B-Physics and Lepton Flavor (Universality) Violation

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In collaboration with

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Outline

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

Outline

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)*
- ...

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).

Flavor physics observables

Precision flavor physics: search of deviations w.r.t. the SM predictions

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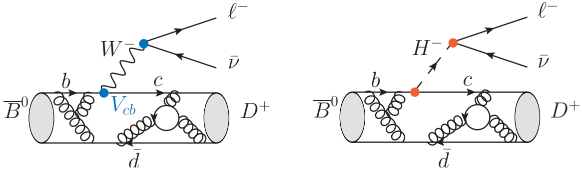
- Flavor changing charged currents: e.g. $b \to c\tau\nu$



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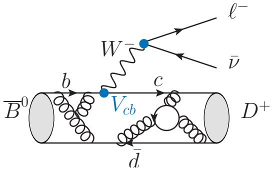

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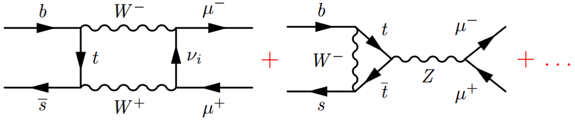

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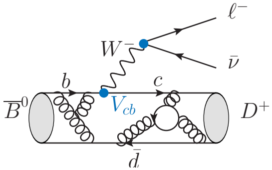

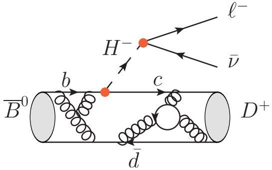

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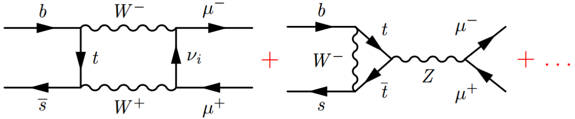

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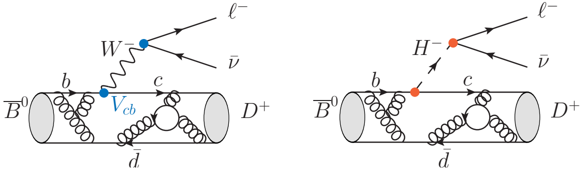

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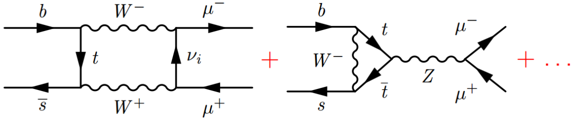


- ◦ Possible mostly due to the maturity of LQCD in determining the relevant hadronic matrix elements (form factors). See FLAG!
- ◦ Particularly interesting due to the deviations from LFU observed in B-meson decays: $B \to D^{(*)}\ell\bar{\nu}$ ($\ell = e, \mu, \tau$) and $B \to K^{(*)}\ell\ell$ ($\ell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

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

- **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

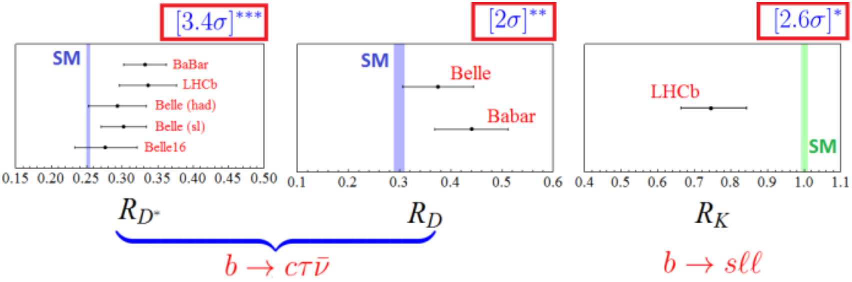
- Lepton Flavor Universality **(LFU)** is not a fundamental symmetry of the SM: accidental in the gauge sector and broken by Yukawas.

- LFU tested in pion and kaon decays – agrees very well with the SM $\Rightarrow$ *To be improved at NA62.* [only e, μ 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]

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



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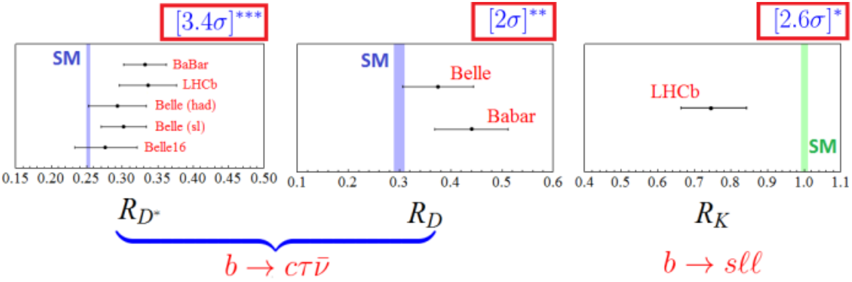


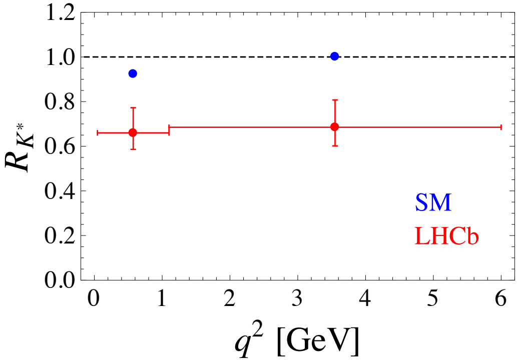
- Recently (FPCP17): LHCb, $R_{D^*} = 0.285(35)$, in agreement with SM.
- More interestingly: LHCb, $R_{J/\Psi} = 0.71(17)(18)$. Larger than the SM prediction (?)

LFUV in B Decays [2017]

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

[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, $R_{K^{(*)}} \neq 1 \;\Leftrightarrow\;$ **LFUV** "$\Rightarrow$" Lepton Flavor Violation **(LFV)**

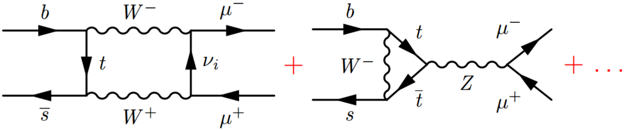
[Glashow, Guadagnoli, Lane. 2014.]

Outline

LFU violation

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

- FCNC process:



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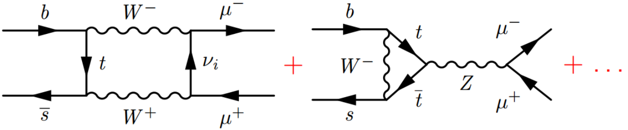

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$$R_K \equiv \left. \frac{\mathcal{B}(B^+ \to K^+\mu\mu)}{\mathcal{B}(B^+ \to K^+ee)} \right|_{q^2 \in [1,6]\ \mathrm{GeV}^2} \overset{\mathrm{SM}}{=} 1.00(1)$$

[Bordone et al. 2016]

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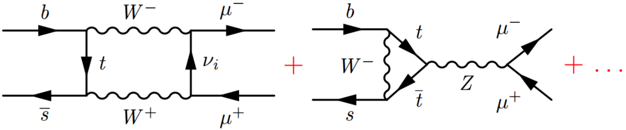

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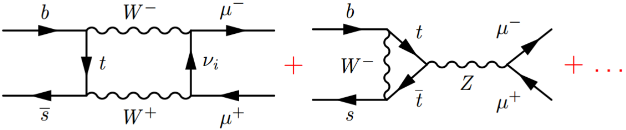

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- 2.5σ **deviation** in two bins for $B \to K^*\mu\mu$: $[0.045, 1.1]$ and $[1.1, 6]$ GeV^2.

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

Explaining R_K

EFT approach

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

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

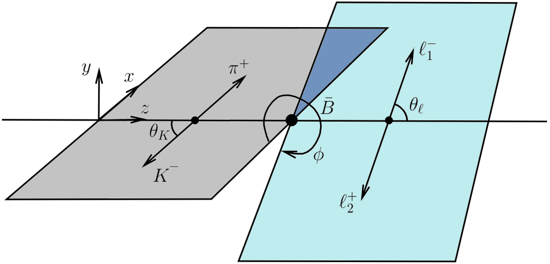
- Operators relevant to $b \to s\ell\ell$ are

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

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

$$\mathcal{O}_7^{(\prime)} = m_b(\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu} \quad \ldots$$

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



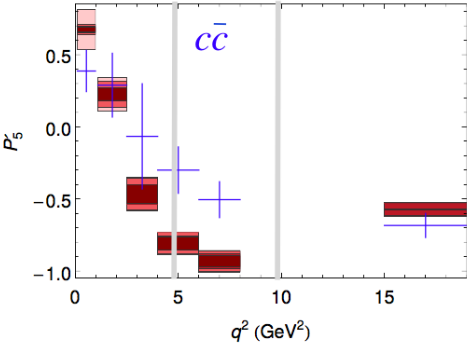
$$I(q^2,\theta_\ell,\theta_K,\phi) = I_1^s(q^2)\sin^2\theta_K + I_1^c(q^2)\cos^2\theta_K + [\boldsymbol{I_2^s(q^2)}\sin^2\theta_K + \boldsymbol{I_2^c(q^2)}\cos^2\theta_K]\cos 2\theta_\ell$$
$$+ I_3(q^2)\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + I_4(q^2)\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$
$$+ \boldsymbol{I_5(q^2)}\sin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

e.g. $P_5'(q^2) = \dfrac{I_5(q^2)}{2\sqrt{-I_2^c(q^2)I_2^s(q^2)}}$

Use LCSR results for the hadronic quantities (at low q^2), combine them with LQCD results when available [Bharucha et al 2015] and make a global fit of LHC data Altmannshofer et al 2016, 2017; Descotes-Genon et al 2015, 2017; Ciuchini et al. 2015, 2017; Hurth et al 2016, 2017.

Conclusions [B-physics anomalies]:

- Measured branching fractions $\mathcal{B}(B \to K\mu\mu)$, $\mathcal{B}(B \to K^*\mu\mu)$, $\mathcal{B}(B_s \to \phi\mu\mu)$ differ from Standard Model (SM)
- Several angular observables deviate from SM (esp. $\langle P_5' \rangle$)

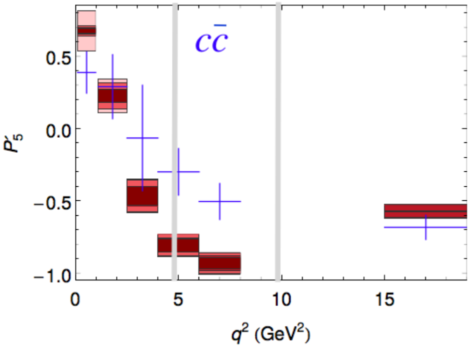


$c\bar{c}$ region sensitive to

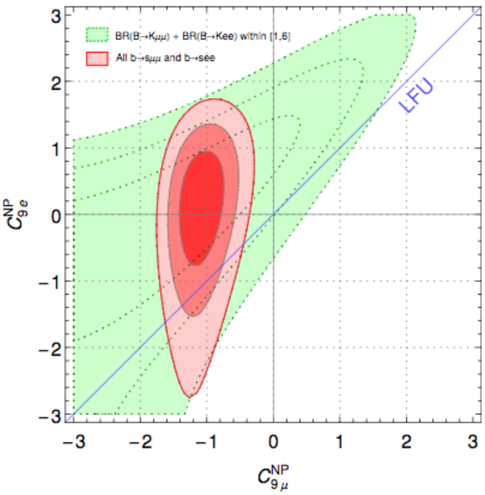
$$\frac{1}{q^2} C_{1,2} \int d^4x e^{iqx} \langle K^* | \mathcal{T}\left[O_{1,2}(0), j^\mu(x)\right] | B \rangle$$

disconnected graphs $[O_2 = \bar{s}_L \gamma^\alpha b_L \, \bar{c}\gamma_\alpha c]$ estimated in [Khodjamirian et al 2010].

Reliability unclear – see Capdevila et al 2017 vs Ciuchini et al 2016!



Global analyses suggest $C_9^\mu < 0$, $C_9^e \approx 0$



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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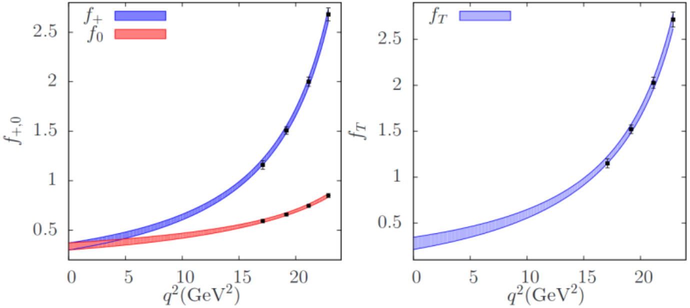
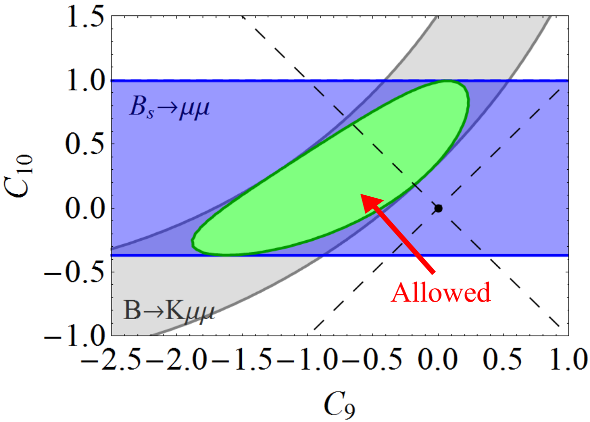
MILC [1509.06235]



Results consistent with HPQCD 1306.2384.



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

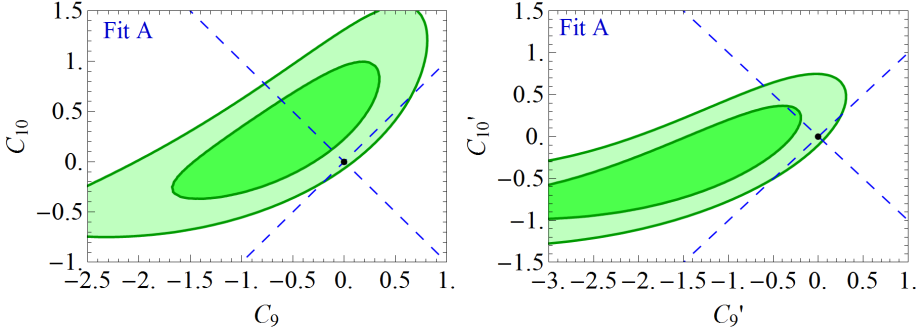
$\Rightarrow$ This value can be used to give **model independent** predictions for $R_{K^{(*)}}$ in the central bin:

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

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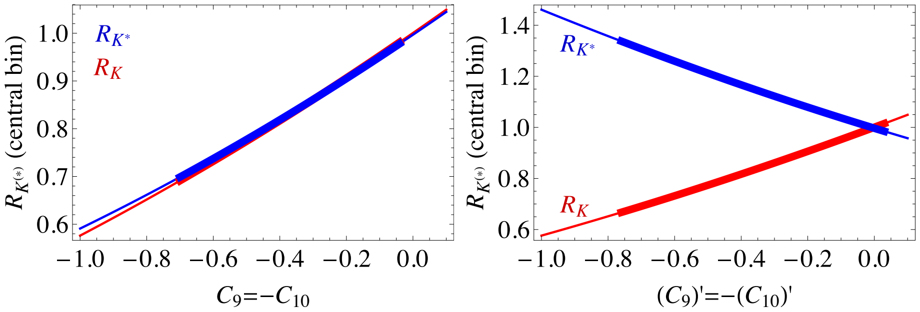
Model independent predictions for R_K and R_{K^*}:

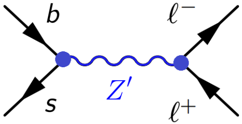


⇒ The scenario $C_9 = -C_{10}$ predicts $R_{K^{(*)}} < 1$, as observed.

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

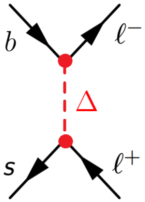
Representative (tree-level) models:

Z' models



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

Leptoquark models



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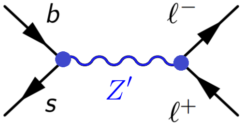

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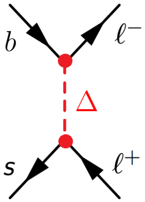

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- Vector leptoquark models also plausible, but non-renormalizable [problematic, how to compute loops? $B_s - \overline{B}_s$ and $\tau \to \mu\gamma$ constraints?]
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- Interesting feature: **LFV** is in general **expected** .

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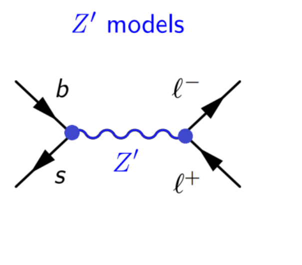

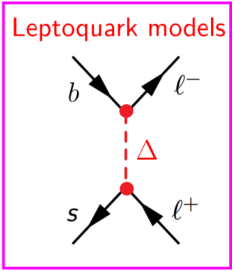

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Explaining R_K

Scalar Leptoquark Models [DB, Kosnik, Sumensari, Zukanovich. 1608.08501]

$\Rightarrow$ Focus on NP couplings to muons only

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

$SU(3)_c \times SU(2)_L \times U(1)_Y$: **N.B.** $Q = Y + T_3$.

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	BNC	Interaction	WC	R_K/R_K^{SM}	$R_{K^*}/R_{K^*}^{\mathrm{SM}}$
$(\bar{3},1)_{4/3}$	✗	$\overline{d_R^C}\boldsymbol{\Delta}\ell_R$	$(C_9)' = (C_{10})'$	$\approx \mathbf{1}$	$\approx \mathbf{1}$
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⇒ Focus on NP couplings to muons only

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

$SU(3)_c \times SU(2)_L \times U(1)_Y$: **N.B.** $Q = Y + T_3$.

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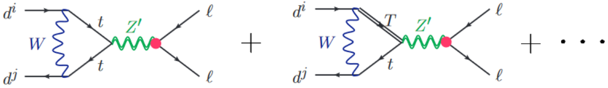
$(\bar{3},3)_{1/3}$	✗	$\overline{Q^C} i\tau_2 \boldsymbol{\tau}\cdot\boldsymbol{\Delta} L$	$C_9 = -C_{10}$	< 1	< 1

⇒ **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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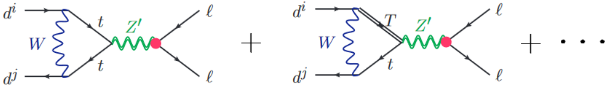
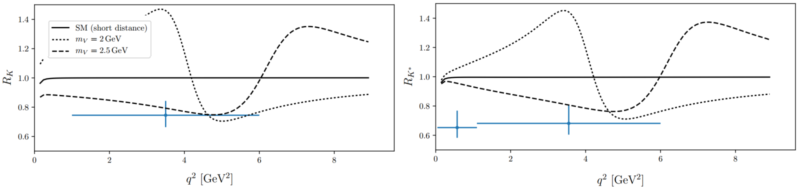


- A light resonance Z' decaying mostly to muons: $B \to K^{(*)}(V \to \mu\mu)$ [Sala, Straub. 1704.06188]



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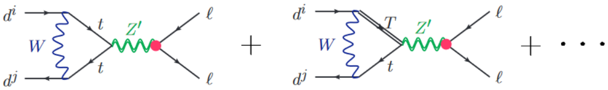

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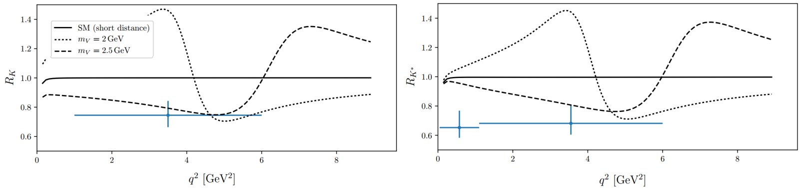

- Loop-level SLQ contributions (revival of a misused idea [Bauer and Neubert, 1511.01900]) [Becirevic, Sumensari 1704.05835]

- 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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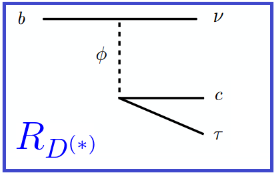
November 9, 2015

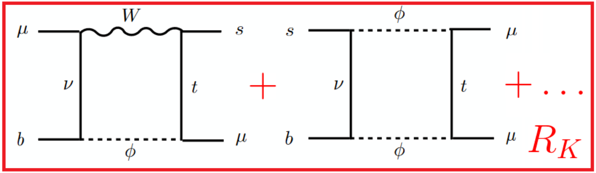
One Leptoquark to Rule Them All:
A Minimal Explanation for $R_{D^{(*)}}$, R_K and $(g-2)_\mu$

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

1511.01900

$$\mathcal{L}_{\Delta^{(1/3)}} = \Delta^{(1/3)*}\left[(g_L)_{ij}\,\overline{Q^C_i}\, i\sigma_2 L_j + (g_R)_{ij}\,\overline{u^C_{R\,i}}\,\ell_{R\,j}\right] + \text{h.c.}$$





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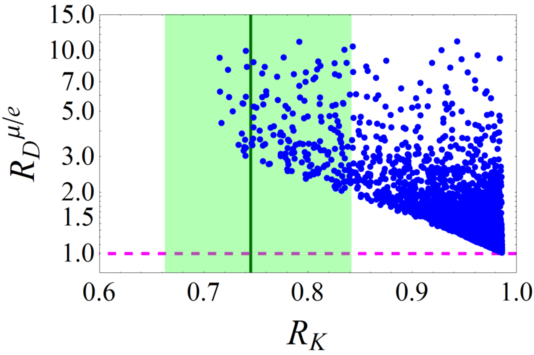
(ammended by hand by a symmetry to forbid the proton decay).

$\Rightarrow$ 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:

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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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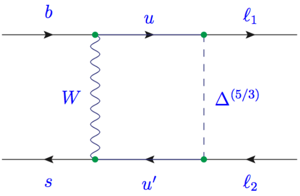
We take

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

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



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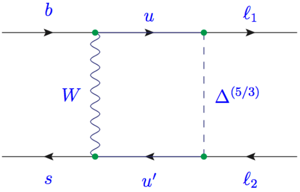

$$C_9 = -C_{10} = \sum_{u,u' \in \{u,c,t\}} \frac{V_{ub}\, V^*_{u's}}{V_{tb}\, V^*_{ts}}\, g_L^{u'\mu} \left(g_L^{u\mu}\right)^* \mathcal{F}(m_u, m_{u'})\,,$$

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

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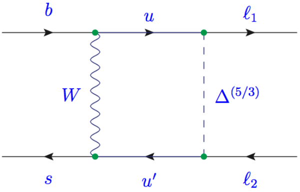

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- We predict $C_9 = -C_{10} < 0$, in agreement with the exp. hints.
- Charm contribution is non-negligible due to CKM enhancement V_{cs}/V_{ts}.

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

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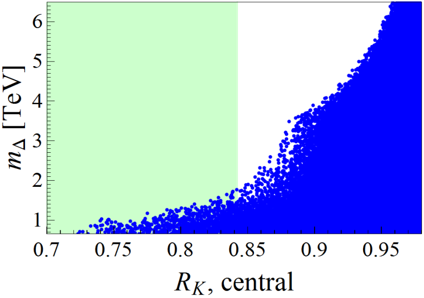
- We can **fully explain** the hints in $b \to s\ell\ell$ for $\boldsymbol{m_\Delta \lesssim 2}$ **TeV**:



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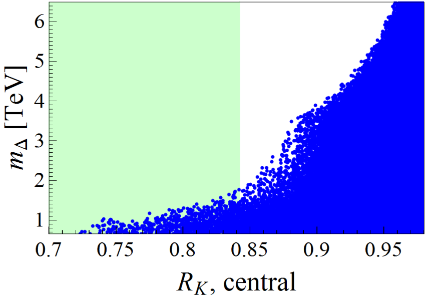

- Predictions to be tested at LHC and Belle-II: $\mathcal{B}(Z \to \mu\tau) \lesssim 10^{-6}$ and $\mathcal{B}(B \to K\mu\tau) \lesssim 10^{-8}$.

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]

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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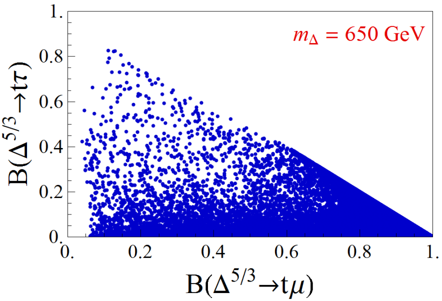
- Predictions for direct searches:

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



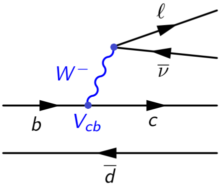
Outline

LFU violation

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

- Tree-level process in the SM:

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



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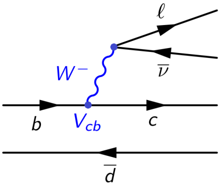

- Non-perturbative QCD $\Longleftrightarrow$ form-factors (Lattice QCD)

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

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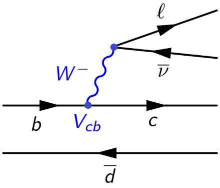

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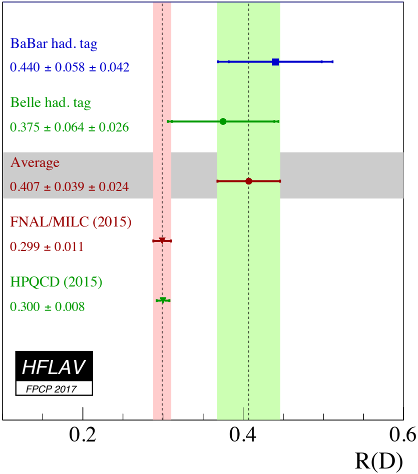
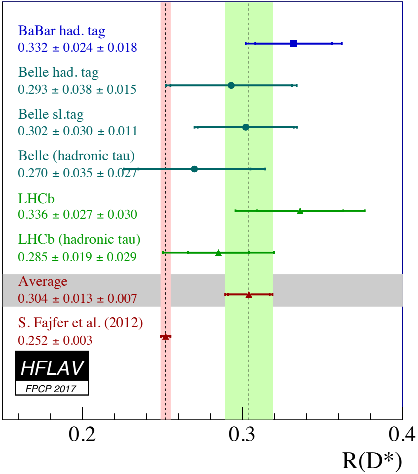
- Situation less clear for $B \to D^*$ $\Rightarrow$ (more FFs, less LQCD results)
  [One form-factor is unknown from LQCD – *systematic error of $R_{D^*}^{\mathrm{SM}}$?*]





- 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 $R_{D^{(*)}}$:

- $SU(2)_L$ triplet of vector bosons with couplings mostly to the 3rd generation – *tension with direct searches*. [Greljo et al., 1506.01705]

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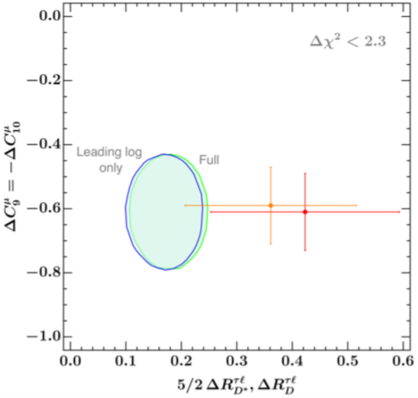
$\Rightarrow$ To be honest, nothing very compelling yet...

Revival of PS model Bordone et al, 1712.01368

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

- $PS = SU(4) \times SU(2)_L \times SU(2)_R$. Model with three PS each talking to a single fermion family. Rich spectrum of states to look for in colliders... however:

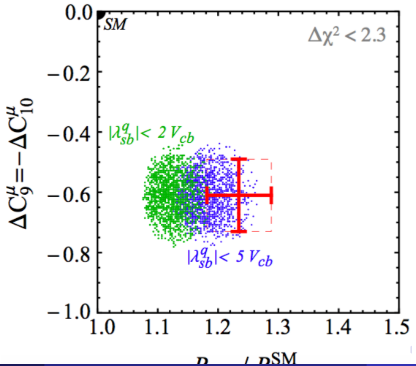


Simultaneously explain $R_{K^{(*)}}$ and $R_{D^{(*)}}$:

- Use

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{\lambda^q_{ij}\lambda^\ell_{\alpha\beta}}{v^2}\left[C_T(\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S(\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$

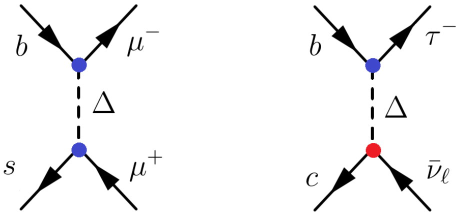
- Flavor structure $U(2)_q \times U(2)_\ell$ & veto flavor blind contractions of light fields.



[DB, Fajfer, Kosnik, Sumensari 1608.08051]

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

$$\mathcal{L}_Y = \boldsymbol{Y^L_{ij}} \bar{L}_i \widetilde{\Delta}^{(1/6)} d_{Rj} + \boldsymbol{Y^R_{ij}} \bar{Q}_i \Delta^{(1/6)} \nu_{Rj} + \text{h.c.}$$



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

Naturally generates $\boldsymbol{R^{\rm NP}_{D^{(*)}} > R^{\rm SM}_{D^{(*)}}}$ if $|Y^L_{b\tau}| \gtrsim |Y^L_{b\mu}|$.

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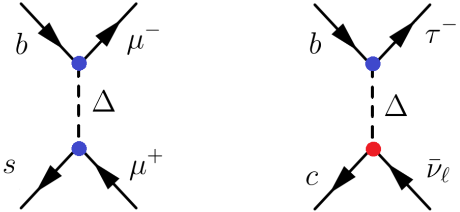
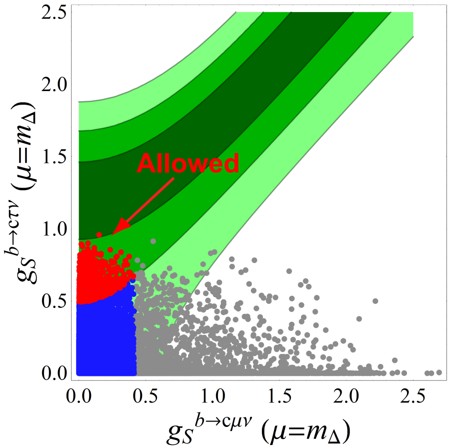
$$\mathcal{L}_Y = \boldsymbol{Y^L_{ij}} \bar{L}_i \widetilde{\Delta}^{(1/6)} d_{Rj} + \boldsymbol{Y^R_{ij}} \bar{Q}_i \Delta^{(1/6)} \nu_{Rj} + \text{h.c.}$$



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

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



$B \to D$ 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:

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

Perspectives and future possibilities

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  - Search of new resonances.
  - Distortions of kinematical distributions of $pp \to \mu^+\mu^-, \tau^+\tau^-$.

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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?

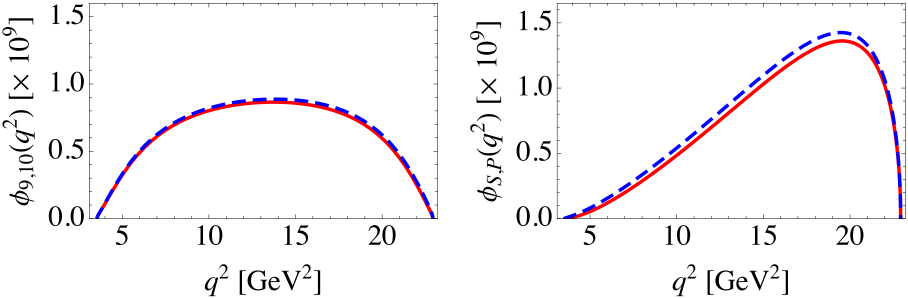
Thank you!

Backup

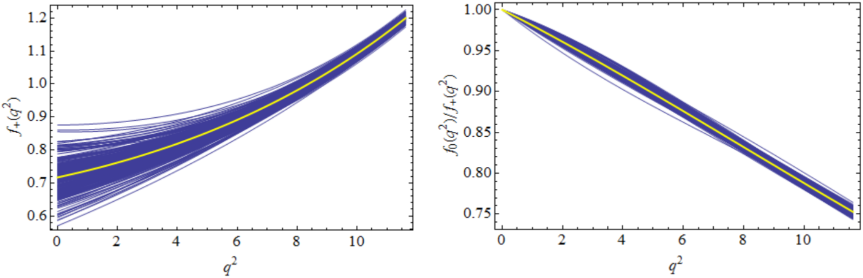
More on B LFV

$$\mathcal{B}(B_s \to \ell_1^- \ell_2^+)^{theo} = \frac{\tau_{B_s}}{64\pi^3}\frac{\alpha^2 G_F^2}{m_{B_s}^3} f_{B_s}^2 |V_{tb} V_{ts}^*|^2 \lambda^{1/2}(m_{B_s}, m_1, m_2)$$

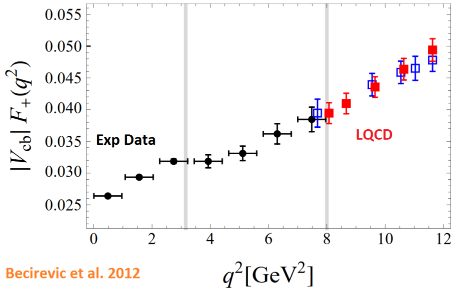
$$\times \left\{ [m_{B_s}^2 - (m_1+m_2)^2] \cdot \left| (C_9 - C_9')(m_1 - m_2) + (C_S - C_S') \frac{m_{B_s}^2}{m_b + m_s} \right|^2 + [m_{B_s}^2 - (m_1 - m_2)^2] \cdot \left| (C_{10} - C_{10}')(m_1 + m_2) + (C_P - C_P') \frac{m_{B_s}^2}{m_b + m_s} \right|^2 \right\}$$



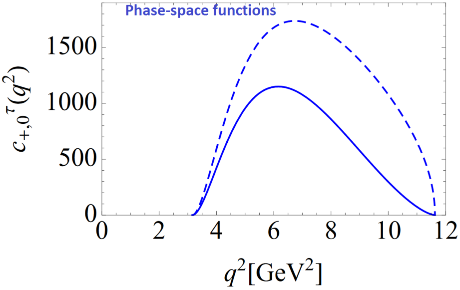
$B \to D$ form factors from LQCD



$B \to D$ vector form factor:



Becirevic et al. 2012



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

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

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

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

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

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

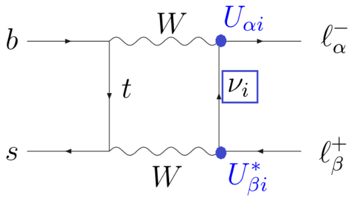
Going from LFC to LFV:

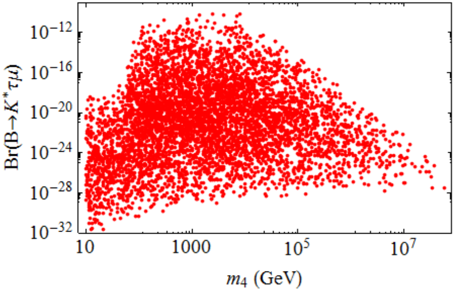
$$A_t = \lim_{m_1\to m_2}\left(A_t^L - A_t^R\right), \qquad A_S = \lim_{m_1\to m_2}\left[\frac{m_1-m_2}{\sqrt{q^2}}\left(A_t^L + A_t^R\right)\right]$$

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

We opt for a pragmatic approach:

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





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

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?

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

$$\begin{aligned} \mathcal{B}(\tau \to \mu\nu\bar{\nu})_{\rm SM} &= 17.29(3)\% \\ \mathcal{B}(\tau \to \mu\nu\bar{\nu})_{\rm exp} &= 17.33(5)\% \quad \text{[Average]} \\ \mathcal{B}(\tau \to \mu\nu\bar{\nu})_{\rm exp} &= 17.41(4)\% \quad \text{[Fit]} \end{aligned}$$

  PDG and HFAG fits amplify the 1.6σ discrepancy of

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

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

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

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

$$I_1^s(q^2) = \left[|A_\perp^L|^2 + |A_\parallel^L|^2 + (L \to R)\right] \frac{\lambda_q + 2[q^4 - (m_1^2 - m_2^2)^2]}{4q^4}$$
$$+ \frac{4m_1 m_2}{q^2} \mathrm{Re}\left(A_\parallel^L A_\parallel^{R*} + A_\perp^L A_\perp^{R*}\right),$$
$$I_1^c(q^2) = \left[|A_0^L|^2 + |A_0^R|^2\right] \frac{q^4 - (m_1^2 - m_2^2)^2}{q^4} + \frac{8m_1 m_2}{q^2} \mathrm{Re}(A_0^L A_0^{R*} - A_t^L A_t^{R*})$$
$$- 2\frac{(m_1^2 - m_2^2)^2 - q^2(m_1^2 + m_2^2)}{q^4} \left(|A_t^L|^2 + |A_t^R|^2\right),$$
$$I_2^s(q^2) = \frac{\lambda_q}{4q^4}[|A_\perp^L|^2 + |A_\parallel^L|^2 + (L \to R)],$$
$$I_2^c(q^2) = -\frac{\lambda_q}{q^4}(|A_0^L|^2 + |A_0^R|^2),$$

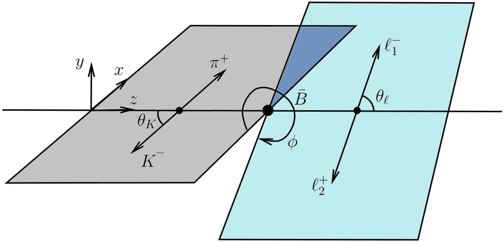
$$A_\perp^{L(R)} = \mathcal{N}_{K^*}\sqrt{2}\lambda_B^{1/2}\left[[(C_9 + C_9') \mp (C_{10} + C_{10}')]\frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(C_7 + C_7')T_1(q^2)\right],$$

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

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

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

- 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:

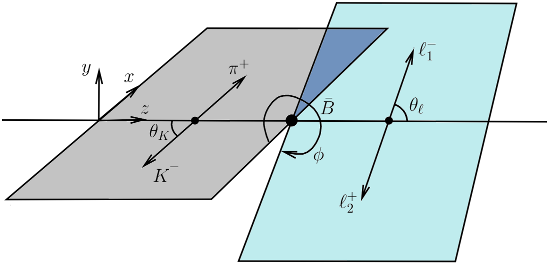
$$p_1^\mu = (E_\alpha, \hat{\mathbf{p}}_\ell|p_\ell|), \quad p_2^\mu = (E_\beta, -\hat{\mathbf{p}}_\ell|p_\ell|),$$

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

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

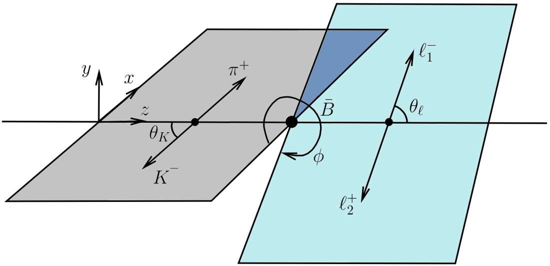
Full decay distribution

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



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

Full decay distribution



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

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

Conditions to fulfill:

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

OR

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

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

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

$\Rightarrow$ induces unknown systematic uncertainties – **LQCD** might help.

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

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:

$\Rightarrow$ Z' couplings are only **fixed by data**.

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

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

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

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

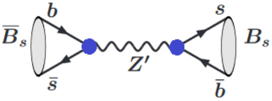
$$\mathcal{L}_{Z'} \supset \boldsymbol{g_{\ell_i\ell_j}^L} \bar{\ell}_i \gamma^\mu P_L \ell_j Z'_\mu + \boldsymbol{g_{sb}^L} \bar{s}\gamma^\mu P_L b Z'_\mu + (L \to R)$$

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

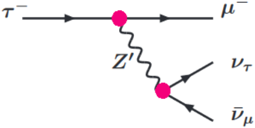
Z' Models

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

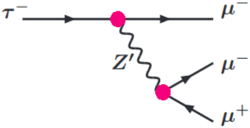
$$\frac{\Delta m_{B_s}^{\rm exp}}{\Delta m_{B_s}^{\rm SM}} - 1 \propto \frac{(g_{sb}^{L(R)})^2}{m_{Z'}^2}$$



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



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

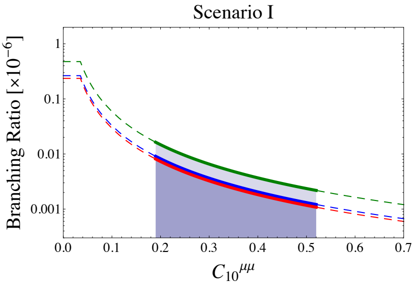


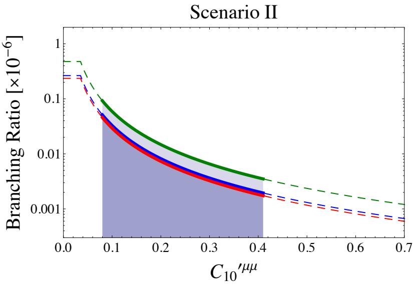
- Tree-level processes $\Rightarrow$ Predictions independent on $m_{Z'}$.
- Couplings to leptons and quarks can be constrained separately.

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

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

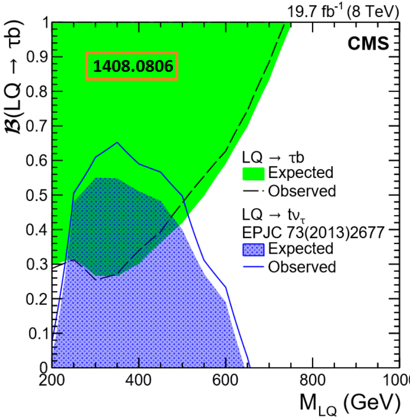
Scenario	I (LH)	II (RH)
$\mathcal{B}(B \to K^*\mu\tau) \leq$	1.6×10^{-8}	9.3×10^{-8}
$\mathcal{B}(B \to K\mu\tau) \leq$	0.9×10^{-8}	5.2×10^{-8}
$\mathcal{B}(B_s \to \mu\tau) \leq$	0.8×10^{-8}	4.6×10^{-8}

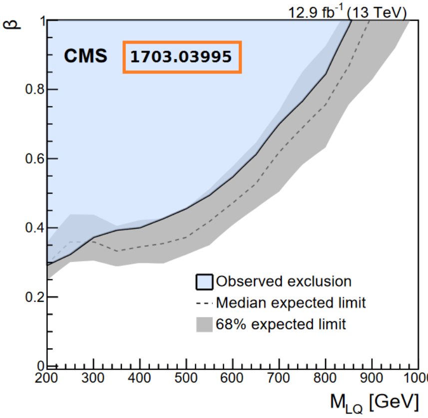




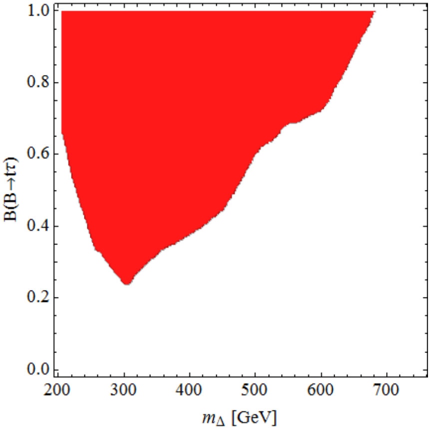
NB. Crivellin et. al. [1504.07928] obtain larger rates due to *inconsistent* treatment of g_{sb}^L and g_{sb}^R.

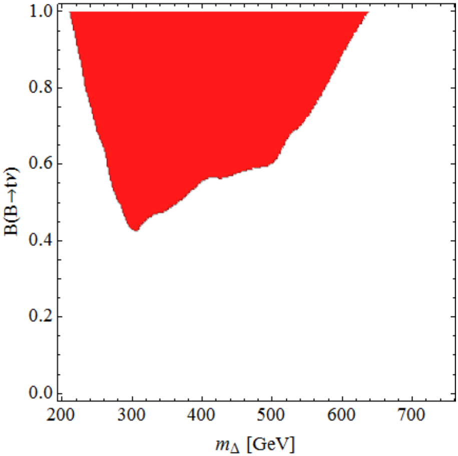
LQ Direct Searches: $\Delta \to \tau b$

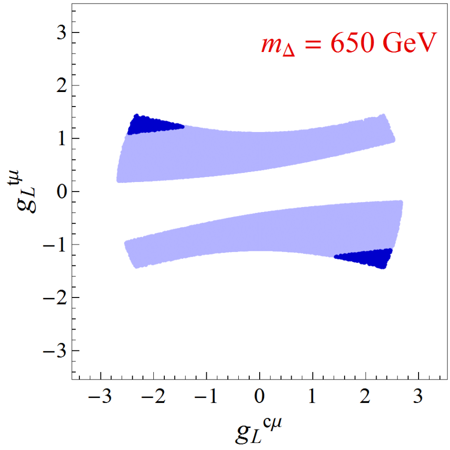




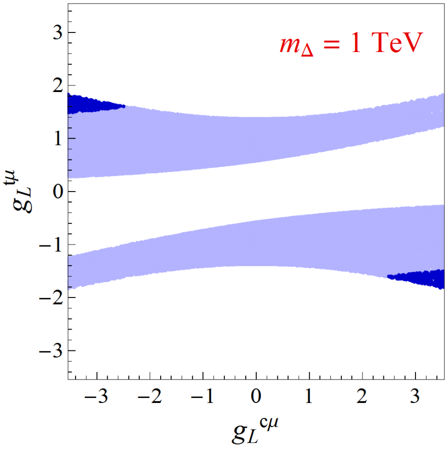
LQ Direct Searches: $(3,2)_{7/6}$





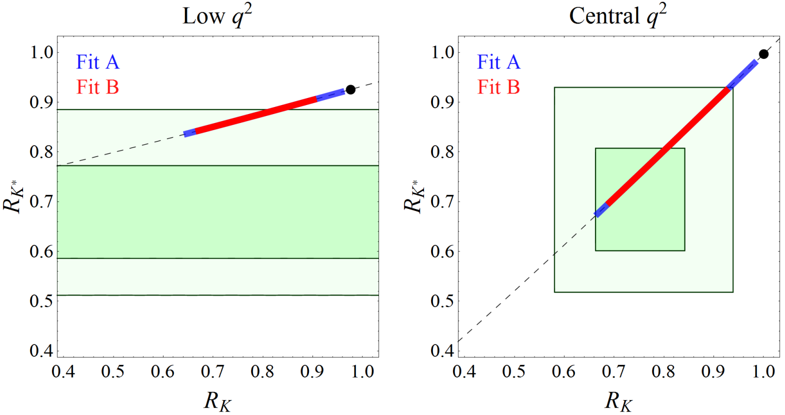


$m_\Delta = 650$ GeV
$g_L^{t\mu}$
$g_L^{c\mu}$
−3
−2
−1
0
1
2
3



$m_\Delta = 1$ TeV
$g_L^{t\mu}$
$g_L^{c\mu}$
−3
−2
−1
0
1
2
3

- **Fit A**: $\mathcal{B}(B_s \to \mu^+\mu^-)$ and $\mathcal{B}(B^+ \to K^+\mu\mu)_{\text{high } q^2}$
- **Fit B**: $\mathcal{B}(B_s \to \mu^+\mu^-)$, $\mathcal{B}(B^+ \to K^+\mu\mu)_{\text{high } q^2}$, 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!