B-Physics and Lepton Flavor (Universality) Violation

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In collaboration with

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hep-ph/1602.00881, 1608.07583 and 1704.05835

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Outline

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

Introduction

- The Standard ~~Model~~ Theory (SM) provides an elegant and accurate description of particle physics.
- Higgs boson discovery $\Rightarrow$ consistent theory up to M_P.
- However, many questions remain unanswered:

Experimentally

- Neutrino oscillation
- Dark Matter*
- Baryon asymmetry (BAU)*
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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).

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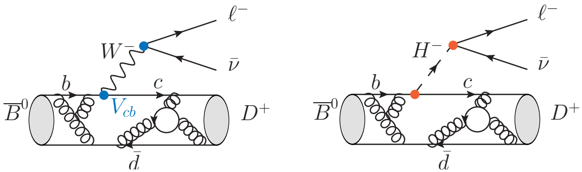
- Flavor changing charged currents: e.g. $b \to c\tau\nu$



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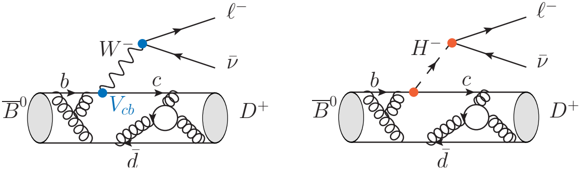

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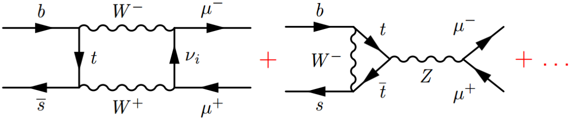

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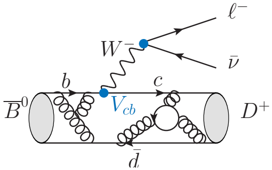

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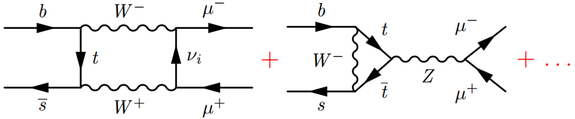

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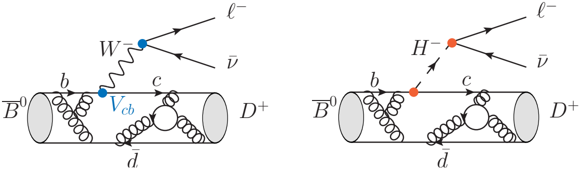

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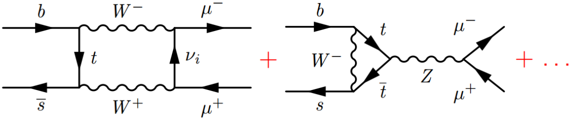


  - Possible mostly due to the maturity of LQCD in determining the relevant hadronic matrix elements (form factors).
  - Particularly interesting due to the deviations from LFU observed in B-meson decays: $B \to D^{(*)}\ell\bar{\nu}$ ($\ell = e, \mu, \tau$) and $B \to K^{(*)}\ell\ell$ ($\ell = e, \mu$).

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

- **Accidental symmetry** of the SM

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

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

- G_ℓ is broken by neutrino masses, but the induced rates are non observable (leptonic GIM, $\Delta m_{ij}^2 \lll m_W^2$):

e.g. $$\mathcal{B}(\mu \to e\gamma) \propto \left| \sum_{i=1}^{3} U_{ei}\, U_{\mu i}^{*} \frac{m_i^2}{m_W^2} \right|^2 \lesssim 10^{-54}\,.$$

- If something is observed, it has to be induced by New Physics $\Rightarrow$ **very clean probes** of New Physics.

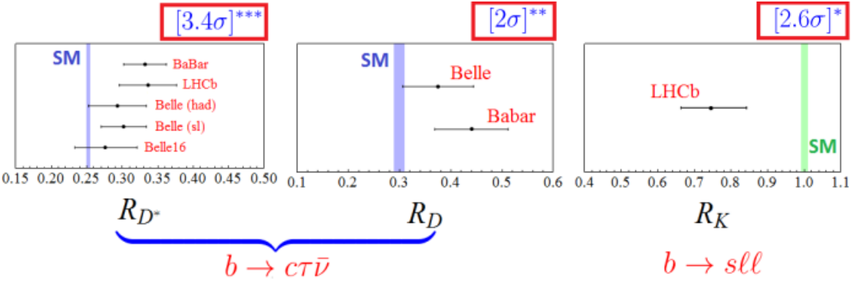
LFU violation in B decays

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 $\Rightarrow$ *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]

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



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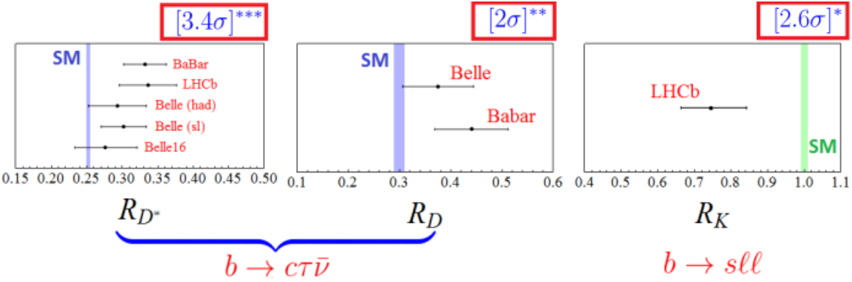


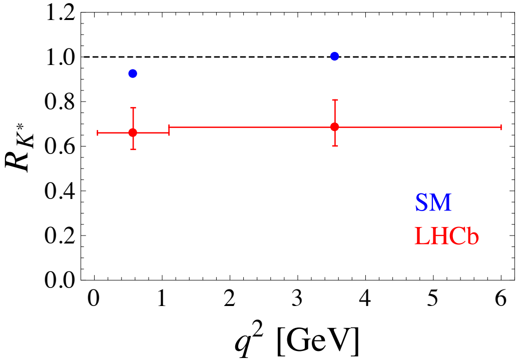
- NEW (FPCP17): LHCb, $R_{D^*} = 0.285(35)$, in agreement with SM.
- NEW: LHCb, $R_{J/\Psi} = 0.71(17)(18)$. Larger than the SM prediction (?)

LFUV in B Decays [2017]

$$R_{K^*} = \frac{\mathcal{B}(B \to K^* \mu\mu)}{\mathcal{B}(B \to K^* ee)}\Bigg|_{q^2 \in [q^2_{\rm min}, q^2_{\rm max}]}$$

[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?

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

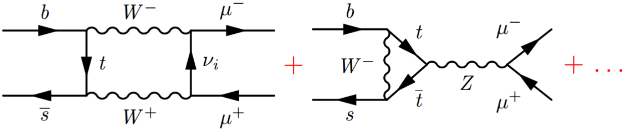
[Glashow, Guadagnoli, Lane. 2014.]

Outline

LFU violation

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

- FCNC process:



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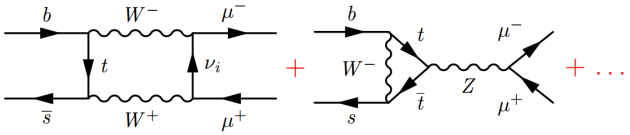

- Form-factor errors cancel out in the ratio ⇒ **Extremely clean prediction**.

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[Bordone et al. 2016]

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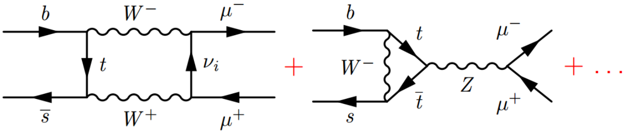

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- 2.6σ **deviation** observed by LHCb:

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

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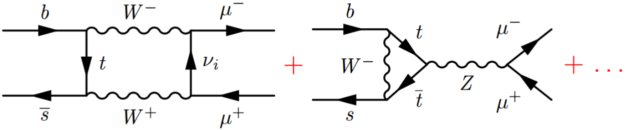

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- 2.5σ **deviation** in two bins for $B \to K^*\mu\mu$: $[0.045, 1.1]$ and $[1.1, 6]$ GeV^2.

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

Explaining R_K

EFT approach

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

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

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

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

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

Fit to clean observables [DB, Kosnik, Sumensari, Zukanovich. 1608.07583]

- Use $f_{B_s}^{Latt.} = 224(5)\ \mathrm{MeV}$ and $\mathcal{B}(B_s \to \mu\mu) = 3.0(6)(^{3}_{2}) \times 10^{-9}$. [LHCb, 2017]

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

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

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

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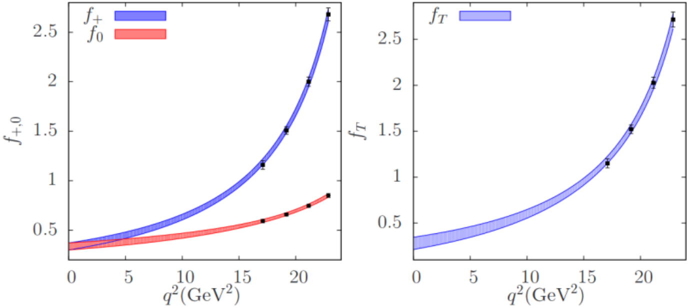
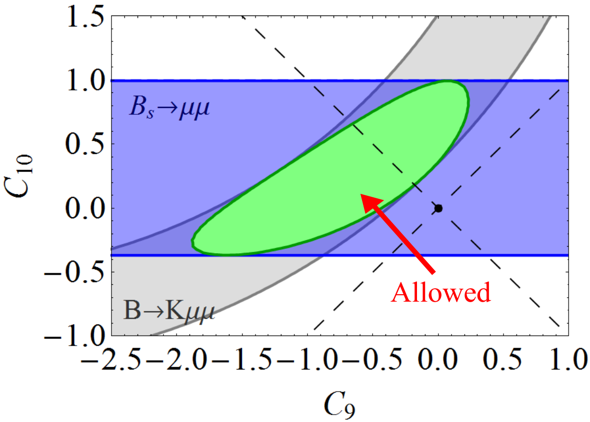
MILC [1509.06235]



Results consistent with HPQCD 1306.2384.



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

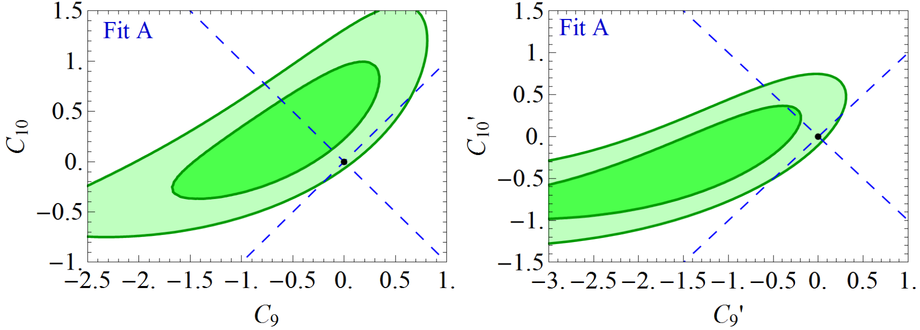
⇒ This value can be used to give **model independent** predictions for $R_{K^{(*)}}$ in the central bin:

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

[DB, Kosnik, Sumensari, Zukanovich 1608.07583]

[Becirevic, Sumensari 1704.05835]

Different choices of WC: (C_9, C_{10}) or (C_9', C_{10}')



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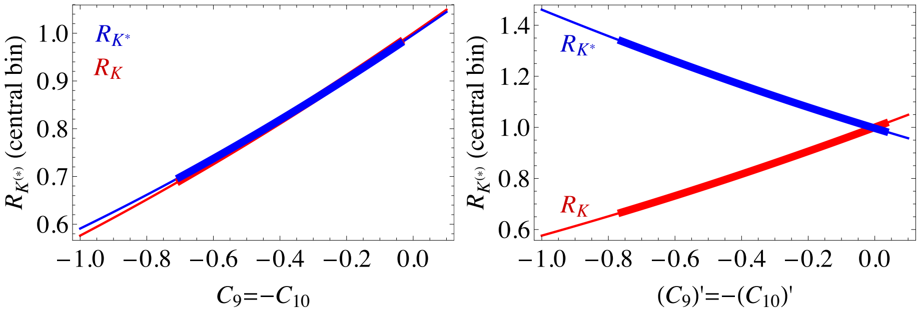
Model independent predictions for R_K and R_{K^*}:

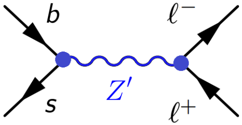


⇒ The scenario $C_9 = -C_{10}$ predicts $R_{K^{(*)}} < 1$, as observed.

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

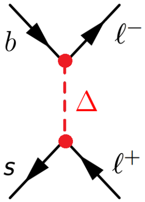
Representative (tree-level) models:

Z' models



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

Leptoquark models



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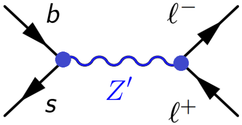

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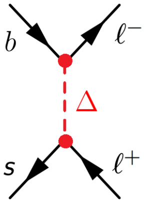

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- Vector leptoquark models also plausible, but non-renormalizable [problematic, how to compute loops? $B_s - \overline{B}_s$ and $\tau \to \mu\gamma$ constraints?]

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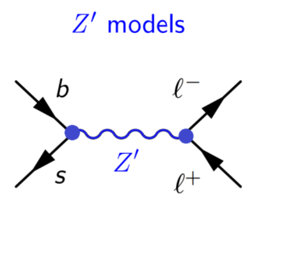

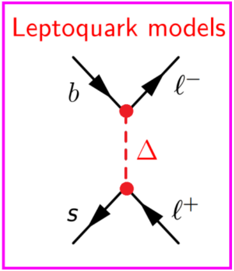

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⇒ Focus on NP couplings to muons only

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

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

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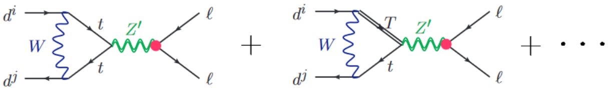
$(\bar{3},3)_{1/3}$	✗	$\overline{Q^C} i\tau_2 \boldsymbol{\tau}\cdot\boldsymbol{\Delta} L$	$C_9 = -C_{10}$	< 1	< 1

⇒ **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

New ideas?

- Z' boson with couplings only to μ, t and a top partner T.
  $\Rightarrow b \to s\ell\ell$ is modified by penguin diagrams [Kamenik et al. 1704.06005].



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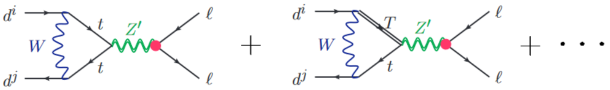
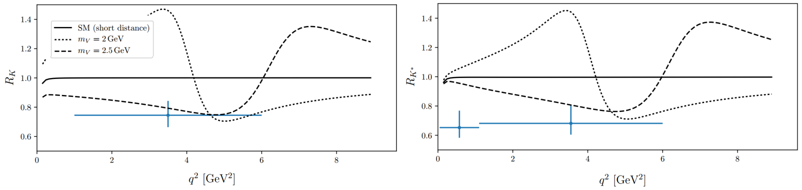


- A light resonance Z' decaying mostly to muons: $B \to K^{(*)}(V \to \mu\mu)$ [Sala, Straub. 1704.06188]



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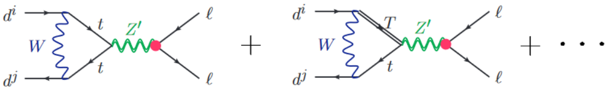

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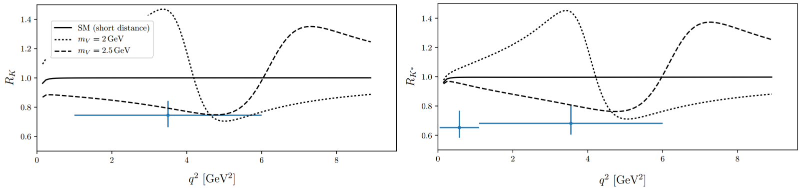

- Loop-level SLQ contributions (revival of a misused idea [Bauer and Neubert, 1511.01900]) [Becirevic, Sumensari 1704.05835]

- What else is **possible** in **minimal SLQ models**?

◦ 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 $m_\Delta \approx 1\ \mathrm{TeV}$.

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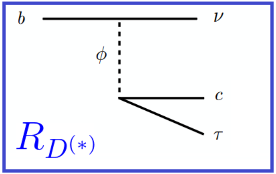
November 9, 2015

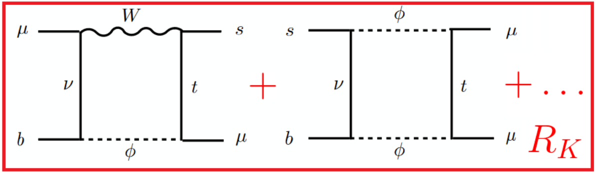
One Leptoquark to Rule Them All:
A Minimal Explanation for $R_{D^{(*)}}$, R_K and $(g-2)_\mu$

Martin Bauer[a] and Matthias Neubert[b,c]

1511.01900

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





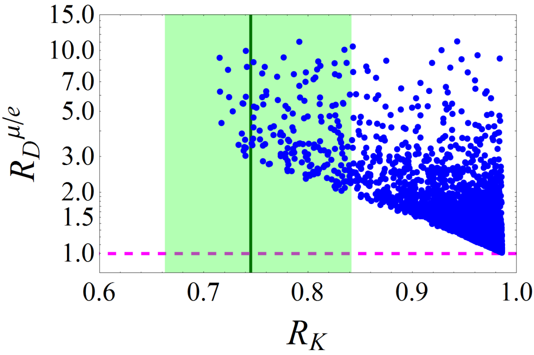
- What else is **possible** in **minimal SLQ models**?

◦ 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.

(ammended by hand by a symmetry to forbid the proton decay).

⇒ Produces **unnaceptably large** values of $R_D^{\mu/e} = \dfrac{\mathcal{B}(B \to D\mu\nu)}{\mathcal{B}(B \to De\nu)}$.

[DB, Kosnik, Sumensari, Zukanovich. 2016]



Can we exploit the same idea in a different way?

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

[DB, Sumensari 1704.05835]

Reminder:

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

What if the tree-level contribution is absent?

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

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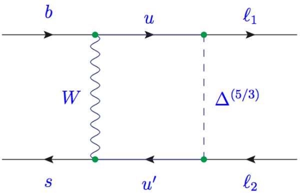
We take

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

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



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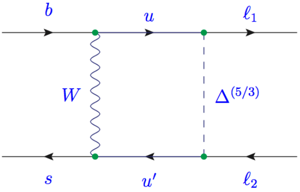

$$C_9 = -C_{10} = \sum_{u,u' \in \{u,c,t\}} \frac{V_{ub}\, V_{u's}^*}{V_{tb}\, V_{ts}^*}\, g_L^{u'\mu} \left(g_L^{u\mu}\right)^* \mathcal{F}(m_u, m_{u'}) \,,$$

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

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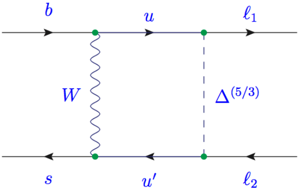

$$C_9 = -C_{10} = \sum_{u,u' \in \{u,c,t\}} \frac{V_{ub}\, V^*_{u's}}{V_{tb}\, V^*_{ts}}\, g_L^{u'\mu} \left(g_L^{u\mu}\right)^* \mathcal{F}(m_u, m_{u'})\,,$$

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

- 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: $(g-2)_\mu$, $\mathcal{B}(\tau \to \mu\gamma)$, $\mathcal{B}(Z \to \ell\ell)$, $\mathcal{B}(B \to K\nu\nu)$, Δm_{B_s}, among others.

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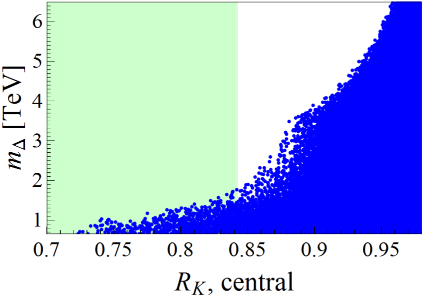
- We can **fully explain** the hints in $b \to s\ell\ell$ for $\boldsymbol{m_\Delta \lesssim 2}$ **TeV**:



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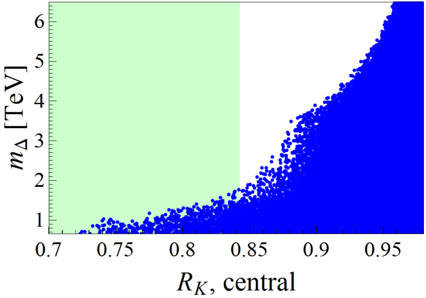


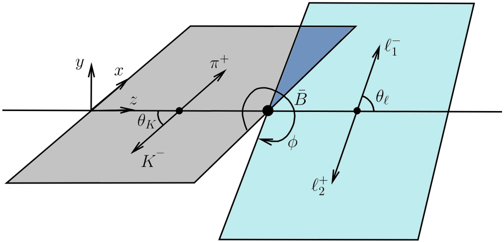
- Predictions to be tested at LHC and Belle-II: $\mathcal{B}(Z \to \mu\tau) \lesssim 10^{-6}$ and $\mathcal{B}(B \to K\mu\tau) \lesssim 10^{-8}$.

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

[DB, Sumensari, Zukanovich, 1602.00881]

A by-product of our work:

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



K^* **rest frame:**

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

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

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]

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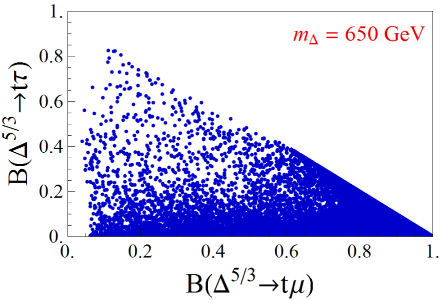
- Predictions for direct searches:

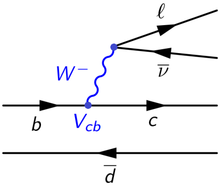
Clean signature in $\mathbf{\Delta^{5/3} \to t\mu}$!



Outline

- Tree-level process in the SM:

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



LFU violation

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

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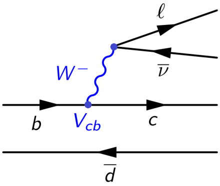

- Non-perturbative QCD $\Longleftrightarrow$ form-factors (Lattice QCD)

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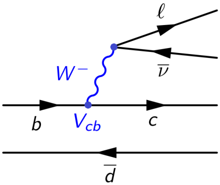

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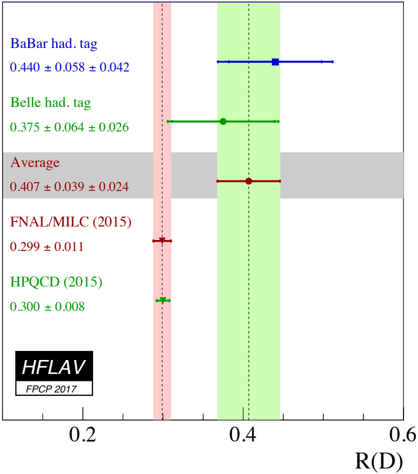
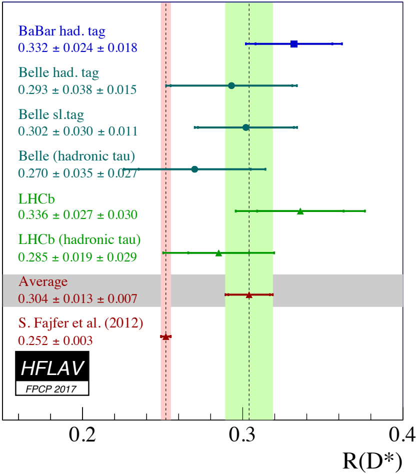
- Situation less clear for $B \to D^*$ $\Rightarrow$ (more FFs, less LQCD results)
  [One form-factor is unknown from LQCD – *systematic error of $R_{D^*}^{\mathrm{SM}}$?*]





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

Theory Challenge

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

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$\Rightarrow$ To be honest, nothing very compelling yet...

Perspectives and future possibilities

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  $\Rightarrow$ 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 [DB, Panes, Sumensari, Zukanovich, to appear].

Outline

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. $\Rightarrow$ 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!