B-Physics Anomalies circa 2017

Damir Bečirević

Lattice 2017, Granada, June 20, 2017.

Outline

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Introduction

- The Standard ~~Model~~ Theory (SM) provides an elegant and accurate description of particle physics.
- 2012 Higgs boson discovery $\Rightarrow$ consistent theory up to Λ_{Pl}.

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- The Standard ~~Model~~ Theory (SM) provides an elegant and accurate description of particle physics.
- 2012 Higgs boson discovery $\Rightarrow$ consistent theory up to $\Lambda_{\rm Pl}$.
- However, many questions remain unanswered:

On the theory side	Experimentally
- Hierarchy problem	- Neutrino oscillation
- Flavor problem	- Dark Matter*
- Strong CP-problem	- Baryon asymmetry (BAU)*
- ...	- ...

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**:

$$G_{\text{SM}} = SU(3)_c \times SU(2)_L \times U(1)_Y \to SU(3)_c \times U(1)_{\text{em}}$$

For a doublet e.g.,

$$D_\mu = \partial_\mu - i g_s t_a A^a_\mu - i g \mathrm{T} \cdot \mathrm{W}_\mu - i g' \frac{Y}{2} B_\mu \to \{g_s, e, \theta_W\}$$

& $v = 246$ GeV and $\lambda \simeq 0.13$ (perturbativity).

- Flavor sector **loose**:

$\Rightarrow$ 13 free parameters (masses and quark mixing) – fixed by data.

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

- Hierarchy of fermion masses and of CKM couplings
$\Leftrightarrow$ Flavor symmetry breaking?

How can we look for New Physics effects?

Directly

Indirectly

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

Outline

LFUV in B Decays

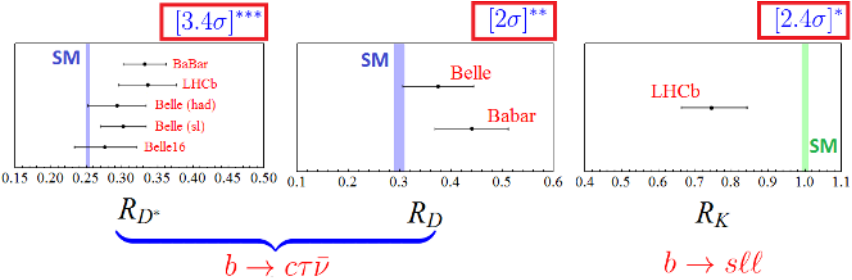
- Lepton Flavor Universality **(LFU)** is not a fundamental symmetry of the SM: accidental in the gauge sector and broken by Yukawas.

- LFU tested in pion and kaon decays – agrees very well with the SM $\Rightarrow$ *To be improved by NA62* [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]

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



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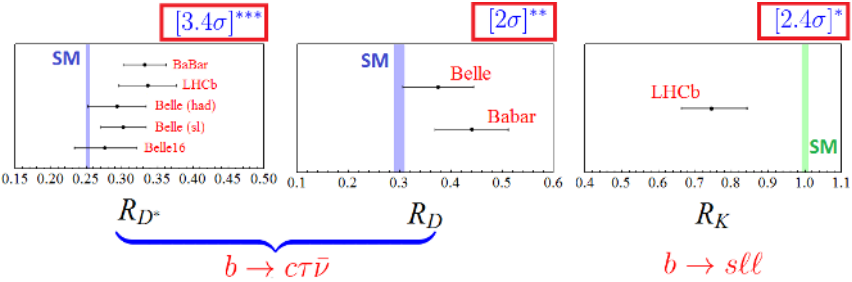


New (cpl weeks ago @ FPCP17): LHCb $R_{D^*} = 0.285(35)$

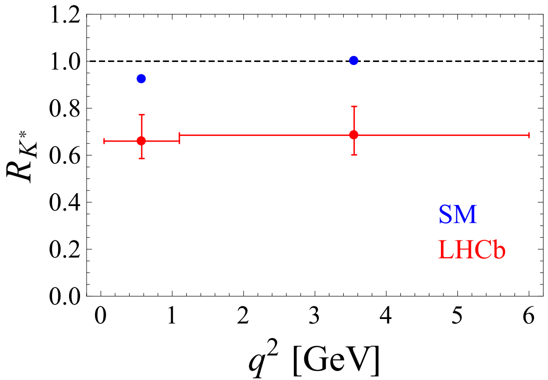
New reassessing the theory error: $0.252(3) \to 0.26(??)$

LFUV in B Decays [2017]

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

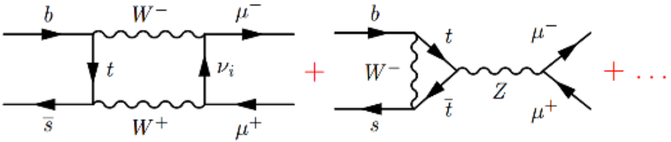
[1705.05802]

- **New results** in two q^2-bins:



Outline

EFT approach



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

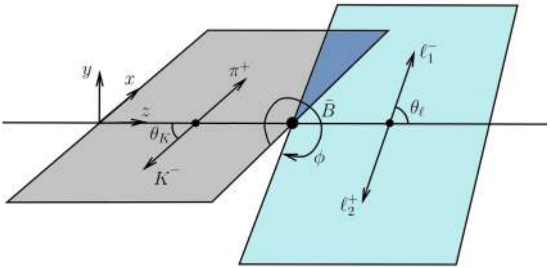
$$\mathcal{H}_{\text{eff}} = -\frac{G_F \alpha}{\pi\sqrt{2}} V_{tb} V_{ts}^* \left[\sum_{i=1}^{6} C_i(\mu)\mathcal{O}_i(\mu) + \sum_{i=7,8,9,10,P,S,\ldots} \left(C_i(\mu)\mathcal{O}_i + C_i'(\mu)\mathcal{O}_i' \right) \right]$$

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

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

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

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

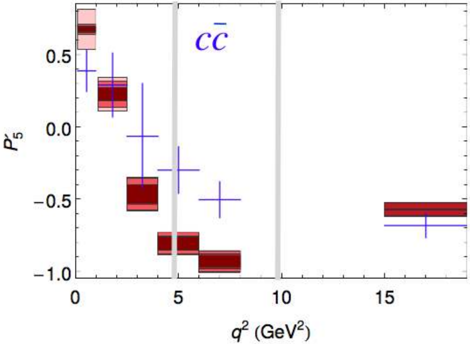


$$\begin{aligned}I(q^2,\theta_\ell,\theta_K,\phi) = & I_1^s(q^2)\sin^2\theta_K + I_1^c(q^2)\cos^2\theta_K + [\boldsymbol{I_2^s(q^2)}\sin^2\theta_K + \boldsymbol{I_2^c(q^2)}\cos^2\theta_K]\cos 2\theta_\ell \\ & + I_3(q^2)\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + I_4(q^2)\sin 2\theta_K\sin 2\theta_\ell\cos\phi \\ & + \boldsymbol{I_5(q^2)}\sin 2\theta_K\sin\theta_\ell\cos\phi + [I_6^s(q^2)\sin^2\theta_K + I_6^c(q^2)\cos^2\theta_K]\cos\theta_\ell \\ & + I_7(q^2)\sin 2\theta_K\sin\theta_\ell\sin\phi + I_8(q^2)\sin 2\theta_K\sin 2\theta_\ell\sin\phi \\ & + I_9(q^2)\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi, \qquad \text{e.g.} \quad P_5'(q^2) = \frac{I_5(q^2)}{2\sqrt{-I_2^c(q^2)I_2^s(q^2)}}\end{aligned}$$

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]:

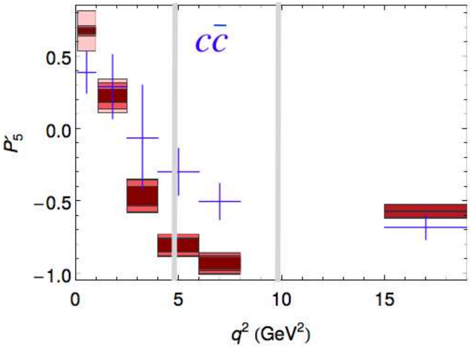
- Measured branching fractions $\mathcal{B}(B \to K\mu\mu)$, $\mathcal{B}(B \to K^*\mu\mu)$, $\mathcal{B}(B_s \to \phi\mu\mu)$ differ from Standard Model (SM)
- Several angular observables deviate from SM (esp. $\langle P_5' \rangle$)



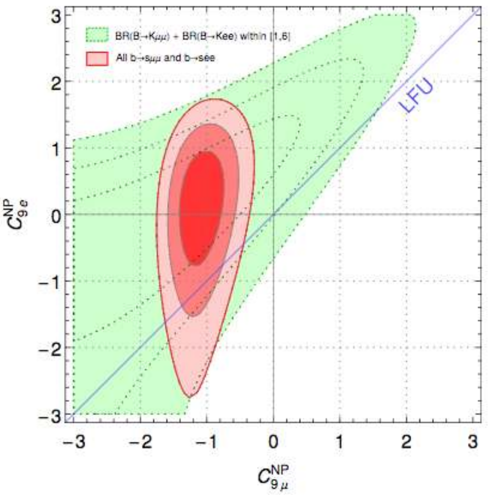
$c\bar{c}$ region sensitive to

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

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!



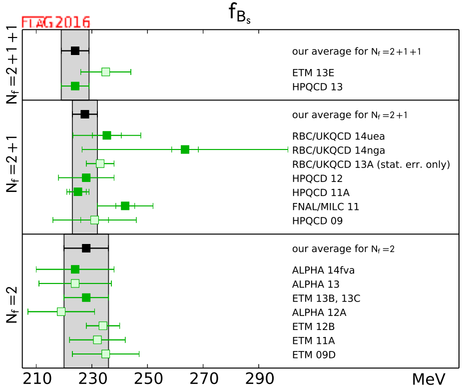
Global analyses suggest $C_9^\mu < 0$, $C_9^e \approx 0$



More convincing way to see deviations from SM

1. Use $f_{B_s}^{\text{latt.}}$ and $\mathcal{B}(B_s \to \mu\mu) = 3.0(6)\,\binom{3}{2} \times 10^{-9}$ [LHCb 2017]

$$\mathcal{B}(B_s \to \mu^+\mu^-) \propto |V_{tb}V_{ts}^*|^2\, f_{B_s}^2 m_\mu^2 \left[\left| C_{10} - C_{10}' + \frac{m_{B_s}^2 (C_P - C_P')}{2m_\mu(m_b+m_s)} \right|^2 + |C_S - C_S'|^2 \frac{m_{B_s}^2(m_{B_s}^2 - 4m_\mu^2)}{4m_\mu^2(m_b+m_s)^2} \right]$$

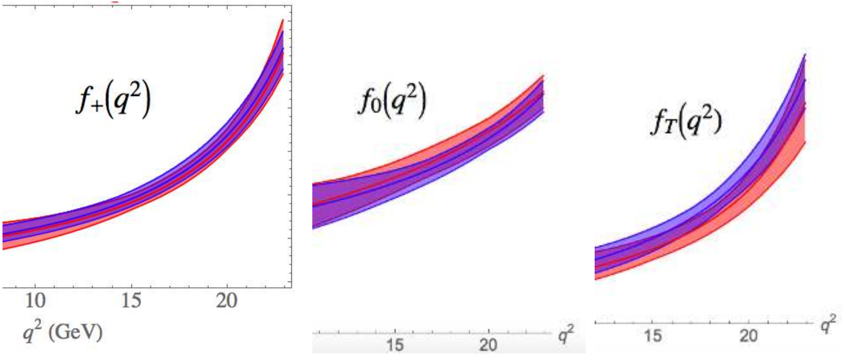


[FLAG 2016]

More convincing way...

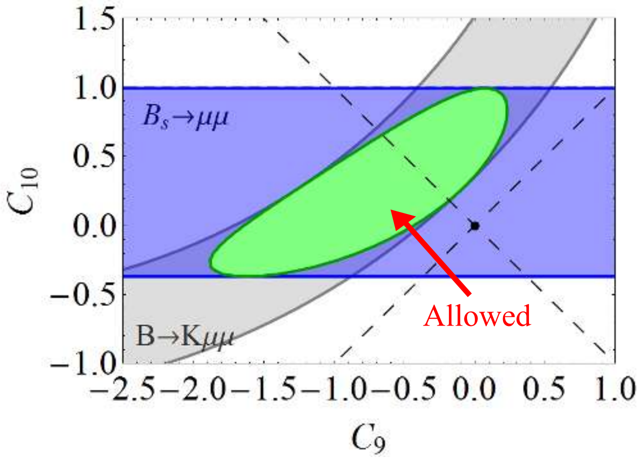
2. Use $f^{BK}_{+,0,T}(q^2)^{\text{latt.}}$ and $\mathcal{B}(B \to K\mu\mu)_{q^2\in[15,22]\text{GeV}^2} = 1.95(16) \times 10^{-7}$ [LHCb 2016]

$$\frac{\mathrm{d}}{\mathrm{d}q^2}\mathcal{B}(B \to K\ell^+\ell^-) = F\left(f_+(q^2), f_0(q^2), f_T(q^2), C_9 + C_9', C_{10} + C_{10}', C_{7,S,P} + C_{7,S,P}'\right)$$



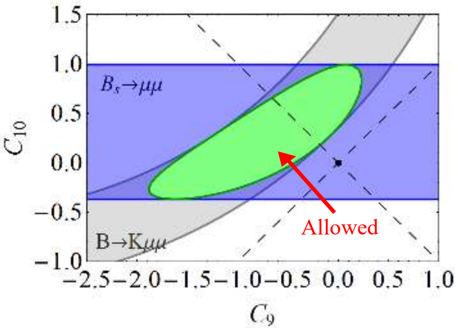
[HPQCD 2013], [Fermilab/MILC 2016]

1. & 2. ⇒ New Physics Wilson coefficients from data



[DB, Kosnik, Sumensari, Zukanovich 2016]

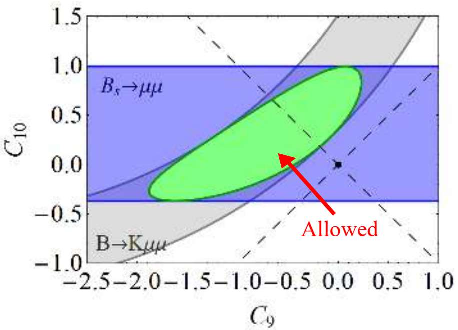
New Physics Wilson coefficients from data



$(C_9)_{\mu\mu} = -(C_{10})_{\mu\mu} \in (-0.76, -0.04)$

Predictions

- C. bin: $\mathbf{R_K^{pred} = 0.82(16)}$, $\mathbf{R_{K^*}^{pred} = 0.83(15)}$



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Predictions

- C. bin: $\mathbf{R_K^{pred} = 0.82(16)}$, $\mathbf{R_{K^*}^{pred} = 0.83(15)}$
- Choosing RH operators, $(C_9)'_{\mu\mu} = -(C_{10})'_{\mu\mu}$

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

[cf. Hiller, Schmaltz 2014]

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

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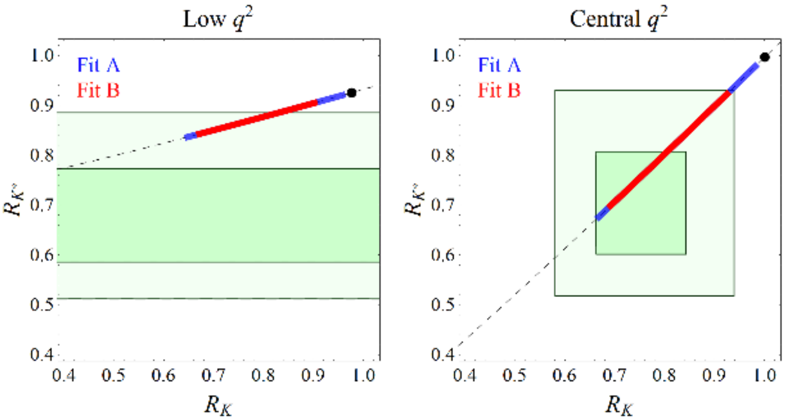

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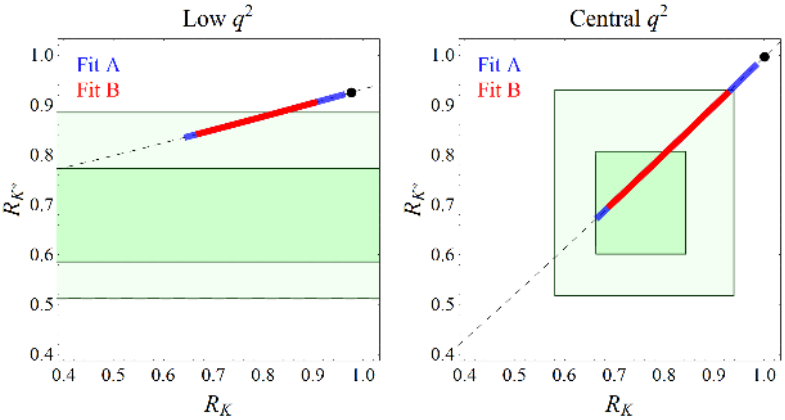


Predictions: $R_K^{\text{high}} \approx R_{K^*}^{\text{high}} = 0.82(20)$ or $0.79(12)$ for $q^2 \in [15, 19]$ GeV^2

$\Rightarrow$ to be tested at LHCb!

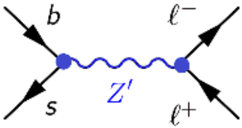
Specific models capable of generating $C_{9,10}$ to accommodate $R_{K^{(*)}}^{\text{exp}}$

– Z'-models
– Leptoquark models
– Heavy resonances (compositeness)
– Extra heavy scalar and fermions

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

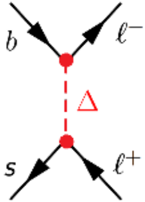
Representative (tree-level) models:

Z' models



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

Leptoquark models



Hiller et al., Dorsner et al., Gripaios et al. , Bhattacharya . . .

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

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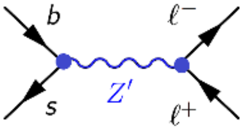

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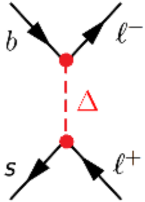


Hiller et al., Dorsner et al., Gripaios et al. , Bhattacharya . . .

- Vector leptoquark models also plausible, but non-renormalizable [loops?]

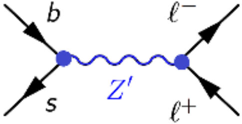
Barbieri et al., Fajfer et al.

- Interesting feature: **LFV** is in general **expected** [Glashow et al. 2014].

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

Representative (tree-level) models:

Z' models



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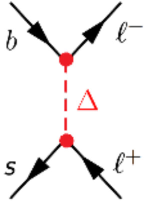
Leptoquark models



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

- Z': $U(1)'$ singlet, anomaly-free after gauging $U(1)_{\mu-\tau}$ [Crivellin et al 2015, Altmannshofer et al 2014/2016]
- $Z' \subset SU(2)'$ triplet [Alonso et al 2015, Bordone et al 2017]
- UV complete if $SU(2)' \times SU(2)" \times U(1)$; LFUV from mixing with VL fermions [Boucenna et al 2016]
- Need extended Higgs sector

Explaining R_K: Illustration

Scalar Leptoquark Models

$\Rightarrow$ Focus on NP with couplings to muons only

[couplings to ee also possible, cf. Hiller, Schmaltz 2014, Datta et al 2017...]

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

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

Explaining R_K: Illustration
Scalar Leptoquark Models

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$(\bar{3},1)_{4/3}$	✗	$\overline{d_R^C}\boldsymbol{\Delta}\ell_R$	$(C_9)' = (C_{10})'$	> 1	> 1
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$(3,2)_{1/6}$	✓	$\overline{d_R}\widetilde{\boldsymbol{\Delta}}^\dagger L$	$(C_9)' = -(C_{10})'$	< 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

$\Rightarrow$ **No fully viable tree level model**

N.B: Triplet may be useful if imposing extra symmetries to forbid proton decay.

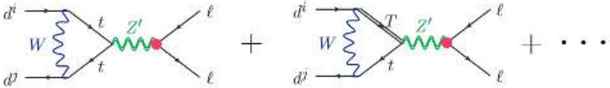
Many papers after the LHCb results on R_{K^*}

B. Capdevila et al [1704.05340], W. Altmannshofer et al [1704.05435], G. D'Amico et al [1704.05438], G. Hiller, I. Nisandzic [1704.05444], L. Geng et ali [1704.05446], M. Ciuchini et al [1704.05447], J. Kamenik et al [1704.06005], F. Sala, D. Straub [1704.06188], S. Di Chiara et al [1704.06200], D. Ghosh [1704.06240], S. Di Chiara et al [1704.06200], S. Di Chiara et al [1704.06200], Alok et al [1704.07397], J. Ellis et al [1705.03447], A. Datta et al [1705.08423], F. Feruglio et al [1705.09015], F. Bashara et al [1705.03465], R. Alonso et al [1705.03858], D. Bardhan et al [1705.09305], C.W. Chiang et al [1706.02696] . . .

Several new ideas

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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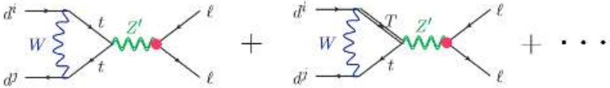
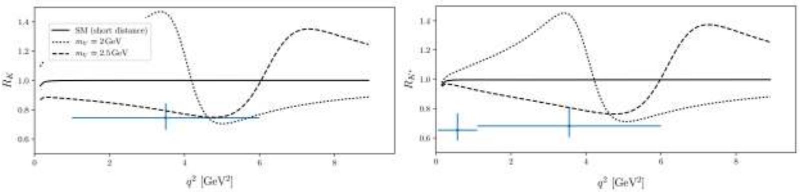


- A light resonance Z' decaying mostly to muons: $B \to K^{(*)}(V \to \mu\mu)$
  [A. Soni at Moriond '15, Sala, Straub. 1704.06188, see also Bashara et al (!)]



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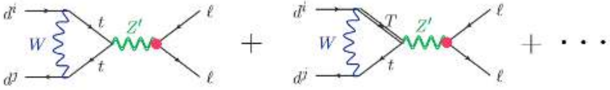

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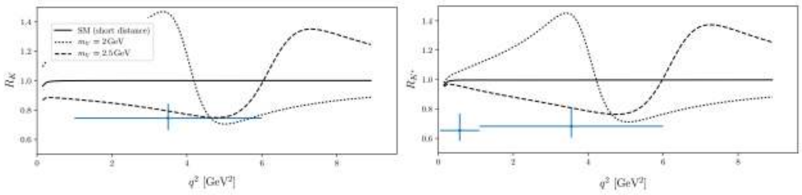

- Loop-level SLQ contributions (revival of idea by [Bauer, Neubert, 1511.01900])
  [DB, Sumensari. 1704.05835]

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

[DB, Sumensari. 1704.05835]

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

$$= (V g_R)_{ij}\,\bar{u}_i P_R \ell_j\, \Delta^{(5/3)} + (g_R)_{ij}\,\bar{d}_i P_R \ell_j\, \Delta^{(2/3)}$$

$$+ (U g_L)_{ij}\,\bar{u}_i P_L \nu_j\, \Delta^{(2/3)} - (g_L)_{ij}\,\bar{u}_i P_L \ell_j\, \Delta^{(5/3)} + \text{h.c.},$$

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

[DB, Sumensari. 1704.05835]

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

$$= (Vg_R)_{ij}\,\bar{u}_i P_R \ell_j\, \Delta^{(5/3)} + (g_R)_{ij}\,\bar{d}_i P_R \ell_j\, \Delta^{(2/3)}$$

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We take (see alternative in [Chauhan et al. 1706.04598]):

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

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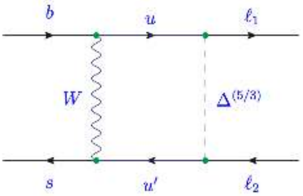
Only diagram induced at one-loop (unitary gauge):



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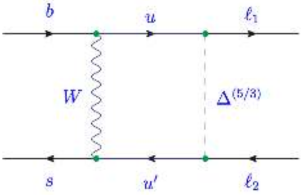

$$C_9 = -C_{10} = \sum_{u,u' \in \{u,c,t\}} \frac{V_{ub}\, V^*_{u's}}{V_{tb}\, V^*_{ts}} g_L^{u'\mu} \left(g_L^{u\mu}\right)^* \mathcal{F}(m_u, m_{u'})\,,$$

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

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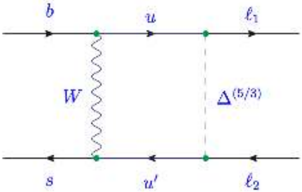

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- Charm contribution is non-negligible due to CKM enhancement V_{cs}/V_{ts}.

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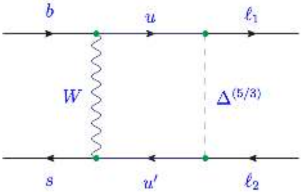

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To be compared with the $(\bar{3},1)_{1/3}$ model (with a similar flavor pattern in Bauer, Neubert, 2016):

$$C_9 = -C_{10} = \frac{m_t^2}{8\pi\alpha_{\rm em} m_\Delta^2} |(V^* g_L)_{t\mu}|^2 > \mathbf{0}$$

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

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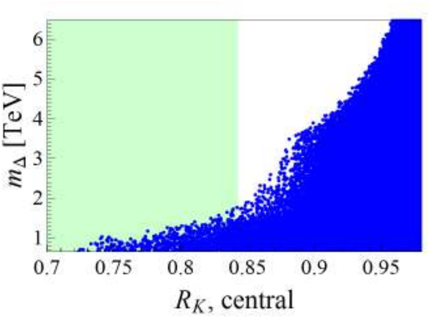
• We can **fully explain** the hints in $b \to s\ell\ell$ for $\boldsymbol{m_\Delta \lesssim 2}$ **TeV**:



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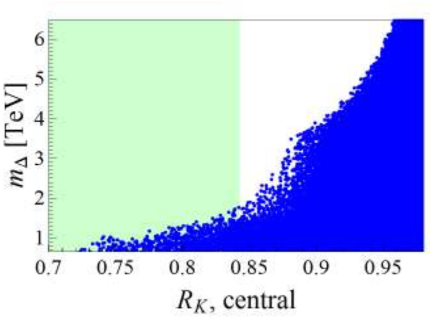


• Predictions to be tested at LHC and Belle-II: $\mathcal{B}(Z \to \mu\tau) \lesssim 10^{-6}$ and $\mathcal{B}(B \to K\mu\tau) \lesssim 10^{-8}$.

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

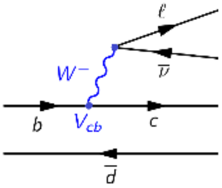
[DB, Sumensari, Zukanovich 2016]

Outline

LFU violation in $b \to c\tau\bar{\nu}$

- 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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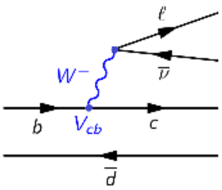

- Non-perturbative QCD $\Longleftrightarrow$ form-factors (Lattice QCD)

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

[FNAL/MILC 2015, HPQCD 2015 ($B_s \to D_s$ in 2017), Atoui et al 2013 ($B_s \to D_s$), RBC-UKQCD @ Latt2017 ($B_s \to D_s$)]

$\to$ Confirmation of $\approx 2\sigma$ deviation wrt $R_D^{\rm exp}$

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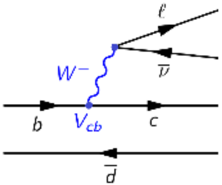

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- Situation less clear for $B \to D^*$ [more FFs, no $w \neq 1$ lattice results, 'scalar' FF $A_0(q^2)$ never computed in LQCD]

  $\mathcal{F}(1)$ in FNAL/MILC 2014, HPQCD 2016

New Physics in $b \to c\ell\bar{\nu}_\ell$: model independent approach

"Model independent" includes following assumptions:

- No right-handed neutrino; charged lepton current remains left handed.
- Keep $V - A$ structure of the lepton current: $L^\mu = \bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell$
- $b \to c\ell\bar{\nu}_\ell$ can then be described by a general effective Hamiltonian:

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cb} \big[(1 + g_V) \bar{c}\gamma_\mu b + (-1 + g_A) \bar{c}\gamma_\mu\gamma_5 b + g_S\, i\partial_\mu(\bar{c}b) + g_P\, i\partial_\mu(\bar{c}\gamma_5 b) + g_T\, i\partial_\nu(\bar{c}i\sigma_{\mu\nu} b) \big] \times L^\mu = \frac{G_F}{\sqrt{2}} V_{cb}\; H_\mu L^\mu$$

$$g_{V,A} \sim \mathcal{O}\left(\frac{v^2}{\Lambda_{\text{NP}}^2}\right), \quad g_{S,P,T,T5} \sim \frac{1}{v}\mathcal{O}\left(\frac{v^2}{\Lambda_{\text{NP}}^2}\right)$$

Full angular distribution can be made at Belle II to understand which/if-a NP operator matters.

New Physics in $b \to c\ell\bar{\nu}_\ell$: model independent approach

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v} H^+ \Big\{ \bar{u} \left[\zeta_d \, V m_d P_R - \zeta_u \, m_u \, V P_L \right] \, d + \zeta_\ell \, \bar{\nu} m_\ell P_R \ell \Big\} + \text{h.c.},$$

Model	ζ_d	ζ_u	ζ_ℓ
Type I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type II	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
Type X (lepton specific)	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type Z (flipped)	$-\tan\beta$	$\cot\beta$	$\cot\beta$

[Celis et al 2012 and 2017, De Fazio et al 2013, Ghosh 2015, Soni et al 2015, Li et al 2016. . .]

Only Type III 2HDM is viable to describe $b \to c$, $b \to u$ and similar TL decays of K and D [Crivellin et al]

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

No compelling solution so far [an illustration below]

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

[BD et al. 2015]

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

$$C_9' = -C_{10}' \propto \frac{Y_{\mu s} Y_{\mu b}^*}{m_\Delta^2}$$

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

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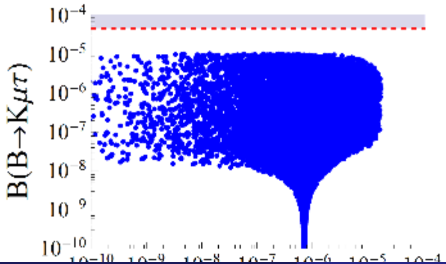
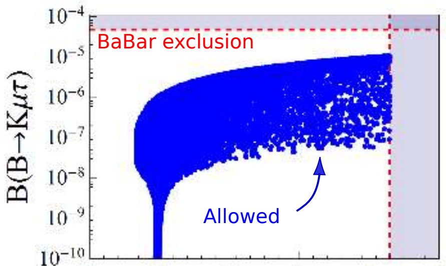
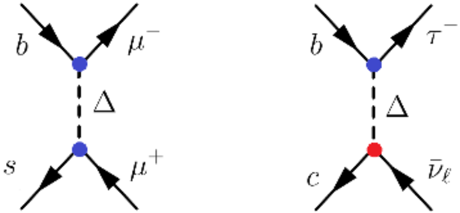
Prediction for LHCb and Belle-II: $\mathcal{B}(B^+ \to K^+ \mu\tau) \leq 4.8 \times 10^{-5}$





Can also explain R_D if to the model $\mathbf{\Delta^{1/6} = (3, 2)_{1/6}}$ we add light 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 $b \to c\tau\bar{\nu}$ $\Rightarrow$ $|\mathcal{M}(B \to D^{(*)}\ell\nu)|^2 = |\mathcal{M}_{\text{SM}}|^2 + |\mathcal{M}_{\text{NP}}|^2$.

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

Theory Challenge

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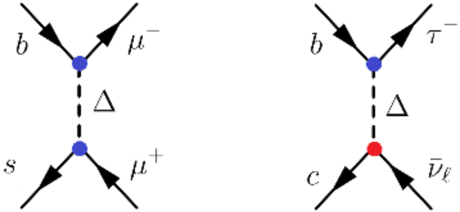

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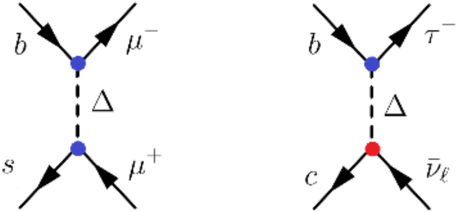

- Passes all flavor tests: $\mathcal{B}(B_s \to \mu^+\mu^-)$, $\mathcal{B}(B \to K\mu\mu)_{\text{high } q^2}$, Δm_{B_s}, $\mathcal{B}(B \to \tau\bar{\nu})$, $\mathcal{B}(D_s \to \tau\bar{\nu})$, $\mathcal{B}(B \to K\nu\bar{\nu})$, $\mathcal{B}(B \to K\mu\tau)$ etc.
- Many experimental signatures for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

Theory Challenge

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

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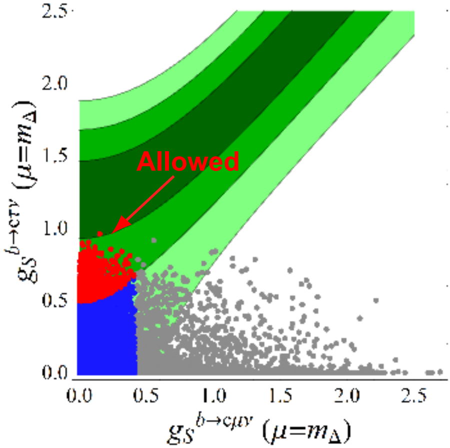


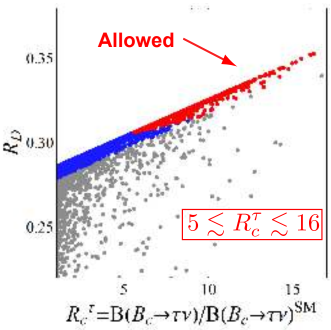
$B \to D$ form factors from LQCD. [FNAL/MILC, 2015]

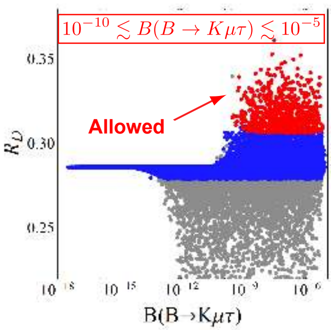
NB both modes get LQ contribution:

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

Theory Challenge

Several distinctive predictions wrt SM:





- **Enhancement** of $\mathcal{B}(B_c \to \tau\bar{\nu})$. Too large wrt τ_{B_c}?
  [Li et al 2016, Alonso et al 2016] [0.5em]
- $R_{\eta_c} \equiv \mathcal{B}(B_c \to \eta_c \tau\nu)/\mathcal{B}(B_c \to \eta_c \ell\nu)$ can be **20% larger** than $R_{\eta_c}^{\text{SM}}$.
  $B_c \to \eta_c$ and $B_c \to J/\psi$ FFs in [Lytle et al HPQCD, Latt2016 and Latt2017]

A little B-physics anomaly

Results of new Belle angular analysis of $\bar{B} \to D^* \ell \nu$ [1702.01521] allow to show that $|V_{cb}|^{\text{excl}}$ depends on parametrization of form factors.

$$\frac{d\Gamma(\bar{B} \to D^*(D\pi)\ell\nu)}{dw\, d\cos\theta_D\, d\cos\theta_\ell\, d\chi} \propto |V_{cb}|^2 \times f\Big(A_1(q^2), V(q^2), A_2(q^2), m_\ell A_0(q^2)\Big)$$
$$= |V_{cb}|^2 \widetilde{f}\Big(A_1(w), R_1(w), R_2(w), m_\ell R_0(w)\Big)_{w=\frac{m_B^2+m_{D*}^2-q^2}{2m_B m_{D*}}}$$

CLN [Caprini et al 1997]:

$$h_{A_1}(w) = h_{A_1}(1)\left[1 + 8\rho^2 z + (53\rho^2 - 15)z^2 - (231\rho^2 - 91)z^3\right]$$
$$R_1(w) = R_1(1) - 0.12(w-1) + 0.05(w-1)^2$$
$$R_2(w) = R_2(1) - 0.11(w-1) - 0.06(w-1)^2$$

$h_{A_1}(1)$ LQCD; Red numbers fixed by HQET and pheno.

BGL [Boyd et al 1997] do not do red step, otherwise parameterization is 'the same' expansion in $z = (\sqrt{w+1} - \sqrt{2})/(\sqrt{w+1} + \sqrt{2})$.

A little B-physics anomaly: Refit Belle distribution

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$R_2(1)$: fit $>$ HQET by more than 2σ Refit [D.Bigi et al 1703.06124, Grinstein, Kobach 1703.08170]

$$|V_{cb}|^{\rm excl}_{\rm CLN} = (38.2 \pm 1.5) \times 10^{-3} \qquad |V_{cb}|^{\rm excl}_{\rm BGL} = (41.7^{+2.0}_{-2.1}) \times 10^{-3}$$
$$|V_{cb}|^{\rm incl}_{1S} = (42.0 \pm 0.5) \times 10^{-3} \qquad |V_{cb}|^{\rm incl}_{\rm kin} = (42.2 \pm 0.8) \times 10^{-3}$$

Both fits (using CLN or BGL) are good $\Rightarrow$ Inconclusive!
Way out: $|V_{cb}|$ from LQCD & Belle II data at small recoil.
See also uncertainties about $m_\ell R_0(w)$

[Falk, Neubert 1992, Bernlochner et al 1703.05330]

Outline

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 (not all though!).
- Simultaneous explanation of $R_{K^{(*)}}$ and $R_{D^{(*)}}$ remains a theory challenge.
- Soon experiment: $R_{D_s^{(*)}}$, $R_{J/\psi}$, $R_{\Lambda_c^{(*)}}$ and ratios of coefficients of the angular distribution $b \to s\ell\ell$ and $b \to c\ell\nu_\ell$ (exclusives) - LHCb, Belle II
- Study other decay modes and keep in mind that:
  SHAPES OF FORM FACTORS ARE VERY IMPORTANT!
  Using other lattice methods is essential - sanity check...
  Badly need a lattice result for $A_0^{BD*}(q^2)$
  Any info about the $c\bar{c}$-contribution to $b \to s\ell\ell$ would be precious ...
- Higgs Flavor Era around the corner?