Family non-universal Z' models

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Based on: arXiv:1505.03079

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

Outline

Motivation: b $\to$ s anomalies

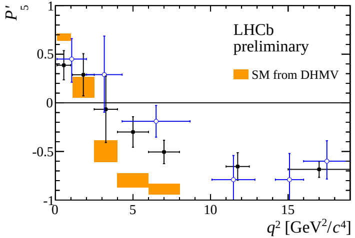
$$R_K = \frac{\text{Br}(\bar{B} \to \bar{K}\mu^+\mu^-)}{\text{Br}(\bar{B} \to \bar{K}e^+e^-)}$$

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

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

[LHCb Collaboration, '14]

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



[LHCb-CONF-2015-002]

2.6 σ discrepancy with the SM

2.9 σ discrepancy with the SM

LHCb **anomalies**

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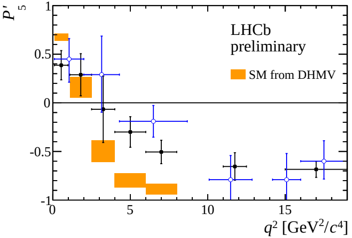

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2.6 σ discrepancy with the SM

2.9 σ discrepancy with the SM

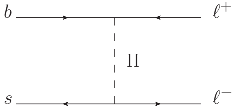
NP hint?

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; ...

Leptoquark models



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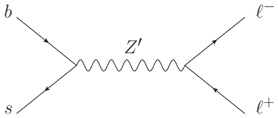
SM hadronic effects?

See talk by Descotes-Genon

Z′ models



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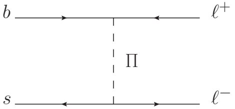

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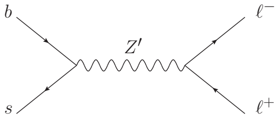

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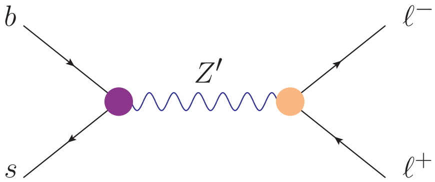
Z′ model building

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



Flavor violating couplings to quarks   Lepton-flavor universality violation

- Often necessary: extend the scalar sector to accommodate quark mass and mixing patterns and to give mass to the Z'
- Wish list: Minimal particle content (no additional fermions)
  All quark couplings exactly related to CKM matrix elements

See talks by Heeck and Vicente for other Z' model implementations!

Branco–Grimus–Lavoura 2HDM (BGL)

Controlled FCNCs [Branco, Grimus, Lavoura '96]

Allow FCNCs in one sector but controlled by the CKM matrix

- ✓ FCNCs under control
  [Botella *et al.* '14; Bhattacharyya, Das, Kundu '14]
- ✓ Imposed by a global symmetry
- ✗ Accidental symmetry in the Lagrangian
  $\Rightarrow$ "Undesired" Goldstone boson

Solutions:

- Soft breaking of the accidental symmetry
- Add extra singlets
- BGL as a flavored PQ symmetry [Celis, JF, Serôdio '14]
- BGL as a gauged symmetry (this talk!)

Top-BGL Yukawa textures

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

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

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

- No FCNCs in the up sector, FCNCs in the down sector proportional to off-diagonal $V_{\rm CKM}$ matrix elements
- Unique implementation in 2HDM [Ferreira, Silva '11; Serôdio '13]
- $v_1 < v_2$ yields a "natural" quark mass hierarchy

Top-BGL charge implementation

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

with

$$\mathcal{X}_L^q = \frac{1}{2}\left[\mathrm{diag}\left(X_{uR}, X_{uR}, X_{tR}\right) + X_{dR}\,\mathbb{1}\right]$$
$$\mathcal{X}_R^u = \mathrm{diag}\left(X_{uR}, X_{uR}, X_{tR}\right)$$
$$\mathcal{X}_R^d = X_{dR}\,\mathbb{1}$$
$$\mathcal{X}^{\Phi} = \frac{1}{2}\mathrm{diag}\,\left(X_{uR} - X_{dR}, X_{tR} - X_{dR}\right)$$

Anomalies in the BGL implementation

The $\mathrm{U}(1)_{\text{BGL}}$ is chiral:

$$\mathrm{U}(1)'[\mathrm{SU}(3)_c]^2 \quad \mathrm{U}(1)'[\mathrm{SU}(2)_L]^2 \quad \mathrm{U}(1)'[\mathrm{U}(1)_Y]^2$$

$$[\mathrm{U}(1)']^2\mathrm{U}(1)_Y \qquad [\mathrm{U}(1)']^3 \qquad \mathrm{U}(1)'[\text{Gravity}]^2$$

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- Anomaly-free model not possible within the quark sector alone
- Minimal ansatz: extend the symmetry to the lepton sector

$$\mathcal{X}_L^\ell = \mathrm{diag}\left(X_{eL}, X_{\mu L}, X_{\tau L}\right)$$
$$\mathcal{X}_R^e = \mathrm{diag}\left(X_{eR}, X_{\mu R}, X_{\tau R}\right)$$

Anomaly free top-BGL implementation

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

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

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

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

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

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

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

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

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

with

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

- 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; Crivellin, D'Ambrosio, Heeck '15]

- One charged lepton gets singled out

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

In the <u>physical eigenbasis</u> the charges get modified

$$\widetilde{\mathcal{X}}^u_L = \mathcal{X}^u_L \qquad \widetilde{\mathcal{X}}^u_R = \mathcal{X}^u_R \qquad \widetilde{\mathcal{X}}^d_R = \mathcal{X}^d_R \qquad \longleftarrow$$

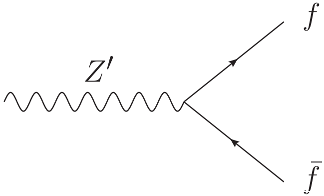
Diagonal & universal in the first two families

$$\widetilde{\mathcal{X}}^d_L = -\frac{5}{4}\mathbb{1} + \frac{9}{4}\begin{pmatrix} |V_{td}|^2 & V_{ts}V^*_{td} & V_{tb}V^*_{td} \\ V_{td}V^*_{ts} & |V_{ts}|^2 & V_{tb}V^*_{ts} \\ V_{td}V^*_{tb} & V_{ts}V^*_{tb} & |V_{tb}|^2 \end{pmatrix}$$

$$\widetilde{\mathcal{X}}^\ell_L = \mathcal{X}^\ell_L \qquad \widetilde{\mathcal{X}}^\ell_L = \mathcal{X}^\ell_L \qquad \longleftarrow$$

Diagonal & family non-universal

Controlled Z'-mediated FCNCs:



$$= g'\gamma^\mu\left(\widetilde{\mathcal{X}}^f_L P_L + \widetilde{\mathcal{X}}^f_R P_R\right)$$

Gauged $U(1)_{BGL}$ highlights

- ✓ Tree level FCNCs in the down-quark sector mediated by Z' and neutral scalars proportional to off-diagonal CKM matrix elements
- ✓ No FCNCs in the up-quark and charge-lepton sectors
- ✓ Flavor-conserving non-universal lepton couplings
- ✓ Only two free parameters related to Z' observables, g' and $M_{Z'}$
- ✓ Six model variations, related to permutations in the lepton sector

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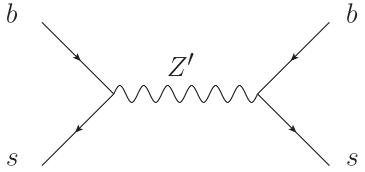
Experimental constraints?

Low-energy constraints

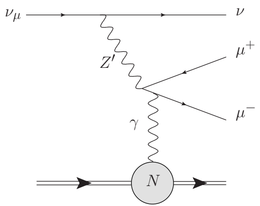
$B_s - \bar{B}_s$ mixing



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

  [FLAG '14; CKMfitter Collaboration '14]

Neutrino trident production



- Vector current dominates

  [Altmannshofer, Gori, Pospelov, Yavin '14]

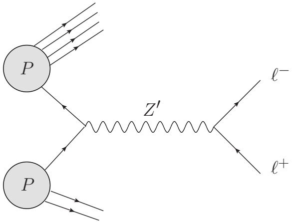
  [CHARM-II '90, CCFR '91, NuTeV '00]

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



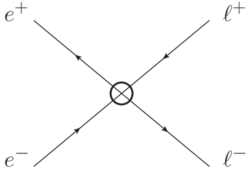
CMS model independent analysis based on the narrow width approximation

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

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

[CMS-EXO-12-061]

LEP contact interactions



Single operator analysis

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

[CERN-PH-EP-2013-022]

Collider flavor ratios

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

What about the b $\rightarrow$ s$\ell^+\ell^-$ anomalies?

Effective Hamiltonian for $b \to s\ell^+\ell^-$

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

where

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

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

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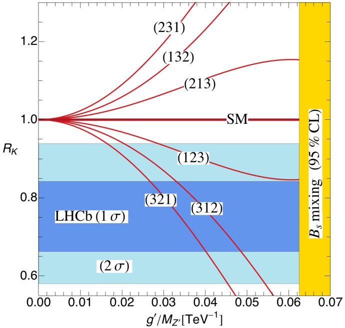
Z′ contributions: ratios and double ratios

- $R_M \equiv \dfrac{\mathrm{Br}(\bar{B} \to \bar{M}\mu^+\mu^-)}{\mathrm{Br}(\bar{B} \to \bar{M}e^+e^-)}$ $M \in \{K, K^*, X_s, K_0(1430), \ldots\}$

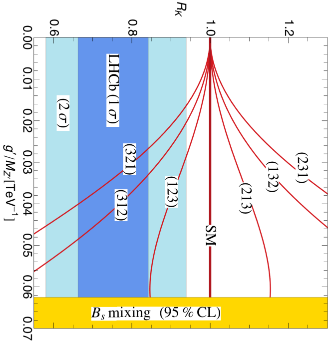


Model	$C_9^{\mathrm{NP}\mu}(1\sigma)$	$C_9^{\mathrm{NP}\mu}(2\sigma)$
(1,2,3)	–	[−2.92, −0.61]
(3,1,2)	[−0.93, −0.43]	[−1.16, −0.17]
(3,2,1)	[−1.20, −0.53]	[−1.54, −0.20]

Good for $B \to K^*\mu^+\mu^-$ ✓

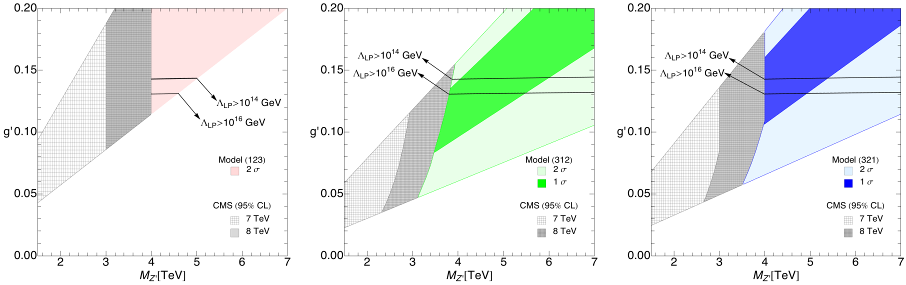
- $\widehat{R}_M \equiv \dfrac{R_M}{R_K} = 1$ Test of the flavor structure of the model!

[Hiller, Schmaltz '15]



War of the NP models
Z′ are already here?

LHC limits on the Z′ and perturbativity bounds



Warning: with the charge normalization we chose, $g' X_{max} \gtrsim 1.5$. Careful when comparing with other models in the literature.

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 conditions give lepton universality violation without lepton flavor violation
  - In progress: this property 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: $R_K = R_{K^*} = R_{X_s} = \dots$
  - Precise values for the $\mu_{e/\mu}$ and $\mu_{e/\tau}$ collider ratios for each model

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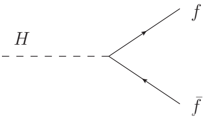
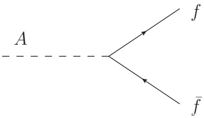
Thank you for listening!

Backup

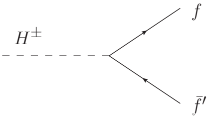
Scalar sector in the top-BGL model



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



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



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

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

- We have a decoupling regime, $\bar{M}_H \equiv M_H \simeq M_A \simeq M_{H^\pm} \simeq M_Z' = \mathcal{O}(\text{TeV})$ (unless Poincaré protection is invoked) [Foot, Kobakhidze, McDonald, Volkas '14]

$\mathbf{Z'}$ 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 $X_{\Phi_2} = 0$, Δ only depends on v_1

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

so $\xi \ll 1$ for large t_β

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

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

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

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	$C_{10}^{\text{NP}\mu}/C_9^{\text{NP}\mu}$	$C_9^{\text{NP}e}/C_9^{\text{NP}\mu}$	$C_{10}^{\text{NP}e}/C_9^{\text{NP}\mu}$	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

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

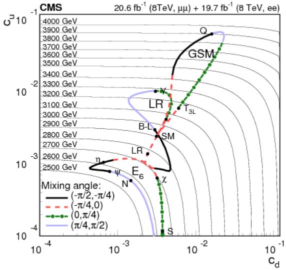
$$\frac{\mathrm{Br}(\bar{B}_s \to \mu^+\mu^-)^{\text{exp}}}{\mathrm{Br}(\bar{B}_s \to \mu^+\mu^-)^{\text{SM}}} = 0.76^{+0.20}_{-0.18} \qquad \frac{\mathrm{Br}(\bar{B}_d \to \mu^+\mu^-)^{\text{exp}}}{\mathrm{Br}(\bar{B}_d \to \mu^+\mu^-)^{\text{SM}}} = 3.7^{+1.6}_{-1.4}$$

[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

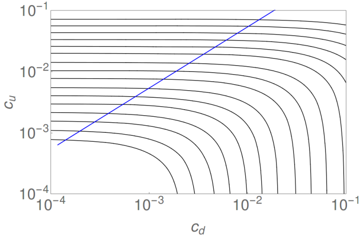
CMS model-independent bounds

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



[CMS-EXO-12-061]

$\Rightarrow$



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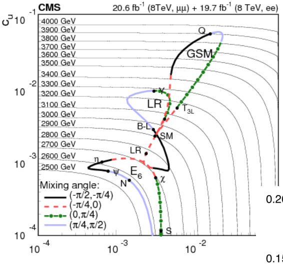
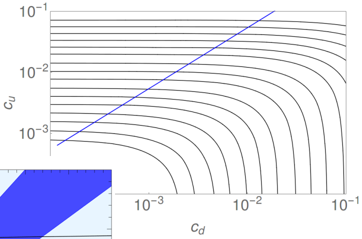


$\Rightarrow$



[CMS-