

Lepton Flavor (Universality) Violation in B Meson Decays

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In collaboration with

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

[hep-ph/1608.07583](#) and [1704.05835](#)



EPS HEP, Venice, July 7, 2017.



Outline

- ① LFU violation in B decays
- ② NP explanations of R_K and R_{K^*}
- ③ A loop-level model to explain $R_K < 1$ and $R_{K^*} < 1$
- ④ Conclusions and Perspectives

Outline

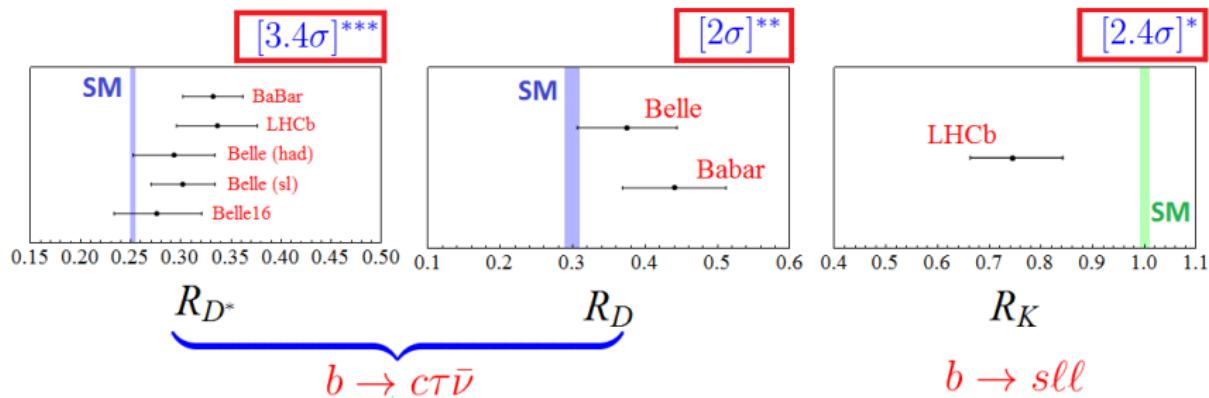
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- 4 Conclusions and Perspectives

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 [only 1st and 2nd fermion generations, though]*.
- Renewed interest in LFUV motivated by the recently found conflicts between theory and experiment in B meson decays.

LFUV in B Decays [pre-2017]

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



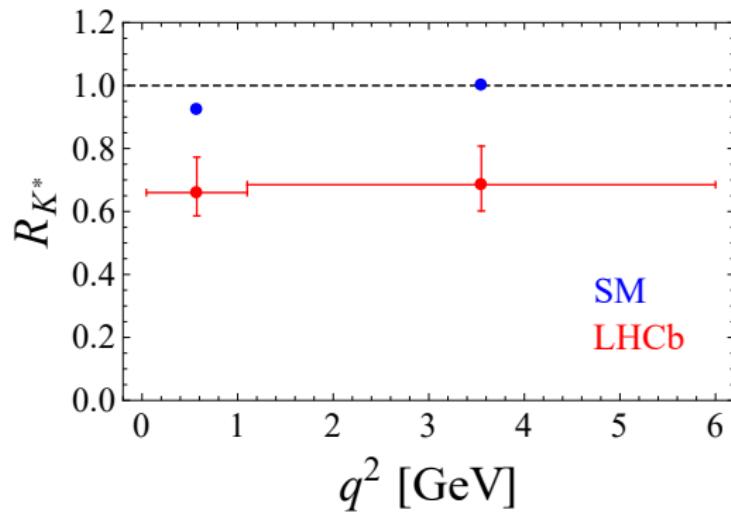
- NEW (FPCP17): LHCb, $R_{D^*} = 0.285(35)$, in agreement with SM.

[See Admir's talk]

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 : $[\approx 2.5\sigma]$



Relevant questions:

- Is there a **model of NP** to accommodate these anomalies?
- What additional **experimental signatures** should we expect?

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In general, $R_K \neq 1 \Leftrightarrow$ **LFUV** “ \Rightarrow ” Lepton Flavor Violation (**LFV**)

[Glashow, Guadagnoli, Lane. 2014.]

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Explaining R_K

EFT approach

[See Admir's talk]

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 $R_{K^{(*)}}^{\text{exp}} < R_{K^{(*)}}^{\text{SM}}$, one needs effective coefficients C_9, C_{10} .
Compatible with results from global analyses: [e.g., Descotes-Genon et al. 2015]

Fit to clean observables

[Becirevic, Kosnik, OS, Zukanovich. 1608.07583]

- Use $f_{B_s}^{Latt.}$ and $\mathcal{B}(B_s \rightarrow \mu\mu) = 3.0(6)(\frac{3}{2}) \times 10^{-9}$. [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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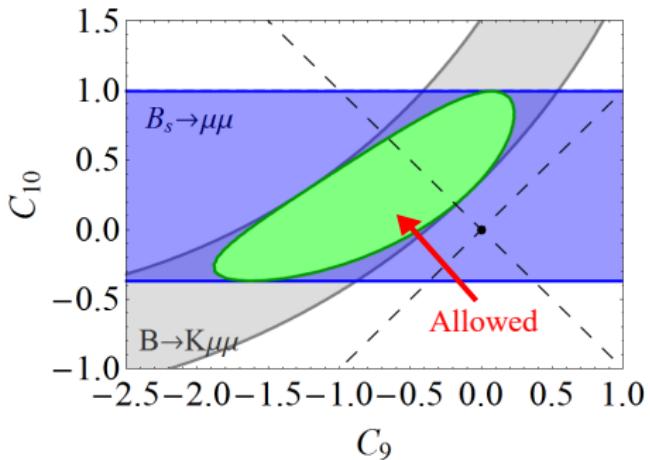
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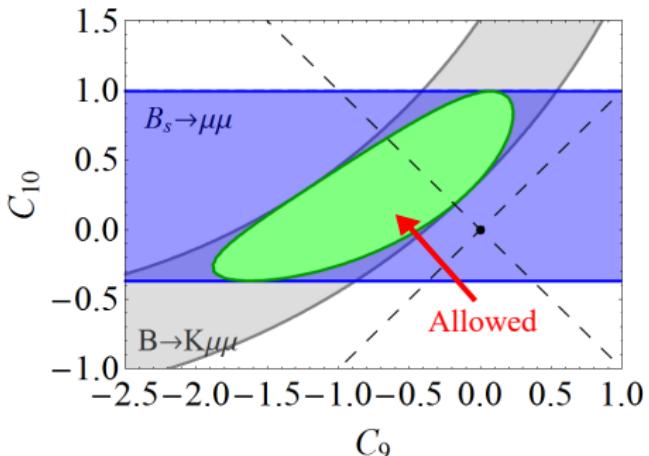
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- We find

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

⇒ This value can be used to give **model independent** predictions for $R_{K(*)}$.

In the central bin:

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

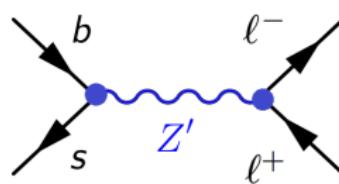
**Are there specific models capable of generating
 $C_{9,10}$ to explain $R_{K^{(*)}}$?**

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

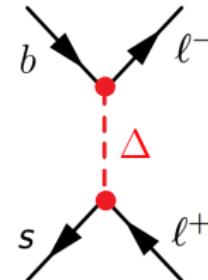
Specific Models

Representative (tree-level) models:

Z' models



Leptoquark models



Buras et al., Altmannshofer et al.,
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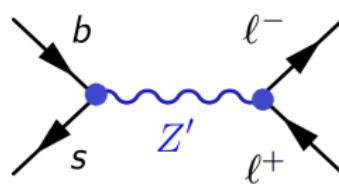
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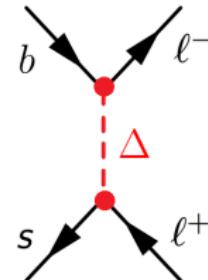
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Gripaios et al. ...

- Vector leptoquark models also plausible, but non-renormalizable
[problematic, how to compute loops? $B_s - \bar{B}_s$ and $\tau \rightarrow \mu\gamma$ constraint?]
Barbieri et al., Fajfer et al., Butazzo 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 $\mathcal{B}(B^+ \rightarrow K^+ \mu\mu)$.

⇒ Focus on NP with couplings **to muons only**

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

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

| | BNC | Interaction | WC | R_K/R_K^{SM} | $R_{K^*}/R_{K^*}^{\text{SM}}$ |
|--|-----|--|-----------------------|-----------------------|-------------------------------|
| $(\bar{\mathbf{3}}, \mathbf{1})_{4/3}$ | ✗ | $\overline{d_R^C} \Delta \ell_R$ | $(C_9)' = (C_{10})'$ | ≈ 1 | ≈ 1 |
| $(\mathbf{3}, \mathbf{2})_{7/6}$ | ✓ | $\overline{Q} \Delta \ell_R$ | $C_9 = C_{10}$ | > 1 | > 1 |
| $(\mathbf{3}, \mathbf{2})_{1/6}$ | ✓* | $\overline{d_R} \tilde{\Delta}^\dagger L$ | $(C_9)' = -(C_{10})'$ | < 1 | > 1 |
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⇒ **No fully viable model.** Triplet can be used if imposing extra **(ad-hoc)** symmetry to forbid **proton decay**.

[Hiller and Nizandzic. 2017]

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[Becirevic, OS. 1704.05835]

Reminder:

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

$$\begin{aligned}
\mathcal{L}_{\Delta^{(7/6)}} &= (\textcolor{blue}{g_R})_{ij} \bar{Q}_i \Delta^{(7/6)} \ell_{Rj} + (\textcolor{magenta}{g_L})_{ij} \bar{u}_{Ri} \tilde{\Delta}^{(7/6)\dagger} L_j + \text{h.c.}, \\
&= (\textcolor{blue}{V} g_R)_{ij} \bar{u}_i P_R \ell_j \Delta^{(5/3)} + (\textcolor{blue}{g_R})_{ij} \bar{d}_i P_R \ell_j \Delta^{(2/3)} \\
&\quad + (\textcolor{magenta}{U} g_L)_{ij} \bar{u}_i P_L \nu_j \Delta^{(2/3)} - (\textcolor{magenta}{g_L})_{ij} \bar{u}_i P_L \ell_j \Delta^{(5/3)} + \text{h.c.},
\end{aligned}$$

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We take

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

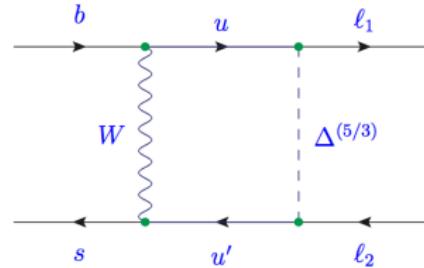
[Equivalent to a flavor symmetry]

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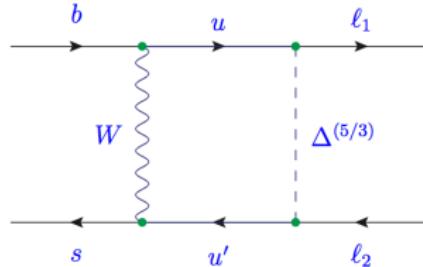
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(unitary gauge):

[Becirevic, OS. 1704.05835]

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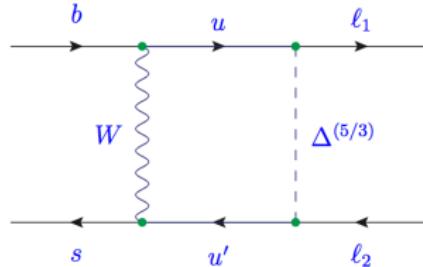


$$C_9 = -C_{10} = \sum_{u,u' \in \{u,c,t\}} \frac{V_{ub} V_{u's}^*}{V_{tb} V_{ts}^*} g_L^{u'\mu} (g_L^{u\mu})^* \mathcal{F}(m_u, m_{u'}) ,$$

with $\mathcal{F}(m_q, m_q) \propto -m_q^2/m_\Delta^2 < 0$.

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Only diagram induced at one-loop (unitary gauge):



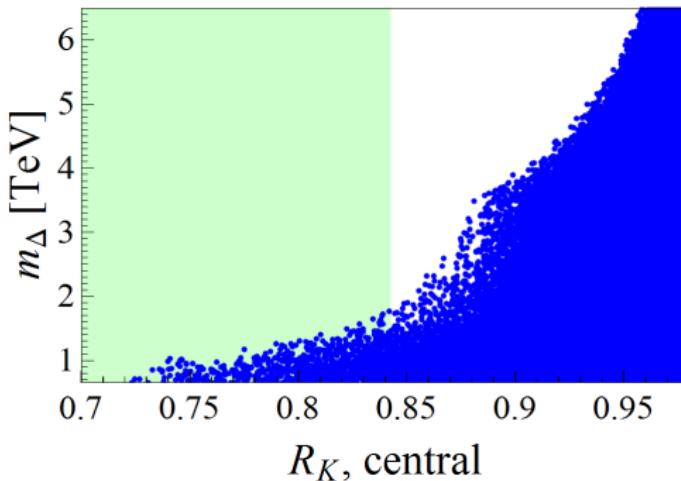
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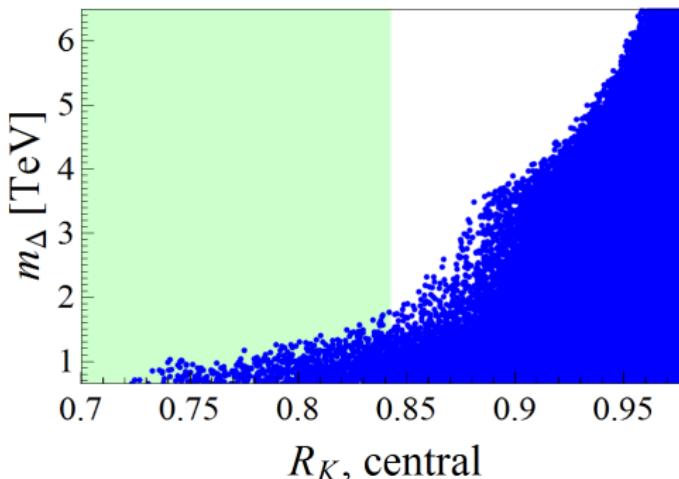
- We predict $C_9 = -C_{10} < 0$, in agreement with the exp. hints.
- Charm contribution is non-negligible due to CKM enhancement V_{cs}/V_{ts} .

- We perform a full flavor analysis including: $(g - 2)_\mu$, $\mathcal{B}(\tau \rightarrow \mu\gamma)$, $\mathcal{B}(Z \rightarrow \ell\ell)$, $\mathcal{B}(B \rightarrow K\nu\nu)$, **collider constraints**, among others.

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- We can **fully explain** the hints in $b \rightarrow s\ell\ell$ for $m_\Delta \lesssim 2$ TeV:



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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]

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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).
- Higgs Flavor Era around the corner?

Thank you!

Back-up

Direct searches

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

[Atlas and CMS, 1503.09049, 1508.04735]

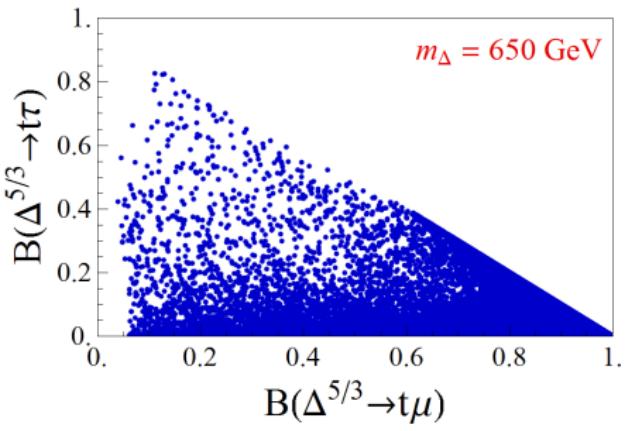
- $\Delta^{5/3} \rightarrow c\mu, t\mu, c\tau, t\tau$
- $\Delta^{2/3} \rightarrow c\nu, t\nu$

Weak exp. limits available for $\Delta^{2/3} \rightarrow t\nu$ and $\Delta^{5/3} \rightarrow t\tau$:

$\Rightarrow m_\Delta \gtrsim 650$ GeV [very very conservative bound...]

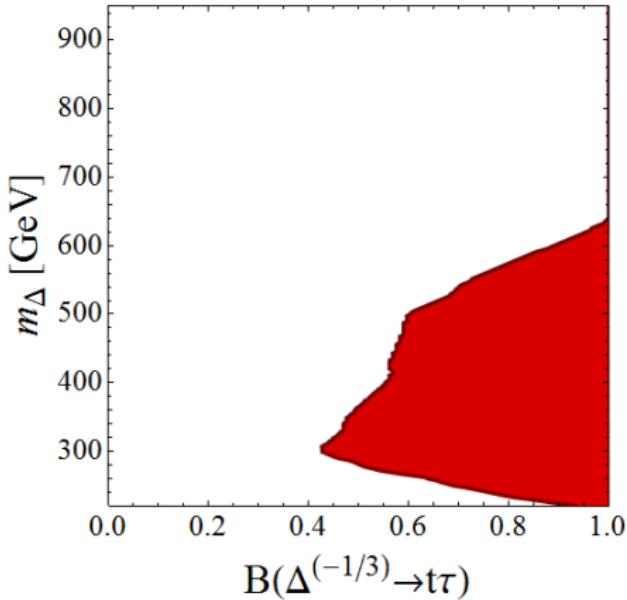
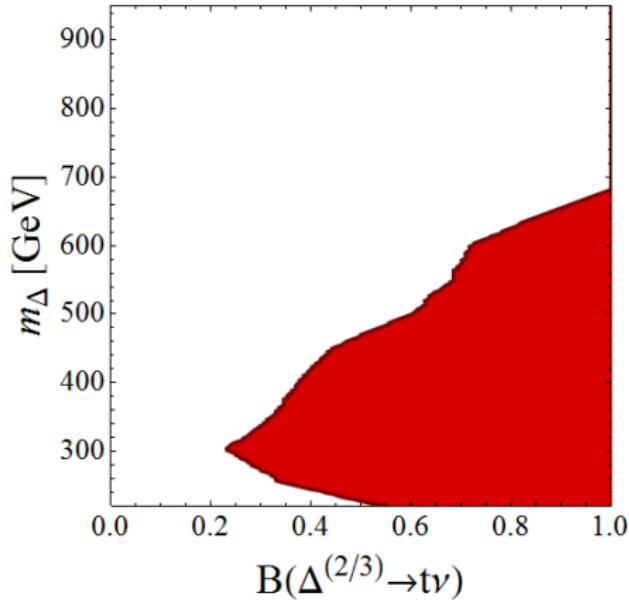
- Predictions for direct searches:

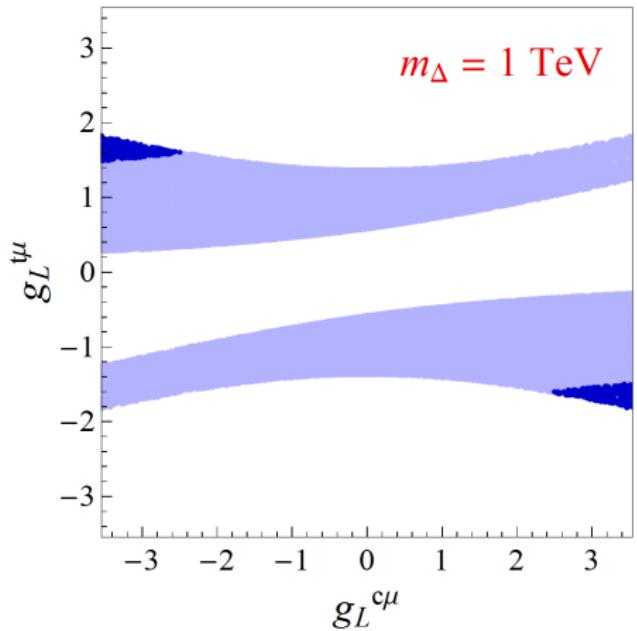
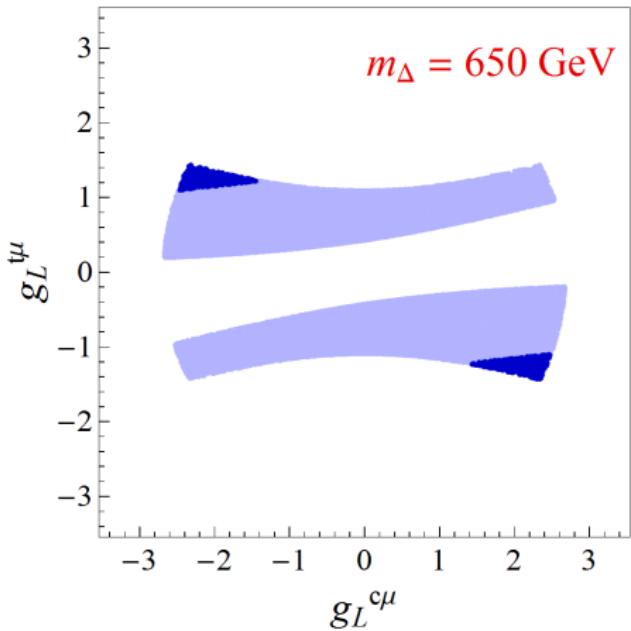
Clean signature in $\Delta^{5/3} \rightarrow t\mu$!



Exclusions from LQ direct searches: $(3, 2)_{7/6}$

[Atlas, 1508.04735. CMS, 1503.09049]



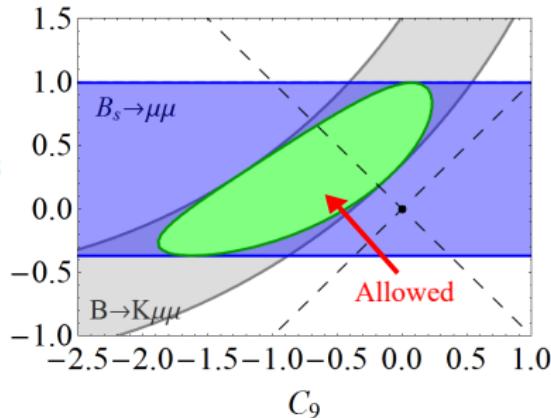


Explaining $R_{K^{(*)}}$: Illustration

[Becirevic, Kosnik, OS, Zukanovich. 1608.07583]

- Wilson coefficients fit:

$$\mathcal{B}(B_s \rightarrow \mu^+ \mu^-) \text{ and } \mathcal{B}(B^+ \rightarrow K^+ \mu\mu)_{\text{high } q^2} \stackrel{?}{=} \\ \Rightarrow (C_9)_{\mu\mu} = -(C_{10})_{\mu\mu} \in (-0.76, -0.04)$$



- Model independent predictions (central bin):

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

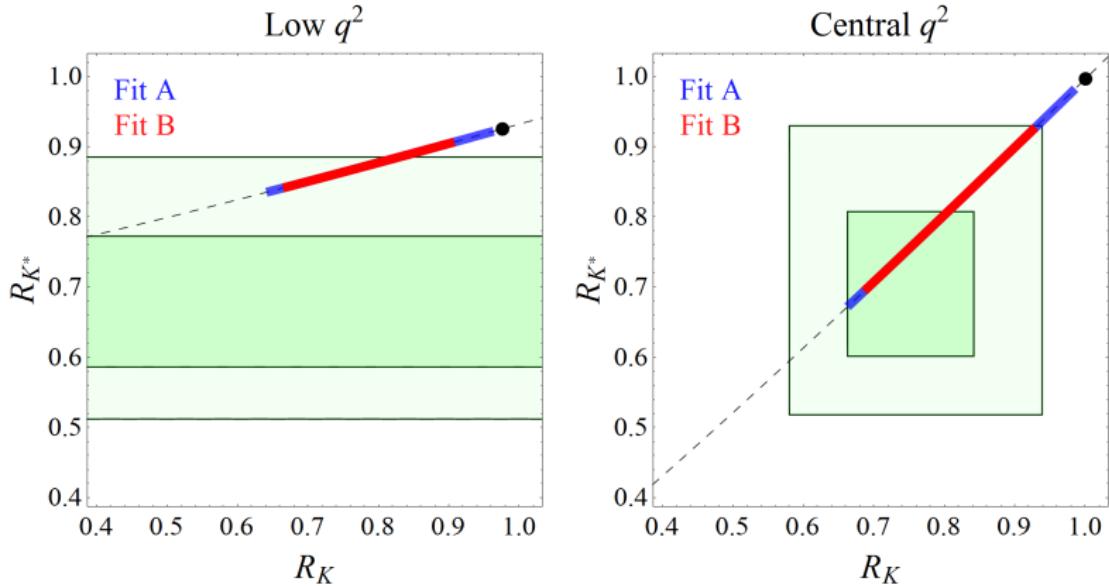
- For a different choice of operators, $(C_9)'_{\mu\mu} = -(C_{10})'_{\mu\mu}$:

$$\Rightarrow R_K^{\text{pred}} = 0.88(8) \text{ and } R_{K^*}^{\text{pred}} = 1.11(8)$$

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

[Hiller, Schmaltz 2014]

- **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 $P_{1,2,3}(q^2)$.

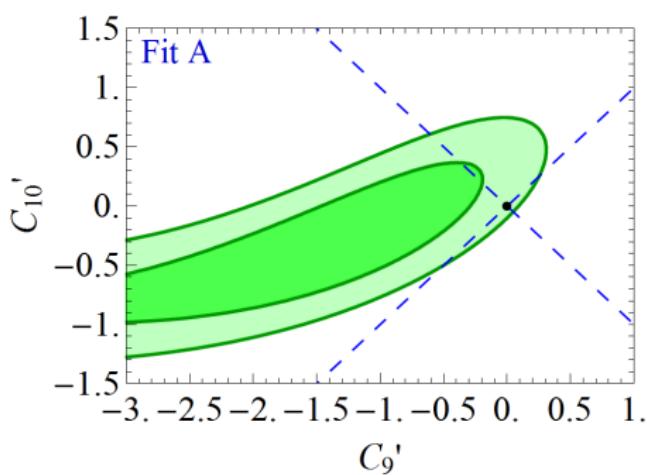
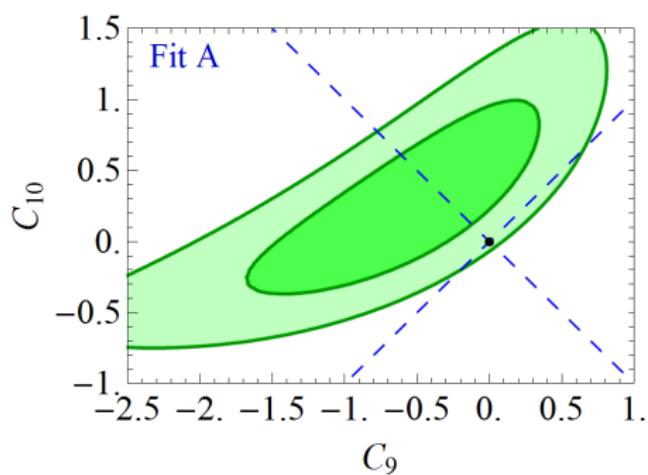


Predictions: $R_K^{\text{high}} \approx R_{K^*}^{\text{high}} = 0.82(20)$ or $0.79(12)$ for $q^2 \in [15, 19] \text{ GeV}^2$
 \Rightarrow to be tested at LHCb!

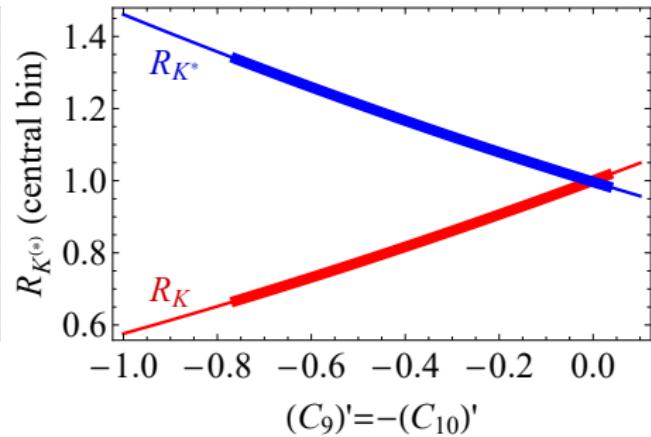
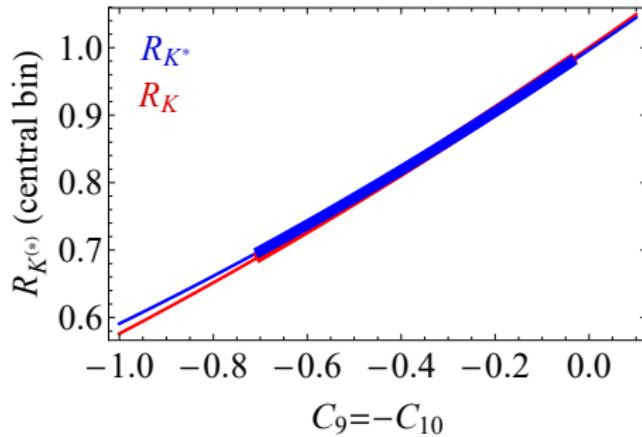
Results: Fit A

[Becirevic, Kosnik, OS, Zukanovich. 1608.07583]

[Becirevic, OS. 1704.05835]



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



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

LFUV in $(\bar{3}, 1)_{1/3}$ model

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

- Loop-level contributions to $b \rightarrow s\ell\ell$: [Bauer and Neubert. 2016]

$$C_9 - C_{10} \propto \frac{|(\textcolor{blue}{V^*} y_L)_{t\mu}|^2}{m_\Delta^2}, \frac{(y_L \cdot y_L^\dagger)_{bs}(y_L^\dagger \cdot y_L)_{\mu\mu}}{m_\Delta^2},$$
$$C_9 + C_{10} \propto \frac{|(g_R)_{t\mu}|^2}{m_\Delta^2}, \frac{(y_L \cdot y_L^\dagger)_{bs}(y_R^\dagger \cdot y_R)_{\mu\mu}}{m_\Delta^2},$$

We take:

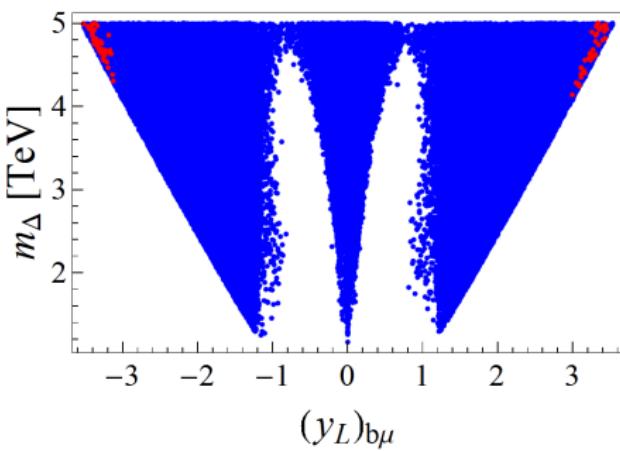
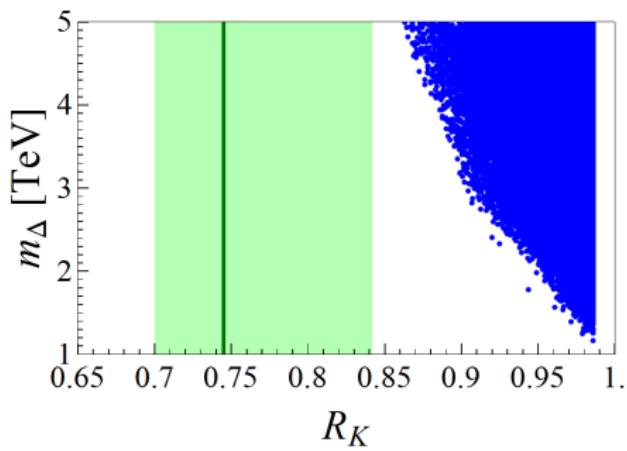
$$y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & (y_L)_{s\mu} & (y_L)_{s\tau} \\ 0 & (y_L)_{b\mu} & (y_L)_{b\tau} \end{pmatrix}, \quad y_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & (y_L)_{c\tau} \\ 0 & (y_R)_{t\mu} & 0 \end{pmatrix}$$

[Becirevic, Kosnik, OS, Zukanovich. 1608.07583], [Gargalionis et al. 2017]

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

LFUV in $(\bar{3}, 1)_{1/3}$ model

We obtained:



- $R_{K^{(*)}}$ (central bin) cannot be explained within 1σ .
- Tension can be alleviated for **heavy masses** and **very large couplings**, i.e. $m_\Delta \gtrsim 4$ TeV and $|(y_L)_{b\mu}| \approx \sqrt{4\pi}$

LFUV in $(\bar{3}, 1)_{1/3}$ model

A **simultaneous explanation** of the $b \rightarrow s\ell\ell$ and $b \rightarrow c\ell\nu$ hints is **difficult**:

