Minimal Z' models for flavor anomalies

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Outline

- Non-universal models and flavor physics
- Anomalies in B Meson decays
- General solutions for minimal Models
- Benchmark models
- LHC and low energy Constraints
- Conclusions

Non-universal models and flavor physics

- The theoretical motivation to study the non-universal models comes from top-bottom approaches, especially in string theory derived constructions, where the U(1)' charges are family dependent.

- Non-universal models have been also used to explain the number of families and the hierarchies in the fermion spectrum observed in nature (The flavor problem).

- The fits involving the recent LHCb anomalies prefer non-universal models

LHCb measurements

$$R_K = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)} = 0.745^{+0.09}_{-0.074}(\text{stat}) \pm 0.036\ (\text{syst});$$

$$R_K = 1.0004(8)$$

$$R_{K^*} = \frac{BR(B \to K^*\mu^+\mu^-)}{BR(B \to K^*e^+e^-)} = \begin{cases} 0.660^{+0.110}_{-0.070} \pm 0.024, & q^2 \in [0.045, 1.1]\text{GeV}^2 \\ 0.685^{+0.113}_{-0.069} \pm 0.047, & q^2 \in [1.1, 6]\text{GeV}^2 \end{cases} ,$$

$$R_{K^*} = 0.920(7)\ \text{y}\ R_{K^*} = 0.996(2),$$

Every one of these measurements deviate from the SM by around start with the first set of slides 2.5σ's

B→s effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{e^2}{16\pi^2} \sum_i (C_i \mathcal{O}_i + C'_i \mathcal{O}'_i) + \text{h.c.}$$

C_i : Wilson coefficients

$\mathcal{O}_i$: Operators

$$\mathcal{O}_9 = (\bar{s}\gamma_\mu P_L b)\ (\bar{\ell}\gamma^\mu \ell)$$
$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b)\ (\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

$$\mathcal{O}'_9 = (\bar{s}\gamma_\mu P_R b)\ (\bar{\ell}\gamma^\mu \ell)$$
$$\mathcal{O}'_{10} = (\bar{s}\gamma_\mu P_R b)\ (\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

Descotes-Genon, L. Hofer, J. Matias and J. Virto 2015

Coefficient	Best fit	1σ	3σ	Pull_{SM}	p-value (%)
$\mathcal{C}_7^{\text{NP}}$	-0.02	$[-0.04, -0.00]$	$[-0.07, 0.03]$	1.2	17.0
$\mathcal{C}_9^{\text{NP}}$	-1.09	$[-1.29, -0.87]$	$[-1.67, -0.39]$	**4.5**	63.0
$\mathcal{C}_{10}^{\text{NP}}$	0.56	$[0.32, 0.81]$	$[-0.12, 1.36]$	2.5	25.0
$\mathcal{C}_{7'}^{\text{NP}}$	0.02	$[-0.01, 0.04]$	$[-0.06, 0.09]$	0.6	15.0
$\mathcal{C}_{9'}^{\text{NP}}$	0.46	$[0.18, 0.74]$	$[-0.36, 1.31]$	1.7	19.0
$\mathcal{C}_{10'}^{\text{NP}}$	-0.25	$[-0.44, -0.06]$	$[-0.82, 0.31]$	1.3	17.0
$\mathcal{C}_9^{\text{NP}} = \mathcal{C}_{10}^{\text{NP}}$	-0.22	$[-0.40, -0.02]$	$[-0.74, 0.50]$	1.1	16.0
$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{10}^{\text{NP}}$	-0.68	$[-0.85, -0.50]$	$[-1.22, -0.18]$	**4.2**	56.0
$\mathcal{C}_{9'}^{\text{NP}} = \mathcal{C}_{10'}^{\text{NP}}$	-0.07	$[-0.33, 0.19]$	$[-0.86, 0.68]$	0.3	14.0
$\mathcal{C}_{9'}^{\text{NP}} = -\mathcal{C}_{10'}^{\text{NP}}$	0.19	$[0.07, 0.31]$	$[-0.17, 0.55]$	1.6	18.0
$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{9'}^{\text{NP}}$	-1.06	$[-1.25, -0.86]$	$[-1.60, -0.40]$	**4.8**	72.0
$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{10}^{\text{NP}} = -\mathcal{C}_{9'}^{\text{NP}} = -\mathcal{C}_{10'}^{\text{NP}}$	-0.69	$[-0.89, -0.51]$	$[-1.37, -0.16]$	**4.1**	53.0
$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{10}^{\text{NP}} = \mathcal{C}_{9'}^{\text{NP}} = -\mathcal{C}_{10'}^{\text{NP}}$	-0.19	$[-0.30, -0.07]$	$[-0.55, 0.15]$	1.7	19.0

The model ingredients

- A miminal content of particles
- Anomaly free
- Must include Yukawa constraints
- Flavor changing neutral currents
- Consistent with LE, Collider constraints and the C_9 and c_{10} Wilson Coefficients
- Zero couplings to the first generation

Particle content of the model

particles	spin	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
l_{Li}	1/2	1	2	-1/2	l_i
e_{Ri}	1/2	1	1	-1	e_i
ν_{Ri}	1/2	1	1	0	ν_i
q_{Li}	1/2	3	2	+1/6	q_i
u_{Ri}	1/2	3	1	+2/3	u_i
d_{Ri}	1/2	3	1	-1/3	d_i
ϕ_i	0	1	2	1/2	Y_{ϕ_i}

QFT anomalies

$$[SU(2)]^2U(1)' : \; 0 = \Sigma q + \frac{1}{3}\Sigma l,$$
$$[SU(3)]^2U(1)' : \; 0 = 2\Sigma q - \Sigma u - \Sigma d,$$
$$[\mathrm{grav}]^2U(1)' : \; 0 = 6\Sigma q - 3(\Sigma u + \Sigma d) + 2\Sigma l - \Sigma \nu - \Sigma e$$
$$[U(1)]^2U(1)' : \; 0 = \frac{1}{3}\Sigma q - \frac{8}{3}\Sigma u - \frac{2}{3}\Sigma d + \Sigma l - 2\Sigma e$$
$$U(1)[U(1)']^2 : \; 0 = \Sigma q^2 - 2\Sigma u^2 + \Sigma d^2 - \Sigma l^2 + \Sigma e^2,$$
$$[U(1)']^3 : \; 0 = 6\Sigma q^3 - 3(\Sigma u^3 + \Sigma d^3) + 2\Sigma l^3 - \Sigma \nu^3 - \Sigma e^3$$

$$\Sigma f = f_1 + f_2 + f_3.$$

Yukawa interactions

$$
\begin{aligned}
\mathcal{L}_Y \supset & \bar{l}_{1_L}\tilde{\phi}_1\nu_{1_R} + \bar{l}_{1L}\phi_1 e_{1_R} + \bar{q}_{1_L}\tilde{\phi}_1 u_{1_R} + \bar{q}_{1_L}\phi_1 d_{1_R} + \\
& \bar{l}_{2_L}\tilde{\phi}_2\nu_{2_R} + \bar{l}_{2L}\phi_2 e_{2_R} + \bar{q}_{2_L}\tilde{\phi}_2 u_{2_R} + \bar{q}_{2_L}\phi_2 d_{2_R} + \\
& \bar{l}_{3_L}\tilde{\phi}_3\nu_{3_R} + \bar{l}_{3_L}\phi_3 e_{3_R} + \bar{q}_{3_L}\tilde{\phi}_3 u_{3_R} + \bar{q}_{3_L}\phi_3 d_{3_R} + \text{h.c.}
\end{aligned}
$$

Solution with anomaly cancellation between different families

f	ϵ^{B_I}
l_i	$-3q_i$
e_i	$-\nu_i - 6q_i$
u_i	$+\nu_i + 4q_i$
d_i	$-\nu_i - 2q_i$
l_j	$+\frac{1}{2}[\nu_j - \nu_k - 3(q_j + q_k)]$
e_j	$-\nu_k - 3(q_j + q_k)$
u_j	$+\frac{1}{2}(\nu_j + \nu_k + 5q_j + 3q_k)$
d_j	$-\frac{1}{2}(\nu_j + \nu_k + q_j + 3q_k)$
l_k	$+\frac{1}{2}[-\nu_j + \nu_k - 3(q_j + q_k)]$
e_k	$-\nu_j - 3(q_j + q_k)$
u_k	$+\frac{1}{2}(\nu_j + \nu_k + 3q_j + 5q_k)$
d_k	$-\frac{1}{2}(\nu_j + \nu_k + 3q_j + q_k)$

$$Y_{\phi_1} = \nu_i + 3q_i \text{ and } Y_{\phi_2} = Y_{\phi_3} = \frac{1}{2}[\nu_j + \nu_k + 3(q_j + q_k)],$$

Low energy observables

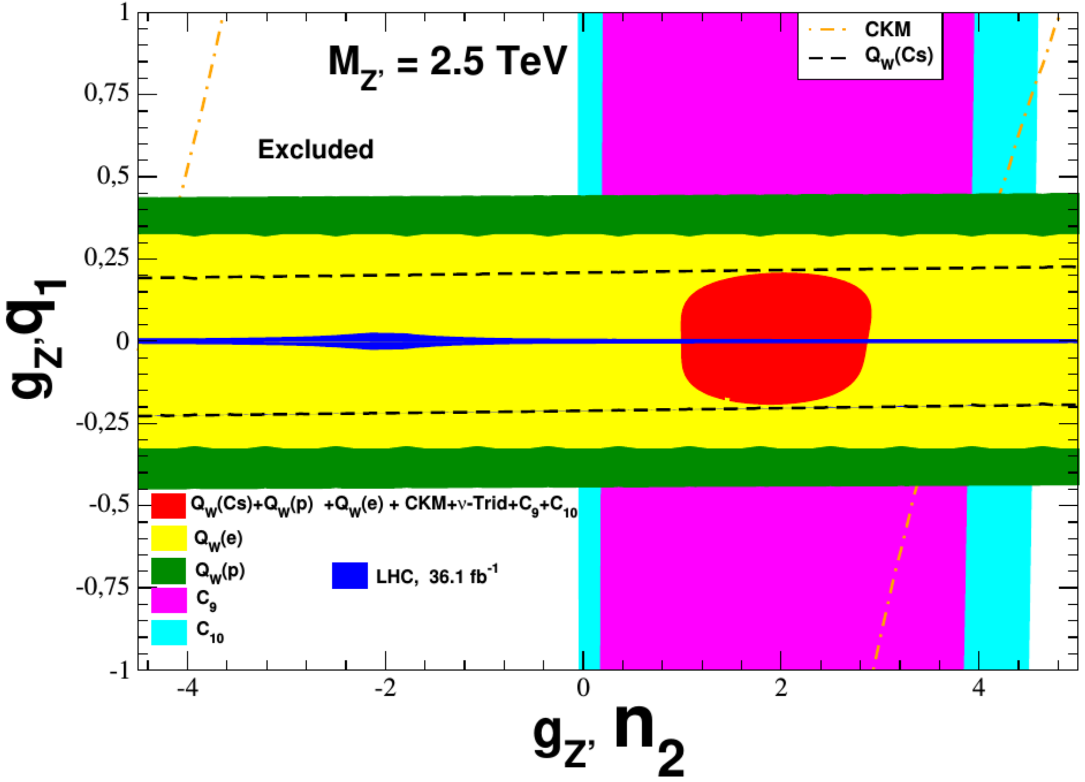
$\mathcal{O}$	Value [43, 50]	SM prediction $\mathcal{O}_{\rm SM}$ [43]	$\Delta\mathcal{O} = \mathcal{O} - \mathcal{O}_{\rm SM}$
$Q_W(p)$	0.064 ± 0.012	0.0708 ± 0.0003	$4\left(\frac{M_Z}{g_1 M_{Z'}}\right)^2 \Delta_A^{ee}\left(2\Delta_V^{uu} + \Delta_V^{dd}\right)$
$Q_W(\mathrm{Cs})$	-72.62 ± 0.43	-73.25 ± 0.02	$Z\Delta Q_W(p) + N\Delta Q_W(n)$
$Q_W(e)$	-0.0403 ± 0.0053	-0.0473 ± 0.0003	$4\left(\frac{M_Z}{g_1 M_{Z'}}\right)^2 \Delta_A^{ee}\Delta_V^{ee}$
$1 - \sum_{q=d,s,b} \|V_{uq}\|^2$	$1 - 0.9999(6)$	0	$\frac{3}{4\pi^2}\frac{M_W^2}{M_{Z'}^2}\left(\ln\frac{M_{Z'}^2}{M_W^2}\right)\Delta_L^{\mu\mu}\left(\Delta_L^{\mu\mu} - \Delta_L^{dd}\right)$
$C_9^{\rm NP}(\mu)$	$-1.29^{+0.21}_{-0.20}$	0	$-\frac{1}{g_1^2 M_{Z'}^2}\frac{\Delta_L^{sb}\Delta_V^{\mu\bar{\mu}}}{V_{ts}^* V_{tb}\sin^2\theta_W}$
$C_{10}^{\rm NP}(\mu)$	$+0.79^{+0.26}_{-0.24}$	0	$-\frac{1}{g_1^2 M_{Z'}^2}\frac{\Delta_L^{sb}\Delta_A^{\mu\bar{\mu}}}{V_{ts}^* V_{tb}\sin^2\theta_W}$
$\frac{\sigma^{\mathrm{SM}+Z'}}{\sigma_{SM}}$	0.83 ± 0.18	1	$\frac{1+\left(1+4s_W^2+\Delta_V^{\mu\mu}\Delta_L^{\nu\nu}v^2/M_{Z'}^2\right)^2}{1+(1+4s_W^2)^2} - 1$

Pulls and best-fit parameters

	$\text{pull}^i = \frac{\mathcal{O}^i_{\text{exp}} - \mathcal{O}^i_{\text{th}}}{\sqrt{\sigma^{i2}_{\text{exp}} + \sigma^{i2}_{\text{th}}}}$							
$\mathcal{O}^i$	$Q_W(p)$	$Q_W(\text{Cs})$	$Q_W(e)$	CKM	C_9	C_{10}	ν-Trident	χ^2_{min}
	-0.566	1.46	1.38	-0.733	-0.789	0.967	-0.985	7.4

$M_{Z'} = 2.5$ TeV	$i = 1$	$i = 2$	$i = 3$
$g_{Z'} l_i$	0	1	-3
$g_{Z'} e_i$	0	0.3523	-3.648
$g_{Z'} n_i$	0	1.648	-2.352
$g_{Z'} q_i$	0	0	2/3
$g_{Z'} u_i$	0	0.6477	1.314
$g_{Z'} d_i$	0	-0.6477	0.01897
$g_{Z'} Y_{\phi_i}$	0	0.03975	

95% C.L. allowed region



Conclusions

- In this work we presented an anomaly-free non-universal Z' family of models, which only includes SM fermions plus right-handed neutrinos and two Higgs doublets.

Conclusions

- By means of an explicit example, we show that it is possible to build a model with zero couplings to the up and down quarks and in general to the fermions of the first family, in such a way that the model evades collider constraints and does not contribute to the corresponding the Wilson coefficients $C_9(e)$ and $C_{10}(e)$. Simultaneously, our solution is flexible enough to accommodate the flavor anomalies in the Wilson coefficients $C_9(\mu)$ and $C_{10}(\mu)$. By requiring that the left-handed couplings of the down and strange couplings be identical it is possible to avoid FCNC.

Thanks!