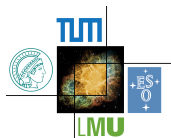


Family non-universal Z' models with protected flavour-changing interactions

Martin Jung

in collaboration with A. Celis, J. Fuentes-Martín and H. Serôdio
PRD92 (2015) 1, 015007 [arXiv:1505.03079]

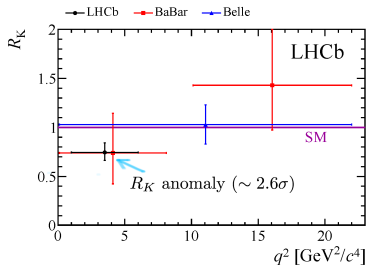
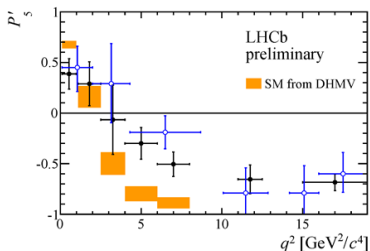


DFG Deutsche
Forschungsgemeinschaft

51st Rencontres de Moriond 2016
La Thuile, Italy
16th of March 2016

Have we seen NP in $b \rightarrow sll$?

The  anomalies [see also talks by J.Albrecht, L.Hofer, G.Hiller, N.Kosnik]



- Global fits necessary
[Descotes-Genon+, Beaujean+, Ghosh+, Altmannshofer+, Hurth+, Sinha+, Ciuchini+]
- QCD under control? [Camalich/Jäger'15, Lyon/Zwicky'14, Ciuchini+'15]
- Agreed: $C_9^\mu \sim -1$ improves fits

$$R_K = \frac{\text{BR}(B \rightarrow K \mu^+ \mu^-)}{\text{BR}(B \rightarrow K e^+ e^-)}$$

$$= 0.745^{+0.090}_{-0.074} \pm 0.036 \stackrel{!}{\approx} 1$$

[Hiller/Krüger, Bobeth+]

Here: data at face value

Some model building

We require:

1. Sizable contributions to $b \rightarrow sl^+l^-$
 - ➔ specifically to C_9 , i.e. vector coupling
2. Lepton non-universal couplings
3. Limited contributions to established constraints:
 - EW precision constraints
 - Unitarity triangle constraints
 - ...



➔ Z' models good candidates

[e.g. Altmannshofer+, Buras+, Crivellin+, Gauld+, Descotes-Genon+, Sierra+]

Alternatives: [e.g. Becirevic+, Bhattacharya+, Gripaios+, Hiller+, Niehoff+]

Wish list:

- Minimal particle content (no new fermions)
- Predictivity for up-, down-, lepton-FCNCs

Incarnations of $U(1)'$

Z' models have been popular for a long time [review e.g. Langacker'08]

Starting a new construction:

1. SM particle content: $L_\alpha - L_\beta$ only option [2×He+'91]

➡ No coupling to quarks, mostly used
in ν sector $\rightarrow L_\mu - L_\tau$

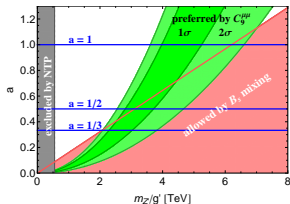
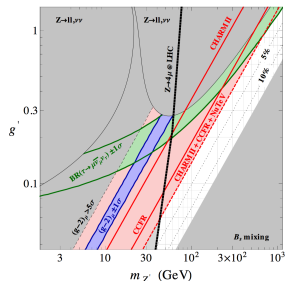
2. Adding vector-like quarks (+scalars) \rightarrow
effective $Z' \bar{q} q'$ -coupling [Altmannshofer+'14]

➡ LHCb anomalies ✓, independent $C_9^{\mu(l)}$
➡ no $Z' ee$ -coupling \rightarrow avoid LEP bounds
➡ $\Delta m_s \rightarrow u, d$ couplings small

3. Gauging $L_\mu - L_\tau - a(B_1 + B_2 - 2B_3)$

\rightarrow new scalars suffice [Crivellin+'15]

➡ LHCb anomalies ✓, $|C_9^\mu| \gg |C_9^{\mu l}|$
➡ L and B separately anomaly-free
➡ down-FCNCs approximately $\sim V_{ti} V_{tj}^*$
➡ arbitrary up-FCNCs




Flavour violation in 2HDMs


Generic 2HDMs: huge flavour violation
 ➡ solution to this a main characteristic


Option 1: Avoid tree-level FCNCs \rightarrow NFC, MFV, Alignment, ...


Option 2: Allow for controlled FCNCs

- Cheng-Sher ansatz/Type III \rightarrow little predictivity
- **Branco-Grimus-Lavoura (BGL) models** [BGL'96]
 - Use flavour symmetry to relate **all** flavour-change to CKM
 ➡ Unique pattern in 2HDMs! [Ferreira/Silva'11, Serôdio'13]
 - Choice: top quark only couples to $\phi_2 \rightarrow$ FCNCs in down-sector

Up Yukawas: $\Delta_1^{\text{BGL}} =$ 

$\Delta_2^{\text{BGL}} =$ 

Down Yukawas: $\Gamma_1^{\text{BGL}} =$ 

$\Gamma_2^{\text{BGL}} =$ 

Gauging BGL models

- BGL via discrete symmetries yields accidental $U(1)$
- Scalars disfavoured as solution for $b \rightarrow s$ anomalies
- ➔ Idea: Gauge BGL models! [[Celis/Fuentes-Martín/MJ/Serôdio](#)]

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Require $U(1)_{\text{BGL}}$ to be anomaly-free: **5 non-linear conditions**

- Automatic in the $SU(3)_C$ sector [Celis+'14]
- **Not possible** using only the SM quark sector
- ➡ Include lepton sector

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Most general charges: arbitrary $X_{\ell L,R}$ with $\ell = e, \mu, \tau$

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- ➔ 1 physical free charge $\rightarrow X_{\phi_2} \equiv 0$, 6 permutations

Patterns in quark sector **imply** (independent of charge choice):

1. Lepton-flavour non-universality
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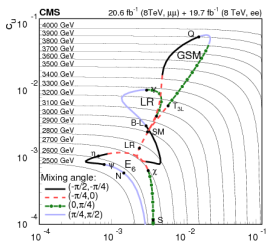
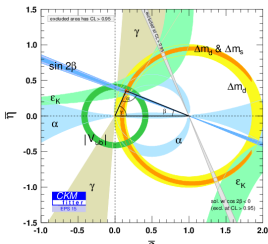
$U(1)'_{\text{BGL}}$ – Overview

**ATTENTION:
ADVERTISEMENT**

Features of the $U(1)'_{\text{BGL}}$ model:

- Controlled tree-level down-FCNCs, determined by CKM
 - left-handed, $C_{9,10}^{e,\mu}$, $|C_{10}^{\ell}| < (\ll) |C_9^{\ell}|$
- No FCNCs in the up-quark sector
- Symmetry yields lepton-flavour non-universality without lepton-flavour violation
- Higgs sector phenomenologically viable, no large effects
- Z' extremely predictive: 2 parameters (plus one charge)

Let's check the available constraints. . .



Phenomenological consequences - Generalities

What can we say without a detailed analysis?

- Strong direct limits \Rightarrow potential Z' is very heavy
 $M_W^2/M_{Z'}^2 \lesssim 0.1\%$
- Most observables are **unaffected!**
- Effects only for SM suppression *in addition to* $G_F + CKM$
 EW penguin decays, mixing, CP violation, leptonic decays, ...
- Z' gives the dominant NP effect almost everywhere

A bit more detail:

- UT analysis basically unaffected (exceptions ϵ_K and $\Delta m_{d,s}$,
 but $\Delta m_d/\Delta m_s = \Delta m_d/\Delta m_s|_{SM}$)
- $\Delta m_d, \Delta m_s, \epsilon_K$ give similar bounds.

From Δm_s : $M_{Z'}/g' \geq 16 \text{ TeV}$ (95% CL)

Improvement here just depends on LQCD!

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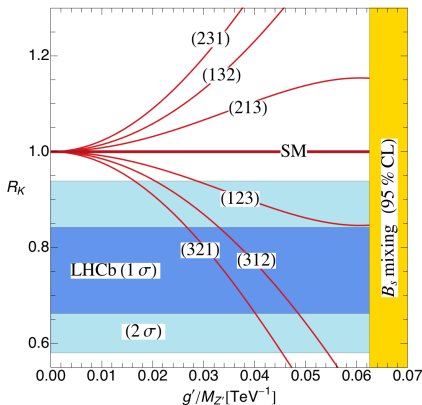
From Δm_s : $M_{Z'}/g' \geq 25 \text{ TeV}$ (95% CL)

Improvement here **thanks to** LQCD! [Bazazov+'16]

R_K and its sisters

$$R_M^q \equiv \frac{\text{Br}(B_q \rightarrow \bar{M}\mu^+\mu^-)}{\text{Br}(B_q \rightarrow \bar{M}e^+e^-)} \quad M \in \{K, K^*, X_s, \phi, \dots\}, \quad q = u, d, s$$

Note: $R(X_s) = 0.42 \pm 0.25$ (Belle) 0.58 ± 0.19 (BaBar)
(but not a consistent picture [cf. Hiller/Schmaltz'15])



Model	$C_9^{\text{NP}\mu}(1\sigma)$	$C_9^{\text{NP}\mu}(2\sigma)$
(1,2,3)	–	$[-2.92, -0.61]$
(3,1,2)	$[-0.93, -0.43]$	$[-1.16, -0.17]$
(3,2,1)	$[-1.20, -0.53]$	$[-1.54, -0.20]$

Fits $B \rightarrow K^* \mu^+ \mu^-$ ✓

Furthermore:

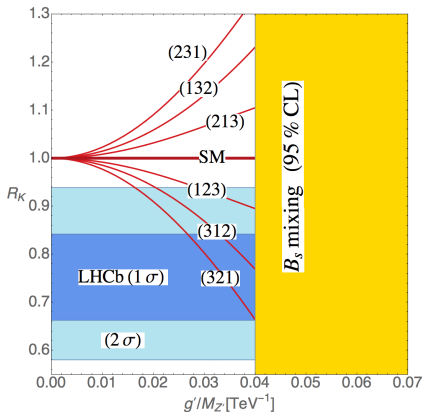
$$\hat{R}_M \equiv \frac{R_M}{R_K} = 1$$

➔ “Easily” verifiable for any charge assignment

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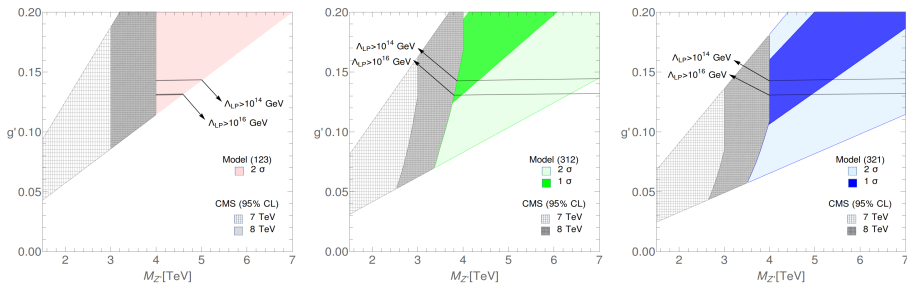
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Combination with direct searches and perturbativity

Obvious way to search for Z' : $\sigma(pp \rightarrow Z'(\rightarrow f\bar{f})X)$

Strong semi-model-independent limits from ATLAS and CMS:

[Carena+'04,Accomando+'11,ATLAS'12,'14,CMS'12,'15]



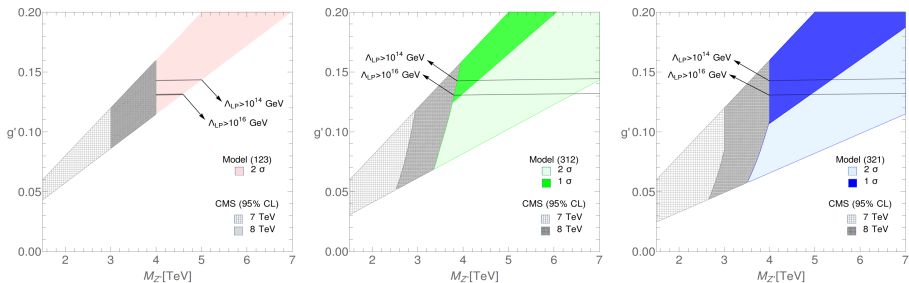
- 2.5 models survive all constraints, $M_{Z'} \geq 3 - 4$ TeV
- Strong upper bound on one model from perturbativity
- Differentiable from each other and different models:
 - (i) Flavour (LNU vs. FCNC)
 - (ii) $\mu_{ff'} = \sigma(Z' \rightarrow f\bar{f})/\sigma(Z' \rightarrow f'\bar{f}')$

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Further constraints

We also considered the following observables:

- Neutrino trident production
- Atomic parity violation
- EDMs (cancellations in the Higgs sector [MJ/Pich'14])
- $g - 2$

All of these are weaker than the ones discussed earlier

Model predicts change in $B_{d,s} \rightarrow \mu\mu$ central values:

[see talks by S.Palestini + S.Swain]

$$\frac{\text{BR}(B_s \rightarrow \mu^+ \mu^-)}{\text{BR}(B_s \rightarrow \mu^+ \mu^-)|_{\text{SM}}} = \frac{\text{BR}(B_d \rightarrow \mu^+ \mu^-)}{\text{BR}(B_d \rightarrow \mu^+ \mu^-)|_{\text{SM}}}$$

👉 wait for additional data, value uncorrelated with Z' observables

Conclusions

$LHCb$ anomalies persist:

- Require large C_9^{NP} , non-universal couplings
- Z' models possible explanations
- ➔ Interplay of flavour-observables and direct searches

$U(1)'_{BGL}$ viable, predictive model:

- Starting point: 2HDM solving FCNC problem
- ➔ No FCNCs for up-quarks
- ➔ Controlled FCNCs on tree-level for down-quarks
- ➔ All flavour-changing interactions determined by CKM
- Gauging symmetry yields LNU, but no LFV
- Z' sector depends only on $g'/M_{Z'}$ and $M_{Z'}$
- ➔ Will be further tested soon

Thank you!



Scalar sector of the $U(1)'_{\text{BGL}}$ model

Higgs sector has 2 doublets Φ_i and 1 complex singlet S :

- vev for S (v_S) yields $U(1)'$ breaking
 - ➡ $v_S/v \gg 1 \Rightarrow$ characterizes scalar sector
- Parameters: 10 dof \Rightarrow 6 scalars, 4 massive Goldstone bosons
- Spectrum: $H_{1,2,3}, H^\pm, A, M_{H_1} \sim v, M_{H^\pm, H_{2,3}, A} \sim v_S$
- Potential CP-invariant because of $U(1)'$
- Spontaneous CP violation is also absent
- H_3 couplings additionally suppressed by v/v_S

Phenomenology:

- BGL structure in 2HDMs viable for $M \sim \text{few} \times 100 \text{ GeV}$
[Botella+'14, Batthacharya+'14]
- Here scalars mostly decoupling \Rightarrow Higgs measurements fine
- Basically one constraint from flavour: $B_{d,s} \rightarrow \mu^+ \mu^-$
 - ➡ Uncorrelated to Z' constraints

Gauging BGL models - including leptons

Most general charges: arbitrary $X_{\ell L,R}$ with $\ell = e, \mu, \tau$

Anomaly conditions from 5 combinations:

- Linear: $U(1)'[SU(2)_L]^2$, $U(1)'[U(1)_Y]^2$, $U(1)'[(\text{gravity})]^2$
- Quadratic: $[U(1)']^2 U(1)_Y$
- Cubic: $[U(1)']^3$
- ➡ Highly non-trivial system to solve, only **one** class of solutions!
- ➡ Involves one free charge (physical choice) with 6 permutations
- ➡ Here: $X_{\phi_2} \equiv 0 \Rightarrow Z - Z'$ mixing suppressed ($\tan \beta \gg 1$)

Patterns in quark sector **imply** (independent of charge choice):

1. Lepton-flavour non-universality
2. Lepton-flavour conservation

Anomaly-free top-BGL implementation [Slide from J. Fuentes-Martín]

$$\psi^0 \rightarrow e^{i\mathcal{X}^\psi} \psi^0$$

Only one class of models (with X_{Φ_2} and X_{dR} free parameters)

$$\mathcal{X}_L^q = \text{diag} \left(-\frac{5}{4}, -\frac{5}{4}, 1 \right) \quad \mathcal{X}_R^u = \text{diag} \left(-\frac{7}{2}, -\frac{7}{2}, 1 \right)$$

$$\mathcal{X}_R^d = \mathbb{1}$$

$$\mathcal{X}_L^\ell = \text{diag} \left(\frac{9}{4}, \frac{21}{4}, -3 \right) \quad \mathcal{X}_R^e = \text{diag} \left(\frac{9}{2}, \frac{15}{2}, -3 \right)$$

$$\mathcal{X}^\Phi = \text{diag} \left(-\frac{9}{4}, 0 \right)$$

- $X_{dR} = 1$, unphysical normalization. But it also normalizes g' !
- $X_{\Phi_2} = 0$ to avoid large $Z - Z'$ mass mixing (for large t_β)
- Six possible model variations $(e, \mu, \tau) = (i, j, k)$

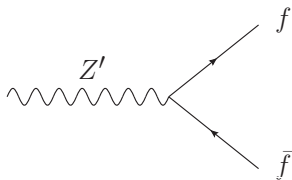
Z' couplings of the $U(1)'_{\text{BGL}}$ model

Mass eigenbasis:

- Couplings to u_L, u_R, d_R : diagonal and 2-family universal (1,2)
- Couplings to ℓ_L, e_R : diagonal and family-non-universal
- Couplings to d_L :

$$\tilde{\chi}_L^d = -\frac{5}{4}\mathbb{1} + \frac{9}{4} \begin{pmatrix} |V_{td}|^2 & V_{ts}V_{td}^* & V_{tb}V_{td}^* \\ V_{td}V_{ts}^* & |V_{ts}|^2 & V_{tb}V_{ts}^* \\ V_{td}V_{tb}^* & V_{ts}V_{tb}^* & |V_{tb}|^2 \end{pmatrix}$$

Controlled Z' -mediated FCNCs:



$$= g' \gamma^\mu \left(\tilde{\chi}_L^f P_L + \tilde{\chi}_R^f P_R \right)$$

Details on direct searches

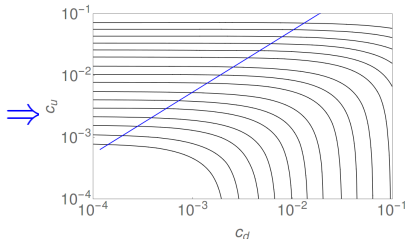
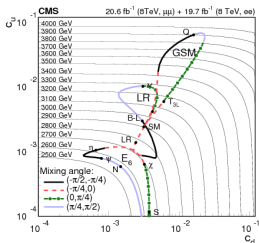
Approximation for NWA, negligible SM interference and flavour-universal quark couplings:

$$\sigma = \frac{\pi}{48s} \left[c_u^f w_u(s, M_{Z'}^2) + c_d^f w_d(s, M_{Z'}^2) \right]$$

$$c_{u,d}^f \simeq g'^2 \left(X_{qL}^2 + X_{(u,d)R}^2 \right) \text{Br}(Z' \rightarrow f\bar{f})$$

Applicable for $g' \leq 0.2$!

➡ First two generations dominate and couple universally
 CMS model-independent bounds: [CMS-EXO-12-061]



Correlations among the effective operators $\mathcal{O}_{9,10}^\ell$

Model	$C_{10}^{\text{NP}\mu} / C_9^{\text{NP}\mu}$	$C_9^{\text{NP}e} / C_9^{\text{NP}\mu}$	$C_{10}^{\text{NP}e} / C_9^{\text{NP}\mu}$
(1,2,3)	3/17	9/17	3/17
(1,3,2)	0	-9/8	-3/8
(2,1,3)	1/3	17/9	1/3
(2,3,1)	0	-17/8	-3/8
(3,1,2)	1/3	-8/9	0
(3,2,1)	3/17	-8/17	0