

New Physics and LF(U)V in B Decays

Olcyr Sumensari

In collaboration with

D. Bečirević, S. Fajfer, N. Košnik and R. Zukanovich Funchal

[hep-ph/1602.00881](https://arxiv.org/abs/hep-ph/1602.00881), [1608.08501](https://arxiv.org/abs/1608.08501) and [1608.07583](https://arxiv.org/abs/1608.07583)



*Current Trends in Flavor Physics
IHP, March 29, 2017*



Outline

- ① Motivation
- ② LFU violation in $b \rightarrow s\ell^+\ell^-$
- ③ LFV in $b \rightarrow s\ell_1\ell_2$
- ④ Brief discussion of LFU violation in $b \rightarrow c\tau\nu$
- ⑤ Conclusions and Perspectives

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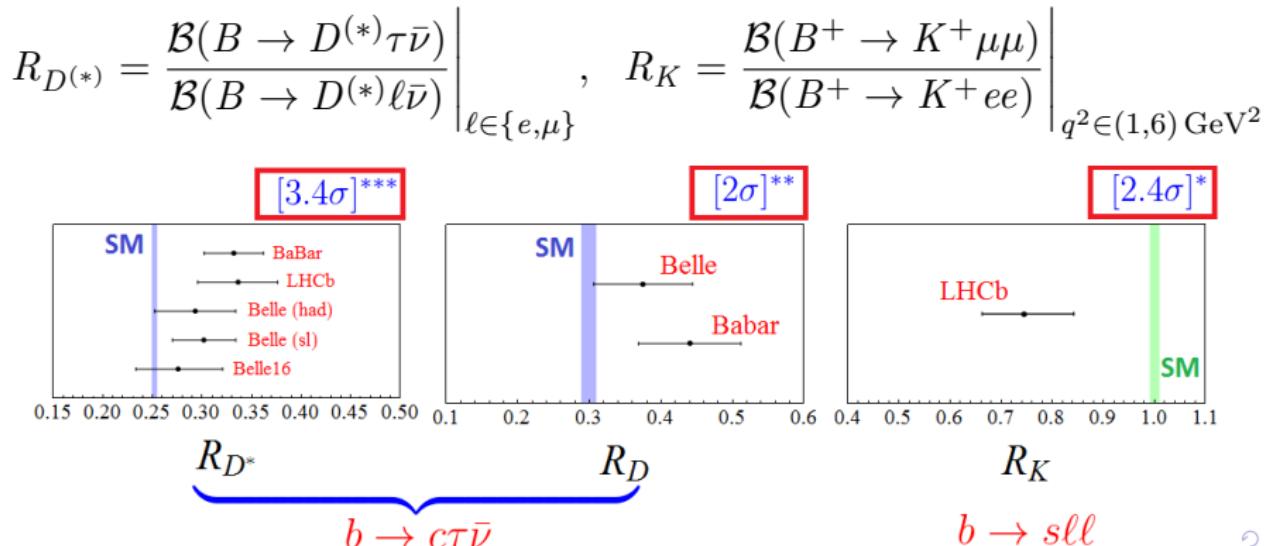
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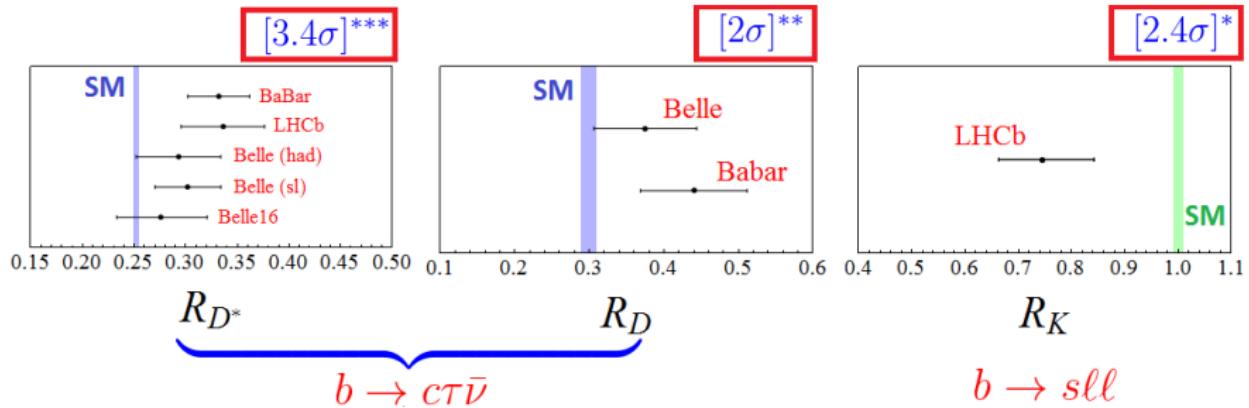
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$$R_{D^{(*)}} = \frac{\mathcal{B}(B \rightarrow D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \rightarrow D^{(*)}\ell\bar{\nu})} \Bigg|_{\ell \in \{e, \mu\}}, \quad R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+\mu\mu)}{\mathcal{B}(B^+ \rightarrow K^+ee)} \Bigg|_{q^2 \in (1,6) \text{ GeV}^2}$$

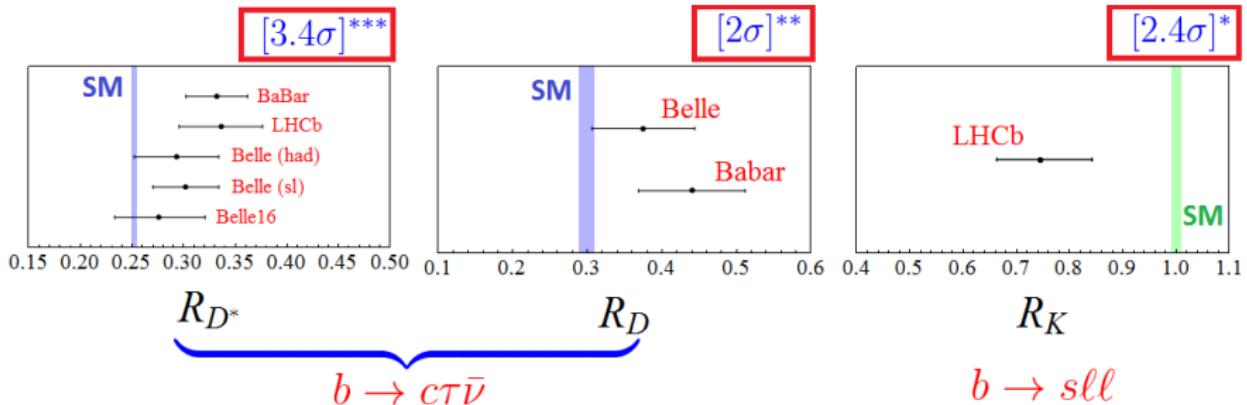
Motivation

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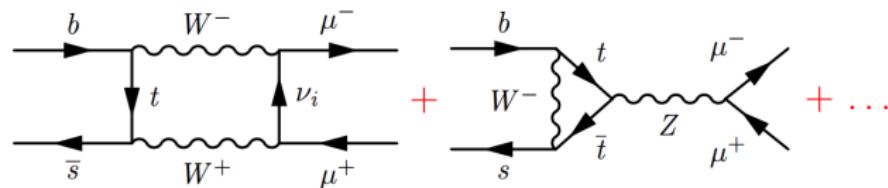
In general, $R_K \neq 1 \Leftrightarrow \text{LFUV} \Rightarrow \text{Lepton Flavor Violation (LFV)}$

[Glashow et al. 2014.]

LFU violation

(i) $b \rightarrow s\mu^+\mu^-$

- FCNC process:



- Form-factors cancel out in the ratio \Rightarrow **Extremely clean prediction**.

$$R_K \equiv \left. \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu\mu)}{\mathcal{B}(B^+ \rightarrow K^+ ee)} \right|_{q^2 \in (1,6) \text{ GeV}^2} \stackrel{\text{SM}}{=} 1.00(1)$$

[Bordone, Isidori, Pattori. 2016]

- **2.4 σ** deviation observed by LHCb:

$$R_K^{\text{exp}} = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$$

Explaining R_K

Explaining R_K

EFT approach

If the LFUV takes place at scales well above EWSB, then use OPE:

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

- Operators relevant to $b \rightarrow s\ell\ell$ are

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

- To explain $R_K < 1$, one needs effective coefficients $C_9^{(\prime)}, C_{10}^{(\prime)}$.

Compatible with results from global analyses: [e.g., Descotes-Genon et al. 2015]

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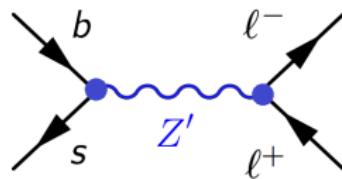
Are there **specific models** capable of generating $C_{9,10}^{(\prime)}$ to explain R_K ?

Explaining R_K

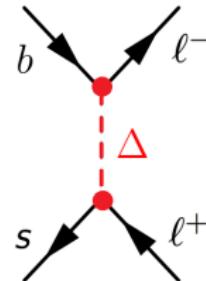
Specific Models

Representative (tree-level) models:

Z' models



Leptoquark models



Buras et al., Altmannshofer et al.,
Crivellin et al., Celis et al. . . .

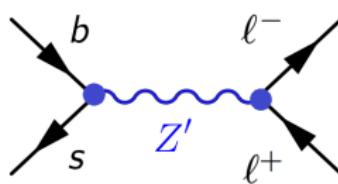
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Explaining R_K

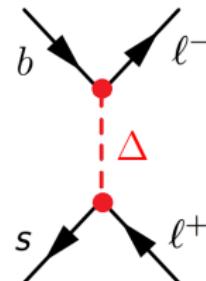
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- Vector leptoquarks models also plausible, but non-renormalizable
[problematic, how to compute loops? $B_s - \bar{B}_s$ constraint?]

Barbieri et al., Fajfer et al.

- Interesting feature: **LFV** is in general **expected**.

Explaining R_K : Illustration

Scalar Leptoquark Models

Analysis of the separate modes: data **prefer** to decrease $\mathcal{B}(B^+ \rightarrow K^+ \mu\mu)$.

⇒ Let us focus on NP with couplings **only to muons**

[although couplings to electrons are also possible, cf. Hiller, Schmaltz 2014]

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Representation under $(SU(3)_c, SU(2)_L)_{U(1)_Y}$:

N.B. $Q = Y + T_3$.

- $(\bar{3}, 3)_{1/3}$ and $(3, 1)_{4/3} \Rightarrow$ Proton destabilizes (\equiv *diquark couplings*)

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- **$(3, 2)_{1/6}$** : Decreases $B \rightarrow K\mu^+\mu^-$ $(C'_9)_{\mu\mu} = -(C'_{10})_{\mu\mu} \quad \bar{L}\tilde{\Delta}^{(1/6)}d_R$

[Kosnik, 2012]

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[Kosnik, 2012]

Interesting: $SU(5)$ unification can be achieved via two LQs $(3, 2)_{1/6}$ in **10** multiplets with $m_{\Delta_1} \lesssim 16$ TeV ⇒ **Back-up!**

[P. Cox, A. Kusenko, OS, T. T. Yanagida, 1612.03923]

Explaining R_K : Illustration

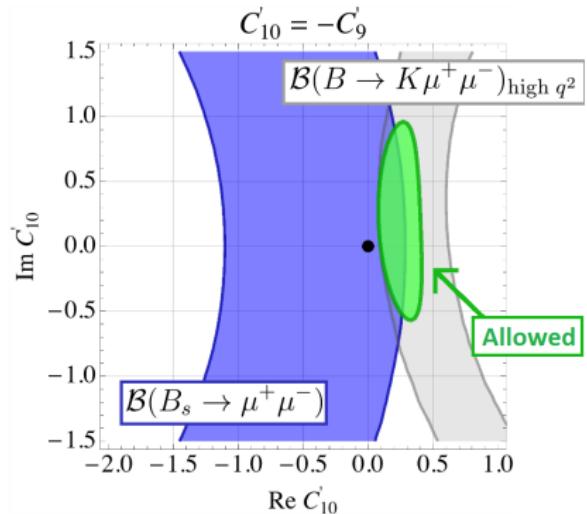
Scalar Leptoquark $(3, 2)_{1/6}$

[Becirevic et al. 2015]

1st step: Wilson coefficients fit.

$$\begin{aligned}\mathcal{B}(B_s \rightarrow \mu^+ \mu^-) \text{ and } \mathcal{B}(B^+ \rightarrow K^+ \mu \mu)_{\text{high } q^2} \\ \Rightarrow (C'_{10})_{\mu\mu} = -(C'_9)_{\mu\mu} \in (0.19, 0.52) \\ \Rightarrow \mathbf{R}_K^{\text{pred}} = \mathbf{0.88(8)}.\end{aligned}$$

$$\begin{aligned}\mathcal{O}'_9 &= (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell) \\ \mathcal{O}'_{10} &= (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\end{aligned}$$



“Model independent” prediction: $R_{K^*} = 1.11(8)$

[RH quark currents imply $R_{K^*} > 1$]

[Hiller, Schmaltz 2014]

Explaining R_K : Illustration

Scalar Leptoquark $(3, 2)_{1/6}$

2nd step: Model dependent interpretation.

$$\mathcal{L}_Y = Y_{ij} \bar{L}_i \tilde{\Delta}^{(1/6)} d_{Rj} + \text{h.c.}$$

$$C'_9 = -C'_{10} \propto \frac{Y_{\mu s} Y_{\mu b}^*}{m_\Delta^2}$$

$$\mathbb{Y} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & Y_{\mu s} & Y_{\mu b} \\ 0 \end{pmatrix}$$

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How can we probe the couplings to τ 's?

- $\tau \rightarrow \mu \phi$ is an useful constraint
- **LFV** in $B_{(s)}$ decays!

LFV in $b \rightarrow s\mu\tau$

Scalar Leptoquark $(3, 2)_{1/6}$

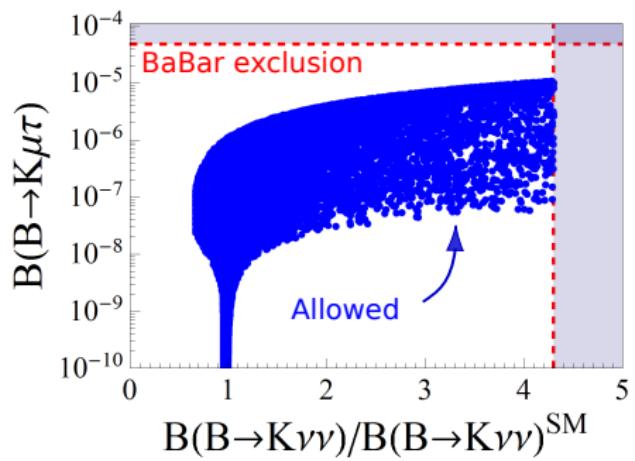
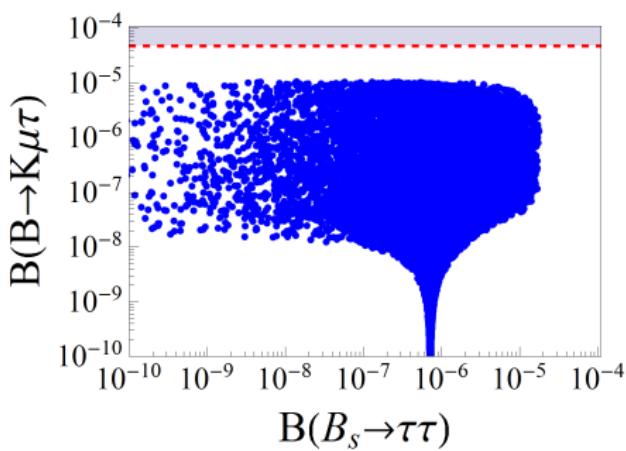
[D. Becirevic, N. Kosnik, OS, R. Zukarnovich. 1608.07583.]

Maximally allowed value lies just below the BaBar limit: $\mathcal{B}(B^+ \rightarrow K^+\mu\tau) \leq 4.8 \times 10^{-5}$ [90% CL].

Can LHCb do better ?

Even weak limits on $B \rightarrow K\mu\tau$ can be useful to constraint $Y_{\tau s}, Y_{\tau b}$ and $B \rightarrow K\nu\nu$ (Belle-2).

$$\mathbb{Y} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & Y_{\mu s} & Y_{\mu b} \\ 0 & Y_{\tau s} & Y_{\tau b} \end{pmatrix}$$



- **Important:** New experimental limits on one channel can set stringent constraints on the others:

$$C_9^{(\prime)} = -C_{10}^{(\prime)} \neq 0 \quad \Rightarrow \quad \mathcal{B}(B_s \rightarrow \ell_1 \ell_2) < \mathcal{B}(B \rightarrow K \ell_1 \ell_2) < \mathcal{B}(B \rightarrow K^* \ell_1 \ell_2)$$
$$\frac{\mathcal{B}(B \rightarrow K^* \mu \tau)}{\mathcal{B}(B \rightarrow K \mu \tau)} \approx 1.8, \quad \frac{\mathcal{B}(B \rightarrow K \mu \tau)}{\mathcal{B}(B_s \rightarrow \mu \tau)} \approx 0.8.$$

[D. Becirevic, R. Zukanovich, OS. 1602.0081]

- **Take-home message:** even not so stringent experimental limits on exclusive B LFV decay modes can be useful to constrain models.

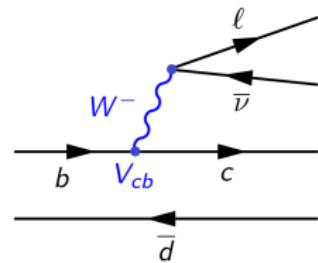
Brief discussion of LFUV in $b \rightarrow c\tau\nu$

LFU violation

(ii) $b \rightarrow c\tau\bar{\nu}$

- Tree-level process in the SM:

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \rightarrow D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \rightarrow D^{(*)}\ell\bar{\nu})}, \quad \ell = e, \mu.$$



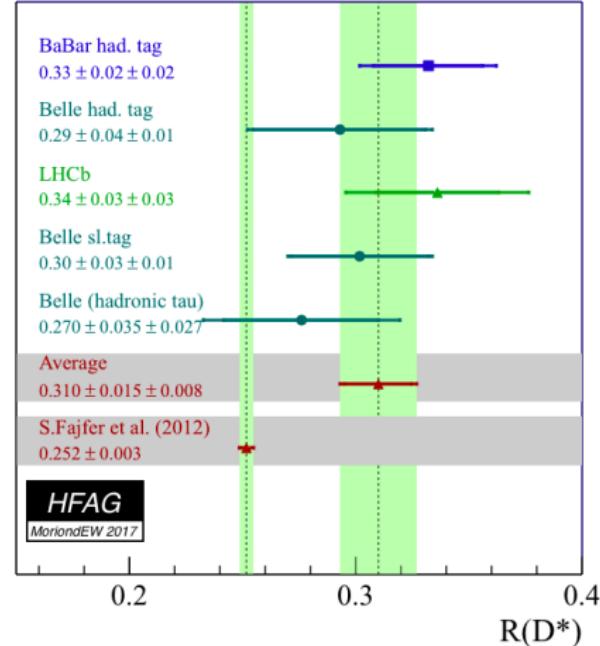
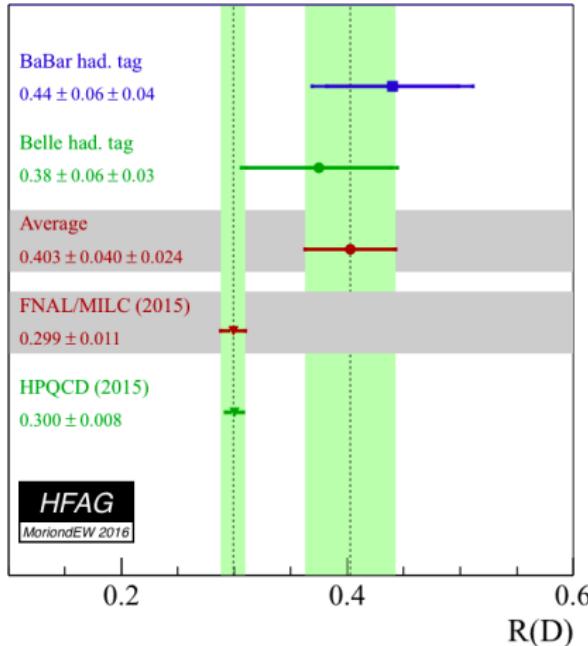
- Non-perturbative QCD \iff form-factors (Lattice QCD)

e.g. for $B \rightarrow D$, $\langle D | \bar{c} \gamma_\mu b | B \rangle \propto f_{0,+}(q^2)$

- Situation less clear for $B \rightarrow D^*$ \Rightarrow (more FFs, less LQCD results)
[One form factor is unknown from LQCD (error associated?)]

LFU violation

(ii) $b \rightarrow c\tau\bar{\nu}$



- **3.9 σ combined** deviation from the SM [theory error under control?]
- **2.2 σ** deviation if **only \mathcal{R}_D** is considered.

Theory Challenge

Simultaneously explain R_K and $R_{D^{(*)}}$:

- $SU(2)_L$ triplet of vector bosons with couplings mostly to the 3rd generation – *slight tension with direct searches.* [Greljo et al., 1506.01705]
- Vector LQ models – *nonrenormalizable* (UV completion unknown).
[Barbieri et al., 1512.01560] \oplus [Fajfer et al., 1511.06024]
- SLQ singlet state $(3, 1)_{-1/3}$ – explains $R_{D^{(*)}}$ at tree-level and R_K through loops – *plausible mechanism?* [Neubert and Bauer, 1511.01900]
 \Rightarrow Challenged in [Becirevic, Kosnik, OS, Zukanovich. 1608.07583] \Rightarrow **Back-up!**
- Another model possible [Becirevic, Fajfer, Kosnik, OS. 1608.08501]

A new model for R_K and R_D

D. Becirevic, S. Fajfer, N. Kosnik, OS. 1608.08051

We can also explain R_D if a **new ingredient** is added to the model
 $\Delta^{1/6} = (3, 2)_{1/6}$: three light RH neutrinos ν_R .

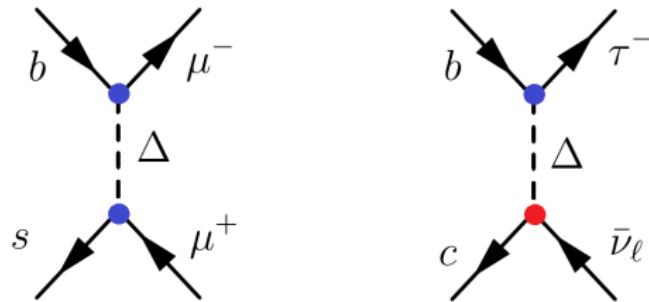
$$\mathcal{L}_Y = \textcolor{blue}{Y}_{ij}^L \bar{L}_i \tilde{\Delta}^{(1/6)} d_{Rj} + \textcolor{red}{Y}_{ij}^R \bar{Q}_i \Delta^{(1/6)} \nu_{Rj} + \text{h.c.}$$

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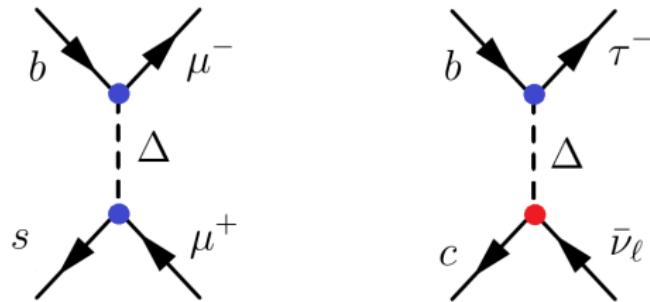


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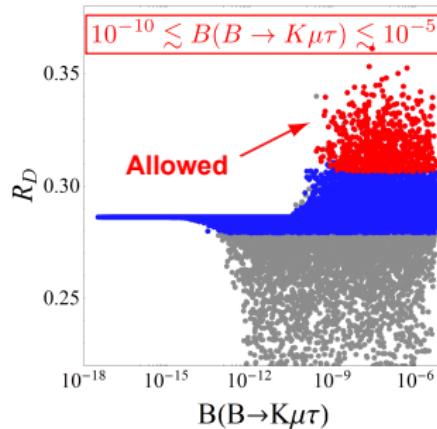
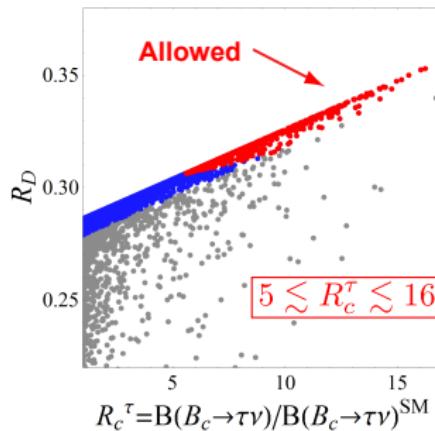
For $b \rightarrow c\tau\bar{\nu}$ $\Rightarrow |\mathcal{M}(B \rightarrow D^{(*)}\ell\nu)|^2 = |\mathcal{M}_{\text{SM}}|^2 + |\mathcal{M}_{\text{NP}}|^2$.

Naturally generates $R_{D^{(*)}}^{\text{NP}} > R_{D^{(*)}}^{\text{SM}}$ if $|Y_{b\tau}^L| \gtrsim |Y_{b\mu}^L|$.

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D. Becirevic, S. Fajfer, N. Kosnik, OS. 1608.08051

Several **distinctive predictions** wrt the SM:



- **Enhancement** of $\mathcal{B}(B_c \rightarrow \tau\bar{\nu})$ wrt $\mathcal{B}(B_c \rightarrow \tau\bar{\nu})^{\text{SM}} = 2.21(12)\%$.
- $R_{\eta_c} \equiv \mathcal{B}(B_c \rightarrow \eta_c \tau\nu)/\mathcal{B}(B_c \rightarrow \eta_c \ell\nu)$ can be **20% larger** than $R_{\eta_c}^{\text{SM}}$.
- Upper and **lower bounds** on the LFV rates.

Conclusions and Perspectives

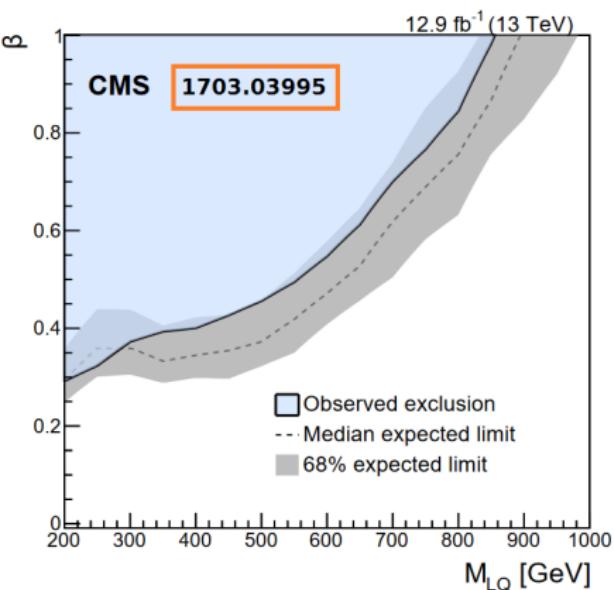
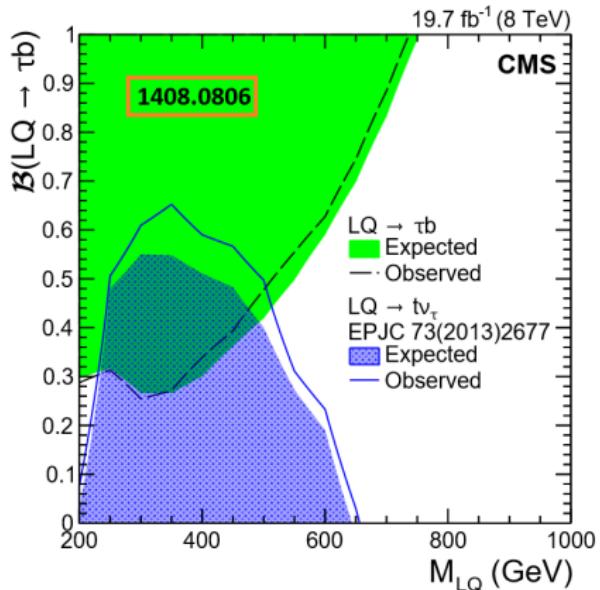
Conclusions and Perspectives

- Interesting hints of LFU violation in R_K and $R_{D^{(*)}}$ – Use the experimental data to do physics!
- Important cross-checks: R_{K^*} and R_ϕ [theoretically clean].
- LFV is expected in most models aiming to explain $R_K^{\text{exp}} < 1$. We give predictions in models with SLQ ($\sim 10^{-5}$) and generic Z' ($\sim 10^{-7}$).
- $R_K^{\text{NP}} < R_K^{\text{SM}}$ and $R_{D^{(*)}}^{\text{NP}} > R_{D^{(*)}}^{\text{SM}}$ can be simultaneously explained in minimal SLQ model with light RH neutrinos
⇒ Model can be tested at LHC(b) and Belle-II.

Thank you!

Back-up

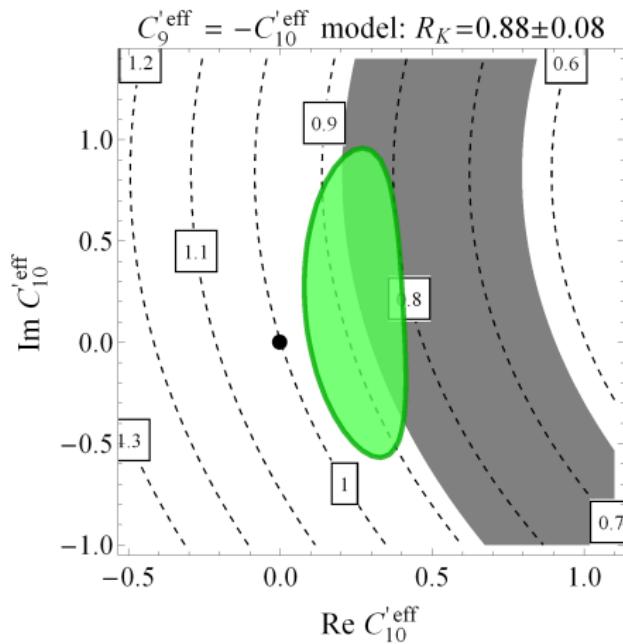
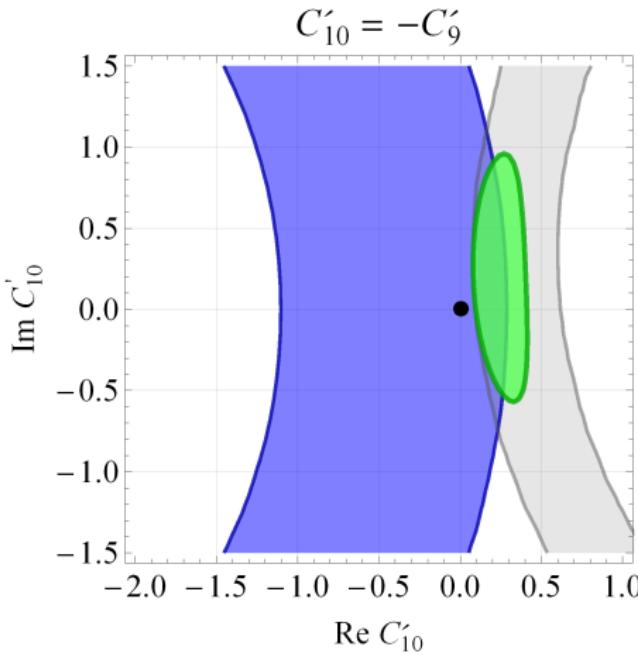
LQ Direct Searches: $\Delta \rightarrow \tau b$



NP fit of $b \rightarrow s\mu^+\mu^-$

[Becirevic et al. 1503.09024]

$\mathcal{B}(B_s \rightarrow \mu\mu)$ and $\mathcal{B}(B^+ \rightarrow K^+\mu\mu)_{\text{high } q^2}$ vs R_K



SLQ (3,2)_{1/6}

$$C_{9'}^{\ell\ell'} = -C_{10'}^{\ell\ell'} = \frac{\pi v^2}{2\lambda_t \alpha_{\text{em}}} \frac{Y_{s\ell} Y_{b\ell'}^*}{m_\Delta^2},$$

$$\begin{aligned} \frac{d\Gamma}{dq^2}(B \rightarrow K\nu\bar{\nu}) &= \frac{|N|^2}{384\pi^3 m_B^3} |f_+(q^2)|^2 \lambda^{3/2}(m_B^2, m_K^2, q^2) \\ &\times \left\{ 3|C_L^{\text{SM}}|^2 + \frac{(Y \cdot Y^\dagger)_{ss}(Y \cdot Y^\dagger)_{bb}}{16N^2 m_\Delta^4} + \frac{2\text{Re}[C_L^{\text{SM}}(Y \cdot Y^\dagger)_{sb}]}{4Nm_\Delta^2} \right\}, \end{aligned}$$

where $N = \frac{G_F V_{tb} V_{ts}^* \alpha}{\sqrt{2}\pi}$ and $C_L^{\text{SM}} = -6.38(6)$.

Explaining R_K : Another Possibility

Z' Models

Z' bosons are usually associated with a new Abelian symmetry $U(1)'$.

A few examples:

- Gauged $L_\mu - L_\tau$ symmetry [Crivellin, D'Ambrosio, Heeck, 1501.00993]
- Gauged $B - L$ charges [Crivellin, D'Ambrosio, Heeck, 1503.03477]

Here, we will consider a **bottom-up approach**:

⇒ Z' couplings are only **fixed by data**.

$$\mathcal{L}_{Z'} \supset g_{\ell_i \ell_j}^L \bar{\ell}_i \gamma^\mu P_L \ell_j Z'_\mu + g_{sb}^L \bar{s} \gamma^\mu P_L b Z'_\mu + (L \rightarrow R)$$

Assumptions: gauge invariance (e.g., $g_{\ell_i \ell_j}^L = g_{\nu_i, \nu_j}^L$) and no couplings to electrons.

LFV in $b \rightarrow s\mu\tau$

Z' Models

[D. Becirevic, R. Zukanovich, OS. 1602.0081]

- Scenario I: $g_{sb}^L, g_{\mu\mu}^L \neq 0$ $(C_9)_{\mu\mu} = -(C_{10})_{\mu\mu} \propto g_{sb}^L g_{\mu\mu}^L$
- Scenario II: $g_{sb}^R, g_{\mu\mu}^R \neq 0$ $(C'_9)_{\mu\mu} = -(C'_{10})_{\mu\mu} \propto g_{sb}^R g_{\mu\mu}^R$

$$\mathcal{L}_{Z'} \supset g_{\ell_i \ell_j}^L \bar{\ell}_i \gamma^\mu P_L \ell_j Z'_\mu + g_{sb}^L \bar{s} \gamma^\mu P_L b Z'_\mu + (L \rightarrow R)$$

LFV in $b \rightarrow s\mu\tau$

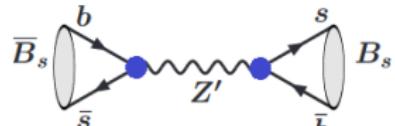
Z' Models

[D. Becirevic, R. Zukanovich, OS. 1602.0081]

$$\frac{\Delta m_{B_s}^{\text{exp}}}{\Delta m_{B_s}^{\text{SM}}} - 1 \propto \frac{(g_{sb}^{L(R)})^2}{m_{Z'}^2}$$

$$\mathcal{B}(\tau \rightarrow \mu\nu_\mu\bar{\nu}_\tau)^{\text{exp}} - \mathcal{B}(\tau \rightarrow \mu\nu_\mu\bar{\nu}_\tau)^{\text{SM}} \propto -\frac{(g_{\mu\tau}^L)^2}{m_{Z'}^2}$$

$$\mathcal{B}(\tau \rightarrow 3\mu) \propto \frac{(g_{\mu\mu}^L)^2 [2(g_{\mu\tau}^L)^2 + (g_{\mu\tau}^R)^2]}{m_{Z'}^4}$$



- Tree-level processes \Rightarrow Predictions independent on $m_{Z'}$.
- Couplings to **leptons** and **quarks** can be constrained separately.

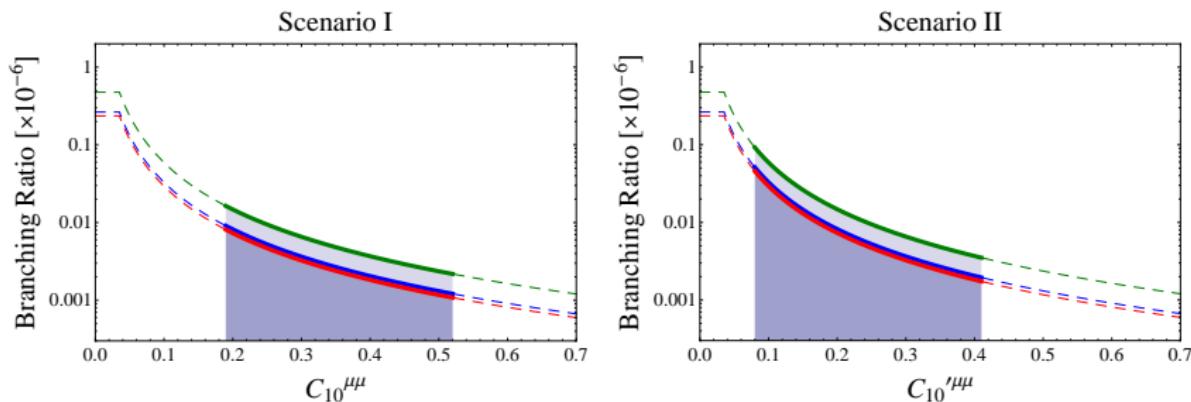
LFV in $b \rightarrow s\mu\tau$

Z' Models

[D. Becirevic, R. Zukanovich, OS. 1602.0081]

Maximal branching ratios \Rightarrow Possibly within reach of LHCb and Belle-2.

Scenario	I (LH)	II (RH)
$\mathcal{B}(B \rightarrow K^* \mu \tau) \leq$	1.6×10^{-8}	9.3×10^{-8}
$\mathcal{B}(B \rightarrow K \mu \tau) \leq$	0.9×10^{-8}	5.2×10^{-8}
$\mathcal{B}(B_s \rightarrow \mu \tau) \leq$	0.8×10^{-8}	4.6×10^{-8}



NB. Crivellin et. al. [1504.07928] obtain larger rates due to *inconsistent* treatment of g_{sb}^L and g_{sb}^R .

On (in)viability of SLQ $(3, 1)_{-1/3}$

November 9, 2015

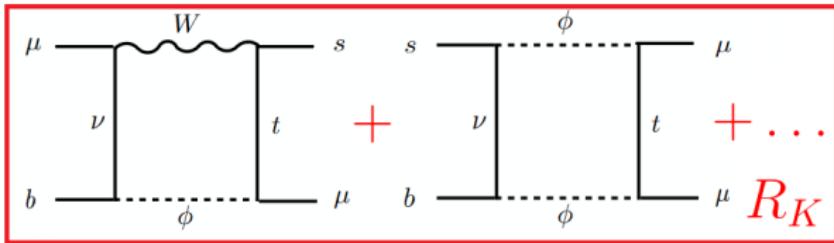
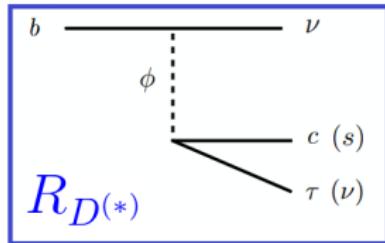
One Leptoquark to Rule Them All: A Minimal Explanation for $R_D^{(*)}$, R_K and $(g - 2)_\mu$

Martin Bauer^a and Matthias Neubert^{b,c}

1511.01900

An interesting idea: to explain R_D at tree-level and R_K at loop-level.

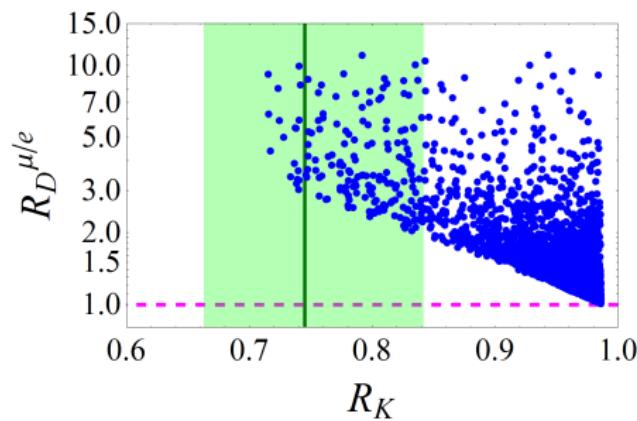
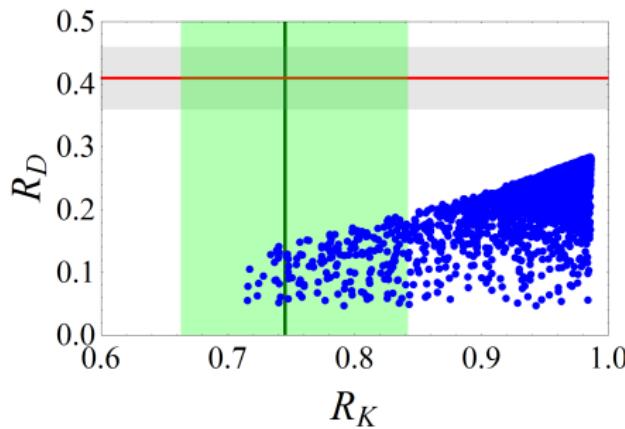
$$\mathcal{L}_{\Delta(1/3)} = \Delta^{(1/3)*} \left[(\textcolor{blue}{V^* g_L})_{ij} \overline{u_i^C} P_L \ell_j - (g_L)_{ij} \overline{d_i^C} P_L \nu_j + (\textcolor{magenta}{g_R})_{ij} \overline{u_i^C} P_R \ell_j \right]$$



On (in)viability of SLQ $(3, 1)_{-1/3}$

Scan Results

[D. Becirevic, N. Kosnik, OS, R. Zukarnovich. 1608.07583]



- Large couplings to the muon (to get R_K) \Rightarrow push R_D to small values.
- Explanation of $R_K \Rightarrow$ unacceptably large $R_D^{\mu/e} = \frac{\mathcal{B}(B \rightarrow D\mu\nu)}{\mathcal{B}(B \rightarrow D e \nu)} \gtrsim 2$.

In conclusion, R_K cannot be explained by this model.

Light Leptoquarks and $SU(5)$ GUT

Can we embed the leptoquark $(3, 2)_{1/6}$ in a UV completion?

An old idea:

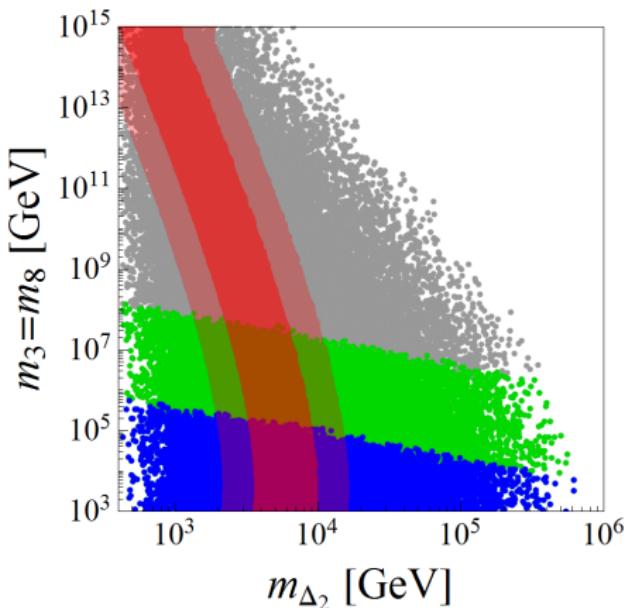
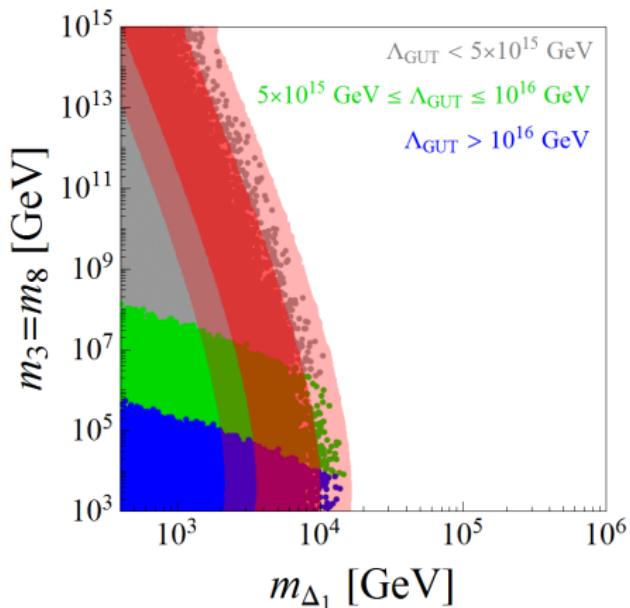
One pair of $(3, 2)_{1/6}$ and one additional Higgs doublet $(1, 2)_{1/2}$ at the EW scale can lead to unification.
[Murayama and Yanagida, 1992.]

Setup:

	\mathcal{G}_{SM}	$U(1)_{\text{PQ}}$
$\bar{5}_F$	$(\bar{3}, 1)_{1/3} \oplus (1, 2)_{-1/2}$	+1
10_F	$(3, 2)_{1/6} \oplus (\bar{3}, 1)_{-2/3} \oplus (1, 1)_1$	+1
5_Δ	$(1, 2)_{1/2} \oplus \dots$	-2
$\bar{5}_\Delta$	$(1, 2)_{-1/2} \oplus \dots$	-2
$(2 \times) \mathbf{10}_\Delta$	$(3, 2)_{1/6} \oplus \dots$	-2
24_Δ	...	

+ desert assumption (only the LQs and the new Higgs are light).

- Λ_{GUT} can be raised by a splitting of 24Δ : $m_{38} = m_3 = m_8 \ll \Lambda_{\text{GUT}}$



The **unification** of gauge couplings gives a **strong constraint** on the lightest LQ mass $m_{\Delta_1} \lesssim 16$ TeV.

Can we consistently predict R_{D^*} in any NP scenario?

Conditions to fulfill:

- **Absence** of couplings to **electrons and muons**,

OR

- $(V - A) \times (V - A)$ effective operator \Rightarrow overall modification of $R_{D^{(*)}}$.

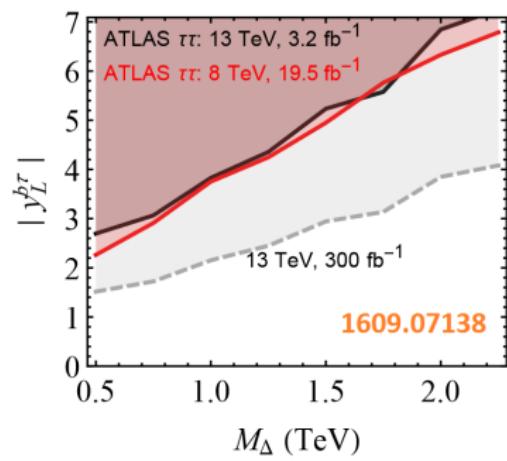
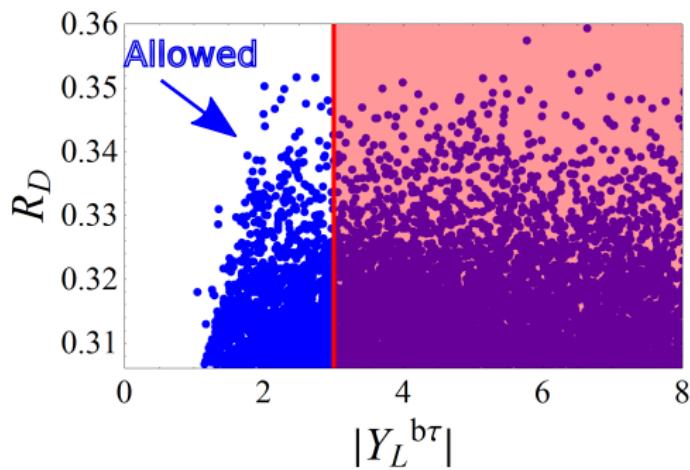
$\Rightarrow V(q^2)$ and $A_{1,2}(q^2)$ can be extracted from $B \rightarrow D^* \ell \nu$ ($\ell = e, \mu$) data.

Caveat: $A_0(q^2)$ cannot be extracted from data (HQET)

\Rightarrow induces unknown systematic uncertainties – LQCD might help!

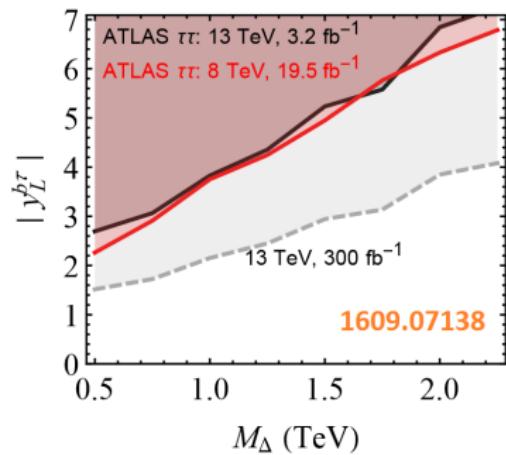
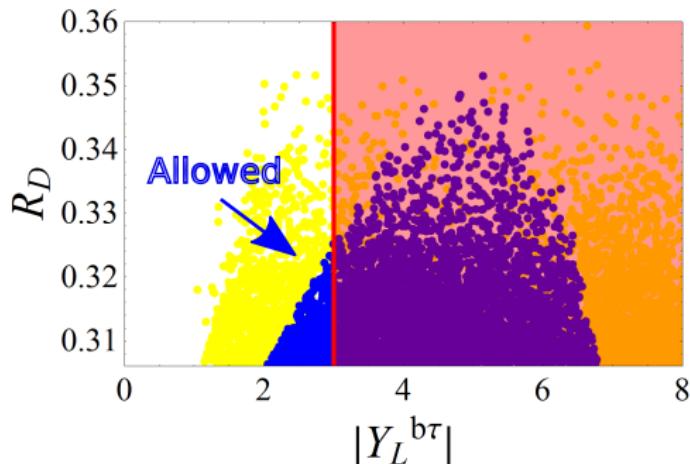
Perfect agreement as of now – only $|Y_L^{b\tau}|$ couplings is constrained:

$$\mathcal{L}_\Delta \ni -\bar{d}_R \mathbf{Y}_L \ell_L \Delta^{2/3}$$



NB. Perturbativity condition $|Y_i| \leq 4\pi$.

If one also imposes $\Gamma_\Delta/m_\Delta \leq 1$:



\Rightarrow We can accommodate R_D^{exp} at the 1.5σ .

NB. LQCD prediction $R_D^{\text{SM}} = 0.286(12) \Rightarrow 14\%$ increase due to NP.