

# B-Physics and Lepton Flavor (Universality) Violation

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In collaboration with

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[hep-ph/1602.00881](https://arxiv.org/abs/hep-ph/1602.00881), [1608.07583](https://arxiv.org/abs/1608.07583) and [1704.05835](https://arxiv.org/abs/1704.05835)

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UNIVERSITÀ  
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DI PADOVA



**elusives**  
neutrinos, dark matter & dark energy physics



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# Outline

- 1 Introduction
- 2 LFU violation in  $b \rightarrow s\ell\ell$
- 3 New ideas for  $b \rightarrow s\ell\ell?$
- 4 Brief discussion  $b \rightarrow c\tau\bar{\nu}$
- 5 Conclusions and Perspectives

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# Introduction

- The Standard Model Theory (SM) provides an elegant and accurate description of particle physics.
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- Neutrino oscillation
- Dark Matter\*
- Baryon asymmetry (BAU)\*
- ...

## On the theory side

- Hierarchy problem
- Flavor problem
- Strong CP-problem
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The SM is an **effective theory** at low energies of a more fundamental theory (still unknown).

# The Standard Model Theory

- Gauge sector entirely **fixed by symmetry**:

$$G = SU(3)_c \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_c \times U(1)_{\text{em}}$$

For a quark doublet e.g.,

$$D_\mu = \partial_\mu - i g_s t_a A_\mu^a - i g T \cdot W_\mu - i g' \frac{Y}{2} B_\mu$$

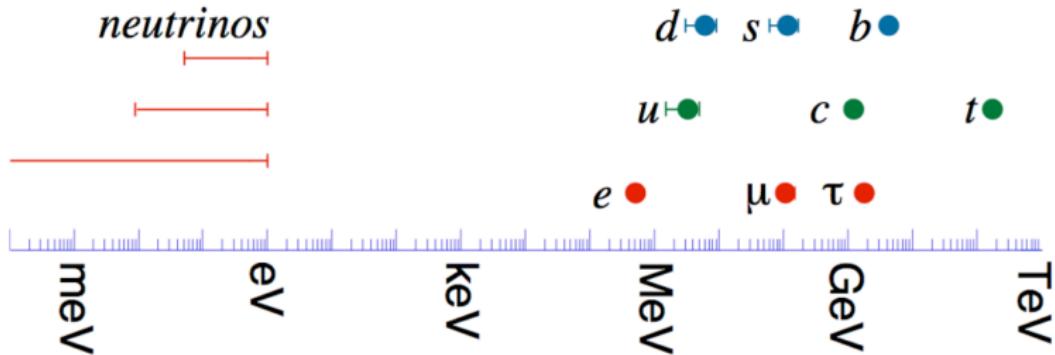
- Flavor sector **loose**:

⇒ 13 free parameters (**masses and quark mixing**) – fixed by data.

$$\mathcal{L}_Y = - Y_\ell \bar{L} \Phi \ell_R - Y_d \bar{Q} \Phi d_R - Y_u \bar{Q} \tilde{\Phi} u_R + \text{h.c.}$$

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- Striking hierarchy  $\Rightarrow$  **Flavor theory?**
- Quarks and leptons mix in completely different ways.

NuFIT 2.0 (2014)

$$|U|_{3\sigma} = \begin{pmatrix} 0.801 \rightarrow 0.845 & 0.514 \rightarrow 0.580 & 0.137 \rightarrow 0.158 \\ 0.225 \rightarrow 0.517 & 0.441 \rightarrow 0.699 & 0.614 \rightarrow 0.793 \\ 0.246 \rightarrow 0.529 & 0.464 \rightarrow 0.713 & 0.590 \rightarrow 0.776 \end{pmatrix}$$

UTFIT 2016

$$|V_{CKM}| = \begin{pmatrix} 0.97431 \pm 0.00015 & 0.22512 \pm 0.00067 & 0.00365 \pm 0.00012 \\ 0.22497 \pm 0.00067 & 0.97344 \pm 0.00015 & 0.04255 \pm 0.00069 \\ 0.00869 \pm 0.00014 & 0.04156 \pm 0.00056 & 0.999097 \pm 0.000024 \end{pmatrix}$$

“Who ordered that?”

- So far **no clear signal** of NP has been found at the LHC.
- Hierarchy and Flavor problems **remain unsolved**.
- Simplicity and beauty have been the guidelines in the quest for NP.  
However, there is **no strong preference** for a specific **NP scenario**.



⇒ It becomes necessary to **use experiments** to **select** among the various NP scenarios.

# How can we look for **New Physics** effects?

## Directly

- **Precision** measurements (e.g. LFU tests)
- Searches for processes **absent** in the SM  
(e.g. LFV or proton decay)

## Indirectly

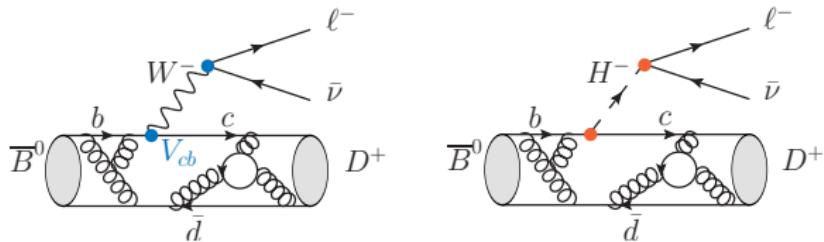
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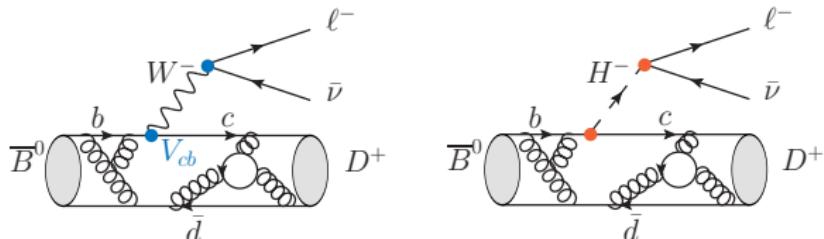
- Flavor changing charged currents: e.g.  $b \rightarrow c\tau\nu$



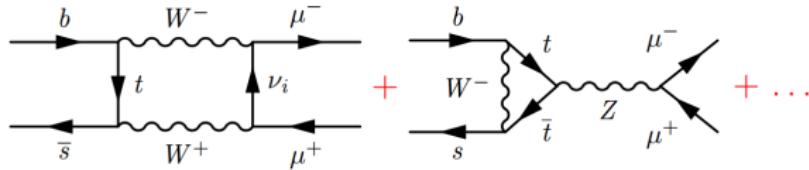
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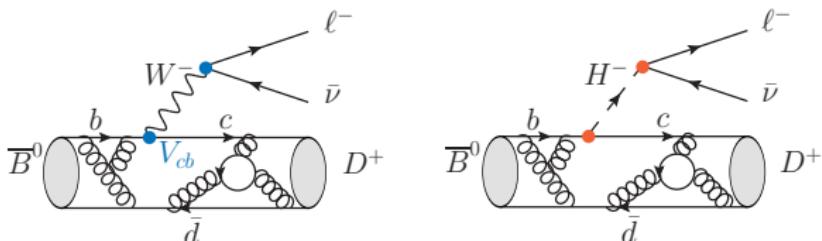
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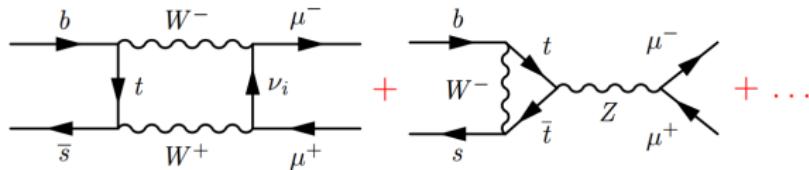
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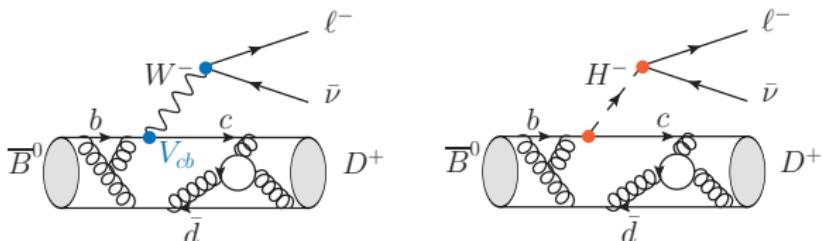


- Possible mostly due to the maturity of LQCD in determining the relevant hadronic matrix elements (form factors).

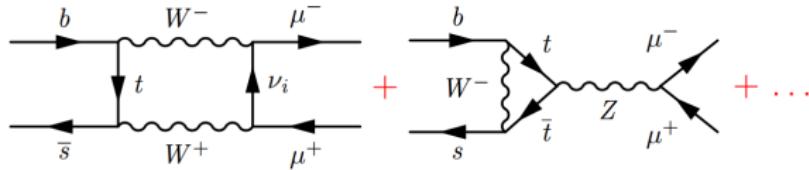
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- Possible mostly due to the maturity of LQCD in determining the relevant hadronic matrix elements (form factors).
- Particularly interesting due to the deviations from LFU observed in  $B$ -meson decays:  $B \rightarrow D^{(*)}\ell\bar{\nu}$  ( $\ell = e, \mu, \tau$ ) and  $B \rightarrow K^{(*)}\ell\ell$  ( $\ell = e, \mu$ ).

## Exploratory flavor physics: Lepton Flavor Violation (absent in the SM)

- Accidental symmetry of the SM

$$G_\ell = U(1)_e \times U(1)_\mu \times U(1)_\tau \times U(1)_B,$$

$\Rightarrow \ell \rightarrow \ell' \gamma$  and  $\ell \rightarrow \ell' \ell' \ell'$  ( $\ell \neq \ell'$ ) are strictly **forbidden**.

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e.g. 
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  - The anomalies in  $B$  decays might imply LFV signatures.

[Glashow et al. 2014]

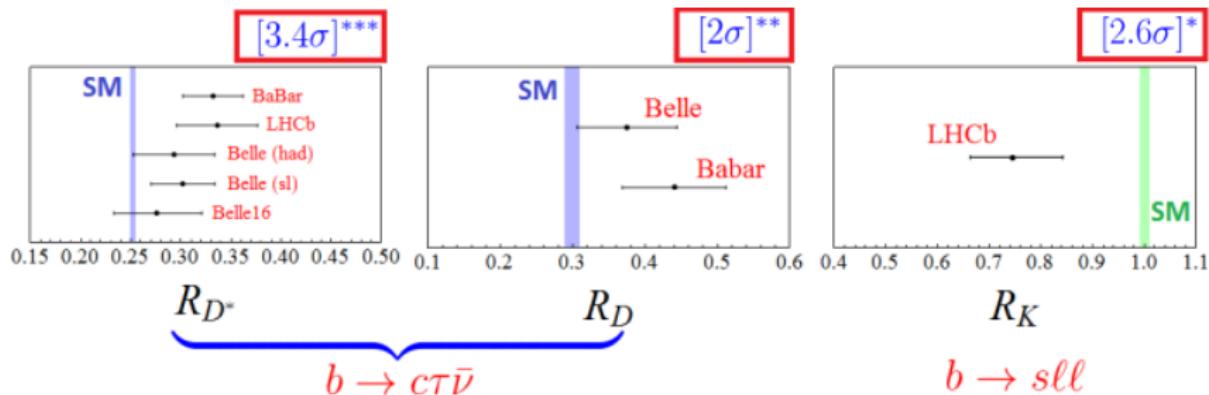
# LFU violation in $B$ decays

# LFUV in $B$ Decays

- Lepton Flavor Universality (**LFU**) is not a fundamental symmetry of the SM: **accidental** in the gauge sector and **broken by Yukawas**.
- LFU tested in pion and kaon decays – agrees very well with the SM  
⇒ *To be improved by NA62.*
- Renewed interest in LFUV motivated by the recently found conflicts between theory and experiment in  $B$  meson decays.

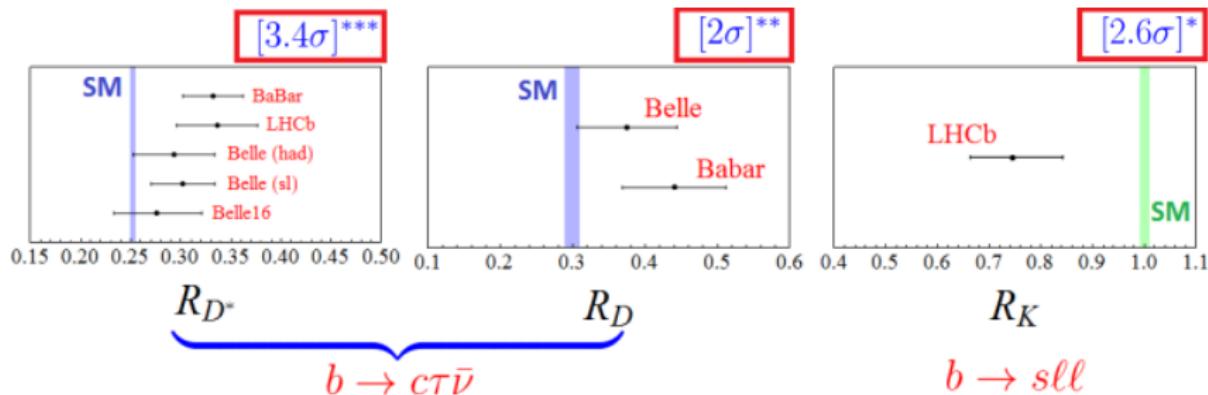
# LFUV in $B$ Decays [pre-2017]

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



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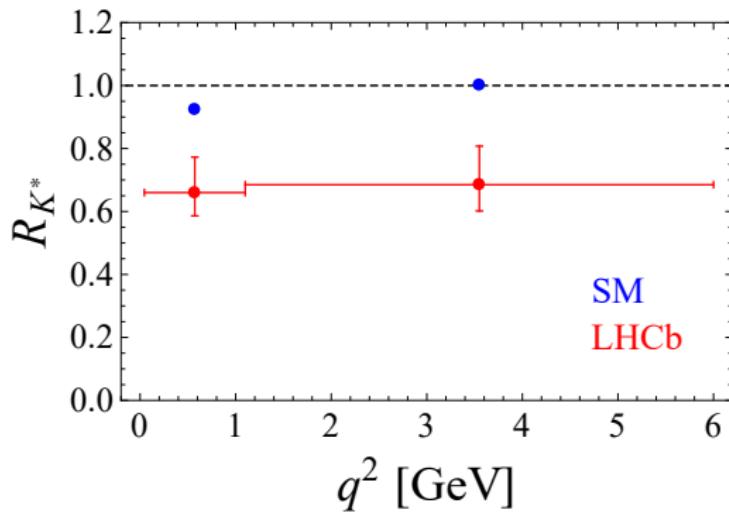


- NEW (FPCP17): LHCb,  $R_{D^*} = 0.285(35)$ , in agreement with SM.
- NEW: LHCb,  $R_{J/\Psi} = 0.71(17)(18)$ . Larger than the SM prediction (?)

# LFUV in $B$ Decays [2017]

$$R_{K^*} = \frac{\mathcal{B}(B \rightarrow K^* \mu\mu)}{\mathcal{B}(B \rightarrow K^* ee)} \Bigg|_{q^2 \in [q_{\min}^2, q_{\max}^2]} \quad [\text{LHCb, 1705.05802}]$$

- **New results** in two bins of  $q^2$ :  $[\approx 2.5\sigma]$



18th of April, *hep-ph*

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## Relevant questions:

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- What additional **experimental signatures** should we expect?

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In general,  $R_{K^{(*)}} \neq 1 \Leftrightarrow \text{LFUV} \Rightarrow \text{Lepton Flavor Violation (LFV)}$

[Glashow, Guadagnoli, Lane. 2014.]

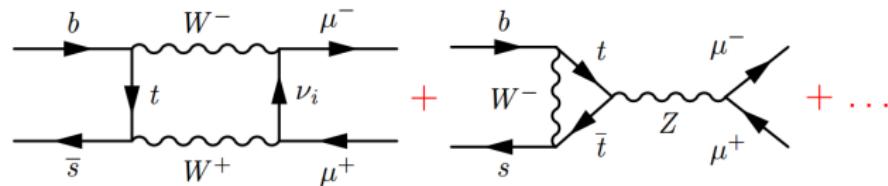
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# LFU violation

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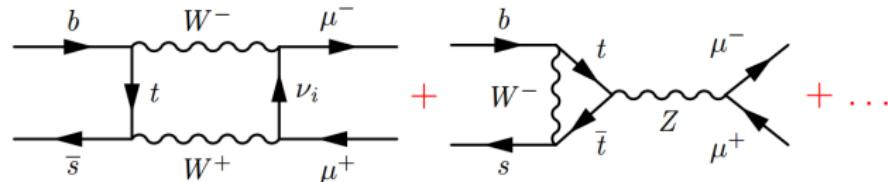
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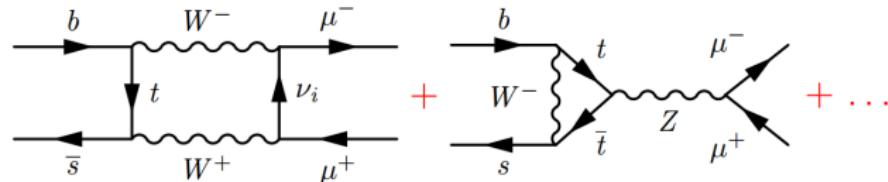
$$R_K \equiv \left. \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu\mu)}{\mathcal{B}(B^+ \rightarrow K^+ ee)} \right|_{q^2 \in [1,6] \text{ GeV}^2} \stackrel{\text{SM}}{=} 1.00(1)$$

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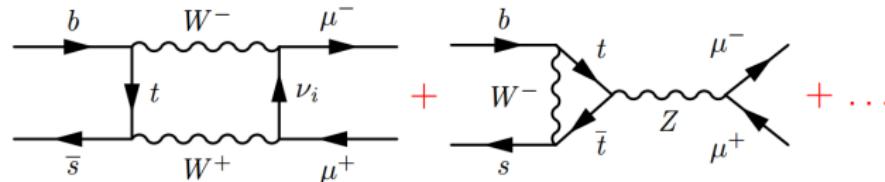
- **2.6 $\sigma$  deviation** observed by LHCb:

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

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- **$2.5\sigma$  deviation** in two bins for  $B \rightarrow K^*\mu\mu$ :  $[0.045, 1.1]$  and  $[1.1, 6]$  GeV $^2$ .

**How can we explain  $R_{K^{(*)}}$ ?**

# 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

$$\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell), \quad \mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma^5 \ell),$$

$$\mathcal{O}_S^{(\prime)} = (\bar{s}P_{R(L)} b)(\bar{\ell}\ell), \quad \mathcal{O}_P^{(\prime)} = (\bar{s}P_{R(L)} b)(\bar{\ell}\gamma_5 \ell),$$

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- To explain  $R_{K^{(*)}}^{\text{exp}} < R_{K^{(*)}}^{\text{SM}}$ , one needs effective coefficients  $C_9, C_{10}$ .

# Fit to clean observables

[Becirevic, Kosnik, OS, Zukanovich. 1608.07583]

- Use  $f_{B_s}^{Latt.} = 224(5)$  MeV and  $\mathcal{B}(B_s \rightarrow \mu\mu) = 3.0(6)(3)_2 \times 10^{-9}$ . [LHCb, 2017]

$$\mathcal{B}(B_s \rightarrow \mu^+ \mu^-) = \mathcal{F}_{B_s} \left( f_{B_s}, C_{10} - C'_{10}, C_P - C'_P, C_S - C'_S \right)$$

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- Use  $f_{+,0,T}^{B \rightarrow K}(q^2)^{Latt.}$  and  $\mathcal{B}(B \rightarrow K\mu\mu)_{q^2 \in [15,22] \text{ GeV}^2} = 1.95(16) \times 10^{-7}$ . [LHCb, 2016]

$$\frac{d\mathcal{B}}{dq^2}(B \rightarrow K\mu^+ \mu^-) = \mathcal{F}_{BK} \left( f_{+,0,T}(q^2), C_9 + C'_9, C_{10} + C'_{10}, C_{7,S,P} + C'_{7,S,P} \right)$$

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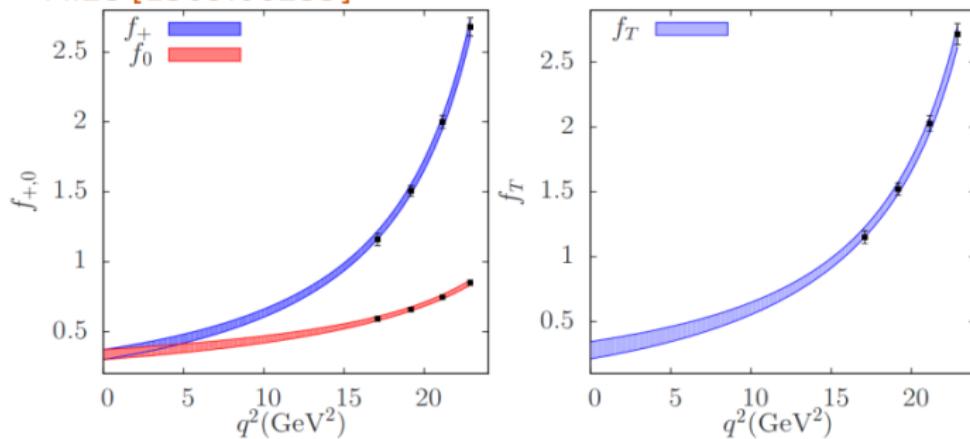
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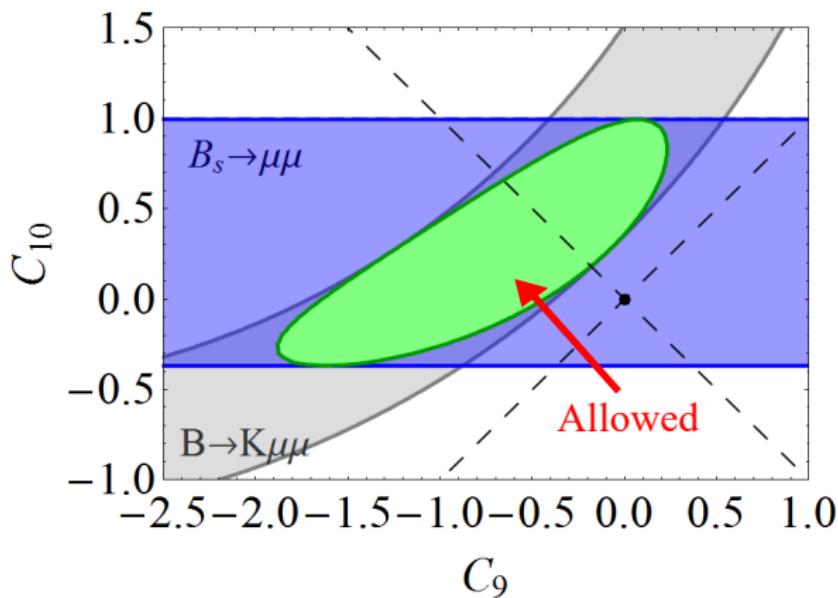
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MILC [1509.06235]



Results consistent with HPQCD 1306.2384.

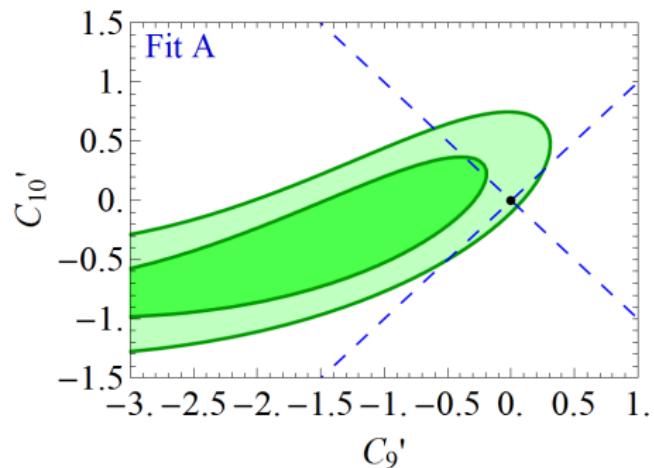
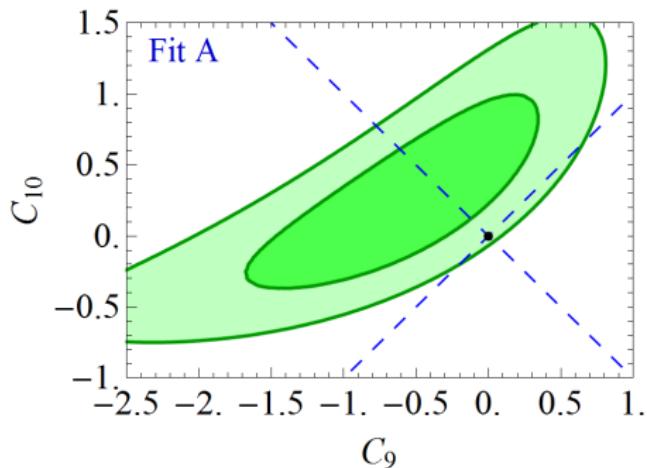


- We find  $C_9 = -C_{10} \in (-0.76, -0.04)$  at  $2\sigma$ .

⇒ This value can be used to give **model independent** predictions for  $R_{K^{(*)}}$  in the central bin:

$$R_K = 0.82(16) \quad \text{and} \quad R_{K^*} = 0.83(15).$$

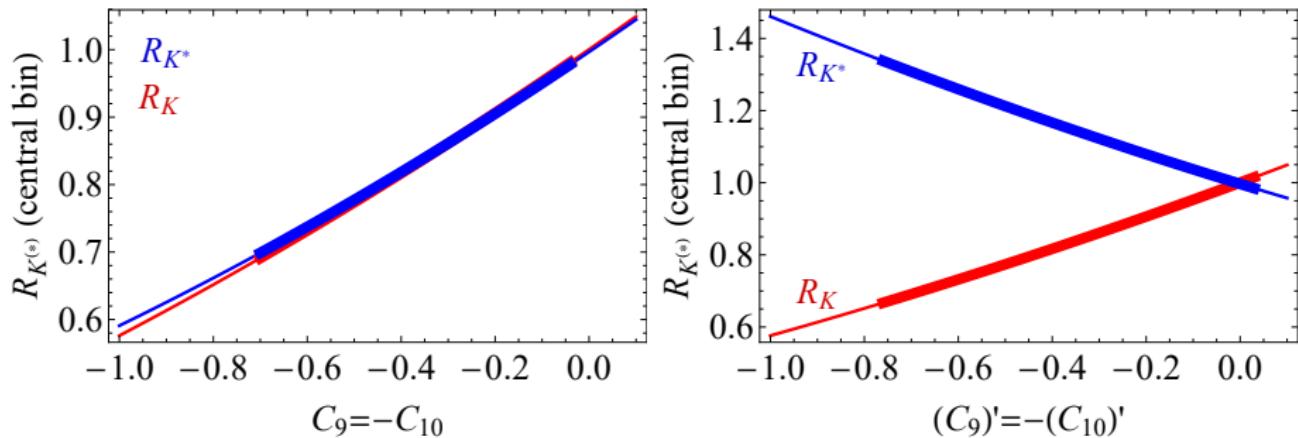
Different choices of WC:  $(C_9, C_{10})$  or  $(C'_9, C'_{10})$



$$\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell),$$

$$\mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma^5 \ell),$$

## Model independent predictions for $R_K$ and $R_{K^*}$ :



⇒ The scenario  $C_9 = -C_{10}$  predicts  $R_{K^{(*)}} < 1$ , as observed.

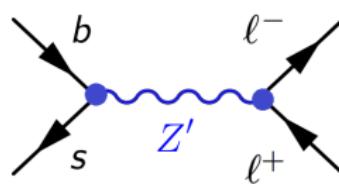
**Are there specific models capable of generating  
 $C_{9,10}$  to explain  $R_{K^{(*)}}$ ?**

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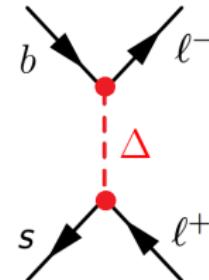
## Specific Models

### Representative (tree-level) models:

$Z'$  models



Leptoquark models



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

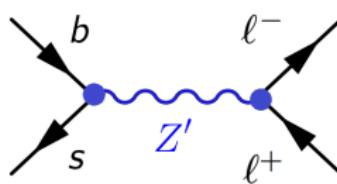
Hiller et al., Becirevic et al.,  
Gripaios et al. . . .

# Explaining $R_{K^{(*)}}$

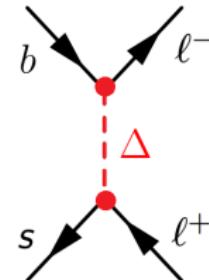
## Specific Models

### Representative (tree-level) models:

**Z' models**



**Leptoquark models**



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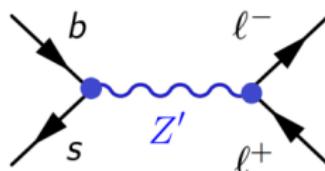
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[problematic, how to compute loops?  $B_s - \bar{B}_s$  and  $\tau \rightarrow \mu\gamma$  constraints?]   
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- Interesting feature: **LFV** is in general **expected** .

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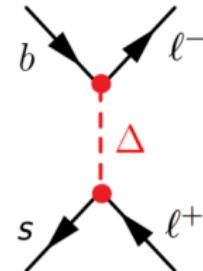
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# Explaining $R_K$

Scalar Leptoquark Models

[Becirevic, Kosnik, OS, Zukanovich. 1608.08501]

⇒ Focus on NP couplings to muons only

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

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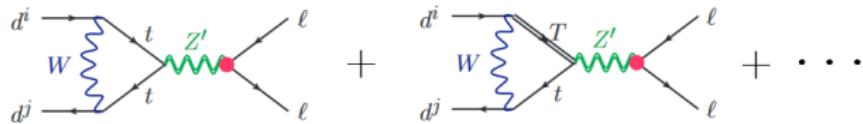
⇒ **No fully viable model.** Triplet can be used, but further symmetries are needed to forbid **proton decay** (see [Dorsner et al. 2017] for a GUT mechanism).

# Outline

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- 3 New ideas for  $b \rightarrow s\ell\bar{\ell}$ ?
- 4 Brief discussion  $b \rightarrow c\tau\bar{\nu}$
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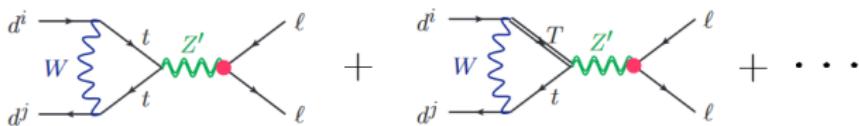
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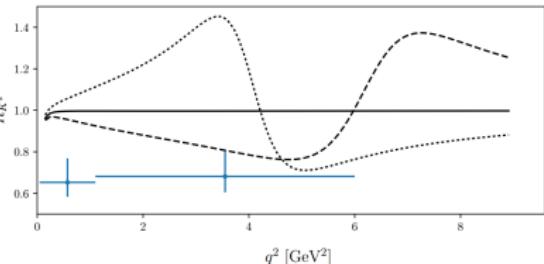
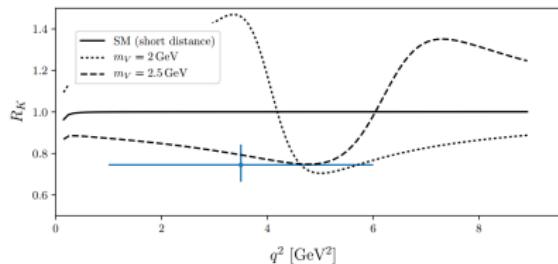


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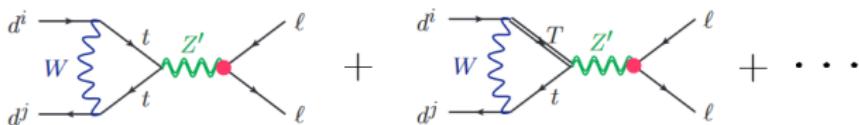


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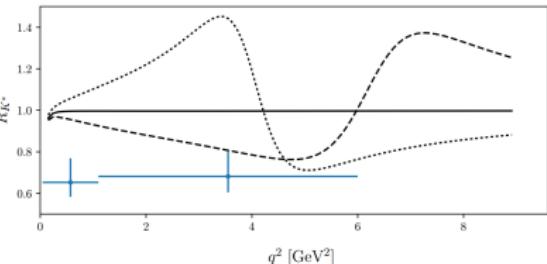
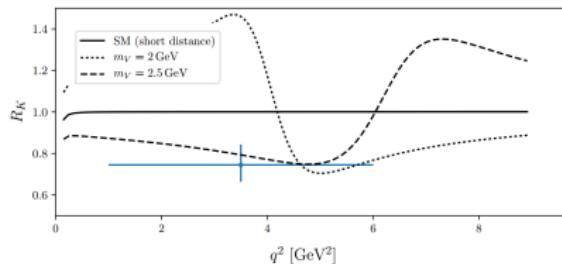


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- Loop-level SLQ contributions (revival of a misused idea [Bauer and Neubert, 1511.01900])

[Becirevic, OS. 1704.05835]

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- A first attempt: to explain  $R_{K^{(*)}}$  at loop-level and  $R_{D^{(*)}}$  at tree-level by invoking the SLQ  $(\bar{3}, 1)_{1/3}$  with  $m_\Delta \approx 1$  TeV.  
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November 9, 2015

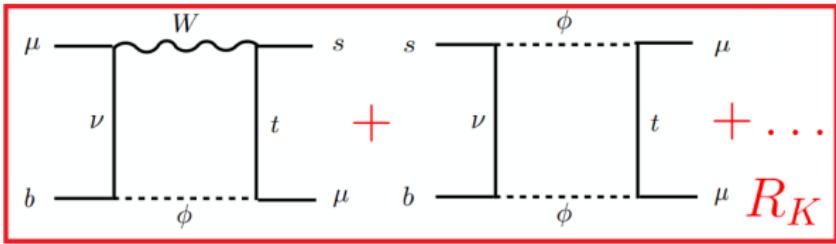
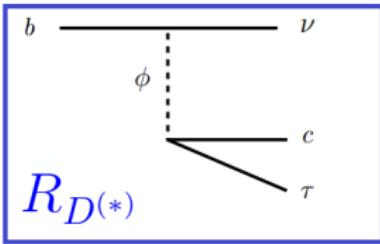


## One Leptoquark to Rule Them All: A Minimal Explanation for $R_{D(*)}$ , $R_K$ and $(g - 2)_\mu$

Martin Bauer<sup>a</sup> and Matthias Neubert<sup>b,c</sup>

**1511.01900**

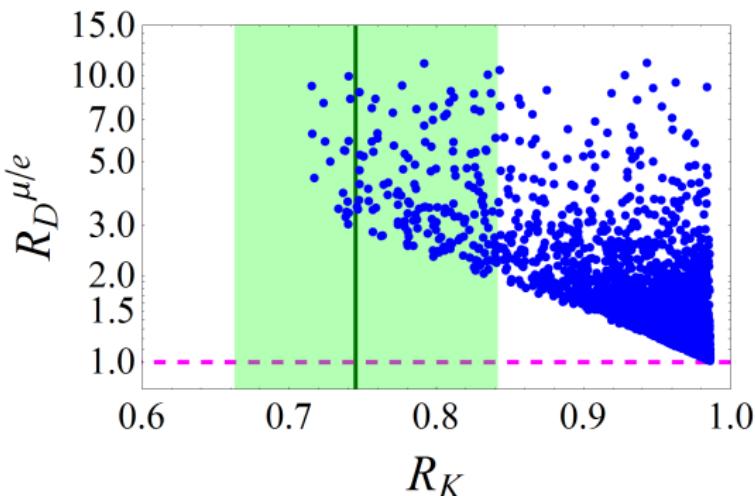
$$\mathcal{L}_{\Delta^{(1/3)}} = \Delta^{(1/3)*} \left[ (g_L)_{ij} \overline{Q_i^C} i\sigma_2 L_j + (g_R)_{ij} \overline{u_R^C} i\tau_R j \right] + \text{h.c.}$$



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⇒ Produces **unacceptably large** values of  $R_D^{\mu/e} = \frac{\mathcal{B}(B \rightarrow D \mu \nu)}{\mathcal{B}(B \rightarrow D e \nu)}$ .  
[Becirevic, Kosnik, OS, Zukanovich. 2016]



Can we exploit the same idea in a different way?

# A SLQ model to explain $R_K < 1$ and $R_{K^*} < 1$

[Becirevic, OS. 1704.05835]

## Reminder:

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What if the tree-level contribution is forbidden by symmetry?

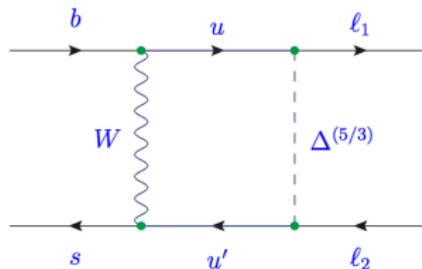
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$$\mathcal{L}_{\Delta^{(7/6)}} = (\textcolor{blue}{g_R})_{ij} \bar{Q}_i \Delta^{(7/6)} \ell_{Rj} + (\textcolor{red}{g_L})_{ij} \bar{u}_{Ri} \widetilde{\Delta}^{(7/6)\dagger} L_j + \text{h.c.},$$

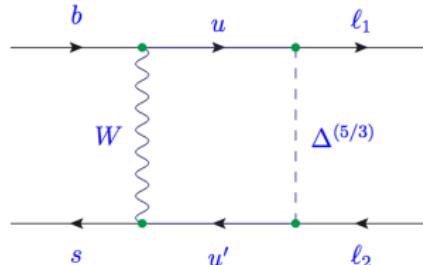
We take

$$g_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & g_L^{c\mu} & g_L^{c\tau} \\ 0 & g_L^{t\mu} & g_L^{t\tau} \end{pmatrix}, \quad g_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & g_R^{b\tau} \end{pmatrix}, \quad Vg_R = \begin{pmatrix} 0 & 0 & V_{ub}g_R^{b\tau} \\ 0 & 0 & V_{cb}g_R^{b\tau} \\ 0 & 0 & V_{tb}g_R^{b\tau} \end{pmatrix},$$

Only diagram induced at one-loop  
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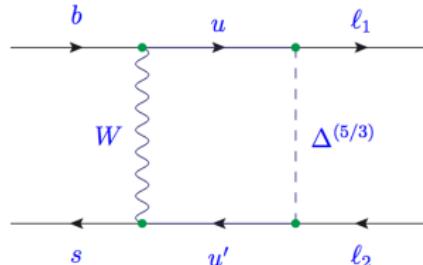
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$$C_9 = -C_{10} = \sum_{u,u' \in \{u,c,t\}} \frac{V_{ub} V_{u's}^*}{V_{tb} V_{ts}^*} g_L^{u'\mu} (g_L^{u\mu})^* \mathcal{F}(m_u, m_{u'}) ,$$

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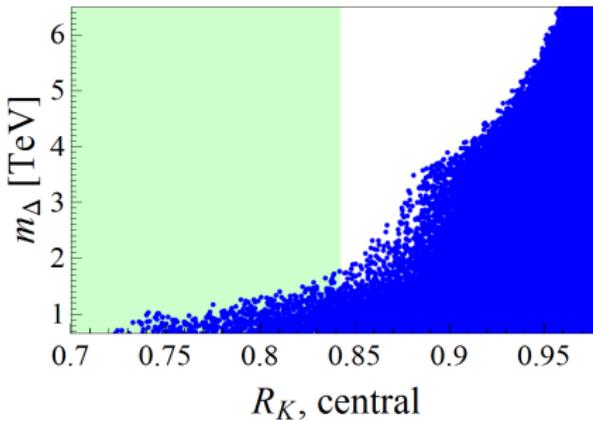
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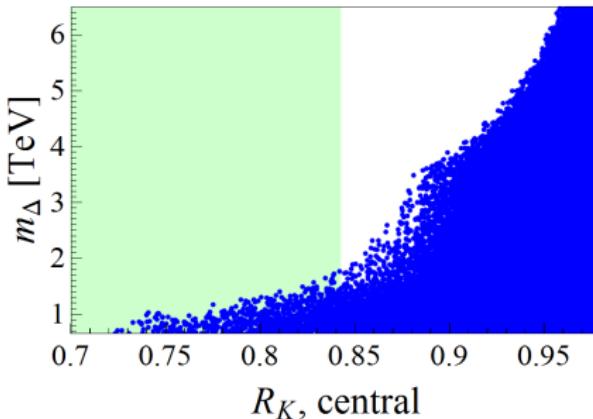
- We predict  $C_9 = -C_{10} < 0$ , in agreement with the exp. hints.
- Charm contribution is non-negligible due to CKM enhancement  $V_{cs}/V_{ts}$ .

- We performed a full flavor analysis including:  $(g - 2)_\mu$ ,  $\mathcal{B}(\tau \rightarrow \mu\gamma)$ ,  $\mathcal{B}(Z \rightarrow \ell\ell)$ ,  $\mathcal{B}(B \rightarrow K\nu\nu)$ ,  $\Delta m_{B_s}$ , among others.

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- Predictions to be tested at LHC and Belle-II:  $\mathcal{B}(Z \rightarrow \mu\tau) \lesssim 10^{-6}$  and  $\mathcal{B}(B \rightarrow K\mu\tau) \lesssim 10^{-8}$ .

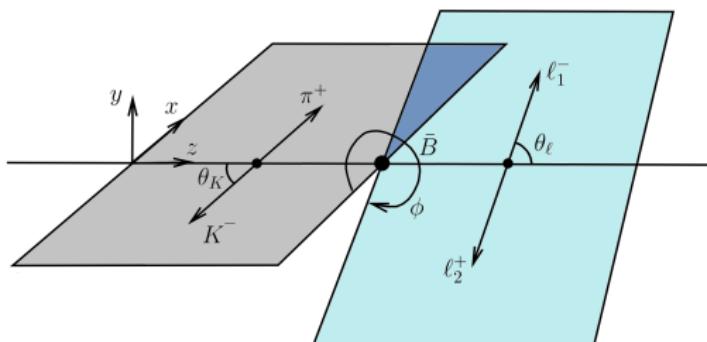
**NB.**

$$\frac{\mathcal{B}(B \rightarrow K^*\mu\tau)}{\mathcal{B}(B \rightarrow K\mu\tau)} \approx 1.8, \quad \frac{\mathcal{B}(B \rightarrow K\mu\tau)}{\mathcal{B}(B_s \rightarrow \mu\tau)} \approx 1.25.$$

[Becirevic, OS, Zukanovich, 1602.00881]

A by-product of our work:

- Most theory papers do not provide the full angular conventions for  $\bar{B} \rightarrow \bar{K}^*\ell\ell$  [**ambiguity** in the **definition of  $\phi$** ].
- We adopt the conventions of [Gratrex, Zwicky. 2015]  $\equiv$  LHCb and find **full agreement** for  $I_i(q^2)$ .

 **$K^*$  rest frame:**

$$p_K^\mu = (E_K, \hat{\mathbf{p}}_K |p_K|), \quad p_\pi^\mu = (E_\pi, -\hat{\mathbf{p}}_K |p_K|),$$

with  $\hat{\mathbf{p}}_K = (-\sin \theta_K, 0, -\cos \theta_K)$ .

**Dilepton rest frame:**

$$p_1^\mu = (E_\alpha, \hat{\mathbf{p}}_\ell |p_\ell|), \quad p_2^\mu = (E_\beta, -\hat{\mathbf{p}}_\ell |p_\ell|),$$

with  $\hat{\mathbf{p}}_\ell = (\sin \theta_\ell \cos \phi, -\sin \theta_\ell \sin \phi, \cos \theta_\ell)$ .

# Direct searches

Decay modes (for  $g_R \approx 0$ ):

[Atlas and CMS, 1503.09049, 1508.04735]

- $\Delta^{5/3} \rightarrow c\mu, t\mu, c\tau, t\tau$
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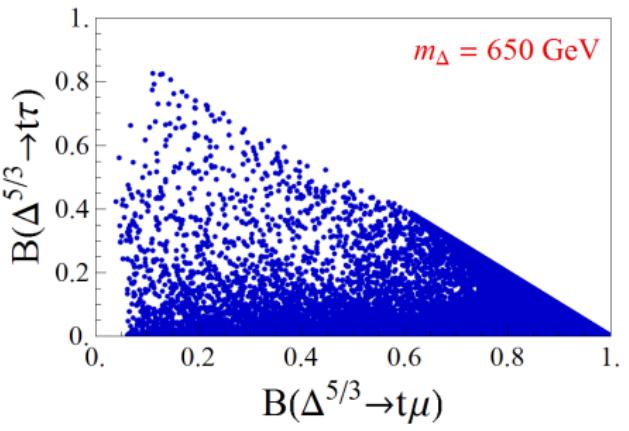
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- Predictions for direct searches:

Clean signature in  $\Delta^{5/3} \rightarrow t\mu$ !



# Outline

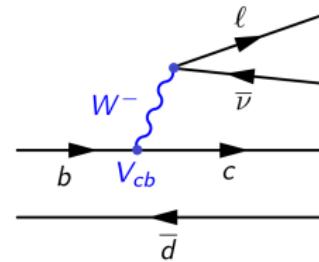
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# LFU violation

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

- Tree-level process in the SM:

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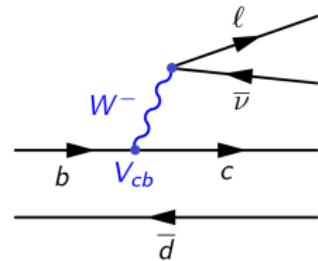


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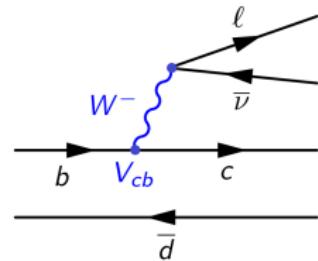
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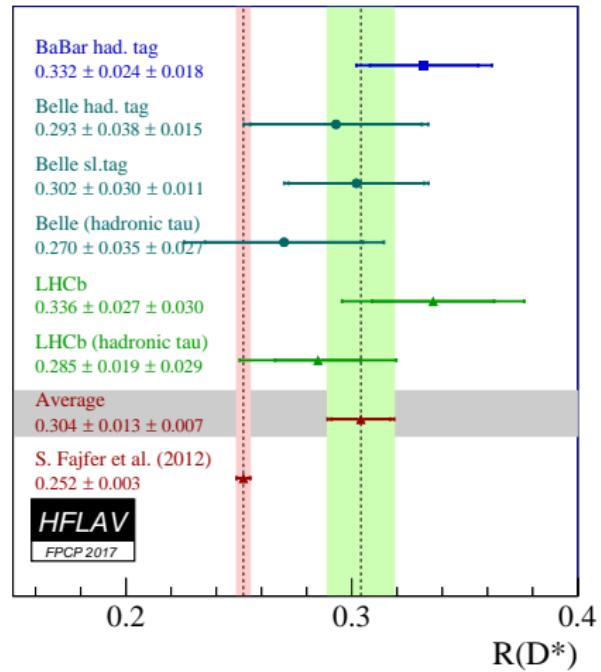
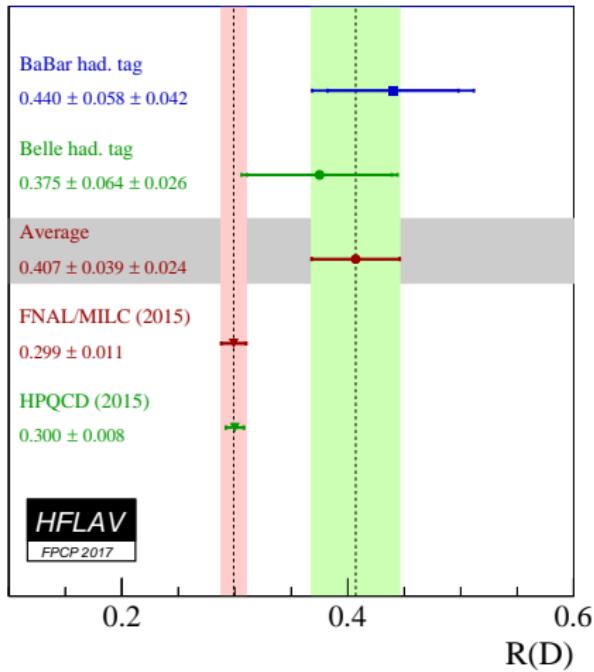
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e.g. for  $B \rightarrow D$ ,  $\langle D | \bar{c} \gamma_\mu b | B \rangle \propto f_{0,+}(q^2)$

- Situation less clear for  $B \rightarrow D^*$   $\Rightarrow$  (more FFs, less LQCD results)  
[One form-factor is unknown from LQCD – *systematic error of  $R_{D^*}^{\text{SM}}$ ?*]



- **$3.9\sigma$  combined** deviation from the SM [theory error under control?]
- **$2.2\sigma$**  deviation if **only  $R_D$**  is considered.
- $2\sigma$  deviation in  $R_{J/\Psi}$ ?

# Theory Challenge

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

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⇒ To be honest, nothing very compelling yet...

## Perspectives and future possibilities

- Measurement of similar  $b \rightarrow s\ell\ell$  ratios are an important cross-check:  $R_\phi$ ,  $R_\Lambda$  etc. Belle-II will confirm/refute  $R_{K^{(*)}}$  in the near future.

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⇒ Significant contributions in [Faroughy et al. 2016] and [Greljo et al. 2017], but there are still directions to be explored.
- IceCube can investigate LQ scenarios difficult to probe at the LHC [Becirevic, Panes, OS, Zukanovich, to appear].

# Outline

- 1 Introduction
- 2 LFU violation in  $b \rightarrow s\ell\bar{\ell}$
- 3 New ideas for  $b \rightarrow s\ell\bar{\ell}$ ?
- 4 Brief discussion  $b \rightarrow c\tau\bar{\nu}$
- 5 Conclusions and Perspectives

# Conclusions and Perspectives

- Interesting hints of LFU violation in  $R_{K^{(*)}}$  and  $R_{D^{(*)}}$  – Use the experimental data to build a model of new physics!
- LFV is expected in most models aiming to explain the LFUV anomalies.
- We propose a new model to explain  $R_{K^{(*)}}$  through loop contributions.  
⇒ Model can be tested at indirect (LHCb and Belle-II) and direct searches (CMS and Atlas).
- Simultaneous explanations of  $R_{K^{(*)}}$  and  $R_{D^{(*)}}$  remain a theory challenge.
- Higgs Flavor Era around the corner?

Thank you!

# Back-up

## Reminder:

	BNC	Interaction	WC	$R_K/R_K^{\text{SM}}$	$R_{K^*}/R_{K^*}^{\text{SM}}$
$(\bar{3}, 1)_{4/3}$	✗	$\overline{d_R^C} \Delta \ell_R$	$(C_9)' = (C_{10})'$	$\approx 1$	$\approx 1$
$(3, 2)_{7/6}$	✓	$\overline{Q} \Delta \ell_R$	$C_9 = C_{10}$	$> 1$	$> 1$
$(3, 2)_{1/6}$	✓	$\overline{d_R} \tilde{\Delta}^\dagger L$	$(C_9)' = -(C_{10})'$	$< 1$	$> 1$
$(\bar{3}, 3)_{1/3}$	✗	$Q^C i \tau_2 \boldsymbol{\tau} \cdot \Delta L$	$C_9 = -C_{10}$	$< 1$	$< 1$

- $R_K^{\text{exp}} < R_K^{\text{SM}}$  can be accommodated by SLQ  $(3, 2)_{1/6}$ :

[Becirevic et al. 2015]

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

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

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

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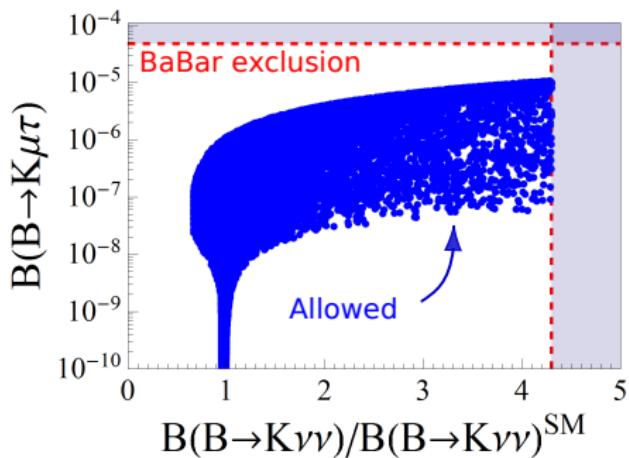
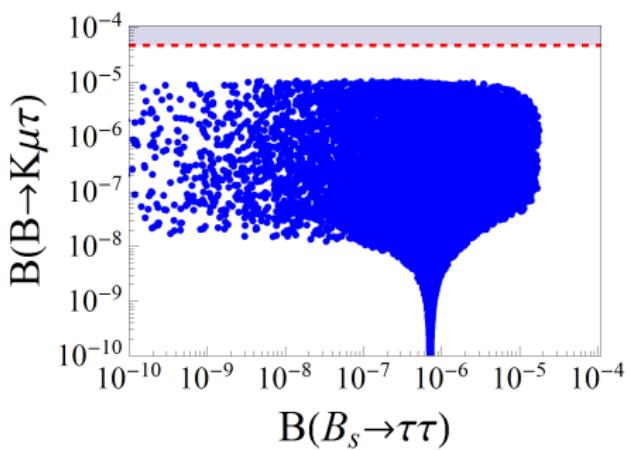
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Prediction for LHCb and Belle-II:  $\mathcal{B}(B^+ \rightarrow K^+ \mu \tau) \leq 4.8 \times 10^{-5}$



[Becirevic, Kosnik, OS, Zukanovich. 1608.07583] ↗

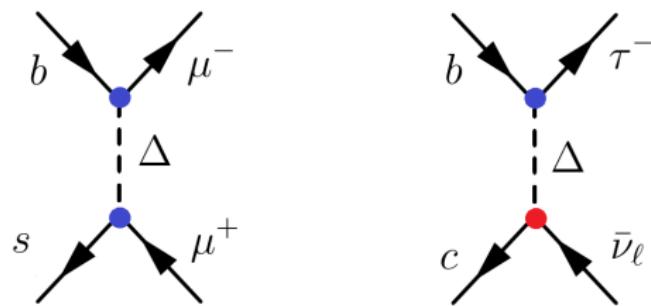
# Theory Challenge

A SLQ Model for  $R_K$  and  $R_D$

[Becirevic, Fajfer, 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  $\nu_R$ .

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



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  $|Y_{b\tau}^L| \gtrsim |Y_{b\mu}^L|$ .

# Theory Challenge

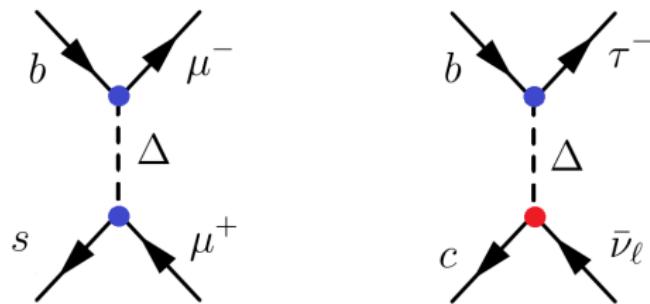
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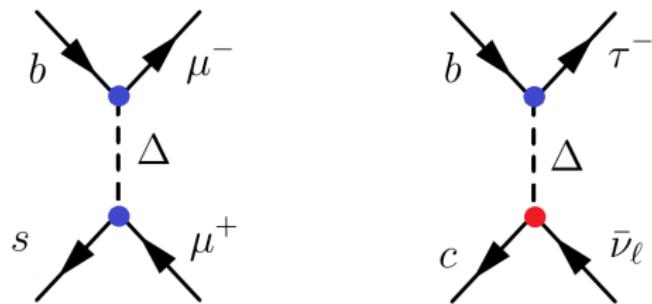
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- Passed all flavor tests:  $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)$ ,  $\mathcal{B}(B \rightarrow K \mu \mu)_{\text{high } q^2}$ ,  $\Delta m_{B_s}$ ,  $\mathcal{B}(B \rightarrow \tau \bar{\nu})$ ,  $\mathcal{B}(D_s \rightarrow \tau \bar{\nu})$ ,  $\mathcal{B}(B \rightarrow K \nu \bar{\nu})$ ,  $\mathcal{B}(B \rightarrow K \mu \tau)$  etc.
- Many experimental signatures for LHCb and Belle-2.

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A SLQ Model for  $R_K$  and  $R_D$

[D. Becirevic, S. Fajfer, N. Kosnik, OS. 1608.08501]

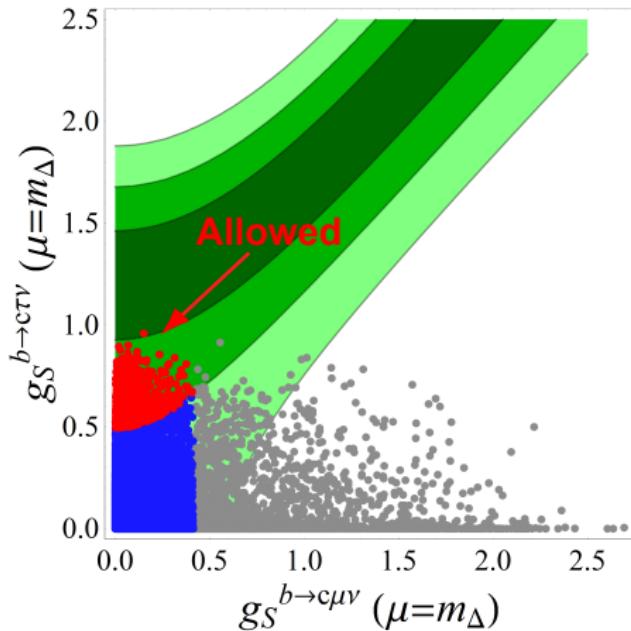
$$\mathcal{H}_{\text{eff}} = 2\sqrt{2}G_F \left[ \mathbf{g}_S(\boldsymbol{\mu})(\bar{c}_L b_R)(\bar{\ell}_L \nu_R) + \mathbf{g}_T(\boldsymbol{\mu})(\bar{c}_L \sigma_{\mu\nu} b_R)(\bar{\ell}_L \sigma^{\mu\nu} \nu_R) \right] + \text{h.c.}$$

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A SLQ Model for  $R_K$  and  $R_D$

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$B \rightarrow D$  form factors from LQCD.  
[MILC & Fermilab. 2015]

Substantial **improvement** wrt the SM prediction:

$$R_D^{\text{SM}} = 0.286(12)$$

Both decay modes get LQ contributions:

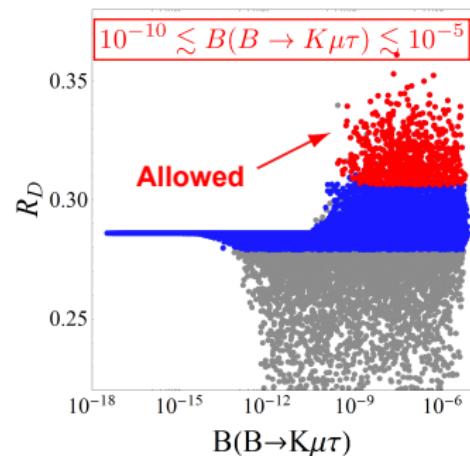
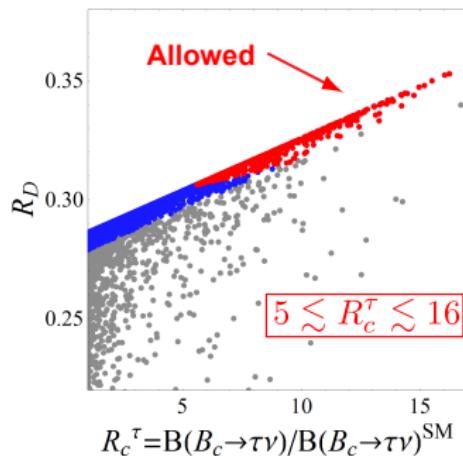
- $B \rightarrow D\tau\nu_x$
- $B \rightarrow D\mu\nu_x$

# Theory Challenge

A SLQ for  $R_K$  and  $R_D$

[D. Becirevic, S. Fajfer, N. Kosnik, OS. 1608.08501]

Several distinctive predictions wrt the SM:



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

# Summary

Is this model a final solution? **No!**

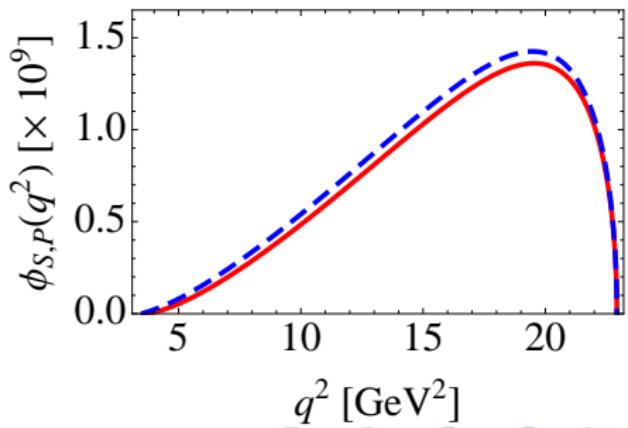
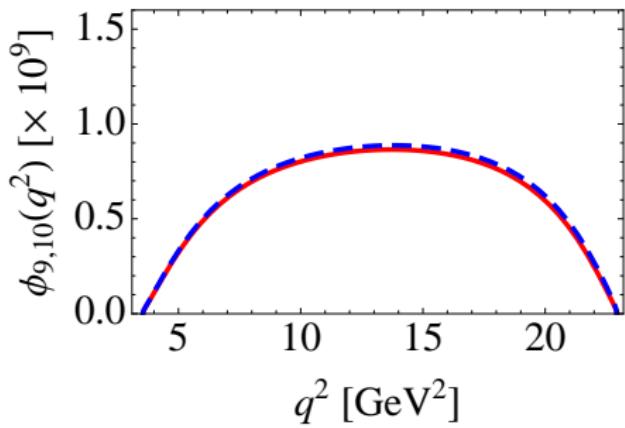
⇒ Prediction  $R_{K^*}^{\text{pred}} \Big|_{\text{central}} = 1.11(8)$  in tension with  $R_{K^*}^{\text{exp}}$ .

But it has some interesting features

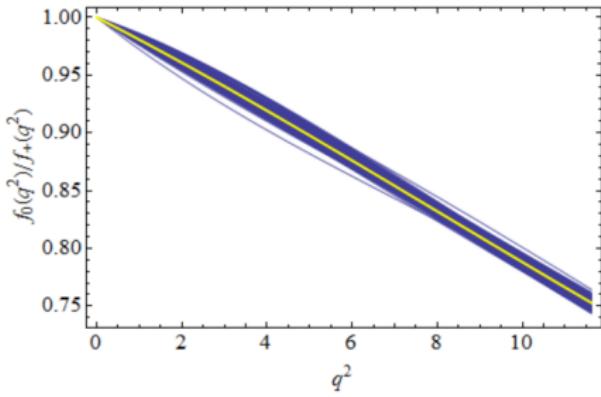
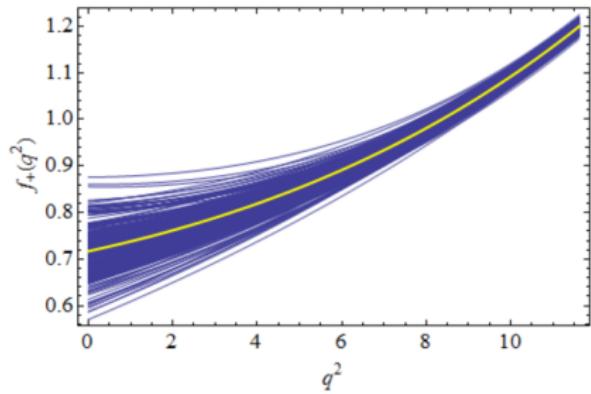
- Naturally accommodates  $R_{D^{(*)}}^{\text{NP}} > R_{D^{(*)}}^{\text{SM}}$ , predicts  $R_{\eta_c}^{\text{NP}} > R_{\eta_c}^{\text{SM}}$  and  $\mathcal{B}(B_c \rightarrow \tau\nu)^{\text{NP}} / \mathcal{B}(B_c \rightarrow \tau\nu)^{\text{SM}} \geq 5.5$ .
- LFUV in the **charged sector** depends on the **existence of  $\nu_R$** .

# More on $B$ LFV

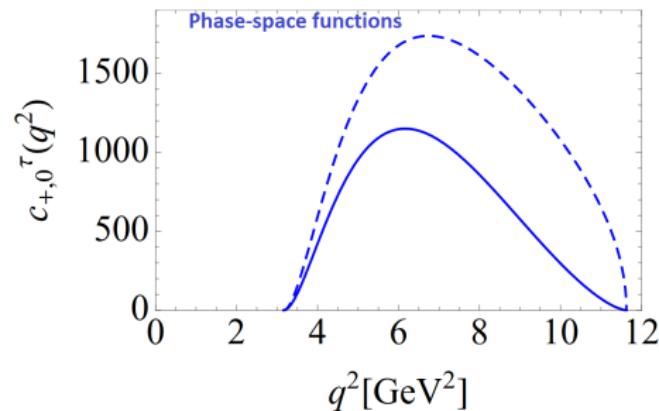
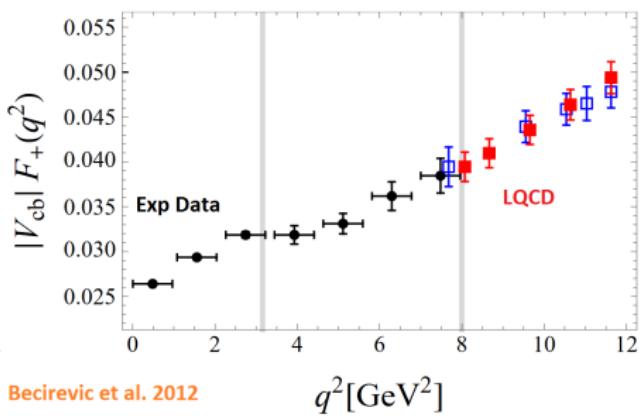
$$\begin{aligned}\mathcal{B}(B_s \rightarrow \ell_1^- \ell_2^+)^{\text{theo}} &= \frac{\tau_{B_s}}{64\pi^3} \frac{\alpha^2 G_F^2}{m_{B_s}^3} f_{B_s}^2 |V_{tb} V_{ts}^*|^2 \lambda^{1/2}(m_{B_s}, m_1, m_2) \\ &\times \left\{ [m_{B_s}^2 - (m_1 + m_2)^2] \cdot \left| (C_9 - C'_9)(\textcolor{red}{m_1 - m_2}) + (C_S - C'_S) \frac{m_{B_s}^2}{m_b + m_s} \right|^2 \right. \\ &\left. + [m_{B_s}^2 - (\textcolor{red}{m_1 - m_2})^2] \cdot \left| (C_{10} - C'_{10})(m_1 + m_2) + (C_P - C'_P) \frac{m_{B_s}^2}{m_b + m_s} \right|^2 \right\}\end{aligned}$$



# $B \rightarrow D$ form factors from LQCD



$B \rightarrow D$  vector form factor:



$$\frac{d\mathcal{B}}{dq^2}(\overline{B} \rightarrow D\ell\bar{\nu}) = |V_{cb}|^2 \mathcal{B}_0 \left[ |F_+(q^2)|^2 c_+^\ell(q^2) + |F_0(q^2)|^2 c_0^\ell(q^2) \right]$$

# SLQ (3,2)<sub>1/6</sub>

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

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

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

# LFV in $b \rightarrow s\ell_1\ell_2$

Helicity Formalism for  $m_1 \neq m_2$

- LFC case ( $m_1 = m_2$ ) –  $A_{\parallel, \perp, 0}^{L,R}$  and  $A_{S,P}$ :

$$\bar{\ell}\gamma_5\ell = \frac{q^\mu(\bar{\ell}\gamma_\mu\gamma_5\ell)}{2m_\ell} \Rightarrow C_{P^{(\prime)}} \text{ can be absorbed in } A_t.$$

$$q^\mu(\bar{\ell}\gamma_\mu\ell) = 0 \Rightarrow C_{S^{(\prime)}} \text{ require a residual HA } A_S.$$

- LFV case ( $m_1 \neq m_2$ ) –  $A_{\parallel, \perp, 0, t}^{L,R}$ :

$$\bar{\ell}_1\gamma_5\ell_2 = \frac{q^\mu(\bar{\ell}_1\gamma_\mu\gamma_5\ell_2)}{m_1 + m_2}, \quad \bar{\ell}_1\ell_2 = \frac{q^\mu(\bar{\ell}_1\gamma_\mu\ell_2)}{m_1 - m_2} \Rightarrow \text{New HA's } A_t^{L,R}$$

Going from LFC to LFV:

$$A_t = \lim_{m_1 \rightarrow m_2} (A_t^L - A_t^R), \quad A_S = \lim_{m_1 \rightarrow m_2} \left[ \frac{m_1 - m_2}{\sqrt{q^2}} (A_t^L + A_t^R) \right]$$

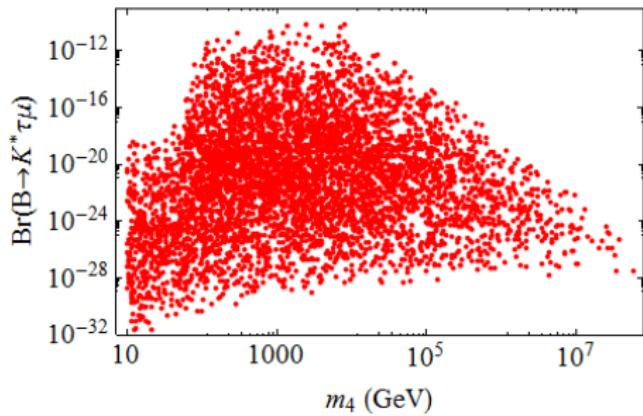
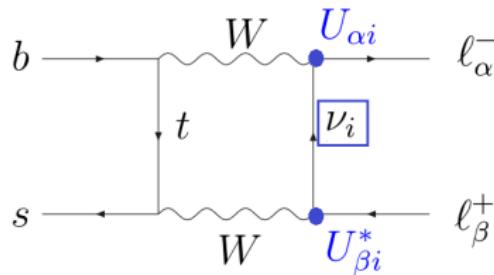
**NB.** The singularity in  $m_1 = m_2$  cancels out in  $I_t(q^2)$ .

# Sterile Neutrinos

## Illustration of LFV Mechanism

We opt for a pragmatic approach:

- The SM is effectively extended by **one sterile neutrino** (**3 ⊕ 1**).
- Free parameters: 1 mass, 3 angles and many phases.
- Many constraints:  $\nu$  osc. data, (semi-)leptonic meson decays, EWPD,  $0\nu\beta\beta$ , cLFV and direct searches.



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

$Z'$  Models – Comments on [Crivellin et al. 1504.07928]

Similar scenarios are considered:  $C_9^{\mu\mu} \neq 0$  and  $C_9^{\mu\mu} = -C_{10}^{\mu\mu} \neq 0$ ; but the rates are ten times larger. Why?

- $2\sigma$  discrepancy in  $\mathcal{B}(\tau \rightarrow \mu\nu\bar{\nu})$ ?

$$\mathcal{B}(\tau \rightarrow \mu\nu\bar{\nu})_{\text{SM}} = 17.29(3)\%$$

$$\mathcal{B}(\tau \rightarrow \mu\nu\bar{\nu})_{\text{exp}} = 17.33(5)\% \quad [\text{Average}]$$

$$\mathcal{B}(\tau \rightarrow \mu\nu\bar{\nu})_{\text{exp}} = 17.41(4)\% \quad [\text{Fit}]$$

PDG and HFAG fits amplify the  $1.6\sigma$  discrepancy of

$$\mathcal{B}(\tau \rightarrow \mu\nu\bar{\nu})/\mathcal{B}(\tau \rightarrow e\nu\bar{\nu})$$

measured by BaBar  $\Rightarrow$  The average should be used instead.

- Main source of **disagreement**:  $B_s - \bar{B}_s$  mixing

If  $b \rightarrow s\mu\mu$  data is analyzed with only  $C_{9,10}$ , then  $g_{sb}^R = 0 \Rightarrow$  **No fine-tuning** in  $B_s - \bar{B}_s$ .

$$I_1^s(q^2) = \left[ |A_{\perp}^L|^2 + |A_{\parallel}^L|^2 + (L \rightarrow R) \right] \frac{\lambda_q + 2[q^4 - (m_1^2 - m_2^2)^2]}{4q^4} + \frac{4m_1 m_2}{q^2} \text{Re} \left( A_{\parallel}^L A_{\parallel}^{R*} + A_{\perp}^L A_{\perp}^{R*} \right),$$

$$I_1^c(q^2) = [|A_0^L|^2 + |A_0^R|^2] \frac{q^4 - (m_1^2 - m_2^2)^2}{q^4} + \frac{8m_1 m_2}{q^2} \text{Re}(A_0^L A_0^{R*} - A_t^L A_t^{R*}) - 2 \frac{(m_1^2 - m_2^2)^2 - q^2(m_1^2 + m_2^2)}{q^4} (|A_t^L|^2 + |A_t^R|^2),$$

$$I_2^s(q^2) = \frac{\lambda_q}{4q^4} [|A_{\perp}^L|^2 + |A_{\parallel}^L|^2 + (L \rightarrow R)],$$

$$I_2^c(q^2) = -\frac{\lambda_q}{q^4} (|A_0^L|^2 + |A_0^R|^2),$$

$$A_{\perp}^{L(R)} = \mathcal{N}_{K^*} \sqrt{2} \lambda_B^{1/2} \left[ [(C_9 + C'_9) \mp (C_{10} + C'_{10})] \frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2} (C_7 + C'_7) T_1(q^2) \right],$$

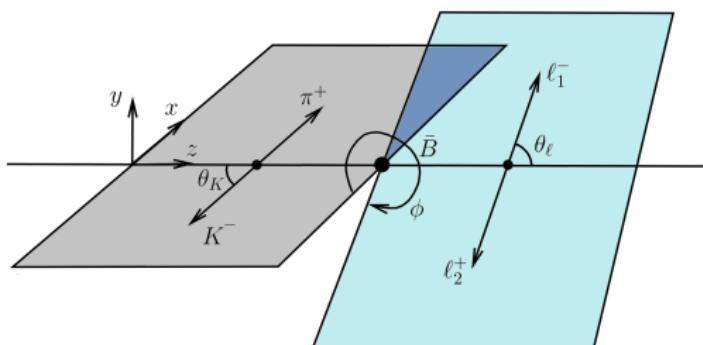
$$A_{\parallel}^{L(R)} = -\mathcal{N}_{K^*} \sqrt{2} (m_B^2 - m_{K^*}^2) \left[ [(C_9 - C'_9) \mp (C_{10} - C'_{10})] \frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2} (C_7 - C'_7) T_2(q^2) \right]$$

$$\begin{aligned} A_0^{L(R)} = & -\frac{\mathcal{N}_{K^*}}{2m_{K^*}\sqrt{q^2}} \left\{ 2m_b(C_7 - C'_7) \left[ (m_B^2 + 3m_{K^*}^2 - q^2)T_2(q^2) - \frac{\lambda_B T_3(q^2)}{m_B^2 - m_{K^*}^2} \right] \right. \\ & \left. + [(C_9 - C'_9) \mp (C_{10} - C'_{10})] \cdot \left[ (m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*})A_1(q^2) - \frac{\lambda_B A_2(q^2)}{m_B + m_{K^*}} \right] \right\} \end{aligned}$$

$$A_t^{L(R)} = -\mathcal{N}_{K^*} \frac{\lambda_B^{1/2}}{\sqrt{q^2}} \left[ (C_9 - C'_9) \mp (C_{10} - C'_{10}) + \frac{q^2}{m_b + m_s} \left( \frac{C_S - C'_S}{m_1 - m_2} \mp \frac{C_P - C'_P}{m_1 + m_2} \right) \right] A_0(q^2),$$

Clarifying the Angular Conventions in  $\bar{B} \rightarrow \bar{K}^*\ell\ell$ 

- Most theory papers do not provide the full angular conventions for  $\bar{B} \rightarrow \bar{K}^*\ell\ell$  [ambiguity in the definition of  $\phi$ ].
- We adopt the conventions of [Gratrex, Zwicky. 2015]  $\equiv$  LHCb and find full agreement for  $I_i(q^2)$ .

 **$K^*$  rest frame:**

$$p_K^\mu = (E_K, \hat{\mathbf{p}}_K |p_K|), \quad p_\pi^\mu = (E_\pi, -\hat{\mathbf{p}}_K |p_K|),$$

with  $\hat{\mathbf{p}}_K = (-\sin \theta_K, 0, -\cos \theta_K)$ .

**Dilepton rest frame:**

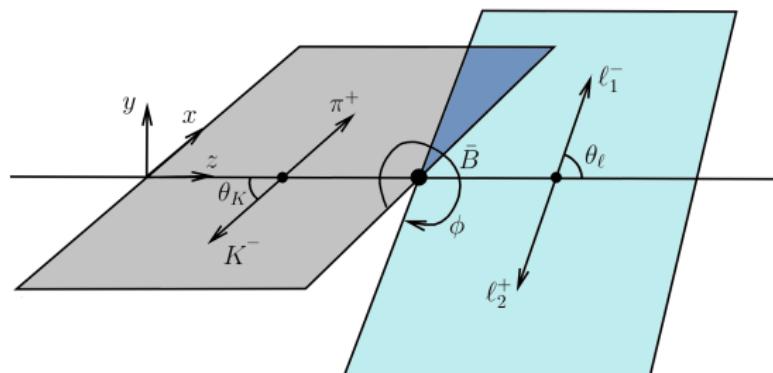
$$p_1^\mu = (E_\alpha, \hat{\mathbf{p}}_\ell |p_\ell|), \quad p_2^\mu = (E_\beta, -\hat{\mathbf{p}}_\ell |p_\ell|),$$

with  $\hat{\mathbf{p}}_\ell = (\sin \theta_\ell \cos \phi, -\sin \theta_\ell \sin \phi, \cos \theta_\ell)$ .

# $B \rightarrow (K^* \rightarrow K^- \pi^+) \mu \mu$ angular distribution

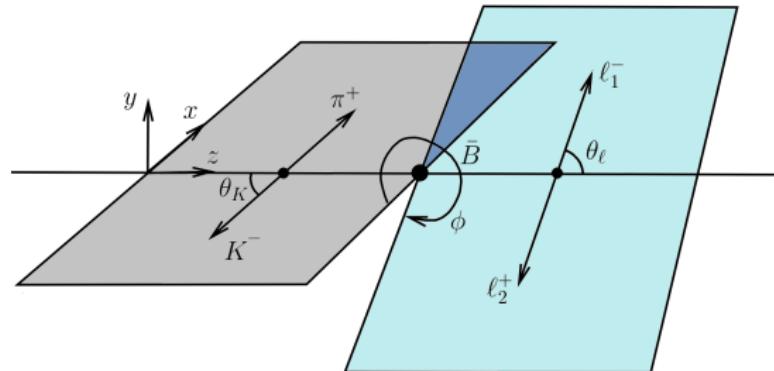
Full decay distribution

$$\frac{d^4\mathcal{B}(B \rightarrow \bar{K}^* \rightarrow (K\pi)\ell^-\ell^+)}{dq^2 d\cos\theta_\ell d\cos\theta_K d\phi} = \frac{9}{32\pi} I(q^2, \theta_\ell, \theta_K, \phi),$$



# $B \rightarrow (K^* \rightarrow K^- \pi^+) \mu\mu$ angular distribution

Full decay distribution



$$\begin{aligned} I(q^2, \theta_\ell, \theta_K, \phi) = & I_1^s(q^2) \sin^2 \theta_K + I_1^c(q^2) \cos^2 \theta_K + [I_2^s(q^2) \sin^2 \theta_K + I_2^c(q^2) \cos^2 \theta_K] \cos 2\theta_\ell \\ & + I_3(q^2) \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + I_4(q^2) \sin 2\theta_K \sin 2\theta_\ell \cos \phi \\ & + I_5(q^2) \sin 2\theta_K \sin \theta_\ell \cos \phi + [I_6^s(q^2) \sin^2 \theta_K + I_6^c(q^2) \cos^2 \theta_K] \cos \theta_\ell \\ & + I_7(q^2) \sin 2\theta_K \sin \theta_\ell \sin \phi + I_8(q^2) \sin 2\theta_K \sin 2\theta_\ell \sin \phi \\ & + I_9(q^2) \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi, \end{aligned}$$

# Un petit détour...

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  $R_{D(*)}$ .

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$\Rightarrow V(q^2)$  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.

# 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**.

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

Assumptions: gauge invariance (e.g.,  $g_{\ell_i \ell_j}^{\textbf{L}} = g_{\nu_i, \nu_j}^{\textbf{L}}$ ) 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 $b \rightarrow s\mu\tau$

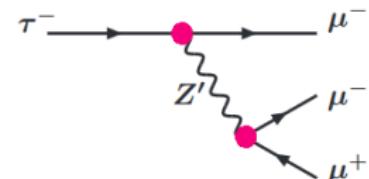
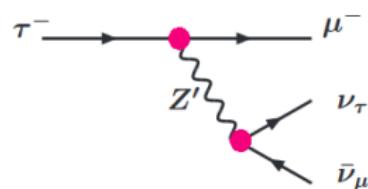
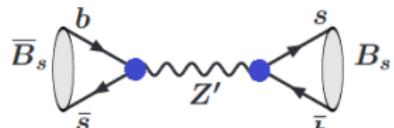
$Z'$  Models

[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.

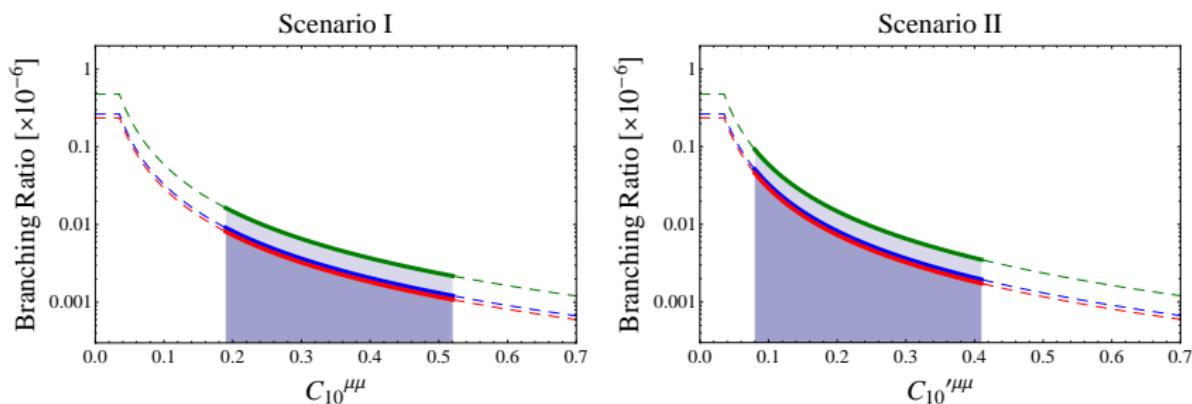
# LFV in $b \rightarrow s\mu\tau$

$Z'$  Models

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

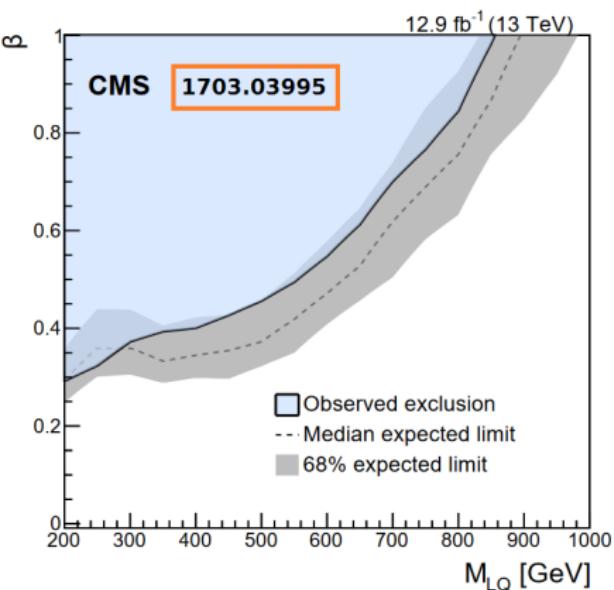
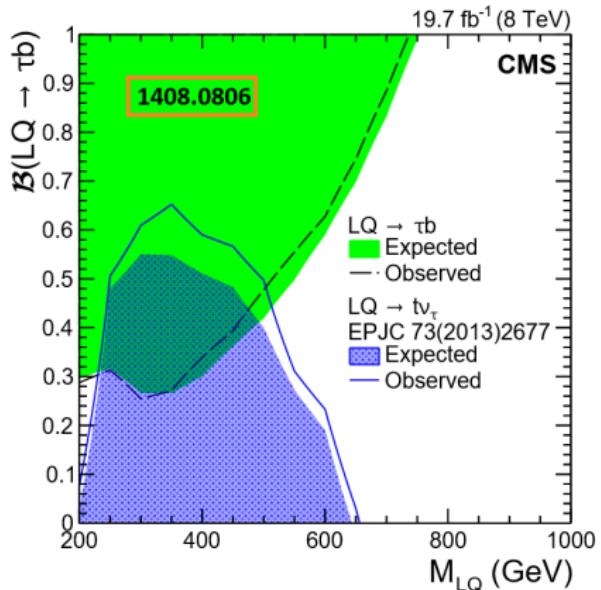
Maximal branching ratios  $\Rightarrow$  Possibly within reach of LHCb and Belle-2.

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

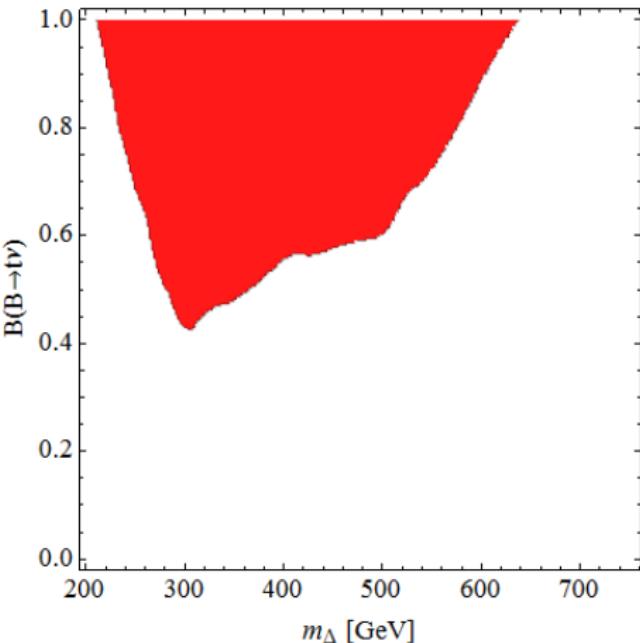
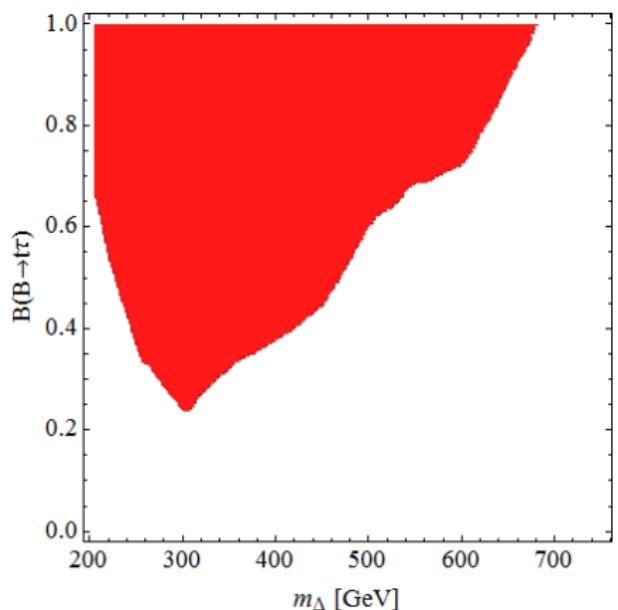


**NB.** Crivellin et. al. [1504.07928] obtain larger rates due to *inconsistent* treatment of  $g_{sb}^L$  and  $g_{sb}^R$ .

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



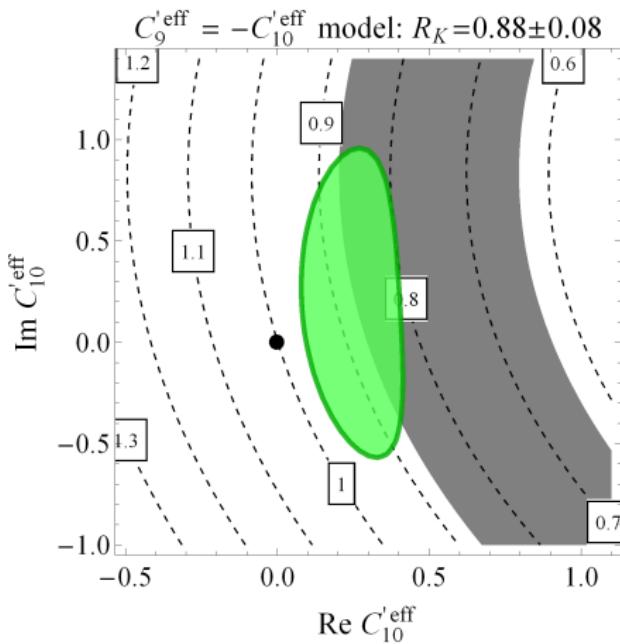
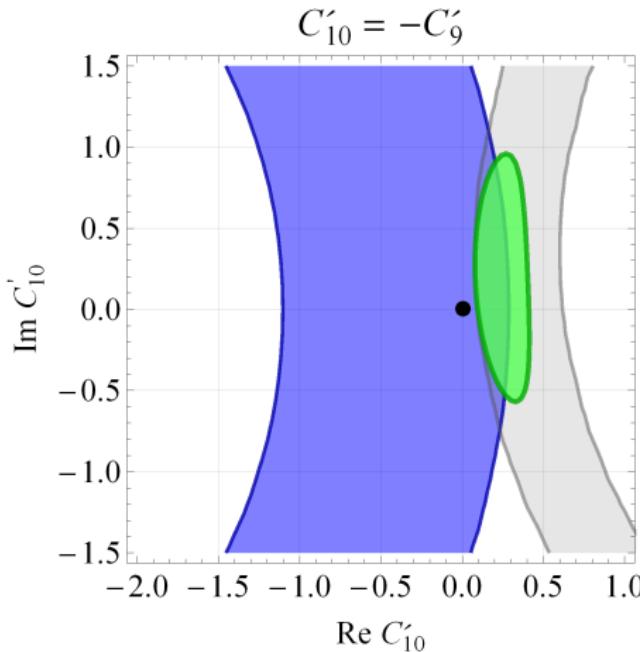
# LQ Direct Searches: $(3, 2)_{7/6}$



# 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  $R_K$



# Light Leptoquarks and $SU(5)$ GUT

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

An old idea:

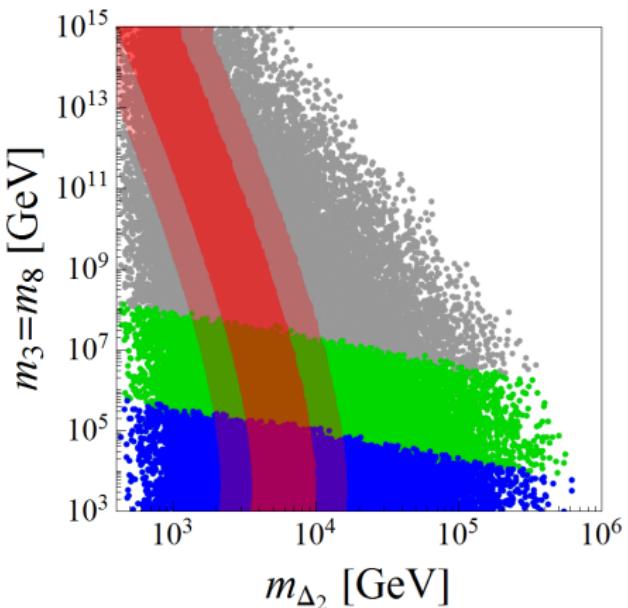
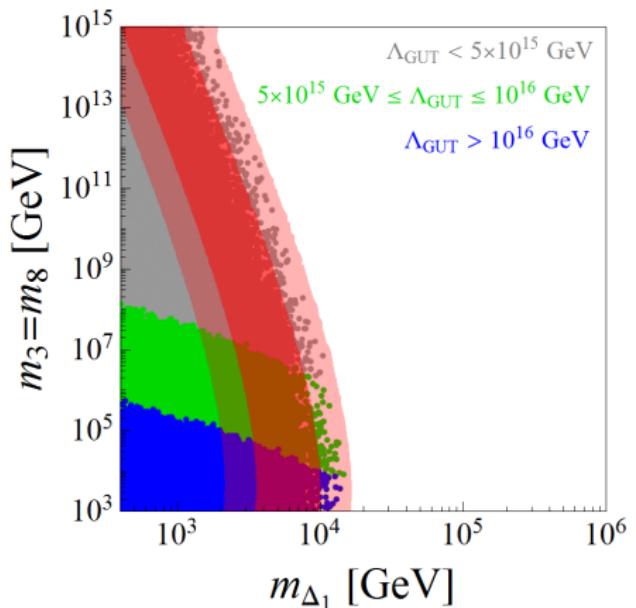
One pair of  $(3, 2)_{1/6}$  and one additional Higgs doublet  $(1, 2)_{1/2}$  at the EW scale can lead to unification.  
[Murayama and Yanagida, 1992.]

Setup:

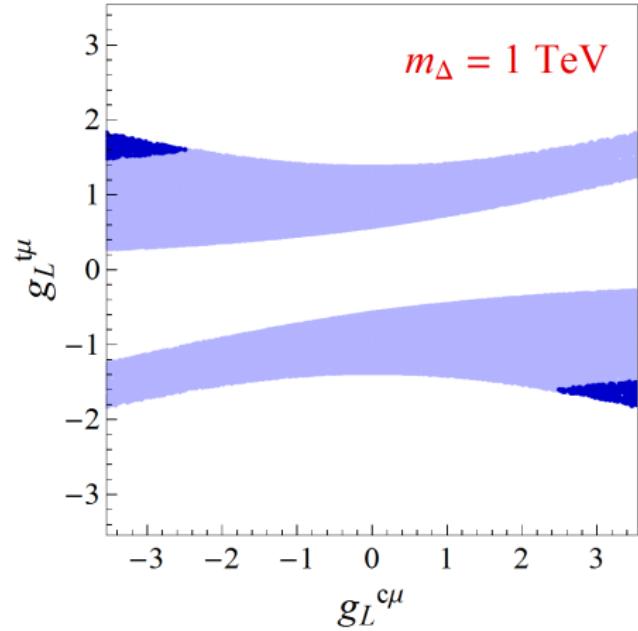
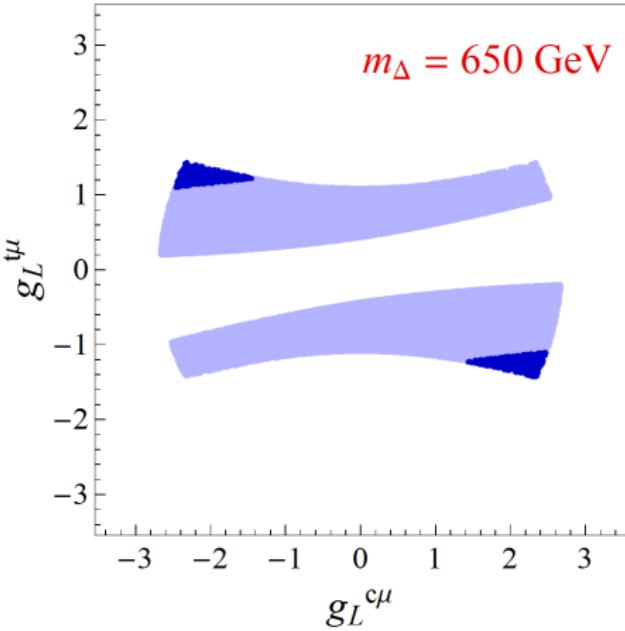
	$\mathcal{G}_{\text{SM}}$	$U(1)_{\text{PQ}}$
$\bar{5}_F$	$(\bar{3}, 1)_{1/3} \oplus (1, 2)_{-1/2}$	+1
$10_F$	$(3, 2)_{1/6} \oplus (\bar{3}, 1)_{-2/3} \oplus (1, 1)_1$	+1
$5_\Delta$	$(1, 2)_{1/2} \oplus \dots$	-2
$\bar{5}_\Delta$	$(1, 2)_{-1/2} \oplus \dots$	-2
$(2 \times) 10_\Delta$	$(3, 2)_{1/6} \oplus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

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

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



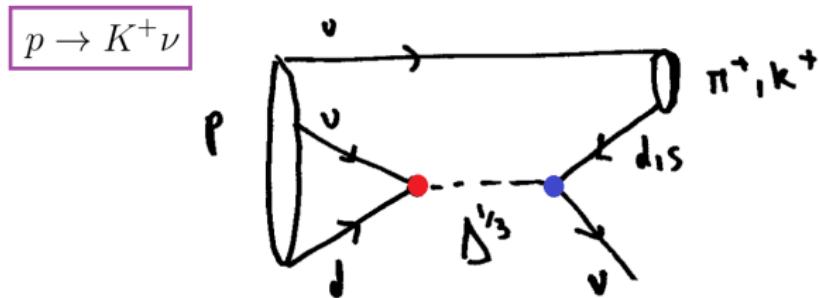
The **unification** of gauge couplings gives a **strong constraint** on the lightest LQ mass  $m_{\Delta_1} \lesssim 16$  TeV.



# Proton decay in $(\bar{3}, 3)_{1/3}$

$$\begin{aligned} \mathcal{L}_3 &= \overline{Q^C} \mathbf{g_L} i\tau_2 \boldsymbol{\tau} \cdot \boldsymbol{\Delta} L + \overline{Q^C} \mathbf{z_L} i\tau_2 (\boldsymbol{\tau} \cdot \boldsymbol{\Delta})^\dagger Q + \text{h.c.} \\ &\supset -\overline{d^C} (\mathbf{z_L} \mathbf{V}^\dagger) u_L \Delta^{(1/3)*} + \sqrt{2} \overline{u^C} (\mathbf{V}^T \mathbf{z_L} \mathbf{V}^\dagger) u_L \Delta^{(4/3)*} + \dots \end{aligned}$$

[ $SU(3)_c$  indices omitted!]



Current limits:  $\tau_p > 5.8 \times 10^{29}$  yr and  $\tau_{p \rightarrow K^+ \nu} > 6.7 \times 10^{32}$  yr [SuperK]

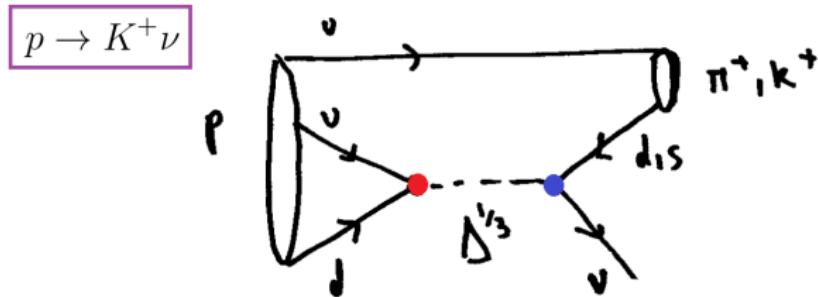
⇒ Moreover,  $p \rightarrow \pi^0 e^+$  is induced at loop-level.

⇒ A symmetry must be **imposed by hand** to forbid  $\mathbf{z_L}$ !

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$$\begin{aligned}\mathcal{L}_3 &= \overline{Q^C} \mathbf{g_L} i\tau_2 \boldsymbol{\tau} \cdot \Delta L + \overline{Q^C} \mathbf{z_L} i\tau_2 (\boldsymbol{\tau} \cdot \Delta)^\dagger Q + \text{h.c.} \\ &\supset -\overline{d^C} (\mathbf{z_L} V^\dagger) u_L \Delta^{(1/3)*} + \sqrt{2} \overline{u^C} (\mathbf{V^T z_L} V^\dagger) u_L \Delta^{(4/3)*} + \dots\end{aligned}$$

[ $SU(3)_c$  indices omitted!]



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⇒ Moreover,  $p \rightarrow \pi^0 e^+$  is induced at loop-level.  
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# On (in)viability of SLQ $(3, 1)_{-1/3}$

[Becirevic, Kosnik, OS, Zukanovich. 1608.07583]

November 9, 2015



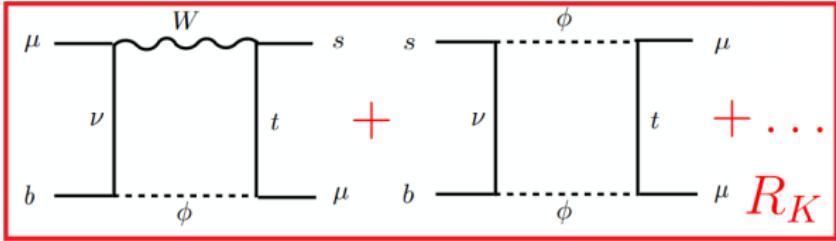
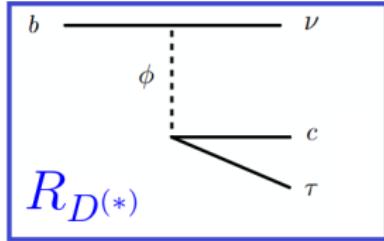
## One Leptoquark to Rule Them All: A Minimal Explanation for $R_D^{(*)}$ , $R_K$ and $(g - 2)_\mu$

Martin Bauer<sup>a</sup> and Matthias Neubert<sup>b,c</sup>

**1511.01900**

The original idea: to explain  $R_D$  at **tree-level** and  $R_K$  at **loop-level**.

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



# On (in)viability of SLQ (3, 1)<sub>-1/3</sub>

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

- Loop-level contributions to  $b \rightarrow s\ell\ell$ :

$$C_9 - C_{10} \propto \frac{|(V^* g_L)_{t\mu}|^2}{m_\Delta^2}, \frac{(g_L \cdot g_L^\dagger)_{bs}(g_L^\dagger \cdot g_L)_{\mu\mu}}{m_\Delta^2},$$

$$C_9 + C_{10} \propto \frac{|(g_R)_{t\mu}|^2}{m_\Delta^2}, \frac{(g_L \cdot g_L^\dagger)_{bs}(g_R^\dagger \cdot g_R)_{\mu\mu}}{m_\Delta^2},$$

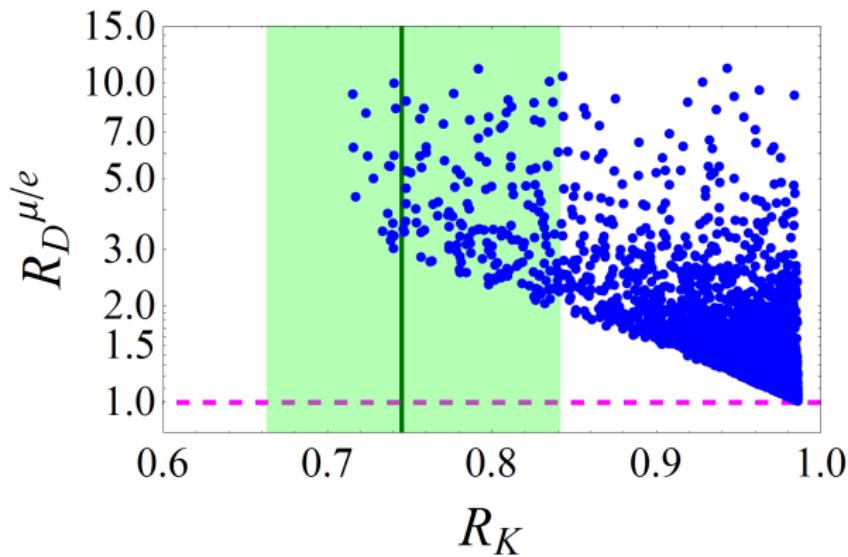
⇒ We take  $g_R = 0$  [to have  $C_9 = -C_{10}$ ], we set the first-generation couplings to be zero [ $\mu \rightarrow e\gamma$ ,  $K \rightarrow \pi\nu\nu$ , APV etc] and  $m_\Delta \approx 1$  TeV.

- Important constraints from  $K$  and  $D$  meson sectors.
- Diquark couplings are present in this model – *Proton stability?*

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

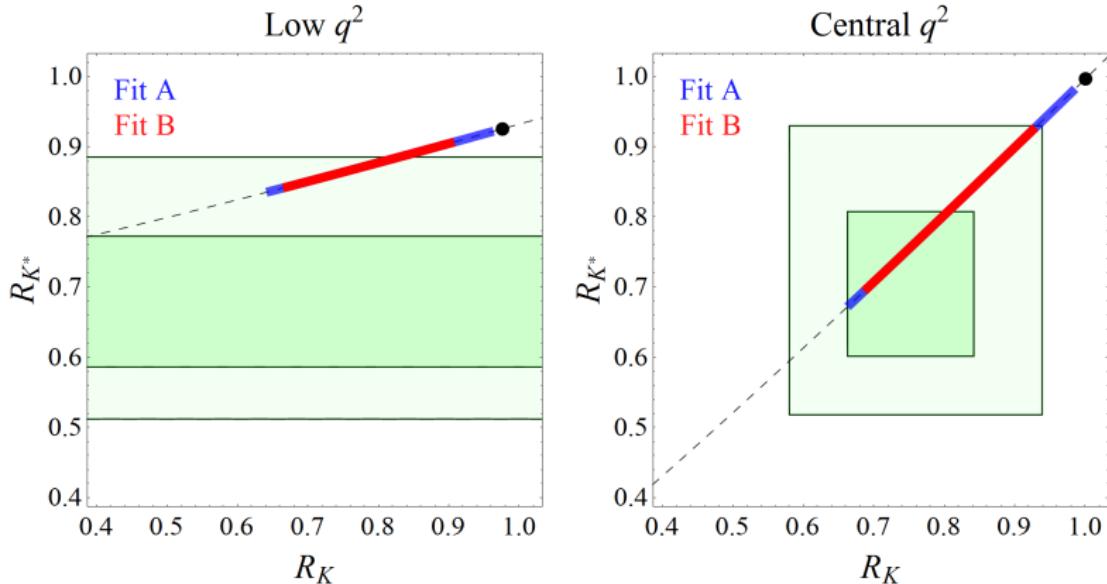
Scan Results

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



- Explanation of  $R_K \Rightarrow$  unacceptably large  $R_D^{\mu/e} = \frac{\mathcal{B}(B \rightarrow D\mu\nu)}{\mathcal{B}(B \rightarrow D\bar{e}\nu)} \gtrsim 2$ .
- In conclusion,  $R_K$  cannot be explained by this model.

- **Fit A:**  $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)$  and  $\mathcal{B}(B^+ \rightarrow K^+ \mu\mu)_{\text{high } q^2}$
- **Fit B:**  $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)$ ,  $\mathcal{B}(B^+ \rightarrow K^+ \mu\mu)_{\text{high } q^2}$ , and  $P_{1,2,3}(q^2)$ .



**Predictions:**  $R_K^{\text{high}} \approx R_{K^*}^{\text{high}} = 0.82(20)$  or  $0.79(12)$  for  $q^2 \in [15, 19] \text{ GeV}^2$   
 $\Rightarrow$  to be tested at LHCb!