

Flavored Z' models with protected flavor-changing interactions



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Based on: [Phys. Rev. D 92, 015007 \(2015\) \[arXiv:1505.03079\]](#)

In collaboration with: Alejandro Celis, Martin Jung and Hugo Serôdio

Motivation: $b \rightarrow s$ anomalies

(See talks by Gaia Lanfranchi & Zoltan Ligeti)

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

$$R_K^{\text{LHCb}} \Big|_{[1,6]} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

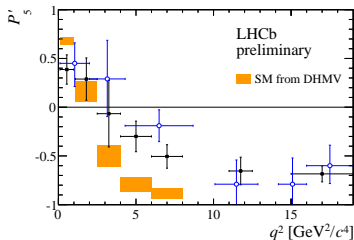
[LHCb Collaboration, '14]

$$R_K^{\text{SM}} = 1 + \mathcal{O}(m_\mu^2/m_b^2)$$

[Hiller, Krüger, '03]

2.6 σ discrepancy with the SM

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



[LHCb-CONF-2015-002]

2.9 σ discrepancy with the SM



anomalies

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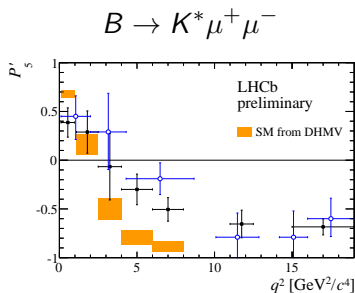
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SM hadronic effects?

anomalies

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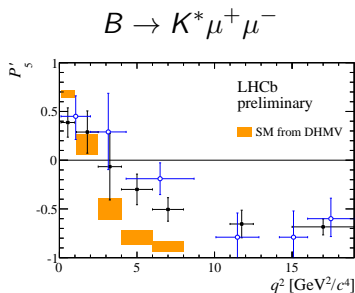
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NP hint?



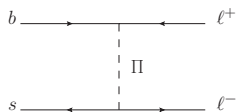
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Motivation: explanations to the $b \rightarrow s$ anomalies

Model independent analyses

Altmannshofer, Straub, Paradisi '11; Bobeth, Hiller, van Dyk, Wacker '11; Altmannshofer, Straub '13/'14; Beaujean, Bobeth, van Dyk, Wacker '12; Descotes-Genon, Matias, Virto '13/'14; Beaujean, Bobeth, van Dyk '13; Hurth, Mahmoudi '13; Ghosh, Nardecchia, Renner '14; Hurth, Mahmoudi, Neshatpour '14; Jäger, Martin Camalich '14...

Leptoquark models

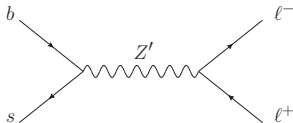


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Composite Higgs models

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Z' models



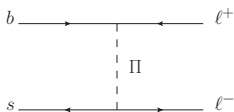
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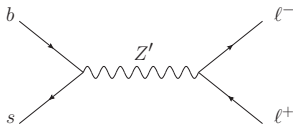


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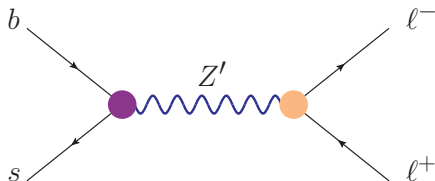
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Z' model building

$$G \equiv SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes \underline{U(1)'}$$



Flavor violating couplings to quarks

Lepton-flavor universality violation

- Often necessary:
 - ▶ Two Higgs doublets to accommodate quark masses and mixing angles
 - ▶ A scalar SM singlet to give mass to the Z'
- **Wish list:**
 - ▶ Minimal particle content (i.e. SM fermions only)
 - ▶ Flavor-violating couplings exactly related to CKM matrix elements

Branco–Grimus–Lavoura 2HDM (BGL)

$$-\mathcal{L}_Y = \overline{Q}_L^0 \left[\Gamma_1^{\text{BGL}} \Phi_1 + \Gamma_2^{\text{BGL}} \Phi_2 \right] d_R^0 + \overline{Q}_L^0 \left[\Delta_1^{\text{BGL}} \tilde{\Phi}_1 + \Delta_2^{\text{BGL}} \tilde{\Phi}_2 \right] u_R^0 + \text{h.c.}$$

$$\text{Up Yukawas: } \Delta_1^{\text{BGL}} = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \Delta_2^{\text{BGL}} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}$$

$$\text{Down Yukawas: } \Gamma_1^{\text{BGL}} = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ 0 & 0 & 0 \end{pmatrix} \quad \Gamma_2^{\text{BGL}} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix}$$

- Yukawa textures imposed by a **global symmetry** [Branco, Grimus, Lavoura '96]
- FCNCs only in the down-quark sector:

$$H \overline{d}_i d_j \propto V_{3i}^* V_{3j} m_{d_j} \quad (V \equiv \text{CKM matrix})$$

- Unique implementation in 2HDM [Ferreira, Silva '11; Serôdio '13]

The model: gauging $U(1)_{\text{BGL}}$

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_{\text{BGL}}$$

$$v_S \gg v \quad \downarrow \quad M_{Z'} \simeq g' v_S |X_S|$$

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

$$v \quad \downarrow$$

$$SU(3)_c \otimes U(1)_{\text{em}}$$

Matter content

- ▶ SM fermions
- ▶ Two Higgs doublets
- ▶ Scalar SM singlet (S)

Symmetry constraints

- Controlled Z' -mediated FCNCs
- $U(1)_{\text{BGL}}$ is chiral \Rightarrow All charges fixed by anomaly cancellation conditions:
 - ▶ Only two free parameters for Z' observables: g' , $M_{Z'}$
 - ▶ Extension to the lepton sector completely determined

Charged-lepton Yukawas in the gauged $U(1)_{BGL}$

$$-\mathcal{L}_{\text{Yuk}}^{\text{c-leptons}} = \bar{\ell}_L \Pi_i \Phi_i e_R + \text{h.c.}$$

with

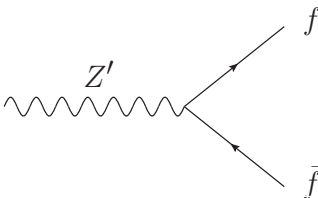
$$\Pi_1 = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \Pi_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}$$

- Non-universal lepton charges...
- But no FCNCs in the charged lepton sector
⇒ This is a counterexample to the general arguments given by Glashow, Guadagnoli, Lane '14

[Bhattacharya *et al.* '14; Boucenna, Valle, Vicente '15]

- **Six model variations**, related to permutations in the lepton sector

Gauged $U(1)_{\text{BGL}}$: Z' couplings



$$= g' \gamma^\mu \left(\Delta_L^f P_L + \Delta_R^f P_R \right)$$

Z' couplings **completely determined** by anomaly cancellation conditions:

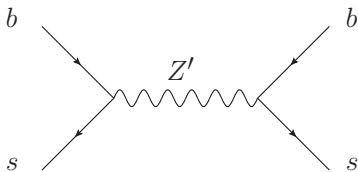
- No FCNCs in the up-quark and charge-lepton sectors
- Non-universal lepton couplings
- Controlled FCNCs for left-handed down-type quarks only

$$\Delta_L^d = \frac{9}{4} \begin{pmatrix} |V_{td}|^2 - \frac{5}{9} & V_{ts} V_{td}^* & V_{tb} V_{td}^* \\ V_{td} V_{ts}^* & |V_{ts}|^2 - \frac{5}{9} & V_{tb} V_{ts}^* \\ V_{td} V_{tb}^* & V_{ts} V_{tb}^* & |V_{tb}|^2 - \frac{5}{9} \end{pmatrix}$$

Experimental constraints?

Low-energy constraints

$B_s - \bar{B}_s$ mixing



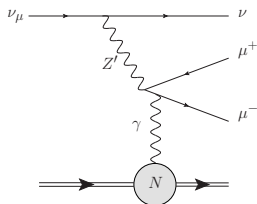
- Up to 20% corrections to Δm_s possible at 95% CL

[FLAG '14; CKMfitter Collaboration '14]

$$\mathbf{B_s \text{ mixing: } M_{Z'}/g' \gtrsim 16 \text{ TeV (95\% CL)}}$$

- Atomic Parity Violation, EDMs, anomalous magnetic moments...

Neutrino trident production



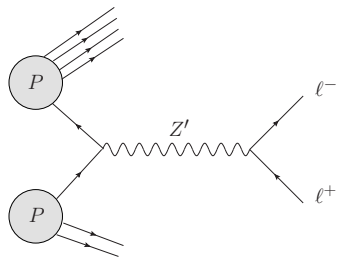
- Vector current dominates

[Altmannshofer, Gori, Pospelov, Yavin '14]

[CHARM-II '90, CCFR '91, NuTeV '00]

Collider constraints: LHC and LEP

Direct searches

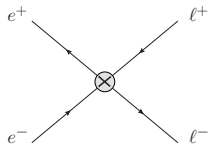


CMS model independent analysis based on the narrow width approximation

$$M_{Z'} \gtrsim 3 - 4 \text{ TeV} \quad (95\% \text{ CL})$$

[CMS-EXO-12-061]

LEP contact interactions



Single operator analysis

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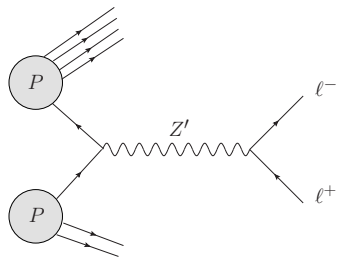
[CERN-PH-EP-2013-022]

Collider flavor ratios

$$\mu_{e/e'} \equiv \frac{\sigma(pp \rightarrow Z' \rightarrow \ell\bar{\ell})}{\sigma(pp \rightarrow Z' \rightarrow \ell'\bar{\ell}')}$$

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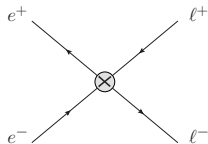


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Precise correlations in our model!

What about the $b \rightarrow sl^+l^-$ anomalies?

Effective Hamiltonian for $b \rightarrow sl^+l^-$

$$\mathcal{H}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} \frac{\alpha}{\pi} V_{tb} V_{ts}^* \sum_i \left(C_i^\ell \mathcal{O}_i^\ell + C_i^{\prime\ell} \mathcal{O}_i^{\prime\ell} \right)$$

where

$$Z' \begin{cases} \mathcal{O}_9^\ell = (\bar{s}\gamma_\mu P_L b) (\bar{l}\gamma^\mu l) & \mathcal{O}'_9 = (\bar{s}\gamma_\mu P_R b) (\bar{l}\gamma^\mu l) \\ \mathcal{O}_{10}^\ell = (\bar{s}\gamma_\mu P_L b) (\bar{l}\gamma^\mu \gamma_5 l) & \mathcal{O}'_{10} = (\bar{s}\gamma_\mu P_R b) (\bar{l}\gamma^\mu \gamma_5 l) \end{cases}$$

$$\text{Higgs} \begin{cases} \mathcal{O}'_S = m_b (\bar{s} P_R b) (\bar{l} l) & \mathcal{O}_S = m_b (\bar{s} P_L b) (\bar{l} l) \\ \mathcal{O}'_P = m_b (\bar{s} P_R b) (\bar{l} \gamma_5 l) & \mathcal{O}_P = m_b (\bar{s} P_L b) (\bar{l} \gamma_5 l) \end{cases}$$

- $\Delta_R^{bs} = 0 \Rightarrow C_{9,10}^{\prime\ell} \simeq 0$
- Z' -mediated Wilson coefficients, $C_{9,10}^\ell$, are **correlated** in our models
- C'_S and C'_P suppressed by m_s/m_b

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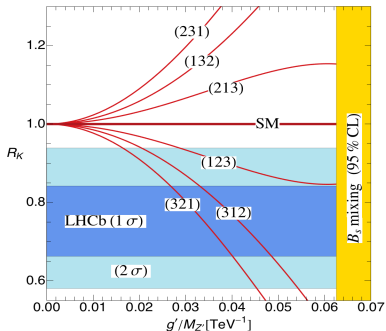
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Z' contributions: ratios and double ratios

- $R_M \equiv \frac{\text{Br}(\bar{B} \rightarrow \bar{M}\mu^+\mu^-)}{\text{Br}(\bar{B} \rightarrow \bar{M}e^+e^-)}$

$$M \in \{K, K^*, X_s, K_0(1430), \dots\}$$



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)	$[-1.20, -0.53]$	$[-1.54, -0.20]$

Good fit for $B \rightarrow K^*\mu^+\mu^-$ ✓

- In our models $\hat{R}_M \equiv \frac{R_M}{R_K} = 1$

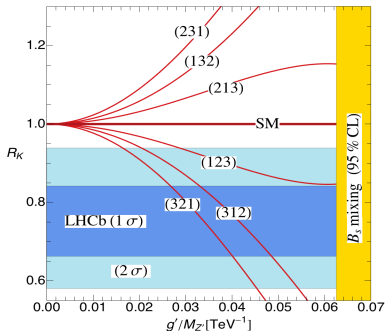
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[Hiller, Schmaltz '15]

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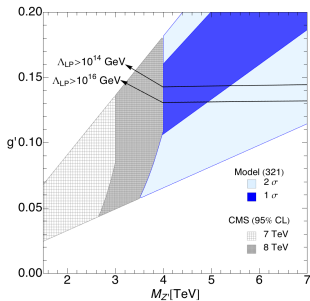
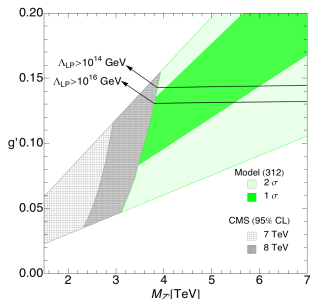
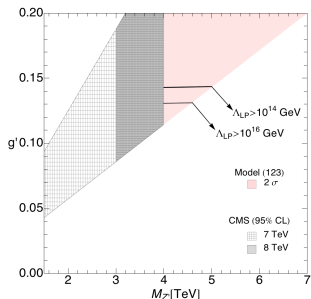
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[Hiller, Schmaltz '15]

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Smoking gun test of the model!

LHC limits on the Z' and perturbativity bounds



Conclusions

A class of minimal Z' models with the following features:

- All the Z' observables determined by only **two parameters**
 - FCNCs only present in the down quark sector and controlled (i.e. of the **Minimal Flavor Violating** type)
 - Non-universal lepton couplings **without charged lepton flavor violation**
 - ▶ **In progress:** this persists even after adding right-handed neutrinos or triplets
- ✓ Three out of six model variations are able to accommodate the $b \rightarrow s \ell^+ \ell^-$ LHCb anomalies
- ✓ Characteristic predictions to discriminate from other models:
- ▶ Equal $B \rightarrow M \ell^+ \ell^-$ ratios: $R_K = R_{K^*} = R_{X_s} = \dots$
 - ▶ Precise values for the $\mu_{e/\mu}$ and $\mu_{e/\tau}$ collider ratios for each model
 - ▶ Charged Lepton flavor conservation

Conclusions

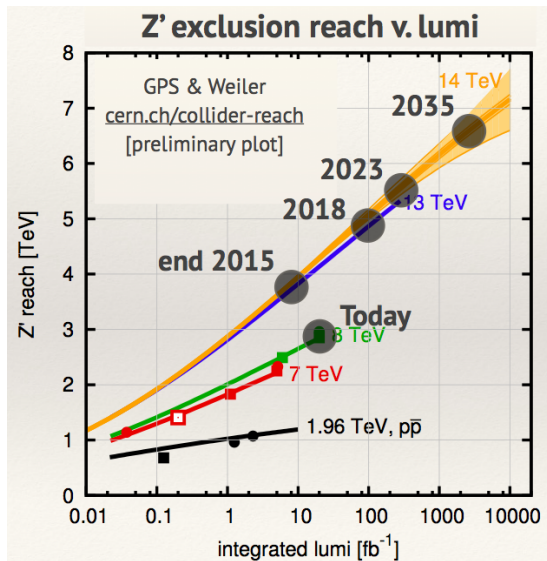
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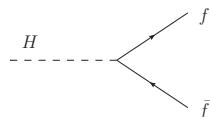
Thank you for listening!

Backup

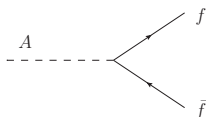
Z' collider prospects



Scalar sector in the top-BGL model

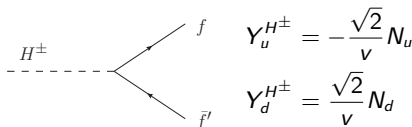


$$Y_f^H = -\frac{N_f}{v}$$



$$Y_u^A = i\frac{N_u}{v}$$

$$Y_d^A = -i\frac{N_d}{v}$$



$$Y_u^{H^\pm} = -\frac{\sqrt{2}}{v} N_u$$

$$Y_d^{H^\pm} = \frac{\sqrt{2}}{v} N_d$$

$$(N_d)_{ij} = \frac{v_2}{v_1} \text{diag}(m_d, m_s, m_b)_{ij} - \left(\frac{v_2}{v_1} + \frac{v_1}{v_2} \right) (V_{CKM}^\dagger)_{i3} (V_{CKM})_{3j} \text{diag}(m_d, m_s, m_b)_{jj}$$

$$N_u = \frac{v_2}{v_1} \text{diag}(m_u, m_c, 0) - \frac{v_1}{v_2} \text{diag}(0, 0, m_t)$$

- We have a **decoupling regime**, $\bar{M}_H \equiv M_H \simeq M_A \simeq M_{H^\pm} \sim \mathcal{O}(\text{TeV})$ (unless Poincaré protection is invoked) [Foot, Kobakhidze, McDonald, Volkas '14]
- S^0 couplings to fermions suppressed, $Y_f^{S^0} \simeq \mathcal{O}(v/v_S)$, and $M_{S^0} \sim \mathcal{O}(\text{TeV})$

Z' charges in the gauged $U(1)_{\text{BGL}}$

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

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

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

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

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

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

- $X_{dR} = 1$, 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' mass and Z – Z' mixing

A scalar SM singlet, S , gives mass to the Z' through the Higgs mechanism ($|\langle S \rangle| = v_s = \mathcal{O}(\text{TeV})$)

$$\mathcal{L}_{Z'} \supset Z'_{\mu\nu} Z'^{\mu\nu} + |D_\mu S|^2 + V(S)$$

Kinetic mixing

Two abelian groups in the model

$$\frac{S_\chi}{2} Z'_{\mu\nu} B^{\mu\nu}$$

- $\chi \neq 0$

[Babu, Kolda, March-Russell '97]

- $\chi = 0$

1. Gauge unification
2. Negligible running

Mass mixing

$$\Delta(v_1, v_2) Z'_{\mu\nu} Z'^{\mu\nu} \Rightarrow \xi \propto \Delta$$

For $X_{\Phi_2} = 0$, Δ only depends on v_1

$$g' \xi \simeq -\frac{9e}{8c_W s_W} \left(\frac{g' v_1}{M_{Z'}} \right)^2$$

so $\xi \ll 1$ for large t_β

Landau poles in the gauged $U(1)_{\text{BGL}}$

$U(1)'$'s gauge couplings cannot be too large

$$\Lambda_{\text{LP}} \simeq M_{Z'} \exp \left[\frac{1}{2 b \alpha'(M_{Z'}^2)} \right]$$

with

$$b = \frac{1}{4\pi} \left[\frac{2}{3} \sum_f X_{fL,R}^2 + \frac{1}{3} \left(2 \sum_i X_{\Phi_i}^2 + X_S^2 \right) \right]$$

For $M_{Z'} \simeq 4 \text{ TeV}$:

- Landau pole at the Planck scale for $g' \lesssim 0.12$
- Maybe some other NP appear at higher scales...
 - ▶ $g' \lesssim 0.13$ for the Grand Unification scale
 - ▶ $g' \lesssim 0.14$ for the see-saw scale

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

Model	$C_{10}^{\text{NP}\mu} / C_9^{\text{NP}\mu}$	$C_9^{\text{NP}e} / C_9^{\text{NP}\mu}$	$C_{10}^{\text{NP}e} / C_9^{\text{NP}\mu}$	κ_9^{μ}
(1,2,3)	3/17	9/17	3/17	-1.235
(1,3,2)	0	-9/8	-3/8	0.581
(2,1,3)	1/3	17/9	1/3	-0.654
(2,3,1)	0	-17/8	-3/8	0.581
(3,1,2)	1/3	-8/9	0	-0.654
(3,2,1)	3/17	-8/17	0	-1.235

$B_{s,d} \rightarrow \mu^+ \mu^-$ decays ($C_{10}^{\text{NP}\mu}$, $C_S^{\text{NP}\mu}$, $C_P^{\text{NP}\mu}$)

$$\frac{\text{Br}(\bar{B}_s \rightarrow \mu^+ \mu^-)^{\text{exp}}}{\text{Br}(\bar{B}_s \rightarrow \mu^+ \mu^-)^{\text{SM}}} = 0.76^{+0.20}_{-0.18}$$

$$\frac{\text{Br}(\bar{B}_d \rightarrow \mu^+ \mu^-)^{\text{exp}}}{\text{Br}(\bar{B}_d \rightarrow \mu^+ \mu^-)^{\text{SM}}} = 3.7^{+1.6}_{-1.4}$$

[CMS and LHCb Collaborations '14]

- Ratios predicted to be equal in our model
- $\mathcal{O}(1\%)$ contribution from the Z'
- Up to a 10% suppression possible for $\bar{B}_s \rightarrow \mu^+ \mu^-$ from the scalar sector