From B anomalies to Kaon physics with scalar leptoquarks

David Marzocca
INFN Trieste

Based on:

V. Gherardi, E. Venturini, D.M. [2003.12525]
V. Gherardi, E. Venturini, D.M. [2008.09548]
S. Trifinopoulos, E. Venturini, D.M. [2106.15630]

Portoroz - 23/09/2021

The question

$b \rightarrow c\,\tau\,\nu$ + $b \rightarrow s\,\mu\,\mu$

$\downarrow$

TeV-scale leptoquark coupled to **2nd** and **3rd** generation

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TeV-scale leptoquark coupled to **2nd** and **3rd** generation

In “realistic" flavor models LQ must also couple to **1st** generation fermions.

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$b \longrightarrow c\, \tau\, \nu$ + $b \longrightarrow s\, \mu\, \mu$

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TeV-scale leptoquark coupled to **2nd** and **3rd** generation

In “realistic" flavor models LQ must also couple to **1st** generation fermions.

What are the implications of this for:

$s \longrightarrow d$ i.e. Kaon physics

$\mu \longrightarrow e$ LFV processes

?

The setup

We need a model able to address **B anomalies**: **U_1**, **S_1+S_3**, **R_2+S_3**

For a complete analysis we need to compute many observables at one-loop: a ***renormalizable*** model is needed to get unambiguous “finite terms”.

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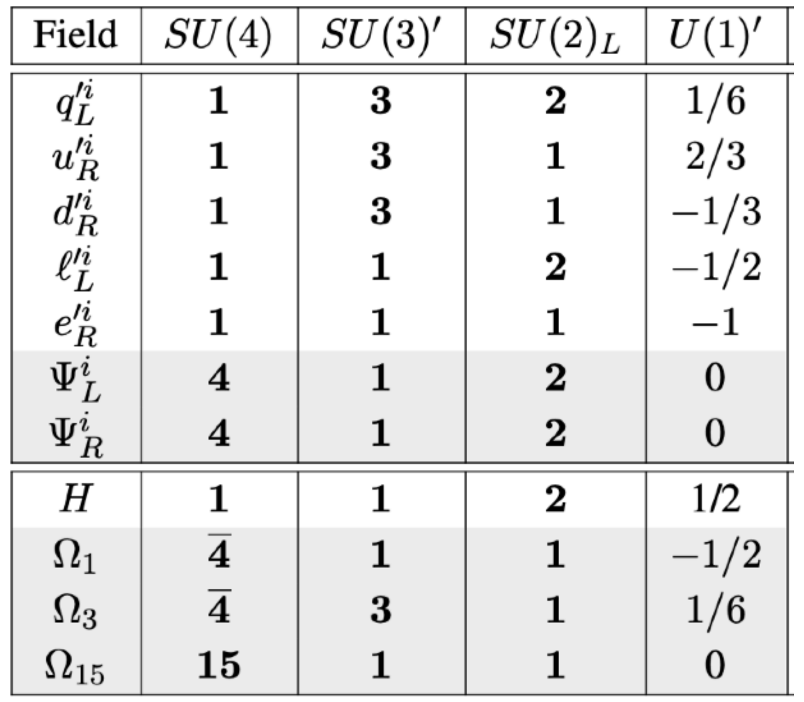
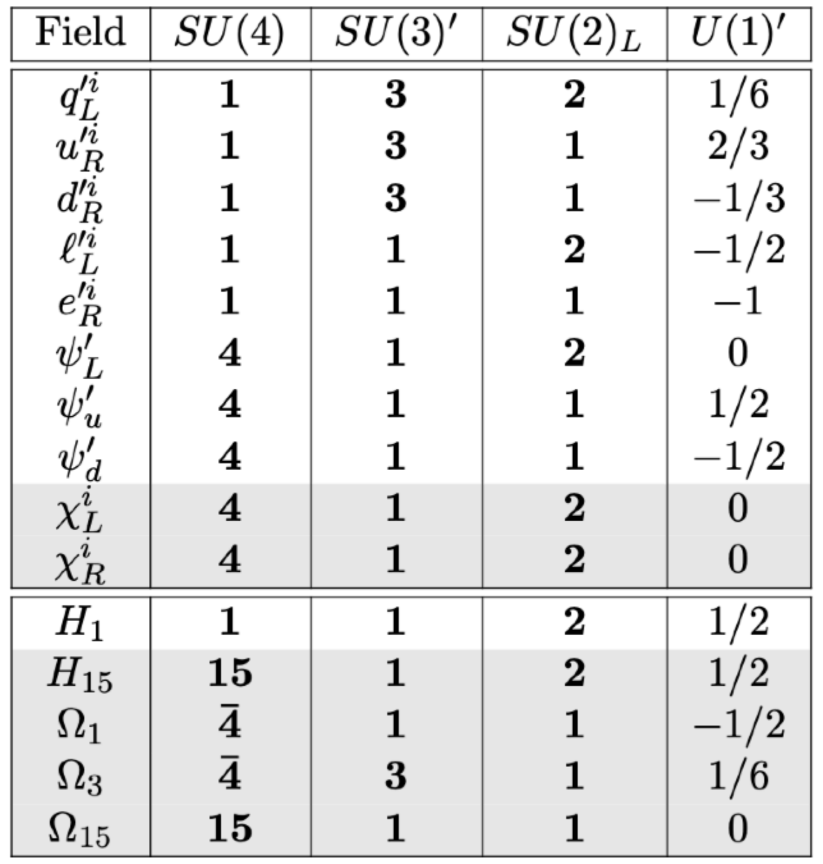
U_1

$SU(4)\times SU(3)\times SU(2)_L\times U(1)_Y$



Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$
$q_L'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	$1/6$
$u_R'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$2/3$
$d_R'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$
$\ell_L'^i$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
$e_R'^i$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	-1
Ψ_L^i	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
Ψ_R^i	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
H	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$
Ω_1	$\overline{\mathbf{4}}$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$
Ω_3	$\overline{\mathbf{4}}$	$\mathbf{3}$	$\mathbf{1}$	$1/6$
Ω_{15}	$\mathbf{15}$	$\mathbf{1}$	$\mathbf{1}$	0

E.g. Di Luzio et al. 1808.00942



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ψ_u'	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{1}$	$1/2$
ψ_d'	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$
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Cornella, Fuentes-Martin, Isidori 1903.11517

+ many other references

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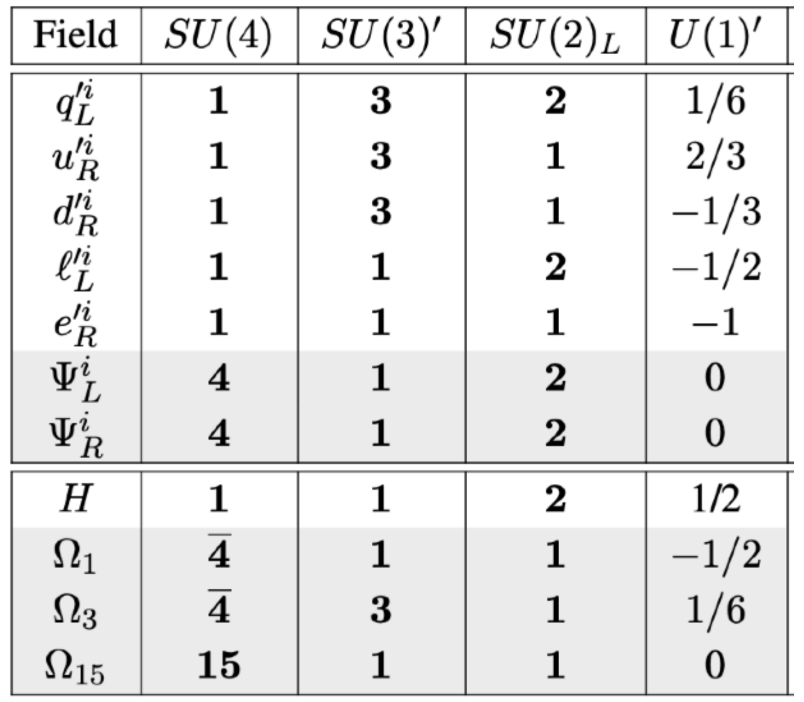

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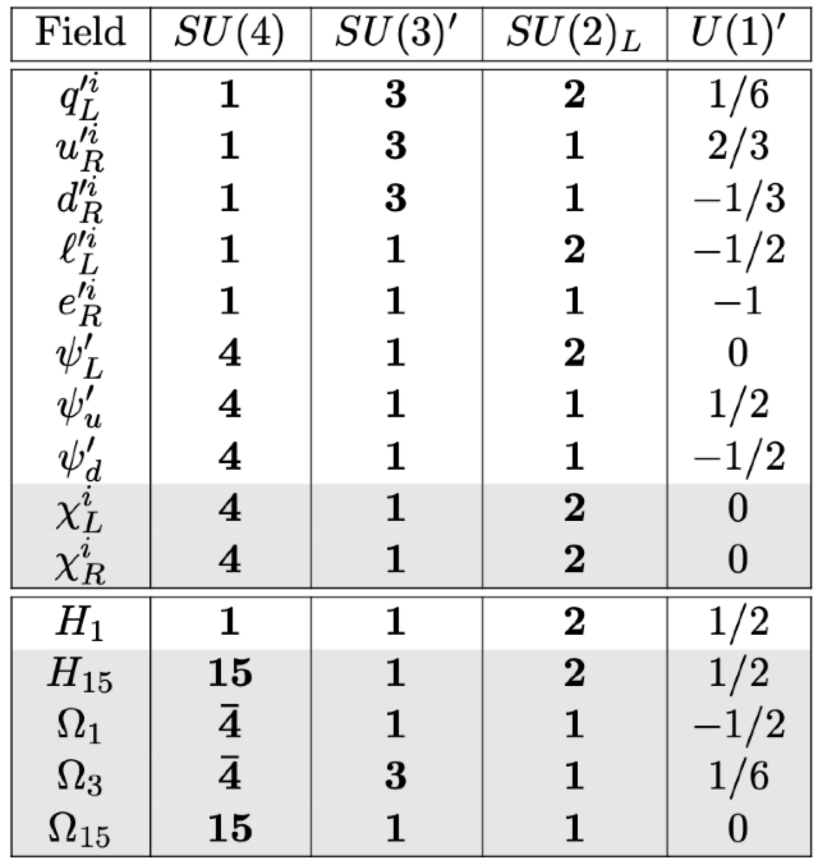

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or

S_1+S_3, R_2+S_3

SM + 2 scalars

S_1 and S_3 scalar leptoquarks

$$\mathcal{L}_{int} \sim \left(\lambda^{1L}_{ij}\, q^i_L\, \varepsilon\, \ell^j_L + \lambda^{1R}_{ij}\, u^i_R\, e^j_R\right) S_1 + \lambda^{3L}_{ij}\, q^i_L\, \varepsilon\, \sigma^A\, \ell^j_L\, S^A_3 + h.c.$$

Scalar Leptoquarks

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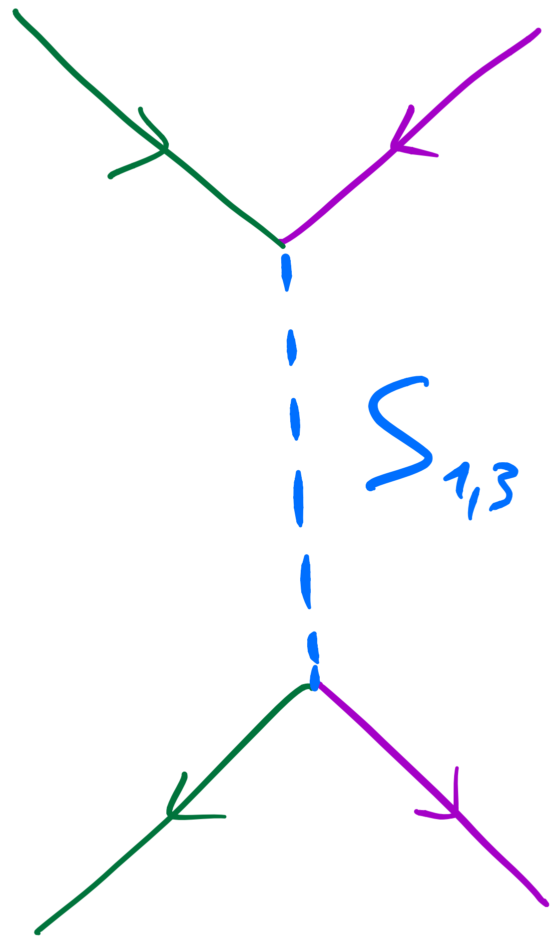

Crivellin et al. 1703.09226; Buttazzo, Greljo, Isidori, DM 1706.07808; D.M. 1803.10972; Arnan et al 1901.06315; Bigaran et al. 1906.01870; Crivellin et al. 1912.04224; Saad 2005.04352; V. Gherardi, E. Venturini, D.M. 2003.12525, 2008.09548; Bordone, Catà, Feldmann, Mandal 2010.03297; Crivellin et al. 2010.06593, 2101.07811; S. Trifinopoulos, E. Venturini, D.M. [2106.15630]; ETC…

Why?

- ***Fully calculable*** already at the simplified model level (unlike vector LQ)
- Can address the **muon (g-2)**.
- Potential **UV origin** from a ***Composite Higgs Model*** scenario, interesting for the potential connection to the ***EW hierarchy problem***.

[D.M. 1803.10972]

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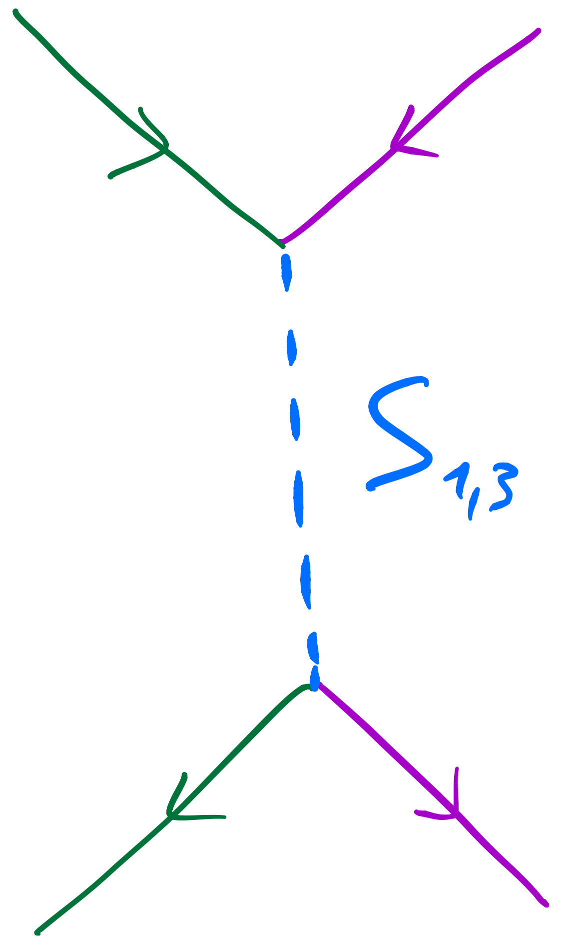

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Several important **observables** constraining this model are induced at one-loop.

We decided to approach this problem systematically in an **EFT approach**, performing a **complete one-loop SMEFT matching** and including and **exhaustive list of observables.**

S_1 and S_3 scalar leptoquarks

1) Match **SM + S_1+S_3** to **SMEFT** @ 1-loop
(SMEFT RGE, SMEFT-LEFT 1-loop matching, LEFT RGE already done in literature)

[Alonso, Jenkins, Manohar, Trott '13]
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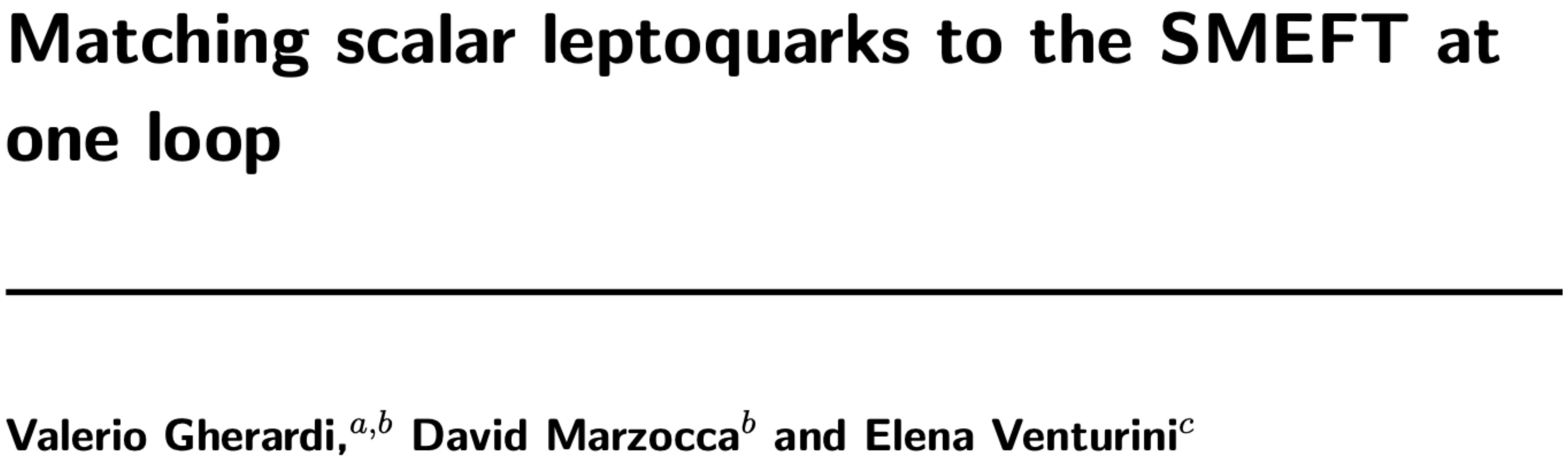

Matching scalar leptoquarks to the SMEFT at one loop

Valerio Gherardi,[a,b] **David Marzocca**[b] **and Elena Venturini**[c]

…. done.

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2) Analysis of B-anomalies, including all observables even remotely sensitive to the relevant couplings

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3) Turn on 1st gen couplings and study **Kaon** & $\mu \to e$ observables.

Flavor symmetries correlate 1st gen to 2nd and 3rd gen couplings:

> case of $U(2)^5$ flavor symmetry.

S. Trifinopoulos, E. Venturini, D.M. [2106.15630]

S_1 and S_3 - global analysis

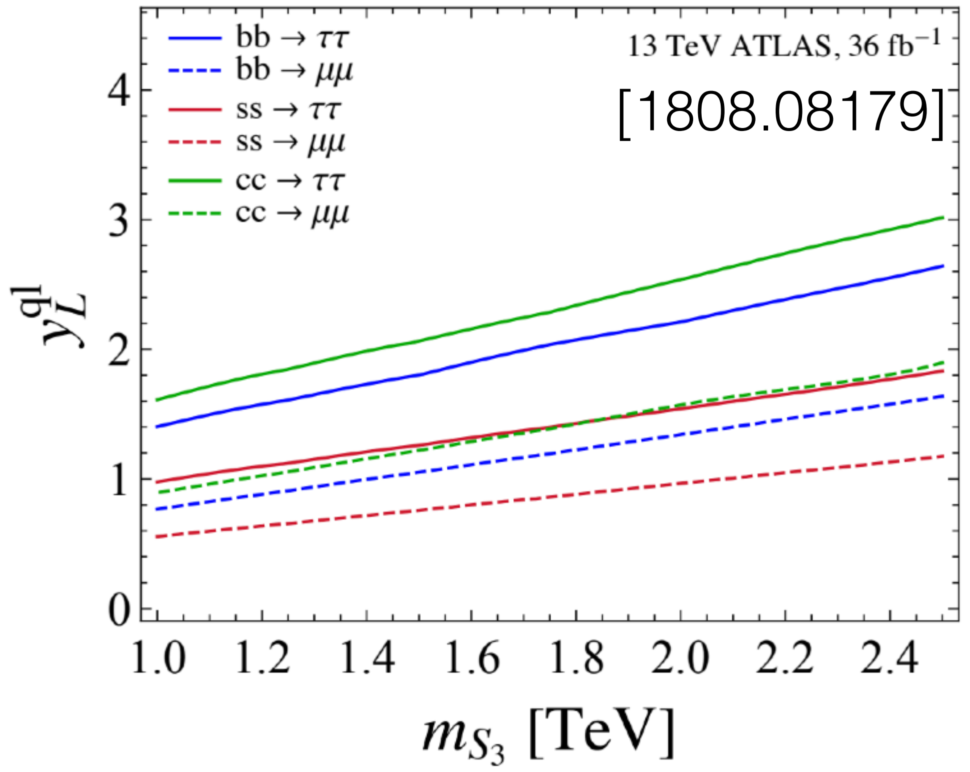
Using the complete one-loop matching to SMEFT, we include in our analysis the following observables.

All these are used to build a **global likelihood**.

$$-2\log\mathcal{L} \equiv \chi^2(\lambda_x, M_x) = \sum_i \frac{(\mathcal{O}_i(\lambda_x, M_x) - \mu_i)^2}{\sigma_i^2}$$

Observable	**Experimental bounds**
Z boson couplings	App. A.12
$\delta g^Z_{\mu_L}$	$(0.3 \pm 1.1)10^{-3}$ [99]
$\delta g^Z_{\mu_R}$	$(0.2 \pm 1.3)10^{-3}$ [99]
$\delta g^Z_{\tau_L}$	$(-0.11 \pm 0.61)10^{-3}$ [99]
$\delta g^Z_{\tau_R}$	$(0.66 \pm 0.65)10^{-3}$ [99]
$\delta g^Z_{b_L}$	$(2.9 \pm 1.6)10^{-3}$ [99]
$\delta g^Z_{c_R}$	$(-3.3 \pm 5.1)10^{-3}$ [99]
N_ν	2.9963 ± 0.0074 [100]

Drell-Yan



Observable	**SM prediction**	**Experimental bounds**
$b \to s\ell\ell$ observables		[37]
$\Delta\mathcal{C}_9^{sb\mu\mu}$	0	-0.43 ± 0.09 [79]
$\mathcal{C}_9^{\text{univ}}$	0	-0.48 ± 0.24 [79]
$b \to c\tau(\ell)\nu$ observables		[37]
R_D	0.299 ± 0.003 [12]	$0.34 \pm 0.027 \pm 0.013$ [12]
R_D^*	0.258 ± 0.005 [12]	$0.295 \pm 0.011 \pm 0.008$ [12]
$P_\tau^{D^*}$	-0.488 ± 0.018 [80]	$-0.38 \pm 0.51 \pm 0.2 \pm 0.018$ [7]
F_L	0.470 ± 0.012 [80]	$0.60 \pm 0.08 \pm 0.038 \pm 0.012$ [81]
$\mathcal{B}(B_c^+ \to \tau^+\nu)$	2.3%	< 10% (95% CL) [82]
$R_D^{\mu/e}$	1	0.978 ± 0.035 [83, 84]
$b \to s\nu\nu$ and $s \to d\nu\nu$		[37]
R_K^ν	1 [85]	< 4.7 [86]
$R_{K^*}^\nu$	1 [85]	< 3.2 [86]
$b \to d\mu\mu$ and $b \to dee$		App. A.5
$\mathcal{B}(B^0 \to \mu\mu)$	$(1.06 \pm 0.09) \times 10^{-10}$ [87, 88]	$(1.1 \pm 1.4) \times 10^{-10}$ [89, 90]
$\mathcal{B}(B^+ \to \pi^+\mu\mu)$	$(2.04 \pm 0.21) \times 10^{-8}$ [87, 88]	$(1.83 \pm 0.24) \times 10^{-8}$ [89, 90]
$\mathcal{B}(B^0 \to ee)$	$(2.48 \pm 0.21) \times 10^{-15}$ [87, 88]	$< 8.3 \times 10^{-8}$ [51]
$\mathcal{B}(B^+ \to \pi^+ ee)$	$(2.04 \pm 0.24) \times 10^{-8}$ [87, 88]	$< 8 \times 10^{-8}$ [51]
B LFV decays		[37]
$\mathcal{B}(B_d \to \tau^\pm\mu^\mp)$	0	$< 1.4 \times 10^{-5}$ [91]
$\mathcal{B}(B_s \to \tau^\pm\mu^\mp)$	0	$< 4.2 \times 10^{-5}$ [91]
$\mathcal{B}(B^+ \to K^+\tau^-\mu^+)$	0	$< 5.4 \times 10^{-5}$ [92]
$\mathcal{B}(B^+ \to K^+\tau^+\mu^-)$	0	$< 3.3 \times 10^{-5}$ [92] $< 4.5 \times 10^{-5}$ [93]

Observable	**SM prediction**	**Experimental bounds**
D leptonic decay		[37] and App. A.4
$\mathcal{B}(D_s \to \tau\nu)$	$(5.169 \pm 0.004) \times 10^{-2}$ [94]	$(5.48 \pm 0.23) \times 10^{-2}$ [51]
$\mathcal{B}(D^0 \to \mu\mu)$	$\approx 10^{-11}$ [95]	$< 7.6 \times 10^{-9}$ [96]
$\mathcal{B}(D^+ \to \pi^+\mu\mu)$	$\mathcal{O}(10^{-12})$ [97]	$< 7.4 \times 10^{-8}$ [98]
Rare Kaon decays ($\nu\nu$)		App. A.1
$\mathcal{B}(K^+ \to \pi^+\nu\nu)$	8.64×10^{-11} [99]	$(11.0 \pm 4.0) \times 10^{-11}$ [100]
$\mathcal{B}(K_L \to \pi^0\nu\nu)$	3.4×10^{-11} [99]	$< 3.6 \times 10^{-9}$ [101]
Rare Kaon decays ($\ell\ell$)		App. A.3 and A.2
$\mathcal{B}(K_L \to \mu\mu)_{SD}$	8.4×10^{-10} [102]	$< 2.5 \times 10^{-9}$ [76]
$\mathcal{B}(K_S \to \mu\mu)$	$(5.18 \pm 1.5) \times 10^{-12}$ [76, 103, 104]	$< 2.5 \times 10^{-10}$ [105]
$\mathcal{B}(K_L \to \pi^0\mu\mu)$	$(1.5 \pm 0.3) \times 10^{-11}$ [106]	$< 4.5 \times 10^{-10}$ [107]
$\mathcal{B}(K_L \to \pi^0 ee)$	$(3.2^{+1.2}_{-0.8}) \times 10^{-11}$ [108]	$< 2.8 \times 10^{-10}$ [109]
LFV in Kaon decays		App. A.3 and A.2
$\mathcal{B}(K_L \to \mu e)$	0	$< 4.7 \times 10^{-12}$ [110]
$\mathcal{B}(K^+ \to \pi^+\mu^- e^+)$	0	$< 7.9 \times 10^{-11}$ [111]
$\mathcal{B}(K^+ \to \pi^+ e^-\mu^+)$	0	$< 1.5 \times 10^{-11}$ [112]
CP-violation		App. A.8
ϵ'_K/ϵ_K	$(15 \pm 7) \times 10^{-4}$ [113]	$(16.6 \pm 2.3) \times 10^{-4}$ [51]

Observable	**SM prediction**	**Experimental bounds**
$\Delta F = 2$ processes		[37]
$B^0 - \overline{B}^0$: $\lvert C^1_{B_d}\rvert$	0	$< 9.1 \times 10^{-7}$ TeV^{-2} [114, 115]
$B^0_s - \overline{B}^0_s$: $\lvert C^1_{B_s}\rvert$	0	$< 2.0 \times 10^{-5}$ TeV^{-2} [114, 115]
$K^0 - \overline{K}^0$: Re$[C^1_K]$	0	$< 8.0 \times 10^{-7}$ TeV^{-2} [114, 115]
$K^0 - \overline{K}^0$: Im$[C^1_K]$	0	$< 3.0 \times 10^{-9}$ TeV^{-2} [114, 115]
$D^0 - \overline{D}^0$: Re$[C^1_D]$	0	$< 3.6 \times 10^{-7}$ TeV^{-2} [114, 115]
$D^0 - \overline{D}^0$: Im$[C^1_D]$	0	$< 2.2 \times 10^{-8}$ TeV^{-2} [114, 115]
$D^0 - \overline{D}^0$: Re$[C^4_D]$	0	$< 3.2 \times 10^{-8}$ TeV^{-2} [114, 115]
$D^0 - \overline{D}^0$: Im$[C^4_D]$	0	$< 1.2 \times 10^{-9}$ TeV^{-2} [114, 115]
$D^0 - \overline{D}^0$: Re$[C^5_D]$	0	$< 2.7 \times 10^{-7}$ TeV^{-2} [114, 115]
$D^0 - \overline{D}^0$: Im$[C^5_D]$	0	$< 1.1 \times 10^{-8}$ TeV^{-2} [114, 115]
LFU in τ decays		[37]
$\lvert g_\mu/g_e\rvert^2$	1	1.0036 ± 0.0028 [116]
$\lvert g_\tau/g_\mu\rvert^2$	1	1.0022 ± 0.0030 [116]
$\lvert g_\tau/g_e\rvert^2$	1	1.0058 ± 0.0030 [116]
LFV observables		[37]
$\mathcal{B}(\tau \to \mu\phi)$	0	$< 1.00 \times 10^{-7}$ [117]
$\mathcal{B}(\tau \to 3\mu)$	0	$< 2.5 \times 10^{-8}$ [118]
$\mathcal{B}(\tau \to \mu\gamma)$	0	$< 5.2 \times 10^{-8}$ [119]
$\mathcal{B}(\tau \to e\gamma)$	0	$< 3.9 \times 10^{-8}$ [119]
$\mathcal{B}(\mu \to e\gamma)$	0	$< 5.0 \times 10^{-13}$ [120]
$\mathcal{B}(\mu \to 3e)$	0	$< 1.2 \times 10^{-12}$ [121]
$\mathcal{B}^{(\text{Ti})}_{\mu e}$	0	$< 5.1 \times 10^{-12}$ [122]
$\mathcal{B}^{(\text{Au})}_{\mu e}$	0	$< 8.3 \times 10^{-13}$ [123]
EDMs		[37]
$\lvert d_e\rvert$	$< 10^{-44}$ e · cm [124, 125]	$< 1.3 \times 10^{-29}$ e · cm [126]
$\lvert d_\mu\rvert$	$< 10^{-42}$ e · cm [125]	$< 1.9 \times 10^{-19}$ e · cm [127]
d_τ	$< 10^{-41}$ e · cm [125]	$(1.15 \pm 1.70) \times 10^{-17}$ e · cm [37]
d_n	$< 10^{-33}$ e · cm [128]	$< 2.1 \times 10^{-26}$ e · cm [129]
Anomalous Magnetic Moments		[37]
$a_e - a_e^{SM}$	$\pm 2.3 \times 10^{-13}$ [130, 131]	$(-8.9 \pm 3.6) \times 10^{-13}$ [132]
$a_\mu - a_\mu^{SM}$	$\pm 43 \times 10^{-11}$ [42]	$(279 \pm 76) \times 10^{-11}$ [40, 42]
$a_\tau - a_\tau^{SM}$	$\pm 3.9 \times 10^{-8}$ [130]	$(-2.1 \pm 1.7) \times 10^{-7}$ [133]

S_1 and S_3 - contributions to anomalies

$$\mathcal{L}_{int} \sim \left(\lambda^{1L}_{ij}\, q^i_L\, \varepsilon\, \ell^j_L + \lambda^{1R}_{ij}\, u^i_R\, e^j_R\right) S_1 + \lambda^{3L}_{ij}\, q^i_L\, \varepsilon\, \sigma^A\, \ell^j_L\, S^A_3 + h.c.$$

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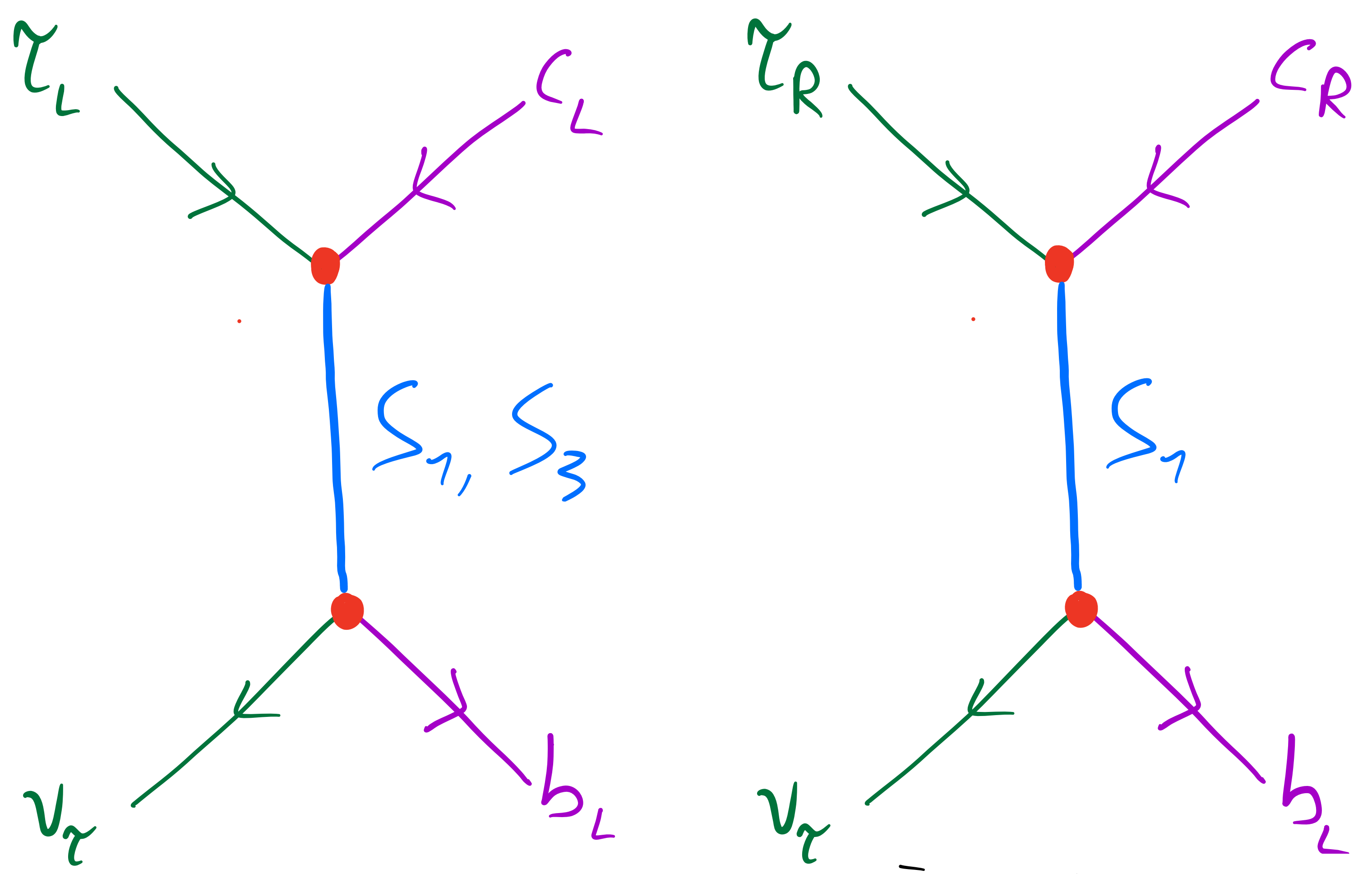
$R(D^{(*)})$



$(\bar{b}_L \gamma_\mu c_L)(\bar{\nu}_\tau \gamma^\mu \tau_L)$

$(\bar{b}_L c_R)(\bar{\nu}_\tau \tau_R)$

$(\bar{b}_L \sigma_{\mu\nu} c_R)(\bar{\nu}_\tau \sigma^{\mu\nu} \tau_R)$

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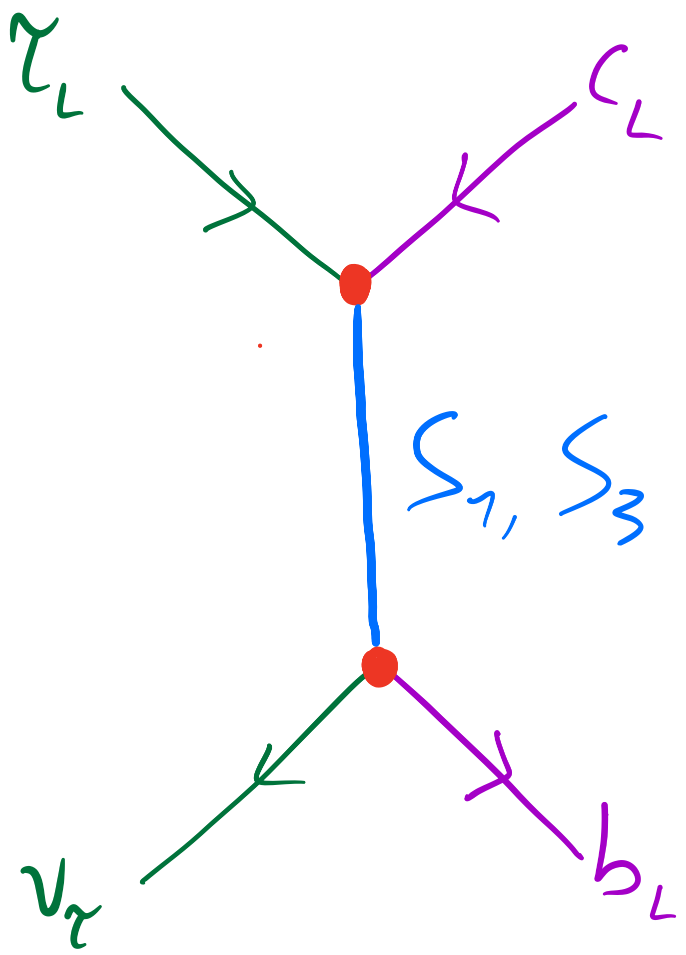
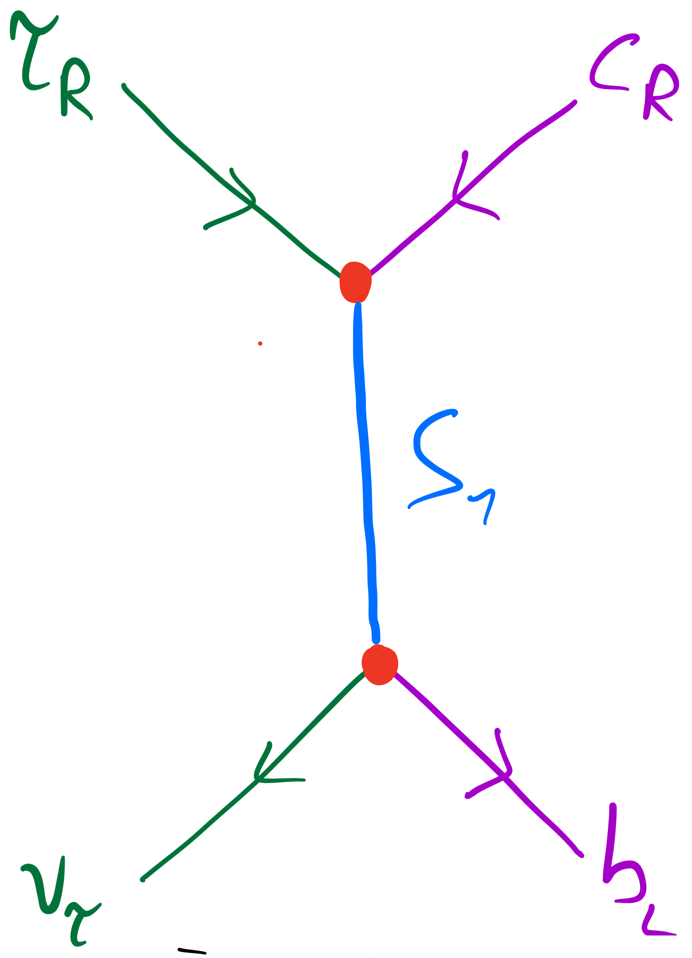
$R(D^{(*)})$



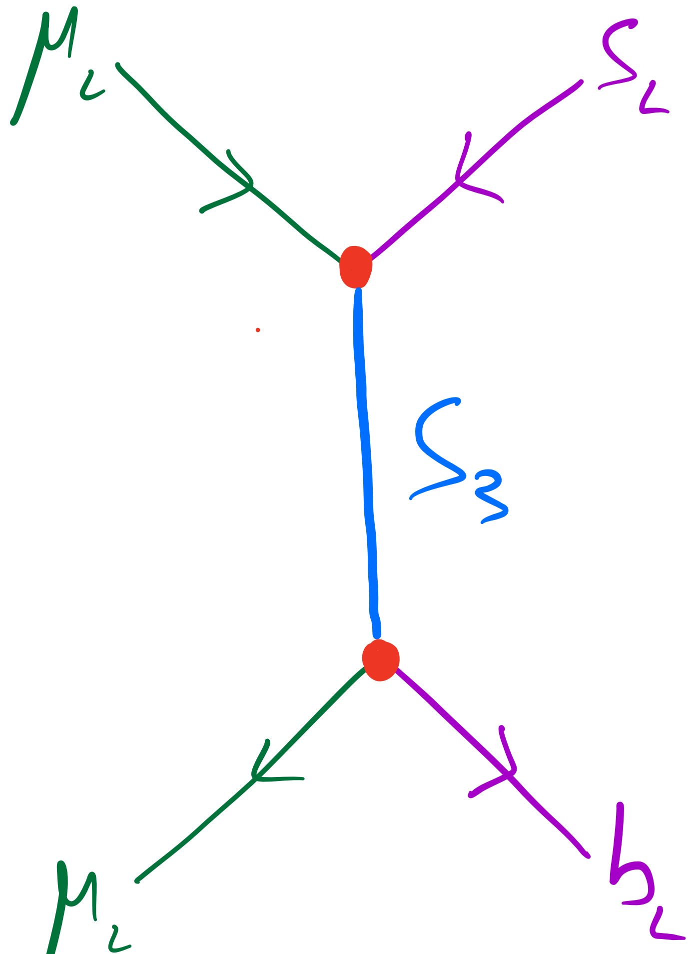
$(\bar{b}_L \gamma_\mu c_L)(\bar{\nu}_\tau \gamma^\mu \tau_L)$



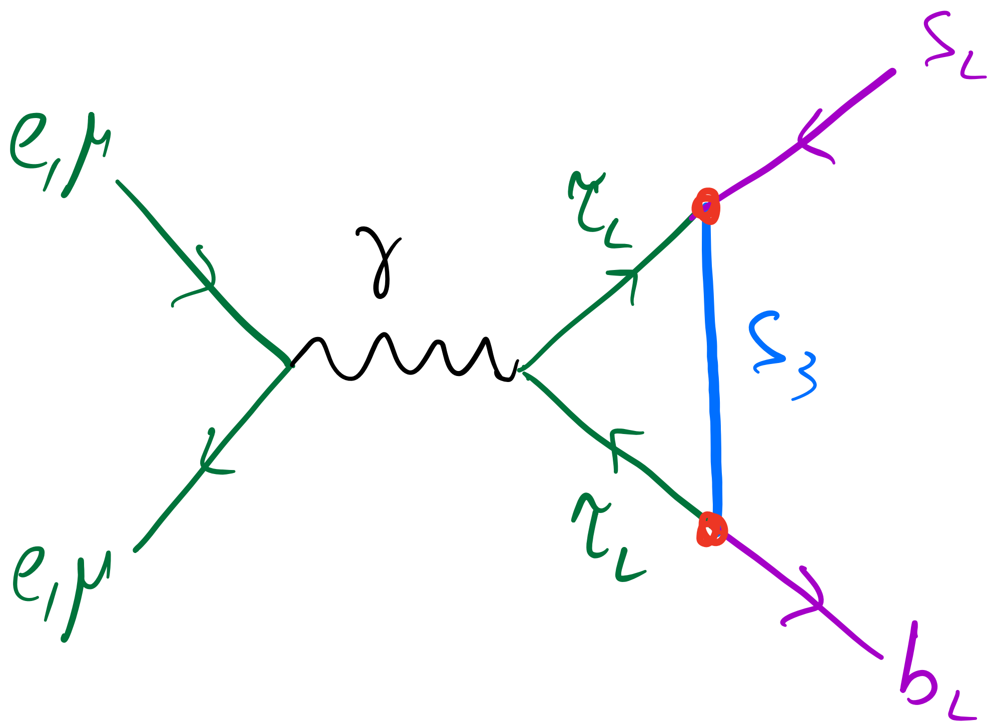
$(\bar{b}_L c_R)(\bar{\nu}_\tau \tau_R)$

$(\bar{b}_L \sigma_{\mu\nu} c_R)(\bar{\nu}_\tau \sigma^{\mu\nu} \tau_R)$

$b \to s \mu\mu$



$C_9^\mu = -C_{10}^\mu$

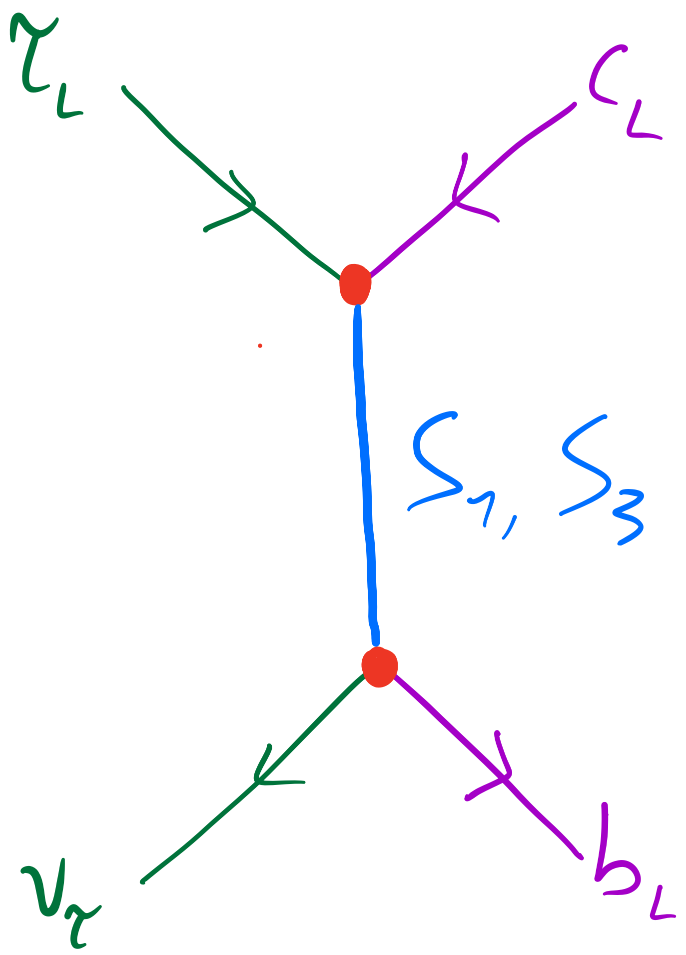


C_9^U

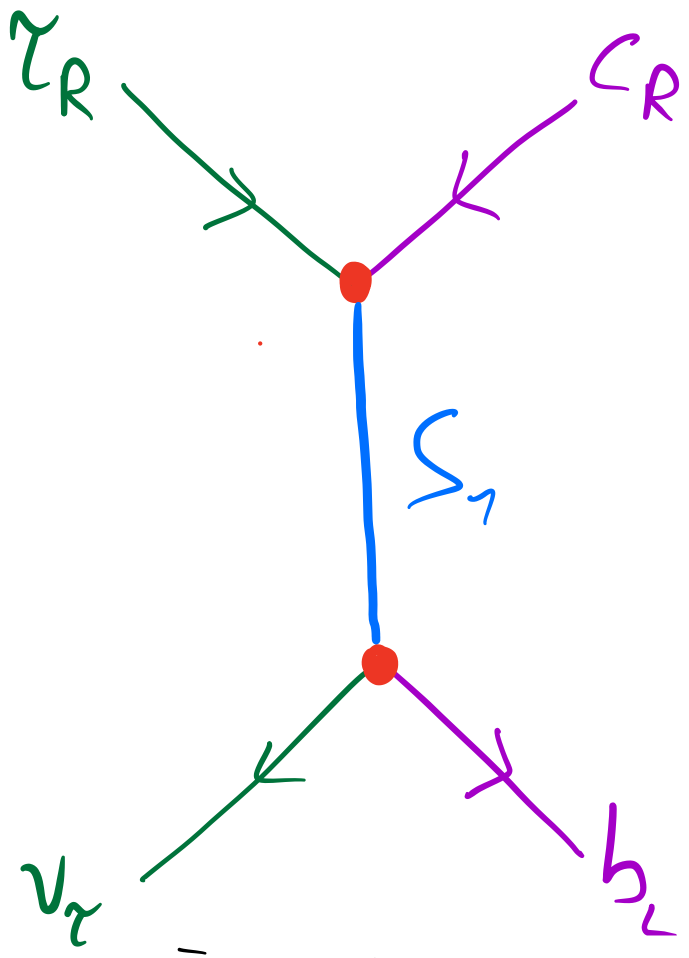
S_1 and S_3 - contributions to anomalies

$$\mathcal{L}_{int} \sim \left(\lambda^{1L}_{ij}\, q^i_L \varepsilon\, \ell^j_L + \lambda^{1R}_{ij}\, u^i_R e^j_R\right) S_1 + \lambda^{3L}_{ij}\, q^i_L \varepsilon \sigma^A \ell^j_L\, S^A_3 + h.c.$$

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



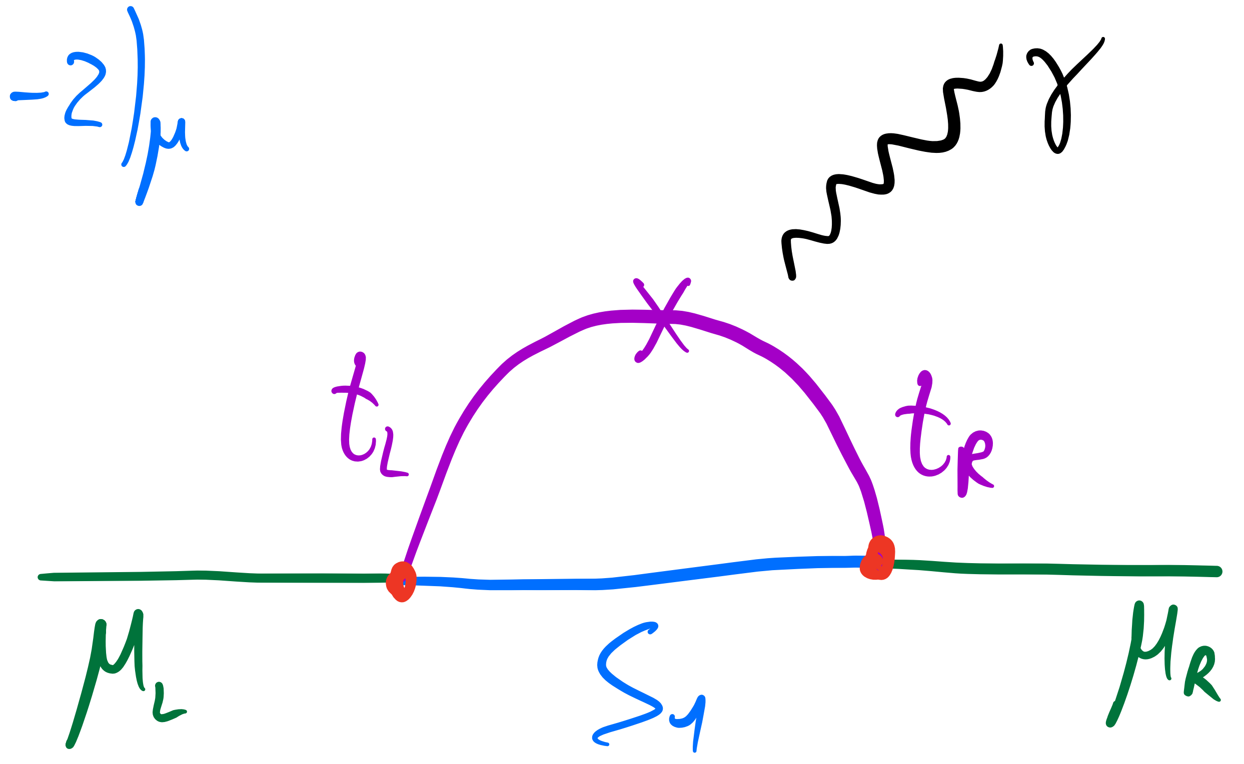
$(\bar b_L \gamma_\mu c_L)(\bar\nu_\tau \gamma^\mu \tau_L)$



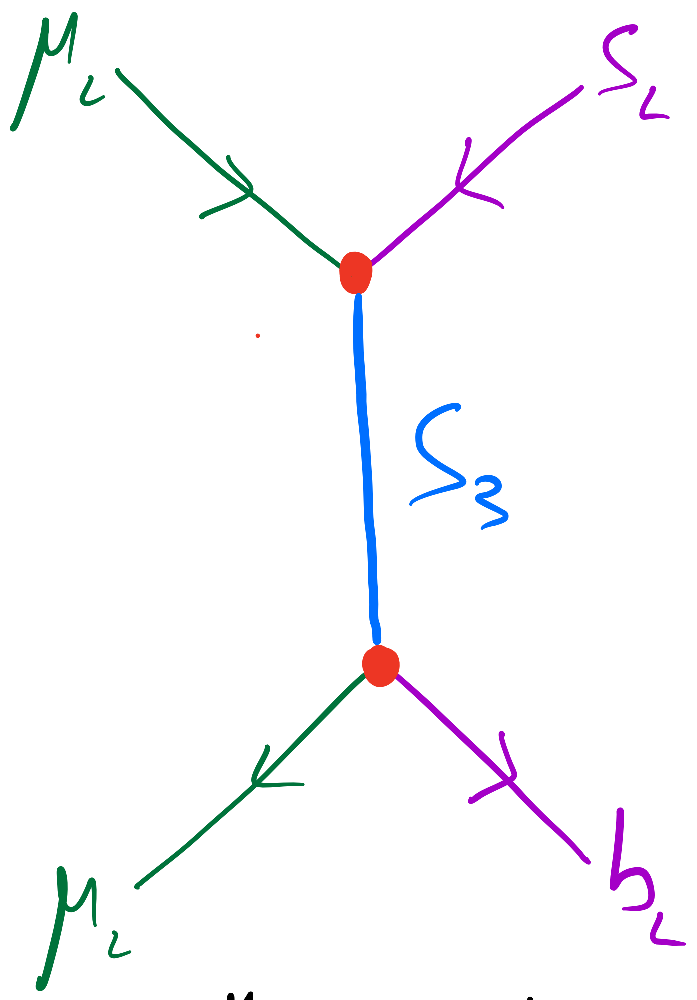
$(\bar b_L c_R)(\bar\nu_\tau \tau_R)$

$(\bar b_L \sigma_{\mu\nu} c_R)(\bar\nu_\tau \sigma^{\mu\nu} \tau_R)$

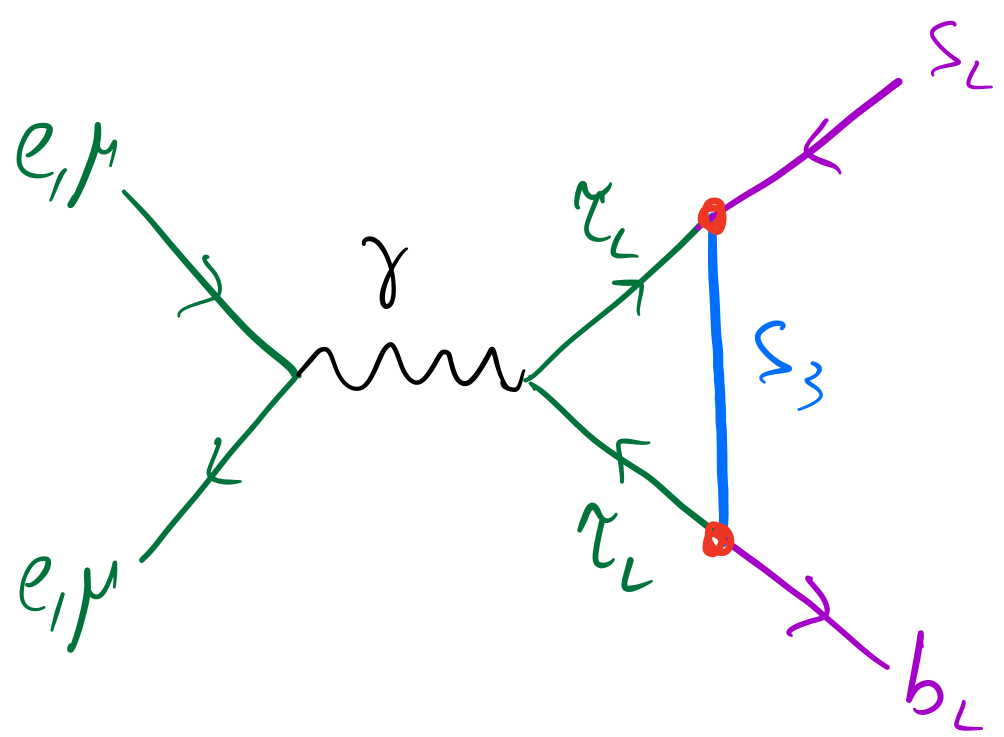
$(g-2)_\mu$



$b \to s \mu\mu$



$C_9^\mu = -C_{10}^\mu$



C_9^U

S_1 and S_3 - combined explanations

$$\mathcal{L}_{int} \sim \left(\lambda^{1L}_{ij}\, q^i_L \,\varepsilon\, \ell^j_L + \lambda^{1R}_{ij}\, u^i_R\, e^j_R\right) S_1 + \lambda^{3L}_{ij}\, q^i_L \,\varepsilon \sigma^A\, \ell^j_L\, S_3^A + h.c.$$

Two ***benchmark*** scenarios:

LH + RH

$$\lambda^{1L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & s\tau \\ 0 & b\mu & b\tau \end{pmatrix} \qquad \lambda^{3L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & s\mu & s\tau \\ 0 & b\mu & b\tau \end{pmatrix} \qquad \lambda^{1R} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & c\tau \\ 0 & t\mu & t\tau \end{pmatrix}$$

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

$b \to s\mu\mu$

$(g-2)_\mu$

Only LH

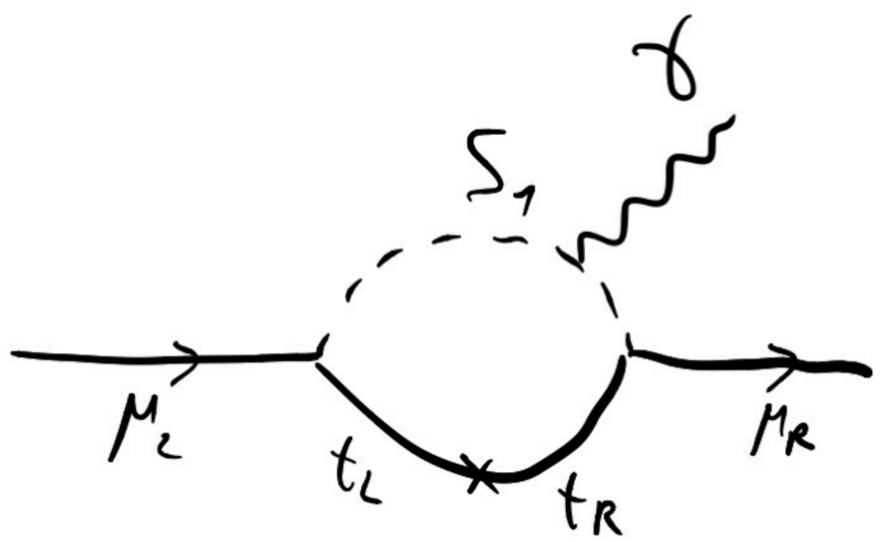
$$\lambda^{1L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & s\tau \\ 0 & 0 & b\tau \end{pmatrix} \qquad \lambda^{3L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & s\mu & s\tau \\ 0 & b\mu & b\tau \end{pmatrix} \qquad \lambda^{1R} = 0$$

$M_{S_{1,3}} \sim 1$ TeV

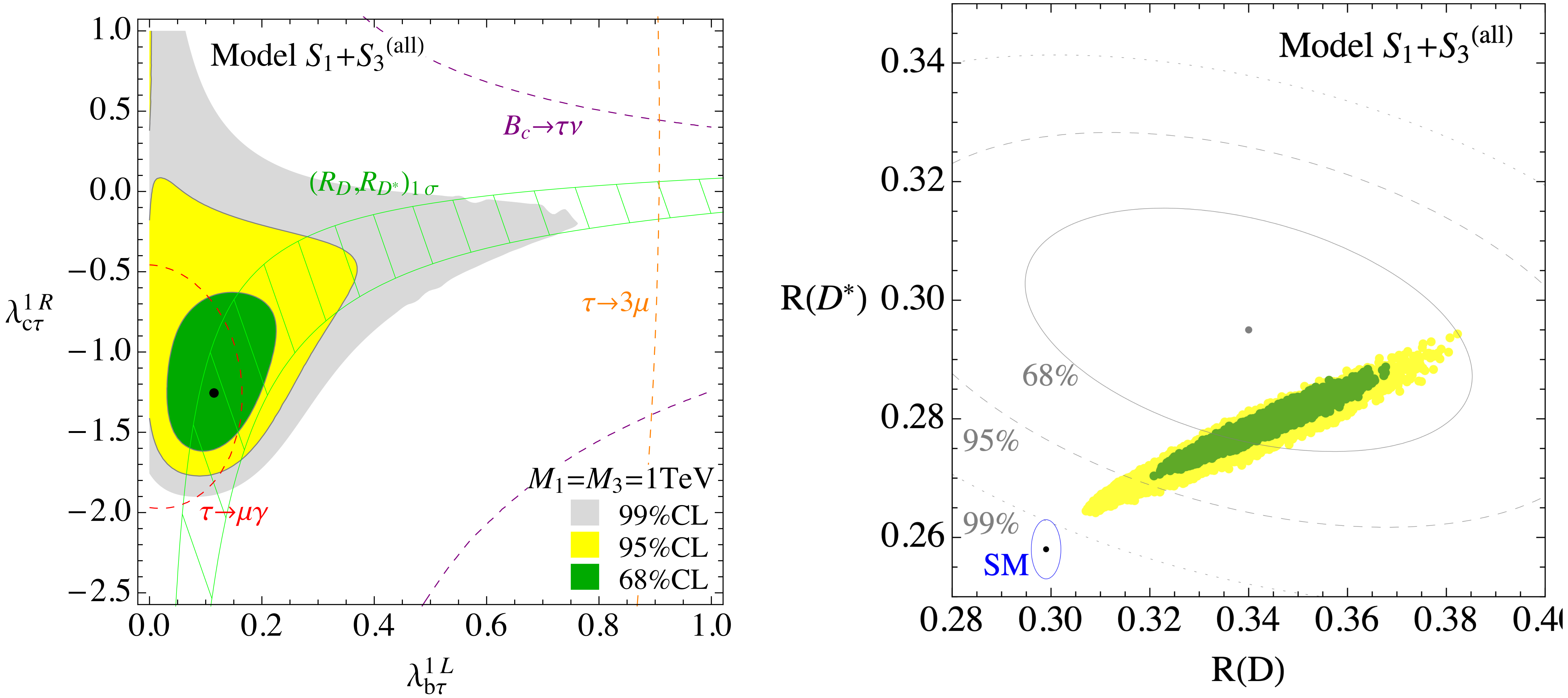
S_1 and S_3 : $R(K^{(*)})$ + $R(D^{(*)})$ + $(g\text{-}2)_\mu$

$$\lambda^{1L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & s\tau \\ 0 & b\mu & b\tau \end{pmatrix} \qquad \lambda^{3L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & s\mu & s\tau \\ 0 & b\mu & b\tau \end{pmatrix}$$

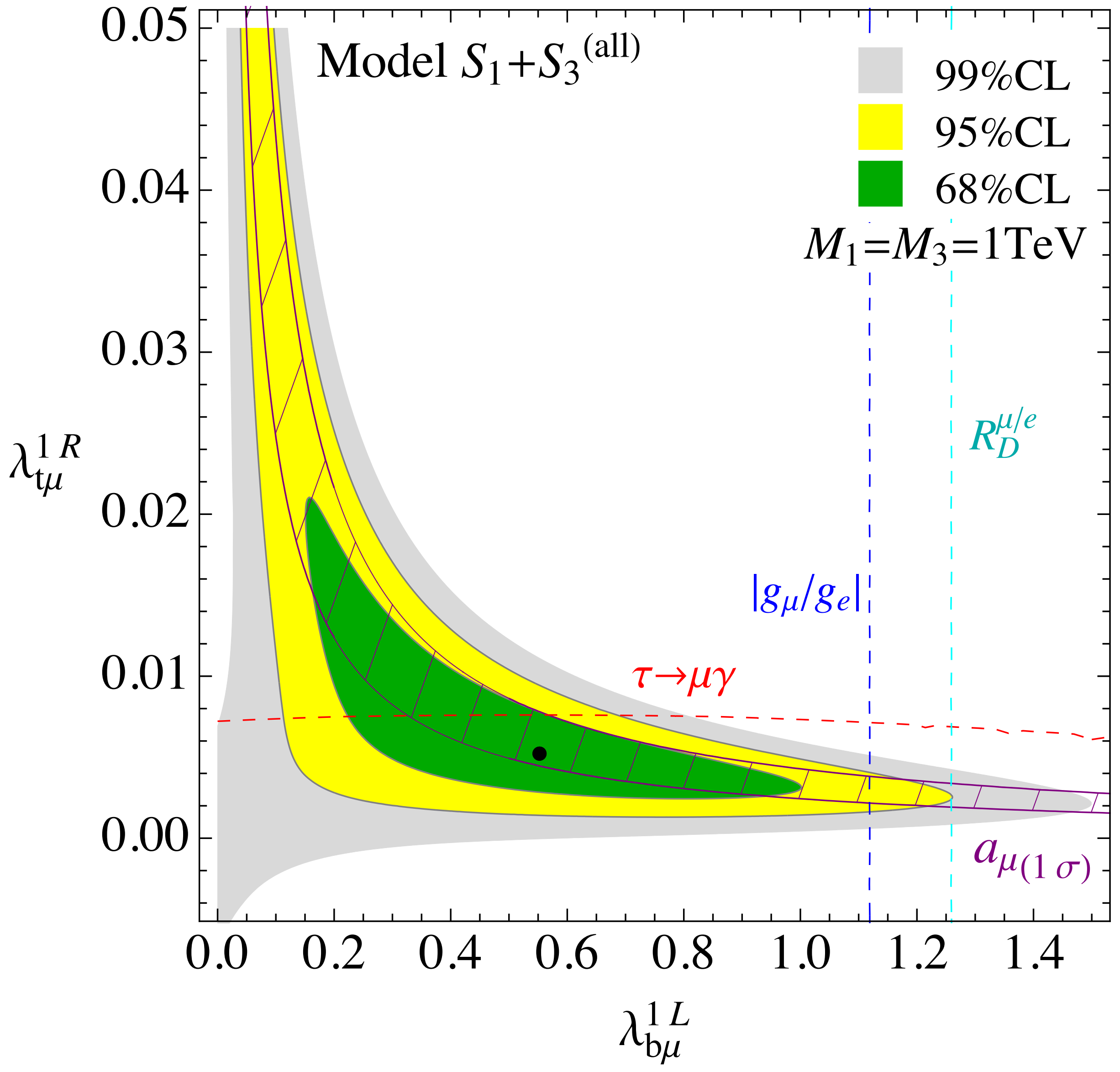
$$\lambda^{1R} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & c\tau \\ 0 & t\mu & t\tau \end{pmatrix}$$



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



$(g\text{-}2)_\mu$



The fit to $b \to s\, \mu\mu$ is very good (same as next slide)

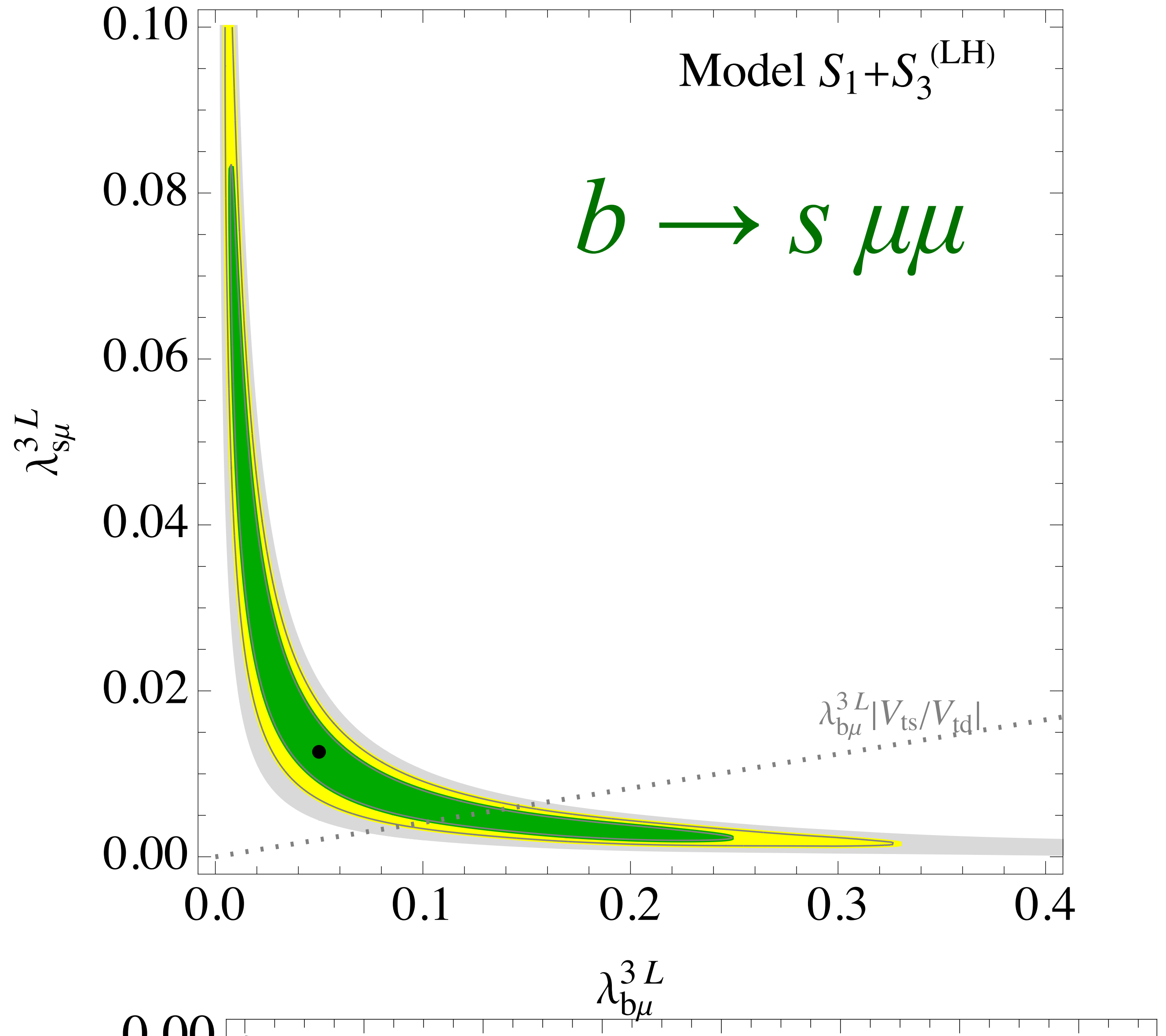
Contribution to **$R(D^{(*)})$** dominated by **S_1**: scalar+tensor op.
Can also fit $(g\text{-}2)_\mu$.

Very good fit of all anomalies!

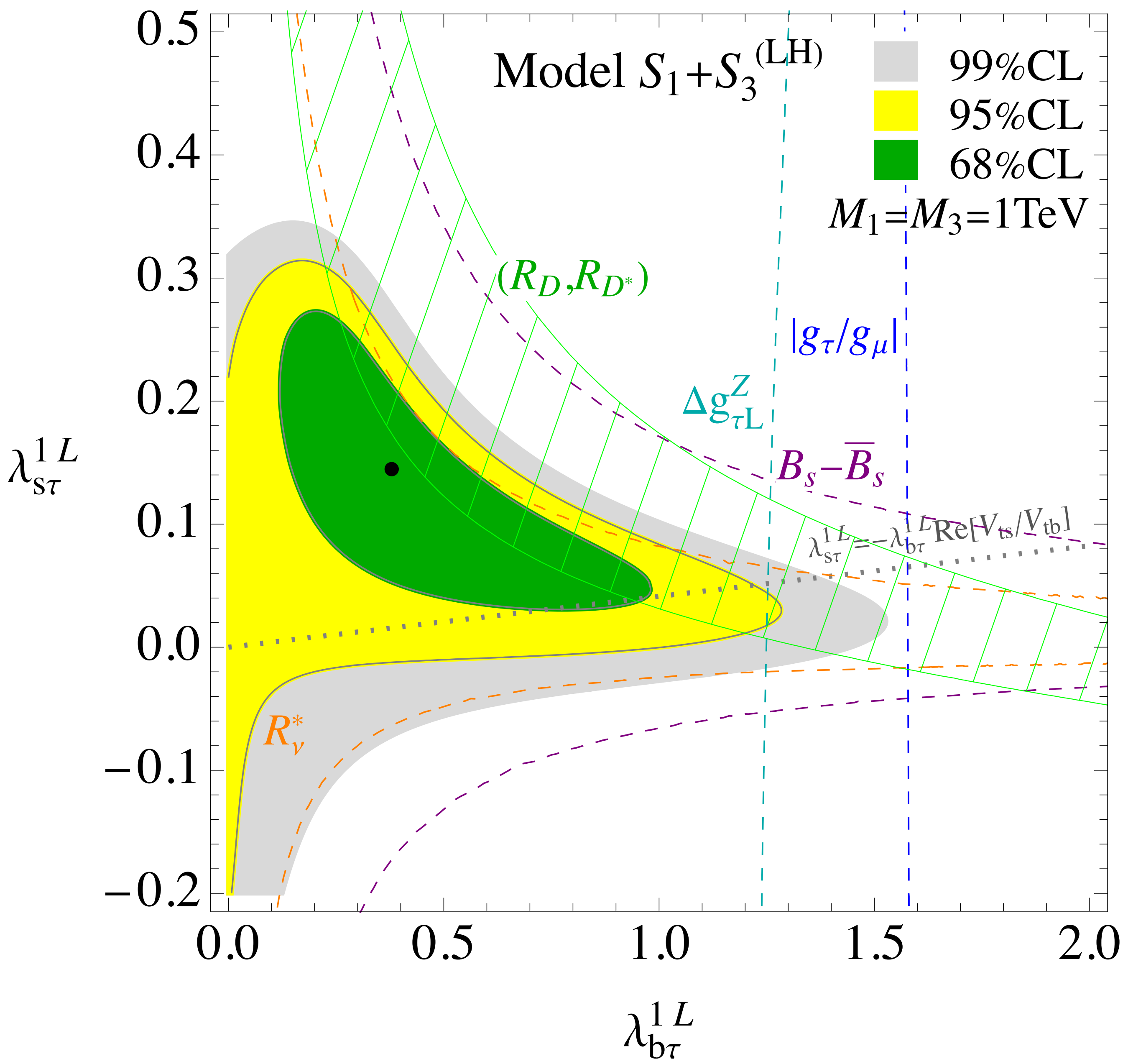
S_1 and S_3 — only LH couplings: $R(K^{(*)}) + R(D^{(*)})$

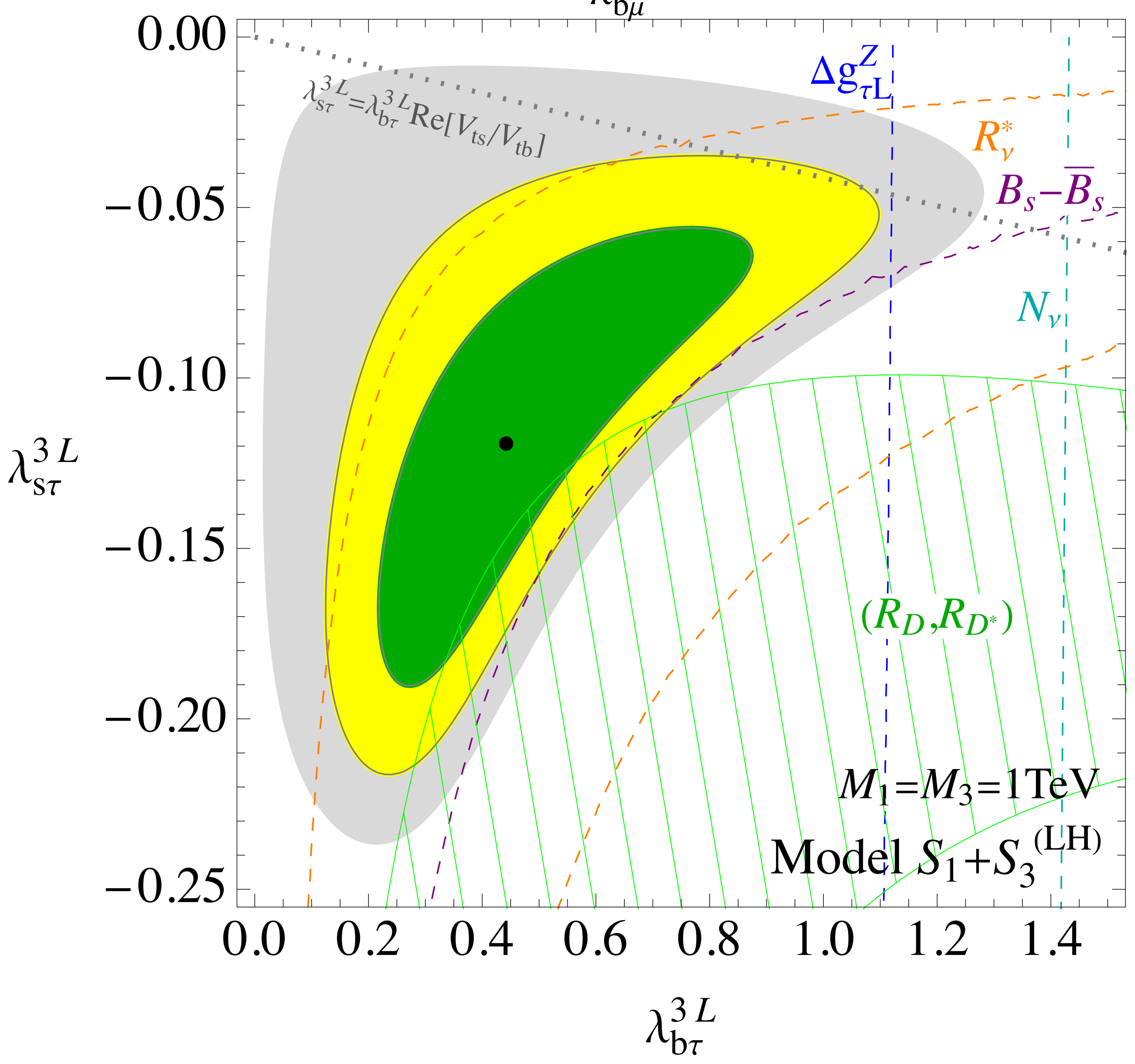
$$\lambda^{1L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & s\tau \\ 0 & 0 & b\tau \end{pmatrix} \quad \lambda^{3L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & s\mu & s\tau \\ 0 & b\mu & b\tau \end{pmatrix}$$

$\lambda^{1R} = 0$ → Cannot fit $(g-2)_\mu$



R(D(*))



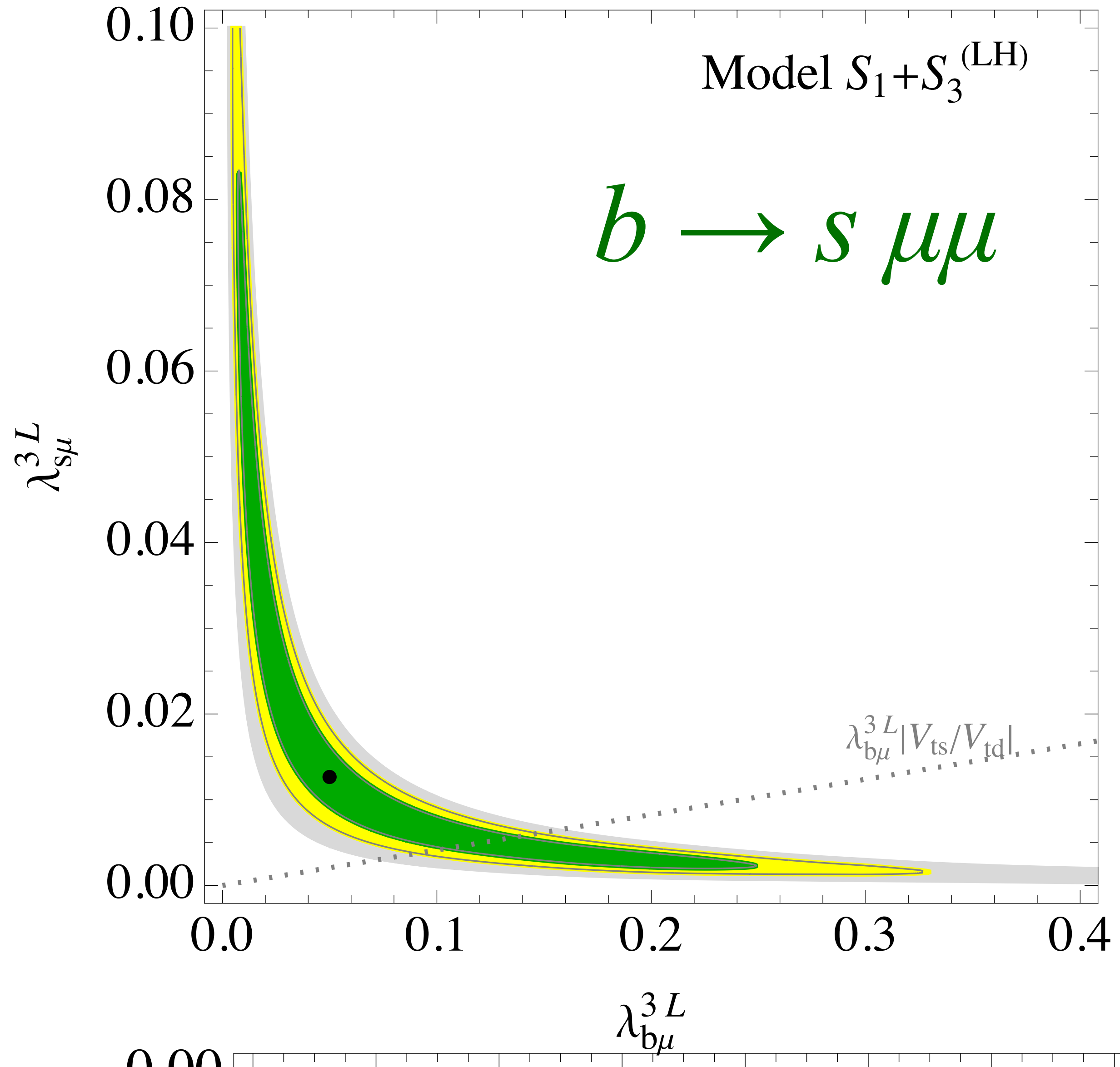


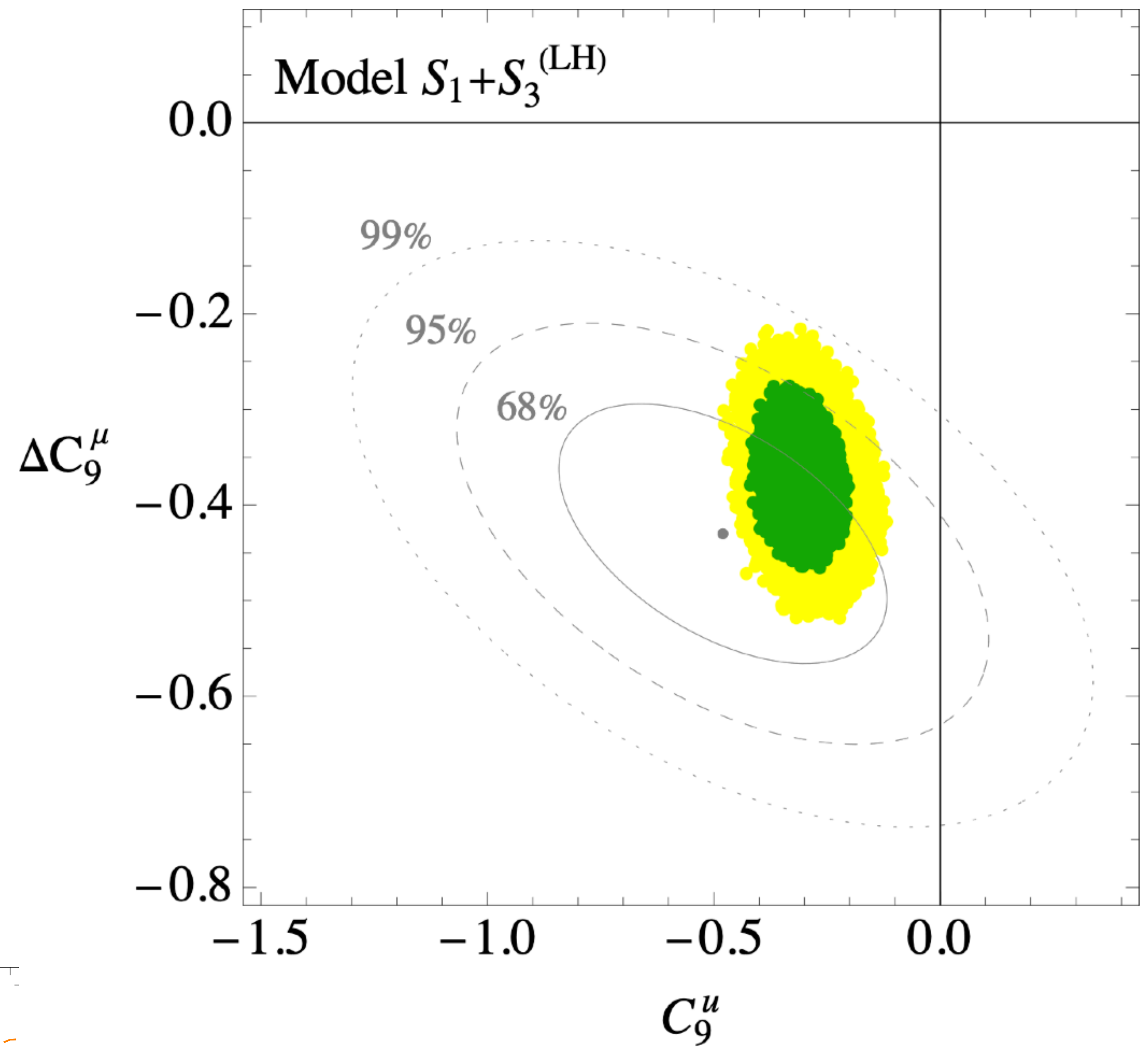
Plots updated w.r.t. [v3:2008.09548]

S_1 and S_3 — only LH couplings: R(K$^{(*)}$) + R(D$^{(*)}$)

$$\lambda^{1L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & s\tau \\ 0 & 0 & b\tau \end{pmatrix} \quad \lambda^{3L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & s\mu & s\tau \\ 0 & b\mu & b\tau \end{pmatrix}$$

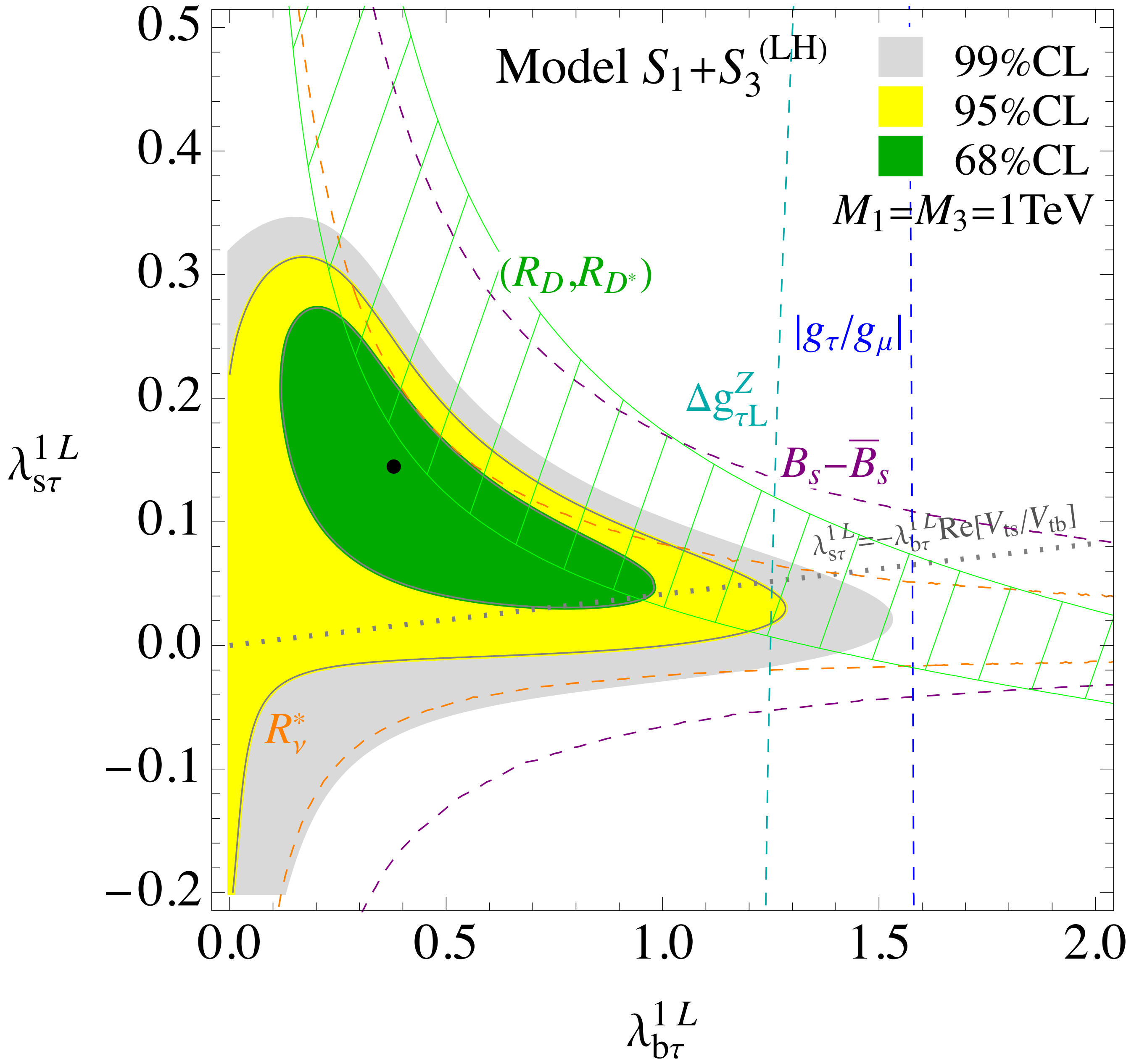
$\lambda^{1R} = 0$ → Cannot fit $(g\text{-}2)_\mu$

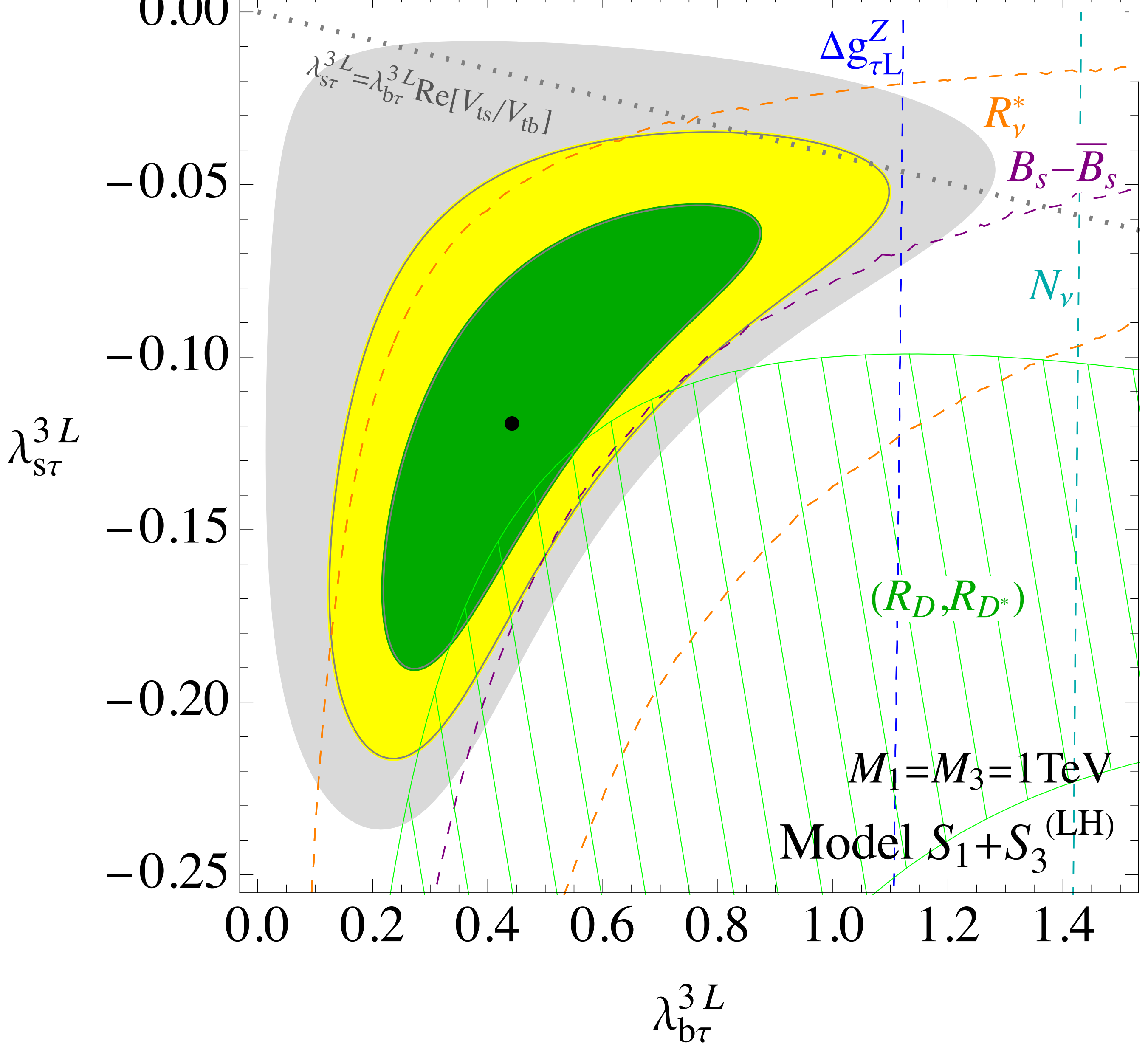


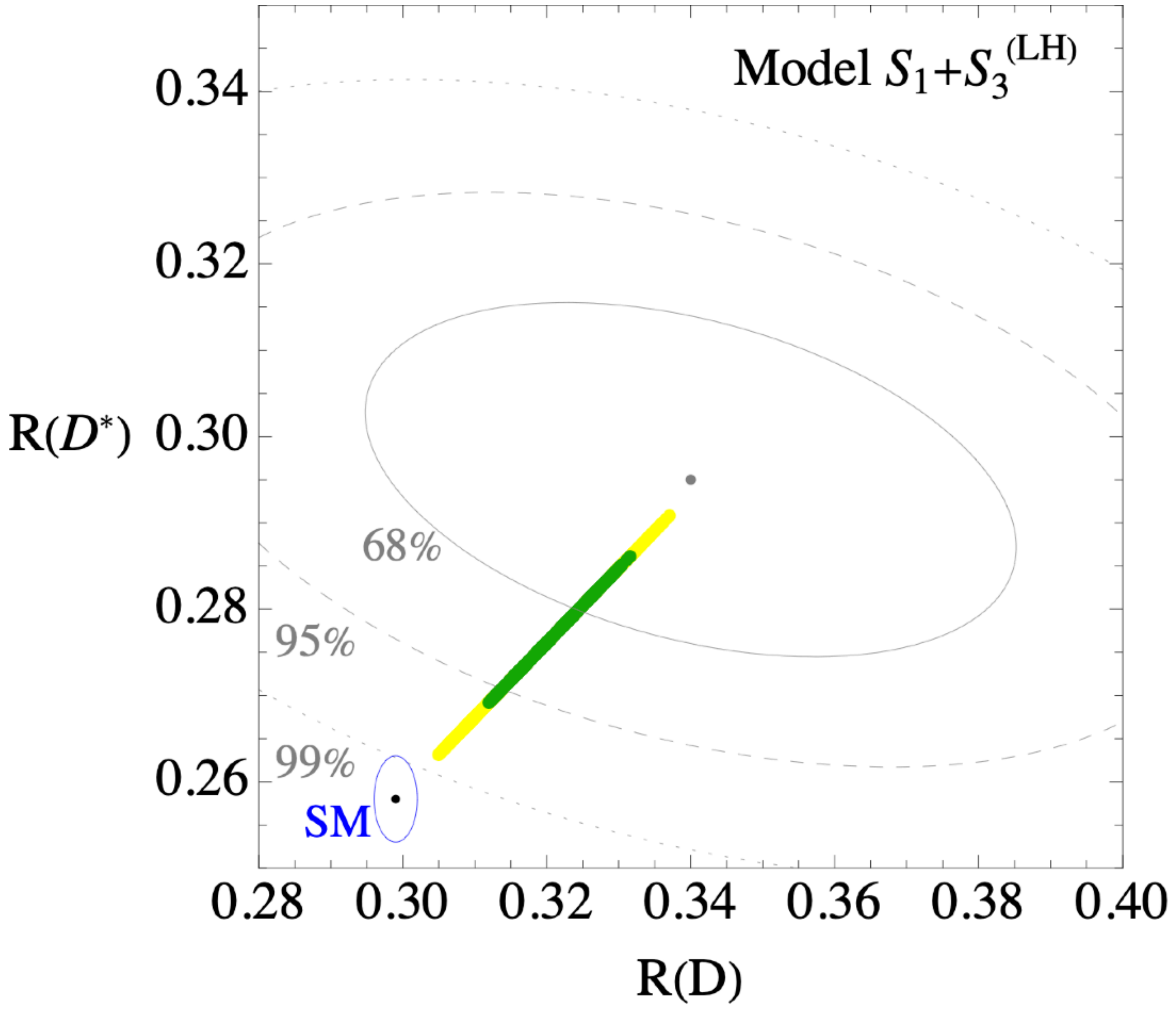


very good fit of B-anomalies

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





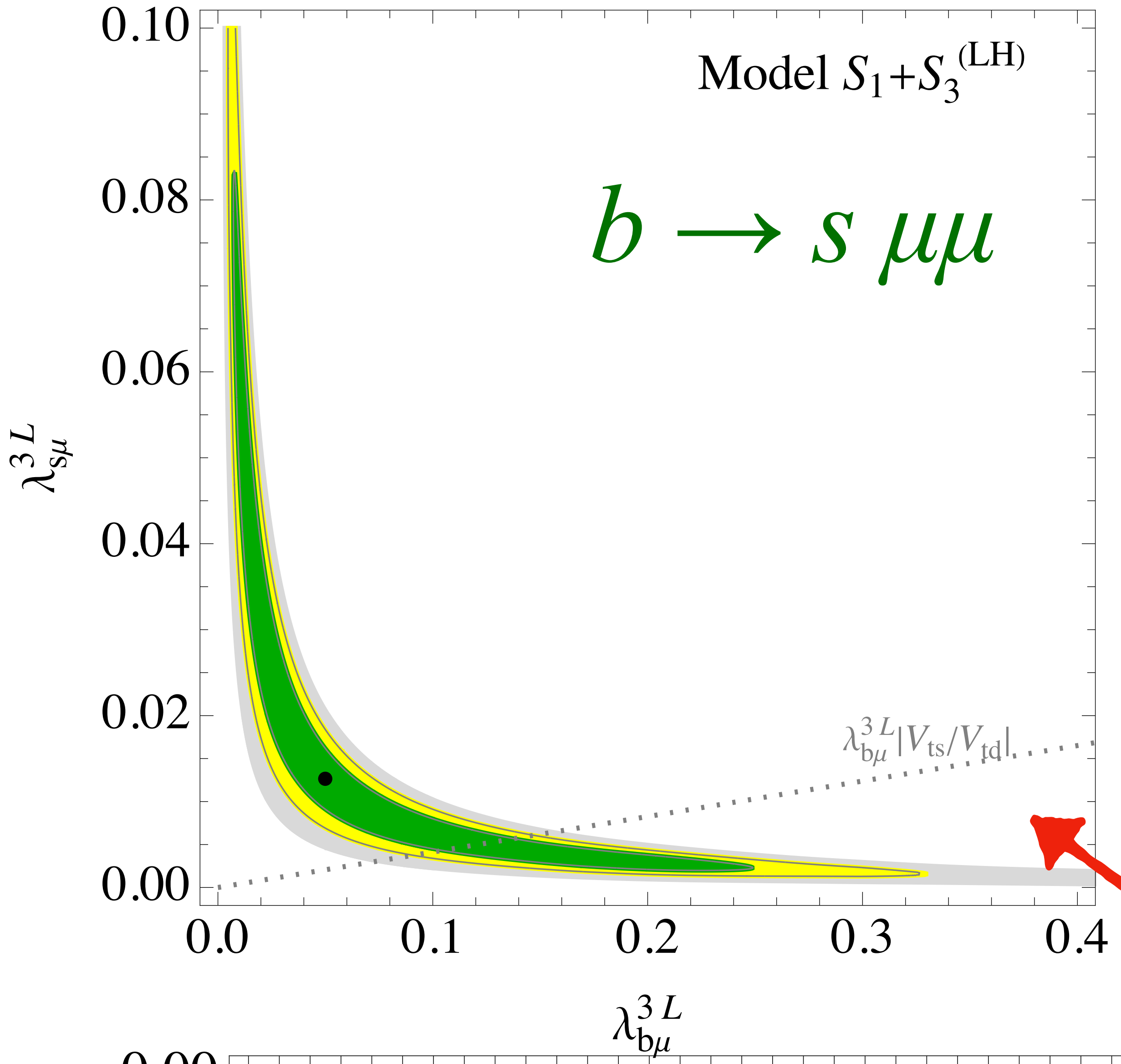


Plots updated w.r.t. [v3:2008.09548]

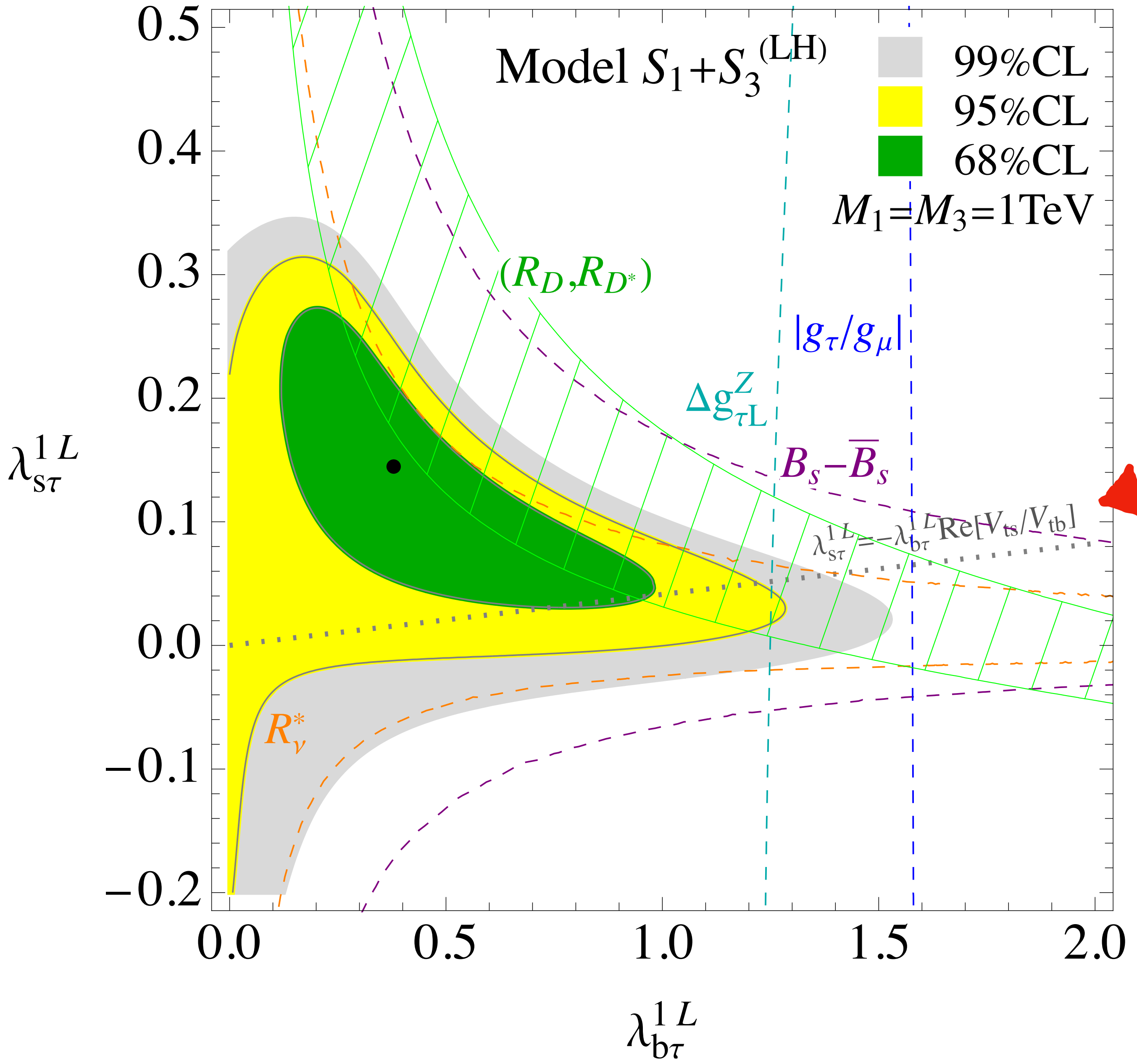
S_1 and S_3 — only LH couplings: $R(K^{(*)}) + R(D^{(*)})$

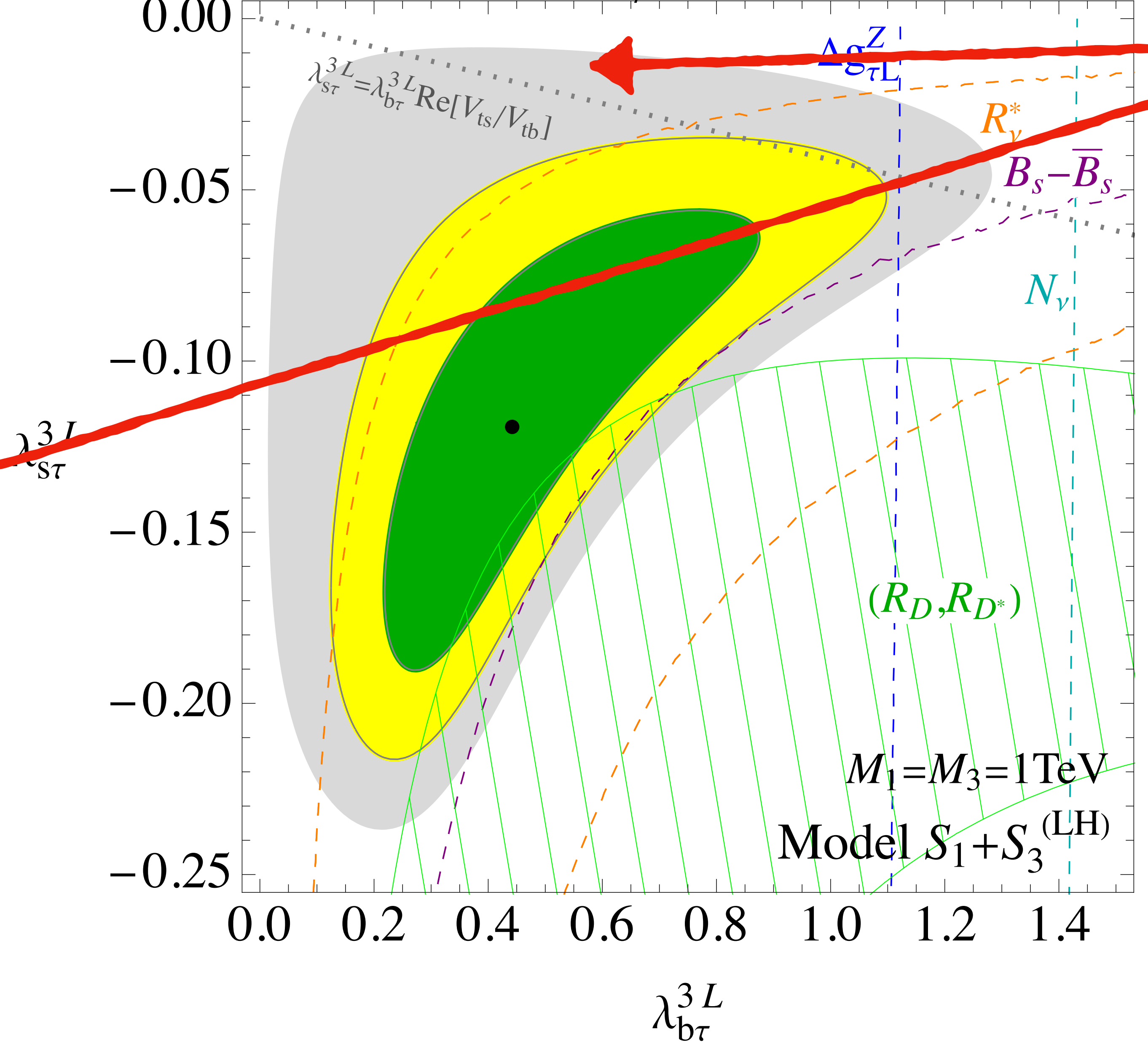
$$\lambda^{1L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & s\tau \\ 0 & 0 & b\tau \end{pmatrix} \quad \lambda^{3L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & s\mu & s\tau \\ 0 & b\mu & b\tau \end{pmatrix}$$

$\lambda^{1R} = 0$ → Cannot fit $(g-2)_\mu$



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





The relation between couplings to s-quark and b-quark is compatible with a $U(2)^5$ flavour symmetry, that would predict:

$$\lambda_{s\alpha} = c_{U(2)} V_{ts} \lambda_{b\alpha}$$

$c_{U(2)} = 1$

$c_{U(2)} \sim \mathcal{O}(1)$

Plots updated w.r.t. [v3:2008.09548]

A hint towards U(2)^5

CC & NC B-anomalies fit with only LH couplings
seems to be consistent with a U(2)^5 flavor symmetry relation

$$\lambda^{1L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & s\tau \\ 0 & 0 & b\tau \end{pmatrix} \qquad \lambda^{3L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & s\mu & s\tau \\ 0 & b\mu & b\tau \end{pmatrix} \qquad \lambda^{1R} = 0$$

$$\lambda_{s\alpha} = c_{\mathrm{U}(2)} V_{ts} \lambda_{b\alpha}$$

$$c_{\mathrm{U}(2)} \sim \mathcal{O}(1)$$

A flavor model typically also predicts **couplings to 1st generation**

Does the picture remain the same?

What is the impact of Kaon or μ → e observables?

Similar question addressed in EFT context or in relation to b→ sμμ only in:

Bordone, Buttazzo, Isidori, Monnard [1705.10729];
Borsato, Gligorov, Guadagnoli, Martinez Santos, Sumensari [1808.02006]
Fajfer, Kosnik, Vale-Silva [1802.00786]

U(2)^5 flavour symmetry

Barbieri et al. [1105.2296, 1203.4218, 1211.5085]

In the limit where only 3rd gen fermions are massive, SM enjoys a global symmetry

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

U(2)⁵ flavour symmetry

Barbieri et al. [1105.2296, 1203.4218, 1211.5085]

In the limit where only 3rd gen fermions are massive, SM enjoys a global symmetry

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

The **minimal breaking** of this symmetry due to Yukawas can be described in terms of some *spurions*, transforming under G_F:

$$\mathbf{V}_q \sim (\mathbf{2},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})\ , \quad \mathbf{V}_\ell \sim (\mathbf{1},\mathbf{2},\mathbf{1},\mathbf{1},\mathbf{1})\ ,$$
$$\mathbf{\Delta}_u \sim (\mathbf{2},\mathbf{1},\bar{\mathbf{2}},\mathbf{1},\mathbf{1})\ , \quad \mathbf{\Delta}_d \sim (\mathbf{2},\mathbf{1},\mathbf{1},\bar{\mathbf{2}},\mathbf{1})\ , \quad \mathbf{\Delta}_e \sim (\mathbf{1},\mathbf{2},\mathbf{1},\mathbf{1},\bar{\mathbf{2}})\ .$$

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

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 $\mathbf{V}_q = \kappa_q (V_{td}^*, V_{ts}^*)^T \quad \kappa_q \sim O(1)$

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

U(2)^5 flavour symmetry and leptoquarks

Applying the same symmetry assumptions to the leptoquark couplings to SM fermions we get a structure:

$$\lambda^{1(3)L} = \lambda^{1(3)} \begin{array}{cccc} e_L & \mu_L & \tau_L & \\ x_{q\ell}^{1(3)}\, s_e V_\ell V_{td} & x_{q\ell}^{1(3)}\, V_\ell V_{td} & x_{q}^{1(3)}\, V_{td} & d_L \\ x_{q\ell}^{1(3)}\, s_e V_\ell V_{ts} & x_{q\ell}^{1(3)}\, V_\ell V_{ts} & x_{q}^{1(3)}\, V_{ts} & s_L \\ x_{\ell}^{1(3)}\, s_e V_\ell & x_{\ell}^{1(3)}\, V_\ell & 1 & b_L \end{array}$$

$$\lambda^{1R} \approx \lambda^{1}_{R} \begin{pmatrix} 0 & 0 \\ 0 & \tilde{x}^{1R}_{t\tau} \end{pmatrix}$$

→ only RH coupling allowed is to $t_R\ \tau_R$.

U(2)⁵ flavour symmetry and leptoquarks

Applying the same symmetry assumptions to the leptoquark couplings to SM fermions we get a structure:

$$\lambda^{1(3)L} = \lambda^{1(3)} \begin{array}{c} \begin{array}{ccc} e_L & \mu_L & \tau_L \end{array} \\ \left(\begin{array}{ccc} x_{q\ell}^{1(3)} s_e V_\ell V_{td} & x_{q\ell}^{1(3)} V_\ell V_{td} & x_q^{1(3)} V_{td} \\ x_{q\ell}^{1(3)} s_e V_\ell V_{ts} & x_{q\ell}^{1(3)} V_\ell V_{ts} & x_q^{1(3)} V_{ts} \\ x_\ell^{1(3)} s_e V_\ell & x_\ell^{1(3)} V_\ell & 1 \end{array}\right) \end{array} \begin{array}{c} d_L \\ s_L \\ b_L \end{array}$$

$$\lambda^{1R} \approx \lambda^1_R \begin{pmatrix} 0 & 0 \\ 0 & \tilde{x}^{1R}_{t\tau} \end{pmatrix}$$

→ only RH coupling allowed is to $t_R\, \tau_R$.

$s_e = \sin\vartheta_e$: rotation diagonalizing electrons and muon masses

V_ℓ : leptonic doublet spurion

$x^{1(3)}$: ***O(1)*** arbitrary complex parameters.

} *Arbitrary parameters*

$U(2)^5$ flavour symmetry and leptoquarks

Applying the same symmetry assumptions to the leptoquark couplings to SM fermions we get a structure:

$$\lambda^{1(3)L} = \lambda^{1(3)} \begin{array}{c} \begin{array}{ccc} e_L & \mu_L & \tau_L \end{array} \\ \left(\begin{array}{ccc} x_{q\ell}^{1(3)} s_e V_\ell V_{td} & x_{q\ell}^{1(3)} V_\ell V_{td} & x_q^{1(3)} V_{td} \\ x_{q\ell}^{1(3)} s_e V_\ell V_{ts} & x_{q\ell}^{1(3)} V_\ell V_{ts} & x_q^{1(3)} V_{ts} \\ x_\ell^{1(3)} s_e V_\ell & x_\ell^{1(3)} V_\ell & 1 \end{array}\right) \end{array} \begin{array}{c} \\ d_L \\ s_L \\ b_L \end{array}$$

$$\lambda^{1R} \approx \lambda_R^1 \begin{pmatrix} 0 & 0 \\ 0 & \tilde{x}_{t\tau}^{1R} \end{pmatrix}$$

→ only RH coupling allowed is to $t_R\ \tau_R$.

$s_e = \sin\vartheta_e$: rotation diagonalizing electrons and muon masses

V_ℓ : leptonic doublet spurion

$x^{1(3)}$: ***O(1)*** arbitrary complex parameters.

} *Arbitrary parameters*

Generic features of $U(2)^5$ symmetry:

- Largest couplings to **b_L**, **t_L**, **τ_L** and **ν_τ**,
- Coupl. to **s_L** suppressed by ~ **V_{ts}**,
- Coupl. to **d_L** suppressed by ~ **V_{td}**,
- Coupl. to **μ_L** suppressed by **V_ℓ**,
- Coupl. to **e_L** suppressed by **s_e V_ℓ**.

U(2)⁵ flavour symmetry and leptoquarks

Applying the same symmetry assumptions to the leptoquark couplings to SM fermions we get a structure:

$$\lambda^{1(3)L} = \lambda^{1(3)} \begin{array}{c} \begin{array}{ccc} e_L & \mu_L & \tau_L \end{array} \\ \left(\begin{array}{ccc} x^{1(3)}_{q\ell}\, s_e V_\ell V_{td} & x^{1(3)}_{q\ell}\, V_\ell V_{td} & x^{1(3)}_{q}\, V_{td} \\ x^{1(3)}_{q\ell}\, s_e V_\ell V_{ts} & x^{1(3)}_{q\ell}\, V_\ell V_{ts} & x^{1(3)}_{q}\, V_{ts} \\ x^{1(3)}_{\ell}\, s_e V_\ell & x^{1(3)}_{\ell}\, V_\ell & 1 \end{array}\right) \end{array} \begin{array}{c} \\ d_L \\ s_L \\ b_L \end{array}$$

$$\lambda^{1R} \approx \lambda^1_R \begin{pmatrix} 0 & 0 \\ 0 & \tilde{x}^{1R}_{t\tau} \end{pmatrix}$$

→ only RH coupling allowed is to $t_R\ \tau_R$.

$s_e = \sin\vartheta_e$: rotation diagonalizing electrons and muon masses

V_ℓ : leptonic doublet spurion

$\}$ *Arbitrary parameters*

$x^{1(3)}$: ***O(1)*** arbitrary complex parameters.

The leptoquark **couplings to first generations** are now **fixed** in terms of couplings to the second generation:

$$\lambda^{1(3)L}_{d\alpha} = \lambda^{1(3)L}_{s\alpha} \frac{V_{td}}{V_{ts}}$$

$$\lambda^{1(3)L}_{ie} = \lambda^{1(3)L}_{i\mu} \sin\vartheta_e$$

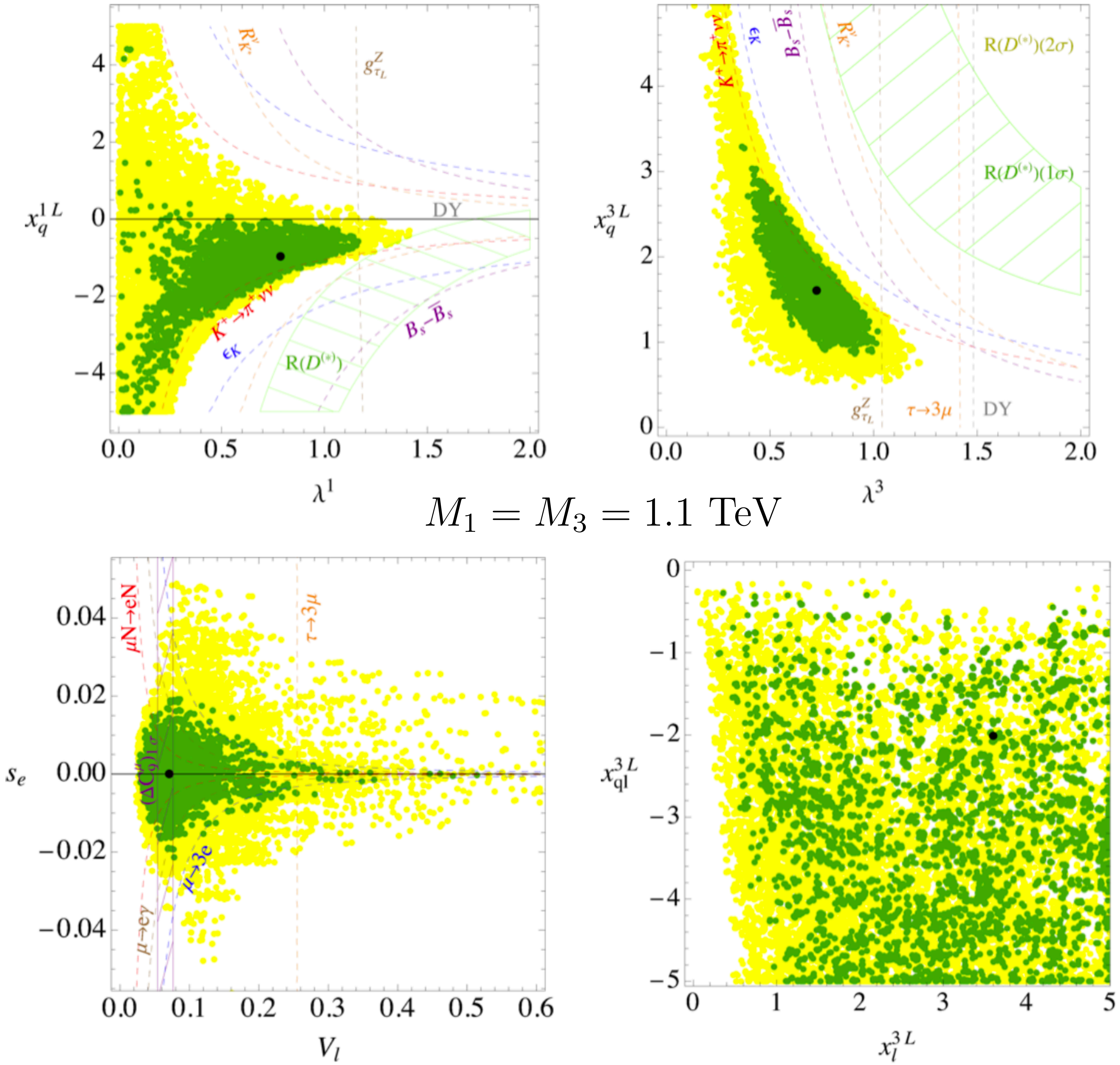
Exact relations (selection rules)

We can now **correlate Kaon physics** observables **to B-anomalies**!

From B to K with LQ and U(2)^5

S. Trifinopoulos, E. Venturini, D.M. [2106.15630]

We perform a global fit in the U(2)^5 flavour structure.



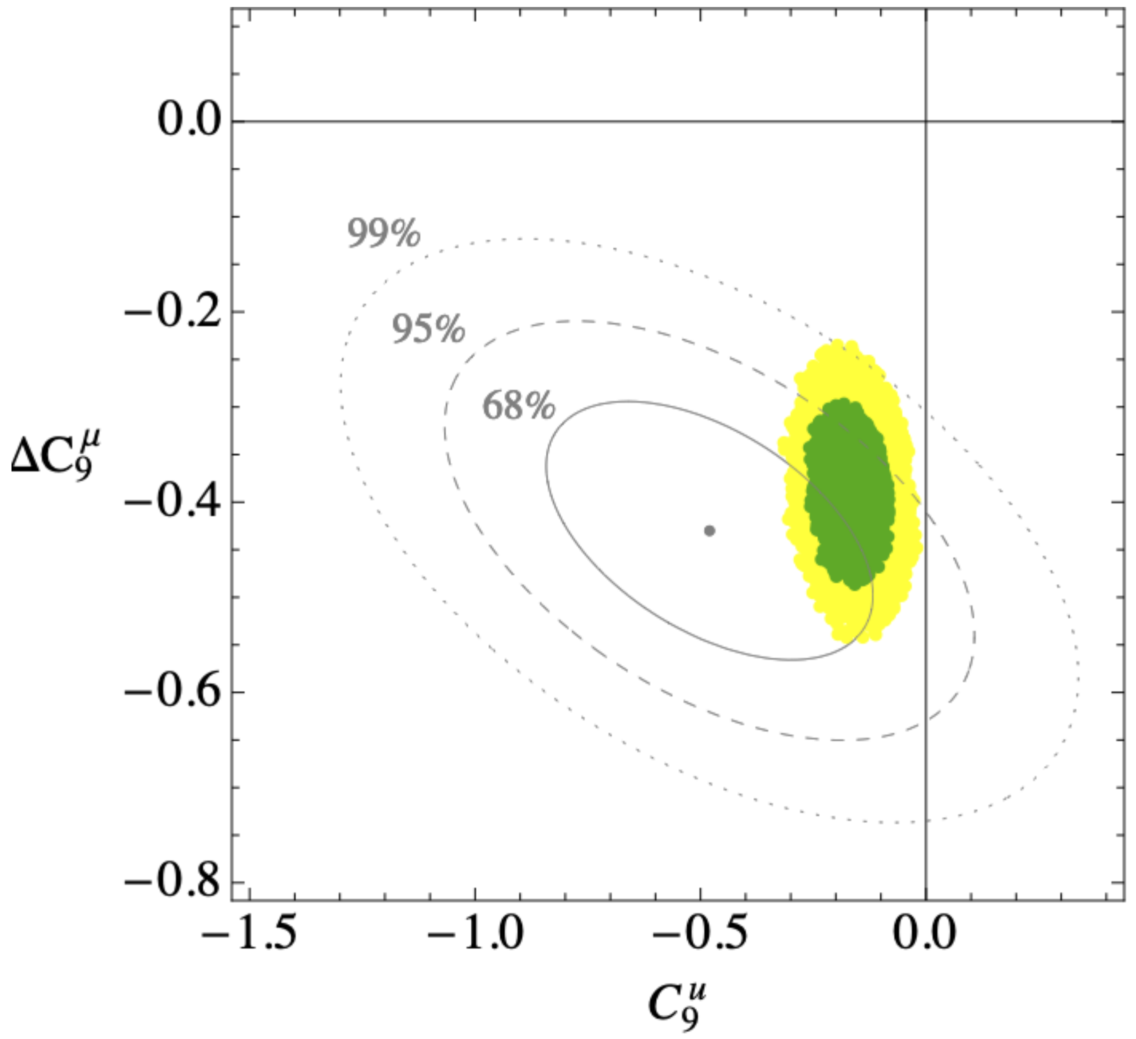
$M_1 = M_3 = 1.1$ TeV

- The parameters are indeed consistent with a U(2)^5 structure: **all x's are O(1)**.

- $V_\ell \sim 0.1, \quad |s_e| \lesssim 0.02$

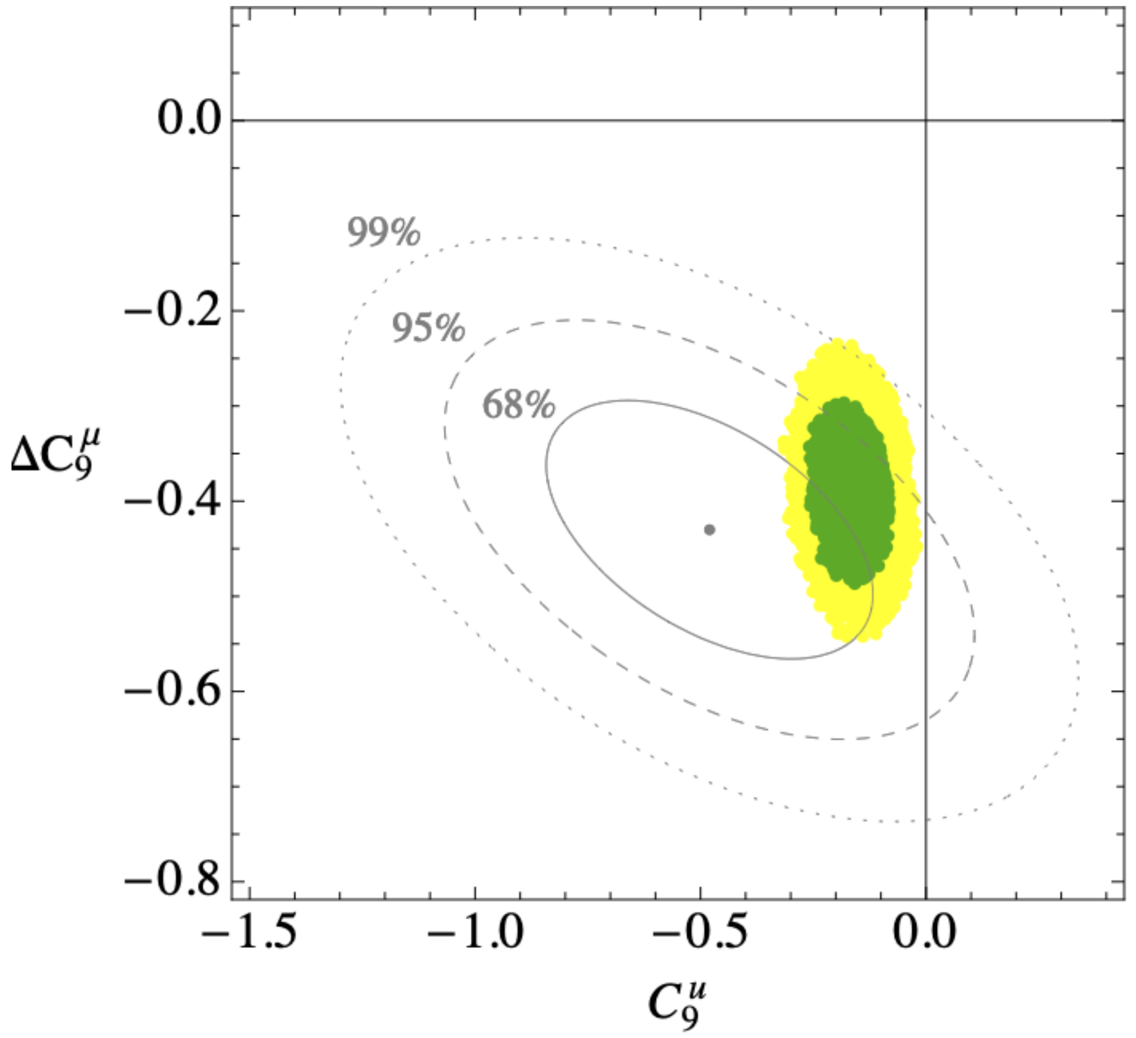
From B to K with LQ and U(2)^5

b→ sμμ can be addressed:

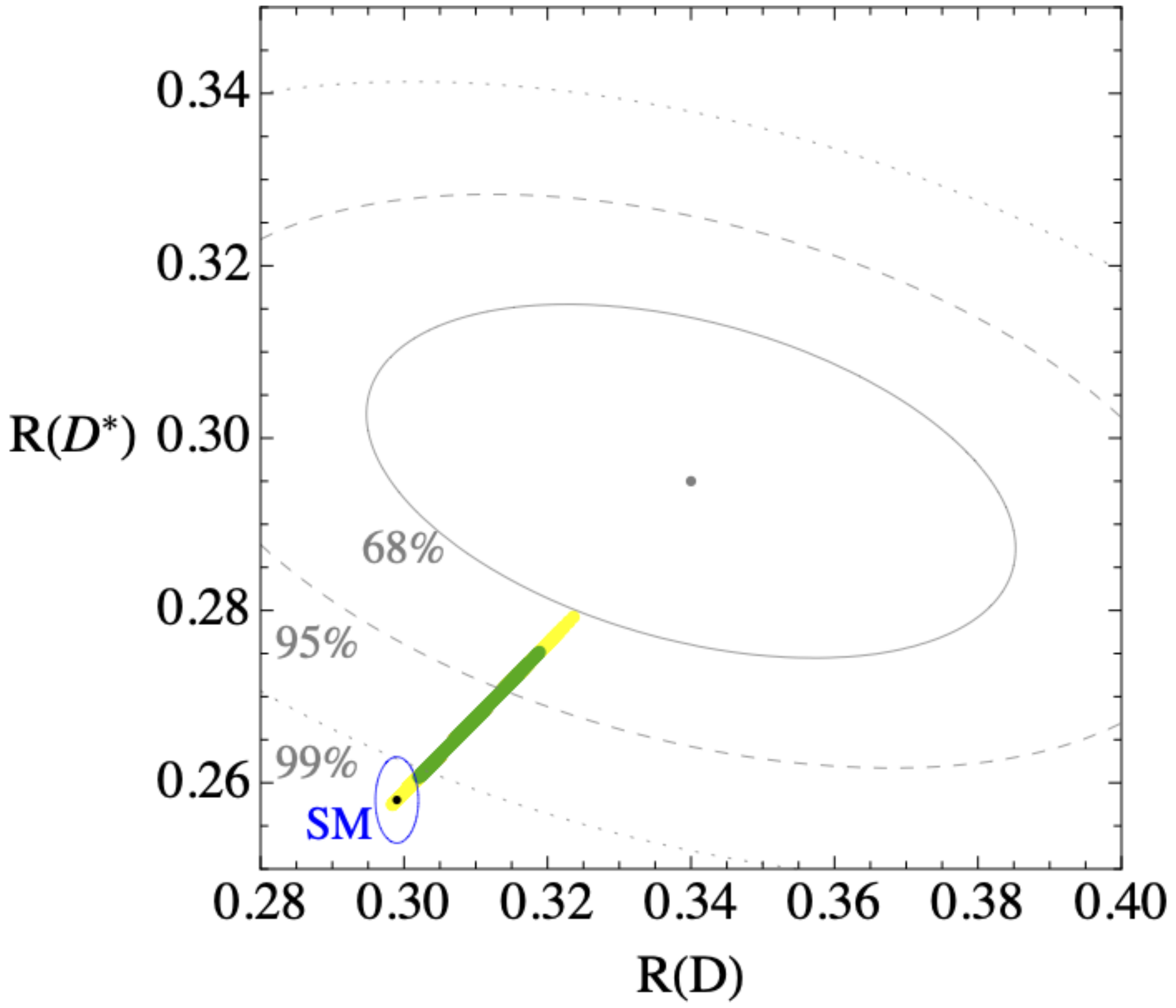


From B to K with LQ and U(2)^5

b→ sμμ can be addressed:

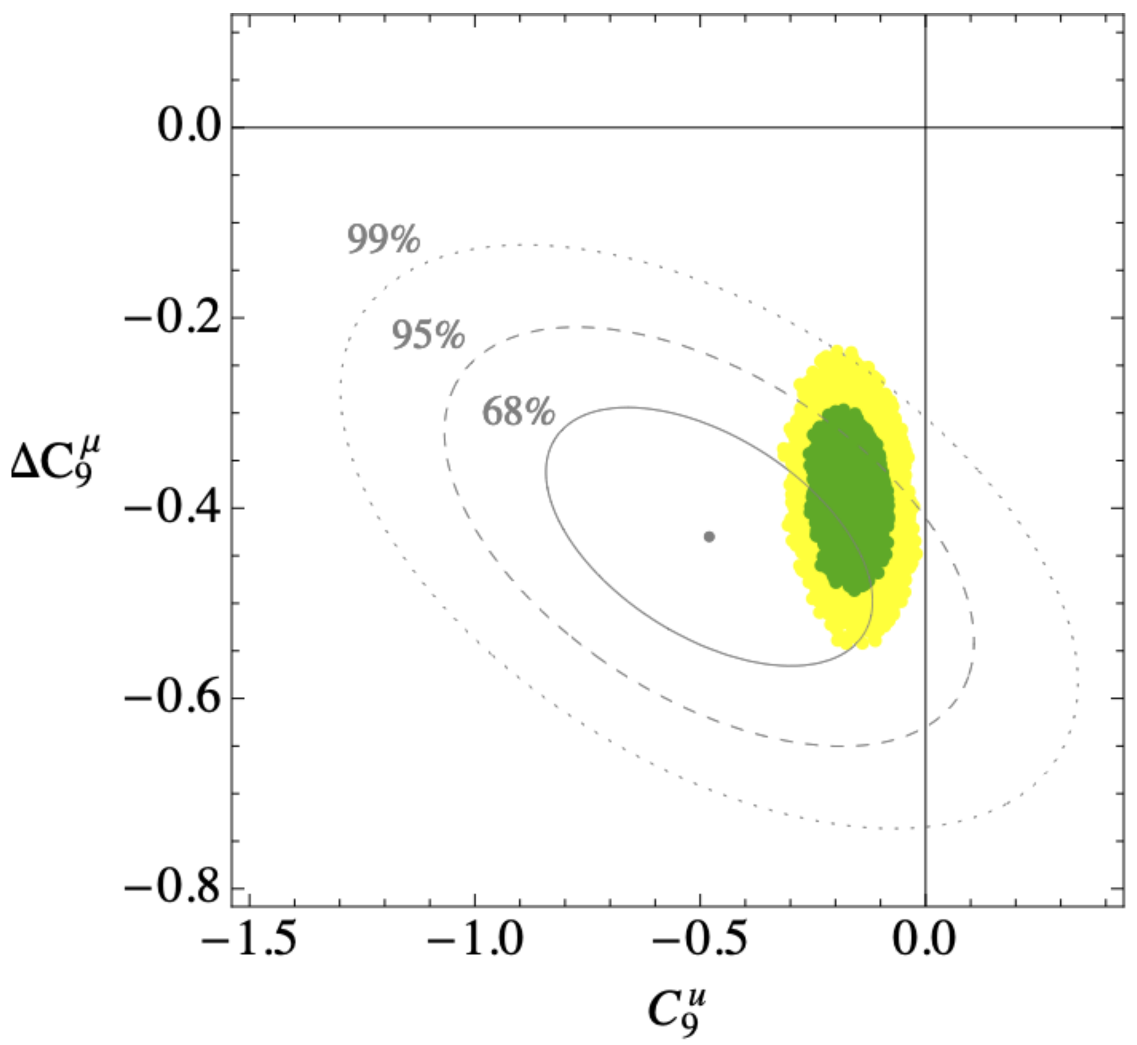


R(D$^{(*)}$) instead can only be addressed at 2σ:

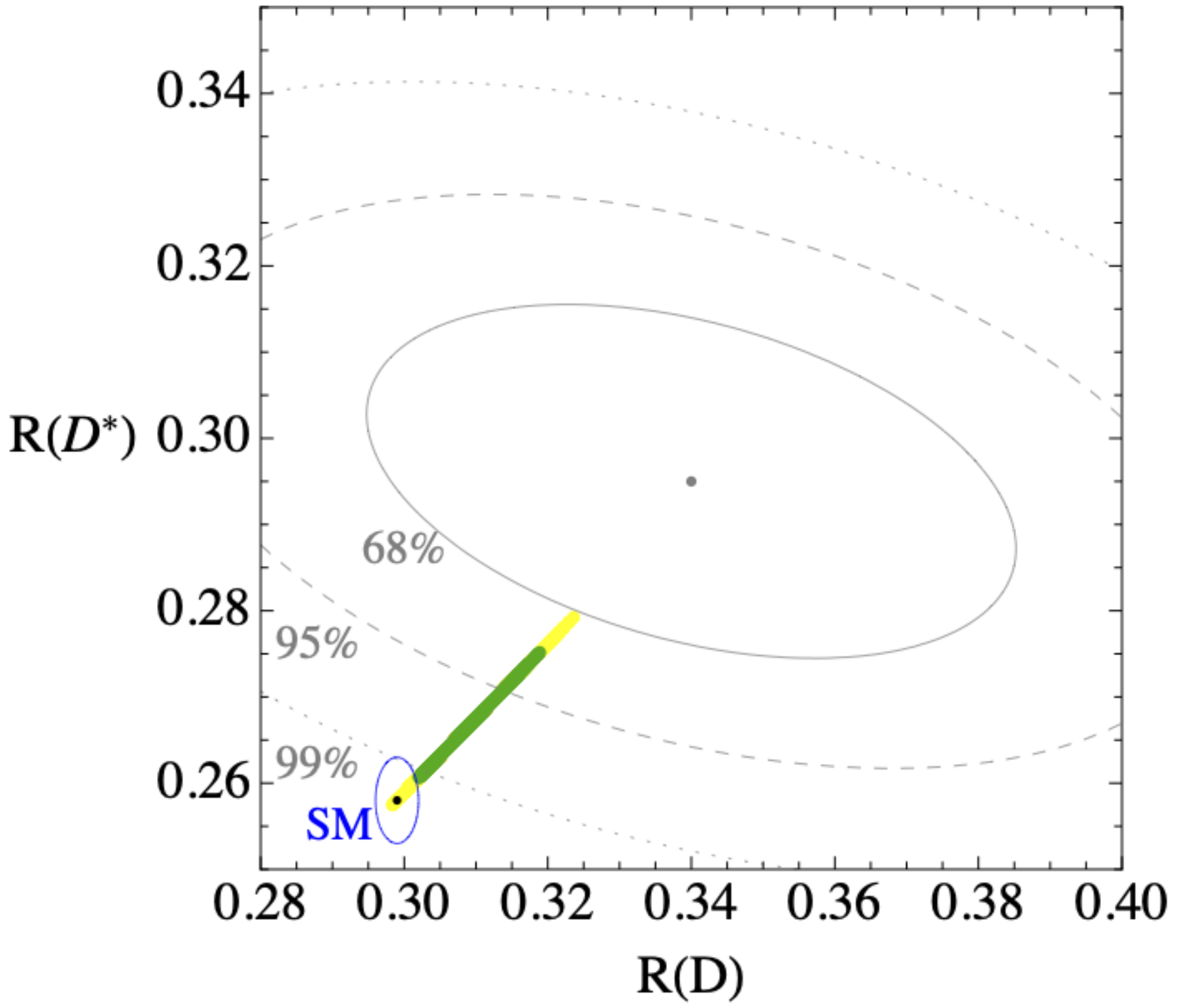


From B to K with LQ and U(2)^5

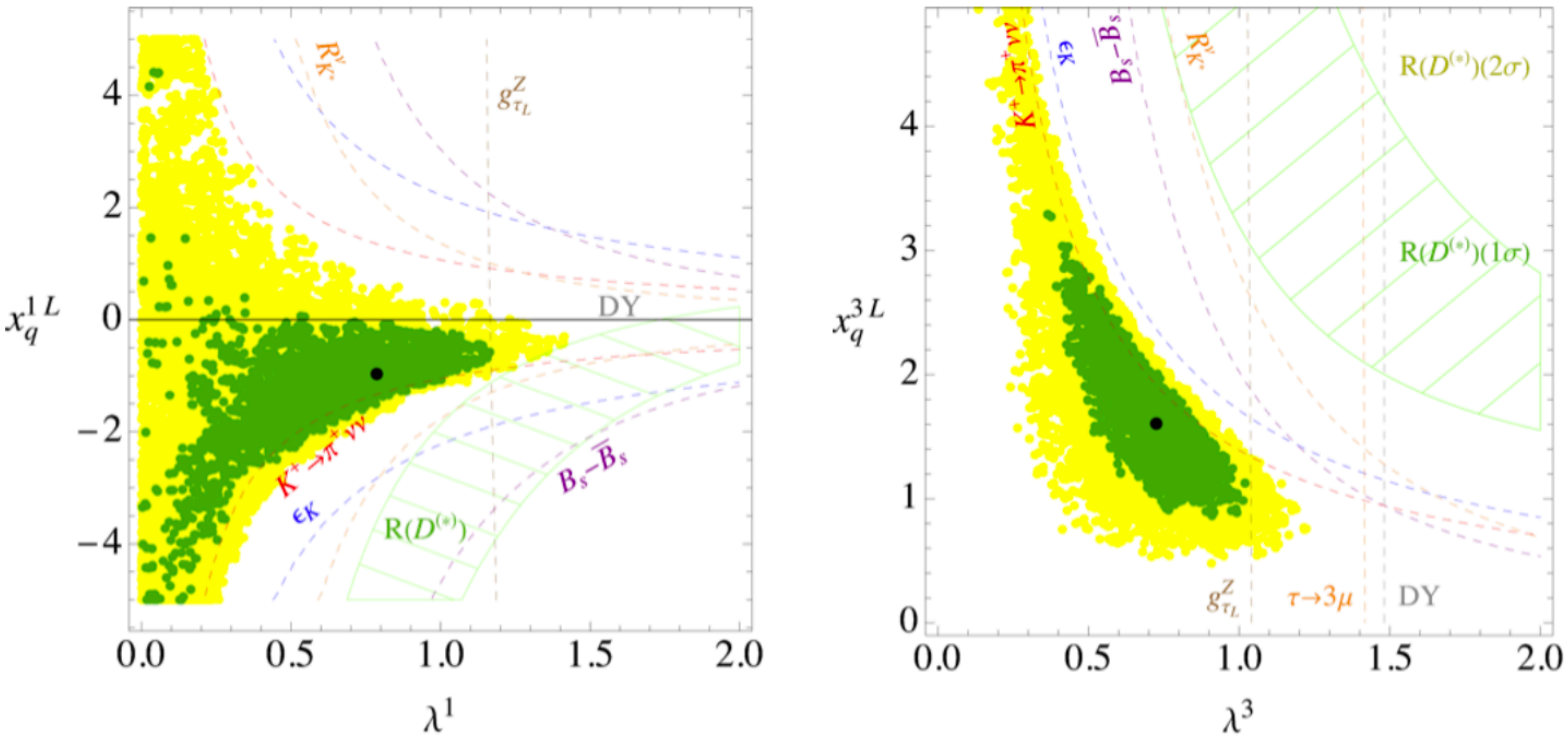
b→ sμμ can be addressed:



R(D(*)) instead can only be addressed at 2σ:



This is due to the **combination** of the constraints from Z→ττ and K+→π+ νν



R(D(*))

$$\frac{\Delta R(D^{(*)})}{R(D^{(*)})_{\rm SM}} \approx v^2\left(1.09\frac{|\lambda^1|^2(1-x_q^{1*}V_{tb}^*)}{2M_1^2}-1.02\frac{|\lambda^3|^2(1-x_q^{3*}V_{tb}^*)}{2M_3^2}\right)$$

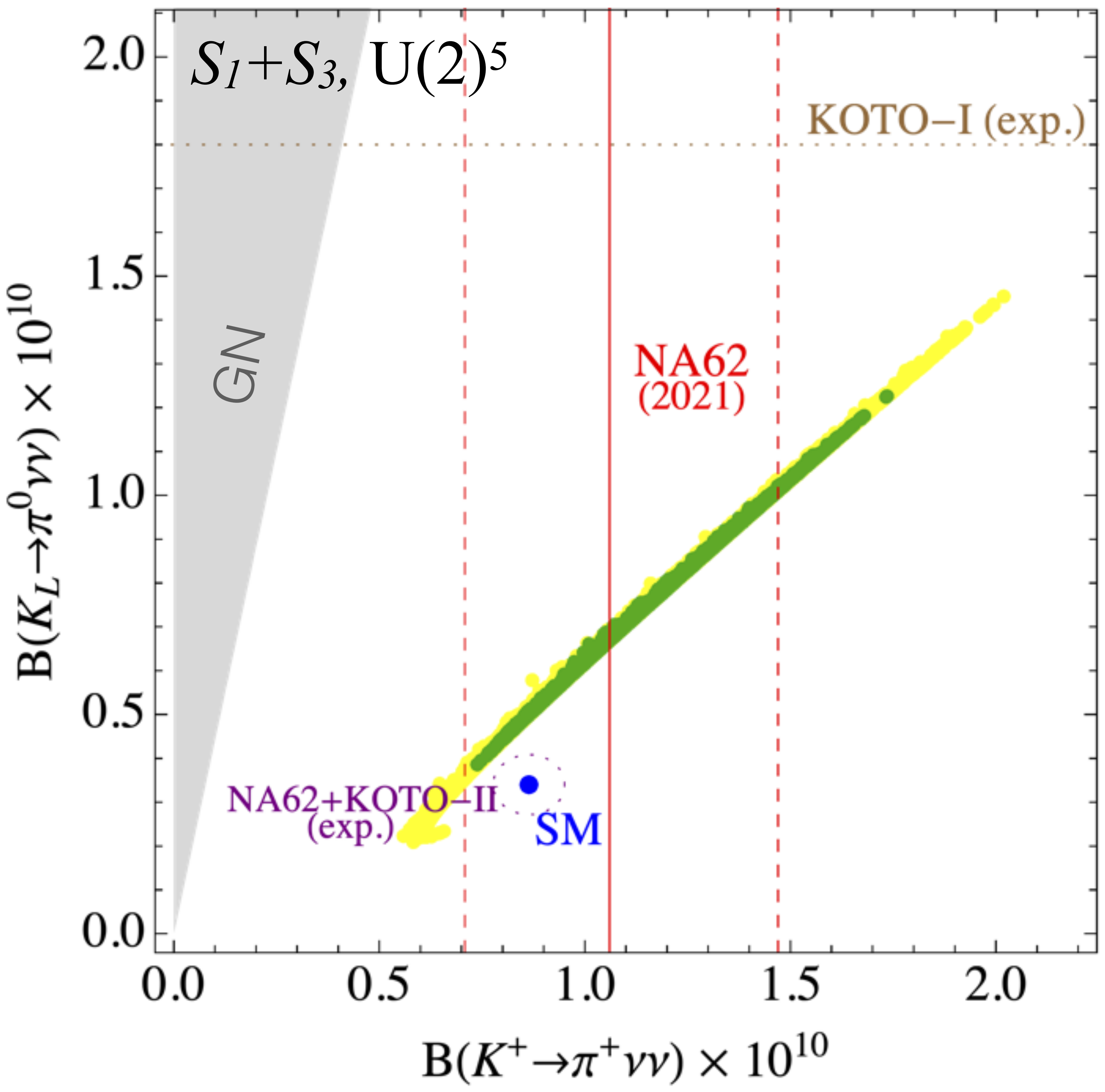
K+→π+ νν

$$[L_{\nu d}^{VLL}]_{\nu_\tau\nu_\tau ds} \approx V_{td}^*V_{ts}\left(\frac{|\lambda^1|^2|x_q^1|^2}{2M_1^2}+\frac{|\lambda^3|^2|x_q^3|^2}{2M_3^2}\right)$$

Z→ττ

$$10^3\delta g^Z_{\tau_L} \approx 0.59\frac{|\lambda^1|^2}{M_1^2/\ \mathrm{TeV}^2}+0.80\frac{|\lambda^1|^2}{M_1^2/\ \mathrm{TeV}^2}$$

Leading effects in Kaon physics



Dominated by **tau neutrinos**, due to largest couplings.

The **NA62** bound is already very constraining for this setup, future updated will put even more tension with R(D$^{(*)}$), or eventually a signal could be observed.

The correlation in the full model is stronger than just in EFT.

[see: Bordone, Buttazzo, Isidori, Monnard 1705.10729]

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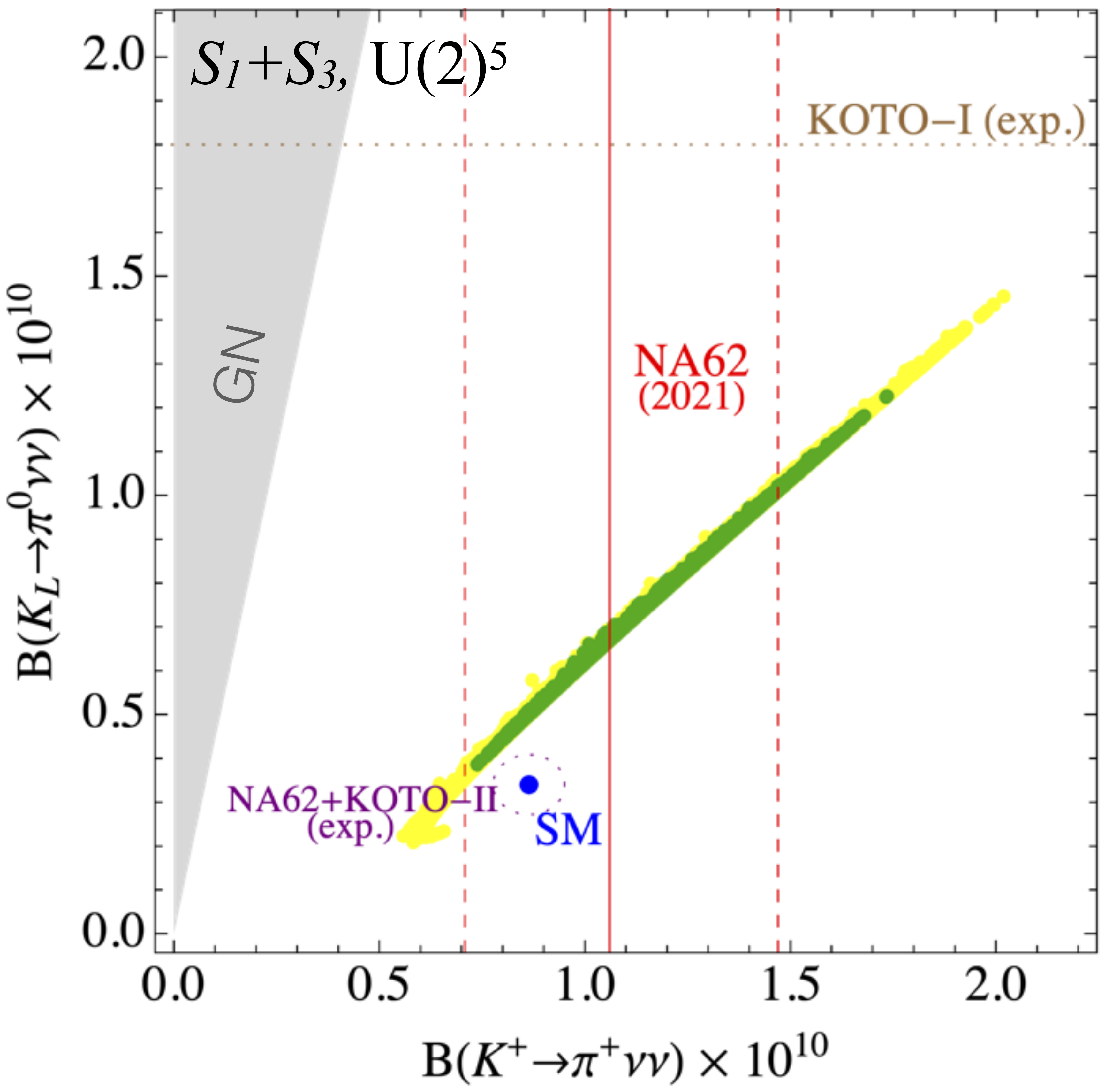

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[see: Bordone, Buttazzo, Isidori, Monnard 1705.10729]

The **phase of NP** contribution is **fixed** to be SM-like:

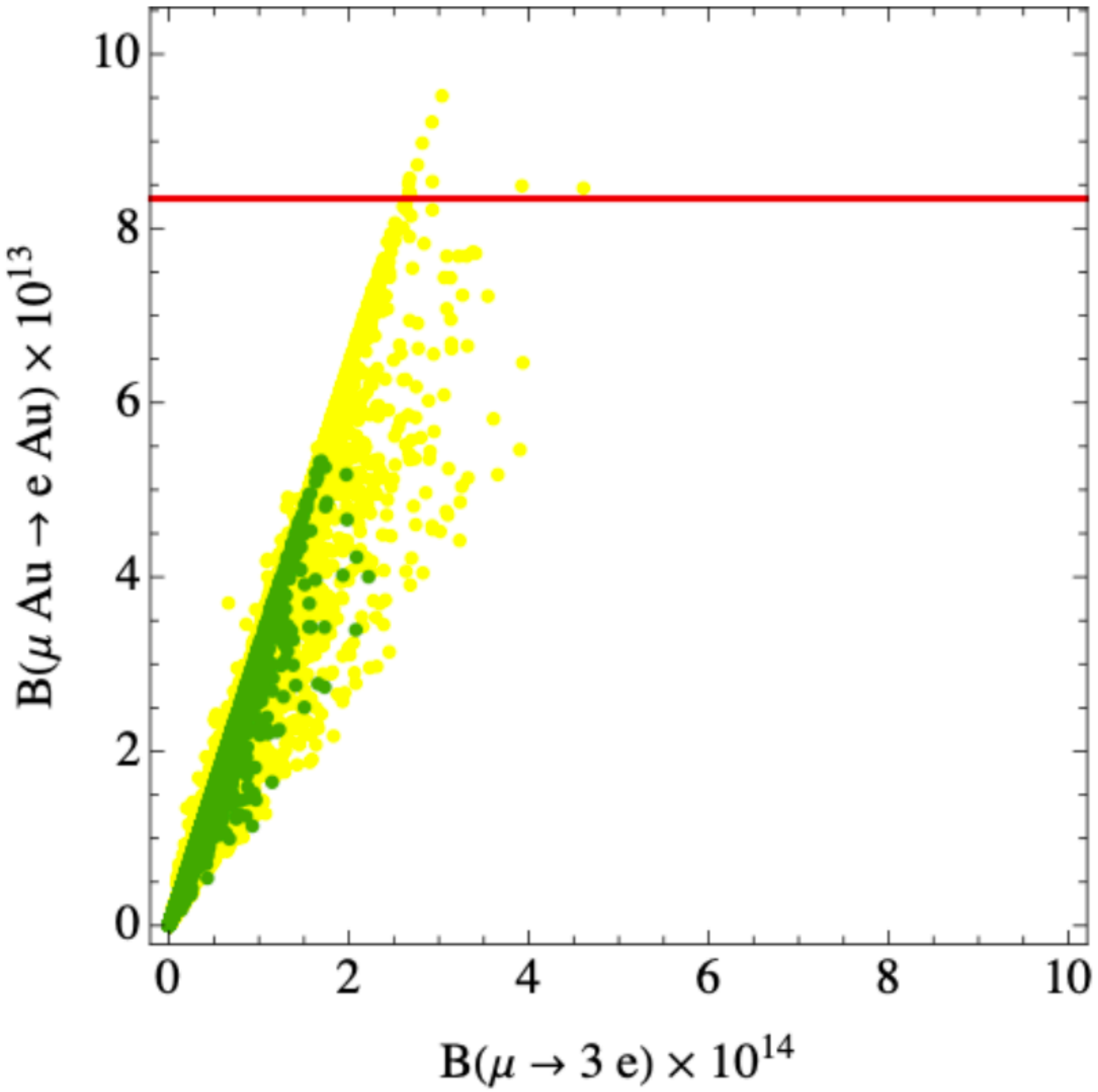
$$\left[L^{VLL}_{\nu d}\right]_{\nu_\tau \nu_\tau ds} \approx V^*_{td} V_{ts} \left(\frac{|\lambda^1|^2 |x^1_q|^2}{2M_1^2} + \frac{|\lambda^3|^2 |x^3_q|^2}{2M_3^2} \right)$$

As consequence, the $K_L \to \pi^0$ mode is fully correlated and below the KOTO stage-I final sensitivity.

About other Kaon decays:

The effect in $K_L \to \mu\mu$ saturates the bound, while the SD contribution to $K_S \to \mu\mu$ is ~10^{-13} (backup slides)
We also obtain Br($K_L \to \mu e$) ~ 10^{-15} and Br($K^+ \to \pi^+ \mu e$) ~ 10^{-18}.

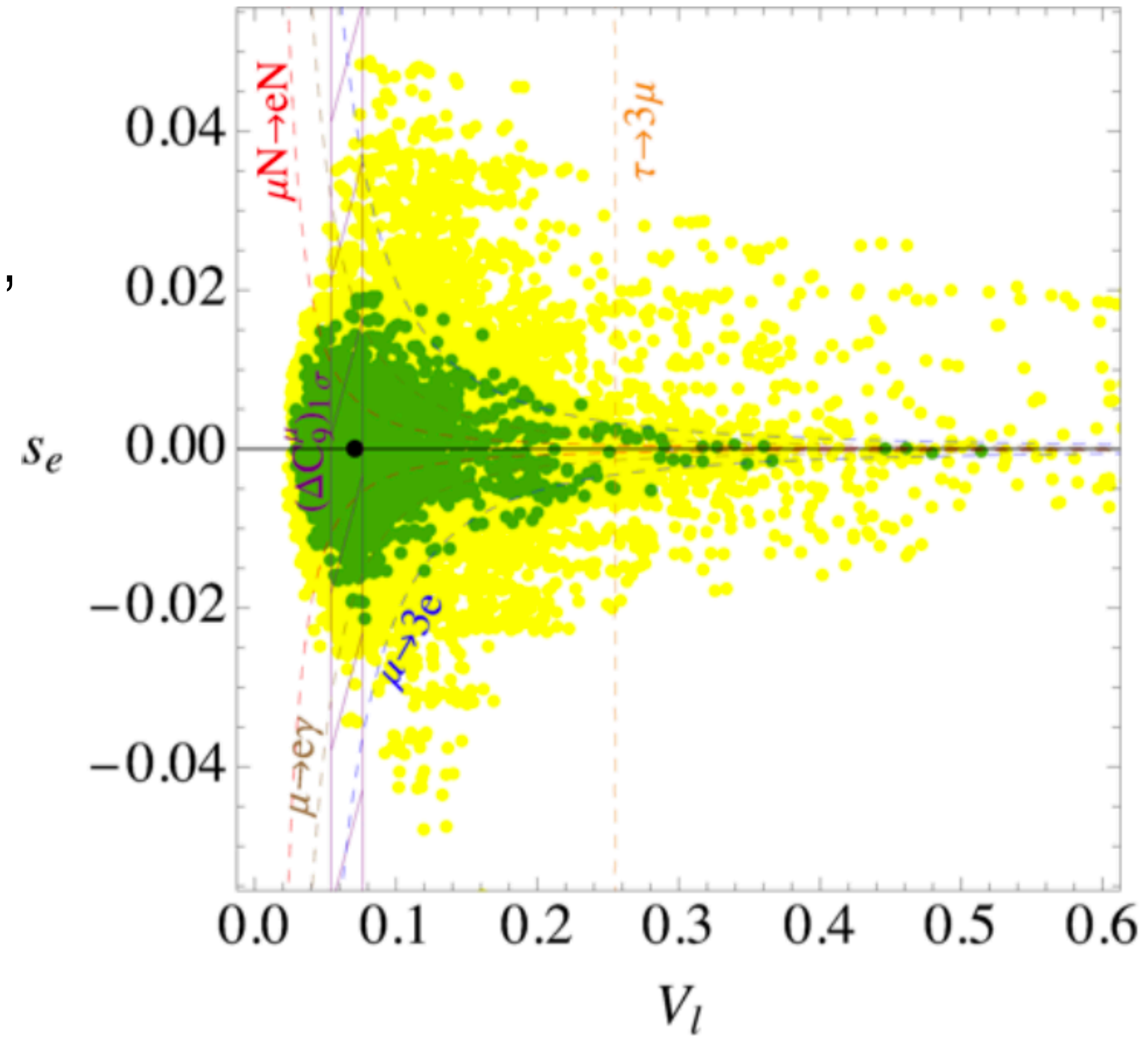
μ → e conversion



μ→e conversion in gold nuclei sets the **strongest constraint on s_e**.

COMET and *Mu2e* will push this bound to ~**10^{-16}**, while *Mu3e* at PSI will push the limit on **Br(μ→3e) to ~10^{-16}**.

These will set much stronger **bounds on s_e**, or could see a New Physics effect.



Conclusions

- **Flavor anomalies** still require data (and theory) to give us a definitive picture.
  This could potentially be our **threshold to an unexpected New Physics sector**!

- **S_1+S_3 scalar leptoquarks** offer a good solutions to **B anomalies** and **$(g-2)_\mu$**,
  > simplified model is **fully calculable**
  > possible UV origin from a **Composite Higgs model**.

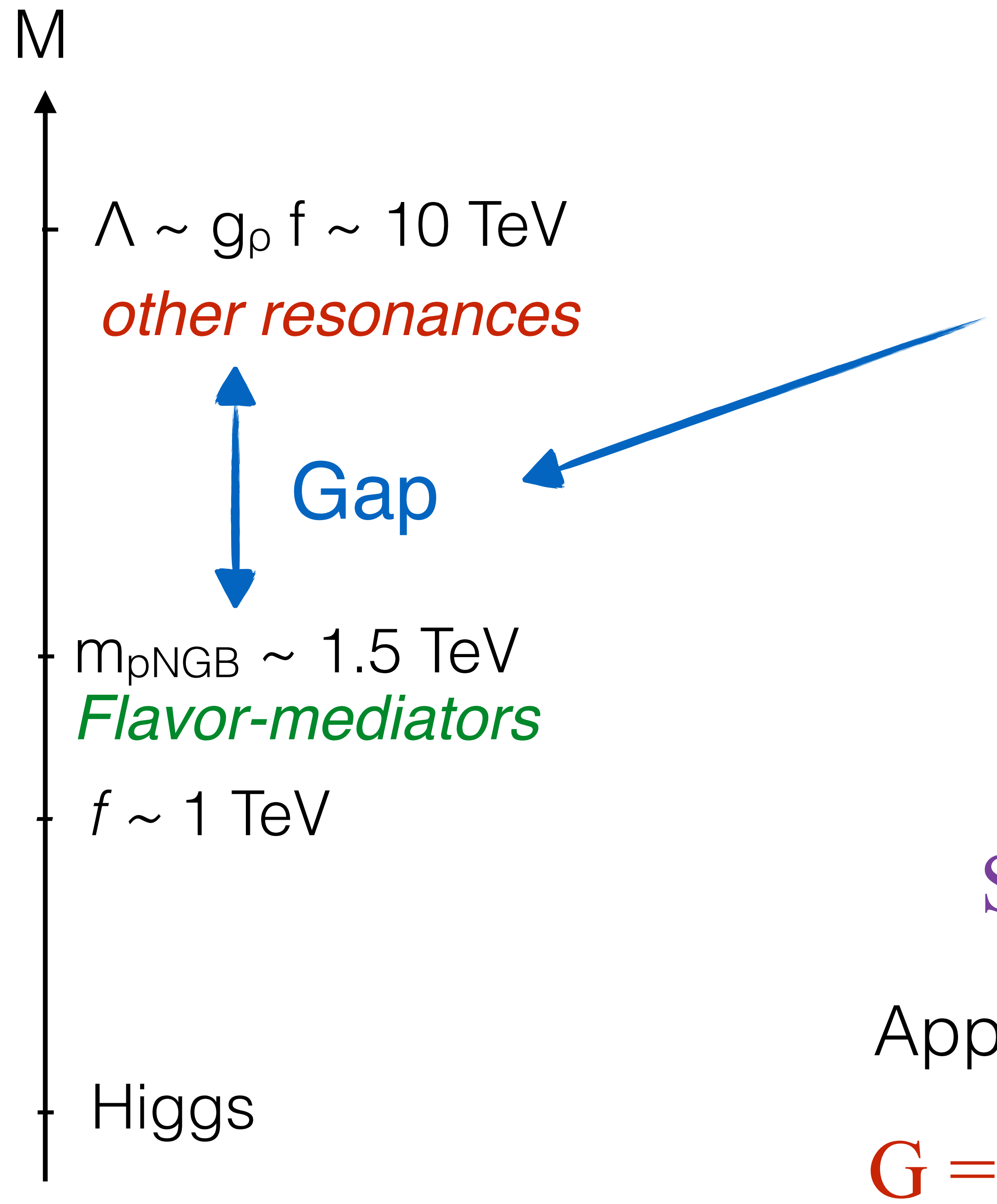
- In order to understand the **underlying flavour structure**
  we need to **connect B-anomalies with other observables**.
  > Rare **Kaon decays** and **μ→e** probes stand out and offer exceptional prospects.

Thank you!

Backup

Fundamental Composite model for LQs + Higgs

[D.M. 1803.10972]



Scalar LQ as pseudo-Goldstone boson

Natural mass splitting between pseudo-Goldstone bosons & the other resonances.
Like between pions and ρ mesons in QCD.

$$m_{SLQ} \ll \Lambda$$

Gauge group:

$$SU(N_{HC}) \times SU(3)_c \times SU(2)_w \times U(1)_Y$$

"HyperColor"

$SU(N_{\rm HC})$ confines at $\Lambda_{\rm HC} \sim 10$ TeV

Extra Dirac fermions:

	$SU(N_{HC})$	$SU(3)_c$	$SU(2)_w$	$U(1)_Y$
Ψ_L	$\mathbf{N_{HC}}$	$\mathbf{1}$	$\mathbf{2}$	Y_L
Ψ_N	$\mathbf{N_{HC}}$	$\mathbf{1}$	$\mathbf{1}$	$Y_L + 1/2$
Ψ_E	$\mathbf{N_{HC}}$	$\mathbf{1}$	$\mathbf{1}$	$Y_L - 1/2$
Ψ_Q	$\mathbf{N_{HC}}$	$\mathbf{3}$	$\mathbf{2}$	$Y_L - 1/3$

Approximate global symmetry, spontaneously broken (as chiral symm. in QCD)

$$G = SU(10)_L \times SU(10)_R \times U(1)_V \xrightarrow{f \sim 1\text{TeV}} H = SU(10)_V \times U(1)_V$$

Many states are present at the **TeV scale** as pseudo-Goldstones, including

Two Higgs doublets: H_{SM} , $\tilde{H}_2$ $\sim (\mathbf{1},\mathbf{2})_{1/2}$

Singlet and Triplet LQ: $S_1 \sim (\mathbf{3},\mathbf{1})_{-1/3}$ + $S_1 \sim (\mathbf{3},\mathbf{3})_{-1/3}$

$S_1 \sim (\bar{\Psi}_Q \Psi_L)$,

$S_3 \sim (\bar{\Psi}_Q \sigma^A \Psi_L)$,

Coupling with SM fermions from 4-Fermi operators

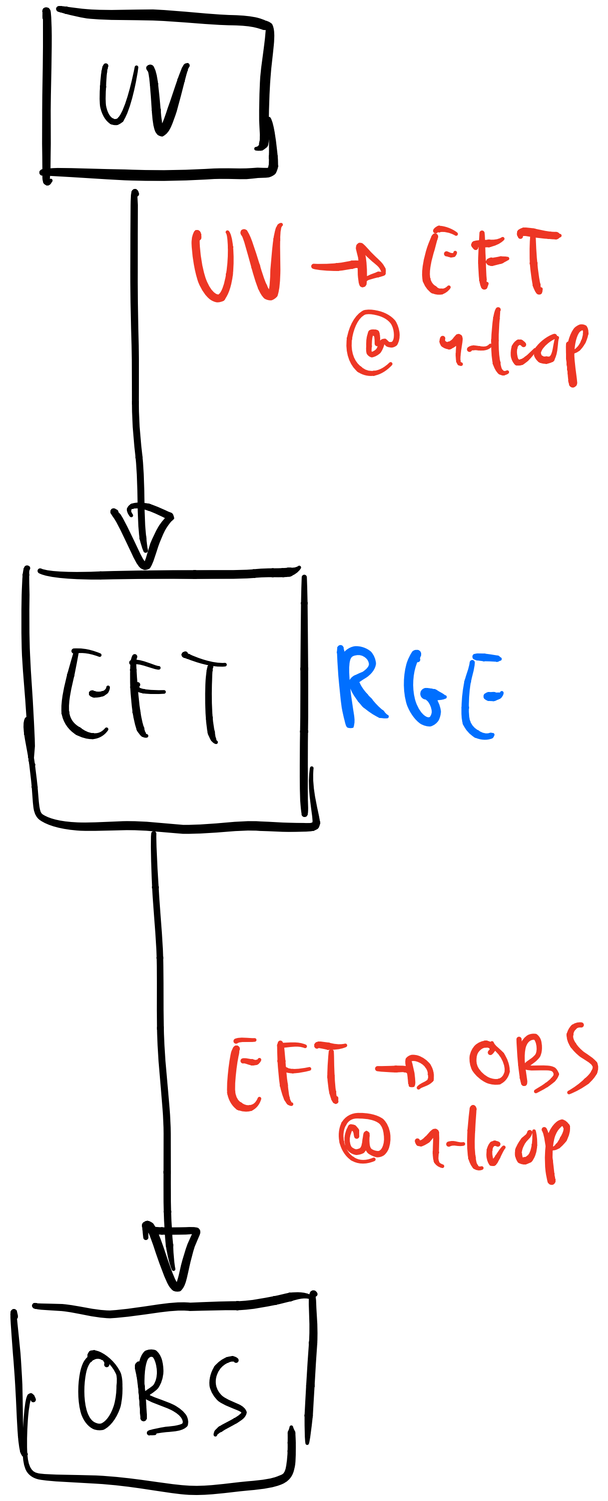
$$\mathcal{L}_{4-\text{Fermi}} \sim \frac{c_{\psi\Psi}}{\Lambda_t^2} \bar{\psi}_{\rm SM}\psi_{\rm SM}\bar{\Psi}\Psi \xrightarrow{E \lesssim \Lambda_{HC}} \sim y_{\psi\phi}\, \bar{\psi}_{\rm SM}\psi_{\rm SM}\, \phi + \ldots$$

Yukawas & LQ couplings

+ approximate $SU(2)^5$ flavor symmetry to protect from unwanted flavor violation

Complete one-loop matching to SMEFT

V. Gherardi, E. Venturini, D.M. [2003.12525]



Other necessary contributions:

SMEFT 1-loop RGE

[Alonso, Jenkins, Manohar, Trott ’13]

SMEFT > LEFT matching @1-loop

[Dekens, Stoffer 1908.05295]

LEFT 1-loop RGE

[Jenkins, Manohar, Stoffer 1711.05270]

Motivations:

1. **finite terms** (non logs) of loop contributions **are important for several observables:**
   Meson mixing, magnetic dipole moments, Z couplings, LFV leptonic decays, etc..

2. Once the matching is performed, a **large number of observables** can be readily evaluated.

3. It is the first such complete matching for a very rich scenario, many operators are induced.
   Useful as cross-check for other techniques that aim to do this more automatically.
   MatchMaker (diagrammatic approach) [Anastasiou, Carmona, Lazopoulos, Santiago, in progress],
   methods based on *Covariant Derivative Expansion* (CDE)
   [Henning, Lu, Murayama ’14, Drozd, Ellis, Quevillion, You, Zhang ’15, ’16, ’17, Fuentes-Martin, Portoles, Ruiz-Femenia]

The alternative is to compute on-shell loops for each observable, as in:

Crivellin et al. 1912.04224; Saad 2005.04352;

“Green’s Basis” of the SMEFT

V. Gherardi, E. Venturini, D.M. [2003.12525]

When off-shell one-loop diagrams are evaluated, also operators outside of the chosen basis (e.g. Warsaw) are generated, which must be reduced to the basis via E.O.M.

The complete **set of independent operators independent upon integration by parts** (but possibly redundant under EOM), is called “***Green's basis***”

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$$\mathcal{G} \equiv \langle e_\beta(p_1)\bar{e}_\alpha(p_2)H_b(q_1)H_a^\dagger(q_2)\rangle$$

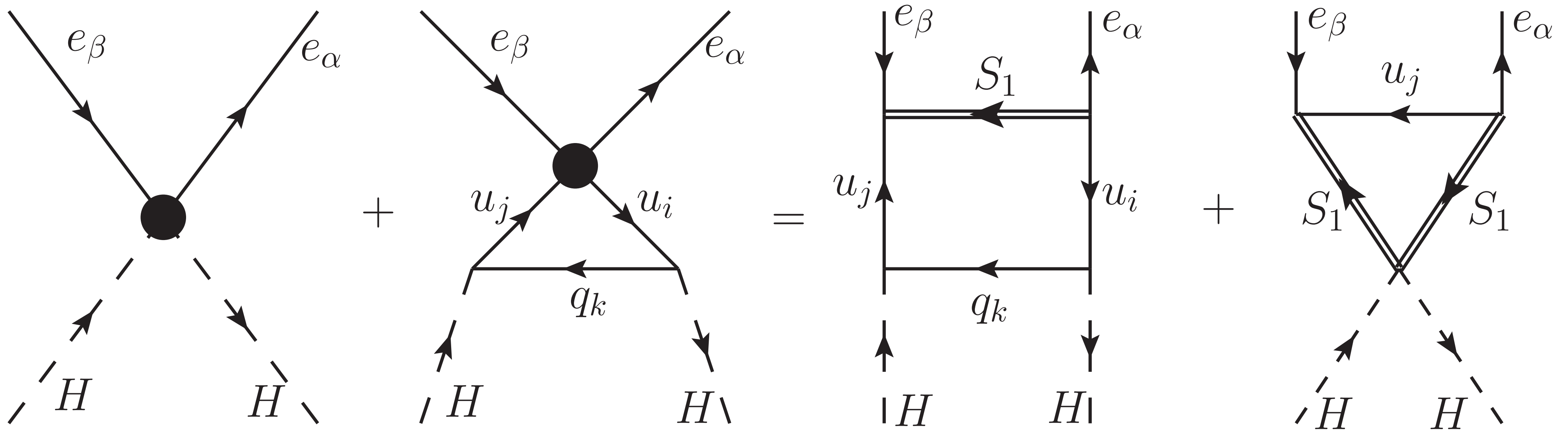

Figure 1: Diagrams for the matching of the $\langle \bar{e}eH^\dagger H\rangle$ Green function.

Relevant Green's basis operators:

$$[\mathcal{O}_{He}]_{\alpha\beta} = (\bar{e}_\alpha\gamma^\mu e_\beta)(H^\dagger i\overleftrightarrow{D}_\mu H)\,,$$

$$[\mathcal{O}'_{He}]_{\alpha\beta} = (\bar{e}_\alpha i\overleftrightarrow{\not{D}}\, e_\beta)(H^\dagger H)\;,$$

$$[\mathcal{O}''_{He}]_{\alpha\beta} = (\bar{e}_\alpha\gamma^\mu e_\beta)\partial_\mu(H^\dagger H)\;.$$

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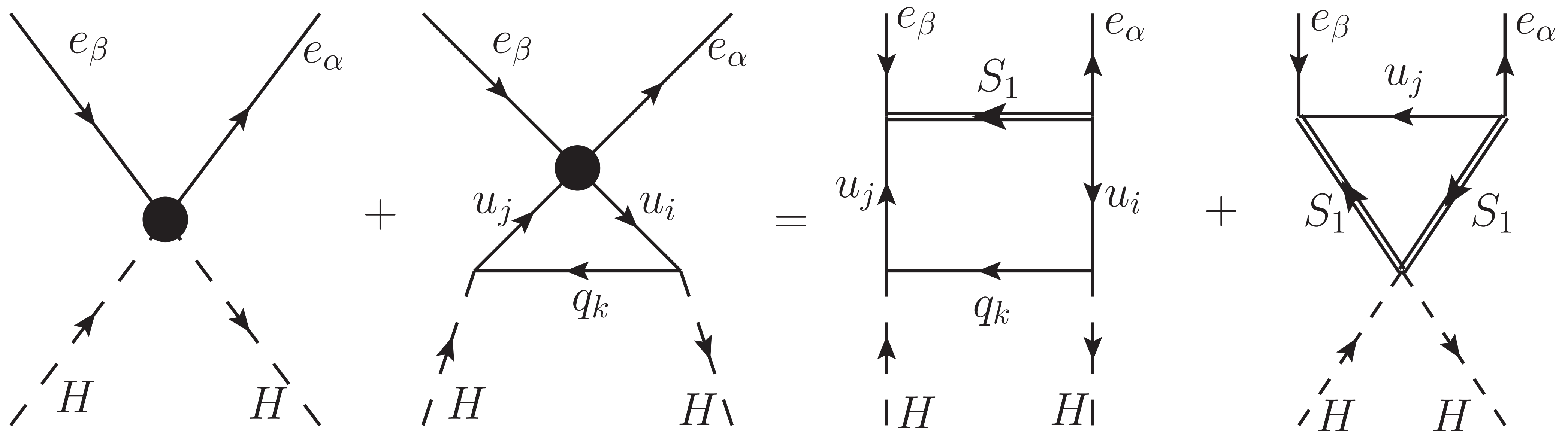

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$$\boxed{[G_{He}(\mu_M)]_{\alpha\beta} = -\frac{N_c(\lambda^{1R\dagger}y_U^T y_U^* \lambda^{1R})_{\alpha\beta}}{32\pi^2 M_1^2}\left(1+\log\frac{\mu_M^2}{M_1^2}\right)} \, ,$$

$$[G'_{He}(\mu_M)]_{\alpha\beta} = -\frac{N_c(\lambda^{1R\dagger}y_U^T y_U^* \lambda^{1R})_{\alpha\beta}}{64\pi^2 M_1^2} + \frac{N_c\lambda_{H1}(\lambda^{1R\dagger}\lambda^{1R})_{\alpha\beta}}{64\pi^2 M_1^2} \, ,$$

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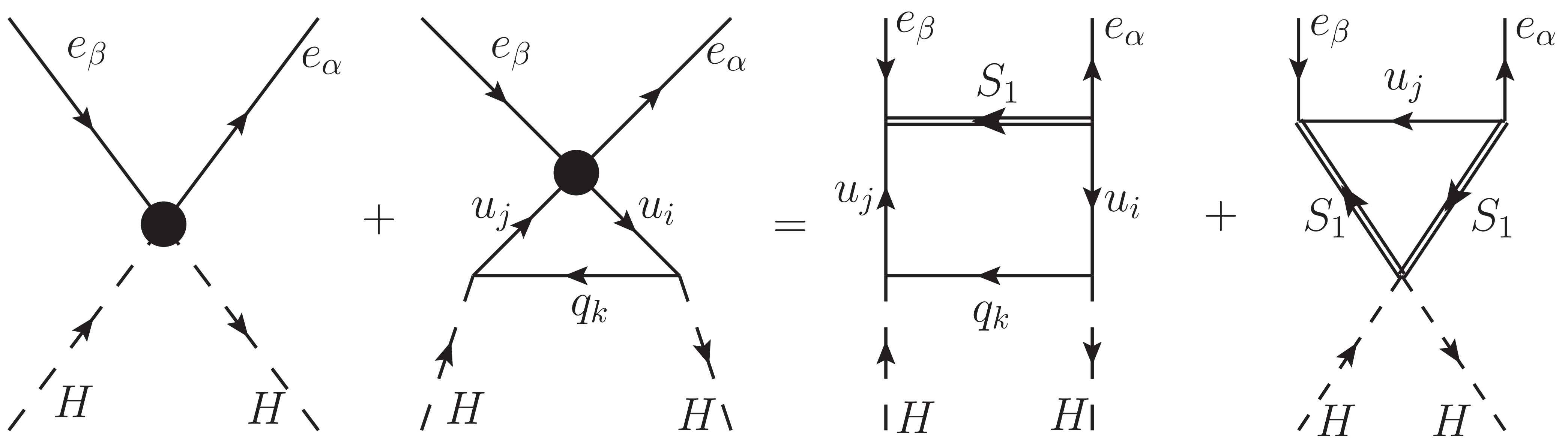

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The last two must be rotated to the Warsaw basis:

$$(O'_{He})_{\alpha\beta} \quad \to (y_E^*)_{\gamma\beta}(O_{eH})^\dagger_{\gamma\alpha} + (y_E)_{\gamma\alpha}(O_{eH})_{\gamma\beta}$$
$$[O''_{He}]_{\alpha\beta} \to i(y_E^*)_{\gamma\beta}\,[O_{eH}]^\dagger_{\gamma\alpha} - i(y_E)_{\gamma\alpha}(O_{eH})_{\gamma\beta}$$

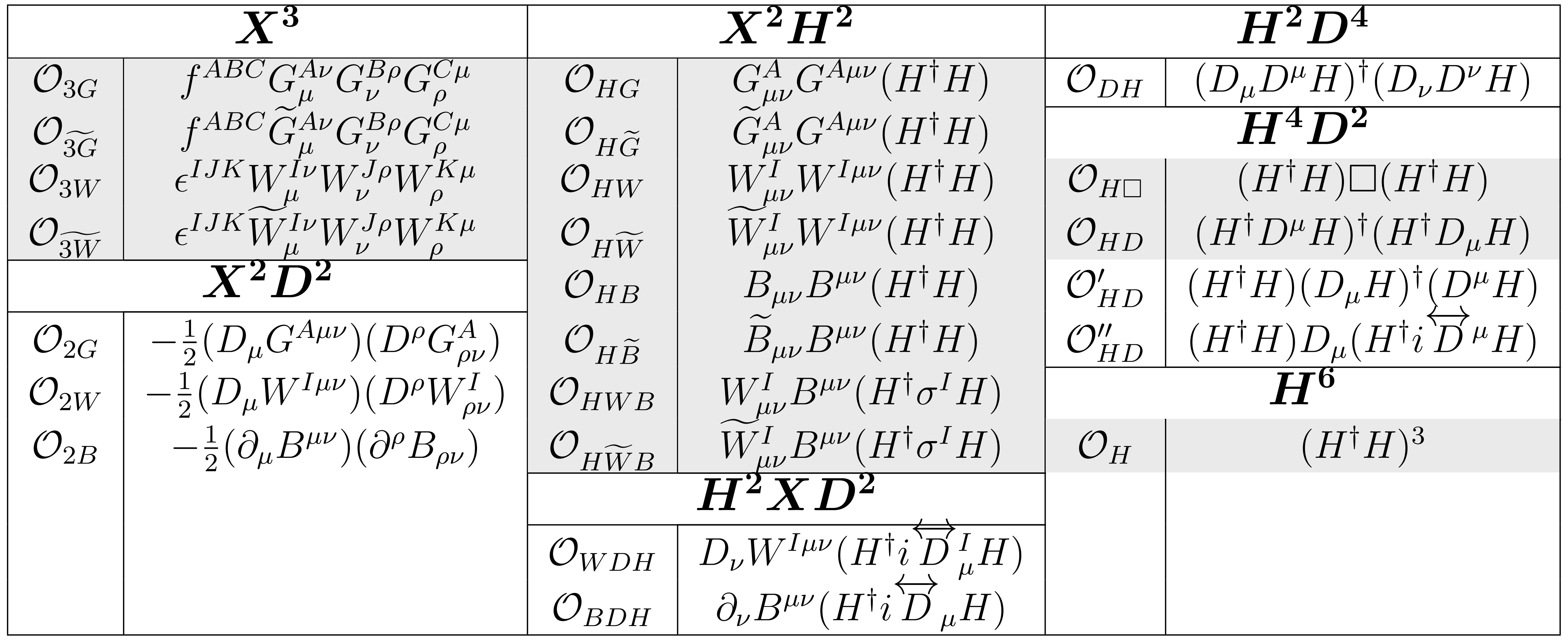
While the first operators receives contributions also from other ones:

$$[C_{He}]^{(1)}_{\alpha\beta} = -\frac{N_c}{30}g'^4 Y_H Y_e\delta_{\alpha\beta}\left(\frac{3Y_{S_3}^2}{M_3^2}+\frac{Y_{S_1}^2}{M_1^2}\right) + \frac{N_c}{12}\left(3\frac{(y_E^\dagger\Lambda_\ell^{(3)}y_E)_{\alpha\beta}}{M_3^2}+\frac{(y_E^\dagger\Lambda_\ell^{(1)}y_E)_{\alpha\beta}}{M_1^2}\right) +$$
$$+\frac{N_c}{3}g'^2 Y_H\left(\frac{8Y_u - Y_{S_1}}{6}+Y_u L_1\right)\frac{(\Lambda_e)_{\alpha\beta}}{M_1^2}\boxed{-\frac{N_c}{2}(1+L_1)\frac{(X_{2U}^{1R})_{\alpha\beta}}{M_1^2}.}$$

“Green’s Basis” of the SMEFT

V. Gherardi, E. Venturini, D.M. [2003.12525]

The **grey ones** are those already present in the **Warsaw basis**



X^3	
$\mathcal{O}_{3G}$	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$
$\mathcal{O}_{\widetilde{3G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$
$\mathcal{O}_{3W}$	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$
$\mathcal{O}_{\widetilde{3W}}$	$\epsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$

X^2D^2	
$\mathcal{O}_{2G}$	$-\frac{1}{2}(D_\mu G^{A\mu\nu})(D^\rho G^A_{\rho\nu})$
$\mathcal{O}_{2W}$	$-\frac{1}{2}(D_\mu W^{I\mu\nu})(D^\rho W^I_{\rho\nu})$
$\mathcal{O}_{2B}$	$-\frac{1}{2}(\partial_\mu B^{\mu\nu})(\partial^\rho B_{\rho\nu})$

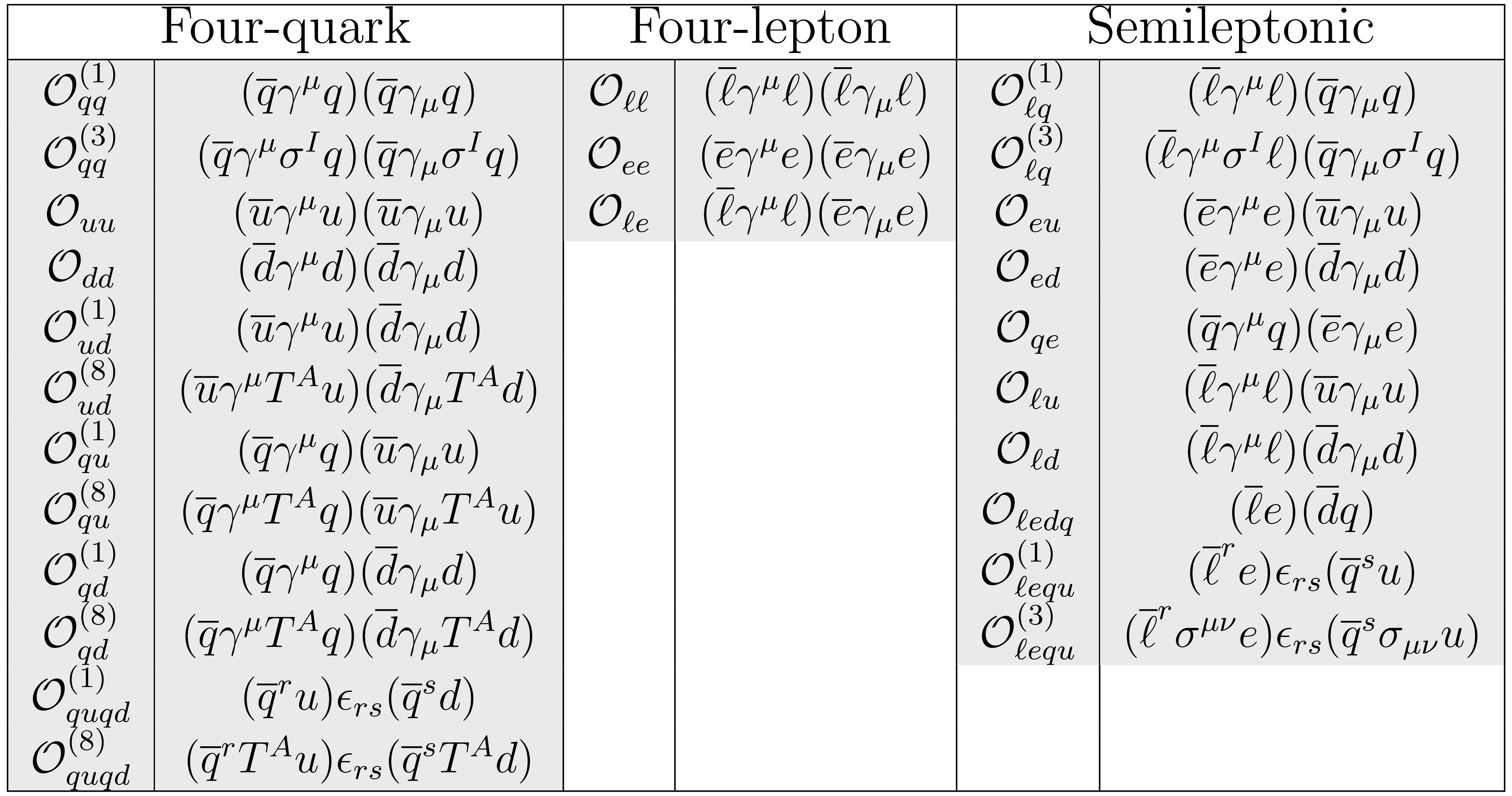
X^2H^2	
$\mathcal{O}_{HG}$	$G^A_{\mu\nu}G^{A\mu\nu}(H^\dagger H)$
$\mathcal{O}_{H\widetilde{G}}$	$\widetilde{G}^A_{\mu\nu}G^{A\mu\nu}(H^\dagger H)$
$\mathcal{O}_{HW}$	$W^I_{\mu\nu}W^{I\mu\nu}(H^\dagger H)$
$\mathcal{O}_{H\widetilde{W}}$	$\widetilde{W}^I_{\mu\nu}W^{I\mu\nu}(H^\dagger H)$
$\mathcal{O}_{HB}$	$B_{\mu\nu}B^{\mu\nu}(H^\dagger H)$
$\mathcal{O}_{H\widetilde{B}}$	$\widetilde{B}_{\mu\nu}B^{\mu\nu}(H^\dagger H)$
$\mathcal{O}_{HWB}$	$W^I_{\mu\nu}B^{\mu\nu}(H^\dagger\sigma^I H)$
$\mathcal{O}_{H\widetilde{W}B}$	$\widetilde{W}^I_{\mu\nu}B^{\mu\nu}(H^\dagger\sigma^I H)$

H^2XD^2	
$\mathcal{O}_{WDH}$	$D_\nu W^{I\mu\nu}(H^\dagger i\overleftrightarrow{D}^I_\mu H)$
$\mathcal{O}_{BDH}$	$\partial_\nu B^{\mu\nu}(H^\dagger i\overleftrightarrow{D}_\mu H)$

H^2D^4	
$\mathcal{O}_{DH}$	$(D_\mu D^\mu H)^\dagger(D_\nu D^\nu H)$

H^4D^2	
$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
$\mathcal{O}_{HD}$	$(H^\dagger D^\mu H)^\dagger(H^\dagger D_\mu H)$
$\mathcal{O}'_{HD}$	$(H^\dagger H)(D_\mu H)^\dagger(D^\mu H)$
$\mathcal{O}''_{HD}$	$(H^\dagger H)D_\mu(H^\dagger i\overleftrightarrow{D}^\mu H)$

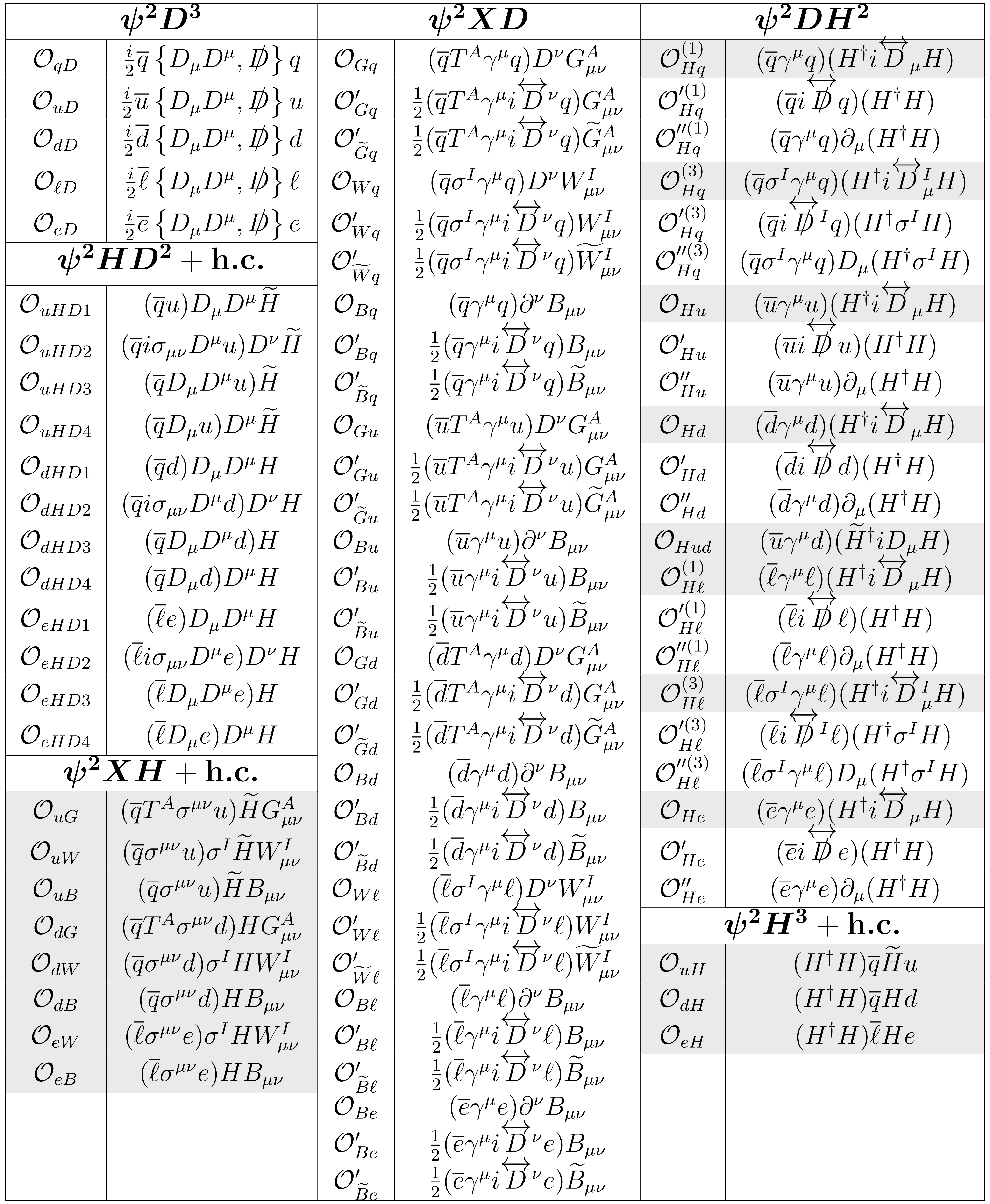
H^6	
$\mathcal{O}_H$	$(H^\dagger H)^3$



Four-quark	
$\mathcal{O}_{qq}^{(1)}$	$(\bar{q}\gamma^\mu q)(\bar{q}\gamma_\mu q)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar{q}\gamma^\mu\sigma^I q)(\bar{q}\gamma_\mu\sigma^I q)$
$\mathcal{O}_{uu}$	$(\bar{u}\gamma^\mu u)(\bar{u}\gamma_\mu u)$
$\mathcal{O}_{dd}$	$(\bar{d}\gamma^\mu d)(\bar{d}\gamma_\mu d)$
$\mathcal{O}_{ud}^{(1)}$	$(\bar{u}\gamma^\mu u)(\bar{d}\gamma_\mu d)$
$\mathcal{O}_{ud}^{(8)}$	$(\bar{u}\gamma^\mu T^A u)(\bar{d}\gamma_\mu T^A d)$
$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}\gamma^\mu q)(\bar{u}\gamma_\mu u)$
$\mathcal{O}_{qu}^{(8)}$	$(\bar{q}\gamma^\mu T^A q)(\bar{u}\gamma_\mu T^A u)$
$\mathcal{O}_{qd}^{(1)}$	$(\bar{q}\gamma^\mu q)(\bar{d}\gamma_\mu d)$
$\mathcal{O}_{qd}^{(8)}$	$(\bar{q}\gamma^\mu T^A q)(\bar{d}\gamma_\mu T^A d)$
$\mathcal{O}_{quqd}^{(1)}$	$(\bar{q}^r u)\epsilon_{rs}(\bar{q}^s d)$
$\mathcal{O}_{quqd}^{(8)}$	$(\bar{q}^r T^A u)\epsilon_{rs}(\bar{q}^s T^A d)$

Four-lepton	
$\mathcal{O}_{\ell\ell}$	$(\bar{\ell}\gamma^\mu\ell)(\bar{\ell}\gamma_\mu\ell)$
$\mathcal{O}_{ee}$	$(\bar{e}\gamma^\mu e)(\bar{e}\gamma_\mu e)$
$\mathcal{O}_{\ell e}$	$(\bar{\ell}\gamma^\mu\ell)(\bar{e}\gamma_\mu e)$

Semileptonic	
$\mathcal{O}_{\ell q}^{(1)}$	$(\bar{\ell}\gamma^\mu\ell)(\bar{q}\gamma_\mu q)$
$\mathcal{O}_{\ell q}^{(3)}$	$(\bar{\ell}\gamma^\mu\sigma^I\ell)(\bar{q}\gamma_\mu\sigma^I q)$
$\mathcal{O}_{eu}$	$(\bar{e}\gamma^\mu e)(\bar{u}\gamma_\mu u)$
$\mathcal{O}_{ed}$	$(\bar{e}\gamma^\mu e)(\bar{d}\gamma_\mu d)$
$\mathcal{O}_{qe}$	$(\bar{q}\gamma^\mu q)(\bar{e}\gamma_\mu e)$
$\mathcal{O}_{\ell u}$	$(\bar{\ell}\gamma^\mu\ell)(\bar{u}\gamma_\mu u)$
$\mathcal{O}_{\ell d}$	$(\bar{\ell}\gamma^\mu\ell)(\bar{d}\gamma_\mu d)$
$\mathcal{O}_{\ell edq}$	$(\bar{\ell}e)(\bar{d}q)$
$\mathcal{O}_{\ell equ}^{(1)}$	$(\bar{\ell}^r e)\epsilon_{rs}(\bar{q}^s u)$
$\mathcal{O}_{\ell equ}^{(3)}$	$(\bar{\ell}^r\sigma^{\mu\nu}e)\epsilon_{rs}(\bar{q}^s\sigma_{\mu\nu}u)$



ψ^2D^3	
$\mathcal{O}_{qD}$	$\frac{i}{2}\bar{q}\left\{D_\mu D^\mu, \not{D}\right\}q$
$\mathcal{O}_{uD}$	$\frac{i}{2}\bar{u}\left\{D_\mu D^\mu, \not{D}\right\}u$
$\mathcal{O}_{dD}$	$\frac{i}{2}\bar{d}\left\{D_\mu D^\mu, \not{D}\right\}d$
$\mathcal{O}_{\ell D}$	$\frac{i}{2}\bar{\ell}\left\{D_\mu D^\mu, \not{D}\right\}\ell$
$\mathcal{O}_{eD}$	$\frac{i}{2}\bar{e}\left\{D_\mu D^\mu, \not{D}\right\}e$

$\psi^2HD^2+\mathrm{h.c.}$	
$\mathcal{O}_{uHD1}$	$(\bar{q}u)D_\mu D^\mu\widetilde{H}$
$\mathcal{O}_{uHD2}$	$(\bar{q}i\sigma_{\mu\nu}D^\mu u)D^\nu\widetilde{H}$
$\mathcal{O}_{uHD3}$	$(\bar{q}D_\mu D^\mu u)\widetilde{H}$
$\mathcal{O}_{uHD4}$	$(\bar{q}D_\mu u)D^\mu\widetilde{H}$
$\mathcal{O}_{dHD1}$	$(\bar{q}d)D_\mu D^\mu H$
$\mathcal{O}_{dHD2}$	$(\bar{q}i\sigma_{\mu\nu}D^\mu d)D^\nu H$
$\mathcal{O}_{dHD3}$	$(\bar{q}D_\mu D^\mu d)H$
$\mathcal{O}_{dHD4}$	$(\bar{q}D_\mu d)D^\mu H$
$\mathcal{O}_{eHD1}$	$(\bar{\ell}e)D_\mu D^\mu H$
$\mathcal{O}_{eHD2}$	$(\bar{\ell}i\sigma_{\mu\nu}D^\mu e)D^\nu H$
$\mathcal{O}_{eHD3}$	$(\bar{\ell}D_\mu D^\mu e)H$
$\mathcal{O}_{eHD4}$	$(\bar{\ell}D_\mu e)D^\mu H$

$\psi^2XH+\mathrm{h.c.}$	
$\mathcal{O}_{uG}$	$(\bar{q}T^A\sigma^{\mu\nu}u)\widetilde{H}G^A_{\mu\nu}$
$\mathcal{O}_{uW}$	$(\bar{q}\sigma^{\mu\nu}u)\sigma^I\widetilde{H}W^I_{\mu\nu}$
$\mathcal{O}_{uB}$	$(\bar{q}\sigma^{\mu\nu}u)\widetilde{H}B_{\mu\nu}$
$\mathcal{O}_{dG}$	$(\bar{q}T^A\sigma^{\mu\nu}d)HG^A_{\mu\nu}$
$\mathcal{O}_{dW}$	$(\bar{q}\sigma^{\mu\nu}d)\sigma^I HW^I_{\mu\nu}$
$\mathcal{O}_{dB}$	$(\bar{q}\sigma^{\mu\nu}d)HB_{\mu\nu}$
$\mathcal{O}_{eW}$	$(\bar{\ell}\sigma^{\mu\nu}e)\sigma^I HW^I_{\mu\nu}$
$\mathcal{O}_{eB}$	$(\bar{\ell}\sigma^{\mu\nu}e)HB_{\mu\nu}$

ψ^2XD	
$\mathcal{O}_{Gq}$	$(\bar{q}T^A\gamma^\mu q)D^\nu G^A_{\mu\nu}$
$\mathcal{O}'_{Gq}$	$\frac{1}{2}(\bar{q}T^A\gamma^\mu i\overleftrightarrow{D}^\nu q)G^A_{\mu\nu}$
$\mathcal{O}'_{\widetilde{G}q}$	$\frac{1}{2}(\bar{q}T^A\gamma^\mu i\overleftrightarrow{D}^\nu q)\widetilde{G}^A_{\mu\nu}$
$\mathcal{O}_{Wq}$	$(\bar{q}\sigma^I\gamma^\mu q)D^\nu W^I_{\mu\nu}$
$\mathcal{O}'_{Wq}$	$\frac{1}{2}(\bar{q}\sigma^I\gamma^\mu i\overleftrightarrow{D}^\nu q)W^I_{\mu\nu}$
$\mathcal{O}'_{\widetilde{W}q}$	$\frac{1}{2}(\bar{q}\sigma^I\gamma^\mu i\overleftrightarrow{D}^\nu q)\widetilde{W}^I_{\mu\nu}$
$\mathcal{O}_{Bq}$	$(\bar{q}\gamma^\mu q)\partial^\nu B_{\mu\nu}$
$\mathcal{O}'_{Bq}$	$\frac{1}{2}(\bar{q}\gamma^\mu i\overleftrightarrow{D}^\nu q)B_{\mu\nu}$
$\mathcal{O}'_{\widetilde{B}q}$	$\frac{1}{2}(\bar{q}\gamma^\mu i\overleftrightarrow{D}^\nu q)\widetilde{B}_{\mu\nu}$
$\mathcal{O}_{Gu}$	$(\bar{u}T^A\gamma^\mu u)D^\nu G^A_{\mu\nu}$
$\mathcal{O}'_{Gu}$	$\frac{1}{2}(\bar{u}T^A\gamma^\mu i\overleftrightarrow{D}^\nu u)G^A_{\mu\nu}$
$\mathcal{O}'_{\widetilde{G}u}$	$\frac{1}{2}(\bar{u}T^A\gamma^\mu i\overleftrightarrow{D}^\nu u)\widetilde{G}^A_{\mu\nu}$
$\mathcal{O}_{Bu}$	$(\bar{u}\gamma^\mu u)\partial^\nu B_{\mu\nu}$
$\mathcal{O}'_{Bu}$	$\frac{1}{2}(\bar{u}\gamma^\mu i\overleftrightarrow{D}^\nu u)B_{\mu\nu}$
$\mathcal{O}'_{\widetilde{B}u}$	$\frac{1}{2}(\bar{u}\gamma^\mu i\overleftrightarrow{D}^\nu u)\widetilde{B}_{\mu\nu}$
$\mathcal{O}_{Gd}$	$(\bar{d}T^A\gamma^\mu d)D^\nu G^A_{\mu\nu}$
$\mathcal{O}'_{Gd}$	$\frac{1}{2}(\bar{d}T^A\gamma^\mu i\overleftrightarrow{D}^\nu d)G^A_{\mu\nu}$
$\mathcal{O}'_{\widetilde{G}d}$	$\frac{1}{2}(\bar{d}T^A\gamma^\mu i\overleftrightarrow{D}^\nu d)\widetilde{G}^A_{\mu\nu}$
$\mathcal{O}_{Bd}$	$(\bar{d}\gamma^\mu d)\partial^\nu B_{\mu\nu}$
$\mathcal{O}'_{Bd}$	$\frac{1}{2}(\bar{d}\gamma^\mu i\overleftrightarrow{D}^\nu d)B_{\mu\nu}$
$\mathcal{O}'_{\widetilde{B}d}$	$\frac{1}{2}(\bar{d}\gamma^\mu i\overleftrightarrow{D}^\nu d)\widetilde{B}_{\mu\nu}$
$\mathcal{O}_{W\ell}$	$(\bar{\ell}\sigma^I\gamma^\mu\ell)D^\nu W^I_{\mu\nu}$
$\mathcal{O}'_{W\ell}$	$\frac{1}{2}(\bar{\ell}\sigma^I\gamma^\mu i\overleftrightarrow{D}^\nu\ell)W^I_{\mu\nu}$
$\mathcal{O}'_{\widetilde{W}\ell}$	$\frac{1}{2}(\bar{\ell}\sigma^I\gamma^\mu i\overleftrightarrow{D}^\nu\ell)\widetilde{W}^I_{\mu\nu}$
$\mathcal{O}_{B\ell}$	$(\bar{\ell}\gamma^\mu\ell)\partial^\nu B_{\mu\nu}$
$\mathcal{O}'_{B\ell}$	$\frac{1}{2}(\bar{\ell}\gamma^\mu i\overleftrightarrow{D}^\nu\ell)B_{\mu\nu}$
$\mathcal{O}'_{\widetilde{B}\ell}$	$\frac{1}{2}(\bar{\ell}\gamma^\mu i\overleftrightarrow{D}^\nu\ell)\widetilde{B}_{\mu\nu}$
$\mathcal{O}_{Be}$	$(\bar{e}\gamma^\mu e)\partial^\nu B_{\mu\nu}$
$\mathcal{O}'_{Be}$	$\frac{1}{2}(\bar{e}\gamma^\mu i\overleftrightarrow{D}^\nu e)B_{\mu\nu}$
$\mathcal{O}'_{\widetilde{B}e}$	$\frac{1}{2}(\bar{e}\gamma^\mu i\overleftrightarrow{D}^\nu e)\widetilde{B}_{\mu\nu}$

ψ^2DH^2	
$\mathcal{O}_{Hq}^{(1)}$	$(\bar{q}\gamma^\mu q)(H^\dagger i\overleftrightarrow{D}_\mu H)$
$\mathcal{O}'^{(1)}_{Hq}$	$(\bar{q}i\overleftrightarrow{\not{D}}q)(H^\dagger H)$
$\mathcal{O}''^{(1)}_{Hq}$	$(\bar{q}\gamma^\mu q)\partial_\mu(H^\dagger H)$
$\mathcal{O}_{Hq}^{(3)}$	$(\bar{q}\sigma^I\gamma^\mu q)(H^\dagger i\overleftrightarrow{D}^I_\mu H)$
$\mathcal{O}'^{(3)}_{Hq}$	$(\bar{q}i\overleftrightarrow{\not{D}}^I q)(H^\dagger\sigma^I H)$
$\mathcal{O}''^{(3)}_{Hq}$	$(\bar{q}\sigma^I\gamma^\mu q)D_\mu(H^\dagger\sigma^I H)$
$\mathcal{O}_{Hu}$	$(\bar{u}\gamma^\mu u)(H^\dagger i\overleftrightarrow{D}_\mu H)$
$\mathcal{O}'_{Hu}$	$(\bar{u}i\overleftrightarrow{\not{D}}u)(H^\dagger H)$
$\mathcal{O}''_{Hu}$	$(\bar{u}\gamma^\mu u)\partial_\mu(H^\dagger H)$
$\mathcal{O}_{Hd}$	$(\bar{d}\gamma^\mu d)(H^\dagger i\overleftrightarrow{D}_\mu H)$
$\mathcal{O}'_{Hd}$	$(\bar{d}i\overleftrightarrow{\not{D}}d)(H^\dagger H)$
$\mathcal{O}''_{Hd}$	$(\bar{d}\gamma^\mu d)\partial_\mu(H^\dagger H)$
$\mathcal{O}_{Hud}$	$(\bar{u}\gamma^\mu d)(\widetilde{H}^\dagger iD_\mu H)$
$\mathcal{O}_{H\ell}^{(1)}$	$(\bar{\ell}\gamma^\mu\ell)(H^\dagger i\overleftrightarrow{D}_\mu H)$
$\mathcal{O}'^{(1)}_{H\ell}$	$(\bar{\ell}i\overleftrightarrow{\not{D}}\ell)(H^\dagger H)$
$\mathcal{O}''^{(1)}_{H\ell}$	$(\bar{\ell}\gamma^\mu\ell)\partial_\mu(H^\dagger H)$
$\mathcal{O}_{H\ell}^{(3)}$	$(\bar{\ell}\sigma^I\gamma^\mu\ell)(H^\dagger i\overleftrightarrow{D}^I_\mu H)$
$\mathcal{O}'^{(3)}_{H\ell}$	$(\bar{\ell}i\overleftrightarrow{\not{D}}^I\ell)(H^\dagger\sigma^I H)$
$\mathcal{O}''^{(3)}_{H\ell}$	$(\bar{\ell}\sigma^I\gamma^\mu\ell)D_\mu(H^\dagger\sigma^I H)$
$\mathcal{O}_{He}$	$(\bar{e}\gamma^\mu e)(H^\dagger i\overleftrightarrow{D}_\mu H)$
$\mathcal{O}'_{He}$	$(\bar{e}i\overleftrightarrow{\not{D}}e)(H^\dagger H)$
$\mathcal{O}''_{He}$	$(\bar{e}\gamma^\mu e)\partial_\mu(H^\dagger H)$

$\psi^2H^3+\mathrm{h.c.}$	
$\mathcal{O}_{uH}$	$(H^\dagger H)\bar{q}\widetilde{H}u$
$\mathcal{O}_{dH}$	$(H^\dagger H)\bar{q}Hd$
$\mathcal{O}_{eH}$	$(H^\dagger H)\bar{\ell}He$

S_1+S_3 leptoquarks - global analysis

We study several scenarios, depending on the “active” couplings.

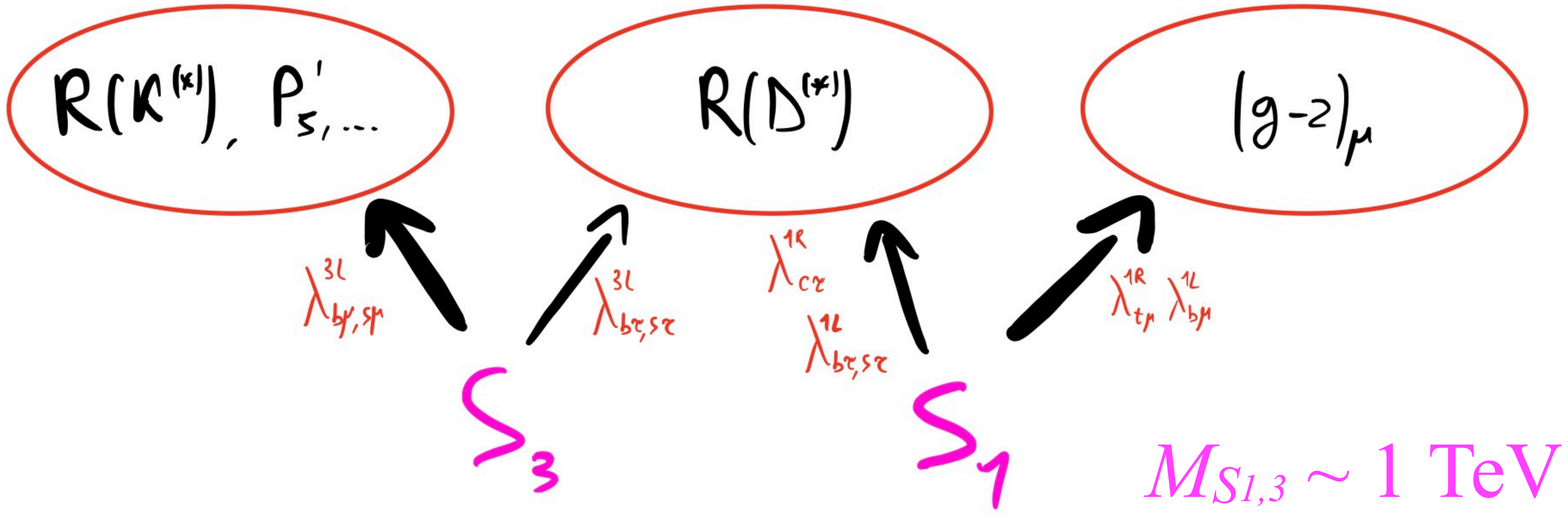
Model	Couplings	CC	NC	$(g-2)_\mu$
${S_1}^{(CC)}$	$\lambda^{1R}_{c\tau}, \lambda^{1L}_{b\tau}$	✓	✗	✗
${S_1}^{(NC)}$	$\lambda^{1L}_{b\mu}, \lambda^{1L}_{s\mu}$	✗	⊗	✗
${S_1}^{(a_\mu)}$	$\lambda^{1R}_{t\mu}, \lambda^{1L}_{b\mu}$	✗	✗	✓
${S_1}^{(CC+a_\mu)}$	$\lambda^{1R}_{t\tau}, \lambda^{1R}_{c\tau}, \lambda^{1R}_{t\mu}, \lambda^{1L}_{b\tau}, \lambda^{1L}_{b\mu}$	✓	✗	✓
${S_3}^{(CC+NC)}$	$\lambda^{3L}_{b\tau}, \lambda^{3L}_{s\tau}, \lambda^{3L}_{b\mu}, \lambda^{3L}_{s\mu}$	✗	✓	✗
$S_1+{S_3}^{(\mathrm{LH})}$	$\lambda^{1L}_{b\tau}, \lambda^{1L}_{s\tau}, \lambda^{3L}_{b\tau}, \lambda^{3L}_{s\tau}, \lambda^{3L}_{b\mu}, \lambda^{3L}_{s\mu}$	✓	✓	✗
$S_1+{S_3}^{(\mathrm{all})}$	$\lambda^{1L}_{b\tau}, \lambda^{1L}_{s\tau}, \lambda^{1L}_{b\mu}, \lambda^{1R}_{t\tau}, \lambda^{1R}_{c\tau}, \lambda^{1R}_{t\mu}, \lambda^{3L}_{b\tau}, \lambda^{3L}_{s\tau}, \lambda^{3L}_{b\mu}, \lambda^{3L}_{s\mu}$	✓	✓	✓
$S_1+{S_3}^{(\mathrm{pot})}$	$\lambda_{H1}, \lambda_{H3}, \lambda_{H13}, \lambda_{\epsilon H3}$	–	–	–

Scalar Leptoquarks S_1 and S_3:

$$\mathcal{L}_{int} \sim \left(\lambda^{1L}_{ij}\, q^i_L\, \varepsilon\, l^j_L + \lambda^{1R}_{ij}\, u^i_R\, e^j_R\right) S_1 + \lambda^{3L}_{ij}\, q^i_L\, \varepsilon\, \sigma^A\, l^j_L\, S^A_3 + h.c.$$

The combination of the two scalars can address both anomalies.

If the S_1 coupling to RH fermions is allowed,
also a solution to $(g\text{-}2)_\mu$ is possible.



$M_{S1,3} \sim 1$ TeV

Couplings to 1st generation have been fixed to zero!

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${S_1}^{(a_\mu)}$	$\lambda^{1R}_{t\mu}, \lambda^{1L}_{b\mu}$	✗	✗	✓
${S_1}^{(CC+a_\mu)}$	$\lambda^{1R}_{t\tau}, \lambda^{1R}_{c\tau}, \lambda^{1R}_{t\mu}, \lambda^{1L}_{b\tau}, \lambda^{1L}_{b\mu}$	✓	✗	✓
${S_3}^{(CC+NC)}$	$\lambda^{3L}_{b\tau}, \lambda^{3L}_{s\tau}, \lambda^{3L}_{b\mu}, \lambda^{3L}_{s\mu}$	✗	✓	✗
$S_1 + {S_3}^{(\mathrm{LH})}$	$\lambda^{1L}_{b\tau}, \lambda^{1L}_{s\tau}, \lambda^{3L}_{b\tau}, \lambda^{3L}_{s\tau}, \lambda^{3L}_{b\mu}, \lambda^{3L}_{s\mu}$	✓	✓	✗
$S_1 + {S_3}^{(\mathrm{all})}$	$\lambda^{1L}_{b\tau}, \lambda^{1L}_{s\tau}, \lambda^{1L}_{b\mu}, \lambda^{1R}_{t\tau}, \lambda^{1R}_{c\tau}, \lambda^{1R}_{t\mu}, \lambda^{3L}_{b\tau}, \lambda^{3L}_{s\tau}, \lambda^{3L}_{b\mu}, \lambda^{3L}_{s\mu}$	✓	✓	✓
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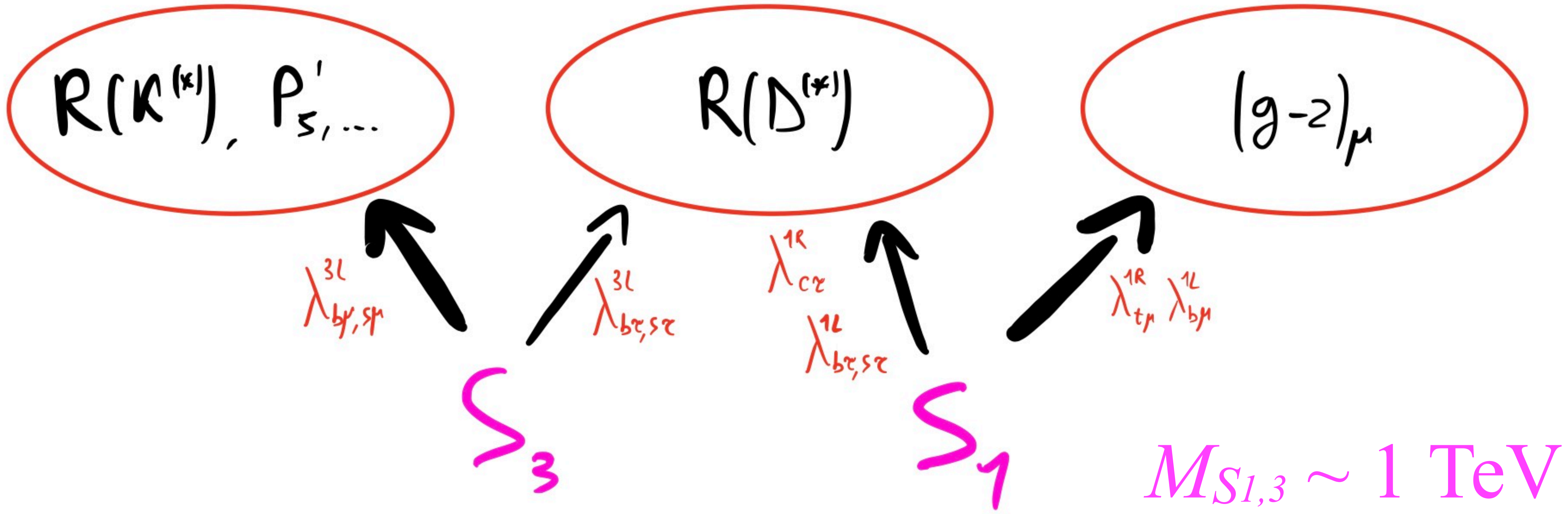

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${S_1}^{(a_\mu)}$	$\lambda^{1R}_{t\mu}, \lambda^{1L}_{b\mu}$	✗	✗	✓
${S_1}^{(CC+a_\mu)}$	$\lambda^{1R}_{t\tau}, \lambda^{1R}_{c\tau}, \lambda^{1R}_{t\mu}, \lambda^{1L}_{b\tau}, \lambda^{1L}_{b\mu}$	✓	✗	✓
${S_3}^{(CC+NC)}$	$\lambda^{3L}_{b\tau}, \lambda^{3L}_{s\tau}, \lambda^{3L}_{b\mu}, \lambda^{3L}_{s\mu}$	✗	✓	✗
$S_1 + {S_3}^{(\mathrm{LH})}$	$\lambda^{1L}_{b\tau}, \lambda^{1L}_{s\tau}, \lambda^{3L}_{b\tau}, \lambda^{3L}_{s\tau}, \lambda^{3L}_{b\mu}, \lambda^{3L}_{s\mu}$ $\lambda^{1R}=0$	✓	✓	✗
$S_1 + {S_3}^{(\mathrm{all})}$	$\lambda^{1L}_{b\tau}, \lambda^{1L}_{s\tau}, \lambda^{1L}_{b\mu}, \lambda^{1R}_{t\tau}, \lambda^{1R}_{c\tau}, \lambda^{1R}_{t\mu}, \lambda^{3L}_{b\tau}, \lambda^{3L}_{s\tau}, \lambda^{3L}_{b\mu}, \lambda^{3L}_{s\mu}$	✓	✓	✓
$S_1 + {S_3}^{(\mathrm{pot})}$	$\lambda_{H1}, \lambda_{H3}, \lambda_{H13}, \lambda_{\epsilon H3}$	–	–	–

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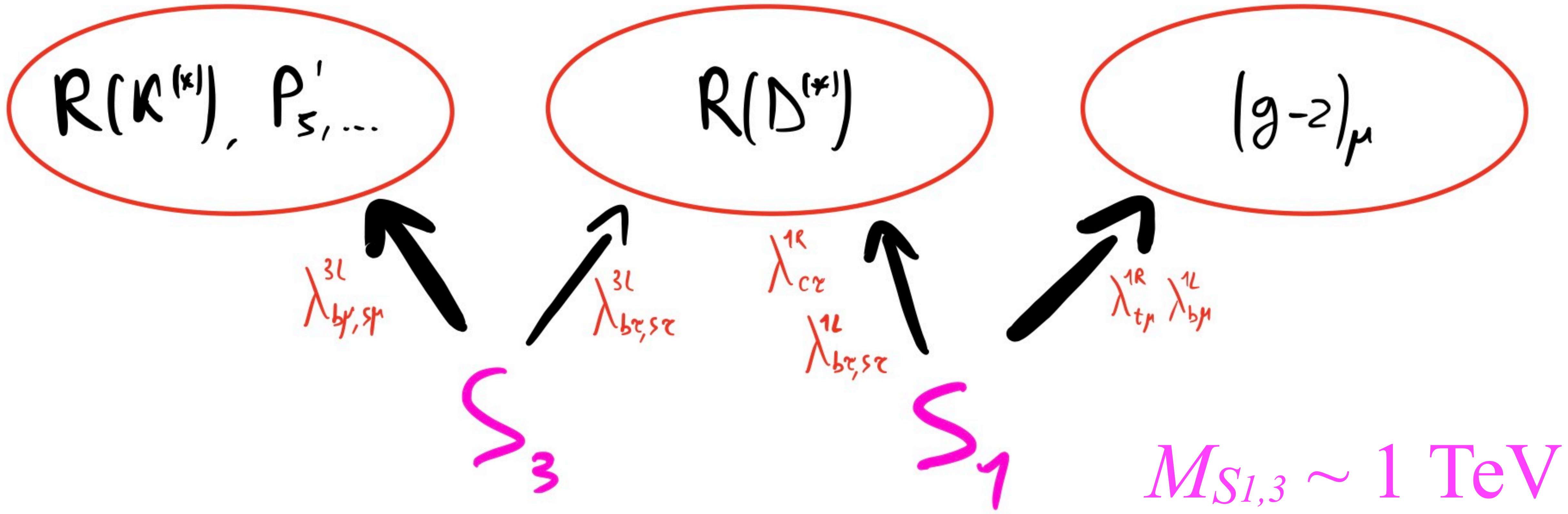


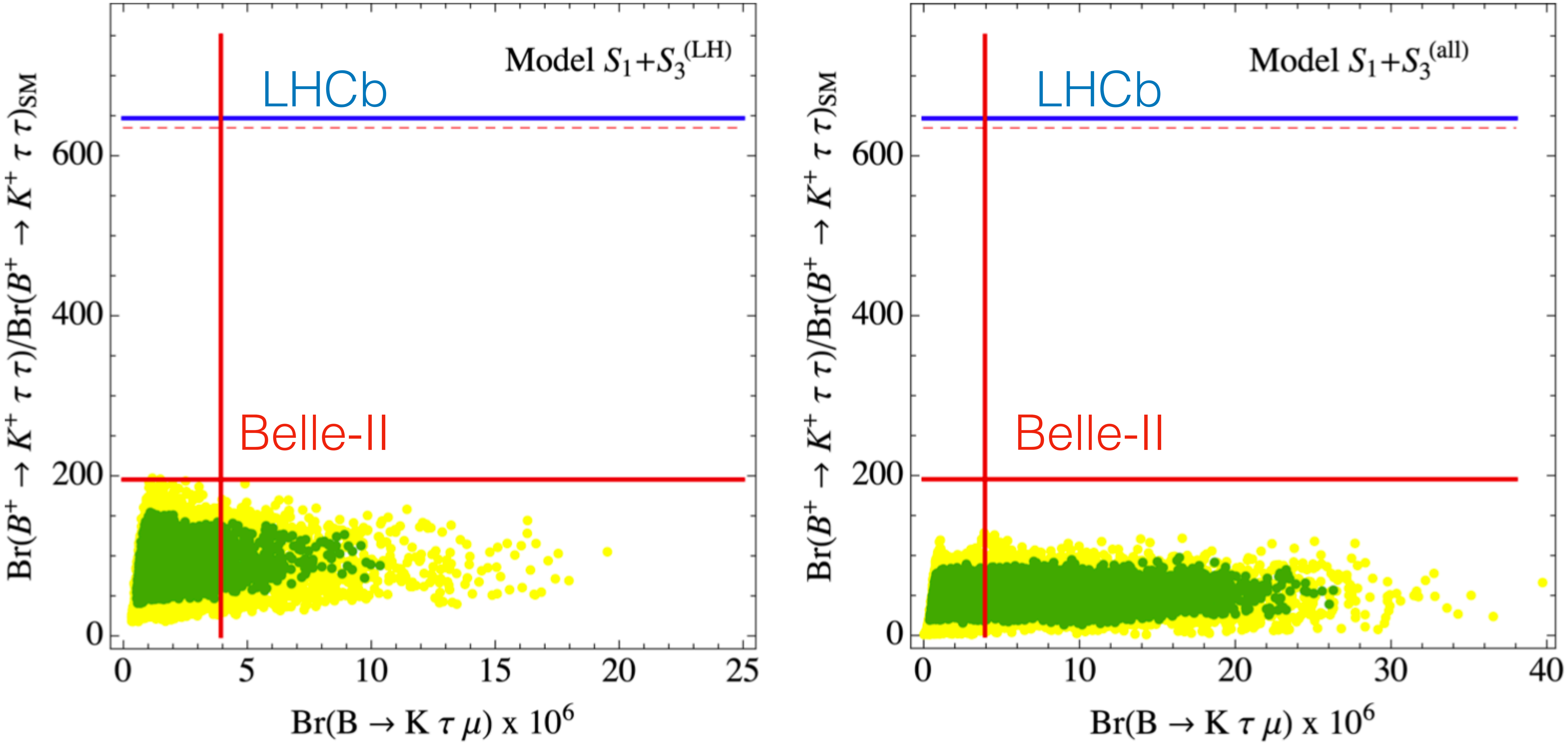
$M_{S1,3} \sim 1$ TeV

Couplings to 1st generation have been fixed to zero!

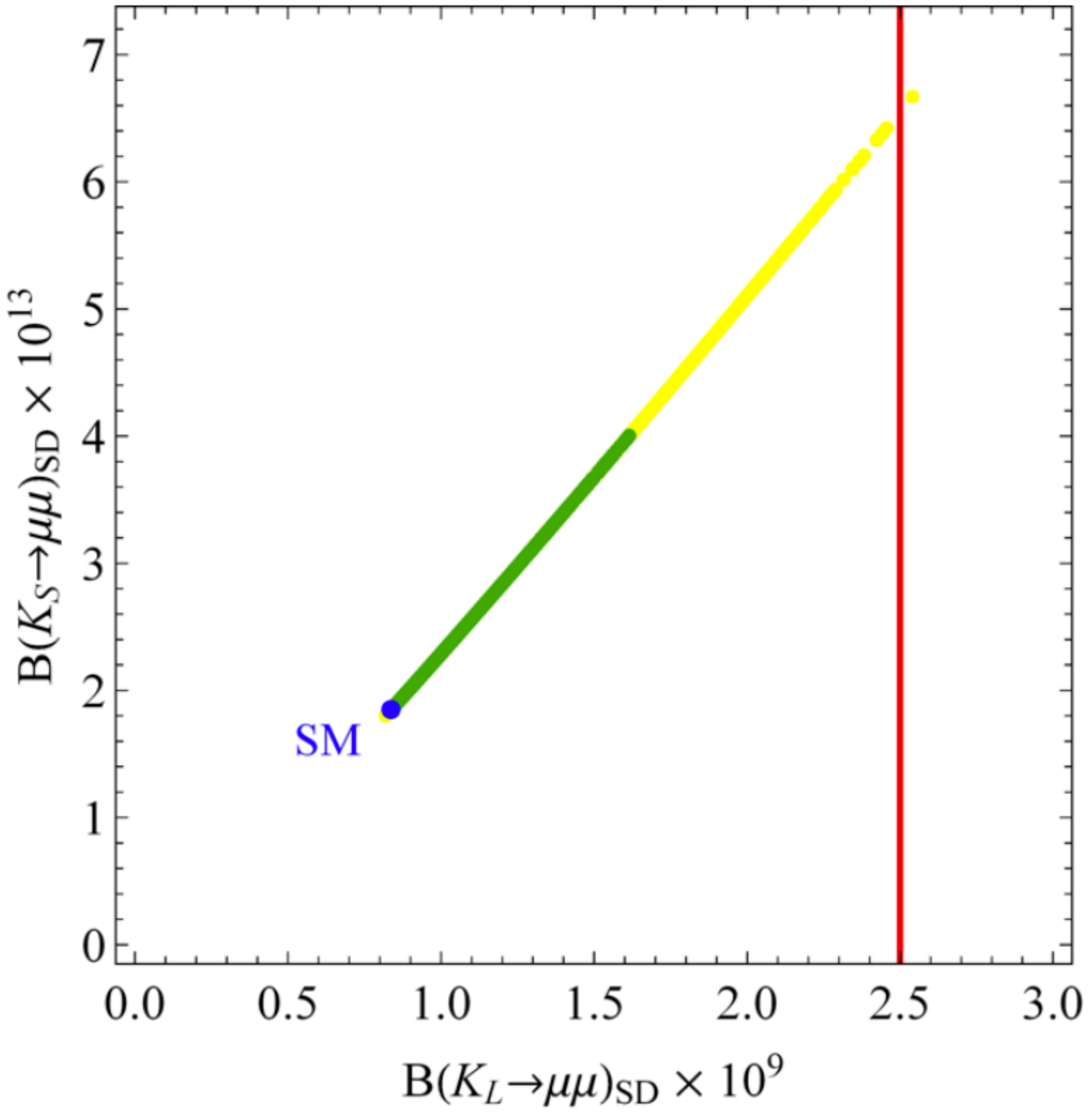
Predictions

The large couplings to τ imply signatures in **DY tails of pp→ τ τ**, deviations in **τ LFU** tests and **τ → μ LFV** tests (Belle-II).

Large effects are also expected in **b → s τ τ** and **b → s τ μ** transitions:



Leading effects in Kaon physics



Also in this case the phase of NP contribution is fixed to be SM-like

$$\Delta C_9^{sd\mu\mu} = -\Delta C_{10}^{sd\mu\mu} \approx \frac{\pi V_{ts}^* V_{td}}{\sqrt{2} G_F \alpha} \frac{|\lambda^3|^2 |V_\ell|^2 |x_{q\ell}^3|^2}{M_3^2}$$

So the two channels are fully correlated.

- In K_L the model saturates the present bound
- in K_S the effect is ~ 10-13, below the SM long-distance contribution.

About other Kaon decays:

We also obtain Br(K_L→μe) ~ 10^{-15} and Br(K^+→π^+μe) ~ 10^{-18}.