# A class of $Z'$ models with non-universal couplings and protected flavor-changing interactions

**Javier Fuentes-Martín (IFIC)**

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on High Energy Physics, June 22-29, 2015.

**Based on:** Phys. Rev. D 92, 015007 (2015) [arXiv:1505.03079]
**In collaboration with:** Alejandro Celis, Martin Jung and Hugo Serôdio

# Motivation: b $\to$ s anomalies

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

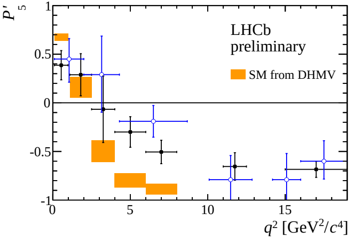
$$R_K^{\mathrm{LHCb}}\Big|_{[1,6]} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

[LHCb Collaboration, '14]

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

[Hiller, Krüger, '03]

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




[LHCb-CONF-2015-002]

2.6 $\sigma$ discrepancy with the SM

2.9 $\sigma$ discrepancy with the SM

**LHCb anomalies**

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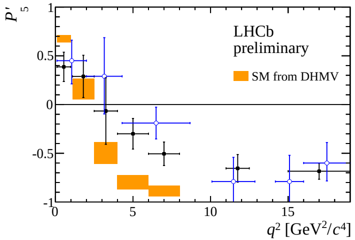


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SM hadronic effects?

See talk by Ayan Paul

LHCb anomalies

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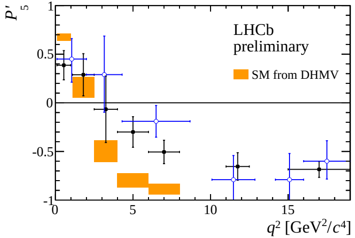


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**NP hint?**

# Motivation: explanations to the $b \to s$ 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...

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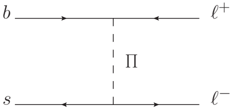


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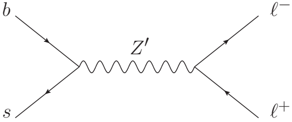
## Composite Higgs models

Altmannshofer, Straub '13; Straub '13; Buras et al. '14; Gripaios, Nardecchia, Renner '14; Niehoff, Stangl, Straub '15...

See talk by Peter Stangl

## Z′ models

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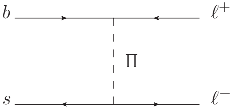


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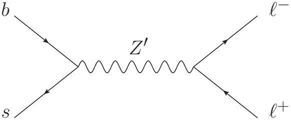


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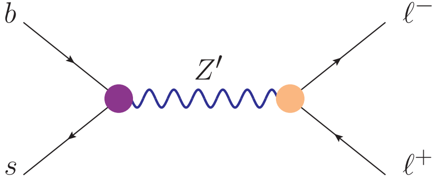
# $Z'$ model building

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




Flavor violating couplings to quarks | Lepton-flavor universality violation

- Often necessary:
  - Two Higgs doublets to accommodate quark masses and mixing angles
  - A scalar 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)

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

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

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

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

$$H\,\overline{d_i} d_j \propto V_{3i}^* V_{3j}\, m_{d_j} \qquad (V \equiv \text{CKM matrix})$$

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

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

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

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

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

$$\downarrow \quad v$$

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

## Matter content

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

## Symmetry constraints

- Controlled $Z'$-mediated FCNCs
- $\mathrm{U}(1)_{\mathrm{BGL}}$ 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 $U(1)_{\mathrm{BGL}}$

$$-\mathcal{L}_{\mathrm{Yuk}}^{\text{c-leptons}} = \overline{\ell_L}\,\Pi_i\,\Phi_i e_R + \mathrm{h.c.}$$

with

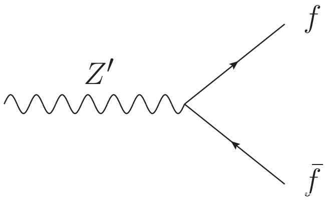
$$\Pi_1 = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad \Pi_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}$$

- Non-universal lepton charges...
- But no FCNCs in the lepton sector
  $\Rightarrow$ 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 $U(1)_{BGL}$: $Z'$ couplings




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

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

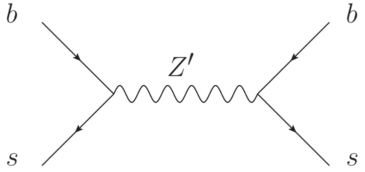
- No FCNCs in the up-quark and charge-lepton sectors
- Non-universal lepton couplings
- Controlled FCNCs for left-handed down-type quarks only

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

# Experimental constraints?

# Low-energy constraints

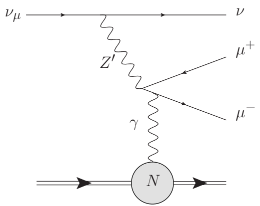
## $B_s - \bar{B}_s$ mixing




- Up to 20% corrections to $\Delta m_s$ possible at 95% CL

[FLAG '14; CKMfitter Collaboration '14]

## Neutrino trident production




- Vector current dominates

[Altmannshofer, Gori, Pospelov, Yavin '14]

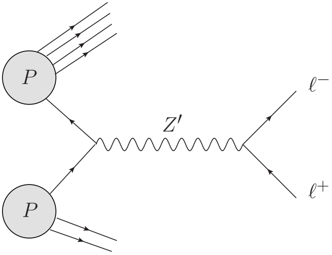
[CHARM-II '90, CCFR '91, NuTeV '00]

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

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

# Collider constraints: LHC and LEP

## Direct searches

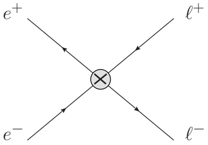



CMS model independent analysis based on the narrow width approximation

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

[CMS-EXO-12-061]

## LEP contact interactions




Single operator analysis

$$M_{Z'}/g' \gtrsim 16 \text{ TeV} \quad (95\% \text{ CL})$$

[CERN-PH-EP-2013-022]

## Collider flavor ratios

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

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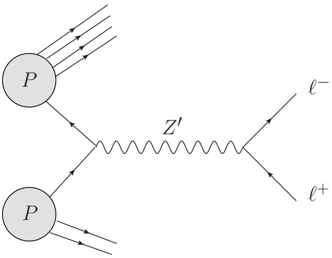


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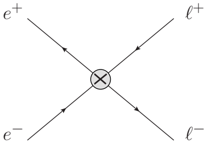


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**Precise correlations in our model!**

# What about the $\mathbf{b} \to \mathbf{s}\ell^+\ell^-$ anomalies?

# Effective Hamiltonian for $\mathbf{b} \to \mathbf{s}\ell^+\ell^-$

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

where

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

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

- $\Delta_R^{bs} = 0 \Rightarrow C_{9,10}'^\ell \simeq 0$
- $Z'$-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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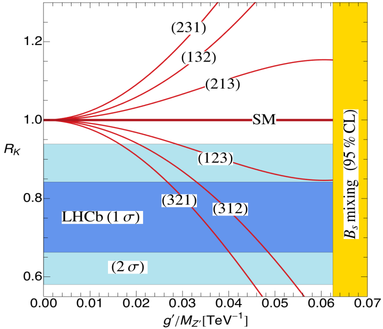
# Z′ contributions: ratios and double ratios

- $R_M \equiv \dfrac{\mathrm{Br}(\bar{B} \to \bar{M}\mu^+\mu^-)}{\mathrm{Br}(\bar{B} \to \bar{M}e^+e^-)}$

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




[arXiv:1505.03079]

| Model | $C_9^{\mathrm{NP}\mu}(1\sigma)$ | $C_9^{\mathrm{NP}\mu}(2\sigma)$ |
|---|---|---|
| (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 for $B \to K^*\mu^+\mu^-$ ✓

$R_{K^*}$ expected to be measured by LHCb soon

- In our models $\widehat{R}_M \equiv \dfrac{R_M}{R_K} = 1$

[Hiller, Schmaltz '15]

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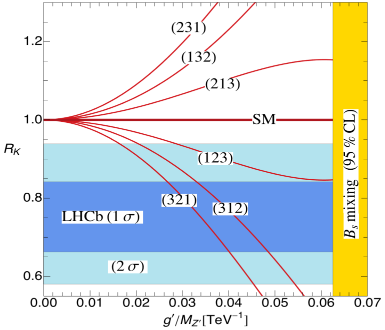


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[Hiller, Schmaltz '15]

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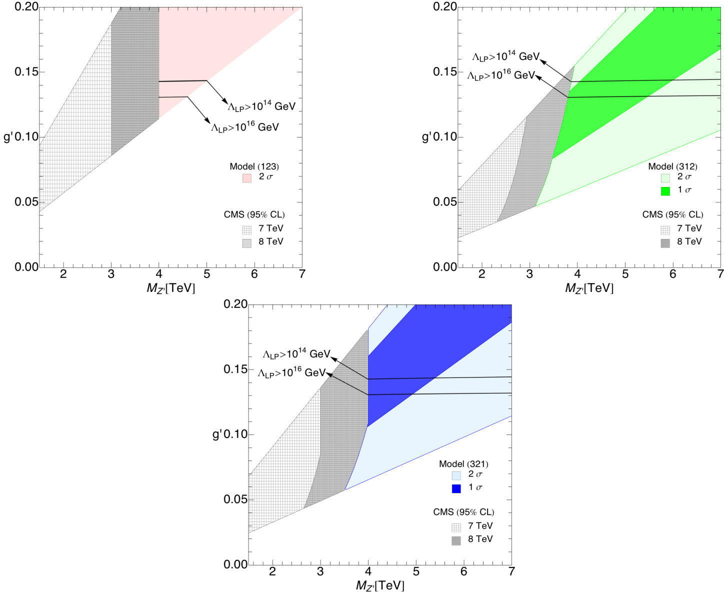
**Smoking gun test of the model!**

# LHC limits on the Z′ and perturbativity bounds



# Conclusions

- ✓ Controlled FCNCs in the down quark sector related in a exact way to the CKM matrix. No FCNCs in the up-quark sector
- ✓ Anomaly cancellation conditions give lepton universality violation without lepton flavor violation
  - In progress: this persists even after adding right-handed neutrinos or triplets
- ✓ All the $Z'$ observables are determined by only two parameters
- ✓ Three out of six model variations are able to accommodate the $b \to s\ell^+\ell^-$ LHCb anomalies
- ✓ Characteristic predictions to discriminate from other models:
  - Equal $B \to M\ell^+\ell^-$ ratios: $R_K = R_{K^*} = R_{X_s} = \ldots$
  - Precise values for the $\mu_{e/\mu}$ and $\mu_{e/\tau}$ collider ratios for each model

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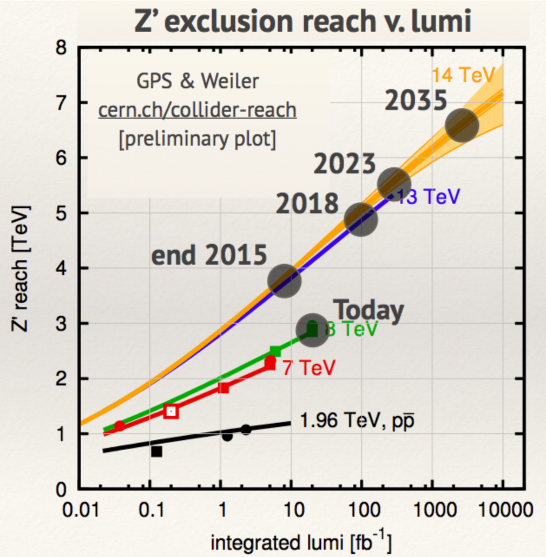
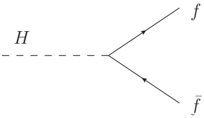
## Thank you for listening!

# Backup

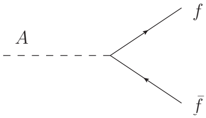
# Z′ collider prospects



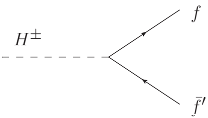
# Scalar sector in the top-BGL model




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




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




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

$$(N_d)_{ij} = \tfrac{v_2}{v_1}\,\mathrm{diag}(m_d, m_s, m_b)_{ij} - \left(\tfrac{v_2}{v_1} + \tfrac{v_1}{v_2}\right)(V^\dagger_{\mathrm{CKM}})_{i3}(V_{\mathrm{CKM}})_{3j}\,\mathrm{diag}(m_d, m_s, m_b)_{jj}$$
$$N_u = \tfrac{v_2}{v_1}\,\mathrm{diag}(m_u, m_c, 0) - \tfrac{v_1}{v_2}\,\mathrm{diag}(0, 0, m_t)$$

- We have a decoupling regime, $\bar{M}_H \equiv M_H \simeq M_A \simeq M_{H^\pm} \sim \mathcal{O}(\mathrm{TeV})$ (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 $M_{S^0} \sim \mathcal{O}(\mathrm{TeV})$

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

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

Only one class of models (with $X_{\Phi_2}$ and $X_{dR}$ free parameters)

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

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

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

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

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

# $\mathbf{Z'}$ mass and $\mathbf{Z - Z'}$ mixing

A scalar 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 $X_{\Phi_2} = 0$, $\Delta$ 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 $t_\beta$

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

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

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

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 $M_{Z'} \simeq 4$ 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 $\mathcal{O}^{\ell}_{9,10}$

| Model | $C_{10}^{\text{NP}\mu}/C_9^{\text{NP}\mu}$ | $C_9^{\text{NP}e}/C_9^{\text{NP}\mu}$ | $C_{10}^{\text{NP}e}/C_9^{\text{NP}\mu}$ | $\kappa_9^{\mu}$ |
|---|---|---|---|---|
| (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) | $3/17$ | $-8/17$ | $0$ | $-1.235$ |

# $\mathbf{B_{s,d}} \to \mu^+\mu^-$ decays ($C_{10}^{\mathrm{NP}\mu}$, $C_S^{\mathrm{NP}\mu}$, $C_P^{\mathrm{NP}\mu}$)

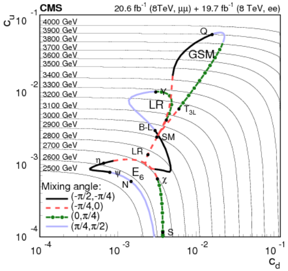
$$\frac{\mathrm{Br}(\bar{B}_s \to \mu^+\mu^-)^{\mathrm{exp}}}{\mathrm{Br}(\bar{B}_s \to \mu^+\mu^-)^{\mathrm{SM}}} = 0.76^{+0.20}_{-0.18} \qquad \frac{\mathrm{Br}(\bar{B}_d \to \mu^+\mu^-)^{\mathrm{exp}}}{\mathrm{Br}(\bar{B}_d \to \mu^+\mu^-)^{\mathrm{SM}}} = 3.7^{+1.6}_{-1.4}$$

[CMS and LHCb Collaborations '14]

- $\mathrm{Br}(\bar{B}_s \to \mu^+\mu^-)/\mathrm{Br}(\bar{B}_d \to \mu^+\mu^-) = 1$ in our model
- $\mathcal{O}(1\%)$ contribution from the $Z'$
- Up to a 10% suppression of $\bar{B}_s \to \mu^+\mu^-$ from the scalar sector

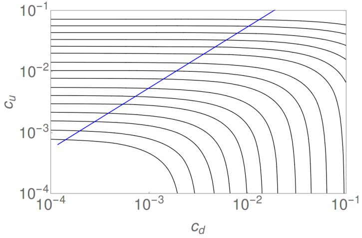
# CMS model-independent bounds

$$\sigma = \frac{\pi}{48s}\left[c_u^f w_u\left(s,\, M_{Z'}^2\right) + c_d^f w_d\left(s,\, M_{Z'}^2\right)\right] \qquad \begin{cases} c_u^f \simeq g'^{\,2}\left(X_{uL}^2 + X_{uR}^2\right) \mathrm{Br}\left(Z' \to f\bar{f}\right) \\ c_d^f \simeq g'^{\,2}\left(X_{uL}^2 + X_{dR}^2\right) \mathrm{Br}\left(Z' \to f\bar{f}\right) \end{cases}$$



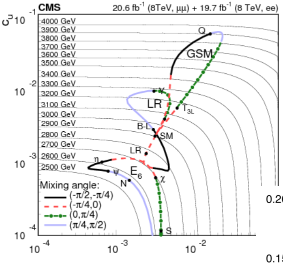

[CMS-EXO-12-061]

$\Rightarrow$



# CMS model-independent bounds

$$\sigma = \frac{\pi}{48s}\left[c_u^f w_u\left(s,\, M_{Z'}^2\right) + c_d^f w_d\left(s,\, M_{Z'}^2\right)\right] \qquad \begin{cases} c_u^f \simeq g'^{\,2}\left(X_{uL}^2 + X_{uR}^2\right) \mathrm{Br}\left(Z' \to f\bar{f}\right) \\ c_d^f \simeq g'^{\,2}\left(X_{uL}^2 + X_{dR}^2\right) \mathrm{Br}\left(Z' \to f\bar{f}\right) \end{cases}$$

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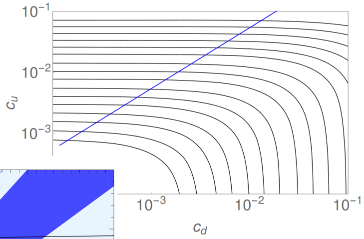


[CMS-