New physics models for the B-anomalies

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Implications of LHCb measurements and future prospects

CERN, October 16, 2019.

Outline

Several discrepancies [$\approx 2-3\sigma$] appeared recently in B-meson decays:

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

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

$\Rightarrow$ Violation of **L**epton **F**lavor **U**niversality (LFU)?

This talk: (i) EFT interpretations

(ii) On the viable leptoquark models

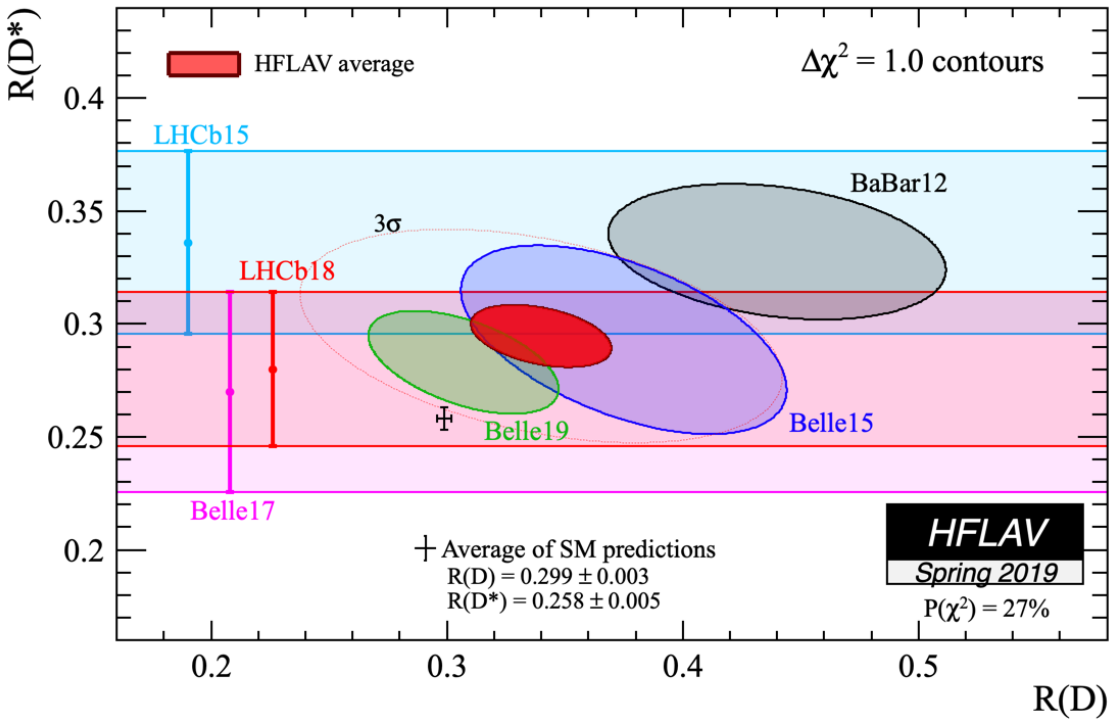
Focus: Main predictions for LHC(b) and Belle-II

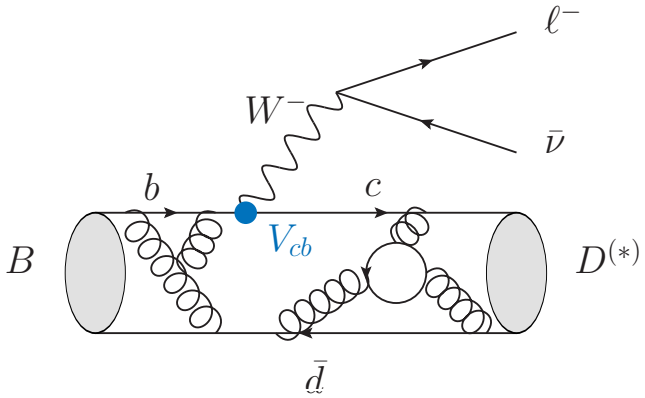
Brief overview of the B-anomalies

(i) $R_{D^{(*)}} = \mathcal{B}(B \to D^{(*)}\tau\bar{\nu})/\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})$

Experiment $[\approx 3.1\sigma]$

See talk G. Pardinas





- R_D and R_{D^*}: $[\approx 2\sigma]$ and $[\approx 3\sigma]$; dominated by BaBar.
- LHCb confirmed tendency $R^{\rm exp}_{J/\psi} > R^{\rm SM}_{J/\psi}$, i.e. $B_c \to J/\psi\ell\bar{\nu}$,

$\Rightarrow$ **Needs clarification** from **Belle-II & LHCb (run-2)** data!

(i) $R_{D^{(*)}} = \mathcal{B}(B \to D^{(*)}\tau\bar{\nu})/\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})$

Theory (tree-level in SM) *See talks by Peñuelas, Jung and Melic*

- R_D: lattice QCD at $q^2 \neq q^2_{\rm max}$ $(w > 1)$ available for both leading (vector) and subleading (scalar) form factors [MILC 2015, HPQCD 2015]

$$\langle D(k)|\bar{c}\gamma^\mu b|B(p)\rangle = \left[(p+k)^\mu - \frac{m_B^2 - m_D^2}{q^2}q^\mu\right] f_+(q^2) + q^\mu \frac{m_B^2 - m_D^2}{q^2} f_0(q^2)$$

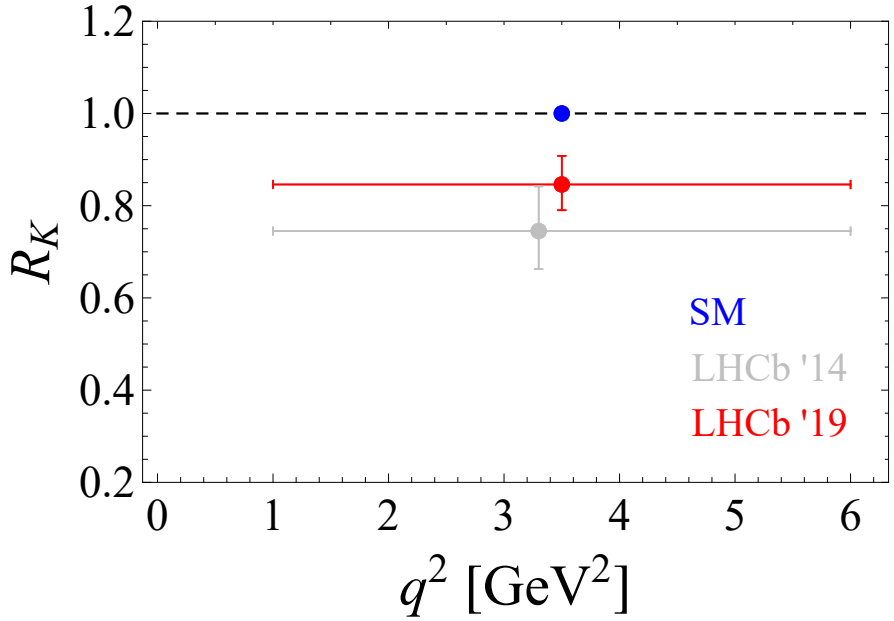
with $f_+(0) = f_0(0)$.

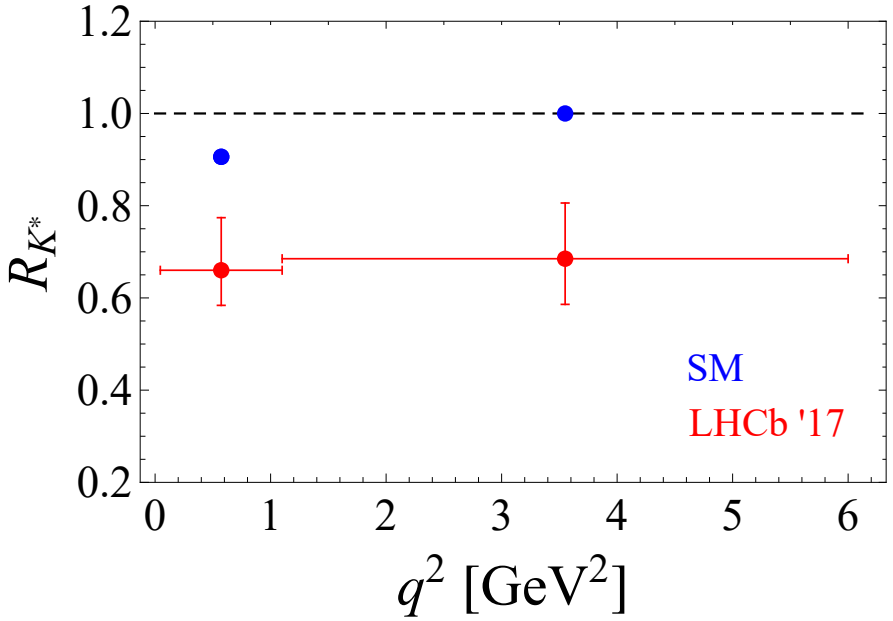
- R_{D^*}: lattice QCD at $q^2 \neq q^2_{\rm max}$ not available, scalar form factor $[A_0(q^2)]$ never computed on the lattice

Use decay angular distributions measured at B-factories to fit the leading form factor $[A_1(q^2)]$ and extract two others as ratios wrt $A_1(q^2)$. All other ratios from HQET (NLO in $1/m_{c,b}$) [Bernlochner et al 2017] but with more generous error bars (truncation errors?) **[Preliminary LQCD results by Fermilab/MILC!]**

(ii) $R_{K^{(*)}} = \mathcal{B}(B \to K^{(*)}\mu\mu)/\mathcal{B}(B \to K^{(*)}ee)$

Experiment $[\approx 4\sigma]$ *See talk by Lisovskyi*





$\Rightarrow$ **Needs confirmation from Belle-II!**

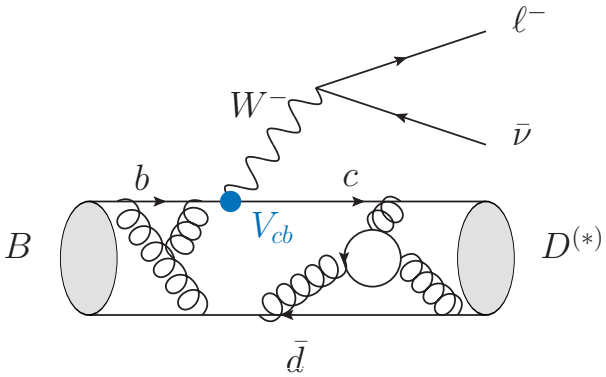
Theory (loop induced in SM) [Kruger, Hiller. '03]

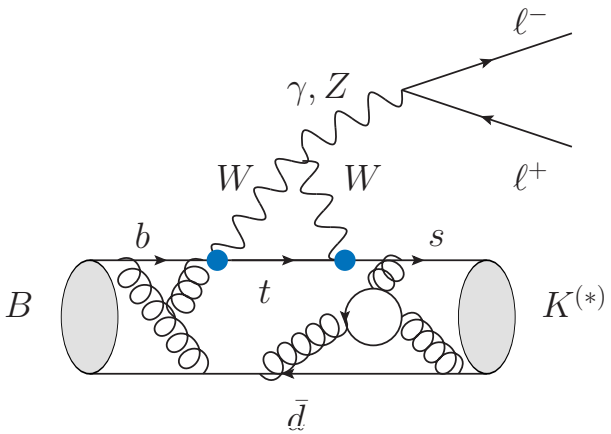
- Hadronic uncertainties cancel to a large extent.
  $\Rightarrow$ Clean observables! [*working below the narrow $c\bar{c}$ resonances*]
- QED corrections important, $R_{K^{(*)}} = 1.00(1)$. [Bordone et al. '16]

EFT interpretations

What is the **scale of New Physics**?

- $R^{\rm exp}_{D^{(*)}} > R^{\rm SM}_{D^{(*)}} \quad \Rightarrow \quad \Lambda_{\rm NP} \lesssim 3$ TeV [perturbative couplings]
- $R^{\rm exp}_{K^{(*)}} < R^{\rm SM}_{K^{(*)}} \quad \Rightarrow \quad \Lambda_{\rm NP} \lesssim 30$ TeV see also [Di Luzio et al. 2017]





i) Effective theory for $b \to c\tau\bar{\nu}$

R_D & R_{D^*}

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

General messages:

See talk by Peñuelas

- $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge invariance:

  $\Rightarrow$ g_{V_R} is LFU at dimension 6 ($W\bar{c}_R b_R$ vertex).

  $\Rightarrow$ Four coefficients left: g_{V_L}, g_{S_L}, g_{S_R} and g_T.

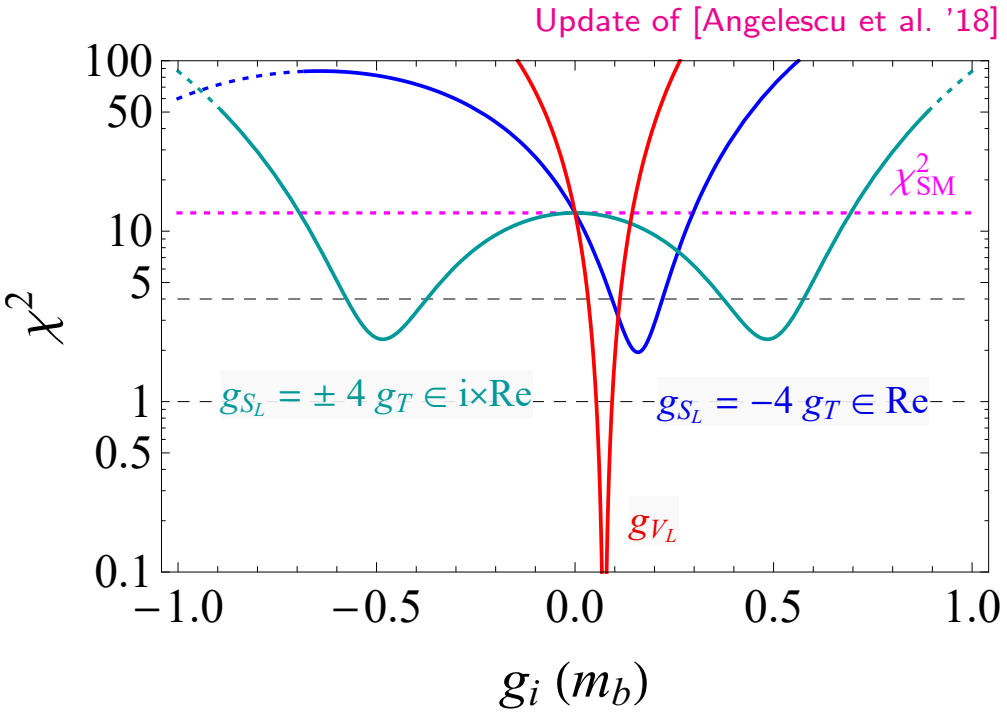
- Several viable solutions to $R_{D^{(*)}}$: [Freytsis et al. 2015]

  ◦ e.g. $g_{V_L} \in (0.05, 0.09)$, but not only!

[Angelescu, Becirevic, Faroughy, **OS**. 1808.08179]

see also [Murgui et al. '19, Shi et al. '19, Blanke et al. '19]

Which Lorentz structure to pick?



Viable solutions (at $\mu \approx 1$ TeV):

$\Rightarrow$ g_{V_L} and $g_{S_L} = \pm 4\, g_T$

See talk by Peñuelas

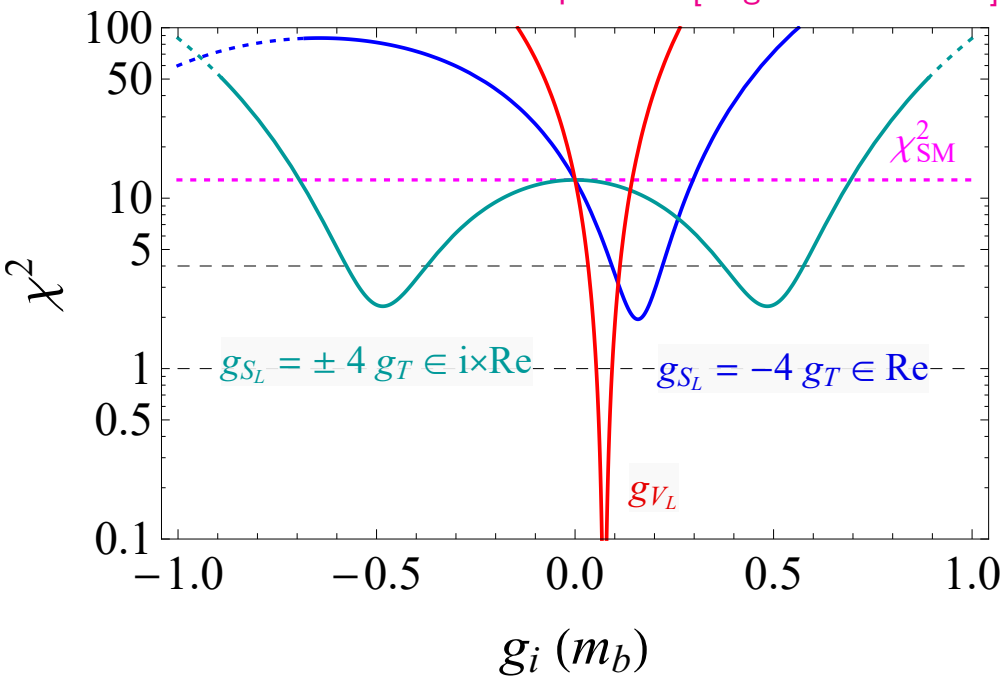
More exp. information is needed:

$\Rightarrow$ e.g. $B \to D^*(D\pi)\tau\bar{\nu}$ angular observables

[Becirevic et al. '19], [Murgui et al. '19]...

Which Lorentz structure to pick?

Update of [Angelescu et al. '18]



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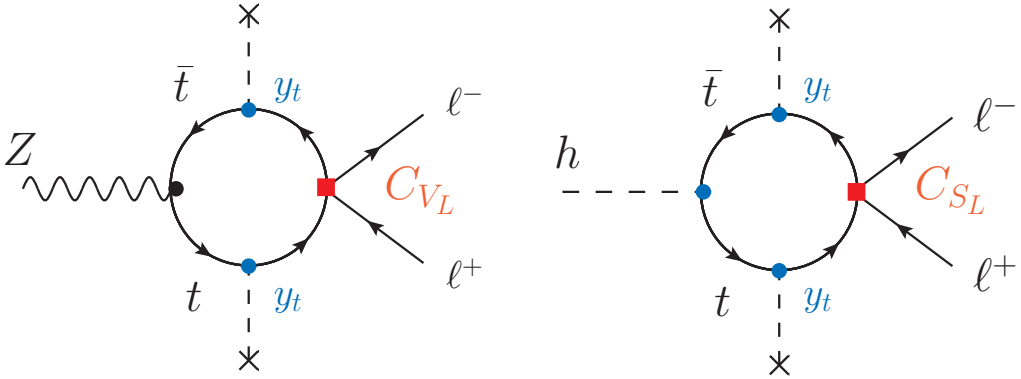


Electroweak observables can also be a useful handle!

[Feruglio et al. '17]

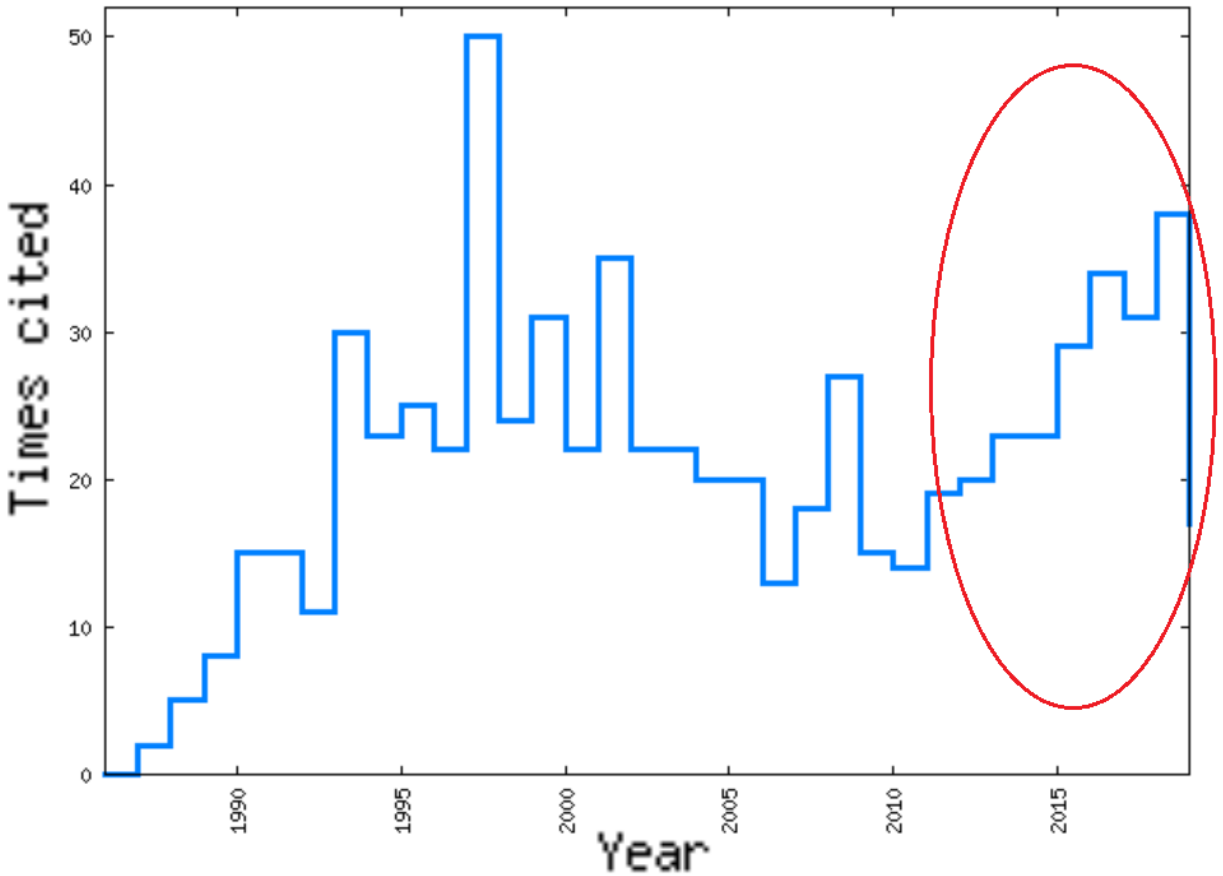
[Feruglio, Paradisi, **OS**. '18]

From EFT to simplified models: Why leptoquarks?

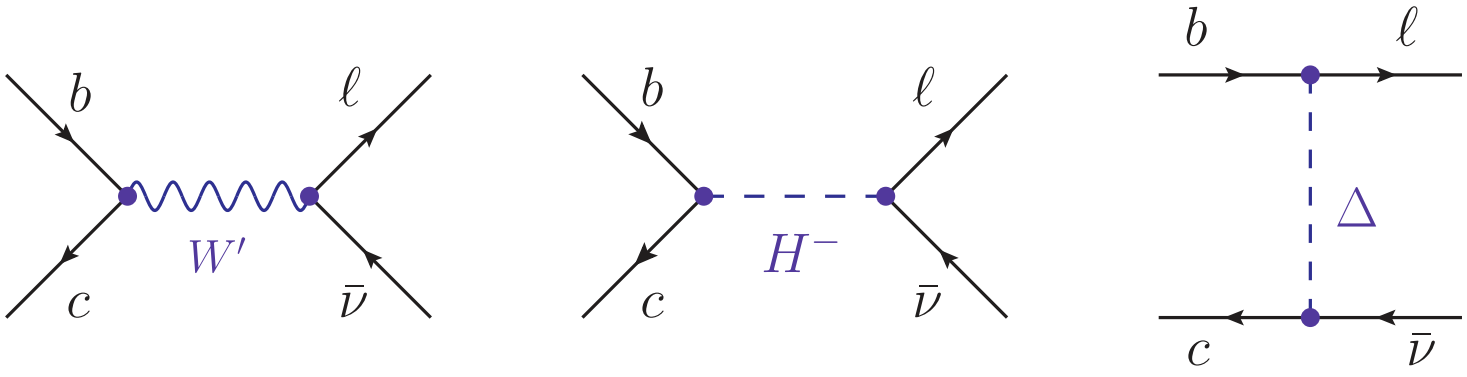
Citation history:

"Leptoquarks in lepton-quark collisions"

[Buchmuller, Ruckl. '87]



$R^{\rm exp}_{D^{(*)}} > R^{\rm SM}_{D^{(*)}}$ require new bosons at the TeV scale:



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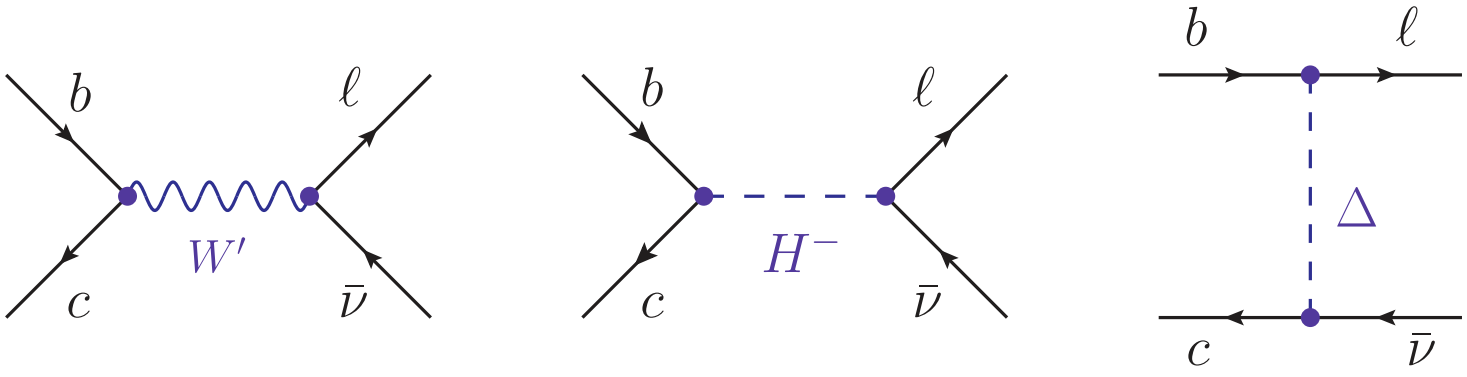

Challenges for New Physics:

- Loop constraints: e.g. $\tau \to \mu\nu\bar\nu$, $Z \to \ell\ell$ [Feruglio et al., '16]
- LHC direct and indirect bounds [Greljo et al. '15, Faroughy et al., '16]

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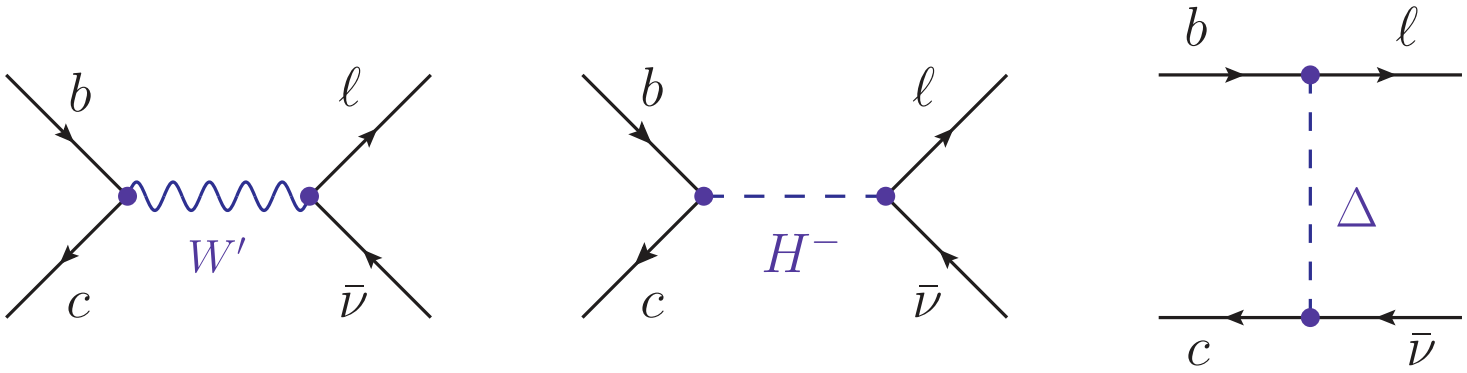

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In summary:

See talks by Peñuelas and Soni

- Charged Higgs solutions are in tension with τ_{B_c} constraint [Alonso et al. '16]
- Minimal W' models: tension with high-p_T constraints
- Scalar and vector **leptoquarks (LQ)** are the **best candidates** so far.

Which LQ for $R_{D^{(*)}}$?

NB. w/o ν_R

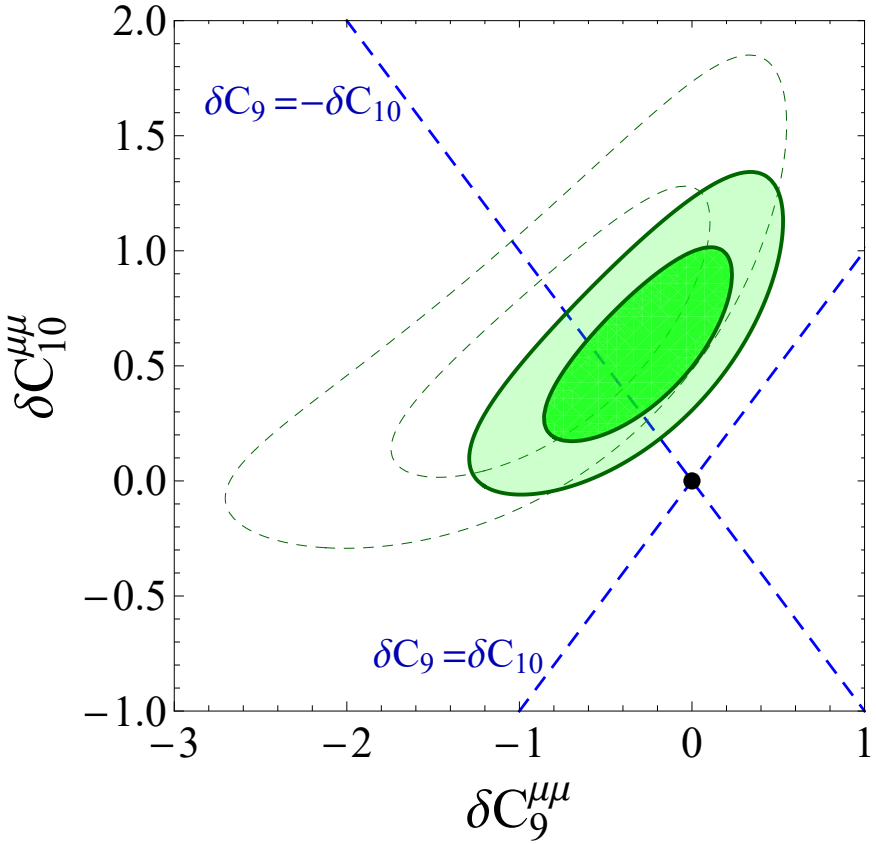
Model	$g_{\rm eff}^{b\to c\tau\bar{\nu}}(\mu = m_\Delta)$	$R_{D^{(*)}}$
$S_1 = (\bar{3}, 1, 1/3)$	g_{V_L}, $g_{S_L} = -4\, g_T$	✓
$R_2 = (3, 2, 7/6)$	$g_{S_L} = 4\, g_T$	✓
$S_3 = (\bar{3}, 3, 1/3)$	g_{V_L}	✗
...	...	...
$U_1 = (3, 1, 2/3)$	g_{V_L}, g_{S_R}	✓
$U_3 = (3, 3, 2/3)$	g_{V_L}	✗
...	...	...

Viable models: [Angelescu, Becirevic, Faroughy, **OS**. 1808.08179]

- U_1 (g_{V_L}), S_1 (g_{V_L} and $g_{S_L} = -4\, g_T$), and R_2 ($g_{S_L} = 4\, g_T \in \mathbb{C}$)
- Possibility to distinguish them by using other $b \to c\ell\nu$ observables!

ii) Effective theory for $b \to s\ell\ell$

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}}\, V_{tb}\, V_{ts}^* \left[C_9(\mu)\, (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell) + C_{10}(\mu)\, (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma^5 \ell) \right] + \ldots$$



Fit to clean quantities: $\mathcal{B}(B_s \to \mu\mu)$ and $R_{K^{(*)}}$.

- Only vector (axial) coefficients can accommodate data.
- $C_9 = -C_{10}$ allowed – predicted by left-handed operator!

See talk by Guadagnoli

Interesting: Conclusion corroborated by global $b \to s\ell\ell$ fit!

cf. e.g. [Capdevilla et al. '19], [Aebischer et al. '19], [Arbey et al.]...

Which LQs for $R_{D^{(*)}}$ and $R_{K^{(*)}}$?

[Angelescu, Becirevic, Faroughy, **OS**. 1808.08179]

See also [Buttazzo et al. '17], [Barbieri et al. '15]

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$S_1 = (\bar{3}, 1, 1/3)$	✓	✗*	✗
$R_2 = (3, 2, 7/6)$	✓	✗*	✗
$S_3 = (\bar{3}, 3, 1/3)$	✗	✓	✗
$U_1 = (3, 1, 2/3)$	✓	✓	✓
$U_3 = (3, 3, 2/3)$	✗	✓	✗

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- Only U_1 can do the job, but UV completion needed.

  $\Rightarrow$ Viable TeV models proposed (with more than one mediator!)

  [Di Luzio et al. '17, Bordone et al. '17, Assad et al. '17, Blanke et al. '17...].

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- Two scalar LQs are also viable:

  $\Rightarrow$ S_1 and S_3 [Crivellin et al. '17, Marzocca. '18], R_2 and S_3 [Becirevic et al. '18].

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

Pati-salam unification: [Pati, Salam. '74]

- $\mathcal{G}_{\rm PS} = SU(4) \times SU(2)_L \times SU(2)_R$ contains U_1 as gauge boson.
- Main difficulty: flavor universal $\Rightarrow$ $m_{U_1} \gtrsim 100$ TeV from FCNC.

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Viable scenario for B-anomalies: [Di Luzio et al. '17]

- $SU(4) \times SU(3)' \times SU(2)_L \times U(1)' \to \mathcal{G}_{\rm SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$
- Flavor violation from (ad-hoc) mixing with vector-like fermions.
- Main feature: $U_1 + Z' + g'$ at the TeV scale.

Rich LHC pheno, cf. [Baker et al. '19], [Di Luzio et al. '18]

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Step beyond: $[\mathrm{PS}]^3 = [SU(4) \times SU(2)_L \times SU(2)_R]^3$ [Bordone et al. '17]

- Hierarchical LQ couplings fixed by symmetry breaking pattern.
- Explanation of fermion masses and mixing (flavor puzzle)!

Two scalar leptoquarks

[Becirevic et al. '18]

- Prefer scalar to vector LQ to remain minimalistic in terms of new parameters and to be able to compute loops.

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- In flavor basis

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

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

  and assume $y_R = y_R^T$ and $y = -y_L$ (GUT aspirations).

- $SU(5)$ embedding is possible with these two light scalar LQs.

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- $SU(5)$ embedding is possible with these two light scalar LQs.

- Data can be fully described by few parameters:

  $\Rightarrow$ 2 masses, 3 couplings and 1 angle.

  $\Rightarrow$ $V - A$ structure for $b \to s\ell\ell$, but NOT for $b \to c\tau\bar{\nu}$ (scalar/tensor).

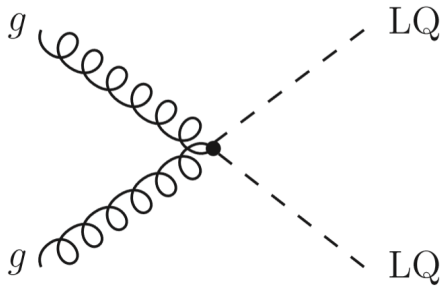
(see back-up for details)

LHC constraints

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

- LQ pair-production via QCD:

[CMS-PAS-EXO-17-003]

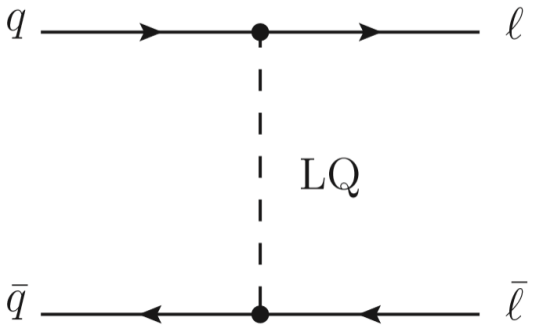


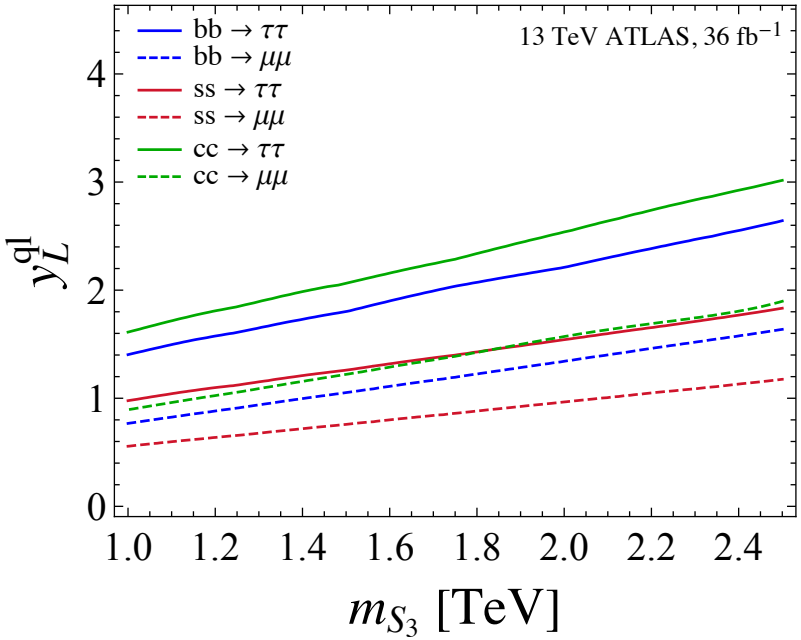
$$m_{S_3} \gtrsim 1.4 \text{ TeV}$$

[*assuming* $\mathcal{B}(S_3 \to b\mu) \approx 1$]

- Di-lepton tails at high-pT:

[ATLAS. 1707.02424,1709.07242]





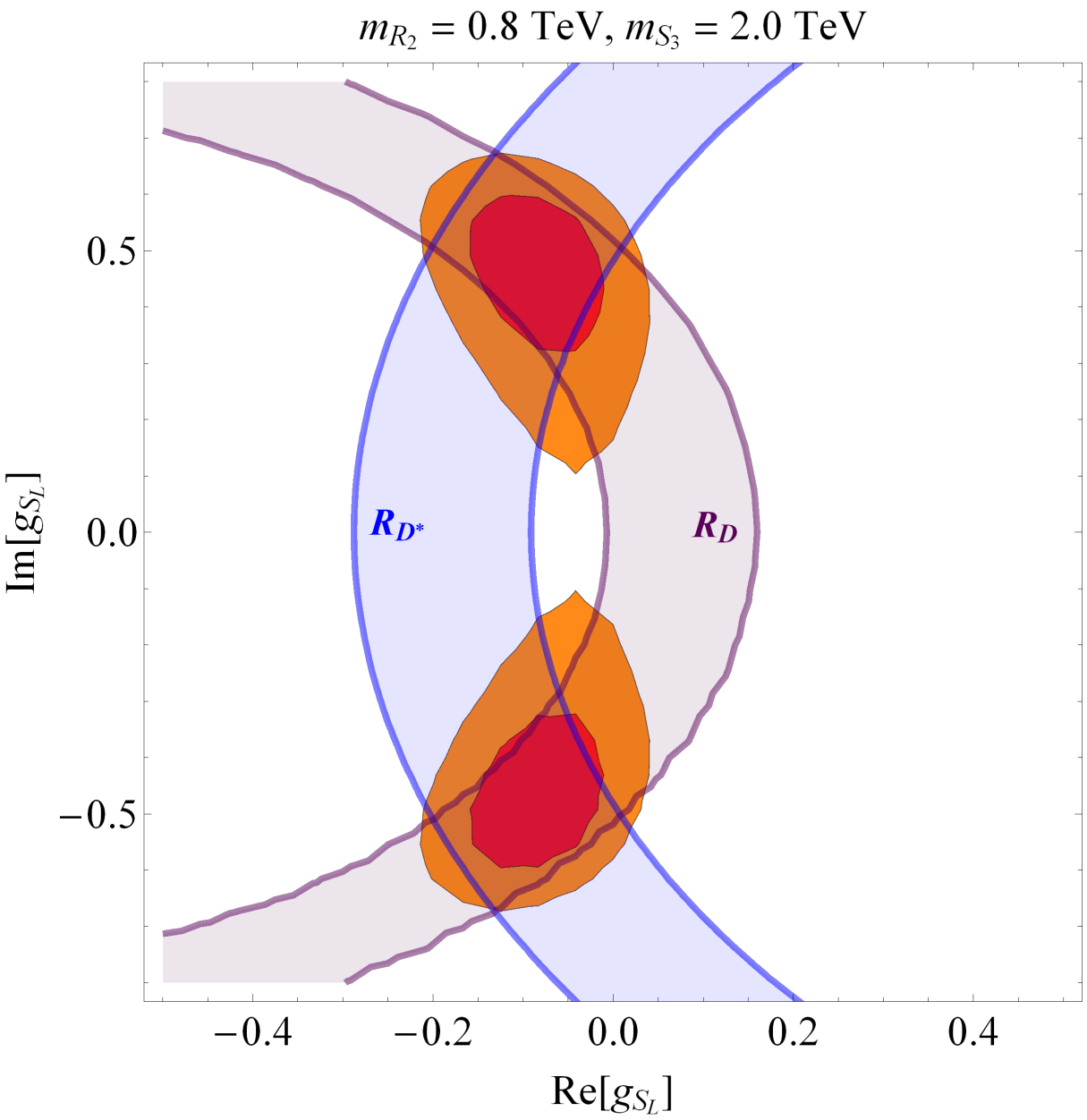
[Angelescu, Becirevic, Faroughy, **OS**. '18]

[Faroughy et al. '15]

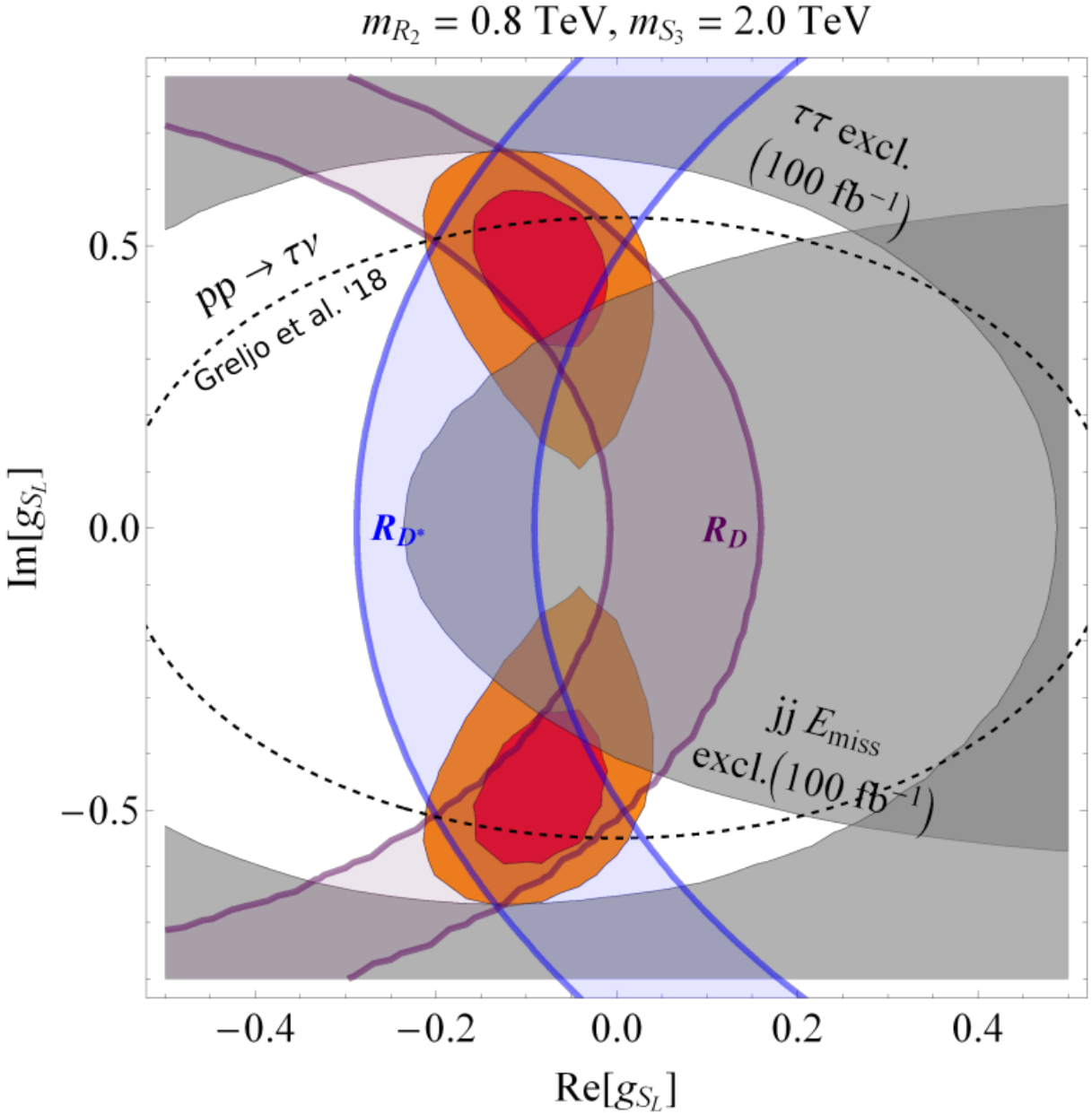
See talk by Soni

Results and predictions:

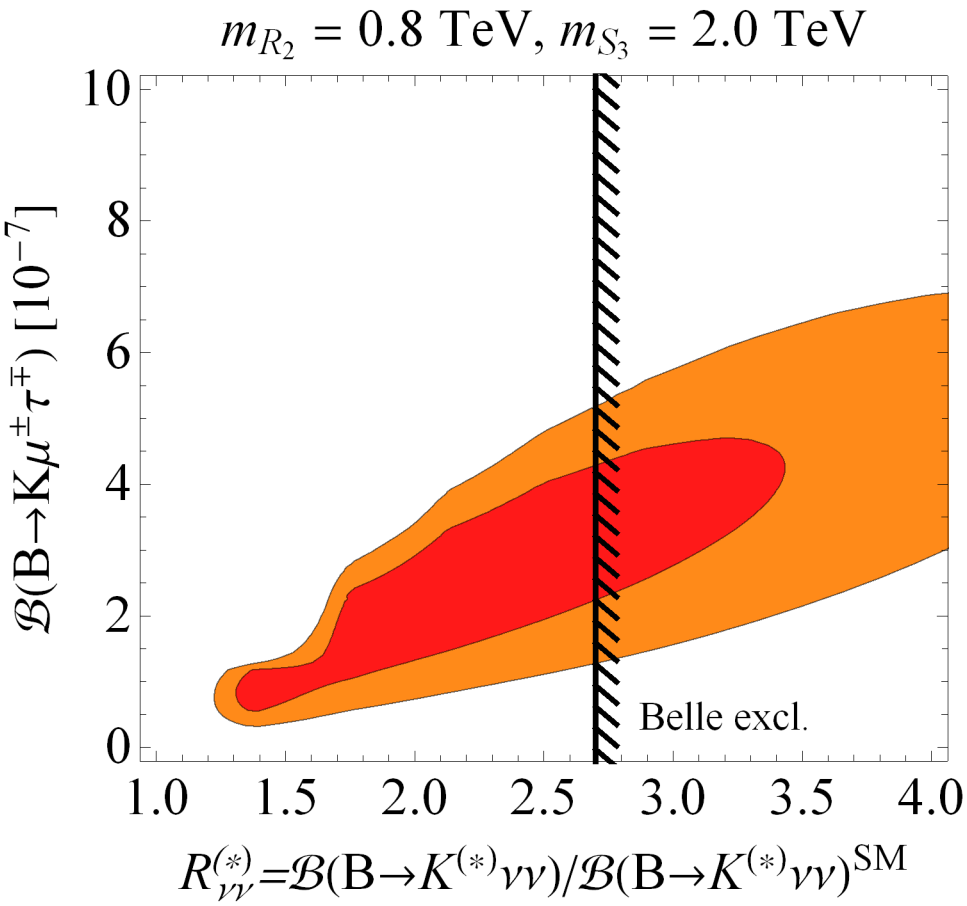
NB. $g_{S_L} = 4\, g_T$



Direct searches (projections to 100 fb^{-1})



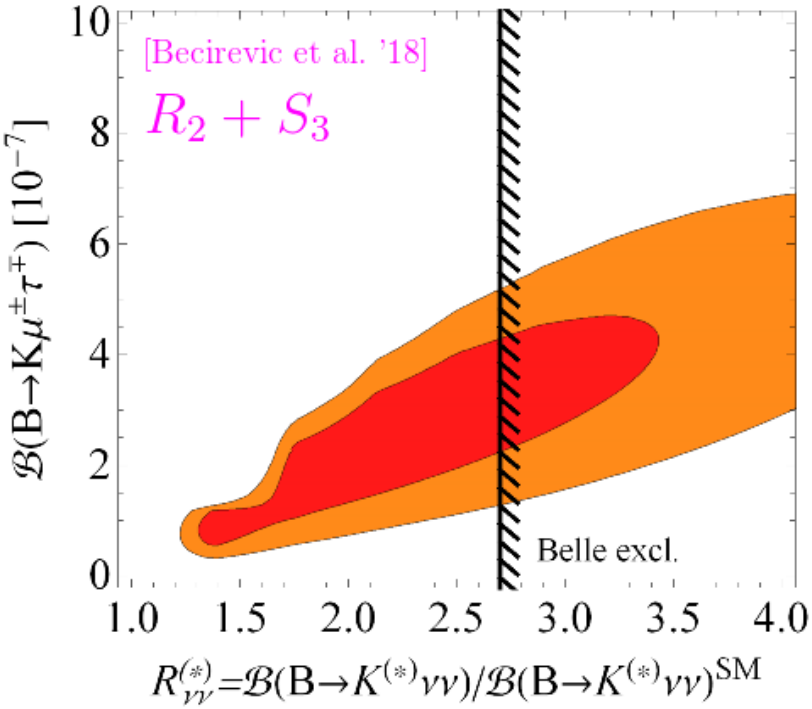
Several **distinctive predictions** wrt the SM: R_2 & S_3 GUT

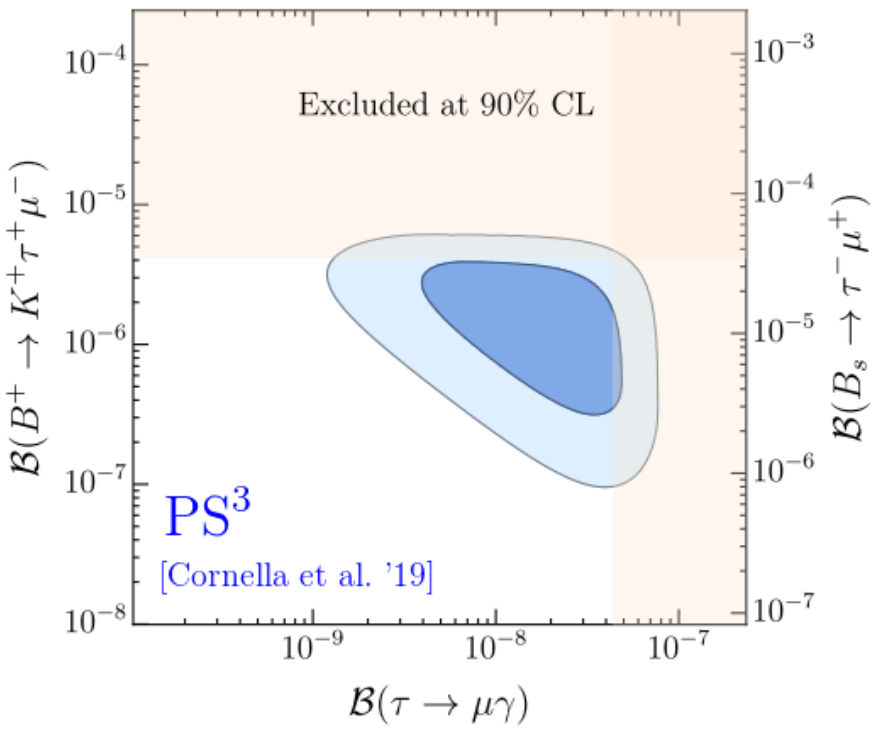


- **Enhancement** of $\mathcal{B}(B \to K\nu\bar{\nu})$ by $\gtrsim 50\%$ wrt to the SM [Belle-II]
- Upper and **lower bounds** on the **LFV** rates: $\mathcal{B}(B \to K\mu\tau) \gtrsim 2 \times 10^{-7}$
- BaBar: $\mathcal{B}(B \to K\mu\tau) < 4.8 \times 10^{-5}$ (90% CL.). Can we do better?

Large effects in $b \to s\mu\tau$ are a common prediction of minimal solutions to the B-anomalies:

see also [Guadagnoli et al. '14]





$\Rightarrow$ LHCb [NEW '19]: $\mathcal{B}(B_s \to \mu\tau) < 4.2 \times 10^{-5}$.

Large effects in $b \to s\mu\tau$ are a common prediction of minimal solutions to the B-anomalies:

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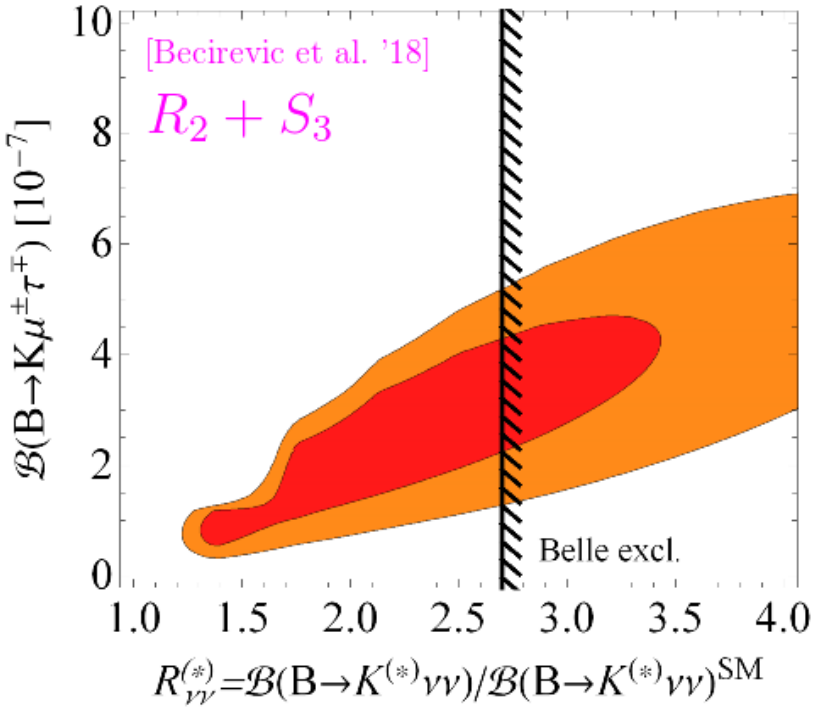
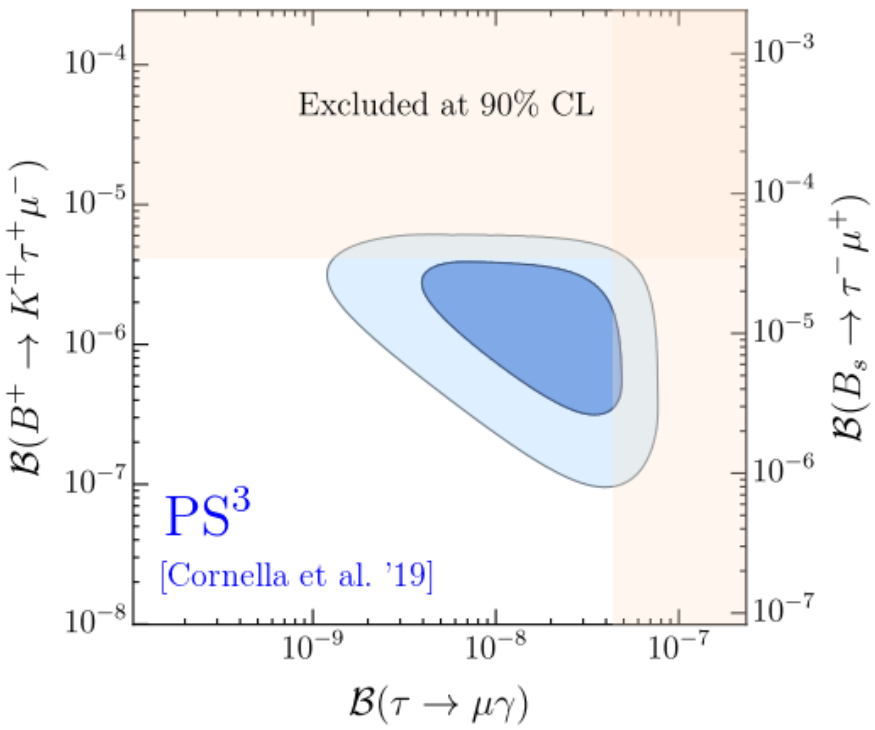




$\Rightarrow$ LHCb [NEW '19]: $\mathcal{B}(B_s \to \mu\tau) < 4.2 \times 10^{-5}$.

i) If purely $(V-A)\times(V-A)$:

$$\frac{\mathcal{B}(B_s \to \mu\tau)}{\mathcal{B}(B \to K\mu\tau)} \simeq 0.8\,, \qquad \frac{\mathcal{B}(B \to K^*\mu\tau)}{\mathcal{B}(B \to K\mu\tau)} \simeq 1.8$$

ii) If scalar operators are present:

$$\frac{\mathcal{B}(B_s \to \mu\tau)}{\mathcal{B}(B \to K^{(*)}\mu\tau)} \gg 1$$

[Becirevic, **OS**, Zukanovich. '16]

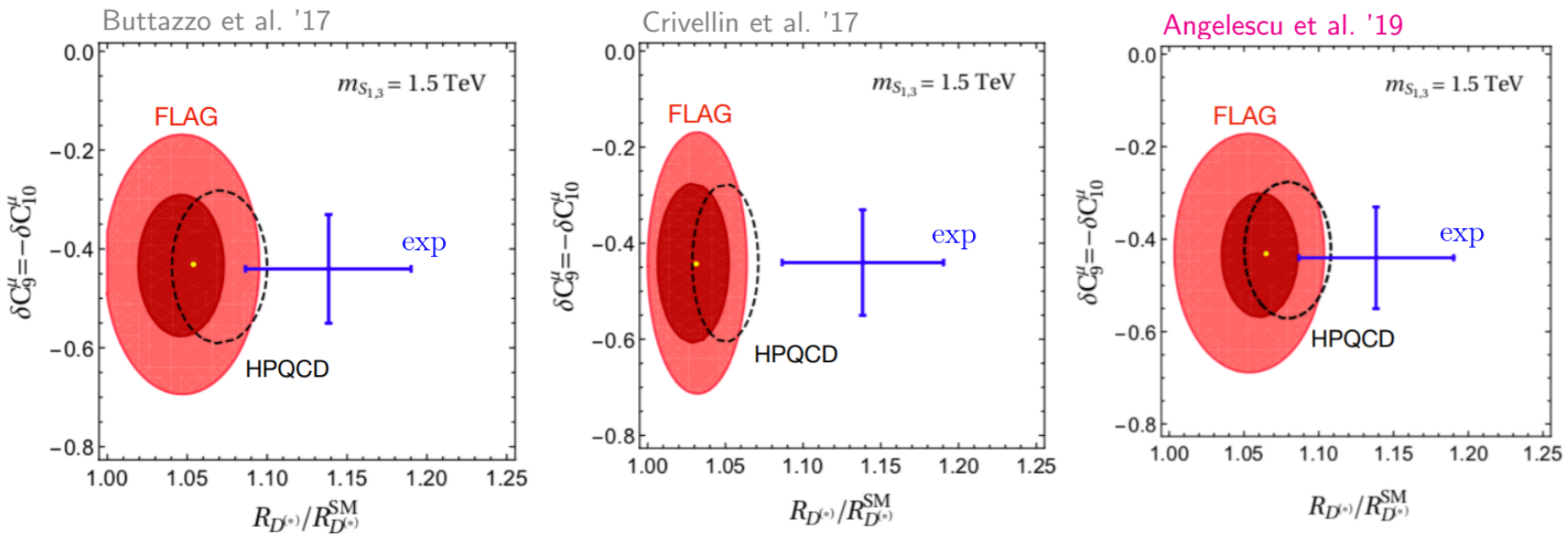
Last but not least...

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

Last but not least...

S_1 & S_3

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



⇒ Good candidate to also explain $(g-2)_\mu$?

[Dorsner, Fajfer, **OS**. '19]

Summary and perspectives

- Flavor anomalies are still there, but the experimental situation after Moriond '19 is (perhaps) less convincing.

  Needs clarification from LHCb and Belle-II!

- We identify/summarize the viable single-mediator scenarios to explain $R_{K^{(*)}}$ and/or $R_{D^{(*)}}$.

  Only the vector U_1 is viable. Two scalar LQs can do the job too.

- There is a pronounced complementarity of flavor physics constraints with those obtained from the direct searches at the LHC.

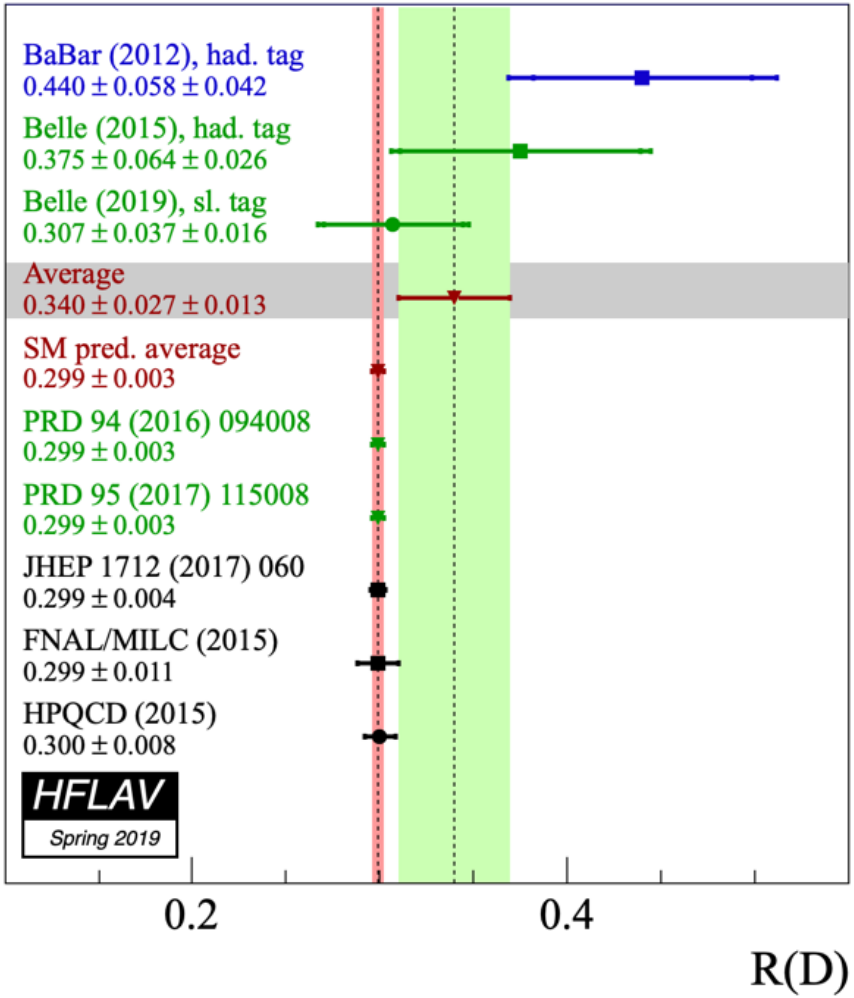
  Minimal scenarios $\Rightarrow$ lower bound $\mathcal{B}(B \to K\mu\tau) \gtrsim \mathcal{O}(10^{-7})$

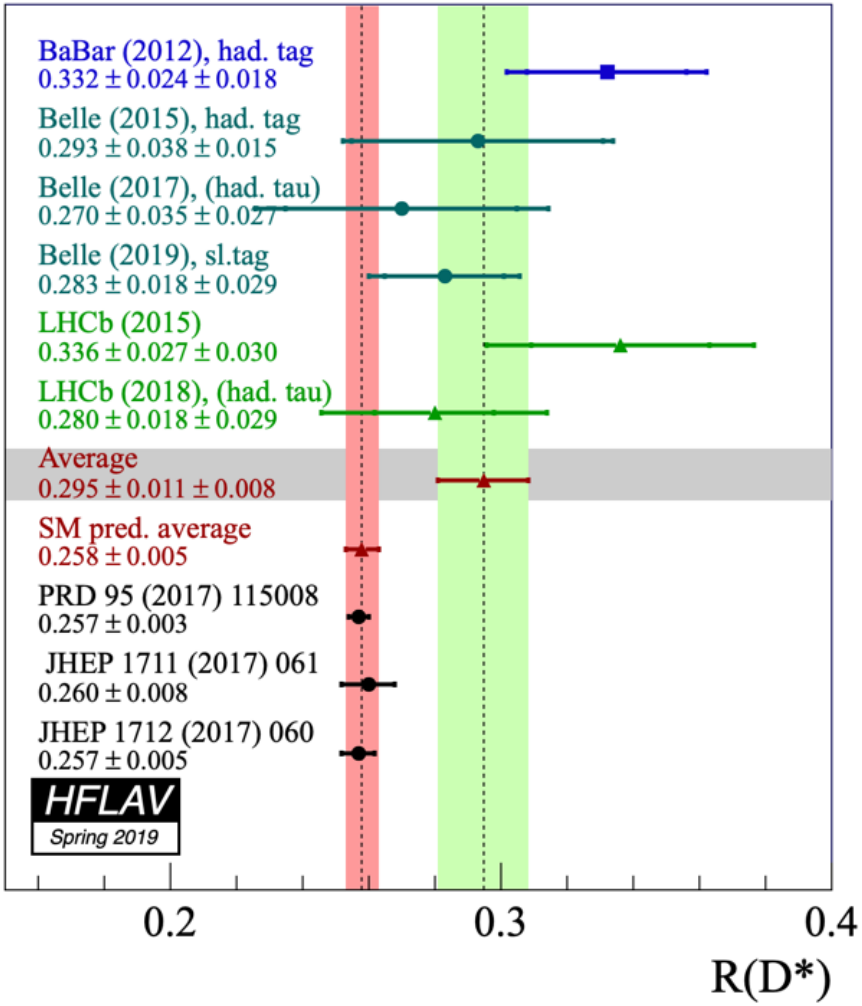
- Building a concrete model to simultaneously explain $R_{K^{(*)}}$ and $R_{D^{(*)}}$ remains challenging.

  Data-driven model building!

Thank you!

Back-up





- 3.1σ combined deviation from the SM [theory error under control?]
- Discrepancy driven by oldest exp. results (BaBar and LHCb).
- Needs confirmation from Belle-II (and LHCb run-2)!

[Feruglio, Paradisi, OS. 1806.10155]

$$\frac{R_{D^{(*)}}}{R^{\rm SM}_{D^{(*)}}} = 1 + a_S^{D^{(*)}} \, |g_S^\tau|^2 + a_P^{D^{(*)}} \, |g_P^\tau|^2 + a_T^{D^{(*)}} \, |g_T^\tau|^2$$

$$+ \, a_{SV_L}^{D^{(*)}} \, {\rm Re}\,[g_S^\tau] + a_{PV_L}^{D^{(*)}} \, {\rm Re}\,[g_P^\tau] + a_{TV_L}^{D^{(*)}} \, {\rm Re}\,[g_T^\tau] \; ,$$

Decay mode	a_S^M	$a_{SV_L}^M$	a_P^M	$a_{PV_L}^M$	a_T^M	$a_{TV_L}^M$
$B \to D$	$1.08(1)$	$1.54(2)$	0	0	$0.83(5)$	$1.09(3)$
$B \to D^*$	0	0	$0.0473(5)$	$0.14(2)$	$17.3(16)$	$-5.1(4)$

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

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

and assume

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

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

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

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

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

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

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

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

- Δm_{B_s}:

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

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

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

Notable flavor constraints...

- $R^{K\ \mathrm{exp}}_{e/\mu} = 2.488(10) \times 10^{-5}$ [PDG], $R^{K\ \mathrm{SM}}_{e/\mu} = 2.477(1) \times 10^{-5}$ [Cirigliano. '07]

$$R^K_{e/\mu} = \frac{\Gamma(K^- \to e^- \bar{\nu})}{\Gamma(K^- \to \mu^- \bar{\nu})}$$

- $R^{D\ \mathrm{exp}}_{\mu/e} = 0.995(45)$ [Belle. '17], $R^{D^*\ \mathrm{exp}}_{\mu/e} = 1.04(5)$ [Belle. '16]

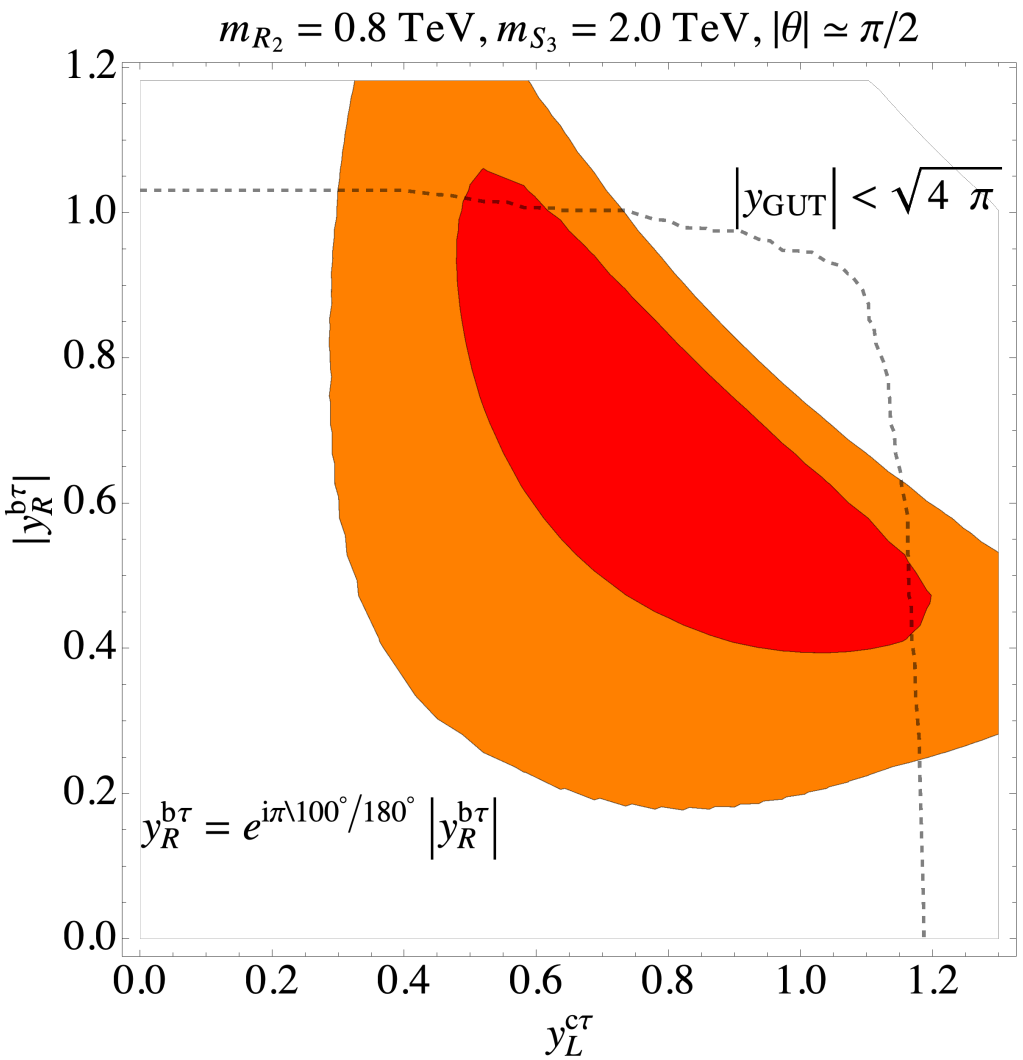
$$R^{D^{(*)}}_{\mu/e} = \frac{\Gamma(B \to D^{(*)} \mu \bar{\nu})}{\Gamma(B \to D^{(*)} e \bar{\nu})}$$

- $\mathcal{B}(\tau \to \mu\phi) < 8.4 \times 10^{-8}$ [Belle,'11], loops: $\mathcal{B}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$ [BaBar. '10]
- Loops: $\Delta m^{\mathrm{exp}}_{B_s} = 17.76(2)\ \mathrm{ps}^{-1}$ [PDG], $\Delta m^{\mathrm{SM}}_{B_s} = (20.1^{+1.2}_{-1.6})\ \mathrm{ps}^{-1}$ [FLAG '19]
- Loops: $Z \to \mu\mu$, $Z \to \tau\tau$, $Z \to \nu\nu$ [LEP] see also [Arnan, Becirevic, Mescia, **OS**. '19]

$$\frac{g^\tau_V}{g^e_V} = 0.959(29)\,, \quad \frac{g^\tau_A}{g^e_A} = 1.0019(15)\,, \quad \frac{g^\mu_V}{g^e_V} = 0.961(61)\,, \quad \frac{g^\mu_A}{g^e_A} = 1.0001(13)$$

$$N^{\mathrm{exp}}_\nu = 2.9840(82)$$

$$16\pi^2 \frac{\mathrm{d}\log y_R^{b\tau}}{\mathrm{d}\log \mu} = |y_L^{c\mu}|^2 + |y_L^{c\tau}|^2 + \frac{9}{2}|y_R^{b\tau}|^2 + \frac{y_t^2}{2} + \ldots$$



$\Rightarrow$ Yukawas remain perturbative after 1-loop running to $\Lambda_{\rm GUT}$!

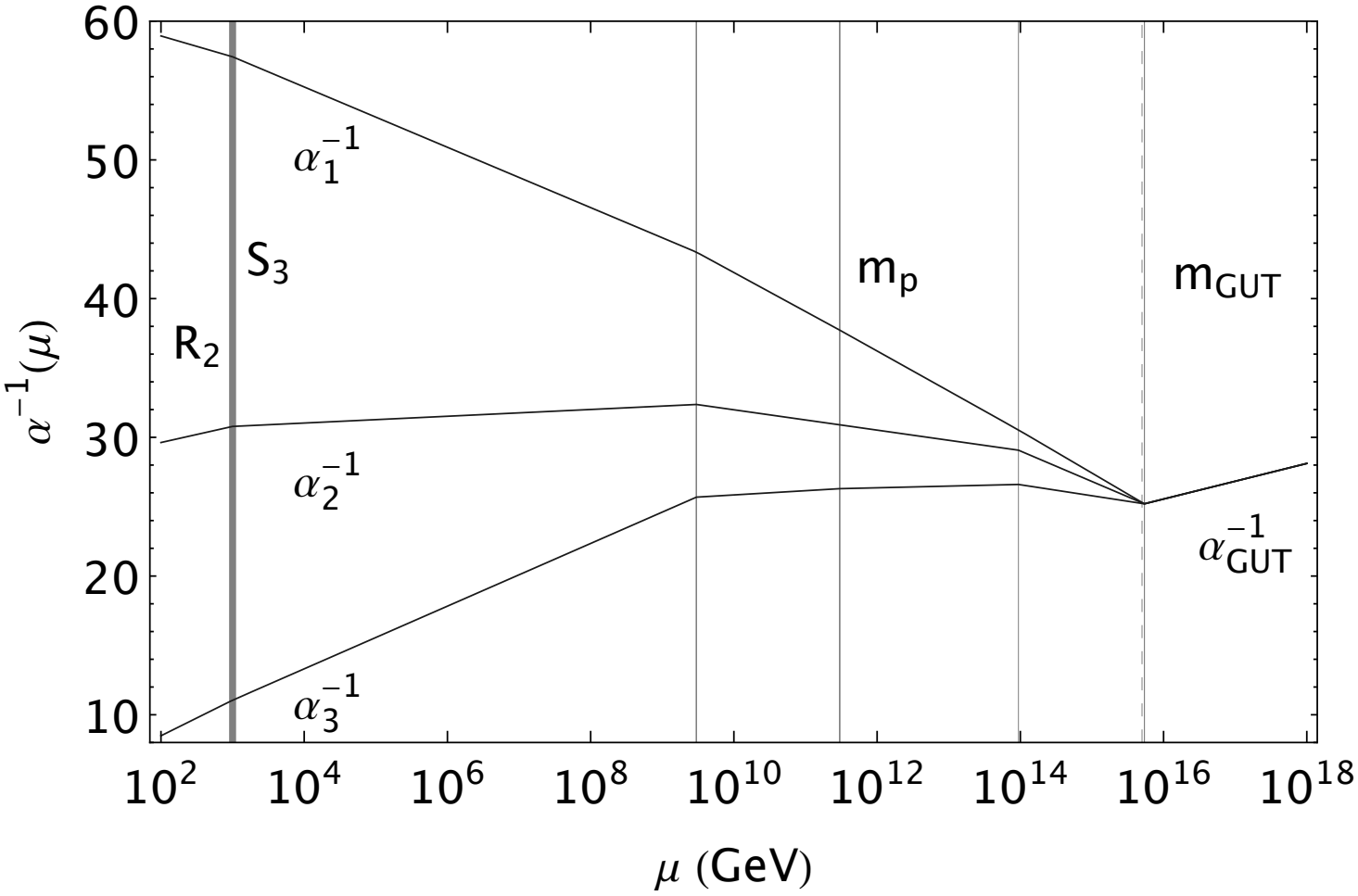
Simple and viable $SU(5)$ GUT

- Choice of Yukawas was biased by $SU(5)$ GUT aspirations
- Scalars: $R_2 \in \underline{\mathbf{45}}, \underline{\mathbf{50}}$, $S_3 \in \underline{\mathbf{45}}$. SM matter fields in $\mathbf{5}_i$ and $\mathbf{10}_i$
- Operators $\mathbf{10}_i \mathbf{10}_j \underline{\mathbf{45}}$ forbidden to prevent proton decay [Dorsner et al. '17]
- Available operators

$$\mathbf{10}_i \mathbf{5}_j \underline{\mathbf{45}}: \quad y_{2\,ij}^{RL}\, \overline{u}_R^i R_2^a \varepsilon^{ab} L^{j,b}, \quad y_{3ij}^{LL}\, \overline{Q^C}^{i,a} \varepsilon^{ab} (\tau^k S_3^k)^{bc} L^{j,c}$$

$$\mathbf{10}_i \mathbf{10}_j \underline{\mathbf{50}}: \quad y_{2\,ij}^{LR}\, \overline{e}_R^i R_2^{a\,*} Q^{j,a}$$

- While breaking $SU(5)$ down to SM the two R_2's mix – one can be light and the other (very) heavy. Thus our initial Lagrangian!
- The **Yukawas** determined from flavor physics observables at low energy **remain perturbative** ($\lesssim \sqrt{4\pi}$) up to the GUT scale, using one-loop running [Wise et al 2014, c.f. back-up]


60
50
40
30
20
10
$\alpha^{-1}(\mu)$
α_1^{-1}
α_2^{-1}
α_3^{-1}
α_{GUT}^{-1}
R_2
S_3
m_p
m_{GUT}
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
μ (GeV)

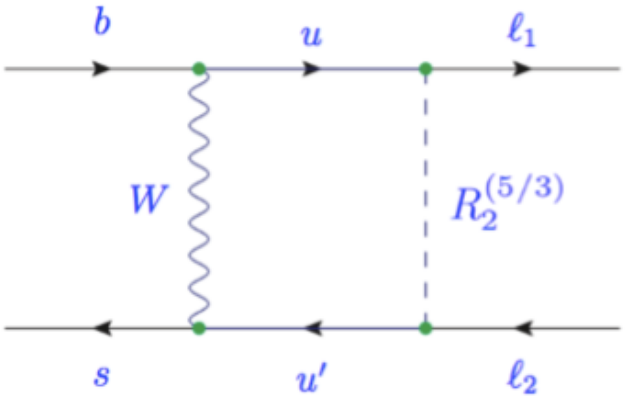
$R_2 = (3, 2, 7/6)$

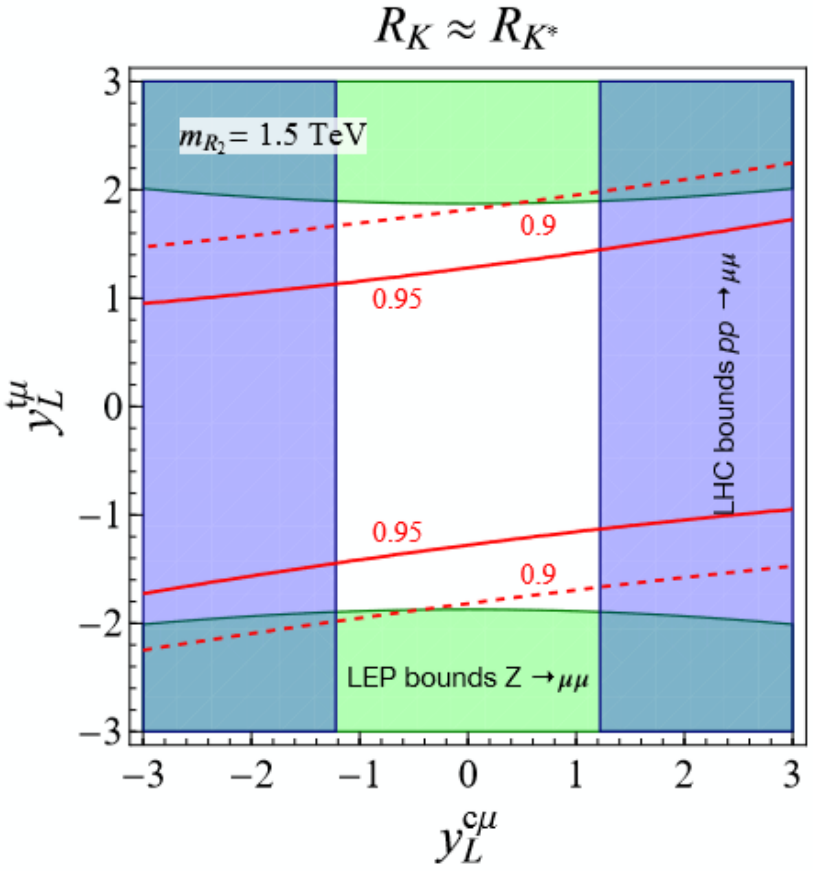
$$\mathcal{L}_{R_2} = y_R^{ij}\,\overline{Q}_i \ell_{R\,j}\,R_2 - \boxed{y_L^{ij}\,\overline{u}_{R\,i} R_2 i\tau_2 L_j} + \text{h.c.}$$

$$C_9^{kl} = C_{10}^{kl}\ \overset{\text{tree}}{=}\ -\frac{\pi v^2}{2V_{tb}V_{ts}^*\alpha_{\text{em}}}\frac{y_R^{sl}\left(y_R^{bk}\right)^*}{m_{R_2}^2}$$

$$C_9^{kl} = -C_{10}^{kl}\ \overset{\text{loop}}{=}\ \sum_{u,u'\in\{u,c,t\}} \frac{V_{ub}V_{u's}^*}{V_{tb}V_{ts}^*} y_L^{u'k}\left(y_L^{ul}\right)^* \mathcal{F}(x_u, x_{u'})$$

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





Update of [Becirevic, **OS**. ′17]

Limits on LQ pair-production

[Angelescu, Becirevic, Faroughy, **OS**. 1808.08179]

Decays	LQs	Scalar LQ limits	Vector LQ limits	$\mathcal{L}_{\rm int}$ / Ref.
$jj\,\tau\bar{\tau}$	S_1, R_2, S_3, U_1, U_3	–	–	–
$b\bar{b}\,\tau\bar{\tau}$	R_2, S_3, U_1, U_3	850 (550) GeV	1550 (1290) GeV	12.9 fb^{-1} [49]
$t\bar{t}\,\tau\bar{\tau}$	S_1, R_2, S_3, U_3	900 (560) GeV	1440 (1220) GeV	35.9 fb^{-1} [50]
$jj\,\mu\bar{\mu}$	S_1, R_2, S_3, U_1, U_3	1530 (1275) GeV	2110 (1860) GeV	35.9 fb^{-1} [51]
$b\bar{b}\,\mu\bar{\mu}$	R_2, U_1, U_3	1400 (1160) GeV	1900 (1700) GeV	36.1 fb^{-1} [52]
$t\bar{t}\,\mu\bar{\mu}$	S_1, R_2, S_3, U_3	1420 (950) GeV	1780 (1560) GeV	36.1 fb^{-1} [53, 54]
$jj\,\nu\bar{\nu}$	R_2, S_3, U_1, U_3	980 (640) GeV	1790 (1500) GeV	35.9 fb^{-1} [55]
$b\bar{b}\,\nu\bar{\nu}$	S_1, R_2, S_3, U_3	1100 (800) GeV	1810 (1540) GeV	35.9 fb^{-1} [55]
$t\bar{t}\,\nu\bar{\nu}$	R_2, S_3, U_1, U_3	1020 (820) GeV	1780 (1530) GeV	35.9 fb^{-1} [55]