Higgs and flavour anomalies

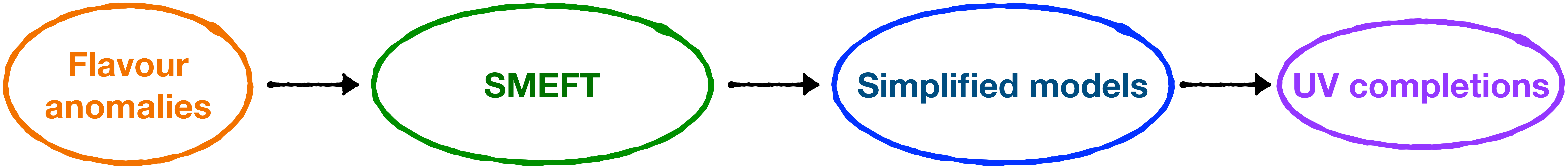
David Marzocca

INFN Trieste

11 - 11 - 2022

Higgs and the Flavour Anomalies

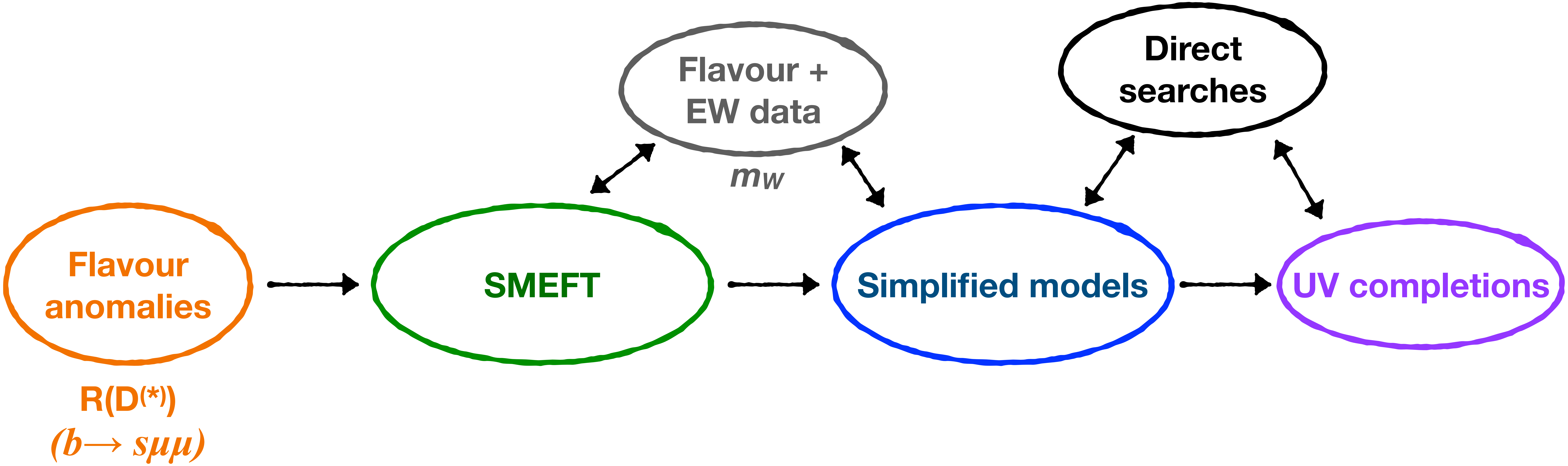
What are the possible connections?



R(D$^{(*)}$)
$(b \to s\mu\mu)$

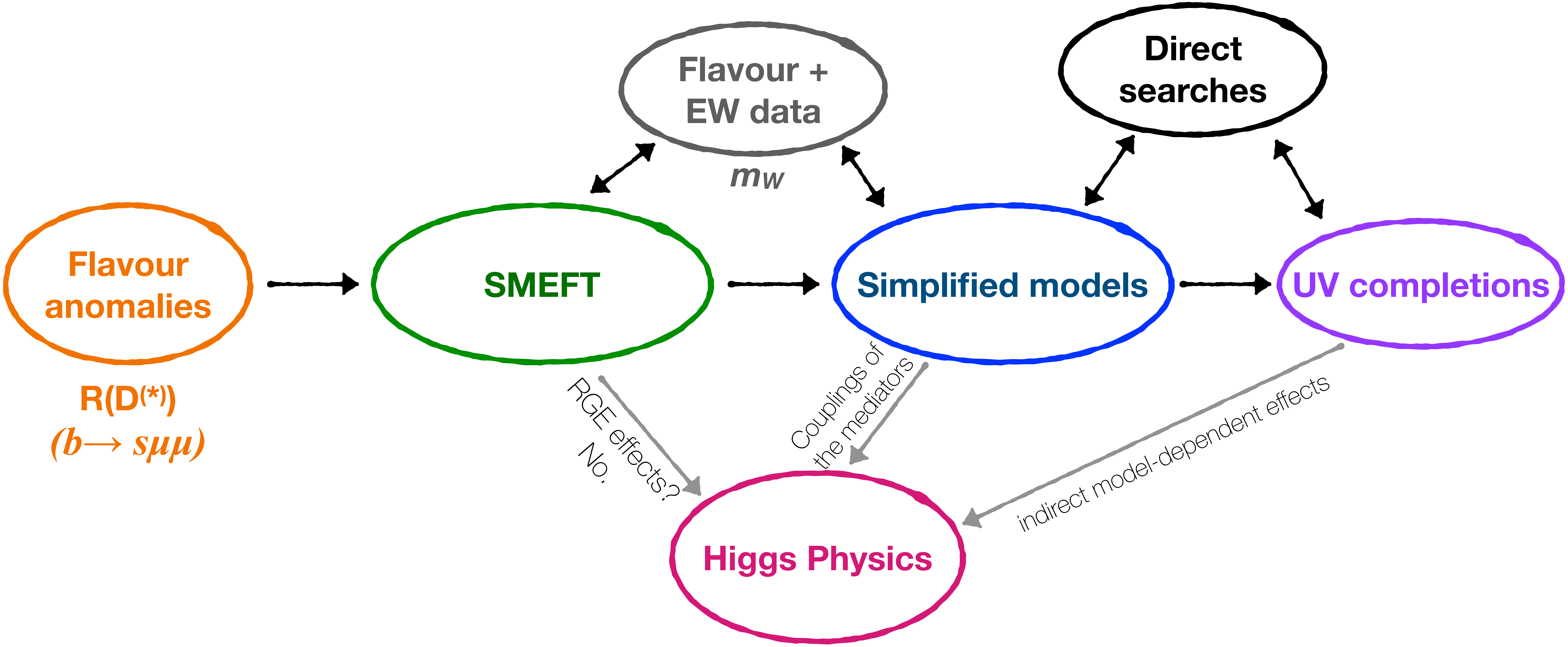
Higgs and the Flavour Anomalies

What are the possible connections?



Higgs and the Flavour Anomalies

What are the possible connections?



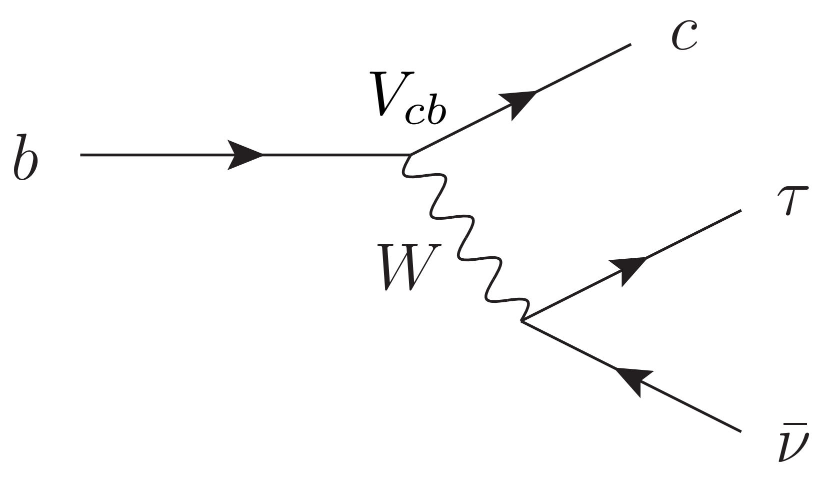
B-anomalies

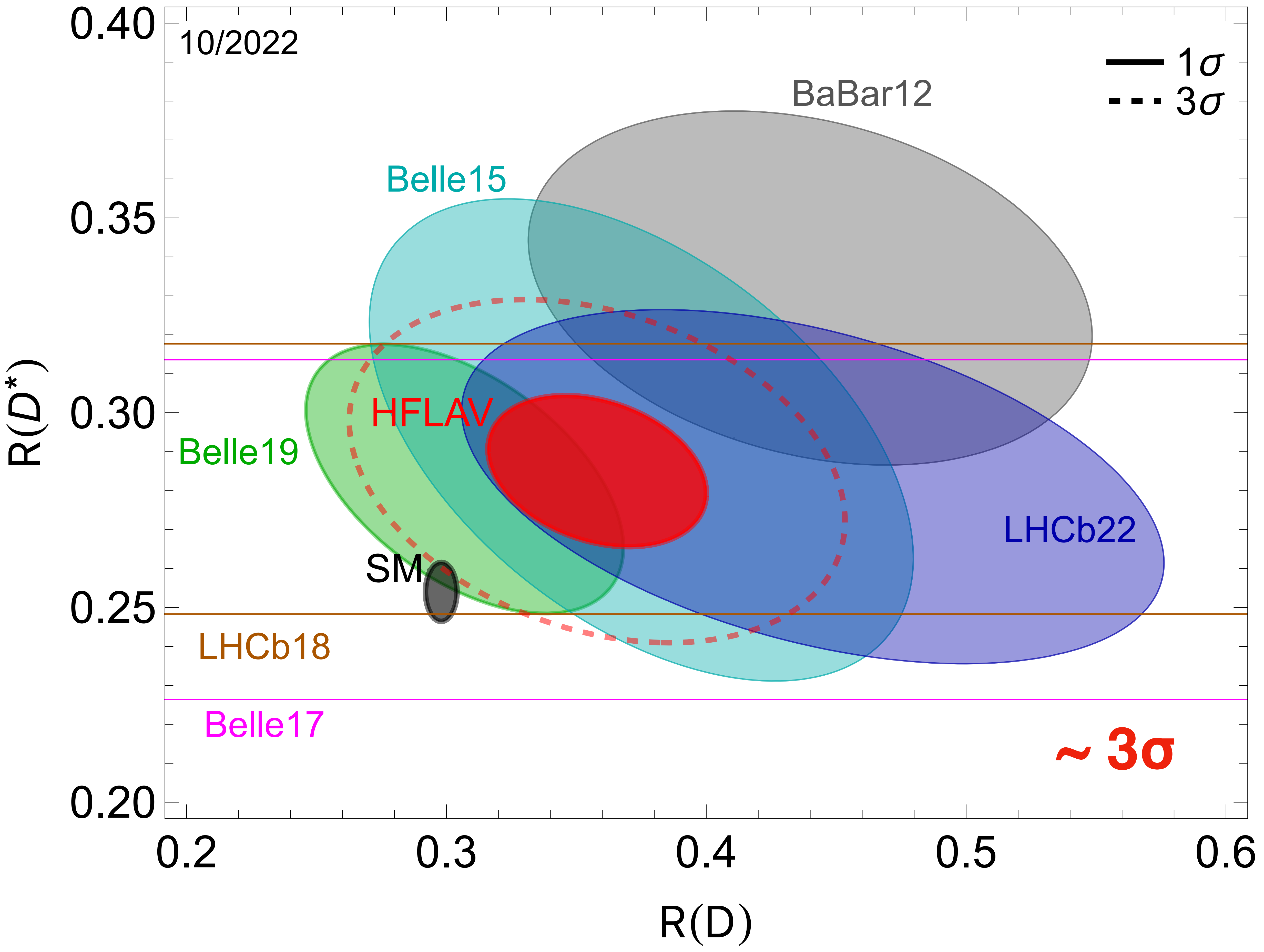
$b \to c\, \tau\, \bar{\nu}_\tau$

Lepton Flavour Universality

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

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





Latest LHCb'22 $R(D^{(*)})$ result still based on Run-1 data.
Waiting for Run-2 results..
Also waiting for the first Belle-II results!

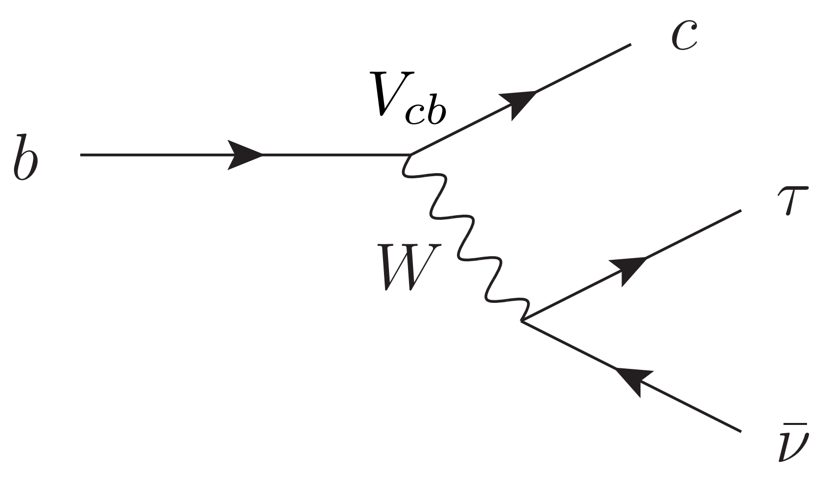
B-anomalies

$b \to c\, \tau\, \bar{\nu}_\tau$

Lepton Flavour Universality

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

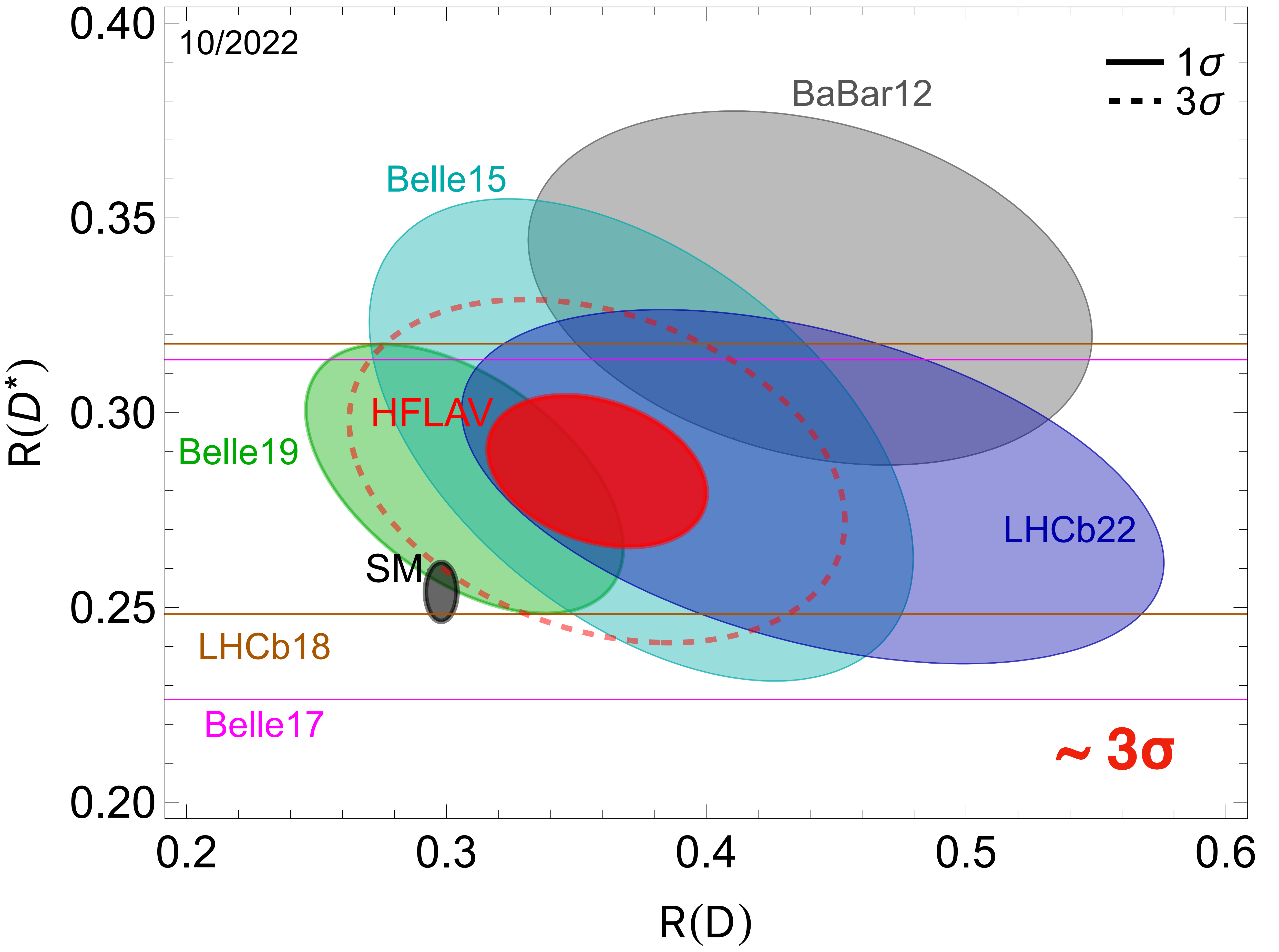
Tree-level SM process
with V_{cb} suppression.



~13% enhancement from the SM amplitude

Requires a **New Physics scale** of

$$C^{R(D^{*})}_{cb\tau\nu} \sim (4\,\mathrm{TeV})^{-2}$$

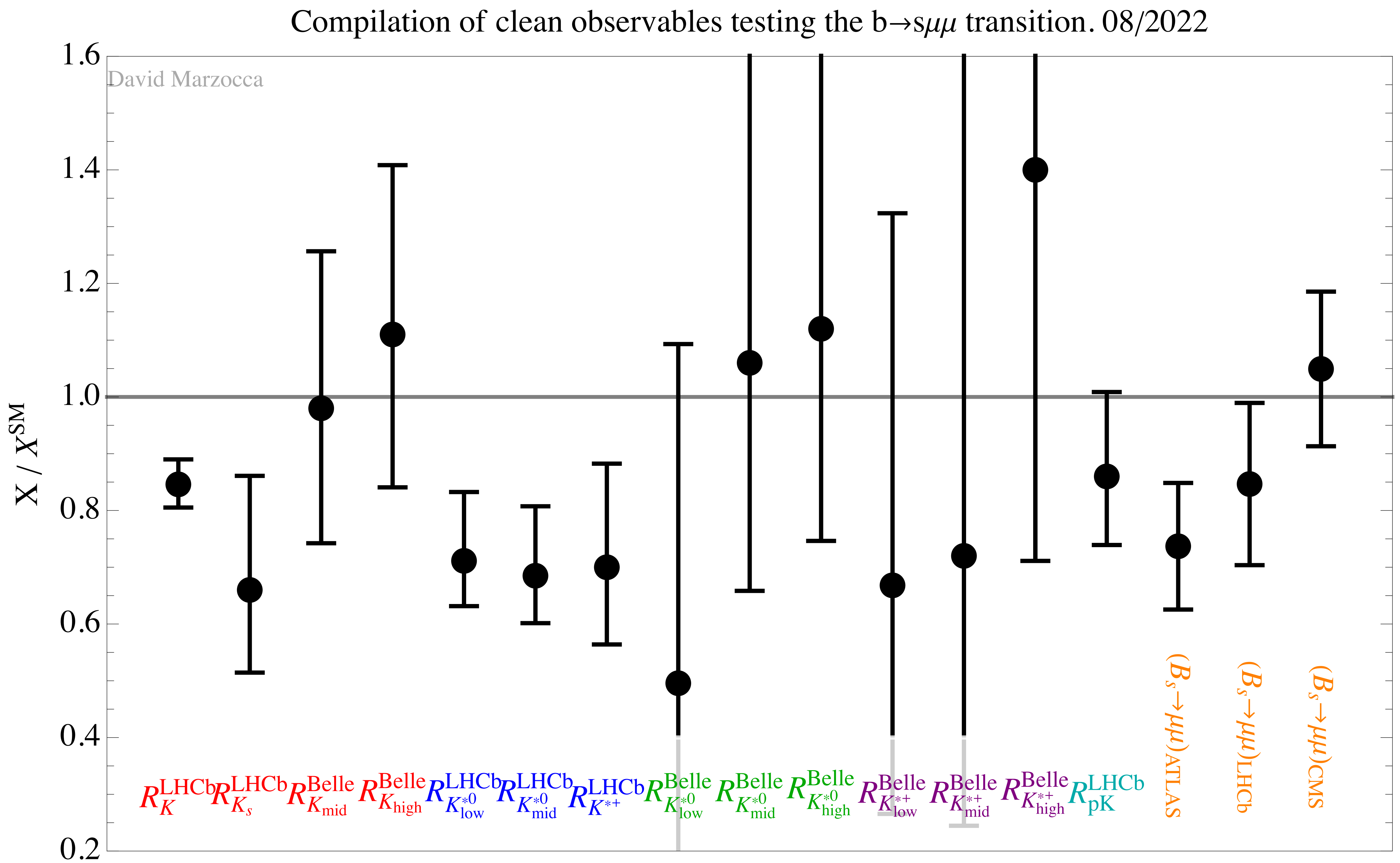


Latest LHCb'22 $R(D^{(*)})$ result still based on Run-1 data.
Waiting for Run-2 results..
Also waiting for the first Belle-II results!

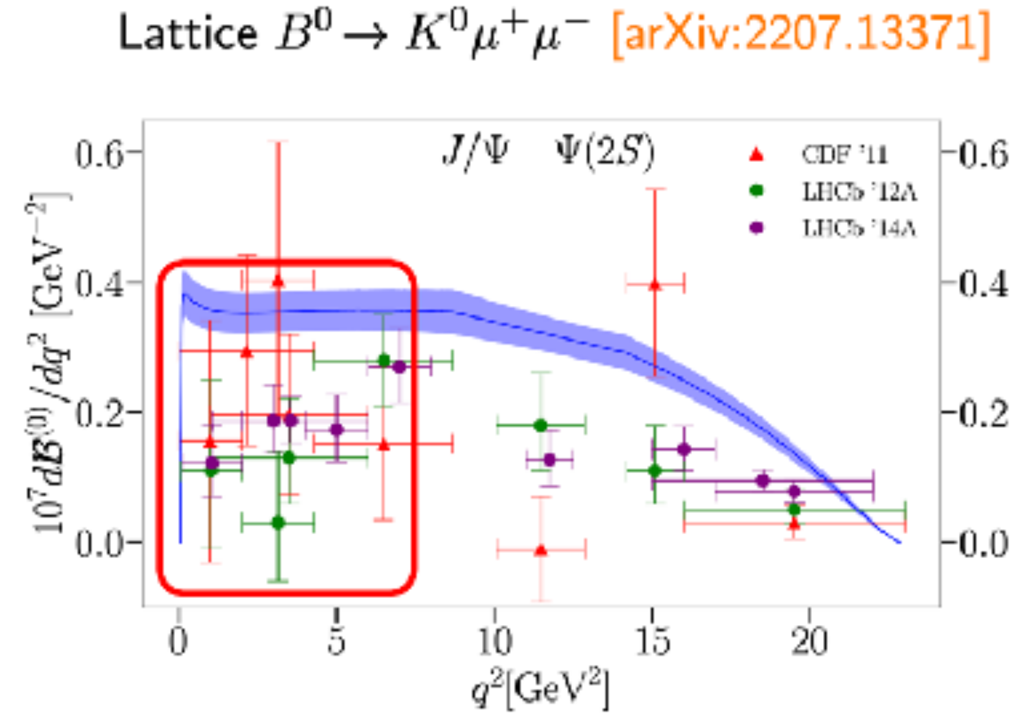
B-anomalies

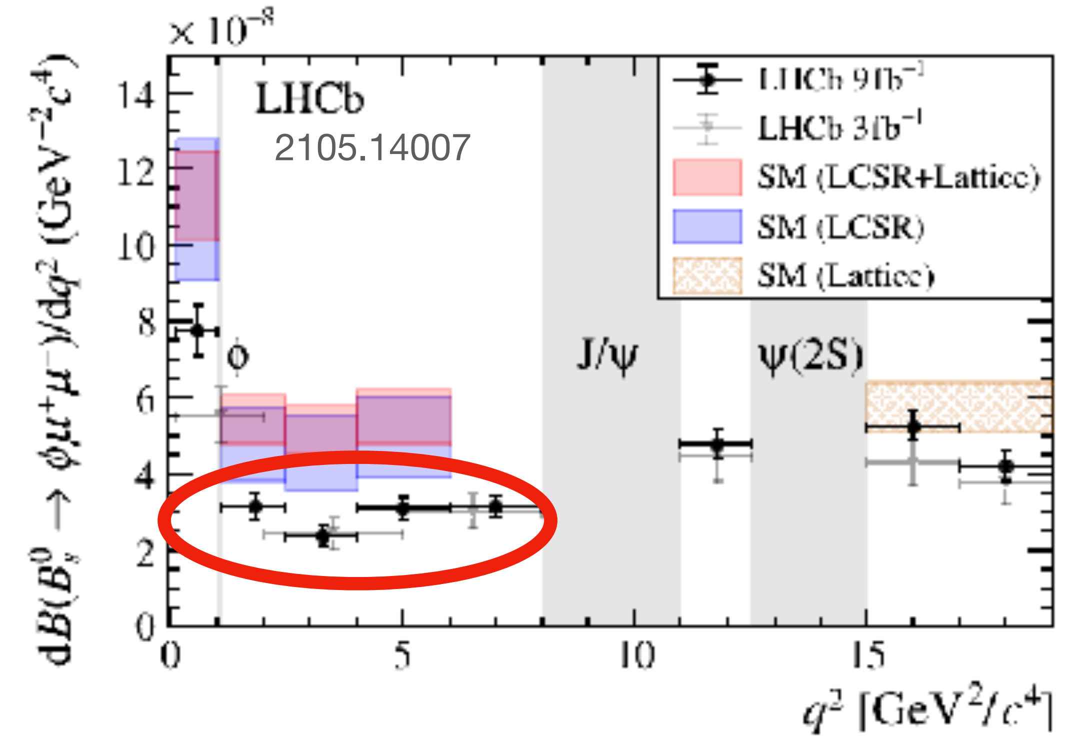
$b \to s\, \mu^+ \mu^-$

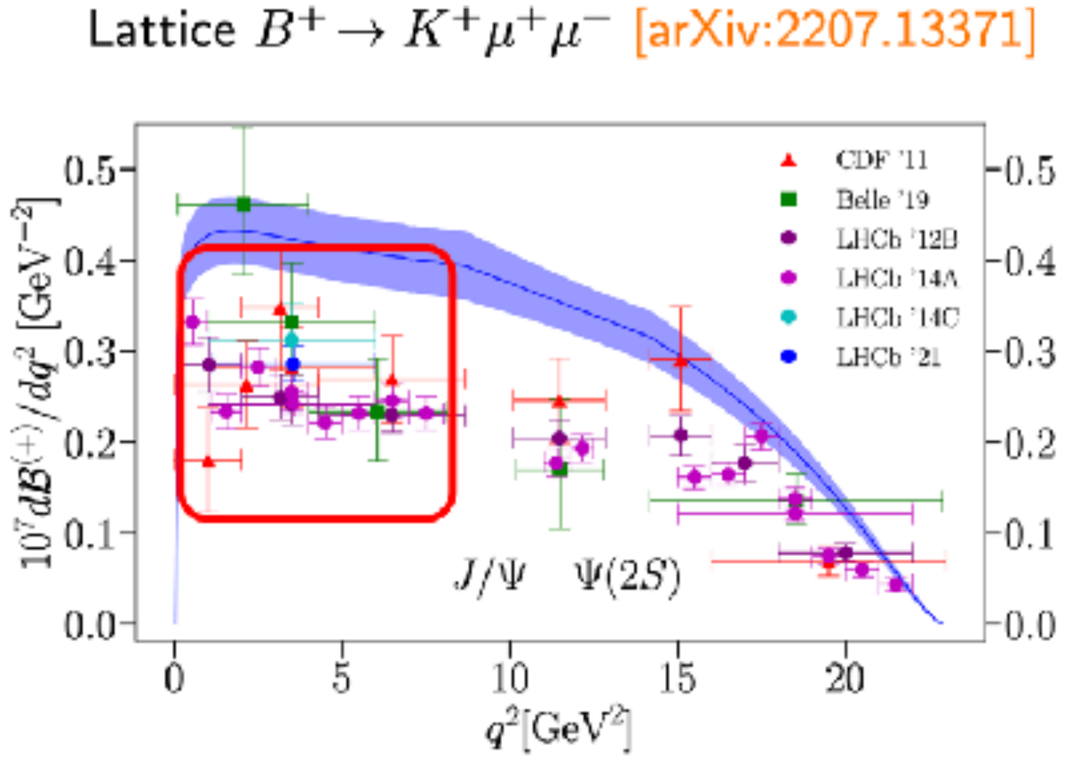
"Clean" observables

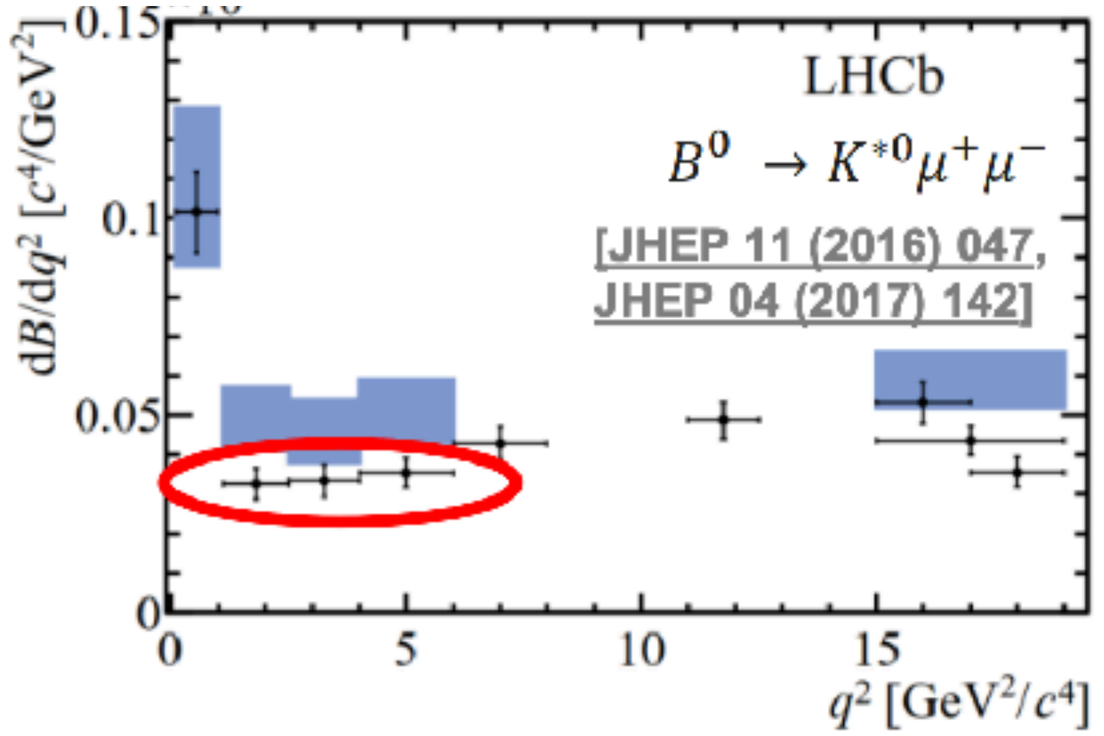


Branching ratios

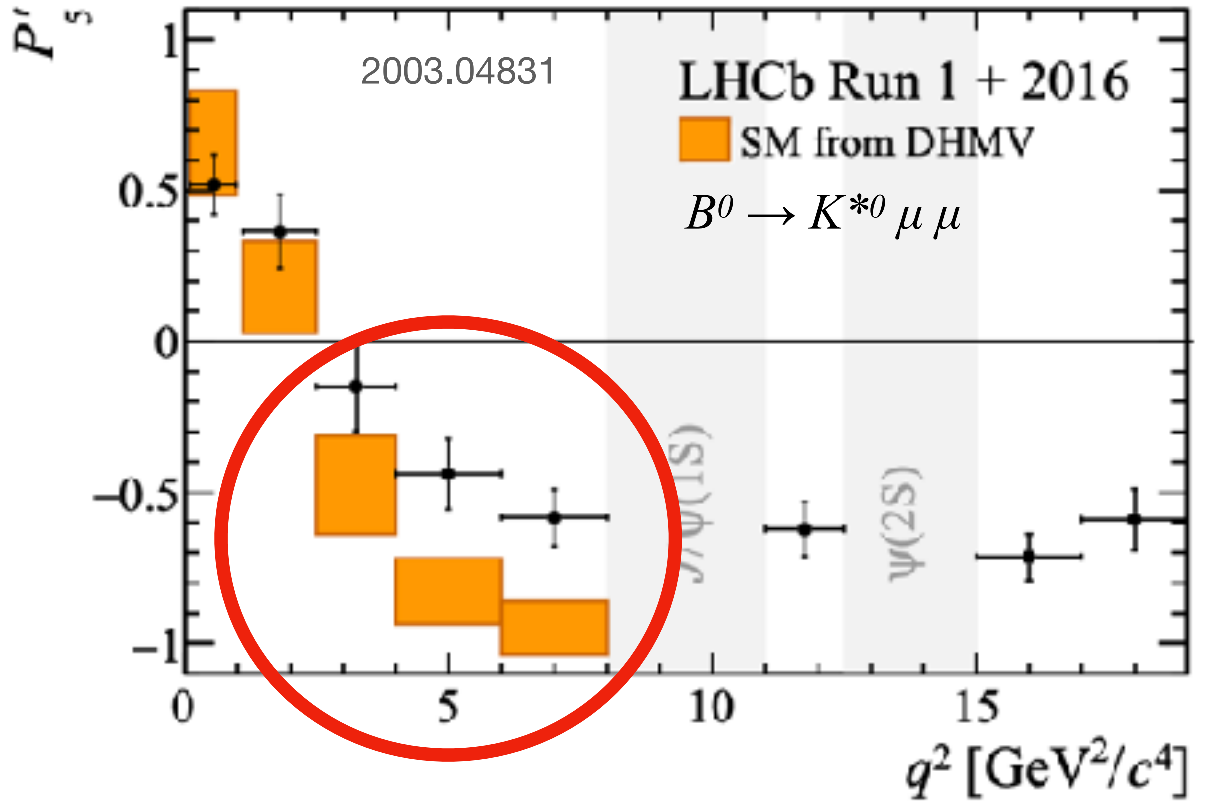








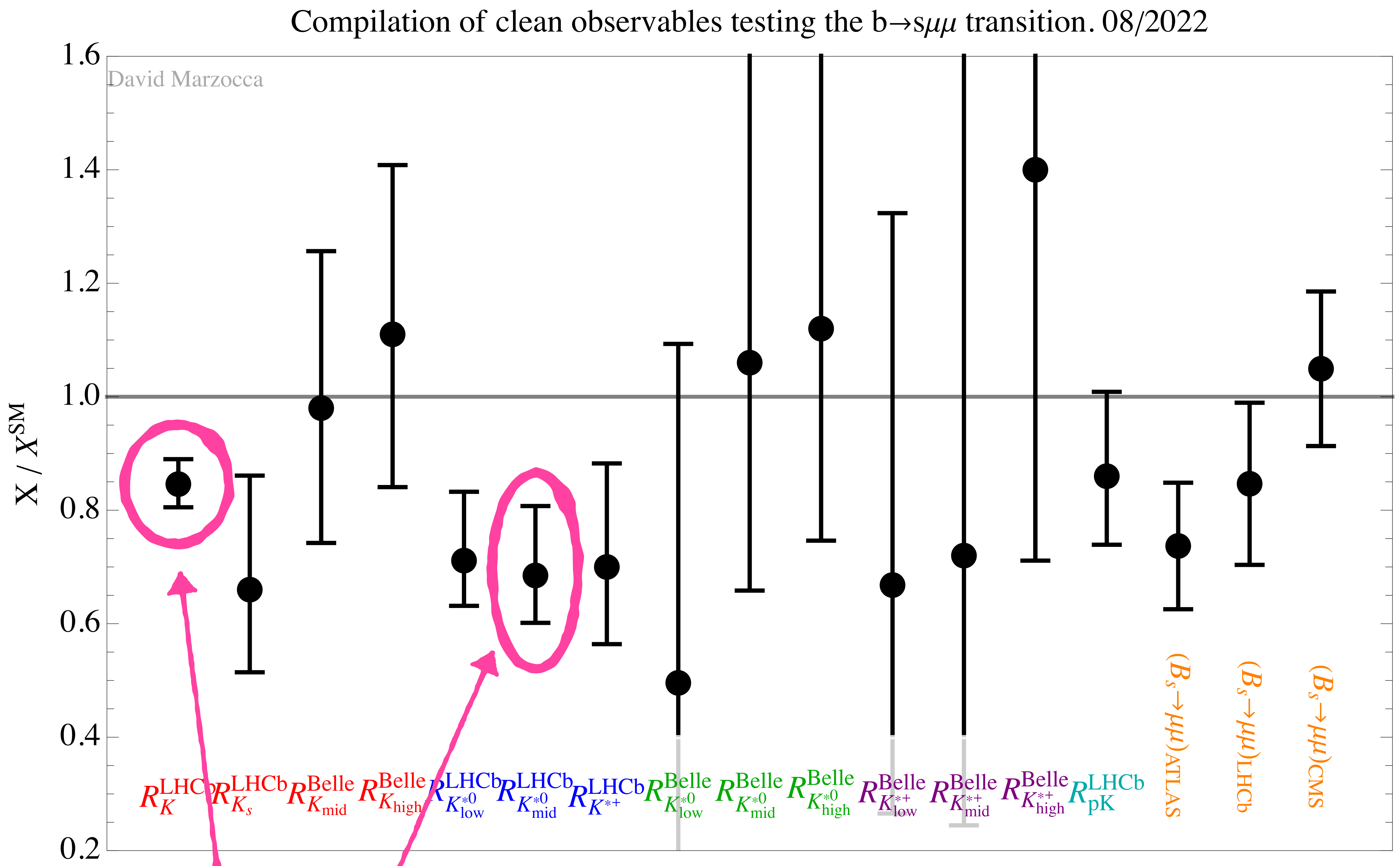
Angular observables



B-anomalies

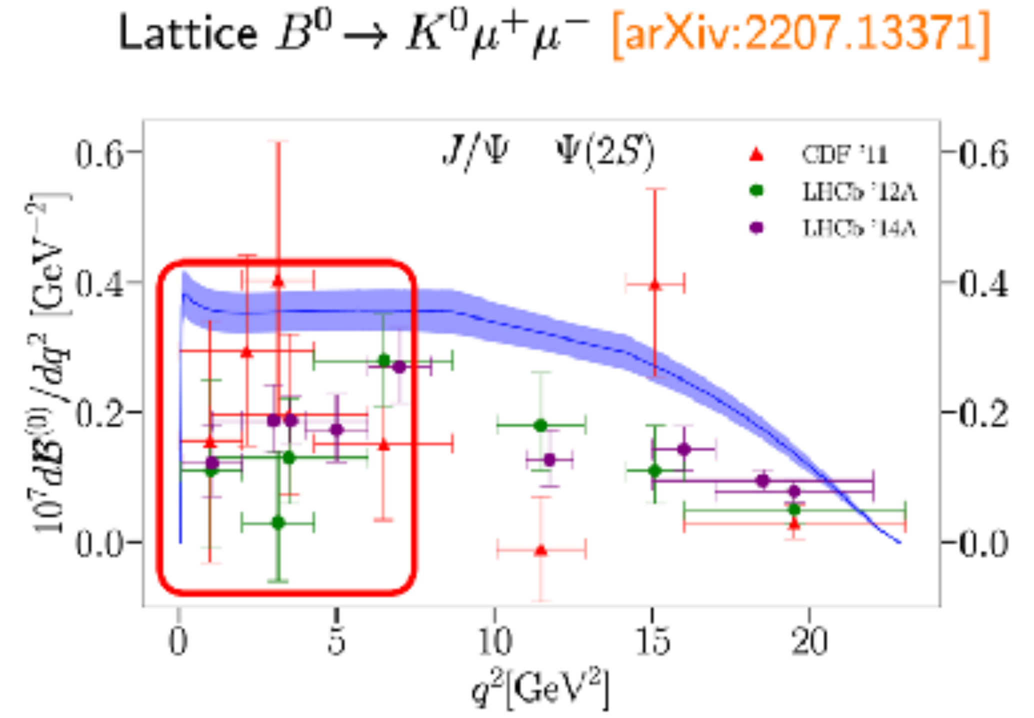
$b \to s\, \mu^+ \mu^-$

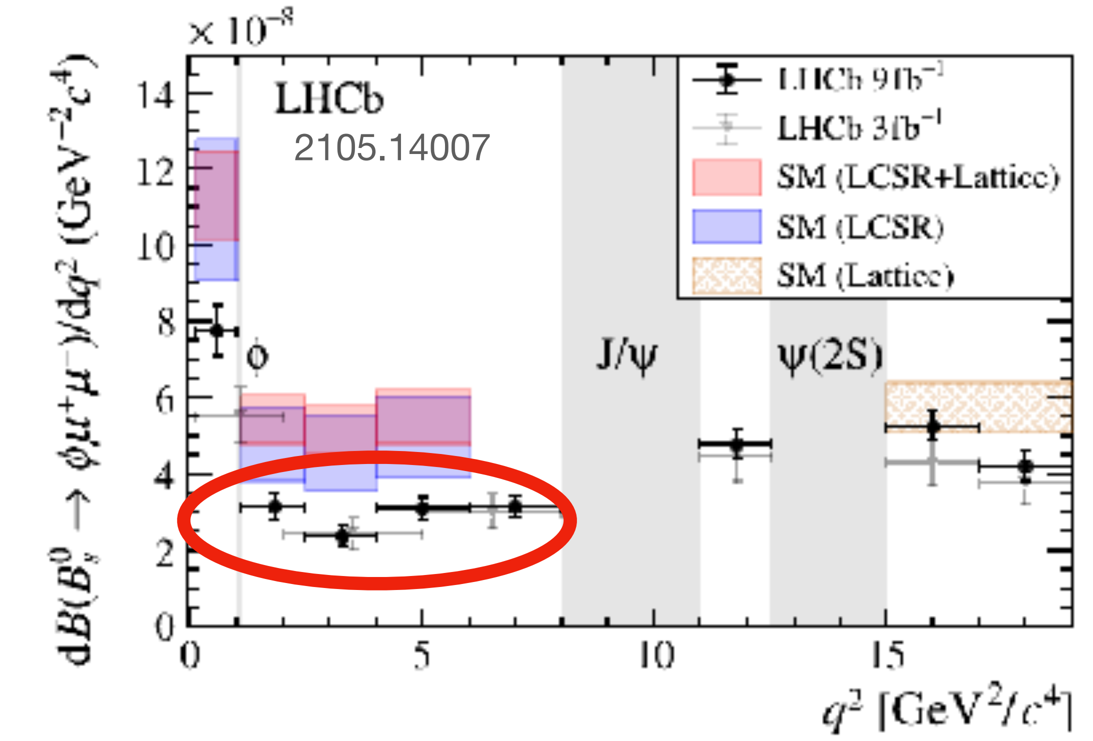
"Clean" observables

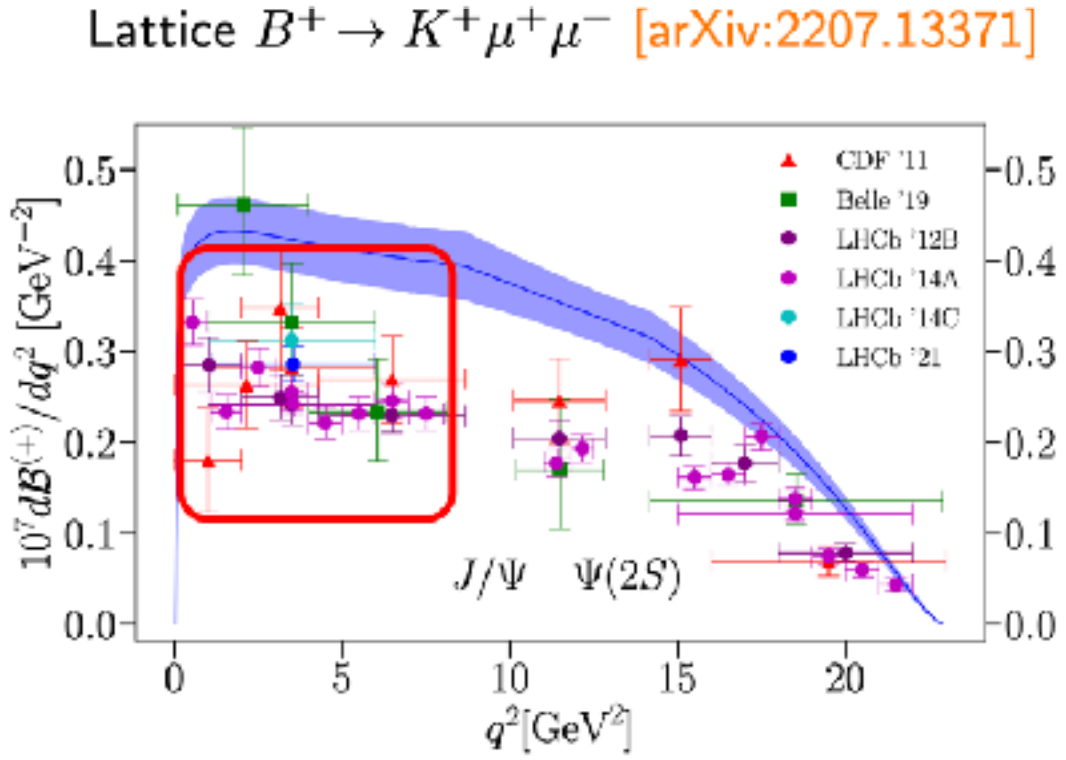


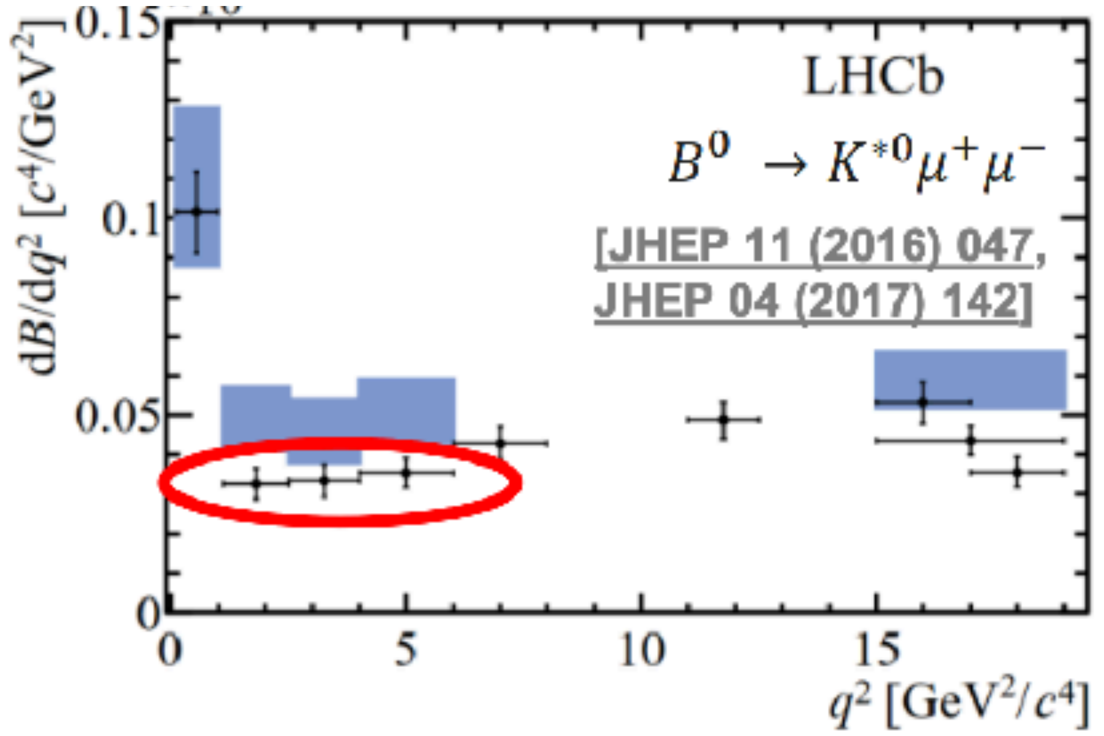
Waiting for the LHCb re-analysis of the Run-2 data for the joint R_K-R_{K^*} measurement.

Branching ratios

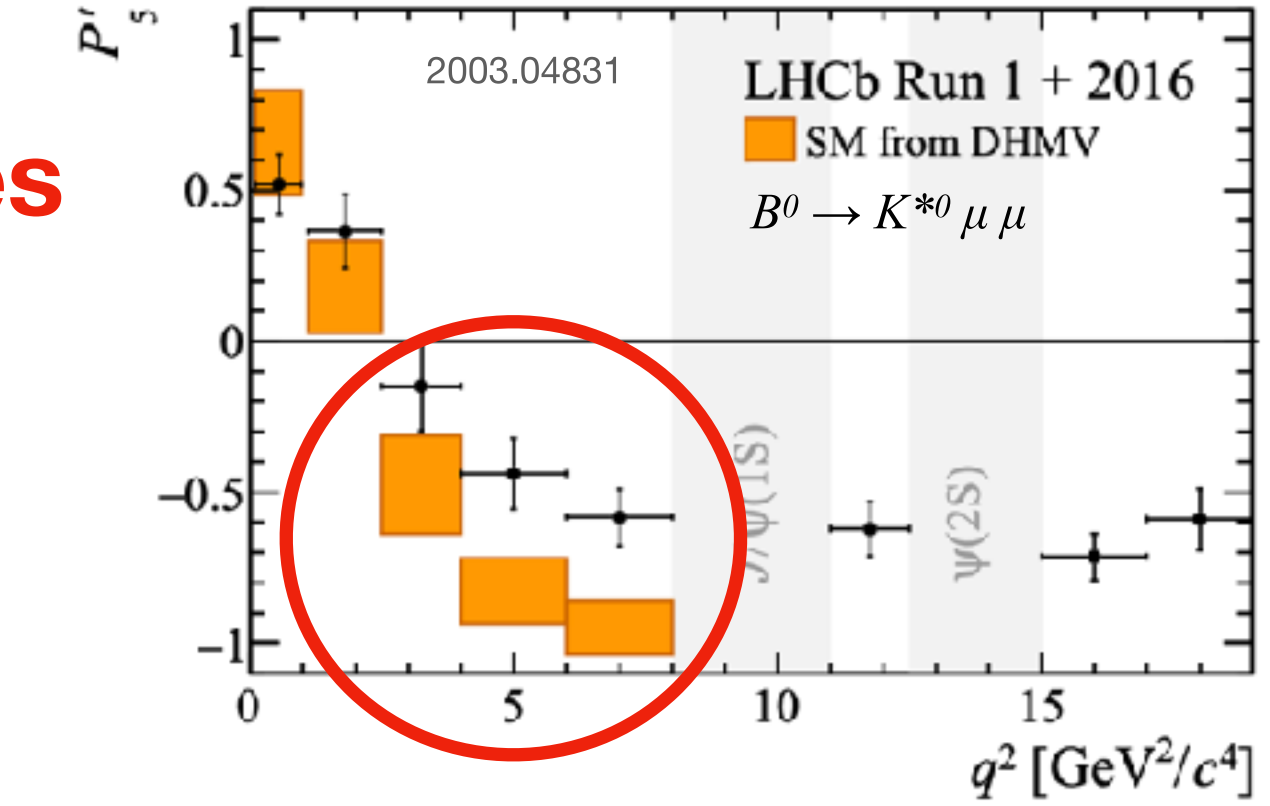








Angular observables

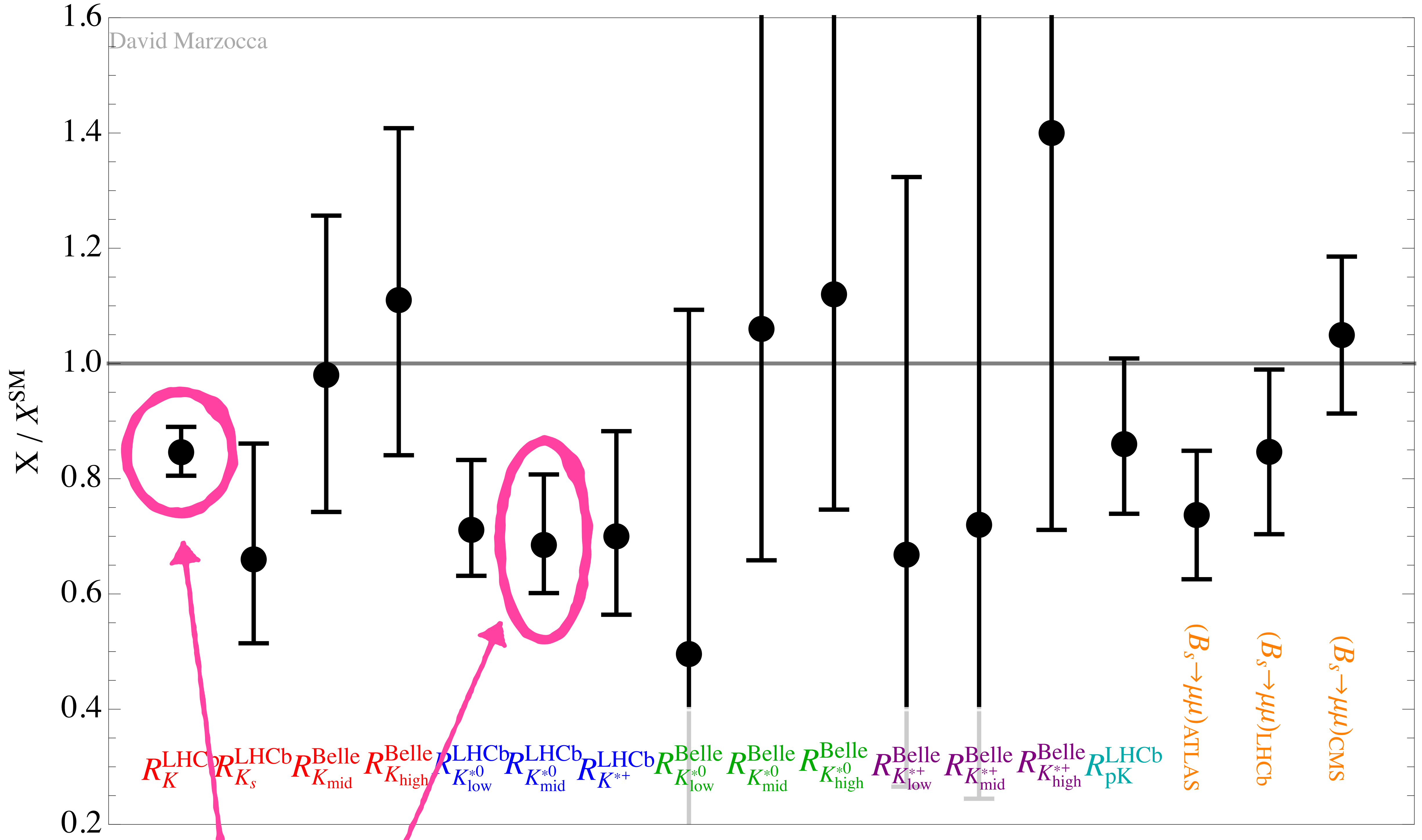


B-anomalies

$b \to s\, \mu^+ \mu^-$

"Clean" observables

Compilation of clean observables testing the b→sμμ transition. 08/2022

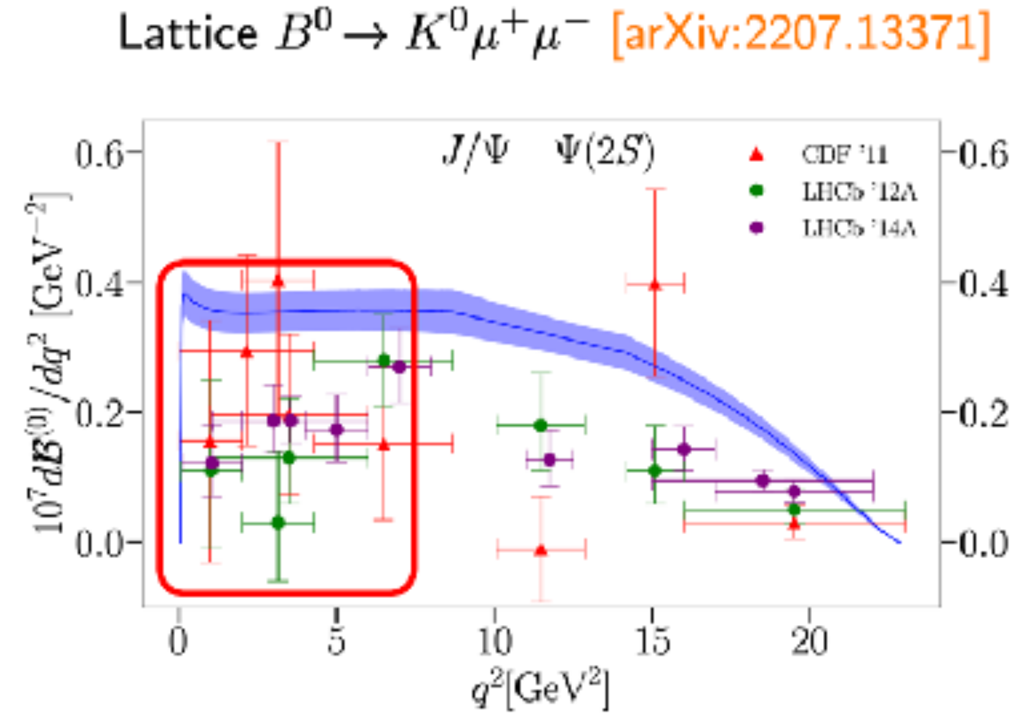


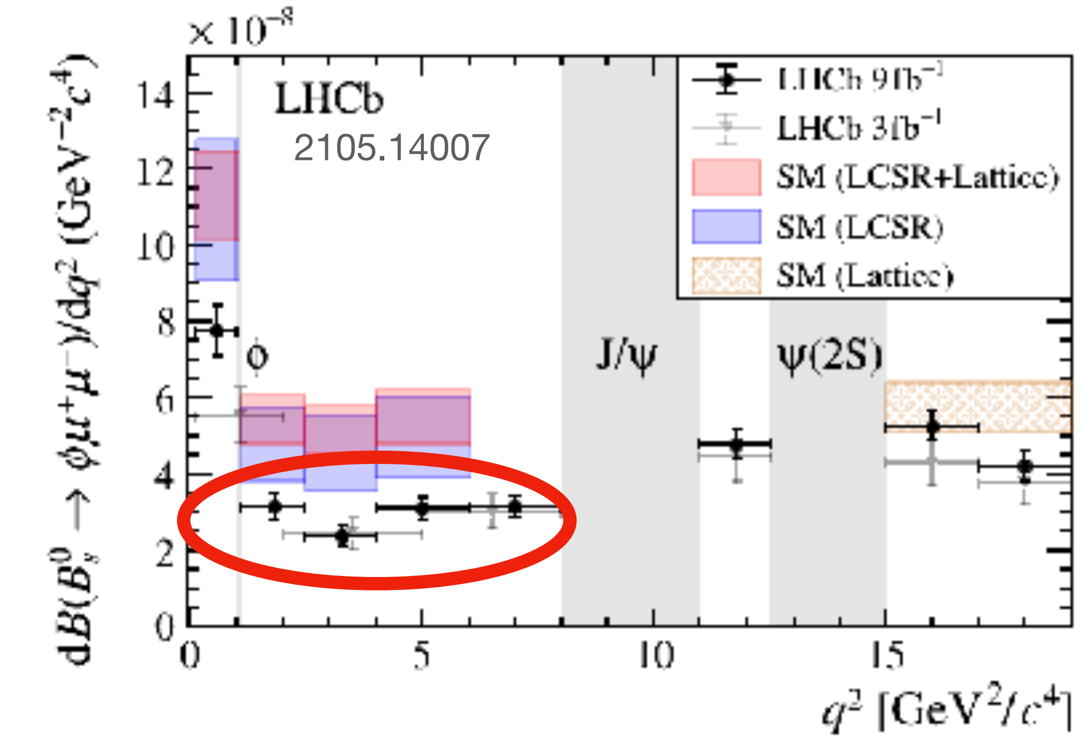
Waiting for the LHCb re-analysis of the Run-2 data for the joint R_K-R_{K^*} measurement.

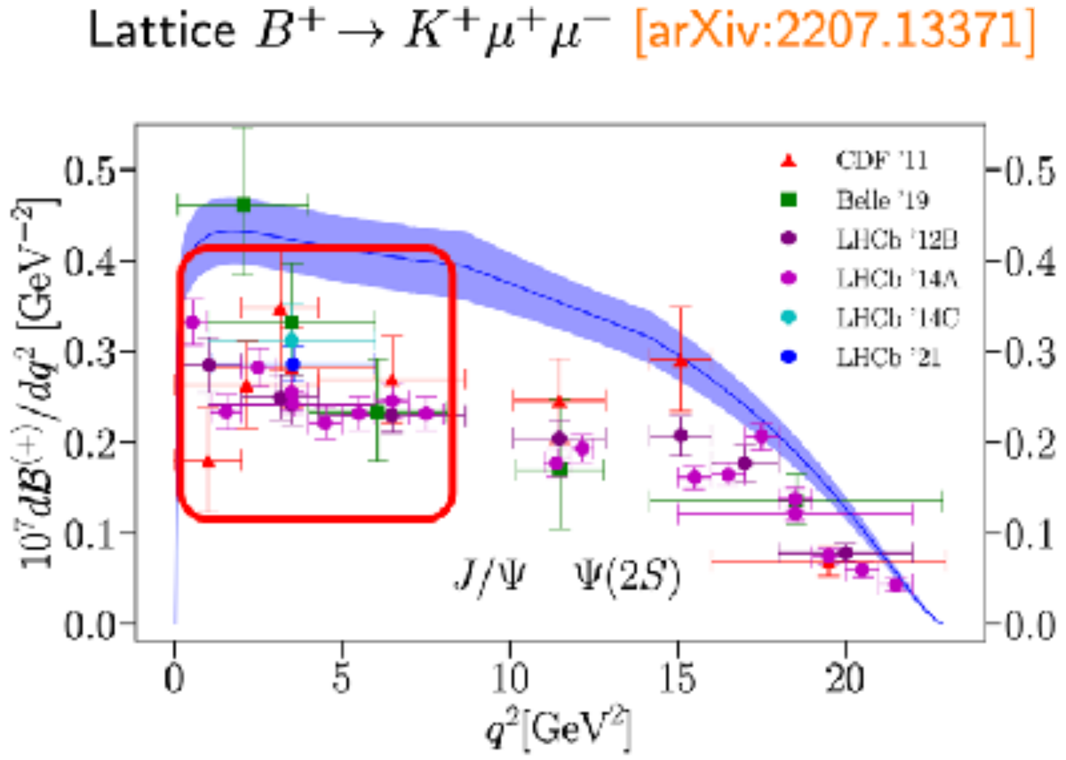
$$\mathcal{L}_{LEFT} = C_{s_L b_L \mu_L \mu_L} (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}_L \gamma^\mu \mu_L)$$

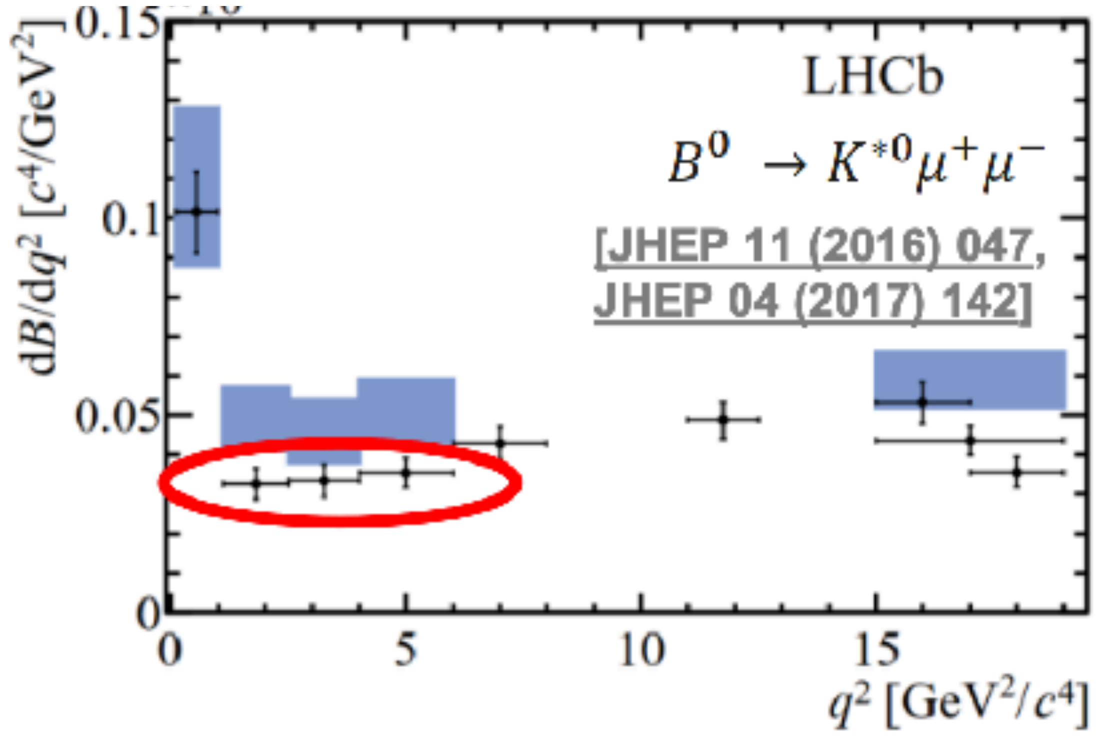
$$C_{s_L b_L \mu_L \mu_L} \approx (37\,\text{TeV})^{-2}$$

Branching ratios

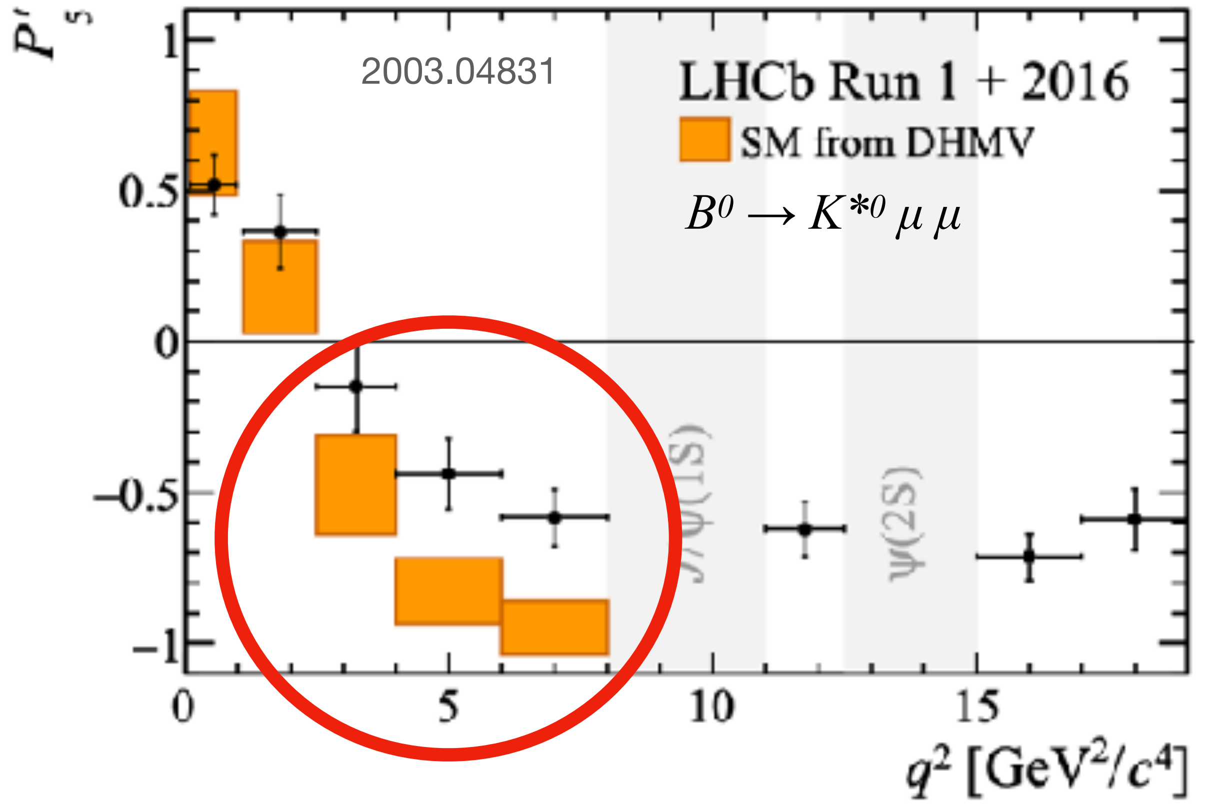






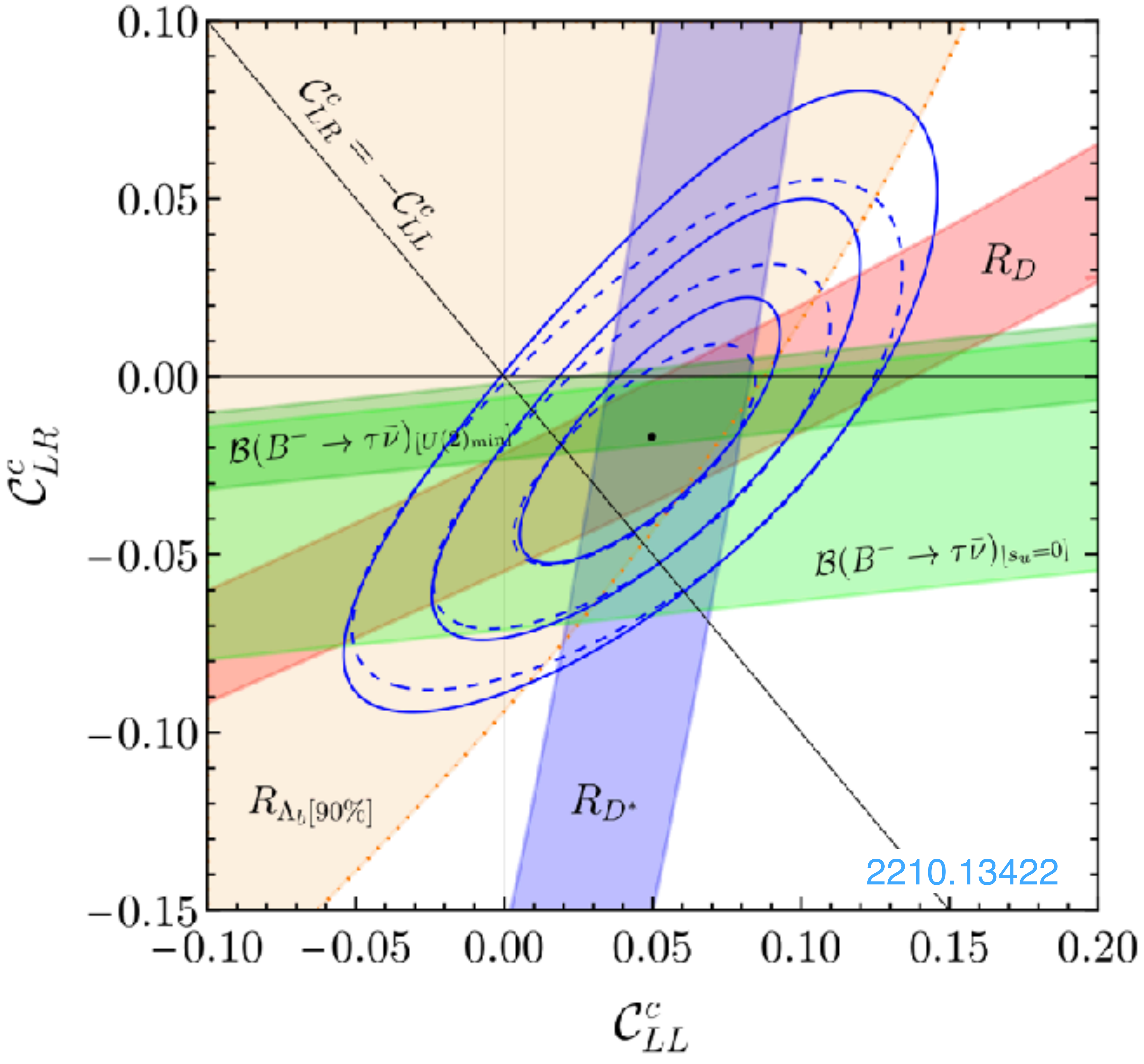


Angular observables



Coherent EFT interpretation

$b \to c\,\tau\,\bar{\nu}_\tau$



$$[O^{(1)}_{\ell q}]_{\alpha\beta ij} = (\bar\ell^\alpha_L \gamma_\mu \ell^\beta_L)(\bar q^i_L \gamma^\mu q^j_L)\,,$$

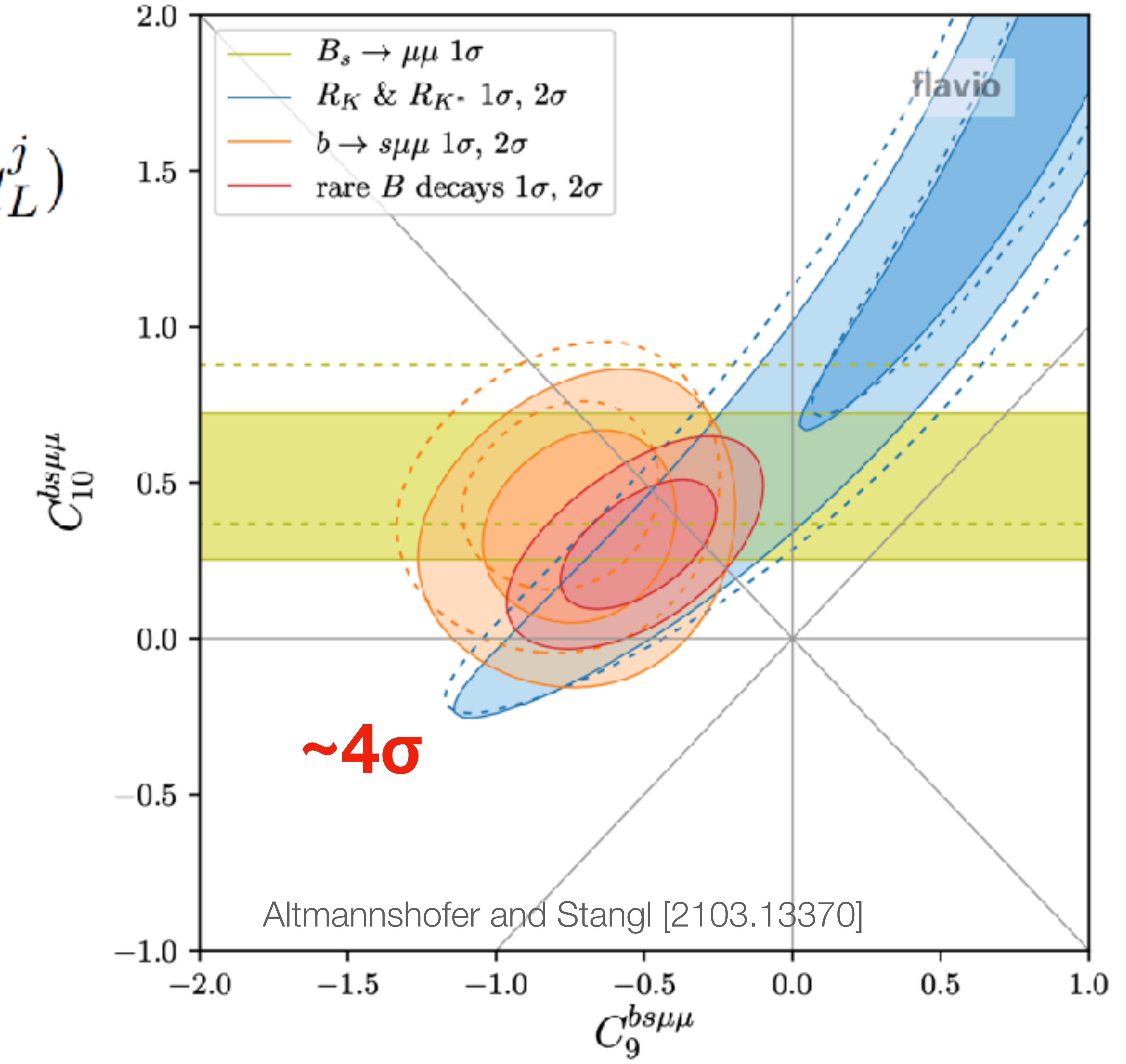
$$[O^{(3)}_{\ell q}]_{\alpha\beta ij} = (\bar\ell^\alpha_L \sigma^I \gamma_\mu \ell^\beta_L)(\bar q^i_L \sigma^I \gamma^\mu q^j_L)$$

$3_q \to 2_q\ 3_\ell\ 3_\ell$ $\qquad$ $3_q \to 2_q\ 2_\ell\ 2_\ell$

$$\sim \frac{1}{(4\,\mathrm{TeV})^2} \gg \sim \frac{1}{(40\,\mathrm{TeV})^2}$$

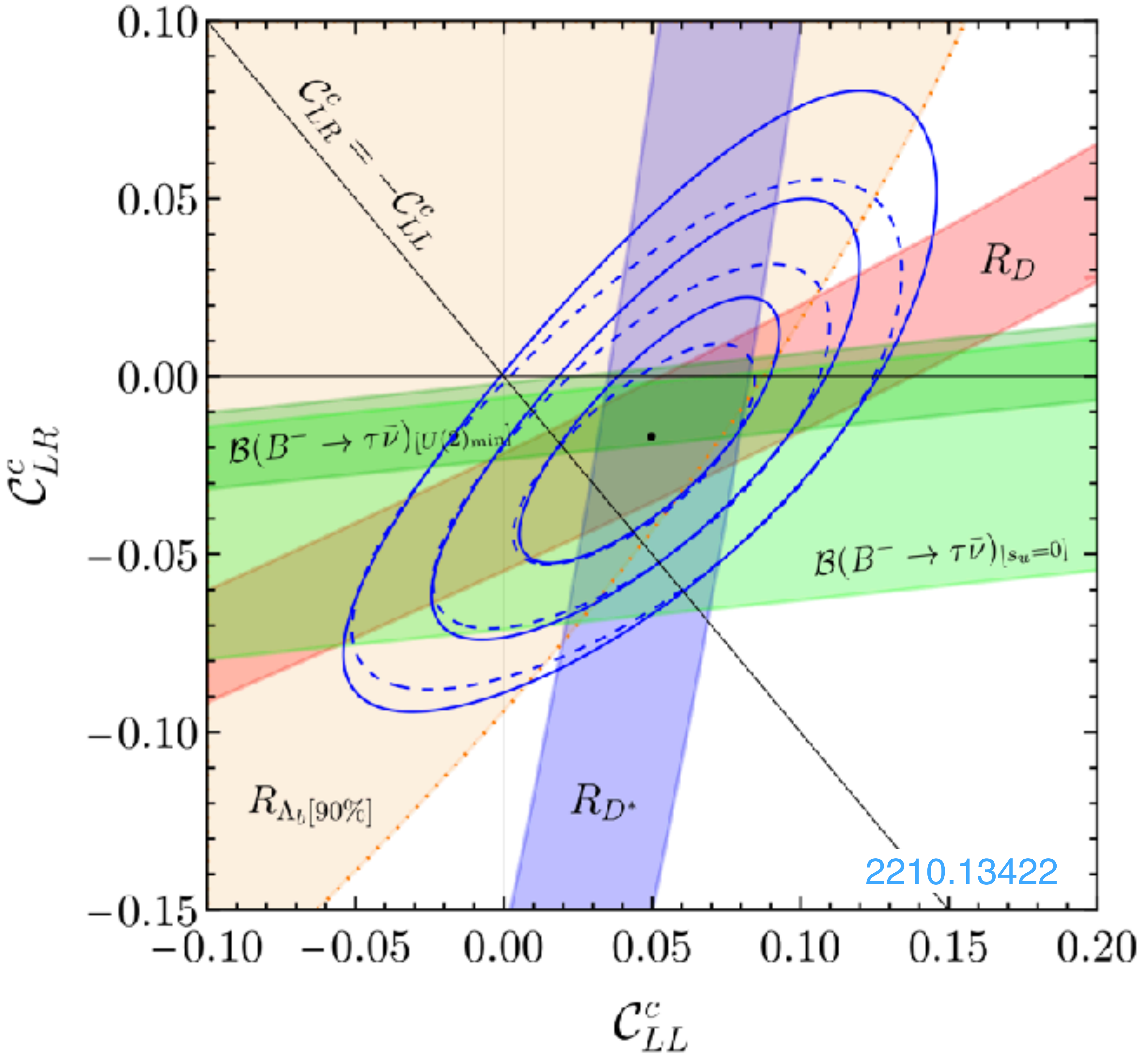
$$\sim c_q \frac{V_{cb}(\lambda_\tau)^2}{\Lambda^2} \qquad \sim c_\mu \frac{V_{ts}(\lambda_\mu)^2}{\Lambda^2}$$

$b \to s\,\mu^+\,\mu^-$



Coherent EFT interpretation

$b \to c\, \tau\, \bar{\nu}_\tau$



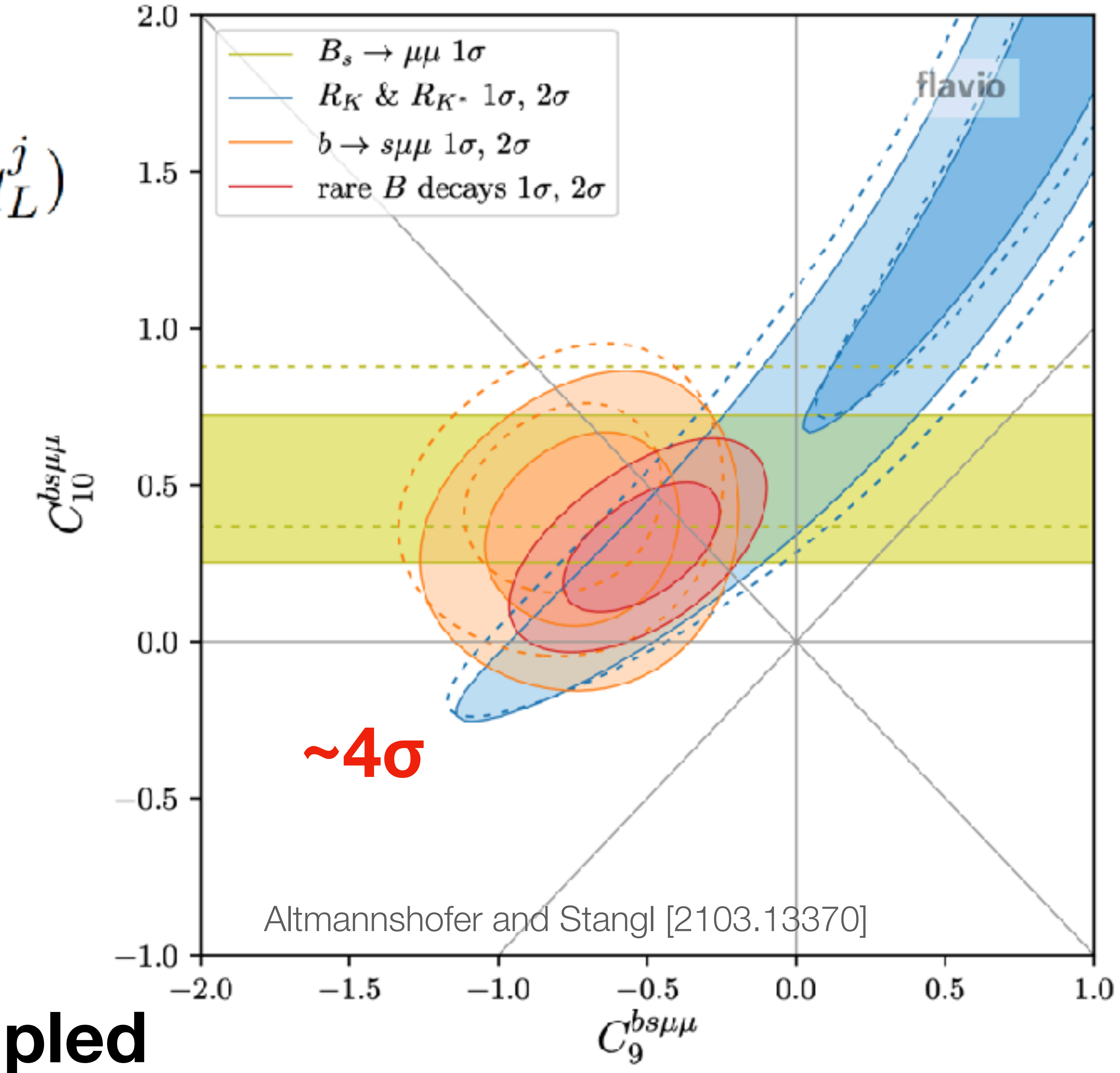
$$[O^{(1)}_{\ell q}]_{\alpha\beta ij} = (\bar{\ell}^\alpha_L \gamma_\mu \ell^\beta_L)(\bar{q}^i_L \gamma^\mu q^j_L)\,,$$
$$[O^{(3)}_{\ell q}]_{\alpha\beta ij} = (\bar{\ell}^\alpha_L \sigma^I \gamma_\mu \ell^\beta_L)(\bar{q}^i_L \sigma^I \gamma^\mu q^j_L)$$

$3_q \to 2_q\, 3_\ell\, 3_\ell$ $\qquad$ $3_q \to 2_q\, 2_\ell\, 2_\ell$

$$\sim \frac{1}{(4\,\mathrm{TeV})^2} \gg \sim \frac{1}{(40\,\mathrm{TeV})^2}$$

$$\sim c_\tau \frac{V_{cb}\,(\lambda_\tau)^2}{\Lambda^2} \qquad \sim c_\mu \frac{V_{ts}\,(\lambda_\mu)^2}{\Lambda^2}$$

$b \to s\, \mu^+\, \mu^-$



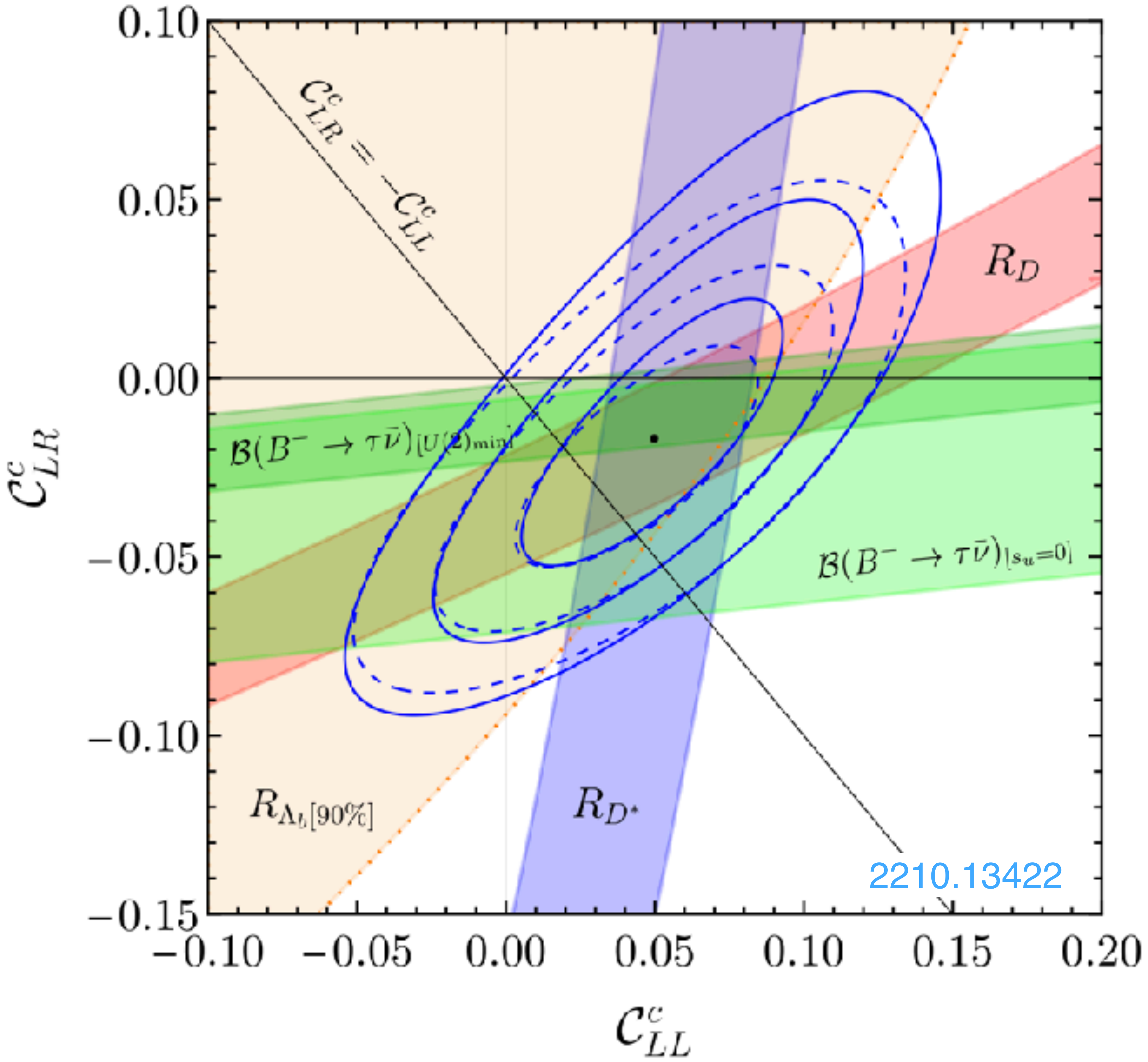
$$\Rightarrow \begin{cases} \lambda_\tau = 1, \quad \lambda_\mu \sim 0.1 \iff \dfrac{\lambda_\mu}{\lambda_\tau} \sim \dfrac{m_\mu}{m_\tau} \\ \Lambda \sim 1\,\mathrm{TeV} \\ c_{\mu,\tau} \gtrsim \mathcal{O}(1) \end{cases}$$

New Physics mainly coupled to the 3rd generation.

R(D$^{(*)}$) anomalies drive most new physics requirements

Coherent EFT interpretation

$b \to c\, \tau\, \bar{\nu}_\tau$



$$[O^{(1)}_{\ell q}]_{\alpha\beta ij} = (\bar{\ell}^\alpha_L \gamma_\mu \ell^\beta_L)(\bar{q}^i_L \gamma^\mu q^j_L)\,,$$

$$[O^{(3)}_{\ell q}]_{\alpha\beta ij} = (\bar{\ell}^\alpha_L \sigma^I \gamma_\mu \ell^\beta_L)(\bar{q}^i_L \sigma^I \gamma^\mu q^j_L)$$

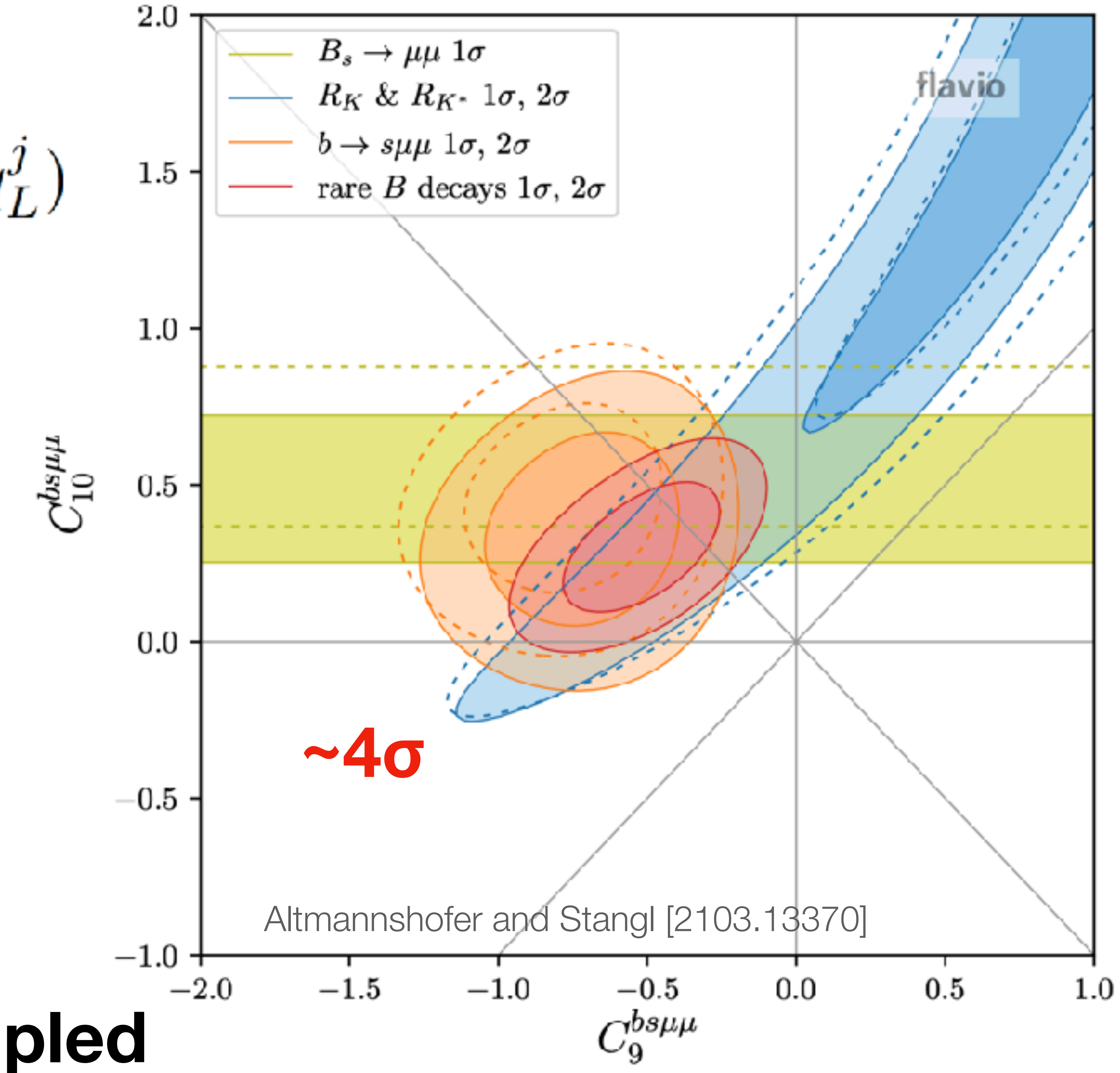
$3_q \to 2_q\, 3_\ell\, 3_\ell \qquad 3_q \to 2_q\, 2_\ell\, 2_\ell$

$$\sim \frac{1}{(4\,\text{TeV})^2} \gg \sim \frac{1}{(40\,\text{TeV})^2}$$

$$\sim c_\tau \frac{V_{cb}(\lambda_\tau)^2}{\Lambda^2} \qquad \sim c_\mu \frac{V_{ts}(\lambda_\mu)^2}{\Lambda^2}$$

$$\Rightarrow \begin{cases} \lambda_\tau = 1,\quad \lambda_\mu \sim 0.1 \iff \dfrac{\lambda_\mu}{\lambda_\tau} \sim \dfrac{m_\mu}{m_\tau} \\ \Lambda \sim 1\,\text{TeV} \\ c_{\mu,\tau} \gtrsim \mathcal{O}(1) \end{cases}$$

$b \to s\, \mu^+ \mu^-$

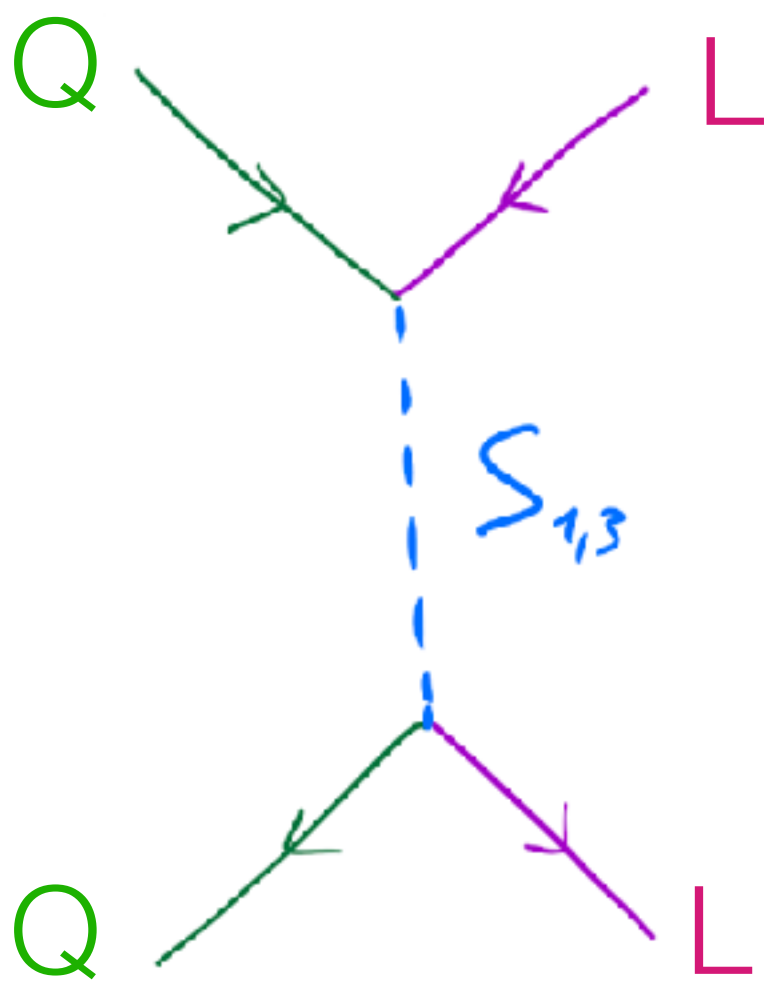


New Physics mainly coupled to the 3rd generation.

R(D(*)) anomalies drive most new physics requirements

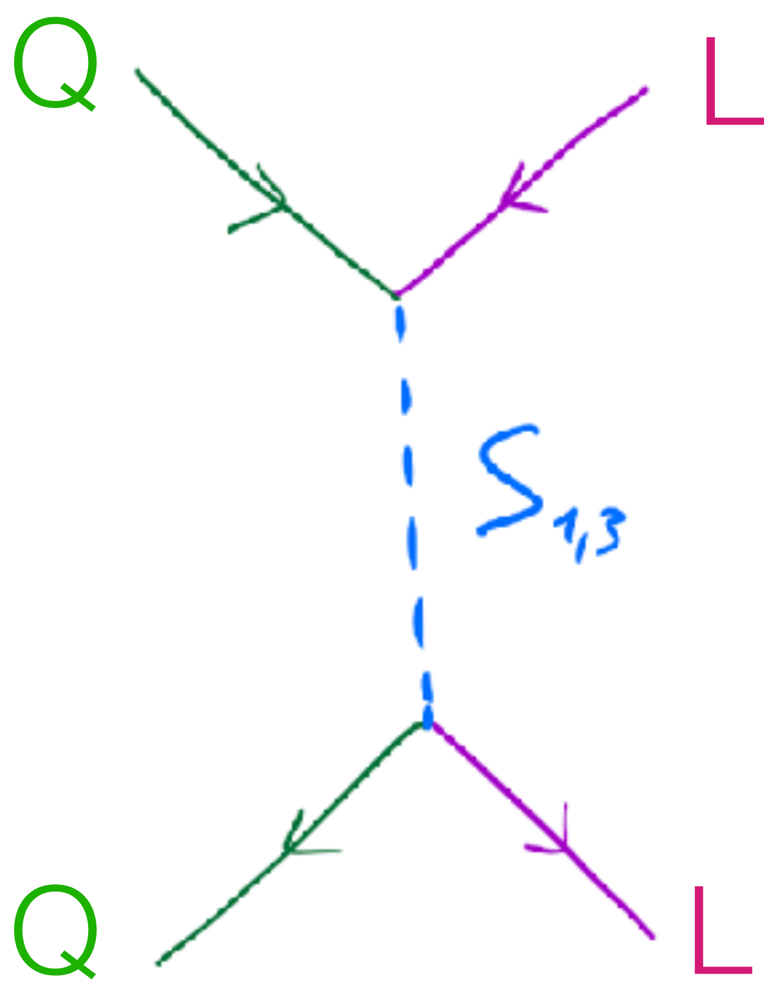
No sizeable effect in Higgs physics from these operators.

Leptoquarks and B-anomalies



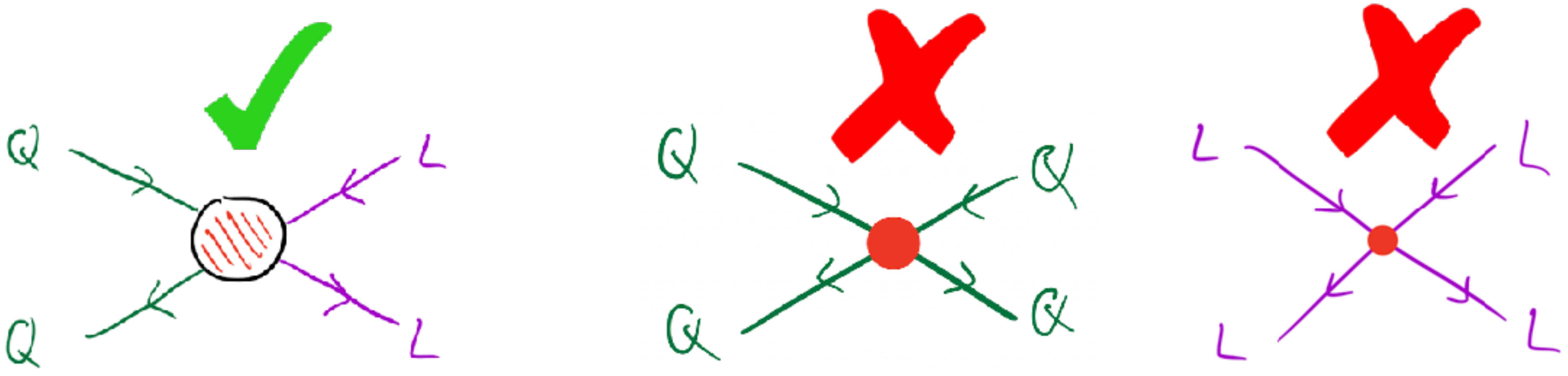
LQ induce semileptonic @ tree level,
4-quark & 4-lepton only at loop level.

Leptoquarks and B-anomalies

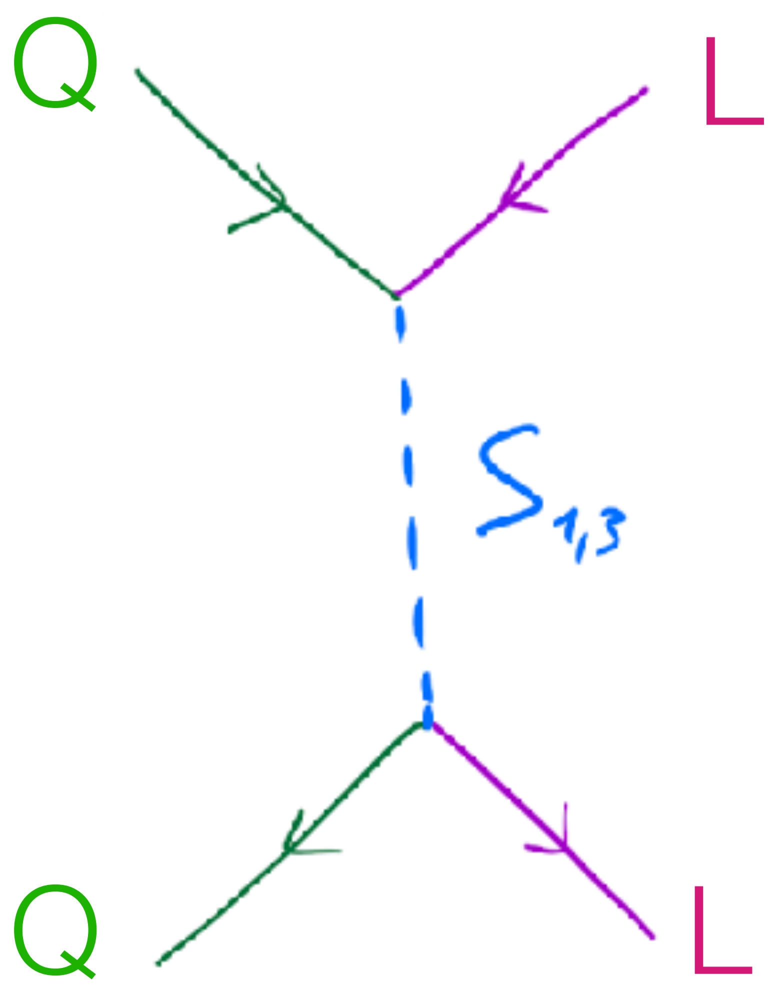


LQ induce semileptonic @ tree level,
4-quark & 4-lepton only at loop level.

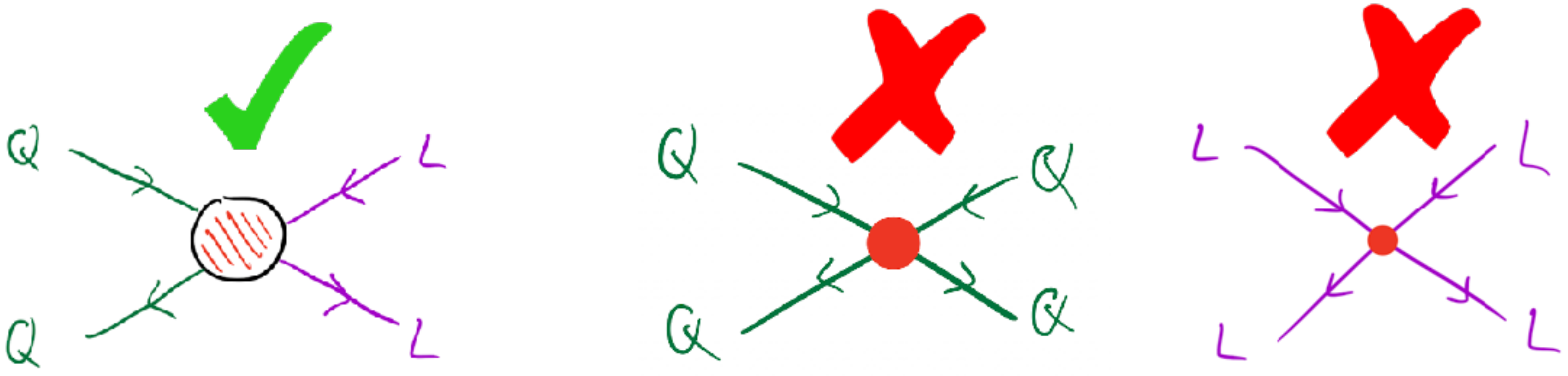
Deviations in **semileptonic** processes,
strong bounds from ΔF=2 & CLFV processes.



Leptoquarks and B-anomalies



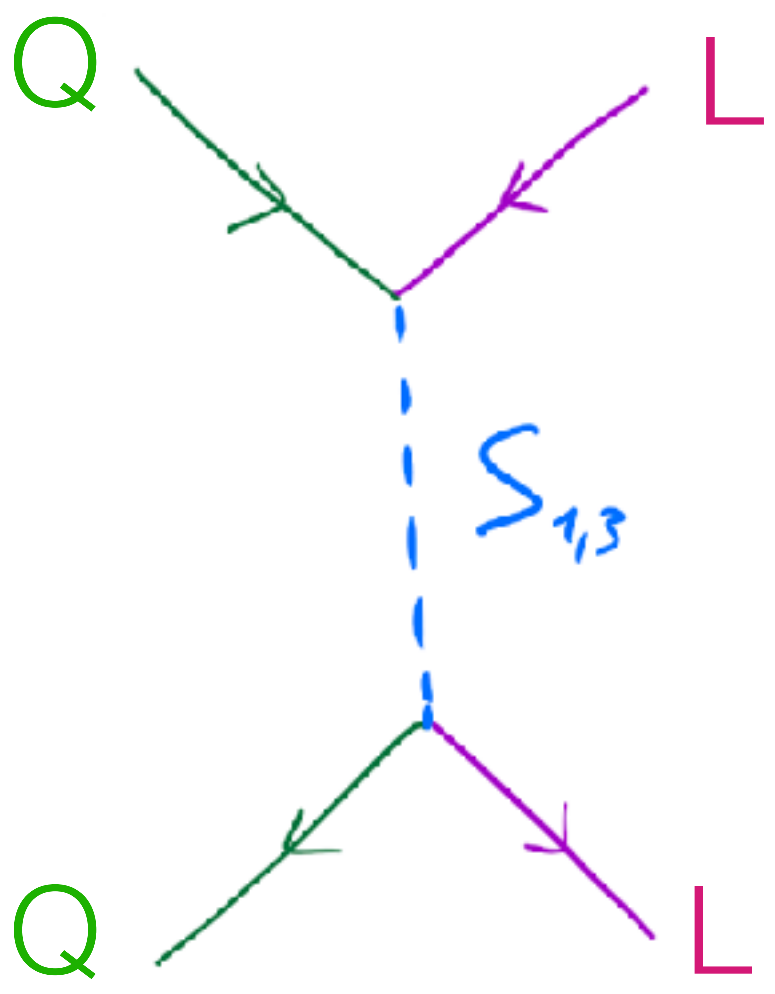
Deviations in **semileptonic** processes,
strong bounds from ΔF=2 & CLFV processes.



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

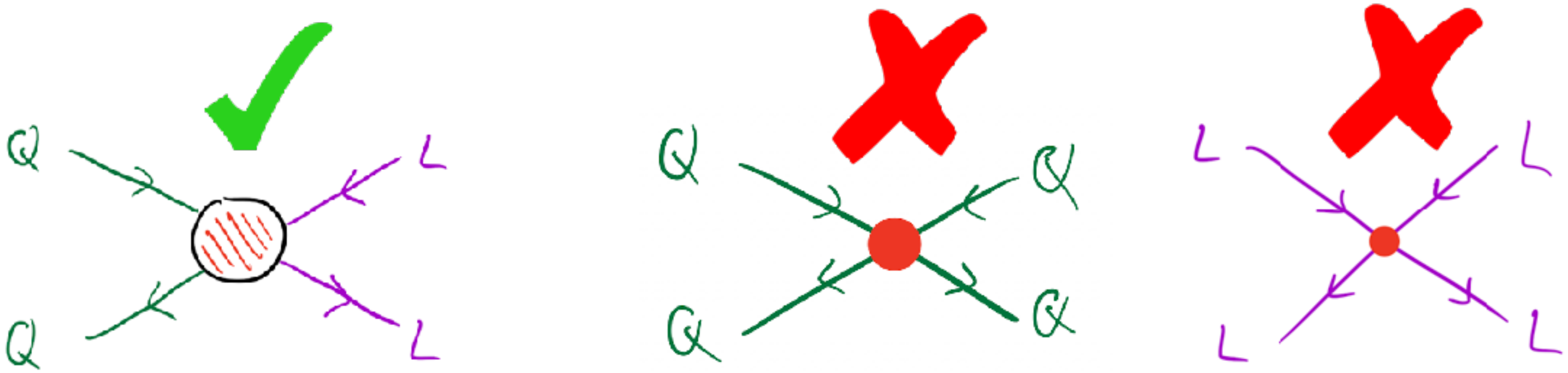
>> Very strong bounds on LQ couplings to 1st generation fermions, e.g. $K_L \to \mu\, e$, etc..

Leptoquarks and B-anomalies



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

Deviations in **semileptonic** processes,
strong bounds from $\Delta F=2$ & CLFV processes.

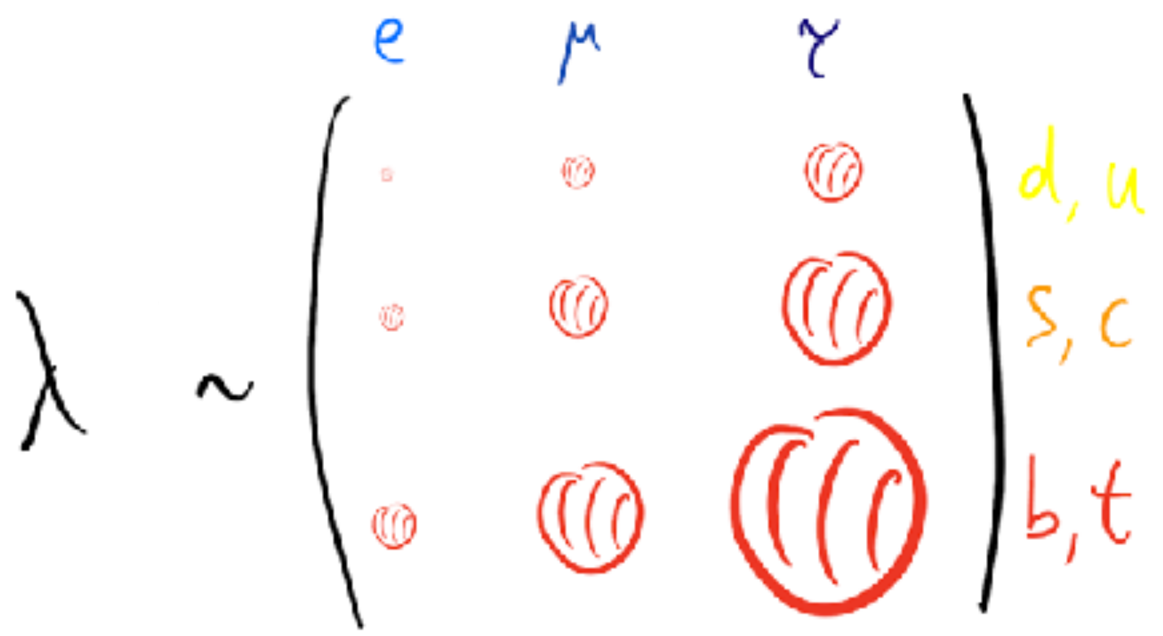


>> Very strong bounds on LQ couplings to 1st generation fermions, e.g. $K_L \to \mu e$, etc..

To address both B-anomalies:

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

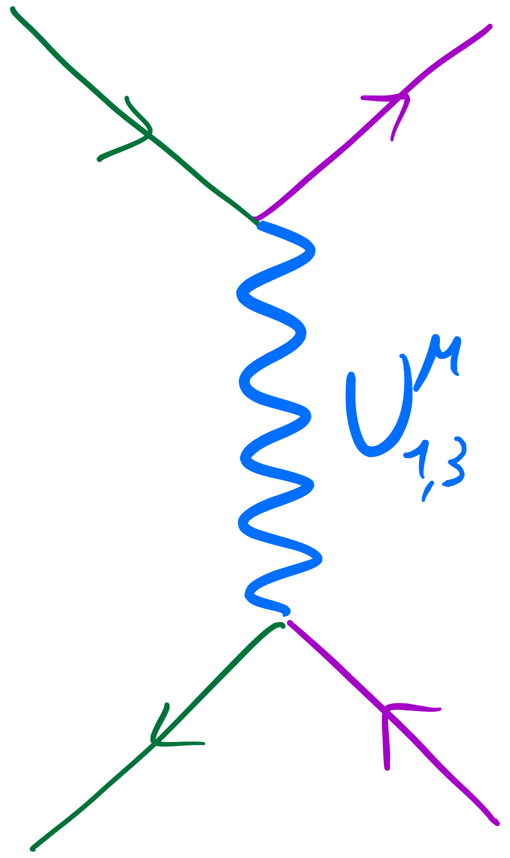
g(3rd) > g(2nd) > g(1st)



Leptoquarks and B-anomalies

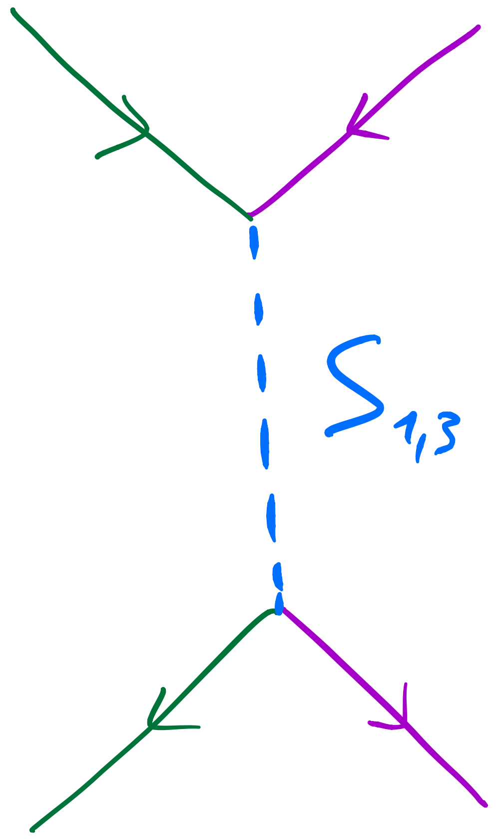
Vector Leptoquark

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



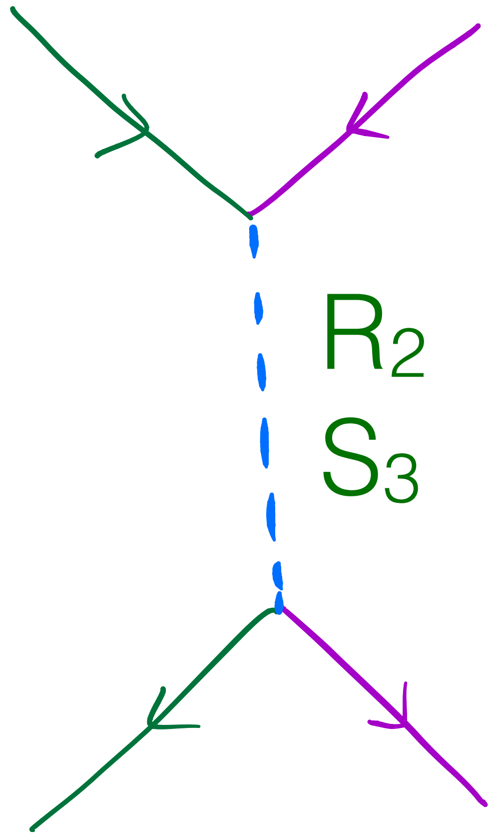
Scalar Leptoquarks

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



Scalar Leptoquarks

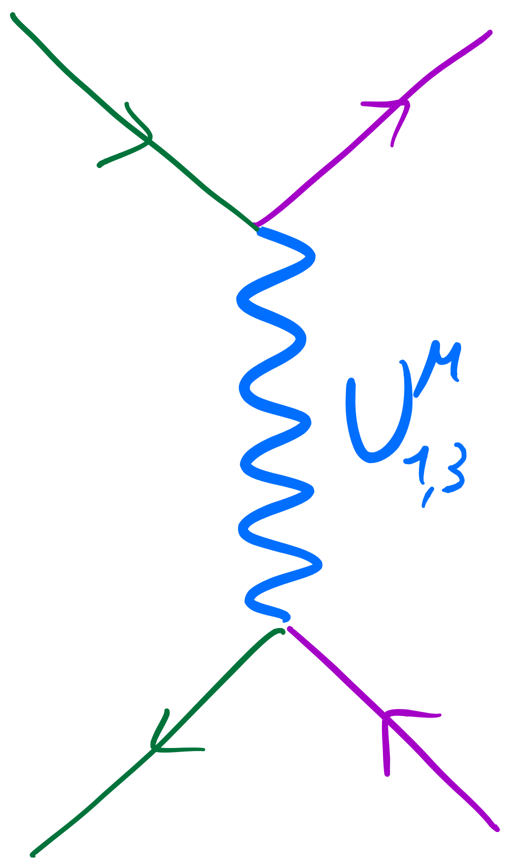
$R_2 = (\mathbf{3}, \mathbf{2}, 7/6)$,
$S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$,



Leptoquarks and B-anomalies

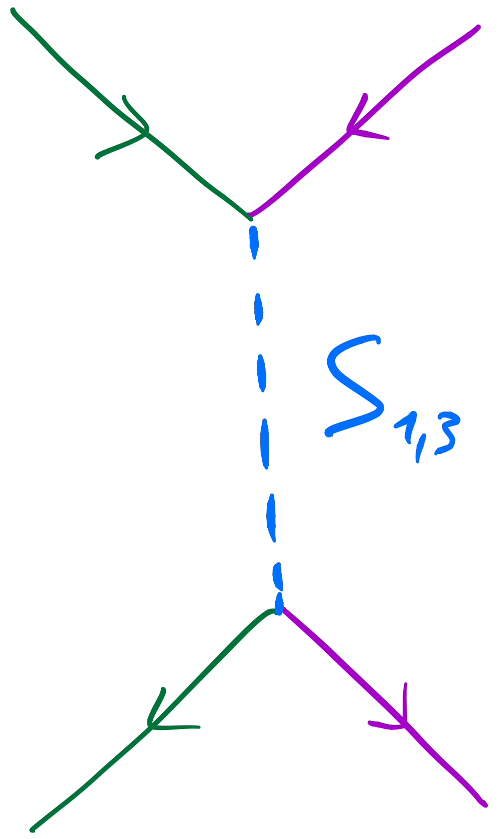
Vector Leptoquark

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



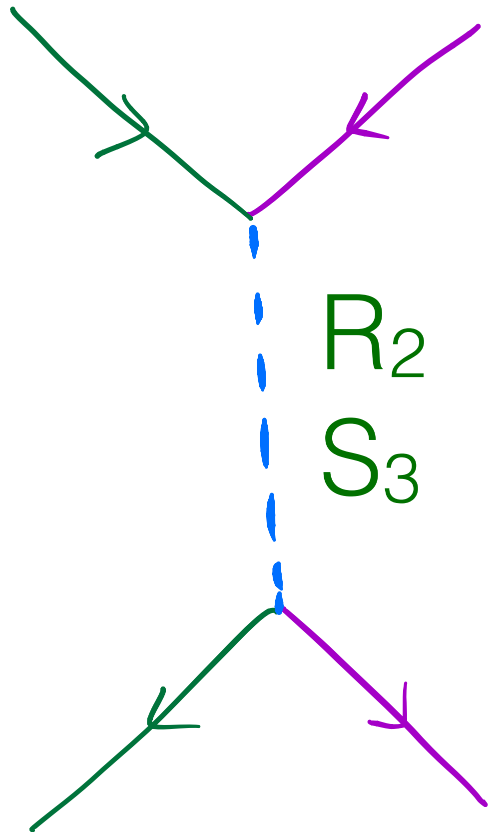
Scalar Leptoquarks

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



Scalar Leptoquarks

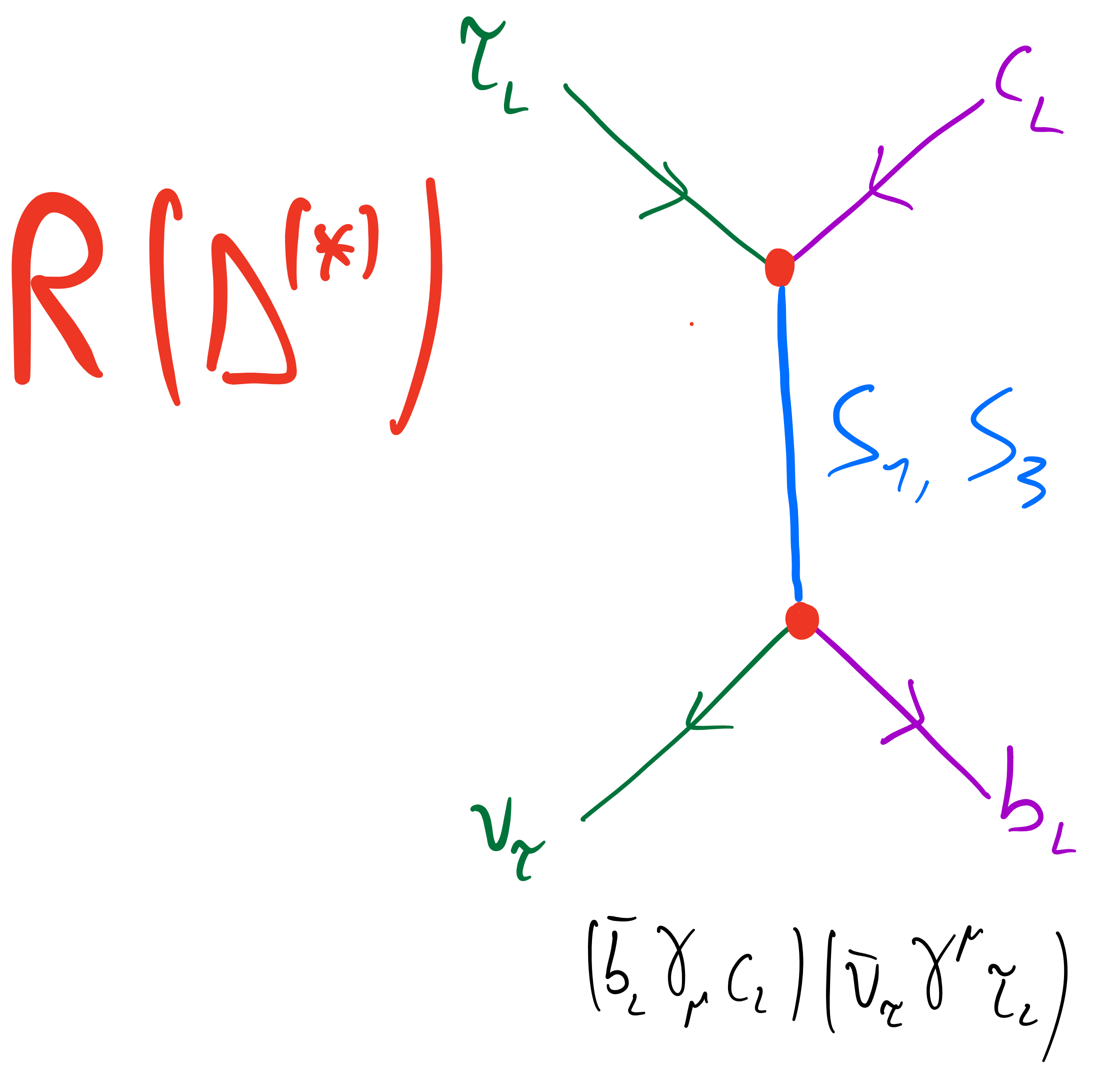
$R_2 = (\mathbf{3}, \mathbf{2}, 7/6)$,
$S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$,

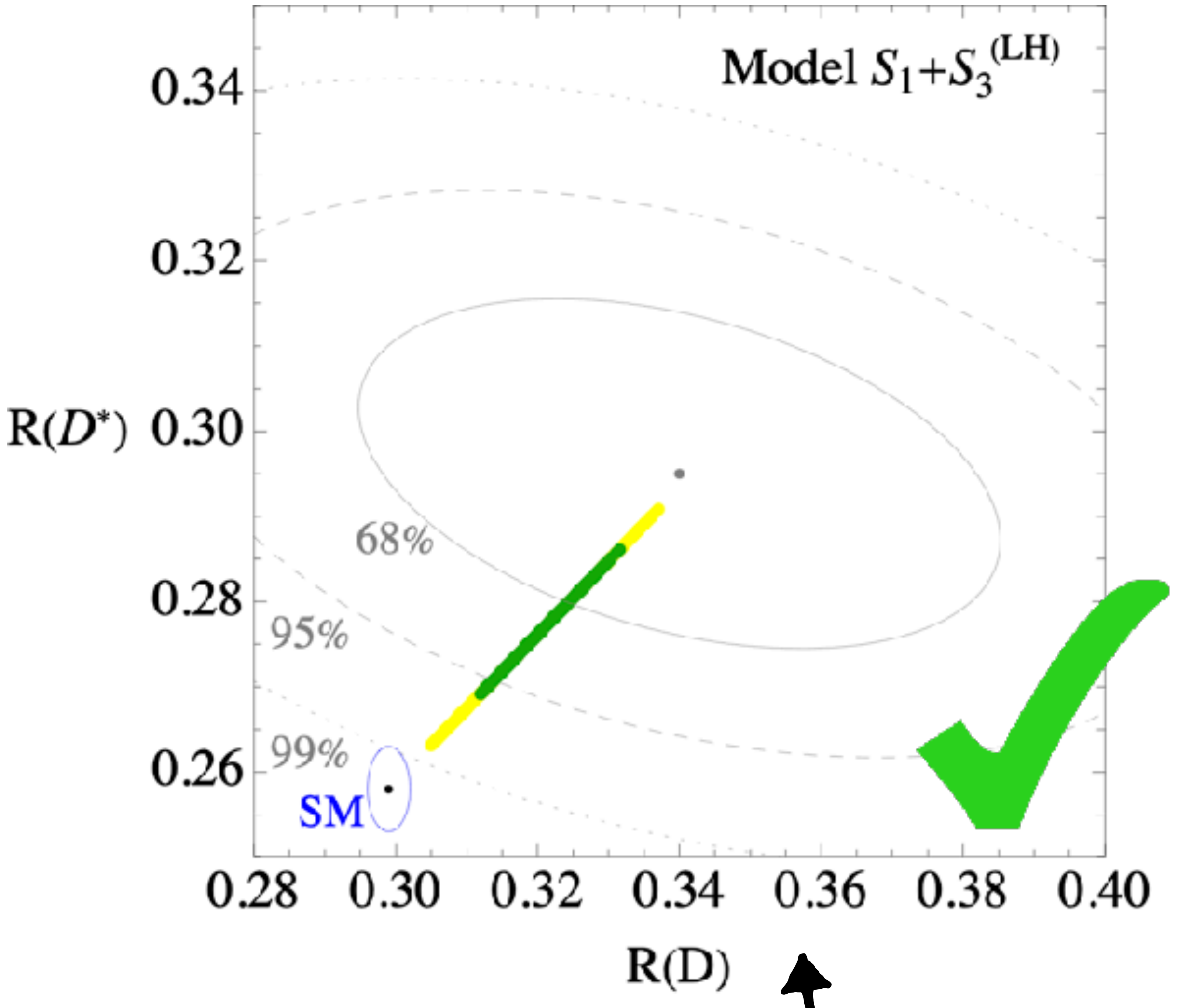


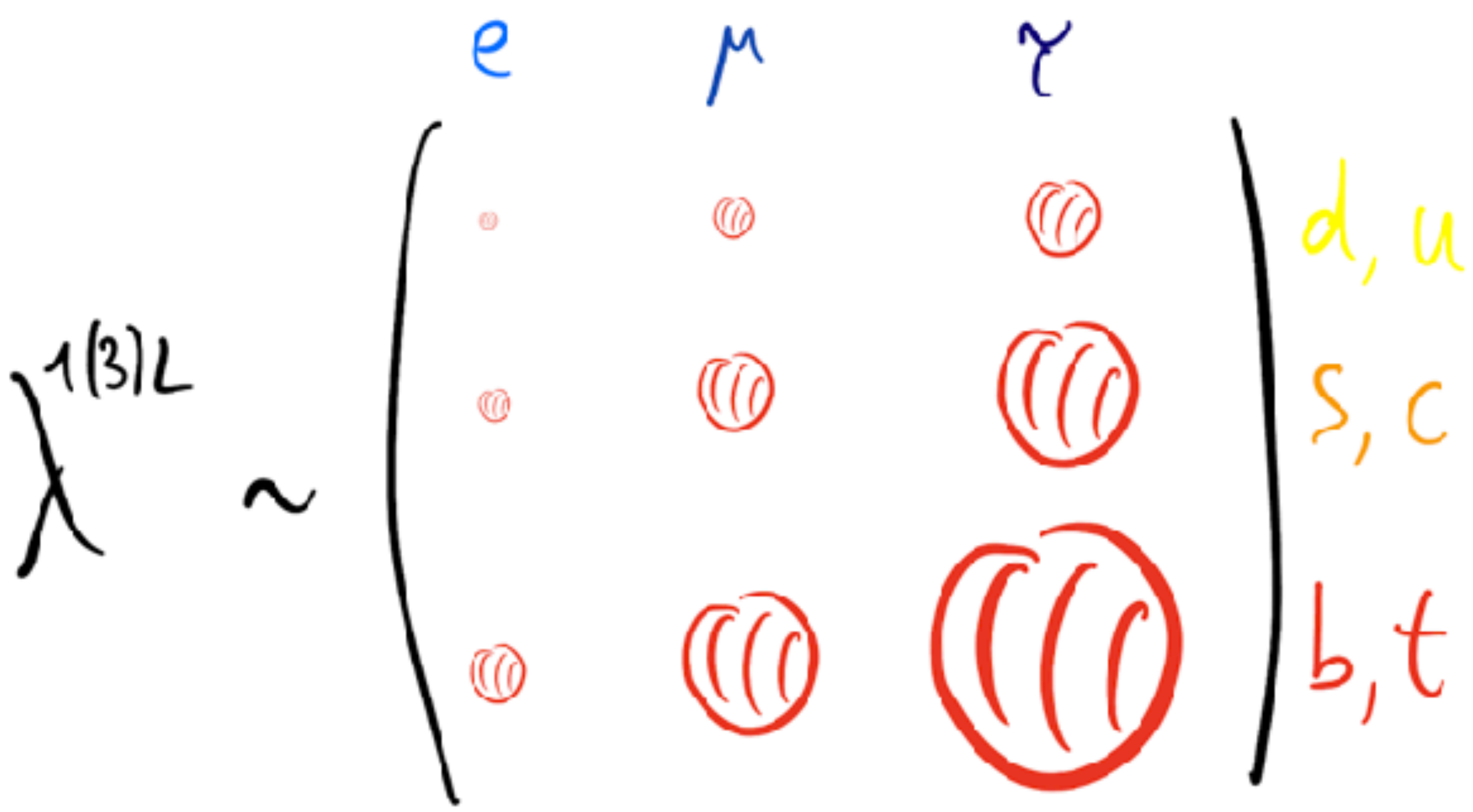
TeV-scale leptoquark coupled to **3rd** and **2nd** generation

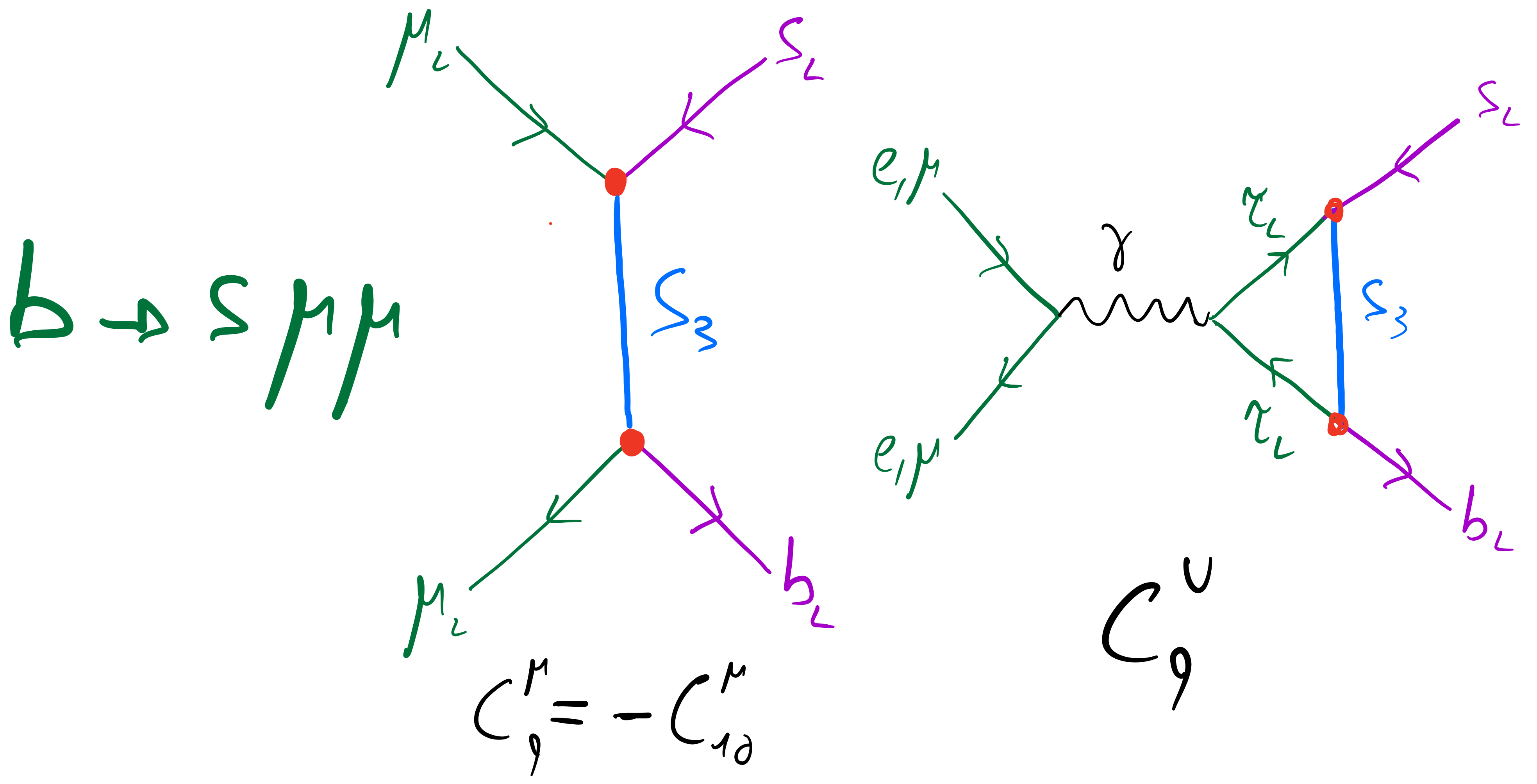
g(3rd) > g(2nd) > g(1st)

S_1 and S_3 - contributions to anomalies

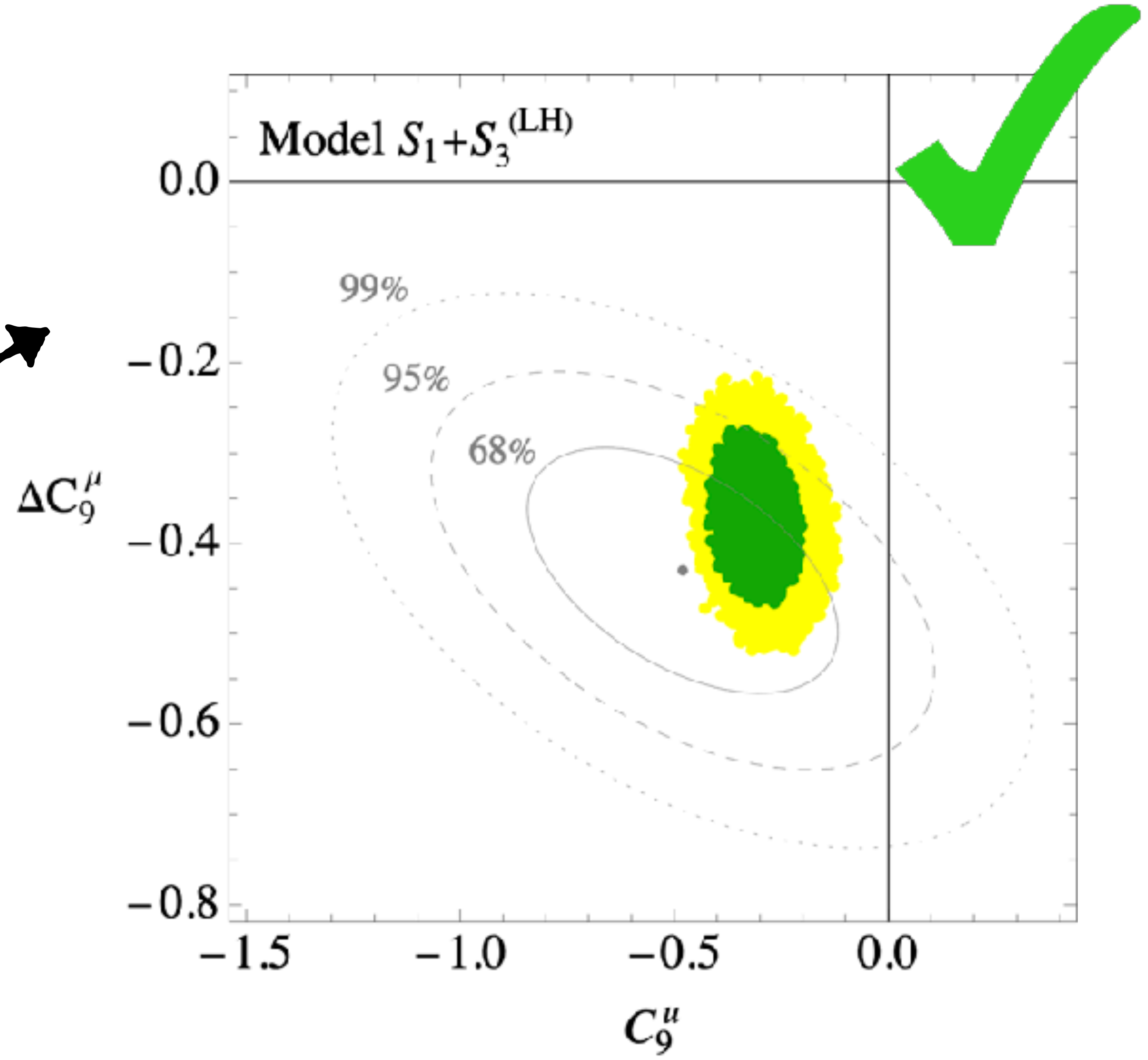








Global fit
with all relevant
flavour,
EW, and **collider**
constraints.
(details in backup)



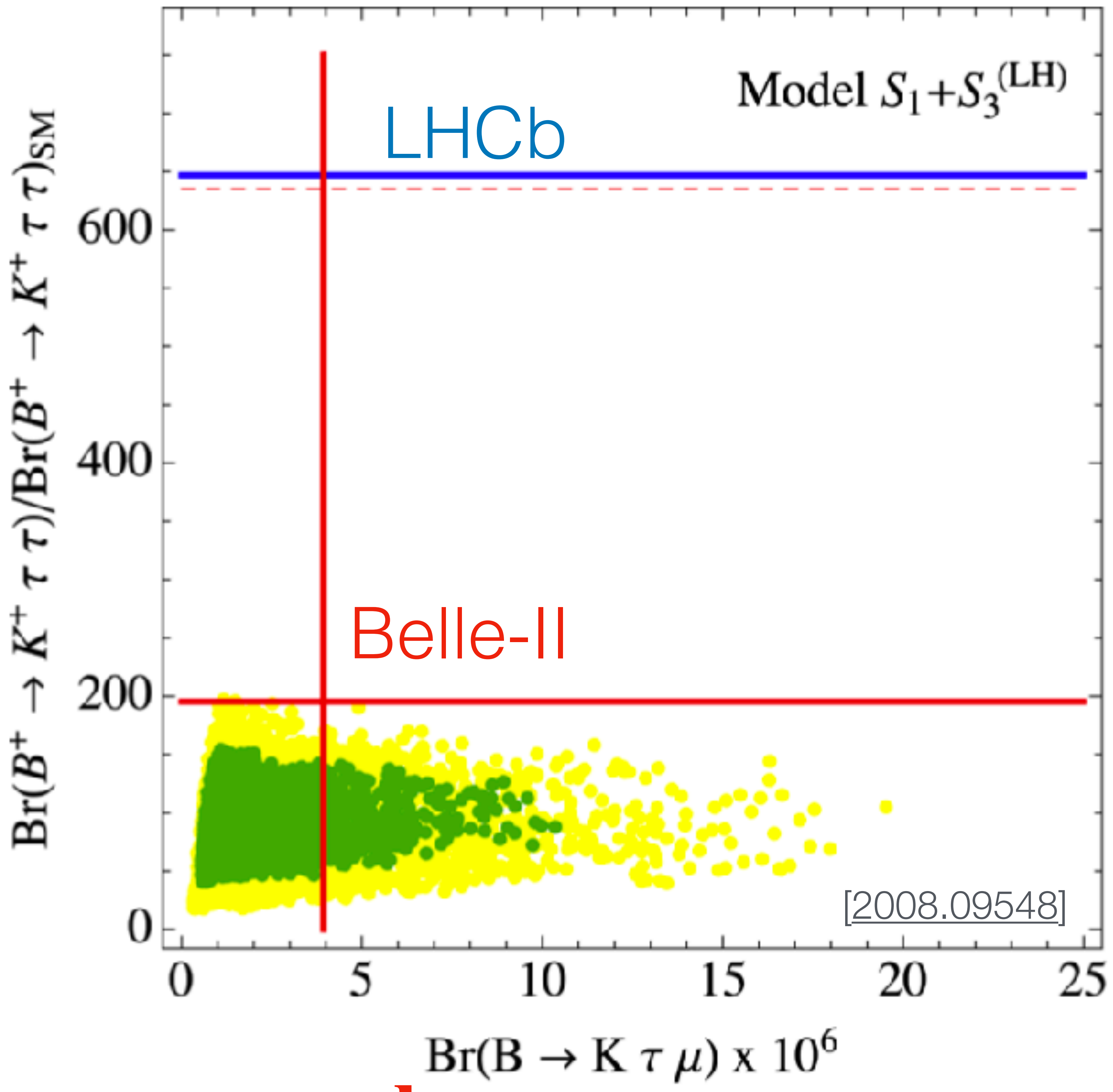
V. Gherardi, E. Venturini, D.M. [2008.09548]

Predictions

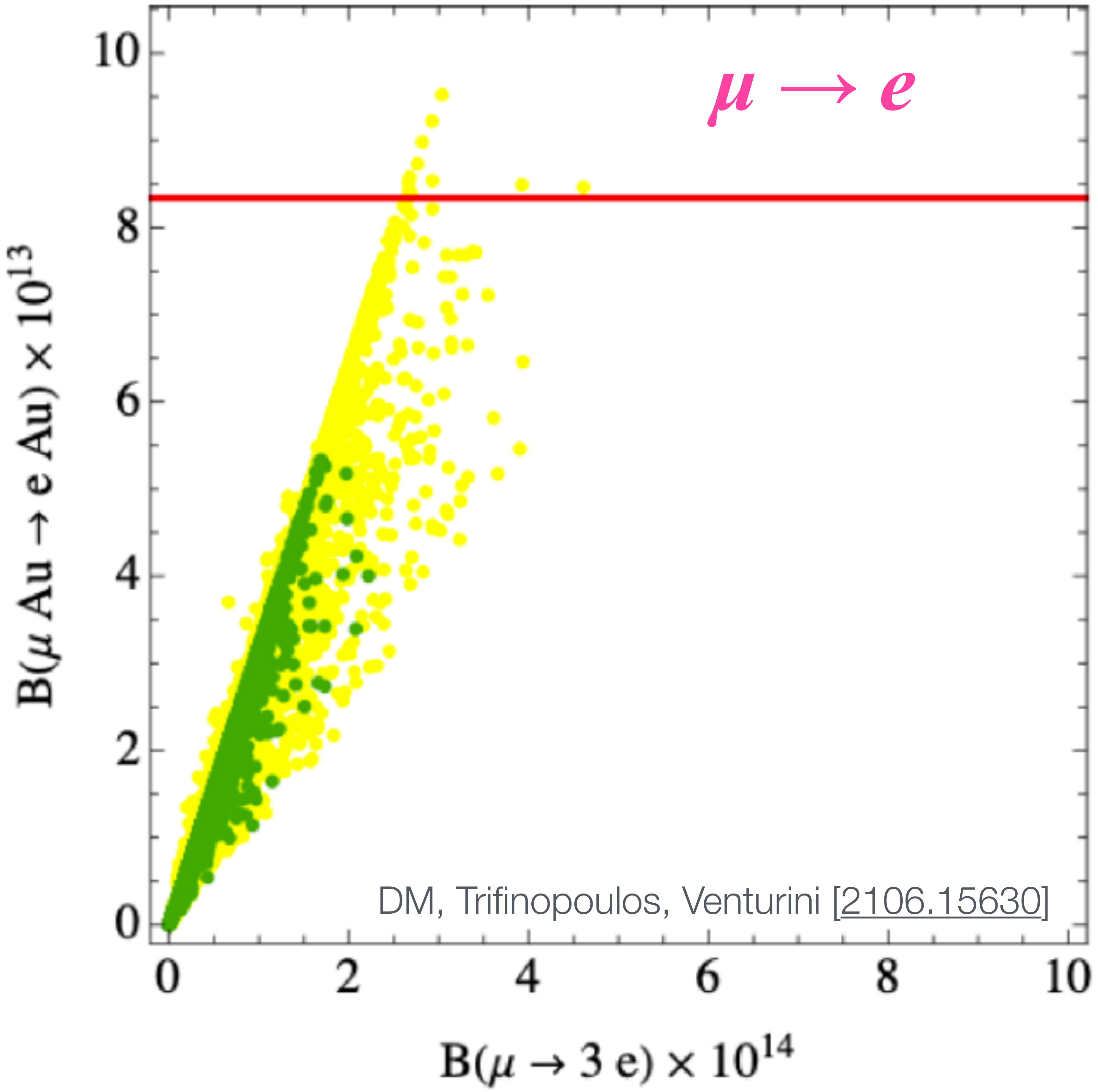
Typical for all models addressing R(D(*)) → The large couplings to τ imply signatures in DY tails of ***pp*→ τ τ**, deviations in **τ LFU** tests and **τ → μ LFV** tests (Belle-II). Also **B_s-mixing** and **B→ K* ν ν̄** are close to present bounds.

Large effects are also expected in **b → s τ τ** and **b → s τ μ** transitions, as well as in ***μ → e***:

b → s τ τ

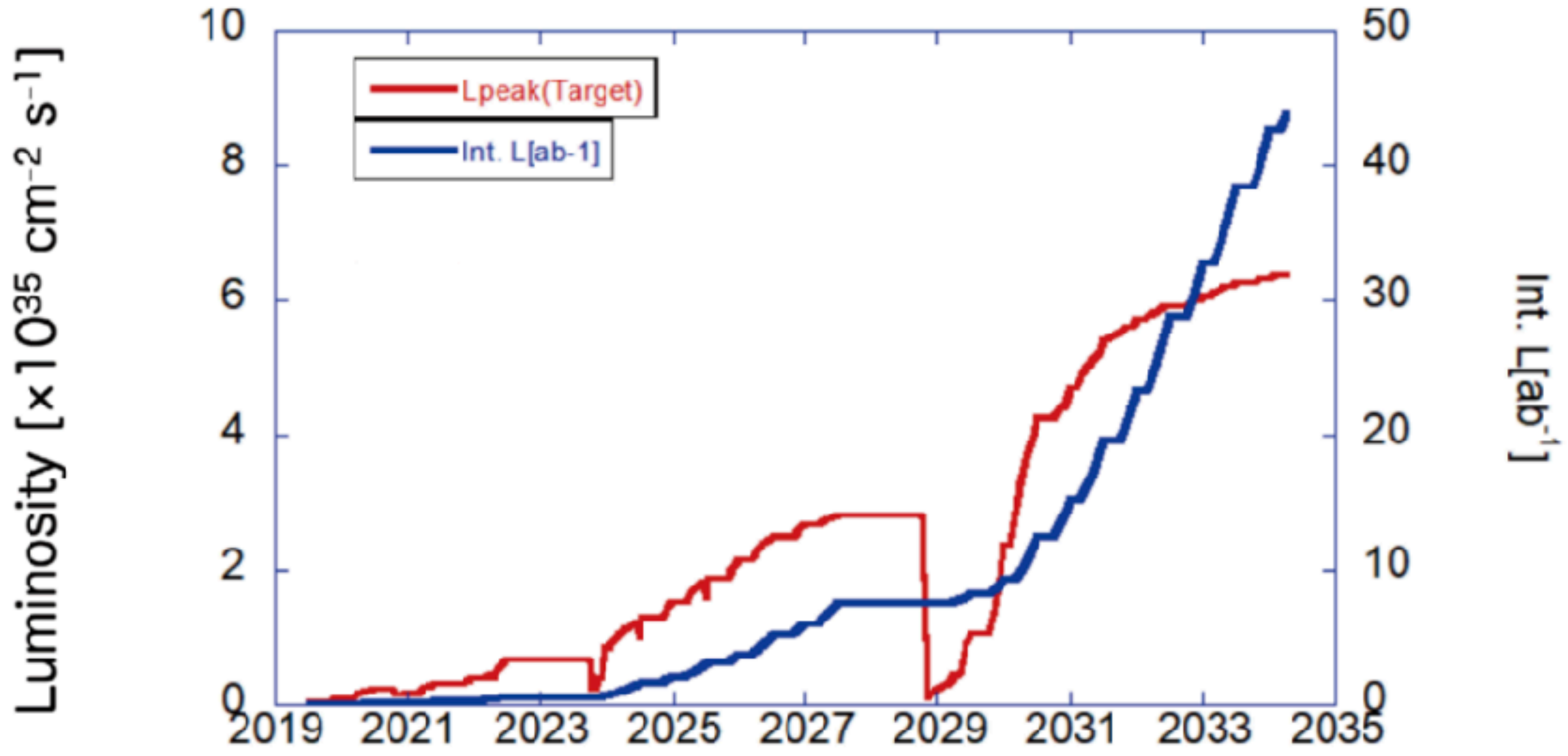


b → s τ μ



Near Future Prospects in Flavour

Belle-II



Belle-II will be able to **completely test R(D(*)) with 5ab^{-1}**.

Measuring R(K(*)) with 3% precision requires 50ab^{-1}.

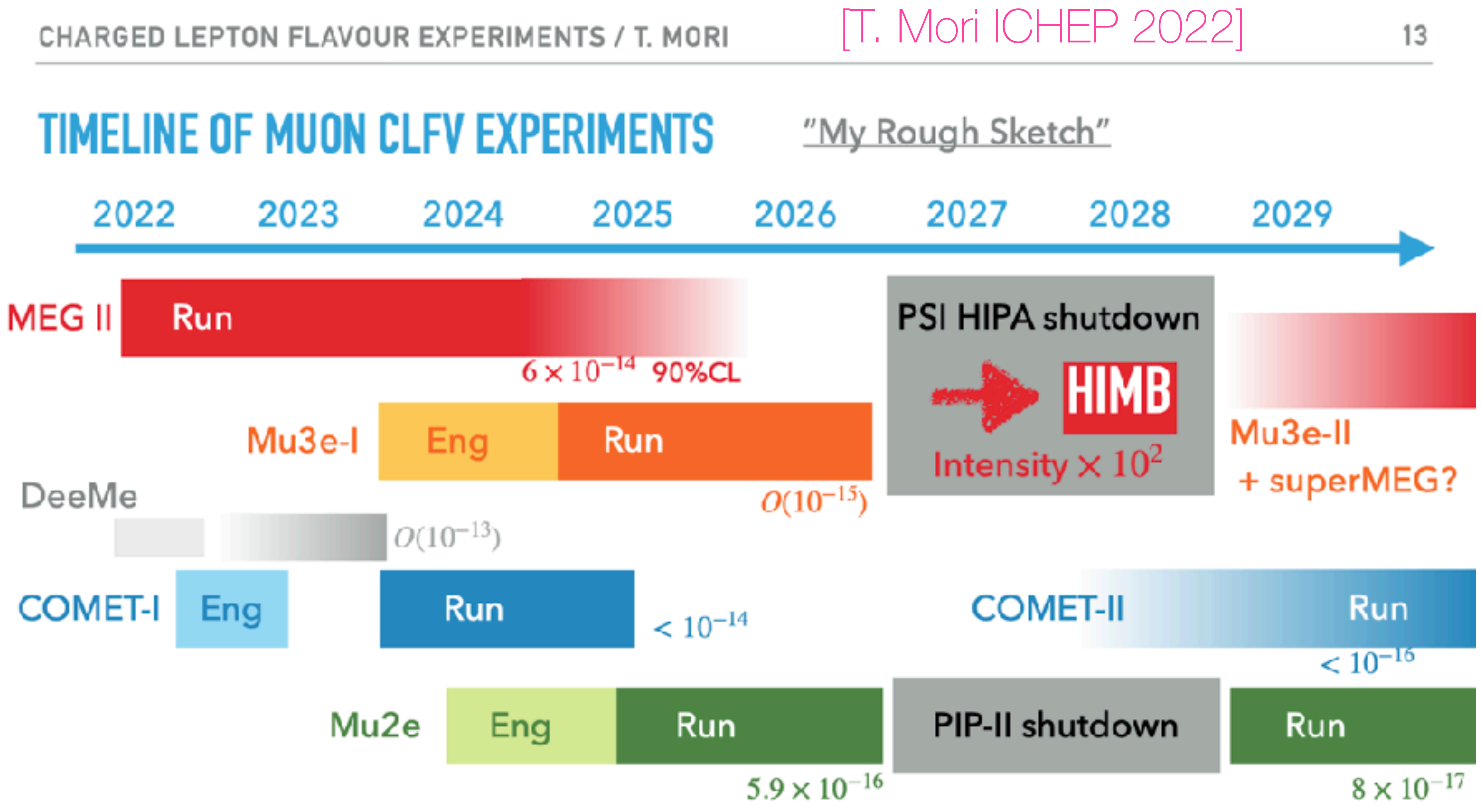
Discover SM value of $B^0 \to K^{*0} \nu \bar{\nu}$ with ~5ab^{-1}.

Bound on $Br(\tau \to \mu \gamma\ (3\mu))$ will **improve by a factor of 6 (60)**.

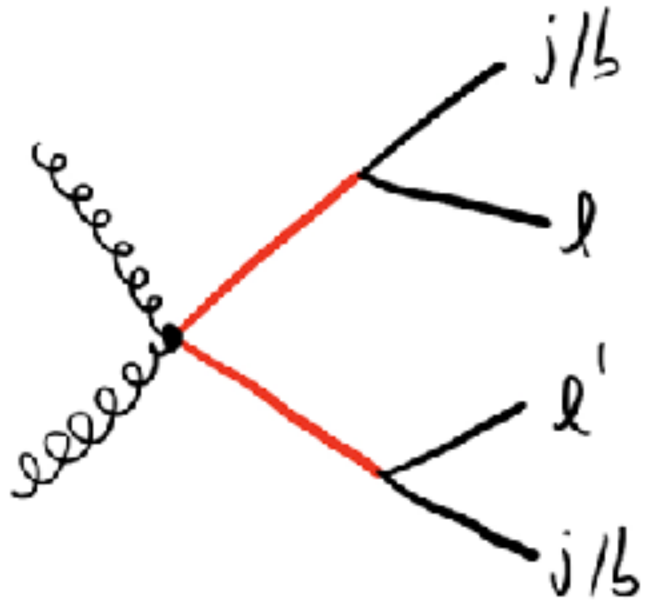
μ → e LFV

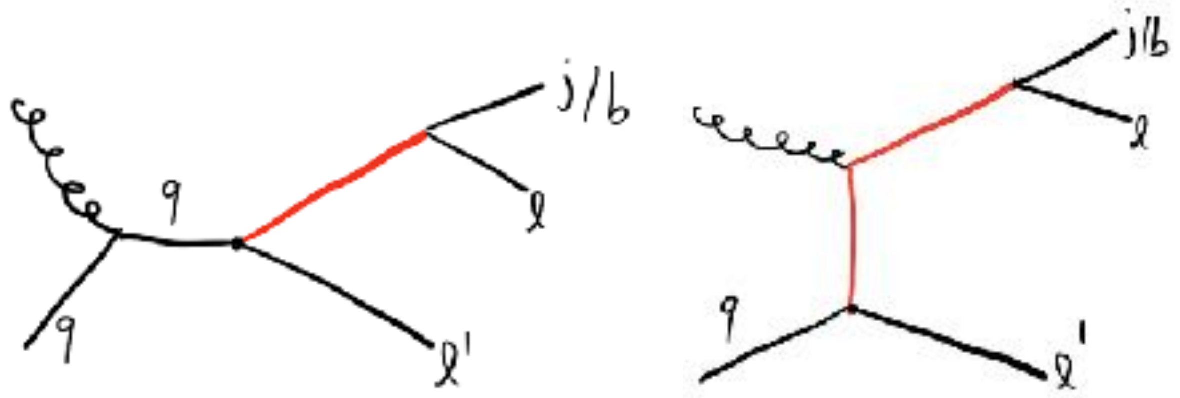
today:

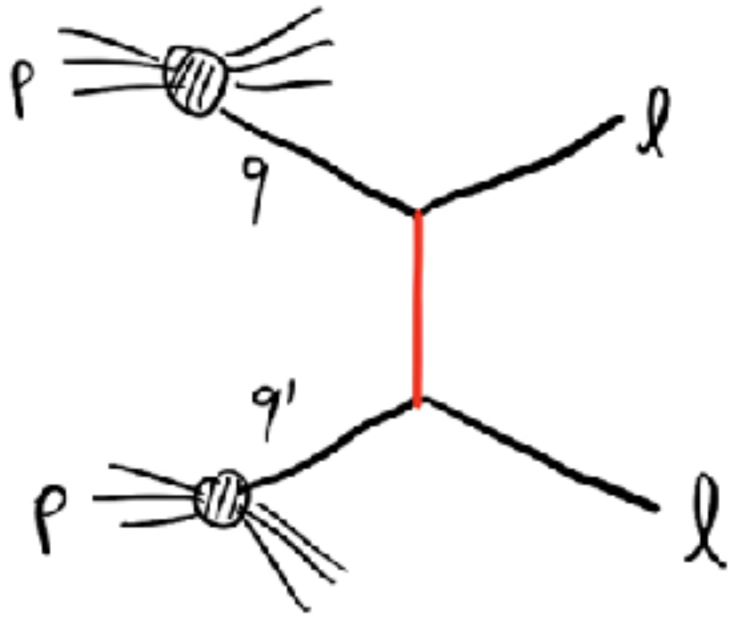
$\mathcal{B}(\mu \to e\gamma)$	$< 5.0 \times 10^{-13}$
$\mathcal{B}(\mu \to 3e)$	$< 1.2 \times 10^{-12}$
$\mathcal{B}_{\mu e}^{(\mathrm{Ti})}$	$< 5.1 \times 10^{-12}$
$\mathcal{B}_{\mu e}^{(\mathrm{Au})}$	$< 8.3 \times 10^{-13}$

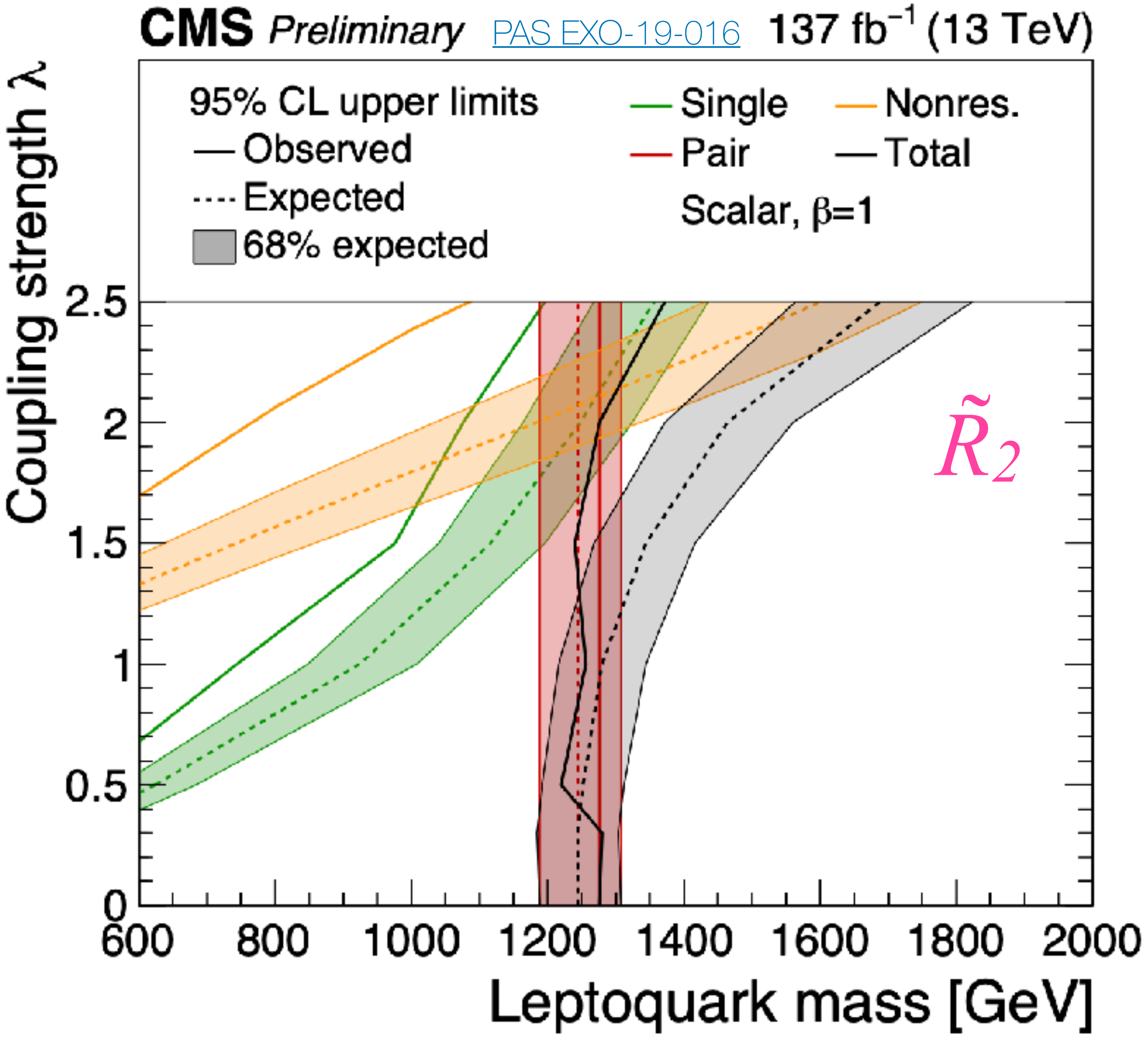


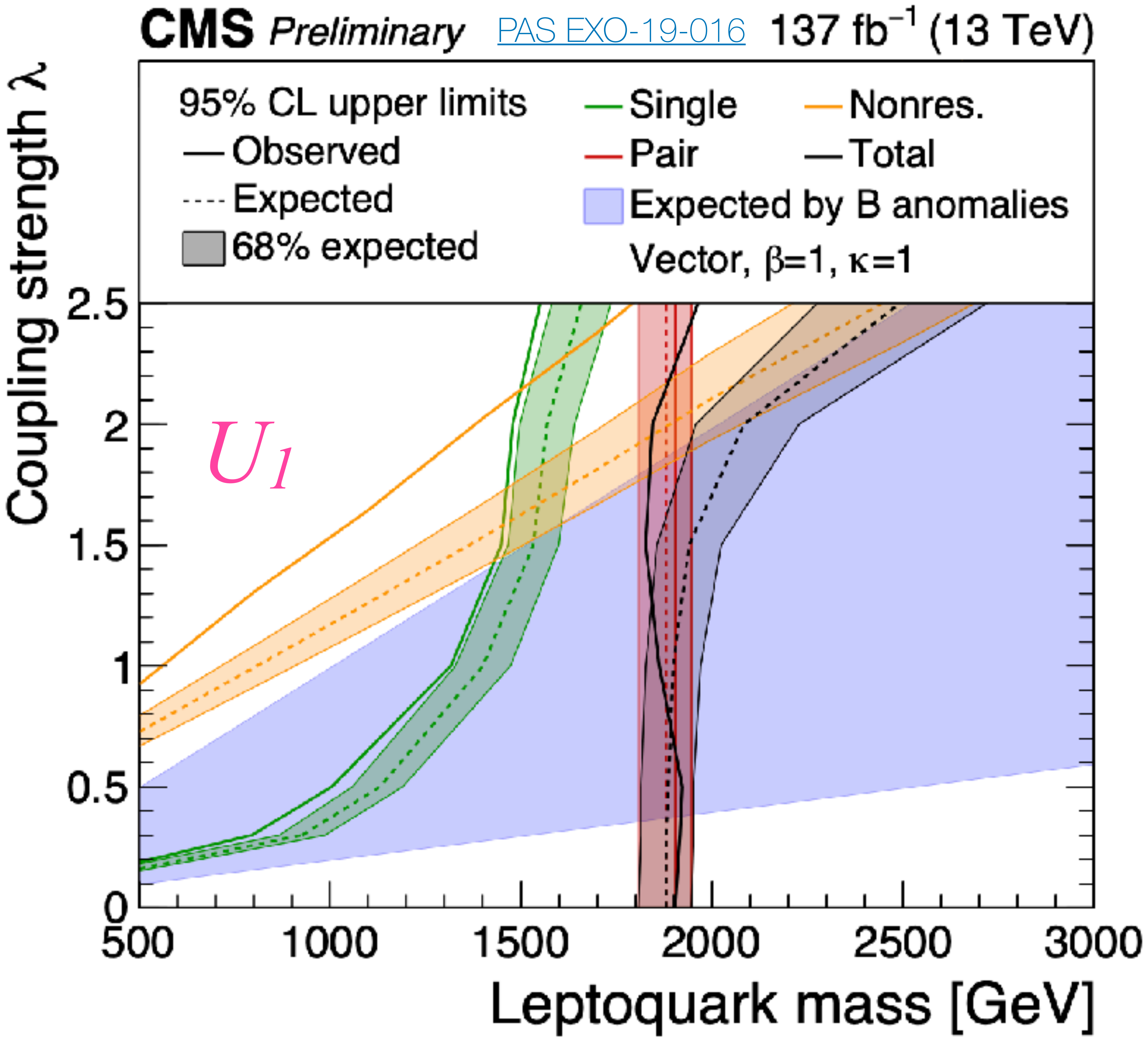
3rd gen LQ searches











scalar $M_{LQ} \gtrsim$ 1.3 TeV

vector $M_{LQ} \gtrsim$ 1.9 TeV

S_1, S_3: Higgs, EW and m_W

The two leptoquarks have potential couplings to the Higgs:

$$\mathcal{L}_{\rm LQ} \supset -\left(\lambda_{H13}(H^\dagger\sigma^I H)S_3^{I\dagger}S_1 + \text{h.c.}\right) - \lambda_{\epsilon H3} i\epsilon^{IJK}(H^\dagger\sigma^I H)S_3^{J\dagger}S_3^K$$
$$- \lambda_{H1}|H|^2|S_1|^2 - \lambda_{H3}|H|^2|S_3^I|^2$$

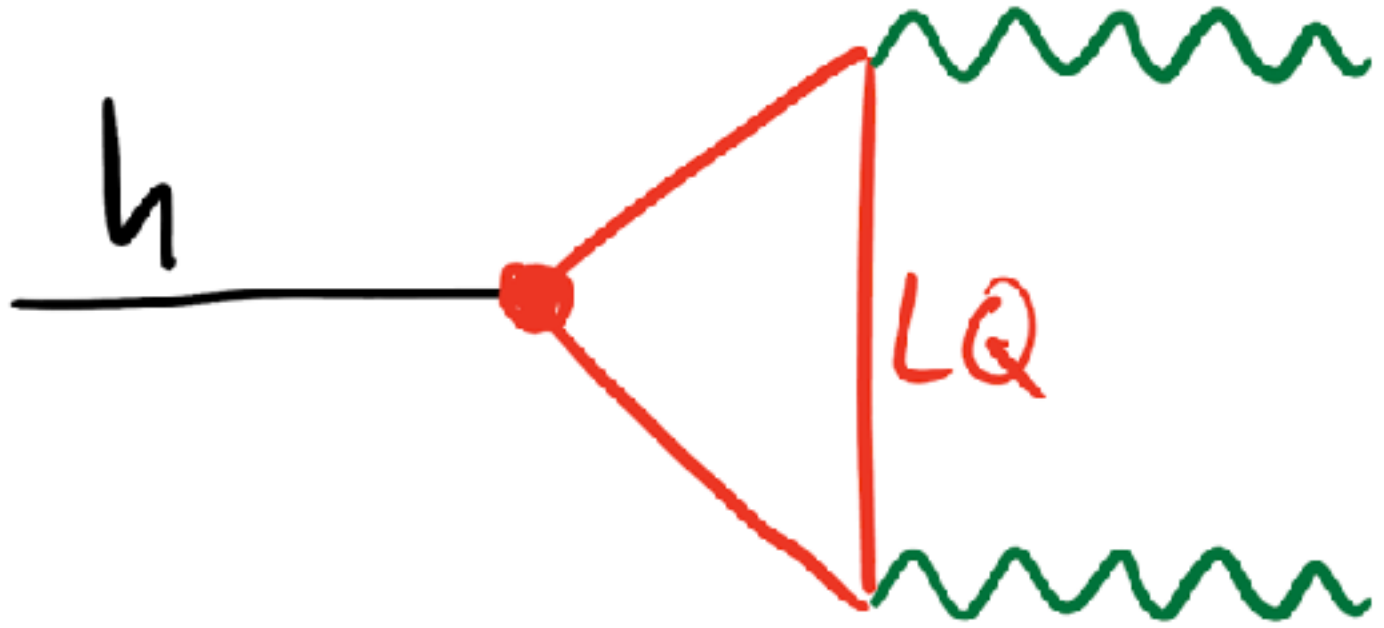
At one loop they **contribute to Higgs couplings**
and S, T paramseters:

S_1, S_3: Higgs, EW and m_W

The two leptoquarks have potential couplings to the Higgs:

$$\mathcal{L}_{\rm LQ} \supset -\left(\lambda_{H13}(H^\dagger\sigma^I H)S_3^{I\dagger}S_1 + \text{h.c.}\right) - \lambda_{\epsilon H3} i\epsilon^{IJK}(H^\dagger\sigma^I H)S_3^{J\dagger}S_3^K$$
$$-\lambda_{H1}|H|^2|S_1|^2 - \lambda_{H3}|H|^2|S_3^I|^2$$

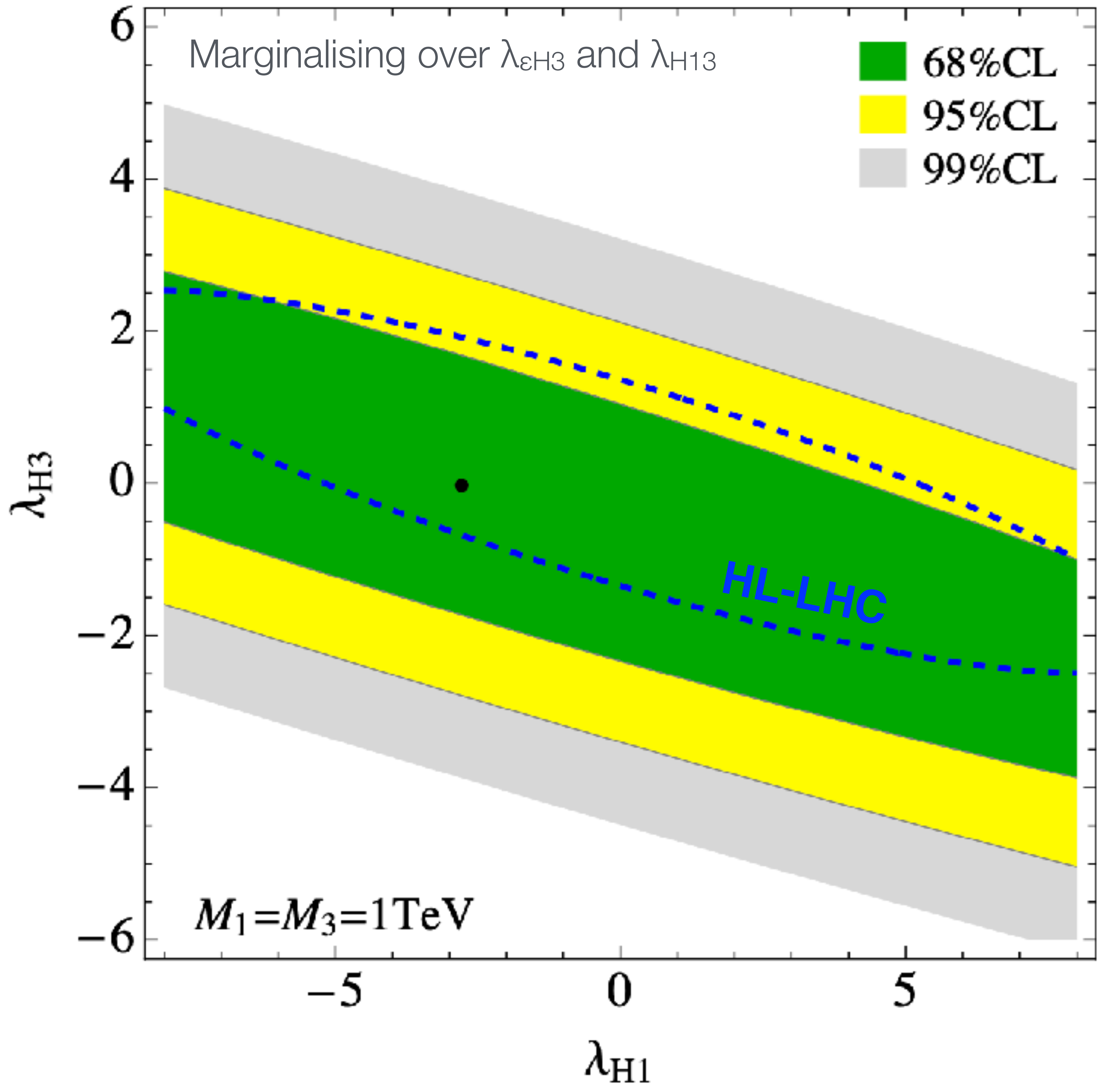
At one loop they **contribute to Higgs couplings and S, T paramseters**:



$$\kappa_g - 1 = -(3.51\lambda_{H3} + 1.17\lambda_{H1}) \times 10^{-2}/m^2\ ,$$
$$\kappa_\gamma - 1 = -(2.32\lambda_{H3} + 0.66\lambda_{\epsilon H3} - 0.11\lambda_{H1}) \times 10^{-2}/m^2\ ,$$
$$\kappa_{Z\gamma} - 1 = -(1.89\lambda_{H3} + 0.23\lambda_{\epsilon H3} - 0.033\lambda_{H1}) \times 10^{-2}/m^2\ .$$

$m = M_{LQ}$ / TeV

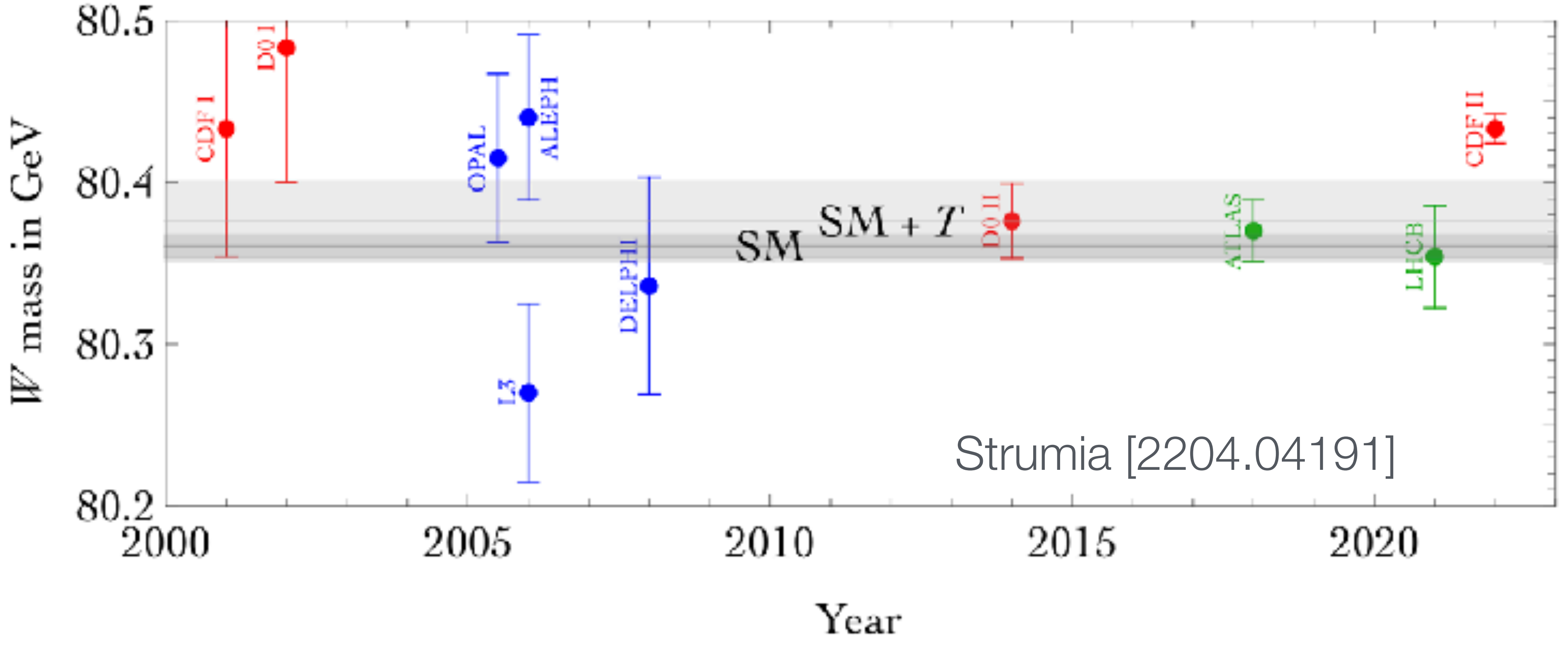
V. Gherardi, E. Venturini, D.M. [2008.09548]
See also 1910.03877, 2006.10758 and 2204.03996



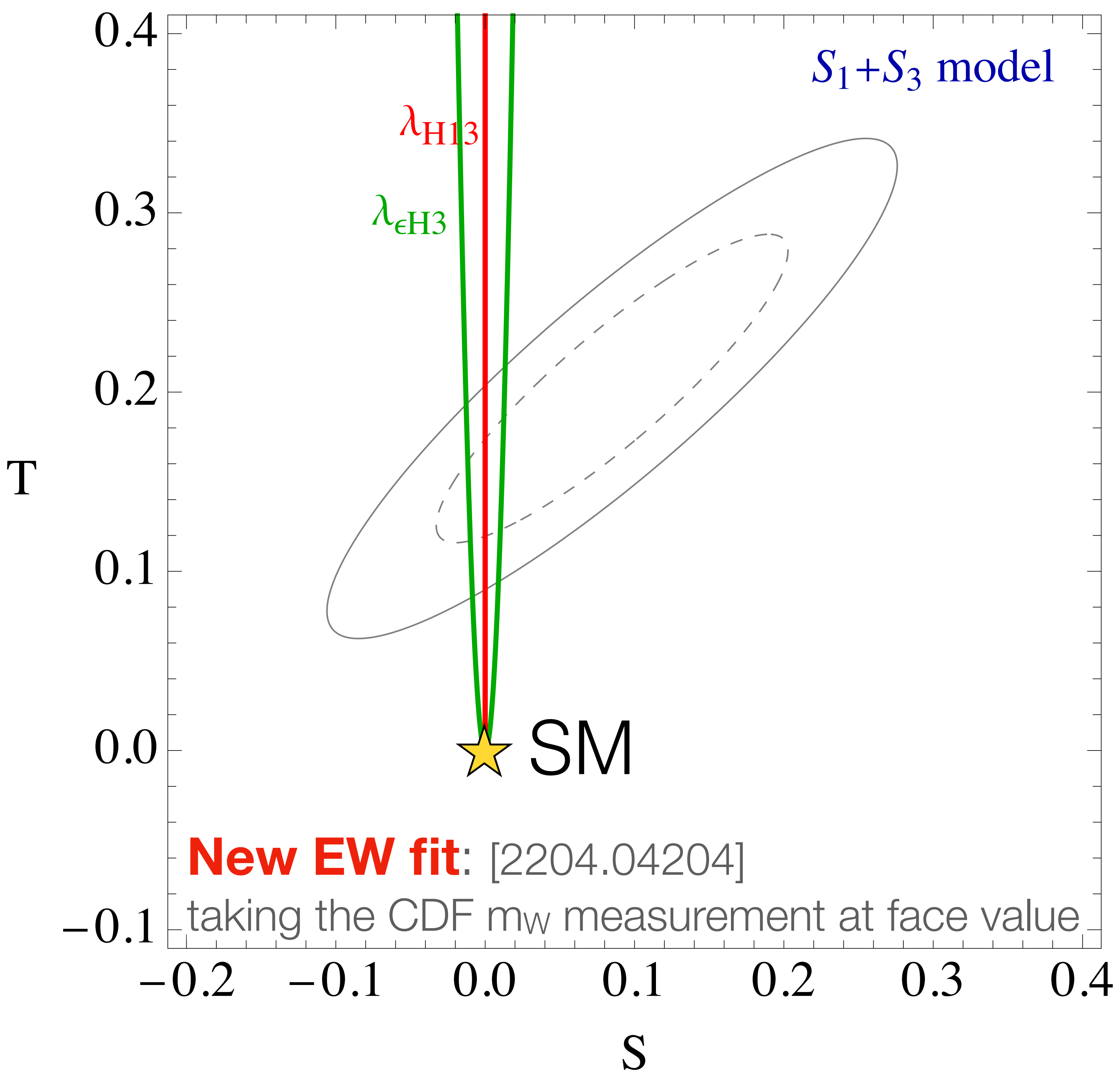
S_1, S_3: Higgs, EW and m_W

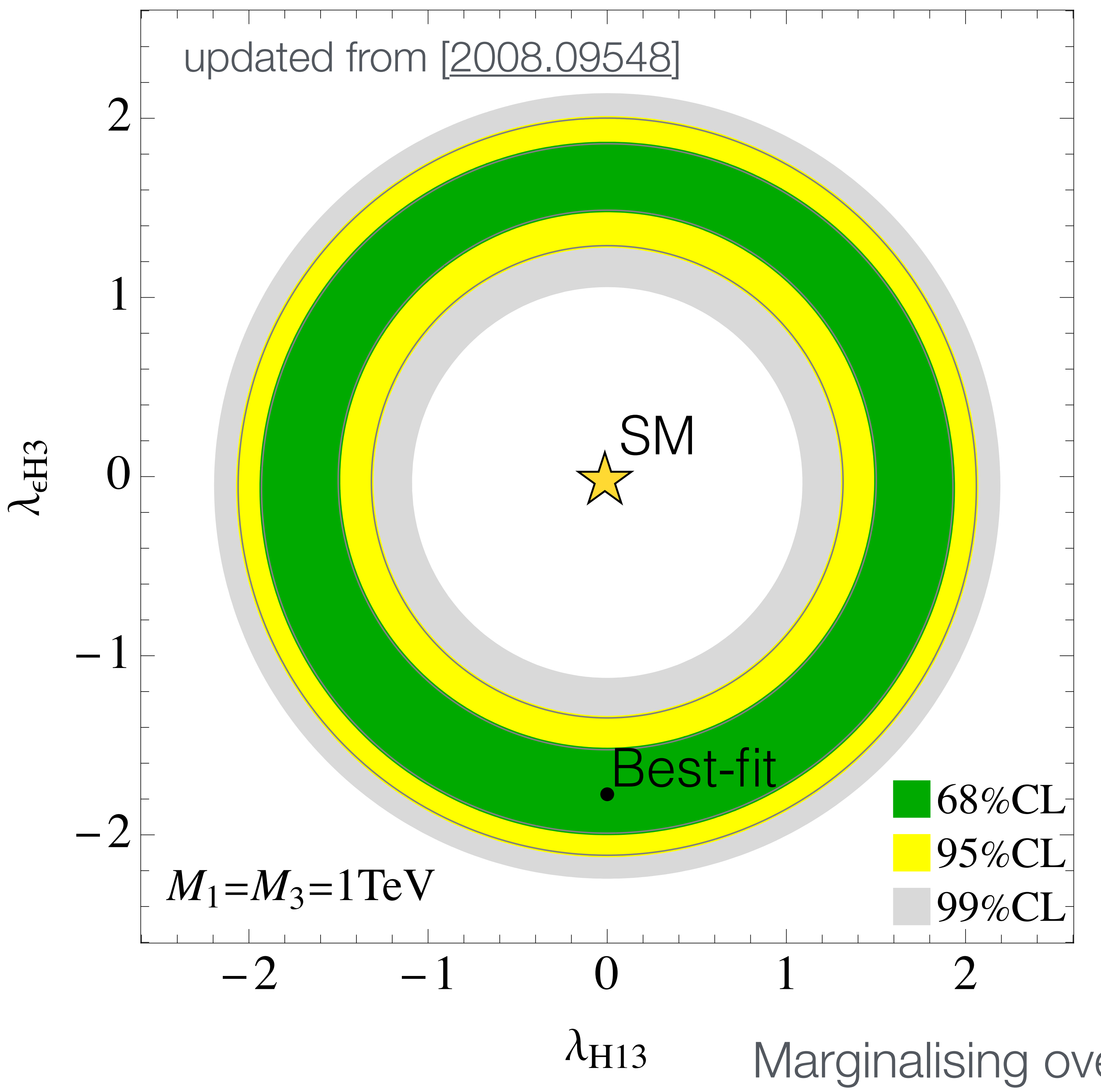
The two leptoquarks have potential couplings to the Higgs:

$$\mathcal{L}_{LQ} \supset -\left(\lambda_{H13}(H^\dagger\sigma^I H)S_3^{I\dagger}S_1 + \text{h.c.}\right) - \lambda_{\epsilon H3} i\epsilon^{IJK}(H^\dagger\sigma^I H)S_3^{J\dagger}S_3^K$$
$$- \lambda_{H1}|H|^2|S_1|^2 - \lambda_{H3}|H|^2|S_3^I|^2$$



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





Marginalising over λ_{H1} and λ_{H3}

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

Intriguing experimental hints for New Physics.

We should wait and see what more data will bring…

meanwhile, they spawned some interesting model building

(a partial selection in what follows)

From Leptoquarks to the Higgs, and back

From B-anomalies

$M_{LQ} \sim$ TeV

Hierarchical couplings to SM fermions

$g(\mathbf{3rd}) > g(\mathbf{2nd}) > g(\mathbf{1st})$

From Leptoquarks to the Higgs, and back

From B-anomalies

$M_{LQ} \sim$ TeV

Hierarchical couplings to SM fermions

$g(3rd) > g(2nd) > g(1st)$

Higgs & EW hierarchy

$M_{BSM} \lesssim$ TeV

Hierarchical Yukawa couplings

$y(3rd) > y(2nd) > y(1st)$

From Leptoquarks to the Higgs, and back

From B-anomalies

$M_{LQ} \sim$ TeV

Hierarchical couplings to SM fermions

$$\mathbf{g(3rd) > g(2nd) > g(1st)}$$

Higgs & EW hierarchy

$M_{BSM} \lesssim$ TeV

Hierarchical Yukawa couplings

$$\mathbf{y(3rd) > y(2nd) > y(1st)}$$

LQ from same UV responsible for the EW scale,
connection between LQ couplings and Yukawa couplings.

Model building for LQs and Higgs

Scalar Leptoquarks + Higgs as pNGB

[0910.1789, 1412.1791, 1803.10972]

or

U_1 Vector Leptoquark as TC Pati Salam + Higgs as pNGB

[2004.11376]

> extensions of Composite Higgs models <

Model building for LQs and Higgs

Scalar Leptoquarks + Higgs as pNGB

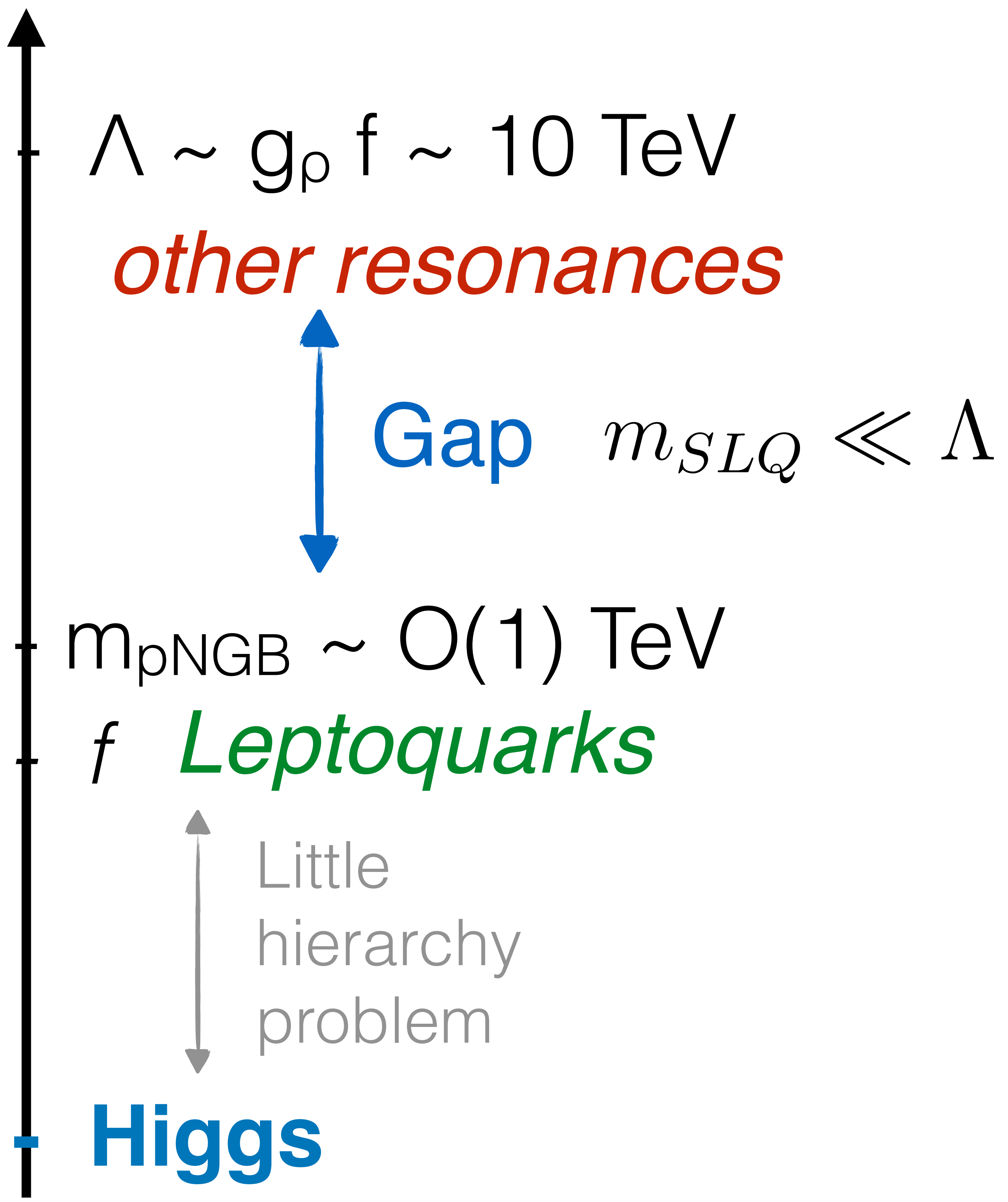
[0910.1789, 1412.1791, 1803.10972]

or

U_1 Vector Leptoquark as TC Pati Salam + Higgs as pNGB [2004.11376]

> extensions of Composite Higgs models <

Higgs Yukawas and LQ couplings can arise from same dynamics.



Model building for LQs and Higgs

Scalar Leptoquarks + Higgs as pNGB

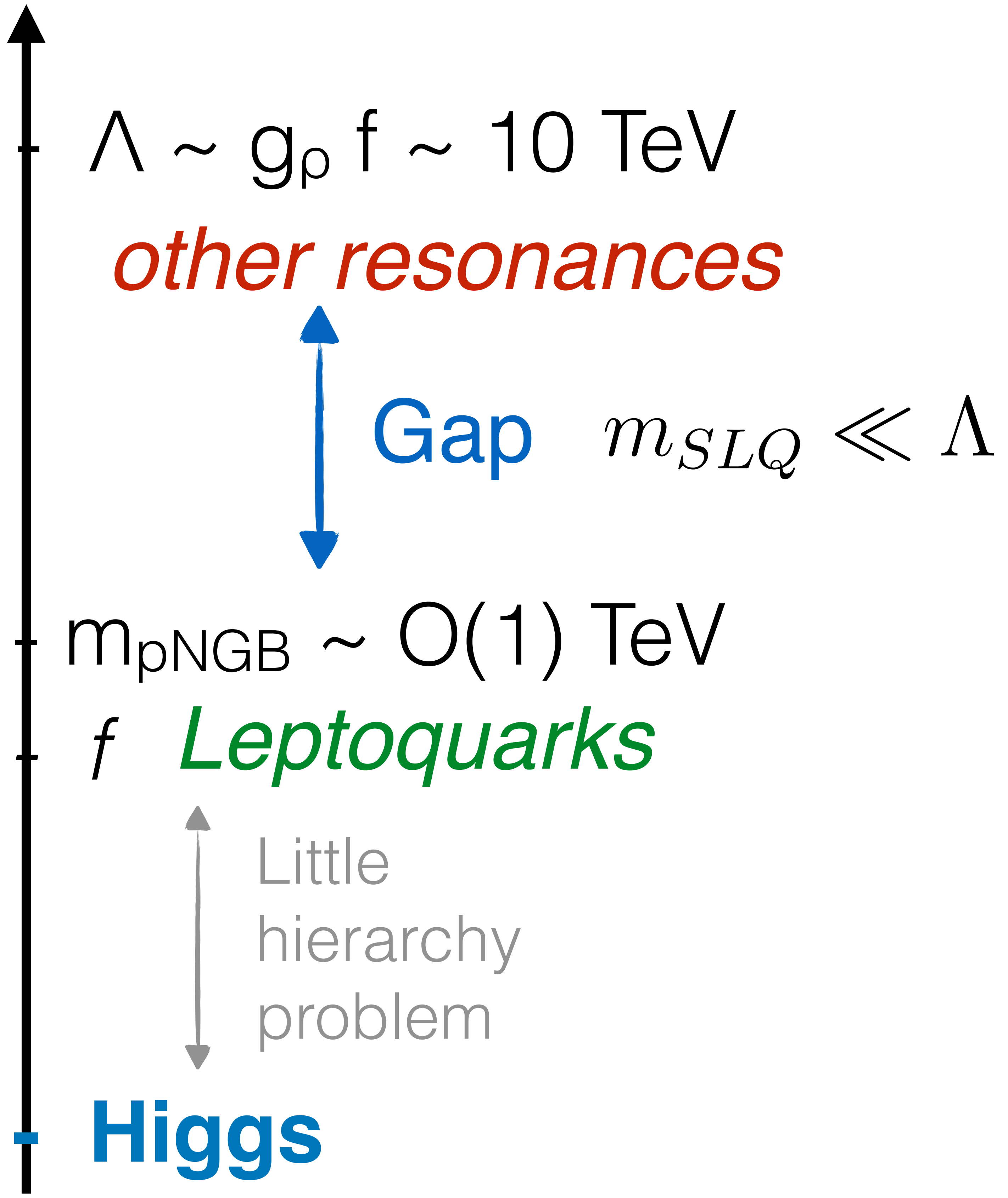
[0910.1789, 1412.1791, 1803.10972]

or

U_1 Vector Leptoquark as TC Pati Salam + Higgs as pNGB [2004.11376]

> extensions of Composite Higgs models <

Higgs Yukawas and LQ couplings can arise from same dynamics.



$$\langle \bar{\Psi}_i \Psi_j \rangle = -B_0 f^2 \delta_{ij}$$

The condensate of the strong sector, that gives the Higgs as pNGB,
also breaks spontaneously an extra SU(4) gauge symmetry.
The NGBs are eaten by the U_1 LQ.

$$M_U \sim g_4 f$$

Model building for LQs and Higgs

Scalar Leptoquarks + Higgs as pNGB

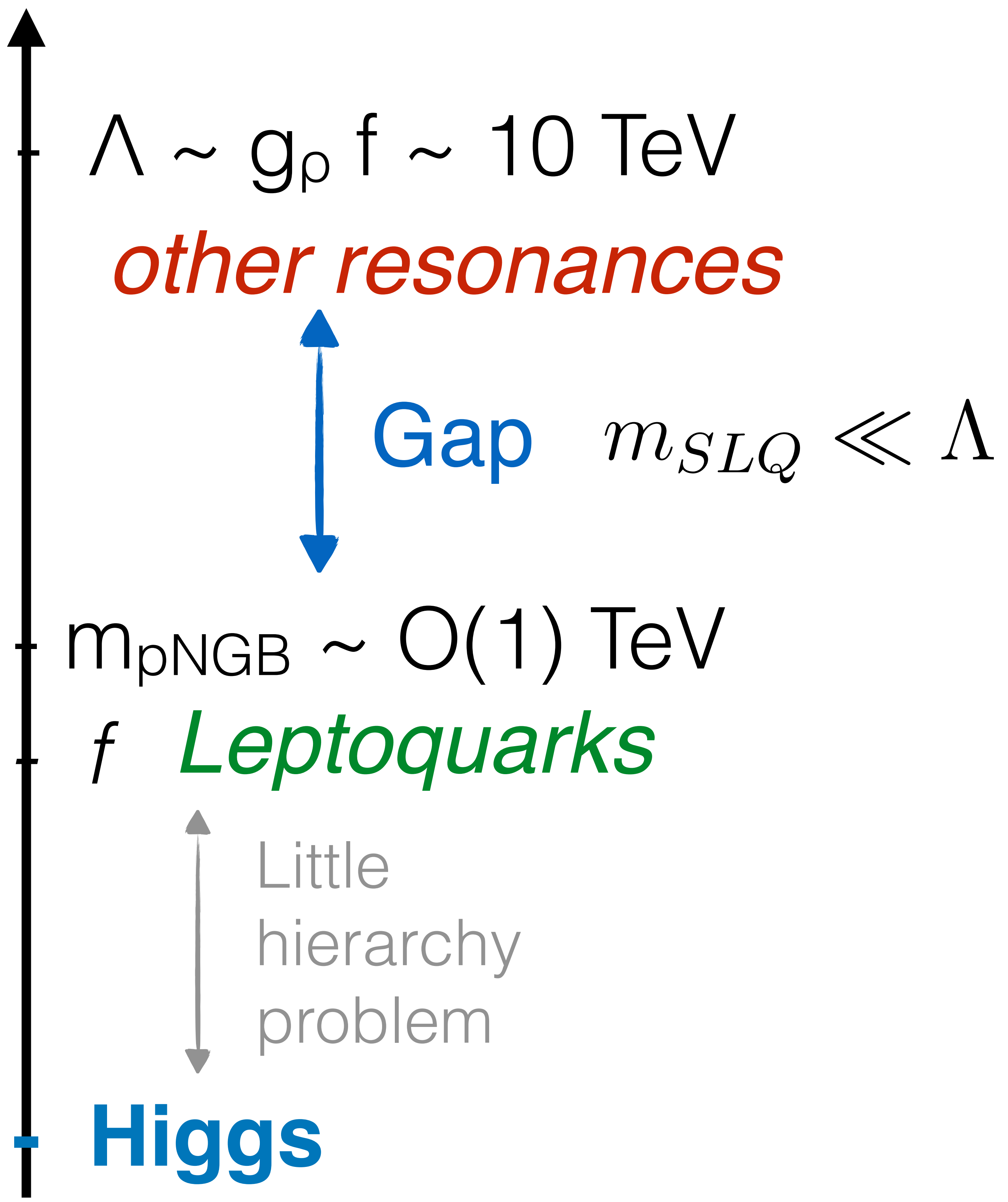
[0910.1789, 1412.1791, 1803.10972]

or

U_1 Vector Leptoquark as TC Pati Salam + Higgs as pNGB [2004.11376]

> extensions of Composite Higgs models <

Higgs Yukawas and LQ couplings can arise from same dynamics.



$$\langle \bar{\Psi}_i \Psi_j \rangle = -B_0 f^2 \delta_{ij}$$

The condensate of the strong sector, that gives the Higgs as pNGB,
also breaks spontaneously an extra SU(4) gauge symmetry.
The NGBs are eaten by the U_1 LQ.

$$M_U \sim g_4 f$$

Deviations in Higgs couplings as in typical Composite Higgs models:

$$\delta\kappa_{V,f} \sim v^2 / f^2 \sim (\text{few})\ \%$$

Conclusions

Several interesting anomalies in B decays, pointing to New Physics at the TeV scale.
Waiting for updates from LHCb and Belle-2.
Correlated signals are expected ($p\,p \to \tau\,\tau$, $b \to s\,\nu\,\nu$, lepton LFV, …).

Connections to Higgs physics are not direct, but the mediators responsible for the anomalies could leave an impact on Higgs couplings.

Flavour anomalies + EW hierarchy problem point both to New Physics at TeV.
A combined solution seems natural. For example:
extensions of Composite Higgs models with scalar or vector leptoquarks.

Deviations in Higgs couplings due to its composite nature are then expected.

S_1 and S_3 - global analysis

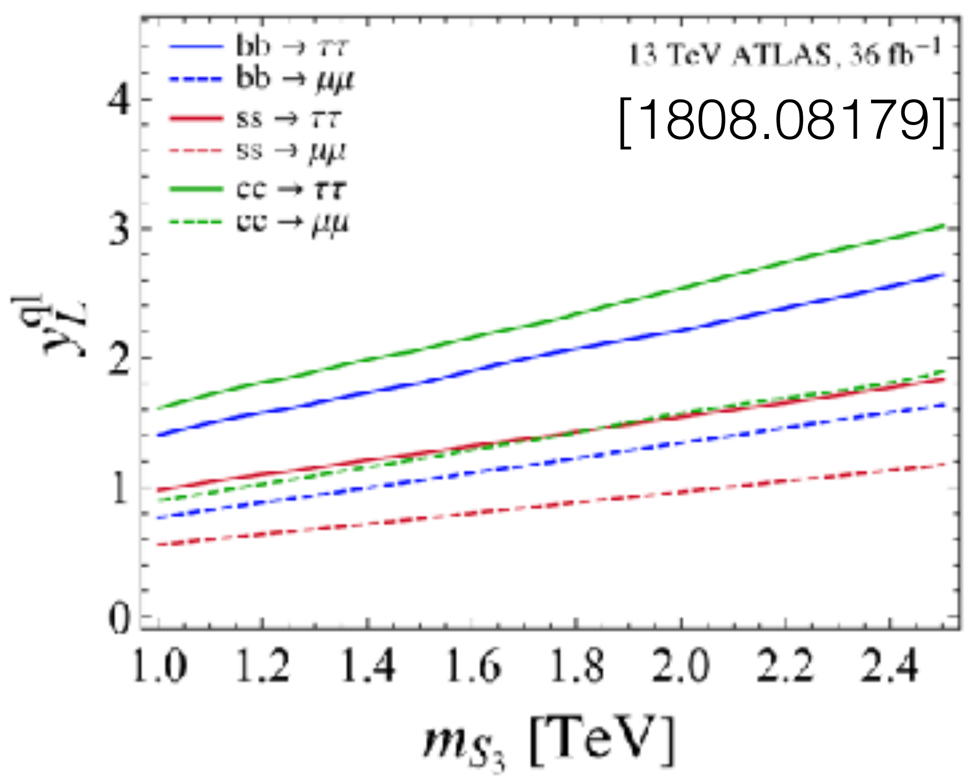
Using the complete one-loop matching to SMEFT, we include in our analysis the following observables.

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]

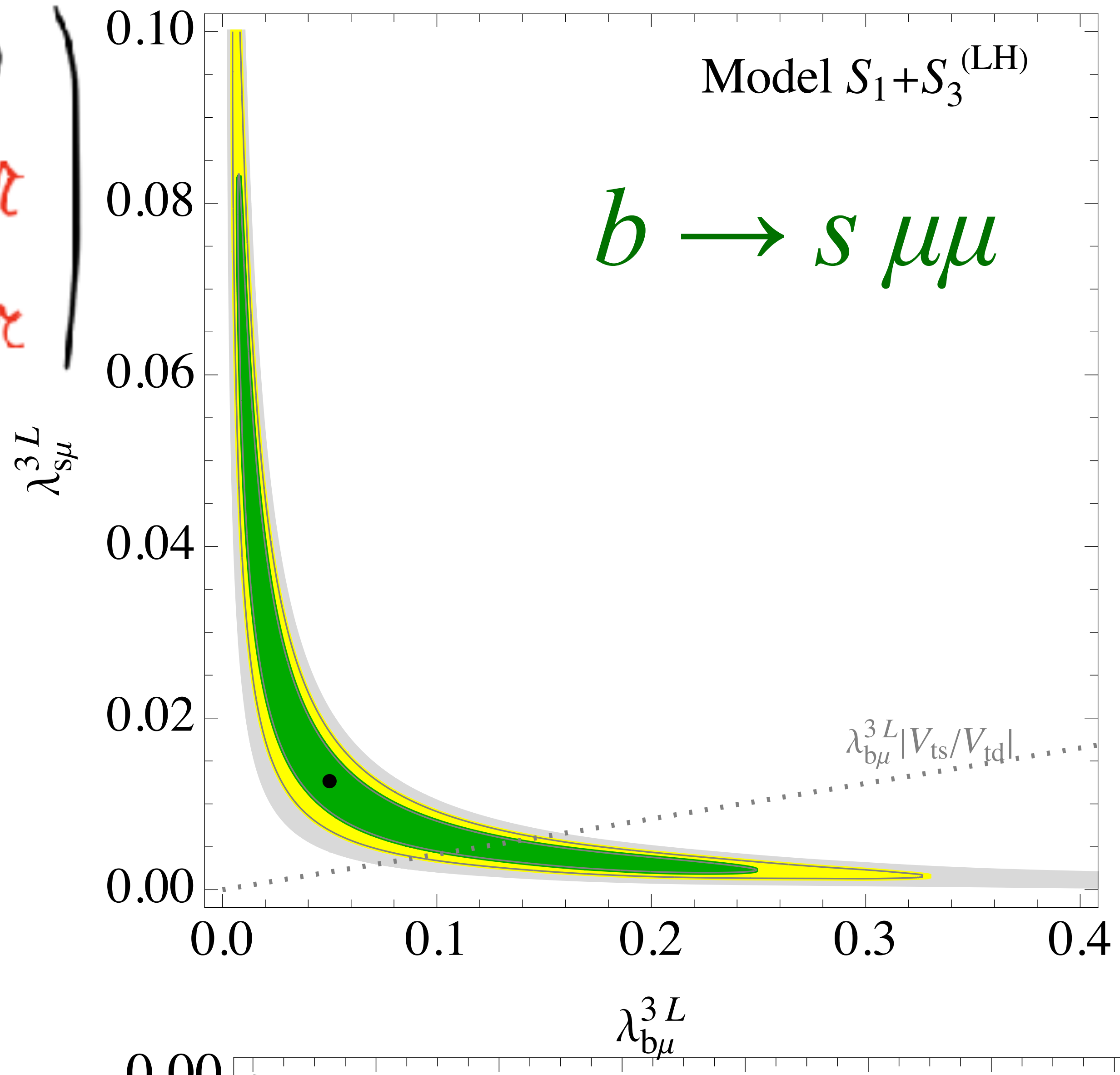
Observable	SM prediction	Experimental bounds
$\Delta F = 2$ processes		[37]
$B^0 - \bar{B}^0$: $\lvert C^1_{B_d}\rvert$	0	$< 9.1 \times 10^{-7}$ TeV^{-2} [114, 115]
$B^0_s - \bar{B}^0_s$: $\lvert C^1_{B_s}\rvert$	0	$< 2.0 \times 10^{-5}$ TeV^{-2} [114, 115]
$K^0 - \bar{K}^0$: Re$[C^1_K]$	0	$< 8.0 \times 10^{-7}$ TeV^{-2} [114, 115]
$K^0 - \bar{K}^0$: Im$[C^1_K]$	0	$< 3.0 \times 10^{-9}$ TeV^{-2} [114, 115]
$D^0 - \bar{D}^0$: Re$[C^1_D]$	0	$< 3.6 \times 10^{-7}$ TeV^{-2} [114, 115]
$D^0 - \bar{D}^0$: Im$[C^1_D]$	0	$< 2.2 \times 10^{-8}$ TeV^{-2} [114, 115]
$D^0 - \bar{D}^0$: Re$[C^4_D]$	0	$< 3.2 \times 10^{-8}$ TeV^{-2} [114, 115]
$D^0 - \bar{D}^0$: Im$[C^4_D]$	0	$< 1.2 \times 10^{-9}$ TeV^{-2} [114, 115]
$D^0 - \bar{D}^0$: Re$[C^5_D]$	0	$< 2.7 \times 10^{-7}$ TeV^{-2} [114, 115]
$D^0 - \bar{D}^0$: 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]

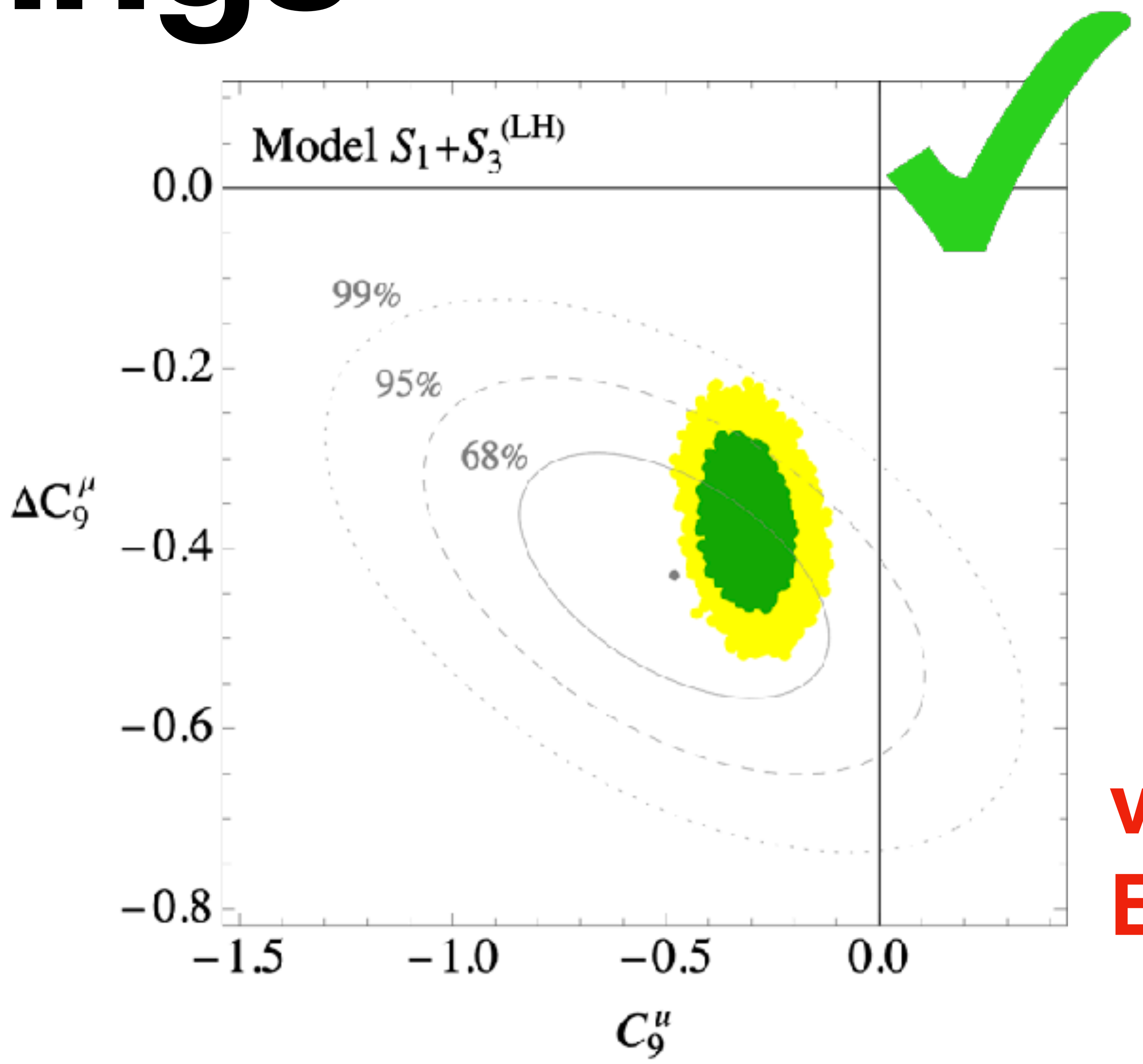
S_1 and S_3 — only LH couplings

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

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

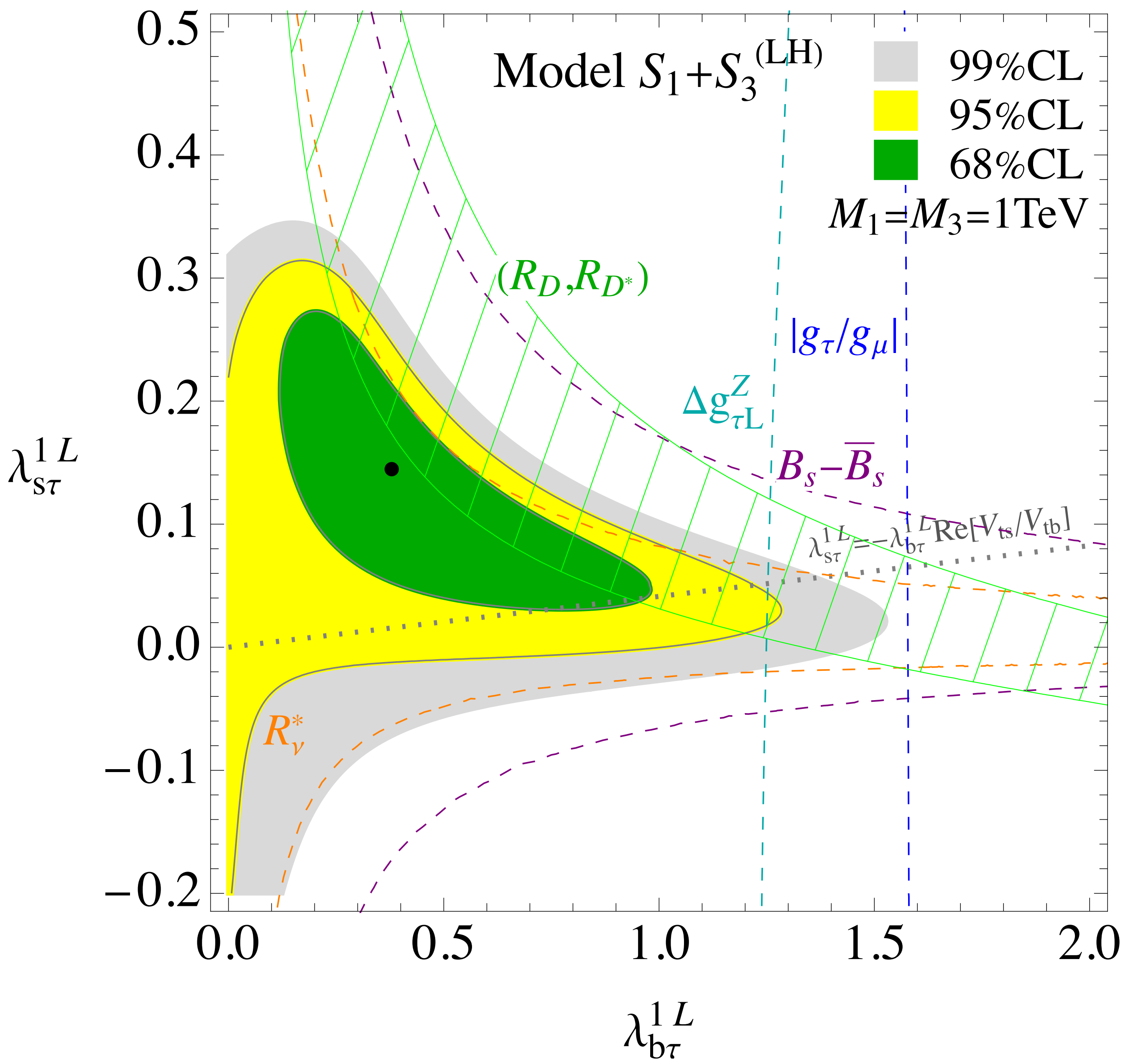
(see backup slides for a S_1+S_3 scenario that addresses also the muon magnetic moment)

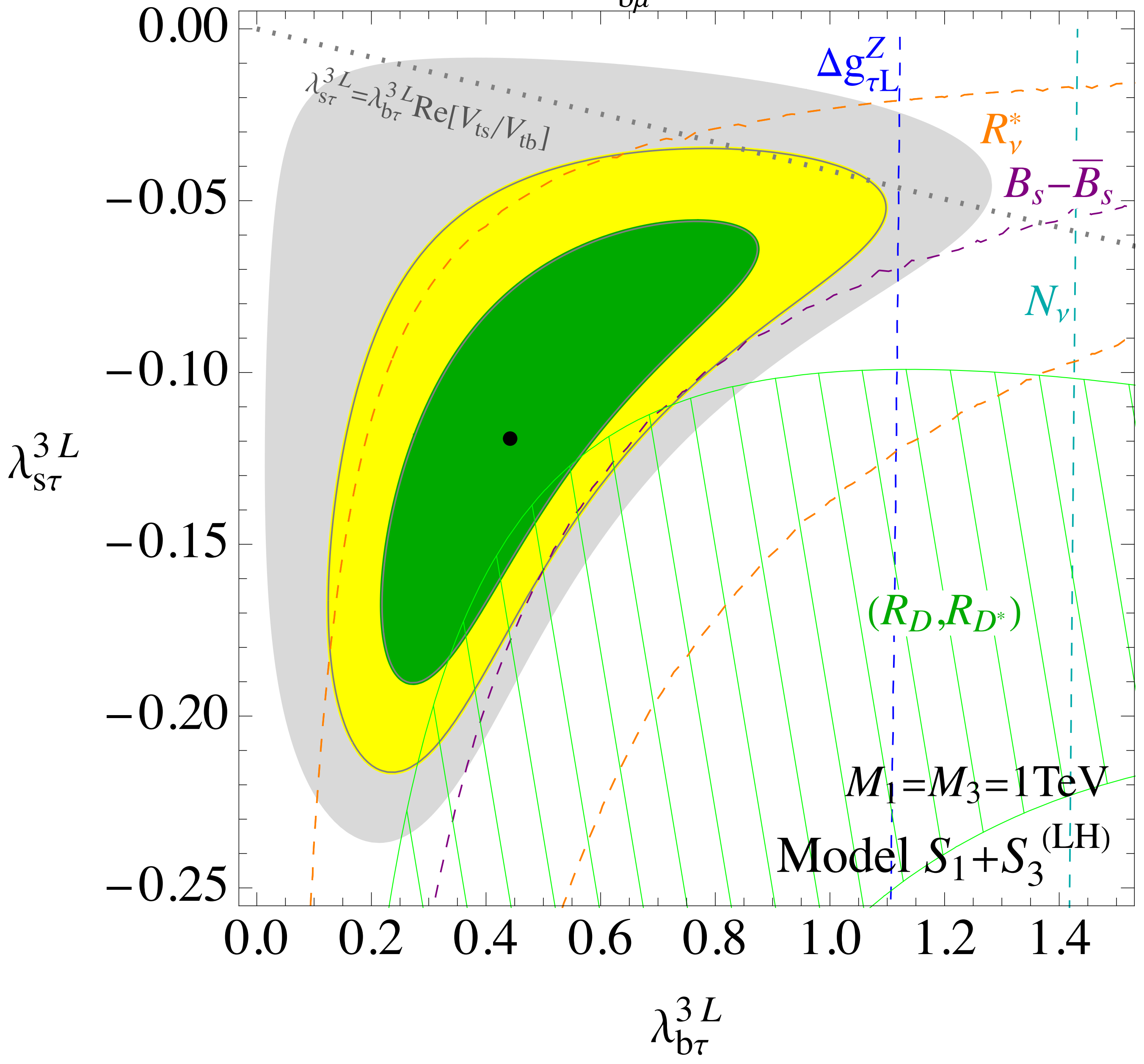


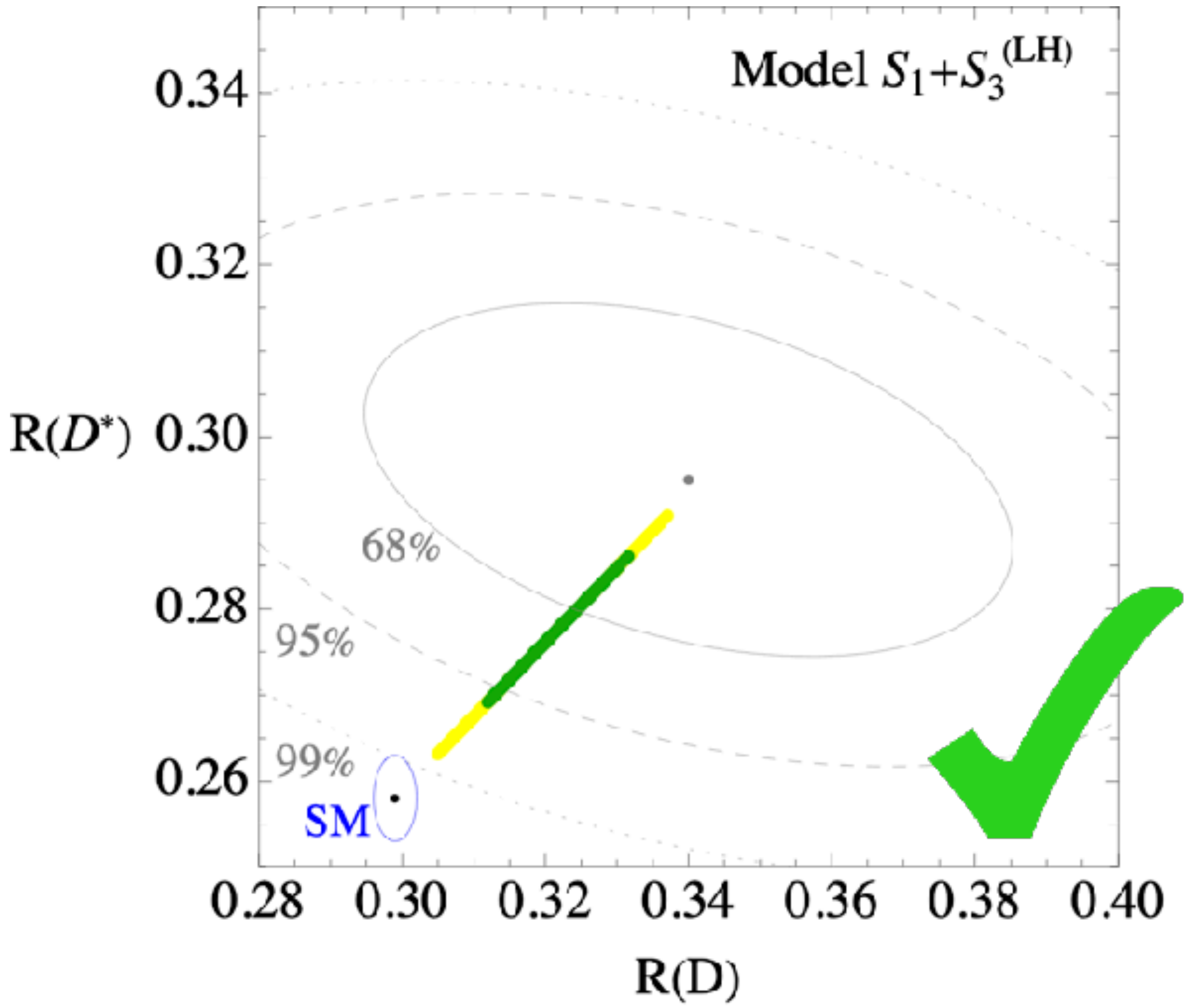


very good fit of B-anomalies

R(D(*))







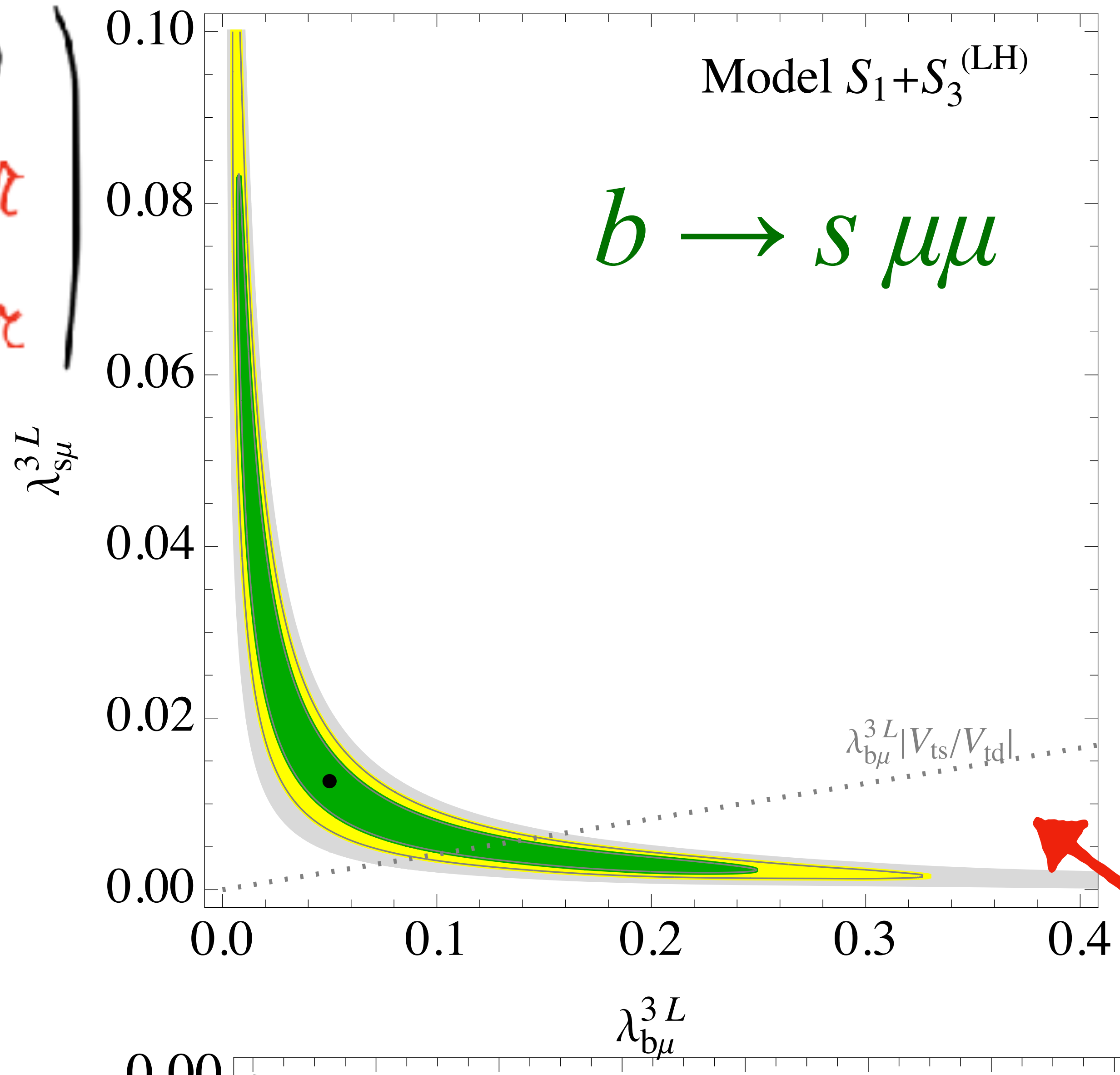
Plots updated w.r.t. [v3:2008.09548]

S_1 and S_3 — only LH couplings

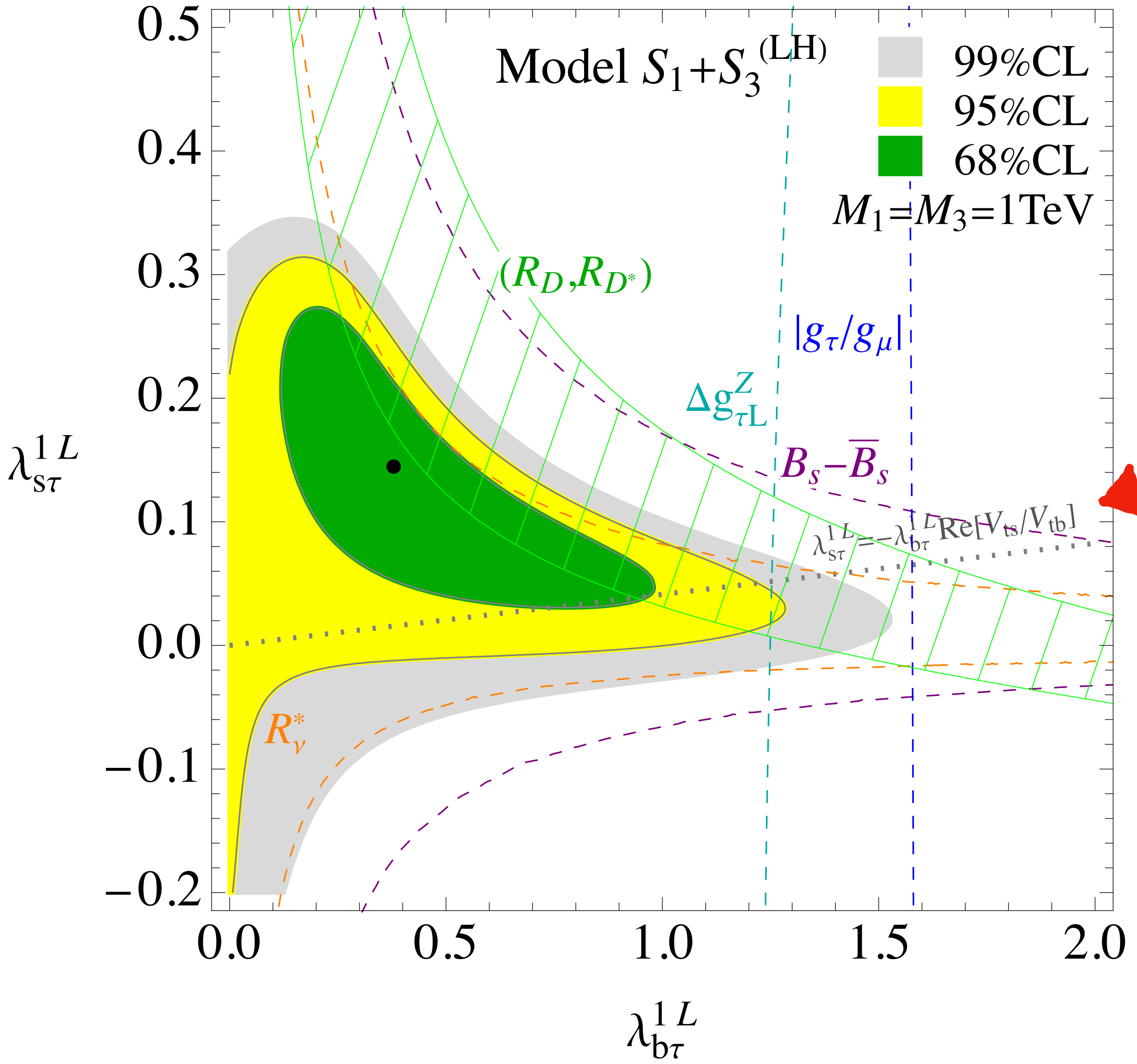
$$\lambda^{1L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & s\tau \\ 0 & 0 & b\tau \end{pmatrix} \quad \lambda^{3L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & s\mu & s\tau \\ 0 & b\mu & b\tau \end{pmatrix}$$

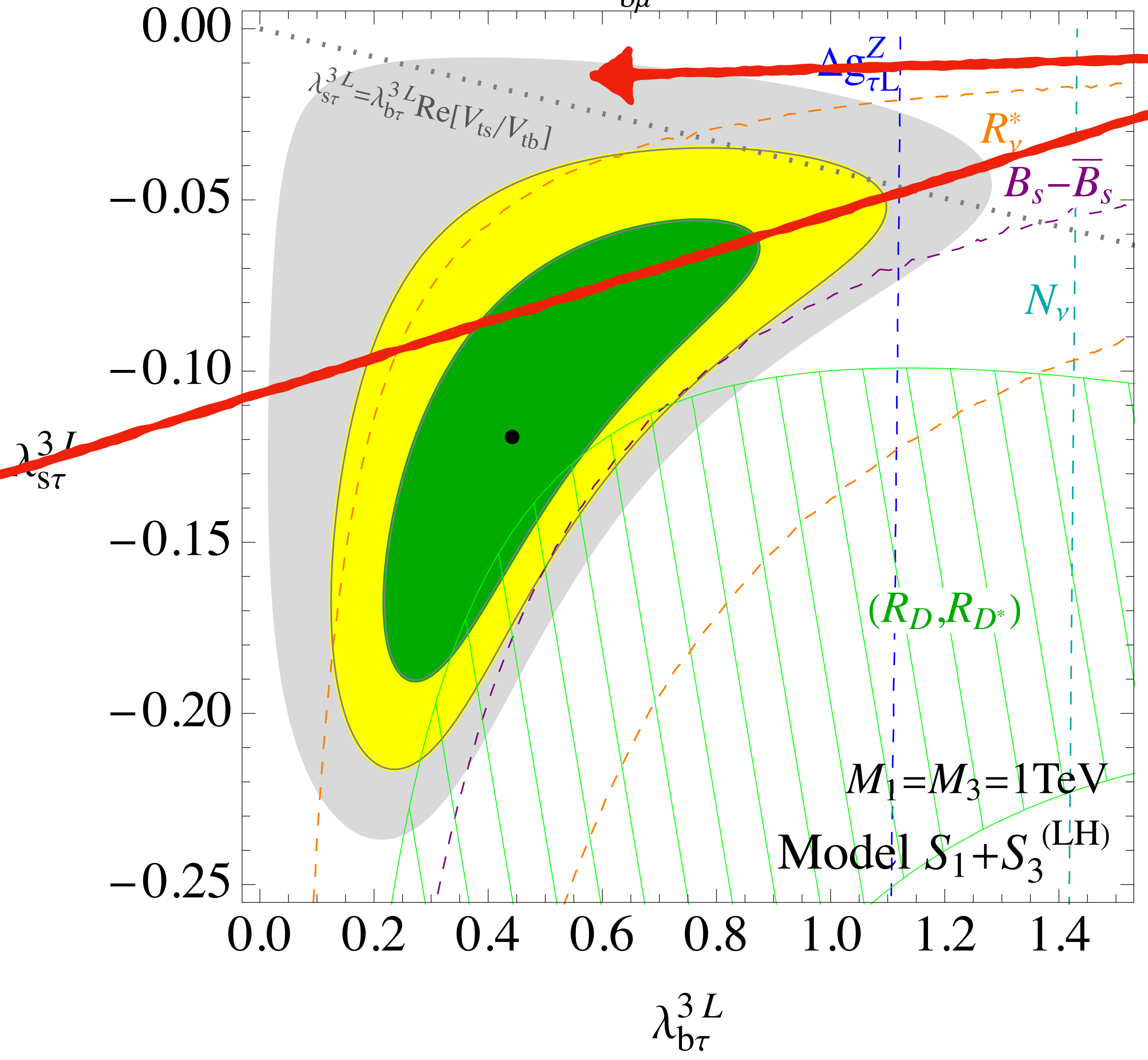
$\boldsymbol{\lambda^{1R} = 0}$ → Cannot fit $(g-2)_\mu$

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



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]

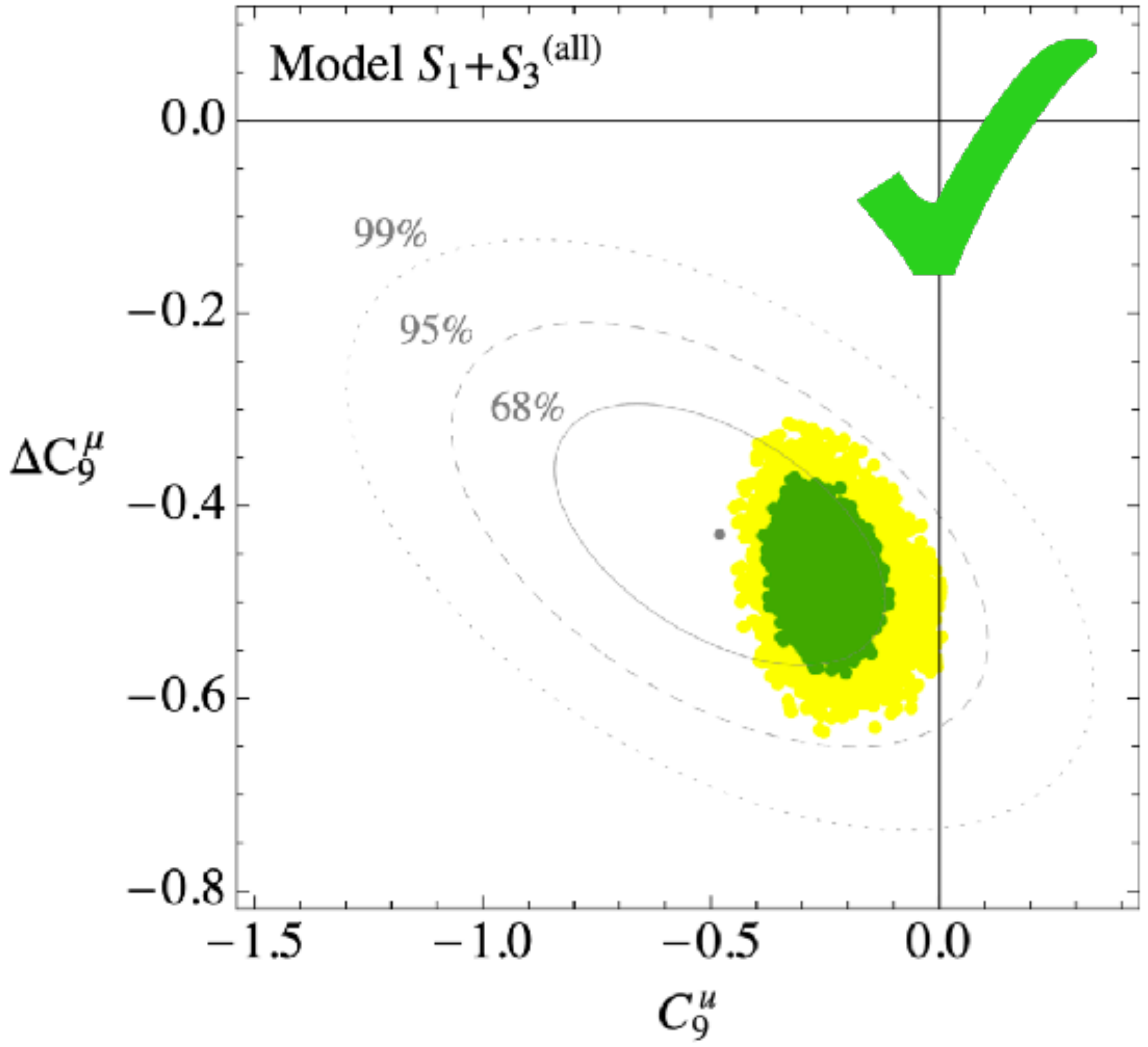
S_1 and S_3 : $R(K^{(*)})$ + $R(D^{(*)})$ + $(g\text{-}2)_\mu$

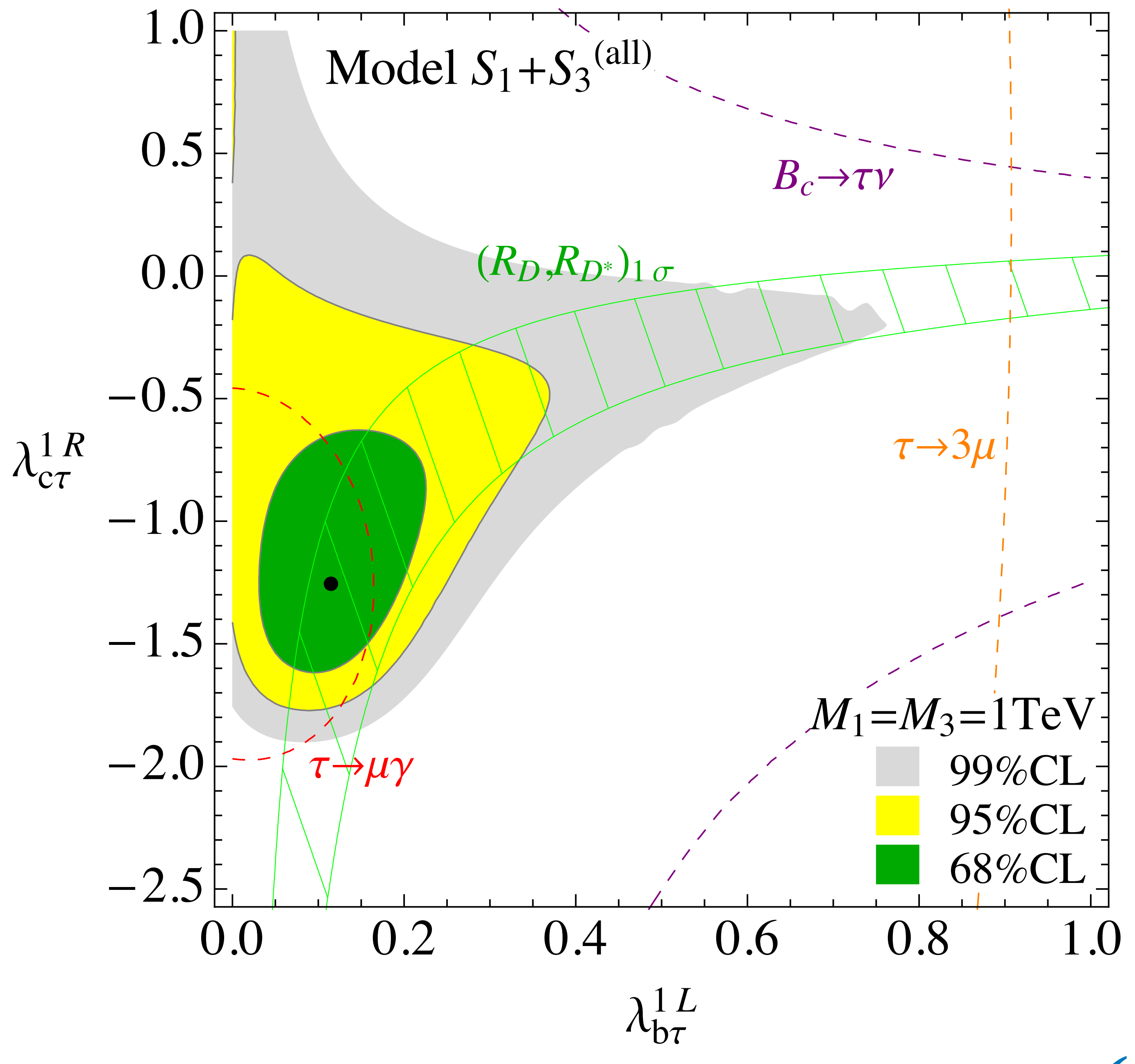
No a-priori flavour structure imposed

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

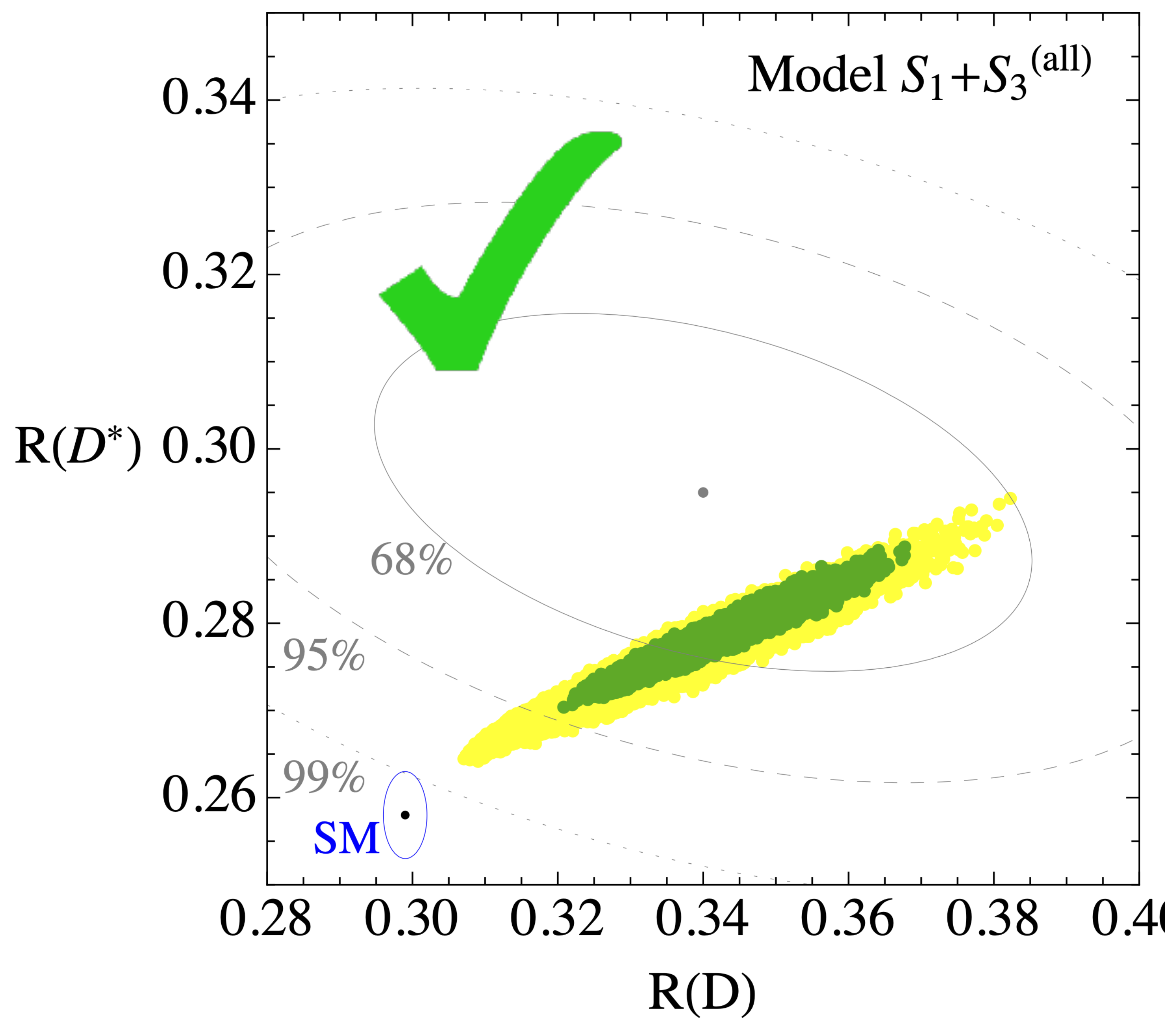
$$\lambda^{1R} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & c\tau \\ 0 & t\mu & t\tau \end{pmatrix}$$

$b \to s \ell \ell$

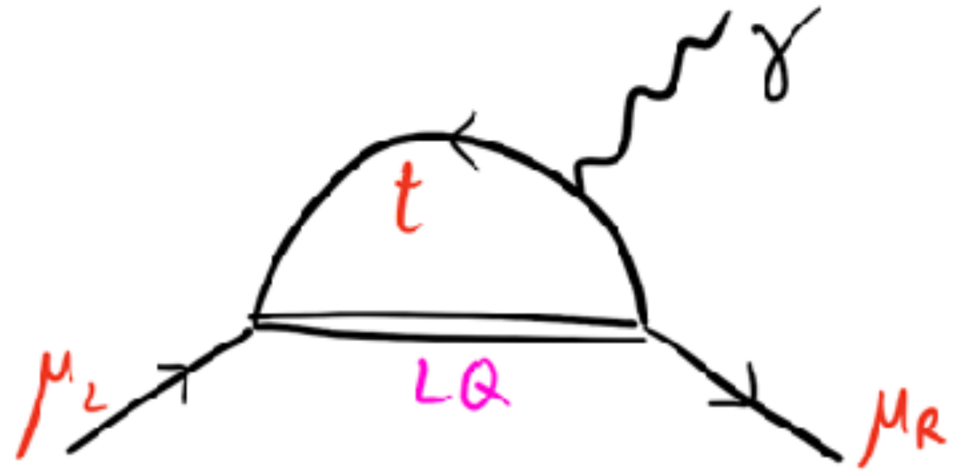


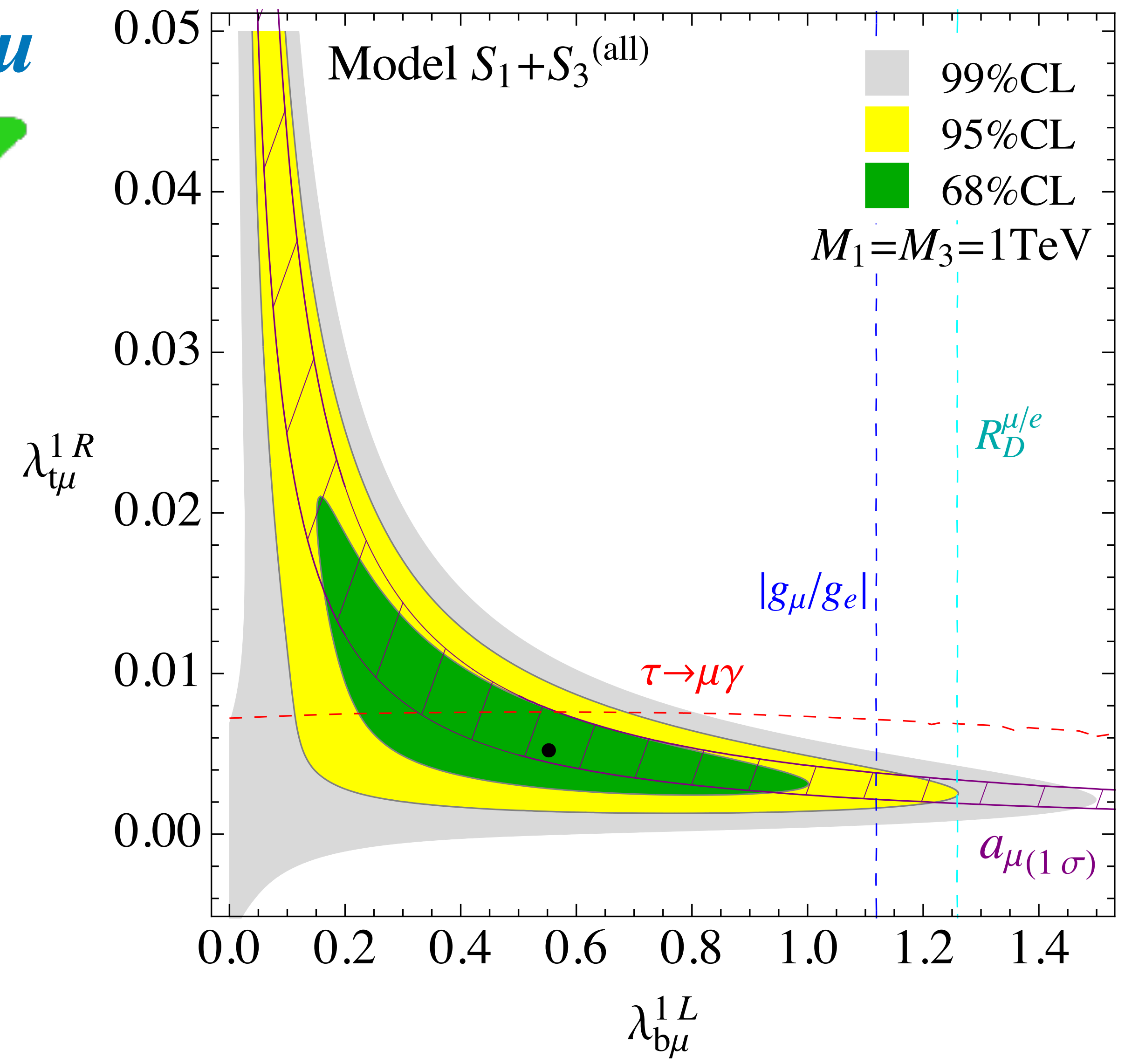


$R(D^{(*)})$



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





Very good fit of all anomalies!

A Fundamental Composite Higgs + LQ Model

Gauge group:

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

"HyperColor"

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

[D.M. 1803.10972]

SU(N_{HC}) confines at $\Lambda_{\mathrm{HC}} \sim 10$ TeV $\langle \bar\Psi_i \Psi_j \rangle = -B_0 f^2 \delta_{ij}$

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

Several states are present at the **TeV scale** as pNGB, including

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

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

H and LQ are close partners!!

$$H_1 \sim i\sigma^2 (\bar\Psi_L \Psi_N)$$
$$H_2 \sim (\bar\Psi_E \Psi_L)$$
$$S_1 \sim (\bar\Psi_Q \Psi_L)$$
$$S_3 \sim (\bar\Psi_Q \sigma^a \Psi_L)$$

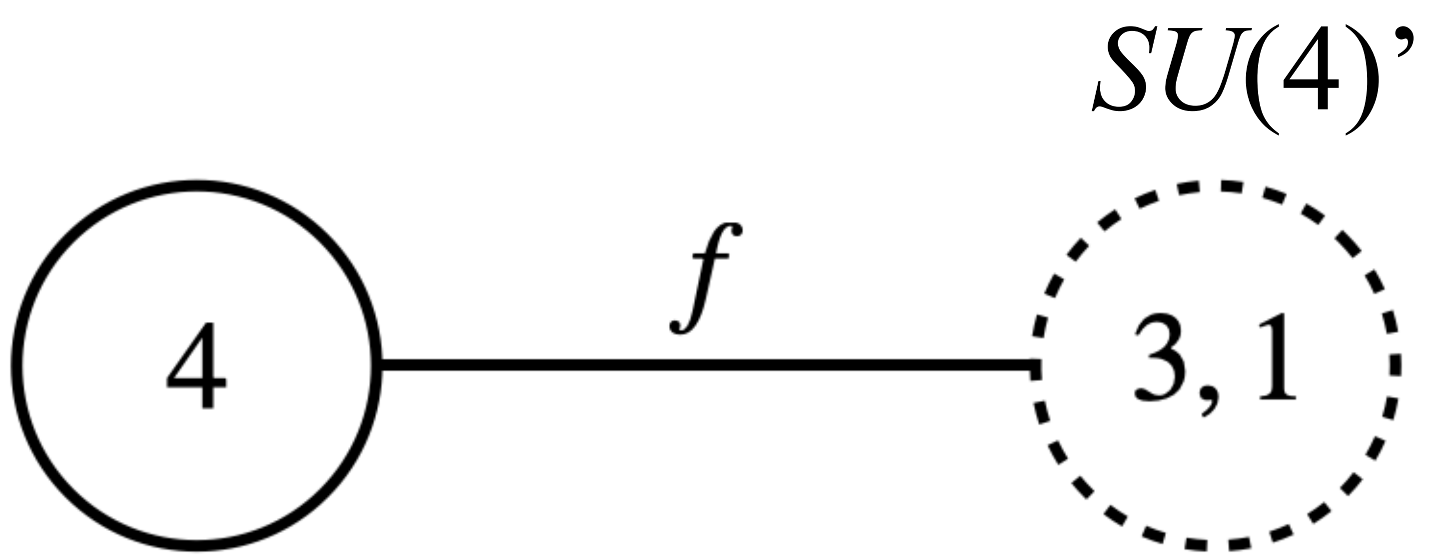
$$\mathcal{L}_{4-\mathrm{Fermi}} \sim \frac{c_{\psi\Psi}}{\Lambda_t^2} \bar\psi_{\mathrm{SM}} \psi_{\mathrm{SM}} \bar\Psi \Psi \xrightarrow{E \lesssim \Lambda_{HC}} \sim y_{\psi\phi}\, \bar\psi_{\mathrm{SM}} \psi_{\mathrm{SM}}\, \phi + \dots$$

Yukawas & LQ couplings

+ impose approximate $U(2)^5$ flavor symmetry

Composite Higgs + Vector LQ

[2004.11376]



$SU(4)$ × $SU(3)' \times U(1)'$

Heavy fermions

Light fermions

$$\langle \bar{\zeta}_L^{\alpha}\, \zeta_R^{\beta} \rangle = -\frac{1}{2} B_\zeta\, f_\zeta^2\, \delta_{\alpha\beta}$$

$\longrightarrow SU(4)_D$

15 eaten NGB:
- heavy coloron
- U_1 LQ
- Z'

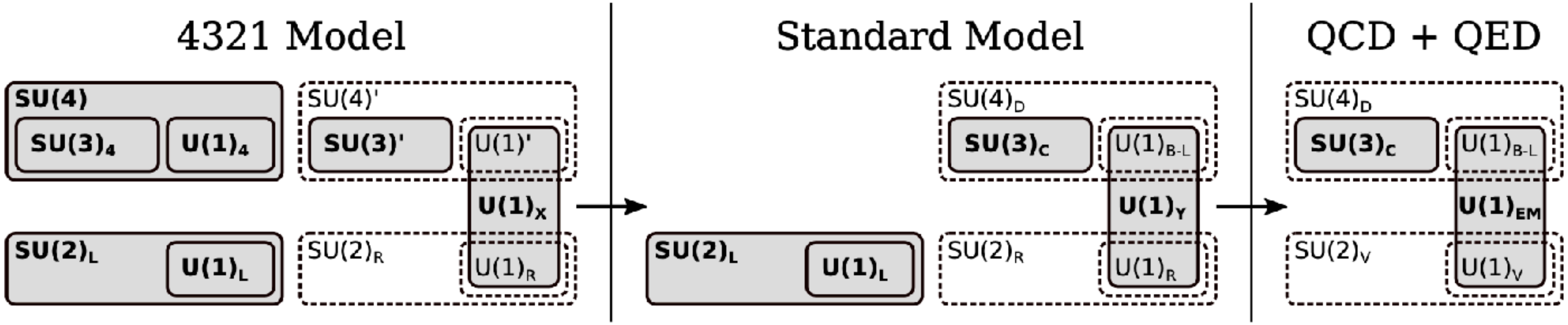
$$M_U \sim g_4 f_\zeta$$

For the Composite Higgs part:

$$\langle \bar{\xi}_L^{i\,c}\, \xi_L^{j} \rangle = \langle \bar{\xi}_R^{i\,c}\, \xi_R^{j} \rangle = -\frac{1}{2} B_\xi\, f_\xi^2\, \epsilon_{ij}$$

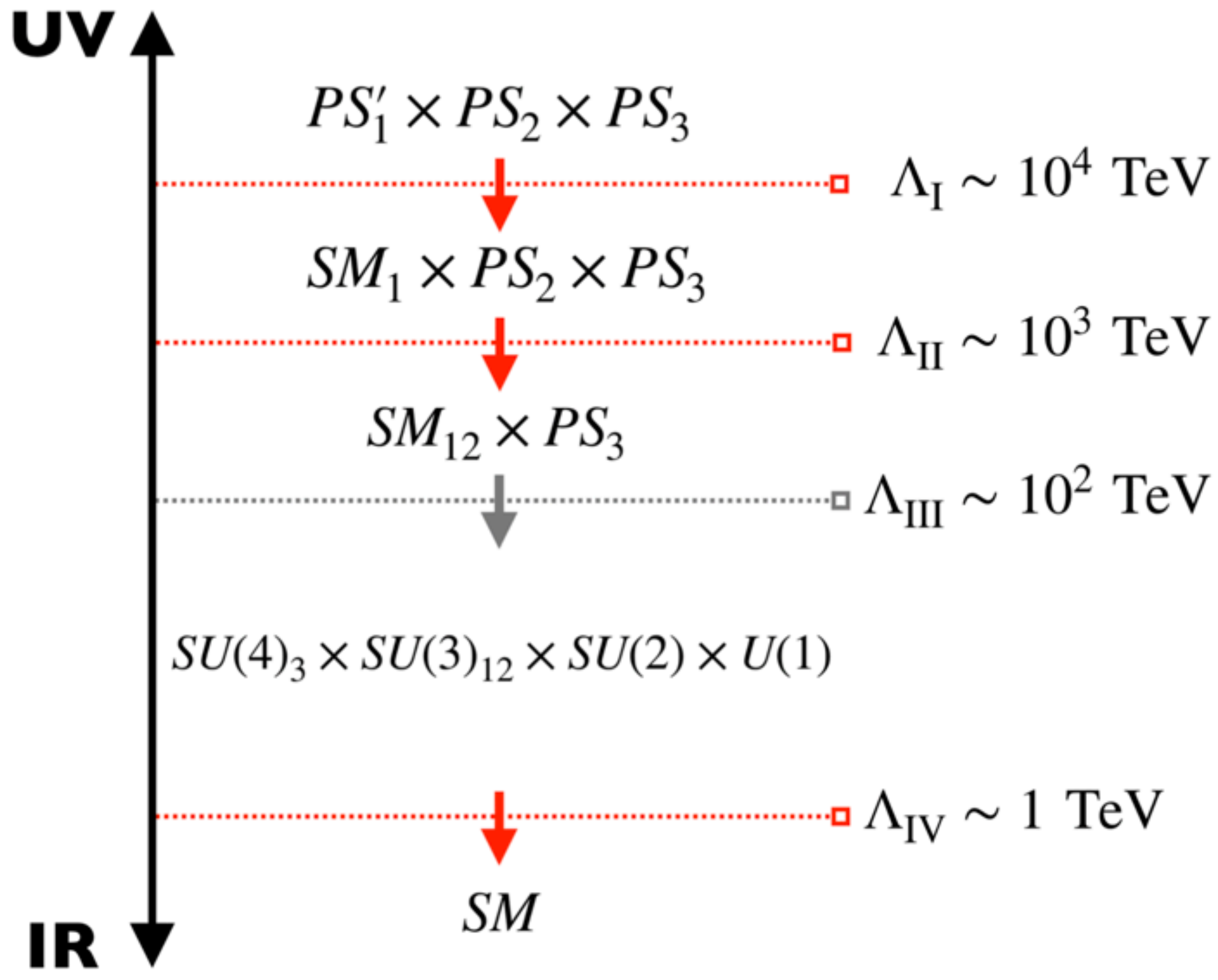
$$SU(4)_{\rm EW} \times U(1)_A \to Sp(4)_{\rm EW}$$

6 pNGB:
- Higgs doublet
- 2 singlets



Vector leptoquark UV models

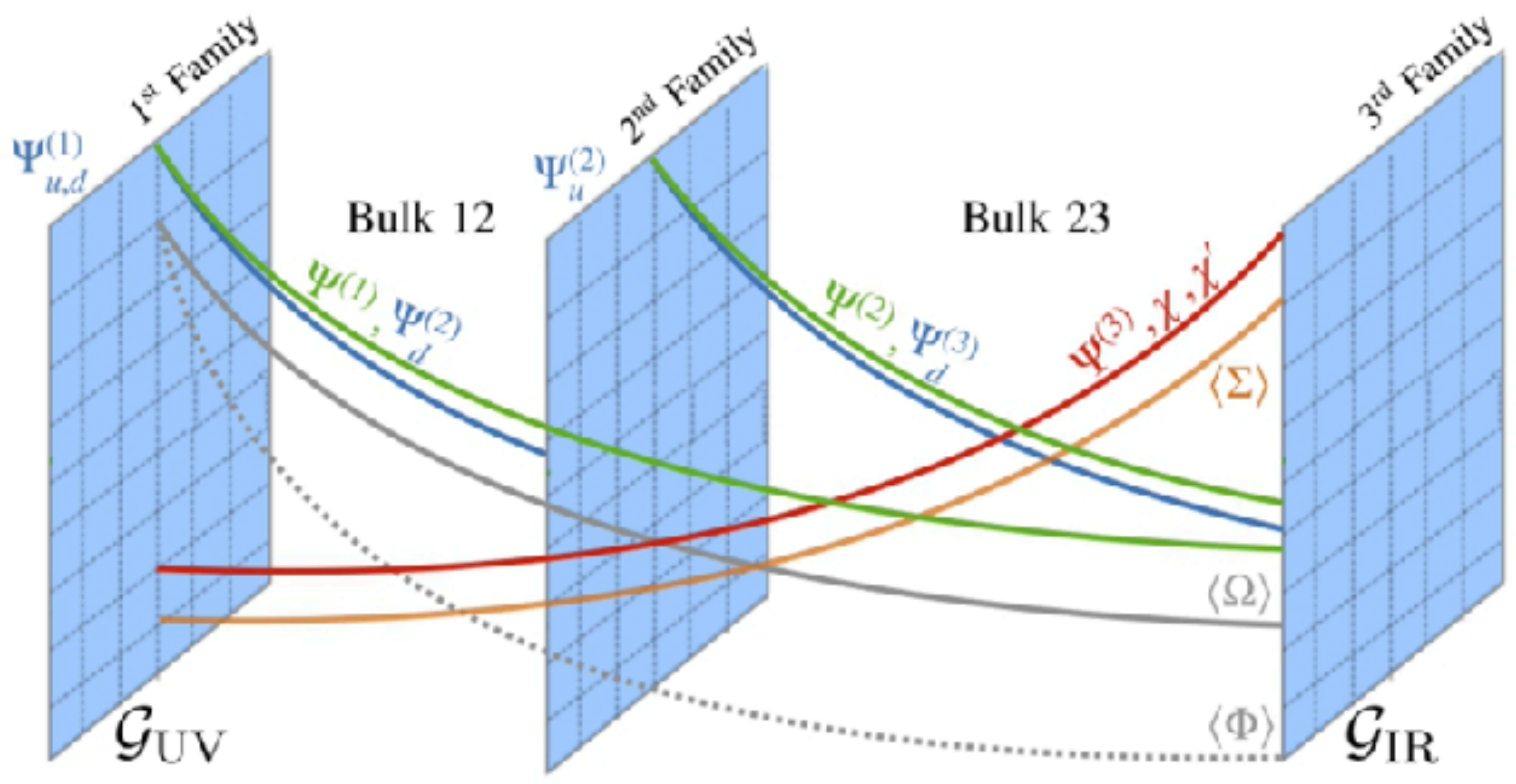
Bordone, Cornella, Fuentes-Martin, Isidori; 1712.01368



Flavour hierarchy ↔ Hierarchy of scales (RG stable)

Accidental approximate U(2)^5 at low energy!

This picture can be embedded in a warped 5D compactification



Fuentes-Martin et al; 2203.01952

EW hierarchy problem can be addressed by adding a further Planck brane.