Minimal Z' models and the LHCb anomalies

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GRUPO DE
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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

- Every one of these measurements deviate from the SM by around 2.5σ's

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

$$R_K = 1.0004(8)$$

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

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

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

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

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

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

Particle content of our model [R.H. Benavides, L. Muñoz, W.A. Ponce, O. Rodríguez, and E. Rojas, work in progress]

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}

Anomalies

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

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

Yukawa interactions

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

Scenario A: the anomaly cancel in every family, we can obtain universal models from this solution

f	ϵ
l_i	$-3q_i$
e_i	$-\nu_i - 6q_i$
u_i	$\nu_i + 4q_i$
d_i	$-\nu_i - 2q_i$

$$\phi_i = \nu_i + 3q_i.$$

Scenario B. Anomalies cancel between different families.

f	$\epsilon(f)$
l_i	$+\nu_i - \Sigma q - \frac{1}{3}\Sigma\nu$
e_i	$+\nu_i - 2\Sigma q - \frac{2}{3}\Sigma\nu$
u_i	$+q_i + \Sigma q + \frac{1}{3}\Sigma\nu$
d_i	$+q_i - \Sigma q - \frac{1}{3}\Sigma\nu$

$$Y_{\phi_{123}} = q_1 + q_2 + q_3 + \frac{1}{3}(\nu_1 + \nu_2 + \nu_3).$$

Scenario C: The anomalies cancel between different families (e.g., L_i-L_j)

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	$-\frac{1}{2}(\nu_j + \nu_k + 3q_j + q_k)$

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

Benchmark models: Vector and tau-philic models

Model	Definition	Constraints	NFP
$Z_V^{\mathbf{A}}$	$\epsilon(f)_L = \epsilon_R(f)$	$n_i = -3q_i,\ i = 1,2,3$	3
$Z_V^{\mathbf{B}}$		$n_k = -n_i - n_j - 3\Sigma q$	5
$Z_V^{\mathbf{C}}$		$n_i = -3q_i,\ n_k = -n_j - 3q_j - 3q_k$	4
$Z_\tau^{\mathbf{A}}$	$\epsilon_{L,R}(e_i) = \epsilon_{L,R}(\nu_i) = 0,\ i = 1,2$	$q_1 = n_1 = q_2 = n_2 = 0$	2
$Z_\tau^{\mathbf{B}}$		$n_1 = n_2 = 0,\ q_2 = -q_1 - \frac{1}{3}(n_3 + 3q_3)$	3
$Z_\tau^{\mathbf{C}}$		$q_1 = n_1 = n_2 = 0,\ q_2 = -\frac{1}{3}(n_3 + 3q_3)$	2

Benchmark models: Lepto-phobic, proton-phobic, neutron-phobic and top-philic models

$Z^{\mathbf{B}}_{\not L}$	$\epsilon_{L,R}(e_i) = \epsilon_{L,R}(\nu_i) = 0$	$n_i = 0,\ n_j = 0,\ n_k = 0\ ,\ q_k = -q_i - q_j$	2
$Z^{\mathbf{C}}_{\not L}$		$n_i = 0,\ n_j = 0,\ n_k = 0\ ,\ q_i = 0,\ q_k = -q_j$	1
$Z^{\mathbf{A,C}}_{\not p}$	$2g_V(u) + g_V(d) = 0$	$n_1 = -9q_1$	5
$Z^{\mathbf{B}}_{\not p}$		$n_3 = -n_1 - n_2 - 3\Sigma q - 18q_1$	5
$Z^{\mathbf{A,C}}_{\not n}$	$g_V(u) + 2g_V(d) = 0$	$n_1 = 3q_1$	5
$Z^{\mathbf{B}}_{\not n}$		$n_3 = -n_1 - n_2 - 3\Sigma q + 18q_1$	5
$Z^{\mathbf{B}}_{t}$	$\epsilon_{L,R}(u_i) = \epsilon_{L,R}(d_i) = 0,\ i = 1, 2$	$q_1 = 0,\ q_2 = 0,\ n_3 = -n_1 - n_2 - 3q_3$	3
$Z^{\mathbf{C}}_{t}$		$q_1 = 0,\ n_1 = 0,\ q_2 = 0,\ n_3 = -n_2 - 3q_3$	2

Benchmark models: Barion-phobic and models without FCNC in the quark sector

$Z^{\mathbf{B}}_{\not{B}}$	$\epsilon_{L,R}(u_i) = \epsilon_{L,R}(d_i) = 0,\ i = 1,2,3$	$q_i = q_j = q_k = 0,\ n_k = -n_i - n_j$	2
$Z^{\mathbf{C}}_{\not{B}}$		$q_i = q_j = q_k = 0,\ n_i = 0,\ n_k = -n_j$	1
$Z^{\mathbf{A}}_{\not{\mathrm{FCNC}}q}$	$\epsilon_{L,R}(u_1(d_1)) = \epsilon_{L,R}(u_2(d_2))$	$q_1 = q_2,\ n_1 = n_2$	3
$Z^{\mathbf{B}}_{\not{\mathrm{FCNC}}q}$		$q_1 = q_2$	5
$Z^{\mathbf{C}}_{\not{\mathrm{FCNC}}q}$		$q_1 = q_2,\ n_3 = 2n_1 - n_2 + 3q_1 - 3q_3$	4

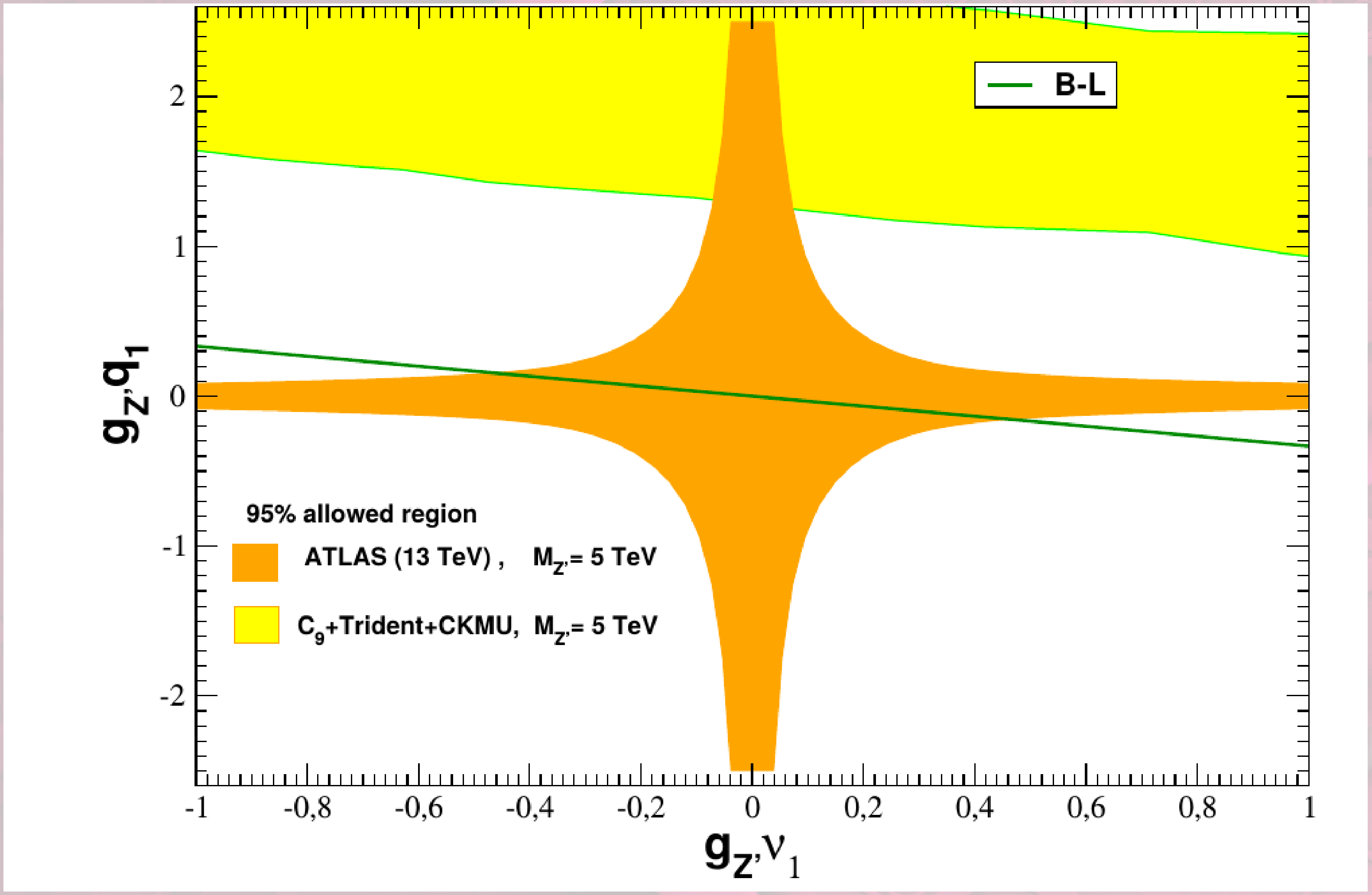
Charges for some benchmark models

f	Scenario $\mathbf{C}$	Vector Models			
f	$a\epsilon^S + b\epsilon^A$	$Z_V^{\mathbf{A}}$	$Z_V^{\mathbf{B}}$	$Z_V^{\mathbf{C}}$	$Z_{\mathrm{CKM}}^{\mathbf{B}}$
ν_i	$a\hat{\nu}_i$	ν_i	ν_i	ν_i	ν_i
l_i	$-3a\hat{q}_i$	ν_i	ν_i	ν_i	$\nu_i - 3q_i - \frac{1}{3}\Sigma\nu$
e_i	$-a(\hat{\nu}_i + 6\hat{q}_i)$	ν_i	ν_i	ν_i	$\nu_i - 6q_i - \frac{2}{3}\Sigma\nu$
q_i	$a\hat{q}_i$	$-\frac{\nu_i}{3}$	q_i	$-\frac{\nu_i}{3}$	q_i
u_i	$+a(\hat{\nu}_i + 4\hat{q}_i)$	$-\frac{\nu_i}{3}$	q_i	$-\frac{\nu_i}{3}$	$4q_i + \frac{1}{3}\Sigma\nu$
d_i	$-a(\hat{\nu}_i + 2\hat{q}_i)$	$-\frac{\nu_i}{3}$	q_i	$-\frac{\nu_i}{3}$	$2q_i - \frac{1}{3}\Sigma\nu$
ν_j	$a\hat{\nu}_j + b\hat{\nu}_j$	ν_j	ν_j	ν_j	ν_j
l_j	$-3a\hat{q}_j + b\hat{\nu}_j$	ν_j	ν_j	ν_j	$\nu_j - 3q_i - \frac{1}{3}\Sigma\nu$
e_j	$-a(\hat{\nu}_j + 6\hat{q}_j) + b\hat{\nu}_j$	ν_j	ν_j	ν_j	$\nu_j - 6q_i - \frac{2}{3}\Sigma\nu$
q_j	$a\hat{q}_j + b\hat{q}_j$	$-\frac{\nu_j}{3}$	q_j	q_j	q_i
u_j	$+a(\hat{\nu}_j + 4\hat{q}_j) + b\hat{q}_j$	$-\frac{\nu_j}{3}$	q_j	q_j	$4q_i + \frac{1}{3}\Sigma\nu$
d_j	$-a(\hat{\nu}_j + 2\hat{q}_j) + b\hat{q}_j$	$-\frac{\nu_j}{3}$	q_j	q_j	$2q_i - \frac{1}{3}\Sigma\nu$
ν_k	$a\hat{\nu}_j - b\hat{\nu}_j$	ν_k	$\nu_i - \Sigma n - 3\Sigma q$	ν_k	ν_k
l_k	$-3a\hat{q}_j - b\hat{\nu}_j$	ν_k	$\nu_i - \Sigma n - 3\Sigma q$	ν_k	$\nu_k - 3q_i - \frac{1}{3}\Sigma\nu$
e_k	$-a(\hat{\nu}_j + 6\hat{q}_j) - b\hat{\nu}_j$	ν_k	$\nu_i - \Sigma n - 3\Sigma q$	ν_k	$\nu_k - 6q_i - \frac{2}{3}\Sigma\nu$
q_k	$a\hat{q}_j - b\hat{q}_j$	$-\frac{\nu_k}{3}$	q_k	$-\frac{1}{3}(\nu_j + \nu_k + 3q_j)$	q_i
u_k	$+a(\hat{\nu}_j + 4\hat{q}_j) - b\hat{q}_j$	$-\frac{\nu_k}{3}$	q_k	$-\frac{1}{3}(\nu_j + \nu_k + 3q_j)$	$4q_i + \frac{1}{3}\Sigma\nu$
d_k	$-a(\hat{\nu}_j + 2\hat{q}_j) - b\hat{q}_j$	$-\frac{\nu_k}{3}$	q_k	$-\frac{1}{3}(\nu_j + \nu_k + 3q_j)$	$2q_i - \frac{1}{3}\Sigma\nu$

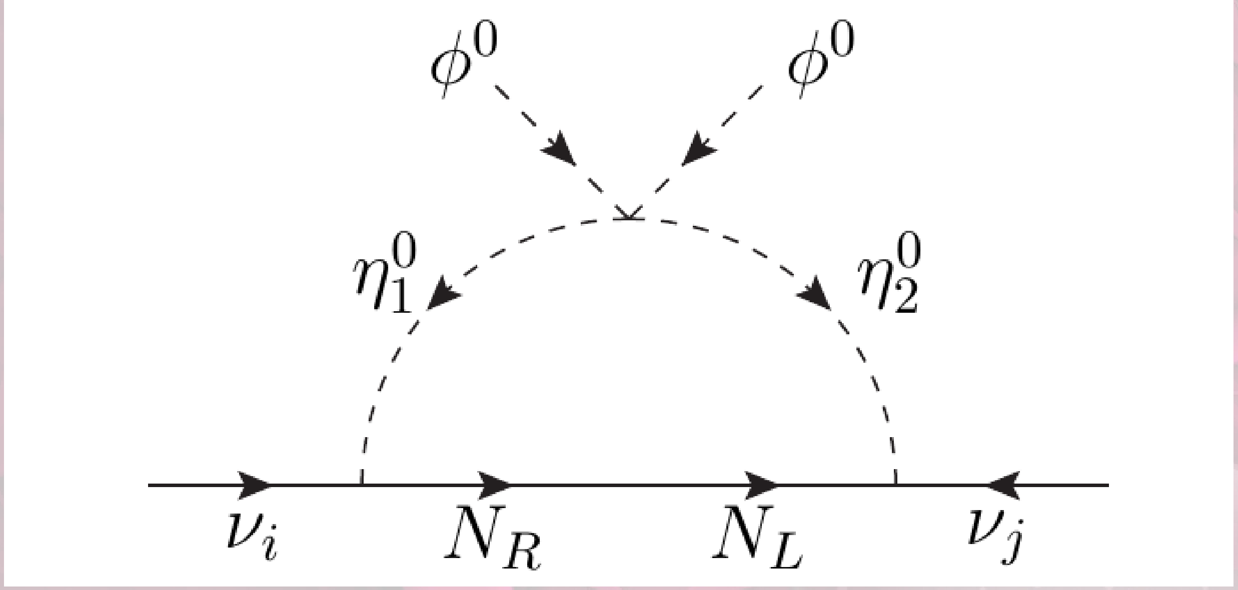
Low-energy observables

$\mathcal{O}$	Value [46, 47]	SM prediction $\mathcal{O}_{\rm SM}$ [46]	$\Delta\mathcal{O} = \mathcal{O} - \mathcal{O}_{\rm SM}$
$Q_W(\rm Cs)$	-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	$-4\left(\frac{g' M_Z}{g^{(1)} M_{Z'}}\right)^2 g'_A(e) g'_V(e)$
$1 - \sum_{q=d,s,b} \|V_{uq}\|^2$	$1 - 0.9999(6)$	0	$\Delta_0 \epsilon_L(\mu)\left(\epsilon_L(\mu) - \epsilon_L(d)\right)$
$C_9^{\rm NP}$	$-1.29^{+0.21}_{-0.20}$	0	$-\frac{1}{g_{SM}^2 M_{Z'}^2} \frac{\Delta_L^{sb}(Z')\Delta_V^{\mu\bar{\mu}}(Z')}{V_{ts}^* V_{tb} \sin^2\theta_W}$
$C_{10}^{\rm NP}$	$+0.79^{+0.26}_{-0.24}$	0	$-\frac{1}{g_{SM}^2 M_{Z'}^2} \frac{\Delta_L^{sb}(Z')\Delta_A^{\mu\bar{\mu}}(Z')}{V_{ts}^* V_{tb} \sin^2\theta_W}$
$\frac{\sigma^{\rm SM+Z'}}{\sigma_{SM}}$	0.83 ± 0.18	1	$\frac{1+\left(1+4s_W^2+2\Delta_L^2(\mu_L)v^2/M_{Z'}^2\right)^2}{1+(1+4s_W^2)^2} - 1$

ATLAS and low energy constraints



By adding two Higgs doublets it is possible to have a minimal non-universal Z’ model with a scotogenic mechanism to generate neutrino masses and dark matter. The U(1) have a double roll, to generate a residual Z_2 discrete symmetry and serve as leverage to accommodate the LHCb anomalies. [D.Blandon, D. Restrepo and E.R work in progress]



Conclusions

- We present the most general solutions for the charges of a Z' with a minimal content of fermions. From our analysis,
- we show the existence of three different scenarios which, as far as we know, are new in the literature.
- These solutions reduce to very well-known cases for particular choices of the free parameters.
- We also define several benchmark models in order to show the flexibility of our parameterizations.
- In order to make a connection with the phenomenology, we show that it is possible to adjust some
- of these benchmark models to several observables, including C_9 and C_{10} which are involved in the LHCb anomalies.
- We use the upper limits on the Z' cross-sections
- of extra gauge vector bosons Z' decaying into dileptons from the ATLAS data at 13 TeV with an accumulated luminosity of $36.1~fb^{-1}$
- to set the 95\% CL allowed regions in the parameter space for a Z' mass of 5~TeV.

By using ATLAS data from the Drell-Yan process pp -> Z, \gamma->l^+l^- we set 95% CL lower limits for the Z' mass for some benchmark models.