Simplified models for combined explanations

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LFUV

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}_{\ell\in(e,\mu)} \qquad \& \qquad R_{D^{(*)}}^{\text{exp}} > R_{D^{(*)}}^{\text{SM}}$$

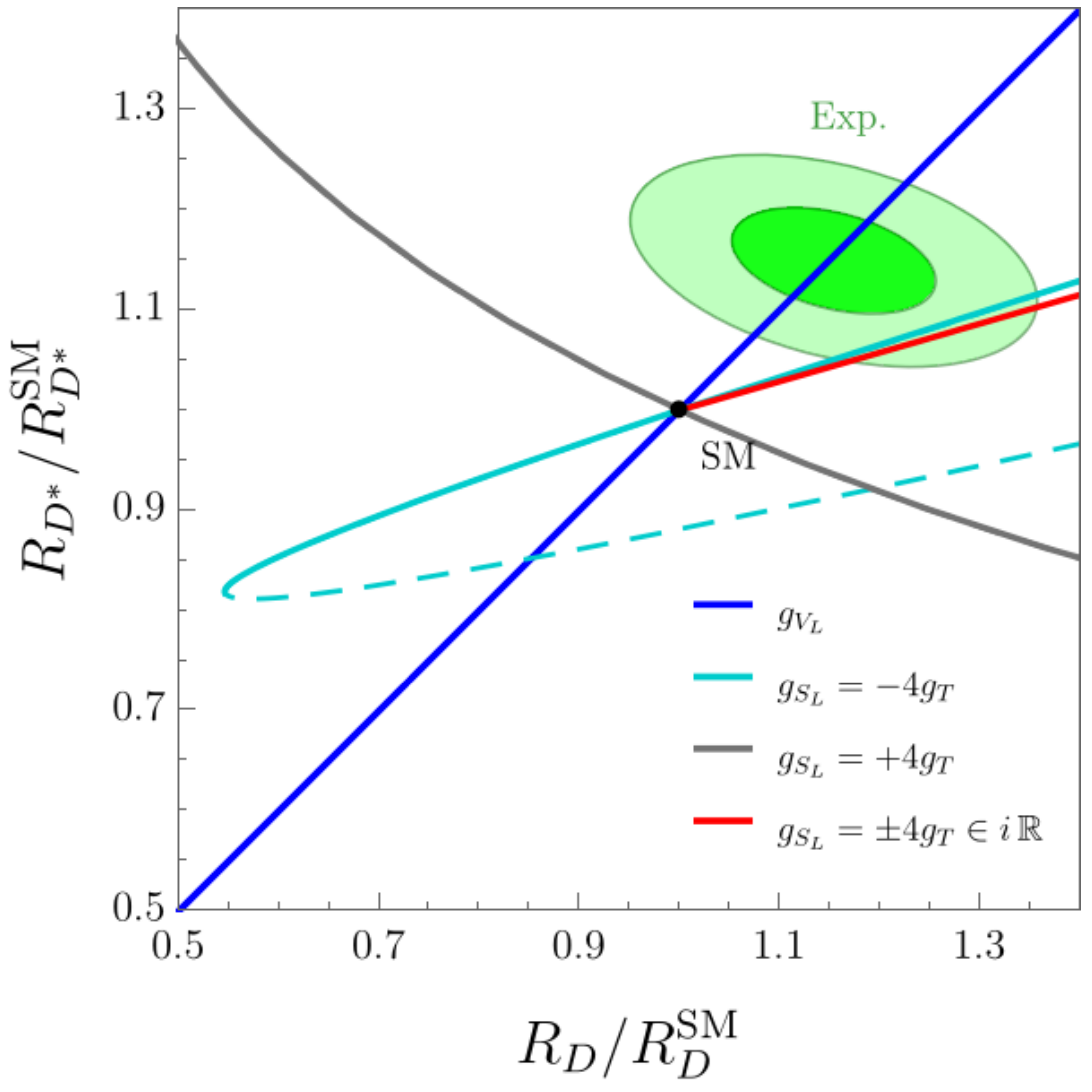
$$R_{K^{(*)}} = \left.\frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}\right|_{q^2\in[q^2_{\min},q^2_{\max}]} \qquad \& \qquad R_{K^{(*)}}^{\text{exp}} < R_{K^{(*)}}^{\text{SM}}$$

$$R_{D^{(*)}}^{\text{exp}} > R_{D^{(*)}}^{\text{SM}} \quad \Rightarrow \quad \Lambda_{\text{NP}} \lesssim 3\ \text{TeV}$$

$$R_{K^{(*)}}^{\text{exp}} < R_{K^{(*)}}^{\text{SM}} \quad \Rightarrow \quad \Lambda_{\text{NP}} \lesssim 30\ \text{TeV}$$

EFT - exclusive $b \to c\ell\nu$

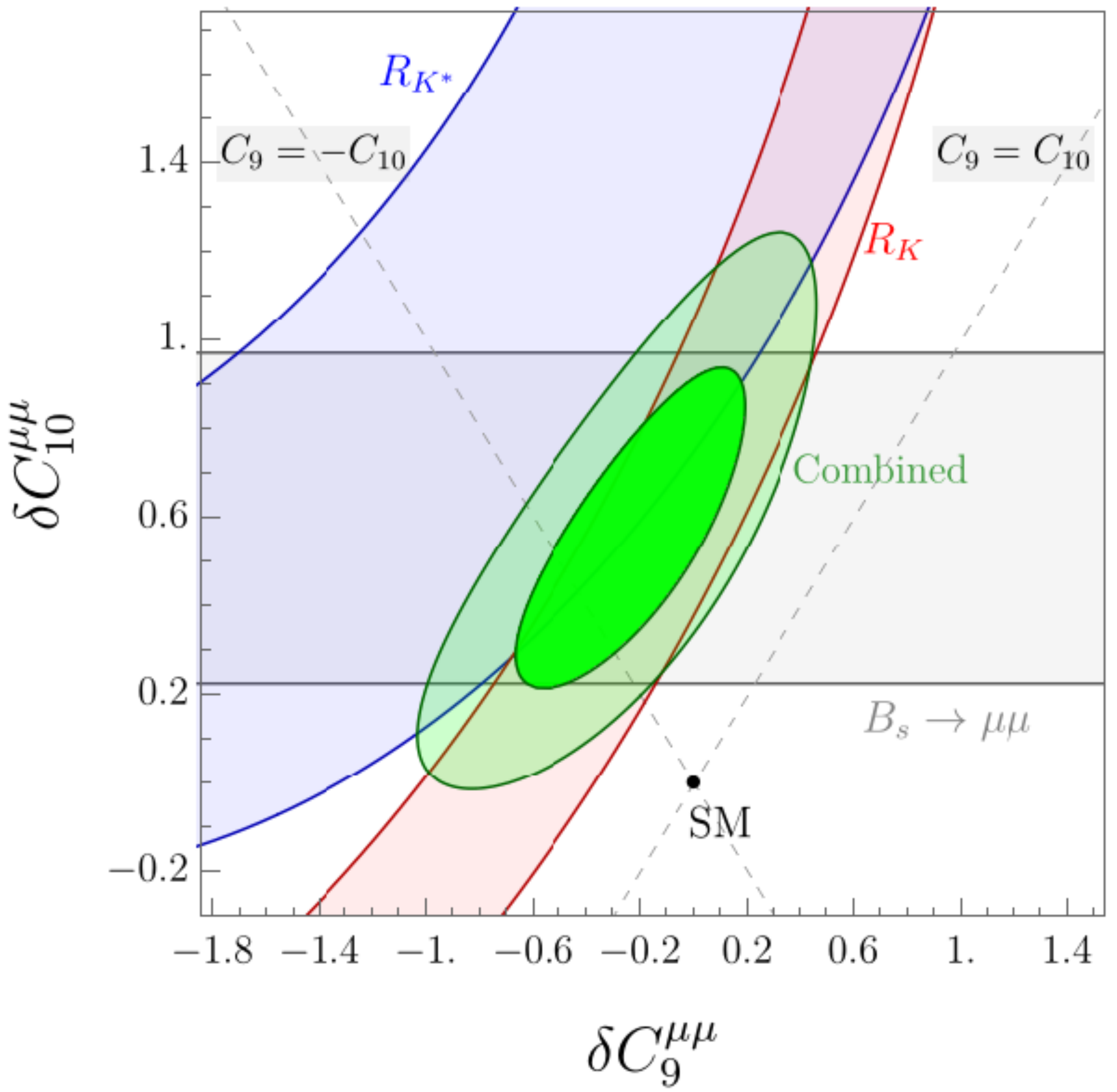
$$\mathcal{L}_{\rm eff} = -2\sqrt{2}G_F V_{cb}\Big[(1+g_{V_L})(\bar{c}_L\gamma_\mu b_L)(\bar{\ell}_L\gamma^\mu\nu_L) + g_{V_R}(\bar{c}_R\gamma_\mu b_R)(\bar{\ell}_L\gamma^\mu\nu_L)$$
$$+ g_{S_R}(\bar{c}_L b_R)(\bar{\ell}_R\nu_L) + g_{S_L}(\bar{c}_R b_L)(\bar{\ell}_R\nu_L) + g_T(\bar{c}_R\sigma_{\mu\nu}b_L)(\bar{\ell}_R\sigma^{\mu\nu}\nu_L)\Big] + \text{h.c.}$$



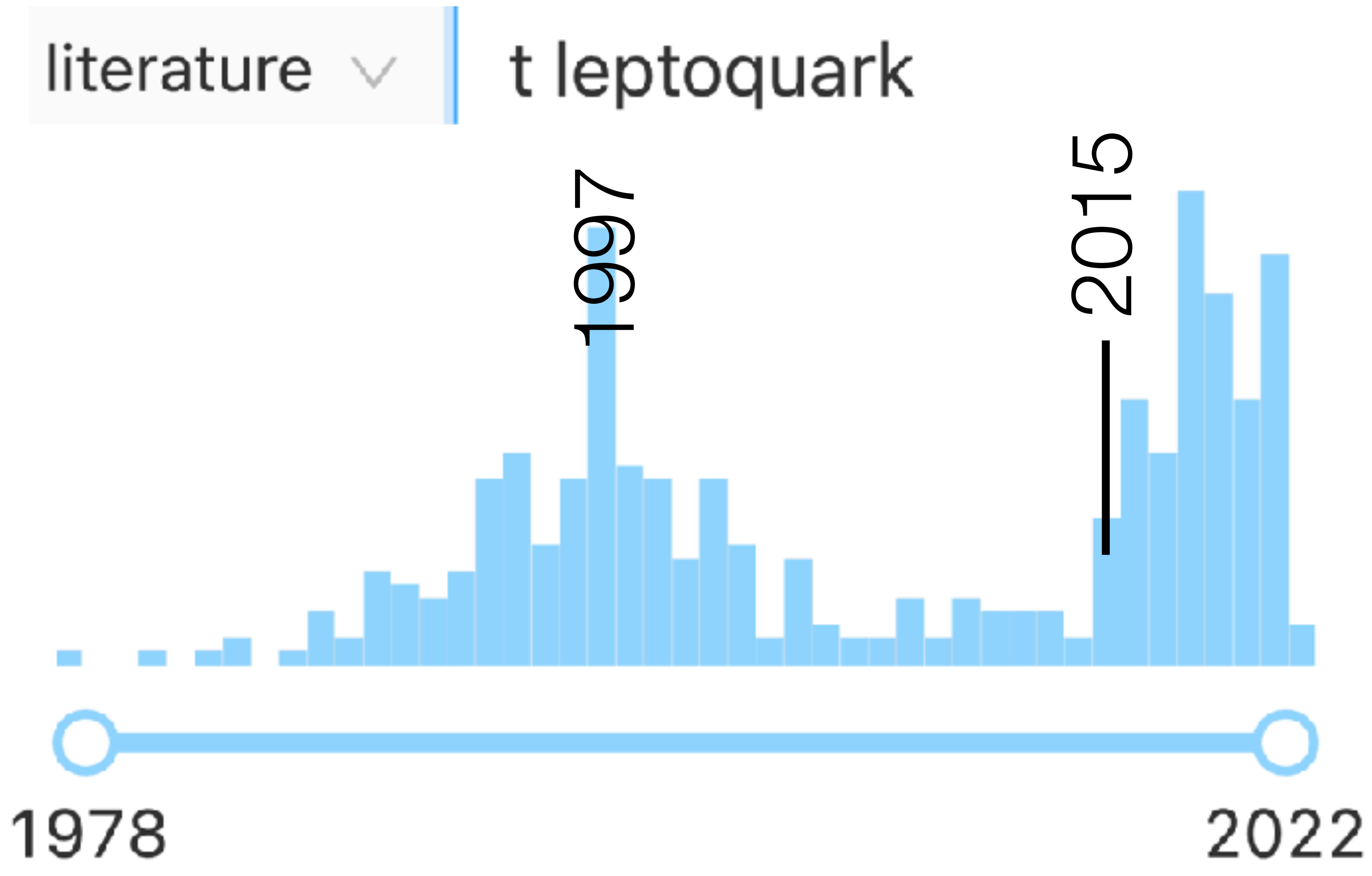
EFT - exclusive $b \to s\ell\ell$

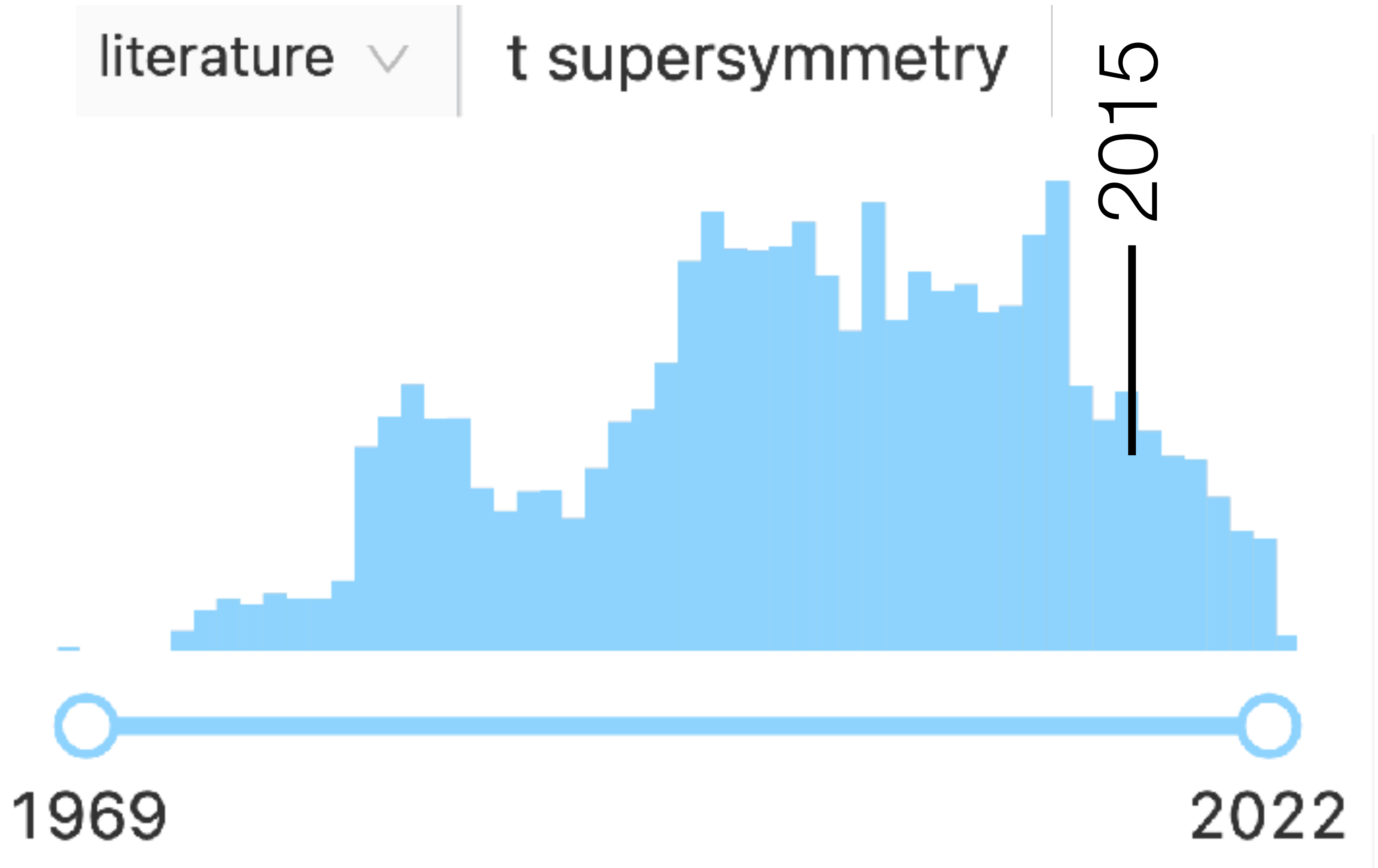
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^*\left[\sum_{i=1}^{6} C_i(\mu)\mathcal{O}_i(\mu) + \sum_{i=7,8,9,10,P,S,\ldots}\Big(C_i(\mu)\mathcal{O}_i + C_i'(\mu)\mathcal{O}_i'\Big)\right] + \text{h.c.}$$

$$\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\ell) \qquad \mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\gamma^5\ell)$$
$$\mathcal{O}_S^{(\prime)} = (\bar{s}P_{R(L)}b)(\bar{\ell}\ell) \qquad \mathcal{O}_P^{(\prime)} = (\bar{s}P_{R(L)}b)(\bar{\ell}\gamma_5\ell)$$
$$\mathcal{O}_7^{(\prime)} = m_b(\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu}$$



Leptoquark is the new SUSY



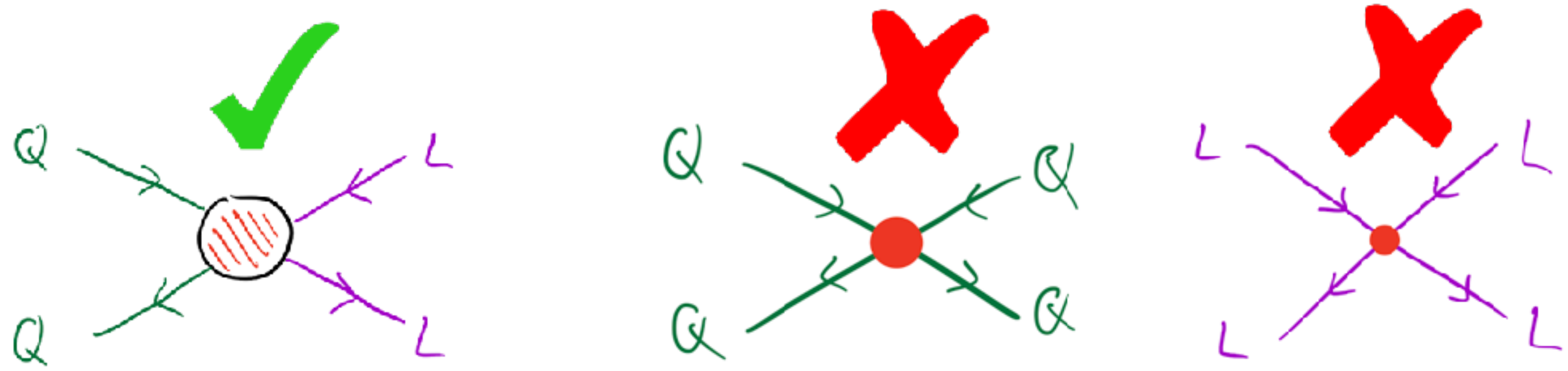


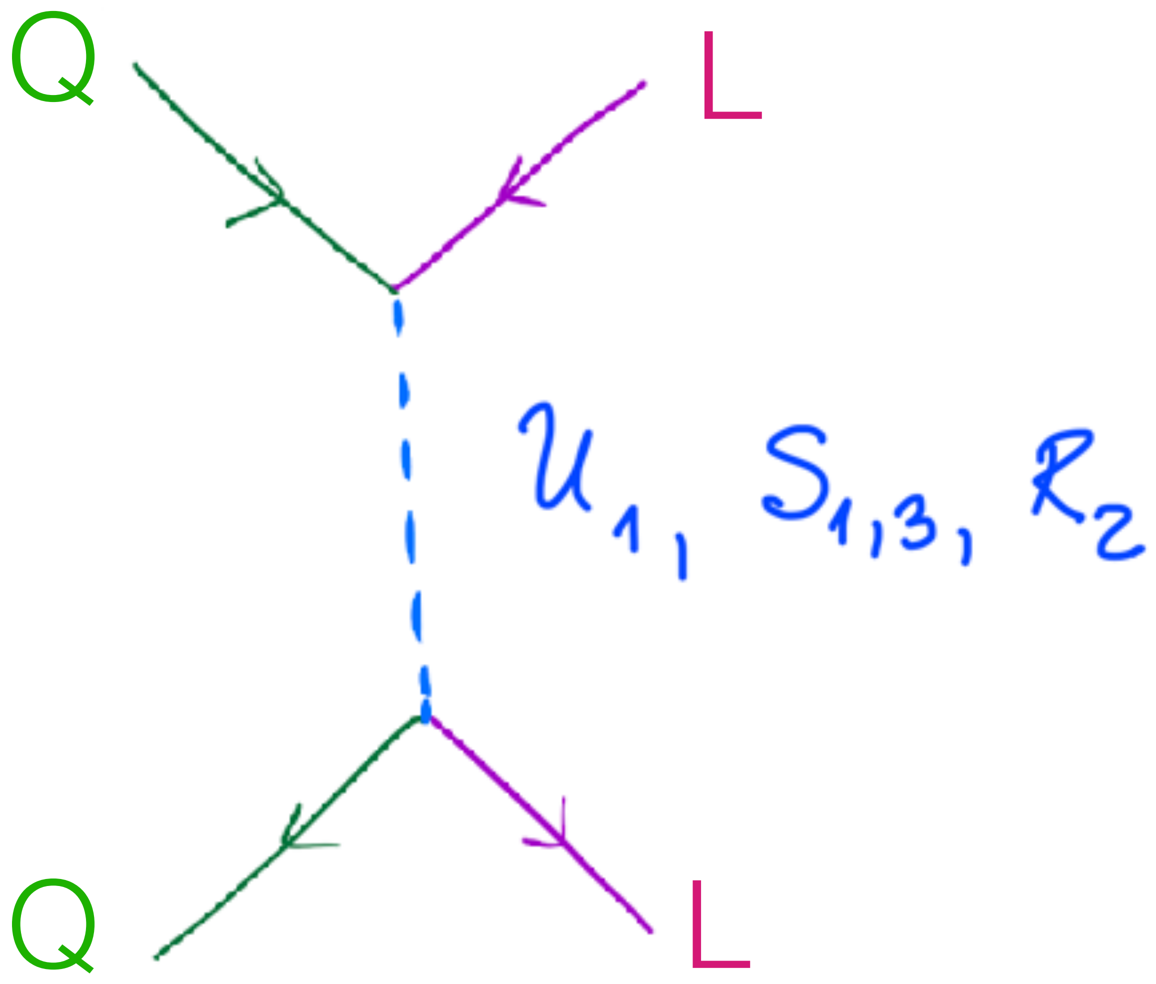
A clear trend…

Why?

Leptoquark Renaissance

Deviations observed in **semileptonic** processes,
strong bounds from ΔF=2 & CLFV processes.





LQ induce semileptonic @ tree level,
4-quark & 4-fermion only at loop level.

Observables

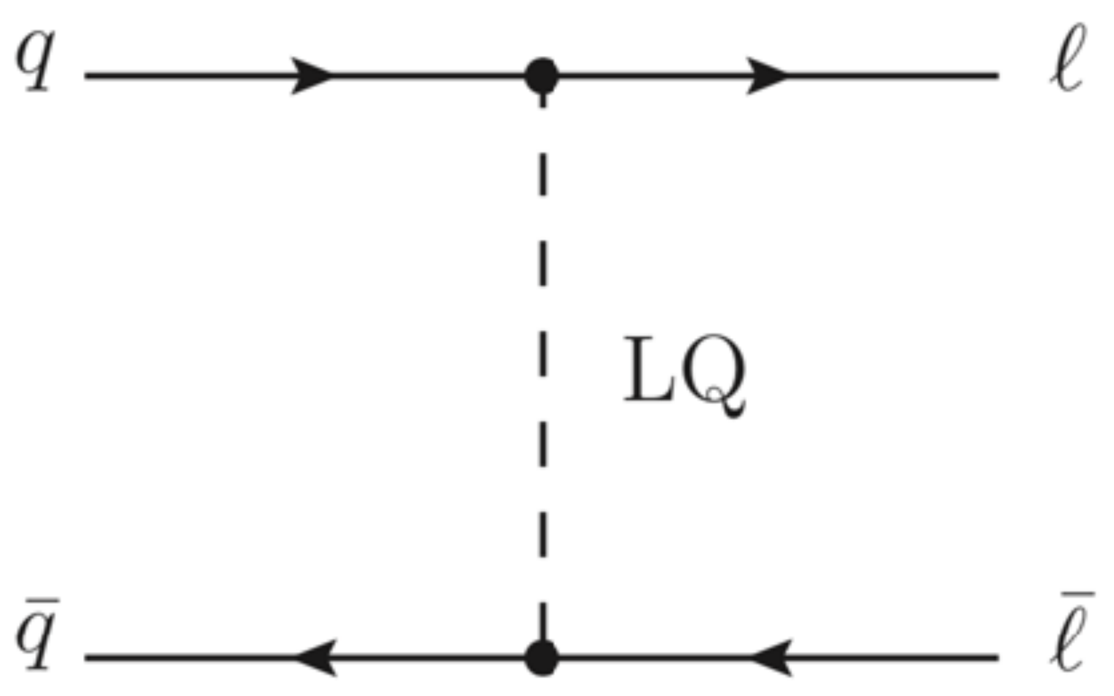
$R_{D^{(*)}}$
$R_{K^{(*)}}$
$B \to K\nu\nu$
$\Delta m_{B_{(s)}}$
$Z \to \mu\mu$
$Z \to \tau\tau$
$Z \to \nu\nu$
$R^{\mu e}{}_D$
$\tau \to \mu\gamma$
$\tau \to \mu\phi$
R_K e/μ
$D_s \to \mu\nu$
$D_s \to \tau\nu$
$B^+ \to \tau\nu$
$\tau \to K\nu / K \to \mu\nu$
$B \to K\mu\tau$

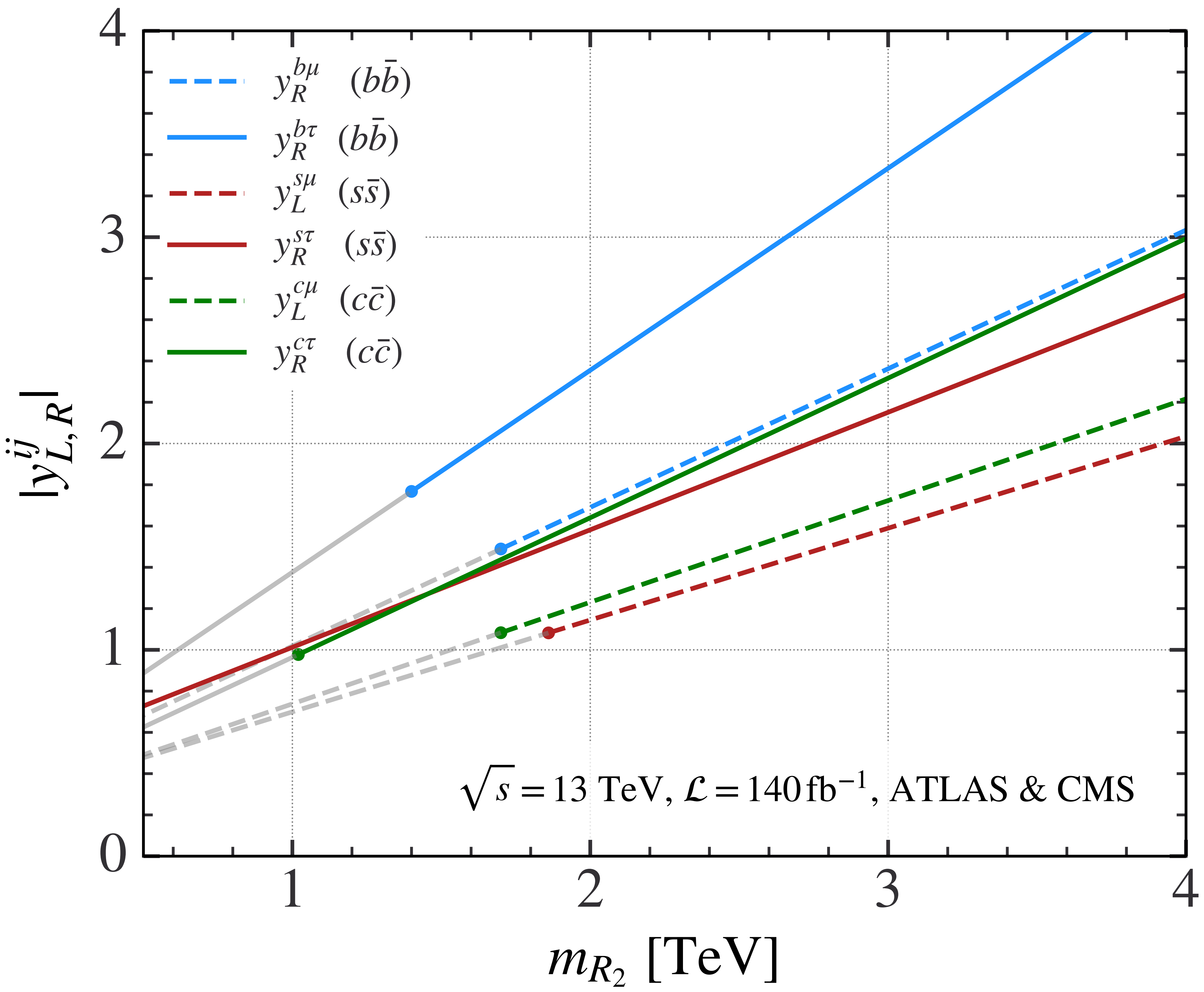
Model	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$ & $R_{K^{(*)}}$
$S_1 = (\bar{3}, 1, 1/3)$	✓	✗	✗
$R_2 = (3, 2, 7/6)$	✓	✓*	✗
$S_3 = (\bar{3}, 3, 1/3)$	✗	✓	✗
$U_1 = (3, 1, 2/3)$	✓	✓	✓
$U_3 = (3, 3, 2/3)$	✗	✓	✗

2103.12504

Model	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$ & $R_{K^{(*)}}$
$S_1 = (\bar{3}, 1, 1/3)$	✓	✗	✗
$R_2 = (3, 2, 7/6)$	✓	✓*	✗
$S_3 = (\bar{3}, 3, 1/3)$	✗	✓	✗
$U_1 = (3, 1, 2/3)$	✓	✓	✓
$U_3 = (3, 3, 2/3)$	✗	✓	✗

From dilepton spectra at high p_T Atlas and CMS 2018-2021





Example R_2

$$\mathcal{L}_{R_2} = y_R^{ij}\,\overline{Q}_i \ell_{Rj}\, R_2 - y_L^{ij}\,\overline{u}_{Ri} R_2 i\tau_2 L_j + \mathrm{h.c.}$$

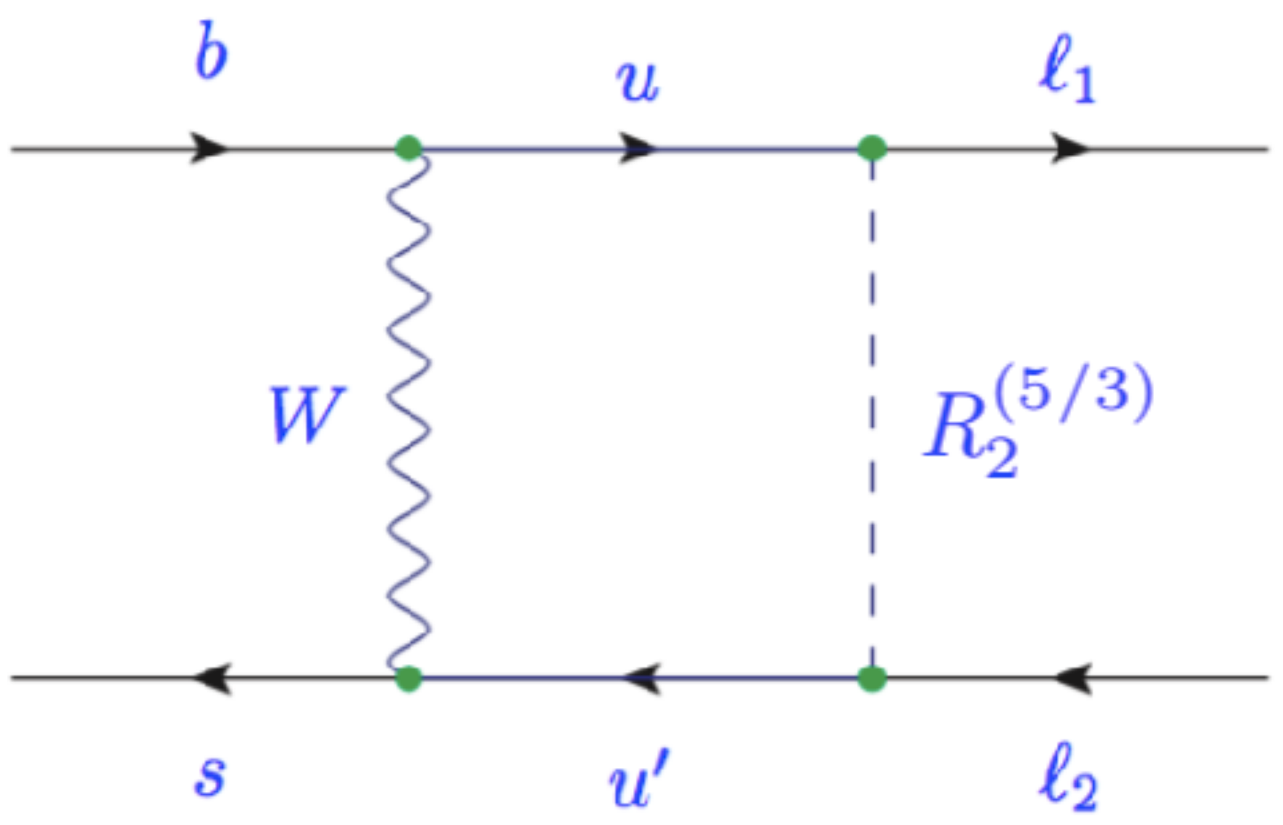
2103.12504

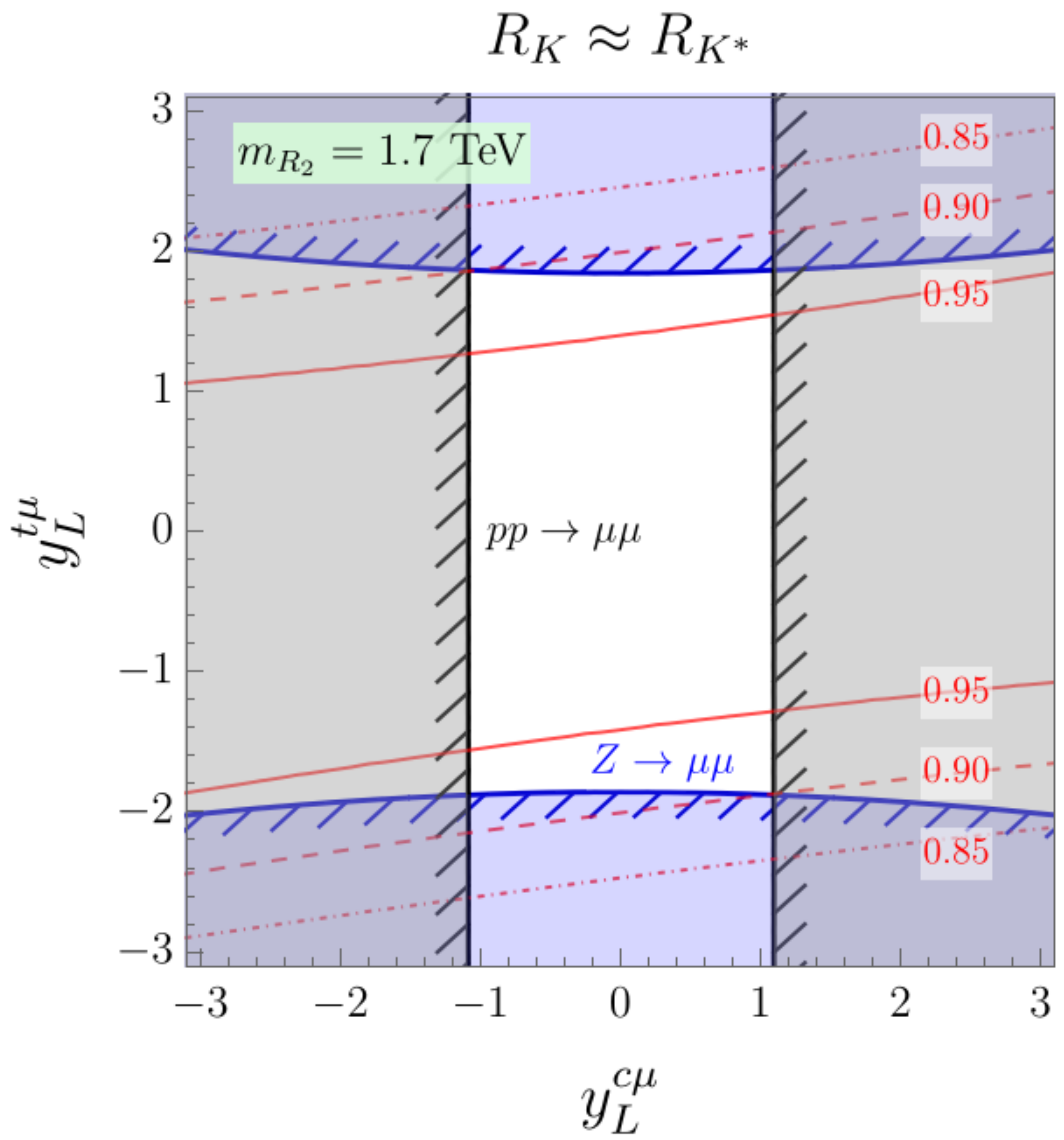
Model	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$ & $R_{K^{(*)}}$
$S_1=(\bar{3},1,1/3)$	✓	✗	✗
$R_2=(3,2,7/6)$	✓	✓*	✗
$S_3=(\bar{3},3,1/3)$	✗	✓	✗
$U_1=(3,1,2/3)$	✓	✓	✓
$U_3=(3,3,2/3)$	✗	✓	✗

$$\mathcal{L}_{R_2} = y_R^{ij}\,\overline{Q}_i \ell_{Rj}\,R_2 - y_L^{ij}\,\overline{u}_{Ri} R_2 i\tau_2 L_j + \text{h.c.}$$

$$C_9^{kl} = C_{10}^{kl} \overset{\text{tree}}{=} -\frac{\pi v^2}{2V_{tb}V_{ts}^*\alpha_{\text{em}}}\frac{y_R^{sl}\left(y_R^{bk}\right)^*}{m_{R_2}^2}\,, \qquad C_9^{kl} = -C_{10}^{kl} \overset{\text{loop}}{=} \sum_{u,u'\in\{u,c,t\}} \frac{V_{ub}V_{u's}^*}{V_{tb}V_{ts}^*} y_L^{u'k}\left(y_L^{ul}\right)^* \mathcal{F}(x_u, x_{u'})$$

$$y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_L^{c\mu} & 0 \\ 0 & y_L^{t\mu} & 0 \end{pmatrix}, \qquad y_R = 0$$





Combining two scalar LQ's

Model	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$ & $R_{K^{(*)}}$
$S_1 = (\bar{3}, 1, 1/3)$	✓	✗	✗
$R_2 = (3, 2, 7/6)$	✓	✓*	✗
$S_3 = (\bar{3}, 3, 1/3)$	✗	✓	✗
$U_1 = (3, 1, 2/3)$	✓	✓	✓
$U_3 = (3, 3, 2/3)$	✗	✓	✗

see 2203.10111 for $R_2 + R_2$ [plus an extra R_2 to capture $(g\text{-}2)_\mu$]

Scenario with R_2 & S_3 Leptoquarks

1806.05689

- In flavor basis

$$\mathcal{L} \supset y_R^{ij}\,\bar{Q}_i \ell_{Rj} R_2 + y_L^{ij}\,\bar{u}_{Ri} L_j \widetilde{R}_2^\dagger + y^{ij}\,\bar{Q}_i^C i\tau_2 (\tau_k S_3^k) L_j + \text{h.c.}$$

$$R_2 = (3, 2, 7/6),\ S_3 = (\bar{3}, 3, 1/3)$$

- In mass-eigenstates basis

$$\begin{aligned}\mathcal{L} \supset\ & (V_{\rm CKM}\, y_R\, E_R^\dagger)^{ij}\, \bar{u}'_{Li} \ell'_{Rj} R_2^{(5/3)} + (y_R\, E_R^\dagger)^{ij}\, \bar{d}'_{Li} \ell'_{Rj} R_2^{(2/3)} \\ & + (U_R\, y_L\, U_{\rm PMNS})^{ij}\, \bar{u}'_{Ri} \nu'_{Lj} R_2^{(2/3)} - (U_R\, y_L)^{ij}\, \bar{u}'_{Ri} \ell'_{Lj} R_2^{(5/3)} \\ & - (y\, U_{\rm PMNS})^{ij}\, \bar{d}'^{C}_{Li} \nu'_{Lj} S_3^{(1/3)} - \sqrt{2}\, y^{ij}\, \bar{d}'^{C}_{Li} \ell'_{Lj} S_3^{(4/3)} \\ & + \sqrt{2}(V^*_{\rm CKM}\, y\, U_{\rm PMNS})_{ij}\, \bar{u}'^{C}_{Li} \nu'_{Lj} S_3^{(-2/3)} - (V^*_{\rm CKM}\, y)_{ij}\, \bar{u}'^{C}_{Li} \ell'_{Lj} S_3^{(1/3)} + \text{h.c.}\end{aligned}$$

and assume

$$\underline{y_R = y_R^T \qquad y = -y_L}$$

$$y_R\, E_R^\dagger = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_R^{b\tau} \end{pmatrix},\quad U_R\, y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_L^{c\mu} & y_L^{c\tau} \\ 0 & 0 & 0 \end{pmatrix},\quad U_R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix}$$

$\boxed{\text{Parameters: } m_{R_2},\ m_{S_3},\ y_R^{b\tau},\ y_L^{c\mu},\ y_L^{c\tau} \text{ and } \theta}$

Embedding to SU(5) GUT feasible

Effective Lagrangian at $\mu \approx m_{\mathrm{LQ}}$:

- $b \to c\tau\bar{\nu}$: **NB**. $\Lambda_{\mathrm{NP}}/g_{\mathrm{NP}} \approx 1$ TeV

$$\propto \frac{y_L^{c\tau}\, y_R^{b\tau\,*}}{m_{R_2}^2}\left[(\bar{c}_R b_L)(\bar{\tau}_R \nu_L) + \frac{1}{4}(\bar{c}_R \sigma_{\mu\nu} b_L)(\bar{\tau}_R \sigma^{\mu\nu}\nu_L)\right] + \ldots$$

- $b \to s\mu\mu$: **NB**. $\Lambda_{\mathrm{NP}}/g_{\mathrm{NP}} \approx 30$ TeV

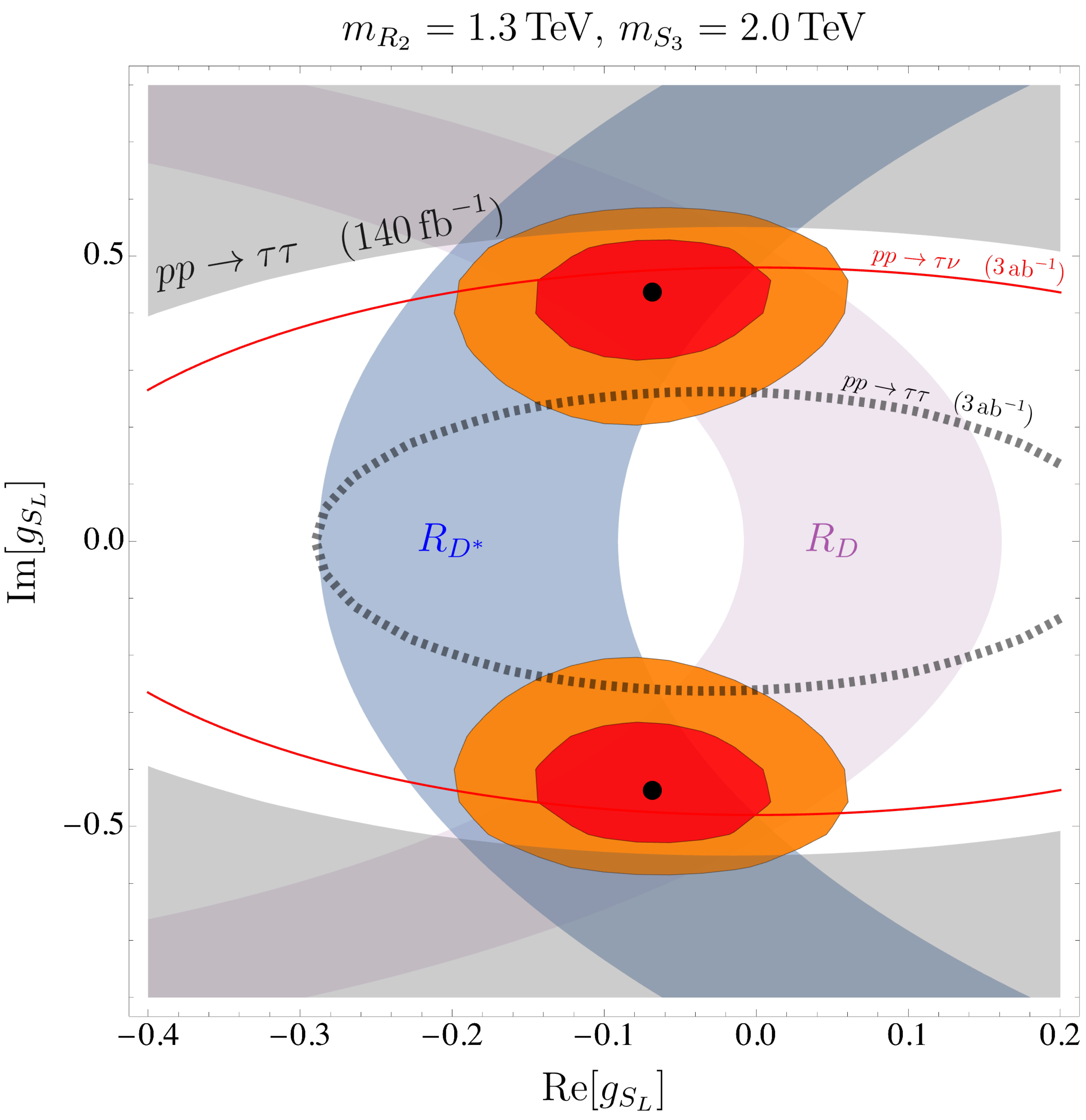
$$\propto \sin 2\theta\, \frac{|y_L^{c\mu}|^2}{m_{S_3}^2}\,(\bar{s}_L\gamma^\mu b_L)(\bar{\mu}_L\gamma_\mu \mu_L)$$

- Δm_{B_s}:

$$\propto \sin^2 2\theta\, \frac{\left[\left(y_L^{c\mu}\right)^2 + \left(y_L^{c\tau}\right)^2\right]^2}{m_{S_3}^2}(\bar{s}_L\gamma^\mu b_L)^2$$

$\Rightarrow$ Suppression mechanism of $b \to s\mu\mu$ wrt $b \to c\tau\bar{\nu}$ for small $\sin 2\theta$.

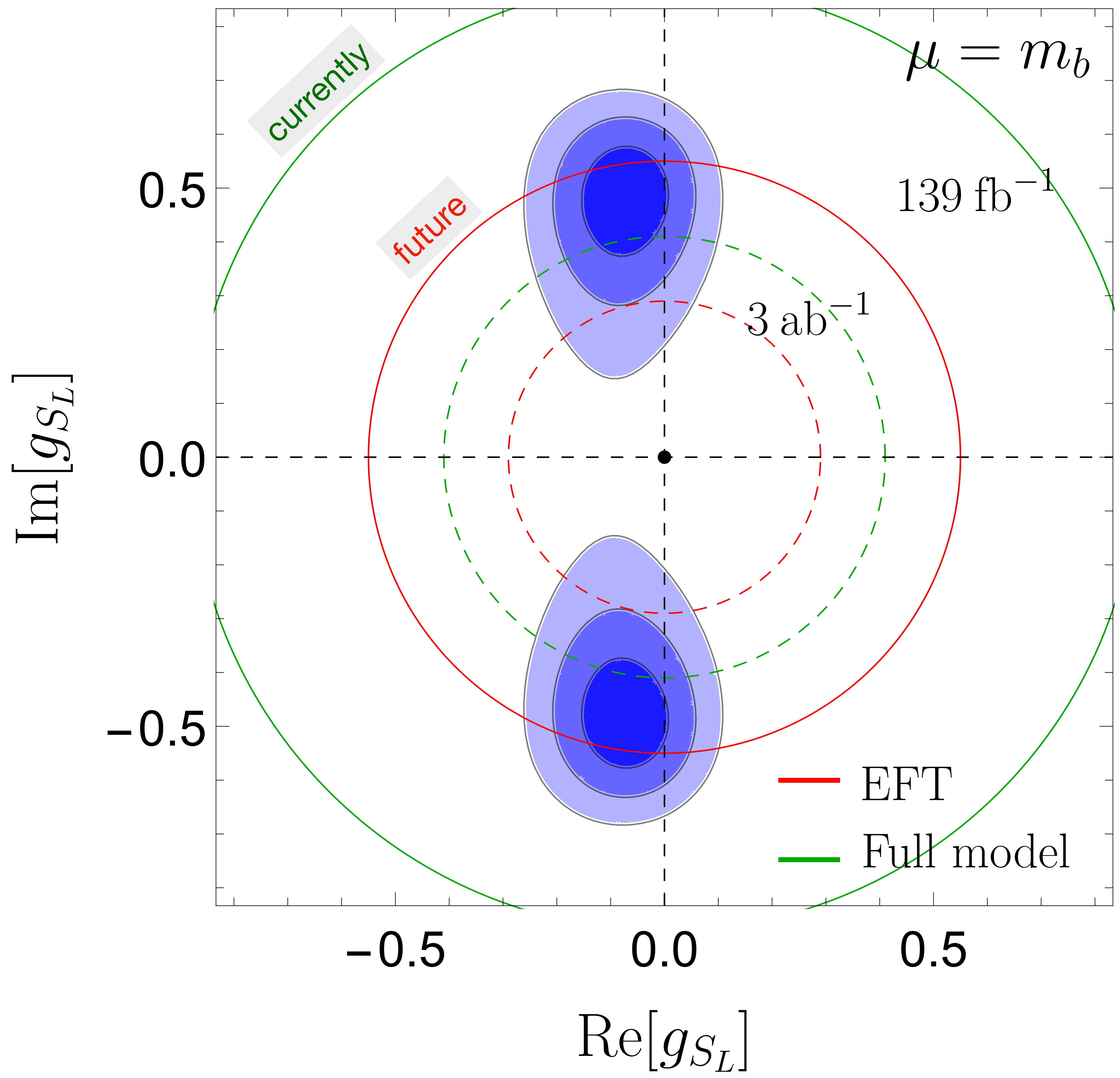
$\Rightarrow$ Phenomenology suggests $\theta \approx \pi/2$ and $y_R^{b\tau}$ complex



Neutrinos incorporated in 2004.07880

Next week on arXiv…

Right now, bounds deduced from $pp \to \tau\nu$ at high p_T not very restrictive

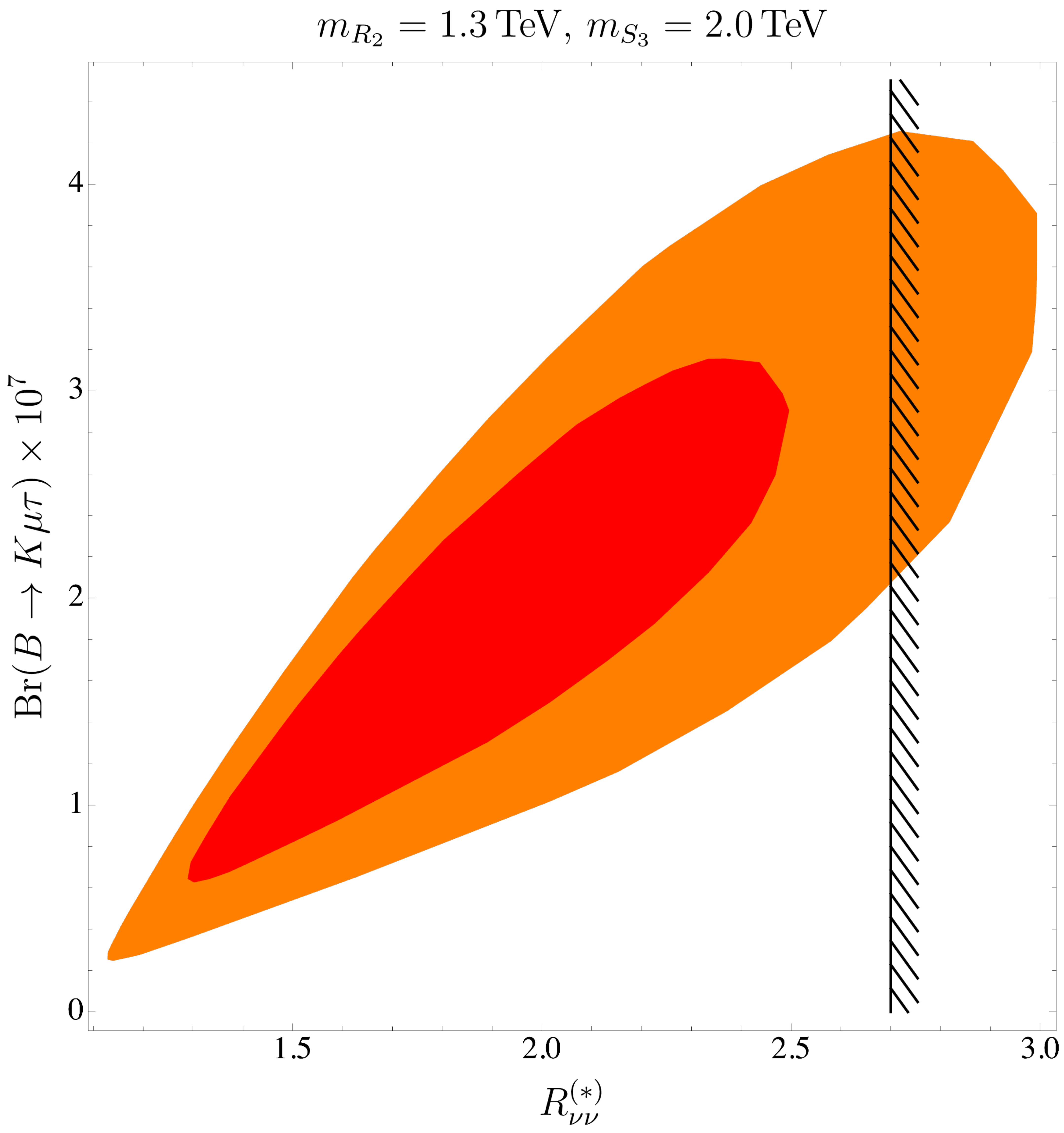


NB: New ATLAS data

2111.04748, 2112.14604

Interesting pheno, ex.

R_2 & S_3



Belle-II results imminent (ICHEP22)

cf. U_1

2103.16558
2009.11296

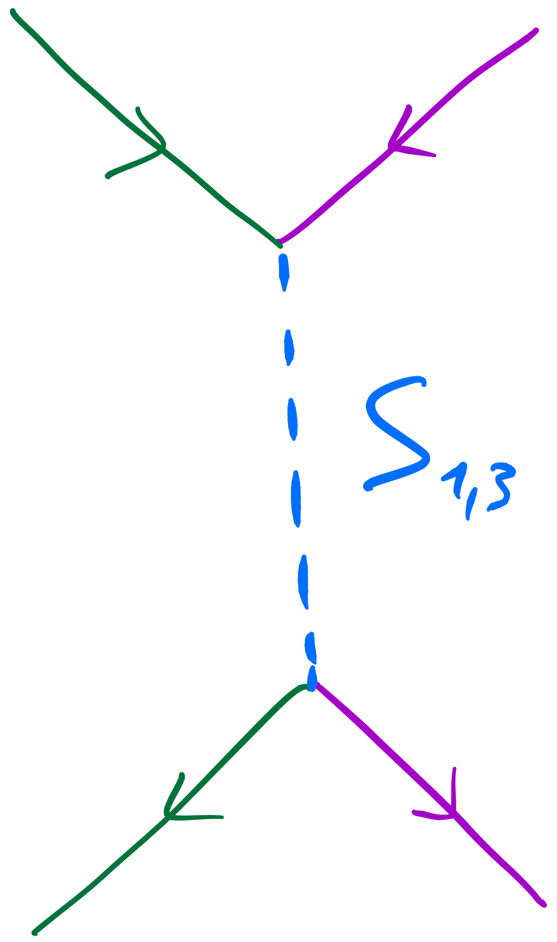
$$R_{\nu\nu}^{(*)} = \frac{\mathcal{B}(B \to K^{(*)}\nu\nu)}{\mathcal{B}(B \to K^{(*)}\nu\nu)^{\text{SM}}}$$

Other observables next week on arXiv…

Phenomenology of S_1 and S_3

Scalar Leptoquarks

$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$,
$S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$,



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…

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

1) Match **SM** + **S_1+S_3** to **SMEFT** @ 1-loop

(SMEFT RGE, SMEFT-LEFT 1-loop matching, LEFT RGE already done in literature)

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

[Alonso, Jenkins, Manohar, Trott ’13]
[Dekens, Stoffer 1908.05295]
[Jenkins, Manohar, Stoffer 1711.05270]

2) Global analysis of B-anomalies + all relevant observables

V. Gherardi, E. Venturini, D.M. [2008.09548]

3) Include 1st gen couplings and study **Kaon** & $\mu \to e$ observables assuming $U(2)^5$ flavor symmetry.

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

S_1 and S_3 - benchmarks

Two ***benchmark*** scenarios:

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

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

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

$$\lambda^{1R} = 0$$

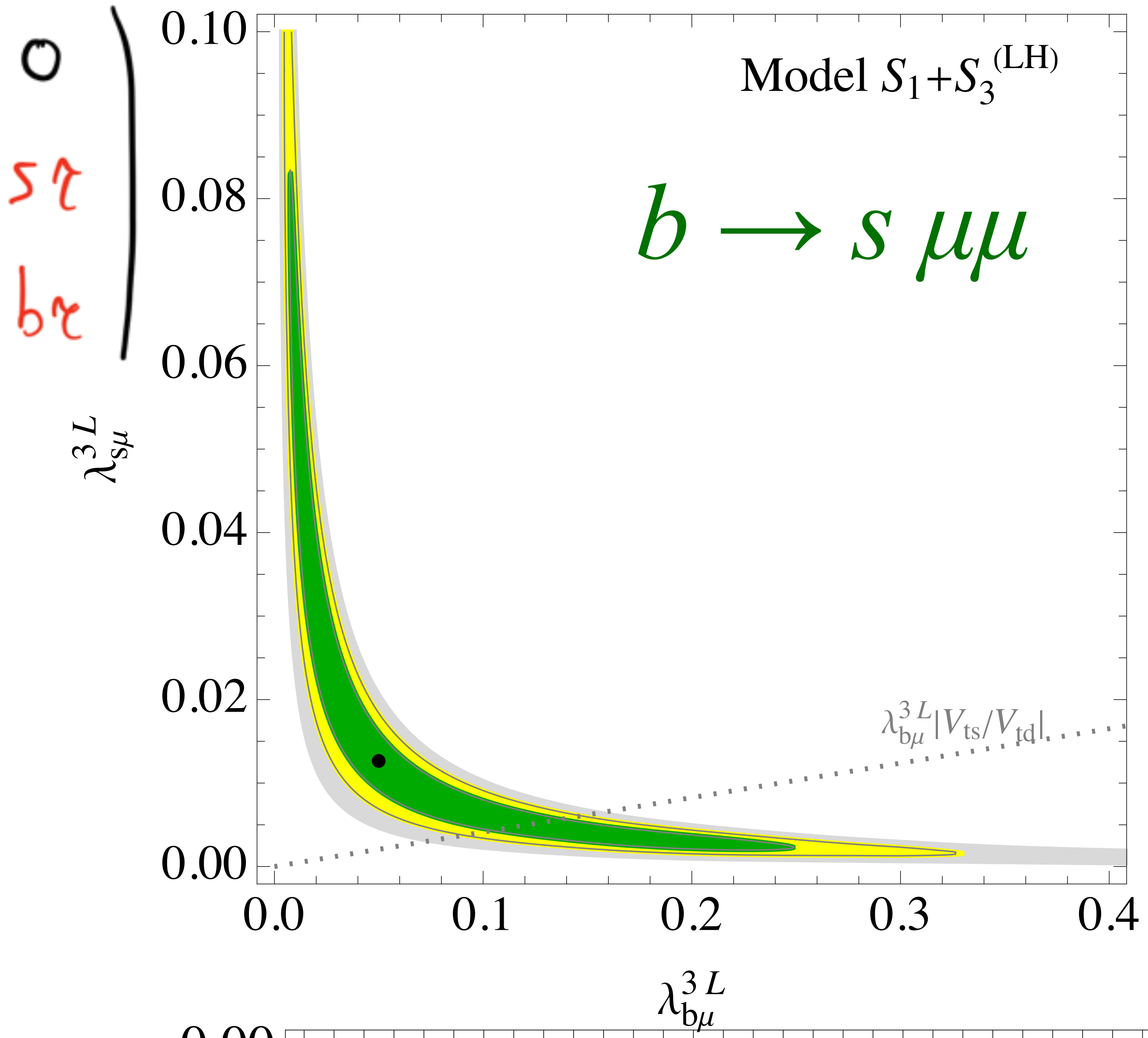
$M_{S_{1,3}} \sim 1\ \mathrm{TeV}$

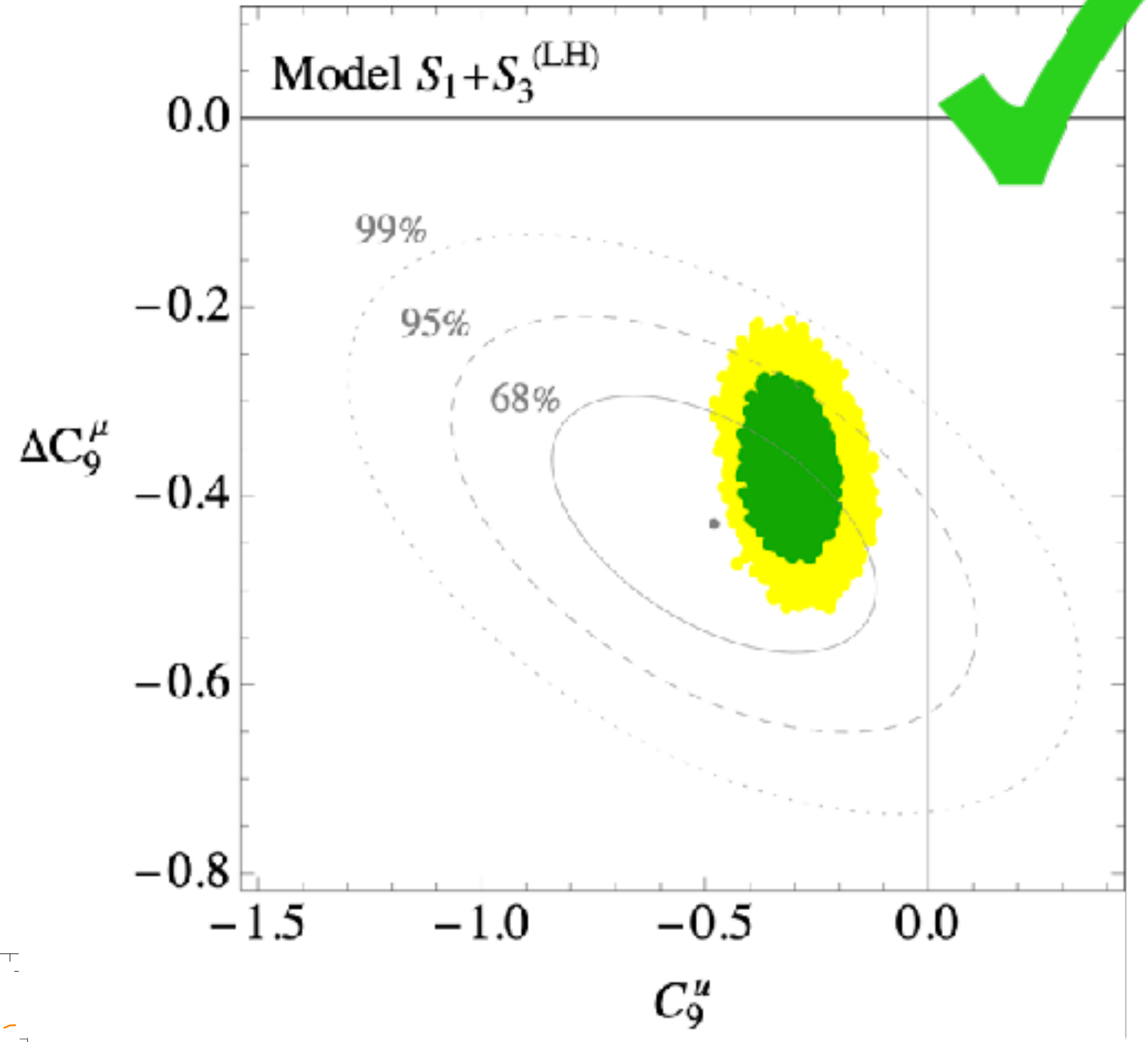
S_1 and S_3 — only LH couplings

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

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

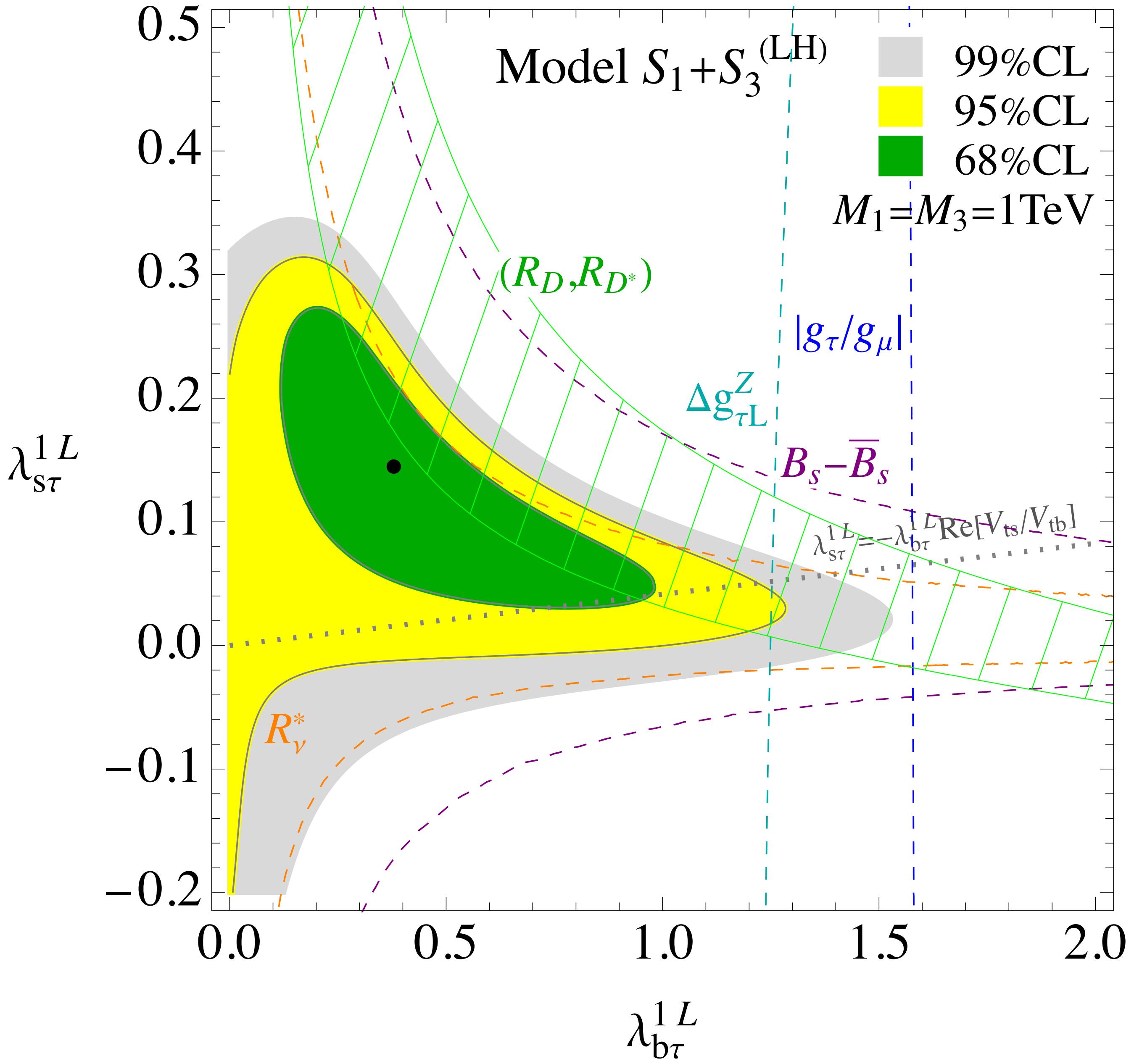
(see backup slides for a S_1+S_3 scenario that addresses also the muon magnetic moment)

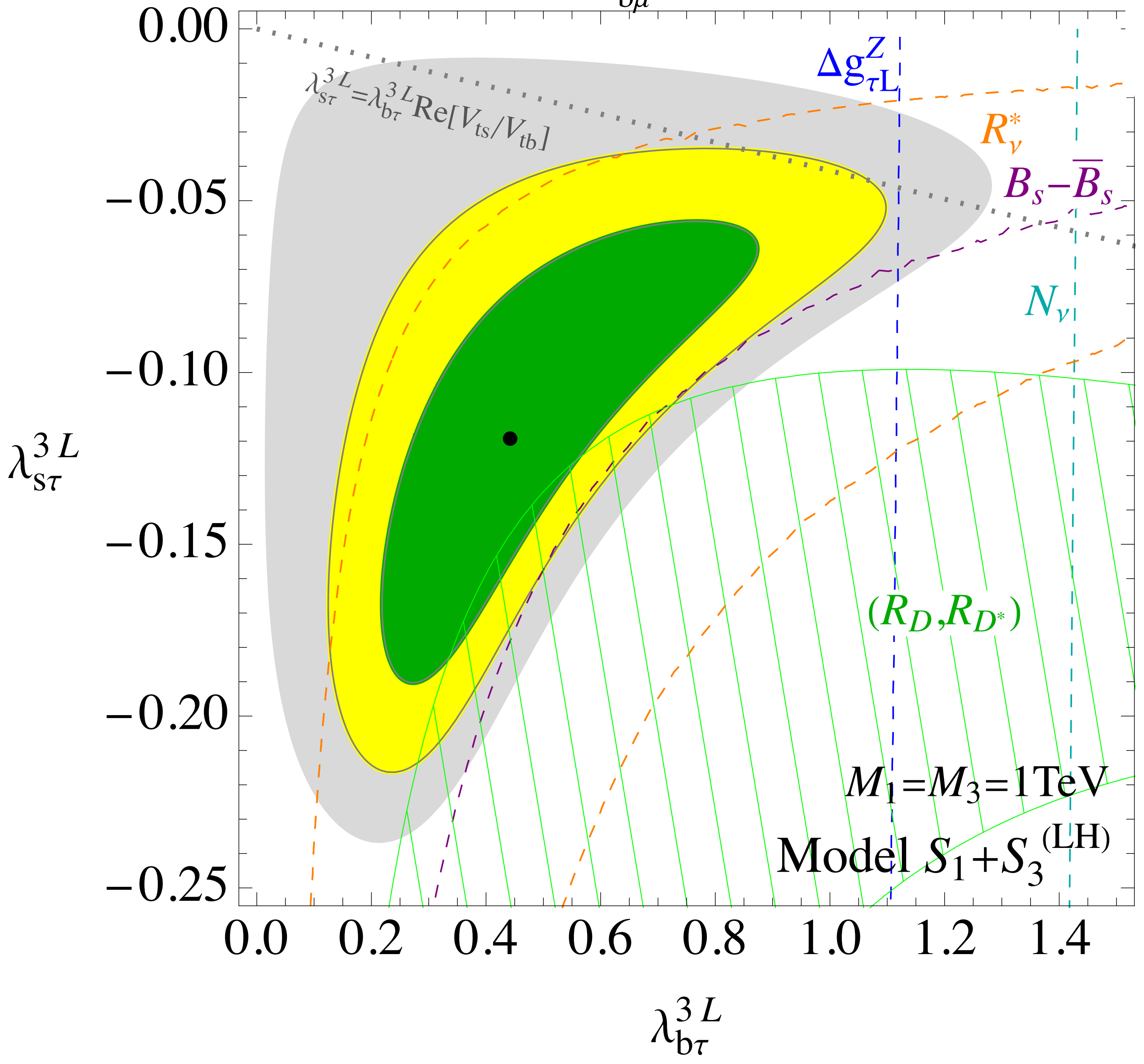


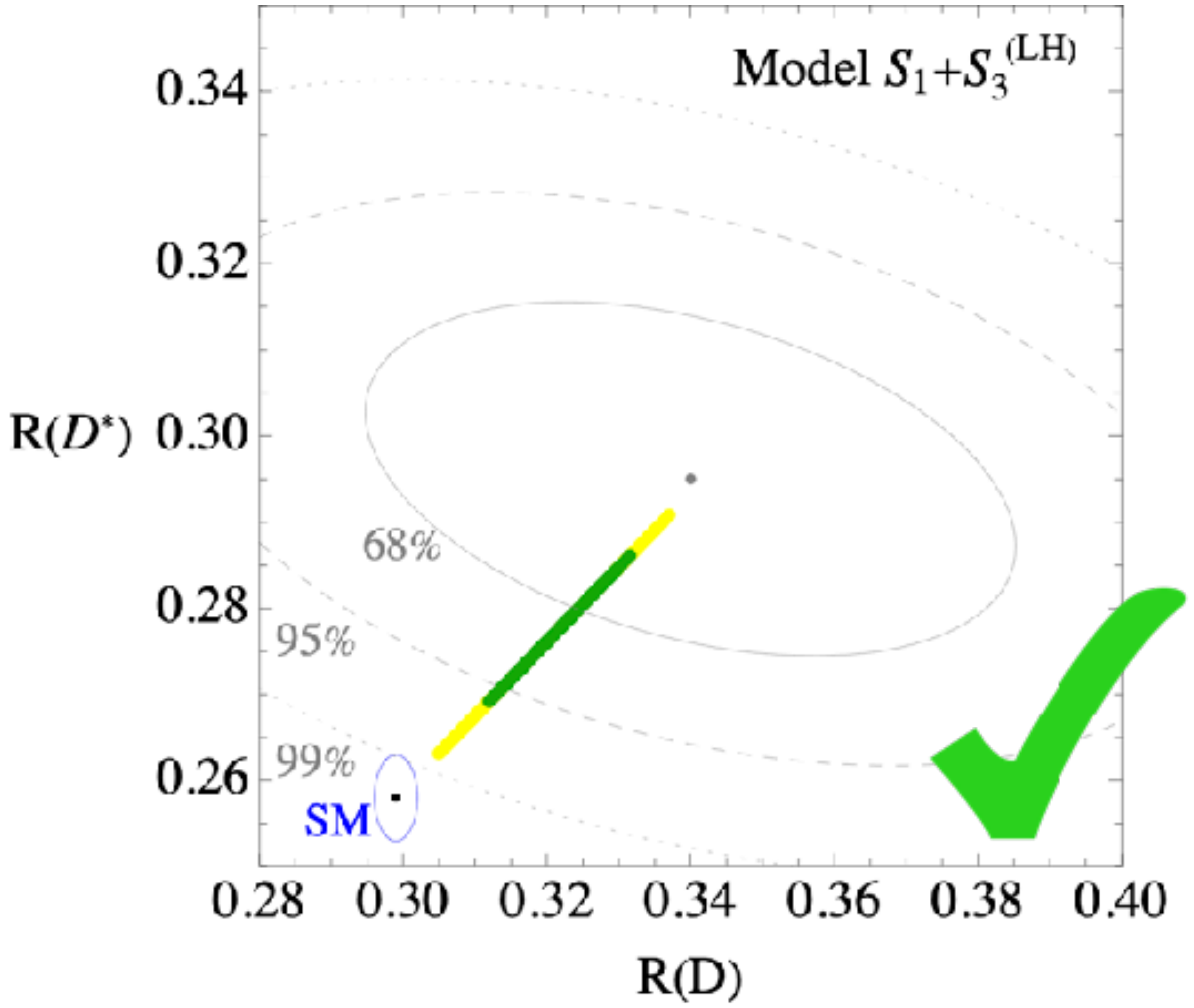


very good fit of B-anomalies

R(D(*))







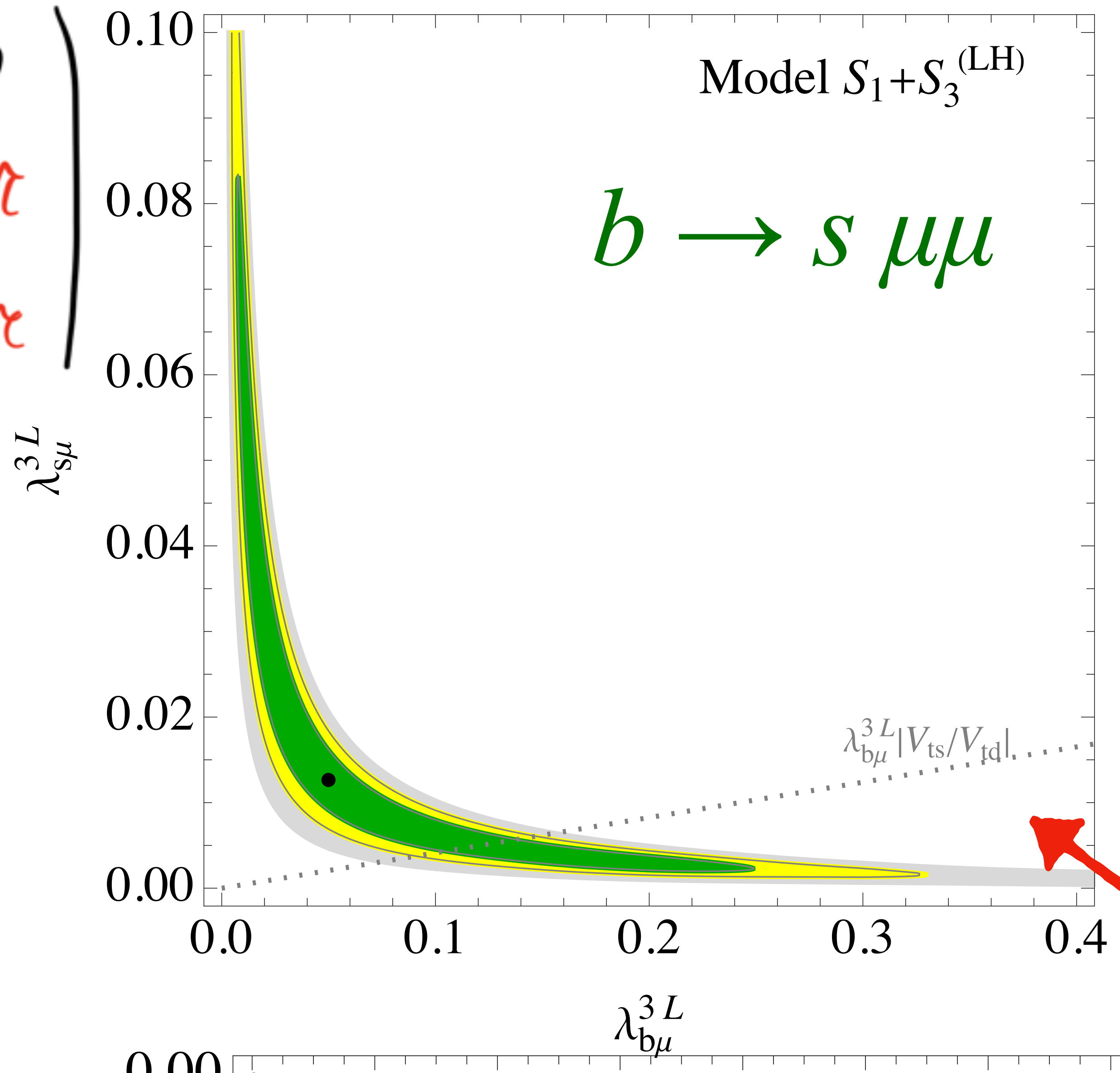
Plots updated w.r.t. [v3:2008.09548]

S_1 and S_3 — only LH couplings

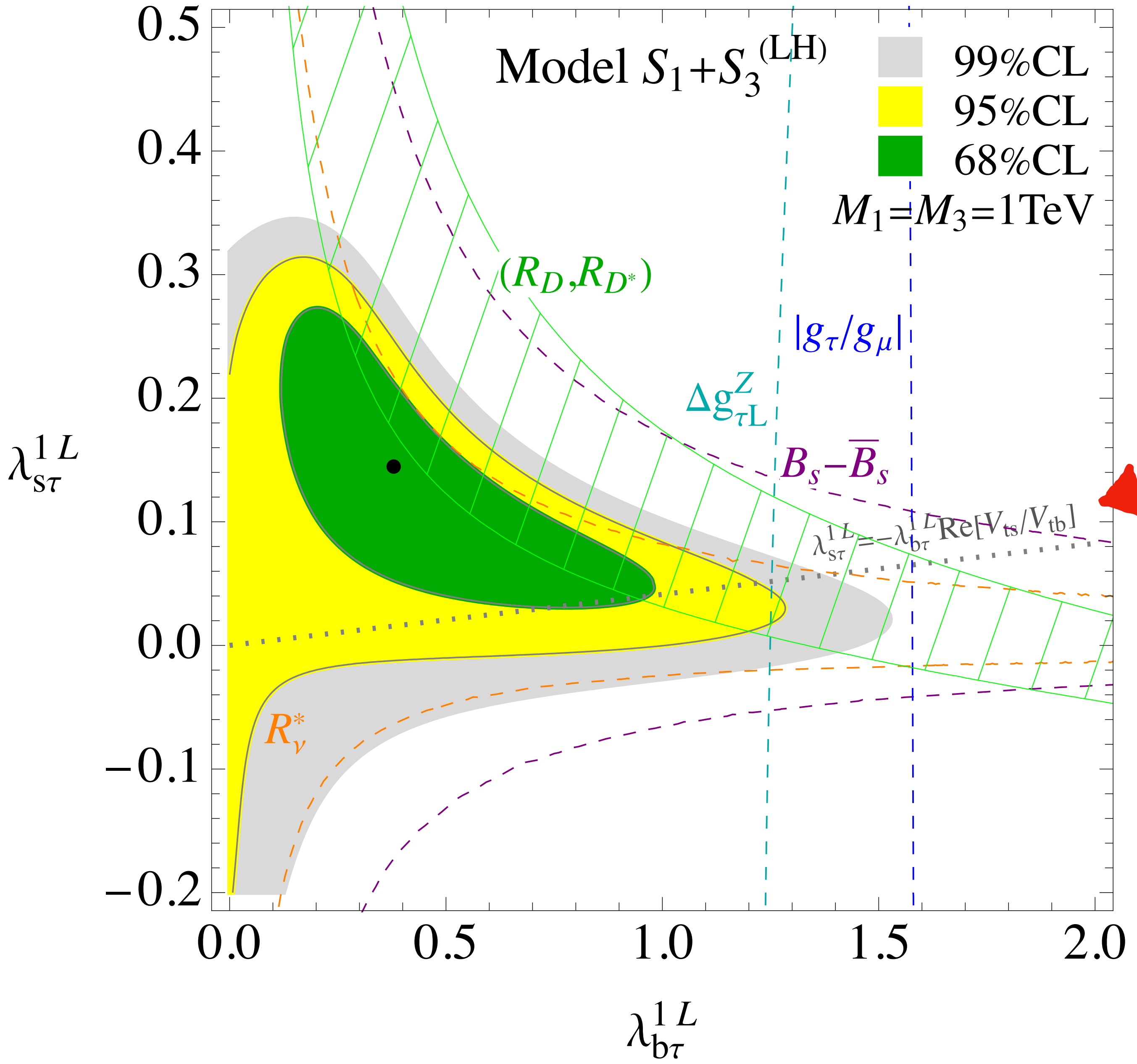
$$\lambda^{1L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & s\tau \\ 0 & 0 & b\tau \end{pmatrix} \quad \lambda^{3L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & s\mu & s\tau \\ 0 & b\mu & b\tau \end{pmatrix}$$

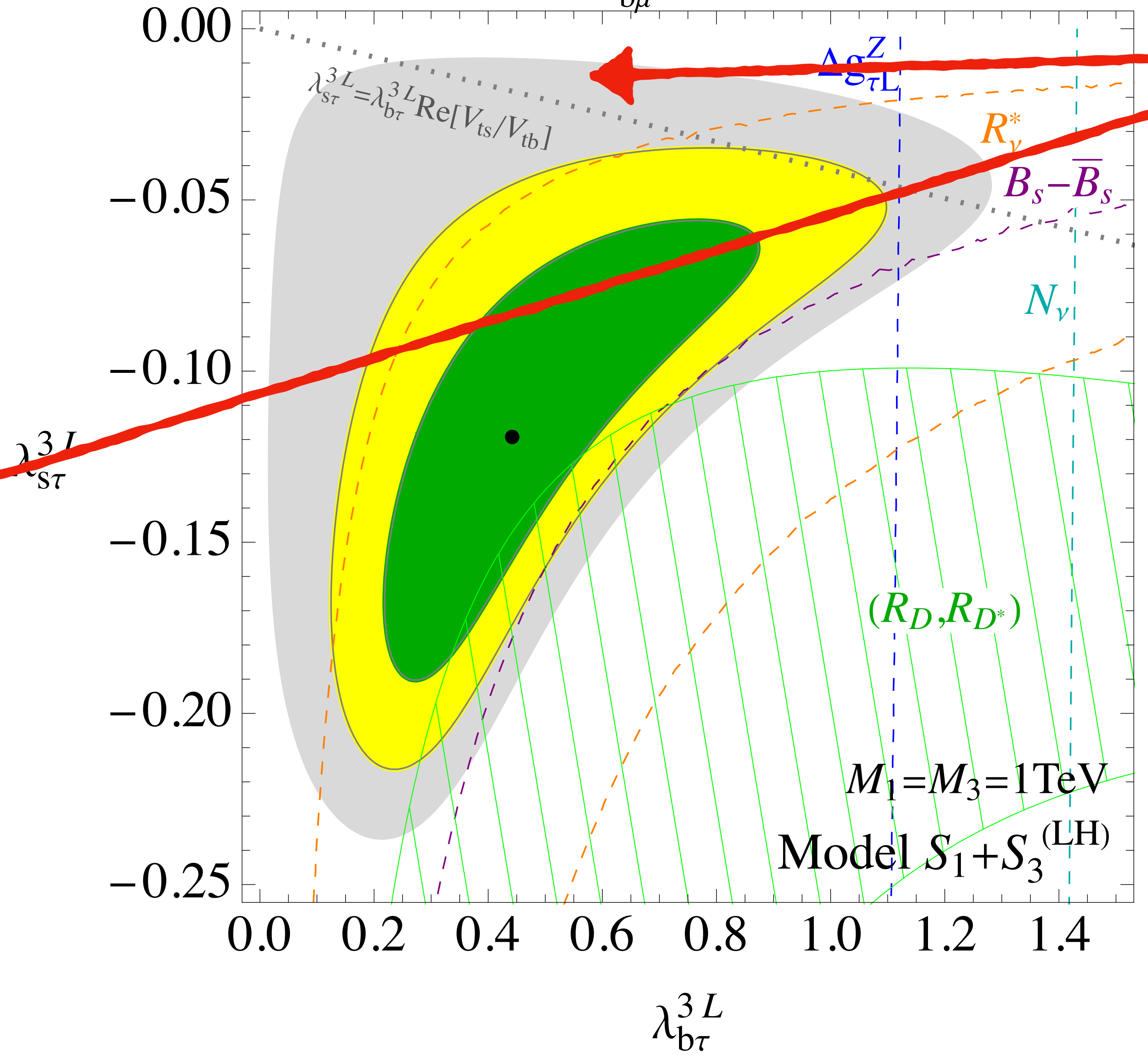
$\lambda^{1R} = 0$ → Cannot fit $(g\text{-}2)_\mu$

(see backup slides for a S_1+S_3 scenario that addresses also the muon magnetic moment)



R(D(*))





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

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

$c_{U(2)} = 1$

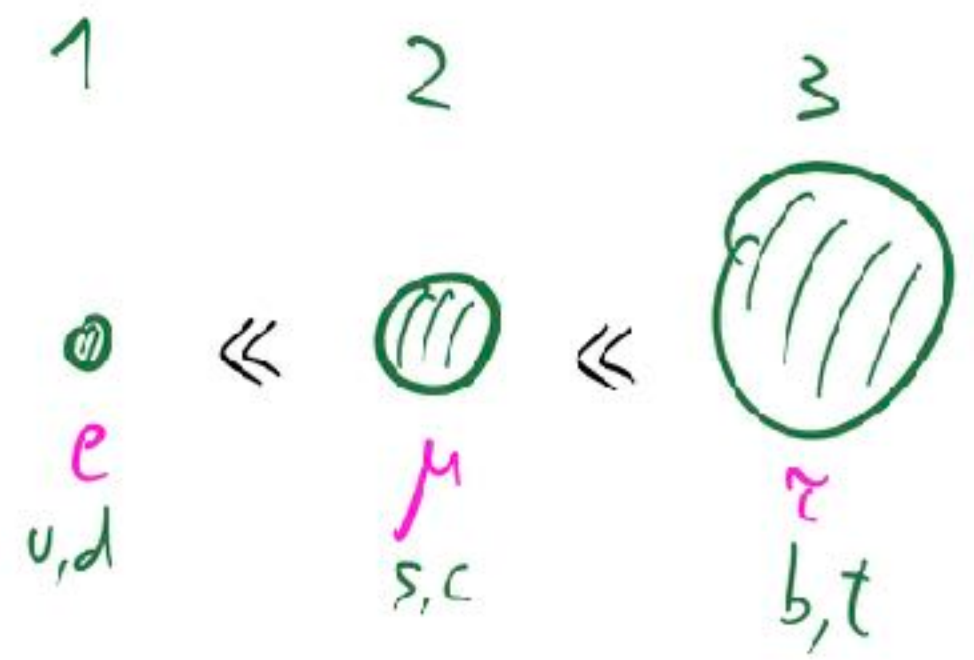
$c_{U(2)} \sim \mathcal{O}(1)$ e.g. 3 - 5

See also Buttazzo, Greljo, Isidori, D.M. 1706.07808

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

A hint for a flavor struture: U(2)^5

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



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

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

Barbieri et al. [1105.2296, 1203.4218, 1211.5085]

The **minimal breaking** of this symmetry to reproduce the SM Yukawas is described by a set of **spurions**:

$$Y_{u,d} \sim \left(\begin{array}{cc} \boxed{\quad \Delta_{u,d} \quad} & \boxed{V_q} \\ 0 \quad 0 & 1 \end{array} \right) \qquad Y_e \sim \left(\begin{array}{cc} \boxed{\quad \Delta_e \quad} & \boxed{V_\ell} \\ 0 \quad 0 & 1 \end{array} \right)$$

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

See also Fuentes-Martin, Isidori, Pagès, Yamamoto [1909.02519] $\kappa_q \sim O(1)$

U(2)⁵ flavour symmetry and leptoquarks

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

$$\lambda^{1(3)L} \sim \begin{pmatrix} \boxed{V_q^*} \times \boxed{V_\ell} & \boxed{V_q^*} \\ \boxed{V_\ell} & 1 \end{pmatrix}$$

i.e.

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

V_ℓ : leptonic doublet spurion

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

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

} ***Arbitrary 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**!

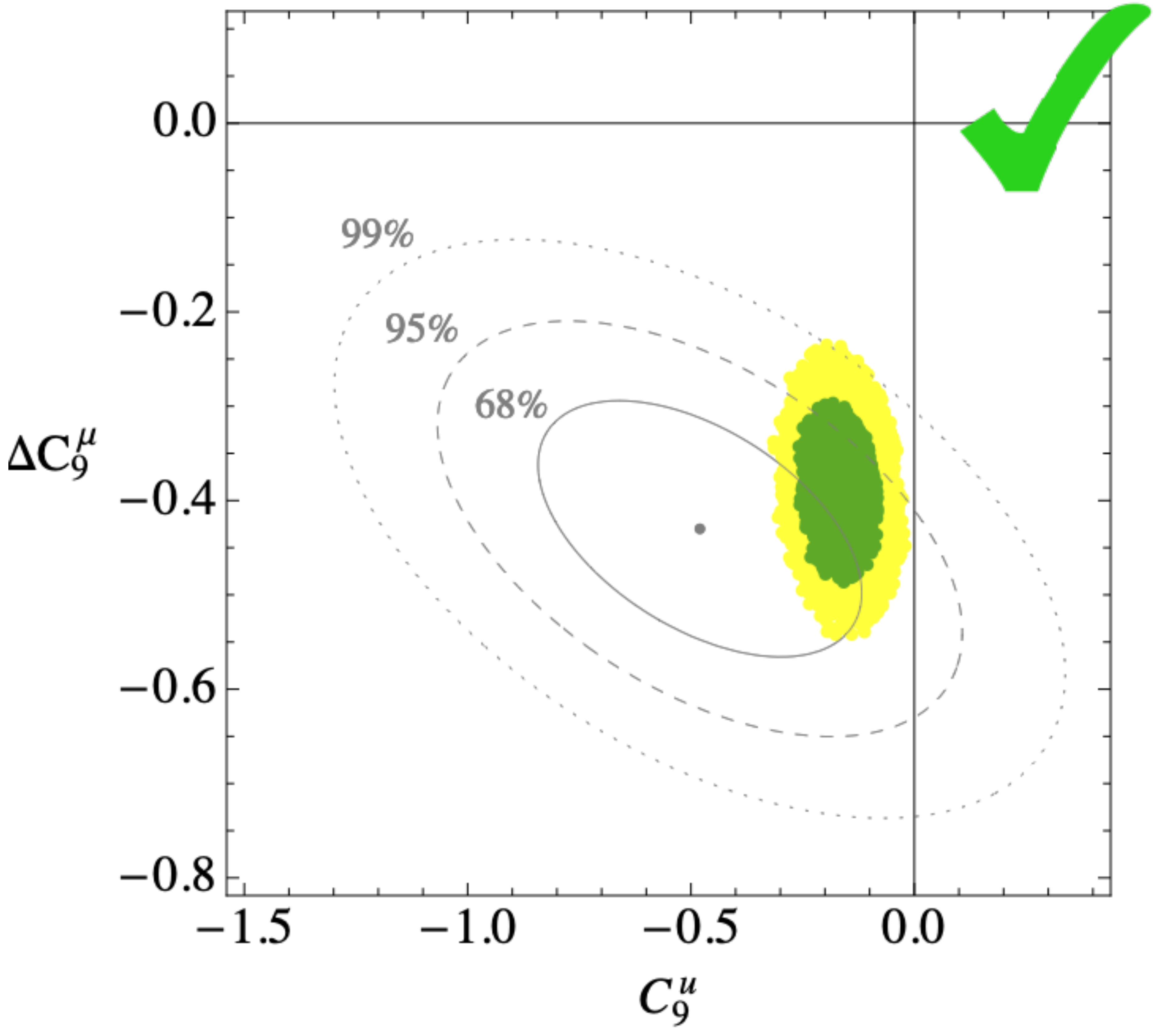
Global analysis with U(2)^5

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

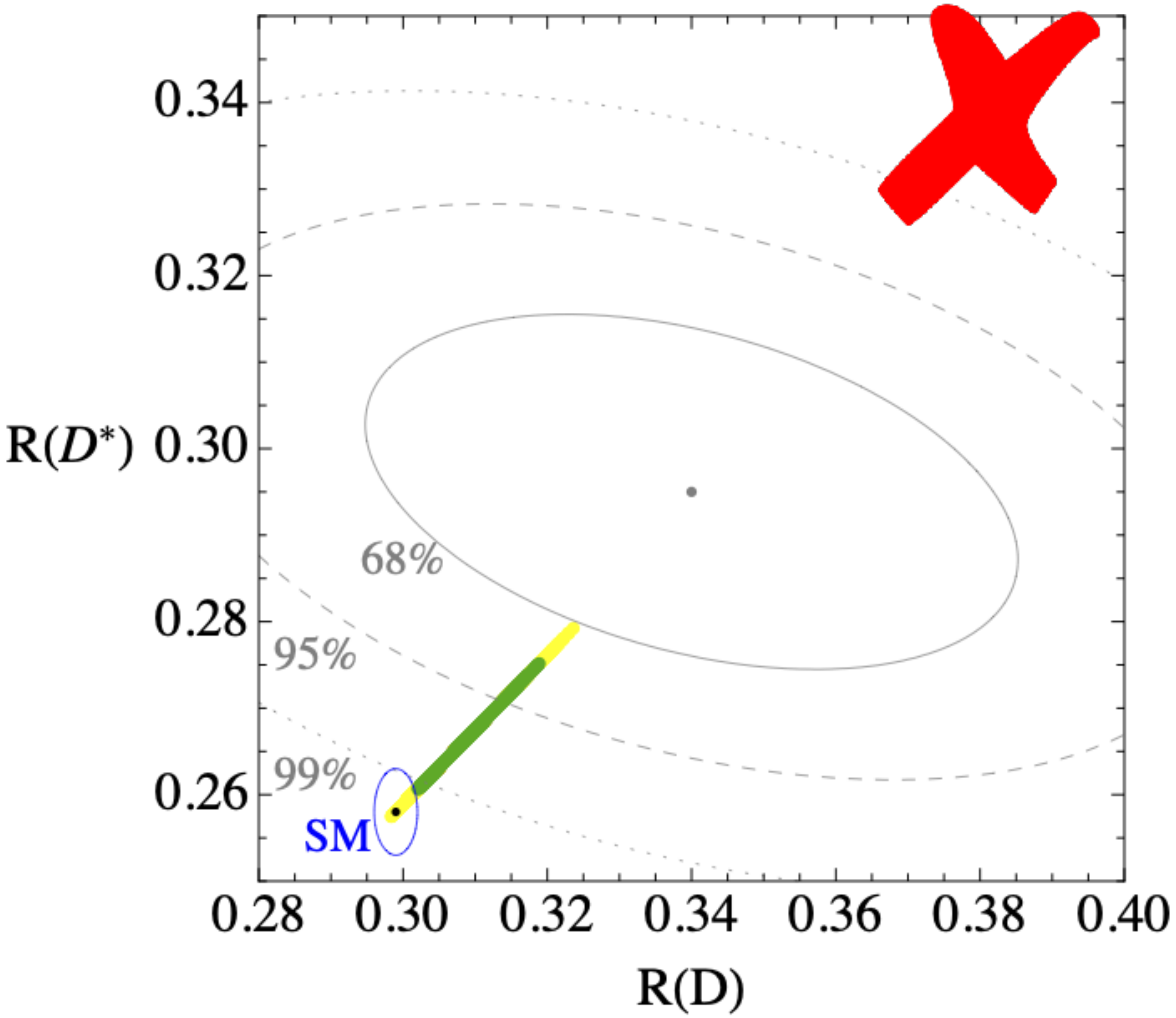
We perform a global fit in the U(2)^5 flavour structure.

The parameters are consistent with the symmetry: **all x's are O(1)**, $V_\ell \sim 0.1$, $|s_e| \lesssim 0.02$

b→ sμμ can be addressed:

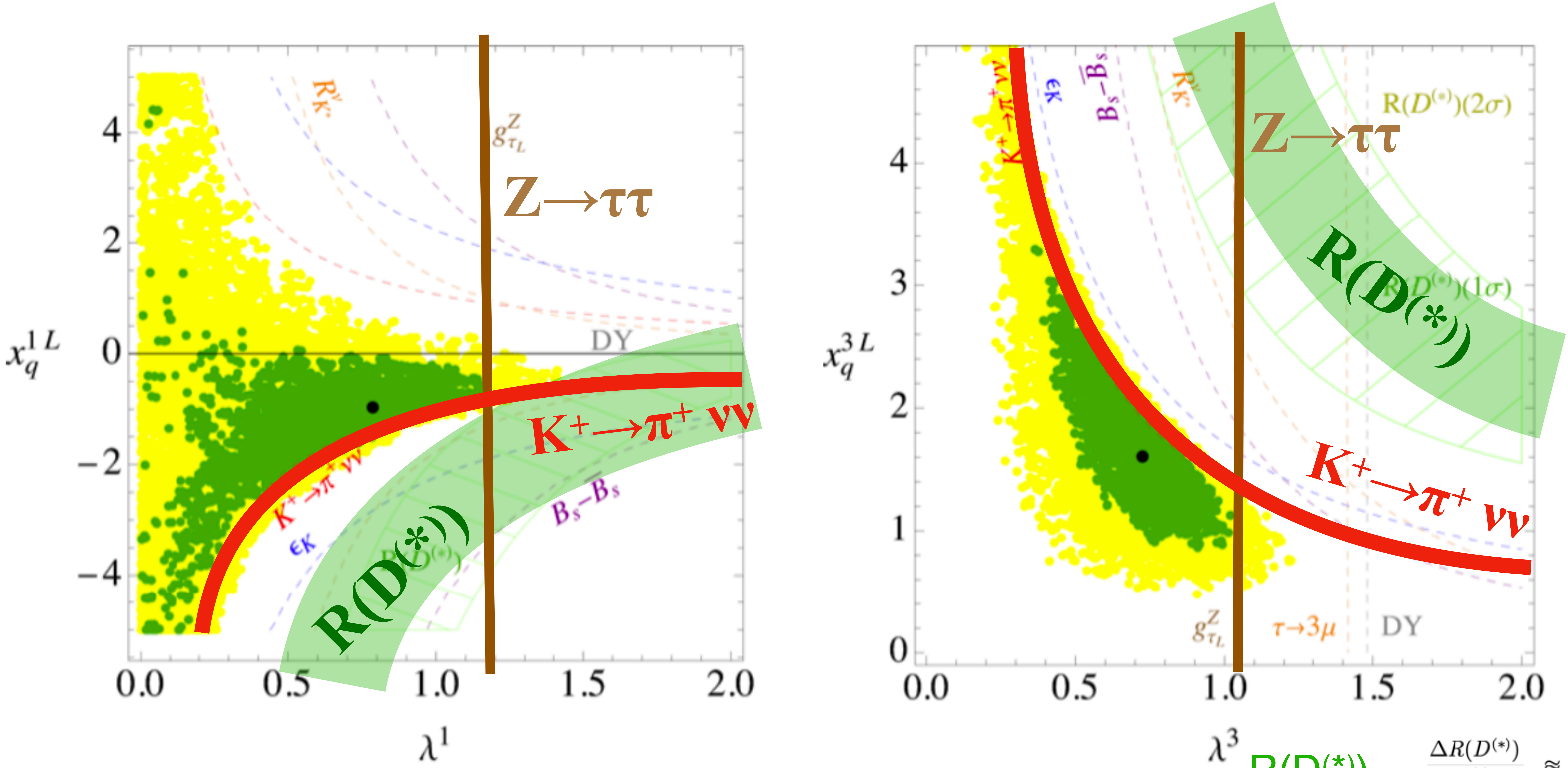


R(D$^{(*)}$) instead can only be addressed at 2σ:



Global analysis with U(2)⁵

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

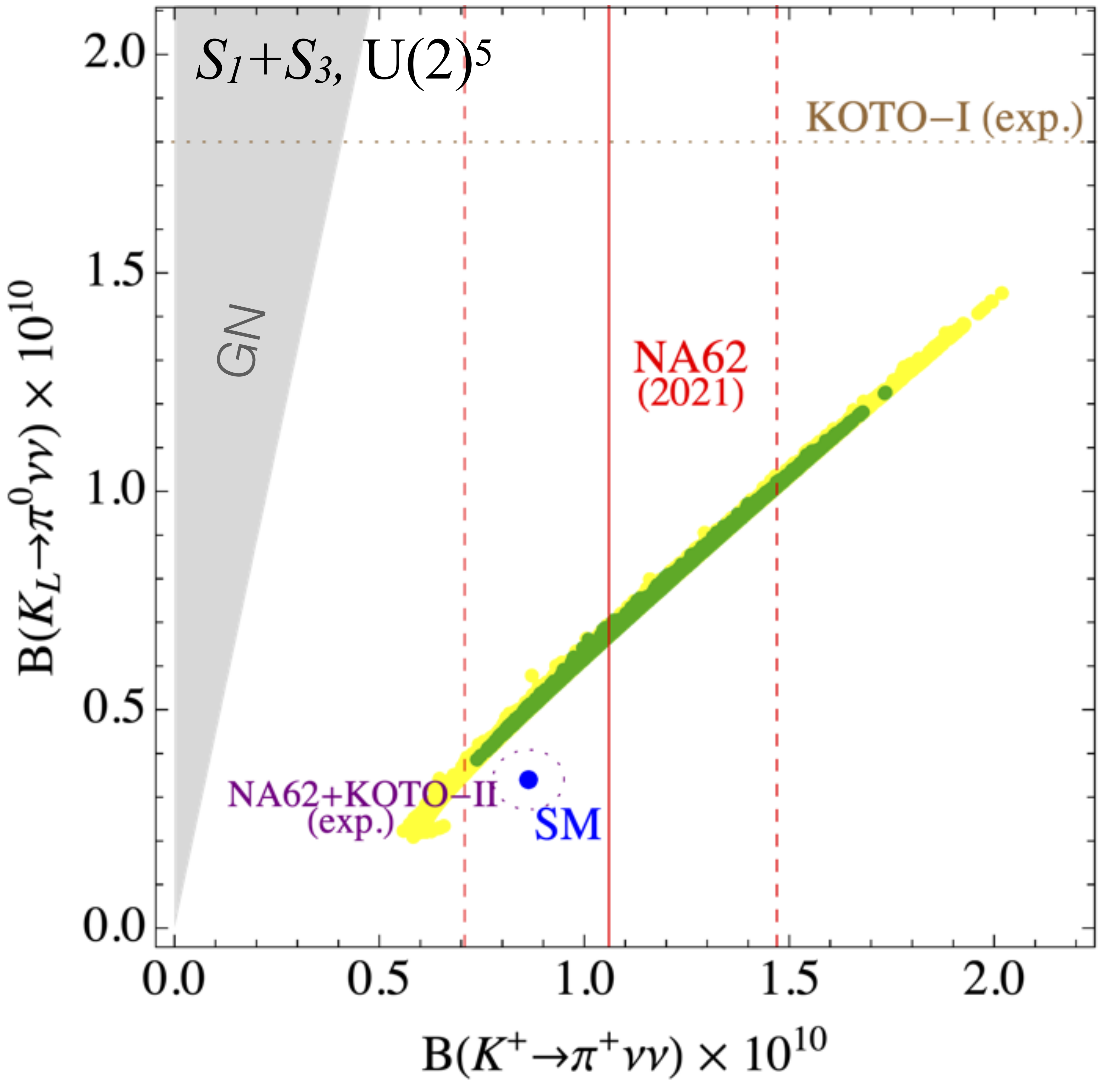


R(D(*)) $\quad \frac{\Delta R(D^{(*)})}{R(D^{(*)})_{\rm SM}} \approx v^2\left(1.09\frac{|\lambda^1|^2(1-x_q^{1*}V_{tb}^*)}{2M_1^2} - 1.02\frac{|\lambda^3|^2(1-x_q^{3*}V_{tb}^*)}{2M_3^2}\right)$

K⁺→π⁺ νν $\quad C_{sd\nu_\tau\nu_\tau} \approx V_{td}^* V_{ts}\left(\frac{|\lambda^1|^2|x_q^1|^2}{2M_1^2} + \frac{|\lambda^3|^2|x_q^3|^2}{2M_3^2}\right)$

Z→ττ $\quad 10^3\delta g^Z_{\tau_L} \approx 0.59\frac{|\lambda^1|^2}{M_1^2/\,{\rm TeV}^2} + 0.80\frac{|\lambda^1|^2}{M_1^2/\,{\rm TeV}^2}$

Leading effect in Kaon physics



$K \to \pi\, \nu\, \nu$

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

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

$C_{sd\nu_\tau\nu_\tau}(\bar\nu_\tau\gamma_\mu\nu_\tau)(\bar d_L\gamma^\mu s_L)$

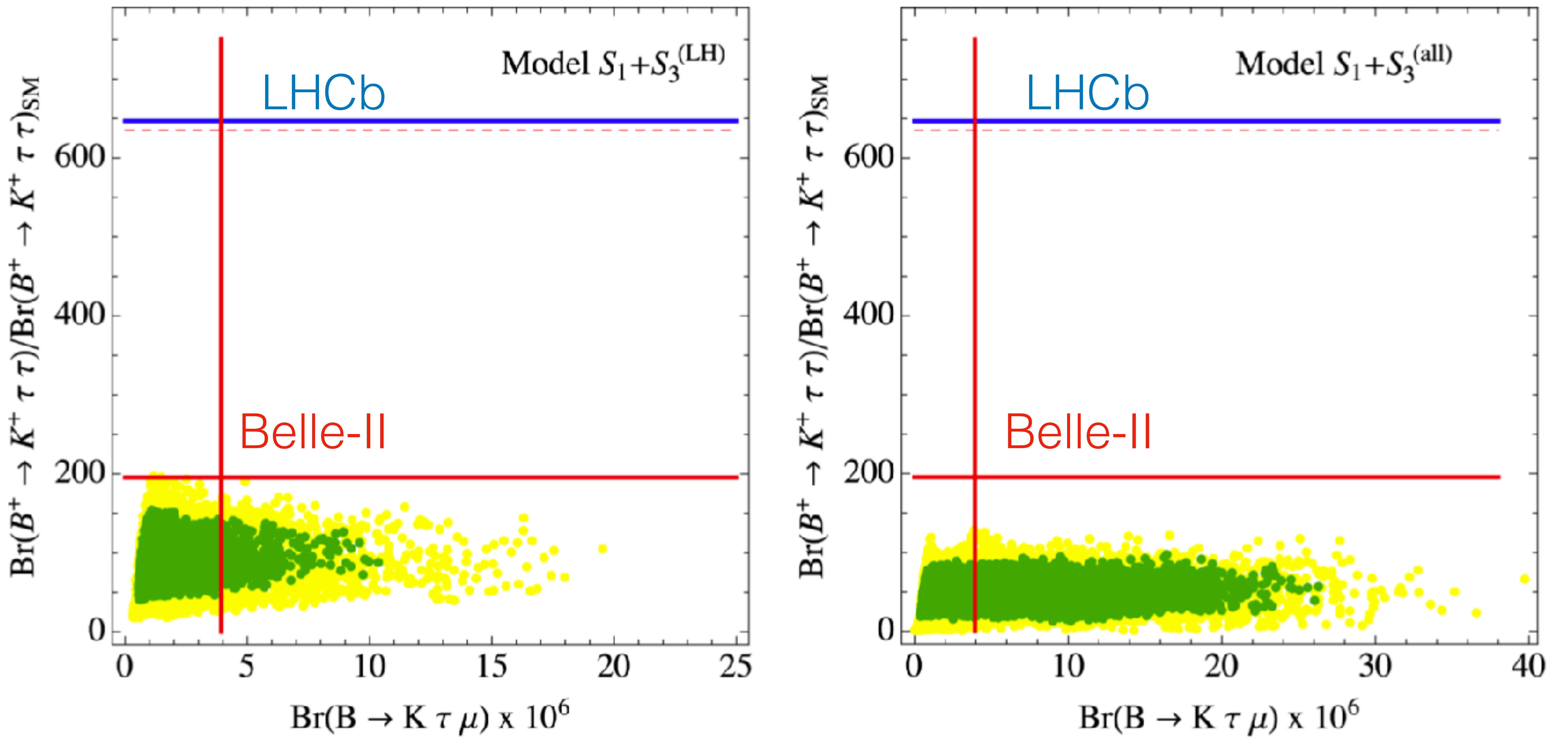
$$C_{sd\nu_\tau\nu_\tau} \approx V_{td}^* V_{ts}\left(\frac{|\lambda^1|^2|x_q^1|^2}{2M_1^2}+\frac{|\lambda^3|^2|x_q^3|^2}{2M_3^2}\right)$$

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

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:



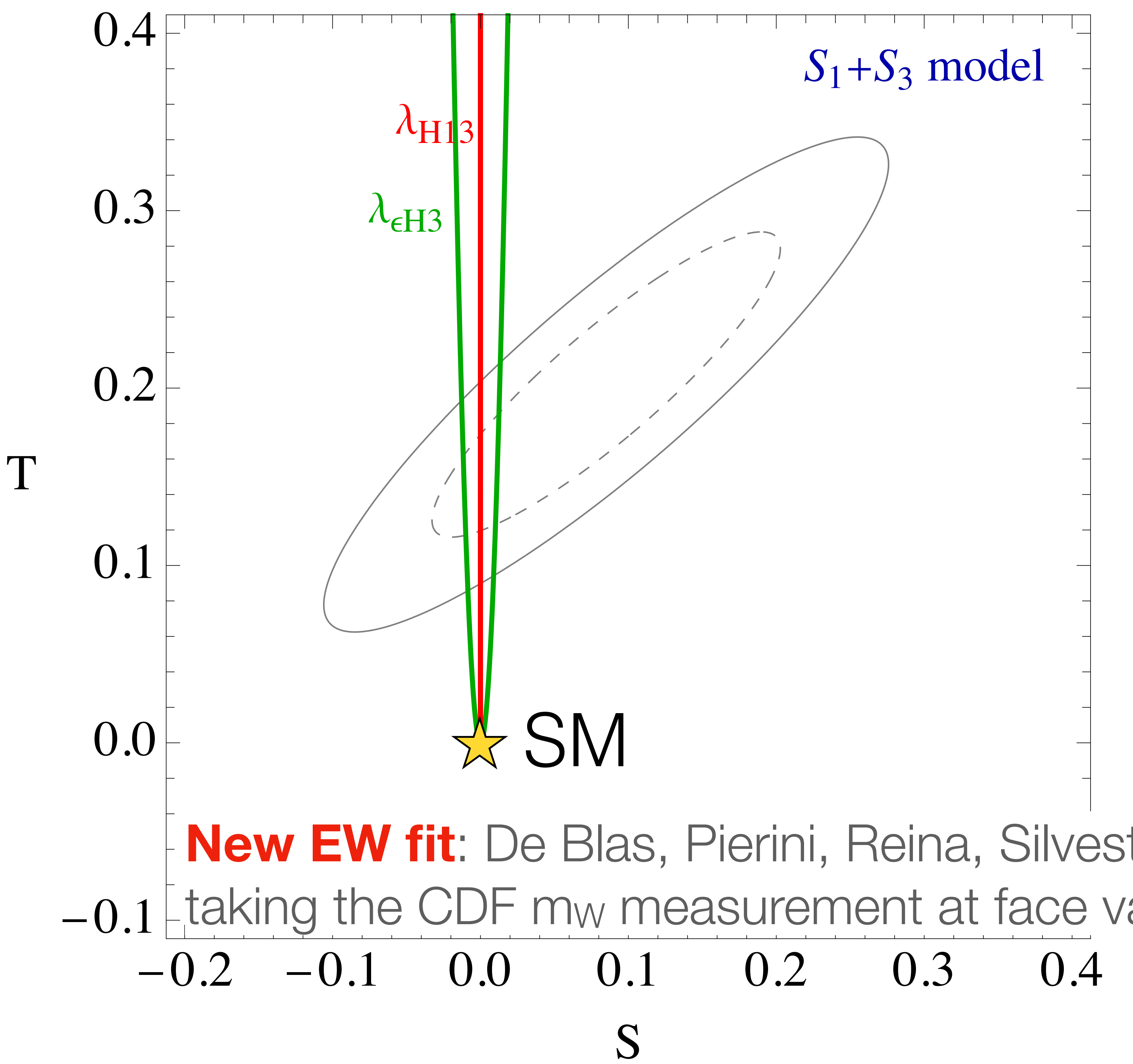
S_1, S_3 & m_W

The two LQ have potential couplings to the Higgs, these contribute to the EW oblique params S and T

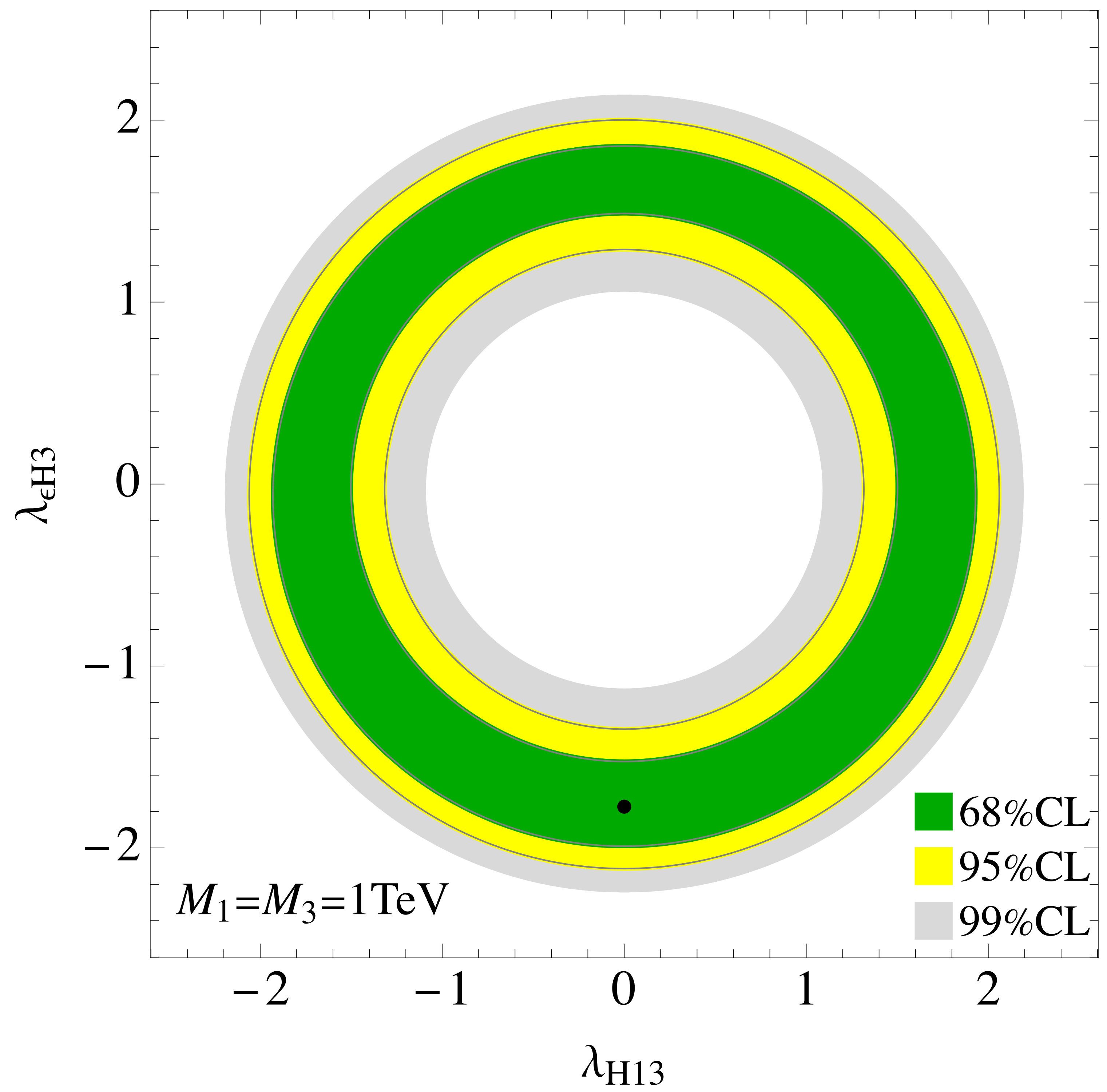
$$\mathcal{L}_{\rm LQ} \supset -\underbrace{\left(\lambda_{H13}(H^\dagger \sigma^I H) S_3^{I\dagger} S_1 + \text{h.c.}\right)}_{S_1\text{-}S_3\text{ mixing}} - \underbrace{\lambda_{\epsilon H3} i\epsilon^{IJK} (H^\dagger \sigma^I H) S_3^{J\dagger} S_3^K}_{\text{only } S_3}$$

V. Gherardi, E. Venturini, D.M. [2008.09548] See also 1910.03877, 2006.10758 and 2204.03996

Could these LQ address the m_W discrepancy recently claimed by CDF? Yes!



New EW fit: De Blas, Pierini, Reina, Silvestrini 2204.04204 taking the CDF m_W measurement at face value



They can fit the anomaly with ~1TeV masses and O(1) couplings

Discussion points

- **To LHCb: is $R_{K^{(*)}} < 1$?**

- **Simplified models** aim to provide **coherent explanations of observed anomalies** with **minimal set of couplings**, compatibly with all existent constraints.
  Many predictions are typically derived

- All combined explanations of B-anomalies predict possible large effects in

  Belle-II: τ *LFU*, $\tau \to \mu\,\gamma$, $\tau \to 3\,\mu$ $\quad b \to s\,\tau\,\tau$, $b \to s\,\tau\,\mu$

  ATLAS, CMS: **High-energy tails of** $pp \to \tau\,\tau$, $\tau\,\nu$

- If couplings to 1st gen are U(2)-like, then expect also possible effects in:

  NA62, KOTO: $K \to \pi\,\nu\,\nu$

  Mu3e, MEG, Mu2e, COMET: $\mu \to 3\,e$, $\mu \to 3\,\gamma$, $\mu \to e$ conversion

- UV completions typically aim at solving also other outstanding SM puzzles (more model dependence):

  Unification [S_3 + R_2 > SU(5); U_1 > Pati Salam], ***EW hierarchy problem*** [S_1 + S_3 > Comp. Higgs.]

Backup

Embedding to SU(5) GUT

- Choice of Yukawas was biased by $SU(5)$ GUT aspirations
- Scalars: $R_2 \in \underline{\mathbf{45}}, \underline{\mathbf{50}}$, $S_3 \in \underline{\mathbf{45}}$. SM matter fields in $\mathbf{5}_i$ and $\mathbf{10}_i$
- Operators $\mathbf{10}_i \mathbf{10}_j \underline{\mathbf{45}}$ forbidden to prevent proton decay [Dorsner et al 2017]
- Available operators

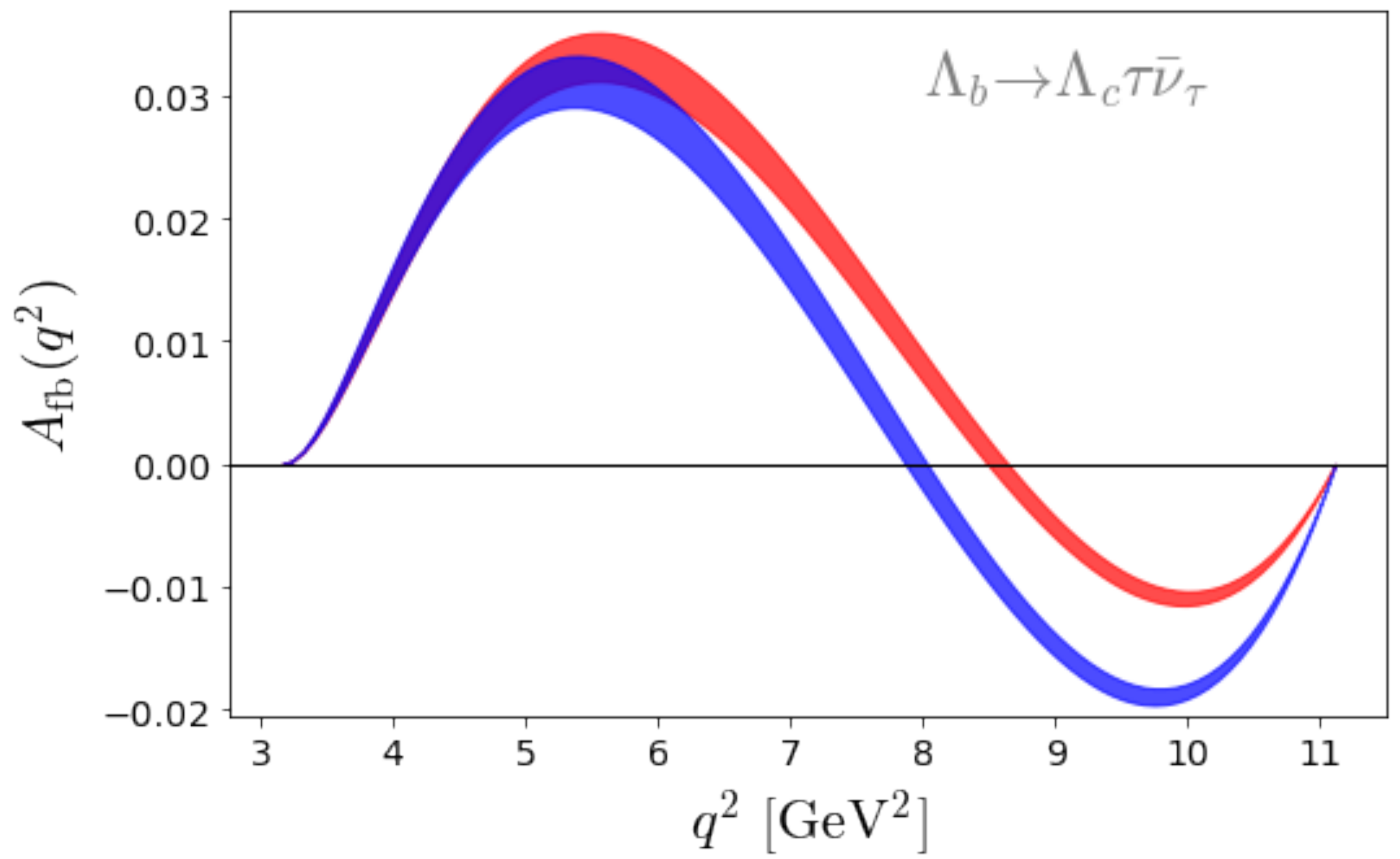
$$\begin{aligned} \mathbf{10}_i \mathbf{5}_j \underline{\mathbf{45}} : &\quad y^{RL}_{2\,ij} \overline{u}^i_R R^a_2 \varepsilon^{ab} L^{j,b}_L, \quad y^{LL}_{3\,ij} \overline{Q^c}^{i,a}_L \varepsilon^{ab} (\tau^k S^k_3)^{bc} L^{j,c}_L \\ \mathbf{10}_i \mathbf{10}_j \underline{\mathbf{50}} : &\quad y^{LR}_{2\,ij} \overline{e}^i_R R^{a\,*}_2 Q^{j,a}_L \end{aligned}$$

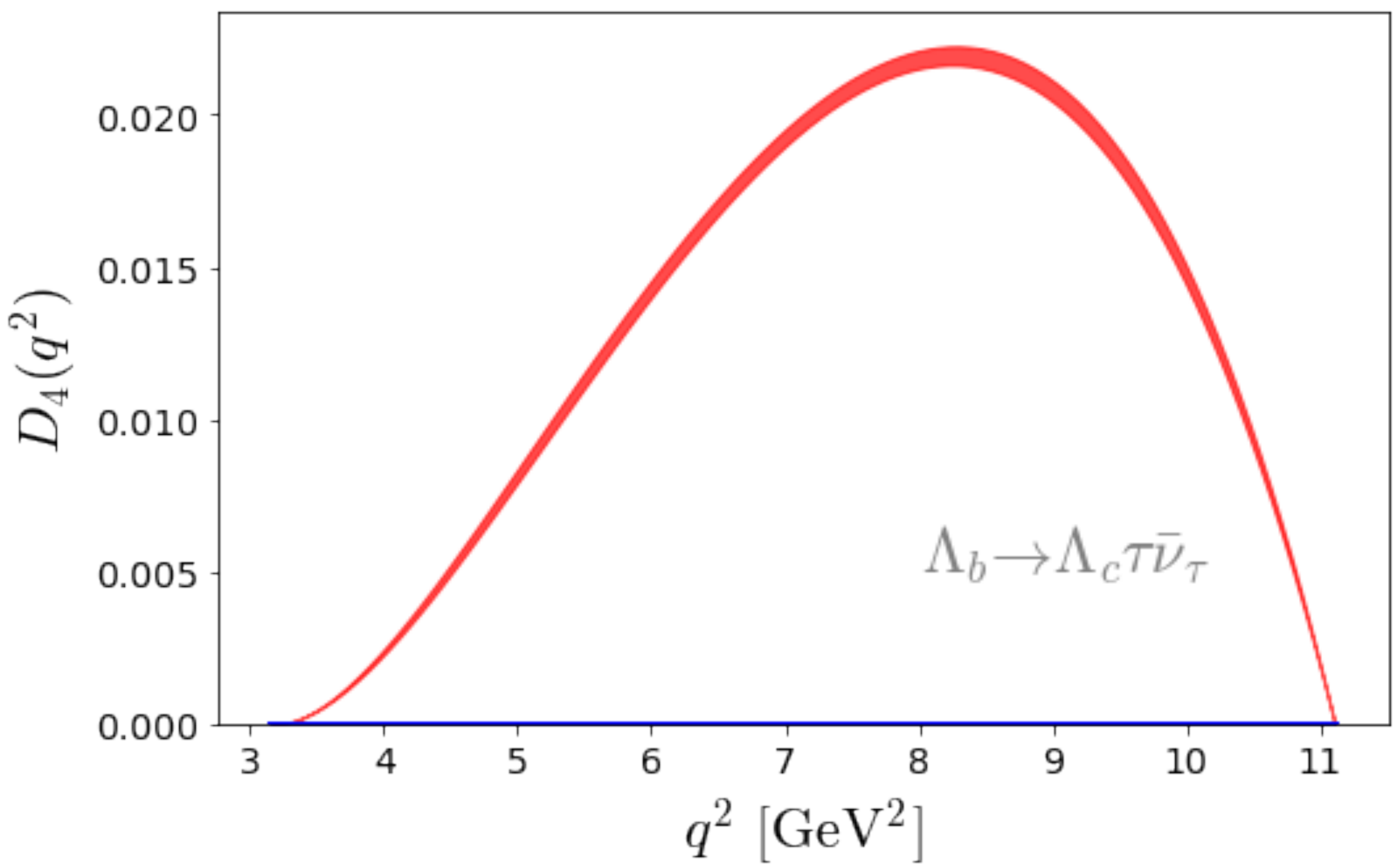
- While breaking $SU(5)$ down to SM the two R_2's mix – one can be light and the other (very) heavy. Thus our initial Lagrangian!
- Interestingly the Yukawa couplings determined from flavor physics observables at low energy remain perturbative (below $\sqrt{4\pi}$) up to the GUT scale $\Lambda_{\rm GUT} = 5 \times 10^{15}$ GeV, if we use 1-loop running [Wise et al 2014]

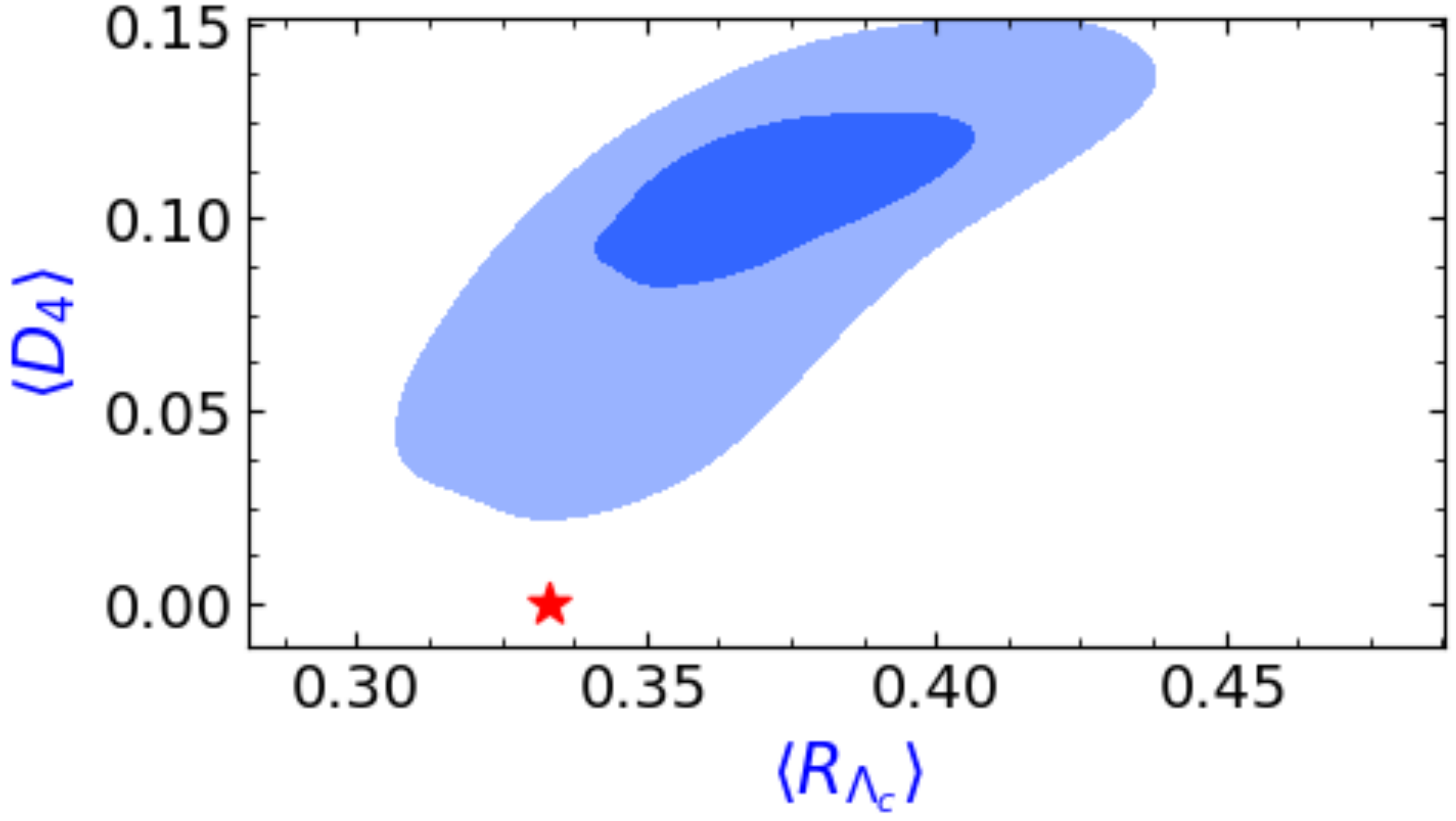
Discriminating power of the angular distribution

Eg. baryons

$$\frac{d^4\mathcal{B}}{dq^2 d\cos\theta_\tau d\cos\theta d\phi} = A_1 + A_2\cos\theta$$
$$+ (B_1 + B_2\cos\theta)\cos\theta_\tau + (C_1 + C_2\cos\theta)\cos^2\theta_\tau$$
$$+ (D_3\sin\theta\cos\phi + D_4\sin\theta\sin\phi)\sin\theta_\tau$$
$$+ (E_3\sin\theta\cos\phi + E_4\sin\theta\sin\phi)\sin\theta_\tau\cos\theta_\tau$$





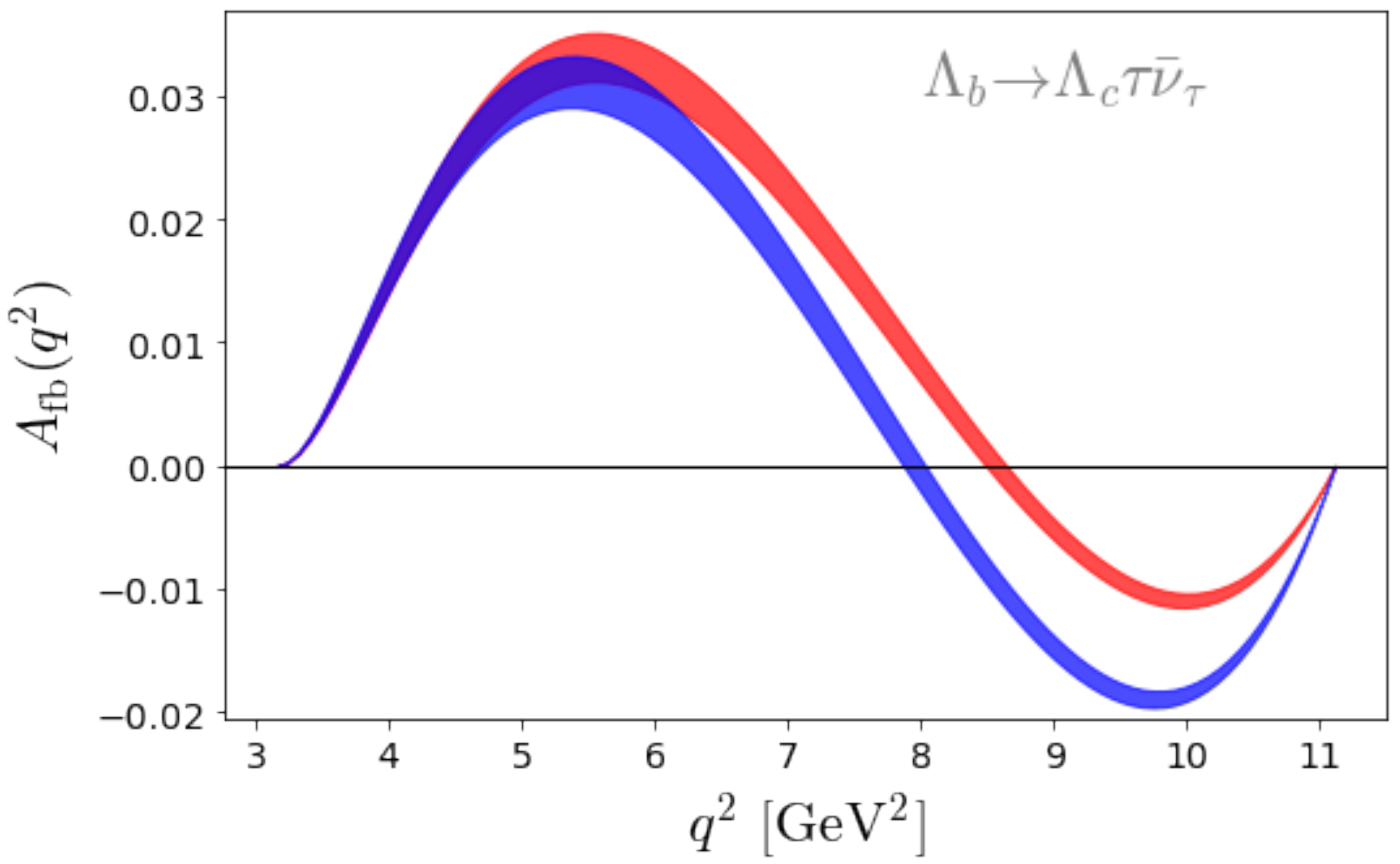


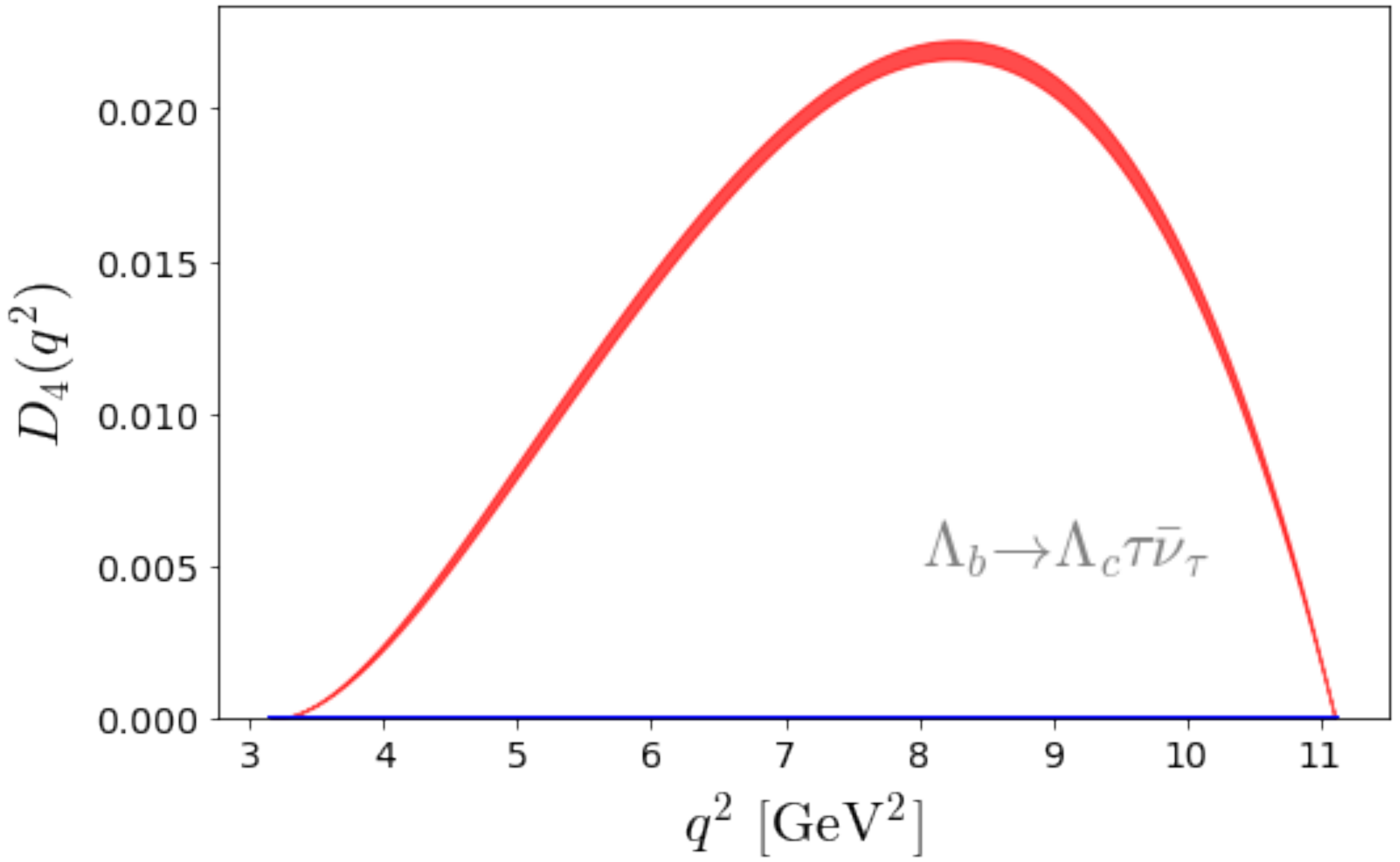
In case of mesons $A_{\rm fb}(q^2)$ and $\langle A_{\rm fb}\rangle$ can help discriminating $S_1 - S_3$ model. Cf. 2106.09610

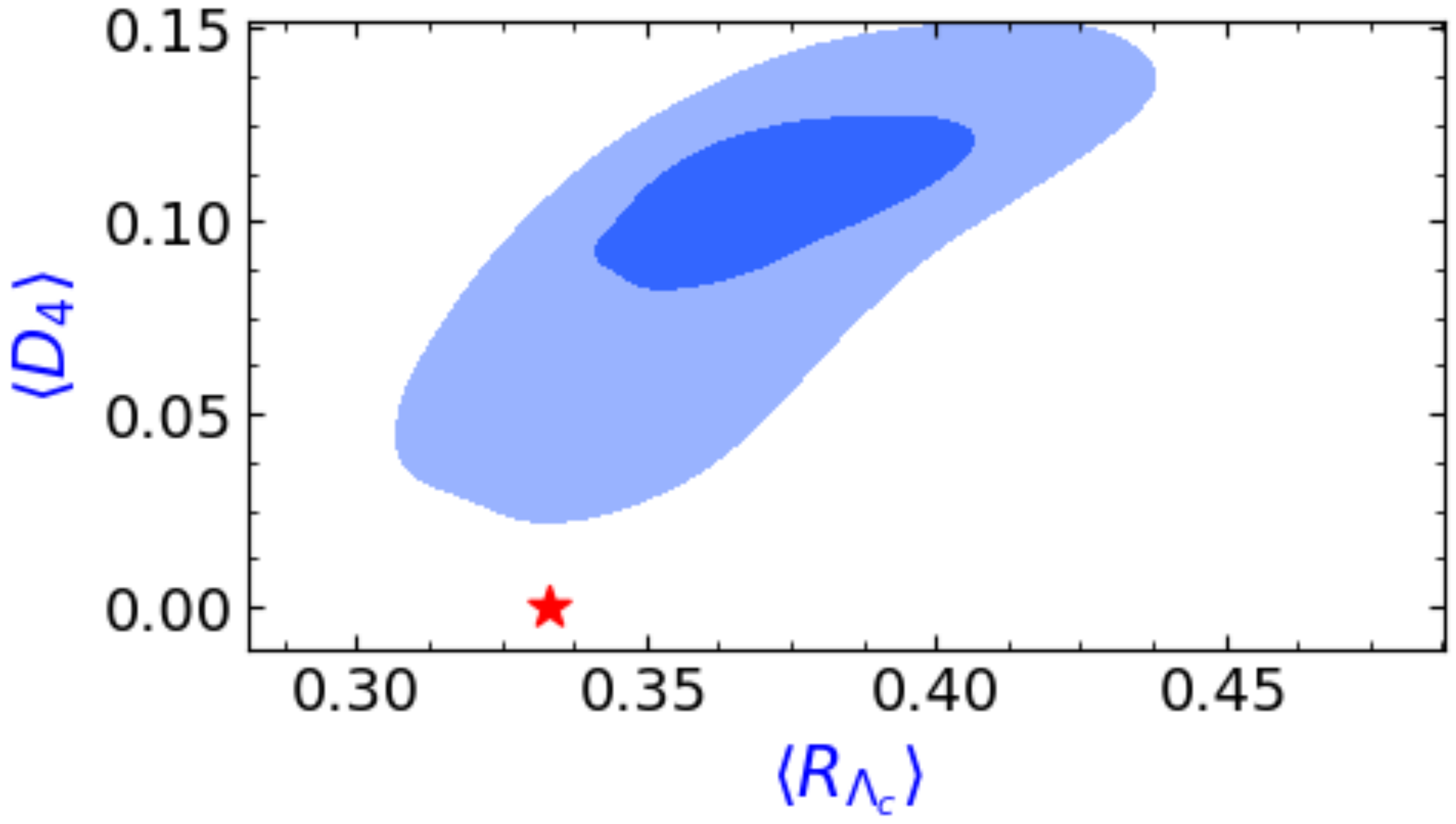
Discriminating power of the angular distribution

Eg. baryons

$$\frac{d^4\mathcal{B}}{dq^2 d\cos\theta_\tau d\cos\theta d\phi} = A_1 + A_2\cos\theta$$
$$+ (B_1 + B_2\cos\theta)\cos\theta_\tau + (C_1 + C_2\cos\theta)\cos^2\theta_\tau$$
$$+ (D_3\sin\theta\cos\phi + D_4\sin\theta\sin\phi)\sin\theta_\tau$$
$$+ (E_3\sin\theta\cos\phi + E_4\sin\theta\sin\phi)\sin\theta_\tau\cos\theta_\tau$$







2201.03497

NEW : $R(\Lambda_c)^{\rm LHCb} = 0.242(76)$ $R(\Lambda_c)^{\rm SM} = 0.333(13)$

From data to theories

UV theory

Full-fledged UV theories, typically many states, symmetries, etc..
> Correlates pheno of different states

Simplified Models

Assume specific mediators
> more correlations, loops, bounds from direct searches

EFT interpretation

Assume $M_{NP} \gg E_{exp}$ (or $M_{NP} \gg m_{EW}$)
> some correlations among observables, little model dependence

Experimental Data

Physical (pseudo-)observables
> only basic assumptions, very minimal model dependence

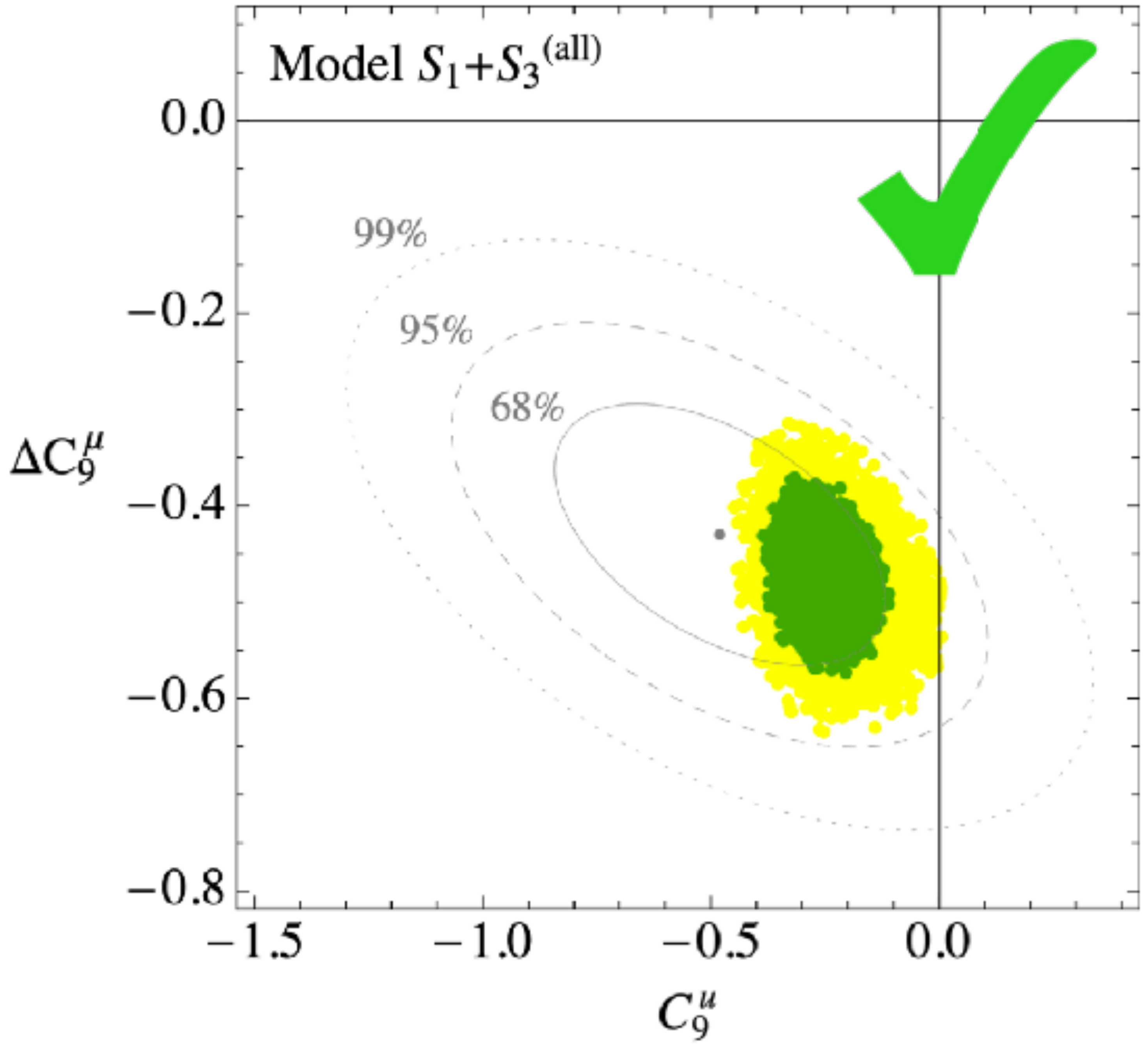
S_1 and S_3 : R($K^{(*)}$) + R($D^{(*)}$) + $(g-2)_\mu$

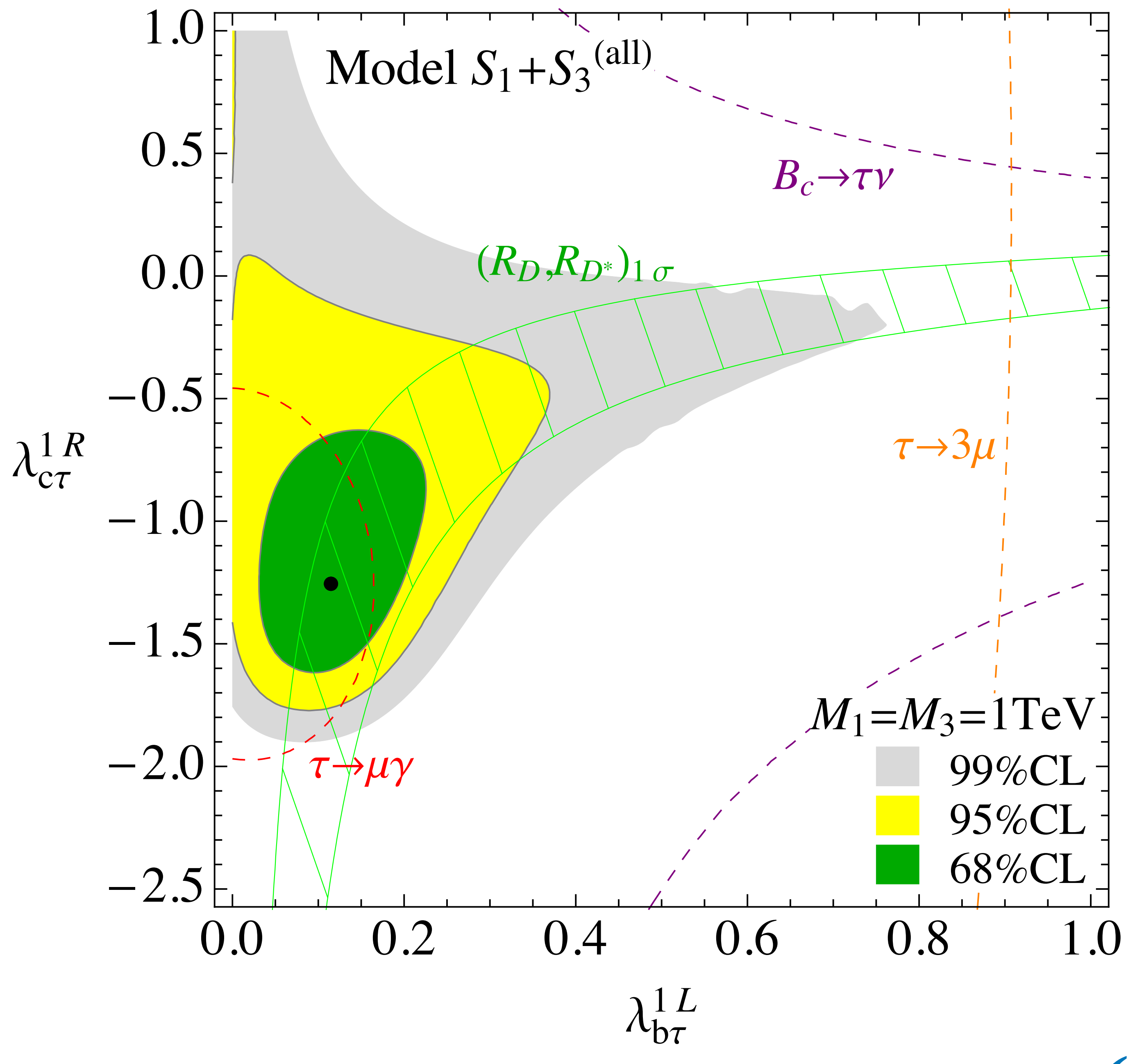
No a-priori flavour structure imposed

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

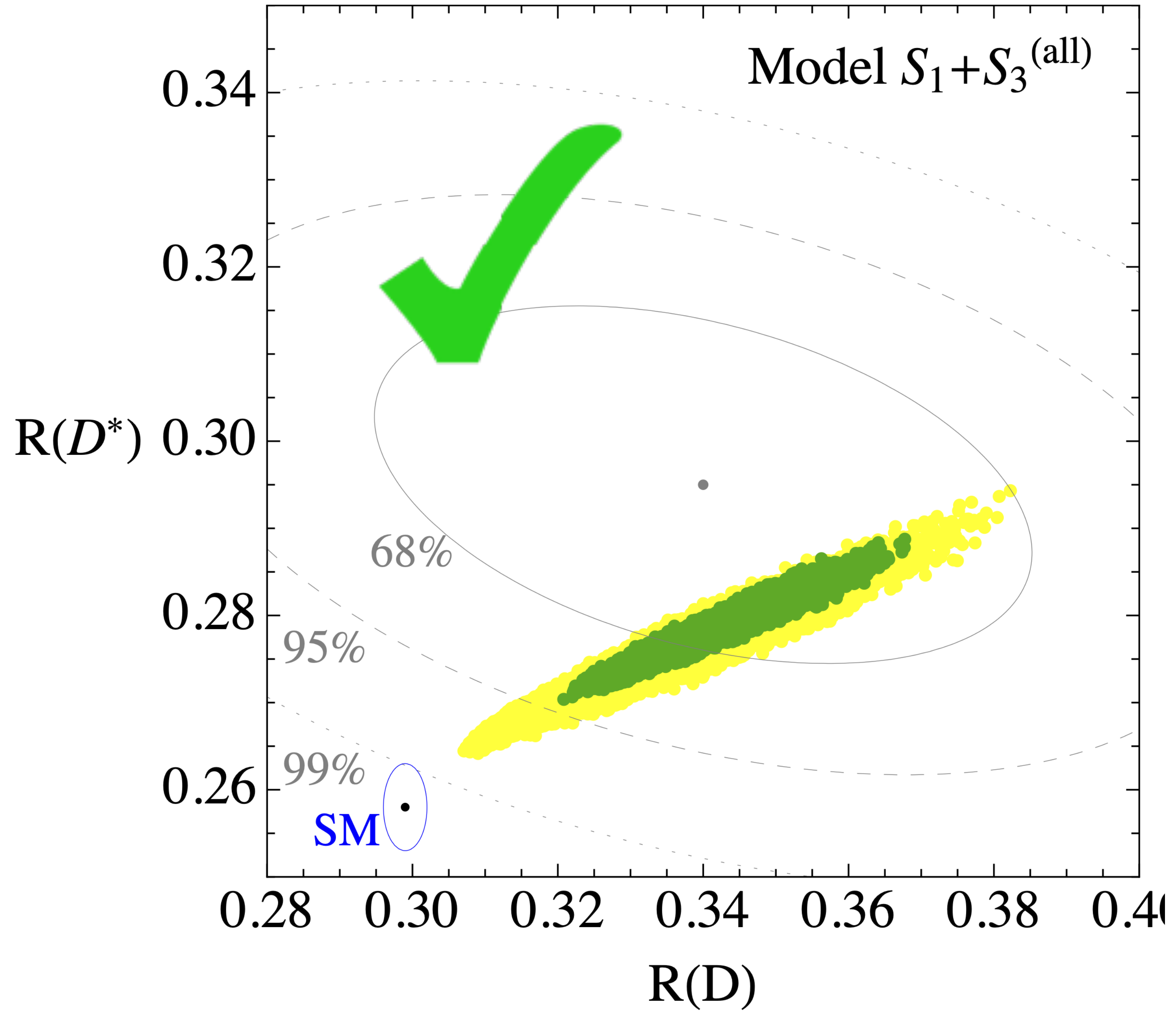
$$\lambda^{1R} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & c\tau \\ 0 & t\mu & t\tau \end{pmatrix}$$

$b \to s\,\ell\,\ell$

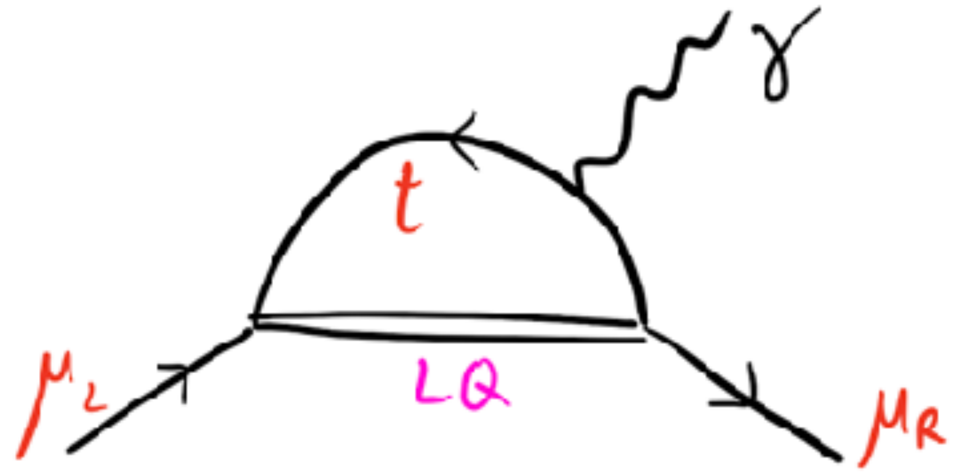


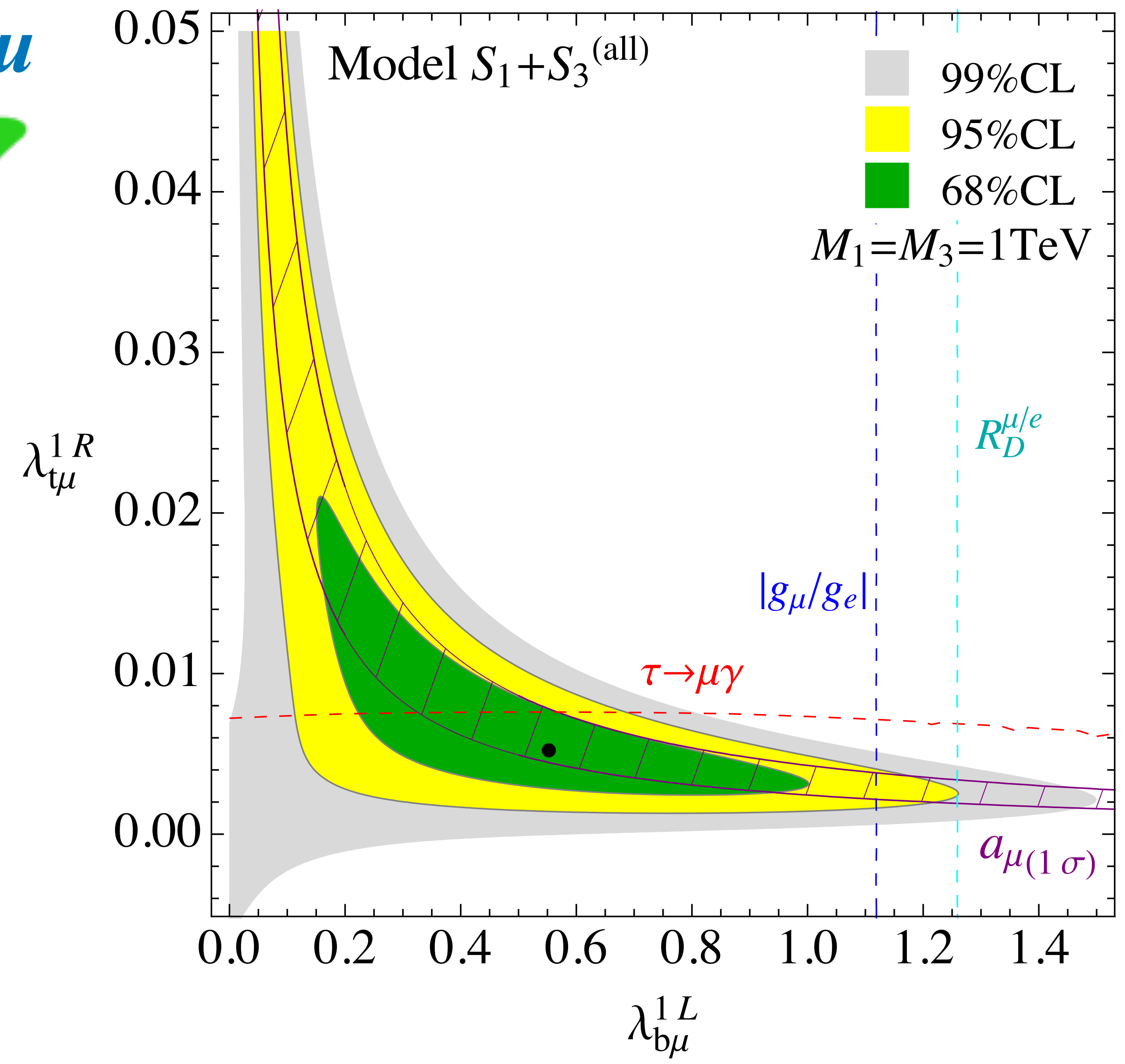


R($D^{(*)}$)



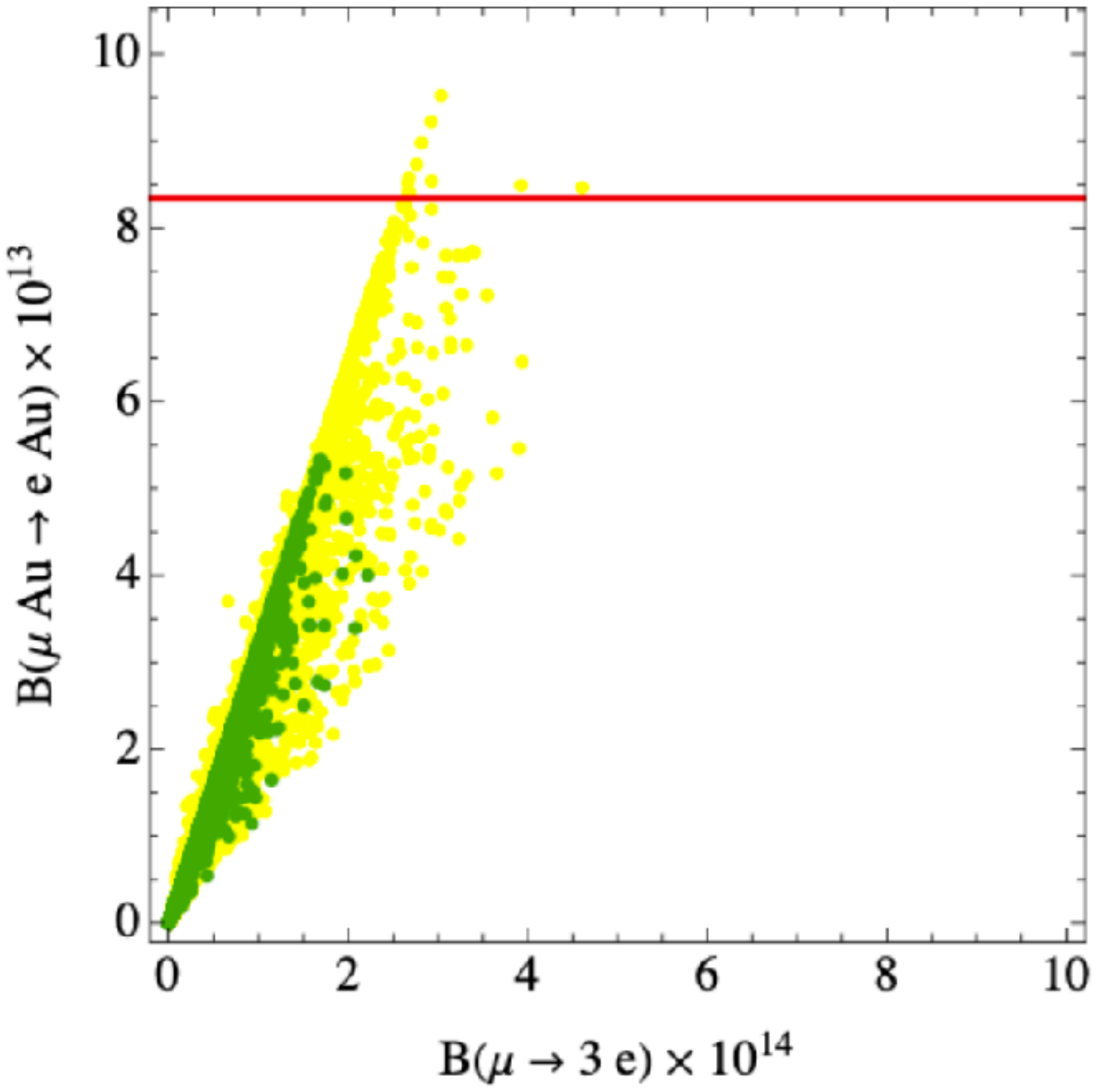
$(g-2)_\mu$





Very good fit of all anomalies!

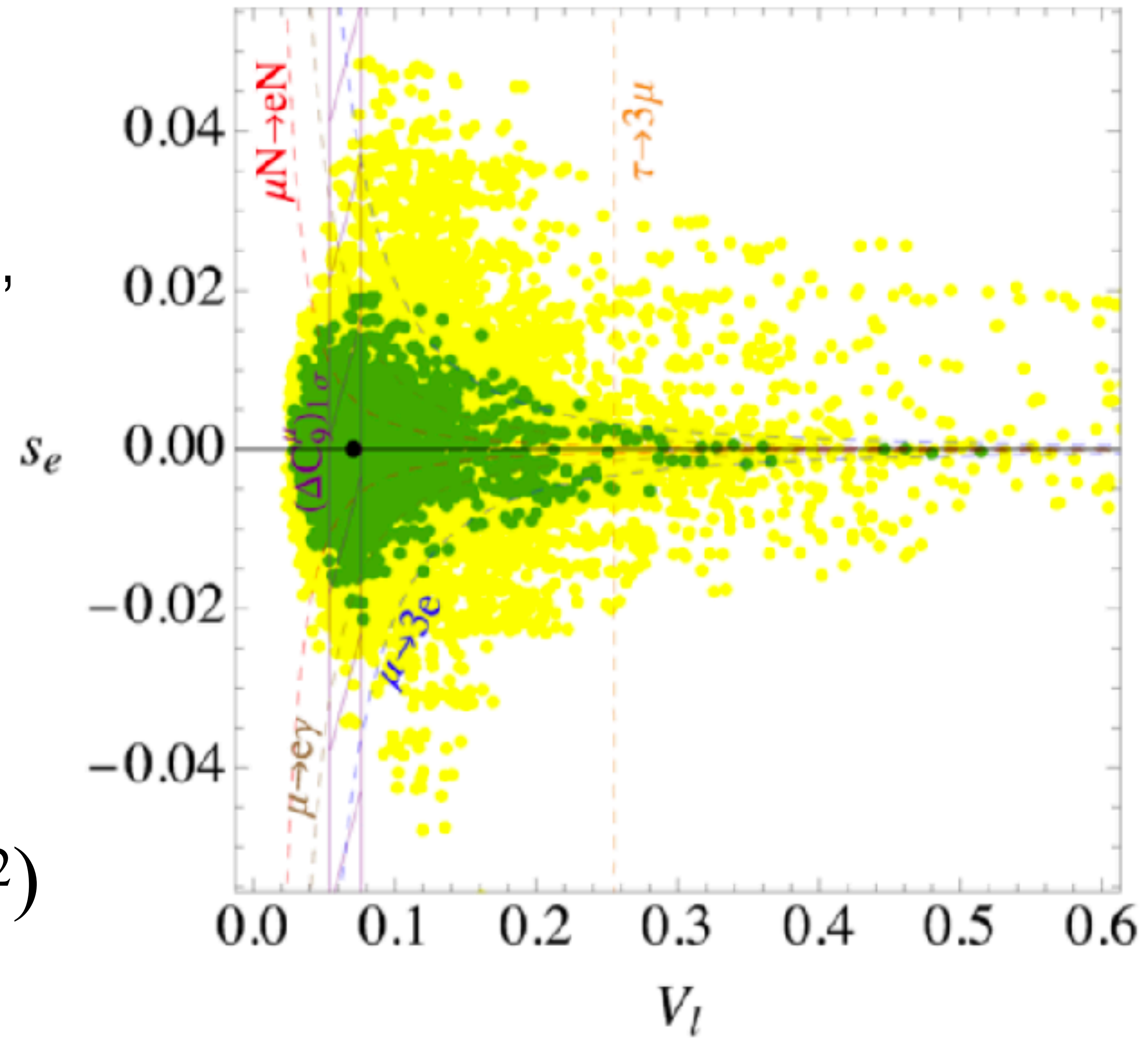
μ → e conversion



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.

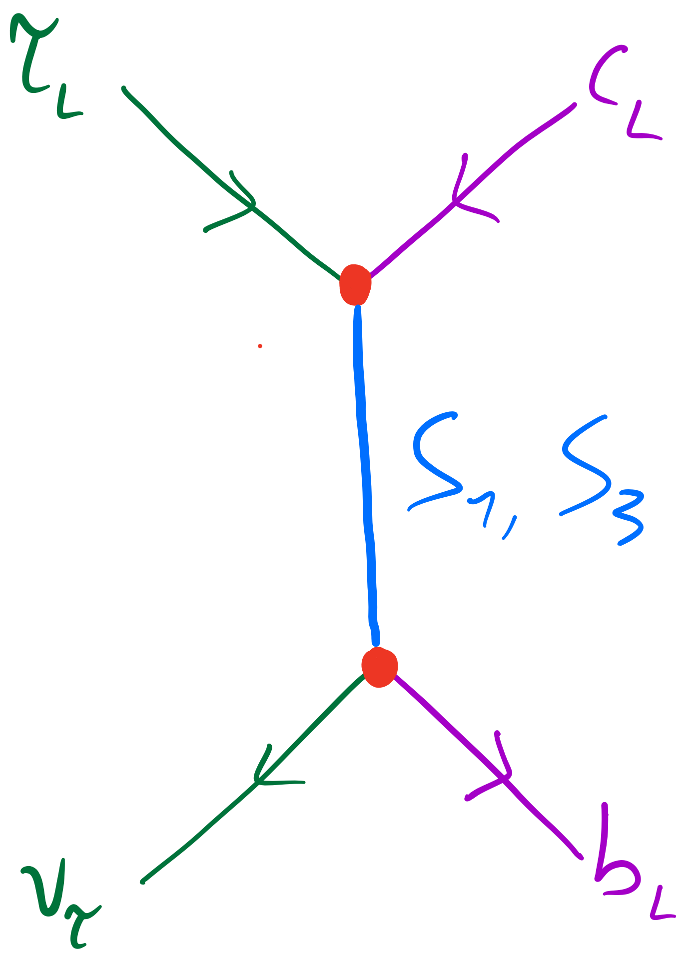


Naive expectation would be $s_e \sim \sqrt{(m_e/m_\mu)} \sim O(10^{-2})$

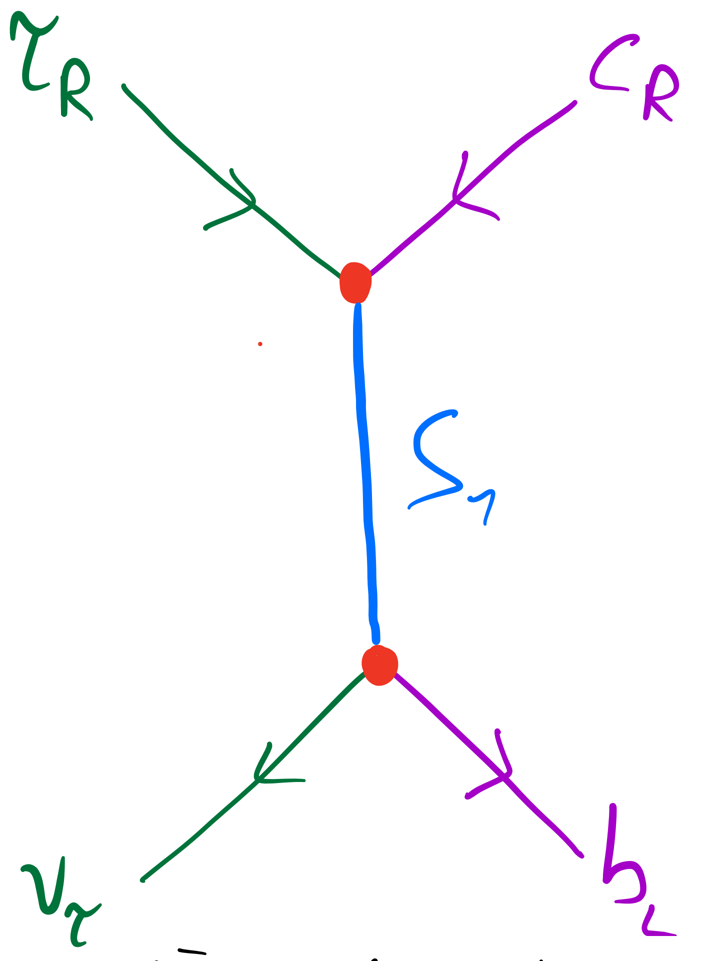
S_1 and S_3 - contributions to anomalies

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

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



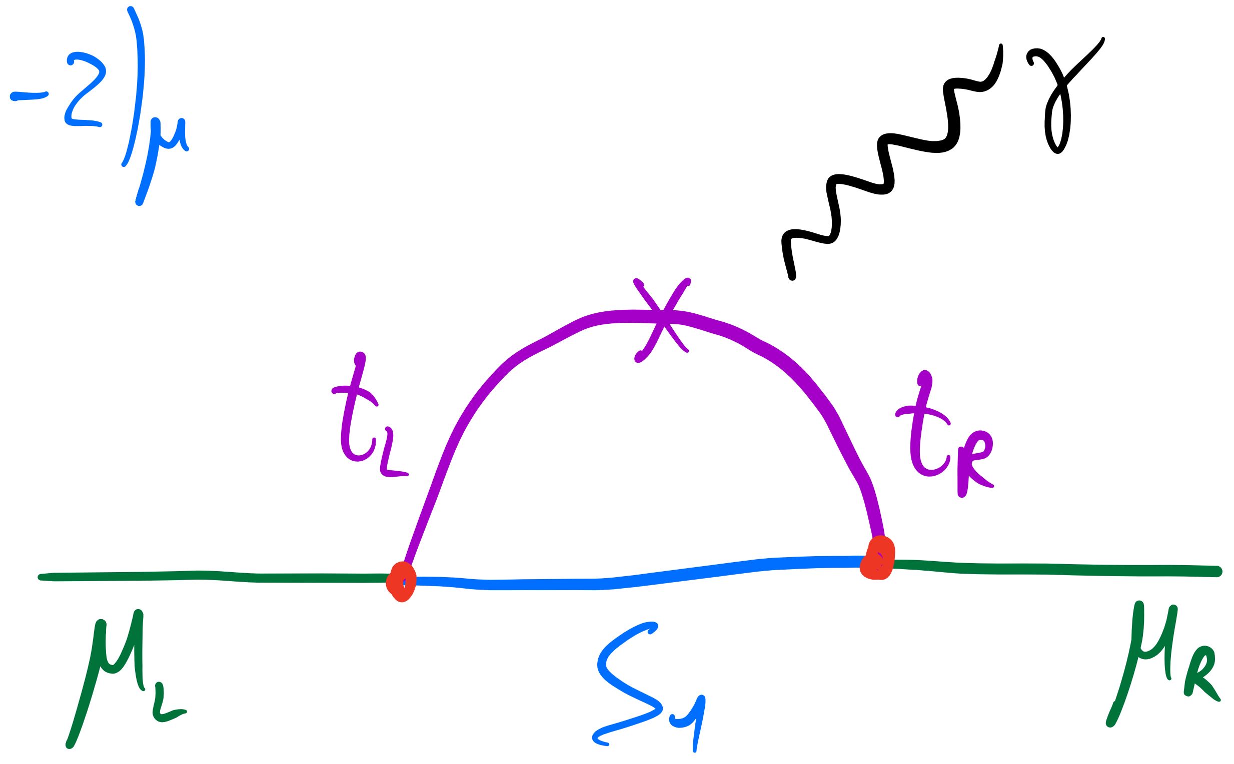
$(\bar{b}_L \gamma_\mu c_L)(\bar{\nu}_\tau \gamma^\mu \tau_L)$



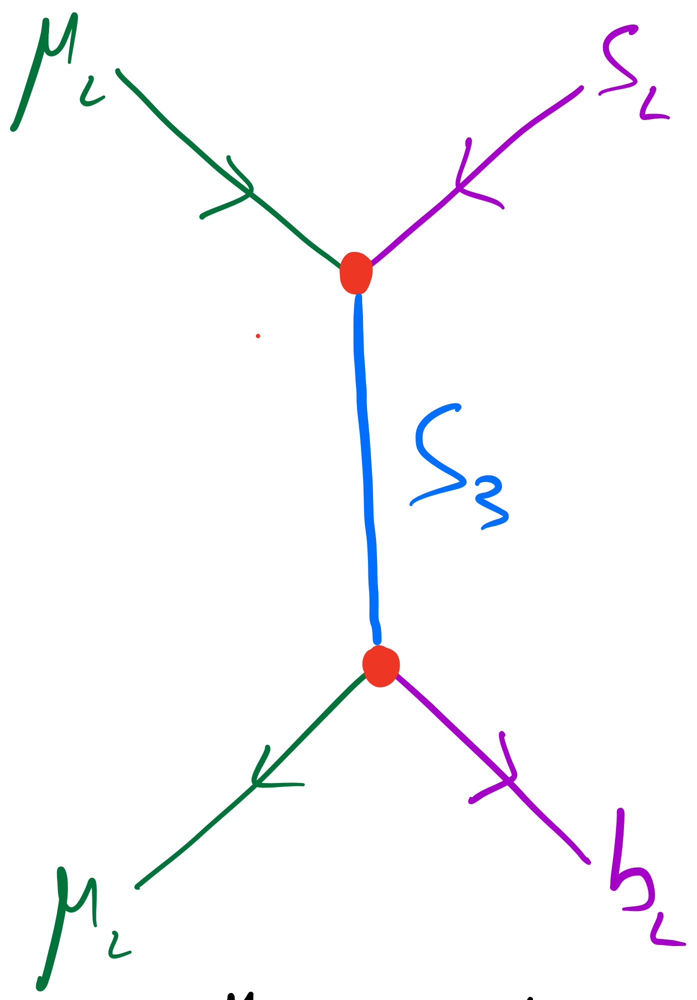
$(\bar{b}_L c_R)(\bar{\nu}_\tau \tau_R)$

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

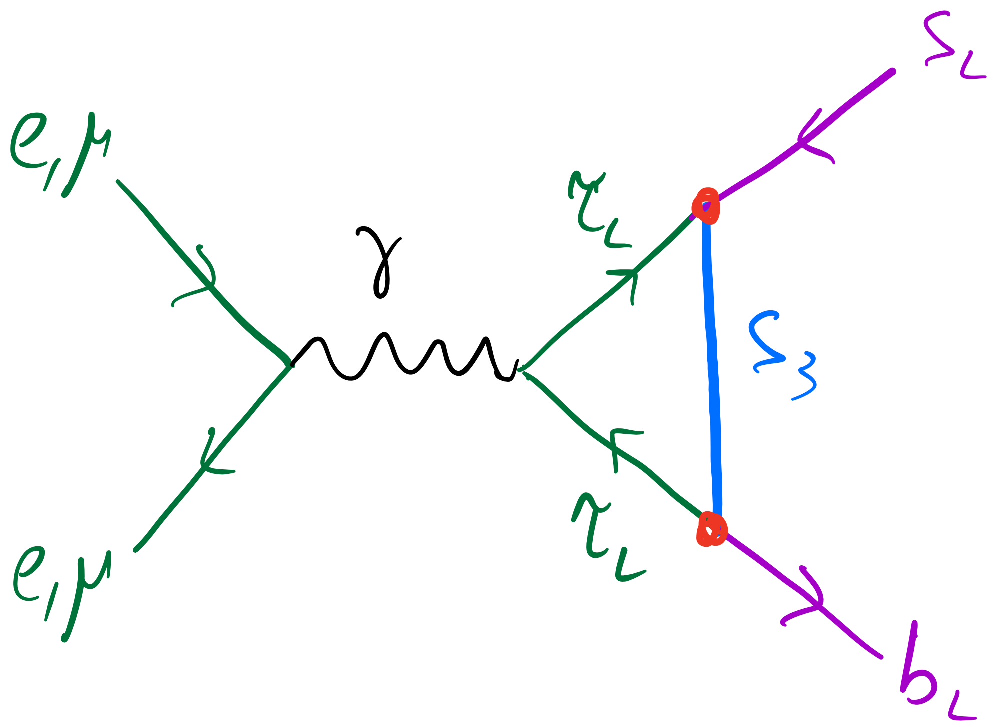
$(g-2)_\mu$



$b \to s\mu\mu$



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



C_9^U

S_1 and S_3 - global analysis

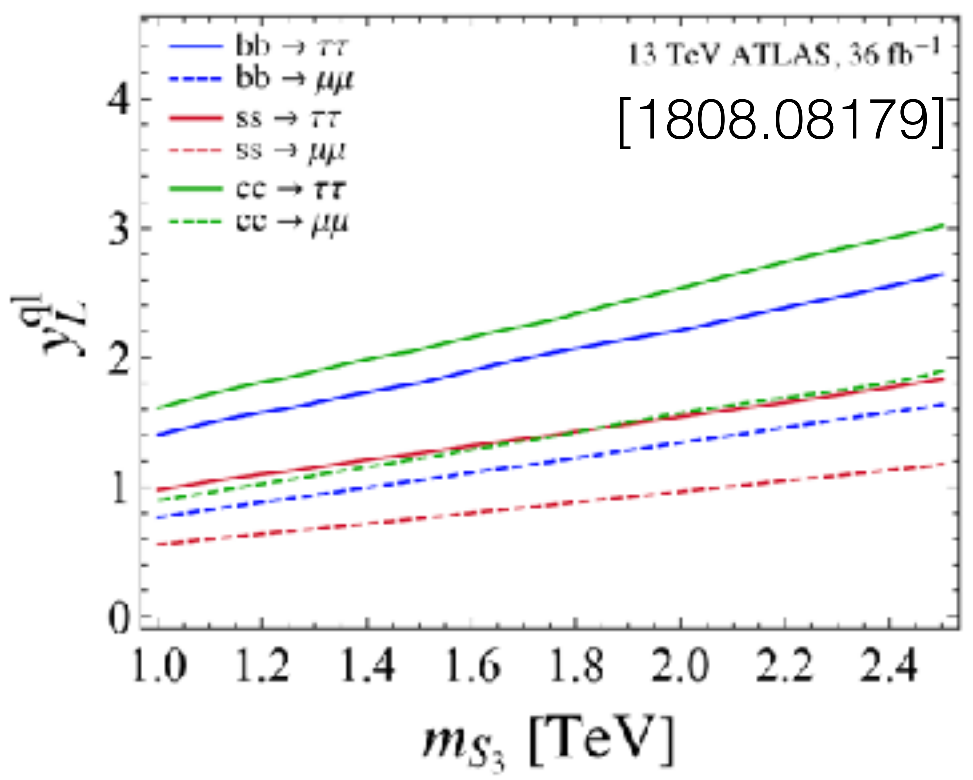
Using the complete one-loop matching to SMEFT, we include in our analysis the following observables.

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]
$\Delta C_9^{sb\mu\mu}$	0	-0.43 ± 0.09 [79]
$C_9^{\rm univ}$	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]

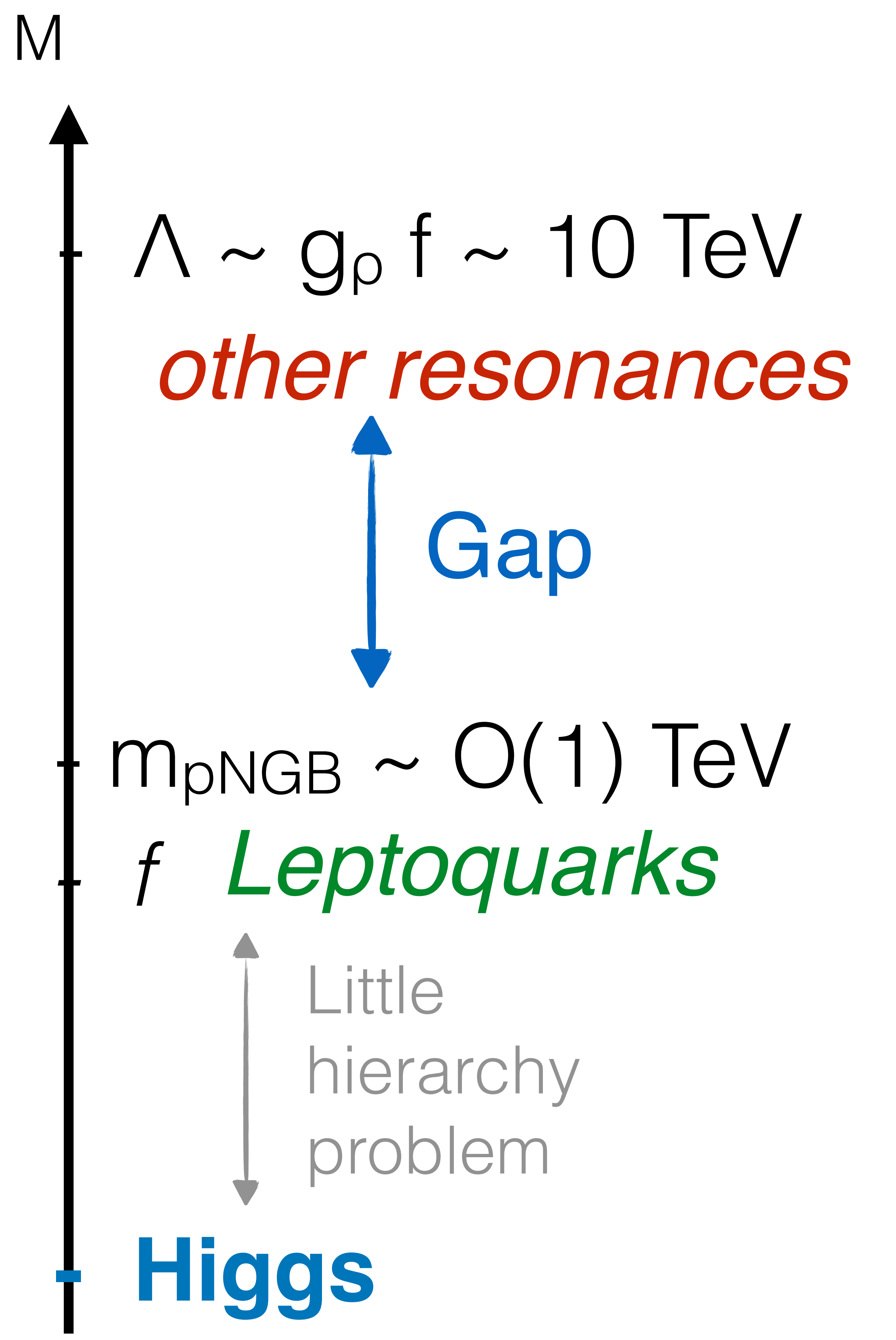
Observable	SM prediction	Experimental bounds
D leptonic decay		[37] and App. A.4
$\mathcal{B}(D_s \to \tau\nu)$	$(5.169 \pm 0.004) \times 10^{-2}$ [94]	$(5.48 \pm 0.23) \times 10^{-2}$ [51]
$\mathcal{B}(D^0 \to \mu\mu)$	$\approx 10^{-11}$ [95]	$< 7.6 \times 10^{-9}$ [96]
$\mathcal{B}(D^+ \to \pi^+\mu\mu)$	$\mathcal{O}(10^{-12})$ [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]
$B_s^0 - \overline{B}_s^0$: $\lvert C^1_{B_s}\rvert$	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]
$\mathcal{B}^{(\rm Ti)}_{\mu e}$	0	$< 5.1 \times 10^{-12}$ [122]
$\mathcal{B}^{(\rm Au)}_{\mu e}$	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]

Scalar LQ & Higgs: both pseudo-Goldstones?

Scalar LQs could arise as pNGB together with the Higgs from the same G/H of the strong sector.

[Gripaios 0910.1789, Gripaios, Nardecchia, Renner 1412.1791]



Low-energy phenomenology dominated by the LQs

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

Having the same origin, it is expected that LQ couplings have same structure as Higgs Yukawa couplings:

possible connection with flavour structure