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

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Experiemnt vs Theory meeting – LIP Minho, Braga

Outline

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

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Introduction

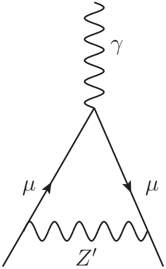
Motivations for $\mathrm{B}-\mathrm{L}$ (Baryon number minus Lepton number) symmetry:

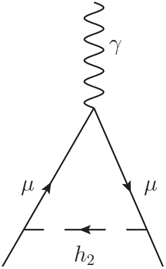
- The SM contains an accidental symmetry that conserves $\mathrm{B}-\mathrm{L}$,
- $\mathrm{B}-\mathrm{L}$ symmetry relevant for baryogenesis through leptogenesis,
  - > sphaleron process violates B but preserves $\mathrm{B}-\mathrm{L}$
- Grand Unified Theories, e.g. $\mathrm{SO}(10)$, E_6, $\mathrm{E}_8, \ldots$ contain gauged $\mathrm{U}(1)_{\mathrm{B}-\mathrm{L}}$,
- The scale of $\mathrm{U}(1)_{\mathrm{B}-\mathrm{L}}$ breaking sets the mass scale of the right-handed Majorana neutrinos.

BSM physics

- **Three** generations of right-handed neutrinos $\rightarrow$ **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 $\mathbb{Z}_2^{\mathrm{DM}}$
    - 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 $\mathrm{U}(1)_{\mathrm{B-L}}$
  - > 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

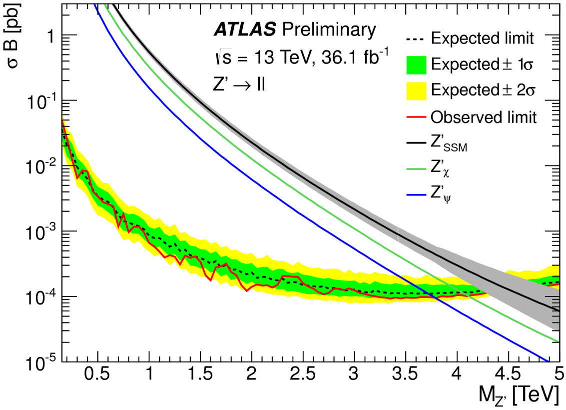
BSM vector bosons and scalars contribute to $(g-2)_\mu$ anomaly





Not studied 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 $m_{Z'} \approx 4\ \mathrm{TeV}$ ATLAS-CONF-2017-027



- Can the minimal B-L SM still address the muon $(g-2)_\mu$ anomaly and how well?

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

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

Scalar sector

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

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

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

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

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

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

✗: There is no solution
✓: There is solution

	$\mu^2 > 0$ $m^2 > 0$	$\mu^2 > 0$ $m^2 < 0$	$\mu^2 < 0$ $m^2 > 0$	$\mu^2 < 0$ $m^2 < 0$
$\lambda_3 < 0$	✗	✓	✓	✓
$\lambda_3 > 0$	✗	✗	✗	✓

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

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

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

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 $\mathrm{U(1)_Y} \times \mathrm{U(1)_{B-L}}$ 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 $\mathrm{U}(1)_\mathrm{Y}$ and $\mathrm{U}(1)_{\mathrm{B-L}}$ gauge couplings
- g_{YB} and g_{BY} result from the kinetic mixing
- With our basis choice

$$\begin{cases} g_Y = g_1 \\ g_{BL} = g'_1 \sec\alpha \\ g_{YB} = -g_1 \tan\alpha \\ g_{BY} = 0 \end{cases}$$

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

- g is $\mathrm{SU(2)_L}$ 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 $m_{Z'} \approx 2g_{BL}x$
  - For $x \gg v$ we also have $m_{Z'} \approx 2g_{BL}x$

Yukawa sector

$$\mathcal{L}_{\text{Yukawa}} = -y_u^{ij}\overline{q_{\text{L}i}}u_{\text{R}j}\widetilde{H} - y_d^{ij}\overline{q_{\text{L}i}}d_{\text{R}j}H - y_e^{ij}\overline{\ell_{\text{L}i}}e_{\text{R}j}H - y_\nu^{ij}\overline{\ell_{\text{L}i}}\nu_{\text{R}j}\widetilde{H} - \frac{1}{2}y_M^{ij}\overline{\nu^c_{\text{R}i}}\nu_{\text{R}j}\chi + \text{c.c.}$$

- $\widetilde{H} = i\sigma^2 H^*$
- Dirac and Majorana masses matrices: $\boldsymbol{m_D} = \frac{\boldsymbol{y_\nu}}{\sqrt{2}}v$ and $\boldsymbol{M} = \frac{\boldsymbol{y_M}}{\sqrt{2}}x$
- 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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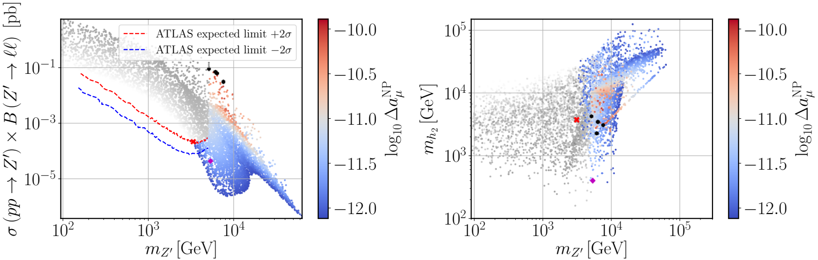
Results

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
   - $(g-2)_\ell$
   - Decay widths and Branching Fractions
3. Generated points with $m_{h_1} = 125.2 \pm 2$ GeV input to `HiggsBounds-4.3.1` and `HiggsSingnals-1.4.0`
4. **Surviving** points passed to `MadGraph5_am5@NLO`



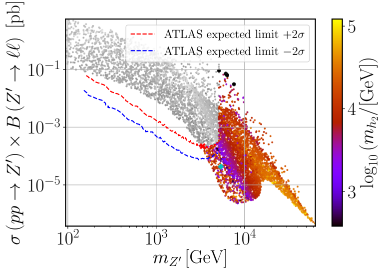
- Applied LEP constraints from 4 fermion contact interactions
- **Model explains $(g-2)_\mu$ for 5 TeV $\lesssim m_{Z'} \lesssim$ 8 TeV within -2.25σ uncertainty (4 black dots).**
- Red cross highlights a benchmark point with $m_{Z'} \approx 3$ TeV regarded as an early-discovery (or early-exclusion) scenario in future LHC runs.
- Magenta diamond corresponds to the lightest BSM Higgs found, $m_{h_2} \approx 396$ GeV

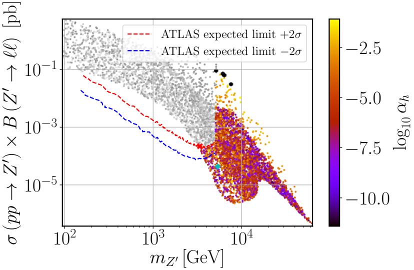
$\Delta a_\mu^{Z'}$ calculated in SARAH and numerically evaluated in SPheno

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

$$\Delta a_\mu^{Z'} \approx -\frac{1}{3\pi^2}\frac{m_\mu^2}{m_{Z'}^2}\left[6 g_{\mathrm{L}}^{\mu\mu Z'} g_{\mathrm{R}}^{\mu\mu Z'} - 4\left(g_{\mathrm{L}}^{\mu\mu Z'\,2} + g_{\mathrm{R}}^{\mu\mu Z'\,2}\right)\right]$$

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

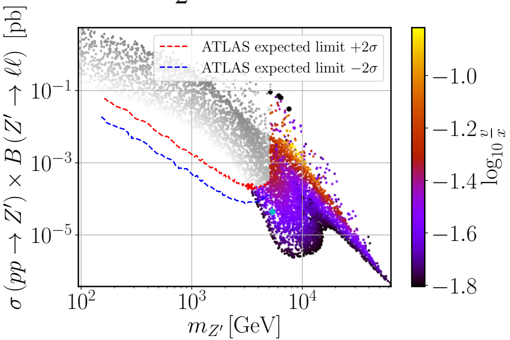




Suppressed by $\sin^2\alpha_h < 0.0064$ and $m_{h_2} > 396$ GeV

Expanding for $v \ll x$

$$g_L^{\ell\ell Z'} \simeq g_{B-L} + \frac{1}{2} g_{YB}\,, \qquad g_R^{\ell\ell Z'} \simeq g_{B-L} + g_{YB}\,.$$

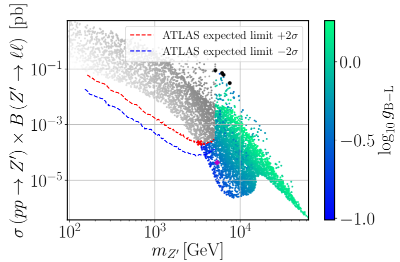


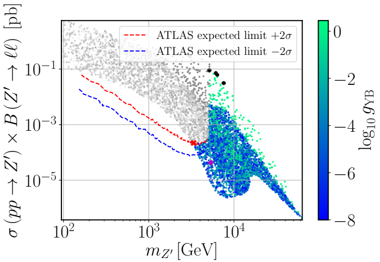
$$\Delta a_\mu^{Z'} \simeq \frac{1}{3\pi^2} \frac{m_\mu^2}{m_{Z'}^2} \left[2\left(g_{B-L}^2 + g_{YB}^2\right) + 3 g_{B-L} g_{YB} \right]$$

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

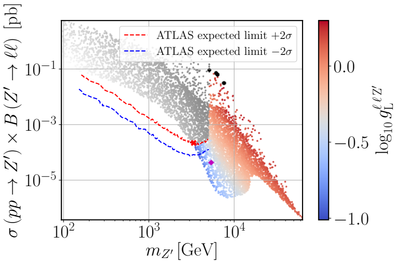
- Note strong correlation between v/x and $\Delta a_\mu^{Z'}$ except for the sparser upper edge!

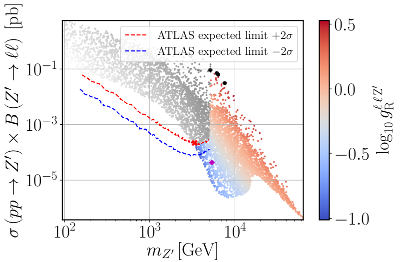
Four-fermion contact interactions constrain $g_{\mathrm{B-L}} < 1.8$ in the B-L SM





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

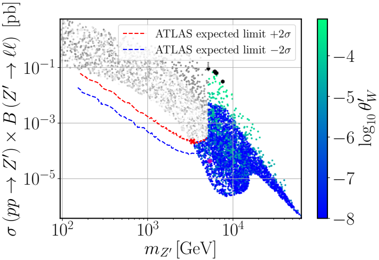


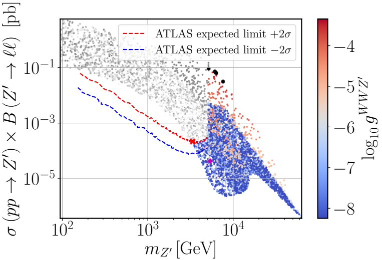


LEP constraints set upper bound $\sin\theta'_W \lesssim 10^{-3}$

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

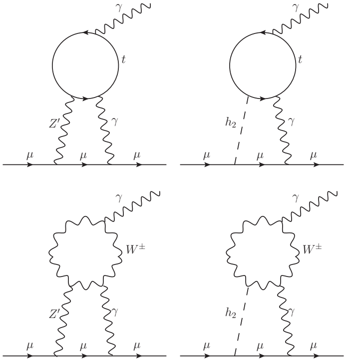
which is respected even for the larger values of g_{YB}:





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

Two-loop Barr-Zee type contributions are subdominant



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

$$\frac{\Delta a_\mu^{\text{Barr-Zee}}}{\Delta a_\mu^{Z'}} \simeq -\frac{1}{65536\pi^2} \frac{g^2\left(g^2+g_{\mathrm{Y}}^2\right)g_{\mathrm{YB}}^3}{\left[3g_{\mathrm{B-L}}g_{\mathrm{YB}}+2\left(g_{\mathrm{B-L}}^2+g_{\mathrm{YB}}^2\right)\right]}\left(\frac{v}{x}\right)^4 \ll 1$$

Benchmark points

$m_{Z'}$	m_{h_2}	x	$\log_{10}\Delta a_\mu^{\rm NP}$	σB	θ'_W	α_h	$g_{\rm B-L}$	$g_{\rm YB}$	$g_{\rm L}^{\ell\ell Z'}$	$g_{\rm R}^{\ell\ell Z'}$
3.13	3.72	15.7	−12.1	2.22×10^{-4}	≈ 0	5.67×10^{-5}	0.0976	2.0×10^{-8}	0.0976	0.0976
5.37	0.396	9.10	−11.7	4.23×10^{-5}	2.55×10^{-7}	9.44×10^{-7}	0.302	8.73×10^{-4}	0.302	0.303
7.59	3.072	4.36	−9.89	0.0302	7.26×10^{-4}	0.0471	0.612	1.99	3.37	2.76
6.13	2.24	6.67	−9.92	0.0696	8.0×10^{-4}	0.0593	0.383	2.80	1.78	3.18
6.373	3.43	6.56	−9.92	0.0615	7.86×10^{-4}	0.0266	0.395	2.82	1.81	3.22
5.14	4.21	2.77	−9.94	0.0896	6.52×10^{-4}	0.0132	0.871	1.86	1.80	2.73

- **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 best $(g-2)_\mu$ points.

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Conclusions and outlook

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

- A heavy Z' between 5 and 8 TeV can explain it up to a 2.25σ uncertainty,
- Needs sizeable kinetic-mixing parameter g_{YB}

New physics searches

- We have identified 6 benchmark points to test the B-L SM at future LHC 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
  - For maximal contribution to the muon $(g-2)_\mu$ anomaly