LFNU in b →s transitions in next-to-minimal 331 models

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Based on work in collab. with S. Descotes-Genon and M. Moscati arXiv:1711.03101

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Motivations

- Anomalies in B decays

Already discussed yesterday, thank you

LHCb has been able to probe very rare b→s ll and challenging b→clv transitions.

Vinícius Franco Lima

- For the first time, we observe in particle physics a large set of **coherent deviations** in observables:
  1. in $b \to s\mu^+\mu^-$: P_5', $\mathcal{B}_{B^+\to K^{*+}\mu^+\mu^-}$, $\mathcal{B}_{B_s\to\phi\mu^+\mu^-}$ (low and large-recoil).
  2. in LFUV observables: R_K,R_{K^*}, $Q_{4,5}$

Joaquim Matias

Siavash Neshatpour

- $B \to K^*\mu^+\mu^-$ angular observable P_5' (or S_5): 2.8 and 3.0σ in [4.0-6.0] and [6.0-8.0] GeV^2 bins with 3 fb^{-1} at LHCb
- BR($B_s \to \phi\mu^+\mu^-$): 3.2σ tension in the [1-6] GeV^2 bin with 3 fb^{-1} at LHCb (2015)

Anomalies in the decay of the B meson were reported through the measurements of the $b \to sll$ transitions in the form of foll. ratio:

LFU violations??

Hiller,Kruger 0310219

$$R_K = \frac{\mathcal{B}(B^+\to K^+\mu^+\mu^-)}{\mathcal{B}(B^+\to K^+e^+e^-)}\Big|_{q^2=1-6\ GeV^2} = 0.745^{+0.090}_{-0.074}\,(stat) \pm 0.036\,(syst)$$

$R_K^{SM} = 1.003$

LHCB 1406.6482

2.7σ

Abhishek Iyer

etc, etc....

Peter Stangl

Flavor anomalies

$b \to s\mu^+\mu^-$ anomaly

Several LHCb measurements deviate from Standard model (SM) predictions by 2-3σ:

- Angular observable P_5' in $B \to K^*\mu^+\mu^-$. LHCb, arXiv:1512.04442
- Branching ratios of $B \to K\mu^+\mu^-$, $B \to K^*\mu^+\mu^-$, and $B_s \to \phi\mu^+\mu^-$.

LHCb, arXiv:1403.8044, arXiv:1506.08777, arXiv:1606.04731

Hints for LFU violation in neutral current decays

Measurements of lepton flavor universality (LFU) ratios $R_K^{[1,6]}$, $R_{K^*}^{[0.045,1.1]}$, $R_{K^*}^{[1.1,6]}$ show deviations from SM by about 2.5σ each. LHCb, arXiv:1406.6482, arXiv:1705.05802

Hints for LFU violation in charged current decays

Measurements of LFU ratios R_D and R_{D^*} by BaBar, Belle, and LHCb show combined deviation from SM by 4σ.

BaBar, arXiv:1205.5442, arXiv:1303.0571
LHCb, arXiv:1506.08614, arXiv:1708.08856
Belle, arXiv:1507.03233, arXiv:1607.07923, arXiv:1612.00529
HFLAV, arXiv:1612.07233

BSM experimental status (also extensively discussed)

Categories of anomalous observables

- Angular observables and branching ratios $\rightarrow$ "hadronically challenged"
- Ratios: theoretically «clean»

OUTLINE

- Focus on $b \rightarrow s\, l\, l$ decays
- Choose a viable 331 model allowing LFNU
- Express Wilson coefficients in that frame
- Compare with global fits & additional constraints

331 models main features: 1)

P. Frampton '92,
F. Pisano and V. Pleitez, '92...

gauge group $SU(3)_c \times SU(3)_L \times U(1)_X$

spontaneously broken to $\to SU(3)_c \times SU(2)_L \times U(1)_Y$

spontaneously broken to $\to SU(3)_c \times U(1)_Q$

$$\boxed{\hat{Q} = a\hat{T}^3 + \frac{\hat{Y}}{2} = a\hat{T}^3 + \beta\hat{T}^8 + X\mathbb{1}}$$

arbitrary a and β

$a = 1$ embed isospin doublets $SU(2)_L \times U(1)_Y$ into $SU(3)_L \times U(1)_X$

$\beta = \pm 1/\sqrt{3}$ no new particle with exotic charges

$$\boldsymbol{\beta = -1/\sqrt{3}}$$

331 models main features: 2)

Anomaly free

Equal number of 3 and $\bar{3}$ fermionic representations

Minimal 331 model example:

e.g. Buras et al. 1211.1237, 1311.6729, 1405.3850, Diaz et al. 0411263, 309280….

quarks in $SU(3)_L$

2 families x3(color) 3

1 family x3(color) $\bar{3}$

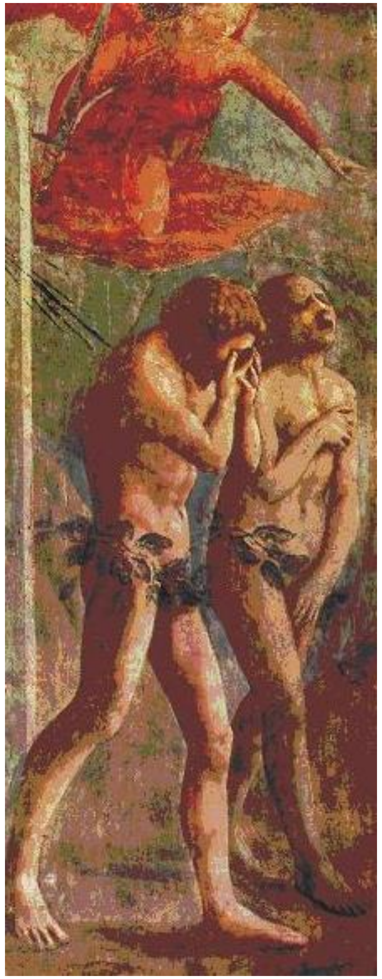
Lepton

All three families fixed to $\bar{3}$

Same representation:
LFNU not allowed

Is that conclusive?

Is there a next-to-minimal 331 model which is compatible with current LFNU hints?



First step towards:

Can 331 models be excluded on the basis of actual anomalies?

Masaccio, 1424

Anomaly cancellation in next-to-minimal 331 models

For the left-handed components

J. M. Cabarcas, et al. 1212.3586, 1310.1407...

- three generations of quarks

$$Q_m^L = \begin{pmatrix} d_m^L \\ -u_m^L \\ B_m^L \end{pmatrix} \sim (3, \bar{3}, 0), \quad m = 1, 2 \qquad Q_3^L = \begin{pmatrix} u_3^L \\ d_3^L \\ T_3^L \end{pmatrix} \sim (3, 3, \frac{1}{3})$$

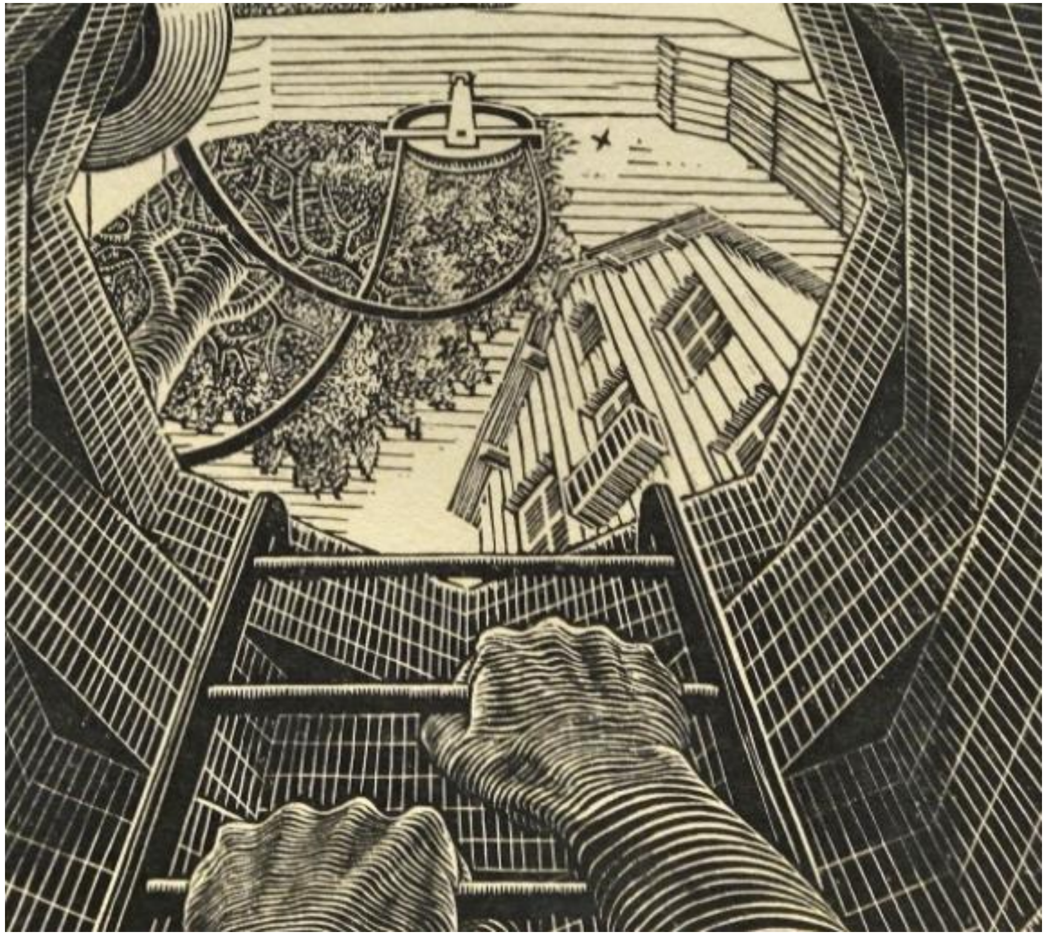
- five generations of leptons

$$\ell_1^L = \begin{pmatrix} e_1^{-L} \\ -\nu_1^L \\ E_1^{-L} \end{pmatrix} \sim (1, \bar{3}, -\frac{2}{3}), \qquad \ell_n^L = \begin{pmatrix} \nu_n^L \\ e_n^{-L} \\ N_n^{0L} \end{pmatrix} \sim (1, 3, -\frac{1}{3}), \qquad n = 2, 3$$

$$\ell_4^L = \begin{pmatrix} N_4^{0L} \\ E_4^{-L} \\ P_4^{0L} \end{pmatrix} \sim (1, 3, -\frac{1}{3}), \qquad \ell_5^L = \begin{pmatrix} (E_4^{-R})^c \\ N_5^{0L} \\ (e_3^{-R})^c \end{pmatrix} \sim (1, 3, \frac{2}{3}).$$

SM particles

Analyzing a next-to-minimal 331 model with 5 lepton generations



Escher, 1946

$SU(3)_L \times U(1)_X$ Gauge Bosons

$$W_\mu = W_\mu^a T^a = \frac{1}{2}\begin{pmatrix} W_\mu^3 + \frac{1}{\sqrt{3}}W_\mu^8 & \sqrt{2}W_\mu^+ & W_\mu^4 - iW_\mu^5 \\ \sqrt{2}W_\mu^- & -W_\mu^3 + \frac{1}{\sqrt{3}}W_\mu^8 & W_\mu^6 - iW_\mu^7 \\ W_\mu^4 + iW_\mu^5 & W_\mu^6 + iW_\mu^7 & -\frac{2}{\sqrt{3}}W_\mu^8 \end{pmatrix}$$

$W_\mu^a \quad a = 1 \ldots 8$

Charged

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp iW_\mu^2) \qquad V_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^6 \mp iW_\mu^7)$$

Neutral

$W^3, W^{4,5}, W^8, X$

Mixing patterns among neutral particles

$$W^3, W^{4,5}, W^8, X \xrightarrow[\Lambda_{NP}]{\theta_{331}} W^3, W^{4,5}, B, Z' \xrightarrow[\Lambda_{EW}]{\theta_W} W^{4,5}, Z', A, Z$$

$$\sin\theta_{331} = \frac{g}{\sqrt{g^2 + \frac{g_X^2}{18}}}$$

g $SU(3)_L$ gauge coupling constant

g_X $U(1)_X$ gauge coupling constant

$$\boxed{\tan\theta_W = -\sqrt{3}\cos\theta_{331}}$$

θ_W Weinberg angle

$$\boxed{\frac{g_X^2}{g^2} = \frac{6\sin^2\theta_W}{1-(1+\beta^2)\sin^2\theta_W}}$$

$$\epsilon = \Lambda_{\mathrm{EW}}/\Lambda_{\mathrm{NP}}$$

$V^{\pm}$ $W^{\pm}$

Massive 1SSB

Massive 2SSB

New particle content

heavy quarks $\boxed{B_{1,2}, T_3}$

heavy leptons $\boxed{E_{1,}^{-} E_4^{-}, N_{2,3,4,5,}^{0} P_4^{0}}$

gauge bosons $\boxed{V^{\pm}, W^{4,5}, Z'}$

extended Higgs sector $\boxed{SU(3)_L \text{triplets } \chi, \eta, \rho \quad \text{sextets } S_1, S_{b,} S_c}$

Yukawa coupling

$$D = \begin{pmatrix} d_1 \\ d_2 \\ d_3 \\ B_1 \\ B_2 \end{pmatrix}, \qquad U = \begin{pmatrix} u_1 \\ u_2 \\ u_3 \\ T_3 \end{pmatrix}$$

$$D^L = V^{(d)} D'^L \qquad D^R = W^{(d)} D'^R$$

$$U^L = V^{(u)} U'^L \qquad U^R = W^{(u)} U'^R$$

Quark masses defined upon rotation of 5 x 5 (4x4) unitary matrices

$$\frac{g}{\sqrt{2}} W_\mu^+ \bar{U}^L \gamma^\mu \mathcal{V} D^L = \frac{g}{\sqrt{2}} W_\mu^+ \bar{U}^L \gamma^\mu \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} D^L = V_{mn}^{CKM} \frac{g}{\sqrt{2}} W_\mu^+ \bar{U}_m'^L \gamma^\mu D_n'^L$$

$$\boxed{V^{CKM} = V^{(u)\dagger} \mathcal{V} V^{(d)}}$$

In general not unitary

Mixing patterns

Order by order diagonalization $\qquad \epsilon = \Lambda_{\mathrm{EW}}/\Lambda_{\mathrm{NP}}$

- at order ϵ^0, the SM fields are massless and they only mix among themselves; massive exotic particles mix also only among themselves;

- at order ϵ^1, there is only mixing between SM and exotic particles;

- the ϵ^2 correction yields a mixing among all the particles of the same flavour vector.

$$\boxed{V^{CKM} = V^{(u)\dagger}\mathcal{V}V^{(d)}}$$

Unitary subspaces

3x 3 SM Unitary at LO

Facing anomalies

Hieronymus Bosch 1482

Effective Analysis $b \to s\, l\, l$ transitions

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i O_i$$

$$O_9^\ell = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell) \qquad O_{9'}^\ell = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)$$

$$O_{10}^\ell = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma^5 \ell) \qquad O_{10'}^\ell = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma^5 \ell)$$

- SM $\boxed{C_9^\ell \simeq 4.1}$ $\boxed{C_{10}^\ell \simeq -4.3}$

- BSM contributions in C_9^μ or $(C_9^\mu, C_{9'}^\mu)$ or (C_9^μ, C_{10}^μ) from both LFUV observables and angular observables: additional operators fitted values constrained to remain small

Descotes-Genon et al., 15, Capdevila et al. 17, Altmannshofer et al., Genget al. 17, Ciuchini et al. 17, Hurth et al. 17….

BSM contributions

neutral gauge bosons $W^{4,5}, Z', Z, A$

Lowest level in ε

Interactions Z and Z′ with RH quarks

$$\mathcal{L}_{Z'} = \frac{\cos\theta_{331}}{g_X} Z'_\mu \left\{ \frac{\sqrt{2} g_X^2}{3\sqrt{3}} \bar{U}^R \gamma^\mu U^R - \frac{g_X^2}{3\sqrt{6}} \bar{D}^R \gamma^\mu D^R \right\}$$

$$\mathcal{L}_Z = \cos\theta_W \, g Z_\mu \left\{ -2\cos^2\theta_{331} \bar{U}^R \gamma^\mu U^R + \cos^2\theta_{331} \bar{D}^R \gamma^\mu D^R \right\}$$

identity in flavour space: no contribution to $C'_{9,10}$

Z'

$(\bar{q}_k\, q_l)(\bar{\ell}_i\, \ell_j)$ flavour strucure

$$\mathcal{H}_{\rm eff} \supset \frac{g_X^2}{54\cos^2\theta_{331}} \frac{1}{M_{Z'}^2} V_{3k}^{(d)*} V_{3l}^{(d)} \frac{4\pi}{\alpha} \left\{ \left[-\frac{1}{2} V_{1i}^{(e)*} V_{1j}^{(e)} + \frac{1-6\cos^2\theta_{331}}{2} W_{3i}^{(e)*} W_{3j}^{(e)} + \frac{1+3\cos^2\theta_{331}}{4} \delta_{ij} \right] O_9^{klij} + \right.$$
$$\left. + \left[\frac{1}{2} V_{1i}^{(e)*} V_{1j}^{(e)} + \frac{1-6\cos^2\theta_{331}}{2} W_{3i}^{(e)*} W_{3j}^{(e)} + \frac{-1+9\cos^2\theta_{331}}{4} \delta_{ij} \right] O_{10}^{klij} \right\}$$

Z

$$\mathcal{H}_{\rm eff} \supset \frac{\cos^2\theta_W (1+\cos^2\theta_{331})}{8} \frac{g^2}{M_Z^2} \frac{4\pi}{\alpha} \sum_\lambda \hat{V}_{\lambda k}^{(d)*} \hat{V}_{\lambda l}^{(d)} \delta_{ij} \left\{ (-1+9\cos^2\theta_{331}) O_9^{klij} + (1+3\cos^2\theta_{331}) O_{10}^{klij} \right\}$$

no other contributions: A diagonal, $W^{4,5}$ higher order in ε

Wilson coefficients and LFV

$$\boxed{\mathcal{H}_{\text{eff}} \supset C_9^{ij} O_9^{ij} + C_{10}^{ij} O_{10}^{ij}}$$

k, l quark index fixed at b, s
i,j lepton flavours

$$C_9^{ij} = f^{Z'}\left[-\frac{1}{2}\lambda_{ij}^{(L)} + \frac{1-2\tan^2\theta_W}{2}\lambda_{ij}^{(R)} + \frac{1+\tan^2\theta_W}{4}\delta_{ij}\right] + f^Z(-1+3\tan^2\theta_W)\delta_{ij}$$

$$C_{10}^{ij} = f^{Z'}\left[\frac{1}{2}\lambda_{ij}^{(L)} + \frac{1-2\tan^2\theta_W}{2}\lambda_{ij}^{(R)} + \frac{-1+3\tan^2\theta_W}{4}\delta_{ij}\right] + f^Z(1+\tan^2\theta_W)\delta_{ij}$$

$$f^{Z'} = -\frac{1}{2\sqrt{2}G_F V_{tb}V_{ts}^*}\frac{4\pi}{\alpha}\frac{1}{3-\tan^2\theta_W}\frac{g^2}{M_{Z'}^2}V_{3k}^{(d)*}V_{3l}^{(d)}$$

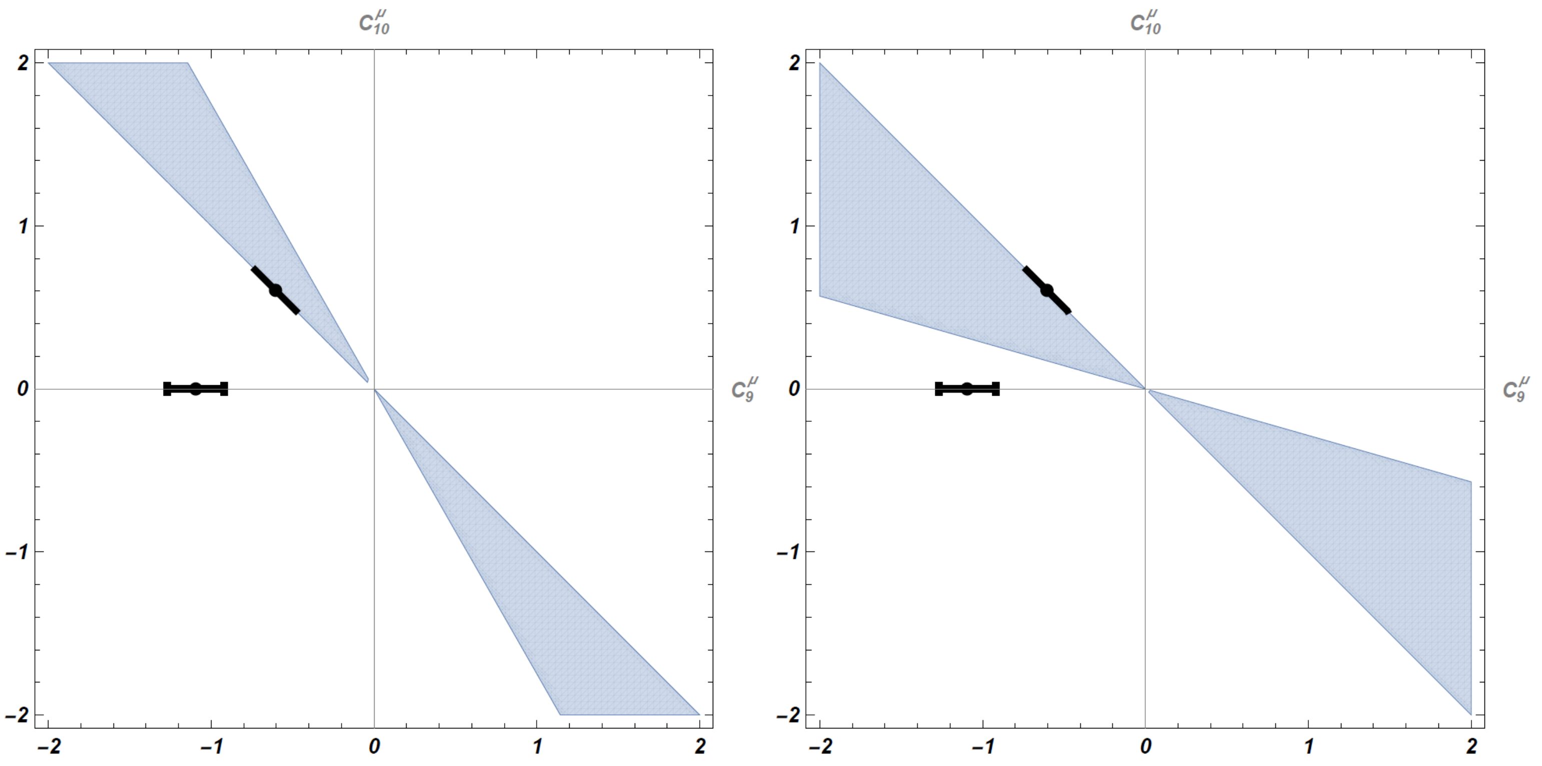
$$f^Z = -\frac{1}{2\sqrt{2}G_F V_{tb}V_{ts}^*}\frac{4\pi}{\alpha}\frac{\cos^2\theta_W(3+\tan^2\theta_W)}{24}\frac{g^2}{M_Z^2}\sum_\lambda \hat{V}_{\lambda k}^{(d)*}\hat{V}_{\lambda l}^{(d)}$$

$$\lambda_{ij}^{(L)} = V_{1i}^{(e)*}V_{1j}^{(e)} \qquad \lambda_{ij}^{(R)} = W_{3i}^{(e)*}W_{3j}^{(e)}$$

Both LFNU and LFV could be induced by Z' (only)

- LFV excluded
- No BSM $C_{9,10}^e$

$\Big\}$ Data and global fits driven constraints (See yesterday talks)



- NP in $\cancel{C_9^\mu = -C_9'^\mu}$ with the 1σ interval [-1.18, -0.84]
- NP in $\cancel{C_9^\mu}$, $\cancel{\text{within}}$ the 1σ interval [-1.27, -0.92]
- NP in $C_9^\mu = -C_{10}^\mu$, within the 1σ interval [-0.73, -0.48].

Global fits

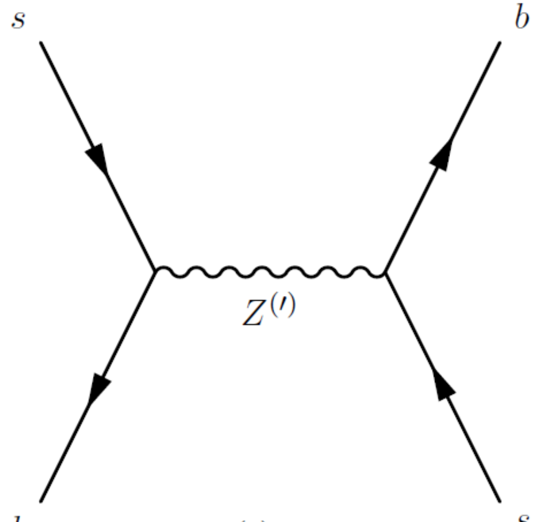
Descotes-Genon et al., 15, Capdevila et al. 17, Altmannshofer et al., Genget al. 17, Ciuchini et al. 17, Hurth et al. 17….

Constraints from $B_s - \overline{B_s}$ mixing

BSM Z contribution: ε suppressed

BSM Z′ contribution

$$\mathcal{H}_{\rm eff} \supset \frac{g_X^2}{54 M_{Z'}^2 \cos^2\theta_{331}} (V_{3k}^{*(d)} V_{3l}^{(d)})^2 (\overline{D_k}\gamma^\mu D_l)(\overline{D_k}\gamma^\mu D_l) =$$
$$= \frac{8 G_F}{\sqrt{2}(3-\tan^2\theta_W)} \frac{M_W^2}{M_{Z'}^2} (V_{3k}^{*(d)} V_{3l}^{(d)})^2 (\overline{D_k}\gamma^\mu D_l)(\overline{D_k}\gamma^\mu D_l)$$



(c)

SM Z contribution

$$\mathcal{H}_{\rm eff}^{\rm SM} = (V_{ts}^* V_{tb})^2 \frac{G_F^2}{4\pi^2} M_W^2 \hat{\eta}_B S\left(\frac{m_t^2}{M_W^2}\right) (\overline{s_L}\gamma^\mu b_L)(\overline{s_L}\gamma^\mu b_L)$$

$S\left(\frac{m_t^2}{M_W^2}\right) \simeq 2.35$, for a top mass of about 165 GeV, and

$\hat{\eta}_B = 0.8393 \pm 0.0034$, which comprises QCD corrections.

$$r_{B_s} = \left|\frac{C_{\rm NP}}{C_{\rm SM}}\right| = \frac{32\pi^2 |V_{32}^{*(d)} V_{33}^{(d)}|^2}{\sqrt{2}(3-\tan^2\theta_W)|V_{ts}^* V_{tb}|^2 G_F M_W^2 \hat{\eta}_B S} \frac{M_W^2}{M_{Z'}^2}$$

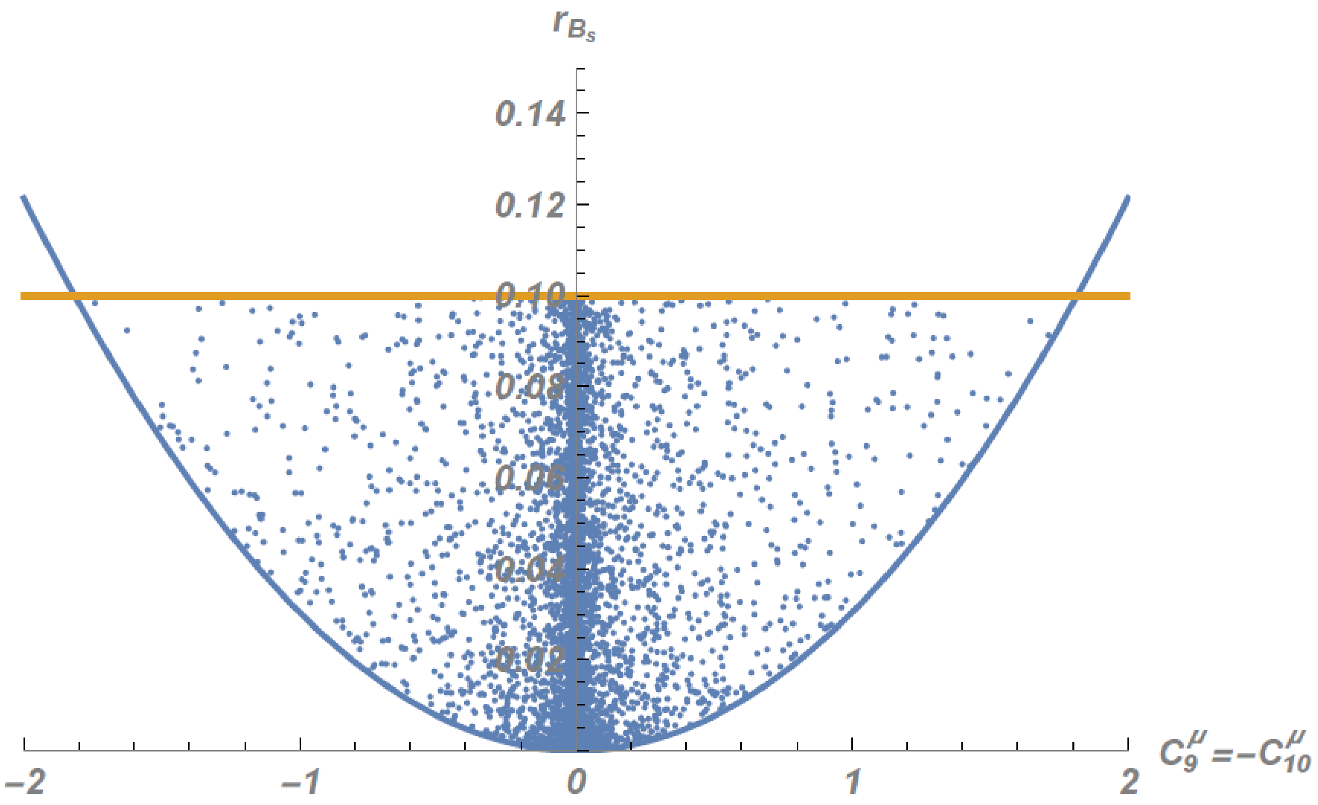


Figure 3: Allowed points in the (C_9^μ, r_{B_s}) plane.

$$d = V_{32}^{*(d)} V_{33}^{(d)}$$

$$d \in [-1,1]$$

$$\frac{M_W}{M_{Z'}} \in [0,0.3]$$

$$r_{B_s} \leq 0.1$$

Agreement global fits
Lenz et al 1203.0238,
J. Charles et al. 1309.2293.

Conclusions

- Preliminary analysis of LFNU of a Z′ model embedded in a more global extension, the 331 model

- next-to-minimal assumptions: 5 lepton families + no LFV + no BSM in C^e

- NP scenarios in agreement with global fits are allowed