Flavour Anomalies: stepping stones to New Physics?

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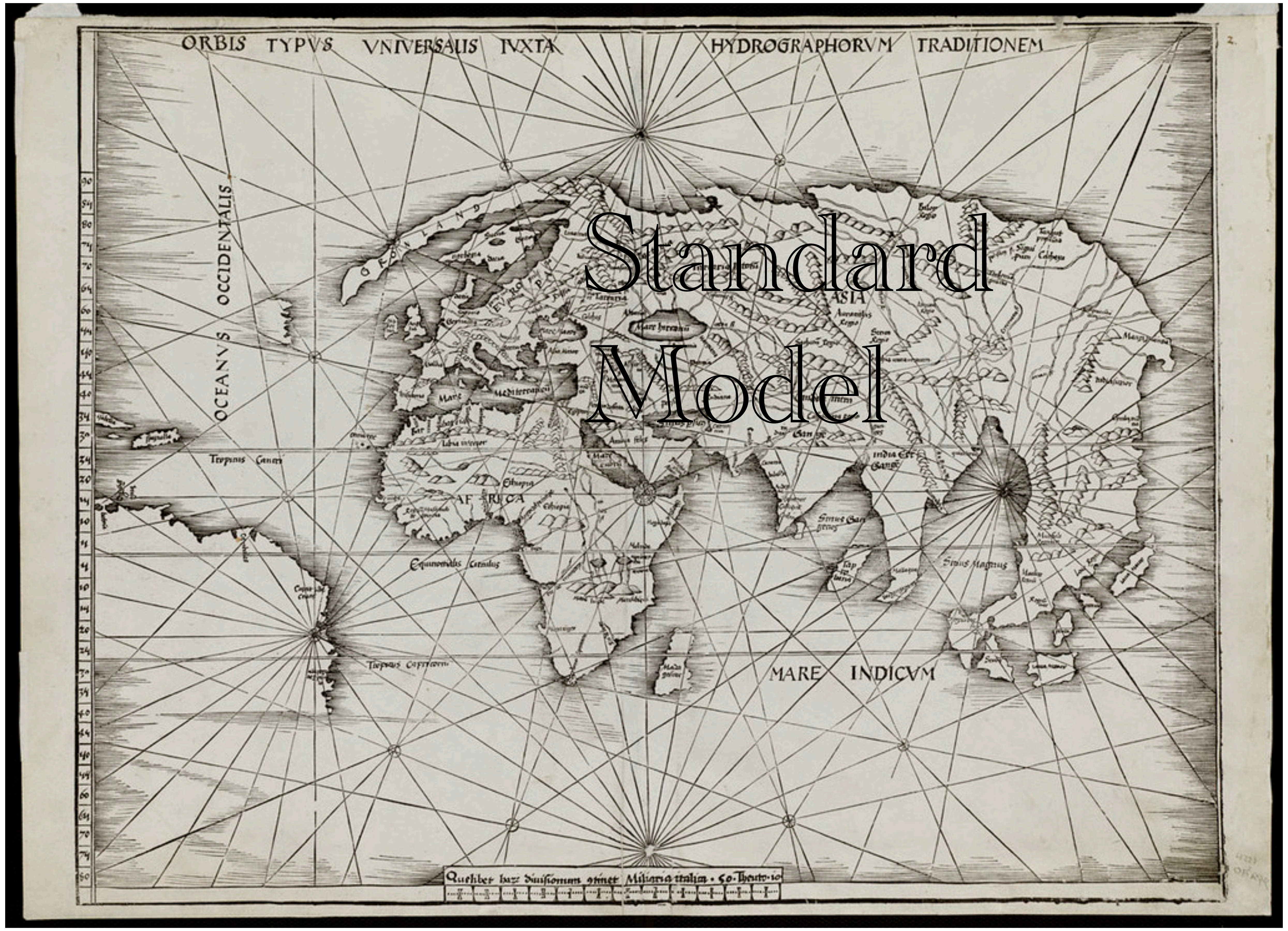
stepping stone
/ˈstɛpɪŋ stəʊn/
noun
plural noun: **stepping stones**
a raised stone used singly or in a series as a place on which to step when crossing a stream or muddy area.
- an action or event that helps one to make progress towards a specified goal.

U. Zurich - 12/10/2021

The ***Standard Model of particle physics*** describes a huge variety of phenomena in a unified and simple theory.



However, we <u>know</u> it must be extended at some energy scales:

- neutrino masses
- astrophysical/cosmological obs.
  (dark matter, dark energy, baryonic asymmetry, inflation)

Our desire for *simplicity* and a sense of *beauty* also motivates extensions of the SM for other reasons:

- hierarchy problem of the EW scale (and CC)
- understanding the hierarchies in fermion masses and mixings
- unification of gauge interactions and fermion representations
- understanding the smallness of CP-violation in strong interactions

Many experiments are exploring the *terra incognita* in all possible directions, but we still don't have a confirmed discovery of a new land.

… every once in a while, possible land is sighted.

Some of these *anomalies* might just be mirages,
however some could also be the first genuine hints of a New Land.

It is important to take each into consideration,
in order to understand how realistic it could be
and to point out the searches in promising directions

A selection of “anomalies” from the SM *

* not including cosmological anomalies from the ΛCDM

Flavour Anomalies

This talk

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

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

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

$(g\text{-}2)_e$

Cabibbo Angle

$p\, p \to e^+ e^-$

$\gamma\gamma$ @ ~~750~~ 151 GeV

Standard Model

Neutrino anomalies:
LSND, Miniboone, reactor, Gallium
5MeV "bump"

Atomki: 17 MeV excess in ^{8}Be decays

No viable NP

$\cancel{B_q \to D_q^{(*)+} \pi^- (K^-)}$

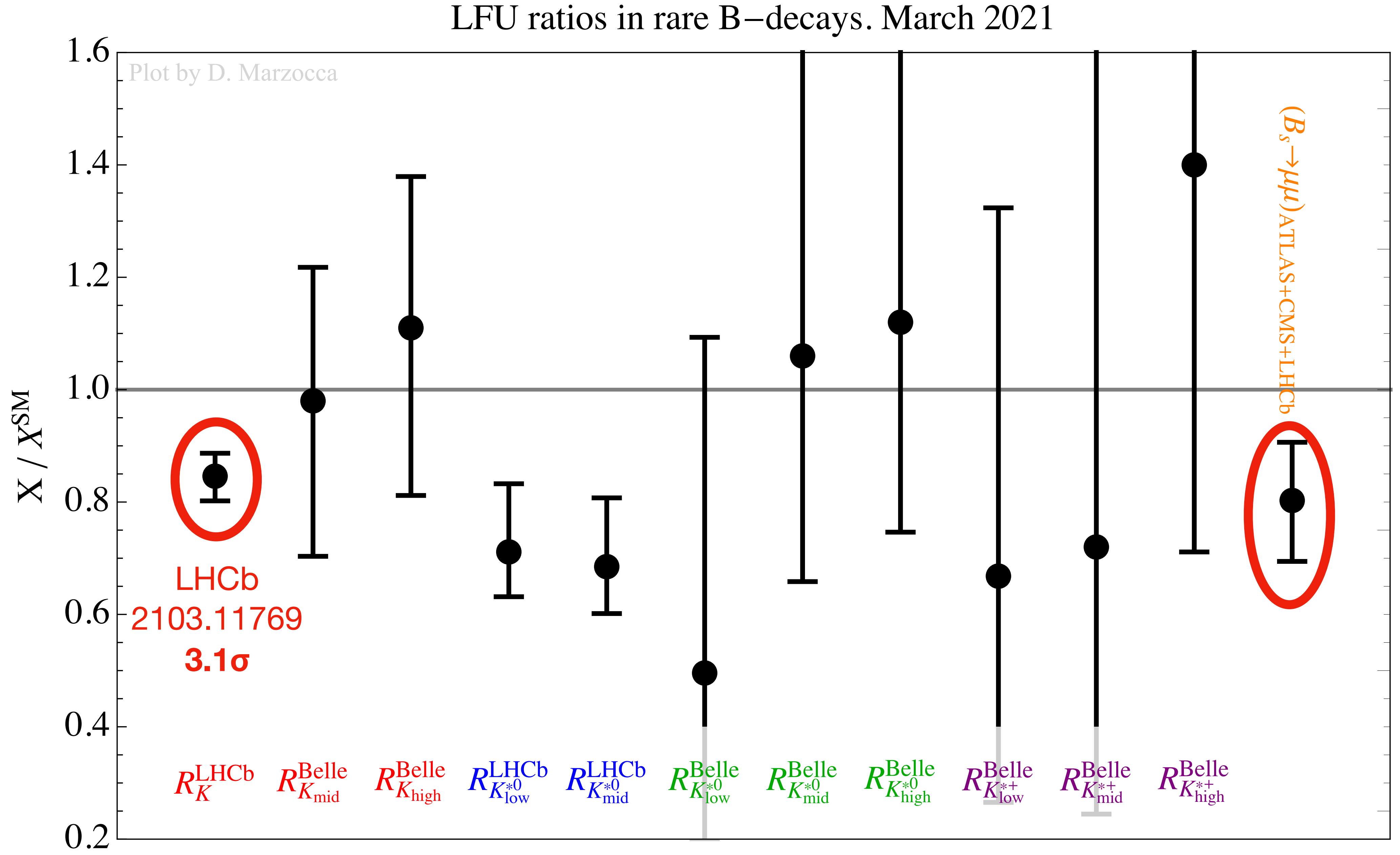
$\cancel{B_{d,s} \to K^{*0} \bar{K}^{*0}}$

Bordone, Greljo, DM [2103.10332]

Alguerò et al. [2011.07867]

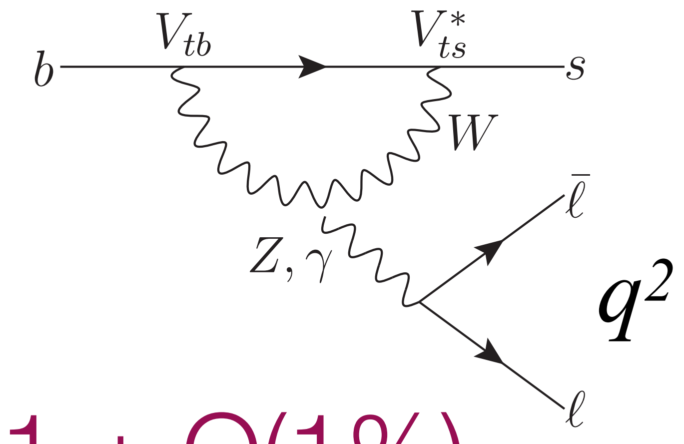
R_K and the other $b \to s\, \mu^+\mu^-$ probes

Compilation of "clean" observables



Lepton Flavour Universality (LFU) ratios

$$R_H \equiv \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\mathcal{B}(B \to H\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\mathcal{B}(B \to He^+e^-)}{dq^2} dq^2}$$



$\overset{\rm SM}{=} 1 \pm O(1\%)$

for $q^2 \gtrsim 1$ GeV

Bordone, Isidori, Pattori [1605.07633]

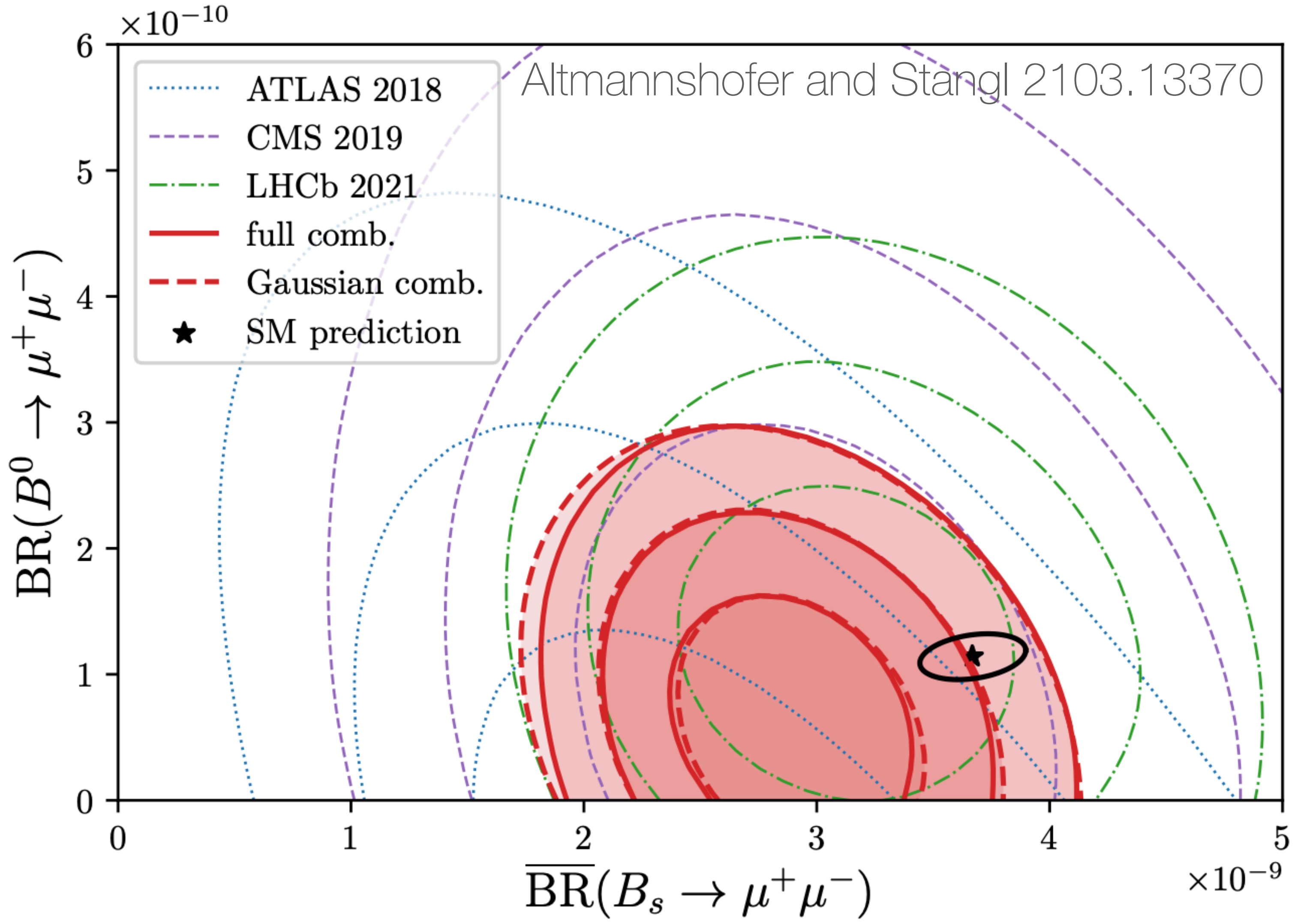
E.g. the most recent one from LHCb [2103.11769]

$$R_K(1.1 < q^2 < 6.0\,{\rm GeV}^2/c^4) = 0.846\,^{+0.042}_{-0.039}\,^{+0.013}_{-0.012}$$

3.1σ

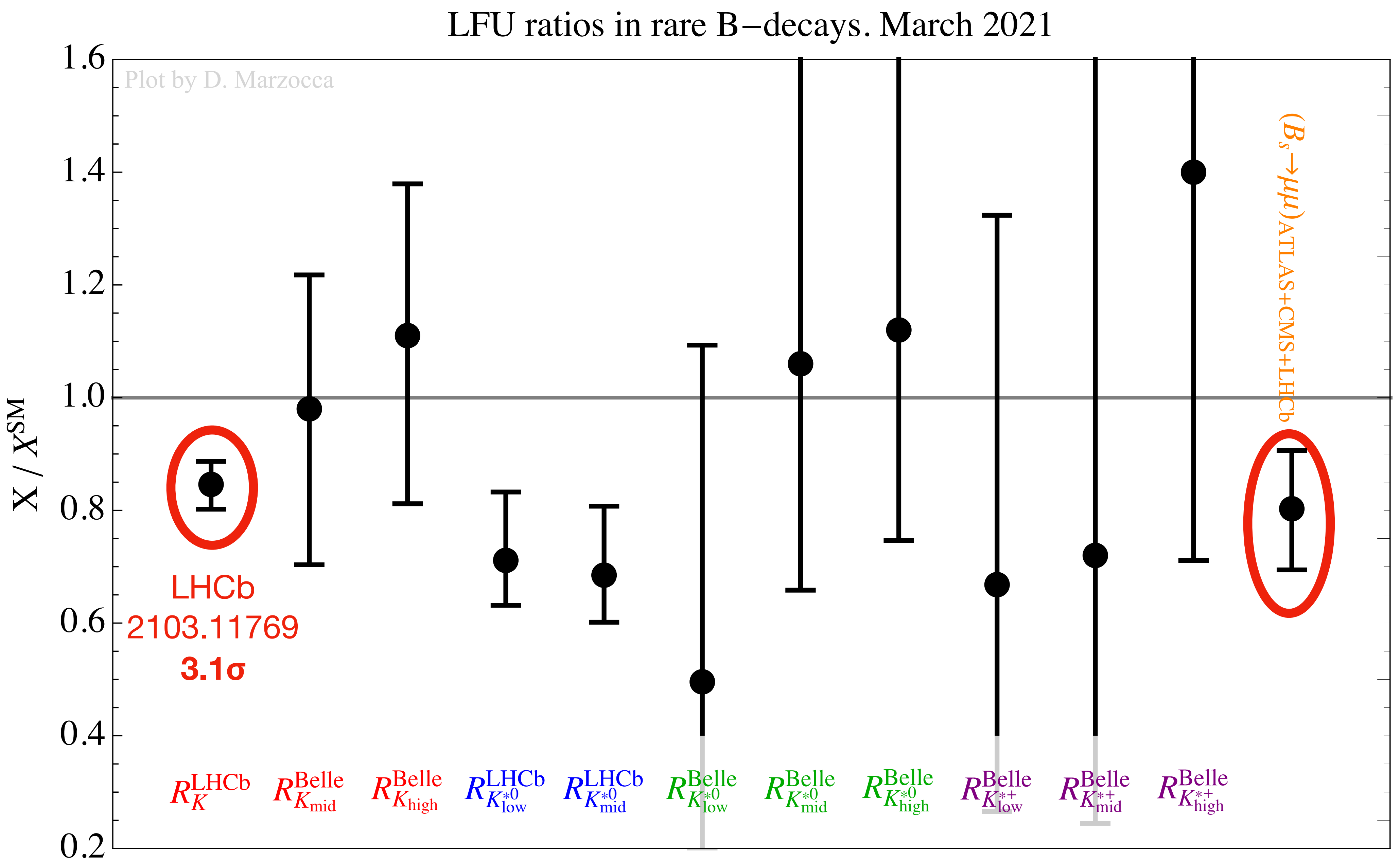
Also the leptonic decay $B_s \to \mu^+ \mu^-$ can be predicted precisely in the SM, and is measured by ATLAS, CMS, and LHCb.

It shows a consistent reduction w.r.t. the SM.

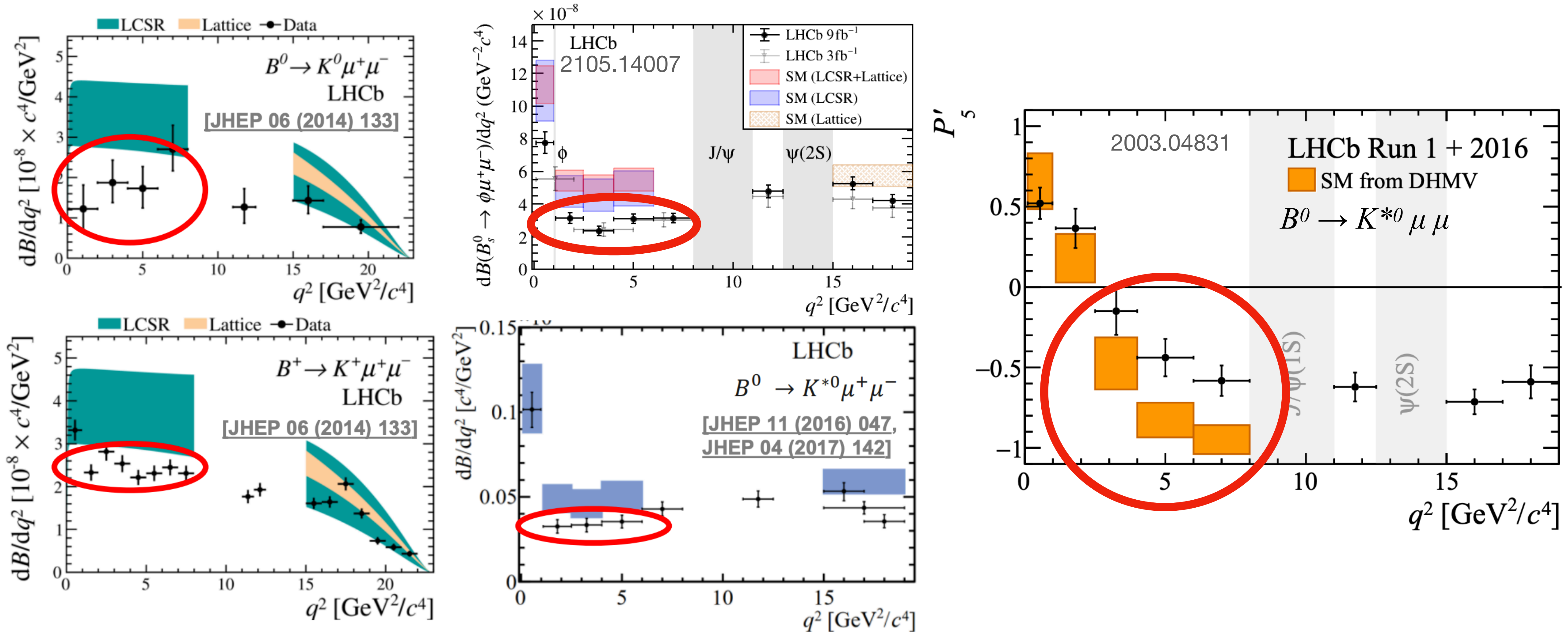


R_K and the other $b \to s\, \mu^+\mu^-$ probes

Compilation of "clean" observables



Angular observables and Br's



Specific NP hypothesis, with less conservative estimates of SM uncertainties show significances in the 5.9 - 7σ range.

Altmannshofera and Staub [2103.13370], Algueró et al. [2104.08921], Geng et al. [2103.12738]

The global significance of the **New Physics hypothesis** in b → sμ⁺μ⁻ (very conservative SM uncertainties estimate) is:

3.9σ Lancierini, Isidori, Owen, Serra [2104.05631]

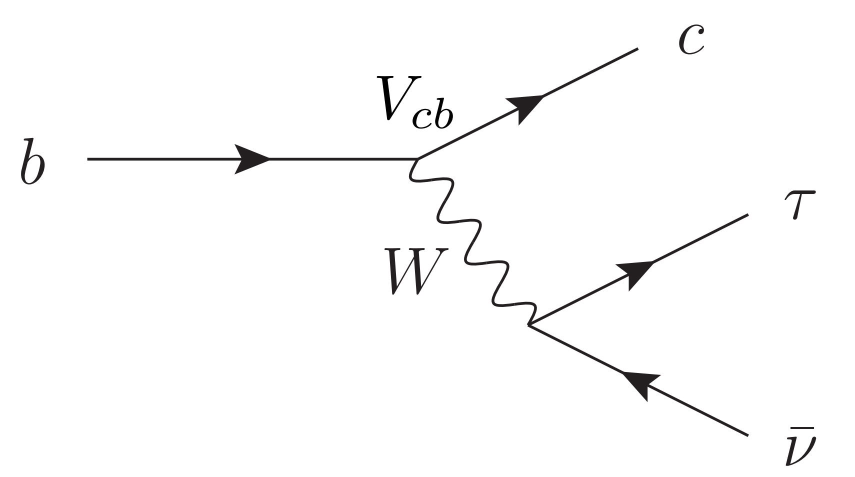
Very good fit to all these deviations with:

$$\mathcal{L}_{LEFT} = C_{s_L b_L \mu_L \mu_L} (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}_L \gamma^\mu \mu_L)$$

$$C_{s_L b_L \mu_L \mu_L} \approx (37\,\mathrm{TeV})^{-2}$$

Charged-current B-anomalies

$b \to c\,\tau\,\nu$ vs. $b \to c\,\ell\,\nu$



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

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

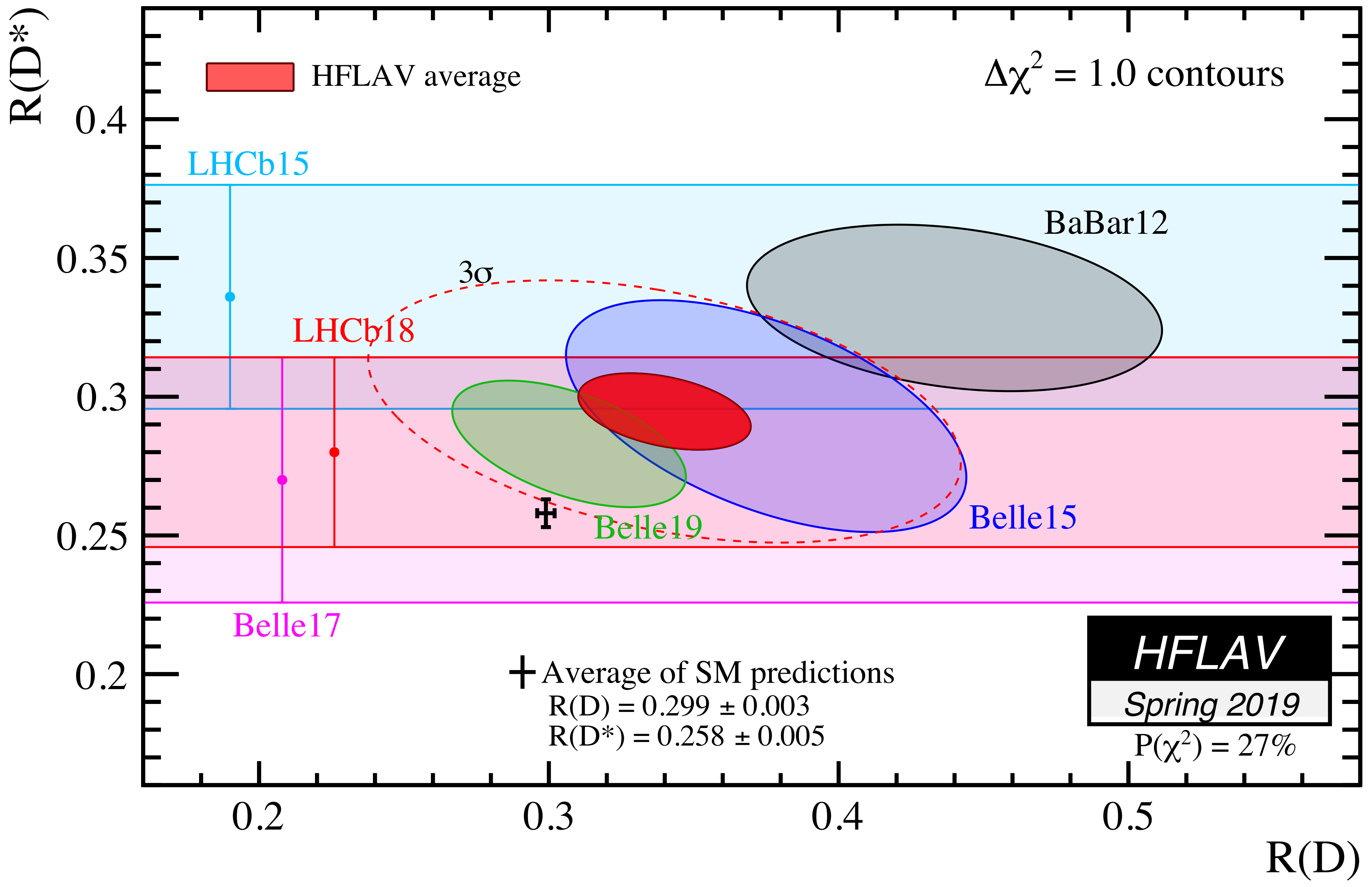
~ 14% enhancement from the SM

~ 3σ from the SM (3.7σ when combined)

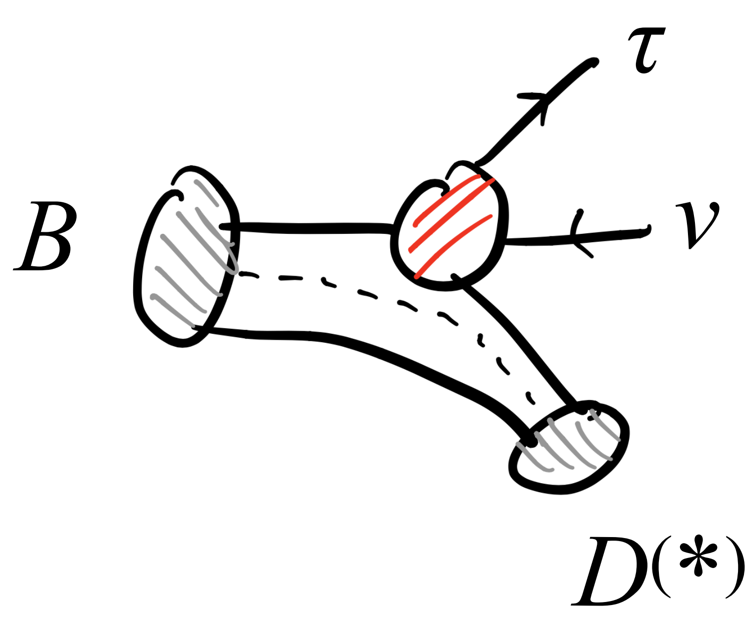
While μ/e universality well tested $R(D)^{\mu/e} = 0.995 \pm 0.045$

Belle - [1510.03657]

All measurements since 2012 consistently above the SM predictions



New Physics interpretations (LEFT):



$$\mathcal{O}_{V_L} = (\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu)$$

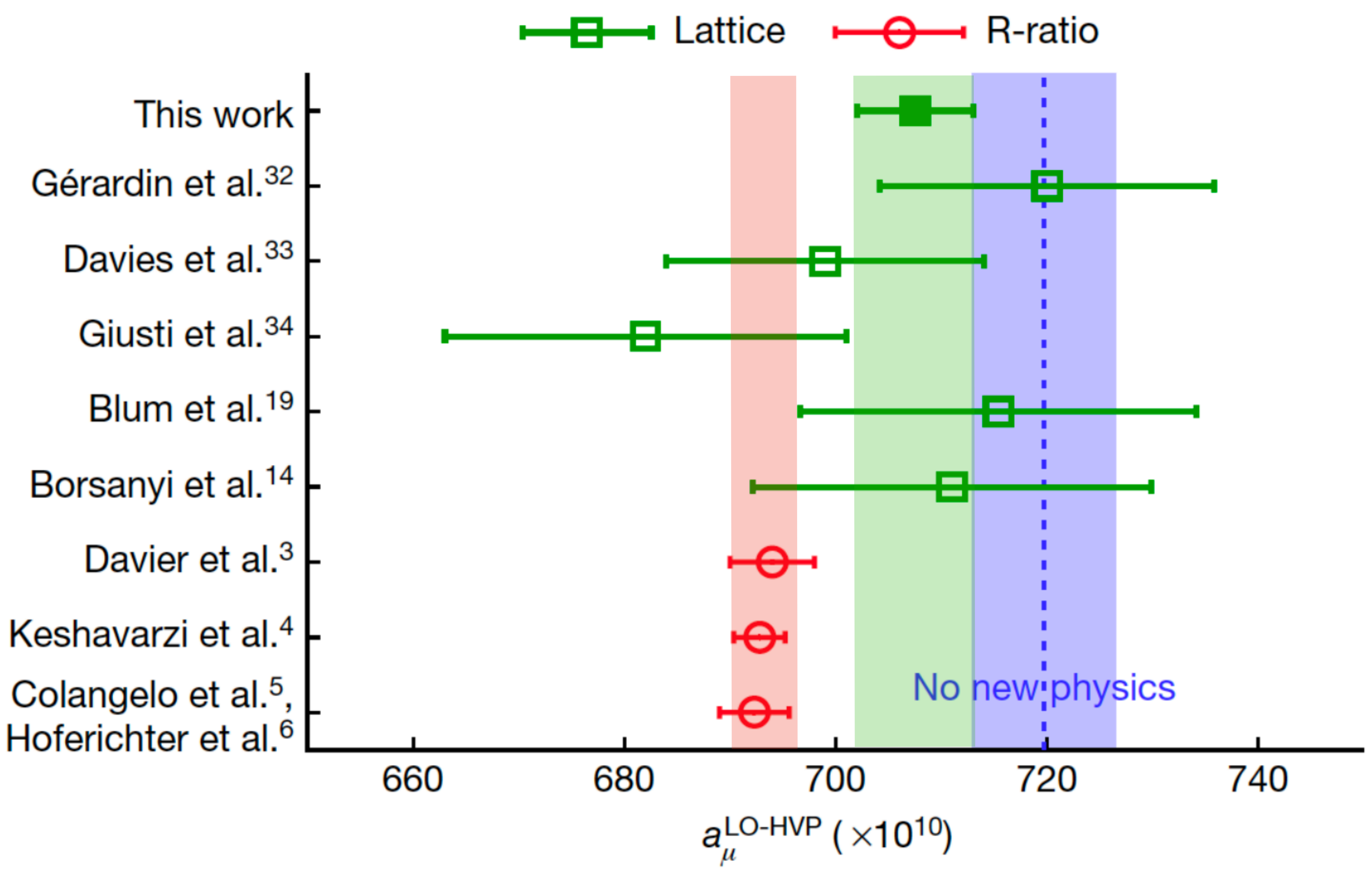
and/or

$$\mathcal{O}_{S_L} = (\bar{c}P_L b)(\bar{\tau}P_L\nu)\,,$$
$$\mathcal{O}_T = (\bar{c}\sigma^{\mu\nu}P_L b)(\bar{\tau}\sigma_{\mu\nu}P_L\nu)$$

With a **New Physics scale** of

$C_{cb\tau\nu} \sim (4\ \mathrm{TeV})^{-2}$

Muon g-2

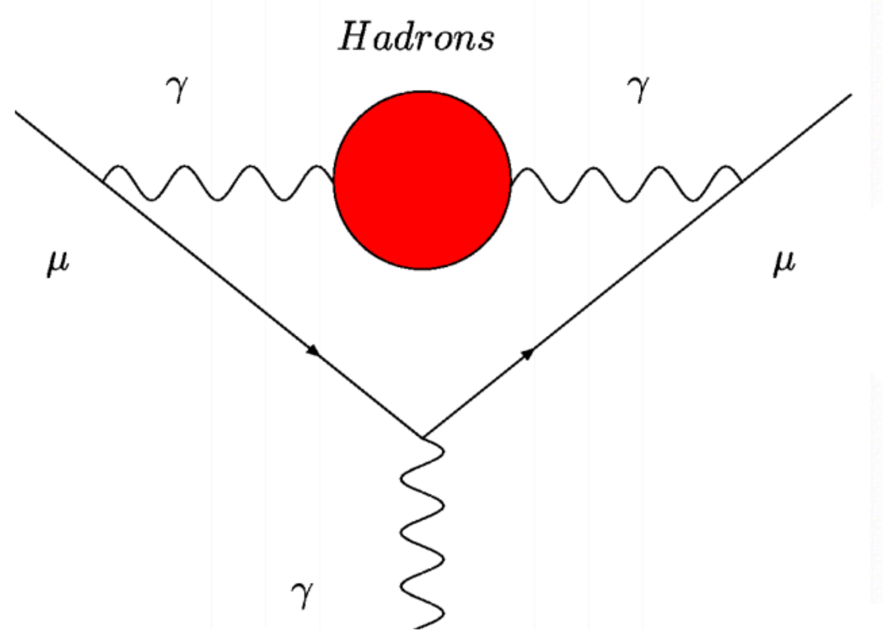


a_μ^{exp} = (116592**2061 ± 41**)×10^{-11} FNAL '21 + BNL '04

a_μ^{THin} = (11659**1810 ± 43**)×10^{-11} TH initiative WP 2006.04822

a_μ^{BMW}= (11659**1954 ± 55**)×10^{-11} Borsanyi et al. Nature 2021, 2002.12347

Main Th. uncertainty in HVP LO contribution:

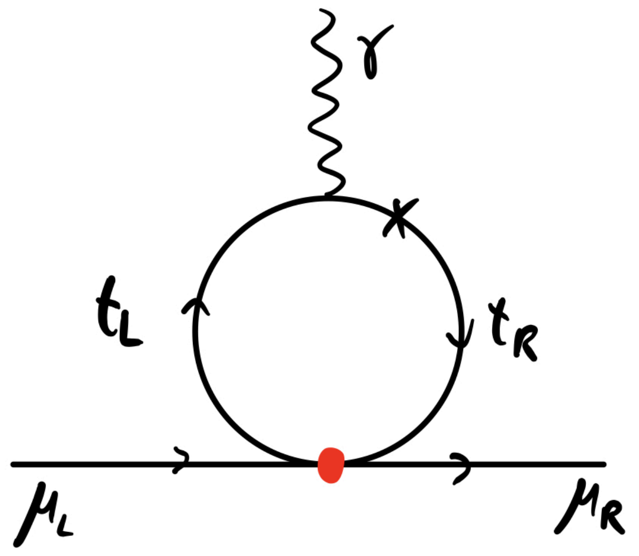


4.2σ or **1.6σ ??**

Let us entertain the possibility that the 4.2σ deviation is real.
New physics contribution arises via the **dipole operator**:

$$\Delta a_\mu = \frac{4 m_\mu}{e} \mathrm{Re}\left[L_{e\gamma}(m_\mu)\right]_{\mu\mu} \qquad \left[O_{e\gamma}\right]_{\alpha\beta} = \bar{e}_L^\alpha \sigma^{\mu\nu} e_R^\beta F_{\mu\nu}$$

NP is enhanced if the chirality flip happens in an internal line with a heavy fermion, as the top quark:



semileptonic tensor
dim-6 operator
with <u>top quark</u>

$$C^{(3)}_{lequ} = (\bar{l}_L \sigma_{\mu\nu} e_R)(\bar{q}_L \sigma^{\mu\nu} u_R)$$

$$\left[L_{e\gamma}(\mu_{EW})\right]_{\mu\mu} = -\frac{e N_c m_t}{6\pi^2}\left[C^{(3)}_{lequ}(\Lambda)\right]_{\mu\mu tt} \log\frac{\Lambda^2}{m_t^2}$$

To fit the deviation (I put Λ=2TeV in the log):
$$C^{(3)}_{lequ}(2\,\mathrm{TeV}) \approx -\frac{1}{(83\,\mathrm{TeV})^2}$$

The same structure of operator can also help in R(D(*)): possible connection?

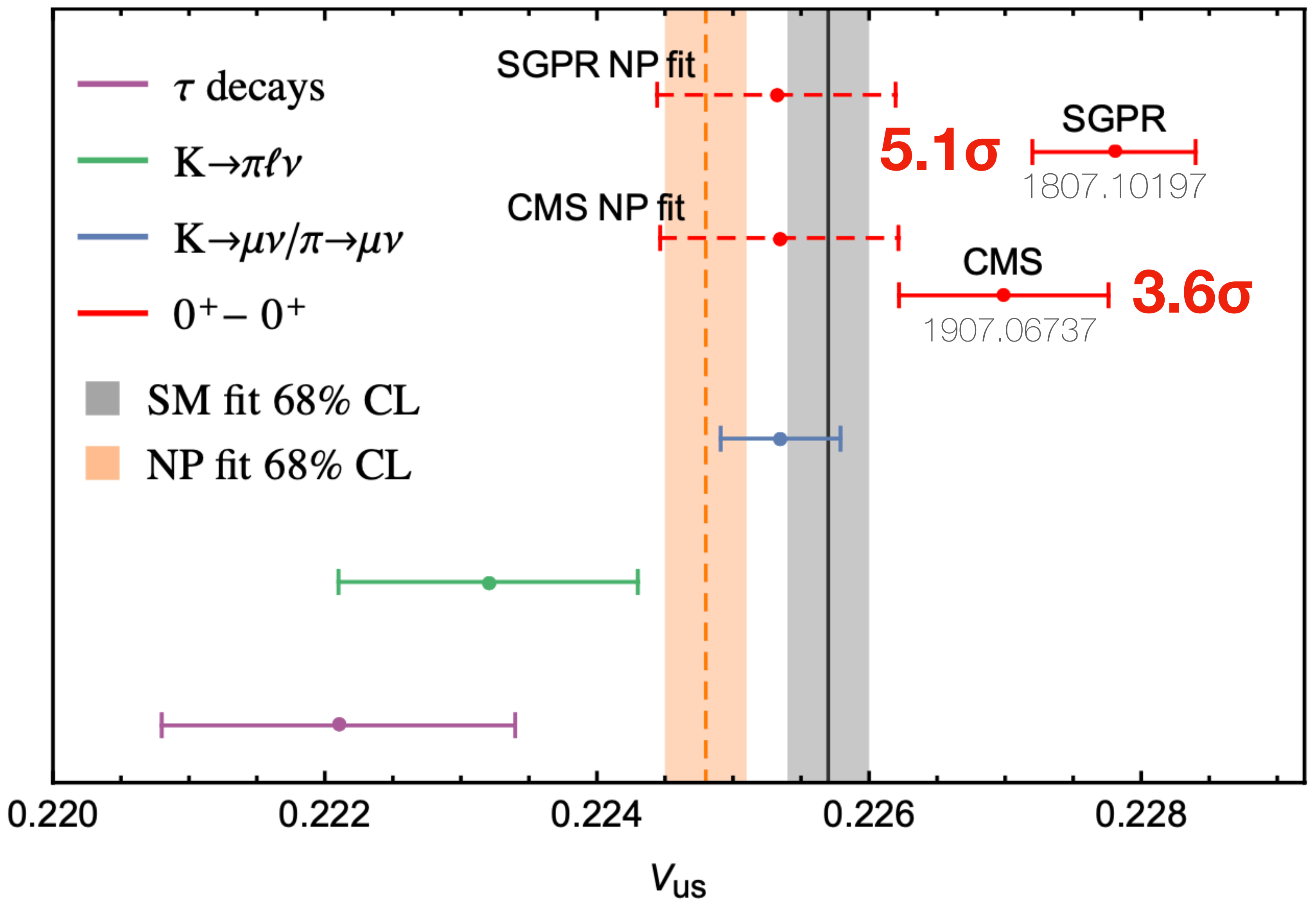
Cabibbo Angle Anomaly

SGPR 1807.10197,
Belfatto, Beradze, Berezhiani 1906.02714,
Grossmann, Passermar, Schacht 1911.07821

Unitarity of the first row of the CKM matrix: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

Neglecting the very small V_{ub}: $V_{ud}^2 + V_{us}^2 = 1$

Assuming unitarity, we can extract the Cabibbo angle from:
- V_{ud}: superallowed $0^+ \to 0^+$ β-decays. SGPR 1807.10197, CMS 1907.06737
- V_{us}: semileptonic Kℓ3 decays.
- $|V_{us}|/|V_{ud}|$: (K→μν) / (π→μν).
- τ decays



Coutinho, Crivellin, Manzari 1912.08823

The effect is *very small*: **(few) × 10^{-3}** of the SM, but **SM is large**: tree x Cabibbo.

Possible New Physics: deviation in the muon decay: mismatch from G_F and G_μ

$$G_\mu = G_F\,(1 + \delta_\mu)$$

This modifies the decays as:

1906.02714

$$|V_{us}| = 0.22333(60) \times (1 + \delta_\mu)$$
$$|V_{us}/V_{ud}| = 0.23130(50)$$
$$|V_{ud}| = 0.97370(14) \times (1 + \delta_\mu) \to |V_{us}| = |V_{us}^{(0)}| \left(1 - \frac{|V_{ud}^{(0)}|^2}{|V_{us}^{(0)}|^2} \delta_\mu \right)$$

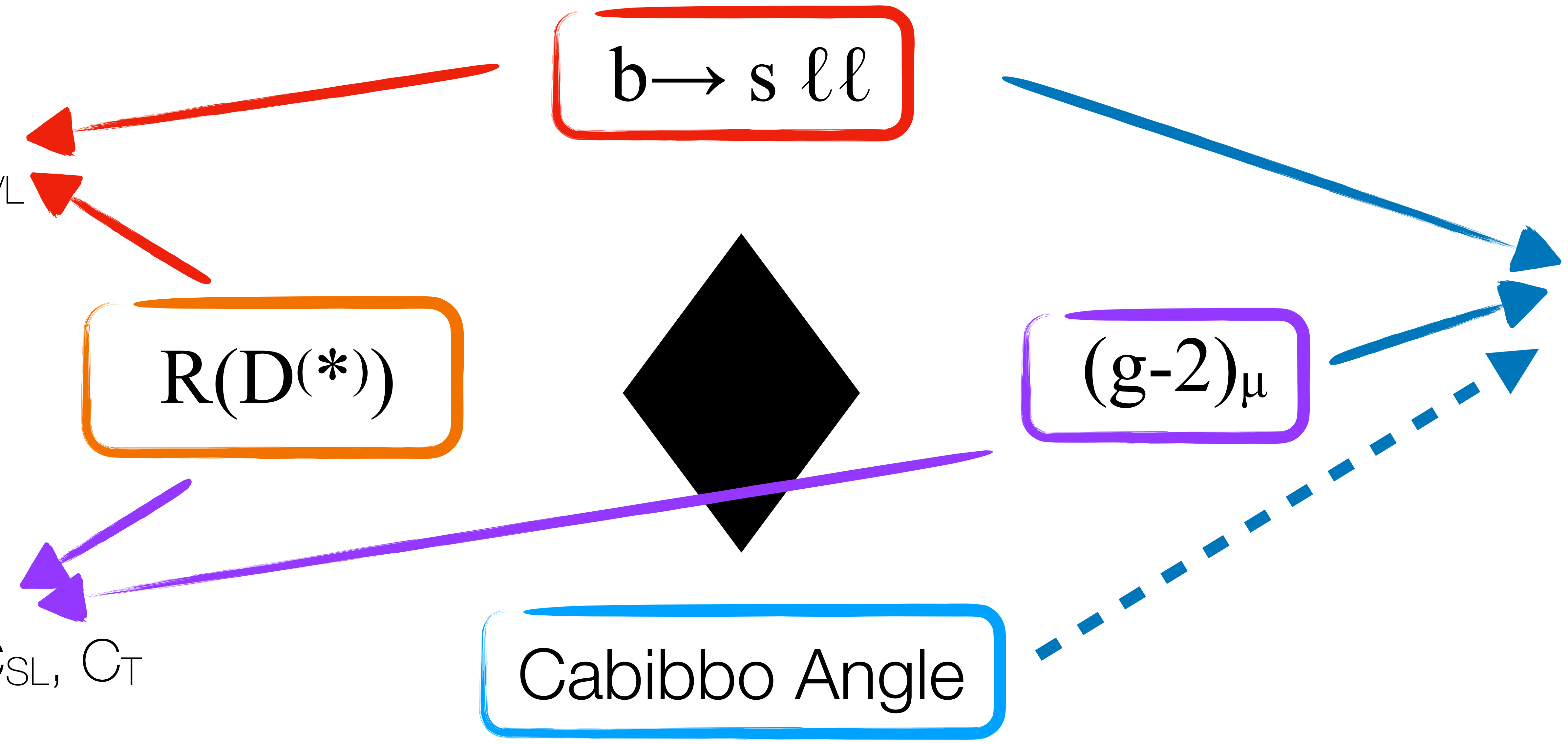
Enhancement ~ 20!

Including the **EW fit constraints**: $\delta(\mu \to e\nu\nu) = 0.00065(15)$

Belfatto, Beradze, Berezhiani 1906.02714,
Crivellin, Kirk, Manzari, Panizzi 2012.09845, 2102.02825

Combined explanations: why?

- LFU violation: $g_e \ll g_\mu \ll g_\tau$
- same underlying type of operator: C_{VL}
- connected by data (RD - C_9^U)



- New Physics in muons

- same underlying type of operator: C_{SL}, C_T

IF all turn out to be due to NP, a **combined explanation** could be an **elegant** and **economical** way to explain the data.

Combined explanations are typically **more constrained by data**, can provide **sharper predictions**.

Combined interpretation of R_K, $R(D^{(*)})$, $(g-2)_\mu$

We must **start with R(D^(*))**: lowest NP scale → most stringent requirements

Tree-level mediators of:

$$\boxed{\mathcal{O}_{V_L} = (\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu)}$$

and/or

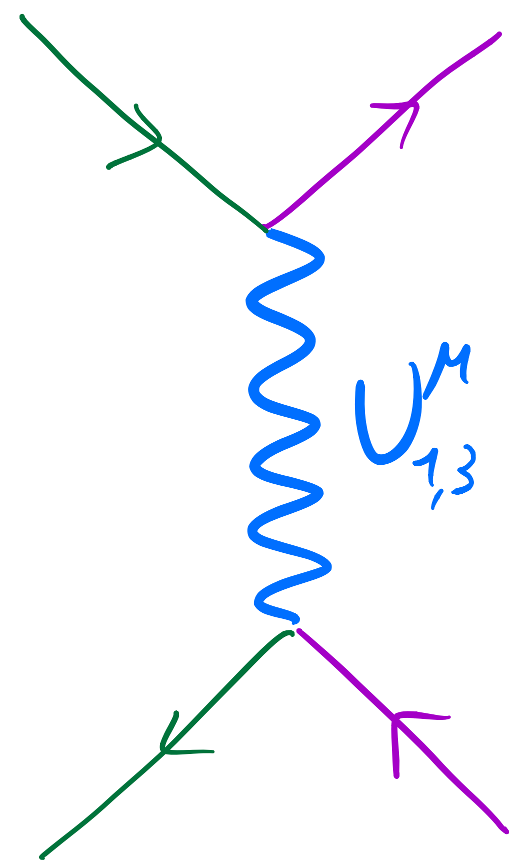
$$\boxed{\begin{aligned}\mathcal{O}_{S_L} &= (\bar{c}P_L b)(\bar{\tau}P_L \nu)\,, \\ \mathcal{O}_T &= (\bar{c}\sigma^{\mu\nu}P_L b)(\bar{\tau}\sigma_{\mu\nu}P_L \nu)\end{aligned}}$$

Needs to escape the constraints from:

Meson mixing
B → K^(*) νν
Z → τ τ
pp → τ τ

Vector Leptoquark

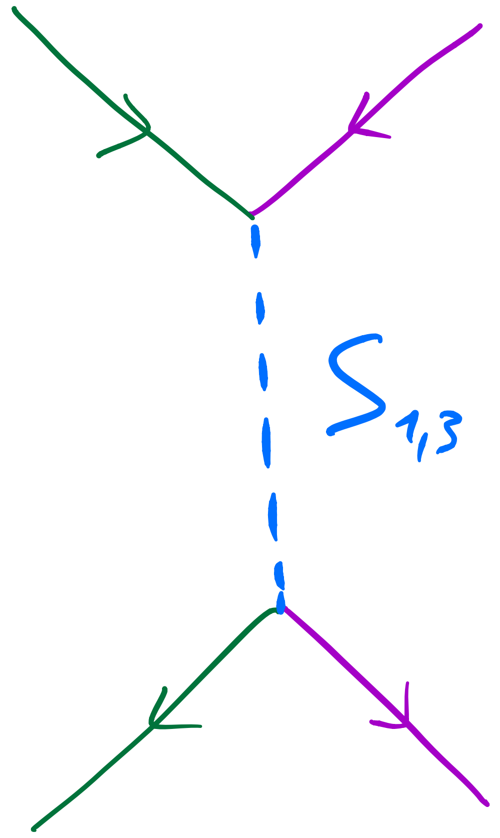
$U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$,



Barbieri et al 1512.01560; Buttazzo, Greljo, Isidori, DM 1706.07808; Di Luzio et al 1708.08450; Bordone et al. 1712.01368; Calibbi et al. '17; Blanke, Crivellin '18; Cornella et al 2103.16558; Angelescu et al 1808.08179

Scalar Leptoquarks

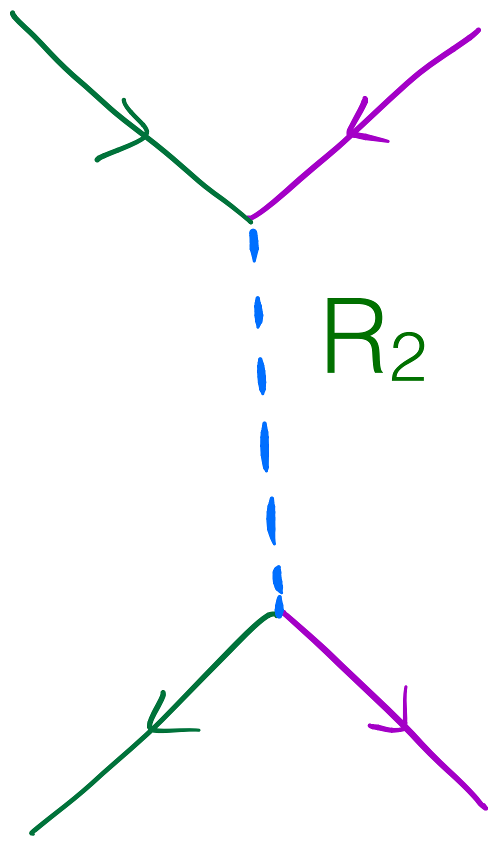
$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$,
$[S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)]$



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; ETC…

Scalar Leptoquarks

$R_2 = (\mathbf{3}, \mathbf{2}, 7/6)$,



Becirevic et al. 1806.05689; Becirevic, Sumensari 1704.05835; Popov et al. 1905.06339; Angelescu et al. 2103.12504; ETC…

mild tension with $B_c \to \tau\nu$ and on the verge of exclusion from mono-τ at LHC

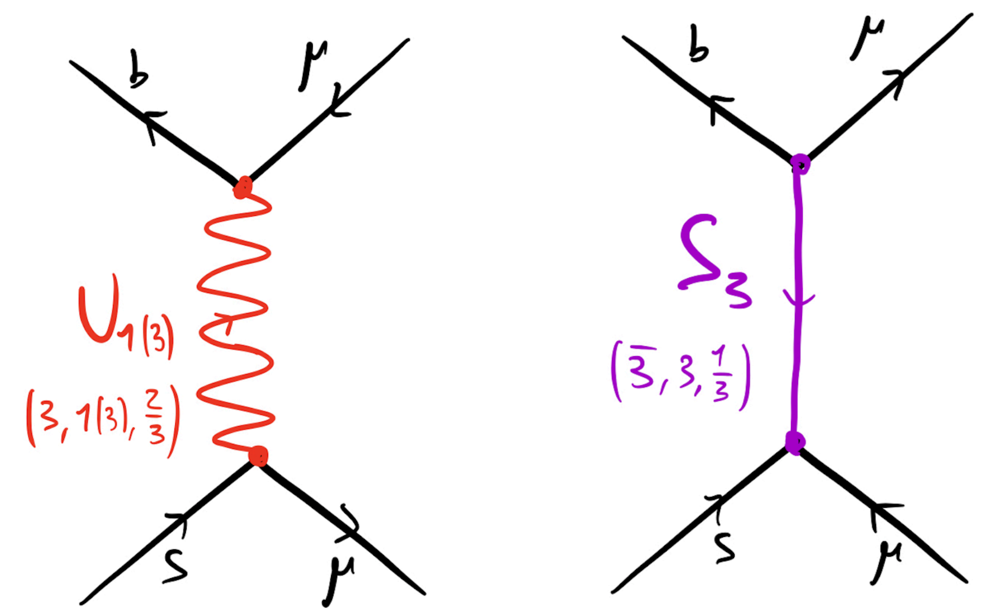
$\mathbf{C_{VL}}$ $\mathbf{(C_{SL}\,,\,C_T)}$

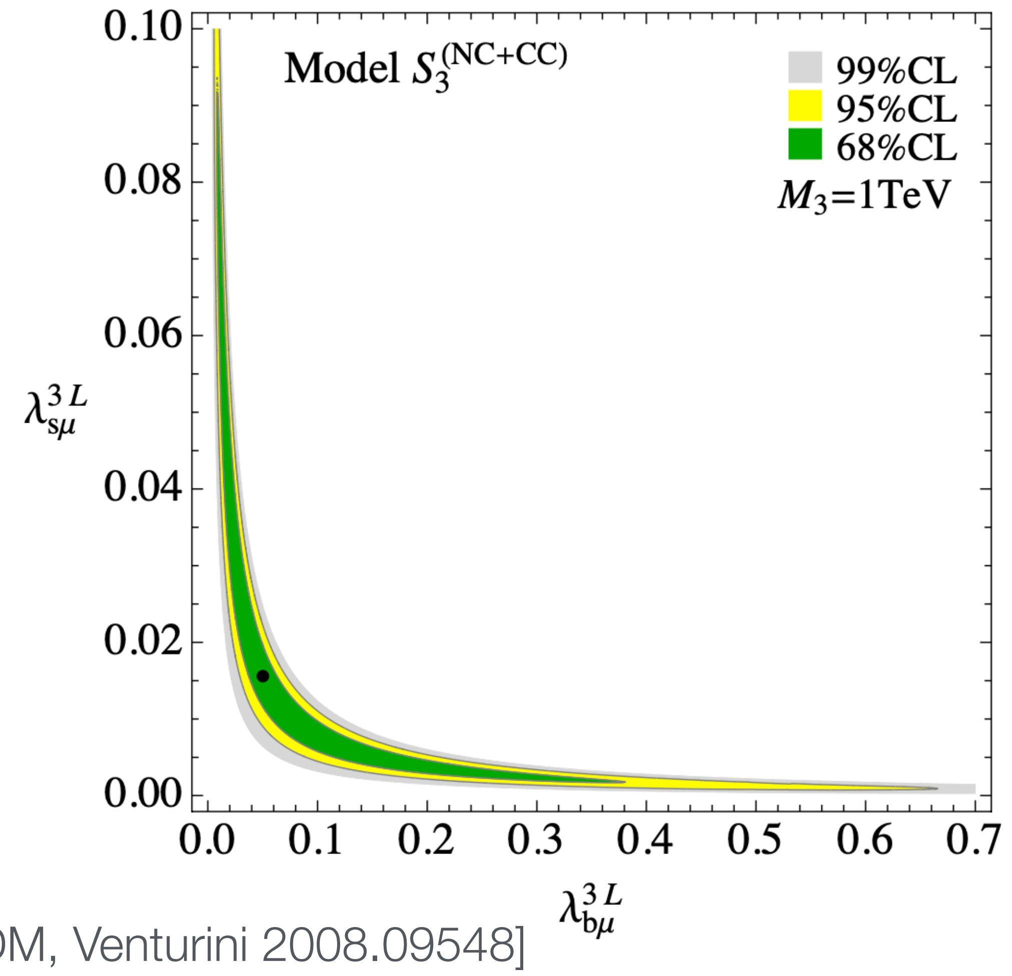
What about **R(K$^{(*)}$)**?

$$\mathcal{L}_{\rm eff} \supset \frac{e^{i\alpha_{bs}}}{\Lambda_{bs}^2}(\bar{s}_L\gamma^\mu b_L)(\bar{\mu}_L\gamma_\mu\mu_L) + h.c.$$

Best-fit for α_{bs}=0: $\Lambda_{bs} \approx 37$ TeV

U$_1$ and **S$_3$** can mediate $b_L \to s_L\, \mu_L\, \mu_L$

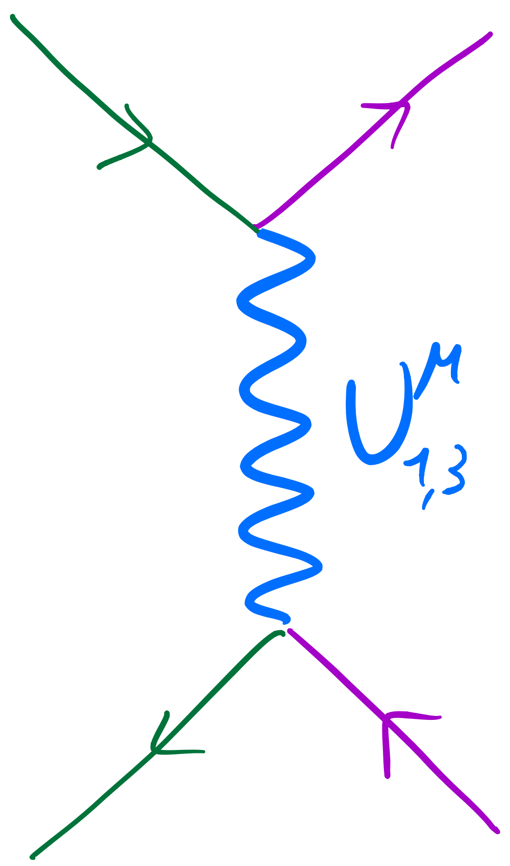




[Gherardi, DM, Venturini 2008.09548]

Vector Leptoquark

U$_1$ = (**3**, **1**, 2/3),



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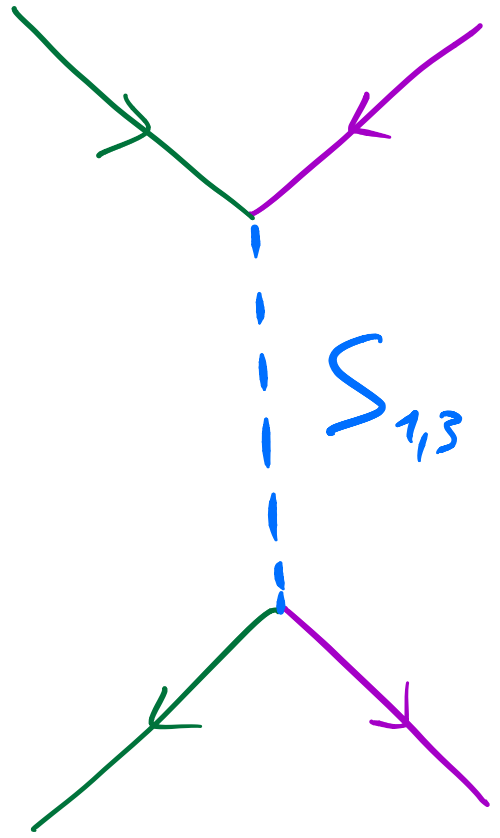
Scalar Leptoquarks

S$_1$ = (**$\bar{3}$**, **1**, 1/3),
S$_3$ = (**$\bar{3}$**, **3**, 1/3),



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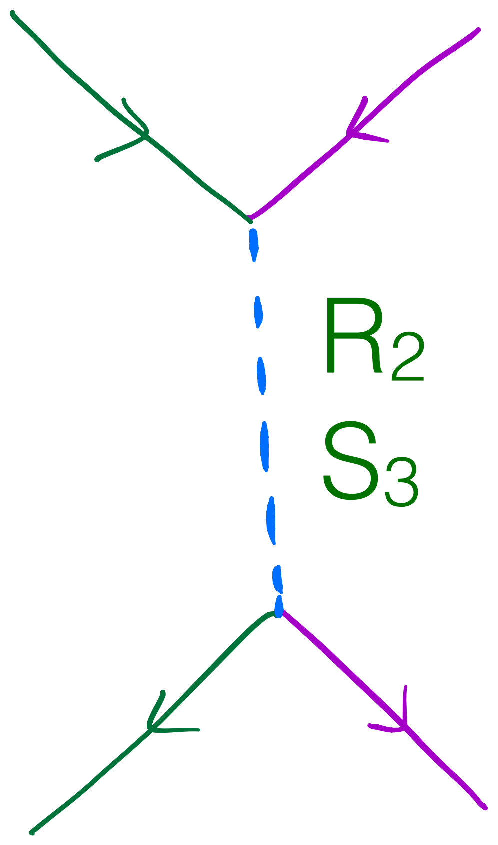
Scalar Leptoquarks

R$_2$ = (**3**, **2**, 7/6),
S$_3$ = (**$\bar{3}$**, **3**, 1/3),



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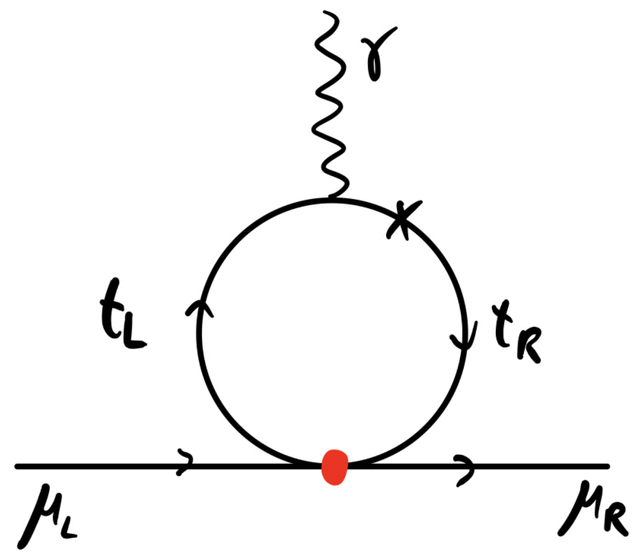
TeV-scale U$_1$ or S$_3$ LQs can fit the anomaly with small couplings.

What about **muon (g-2)**?

Leptoquarks with couplings to **μ_L μ_R t_L t_R** can generate a_μ with *TeV masses* and *small couplings*:

S_1 or **R_2**

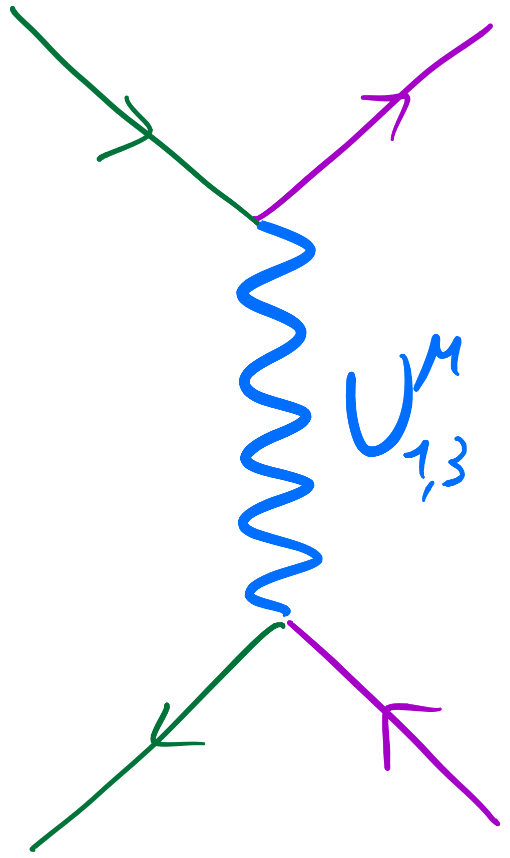


$$[L_{e\gamma}(\mu_{ew})]_{\mu\mu} = -\frac{e N_c m_t}{6\pi^2}\,[C^{(3)}_{lequ}(\Lambda)]_{\mu\mu tt}\,\log\frac{\Lambda^2}{m_t^2}$$

$$C^{(3)}_{lequ} = (\bar{l}_L \sigma_{\mu\nu} e_R)(\bar{q}_L \sigma^{\mu\nu} u_R)$$

Vector Leptoquark

$U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$,

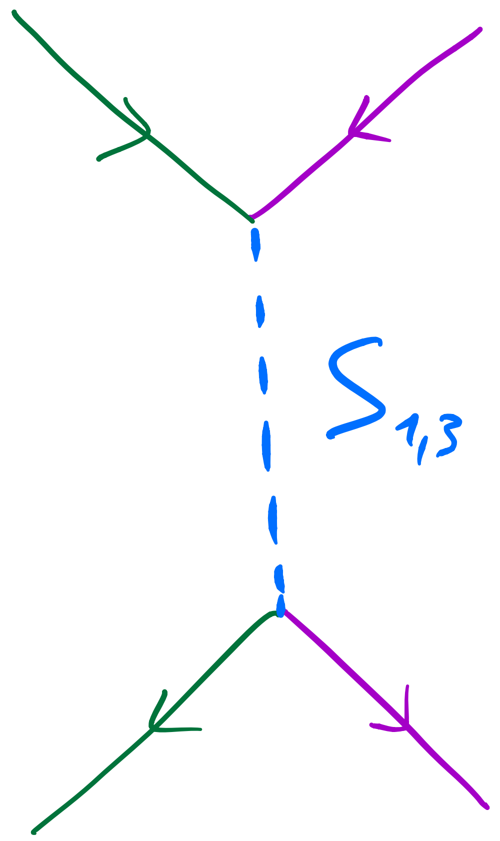


No $(g\text{-}2)_\mu$

Barbieri et al 1512.01560; Buttazzo, Greljo, Isidori, DM 1706.07808; Di Luzio et al 1708.08450; Bordone et al. 1712.01368; Calibbi et al. '17; Blanke, Crivellin '18; Cornella et al 2103.16558; Angelescu et al 1808.08179

Scalar Leptoquarks

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



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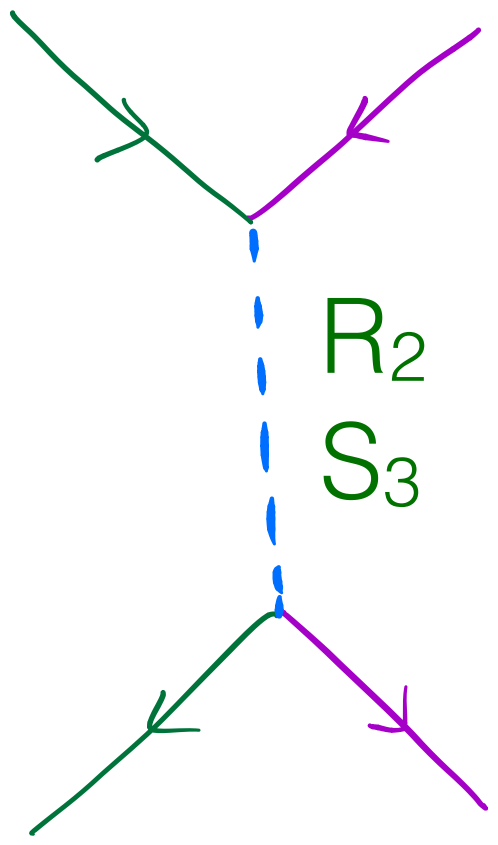
Scalar Leptoquarks

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

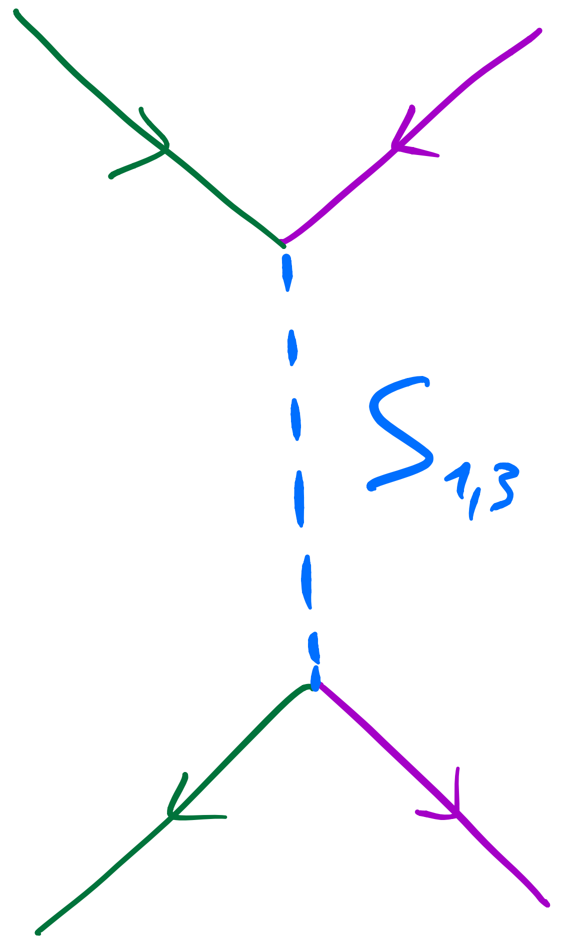


Becirevic et al. 1806.05689; Becirevic, Sumensari 1704.05835; Popov et al. 1905.06339; Angelescu et al. 2103.12504; ETC…

S_1 and S_3 scalar leptoquarks

Scalar Leptoquarks

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



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

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]

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

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

2) Analysis of B-anomalies, including all observables sensitive to the relevant couplings
V. Gherardi, E. Venturini, D.M. [2008.09548]

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]

Matching to SMEFT

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

We match **off-shell Green's functions** for **One-Light-Particle-Irreducible** (**1LPI**) diagrams

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

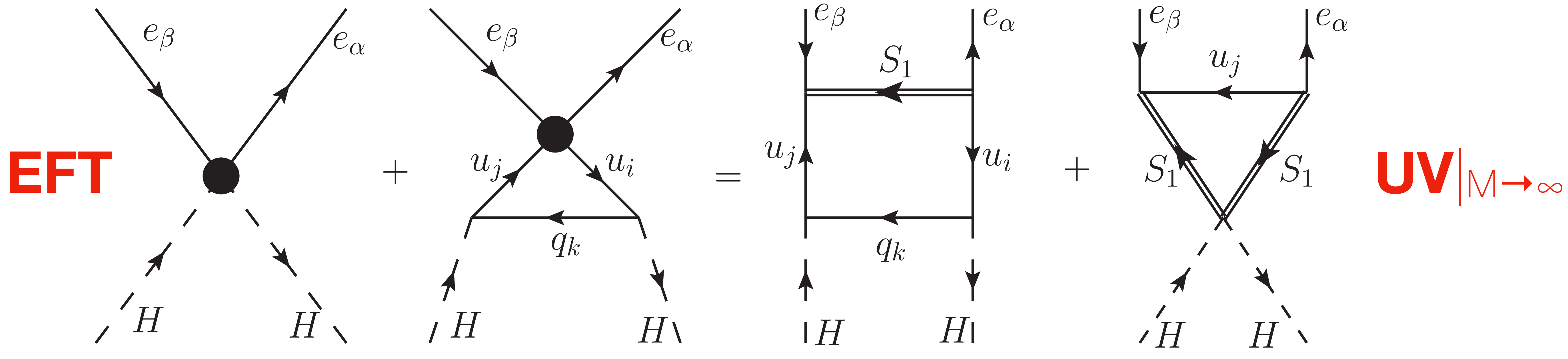


Figure 1: Diagrams for the matching of the $\langle \bar{e}eH^\dagger H\rangle$ Green function.

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

This procedure gives the matching for **operators** that are **independent under IBP and Fierz**, but are **redundant upon using field redefinitions**: **Green's basis**. Jiang et al. [1811.08878]
We obtained the *complete Green's basis at dim-6* and set of reduction equations to the Warsaw basis

Ours is the first such complete matching for a **very rich scenario**: most dim-6 operators are induced.
Useful as cross-check for *functional* techniques and upcoming *computational* methods.

"*Universal Scalar Leptoquark Action for Matching*" Dedes, Mantzaropoulos [2108.10055]

CoDEx Bakshi, Chakrabortty, Patra
Matchete Fuentes-Martìn, König, Pagès, Thomsen, Wilsch
Matchmaker Anastasiou, Carmona, Lazopoulos, Santiago

S_1 and S_3 - global analysis

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

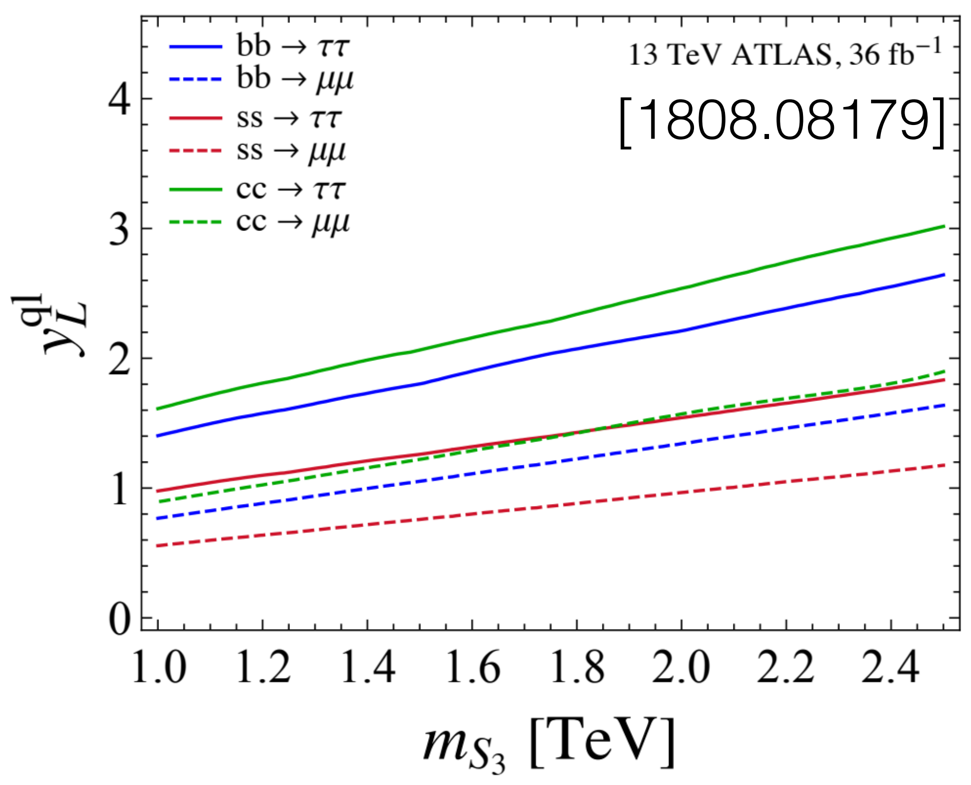
Using the complete one-loop matching to SMEFT, we include in our analysis the following observables.

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]

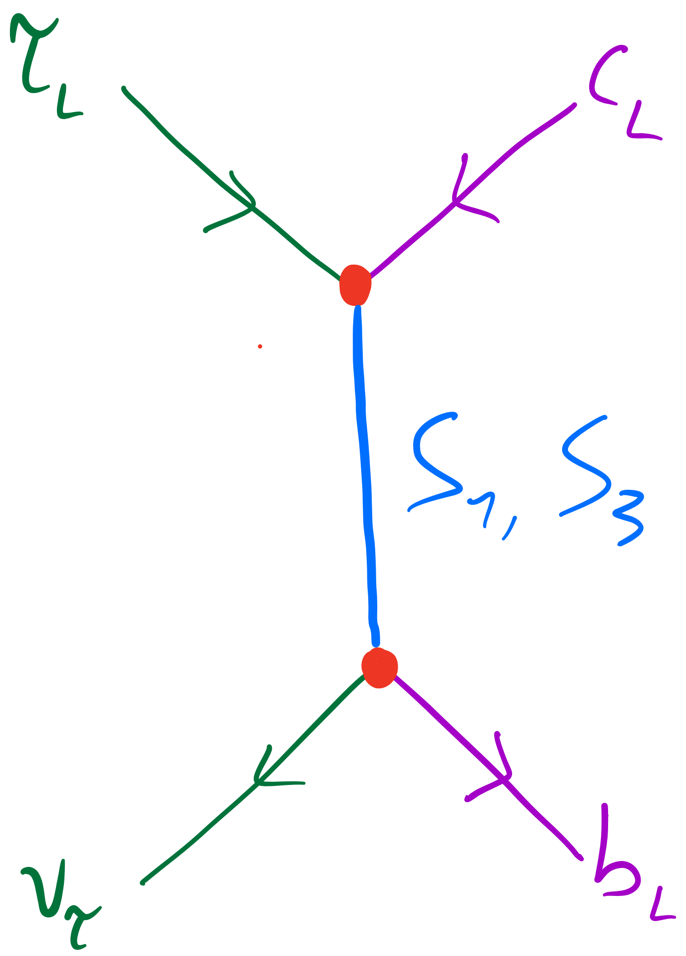
Observable	SM prediction	Experimental bounds
D leptonic decay		[37] and App. A.4
$\mathcal{B}(D_s \to \tau\nu)$	$(5.169 \pm 0.004) \times 10^{-2}$ [94]	$(5.48 \pm 0.23) \times 10^{-2}$ [51]
$\mathcal{B}(D^0 \to \mu\mu)$	$\approx 10^{-11}$ [95]	$< 7.6 \times 10^{-9}$ [96]
$\mathcal{B}(D^+ \to \pi^+\mu\mu)$	$\mathcal{O}(10^{-12})$ [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]
$\mathcal{B}(K_L \to \pi^0ee)$	$(3.2^{+1.2}_{-0.8}) \times 10^{-11}$ [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]

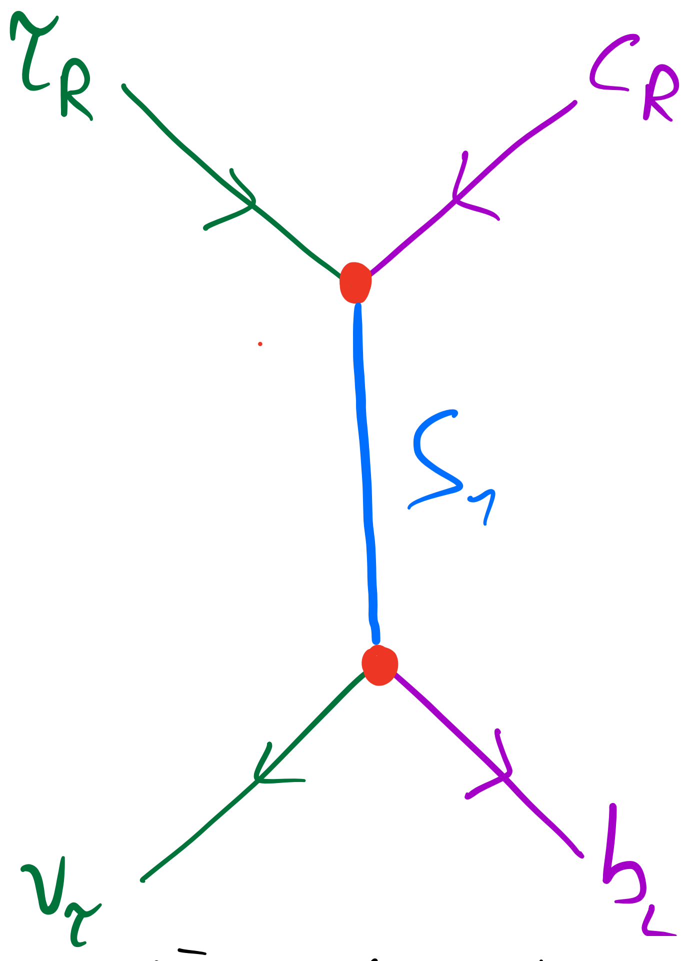
S_1 and S_3 - contributions to anomalies

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

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



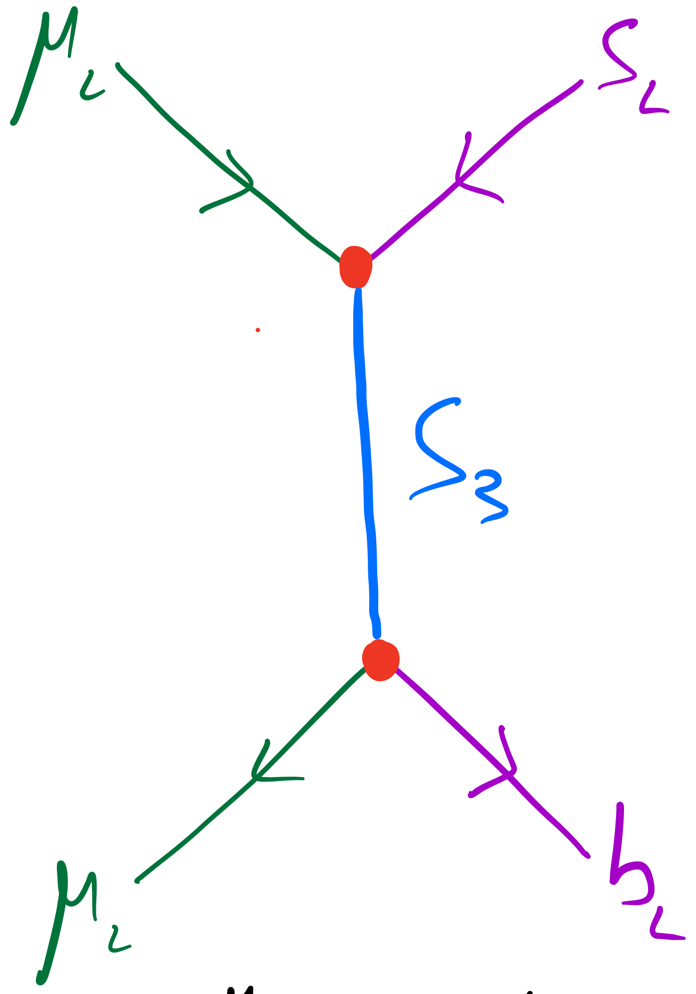
$(\bar b_L \gamma_\mu c_L)(\bar\nu_\tau \gamma^\mu \tau_L)$



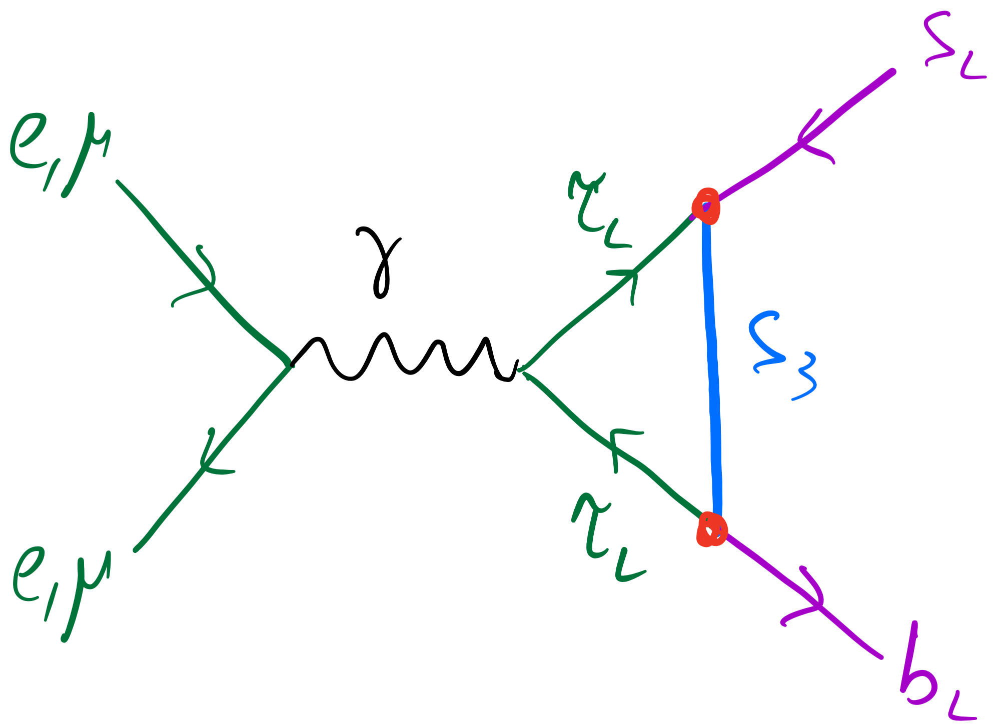
$(\bar b_L c_R)(\bar\nu_\tau \tau_R)$

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

$b \to s \mu\mu$

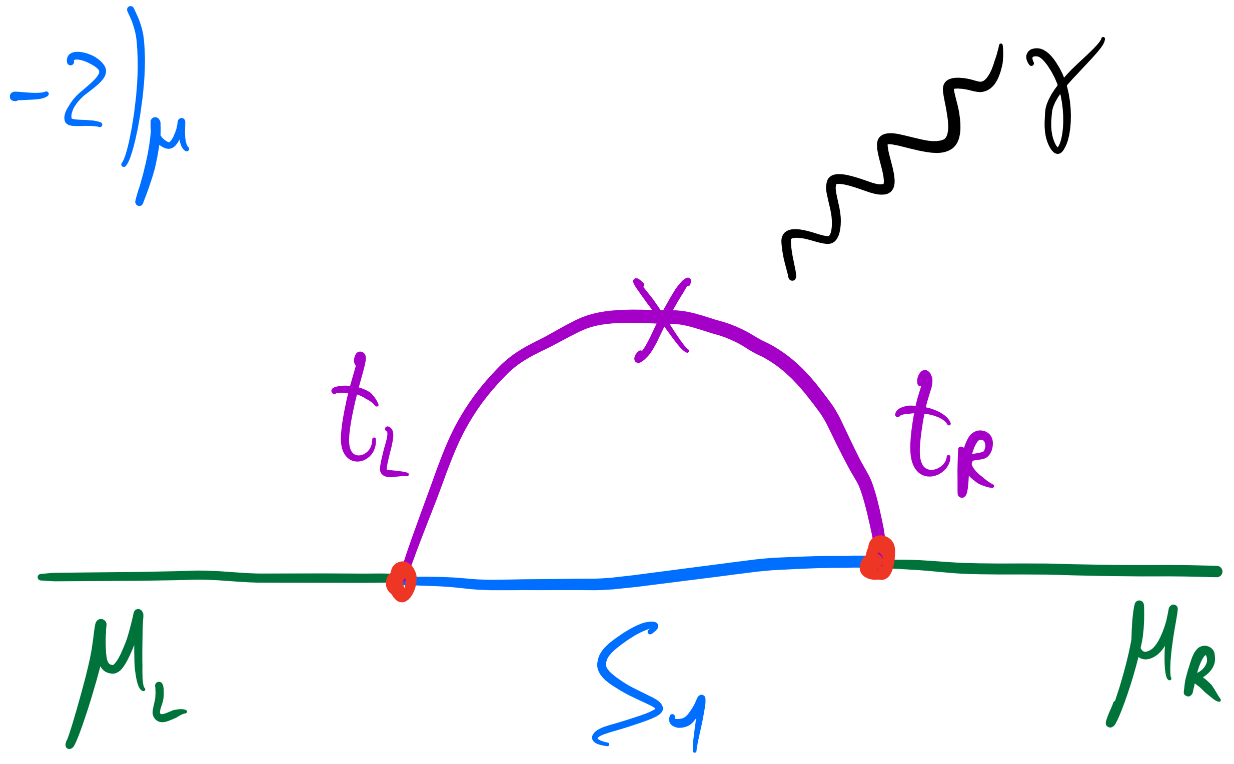


$C_9^\mu = -C_{10}^\mu$



C_9^U

$(g-2)_\mu$



S_1 and S_3 - benchmarks

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

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

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

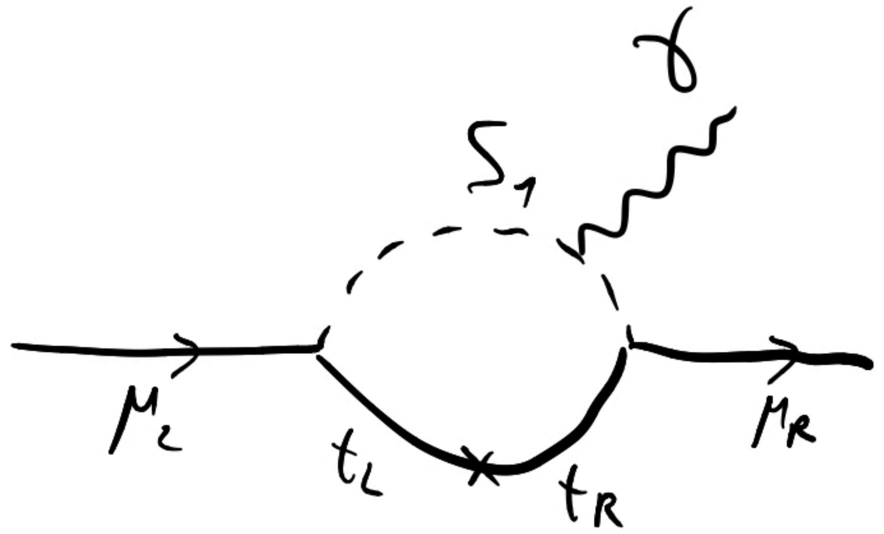
$$\lambda^{1R} = 0$$

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

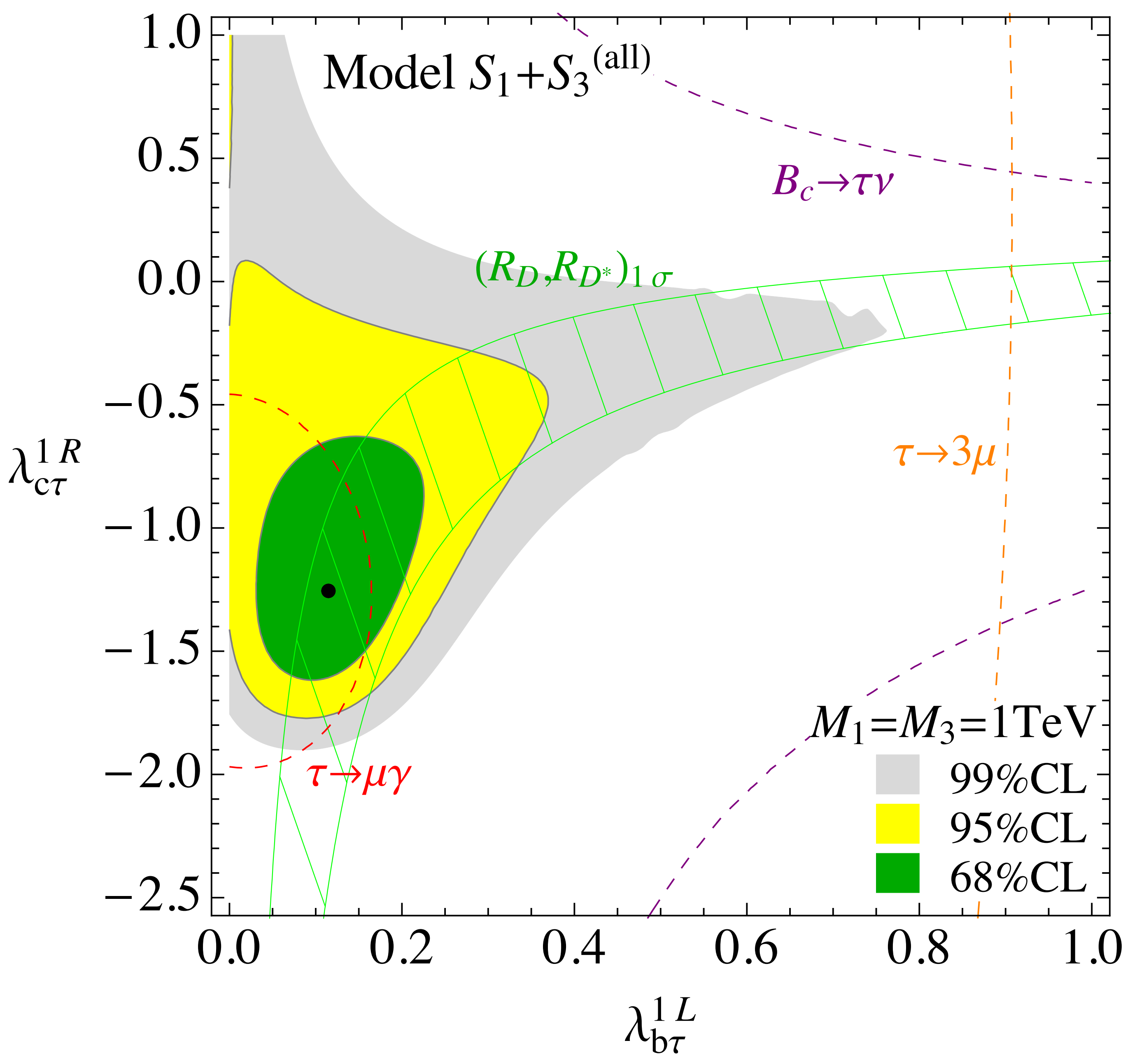
S_1 and S_3 : $R(K^{(*)})$ + $R(D^{(*)})$ + $(g-2)_\mu$

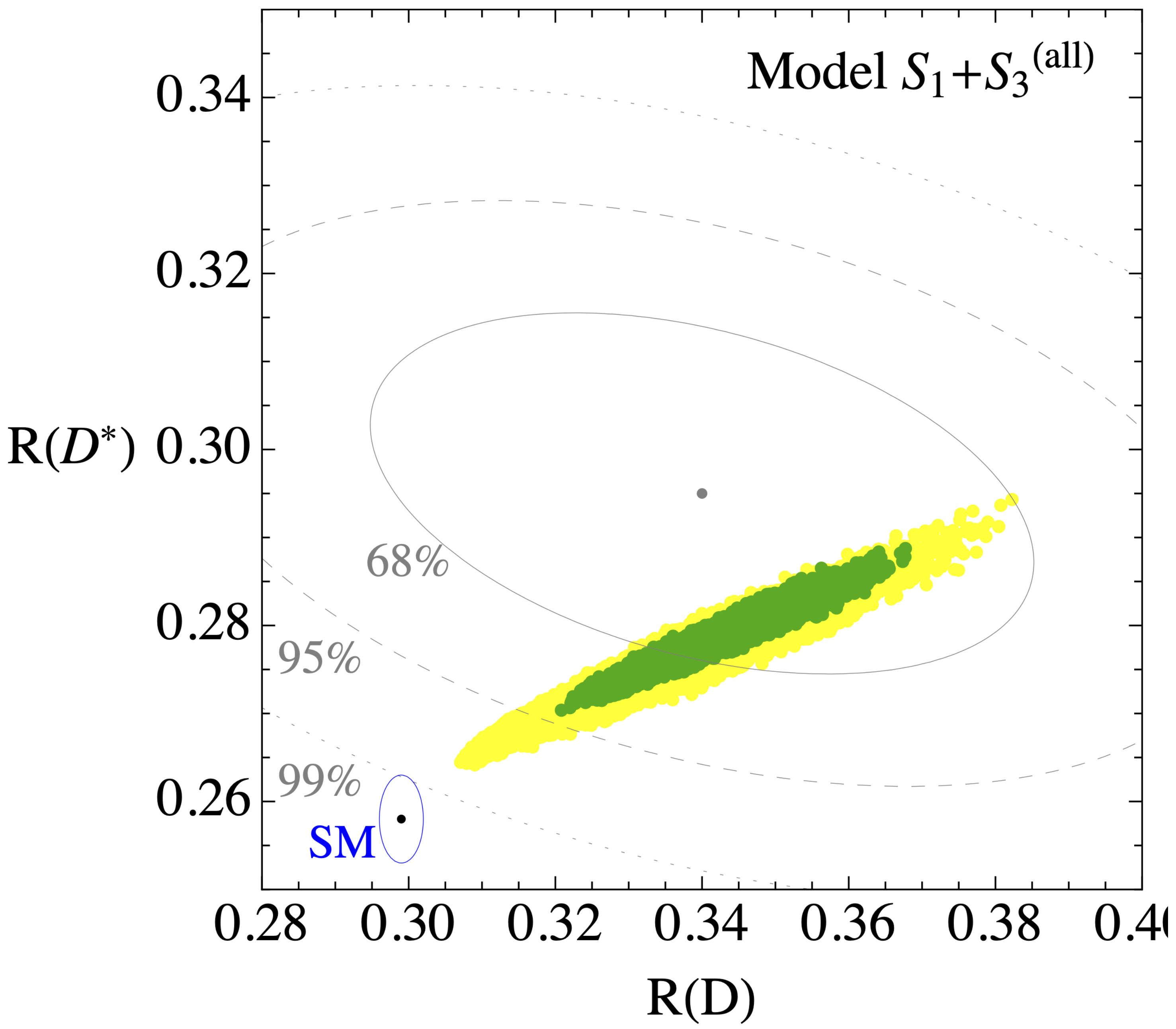
$$\lambda^{1L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & s\tau \\ 0 & b\mu & b\tau \end{pmatrix} \qquad \lambda^{3L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & s\mu & s\tau \\ 0 & b\mu & b\tau \end{pmatrix}$$

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

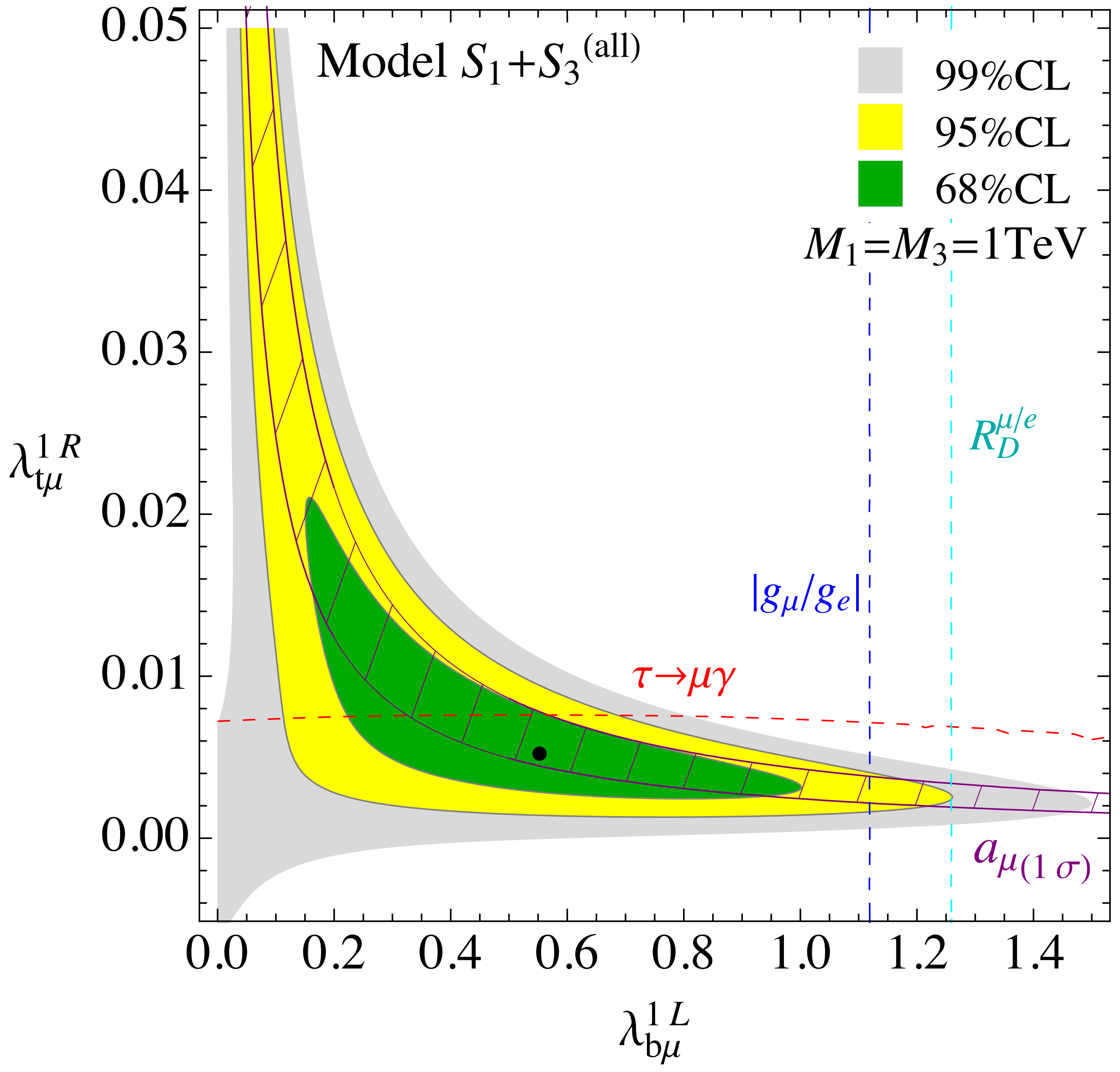


$R(D^{(*)})$





$(g-2)_\mu$



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

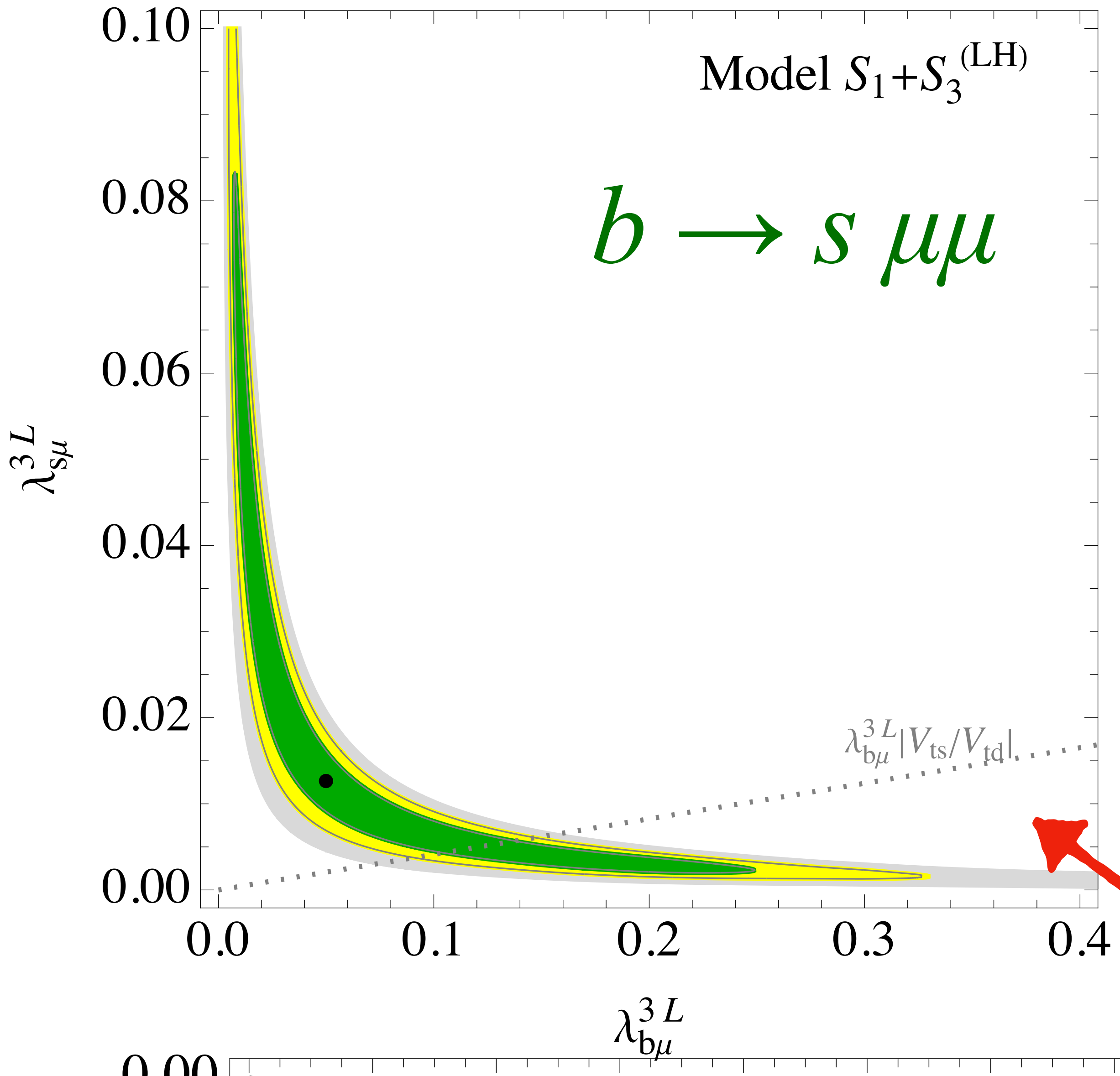
Contribution to **$R(D^{(*)})$** dominated by **S_1**: scalar+tensor op.
Can also fit $(g\text{-}2)_\mu$.

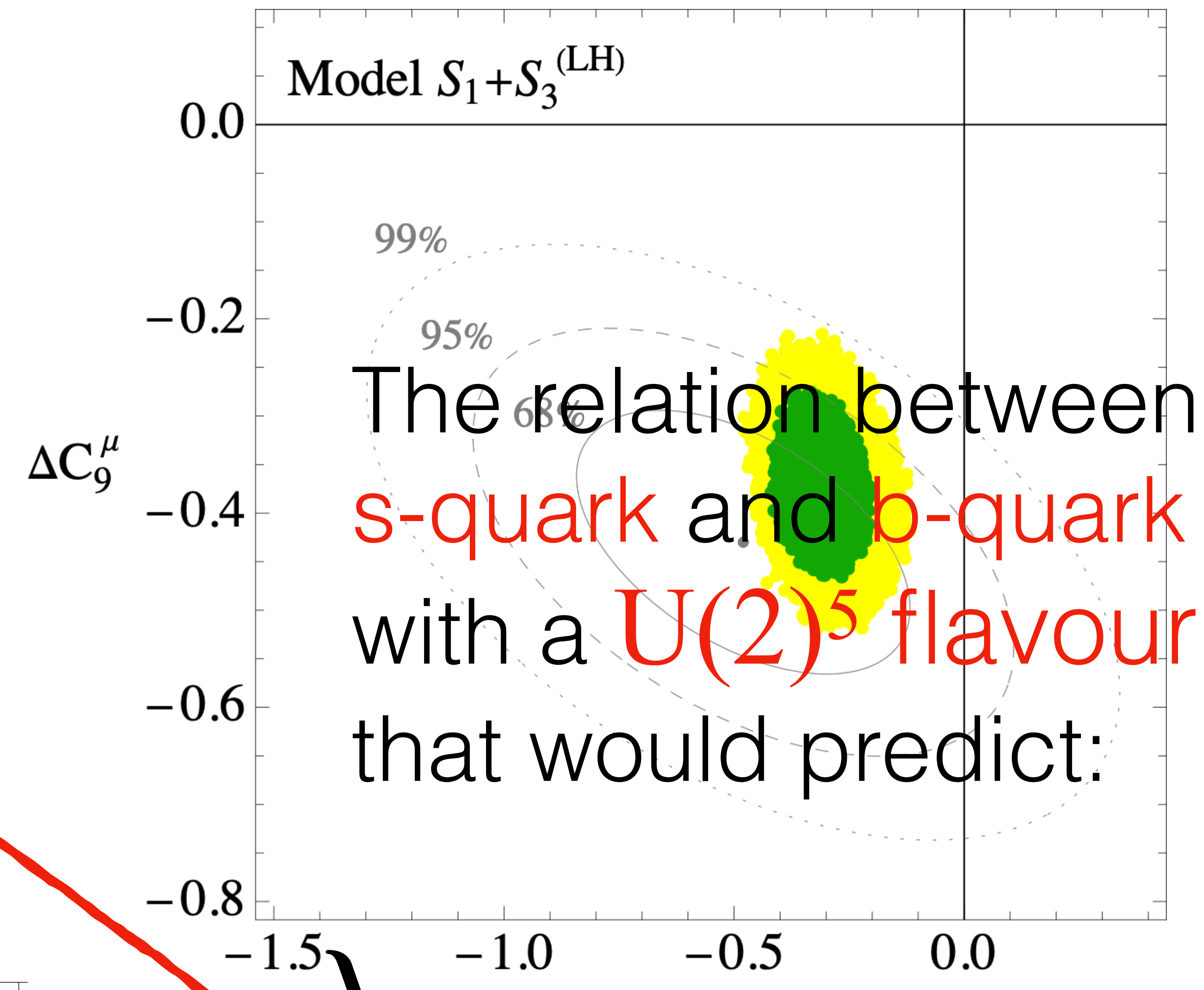
Very good fit of all anomalies!

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 $(g-2)_\mu$





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

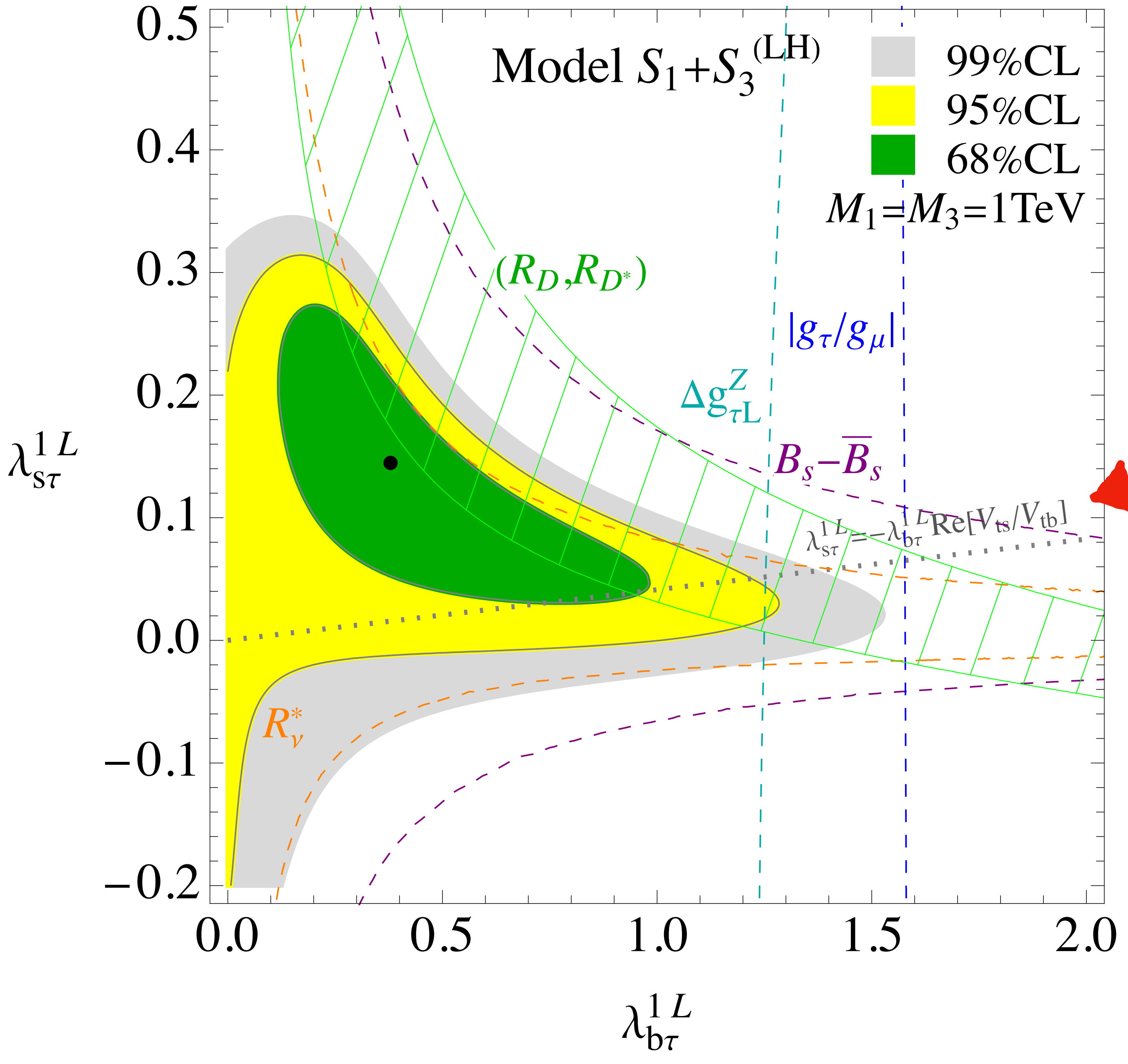
very good fit of B-anomalies

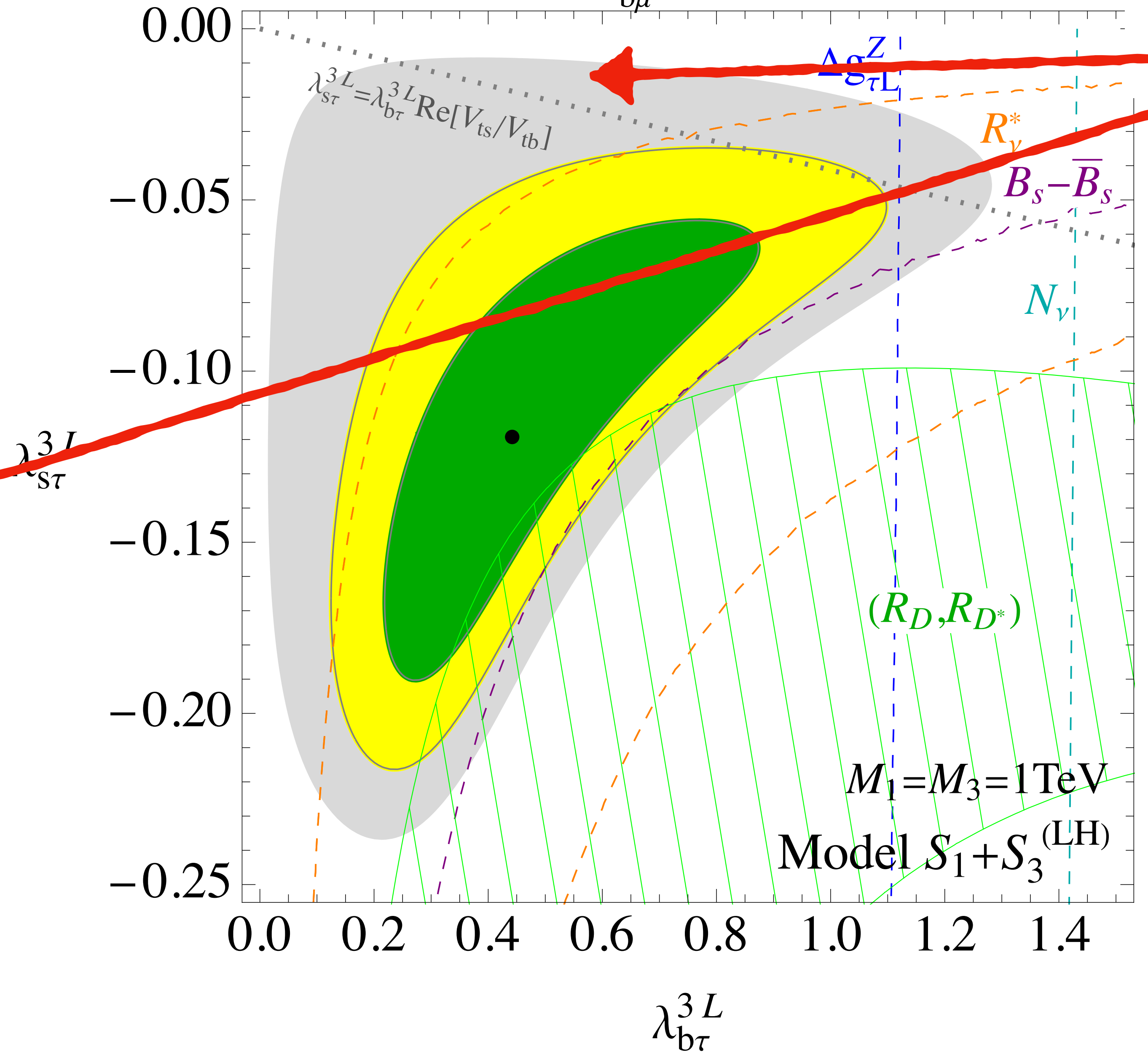
$$\lambda_{s\alpha} = c_{U(2)} V_{ts} \lambda_{b\alpha}$$

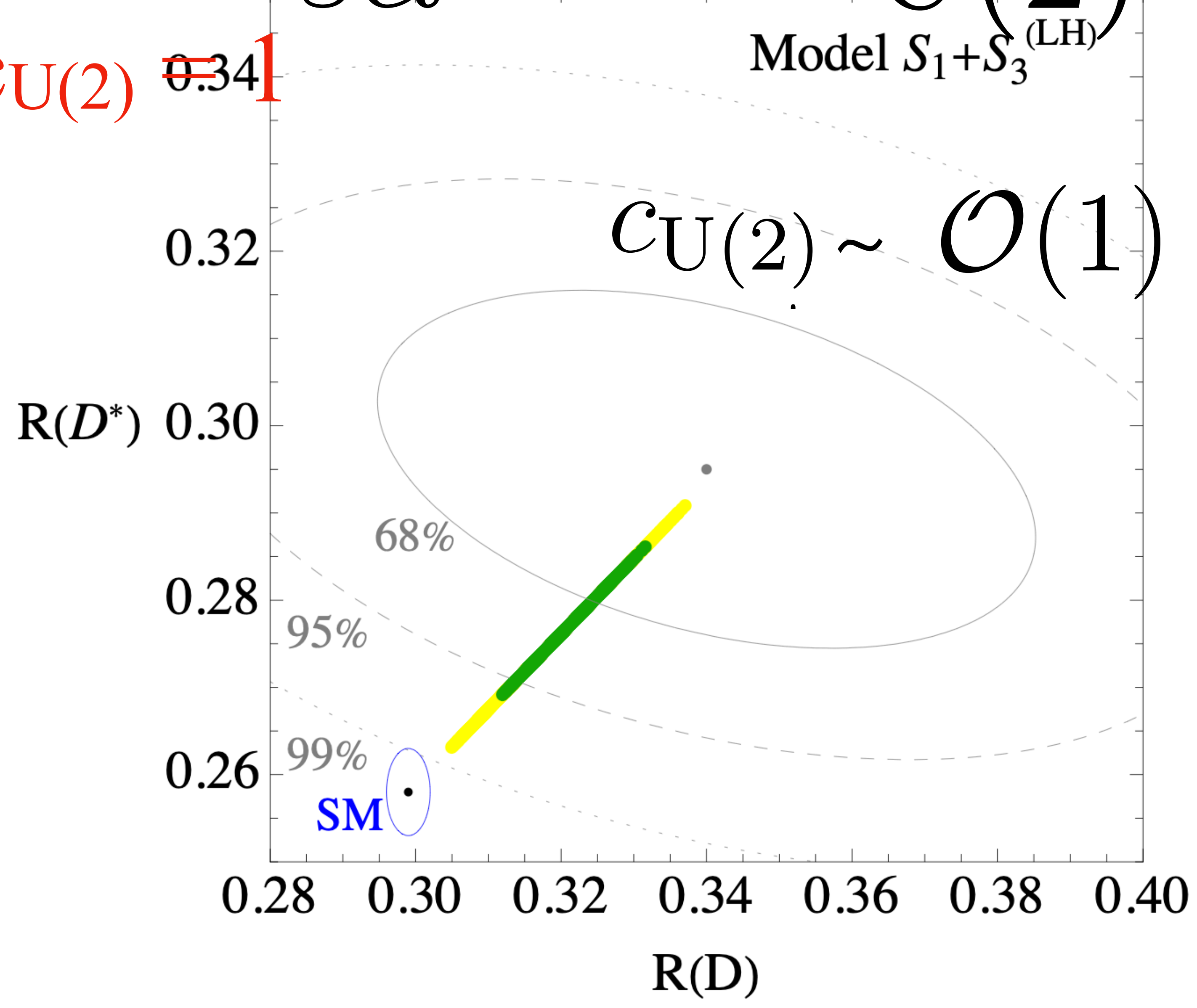
$c_{U(2)} = 1$

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

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





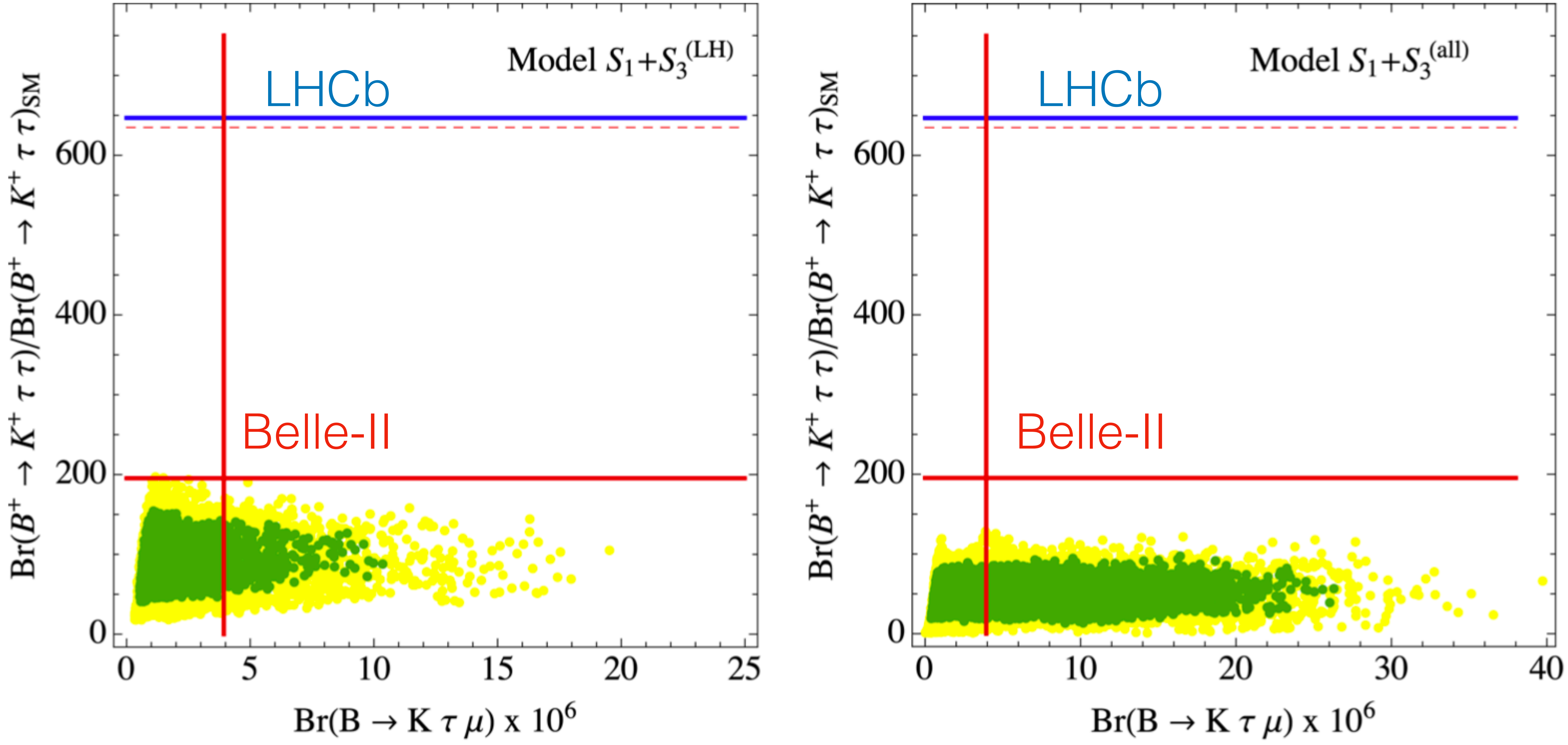


Plots updated w.r.t. [v3:2008.09548]

Predictions

Typical for all models addressing B-anomalies → The large couplings to τ imply signatures in DY tails of $pp \to \tau\,\tau$, deviations in **τ LFU** tests and **τ → μ LFV** tests (Belle-II). Also **B_s-mixing** is typically close to present bounds.

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



From B to Kaon physics with scalar leptoquarks and U(2)^5 flavor symmetry

D.M., S. Trifinopoulos, E. Venturini, in preparation [2106.yyyy]

The motivation

$\boldsymbol{b \longrightarrow c\, \tau\, \nu}$ + $\boldsymbol{b \longrightarrow s\, \mu\, \mu}$

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

?

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

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

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

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

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

$x_{t,b,\tau}$ are $\mathcal{O}(1)$

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:

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

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

→ 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

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

$\Big\}$ *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:

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

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

→ 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.

$\Big\}$ *Arbitrary parameters*

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

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

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

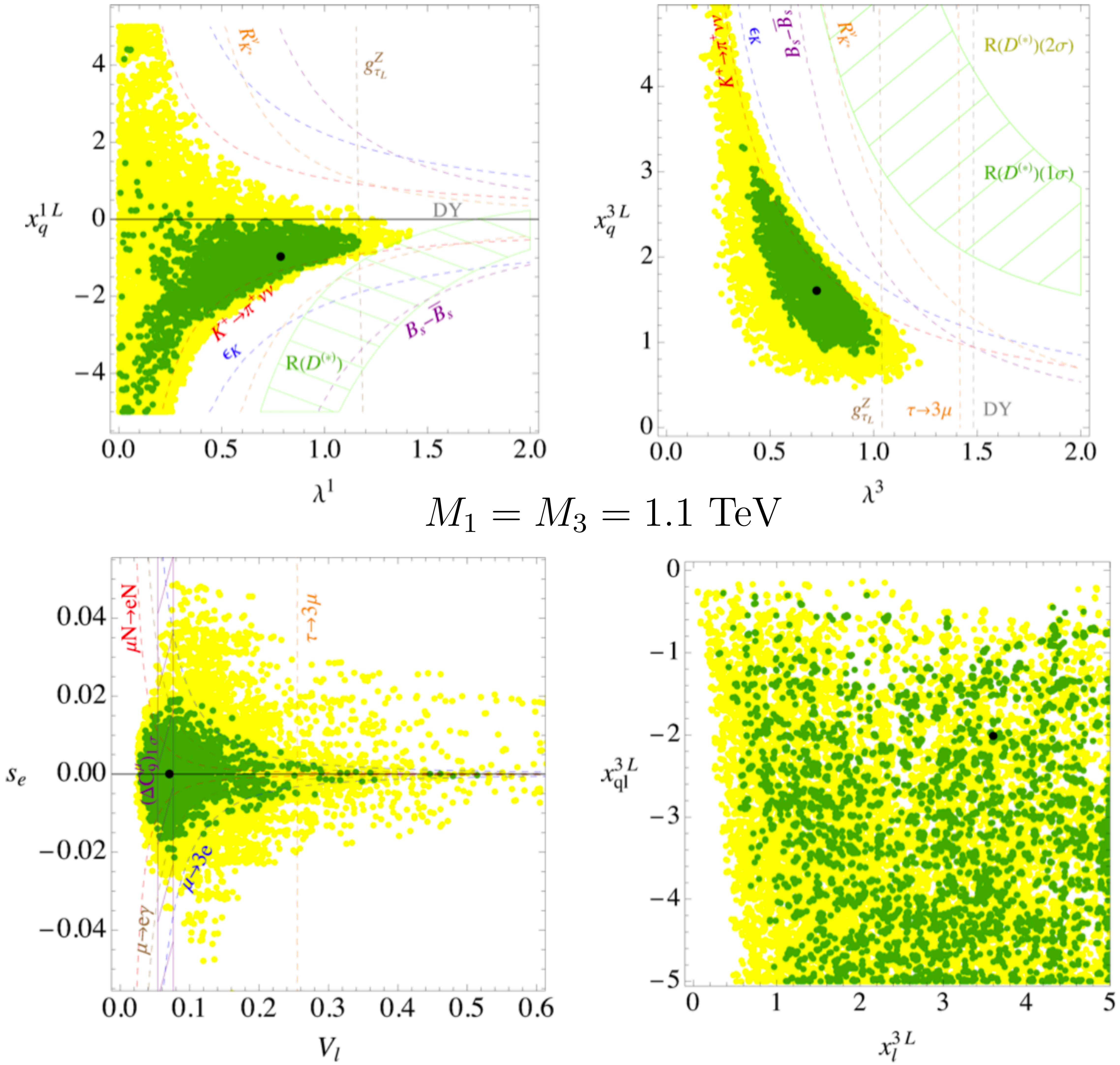
Exact relations (selection rules)

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

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.

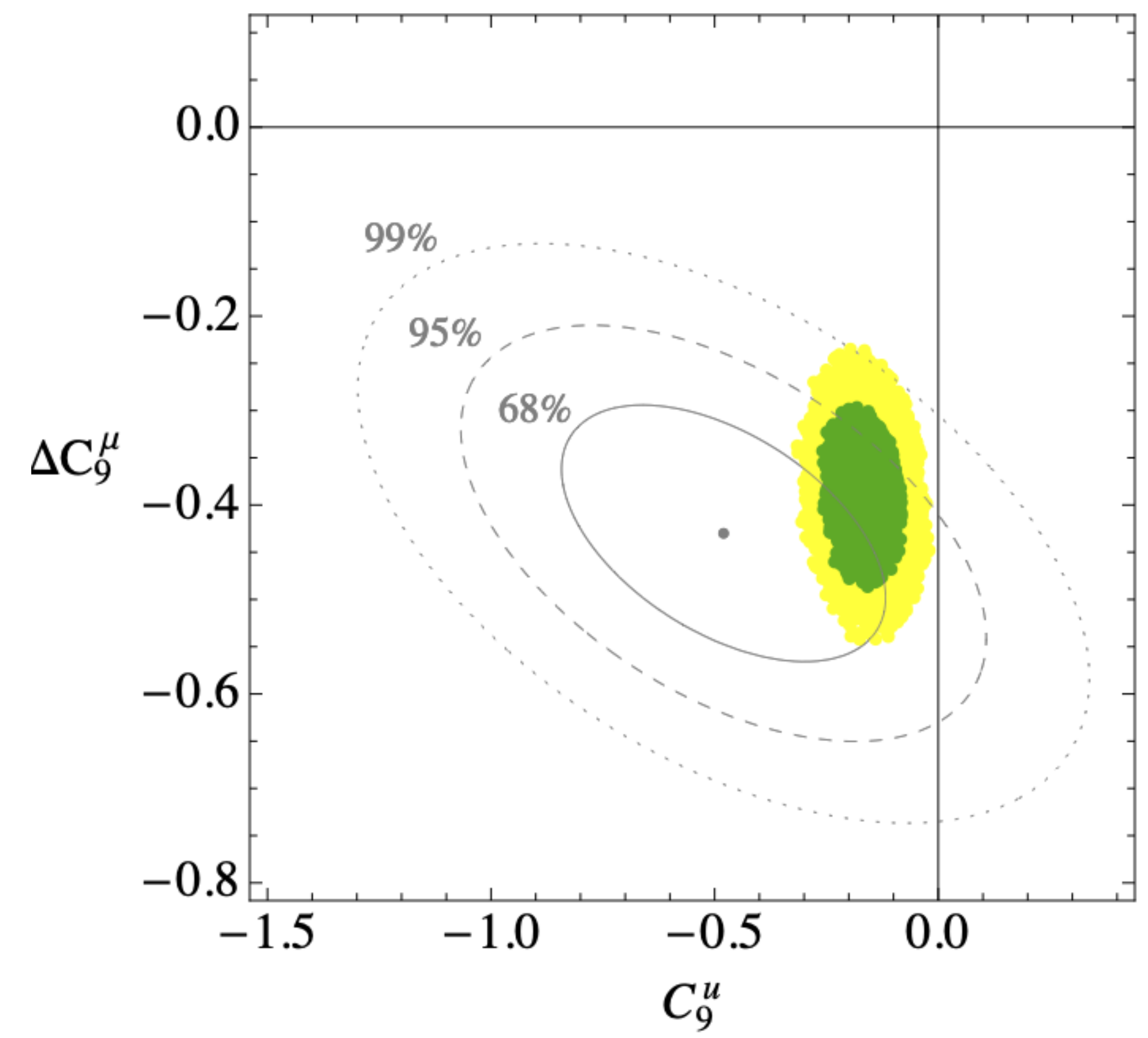


- The parameters are indeed consistent with a U(2)^5 structure: **all x's are O(1)**.

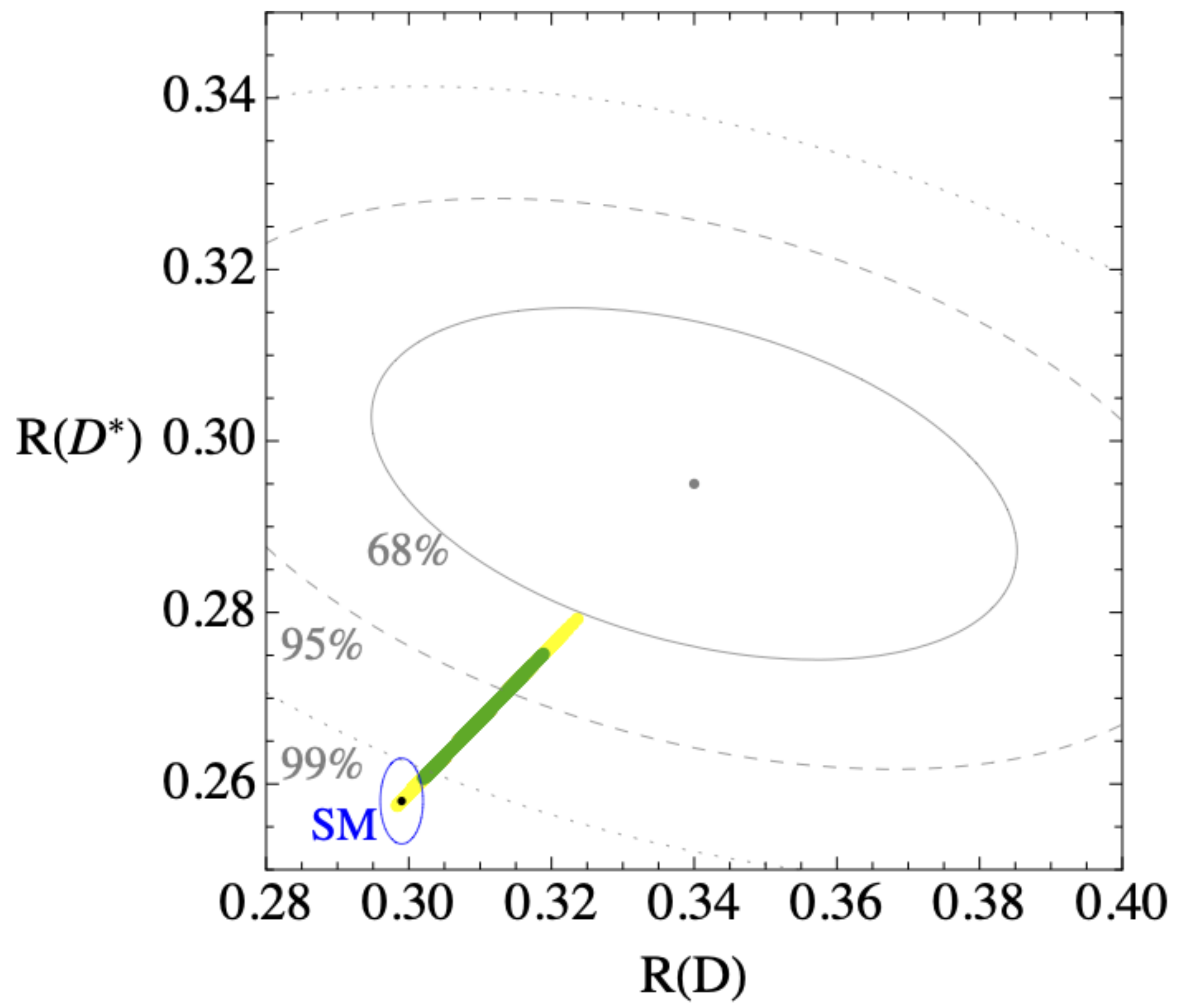
- $V_\ell \sim 0.1, \quad |s_e| \lesssim 0.02$

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

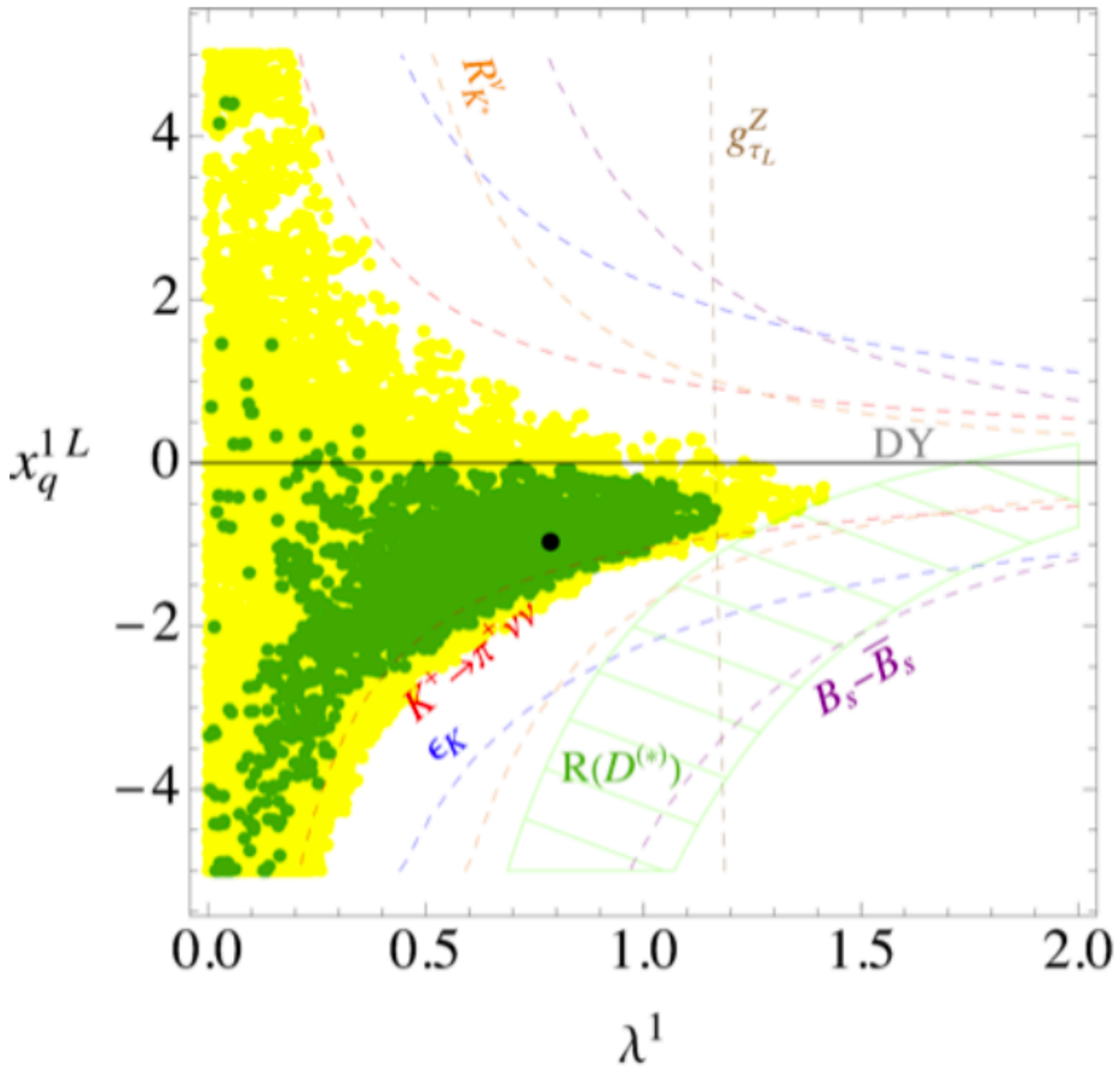
b→ sμμ can be addressed:

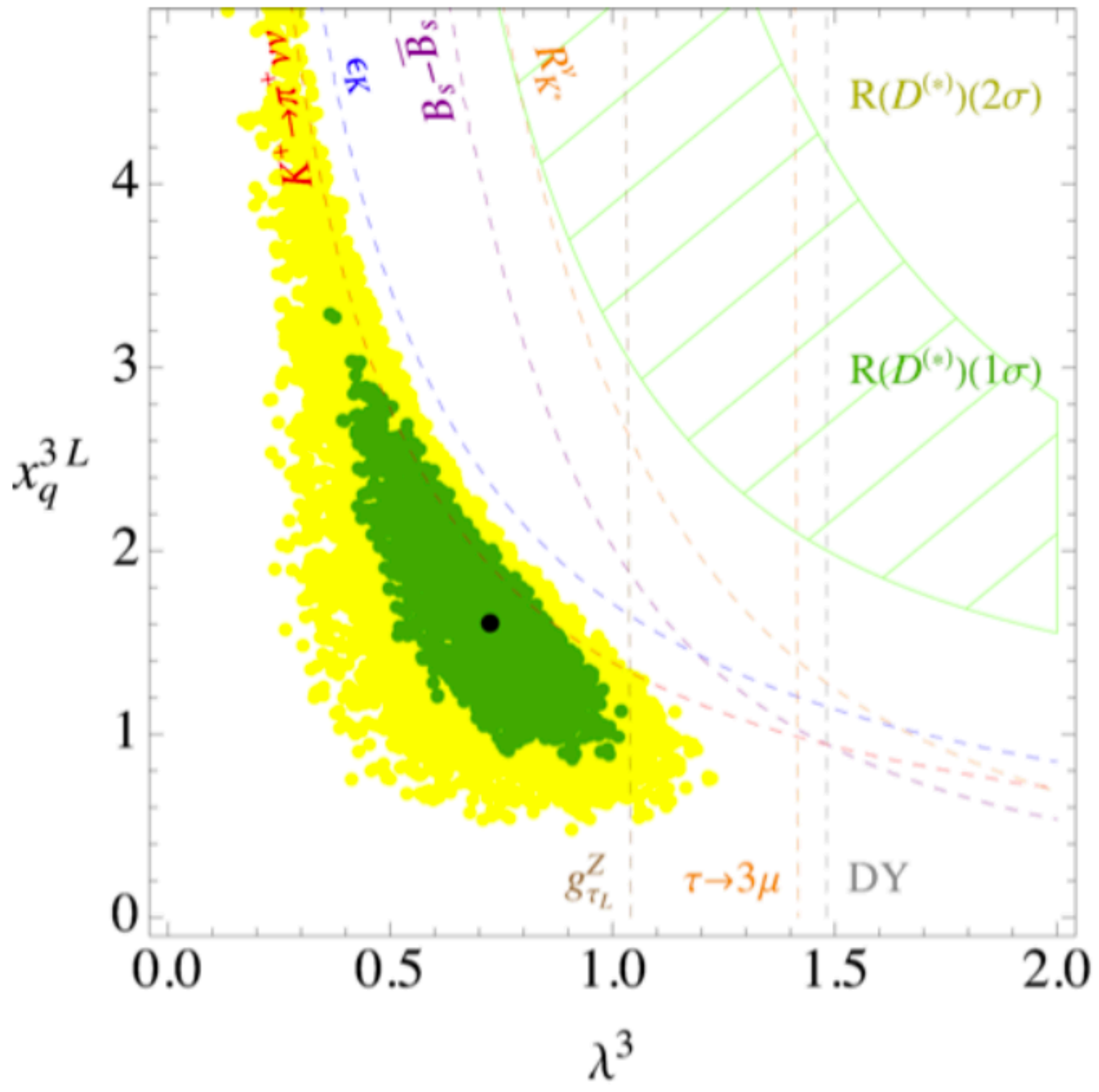


R(D$^{(*)}$) instead can only be addressed at 2σ:



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



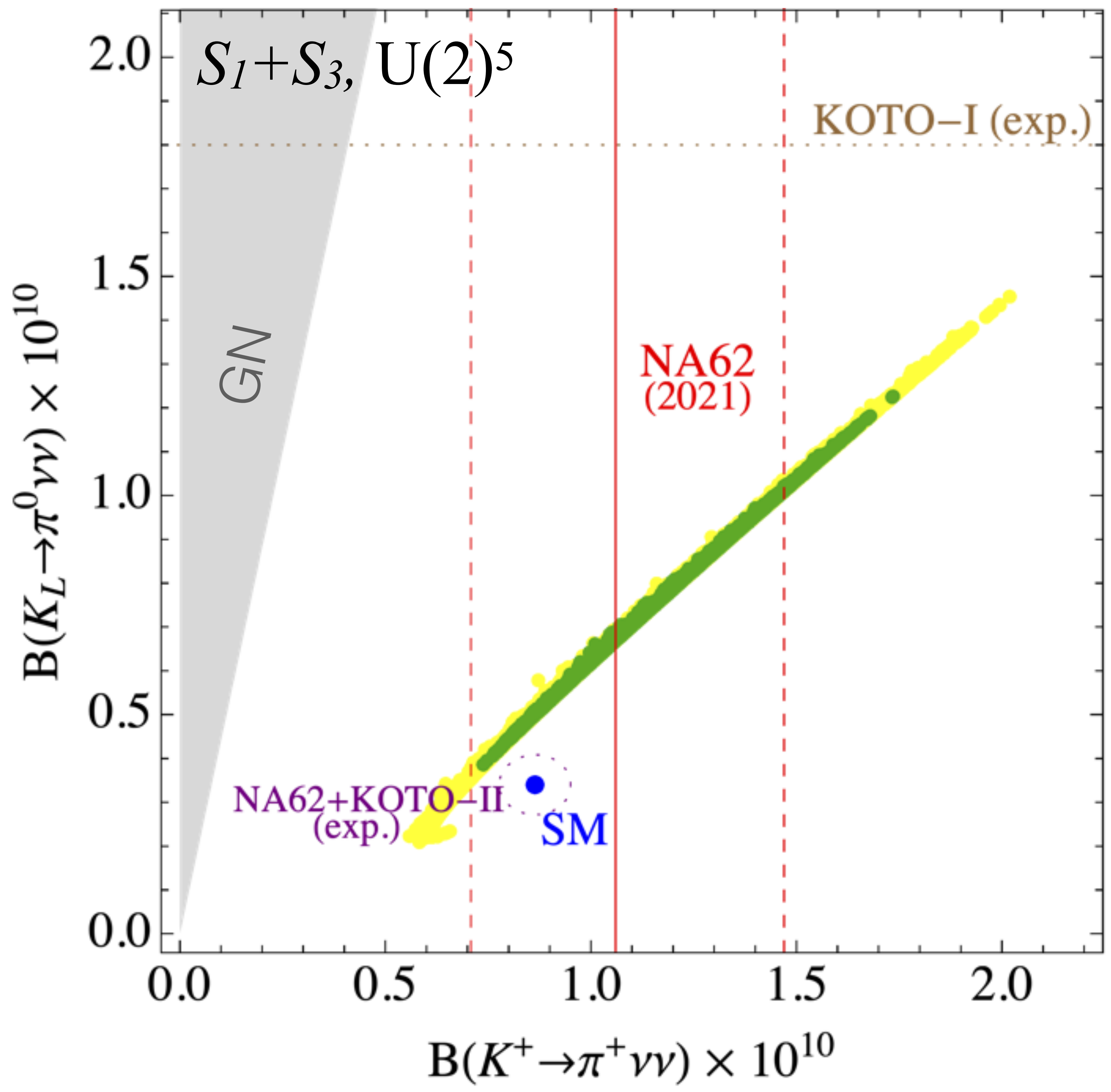


R(D$^{(*)}$)
$$\frac{\Delta R(D^{(*)})}{R(D^{(*)})_{\rm SM}} \approx v^2\left(1.09\frac{|\lambda^1|^2(1-x_q^{1*}V_{tb}^*)}{2M_1^2} - 1.02\frac{|\lambda^3|^2(1-x_q^{3*}V_{tb}^*)}{2M_3^2}\right)$$

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

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.

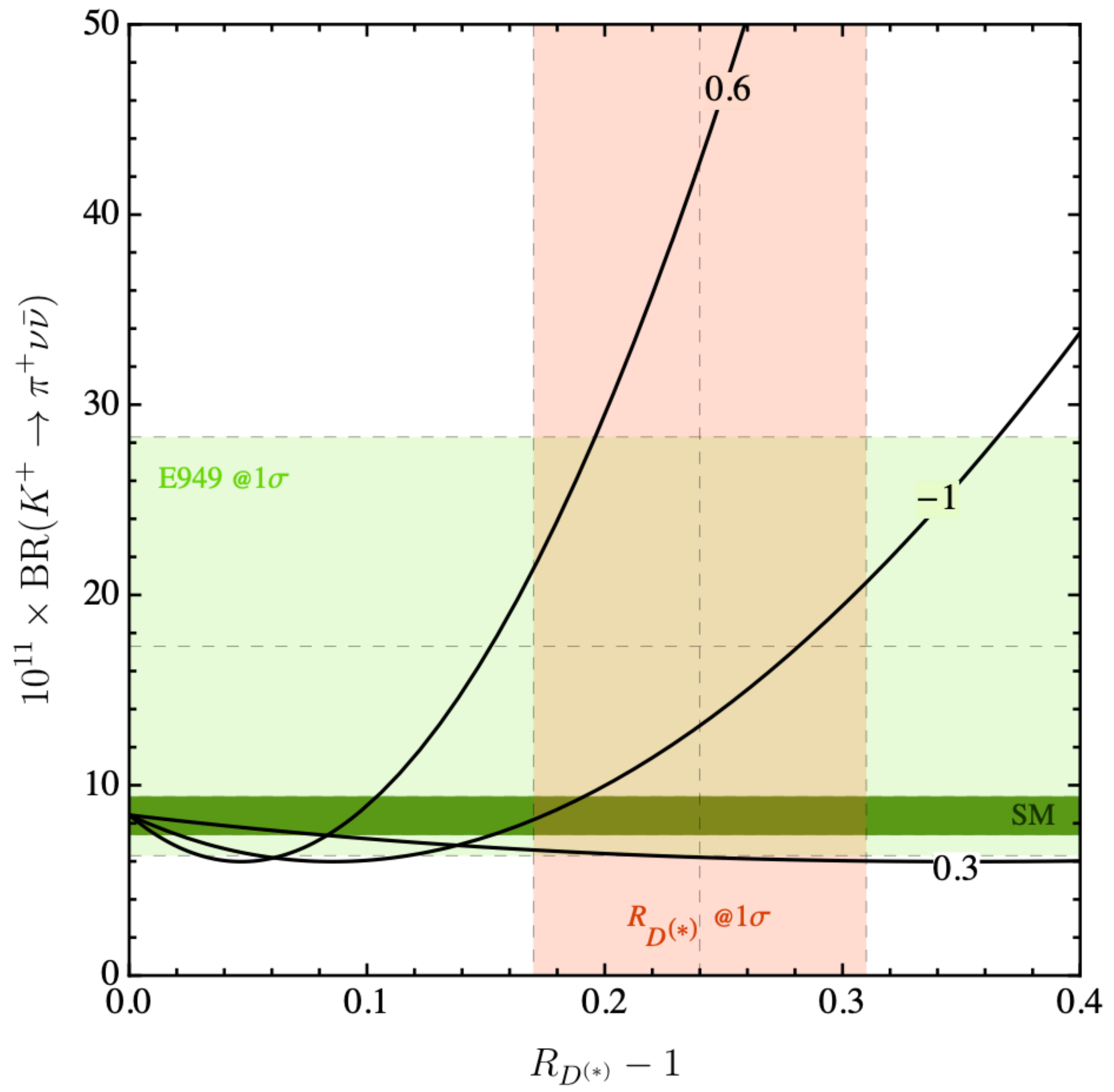
The correlation in the full model is stronger than just in EFT.

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

The **phase of NP** contributi

$$\left[L^{VLL}_{\nu d}\right]_{\nu_\tau\nu_\tau ds} \approx V^*_{td}V_{ts}\Big($$

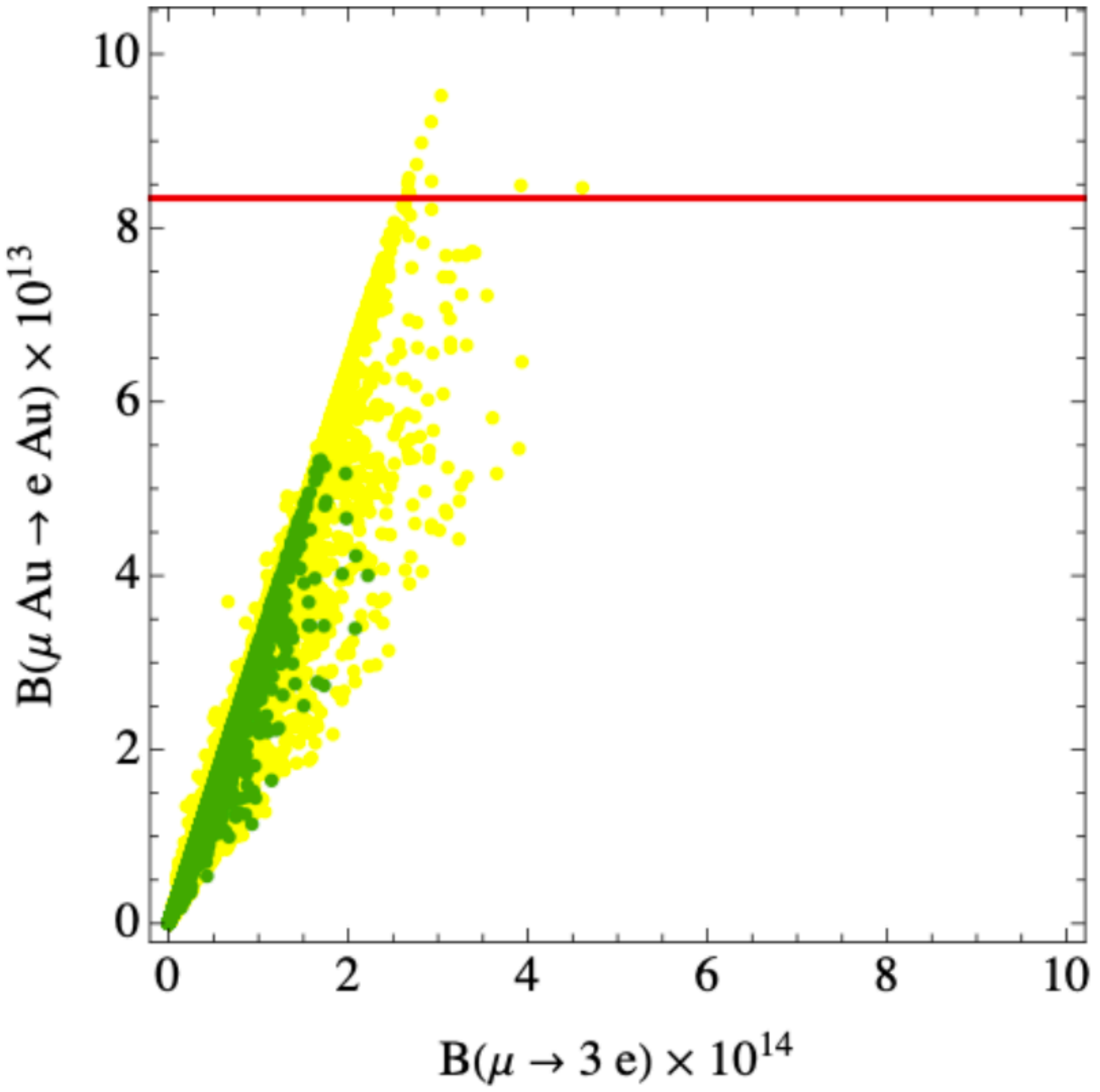
As consequence, the $K_L\to\pi$
below the KOTO stage-I fina



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} (ba
We also obtain Br($K_L\to\mu e$) ~ 10^{-15} and Br($K^+\to\pi^+\mu e$) ~ 10^{-18}.

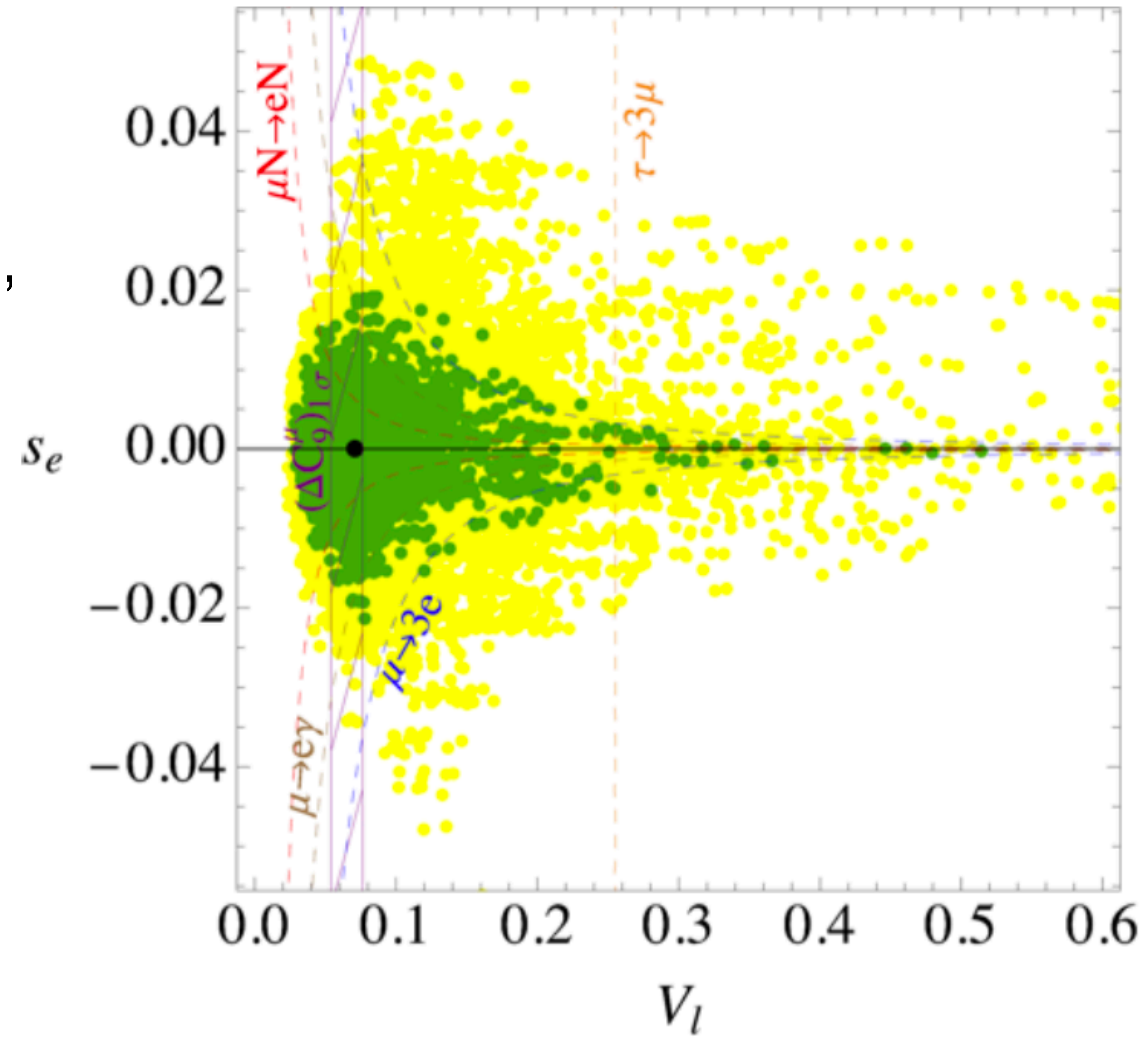
μ → e conversion



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.



Combined interpretation of R_K, $R(D^{(*)})$, $(g\text{-}2)_\mu$, and CAA

DM, Sokratis Trifinopoulos
PRL **127**, 061803 (2021) [2104.05730]

$$S_1 \sim (\bar{\mathbf{3}}, \mathbf{1})_{1/3} \ , \qquad \phi^+ \sim (\mathbf{1}, \mathbf{1})_1$$

A do-it-all model?

Let us consider a simplified model with only these two new weak-singlets states:

$$S_1 \sim (\bar{\mathbf{3}}, \mathbf{1})_{1/3}\ , \qquad \phi^+ \sim (\mathbf{1}, \mathbf{1})_1$$

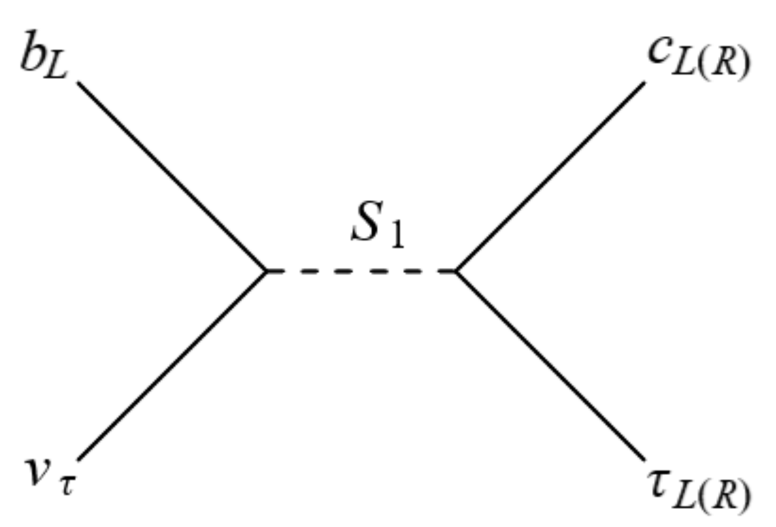
Note: same gauge quantum numbers as **sbottom** and **stau**, but different **L** and **B** assignments.

ϕ^+ couples to di-leptons:

$$\mathcal{L}_{S1+\phi} = \boxed{\frac{1}{2}\lambda_{\alpha\beta}\bar{\ell}^c_\alpha \epsilon \ell_\beta \phi^+} + \lambda^{1L}_{i\alpha}\bar{q}^c_i \epsilon \ell_\alpha S_1 + \lambda^{1R}_{i\alpha}\bar{u}^c_i e_\alpha S_1 + \text{h.c.}$$

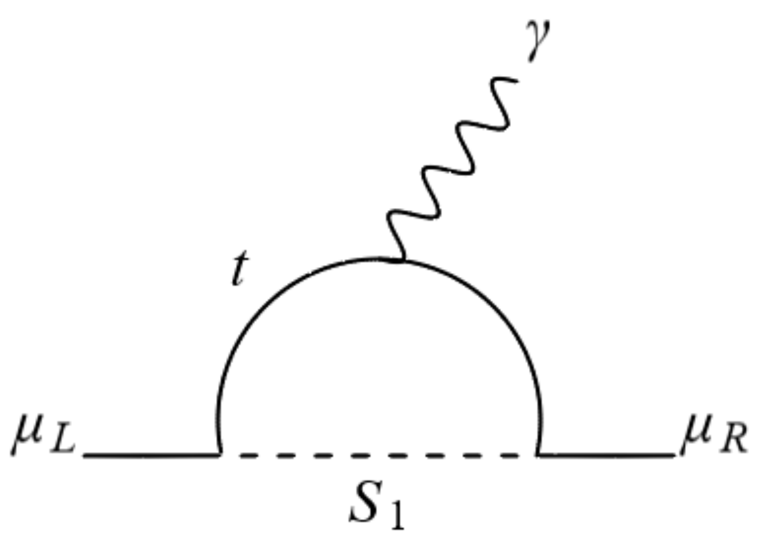
S_1

R(D(*))



$$R_D \approx 0.299 - 0.235\frac{\lambda^{1L}_{b\tau}\lambda^{1R}_{c\tau}}{m_1^2}(1 + 0.05\log m_1^2)$$
$$R_{D^*} \approx 0.258 - 0.088\frac{\lambda^{1L}_{b\tau}\lambda^{1R}_{c\tau}}{m_1^2}(1 + 0.02\log m_1^2)$$

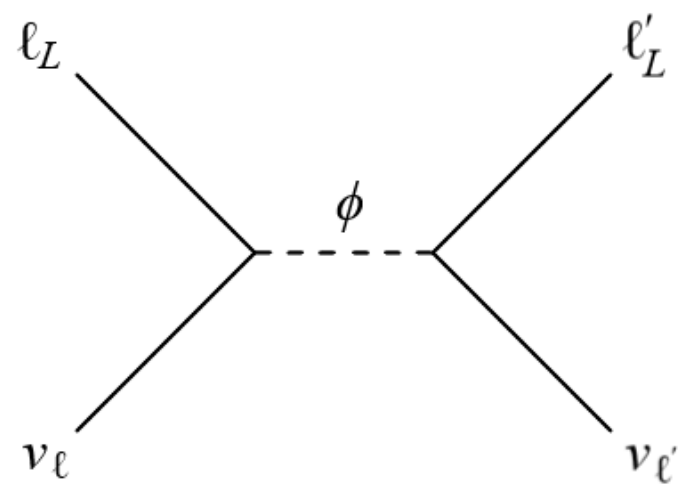
(g-2)$_\mu$



$$\Delta a_\mu \approx \frac{m_\mu m_t \lambda^{1L}_{b\mu}\lambda^{1R}_{t\mu}}{4\pi^2 M_1^2}\left(\log M_1^2/m_t^2 - \frac{7}{4}\right)$$

ϕ^+

CAA

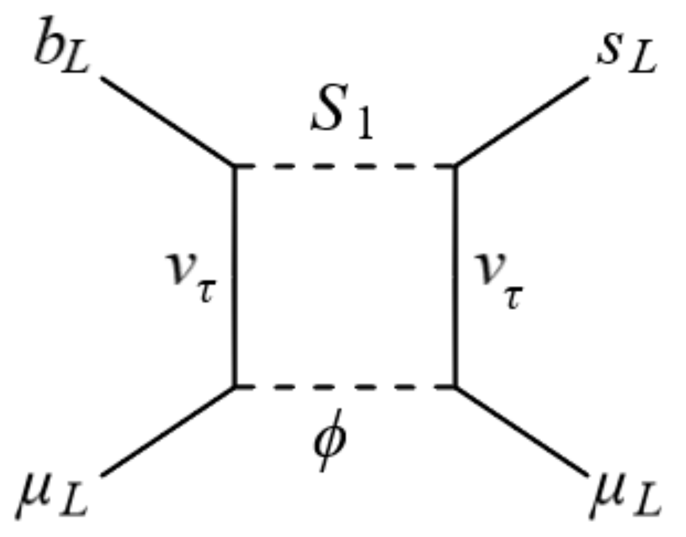


Crivellin, Kirk, Manzari, Panizzi 2012.09845; Felkl, Herrero-Garcia, Schmidt 2102.09898

$$\delta(\mu \to e\nu\nu) \approx \frac{v^2|\lambda_{12}|^2}{4M_\phi^2} + \frac{3m_t^2|\lambda^{1L}_{b\mu}|^2}{32\pi^2 M_1^2}\left(\frac{1}{2} - \log\frac{M_1^2}{m_t^2}\right)$$

S_1 + ϕ^+

R_K



$$\mathcal{O}^{bs\mu\mu}_{LL(LR)} = (\bar{s}\gamma^\alpha P_L b)(\bar{\mu}\gamma_\alpha P_{L(R)}\mu)$$
$$C_{LL} \approx -\lambda^{1L}_{b\tau}\lambda^{1L\,*}_{s\tau}\left(\frac{|\lambda^{1L}_{b\mu}|^2}{64\pi^2 M_1^2} + \frac{|\lambda_{\mu\tau}|^2\log M_1^2/M_\phi^2}{64\pi^2(M_\phi^2 - M_1^2)}\right)$$
$$C_{LR} \approx -\frac{|\lambda^{1R}_{c\mu}|^2\lambda^{1L}_{b\tau}\lambda^{1L\,*}_{s\tau}}{64\pi^2 M_1^2}\ .$$

$$C^1_{B_s} = \frac{(\lambda^{1L\,*}_{b\tau}\lambda^{1L}_{s\tau})^2}{128\pi^2 M_1^2}\ , \qquad C^1_D = \frac{(V_{ci}\lambda^{1L\,*}_{i\alpha}\lambda^{1L}_{j\alpha}V^*_{uj})^2}{128\pi^2 M_1^2}$$

Large masses are preferred to avoid meson mixing.

We fix: $M_1 = M_\phi = 5.5\text{TeV}$

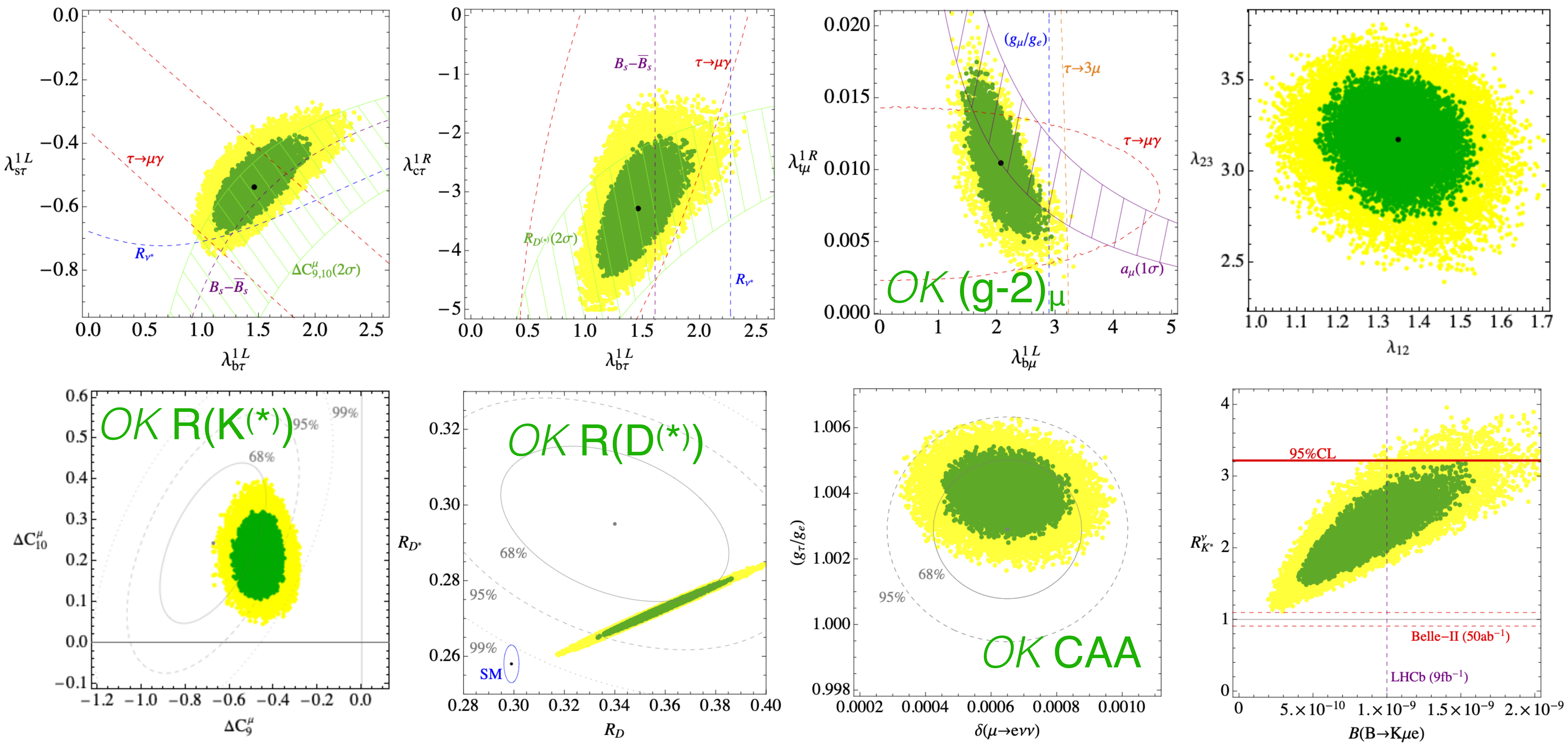
A do-it-all model?

DM, Sokratis Trifinopoulos 2104.05730

We do a global analysis including all the observables

$$M_1 = M_\phi = 5.5\mathrm{TeV}$$

Observable	Experimental value
R_D	0.34 ± 0.029 [56]
R_{D^*}	0.295 ± 0.013 [56]
ΔC_9^μ	-0.675 ± 0.16 [20]
ΔC_{10}^μ	0.244 ± 0.13 [20]
Δa_μ	$(2.51 \pm 0.59) \times 10^{-9}$ [27, 28]
$\delta(\mu \to e\nu\nu)$	$(6.5 \pm 1.5) \times 10^{-4}$ [41]
$R_D^{\mu/e}$	0.978 ± 0.035 [57, 58]
$\mathcal{B}(B_c \to \tau\nu)$	< 0.1 [59]
$R^\nu_{K^{(*)}}$	< 2.7 [60]
$C^1_{B_s}$	$< 2.01 \times 10^{-5}$ TeV^{-2} [61]
$\lvert\mathrm{Re}(C^1_D)\rvert$	$< 3.57 \times 10^{-7}$ TeV^{-2} [61]
$\lvert\mathrm{Im}(C^1_D)\rvert$	$< 2.23 \times 10^{-8}$ TeV^{-2} [61]
$\frac{g_\tau}{g_e}$	1.0058 ± 0.0030 [56]
$\frac{g_\tau}{g_\mu}$	1.0022 ± 0.0030 [56]
$\frac{g_\mu}{g_e}$	1.0036 ± 0.0028 [56]
$\delta g^Z_{\tau_L}$	$(-0.11 \pm 0.61) \times 10^{-3}$ [62]
$\delta g^Z_{\tau_R}$	$(0.66 \pm 0.65) \times 10^{-3}$ [62]
$\delta g^Z_{\mu L}$	$(0.3 \pm 1.1) \times 10^{-3}$ [62]
$\delta g^Z_{\mu R}$	$(0.2 \pm 1.3) \times 10^{-3}$ [62]
$\mathcal{B}(\tau \to \mu\gamma)$	$< 4.4 \times 10^{-8}$ [63]
$\mathcal{B}(\tau \to 3\mu)$	$< 2.1 \times 10^{-8}$ [63]



- **Good fit** of all anomalies
- **Cancellation** of approx. **1 part in 3** required to avoid τ→μγ: via $\lambda^{1R}_{c\mu}$
- **Large couplings** required, due to the large masses needed to avoid meson mixing.

Conclusions

- **Flavor anomalies** still require data (and theory) to give us a definitive picture, some could stay, some could go.
- If any will remain, it will be a revolutionary **stepping stone to an unexpected New Physics sector**!

We must **keep an open mind** and **explore all possibilities**.

- Exploring combined explanations is a useful exploratory exercise, it allows us to **connect B-anomalies with other observables**, both at high and low energy.
- Observations or limits from correlated effects in completely different processes will be crucial to understand the underlying UV physics and its flavor structure.

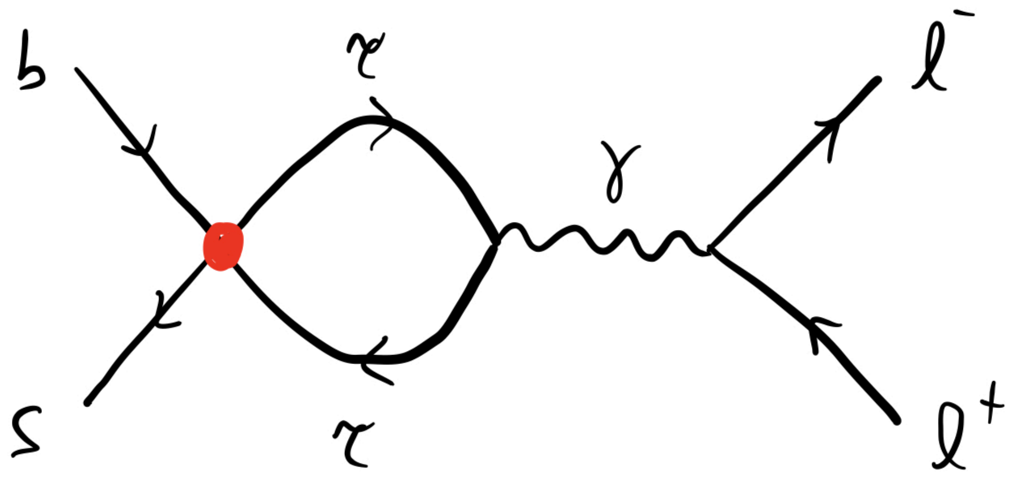
Thank you!

Backup

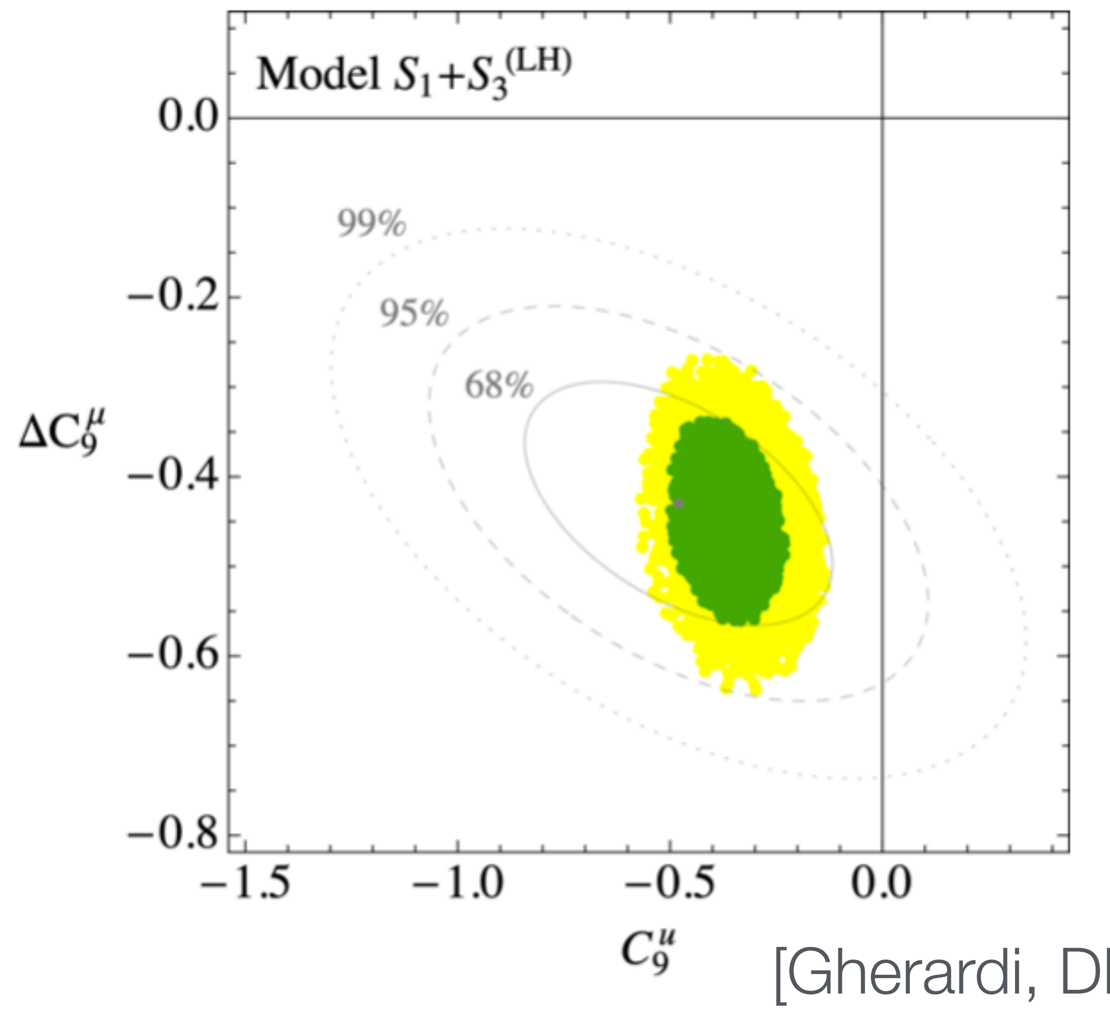
From R_K to $R(D^{(*)})$ anomalies

A large coupling to the τ induces an RG-enhanced **lepton-flavor universal** contribution proportional to C_9^U

Capdevila et al. 1712.01919, Crivellin et al. 1807.02068



$$\mathcal{C}_9^{\mathrm{U}} \approx 7.5\left(1-\sqrt{\frac{R_{D^{(*)}}}{R_{D^{(*)}\mathrm{SM}}}}\right)\left(1+\frac{\log(\Lambda^2/(1\mathrm{TeV}^2))}{10.5}\right)$$



Correct size obtained with the preferred value of $R(D^{(*)})$.

[Gherardi, DM, Venturini 2008.09548]

$\mathbf{R_K}$ $\longrightarrow$ $\sim \dfrac{g_\mu V_{ts}}{\Lambda^2}(\bar{b}_L\gamma_\alpha s_L)(\bar{\mu}_L\gamma^\alpha\mu_L)$

$\Lambda/\sqrt{g_\mu} \sim 7$ **TeV**

CKM-like flavor structure

SM gauge invariance $SU(2)_L$

$$\boxed{C_T\ (\bar{Q}_L^i\gamma_\mu\sigma^a Q_L^j)(\bar{L}_L^\alpha\gamma^\mu\sigma^a L_L^\beta)} + C_S\ (\bar{Q}_L^i\gamma_\mu Q_L^j)(\bar{L}_L^\alpha\gamma^\mu L_L^\beta)$$

Usually UV physics generates both.
The exception are Z' models, which generate only the singlet

$$\sim \frac{g_\mu V_{cb}}{\Lambda^2}(\bar{b}_L\gamma_\alpha c_L)(\bar{\nu}_L^\mu\gamma^\alpha\mu_L)$$

Charged-current in muons

Generalising lepton flavour

$$\sim \frac{g_\tau V_{cb}}{\Lambda^2}(\bar{b}_L\gamma_\alpha c_L)(\bar{\nu}_L^\tau\gamma^\alpha\tau_L)$$

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

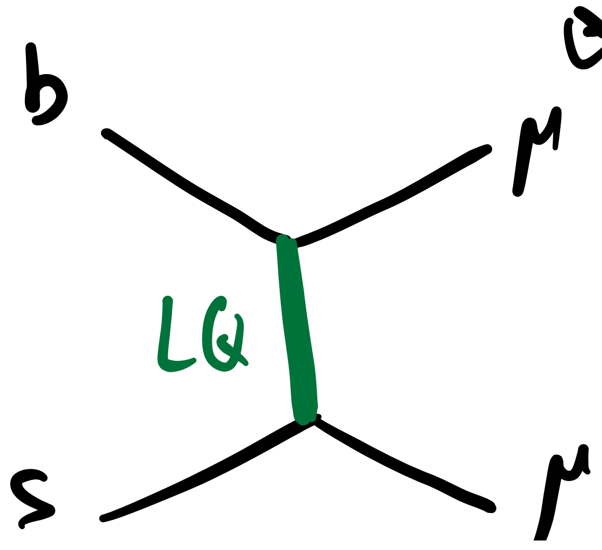
$\Lambda/\sqrt{g_\tau} \sim$ **1 TeV**

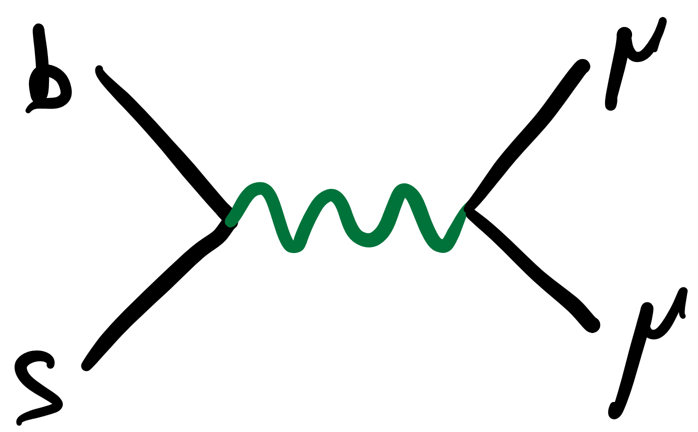
If $g_e \ll g_\mu \ll g_\tau$ same hierarchy as $m_e \ll m_\mu \ll m_\tau$

Required for R_K

UV completions for $b \to s\, \mu^+\mu^-$ anomalies

TREE LEVEL





Leptoquark

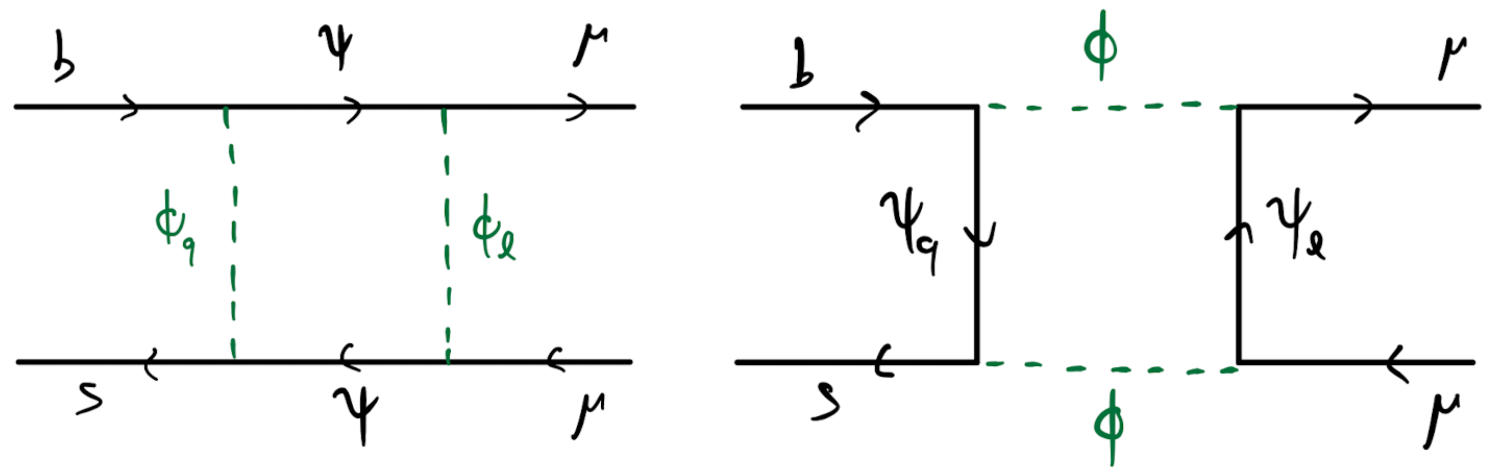
vector U_1 or scalar S_3

Z'

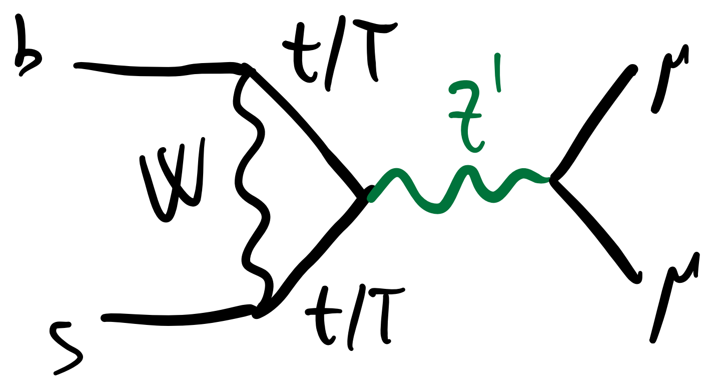
LOOP LEVEL

LFU anomalies from boxes

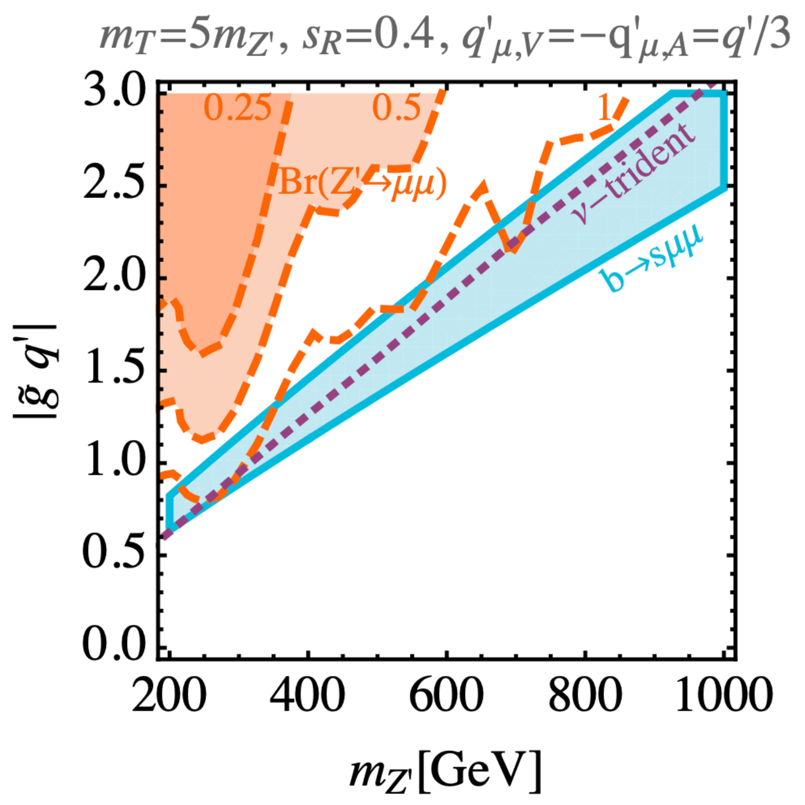
e.g. Arcadi, Calibbi, Fedele, Mescia 2104.03228



Top-philic Z'

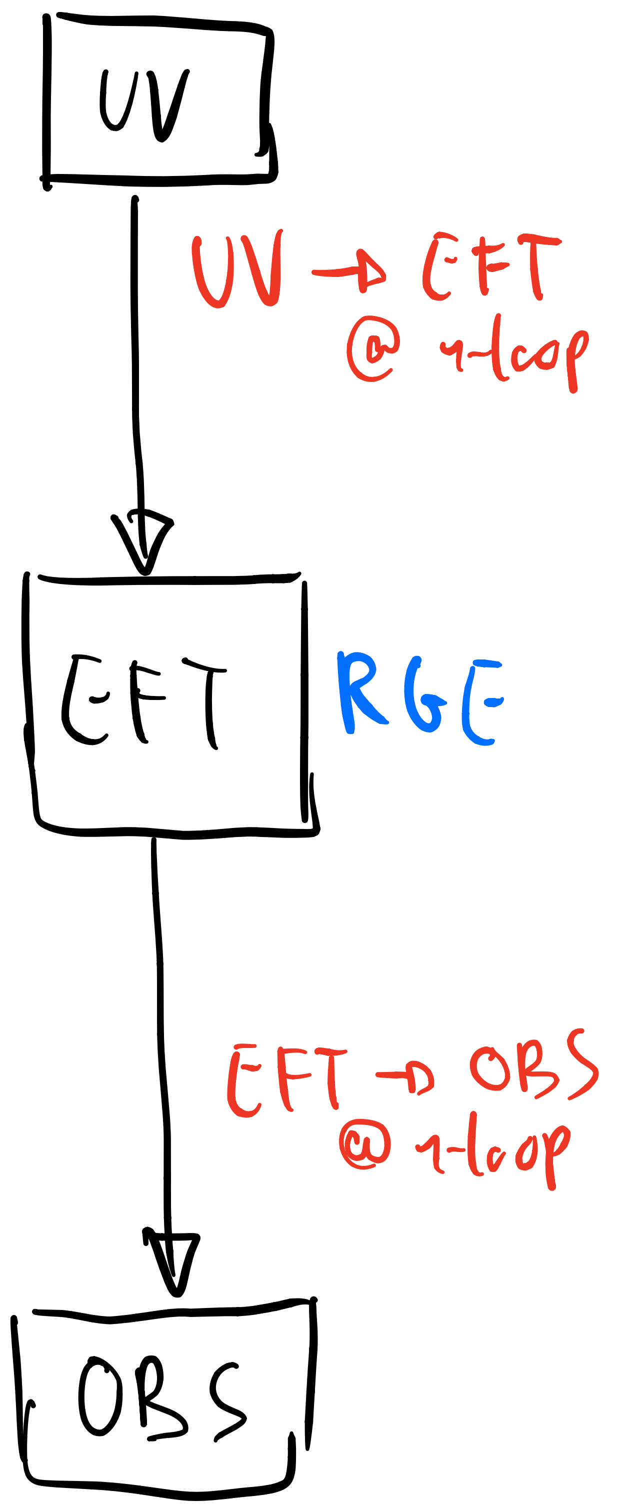


Kamenik, Soreq, Zupan [1704.06005]



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***”

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

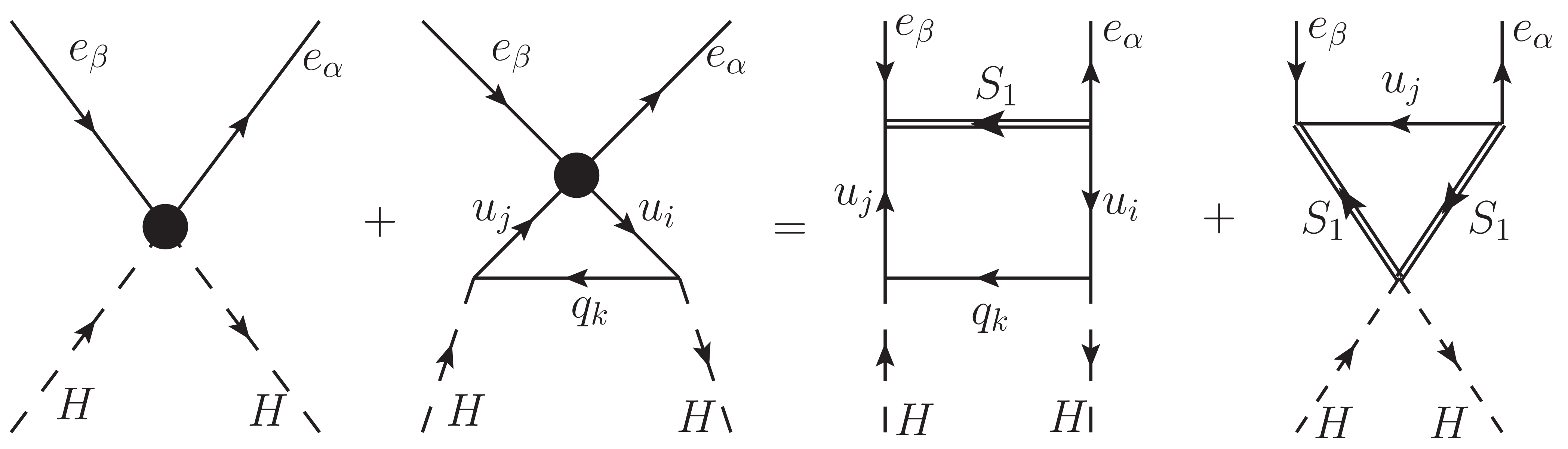


Figure 1: Diagrams for the matching of the $\langle \bar{e}eH^\dagger H\rangle$ Green function.

Relevant Green’s basis operators:

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

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

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

Matching conditions in the Green’s basis:

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

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

$$[G''_{He}(\mu_M)]_{\alpha\beta} = 0\,.$$

The last two must be rotated to the Warsaw basis:

$$(O'_{He})_{\alpha\beta} \to (y_E^*)_{\gamma\beta}(O_{eH})^\dagger_{\gamma\alpha} + (y_E)_{\gamma\alpha}(O_{eH})_{\gamma\beta}$$

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

While the first operators receives contributions also from other ones:

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

“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		X^2H^2		H^2D^4	
$\mathcal{O}_{3G}$	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_{HG}$	$G^A_{\mu\nu}G^{A\mu\nu}(H^\dagger H)$	$\mathcal{O}_{DH}$	$(D_\mu D^\mu H)^\dagger(D_\nu D^\nu H)$
$\mathcal{O}_{3\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_{H\widetilde{G}}$	$\widetilde{G}^A_{\mu\nu}G^{A\mu\nu}(H^\dagger H)$	H^4D^2	
$\mathcal{O}_{3W}$	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{HW}$	$W^I_{\mu\nu}W^{I\mu\nu}(H^\dagger H)$	$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
$\mathcal{O}_{3\widetilde{W}}$	$\epsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{H\widetilde{W}}$	$\widetilde{W}^I_{\mu\nu}W^{I\mu\nu}(H^\dagger H)$	$\mathcal{O}_{HD}$	$(H^\dagger D^\mu H)^\dagger(H^\dagger D_\mu H)$
X^2D^2		$\mathcal{O}_{HB}$	$B_{\mu\nu}B^{\mu\nu}(H^\dagger H)$	$\mathcal{O}'_{HD}$	$(H^\dagger H)(D_\mu H)^\dagger(D^\mu H)$
$\mathcal{O}_{2G}$	$-\frac{1}{2}(D_\mu G^{A\mu\nu})(D^\rho G^A_{\rho\nu})$	$\mathcal{O}_{H\widetilde{B}}$	$\widetilde{B}_{\mu\nu}B^{\mu\nu}(H^\dagger H)$	$\mathcal{O}''_{HD}$	$(H^\dagger H)D_\mu(H^\dagger i\overleftrightarrow{D}^\mu H)$
$\mathcal{O}_{2W}$	$-\frac{1}{2}(D_\mu W^{I\mu\nu})(D^\rho W^I_{\rho\nu})$	$\mathcal{O}_{HWB}$	$W^I_{\mu\nu}B^{\mu\nu}(H^\dagger\sigma^I H)$	H^6	
$\mathcal{O}_{2B}$	$-\frac{1}{2}(\partial_\mu B^{\mu\nu})(\partial^\rho B_{\rho\nu})$	$\mathcal{O}_{H\widetilde{W}B}$	$\widetilde{W}^I_{\mu\nu}B^{\mu\nu}(H^\dagger\sigma^I H)$	$\mathcal{O}_H$	$(H^\dagger H)^3$
		H^2XD^2			
		$\mathcal{O}_{WDH}$	$D_\nu W^{I\mu\nu}(H^\dagger i\overleftrightarrow{D}^I_\mu H)$		
		$\mathcal{O}_{BDH}$	$\partial_\nu B^{\mu\nu}(H^\dagger i\overleftrightarrow{D}_\mu H)$		

Four-quark		Four-lepton		Semileptonic	
$\mathcal{O}^{(1)}_{qq}$	$(\bar{q}\gamma^\mu q)(\bar{q}\gamma_\mu q)$	$\mathcal{O}_{\ell\ell}$	$(\bar{\ell}\gamma^\mu\ell)(\bar{\ell}\gamma_\mu\ell)$	$\mathcal{O}^{(1)}_{\ell q}$	$(\bar{\ell}\gamma^\mu\ell)(\bar{q}\gamma_\mu q)$
$\mathcal{O}^{(3)}_{qq}$	$(\bar{q}\gamma^\mu\sigma^I q)(\bar{q}\gamma_\mu\sigma^I q)$	$\mathcal{O}_{ee}$	$(\bar{e}\gamma^\mu e)(\bar{e}\gamma_\mu e)$	$\mathcal{O}^{(3)}_{\ell q}$	$(\bar{\ell}\gamma^\mu\sigma^I\ell)(\bar{q}\gamma_\mu\sigma^I q)$
$\mathcal{O}_{uu}$	$(\bar{u}\gamma^\mu u)(\bar{u}\gamma_\mu u)$	$\mathcal{O}_{\ell e}$	$(\bar{\ell}\gamma^\mu\ell)(\bar{e}\gamma_\mu e)$	$\mathcal{O}_{eu}$	$(\bar{e}\gamma^\mu e)(\bar{u}\gamma_\mu u)$
$\mathcal{O}_{dd}$	$(\bar{d}\gamma^\mu d)(\bar{d}\gamma_\mu d)$			$\mathcal{O}_{ed}$	$(\bar{e}\gamma^\mu e)(\bar{d}\gamma_\mu d)$
$\mathcal{O}^{(1)}_{ud}$	$(\bar{u}\gamma^\mu u)(\bar{d}\gamma_\mu d)$			$\mathcal{O}_{qe}$	$(\bar{q}\gamma^\mu q)(\bar{e}\gamma_\mu e)$
$\mathcal{O}^{(8)}_{ud}$	$(\bar{u}\gamma^\mu T^A u)(\bar{d}\gamma_\mu T^A d)$			$\mathcal{O}_{\ell u}$	$(\bar{\ell}\gamma^\mu\ell)(\bar{u}\gamma_\mu u)$
$\mathcal{O}^{(1)}_{qu}$	$(\bar{q}\gamma^\mu q)(\bar{u}\gamma_\mu u)$			$\mathcal{O}_{\ell d}$	$(\bar{\ell}\gamma^\mu\ell)(\bar{d}\gamma_\mu d)$
$\mathcal{O}^{(8)}_{qu}$	$(\bar{q}\gamma^\mu T^A q)(\bar{u}\gamma_\mu T^A u)$			$\mathcal{O}_{\ell edq}$	$(\bar{\ell}e)(\bar{d}q)$
$\mathcal{O}^{(1)}_{qd}$	$(\bar{q}\gamma^\mu q)(\bar{d}\gamma_\mu d)$			$\mathcal{O}^{(1)}_{\ell equ}$	$(\bar{\ell}^r e)\epsilon_{rs}(\bar{q}^s u)$
$\mathcal{O}^{(8)}_{qd}$	$(\bar{q}\gamma^\mu T^A q)(\bar{d}\gamma_\mu T^A d)$			$\mathcal{O}^{(3)}_{\ell equ}$	$(\bar{\ell}^r\sigma^{\mu\nu}e)\epsilon_{rs}(\bar{q}^s\sigma_{\mu\nu}u)$
$\mathcal{O}^{(1)}_{quqd}$	$(\bar{q}^r u)\epsilon_{rs}(\bar{q}^s d)$				
$\mathcal{O}^{(8)}_{quqd}$	$(\bar{q}^r T^A u)\epsilon_{rs}(\bar{q}^s T^A d)$				

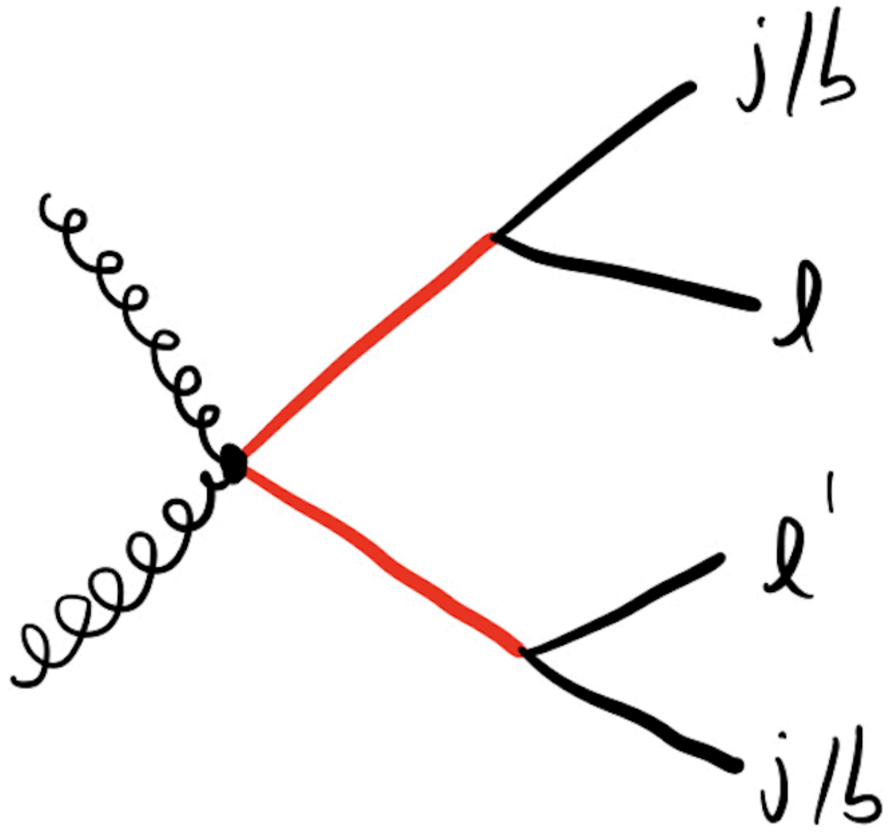
ψ^2D^3	
$\mathcal{O}_{qD}$	$\frac{i}{2}\bar{q}\left\{D_\mu D^\mu, \not{D}\right\}q$
$\mathcal{O}_{uD}$	$\frac{i}{2}\bar{u}\left\{D_\mu D^\mu, \not{D}\right\}u$
$\mathcal{O}_{dD}$	$\frac{i}{2}\bar{d}\left\{D_\mu D^\mu, \not{D}\right\}d$
$\mathcal{O}_{\ell D}$	$\frac{i}{2}\bar{\ell}\left\{D_\mu D^\mu, \not{D}\right\}\ell$
$\mathcal{O}_{eD}$	$\frac{i}{2}\bar{e}\left\{D_\mu D^\mu, \not{D}\right\}e$
$\psi^2HD^2 + \text{h.c.}$	
$\mathcal{O}_{uHD1}$	$(\bar{q}u)D_\mu D^\mu\widetilde{H}$
$\mathcal{O}_{uHD2}$	$(\bar{q}i\sigma_{\mu\nu}D^\mu u)D^\nu\widetilde{H}$
$\mathcal{O}_{uHD3}$	$(\bar{q}D_\mu D^\mu u)\widetilde{H}$
$\mathcal{O}_{uHD4}$	$(\bar{q}D_\mu u)D^\mu\widetilde{H}$
$\mathcal{O}_{dHD1}$	$(\bar{q}d)D_\mu D^\mu H$
$\mathcal{O}_{dHD2}$	$(\bar{q}i\sigma_{\mu\nu}D^\mu d)D^\nu H$
$\mathcal{O}_{dHD3}$	$(\bar{q}D_\mu D^\mu d)H$
$\mathcal{O}_{dHD4}$	$(\bar{q}D_\mu d)D^\mu H$
$\mathcal{O}_{eHD1}$	$(\bar{\ell}e)D_\mu D^\mu H$
$\mathcal{O}_{eHD2}$	$(\bar{\ell}i\sigma_{\mu\nu}D^\mu e)D^\nu H$
$\mathcal{O}_{eHD3}$	$(\bar{\ell}D_\mu D^\mu e)H$
$\mathcal{O}_{eHD4}$	$(\bar{\ell}D_\mu e)D^\mu H$
$\psi^2XH + \text{h.c.}$	
$\mathcal{O}_{uG}$	$(\bar{q}T^A\sigma^{\mu\nu}u)\widetilde{H}G^A_{\mu\nu}$
$\mathcal{O}_{uW}$	$(\bar{q}\sigma^{\mu\nu}u)\sigma^I\widetilde{H}W^I_{\mu\nu}$
$\mathcal{O}_{uB}$	$(\bar{q}\sigma^{\mu\nu}u)\widetilde{H}B_{\mu\nu}$
$\mathcal{O}_{dG}$	$(\bar{q}T^A\sigma^{\mu\nu}d)HG^A_{\mu\nu}$
$\mathcal{O}_{dW}$	$(\bar{q}\sigma^{\mu\nu}d)\sigma^I HW^I_{\mu\nu}$
$\mathcal{O}_{dB}$	$(\bar{q}\sigma^{\mu\nu}d)HB_{\mu\nu}$
$\mathcal{O}_{eW}$	$(\bar{\ell}\sigma^{\mu\nu}e)\sigma^I HW^I_{\mu\nu}$
$\mathcal{O}_{eB}$	$(\bar{\ell}\sigma^{\mu\nu}e)HB_{\mu\nu}$

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

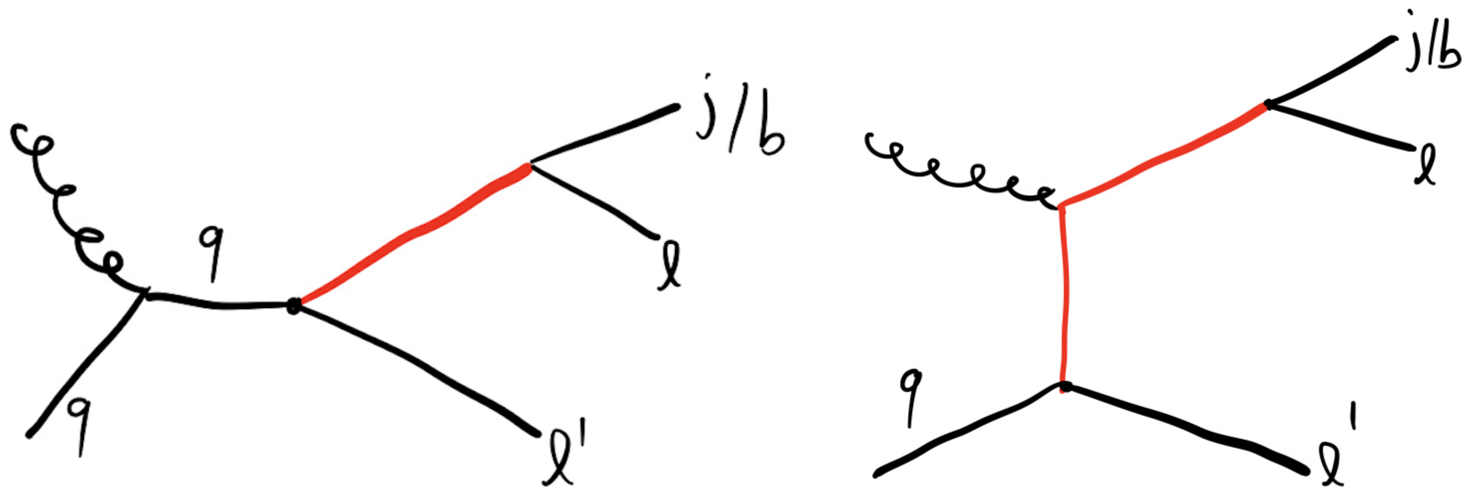
ψ^2DH^2	
$\mathcal{O}^{(1)}_{Hq}$	$(\bar{q}\gamma^\mu q)(H^\dagger i\overleftrightarrow{D}_\mu H)$
$\mathcal{O}'^{(1)}_{Hq}$	$(\bar{q}i\overleftrightarrow{\not{D}}q)(H^\dagger H)$
$\mathcal{O}''^{(1)}_{Hq}$	$(\bar{q}\gamma^\mu q)\partial_\mu(H^\dagger H)$
$\mathcal{O}^{(3)}_{Hq}$	$(\bar{q}\sigma^I\gamma^\mu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

The Threefold Way of LQ Searches at LHC

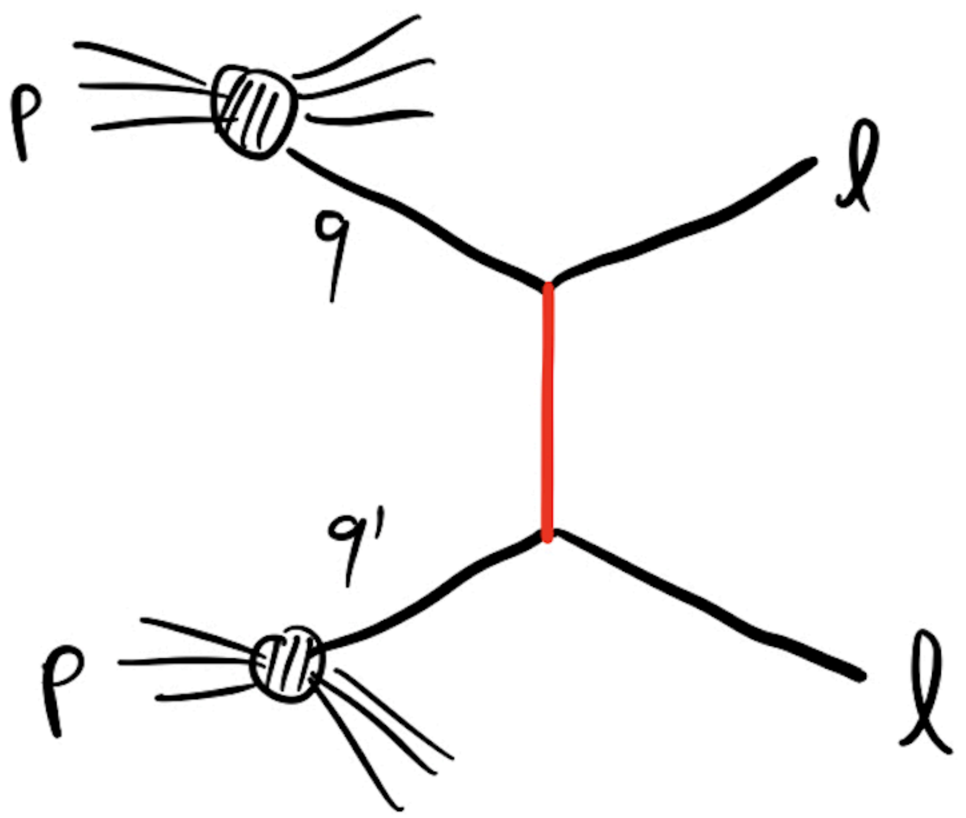
QCD
pair-production

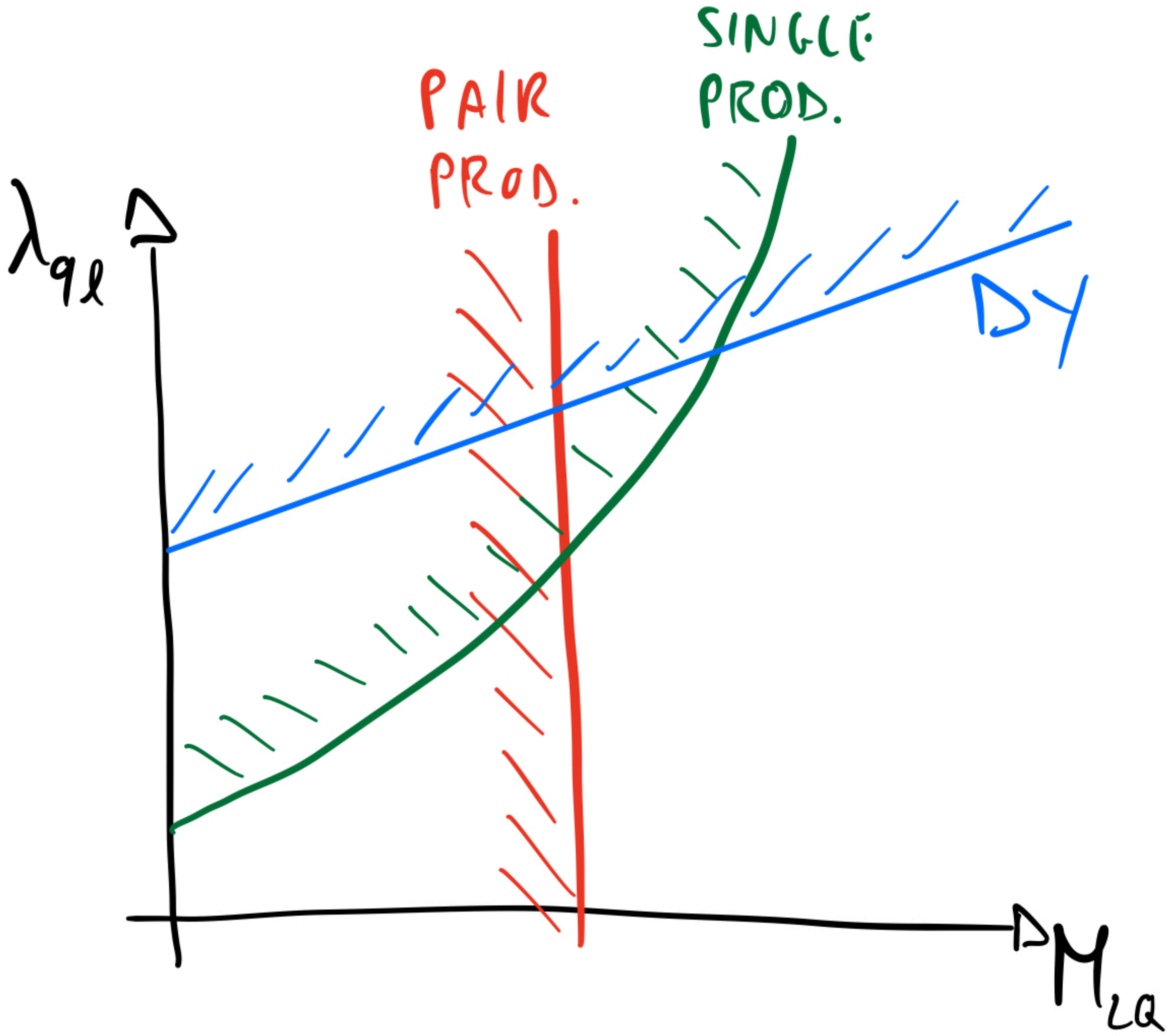


single-production



High-p_T Drell-Yan



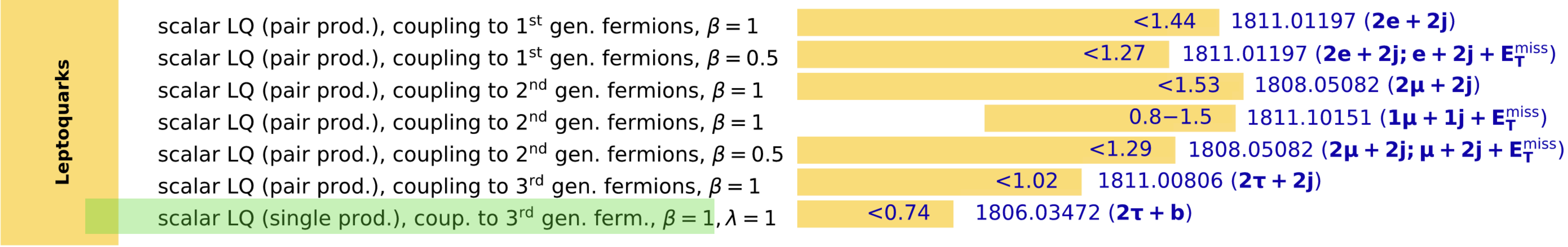


[Diaz, Schmaltz, Zhong 1706.05033, 1810.10017; Dorsner, Greljo 1801.07641]

In order to cover all couplings it is important to consider all combinations of different lepton & quark combinations in final state!

Leptoquark searches at CMS and ATLAS

CMS



CMS ττbb 1703.03995, 1811.00806
CMS ττtt 1803.02864
CMS μμjj & μνjj CMS PAS EXO-17-003
CMS μμtt 1809.05558
CMS νν+(jj,bb,tt) 1805.10228

ATLAS lljj, lνjj 1902.00377
ATLAS lljj 2006.05872
ATLAS tt(ee,μμ) 2010.02098
ATLAS LQ→(tν,bτ) 1902.08103
ATLAS LQ→(bν,tτ) 2101.12527
ATLAS ttττ 2101.11582