Lepton universality in B-decays and top-quark physics

David Marzocca
INFN Trieste

TOP 2021 - 16/09/2021

Layout of the talk

Introduction on the **LFU Anomalies** and their **New Physics interpretations**

Neutral-current and Charged-current anomalies

$b \to s\,\mu\mu$ & $R(D^{(*)})$ + $(g-2)_\mu$

Layout of the talk

Introduction on the **LFU Anomalies** and their **New Physics interpretations**

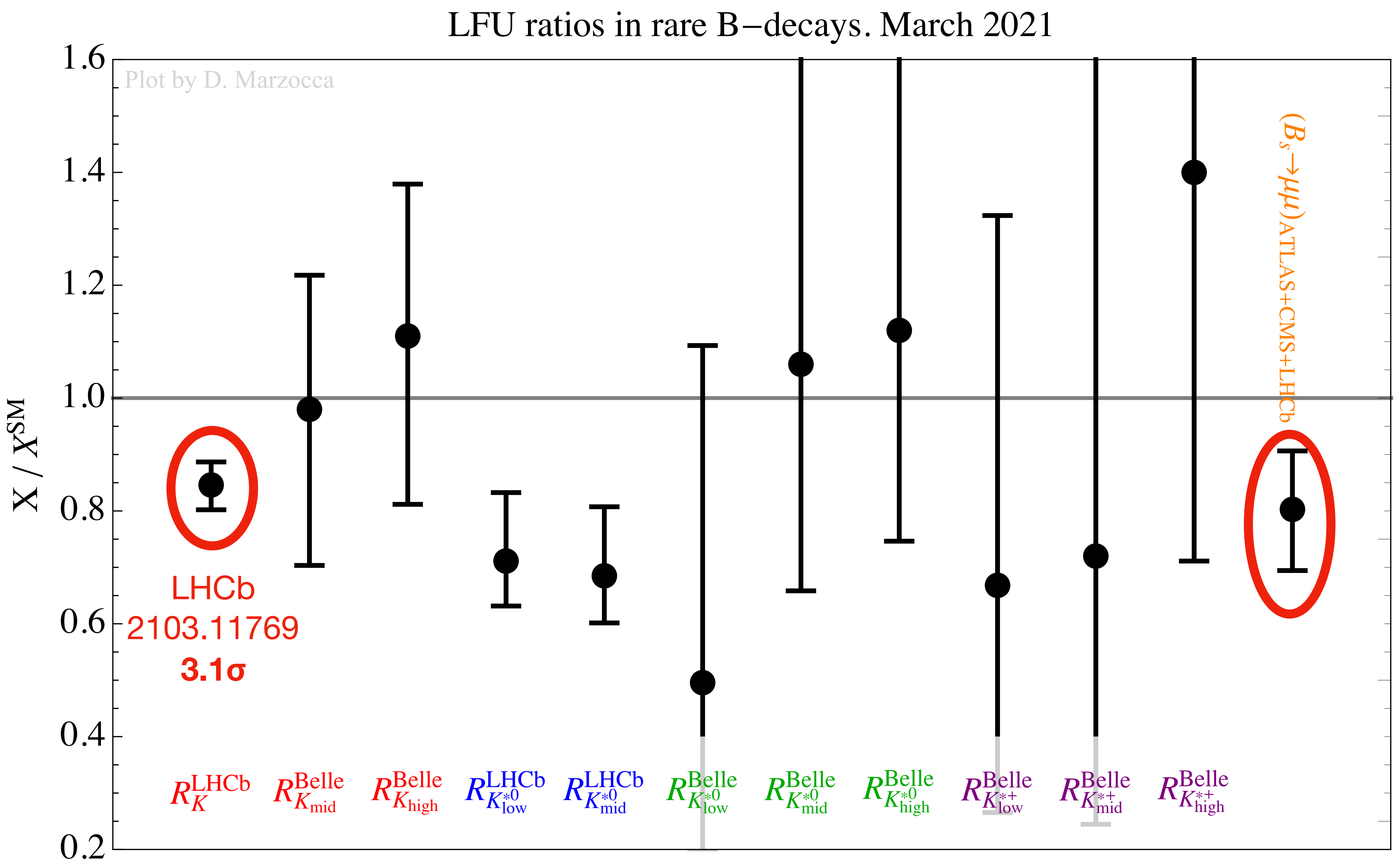
Neutral-current and Charged-current
anomalies

$b \to s\,\mu\mu$ & $R(D^{(*)})$ **+ $(g-2)_\mu$**

Implications for top physics: top **decays**, **production**, **tops in final states**

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

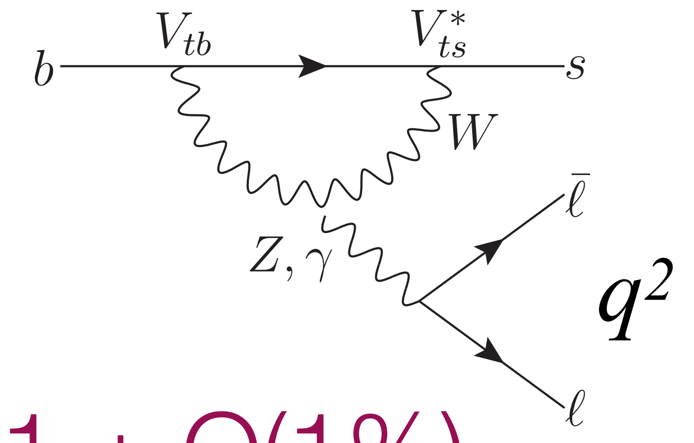
Compilation of "clean" observables



LHCb
2103.11769
3.1σ

Lepton Flavour Universality (LFU) ratios

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



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

for $q^2 \gtrsim 1$ GeV

Bordone, Isidori, Pattori [1605.07633]

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

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

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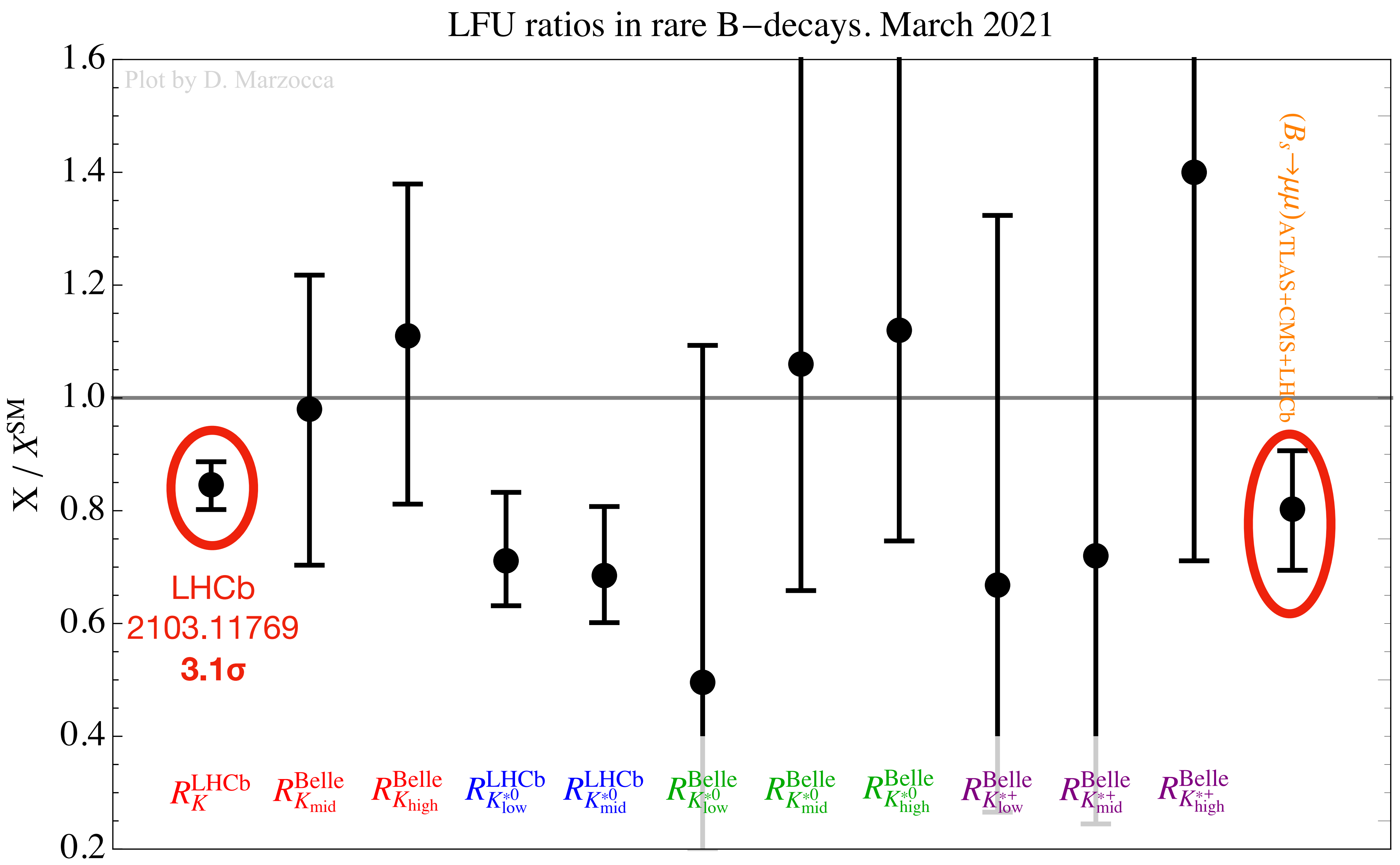

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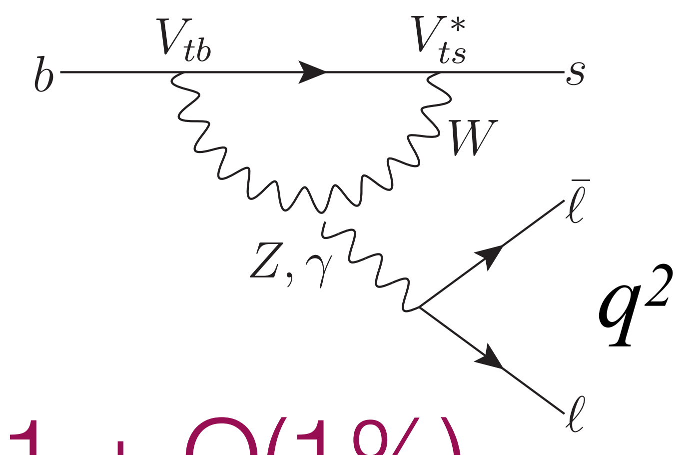

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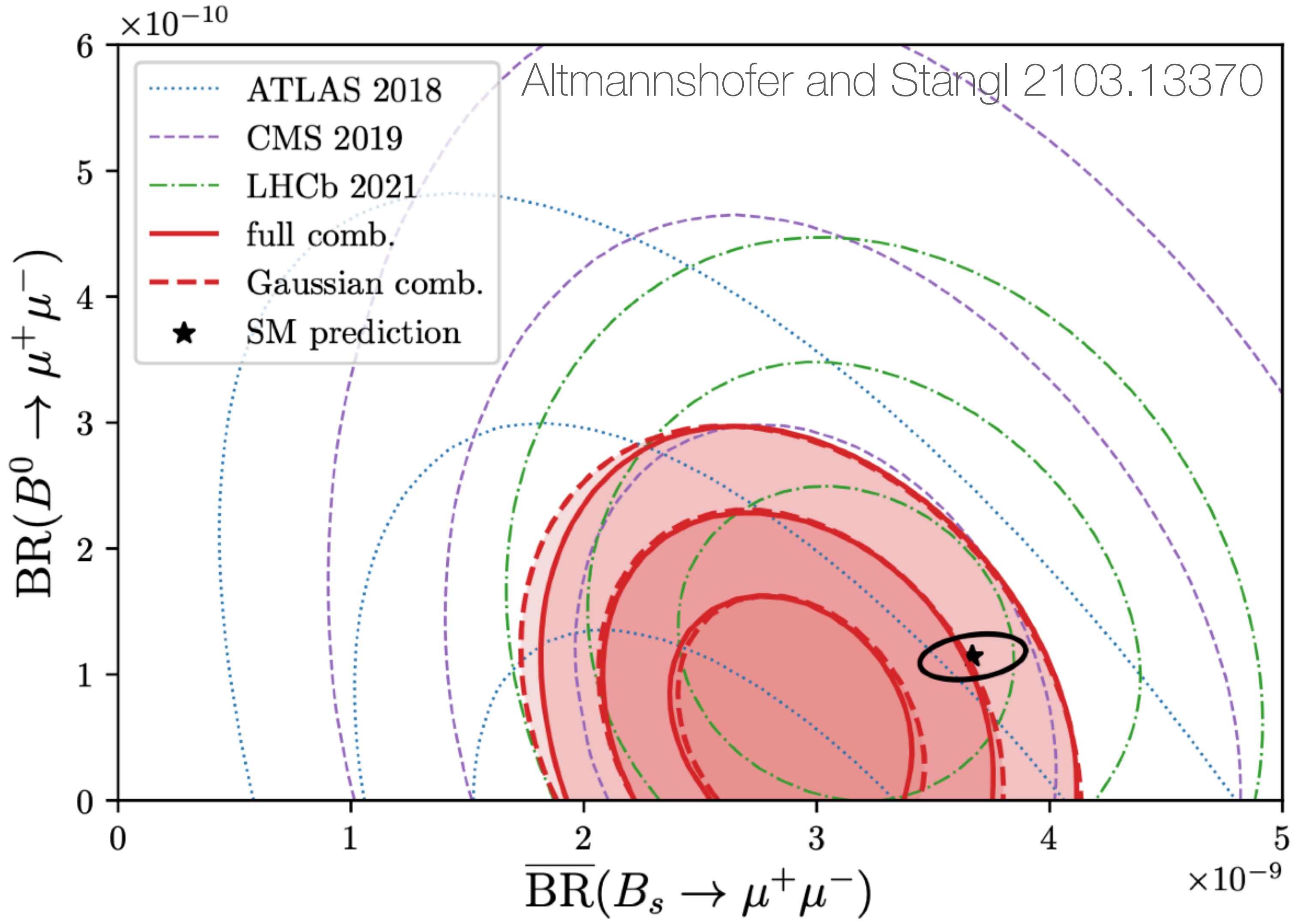

Also the leptonic decay $B_s \to \mu^+ \mu^-$
can be predicted precisely in the SM,
and is measured by ATLAS, CMS, and LHCb.

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

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

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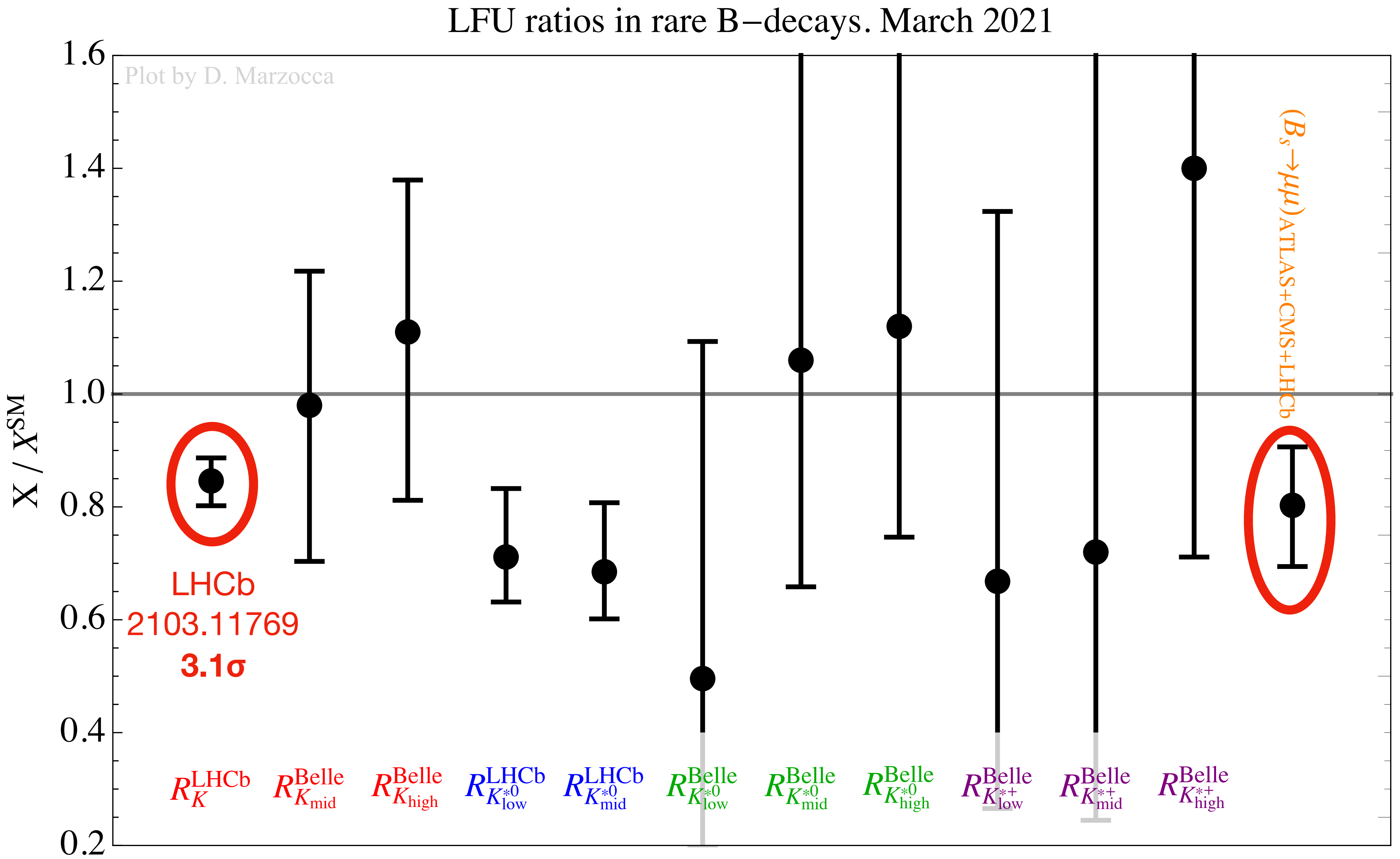

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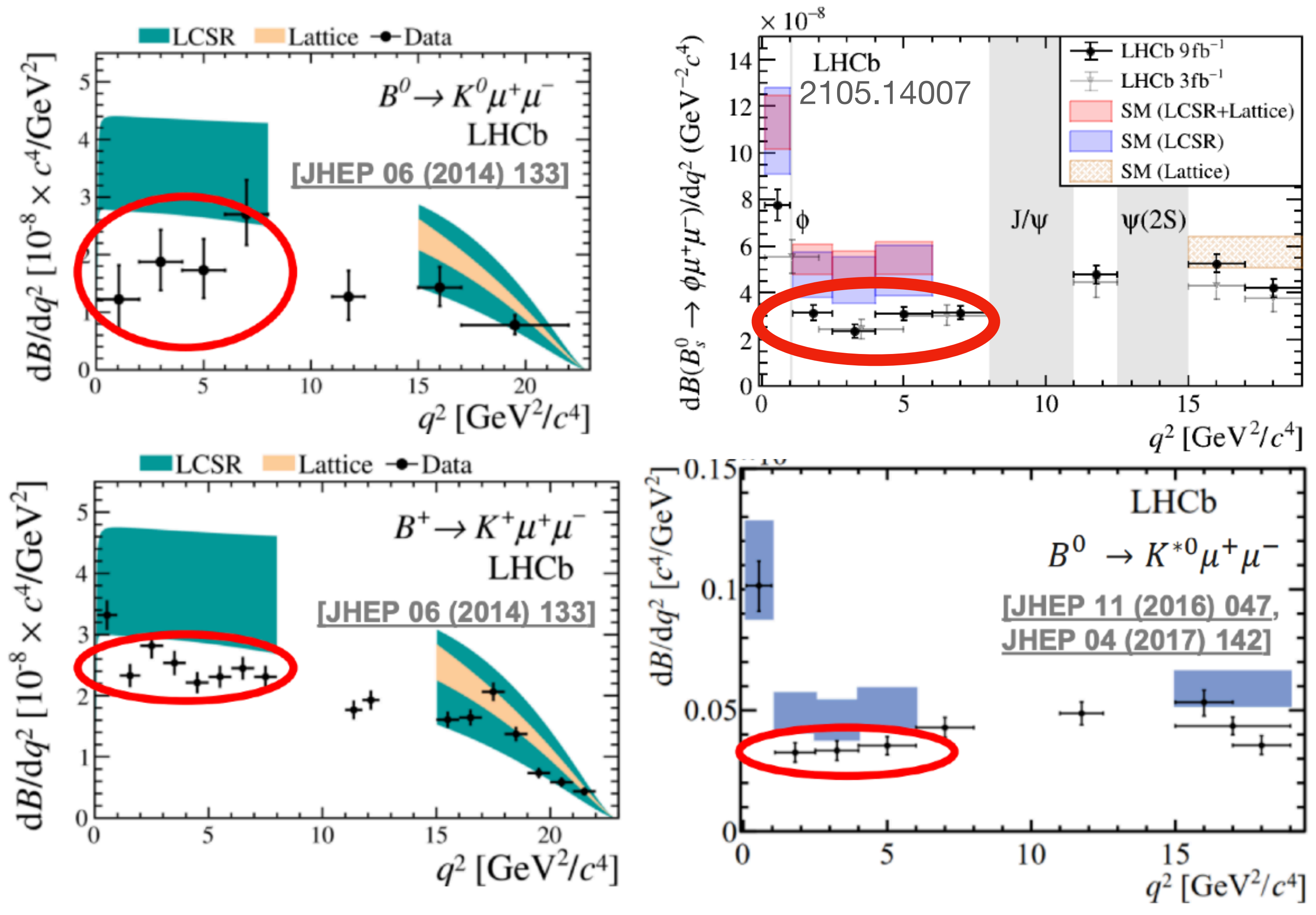
Angular observables and Br’s

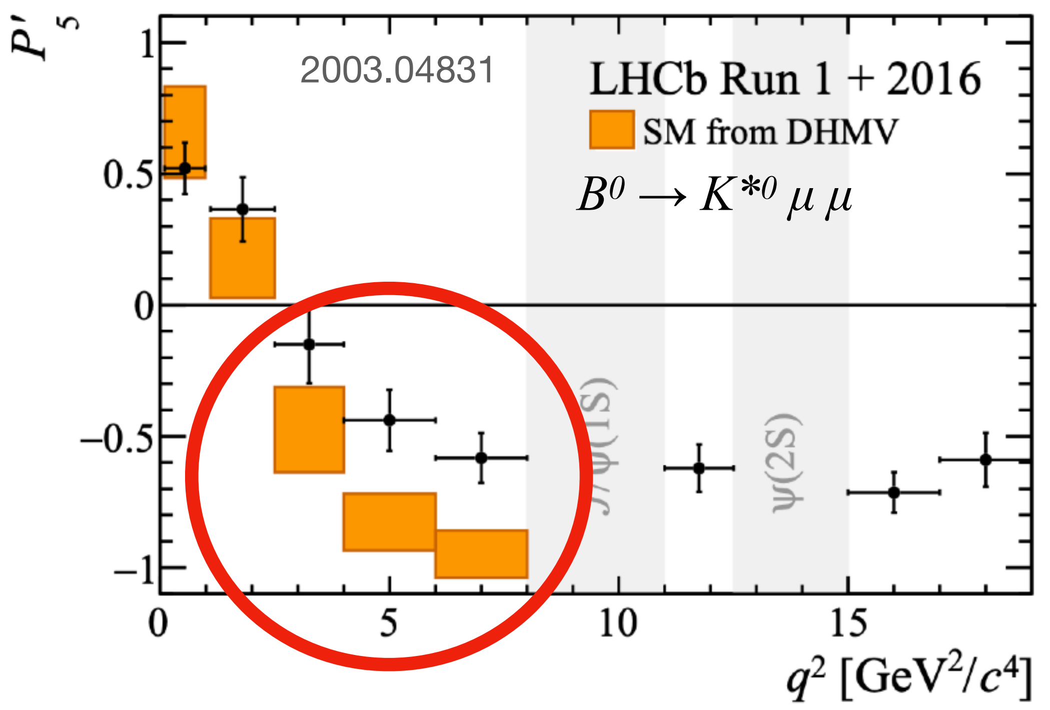


[JHEP 06 (2014) 133]

[JHEP 06 (2014) 133]

2105.14007

[JHEP 11 (2016) 047,
JHEP 04 (2017) 142]



2003.04831

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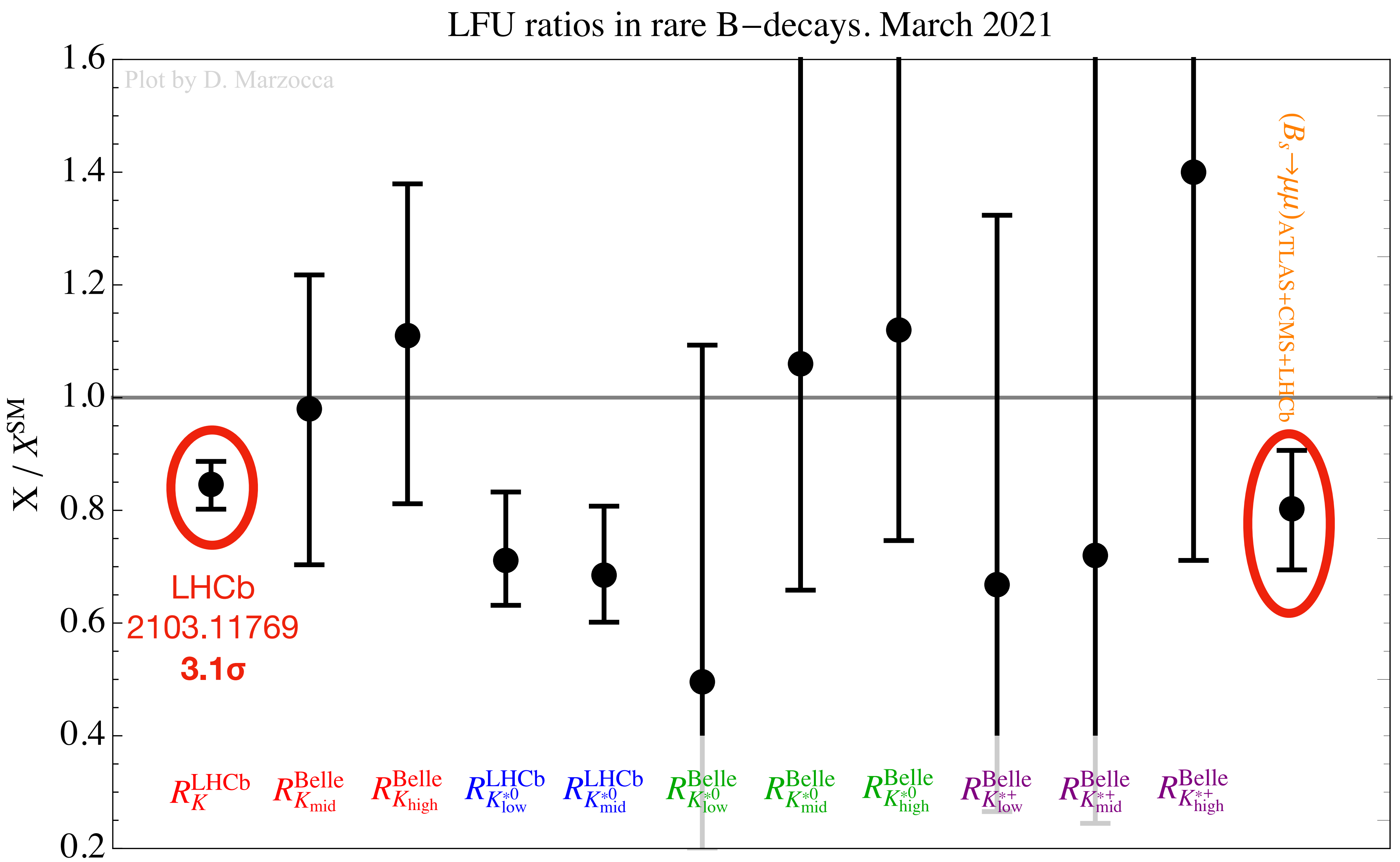

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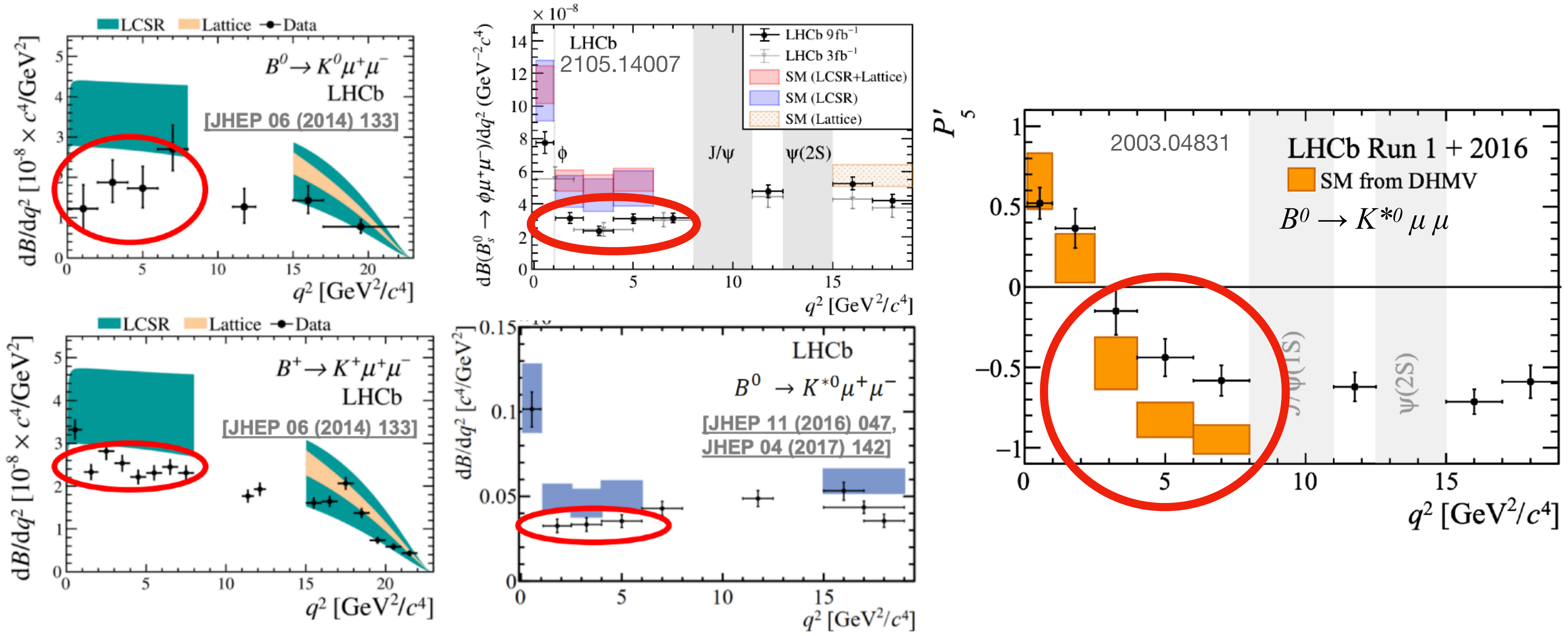

The global significance of the **New Physics hypothesis** in b → s$\mu^+\mu^-$ (very conservative SM uncertainties estimate) is:

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

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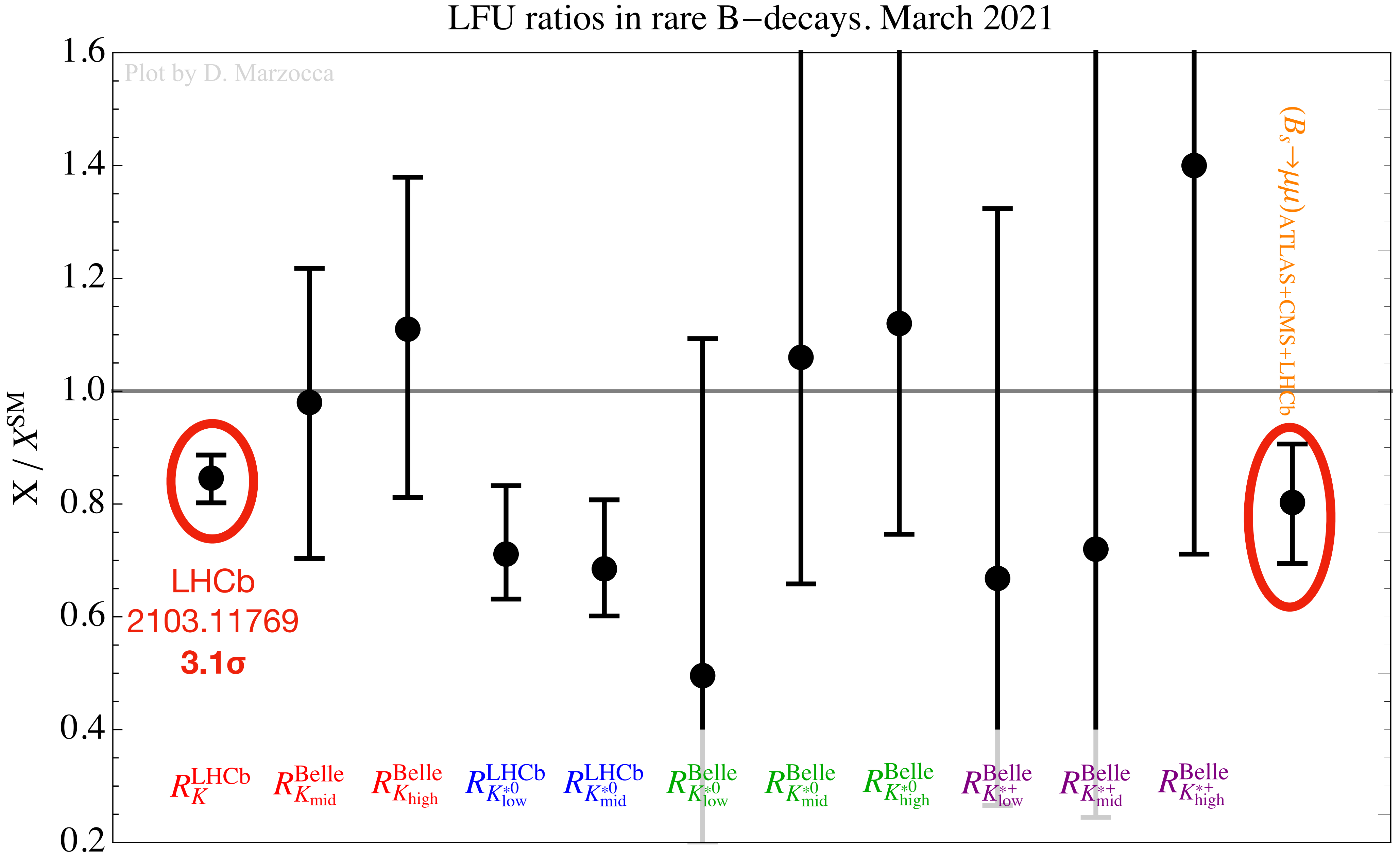

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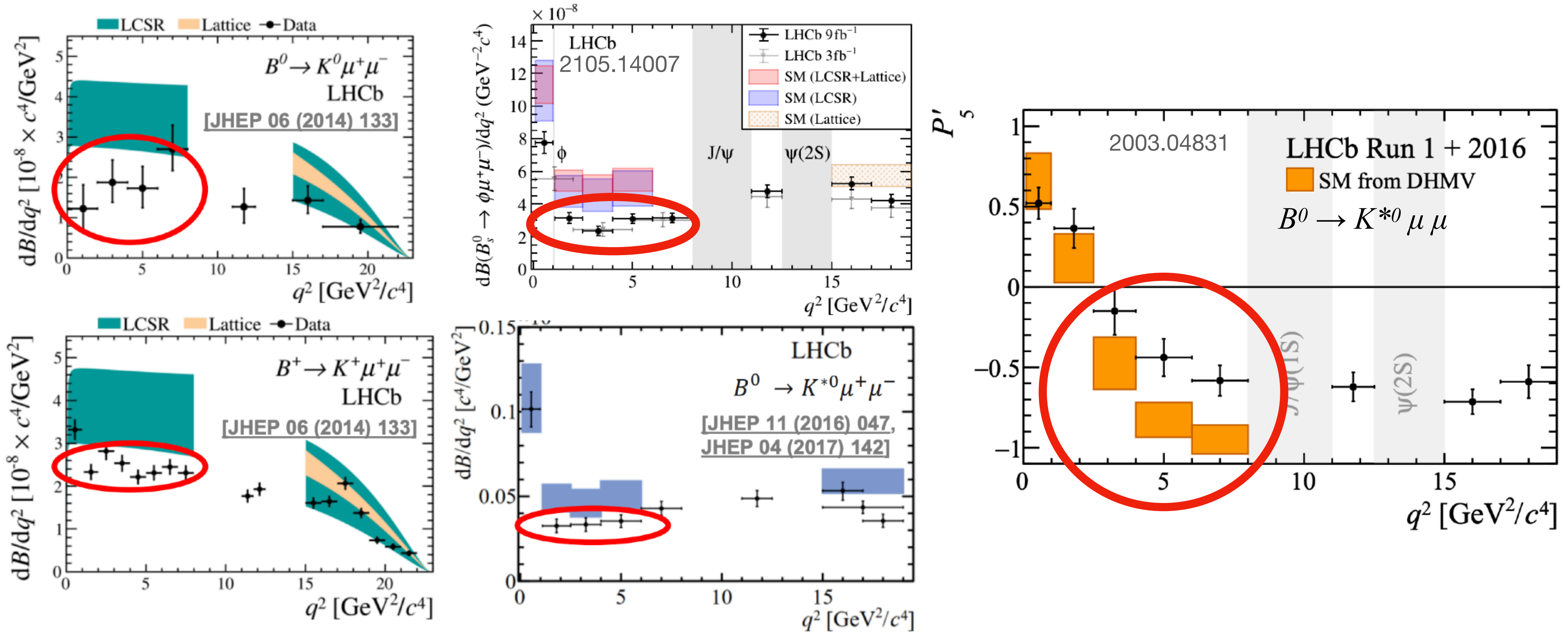

Specific NP hypothesis, with less conservative estimates of SM uncertainties show significances in the 5.9 - 7σ range.

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:

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Very good fit to all these deviations with:

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

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

EFT interpretation and tops

The mediator's mass should be **$M_X \gtrsim$ 10 GeV** to not disrupt the shape of the q^2 distributions.

Low-Energy EFT (LEFT)

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If the mediator is *above the EW scale*: **SMEFT**

$$q_L^i = \left(V_{ji}^* u_L^j\,,\ d_L^i\right)^T$$

down-quark
mass basis

$$O_{\ell q}^{(1)} = \left(\bar{\ell}_L^2 \gamma^\mu \ell_L^2\right)\left(\bar{q}_L^i \gamma_\mu q_L^j\right)$$

$$O_{\ell q}^{(3)} = \left(\bar{\ell}_L^2 \gamma^\mu \sigma^A \ell_L^2\right)\left(\bar{q}_L^i \gamma_\mu \sigma^A q_L^j\right)$$

$$C_{s_L b_L \mu_L \mu_L} \propto \left[C_{\ell q}^{(1)}\right]^{2223} + \left[C_{\ell q}^{(3)}\right]^{2223}$$

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Depending on the specific UV completion (combination of singlet and triplet operators), a combination of these two operators is induced by $SU(2)_L$ invariance with the same scale of ~ 37 TeV.

$$V_{cs} V_{tb}^* \left(\bar{\mu}_L \gamma^\mu \mu_L\right)\left(\bar{c}_L \gamma^\mu t_L\right)$$

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FCNC top decays

$t \to c\,\bar{\mu}\,\mu,\; c\,\bar{\nu}\,\nu$

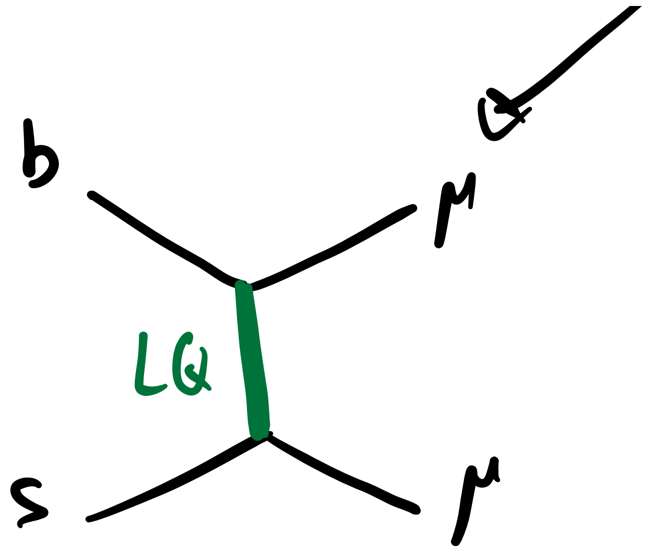
$$\Gamma \sim \frac{|C|^2 m_t^5}{1536\,\pi^3}$$

Br ~ 10^{-12}

Not observable

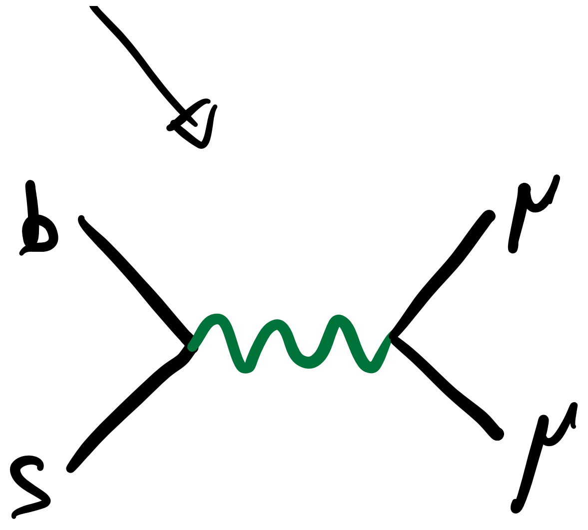
UV completions for $b \to s\, \mu^+\mu^-$ anomalies

TREE LEVEL



Leptoquark

vector U_1 or scalar S_3



Z’

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

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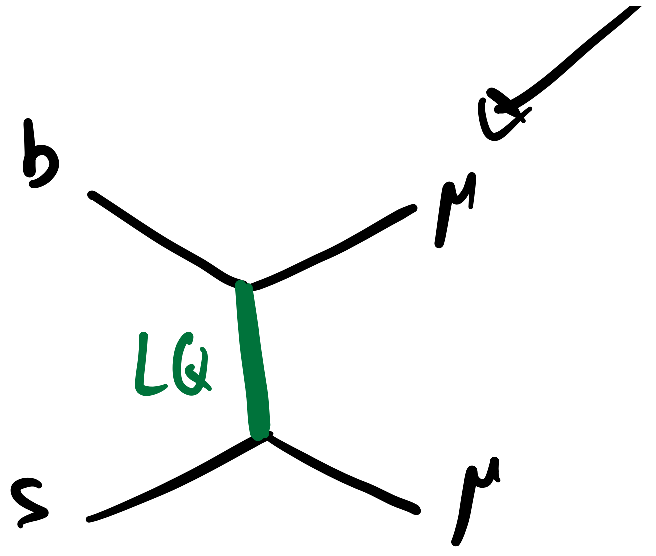

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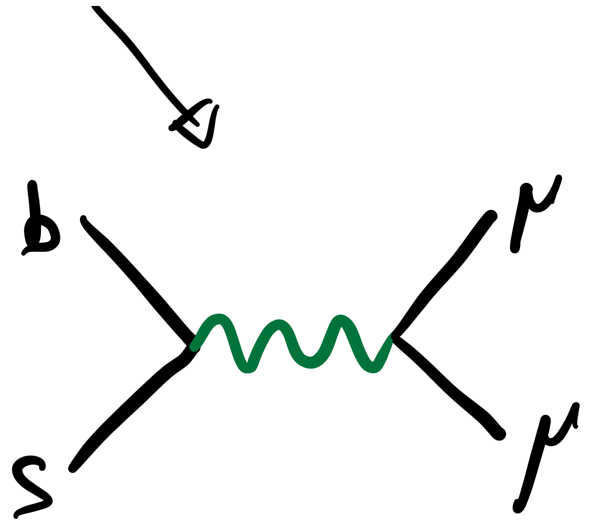
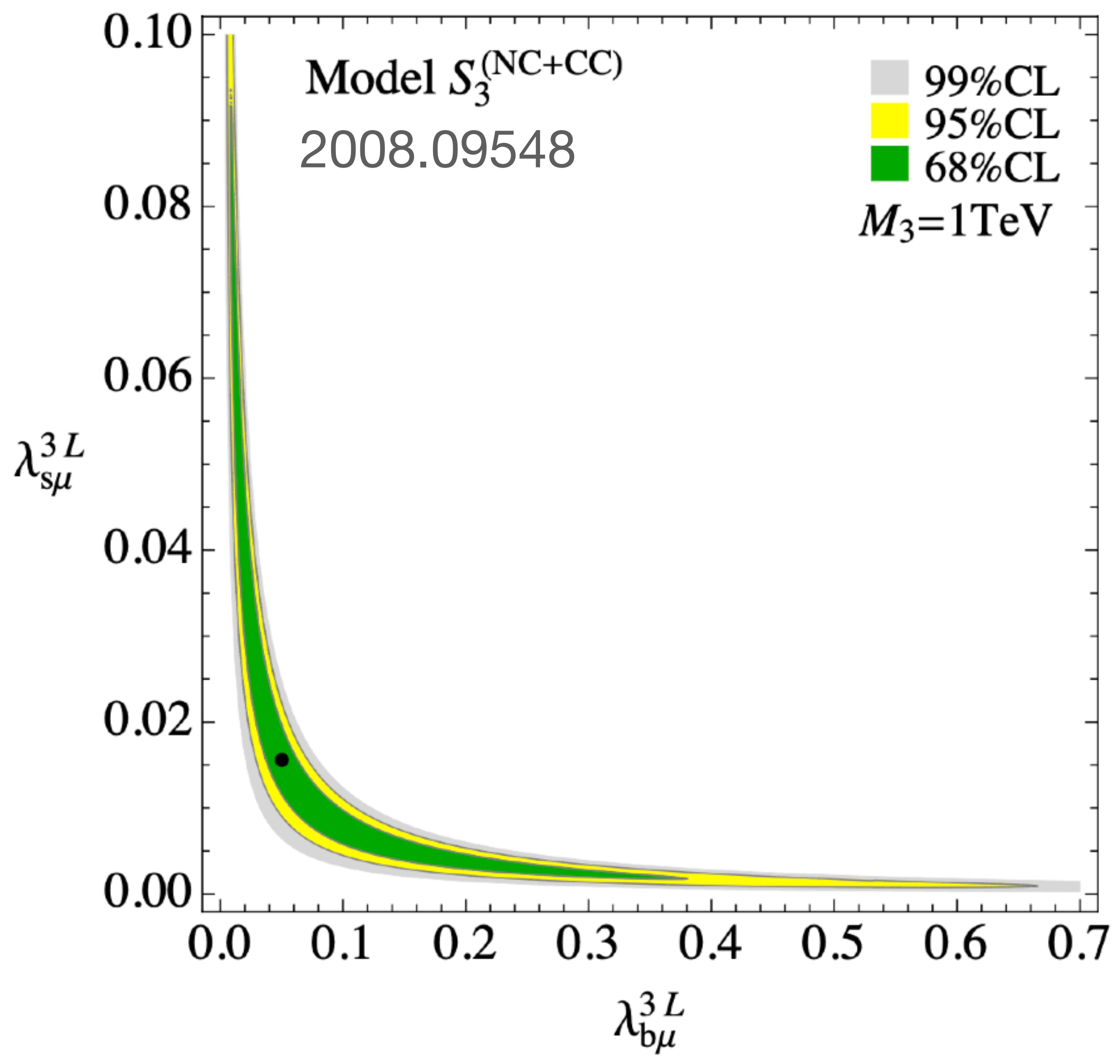


Z'

A TeV scale LQ
small couplings
no issues from flavour

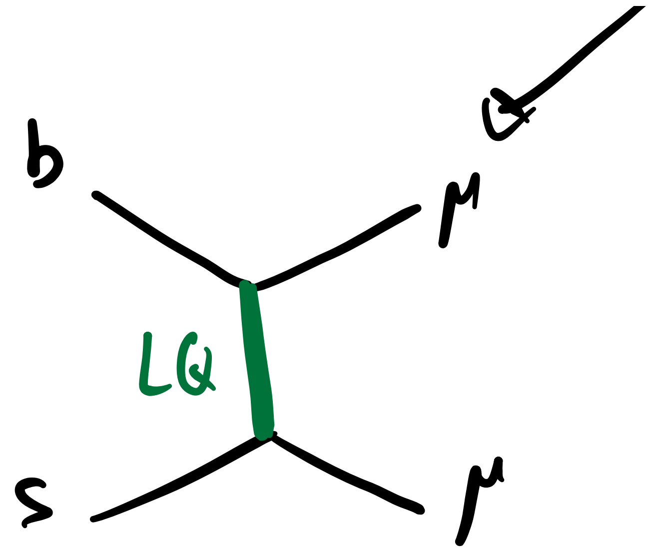


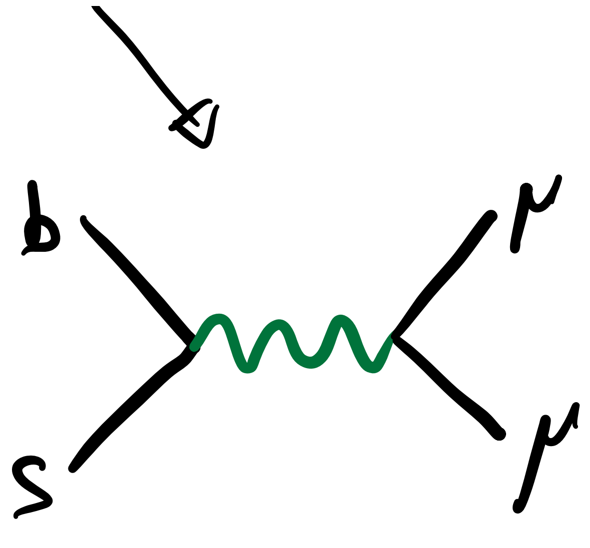
Decay channels involving top quark are important for direct searches at LHC

$S_3 \to t\,\mu,\; t\,\nu,\; b\,\tau,\; b\,\nu$

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

TREE LEVEL





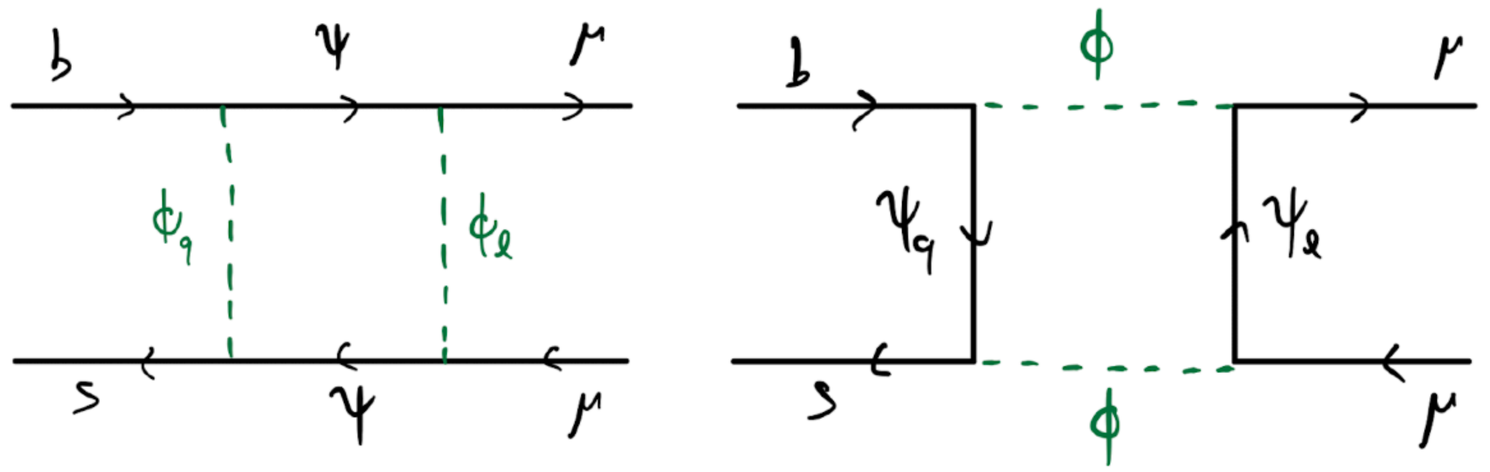
Leptoquark
vector U_1 or scalar S_3

Z'

LOOP LEVEL

LFU anomalies from boxes

Arcadi, Calibbi, Fedele, Mescia 2104.03228



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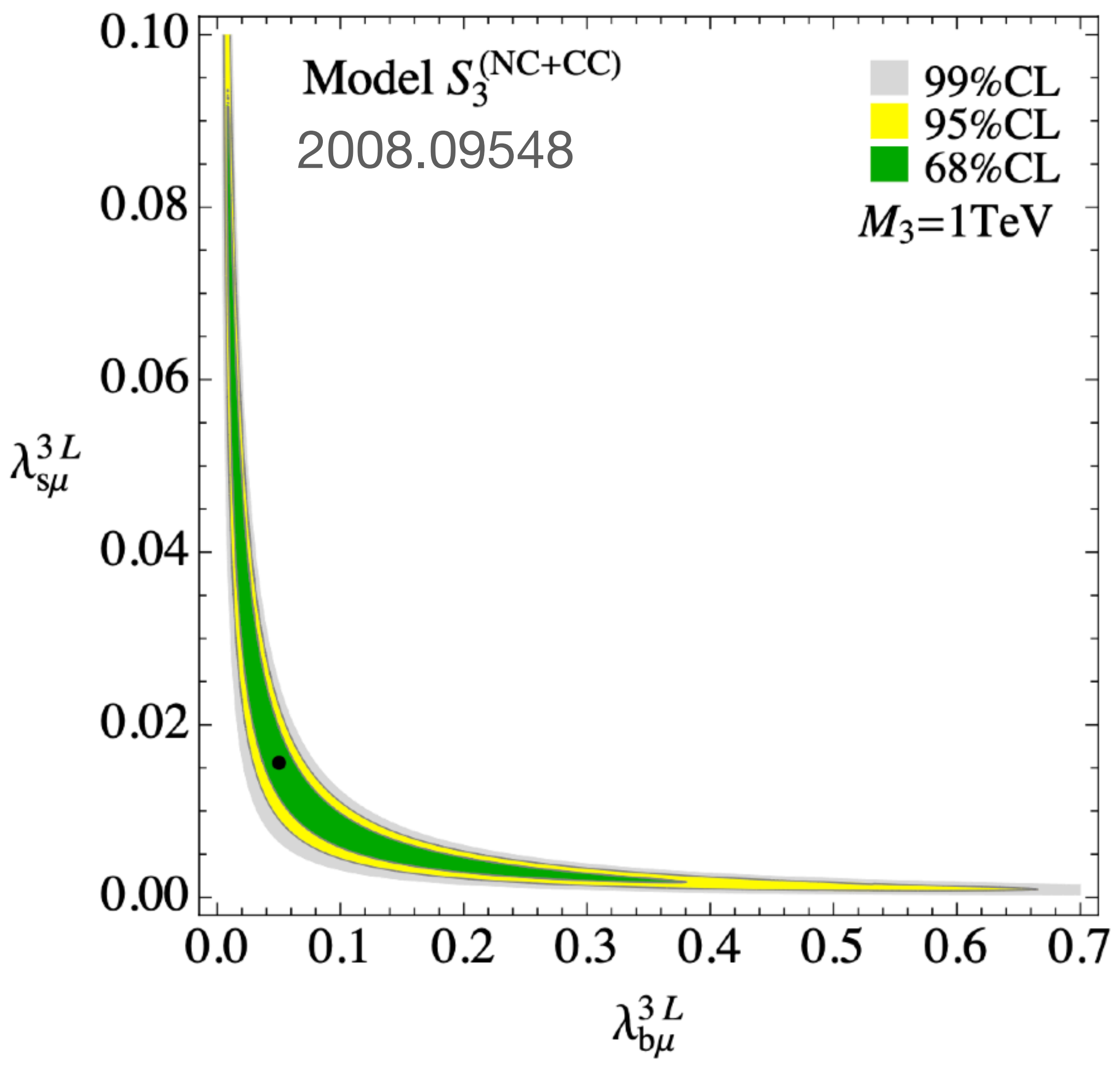

2008.09548

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

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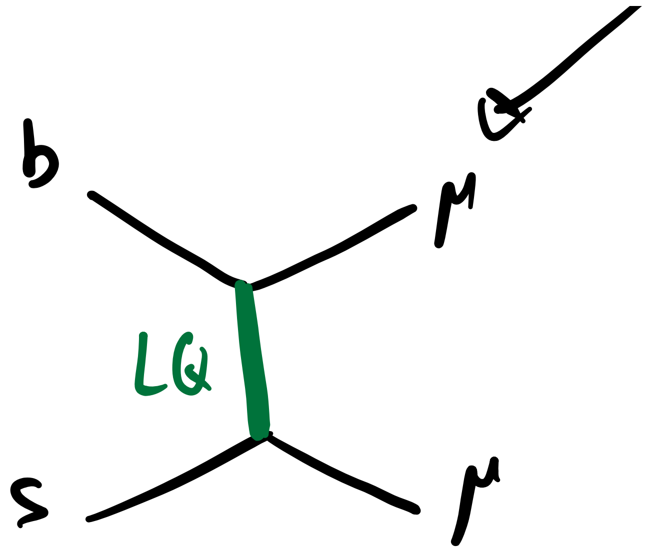

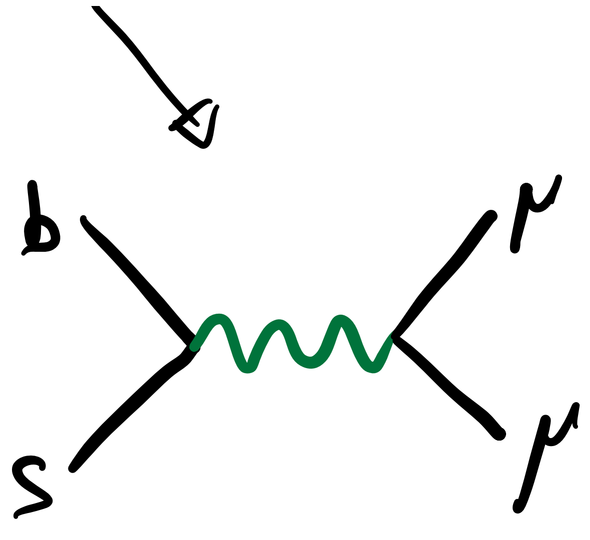

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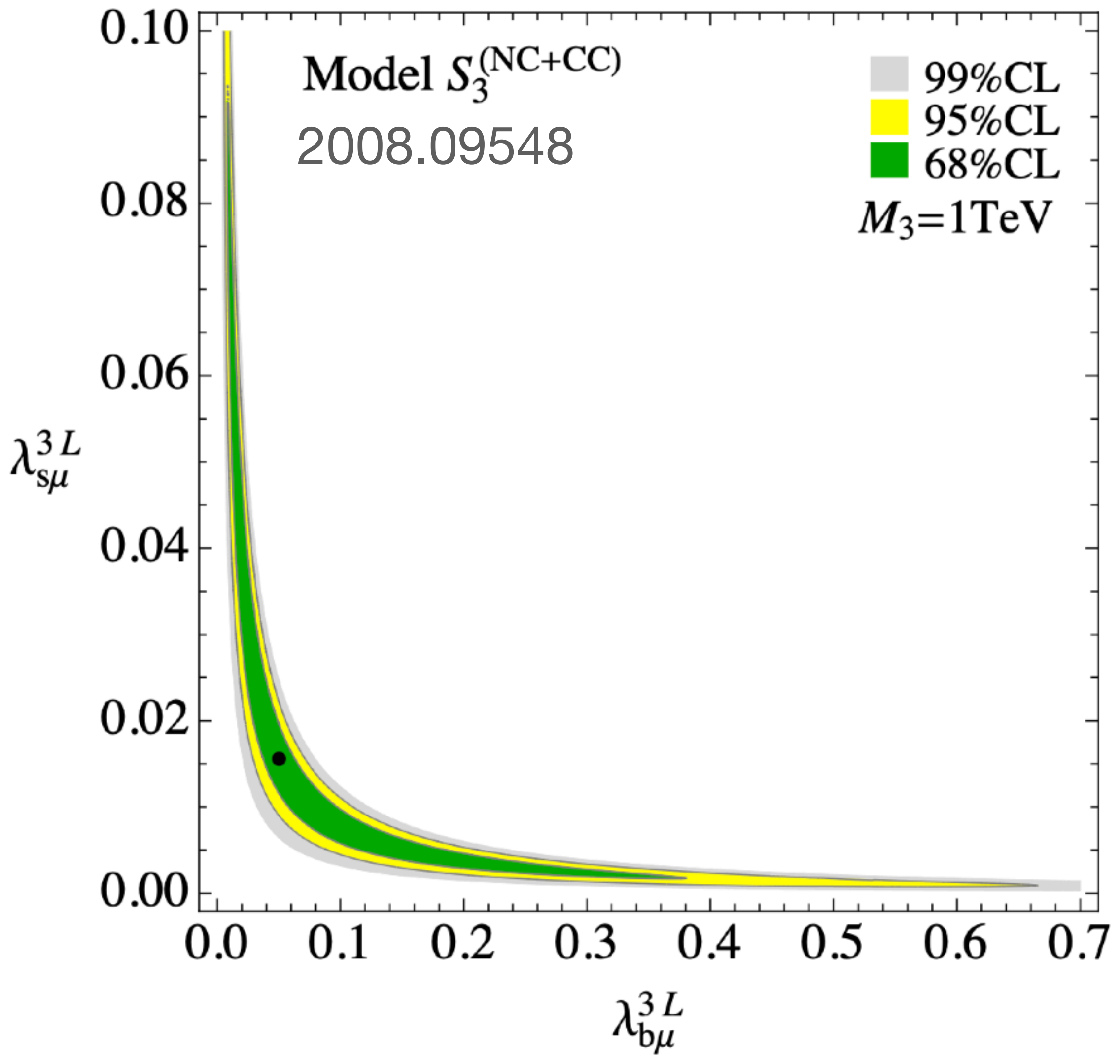

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S_3 → t μ, t ν, b τ, b ν

LOOP LEVEL

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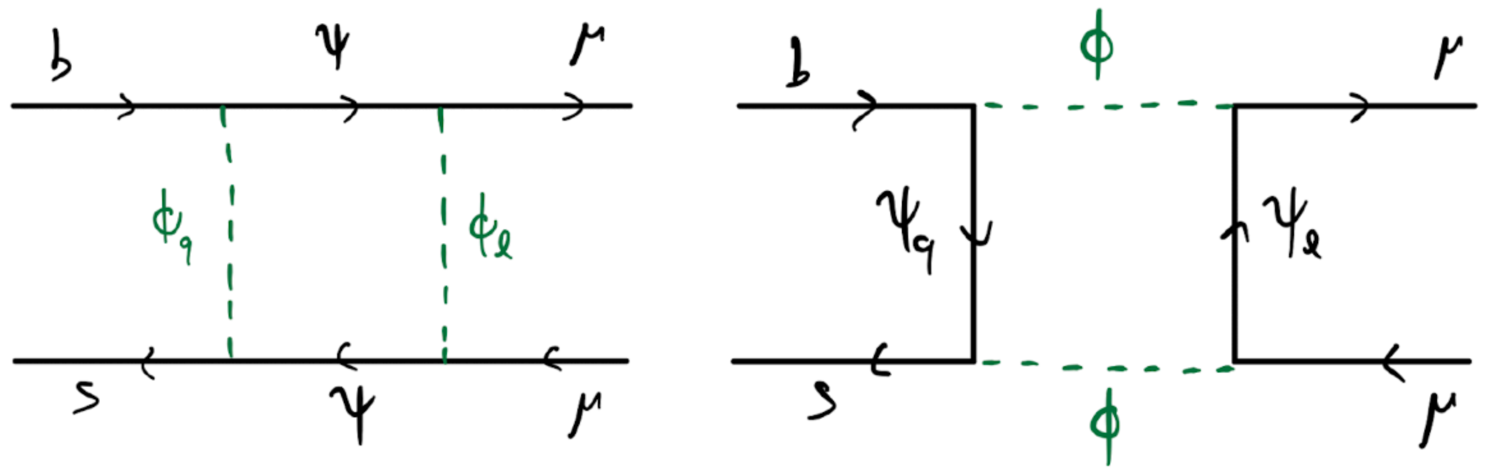
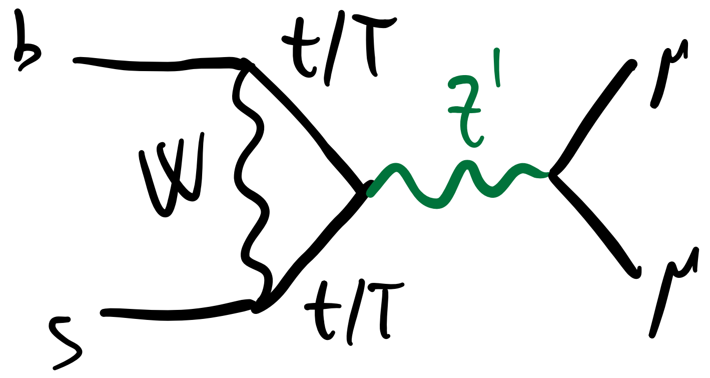
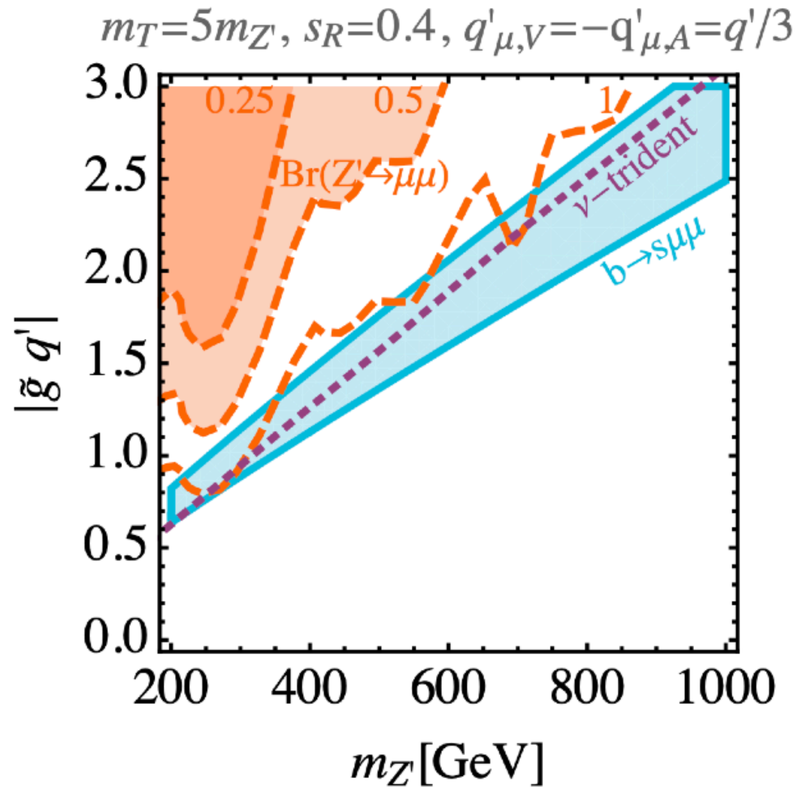


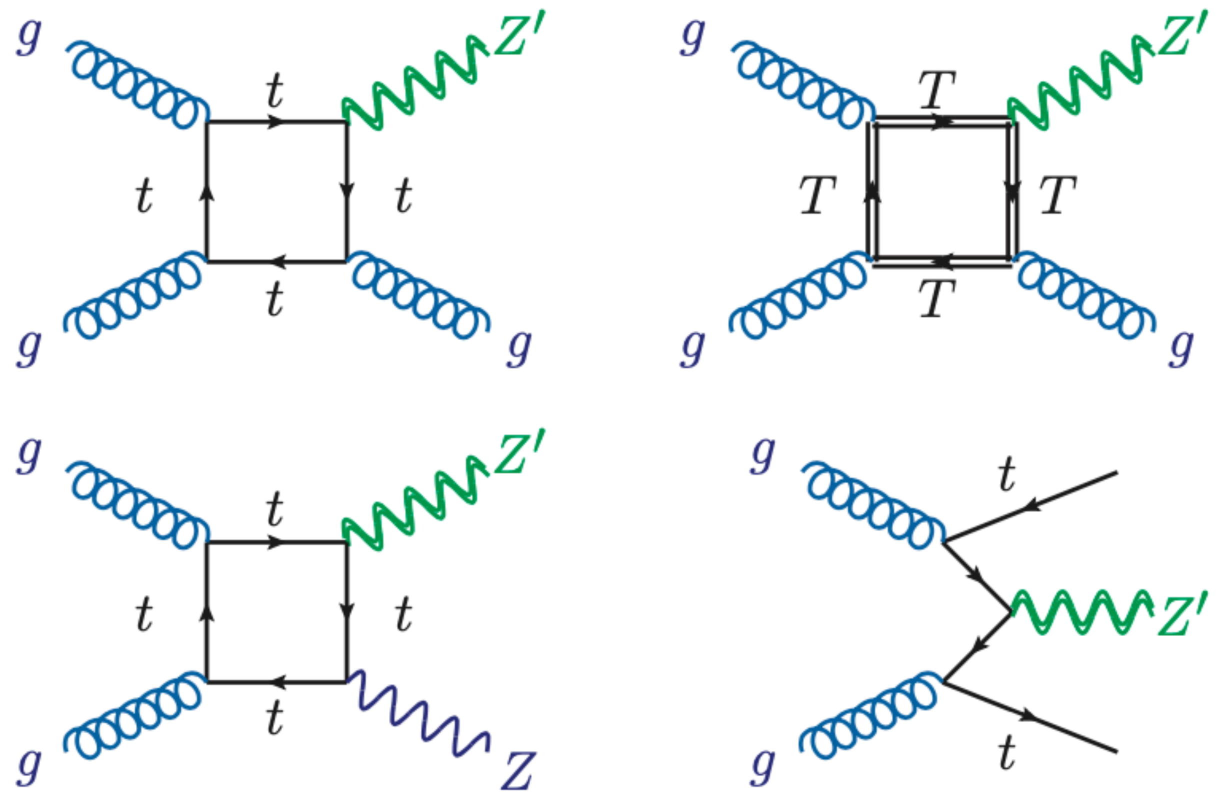
Top-philic Z'



Kamenik, Soreq, Zupan [1704.06005]



Production & decay



pp → t $\bar{t}$ Z'
pp → j Z'
pp → Z Z'

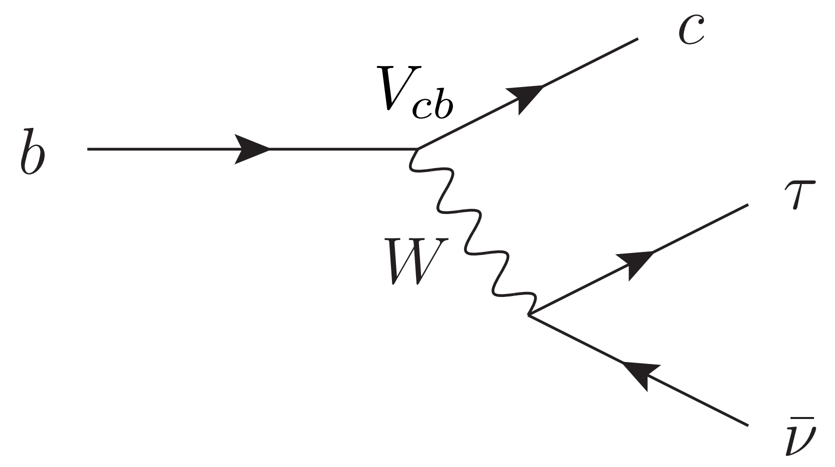
Z' → μ $\bar{\mu}$, ν $\bar{\nu}$, t $\bar{t}$, b $\bar{b}$

Similar Br to muons and tops

Charged-current B-anomalies $b \to c\,\tau\,\nu$ vs. $b \to c\,\ell\,\nu$

Charged-current B-anomalies

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



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

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

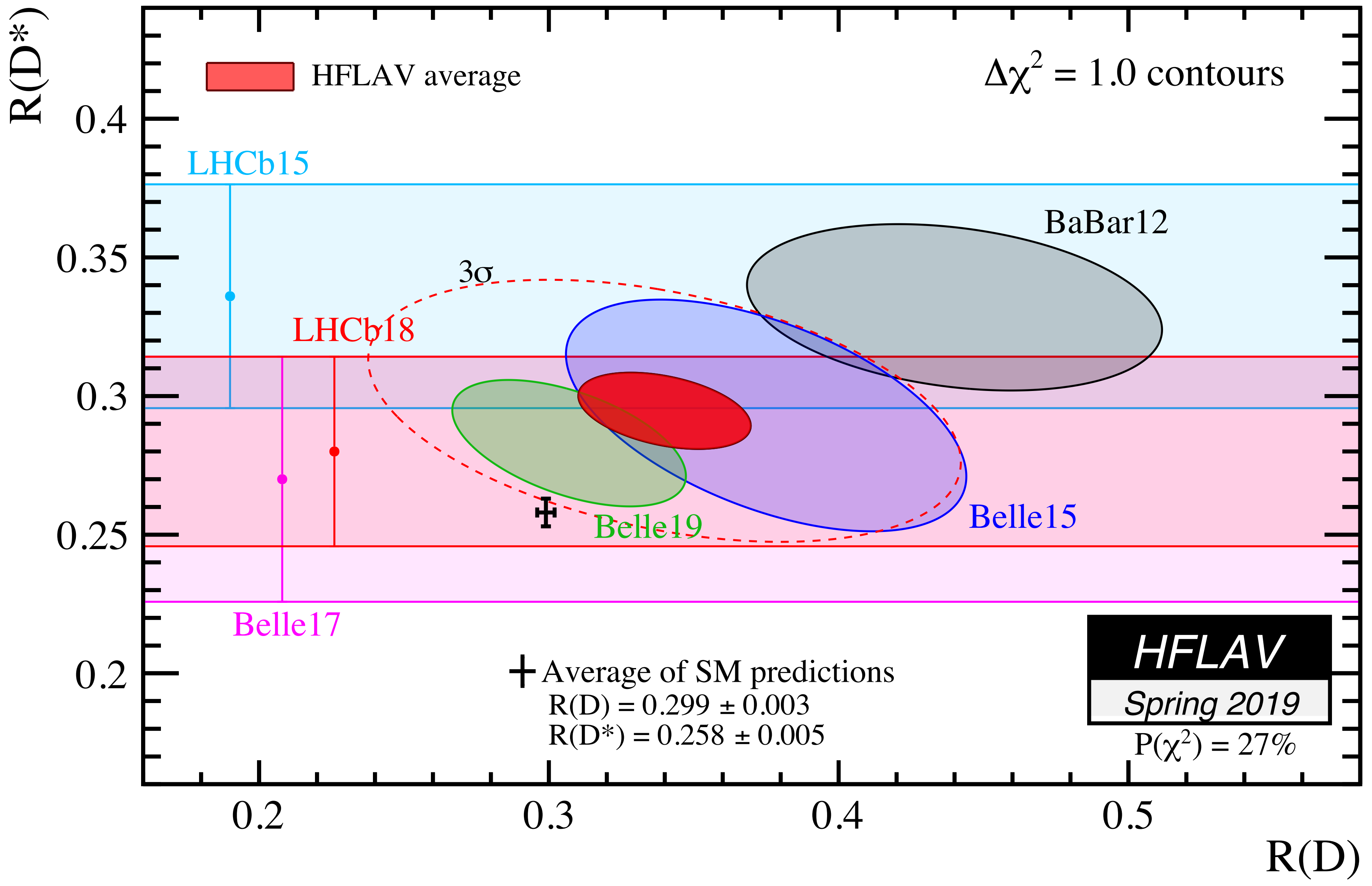
~ 14% enhancement from the SM

~ 3σ from the SM (3.7σ when combined)

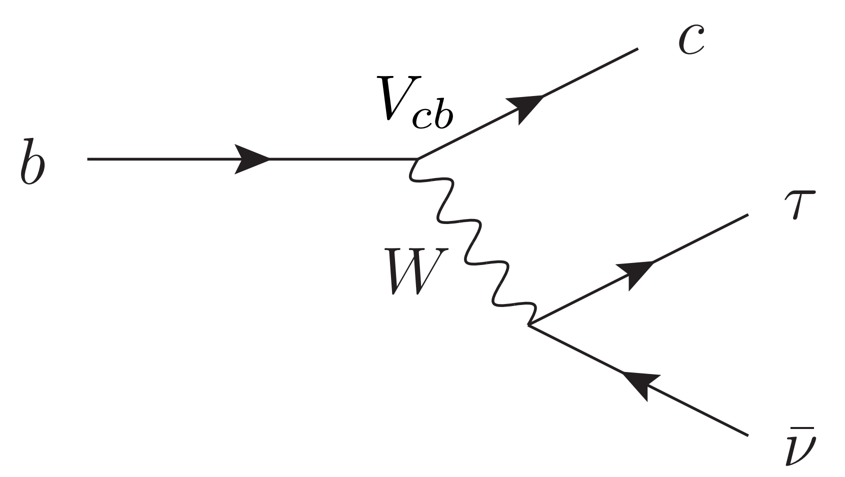
While μ/e universality well tested $R(D)^{\mu/e} = 0.995 \pm 0.045$

Belle - [1510.03657]

All measurements since 2012
consistently above the SM predictions



Charged-current B-anomalies $b \to c\,\tau\,\nu$ vs. $b \to c\,\ell\,\nu$



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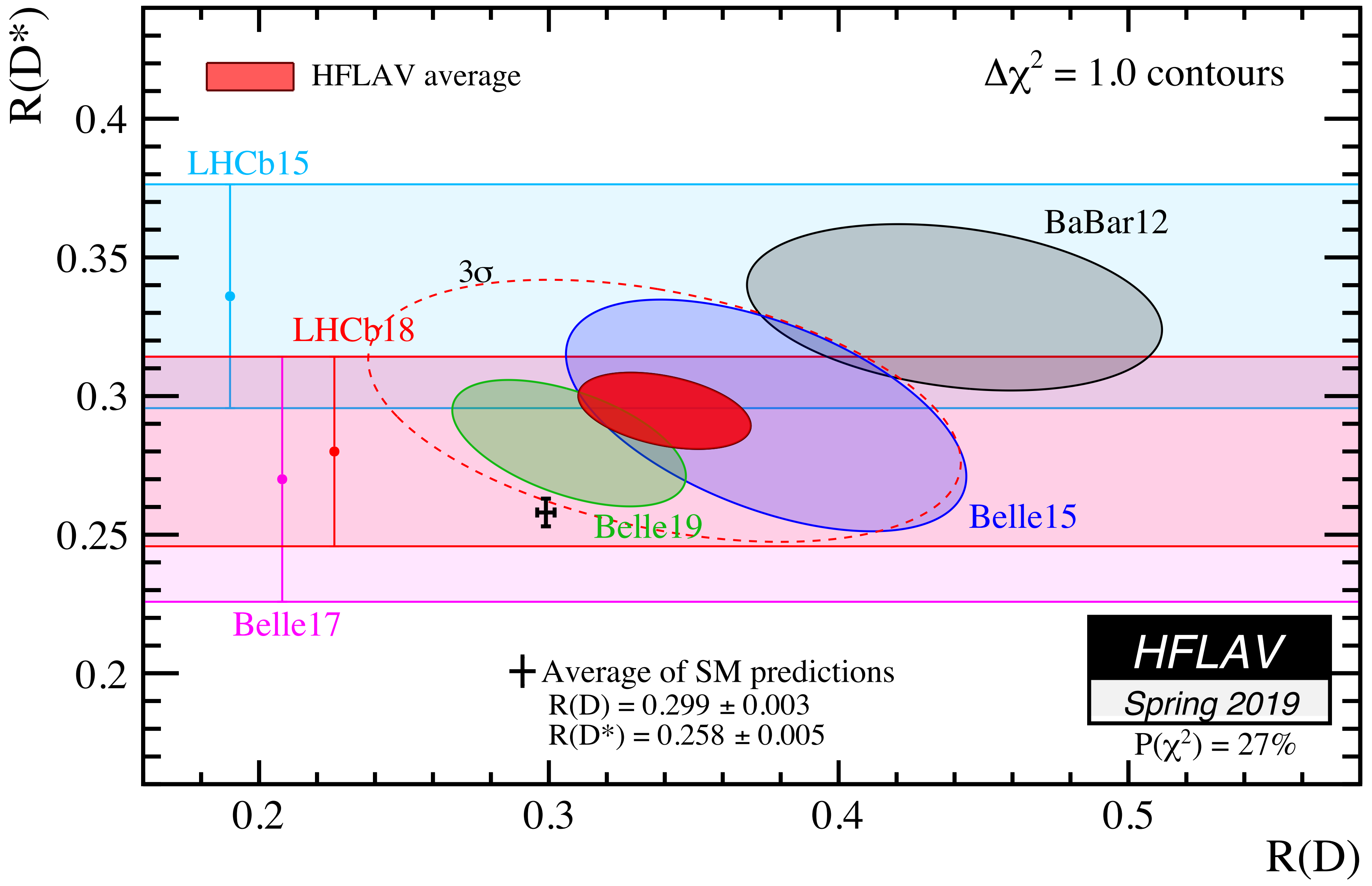
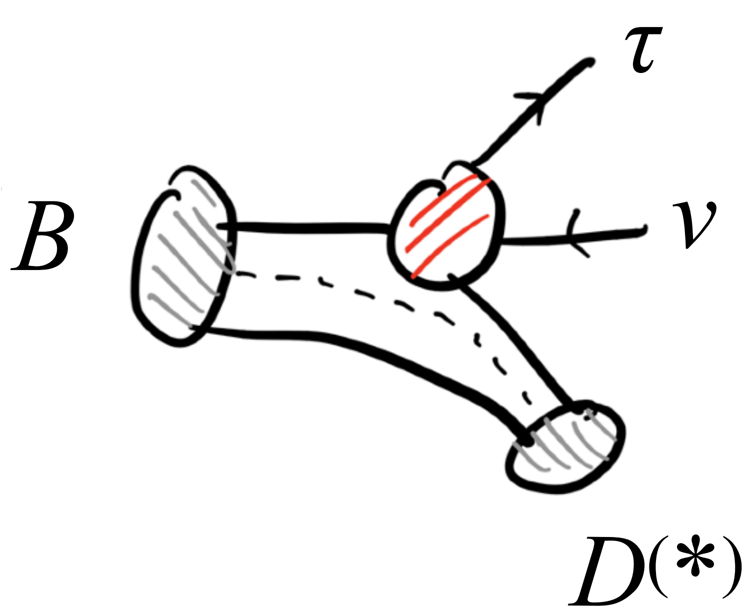


+ Average of SM predictions
R(D) = 0.299 ± 0.003
R(D*) = 0.258 ± 0.005

New Physics interpretations (LEFT):



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

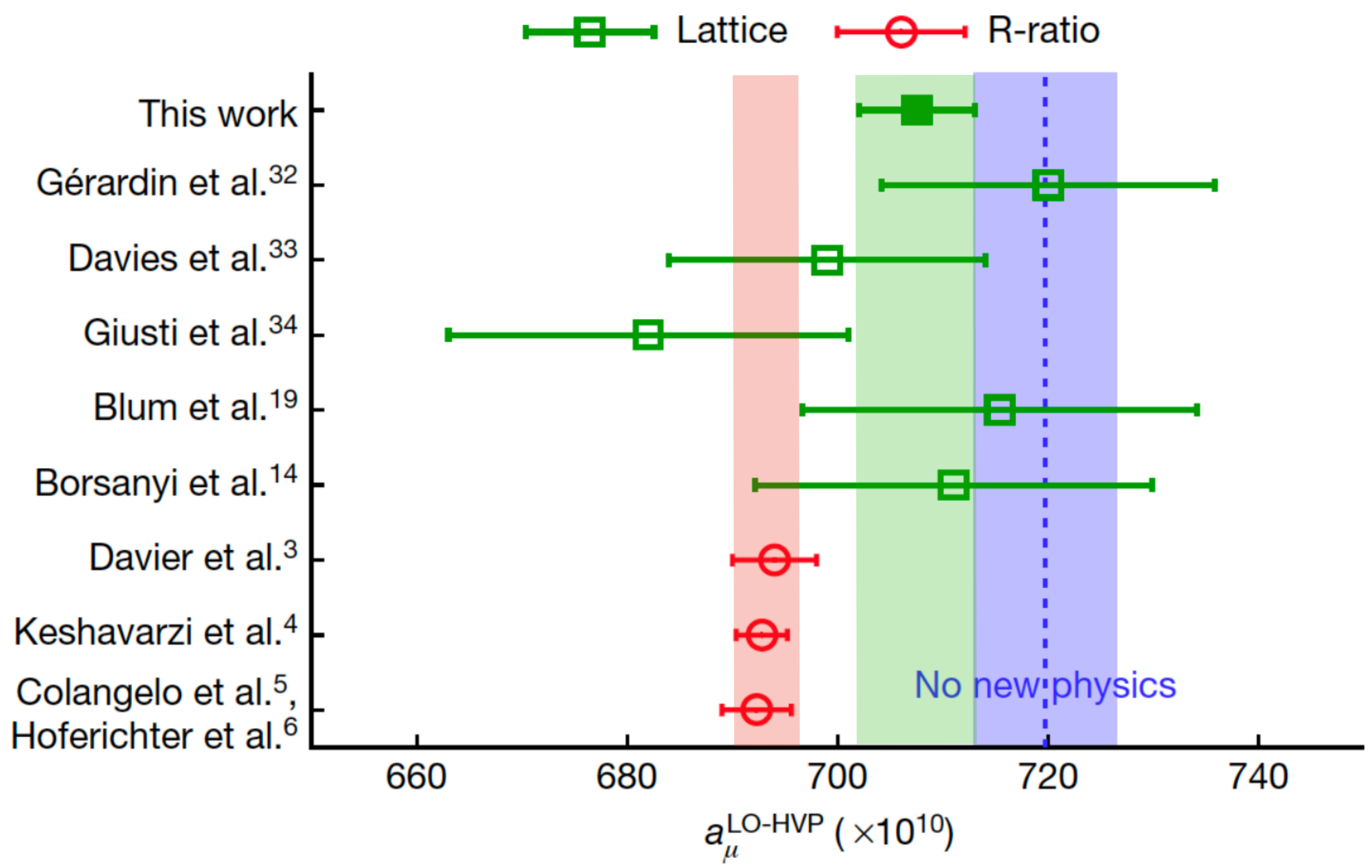
and/or

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

With a **New Physics scale** of

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

Muon g-2



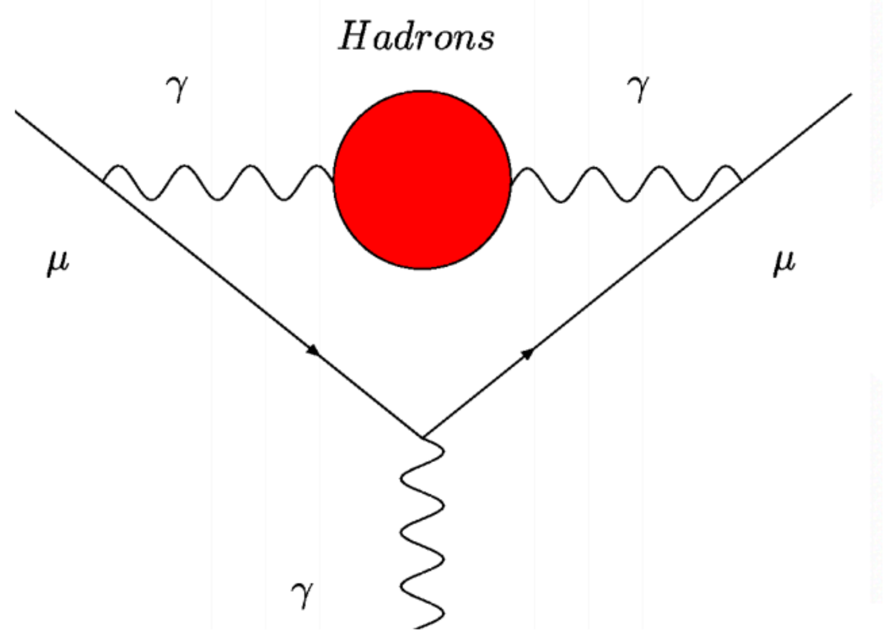
$a_\mu^{exp} = (116592\mathbf{2061 \pm 41})\times 10^{-11}$ FNAL '21 + BNL '04

$a_\mu^{THin} = (116591\mathbf{810 \pm 43})\times 10^{-11}$ TH initiative WP 2006.04822

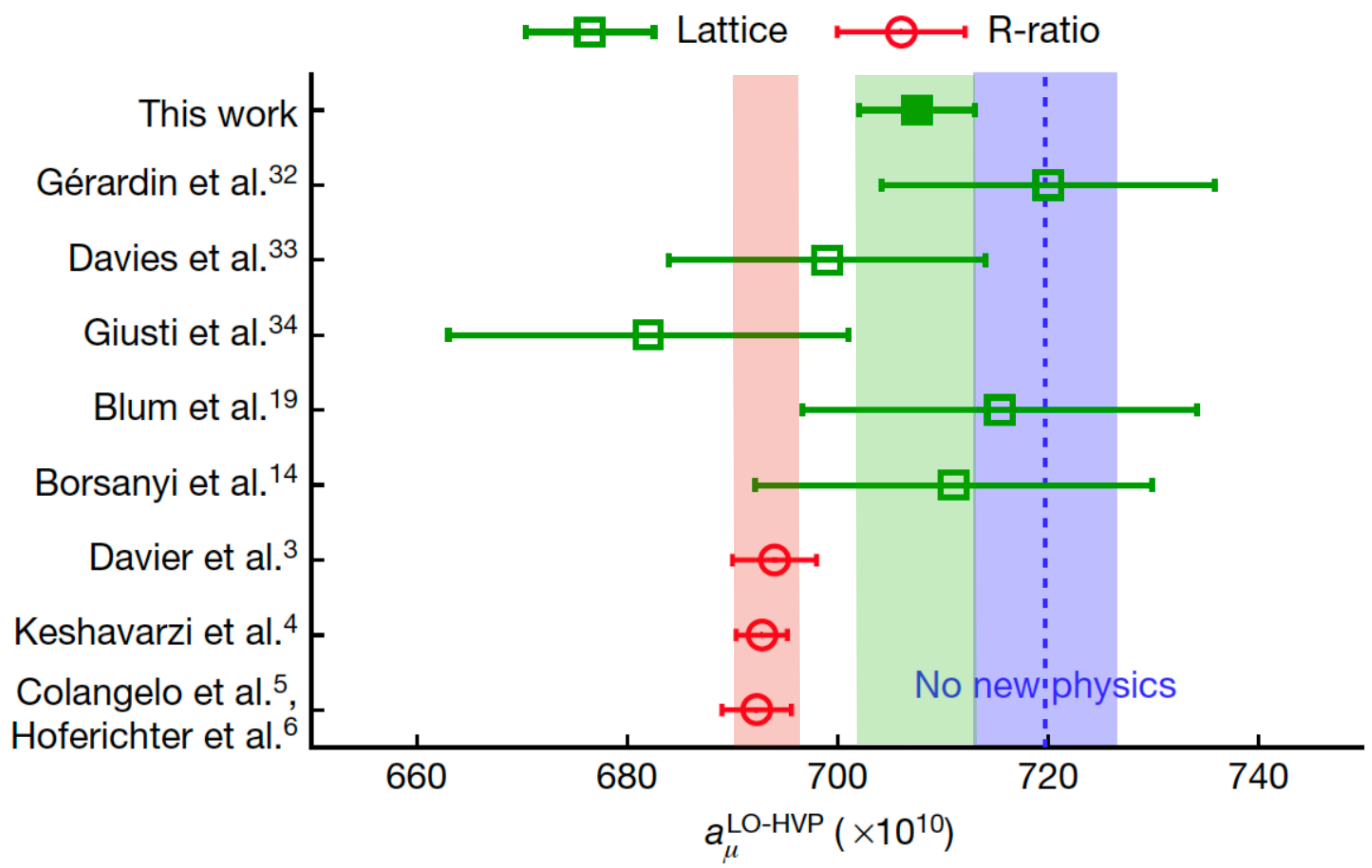
$a_\mu^{BMW} = (116591\mathbf{954 \pm 55})\times 10^{-11}$ Borsanyi et al. Nature 2021, 2002.12347

4.2σ or **1.6σ ??**

Main Th. uncertainty in HVP LO contribution:



Muon g-2



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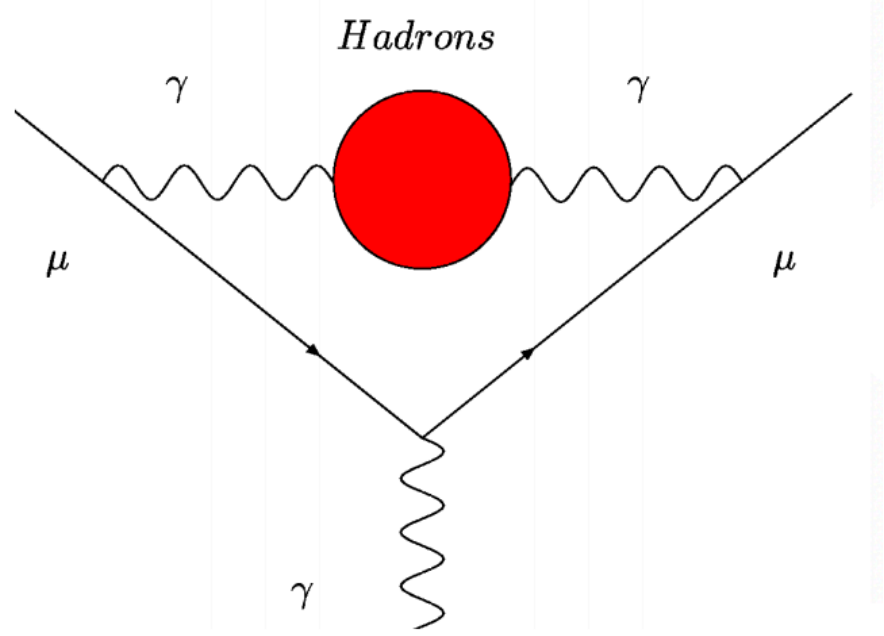


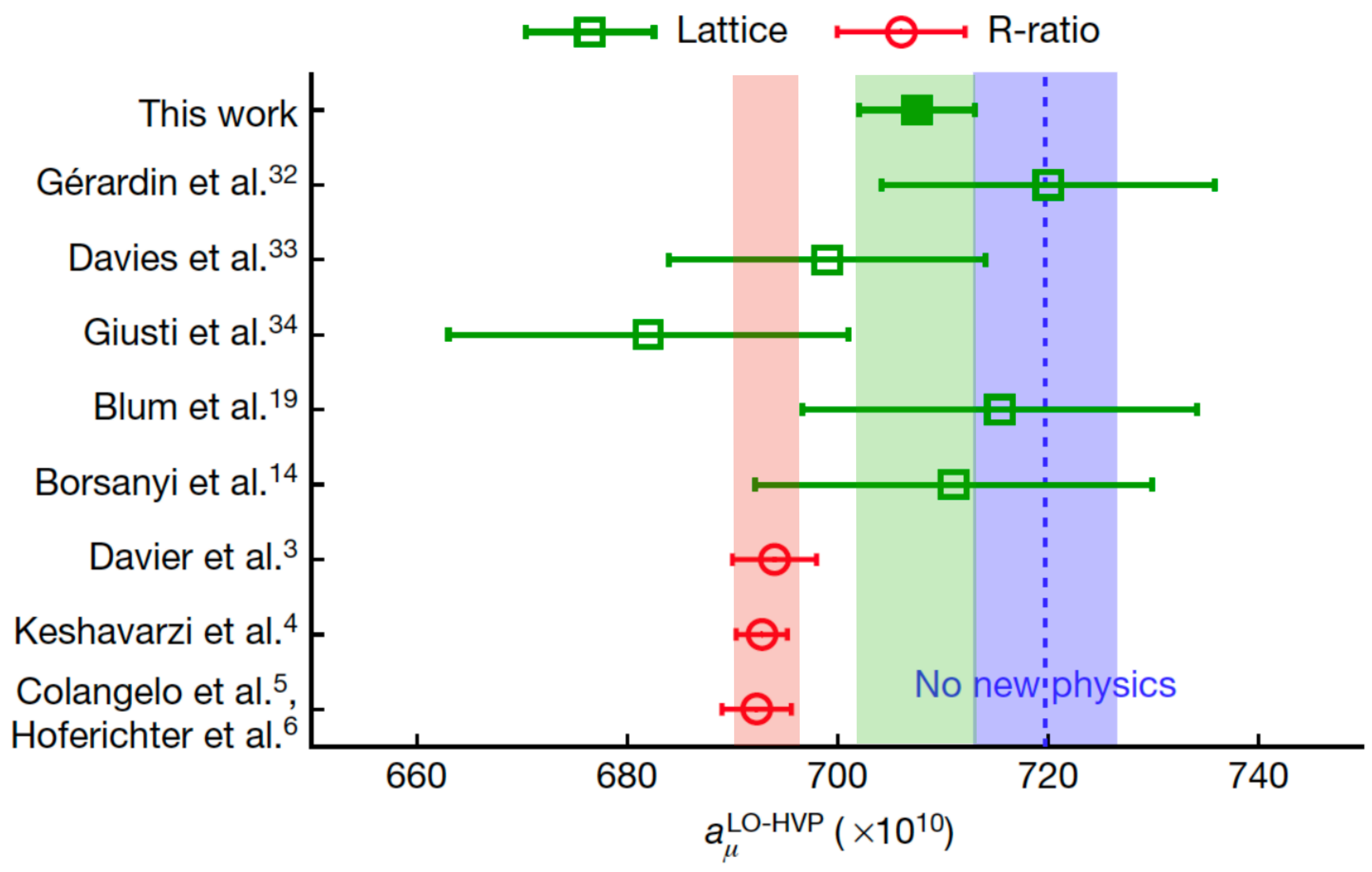
4.2σ or **1.6σ ??**

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

$$\Delta a_\mu = \frac{4 m_\mu}{e} \mathrm{Re}\left[L_{e\gamma}(m_\mu)\right]_{\mu\mu}$$

$$[O_{e\gamma}]_{\alpha\beta} = \bar{e}_L^{\alpha} \sigma^{\mu\nu} e_R^{\beta} F_{\mu\nu}$$

Muon g-2



$a_\mu^{exp} = (11659\mathbf{2061} \pm \mathbf{41})\times10^{-11}$ FNAL '21 + BNL '04

$a_\mu^{THin} = (11659\mathbf{1810} \pm \mathbf{43})\times10^{-11}$ TH initiative WP 2006.04822

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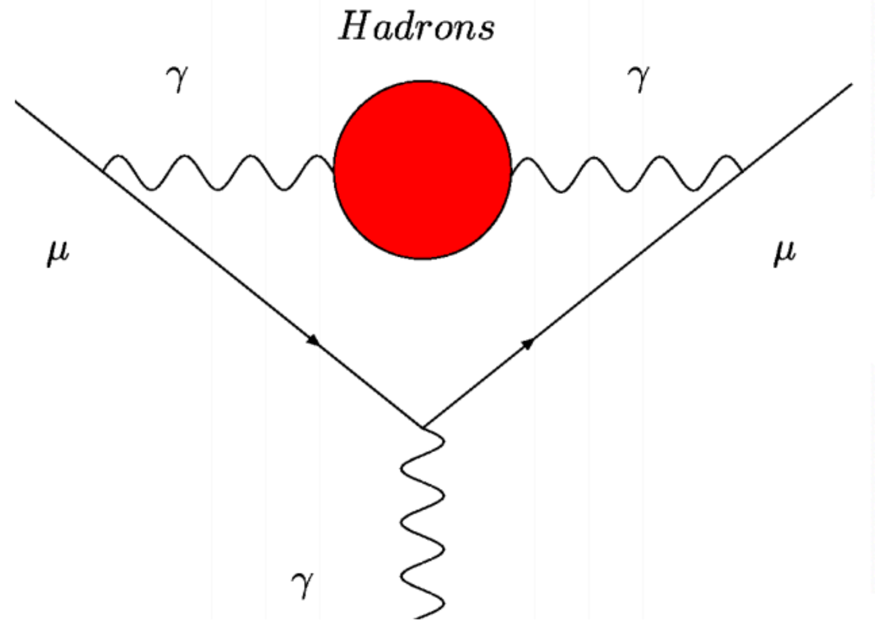

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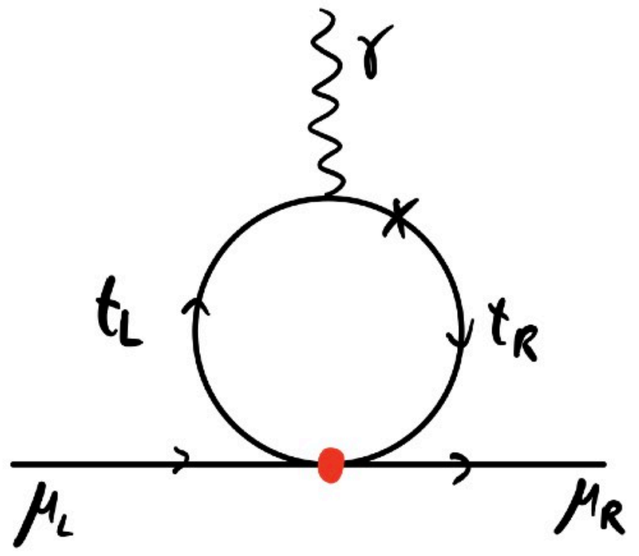
NP is enhanced if the chirality flip happens in an internal line with a heavy fermion, as the **top quark**:



semileptonic tensor
dim-6 operator
with **top quark**

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

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

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?

Towards NP interpretations of $R(D^{(*)})$

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

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

$$\mathcal{O}_{S_L} = (\bar{c} P_L b)(\bar{\tau} P_L \nu)\,,$$

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

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

→

Charged-current

+

low EFT scale

→

Required **tree-level** mediator.
Only viable ones are **leptoquarks**.

$$\mathbf{M_X \gtrsim 1\ TeV}$$ (QCD pair-production limits)

Towards NP interpretations of $R(D^{(*)})$

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

Charged-current
+
low EFT scale

→

Required **tree-level** mediator.
Only viable ones are **leptoquarks**.

$M_X \gtrsim 1$ TeV (QCD pair-production limits)

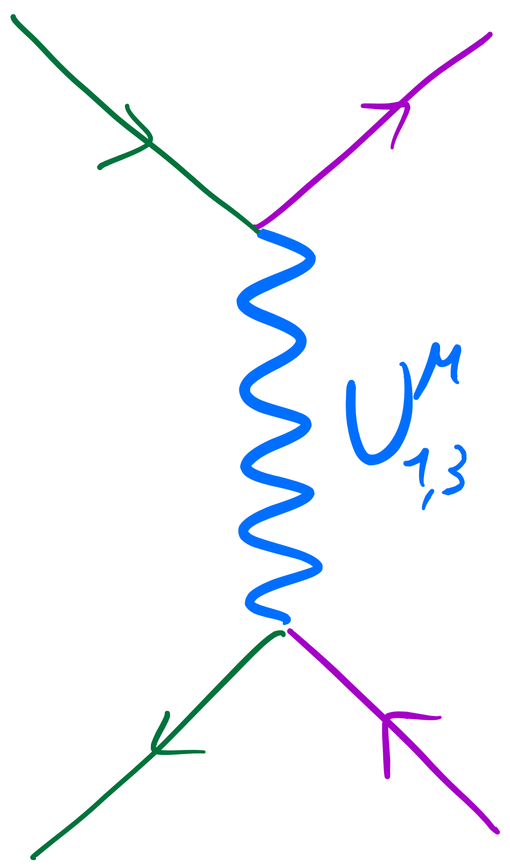
Given the low scale, several observables strongly constrain possible UV completions.

Most relevant:

Meson mixing
$B \to K^{(*)} \nu\nu$
$Z \to \tau\tau$
$pp \to \tau\tau$

Vector Leptoquark

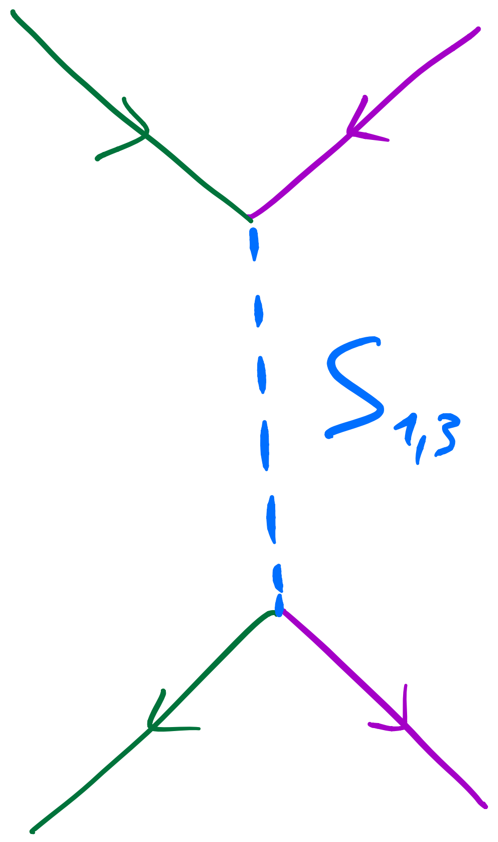
$U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$,



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

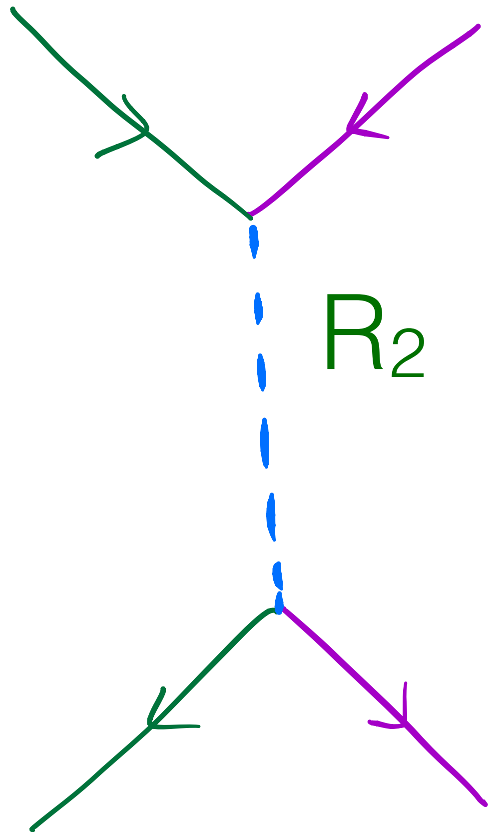
$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$,
$[S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)]$



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

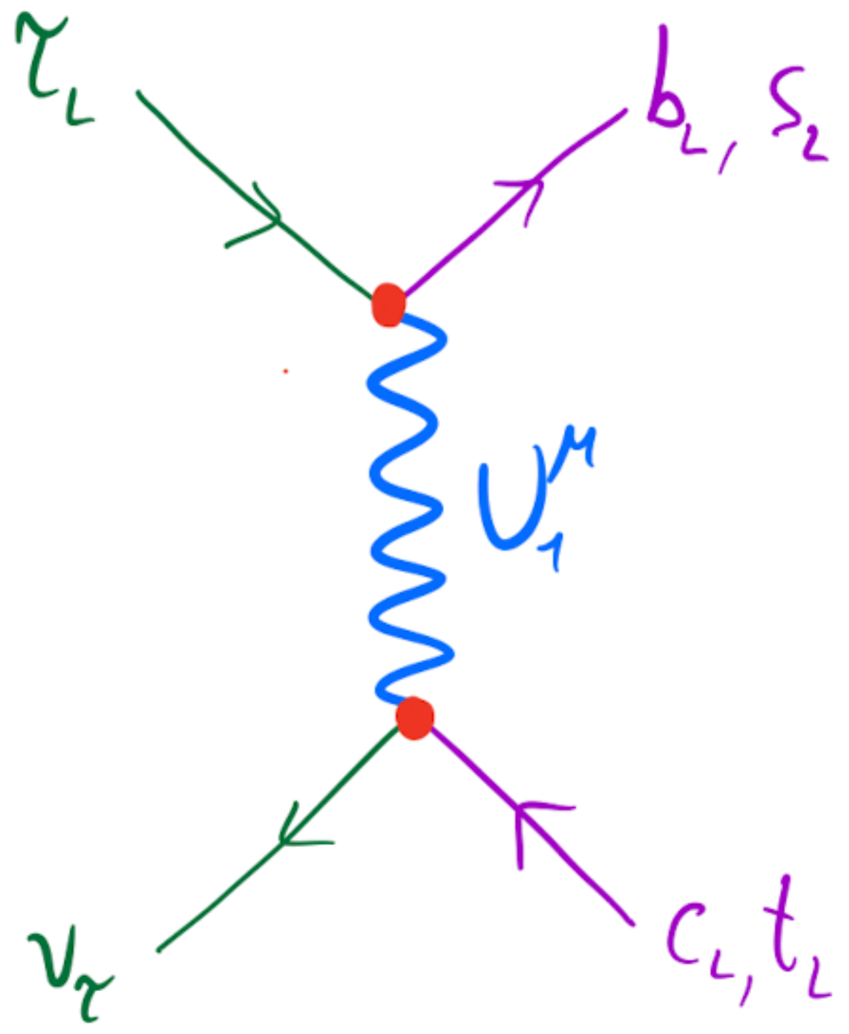
$R_2 = (\mathbf{3}, \mathbf{2}, 7/6)$,



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

U_1 vector leptoquark

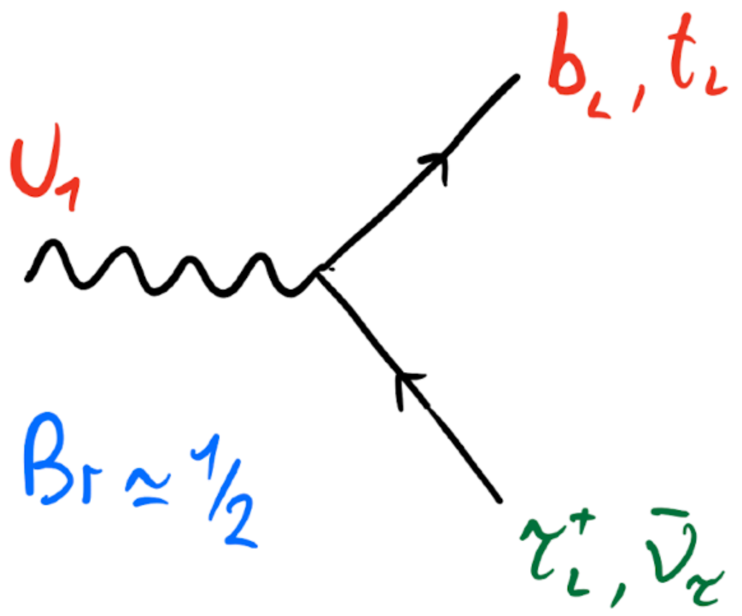


$$\mathcal{L}_{int} = U_1^\mu \left(g_{b\tau}\, \bar{q}_L^3 \gamma_\mu \ell_L^3 + g_{s\tau}\, \bar{q}_L^2 \gamma_\mu \ell_L^3 \right) + h.c.$$

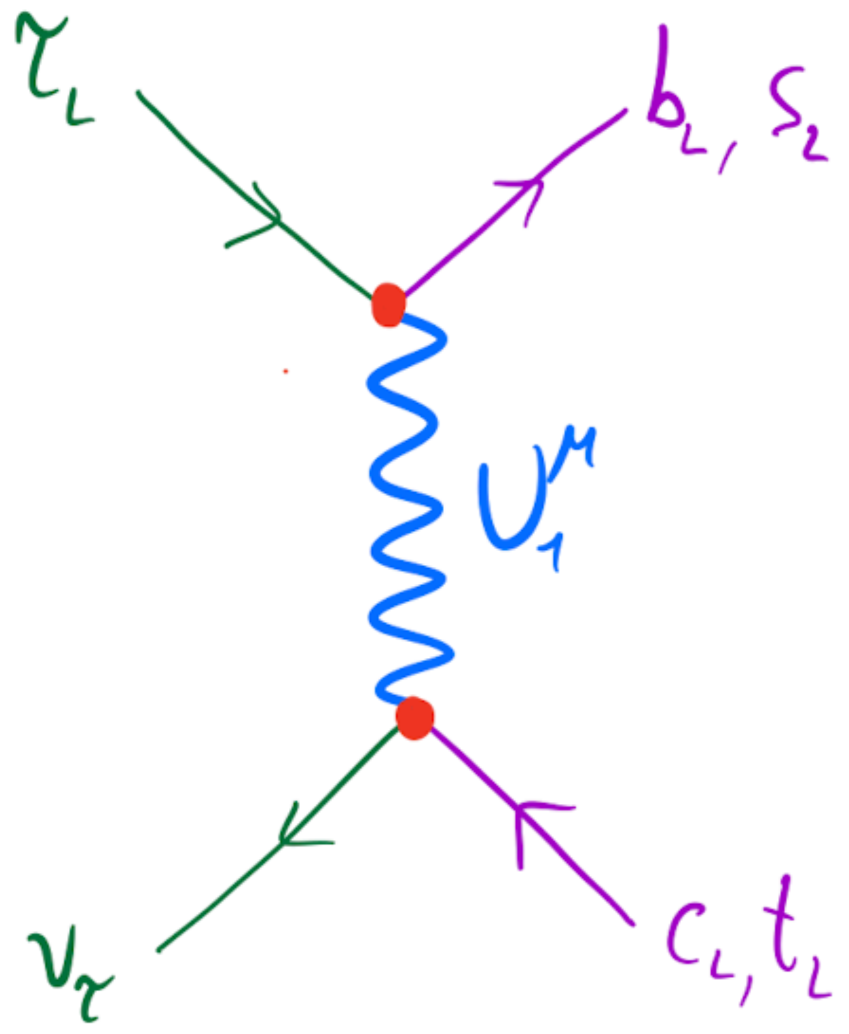
Couplings to 3rd generation are typically largest

$$M_{U_1} \sim 1\,\mathrm{TeV} \longrightarrow g_{b\tau} \sim \mathcal{O}(1)\,, \quad g_{s\tau} \sim \mathcal{O}(0.2)$$

Leading Br



U₁ vector leptoquark



$$\mathcal{L}_{int} = U_1^\mu \left(g_{b\tau}\, \bar{q}^3_L \gamma_\mu \ell^3_L + g_{s\tau}\, \bar{q}^2_L \gamma_\mu \ell^3_L \right) + h.c.$$

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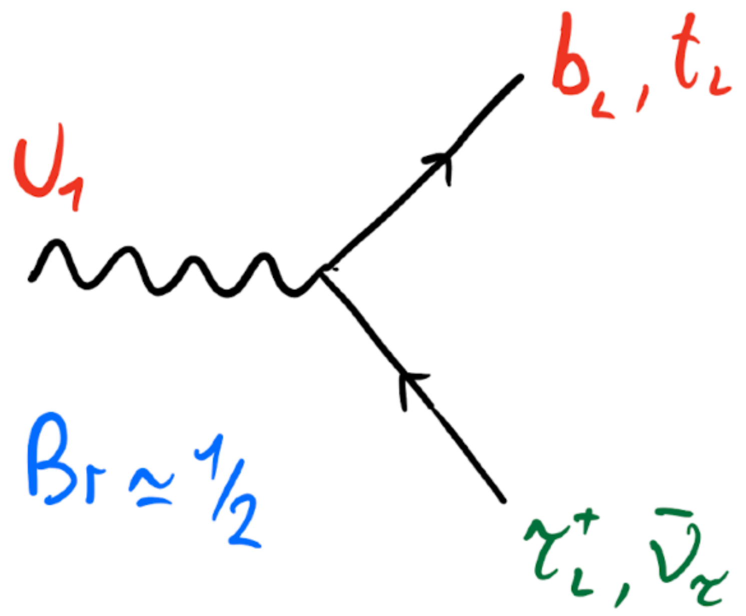
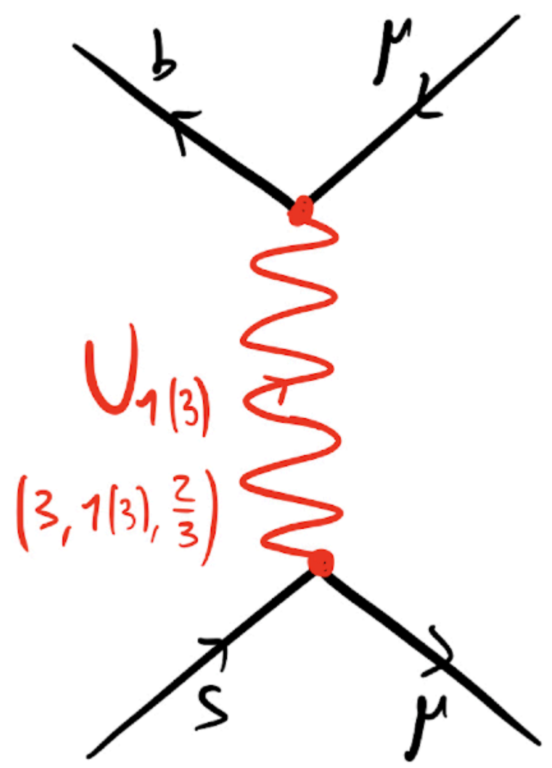


Can mediate bL → sL μL μL

with smaller couplings



Cannot mediate also (g-2)$_\mu$

- required also sizeable coupling to b_R μ_R
- Excluded by B_s → μ μ

S_1 and S_3 scalar leptoquarks

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

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

Scalar Leptoquarks

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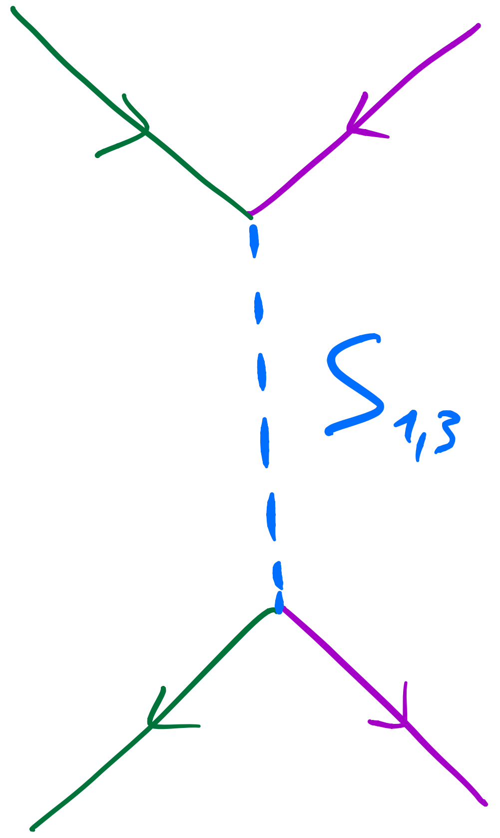
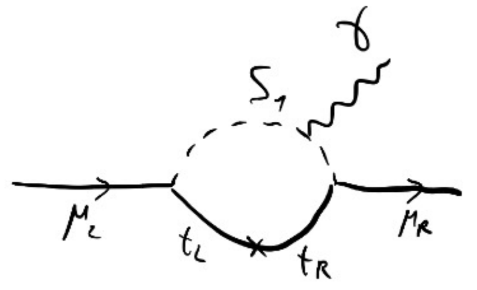
$S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$,



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

- *Fully calculable* already at the simplified model level (unlike vector LQ)
- Potential UV completions in a *Composite Higgs Models* scenario, interesting for the potential connection to the *EW hierarchy problem*. [D.M. 1803.10972]
- Can address the **muon (g-2)**.



S_1 and S_3 scalar leptoquarks

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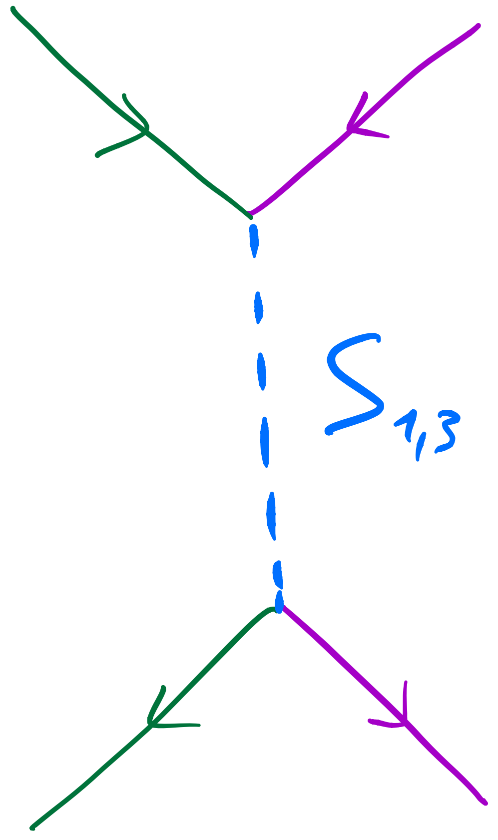

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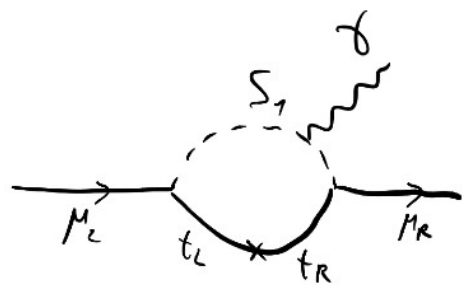
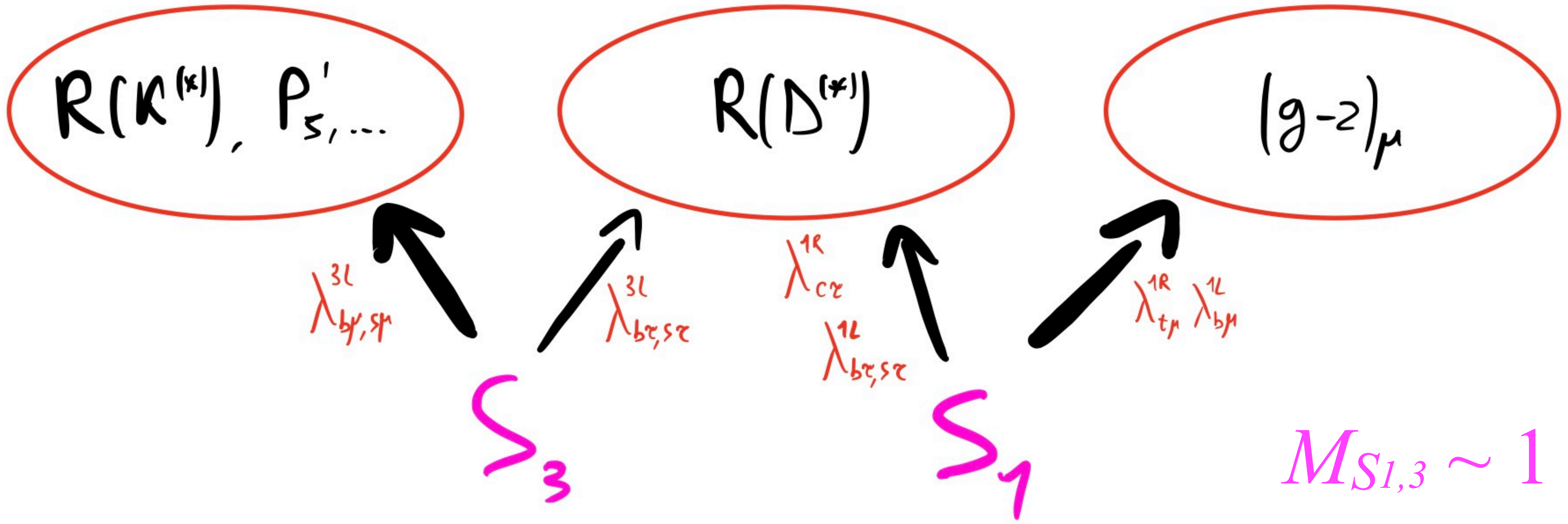


The combination of the two scalars can address both anomalies.

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



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

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

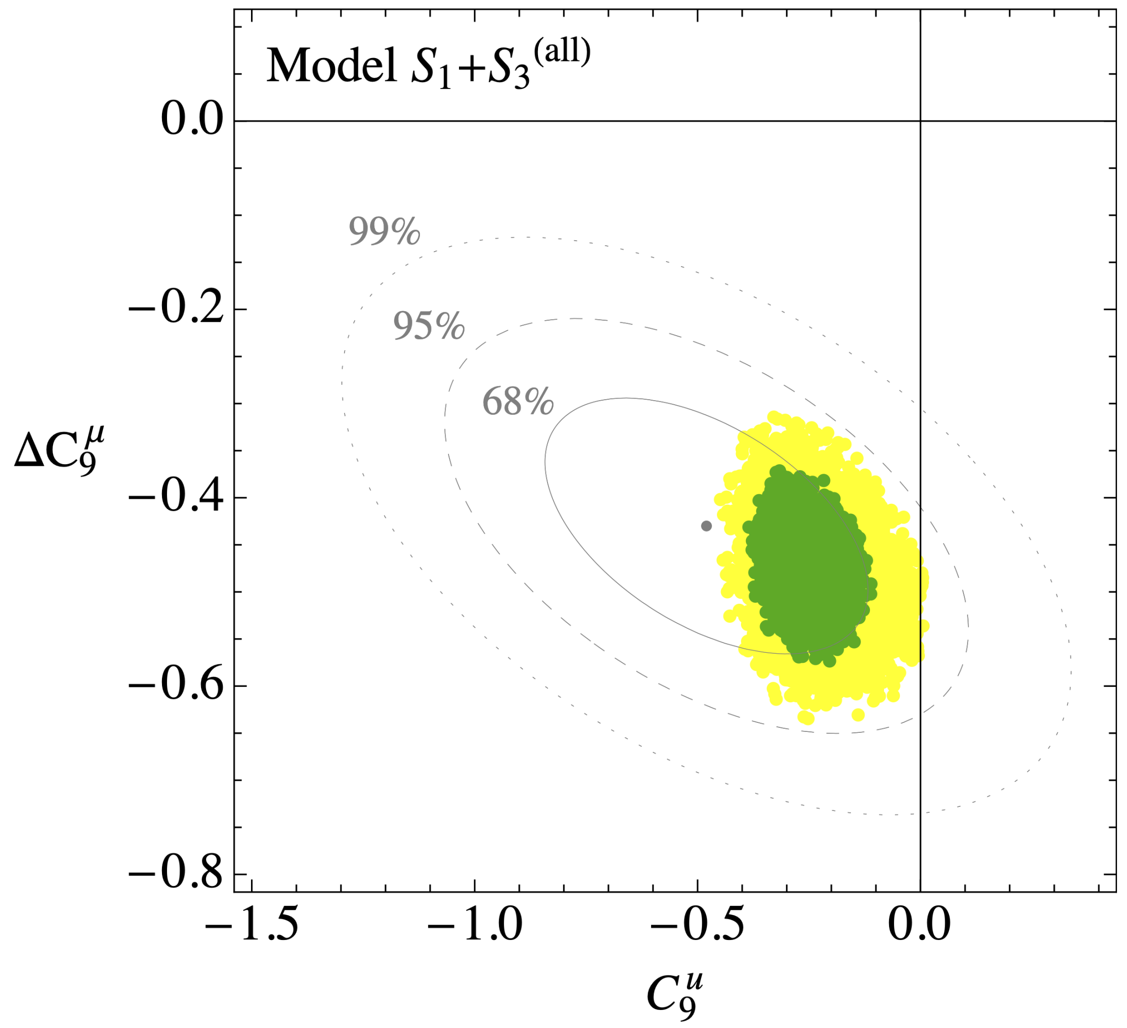
V. Gherardi, E. Venturini, D.M. [2008.09548]

10 active couplings

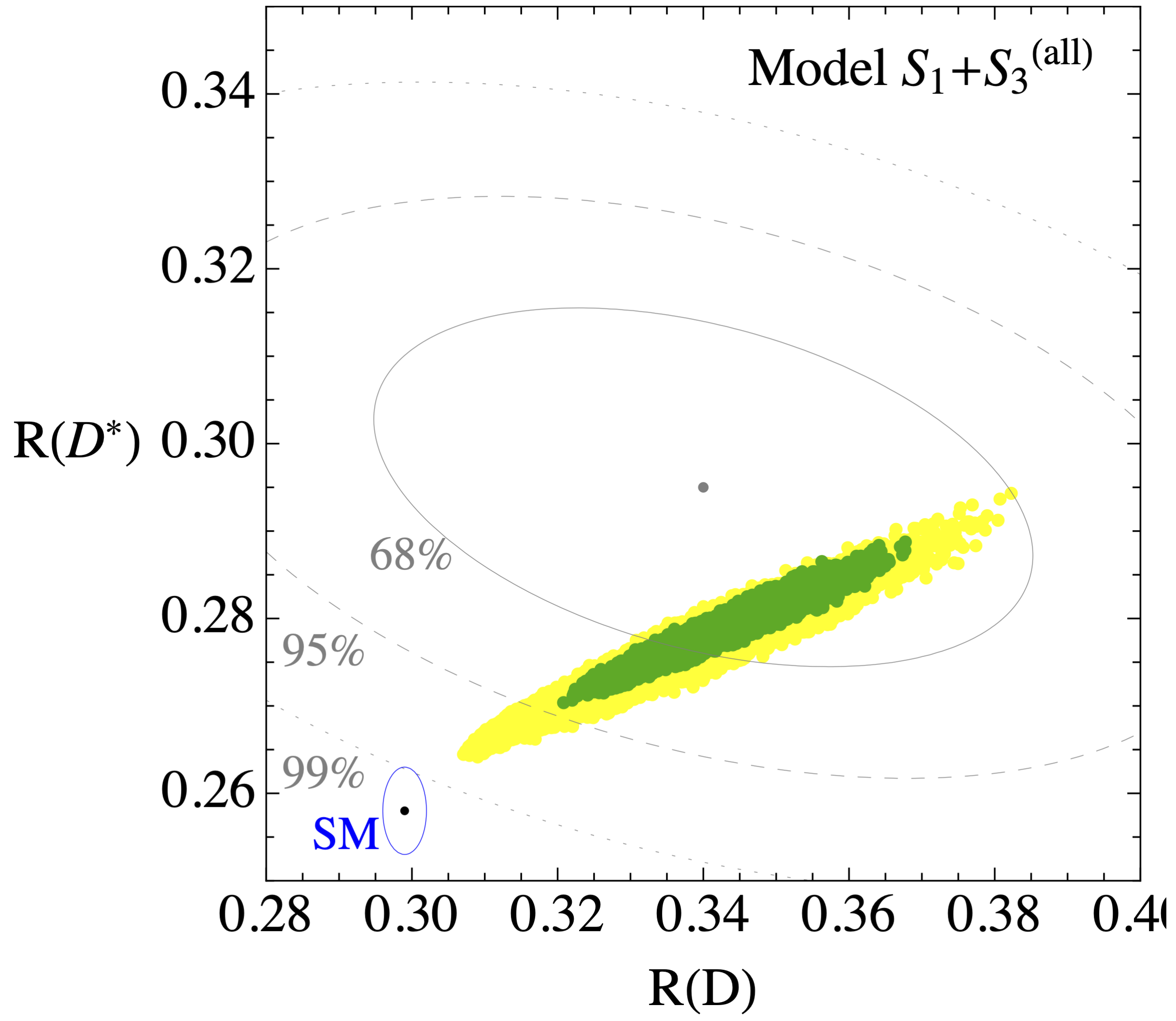
$$\lambda^{1L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & s\tau \\ 0 & b\mu & b\tau \end{pmatrix} \quad \lambda^{3L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & s\mu & s\tau \\ 0 & b\mu & b\tau \end{pmatrix}$$

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

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

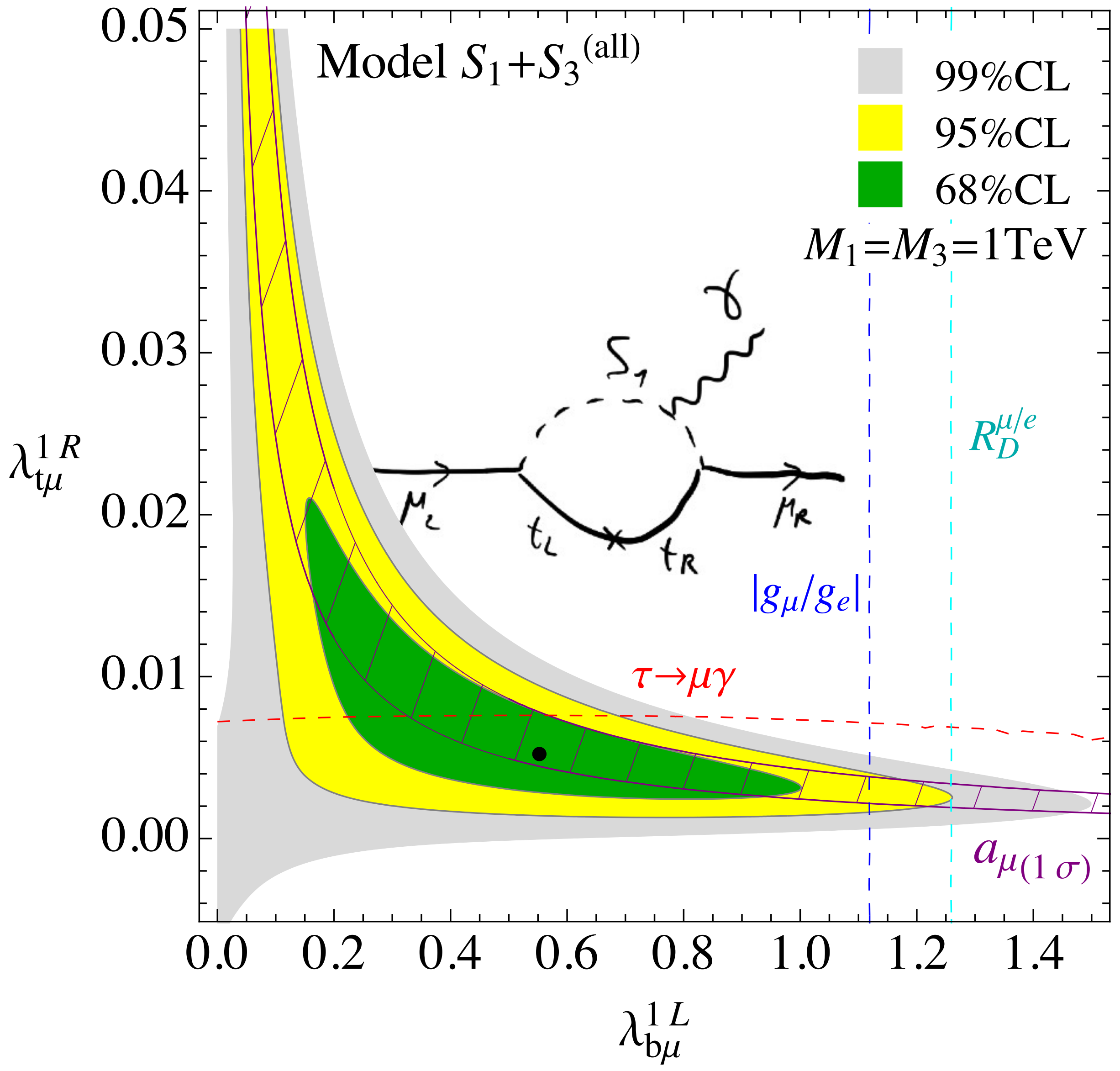


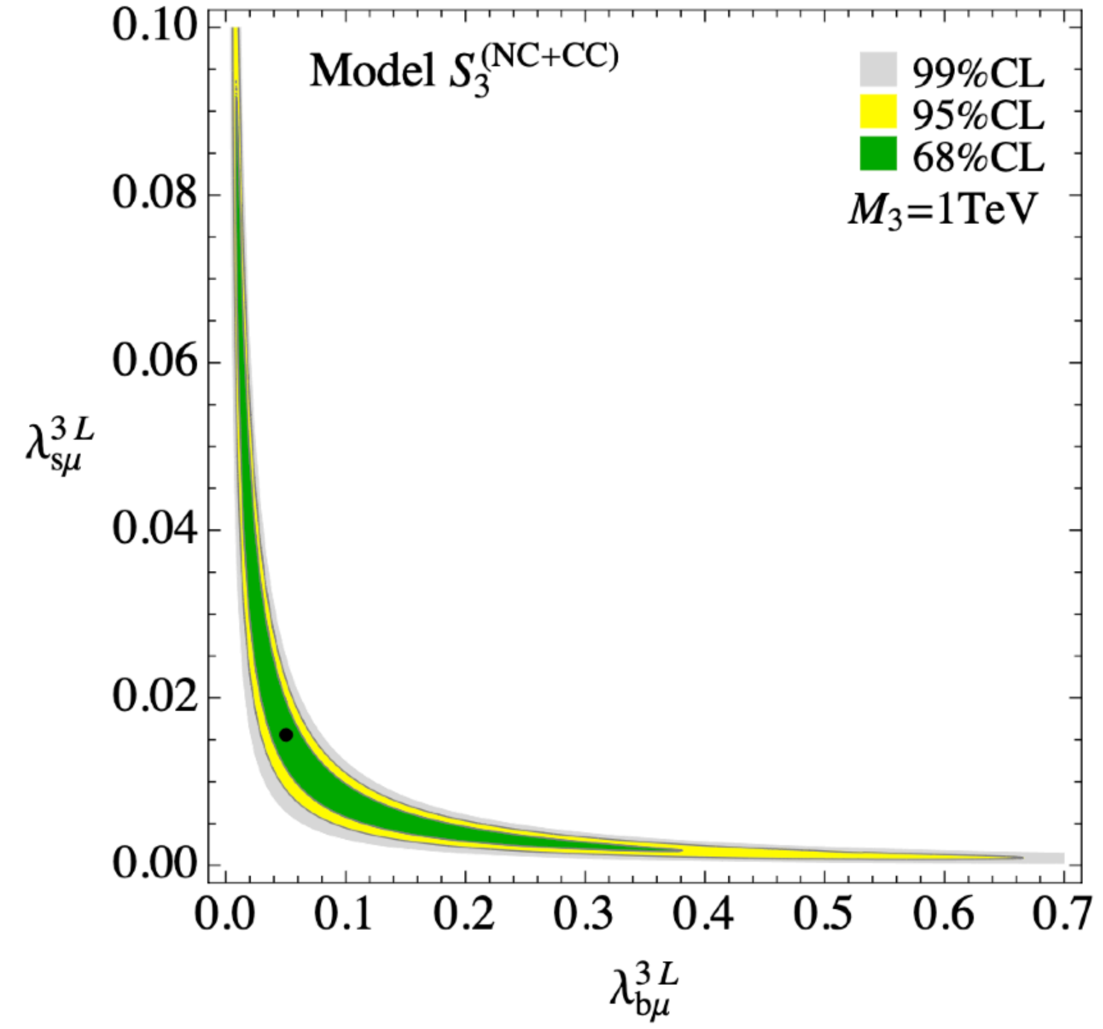
R(D$^{(*)}$)

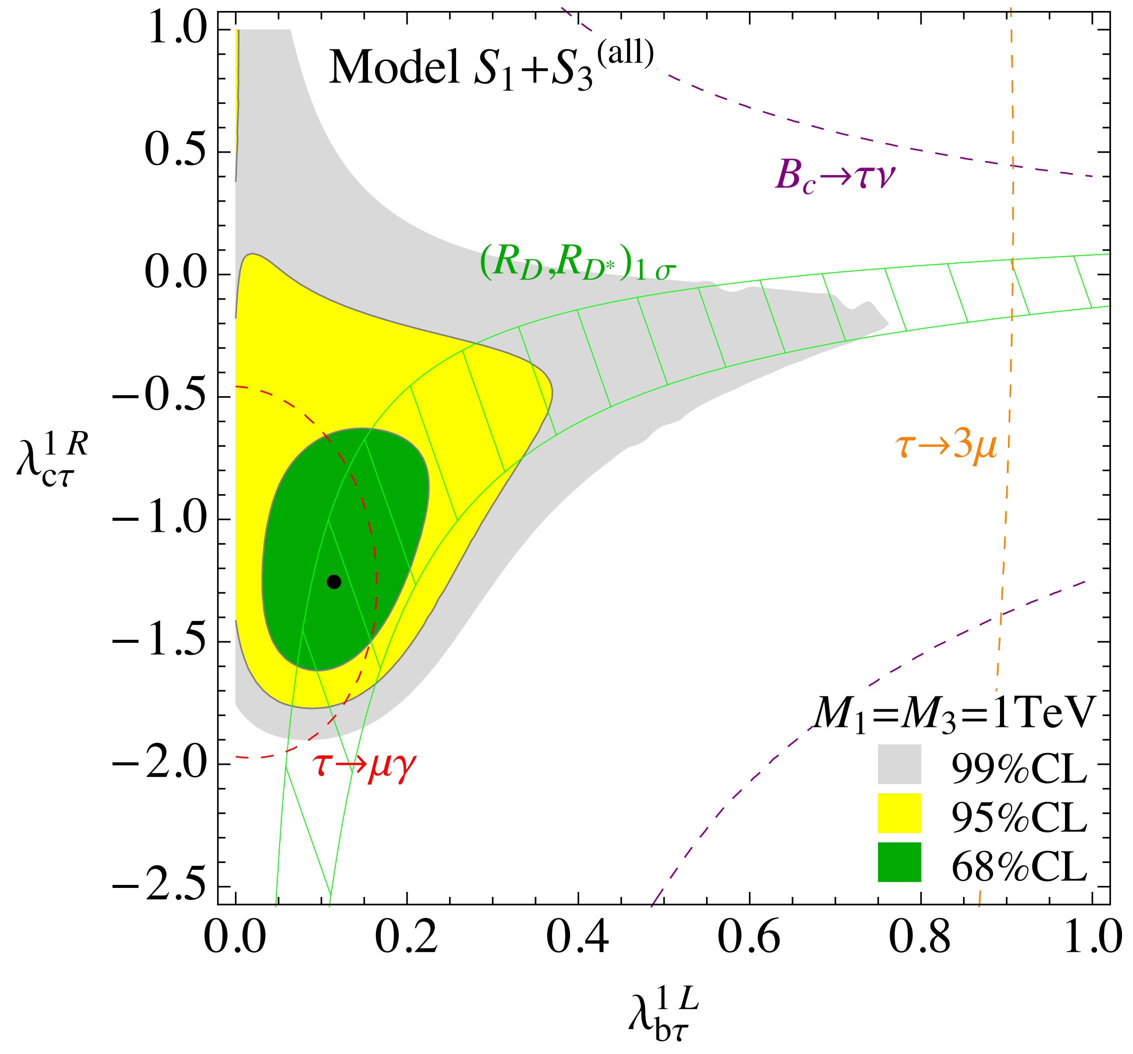


A **very good fit** of all three classes of anomalies can be achieved,
while being consistent with all phenomenological bounds.

(g-2)$_\mu$







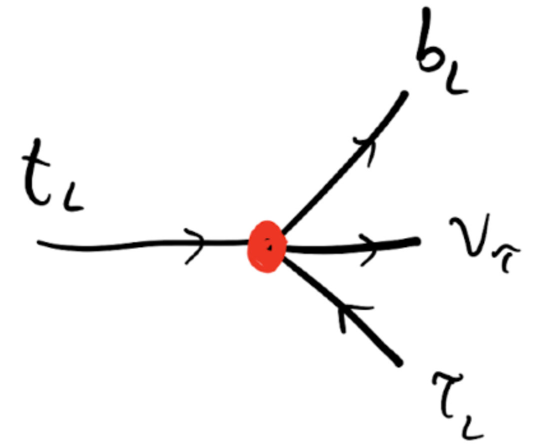
Implications for top physics - top decays

Implications for top physics - top decays

CC top decays

Solutions addressing $R(D^{(*)})$ only via LH couplings contribute to

$$\left[\tilde{O}^{(3)}_{\ell q}\right]^{3333} = \left(\bar{\ell}^3_L \gamma_\mu \ell^3_L\right)\left(\bar{q}^3_L \gamma^\mu q^3_L\right) \supset V^*_{tb}\left(\bar{\nu}_\tau \gamma_\mu \tau_L\right)\left(\bar{b}_L \gamma^\mu t_L\right)$$



Buttazzo, Greljo, Isidori, DM 1706.07808

with a typical size of O(few %) of the SM amplitude: $C_{tb\tau\nu} \sim (2\text{TeV})^{-2}$ → $Br_{BSM} \sim 10^{-7}$

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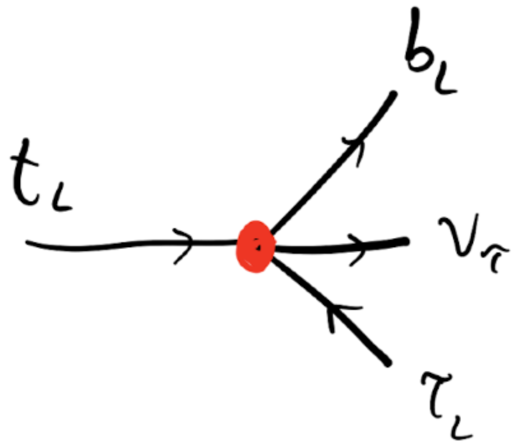


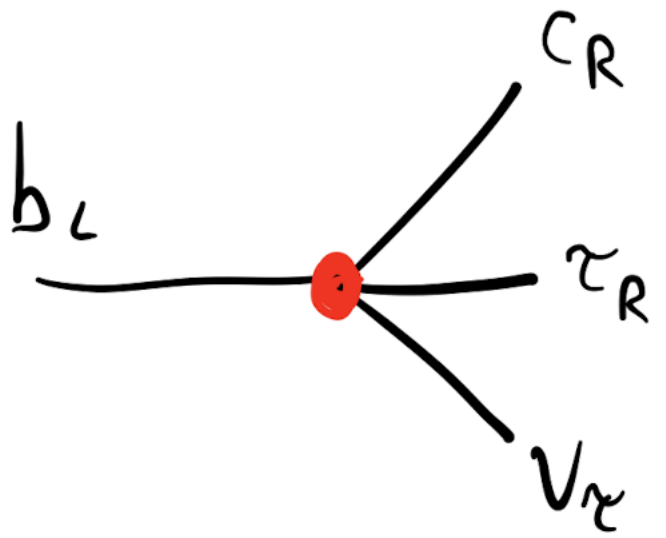
Buttazzo, Greljo, Isidori, DM 1706.07808

with a typical size of O(few %) of the SM amplitude: $C_{tb\tau\nu} \sim (2\text{TeV})^{-2}$ → Br$_{BSM}$ ~ 10^{-7}

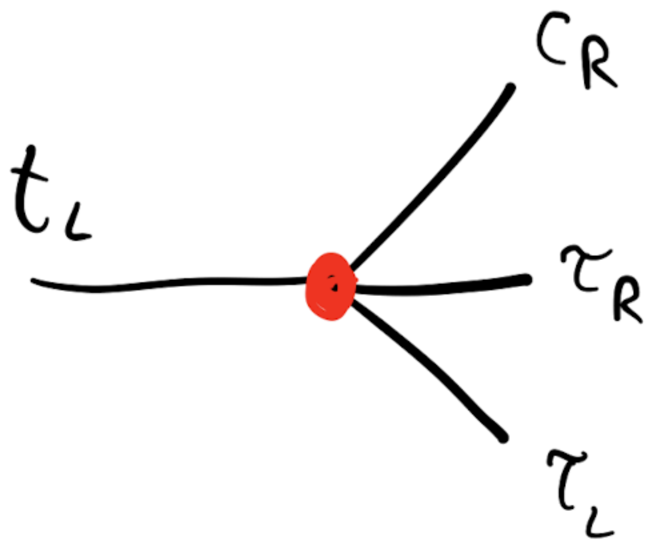
FCNC top decays

Solutions addressing R(D$^{(*)}$) via mixed LH and RH interactions, such as via **S$_1$** and **R$_2$** leptoquarks, also require a sizeable coupling to **c$_R$**.

$$\mathcal{L}_{EFT} = \frac{\lambda^{1R}_{c\tau}\lambda^{1L*}_{b\tau}}{2M_1^2}\left[\left(\bar{\ell}^3_L \tau_R\right)\epsilon\left(\bar{q}^3_L c_R\right) - \frac{1}{4}\left(\bar{\ell}^3_L \sigma_{\mu\nu}\tau_R\right)\epsilon\left(\bar{q}^3_L \sigma^{\mu\nu} c_R\right)\right] \longrightarrow$$



Directly correlated with R(D$^{(*)}$)

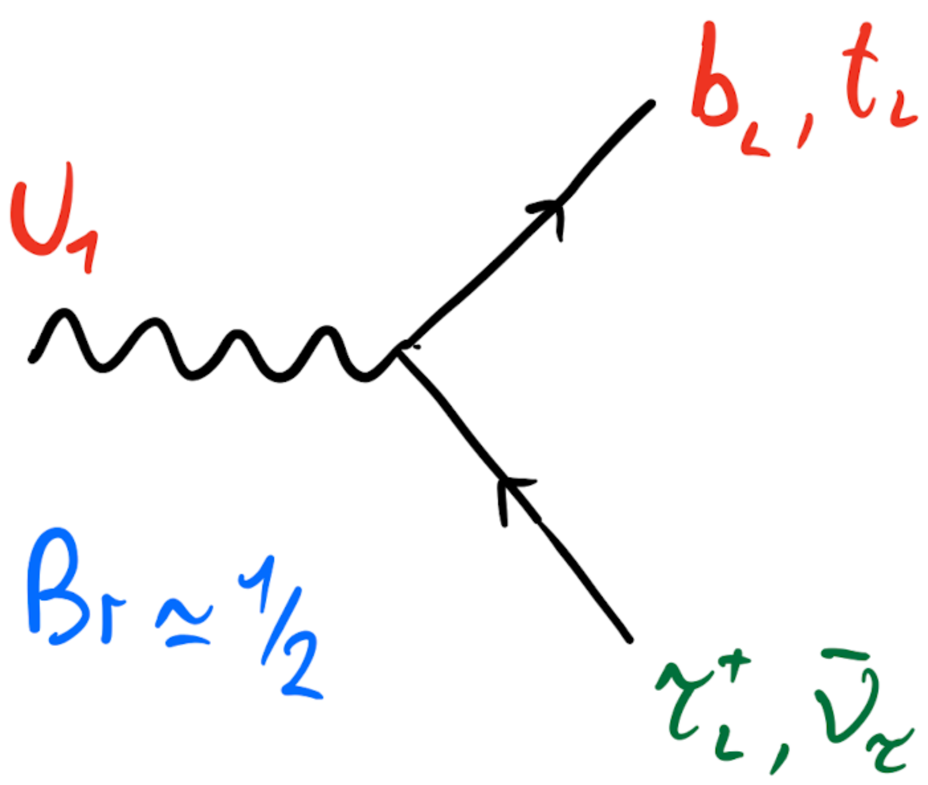


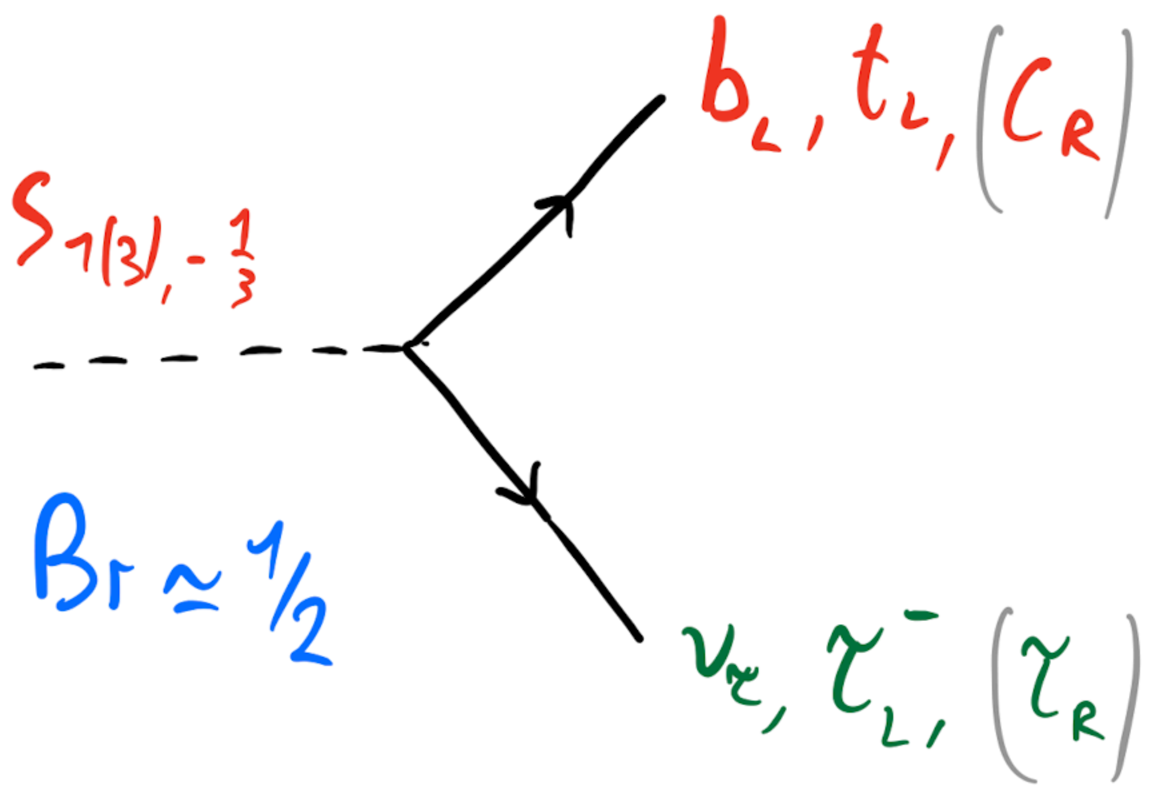
$$\sim \frac{\lambda^R_{c\tau}\lambda^L_{b\tau}}{M_1^2} \sim (2\,\text{TeV})^{-2}$$

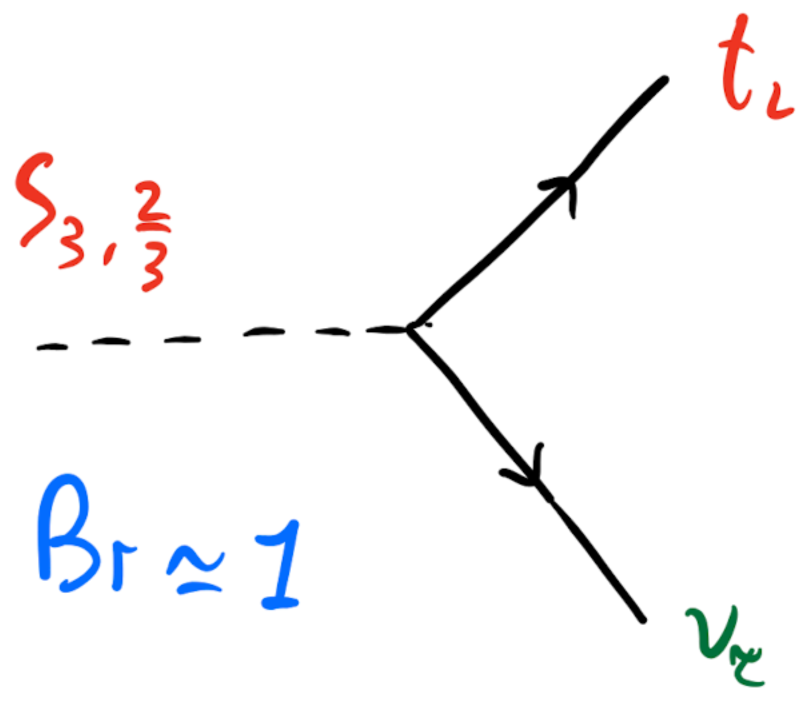
Br$_{FCNC}$ ~ 10^{-7}

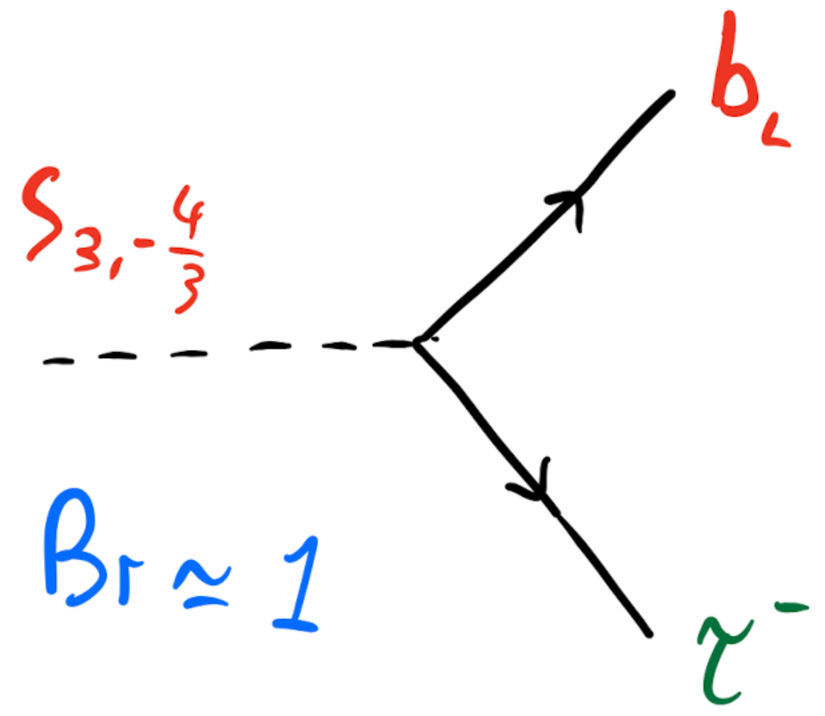
Implications for top physics - decays to top

In **direct searches** (pair-production and single-production)
decays to tops are typically with **large Br** and complementary to b quark.



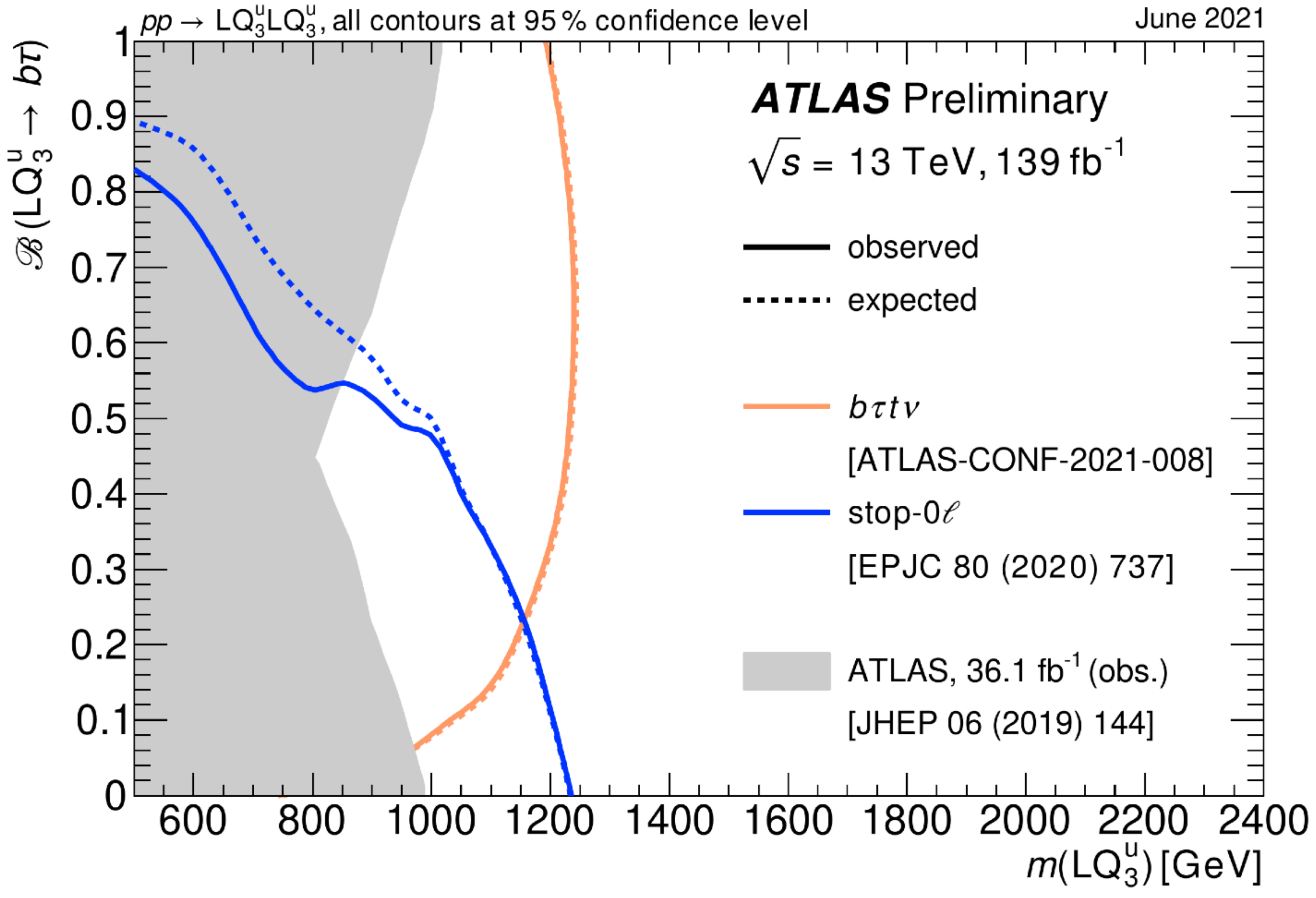


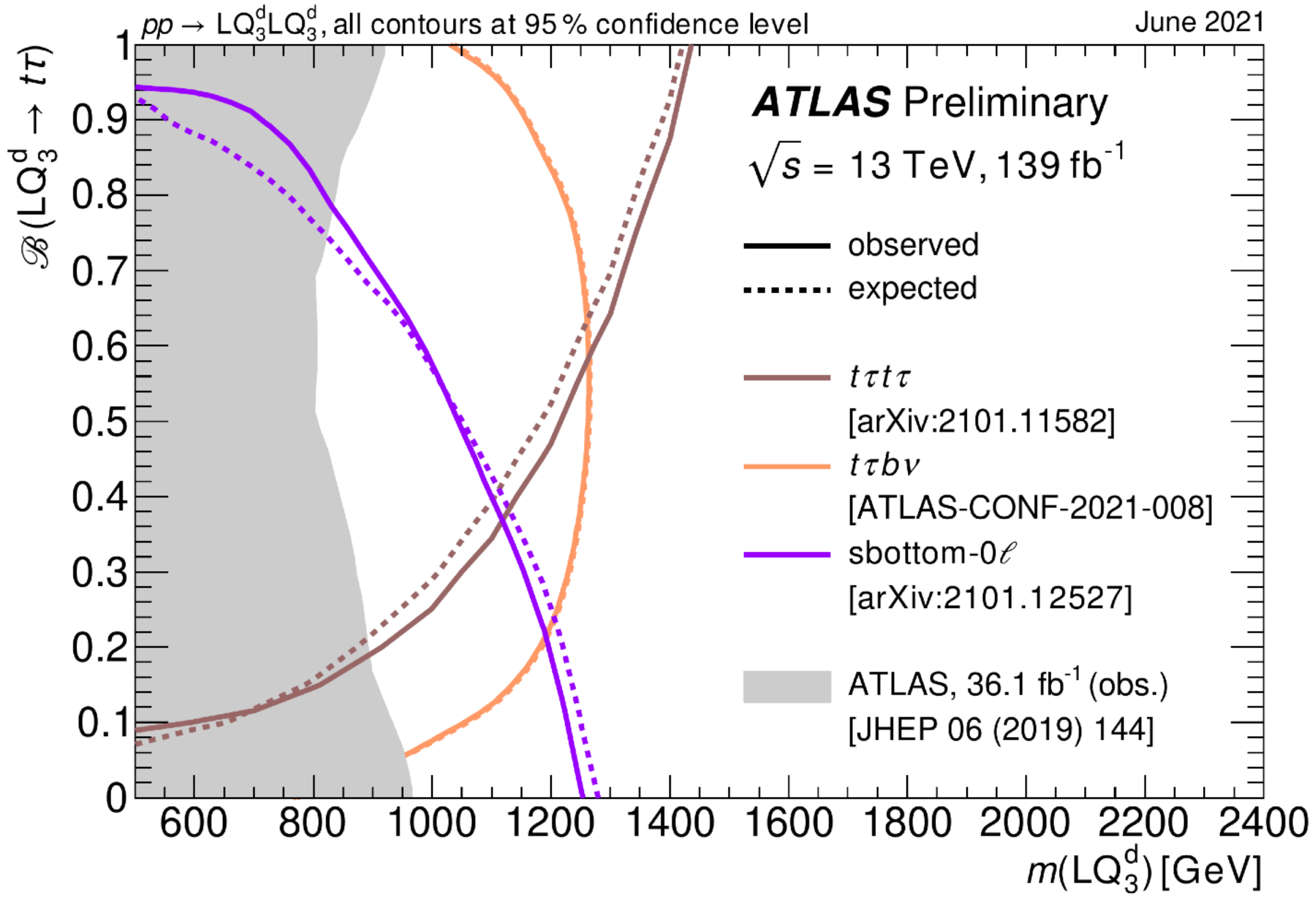




ATLAS lljj, lνjj 1902.00377
ATLAS lljj 2006.05872
ATLAS tt(ee,μμ) 2010.02098
ATLAS LQ→(tν,bτ) 1902.08103
ATLAS LQ→(bν,tτ) 2101.12527
ATLAS ttττ 2101.11582

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





Conclusions

- **Flavor anomalies** still require data (and theory) to give us a definitive picture.
  Experimental updates are expected in within the next few years, that could clarify the situation.

- Expectations are high, as this could potentially be our **threshold to an unexpected New Physics sector**!

From B-anomalies to top quarks

- While in most models NP has **sizeable couplings to top quark**,
  effects in top decays are expected to be **very small**, due to the large scale of NP.

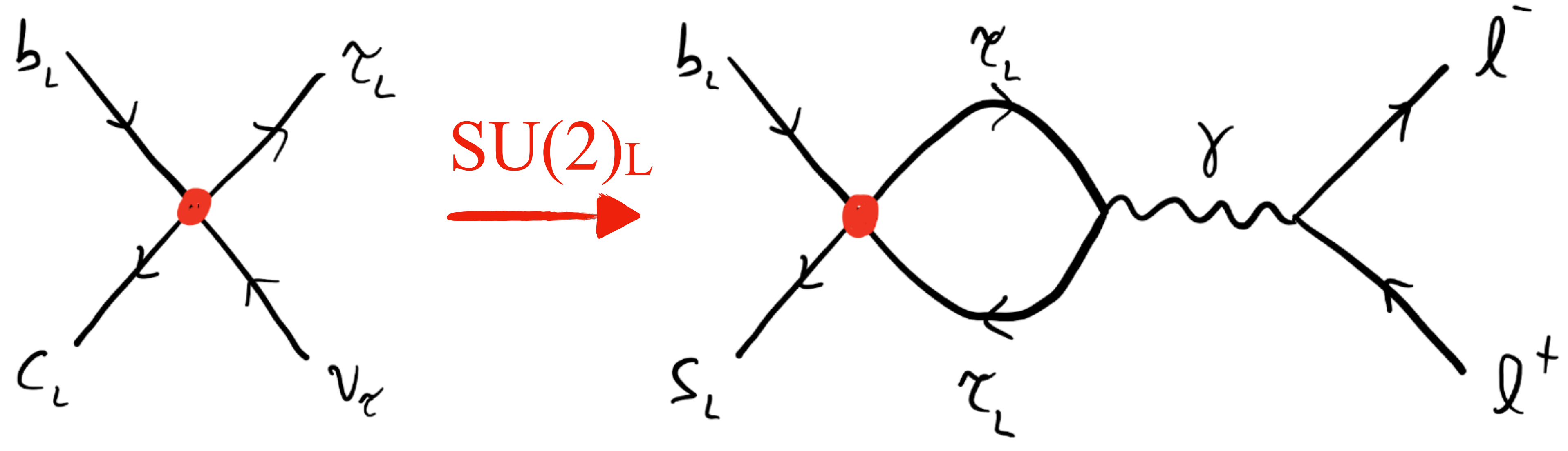
- In **top-philic Z’** models (for NC B-anomalies) **associated production of Z’ with $t\,\bar{t}$** could have a large cross section.

- Top quarks play instead a **major role as final states of leptoquark searches**, crucial to discovery or putting limits.

Thank you!

Backup

Hints of a connection: R_K & $R(D^{(*)})$

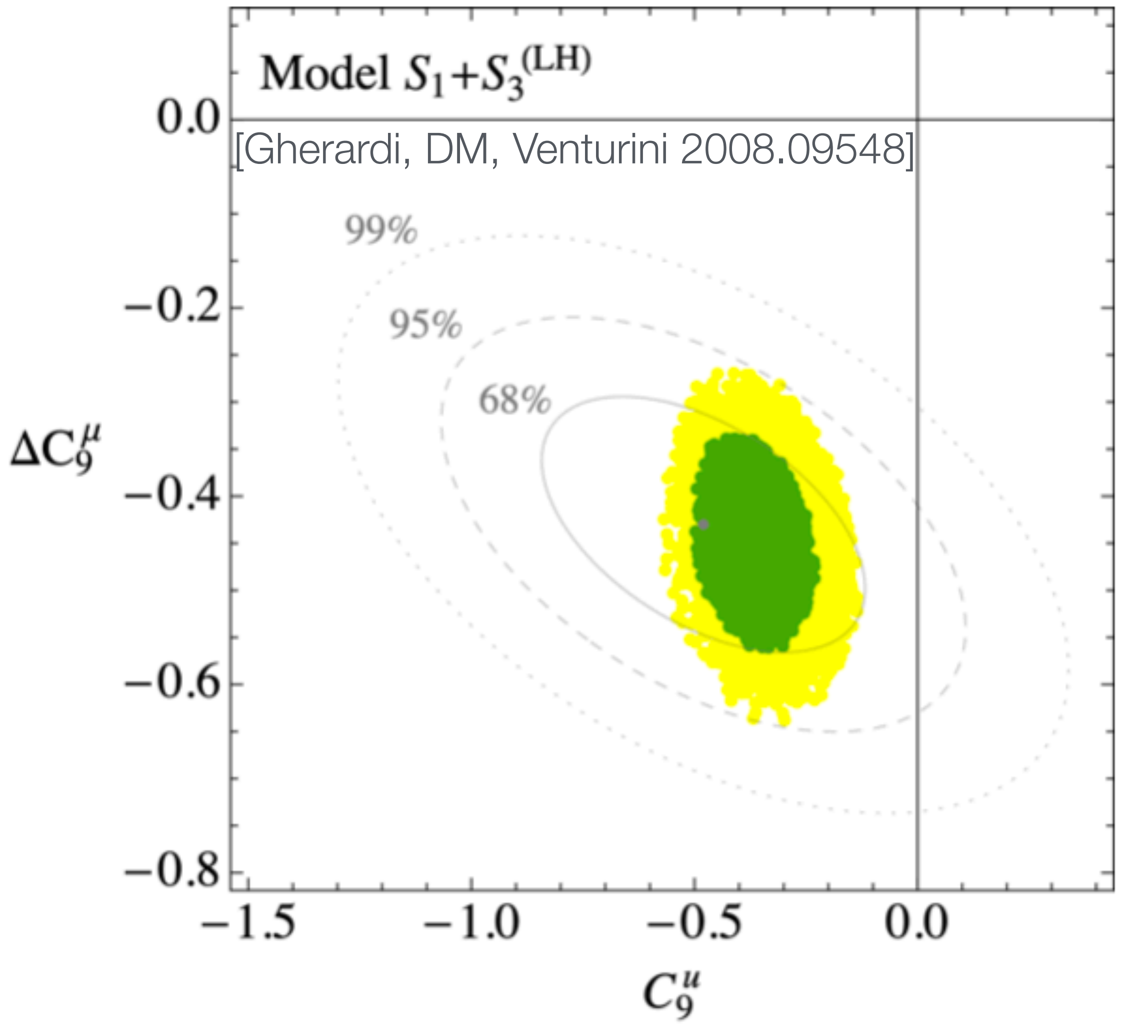


Lepton-Flavor Universal and **vector-like** contribution to **b_L s_L μ μ**. (coeff. C_9^U)

Capdevila et al. 1712.01919, Crivellin et al. 1807.02068

$$C_9^{\rm U} \approx 7.5 \left(1-\sqrt{\frac{R_{D^{(*)}}}{R_{D^{(*)}\rm SM}}}\right)\left(1+\frac{\log(\Lambda^2/(1\,{\rm TeV}^2))}{10.5}\right)$$

A small contribution to C_9^U is preferred by the fits (<2σ)



[Gherardi, DM, Venturini 2008.09548]

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

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)$_L$

$$\boxed{C_T\ (\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L)} + C_S\ (\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)$$

Usually UV physics generates both.

The exception are Z' models, which generate only the singlet

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

Charged-current in muons

Generalising lepton flavour

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

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

S_1+S_3 leptoquarks - global analysis

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

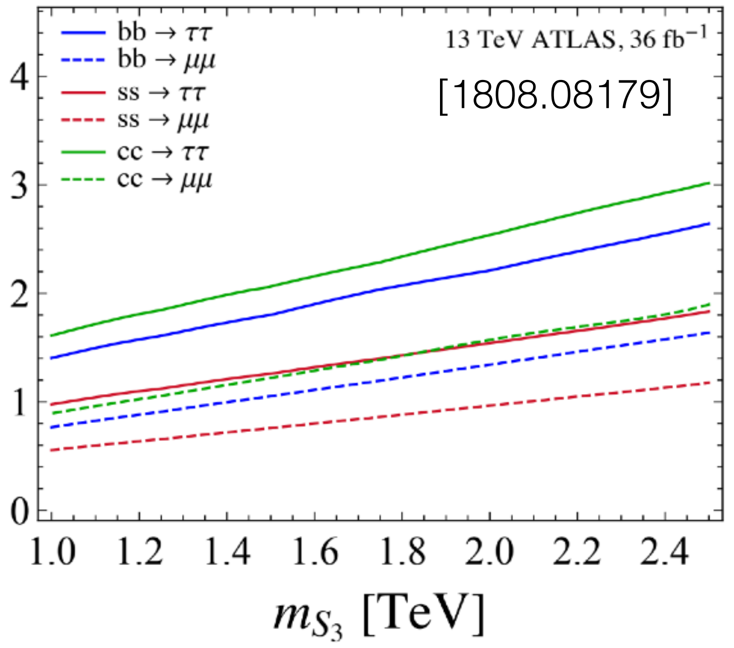
Using the complete one-loop matching to SMEFT, we include in our analysis all these observables.

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

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

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

Drell-Yan



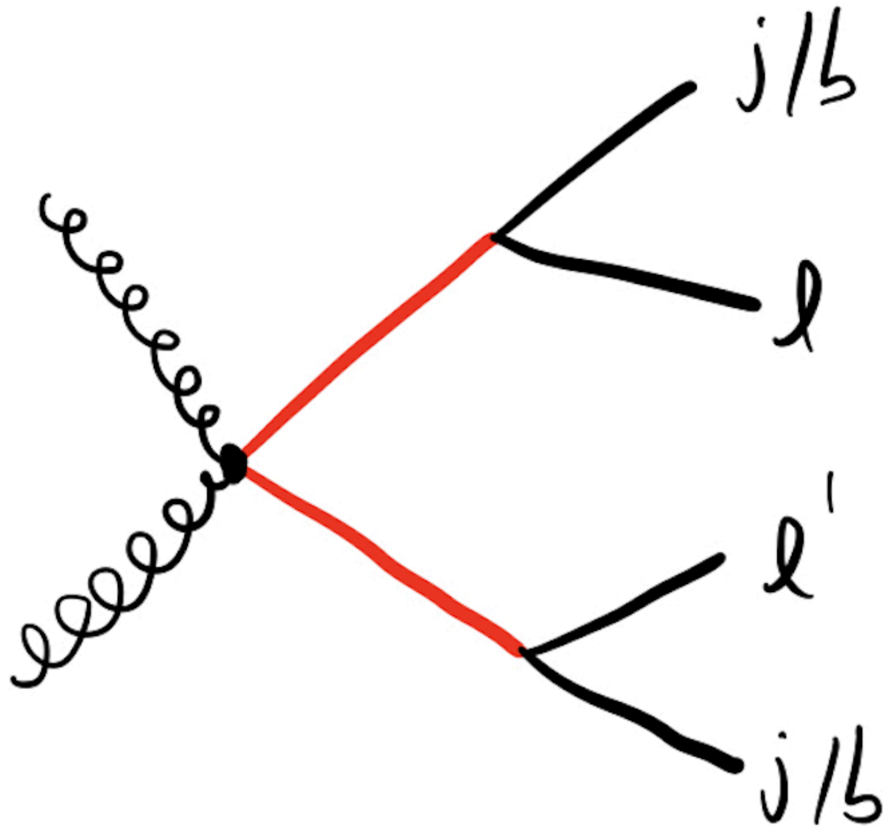
Observable	**SM prediction**	**Experimental bounds**
$b \to s\ell\ell$ observables		[37]
$\Delta\mathcal{C}_9^{sb\mu\mu}$	0	-0.43 ± 0.09 [79]
$\mathcal{C}_9^{\text{univ}}$	0	-0.48 ± 0.24 [79]
$b \to c\tau(\ell)\nu$ observables		[37]
R_D	0.299 ± 0.003 [12]	$0.34 \pm 0.027 \pm 0.013$ [12]
R_D^*	0.258 ±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

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

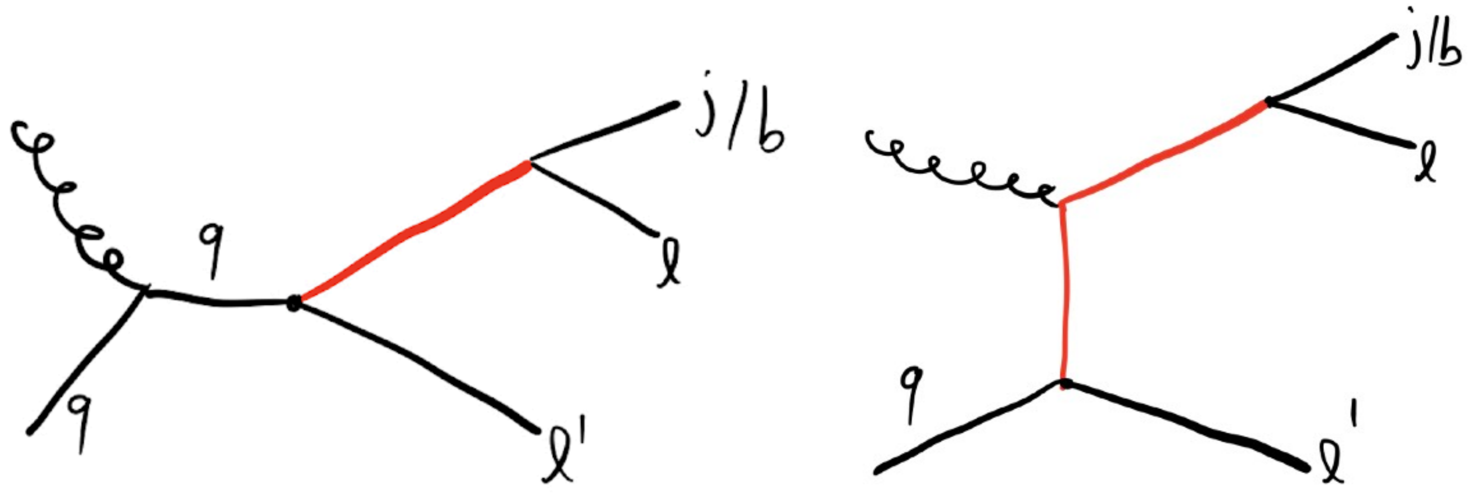
Observable	**SM prediction**	**Experimental bounds**
$\Delta F = 2$ processes		[37]
$B^0 - \overline{B}^0$: $\lvert C^1_{B_d}\rvert$	0	$< 9.1 \times 10^{-7}$ TeV^{-2} [114, 115]
$B^0_s - \overline{B}^0_s$: $\lvert C^1_{B_s}\rvert$	0	$< 2.0 \times 10^{-5}$ TeV^{-2} [114, 115]
$K^0 - \overline{K}^0$: $\text{Re}[C^1_K]$	0	$< 8.0 \times 10^{-7}$ TeV^{-2} [114, 115]
$K^0 - \overline{K}^0$: $\text{Im}[C^1_K]$	0	$< 3.0 \times 10^{-9}$ TeV^{-2} [114, 115]
$D^0 - \overline{D}^0$: $\text{Re}[C^1_D]$	0	$< 3.6 \times 10^{-7}$ TeV^{-2} [114, 115]
$D^0 - \overline{D}^0$: $\text{Im}[C^1_D]$	0	$< 2.2 \times 10^{-8}$ TeV^{-2} [114, 115]
$D^0 - \overline{D}^0$: $\text{Re}[C^4_D]$	0	$< 3.2 \times 10^{-8}$ TeV^{-2} [114, 115]
$D^0 - \overline{D}^0$: $\text{Im}[C^4_D]$	0	$< 1.2 \times 10^{-9}$ TeV^{-2} [114, 115]
$D^0 - \overline{D}^0$: $\text{Re}[C^5_D]$	0	$< 2.7 \times 10^{-7}$ TeV^{-2} [114, 115]
$D^0 - \overline{D}^0$: $\text{Im}[C^5_D]$	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]
$\lvert d_e\rvert$	$< 10^{-44}\,\text{e}\cdot\text{cm}$ [124, 125]	$< 1.3 \times 10^{-29}\,\text{e}\cdot\text{cm}$ [126]
$\lvert d_\mu\rvert$	$< 10^{-42}\,\text{e}\cdot\text{cm}$ [125]	$< 1.9 \times 10^{-19}\,\text{e}\cdot\text{cm}$ [127]
d_τ	$< 10^{-41}\,\text{e}\cdot\text{cm}$ [125]	$(1.15 \pm 1.70) \times 10^{-17}\,\text{e}\cdot\text{cm}$ [37]
d_n	$< 10^{-33}\,\text{e}\cdot\text{cm}$ [128]	$< 2.1 \times 10^{-26}\,\text{e}\cdot\text{cm}$ [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]

The Threefold Way of LQ Searches at LHC

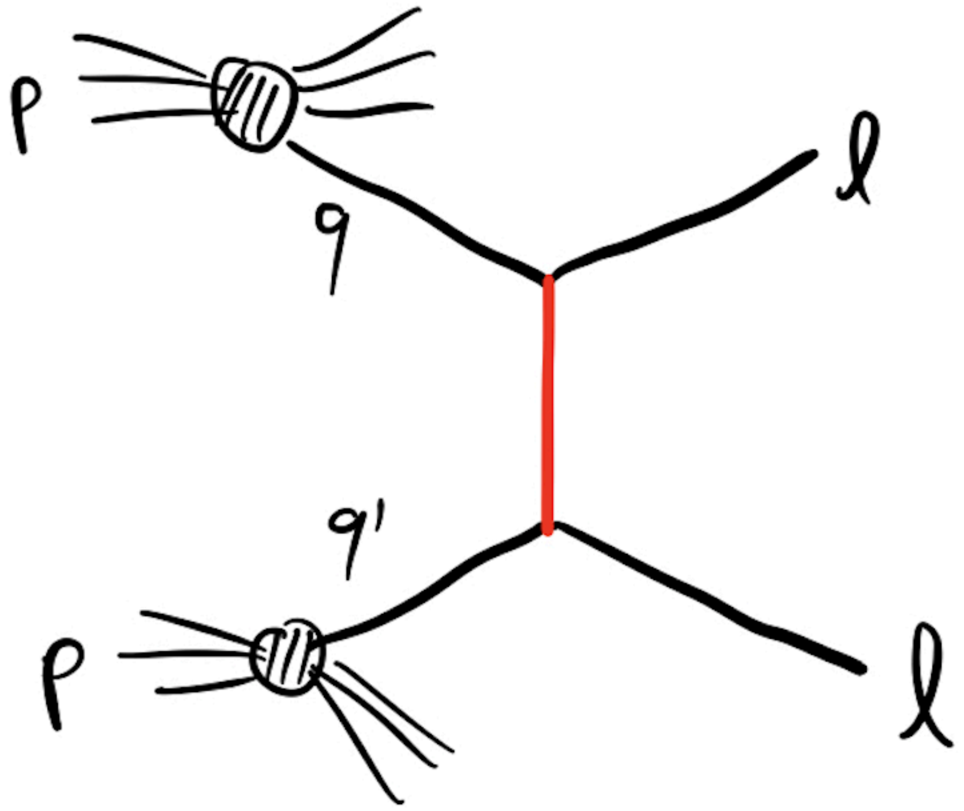
QCD
pair-production

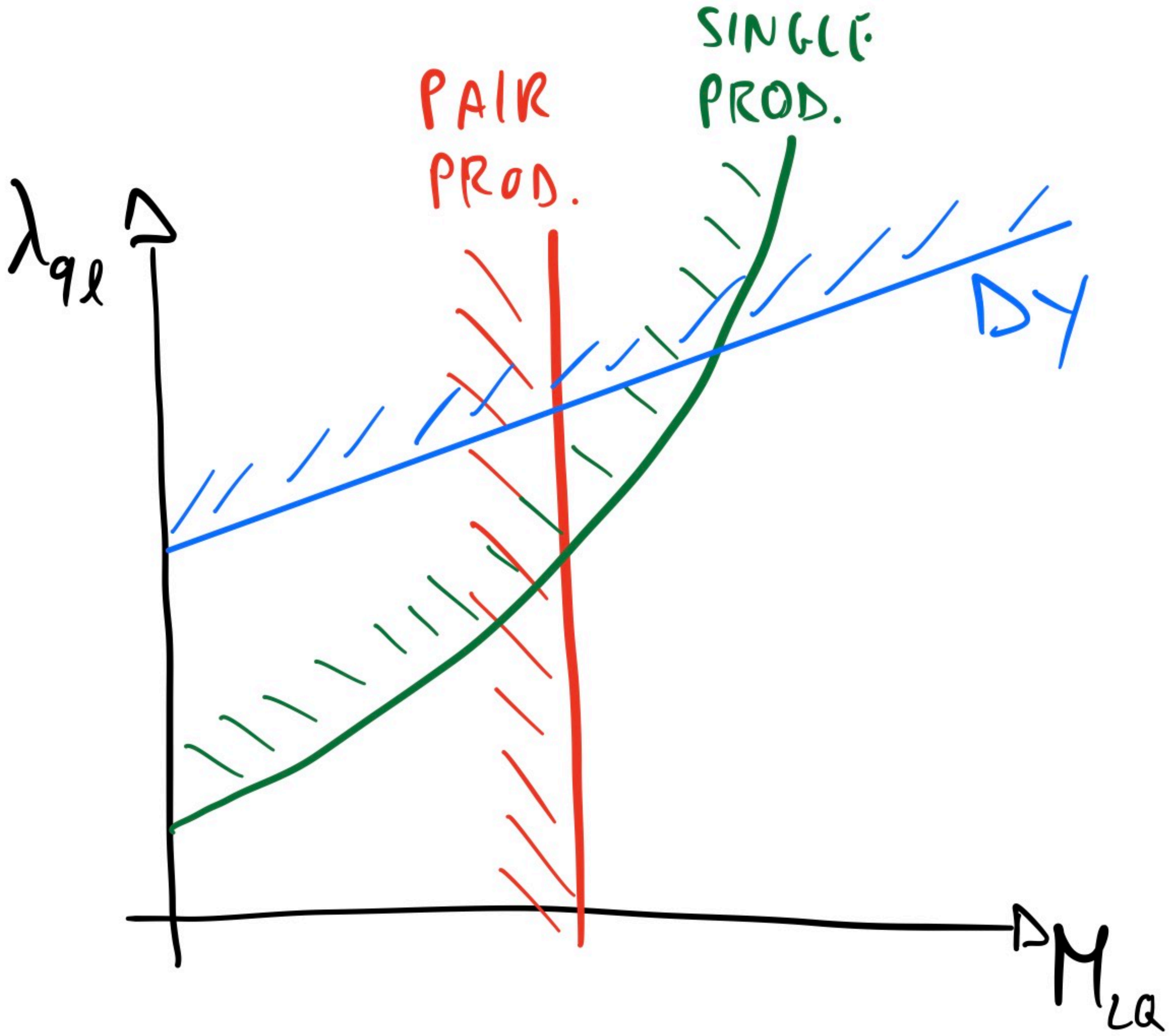


single-production



High-p_T Drell-Yan



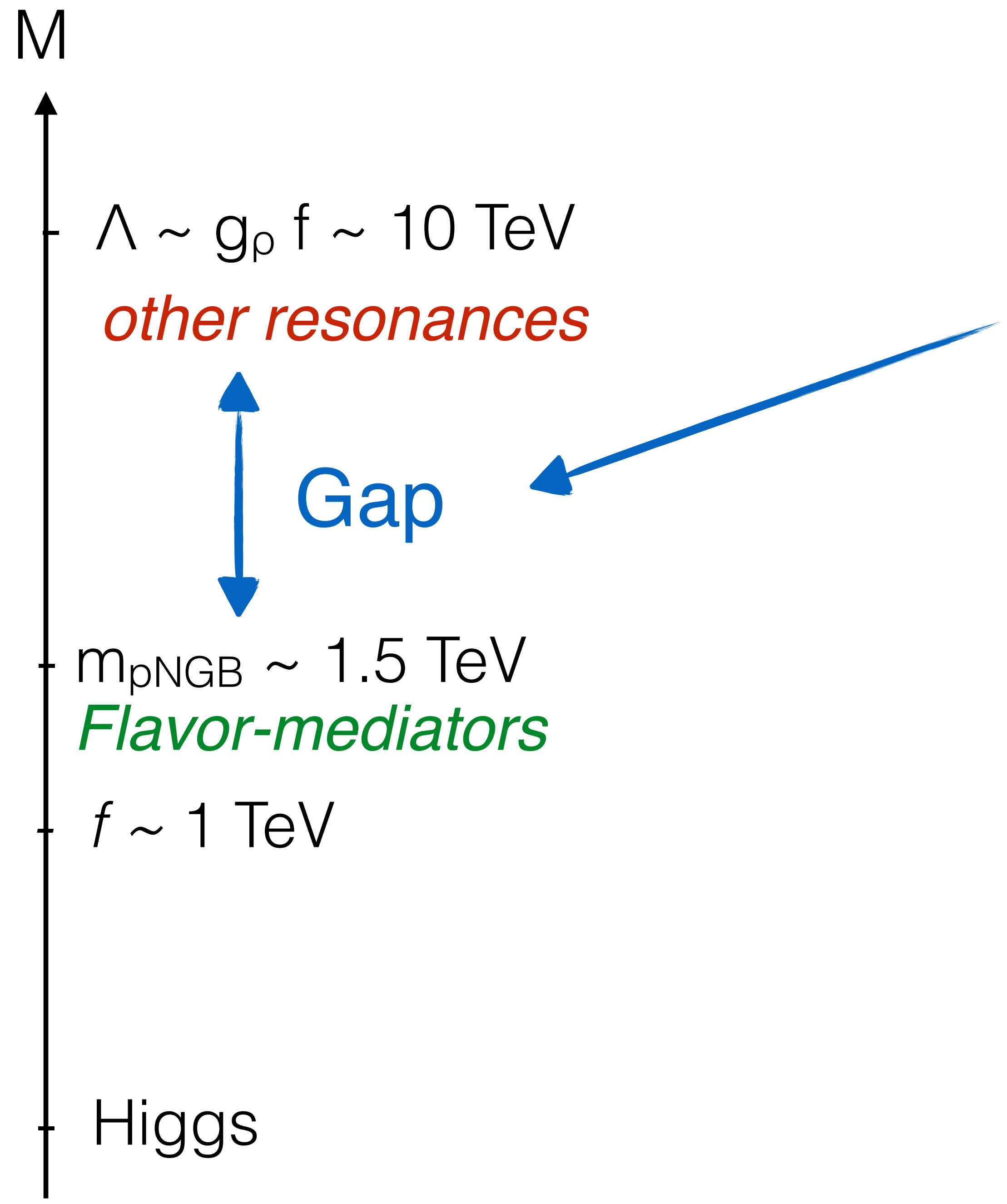


[Diaz, Schmaltz, Zhong 1706.05033, 1810.10017; Dorsner, Greljo 1801.07641]

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

Fundamental Composite model for LQs + Higgs

[D.M. 1803.10972]



Scalar LQ as pseudo-Goldstone boson

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

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

Gauge group:

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

"HyperColor"

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

Extra Dirac fermions:

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

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

$$G = \mathrm{SU}(10)_{\mathrm{L}} \times \mathrm{SU}(10)_{\mathrm{R}} \times \mathrm{U}(1)_{\mathrm{V}} \xrightarrow{f \sim 1\mathrm{TeV}} H = \mathrm{SU}(10)_{\mathrm{V}} \times \mathrm{U}(1)_{\mathrm{V}}$$

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

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

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

Coupling with SM fermions from 4-Fermi operators

Yukawas &
LQ couplings

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

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