Models with tree-level Z' to explain the $b \to s\ell^+\ell^-$ anomalies

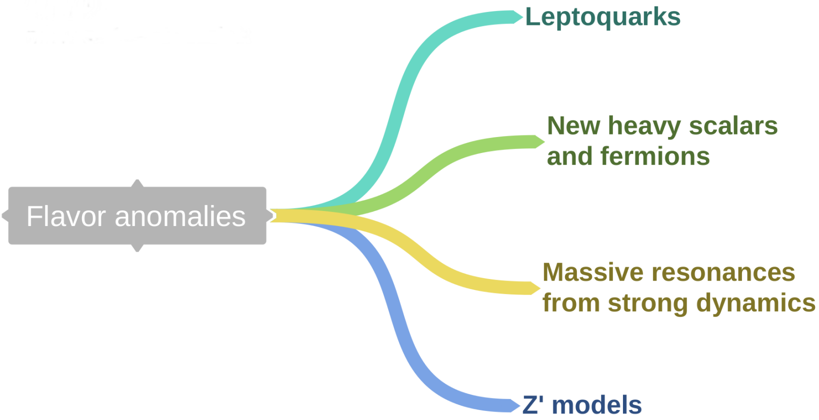
Javier Fuentes-Martín

IFIC, Universitat de València-CSIC

Instant workshop on B meson anomalies

CERN, May 18, 2017

New Physics explanations for $b \to s\ell^+\ell^-$ anomalies

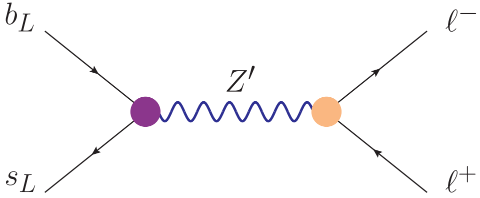


Here I will discuss (heavy) tree-level Z' models. See following talks for other explanations

Z' model building

$$\mathrm{G} \equiv \mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathbf{G_E}$$

B_s mixing



Neutrino trident production (for $\ell = \mu$)

Flavor violating couplings to quarks (in left-handed quarks)

Lepton-flavor universality violation

Z' model building

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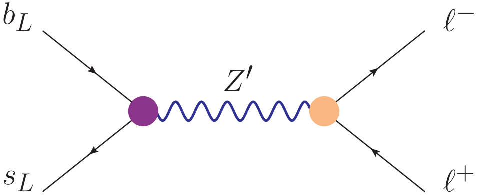

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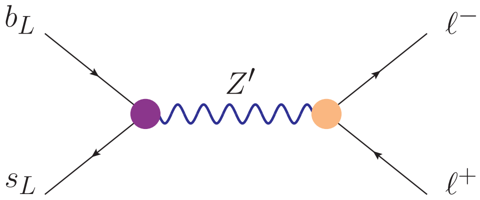


Neutrino trident production (for $\ell = \mu$)

Flavor violating couplings to quarks (in left-handed quarks)

Lepton-flavor universality violation

What should $\mathbf{G_E}$ be?

- **$\mathbf{SU(2)_L}$ singlet case**: $\mathbf{G_E^{min}} \equiv U(1)'$
- **$\mathbf{SU(2)_L}$ triplet case**: $\mathbf{G_E^{min}} \equiv SU(2)'$

$\mathbf{G} \equiv \mathbf{SU(3)}_c \times \mathbf{SU(2)}_L \times \mathbf{U(1)}_Y \times \mathbf{G_E}$

Shopping list:

- **Singlet case**: $\mathbf{G_E} \equiv \mathrm{U}(1)'$, $\mathrm{U}(1)' \times \mathrm{U}(1)''$
- **Triplet case**: $\mathbf{G_E} \equiv \mathrm{SU}(2)'$

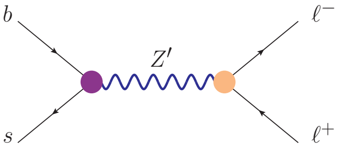
Extra requirements:

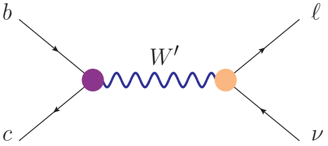
- Extended scalar sector to give mass to the Z' and/or to accommodate quark masses and mixing angles

Wish list:

- Minimal particle content (e.g. SM fermions only)
- Couplings controlled by the flavor symmetry (i.e. no *ad-hoc* assumptions on the parameters)
- Interplay with other NP (i.e. Dark Matter, Flavor puzzle,...)

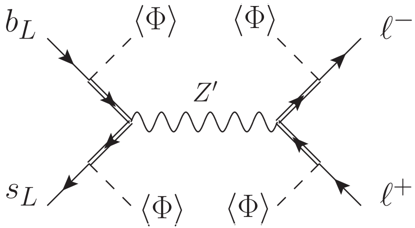
Models with an extra $\mathrm{SU}(2)'$





- The triplet operator $\mathcal{O}_{\ell q}^{(3)}$ can provide a simultaneous explanation to the $b \to s\ell^+\ell^+$ and $R(D^{(*)})$ anomalies **See talks by Isidori and Crivellin**
  e.g. Alonso, Grinstein, Camalich, 1505.05164 ; Bordone, Isidori, Trifinopoulos, 1702.07238
- Dynamical $\mathrm{SU}(2)'$ model Greljo, Isidori, Marzocca, 1506.01705
- Ultraviolet complete $\mathrm{SU}(2)'$ model Boucenna et al., 1604.03088, 1608.01349
  - $\mathrm{SU}(2)_1 \times \mathrm{SU}(2)_2 \times \mathrm{U}(1)_\mathrm{Y}$
  - Non-universality induced through mixing with VL fermions
- Tensions with direct searches at LHC Faroughy, Greljo, Kamenik, 1609.07138
- Quantum corrections are important **See talk by Paradisi**

$\mathrm{U}(1)'$ models with vector-like fermions



Sierra, Staub, Vicente, 1503.06077

- Extend the SM with an extra gauged dark $\mathrm{U}(1)_\mathrm{X}$
- Add heavy vector-like fermions charged under $\mathrm{U}(1)_\mathrm{X}$
- SM-VL mixing induces effective SM Z' couplings

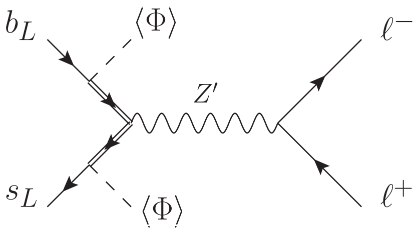
✓ Interesting interplay with DM

✓ Very general framework

✗ The mixing parameters are ad hoc

✗ Lack of predictability. The SM-VL mixings are unknown

$\mathrm{U}(1)'$ models with vector-like fermions



Altmannshofer, Gori, Pospelov, Yavin, 1403.1269

Crivellin, D'Ambrosio, Heeck, 1501.00993

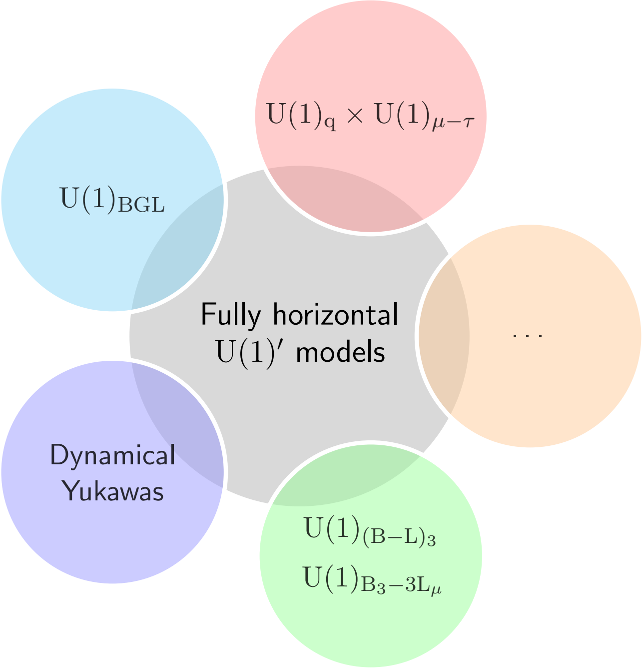
- Gauge the $\mathrm{U}(1)_{\mu-\tau}$ symmetry
- Automatically anomaly-free with the SM alone
- Good zeroth order approximation to neutrino mixing with quasi-degenerate masses
- SM-VL mixing induces effective SM Z' couplings with quarks

✓ Predictions in the lepton sector

✓ Interesting interplay with DM
Altmannshofer et al., 1609.04026

✗ The mixing parameters are ad hoc

✗ Lack of predictability in the quark sector


$U(1)_{BGL}$
$U(1)_q \times U(1)_{\mu-\tau}$
Fully horizontal
$U(1)'$ models
...
Dynamical
Yukawas
$U(1)_{(B-L)_3}$
$U(1)_{B_3-3L_\mu}$

Gauged $\mathbf{U(1)' \subset U(1)_{B_1+B_2-2B_3} \times U(1)_{\mu-\tau}}$

Crivellin, D'Ambrosio, Heeck, 1503.03477

$$-\mathcal{L}_{\mathsf{Y}} = \overline{Q_L^0}\,\left[Y_1^u\,\widetilde{\Phi}_1 + Y_2^u\,\widetilde{\Phi}_2\right] u_R^0 + \overline{Q_L^0}\,\left[Y_1^d\,\Phi_1 + Y_2^d\,\Phi_2\right] d_R^0 + \text{h.c.}$$

$$Y_1^u = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & \times \end{pmatrix} \quad Y_2^u = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & 0 \end{pmatrix}$$

$$Y_1^d = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & \times \end{pmatrix} \quad Y_2^d = \begin{pmatrix} 0 & 0 & \times \\ 0 & 0 & \times \\ 0 & 0 & 0 \end{pmatrix}$$

- The model predicts approximate MFV-like FCNCs

$$Z'\bar{d}_{Li}d_{Lj} \sim g'\left(\boldsymbol{V_{ti}^* V_{tj}} - \frac{1}{3}\delta_{ij}\right) \qquad Z'\bar{d}_{Ri}d_{Rj} \sim -\frac{g'}{3}\,\mathrm{diag}\,(1,1,-2)$$

- RH FCNCs for up quarks assumed to vanish (no symmetry protection)

Flavor anomalies from dynamical Yukawas

Crivellin, JF, Greljo, Isidori, 1611.02703

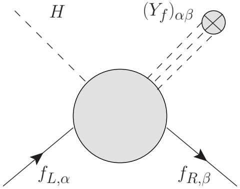
Dynamical Yukawa couplings

Anselm, Berezhiani, 96'; Berezhiani, Rossi, 01', ...

In the limit $Y_{u,d,e,\nu} \to 0$ (and 3 right-handed Majorana neutrinos):

$$\mathcal{G} = \mathbf{SU(3)}_{\boldsymbol{Q}} \times \mathbf{SU(3)}_{\boldsymbol{D}} \times \mathbf{SU(3)}_{\boldsymbol{U}} \times \mathbf{SU(3)}_{\boldsymbol{\ell}} \times \mathbf{SU(3)}_{\boldsymbol{E}} \times \boldsymbol{\mathcal{O}(3)}_{\boldsymbol{\nu_R}}$$

- Promote this symmetry to a local symmetry of nature
- Yukawas arise from dynamical fields:



$\phi \sim (3, \bar{3})$

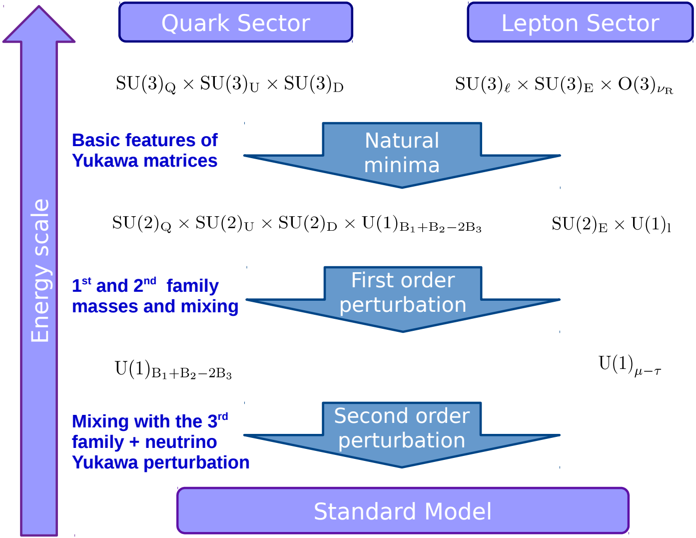
$V(\phi)$ invariant under $\mathcal{G}$

$Y_f \sim \frac{\langle\phi\rangle}{\Lambda}$ or $\frac{\Lambda}{\langle\phi\rangle}$ or ...

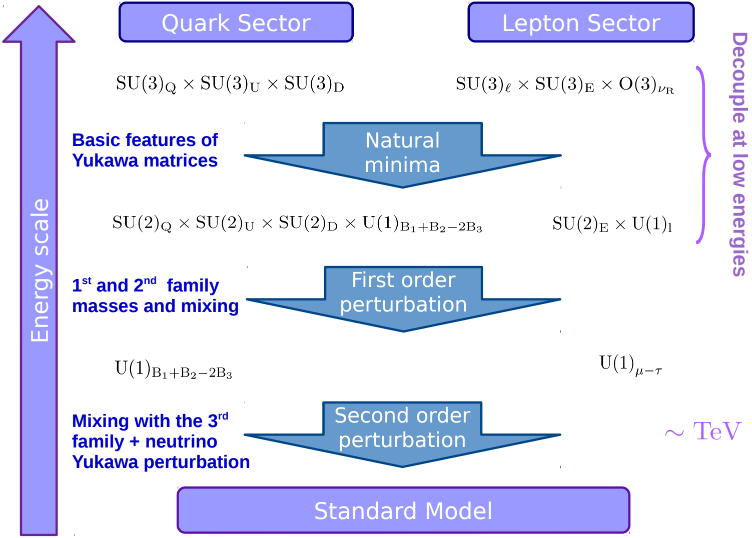
- The vevs of the Yukawa flavons yield a sequential breaking of $\mathcal{G}$ and can potentially explain the SM Yukawa structure

Alonso, Gavela, Isidori, Maiani, 1306.5927

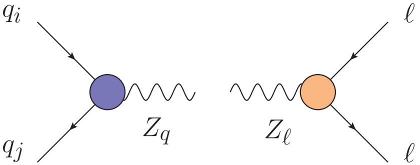
Dynamical Yukawas: The big picture



Dynamical Yukawas: The big picture



$\mathbf{U(1)_{B_1+B_2-2B_3} \times U(1)_{\mu-\tau}}$ couplings



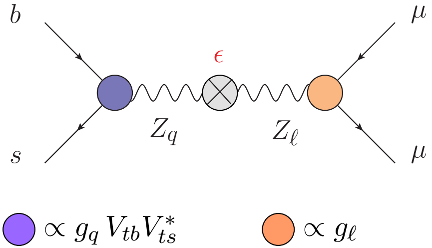
$\propto g_q \left[V_{ti} V_{tj}^* - \delta_{ij} \frac{1}{3} \right]$

(MFV-like FCNCs)

$\propto g_\ell \, \mathrm{diag}(0, 1, -1)$

Maximal LFNU (and no cLFV)

$\mathrm{U}(1)_{\mathrm{B_1+B_2-2B_3}} \times \mathrm{U}(1)_{\mu-\tau}$ couplings



To explain the $b \to s\ell^+\ell^-$ anomalies **both Z' should mix (mass mixing)**

$$C_9^\mu\big|_{\mathrm{NP}} = -\left(\frac{g_q \Lambda_v}{M_{Z_2}}\right)\left(\frac{g_\ell \Lambda_v}{M_{Z_1}}\right)\epsilon + \mathcal{O}\left(\epsilon^2\right)$$

$\epsilon \sim \mathcal{O}\,(0.1)$
mixing parameter

$\Lambda_v \simeq 7$ TeV

Z' models with protected flavor-changing interactions

Celis, JF, Jung, Serôdio, 1505.03079

Top BGL model

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

Top-BGL symmetry Branco, Grimus, Lavoura, Phys.Lett. B380 (1996)

$$Y_1^u|_{\text{BGL}} = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad Y_2^u|_{\text{BGL}} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}$$

$$Y_1^d|_{\text{BGL}} = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ 0 & 0 & 0 \end{pmatrix} \quad Y_2^d|_{\text{BGL}} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix}$$

- FCNCs only in the down-quark sector and controlled exactly by the CKM

$$H\bar{d}_{Li}d_{Lj} \propto (\mathbf{V}_{\mathsf{CKM}})^*_{\mathbf{ti}}(\mathbf{V}_{\mathsf{CKM}})_{\mathbf{tj}}\, m_{d_j}$$

- By gauging the top-BGL symmetry, the resulting Z' inherits the same MFV-like structure for the FCNCs

Gauged top-BGL

The most general top $\mathrm{U}(1)_{\mathrm{BGL}}$ symmetry is

$$
\begin{aligned}
Q_{q_L} &= \frac{1}{2}\left[\mathrm{diag}\left(X_{uR}, X_{uR}, X_{tR}\right) + X_{dR}\,\mathbb{1}\right] \\
Q_{u_R} &= \mathrm{diag}\left(X_{uR}, X_{uR}, X_{tR}\right) \\
Q_{d_R} &= X_{dR}\,\mathbb{1} \\
Q_{\Phi} &= \frac{1}{2}\mathrm{diag}\left(X_{uR} - X_{dR}, X_{tR} - X_{dR}\right)
\end{aligned}
$$

and $X_{uR} \neq X_{tR}$

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

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

- Only one solution to the anomaly conditions!... and just one free charge

Anomaly-free top-BGL implementation

$$Y_1^e = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad Y_2^e = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}$$

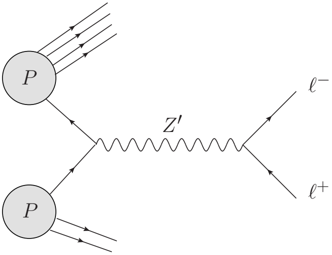
- **Six possible lepton-charge permutations:** $(e, \mu, \tau) = (i, j, k)$
- Non-universal lepton charges...

  ... yet no FCNCs in the charged lepton sector

  (automatic symmetry protection)
- All $\mathcal{C}_{9,10}^{\ell}|_{\rm NP}$ WCs are generated and are fixed by the symmetry ($\mathcal{C}_9^{\mu}$ gets the dominant value for the working permutations)
- Unavoidably large diagonal couplings to light quarks

Bounds from LHC direct searches

Resonant production

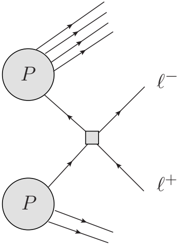


$$\boxed{M_{Z'} \gtrsim 1-5 \text{ TeV}}$$

Limited by the current mass reach

ATLAS-CONF-2017-027

Non-resonant production ($s \ll M_{Z'}$)



- Important constraints beyond the kinematic reach
- Tensions in models with large diagonal couplings to light quarks

Greljo, Marzocca, 1704.09015

LHC-"safe" solutions

LHC bounds suggest that light-quark diagonal couplings should be suppressed:

- Models with vector-like quarks

  e.g. Altmannshofer, Gori, Pospelov, Yavin, 1403.1269

- Models with more than one mediator (mixing suppression)
  - e.g. $\mathrm{U}(1)_{\mathrm{B}_1+\mathrm{B}_2-2\mathrm{B}_3} \times \mathrm{U}(1)_{\mu-\tau}$ Crivellin, JF, Greljo, Isidori, 1611.02703

- Fully horizontal Z' models with third-family charges only
  - $\mathrm{U}(1)_{(B-L)_3}$ Alonso, Cox, Han, Yanagida, 1705.03858
    - ⋆ Well motivated from GUT: $(\mathrm{SU}(10))^3 \to \mathrm{SU}(5) \times \mathrm{U}(1)_{(B-L)_3}$
  - $\mathrm{U}(1)_{B_3-3L_\mu}$ Bonilla, Modak, Srivastava, Valle, 1705.00915
    - ⋆ Interesting textures in the neutrino mass matrix

      Bhatia, Chakraborty, Dighe, 1701.05825
  - $\mathrm{U}(1)_{\mathrm{BGL}}$ models?

LHC-"safe" top-BGL implementation

The most general top $\mathrm{U}(1)_{\mathrm{BGL}}$ symmetry is

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\end{aligned}
$$

LHC-"safe" top-BGL implementation

The most general top $\mathrm{U}(1)_{\mathrm{BGL}}$ symmetry is

$$
\begin{aligned}
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Q_{u_R} &= \operatorname{diag}\left(X_{uR}, X_{uR}, X_{tR}\right) \\
Q_{d_R} &= X_{dR}\,\mathbb{1} \\
Q_{\Phi} &= \frac{1}{2}\operatorname{diag}\left(X_{uR} - X_{dR}, X_{tR} - X_{dR}\right)
\end{aligned}
$$

- Null charges to light quarks: $X_{uR} = X_{dR} = 0$

LHC-“safe” top-BGL implementation

The LHC-“safe” top $\mathrm{U}(1)_{\mathrm{BGL}}$ symmetry is

$$\begin{aligned} Q_{q_L} &= \frac{1}{2}\mathrm{diag}\,(0,0,X_{tR}) \\ Q_{u_R} &= \mathrm{diag}\,(0,0,X_{tR}) \\ Q_{d_R} &= \mathrm{diag}\,(0,0,0) \\ Q_{\Phi} &= \frac{1}{2}\,\mathrm{diag}\,(0,X_{tR}) \end{aligned}$$

- Null charges to light quarks: $X_{uR} = X_{dR} = 0$
- Anomaly-free implementation not possible with the SM fermions alone
- **Next-to-minimal ansatz:** Extra fermions + interplay with other NP
  - Fermion Dark Matter candidate
  - Neutrino masses: SM singlets (type-I see-saw) and/or $\mathrm{SU}(2)$ triplets (type-III see-saw)

LHC-“safe” anomaly-free top-BGL implementation

An example from Ellis, Fairbairn, Tunney, 1705.03447
(χ is a fermion Dark Matter candidate)

$$Q_{q_L} = \frac{1}{2}\mathrm{diag}\,(0,0,1) \qquad Q_{\ell_L} = \frac{1}{2}\,\mathrm{diag}\,(0,-3,0)$$

$$Q_{u_R} = \mathrm{diag}\,(0,0,1) \qquad Q_{e_R} = \mathrm{diag}\,(0,-2,0)$$

$$Q_{d_R} = \mathrm{diag}\,(0,0,0) \qquad Q_{\chi_L} = 1 \qquad Q_{\chi_R} = 0$$

- ✓ BGL Yukawa structure when $X_{\Phi_1} = 0$ and $X_{\Phi_2} = 1/2$
  $\Longrightarrow$ Symmetry protection for FCNCs
- ✓ Anomaly-free implementation
- LHC and DM bounds relaxed

Other implementations are currently under investigation

[Celis,JF,Jung,Serôdio]

So... summing up

Conclusions

- **Z' models provide one of the simplest explanation to the anomalies**
- **Many well-motivated implementations... but each of them give characteristic predictions that can be tested in the near future**
- **Interesting interplay between low- and high-pT searches. While global fits select interesting scenarios, LHC searches already constraint some explanations**

So... summing up

Conclusions

- Z' models provide one of the simplest explanation to the anomalies
- Many well-motivated implementations... but each of them give characteristic predictions that can be tested in the near future
- Interesting interplay between low- and high-pT searches. While global fits select interesting scenarios, LHC searches already constraint some explanations

Thanks!