

How well can a heavy $U(1)_{B-L}$ Z' gauge boson address the muon $(g - 2)_\mu$ anomaly?

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Outline

- 1 Introduction
- 2 The minimal $U(1)_{B-L}$ extension of the SM
- 3 Results
- 4 Conclusions and outlook

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Introduction

Motivations for $B - L$ (Baryon number minus Lepton number) symmetry:

- The SM contains an accidental symmetry that conserves $B - L$,
- $B - L$ symmetry relevant for baryogenesis through leptogenesis,
 - > sphaleron process violates B but preserves $B - L$
- Grand Unified Theories, e.g. $SO(10)$, E_6 , E_8, \dots contain gauged $U(1)_{B-L}$,
- The scale of $U(1)_{B-L}$ breaking sets the mass scale of the right-handed Majorana neutrinos.

BSM physics

- **Three** generations of right-handed neutrinos → **no gauge anomalies**
 - > Lightest is sterile and can be keV to TeV dark matter candidate.
Kaneta, Kang, Lee: JHEP 1702 (2017) 031
 - > Or stabilized via a \mathbb{Z}_2^{DM}
 - Annihilation via Z' portal Okada: Adv.High Energy Phys. 2018 (2018) 5340935
 - Annihilation via Higgs portal Okada, Seto: Phys.Rev. D82 (2010) 023507

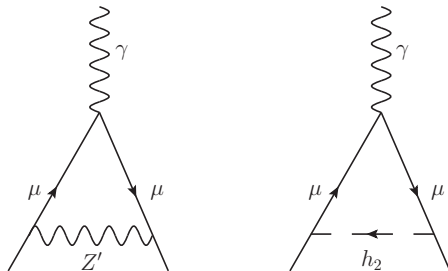
- Model contains a complex-singlet scalar χ whose VEV breaks $U(1)_{\text{B-L}}$
 - > Scalar sector studies: Basso, Moretti, Pruna: Eur.Phys.J. C71 (2011) 1724, Phys.Rev. D82 (2010) 055018
 - > Enhanced vacuum stability compared to the SM

- Model contains an extra Z' gauge boson Basso, Belyaev, Moretti, Pruna: JHEP 0910 (2009) 006 ; Basso, Belyaev, Moretti, Shepherd-Themistocleous: Phys.Rev. D80 (2009) 055030

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 268(63)(43) \times 10^{-11}$$

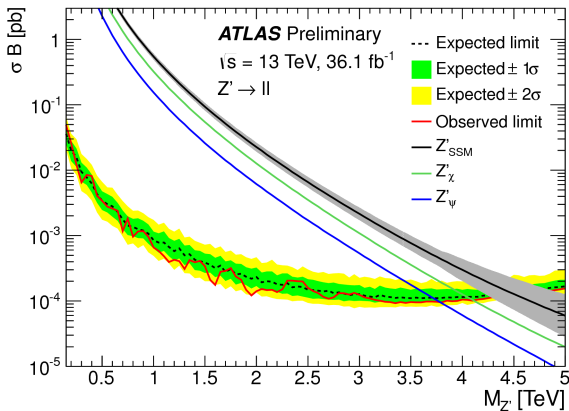
3.39 σ tension with the combined exp+th error

BSM vector bosons and scalars contribute to $(g - 2)_\mu$ anomaly



We revisit this anomaly in the B-L-SM (recently discussed in the supersymmetric version B-L-SSM [Yang, Feng et al. Phys.Rev. D99 \(2019\) no.1, 015002](#))

Direct Z' searches exclude masses below $m_{Z'} \approx 4$ TeV [ATLAS-CONF-2017-027](#)



- What is the maximal contribution to the muon $(g-2)_{\mu}$ anomaly that these limits allow and which constraints does it pose for a new scalar boson?

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The minimal $U(1)_{B-L}$ extension of the SM

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
q_L	3	2	1/6	1/3
u_R	3	1	2/3	1/3
d_R	3	1	-1/3	1/3
ℓ_L	1	2	-1/2	-1
e_R	1	1	-1	-1
ν_R	1	1	0	-1
H	1	2	1/2	0
χ	1	1	0	2

Scalar sector

$$V(H, \chi) = m^2 H^\dagger H + \mu^2 \chi^* \chi + \lambda_1 (H^\dagger H)^2 + \lambda_2 (\chi^* \chi)^2 + \lambda_3 \chi^* \chi H^\dagger H$$

- Boundedness from below: $4\lambda_1\lambda_2 - \lambda_3^2 > 0$ and $\lambda_1, \lambda_2 > 0$

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} -i(\omega_1 - i\omega_2) \\ v + (h + iz) \end{pmatrix} \quad \chi = \frac{1}{\sqrt{2}} [x + (h' + iz')]$$

- $\omega^\pm = \omega_1 \mp i\omega_2$, z and z' are Goldstone bosons eaten by W^\pm , Z and Z'

$$\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad \langle \chi \rangle = \frac{x}{\sqrt{2}} \quad \Rightarrow \quad \begin{cases} v^2 = \frac{-\lambda_2 m^2 + \frac{\lambda_3}{2} \mu^2}{\lambda_1 \lambda_2 - \frac{1}{4} \lambda_3^2} > 0 \\ x^2 = \frac{-\lambda_1 \mu^2 + \frac{\lambda_3}{2} m^2}{\lambda_1 \lambda_2 - \frac{1}{4} \lambda_3^2} > 0 \end{cases}$$

$$\begin{cases} \lambda_2 m^2 < \frac{\lambda_3}{2} \mu^2 \\ \lambda_1 \mu^2 < \frac{\lambda_3}{2} m^2 \\ 4\lambda_1 \lambda_2 - \lambda_3^2 > 0 \\ \lambda_1, \lambda_2 > 0 \end{cases}$$

\times : There is no solution
 \checkmark : There is solution

	$\mu^2 > 0$ $m^2 > 0$	$\mu^2 > 0$ $m^2 < 0$	$\mu^2 < 0$ $m^2 > 0$	$\mu^2 < 0$ $m^2 < 0$
$\lambda_3 < 0$	\times	\checkmark	\checkmark	\checkmark
$\lambda_3 > 0$	\times	\times	\times	\checkmark

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos \alpha_h & -\sin \alpha_h \\ \sin \alpha_h & \cos \alpha_h \end{pmatrix} \begin{pmatrix} h \\ h' \end{pmatrix}$$

Heavy Z' implies that $x \gg v$ for most of the parameters points:

$$\sin \alpha_h \approx \frac{1}{2} \frac{\lambda_3}{\lambda_2} \frac{v}{x} \quad m_{h_1}^2 \approx 2\lambda_1 v^2 \quad m_{h_2}^2 \approx 2\lambda_2 x^2$$

Gauge Kinetic Mixing

$$\mathcal{L}_{\text{bosons}} = |D_\mu H|^2 + |D_\mu \chi|^2 - V(H, \chi) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{1}{2} \kappa F_{\mu\nu} F'^{\mu\nu}$$

- κ is a $U(1)_Y \times U(1)_{B-L}$ gauge kinetic-mixing parameter
- Field strength tensors $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ and $F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$
- Redefine $\kappa = \sin \alpha$ and gauge fields as (convenient basis choice)

$$\begin{pmatrix} A_\mu \\ A'_\mu \end{pmatrix} = \begin{pmatrix} 1 & -\tan \alpha \\ 0 & \sec \alpha \end{pmatrix} \begin{pmatrix} B_\mu \\ B'_\mu \end{pmatrix},$$

- Kinetic terms acquire canonical form

$$\mathcal{L}_{\text{kinetic}} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} B'_{\mu\nu} B'^{\mu\nu}$$

Redefined covariant derivative absorbs the kinetic mixing information:

$$D_\mu = \partial_\mu + i(g_Y Y + g_{BY} Y_{B-L}) B_\mu + i(g_{BL} Y_{B-L} + g_{YB} Y) B'_\mu$$

- g_1 and g'_1 are $U(1)_Y$ and $U(1)_{B-L}$ gauge couplings
- g_{YB} and g_{BY} result from the kinetic mixing
- With our basis choice

$$\begin{cases} g_Y = g_1 \\ g_{BL} = g'_1 \sec \alpha \\ g_{YB} = -g_1 \tan \alpha \\ g_{BY} = 0 \end{cases} \quad \text{No mixing limit: } \sec \alpha = 1 \Rightarrow g_{BL} = g'_1$$

Gauge kinetic-mixing induces mixing between Z' , Z and γ

$$\begin{pmatrix} \gamma_\mu \\ Z_\mu \\ Z'_\mu \end{pmatrix} = \begin{pmatrix} \cos \theta_W & \sin \theta_W & 0 \\ -\sin \theta_W \cos \theta'_W & \cos \theta_W \cos \theta'_W & \sin \theta'_W \\ \sin \theta_W \sin \theta'_W & -\cos \theta'_W \sin \theta'_W & \cos \theta'_W \end{pmatrix} \begin{pmatrix} B_\mu \\ A^3_\mu \\ B'_\mu \end{pmatrix}$$

Again in the limit $x \gg v$

$$\sin \theta'_W \approx \frac{1}{8} \frac{g_{YB} g_{B-L}}{\left(\frac{v}{x}\right)^2 \sqrt{g^2 + g_Y^2}}$$

- g is $SU(2)_L$ gauge coupling
- $\sin \theta'_W = 0$ for no kinetic mixing, $g_{YB} = 0$, and $Z'_\mu = B'_\mu$
 - > For $g_{YB} = 0$ we have $m_Z = \frac{1}{2}v\sqrt{g^2 + g_Y^2}$ and $m_{Z'} \approx 2g_{B-L}x$
 - > For $x \gg v$ we also have $m_{Z'} \approx 2g_{B-L}x$

Yukawa sector

$$\mathcal{L}_{\text{Yukawa}} = -y_u^{ij} \overline{q_{Li}} u_{Rj} \tilde{H} - y_d^{ij} \overline{q_{Li}} d_{Rj} H - y_e^{ij} \overline{\ell_{Li}} e_{Rj} H - y_\nu^{ij} \overline{\ell_{Li}} \nu_{Rj} \tilde{H} - \frac{1}{2} y_M^{ij} \overline{\nu_{Ri}^c} \nu_{Rj} \chi + \text{c.c.}$$

- $\tilde{H} = i\sigma^2 H^*$
- Dirac and Majorana masses matrices: $m_D = \frac{y_\nu}{\sqrt{2}} \nu$ and $M = \frac{y_M}{\sqrt{2}} \chi$
- Neutrino masses via see-saw mechanism: $\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix} \rightarrow \begin{cases} m_{\nu_l} \approx \frac{m_D^2}{M} \\ m_{\nu_h} \approx M \end{cases}$
- Small mixing angle: $\tan \alpha_\nu \approx -2 \sqrt{\frac{m_{\nu_l}}{m_{\nu_h}}}$

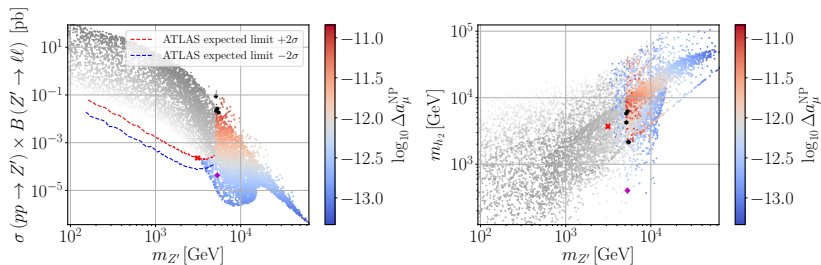
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Results

λ_1	$\lambda_{2,3}$	g_{BL}	g_{YB}	x [TeV]
$[10^{-2}, 10^{0.5}]$	$[10^{-8}, 10]$	$[10^{-8}, 3]$	$[10^{-8}, 3]$	$[0.5, 20.5]$

- 1 Model file: SARAH-4.12.3
- 2 Spectrum generator: SPheno-4.0.3
 - Unitarity
 - One-loop mass spectrum and two-loop Higgs mass
 - Mixing angles
 - EW precision observables STU
 - $(g-2)_e$
 - Decay widths and Branching Fractions
- 3 Generated points with $m_{h_1} = 125.1 \pm 0.14$ GeV input to HiggsBounds-4.3.1 and HiggsSignals-1.4.0
- 4 **Surviving** points passed to MadGraph5_am5@NLO

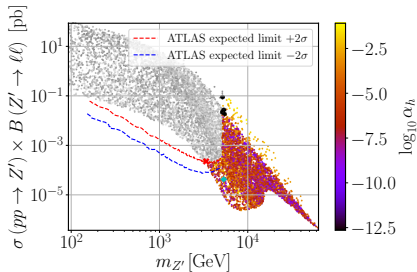
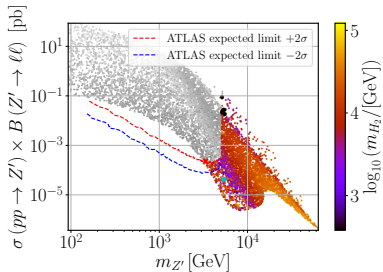


- Applied LEP constraints from 4 fermion contact interactions
- Tension between measured and B-L-SM prediction for Δa_μ only improved by 0.03σ for $5 \text{ TeV} \lesssim m_{Z'} \lesssim 5.5 \text{ TeV}$ (4 black dots).
- **Red cross highlights a benchmark point with $m_{Z'} \approx 3 \text{ TeV}$ regarded as an early-discovery (or early-exclusion) scenario in future LHC runs.**
- **Magenta diamond corresponds to the lightest BSM Higgs found, $m_{h_2} \approx 396 \text{ GeV}$**

- When $\frac{m_\mu}{m_{Z'}} \ll 1$ the Z' contribution reads

$$\Delta a_\mu^{Z'} \approx \frac{1}{3\pi^2} \frac{m_\mu^2}{m_{Z'}^2} \left[3g_L^{\mu\mu Z'} g_R^{\mu\mu Z'} - \left(g_L^{\mu\mu Z'^2} + g_R^{\mu\mu Z'^2} \right) \right].$$

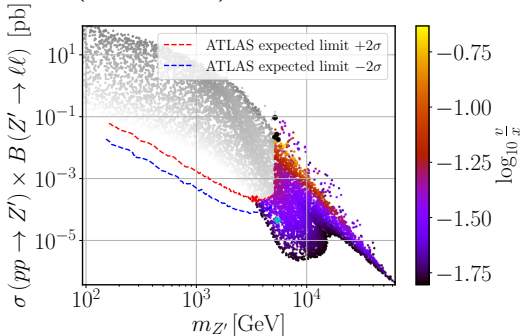
Contribution from h_2 is tiny: $\Delta a_\mu^{h_2} \propto \frac{m_\mu^2}{m_{h_2}^2} (y_\mu \sin \alpha_h)^2$



Suppressed by $\sin^2 \alpha_h < 0.0064$ and $m_{h_2} > 396$ GeV

Expanding for $v \ll x$

$$g_L^{\ell\ell Z'} \simeq \frac{1}{2} \left(g_{B-L} + \frac{1}{2} g_{YB} \right), \quad g_R^{\ell\ell Z'} \simeq \frac{1}{2} \left(g_{B-L} + g_{YB} \right).$$

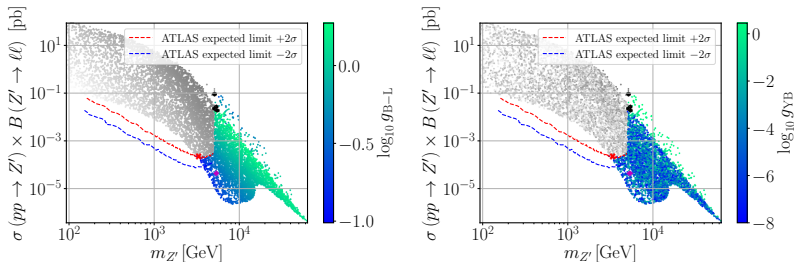


$$\Delta a_{\mu}^{Z'} \simeq \frac{1}{48\pi^2} \frac{m_{\mu}^2}{m_{Z'}^2} [6g_{B-L} g_{YB} + 4g_{B-L}^2 + g_{YB}^2]$$

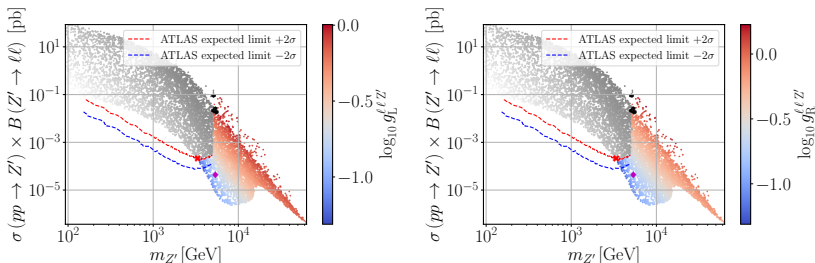
To enhance $\Delta a_{\mu}^{Z'}$ for heavy Z' one needs sizeable g_{B-L} and/or g_{YB}

- Note strong correlation between $\left(\frac{v}{x}\right)^2$ and $\Delta a_{\mu}^{Z'}$ except for the sparser upper edge!

Four-fermion contact interactions constrain $g_{B-L} < 1.8$ in the B-L SM



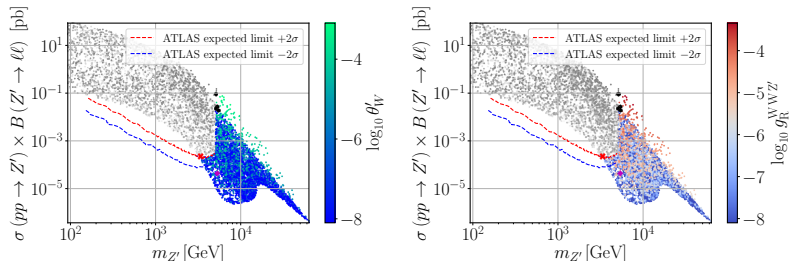
Enhancement of $\Delta a_{\mu}^{Z'}$ is maximized with sizeable g_{YB} , thus large $g_{L,R}^{\ell Z'}$



LEP constraints set upper bound $\sin \theta'_W \lesssim 10^{-3}$

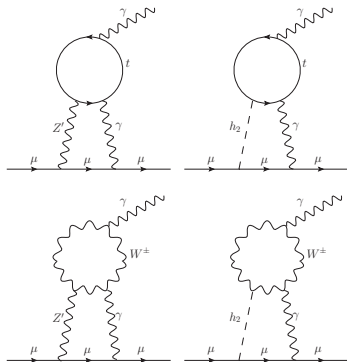
$$\sin \theta'_W \approx \frac{1}{8} \frac{g_{YB}}{g_{B-L}} \left(\frac{v}{x}\right)^2 \sqrt{g^2 + g_Y^2}$$

which is respected even for the larger values of g_{YB} :



Small coupling of Z' to W bosons: $g^{WWZ'} \simeq \frac{1}{16} \frac{g_{YB}}{g_{B-L}} \left(\frac{v}{x}\right)^2$.

Two-loop Barr-Zee type contributions are subdominant



Larger contribution from the top-left diagram due to $g_{L,R}^{tZ'} \gg g^{WWZ'}$, α_h , however:

$$\frac{\Delta a_\mu^{\gamma Z'}}{\Delta a_\mu^{Z'}} \simeq -\frac{1}{4096\pi^2} \frac{g^2 (g^2 + g_Y^2) g_{YB}^3}{[6g_{B-L} g_{YB} + 4g_{B-L}^2 + g_{YB}^2]} \left(\frac{v}{x}\right)^4 \ll 1$$

Benchmark points

$m_{Z'}$	m_{h_2}	x	$\log_{10} \Delta a_{\mu}^{\text{NP}}$	σB	θ'_W	α_h	g_{B-L}	g_{YB}	$g_L^{\ell Z'}$	$g_R^{\ell Z'}$
3.13	3.72	15.7	-13.04	2.22×10^{-4}	≈ 0	5.67×10^{-5}	0.0976	≈ 0	0.0488	0.0488
5.37	0.396	9.10	-12.52	4.23×10^{-5}	2.55×10^{-7}	9.44×10^{-7}	0.302	8.73×10^{-4}	0.151	0.151
5.14	4.21	2.77	-10.8	0.0896	6.52×10^{-4}	0.0132	0.871	1.86	0.901	1.37
5.37	6.16	1.82	-10.9	0.0260	1.97×10^{-4}	0.00109	1.44	0.625	0.876	1.03
5.13	5.82	1.37	-10.96	0.0215	3.44×10^{-5}	1.79×10^{-5}	1.69	0.0845	0.867	0.888
5.45	2.14	1.06	-10.96	0.0182	≈ 0	0.00197	1.87	≈ 0	0.937	0.937

- **First line:** Early discovery/exclusion scenario with the lightest Z' found in the scan,
- **Second line:** Lightest new scalar found in the scan,
- **Third to fourth lines:** Four points that maximize $(g-2)_{\mu}$ with $\Delta a_{\mu}^{\text{max}} = 1.58 \times 10^{-11}$ on top of SM contribution.

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Conclusions and outlook

Muon $(g-2)_\mu$ anomaly:

- Can be maximized with sizeable g_{B-L} or g_{YB} gauge couplings but tension to th-exp combined error is only marginally improved in comparison to SM

Our result offers an important piece of information that can be relevant for upcoming a_μ precision measurements as well as for building less minimal models containing heavy Z' bosons and capable of a better explanation of the muon $(g-2)_\mu$ anomaly.

Potential for new physics searches

- For a relatively light new scalar, $m_{h_2} \approx 400$ GeV
- For an early discovery/exclusion Z' boson $m_{Z'} \approx 3.1$ TeV