Flavoured $B-L$ symmetry: from B decays to dark matter

(arXiv:1705.03858)

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Motivation

A well-motivated extension of the Standard Model is the addition of 3 right-handed neutrinos, which allows for the generation of small neutrino masses via the seesaw mechanism, and the observed baryon asymmetry through leptogenesis.

This model possesses an exact $B-L$ global symmetry in the limit of vanishing Majorana masses. It is natural to promote such a global symmetry to a local one; however the large RH neutrino masses needed for leptogenesis then lead to a very high breaking scale for the $B-L$ symmetry.

However, *two* superheavy RH neutrinos are sufficient for both seesaw and leptogenesis. It is therefore interesting to consider the possibility that a *flavoured* $B-L$ gauge symmetry could survive at low energies ($\sim$ TeV). The third RH neutrino is then light and can provide a dark matter candidate.

$U(1)_{(B-L)_3}$ Model

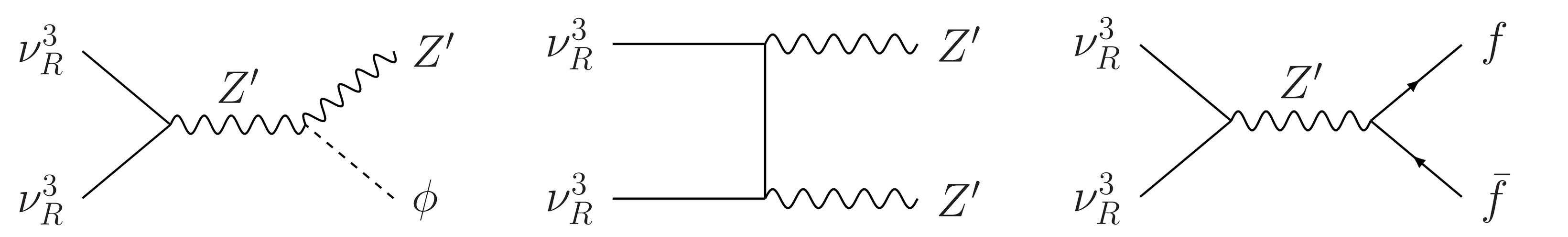
We introduce a *flavoured* $B-L$ gauge symmetry under which only the 3rd generation fermions are charged. The SM quarks and leptons take the following $U(1)_{(B-L)_3}$ charges in flavour space:

$$T^q = \frac{1}{3}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad T^l = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

The $U(1)$ symmetry is *vectorial*, with the same charges for LH and RH fields, and is anomaly free. The SM Higgs is taken to be neutral under $U(1)_{(B-L)_3}$.

RH Neutrino Dark Matter

- The third RH neutrino obtains a Majorana mass upon spontaneous breaking of $U(1)_{(B-L)_3}$ by a scalar, $\phi\,(+2)$.
- Imposing an additional $\mathbb{Z}_2$ symmetry renders ν_R^3 stable, and a viable dark matter candidate.
- $\mathbb{Z}_2$ symmetry is further motivated by structure of the neutrino mass matrix.
- Produced via thermal freeze-out; annihilation through $U(1)_{(B-L)_3}$ gauge interactions:



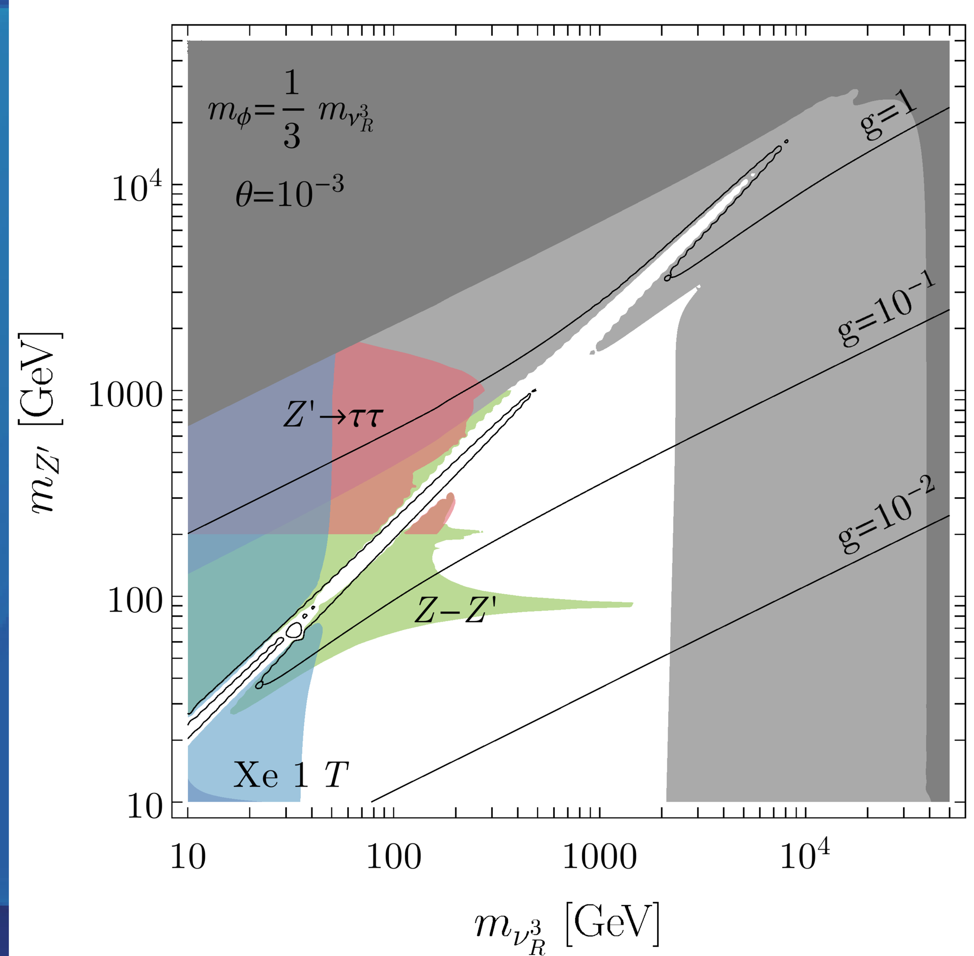


Figure: All regions satisfy correct relic density. Coloured regions are excluded by experiment, and dark (light) grey regions by perturbative unitarity (perturbativity up to M_{Pl}).

- **Direct detection**
  Generally suppressed due to Majorana dark matter and no Z' coupling to light quarks. However, can have a significant cross-section via ϕ-Higgs mixing.
- **Indirect detection**
  Annihilation cross-section is velocity-suppressed over much of the parameter space. $\nu_R^3\nu_R^3 \to \phi Z'$ is s-wave and can be probed with future gamma-ray experiments.
- **LHC searches**
  Small production cross-section, $\bar{b}b \to Z'$. Strongest bound is from $Z' \to \tau\tau$.
- **Electroweak precision**
  Kinetic mixing between Z' and Z is strongly constrained.
  Non-zero mixing is generated by RGE evolution, even if vanishing at high scales.
- **Perturbativity**
  Perturbative unitarity excludes large dark matter and Z' masses. Bounds become significantly stronger if requiring perturbativity of couplings up to M_{Pl}.

Anomalies in $b \to s\mu\mu$

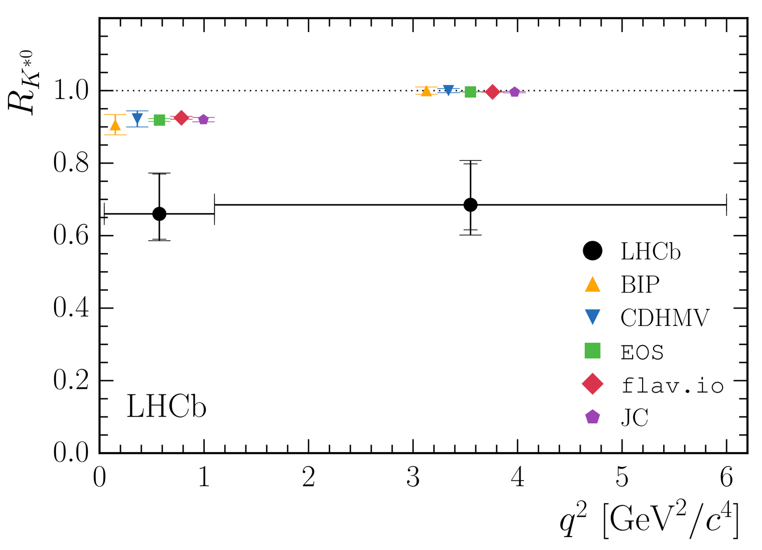
Recently, there have been several intriguing hints of lepton flavour universality (LFU) violation in B decays. Measurements by LHCb [1, 2] of the theoretically clean ratios

$$\mathcal{R}_K^{(*)} = \frac{\Gamma\left(B \to K^{(*)}\mu^+\mu^-\right)}{\Gamma\left(B \to K^{(*)}e^+e^-\right)}$$

show a deficit with respect to the SM prediction, leading to a combined tension with the SM of around 4σ.

It is well-known that this tension can be alleviated via a new physics contribution to the effective operators:

$$\mathcal{O}_9^l = \frac{\alpha}{4\pi}\left(\bar{s}\gamma_\mu b_L\right)\left(\bar{l}\gamma_\mu l\right)$$
$$\mathcal{O}_{10}^l = \frac{\alpha}{4\pi}\left(\bar{s}\gamma_\mu b_L\right)\left(\bar{l}\gamma_\mu \gamma^5 l\right)$$
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}}V_{tb}V_{ts}^*\left(C_9^l\mathcal{O}_9^l + C_{10}^l\mathcal{O}_{10}^l\right)$$



Flavour Phenomenology

- Z' interactions are generally not flavour diagonal after rotation to the mass basis.
- Can be additional mixing angles involving the 3rd generation, beyond those present in V_{CKM} and U_{PMNS}.
- To explain the LFU anomalies, two new angles $(\theta_l,\,\theta_q)$ are sufficient:

$$U_{e_L} = R^{23}(\theta_l), \quad U_{\nu_L} = R^{23}(\theta_l)U_{PMNS}, \quad U_{d_L} = R^{23}(\theta_q), \quad U_{u_L} = R^{23}(\theta_q)V_{CKM}^\dagger$$

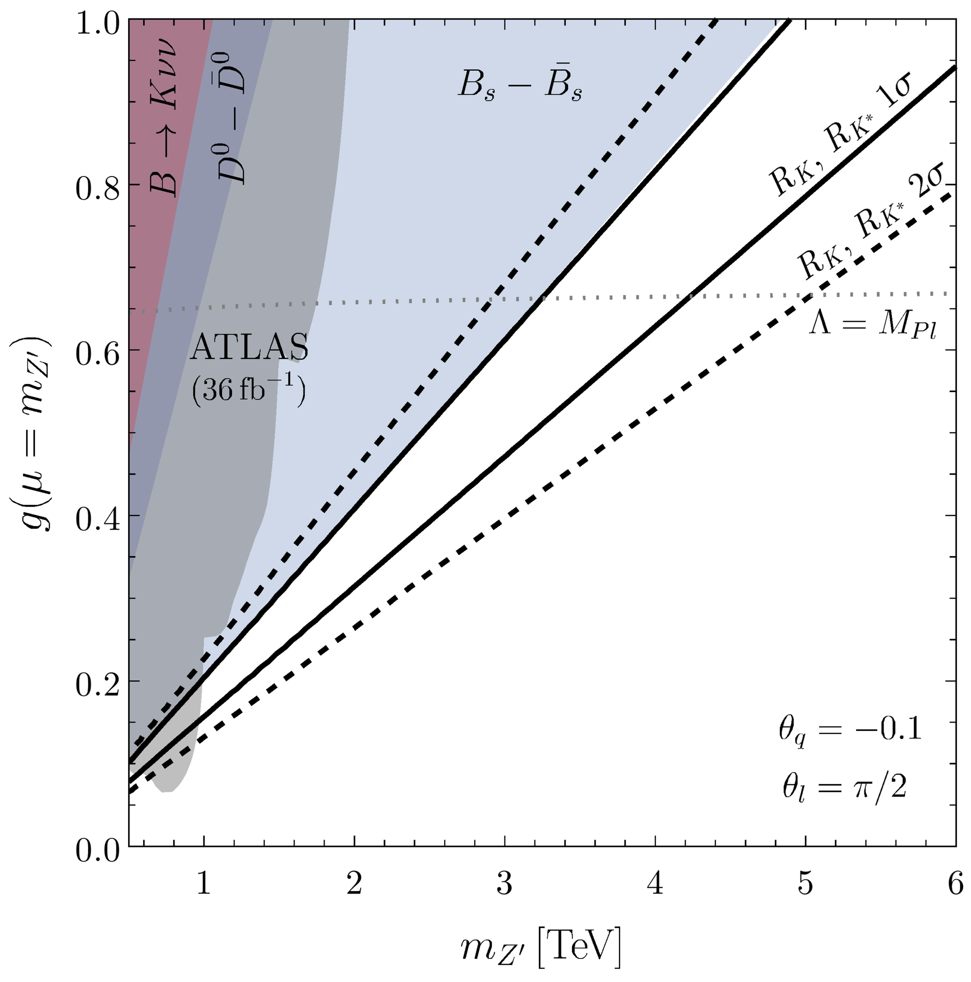


Figure: Best-fit region to the LFU anomalies (solid/dashed lines). Shaded regions are excluded by existing measurements at 95% CL.

- **LFU anomalies**
  Integrating out Z' gives a contribution to the Wilson coefficients:
  $$\delta C_9^\mu = -\delta C_{10}^\mu = -\frac{\pi}{\alpha\sqrt{2}G_F V_{tb}V_{ts}^*}\frac{g^2 s_{\theta_q}c_{\theta_q}s_{\theta_l}^2}{3m_{Z'}^2}$$
  The best-fit region to the $b \to s\mu\mu$ anomalies is $\delta C_9^\mu \in [-0.81\ -0.48]$ [3].
  Can be explained with Z' masses $\mathcal{O}$(TeV) and $s_{\theta_l} \approx 1$.
- **Meson mixing**
  Strongest constraints on this model are from the mass difference in $B_s - \bar{B}_s$ mixing.
- **B decays**
  $B_s \to \mu\mu$: affected by δC_{10}^μ; measured value consistent with both SM and best-fit region for the anomalies.
  $B \to K^{(*)}\nu\bar{\nu}$: contribution guaranteed by $SU(2)_L$ gauge invariance, but existing bounds are sub-dominant.
- **Lepton flavour violation**
  Strongest bounds are from $\tau \to 3\mu$. Constrains mixing angle in the lepton sector θ_l, and disfavours maximal mixing.
- **LHC Z' searches**
  Important bounds from $Z' \to \mu\mu$ searches, but generally weaker than in other models. A light Z' below LHC searches also remains a possibility.

References

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