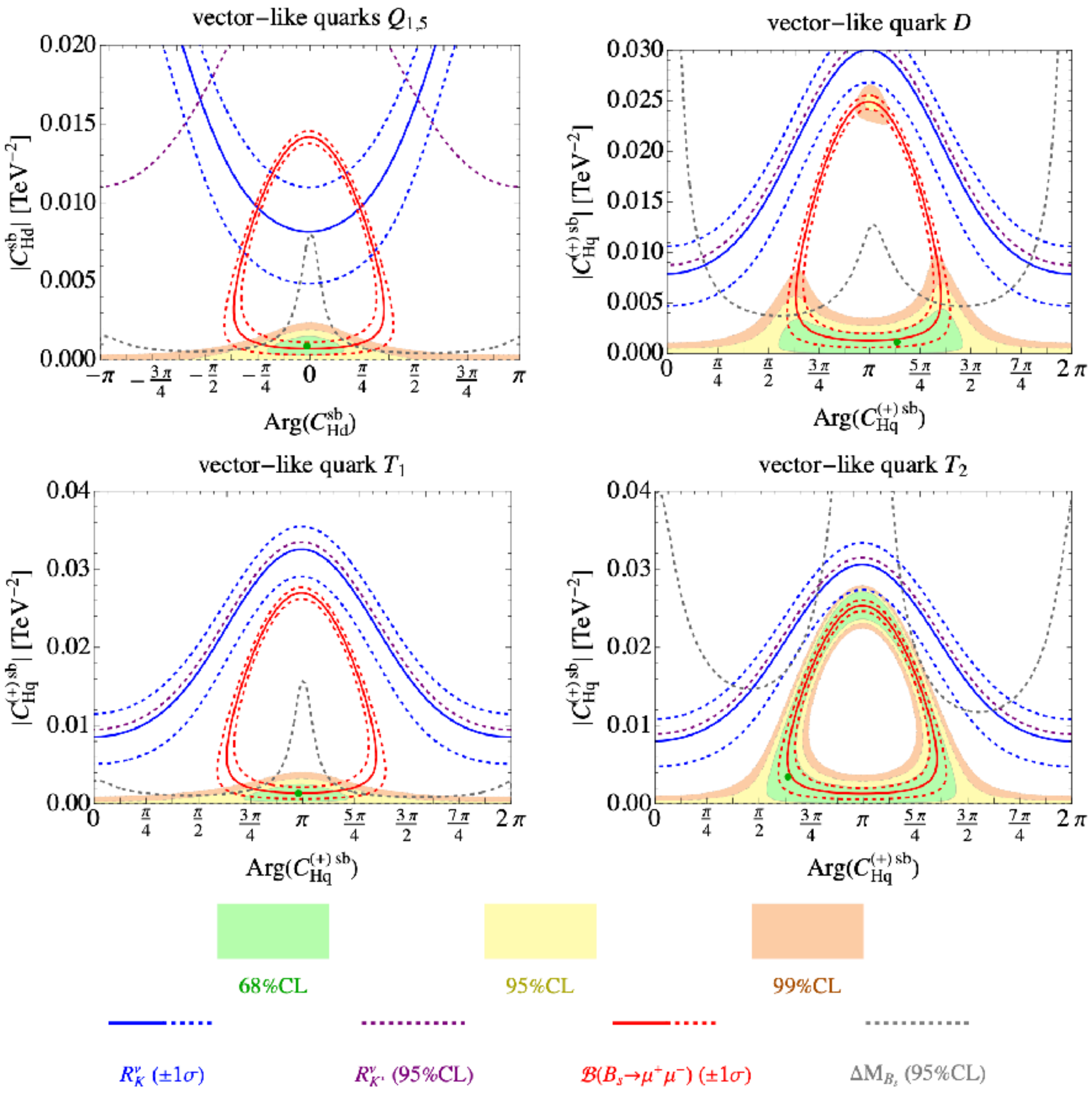


Fits of the s-b couplings - VLQ

Given the multiple possible combinations of coefficients, we assume they are induce by specific heavy UV states.

In this case: vector-like quarks:

Simplified model	Spin	SM irrep	SMEFT couplings
D	$1/2$	$(\mathbf{3}, \mathbf{1}, -1/3)$	$C_{Hq}^{(1)} = C_{Hq}^{(3)}$
T_1	$1/2$	$(\mathbf{3}, \mathbf{3}, -1/3)$	$C_{Hq}^{(1)} = -3C_{Hq}^{(3)}$
T_2	$1/2$	$(\mathbf{3}, \mathbf{3}, 2/6)$	$C_{Hq}^{(1)} = 3C_{Hq}^{(3)}$
Q_1	$1/2$	$(\mathbf{3}, \mathbf{2}, 1/6)$	C_{Hd}
Q_5	$1/2$	$(\mathbf{3}, \mathbf{2}, -5/6)$	C_{Hd}



A good fit of the R^{ν}_{K} excess is never allowed.

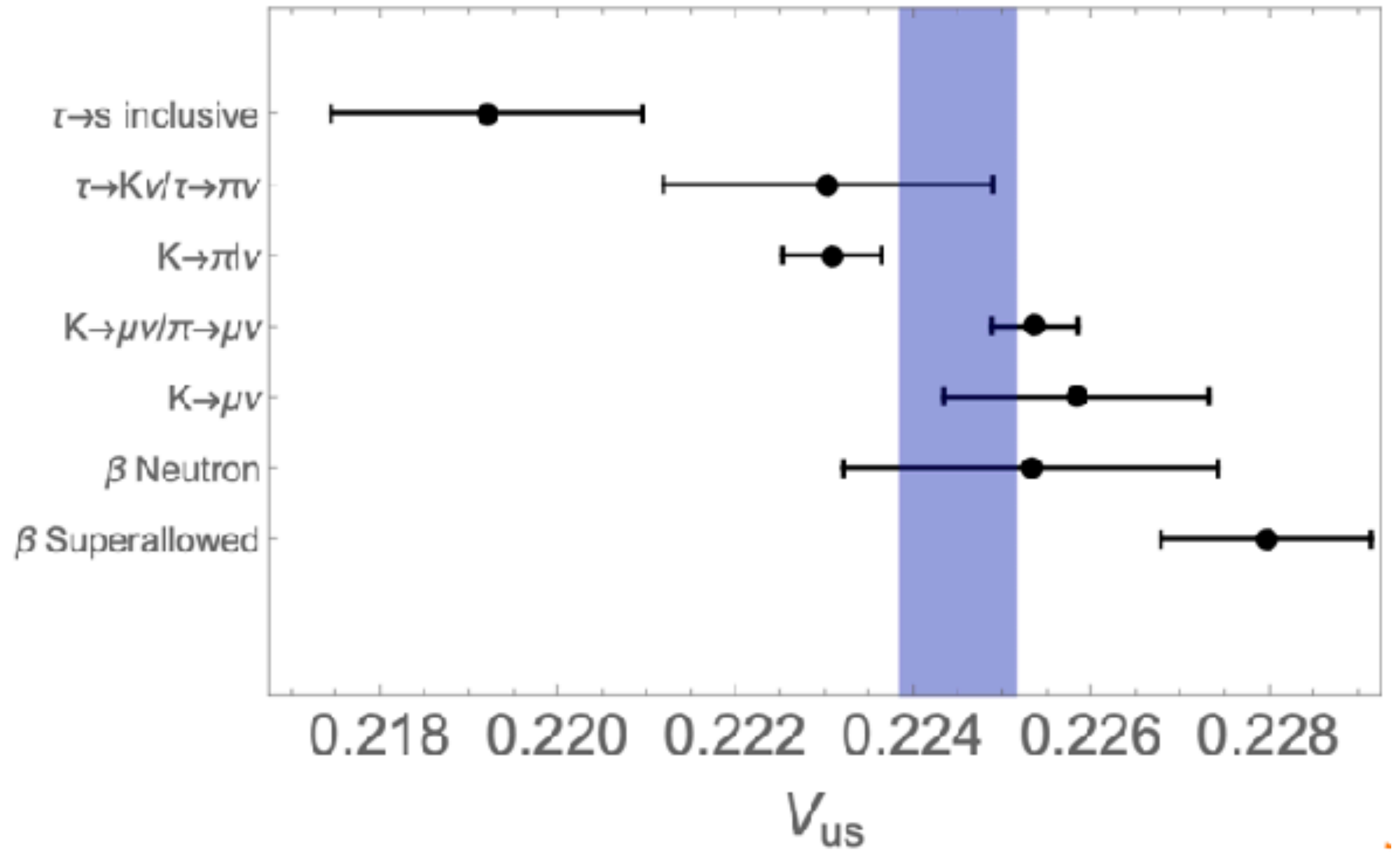
L. Allwicher, D. Becirevic, G. Piazza, S. Rosauro-Alcaraz and O. Sumensari [2309.02246]

Observables included

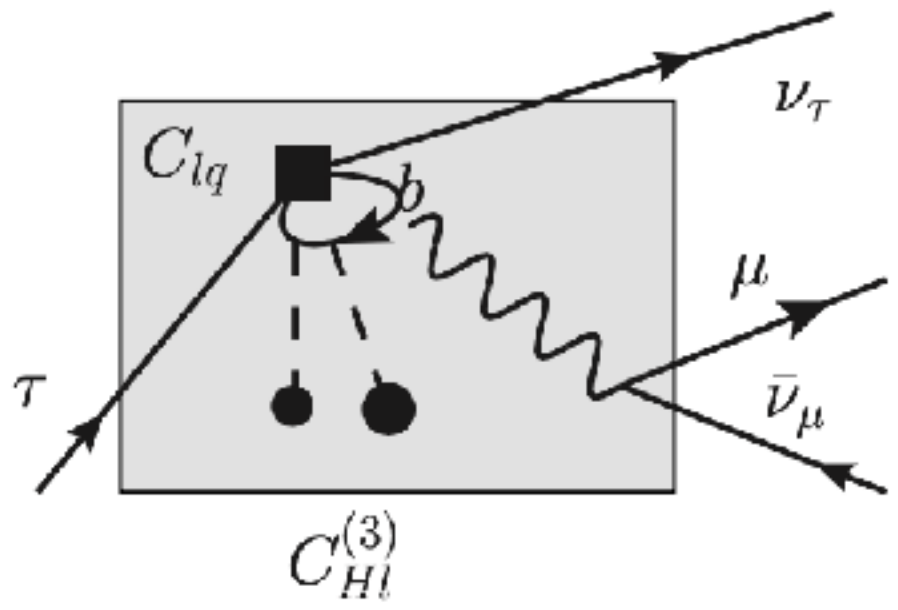
Cabibbo angle

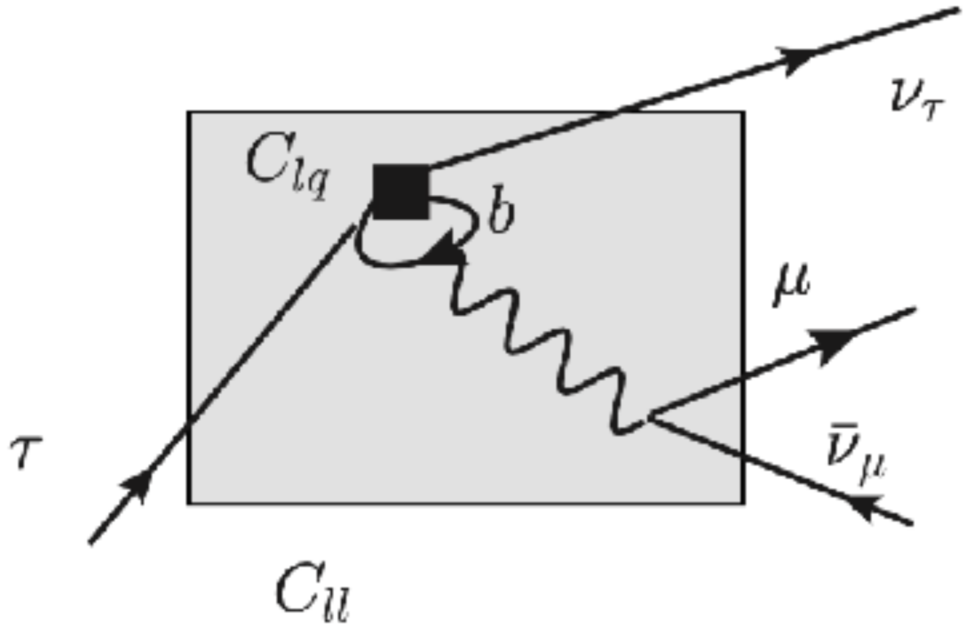
unitarity relation (V_{ub} negligible):

$$|V_{ud}|^2 + |V_{us}|^2 = 1$$

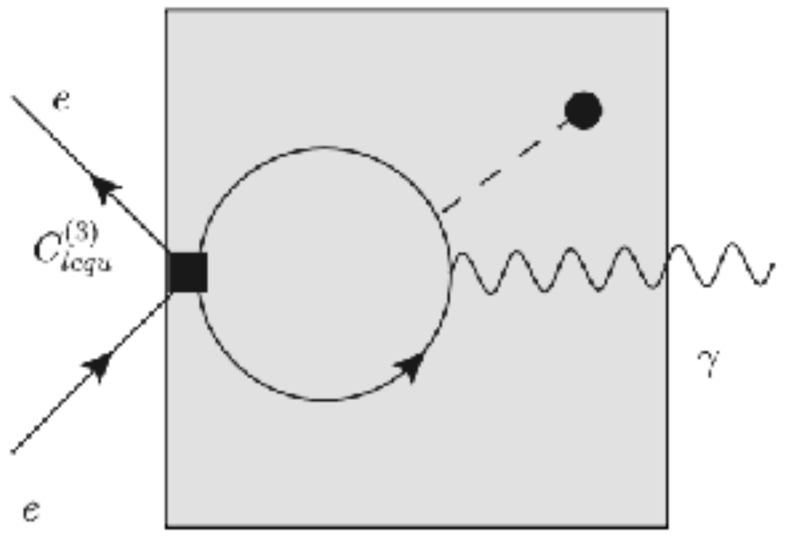


LFU





Magnetic Moments



Higgs and EW

$$\delta g_L^{Z\ell} \longleftarrow C_{uB},\ C_{uW}, C_{Hu},\ C_{Hq}^{(1,3)},\ C_{lq}^{(1,3),\ell\ell},\ C_{lu}^{\ell\ell},\ \ldots$$

$$\delta g_L^{W\ell} \longleftarrow C_{uB},\ C_{uW},\ C_{Hu},\ C_{Hq}^{(1,3)},\ C_{lq}^{(3),\ell\ell},\ \ldots$$

$$\delta g_R^{Z\ell} \longleftarrow C_{uB},\ C_{uW},\ C_{Hu},\ C_{Hq}^{(1,3)},\ C_{eu}^{\ell\ell},\ C_{qe}^{\ell\ell},\ \ldots$$

$$\delta g_L^{Zb} \longleftarrow C_{Hq}^{(1,3)},\ C_{Hu},\ C_{qq}^{(1,3)},\ \ldots$$

$$\delta g_R^{Zb} \longleftarrow C_{Hq}^{(1)},\ C_{Hu},\ C_{qq}^{(1,3)},\ C_{uB},\ C_{uW},\ \ldots$$

$$c_{\gamma\gamma} \longleftarrow C_{uB},\ C_{uW},\ C_{uG}$$

$$c_{gg} \longleftarrow C_{uG}$$

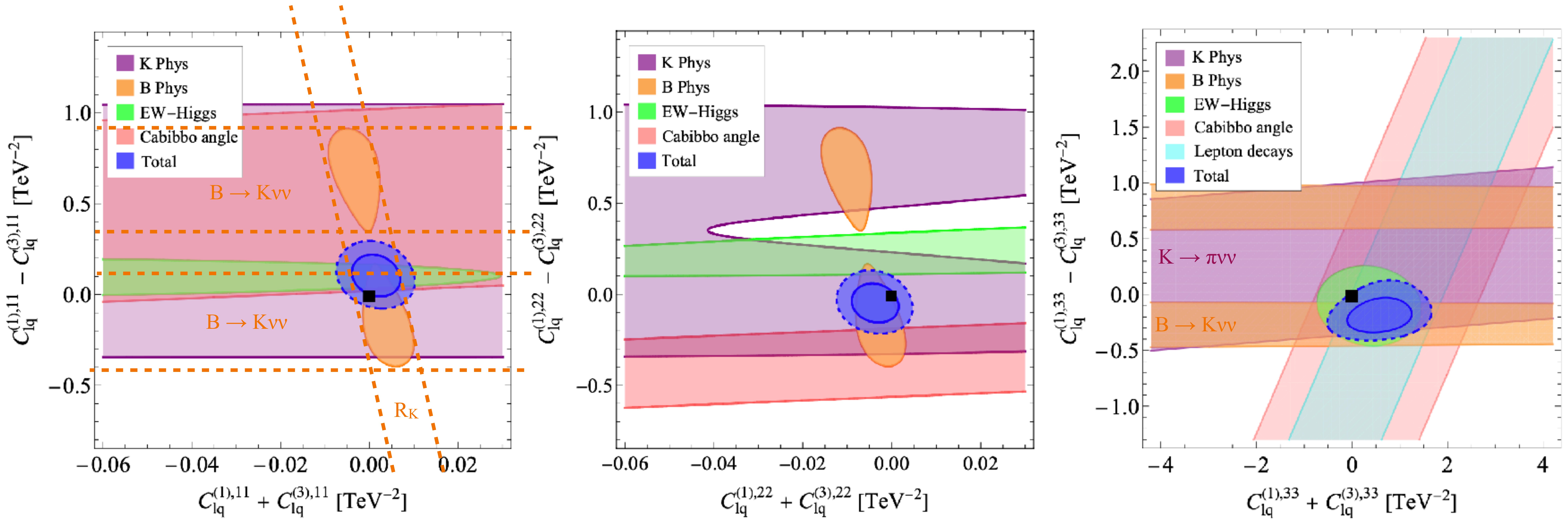
$$[C_{eH}]_{\alpha\alpha} \longleftarrow C_{lequ}^{(1),\alpha\alpha}$$

$$[C_{uH}]_{33} \longleftarrow C_{uH},\ C_{uG},\ C_{Hq}^{(1,3)},\ C_{qu}^{(1,8)},\ \ldots$$

B physics

	Tree level matching	RG and 1-loop matching
$R^{\nu}_{K^{(*)}}$ $K \to \pi\nu\bar{\nu}$	$C_{Hq}^{(1,3)}$, $C_{lq}^{(1,3),\alpha\beta}$	C_{Hu}, $C_{qq}^{(1,3)}$, $C_{lu}^{\alpha\beta}$, $C_{qe}^{\alpha\beta}$ $C_{qu}^{(1,8)}$, C_{uu}, C_{uW}
$B \to K^{(*)}\ell_\alpha\ell_\beta$ $B_{s,d} \to \ell_\alpha\ell_\beta$ $K \to \pi\ell_\alpha\ell_\beta$ $K \to \ell_\alpha\ell_\beta$	$C_{Hq}^{(1,3)}$, $C_{lq}^{(1,3),\alpha\beta}$, $C_{qe}^{\alpha\beta}$	$C_{qq}^{(1,3)}$, $C_{lu}^{\alpha\beta}$, $C_{eu}^{\alpha\beta}$
$R_{K^{(*)}}$	$C_{lq}^{(1,3),\ell\ell}$, $C_{qe}^{\ell\ell}$	$C_{lu}^{\ell\ell}$
$B \to X_s\gamma$		$C_{Hq}^{(1,3)}$, C_{uB}, C_{uW}, C_{uG}

2D fits



With electrons and muons: **EW bounds** do **not allow** a combined explanations of **Cabibbo anomaly** and **B→Kνν**

Gaussian Fit ex. semileptonics

$$\vec{C} = (C_{qq}^{(+)}, C_{qq}^{(-)}, C_{uu}, C_{qu}^{(1)}, C_{qu}^{(8)}, C_{Hq}^{(+)}, C_{Hq}^{(-)}, C_{Hu}, C_{uH}, C_{uG}, C_{uW}, C_{uB})$$

$$\Delta\chi^2 \equiv \chi^2_{\rm SM} - \chi^2_{\rm best-fit} \approx 10.9$$

(only mild improvements in several observables, not a single "anomaly")

Due to flat directions, we report the result in terms of the eigenvectors of the Hessian matrix around the minimum

$$\chi^2 = \chi^2_{\rm best-fit} + (C_i - \mu_{C_i})(\sigma^2)^{-1}_{ij}(C_j - \mu_{C_j}) = \chi^2_{\rm best-fit} + \frac{(K_i - \mu_{K_i})^2}{\sigma^2_{K_i}}$$

$$\vec{K} = U_{KC}\vec{C}$$

Coefficient	Gaussian fit [TeV^{-2}]	Coefficient	Gaussian fit [TeV^{-2}]
K_1	0.0019 ± 0.0023	K_7	0.54 ± 0.79
K_2	0.0179 ± 0.0083	K_8	0.74 ± 0.88
K_3	-0.002 ± 0.015	K_9	-0.8 ± 1.3
K_4	-0.016 ± 0.021	K_{10}	-0.7 ± 1.8
K_5	0.044 ± 0.029	K_{11}	12 ± 13
K_6	-0.30 ± 0.38	K_{12}	-11 ± 16

Flat directions:

$$K_{11} \approx -0.80 C_{qq}^{(-)} + 0.45 C_{uu} - 0.36 C_{qu}^{(1)} - 0.12 C_{Hu} + \ldots\ ,$$
$$K_{12} \approx +0.40 C_{qq}^{(-)} + 0.88 C_{uu} + 0.24 C_{qu}^{(1)} - 0.09 C_{Hu} + \ldots\ .$$