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TÉCNICO LISBOA
CFTP
Centro de Física Teórica de Partículas

Looking closer at the $U(1)_{B\text{-}L}$ explanation of the ATOMKI nuclear anomalies

Based on 10.1007/JHEP04(2024)003 [**arXiv:2311.18004** [**hep-ph**]]

Bernardo Gonçalves

In collaboration with Pedro Ferreira and Filipe Joaquim

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Outline

- The ATOMKI anomalies
- Can the B-L gauge boson be the X(17)?
- Adding VLLs
  - ➢ Large mixing / unity charge
  - ➢ Small mixing / large charges
- Long story short

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The ATOMKI anomalies

PRL **116,** 042501 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016

Observation of Anomalous Internal Pair Creation in ^{8}Be: A Possible Indication of a Light, Neutral Boson

A. J. Krasznahorkay,* M. Csatlós, L. Csige, Z. Gácsi, J. Gulyás, M. Hunyadi, I. Kuti, B. M. Nyakó, L. Stuhl, J. Timár, T. G. Tornyi, and Zs. Vajta
Institute for Nuclear Research, Hungarian Academy of Sciences (MTA Atomki), P.O. Box 51, H-4001 Debrecen, Hungary

T. J. Ketel
Nikhef National Institute for Subatomic Physics, Science Park 105, 1098 XG Amsterdam, Netherlands

A. Krasznahorkay
CERN, CH-1211 Geneva 23, Switzerland and Institute for Nuclear Research, Hungarian Academy of Sciences (MTA Atomki), P.O. Box 51, H-4001 Debrecen, Hungary
(Received 7 April 2015; published 26 January 2016)

Electron-positron angular correlations were measured for the isovector magnetic dipole 17.6 MeV ($J^\pi = 1^+$, $T = 1$) state → ground state ($J^\pi = 0^+$, $T = 0$) and the isoscalar magnetic dipole 18.15 MeV ($J^\pi = 1^+$, $T = 0$) state → ground state transitions in ^{8}Be. Significant enhancement relative to the internal pair creation was observed at large angles in the angular correlation for the isoscalar transition with a confidence level of $> 5\sigma$. This observation could possibly be due to nuclear reaction interference effects or might indicate that, in an intermediate step, a neutral isoscalar particle with a mass of $16.70 \pm 0.35(\text{stat}) \pm 0.5(\text{syst})\ \text{MeV}/c^2$ and $J^\pi = 1^+$ was created.

DOI: 10.1103/PhysRevLett.116.042501

The ATOMKI anomalies

PRL **117,** 071803 (2016) PHYSICAL REVIEW LETTERS week ending 12 AUGUST 2016

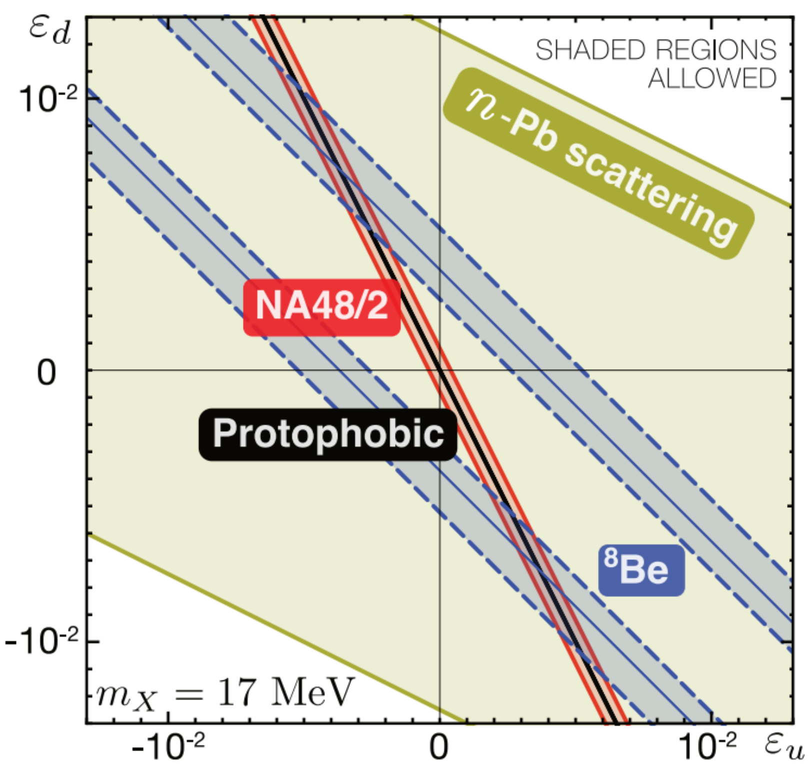
Protophobic Fifth-Force Interpretation of the Observed Anomaly in ^{8}Be Nuclear Transitions

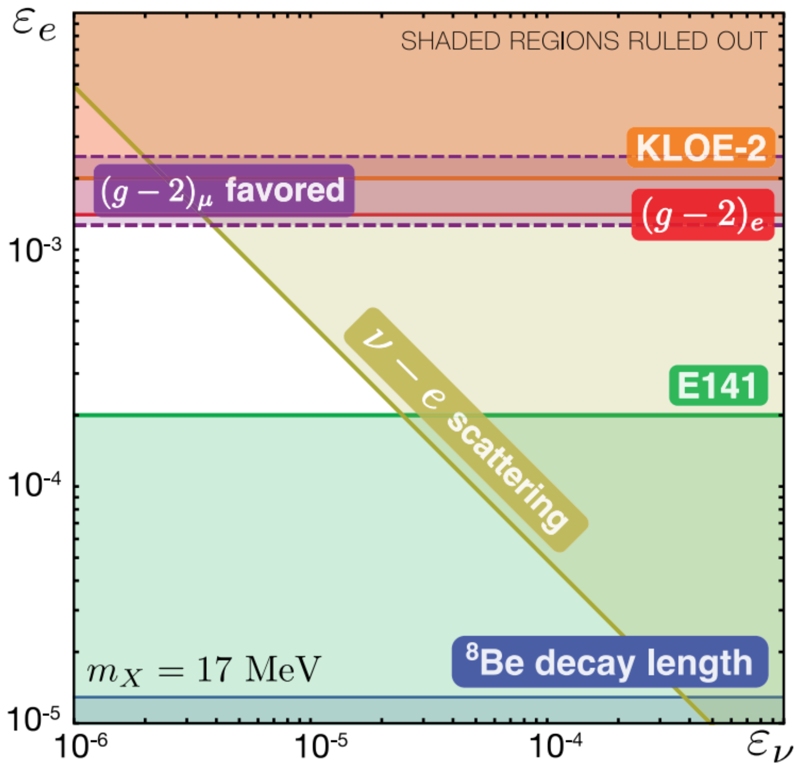
Jonathan L. Feng,[1] Bartosz Fornal,[1] Iftah Galon,[1] Susan Gardner,[1,2] Jordan Smolinsky,[1] Tim M. P. Tait,[1] and Philip Tanedo[1]
[1]*Department of Physics and Astronomy, University of California, Irvine, California 92697-4575, USA*
[2]*Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506-0055, USA*
(Received 3 May 2016; published 11 August 2016)

Recently a 6.8σ anomaly has been reported in the opening angle and invariant mass distributions of e^+e^- pairs produced in ^{8}Be nuclear transitions. The data are explained by a 17 MeV vector gauge boson X that is produced in the decay of an excited state to the ground state, $^8\text{Be}^* \to {}^8\text{Be}\,X$, and then decays through $X \to e^+e^-$. The X boson mediates a fifth force with a characteristic range of 12 fm and has millicharged couplings to up and down quarks and electrons, and a proton coupling that is suppressed relative to neutrons. The protophobic X boson may also alleviate the current 3.6σ discrepancy between the predicted and measured values of the muon's anomalous magnetic moment.

DOI: 10.1103/PhysRevLett.117.071803

The ATOMKI anomalies





X(17)

$$\mathcal{L} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{1}{2}m_X^2 X_\mu X^\mu - X^\mu J_\mu$$

$$J_\mu = \sum_f e\varepsilon_f \bar{f}\gamma_\mu f$$

$$\varepsilon_p = 2\varepsilon_u + \varepsilon_d$$

$$\varepsilon_n = \varepsilon_u + 2\varepsilon_d$$

Required charges to explain the Be-8 anomaly; taken from arXiv:1604.07411 [hep-ph].

Can the B-L gauge boson be the X(17)?

PHYSICAL REVIEW D **95,** 035017 (2017)

Particle physics models for the 17 MeV anomaly in beryllium nuclear decays

Jonathan L. Feng,[1,*] Bartosz Fornal,[1] Iftah Galon,[1] Susan Gardner,[1,2]
Jordan Smolinsky,[1] Tim M. P. Tait,[1] and Philip Tanedo[1,3]

[1]*Department of Physics and Astronomy, University of California, Irvine, California 92697-4575, USA*
[2]*Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506-0055, USA*
[3]*Department of Physics and Astronomy, University of California, Riverside, California 92521, USA*

(Received 26 August 2016; published 16 February 2017)

The 6.8σ anomaly in excited ^{8}Be nuclear decays via internal pair creation is fit well by a new particle interpretation. In a previous analysis, we showed that a 17 MeV protophobic gauge boson provides a particle physics explanation of the anomaly consistent with all existing constraints. Here we begin with a review of the physics of internal pair creation in ^{8}Be decays and the characteristics of the observed anomaly. To develop its particle interpretation, we provide an effective operator analysis for excited ^{8}Be decays to particles with a variety of spins and parities and show that these considerations exclude simple models with scalar particles. We discuss the required couplings for a gauge boson to give the observed signal, highlighting the significant dependence on the precise mass of the boson and isospin mixing and breaking effects. We present anomaly-free extensions of the Standard Model that contain protophobic gauge bosons with the desired couplings to explain the ^{8}Be anomaly. In the first model, the new force carrier is a $U(1)_B$ gauge boson that kinetically mixes with the photon; in the second model, it is a $U(1)_{B-L}$ gauge boson with a similar kinetic mixing. In both cases, the models predict relatively large charged lepton couplings ~0.001 that can resolve the discrepancy in the muon anomalous magnetic moment and are amenable to many experimental probes. The models also contain vectorlike leptons at the weak scale that may be accessible to near future LHC searches.

DOI: 10.1103/PhysRevD.95.035017

Can the *B-L* gauge boson be the X(17)?

Let us consider the vanilla gauged $U(1)_{B\text{-}L}$ model

Can the *B-L* gauge boson be the X(17)?

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$$D_\mu = D_\mu^{\rm SM} + ie(\varepsilon\, Q + \varepsilon_{B-L}\, Q^{B-L})\, Z'_\mu$$

X(17)

$$m_{Z'} \simeq 2\, e\, |\varepsilon_{B-L}| w$$

$$\langle S \rangle = w/\sqrt{2}$$

	Fields	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_\mathrm{L}$	$\mathrm{U}(1)_Y$	Q_{B-L}
Vanilla $B-L$	$q_{i\mathrm{L}} = (u_{i\mathrm{L}}, d_{i\mathrm{L}})^T$	**3**	**2**	$1/6$	$1/3$
	$u_{i\mathrm{R}}$	**3**	**1**	$2/3$	$1/3$
	$d_{i\mathrm{R}}$	**3**	**1**	$-1/3$	$1/3$
	$l_{i\mathrm{L}} = (\nu_{i\mathrm{L}}, e_{i\mathrm{L}})^T$	**1**	**2**	$-1/2$	-1
	$e_{i\mathrm{R}}$	**1**	**1**	-1	-1
	$N_{i\mathrm{R}}$	**1**	**1**	0	-1
	Φ	**1**	**2**	$1/2$	0
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New scalar χ lighter than the Higgs

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Couplings	Vanilla $B-L$	Experimental range
ε_n^V		$2 \times 10^{-3}\ [4.1 \times 10^{-3}] \lesssim \lvert\varepsilon_n^V\rvert \lesssim 15 \times 10^{-3}\ [5.3 \times 10^{-3}]$
ε_p^V		$[0.7 \times 10^{-3}] \lesssim \lvert\varepsilon_p^V\rvert \lesssim 1.2 \times 10^{-3}\ [1.9 \times 10^{-3}]$
ε_{ee}^V		$0.4 \times 10^{-3}\ [0.63 \times 10^{-3}] \lesssim \lvert\varepsilon_{ee}^V\rvert \lesssim 2 \times 10^{-3}\ [1.2 \times 10^{-3}]$
ε_{ee}^A		$\lvert\varepsilon_{ee}^A\rvert \lesssim 2.6 \times 10^{-9}$
$\varepsilon_{\nu_e\nu_e}^A$		$\lvert\varepsilon_{\nu_e\nu_e}^A\rvert \lesssim 1.2 \times 10^{-5}\ [(3.5-4.5) \times 10^{-6}]$
$\varepsilon_{\nu_\mu\nu_\mu}^A$		$\lvert\varepsilon_{\nu_\mu\nu_\mu}^A\rvert \lesssim 12.2 \times 10^{-5}$

Bounds taken from arXiv:2005.00028 [hep-ph], with updated values from arXiv:2304.09877 [hep-ph] in parenthesis.

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$$\varepsilon_u = \tfrac{2}{3}\varepsilon + \tfrac{1}{3}\varepsilon_{B-L} \qquad \varepsilon_d = -\tfrac{1}{3}\varepsilon + \tfrac{1}{3}\varepsilon_{B-L}$$

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$$g^V_{\nu_a\nu_b} = \sum_c \varepsilon_{B-L}\, \mathrm{Im}\left(Q_c^{B-L}\, (U_\nu^*)^{ca}\, U_\nu^{cb}\right)$$

$$g^A_{\nu_a\nu_b} = -\sum_c \varepsilon_{B-L}\, \mathrm{Re}\left(Q_c^{B-L}\, (U_\nu^*)^{ca}\, U_\nu^{cb}\right)$$

Majorana neutrinos

Bounds taken from arXiv:2005.00028 [hep-ph], with updated values from arXiv:2304.09877 [hep-ph] in parenthesis.

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The vanilla B-L scenario is NOT enough!

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Adding VLLs

	Fields	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	Q_{B-L}	
Vanilla $B-L$	$q_{i\mathrm{L}} = (u_{i\mathrm{L}}, d_{i\mathrm{L}})^T$	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$1/3$	Vanilla $B-L$ + VLLs
	$u_{i\mathrm{R}}$	$\mathbf{3}$	$\mathbf{1}$	$2/3$	$1/3$	
	$d_{i\mathrm{R}}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	$1/3$	
	$l_{i\mathrm{L}} = (\nu_{i\mathrm{L}}, e_{i\mathrm{L}})^T$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	-1	
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	$N_{i\mathrm{R}}$	$\mathbf{1}$	$\mathbf{1}$	0	-1	
	Φ	$\mathbf{1}$	$\mathbf{2}$	$1/2$	0	
	S	$\mathbf{1}$	$\mathbf{1}$	0	2	
	$L_{i\mathrm{L,R}} = (\mathcal{N}_{i\mathrm{L,R}}, \mathcal{E}_{i\mathrm{L,R}})^T$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	1	
	$E_{i\mathrm{L,R}}$	$\mathbf{1}$	$\mathbf{1}$	-1	1	

Adding VLLs

$$\mathcal{L}_{\text{lepton}} = -\, y_l^{ij}\,\overline{l}_{i\text{L}}\Phi\, e_{j\text{R}} - y_\nu^{ij}\;\overline{l}_{i\text{L}}\tilde{\Phi}\, N_{j\text{R}} - \frac{1}{2} y_M^{ij} S\,\overline{N^c_{i\text{R}}} N_{j\text{R}} - \lambda_{\text{L}}^{ij} S^*\,\overline{l}_{i\text{L}} L_{j\text{R}} - \lambda_{\text{E}}^{ij} S\,\overline{E}_{i\text{L}} e_{j\text{R}}$$
$$- M_{\text{L}}^{ij}\overline{L}_{i\text{L}} L_{j\text{R}} - M_{\text{E}}^{ij}\overline{E}_{i\text{L}} E_{j\text{R}} - h^{ij}\,\overline{L}_{i\text{L}}\Phi\, E_{j\text{R}} - k^{ij}\,\overline{E}_{i\text{L}}\Phi^\dagger\, L_{j\text{R}} + \text{H.c.}\,,\;\; i,j = 1,2,3$$

$$\mathcal{L}_{\text{c.l.}} = \overline{\psi^\ell_{\text{L}}}\,\mathcal{M}_\ell\,\psi^\ell_{\text{R}} + \text{H.c.}\,,\quad \psi^\ell_{\text{L,R}} = (e_{\text{L,R}}\,,\quad \mathcal{E}_{\text{L,R}}\,,\quad E_{\text{L,R}})^T\,,\quad \mathcal{M}_\ell = \begin{pmatrix} y_l\,\frac{v}{\sqrt{2}} & \lambda_{\text{L}}\,\frac{w}{\sqrt{2}} & 0 \\ 0 & M_{\text{L}} & h\,\frac{v}{\sqrt{2}} \\ \lambda_{\text{E}}\,\frac{w}{\sqrt{2}} & k\,\frac{v}{\sqrt{2}} & M_{\text{E}} \end{pmatrix}$$

Adding VLLs

$$\mathcal{L}_{\text{lepton}} = - y_l^{ij}\, \overline{l_{i\text{L}}} \Phi\, e_{j\text{R}} - y_\nu^{ij}\, \overline{l_{i\text{L}}} \tilde{\Phi}\, N_{j\text{R}} - \frac{1}{2} y_M^{ij} S\, \overline{N^c_{i\text{R}}} N_{j\text{R}} - \lambda_{\text{L}}^{ij} S^*\, \overline{l_{i\text{L}}} L_{j\text{R}} - \lambda_{\text{E}}^{ij} S\, \overline{E_{i\text{L}}} e_{j\text{R}}$$
$$- M_{\text{L}}^{ij} \overline{L_{i\text{L}}} L_{j\text{R}} - M_{\text{E}}^{ij} \overline{E_{i\text{L}}} E_{j\text{R}} - h^{ij}\, \overline{L_{i\text{L}}} \Phi\, E_{j\text{R}} - k^{ij}\, \overline{E_{i\text{L}}} \Phi^\dagger\, L_{j\text{R}} + \text{H.c.}\,, \;\; i, j = 1, 2, 3$$

$$\mathcal{M}_\ell = \begin{pmatrix} y_l \frac{v}{\sqrt{2}} & \lambda_{\text{L}} \frac{w}{\sqrt{2}} & 0 \\ 0 & M_{\text{L}} & h \frac{v}{\sqrt{2}} \\ \lambda_{\text{E}} \frac{w}{\sqrt{2}} & k \frac{v}{\sqrt{2}} & M_{\text{E}} \end{pmatrix}$$

Adding VLLs

$$\mathcal{L}_{\text{lepton}} = -\, y_l^{ij}\, \overline{l}_{i\text{L}} \Phi\, e_{j\text{R}} - y_\nu^{ij}\, \overline{l}_{i\text{L}} \tilde{\Phi}\, N_{j\text{R}} - \frac{1}{2} y_M^{ij} S\, \overline{N^c_{i\text{R}}} N_{j\text{R}} - \lambda_\text{L}^{ij} S^*\, \overline{l}_{i\text{L}} L_{j\text{R}} - \lambda_\text{E}^{ij} S\, \overline{E}_{i\text{L}} e_{j\text{R}}$$
$$- M_\text{L}^{ij} \overline{L}_{i\text{L}} L_{j\text{R}} - M_\text{E}^{ij} \overline{E}_{i\text{L}} E_{j\text{R}} - h^{ij}\, \overline{L}_{i\text{L}} \Phi\, E_{j\text{R}} - k^{ij}\, \overline{E}_{i\text{L}} \Phi^\dagger\, L_{j\text{R}} + \text{H.c.}\,, \quad i,j = 1,2,3$$

$$\mathcal{L}_{\text{n.l.}} = \overline{\psi_\text{L}^{\nu\, c}}\, \mathcal{M}_\nu\, \psi_\text{L}^\nu + \text{H.c.}\,, \quad \psi_\text{L}^\nu = (\nu\,, \quad N^c\,, \quad \mathcal{N}\,, \quad \mathcal{N}^c)_\text{L}^T\,, \quad \mathcal{M}_\nu = \begin{pmatrix} 0 & y_\nu \frac{v}{\sqrt{2}} & 0 & \lambda_\text{L} \frac{w}{\sqrt{2}} \\ y_\nu \frac{v}{\sqrt{2}} & y_M \frac{w}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & 0 & M_\text{L} \\ \lambda_\text{L} \frac{w}{\sqrt{2}} & 0 & M_\text{L} & 0 \end{pmatrix}$$

Adding VLLs

$$\mathcal{L}_{\text{lepton}} = -\, y_l^{ij}\,\overline{l}_{i\text{L}}\Phi\, e_{j\text{R}} - y_\nu^{ij}\,\overline{l}_{i\text{L}}\tilde{\Phi}\, N_{j\text{R}} - \frac{1}{2} y_M^{ij} S\,\overline{N_{i\text{R}}^c} N_{j\text{R}} - \lambda_{\text{L}}^{ij} S^*\,\overline{l}_{i\text{L}} L_{j\text{R}} - \lambda_{\text{E}}^{ij} S\,\overline{E}_{i\text{L}} e_{j\text{R}}$$
$$- M_{\text{L}}^{ij}\overline{L}_{i\text{L}} L_{j\text{R}} - M_{\text{E}}^{ij}\overline{E}_{i\text{L}} E_{j\text{R}} - h^{ij}\,\overline{L}_{i\text{L}}\Phi\, E_{j\text{R}} - k^{ij}\,\overline{E}_{i\text{L}}\Phi^\dagger\, L_{j\text{R}} + \text{H.c.}\,,\ \ i,j = 1,2,3$$

$$\mathcal{M}_\ell = \begin{pmatrix} y_l \frac{v}{\sqrt{2}} & \lambda_{\text{L}} \frac{w}{\sqrt{2}} & 0 \\ 0 & M_{\text{L}} & h \frac{v}{\sqrt{2}} \\ \lambda_{\text{E}} \frac{w}{\sqrt{2}} & k \frac{v}{\sqrt{2}} & M_{\text{E}} \end{pmatrix}$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & y_\nu \frac{v}{\sqrt{2}} & 0 & \lambda_{\text{L}} \frac{w}{\sqrt{2}} \\ y_\nu \frac{v}{\sqrt{2}} & y_M \frac{w}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & 0 & M_{\text{L}} \\ \lambda_{\text{L}} \frac{w}{\sqrt{2}} & 0 & M_{\text{L}} & 0 \end{pmatrix}$$

Adding VLLs

$$\mathcal{L}_{\text{lepton}} = - y_l^{ij} \, \overline{l}_{i\text{L}} \Phi \, e_{j\text{R}} - y_\nu^{ij} \, \overline{l}_{i\text{L}} \tilde{\Phi} \, N_{j\text{R}} - \frac{1}{2} y_M^{ij} S \, \overline{N_{i\text{R}}^c} N_{j\text{R}} - \lambda_{\text{L}}^{ij} S^* \, \overline{l}_{i\text{L}} L_{j\text{R}} - \lambda_{\text{E}}^{ij} S \, \overline{E}_{i\text{L}} e_{j\text{R}}$$
$$- M_{\text{L}}^{ij} \overline{L}_{i\text{L}} L_{j\text{R}} - M_{\text{E}}^{ij} \overline{E}_{i\text{L}} E_{j\text{R}} - h^{ij} \, \overline{L}_{i\text{L}} \Phi \, E_{j\text{R}} - k^{ij} \, \overline{E}_{i\text{L}} \Phi^\dagger \, L_{j\text{R}} + \text{H.c.} \, , \; i,j = 1,2,3$$

$$\mathcal{M}_\ell = \begin{pmatrix} y_l \frac{v}{\sqrt{2}} & \lambda_{\text{L}} \frac{w}{\sqrt{2}} & 0 \\ 0 & M_{\text{L}} & h \frac{v}{\sqrt{2}} \\ \lambda_{\text{E}} \frac{w}{\sqrt{2}} & k \frac{v}{\sqrt{2}} & M_{\text{E}} \end{pmatrix}$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & y_\nu \frac{v}{\sqrt{2}} & 0 & \lambda_{\text{L}} \frac{w}{\sqrt{2}} \\ y_\nu \frac{v}{\sqrt{2}} & y_M \frac{w}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & 0 & M_{\text{L}} \\ \lambda_{\text{L}} \frac{w}{\sqrt{2}} & 0 & M_{\text{L}} & 0 \end{pmatrix}$$

Adding VLLs

$$\mathcal{M}_\ell = \begin{pmatrix} y_l \frac{v}{\sqrt{2}} & \lambda_{\rm L} \frac{w}{\sqrt{2}} & 0 \\ 0 & M_{\rm L} & h \frac{v}{\sqrt{2}} \\ \lambda_{\rm E} \frac{w}{\sqrt{2}} & k \frac{v}{\sqrt{2}} & M_{\rm E} \end{pmatrix}$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & y_\nu \frac{v}{\sqrt{2}} & 0 & \lambda_{\rm L} \frac{w}{\sqrt{2}} \\ y_\nu \frac{v}{\sqrt{2}} & y_M \frac{w}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & 0 & M_{\rm L} \\ \lambda_{\rm L} \frac{w}{\sqrt{2}} & 0 & M_{\rm L} & 0 \end{pmatrix}$$

$$\mathcal{M}_\ell^{\rm diag} = U_{\rm L}^\dagger \mathcal{M}_\ell U_{\rm R}$$

$$\mathcal{M}_\nu^{\rm diag} = U_\nu^T \mathcal{M}_\nu U_\nu$$

Adding VLLs

$$\mathcal{M}_\ell = \begin{pmatrix} y_l \frac{v}{\sqrt{2}} & \lambda_L \frac{w}{\sqrt{2}} & 0 \\ 0 & M_L & h \frac{v}{\sqrt{2}} \\ \lambda_E \frac{w}{\sqrt{2}} & k \frac{v}{\sqrt{2}} & M_E \end{pmatrix}$$

$$\Lambda_{L,E} \equiv \frac{\lambda_{L,E}\, w}{\sqrt{2}\, M_{L,E}}$$

$$\mathcal{M}_\ell^{\text{diag}} = U_L^\dagger\, \mathcal{M}_\ell\, U_R$$

Adding VLLs

$$\mathcal{M}_\ell = \begin{pmatrix} y_l \frac{v}{\sqrt{2}} & \lambda_L \frac{w}{\sqrt{2}} & 0 \\ 0 & M_L & h \frac{v}{\sqrt{2}} \\ \lambda_E \frac{w}{\sqrt{2}} & k \frac{v}{\sqrt{2}} & M_E \end{pmatrix}$$

$$U_L = \begin{pmatrix} \frac{1}{\sqrt{1+\Lambda_L^2}} & \frac{\Lambda_L}{\sqrt{1+\Lambda_L^2}} & 0 \\ -\frac{\Lambda_L}{\sqrt{1+\Lambda_L^2}} & \frac{1}{\sqrt{1+\Lambda_L^2}} & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad U_R = \begin{pmatrix} \frac{1}{\sqrt{1+\Lambda_E^2}} & 0 & \frac{\Lambda_E}{\sqrt{1+\Lambda_E^2}} \\ 0 & 1 & 0 \\ -\frac{\Lambda_E}{\sqrt{1+\Lambda_E^2}} & 0 & \frac{1}{\sqrt{1+\Lambda_E^2}} \end{pmatrix}$$

$$\mathcal{M}_\ell^{\text{diag}} = U_L^\dagger \, \mathcal{M}_\ell \, U_R$$

Adding VLLs

$$\mathcal{M}_\ell = \begin{pmatrix} y_l \frac{v}{\sqrt{2}} & \lambda_\mathrm{L} \frac{w}{\sqrt{2}} & 0 \\ 0 & M_\mathrm{L} & h \frac{v}{\sqrt{2}} \\ \lambda_\mathrm{E} \frac{w}{\sqrt{2}} & k \frac{v}{\sqrt{2}} & M_\mathrm{E} \end{pmatrix}$$

$$U_\mathrm{L} = \begin{pmatrix} \frac{1}{\sqrt{1+\Lambda_\mathrm{L}^2}} & \frac{\Lambda_\mathrm{L}}{\sqrt{1+\Lambda_\mathrm{L}^2}} & 0 \\ -\frac{\Lambda_\mathrm{L}}{\sqrt{1+\Lambda_\mathrm{L}^2}} & \frac{1}{\sqrt{1+\Lambda_\mathrm{L}^2}} & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad U_\mathrm{R} = \begin{pmatrix} \frac{1}{\sqrt{1+\Lambda_\mathrm{E}^2}} & 0 & \frac{\Lambda_\mathrm{E}}{\sqrt{1+\Lambda_\mathrm{E}^2}} \\ 0 & 1 & 0 \\ -\frac{\Lambda_\mathrm{E}}{\sqrt{1+\Lambda_\mathrm{E}^2}} & 0 & \frac{1}{\sqrt{1+\Lambda_\mathrm{E}^2}} \end{pmatrix}$$

$$g_{\mathrm{L,R}}^{Z\ell_1^\pm \ell_1^\mp} = \frac{g}{c_W} \sum_{i=1}^{3} \left(T_i^3 - s_W^2 Q_i\right) \left(U_{\mathrm{L,R}}^\dagger\right)_{1i} \left(U_{\mathrm{L,R}}\right)_{i1}$$

$$\mathcal{M}_\ell^{\mathrm{diag}} = U_\mathrm{L}^\dagger \, \mathcal{M}_\ell \, U_\mathrm{R}$$

Adding VLLs

$$\mathcal{M}_\ell = \begin{pmatrix} y_l \frac{v}{\sqrt{2}} & \lambda_L \frac{w}{\sqrt{2}} & 0 \\ 0 & M_L & h \frac{v}{\sqrt{2}} \\ \lambda_E \frac{w}{\sqrt{2}} & k \frac{v}{\sqrt{2}} & M_E \end{pmatrix}$$

$$U_L = \begin{pmatrix} \frac{1}{\sqrt{1+\Lambda_L^2}} & \frac{\Lambda_L}{\sqrt{1+\Lambda_L^2}} & 0 \\ -\frac{\Lambda_L}{\sqrt{1+\Lambda_L^2}} & \frac{1}{\sqrt{1+\Lambda_L^2}} & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad U_R = \begin{pmatrix} \frac{1}{\sqrt{1+\Lambda_E^2}} & 0 & \frac{\Lambda_E}{\sqrt{1+\Lambda_E^2}} \\ 0 & 1 & 0 \\ -\frac{\Lambda_E}{\sqrt{1+\Lambda_E^2}} & 0 & \frac{1}{\sqrt{1+\Lambda_E^2}} \end{pmatrix}$$

$$g_{L,R}^{Z\ell_1^\pm \ell_1^\mp} = \frac{g}{c_W} \sum_{i=1}^{3} \left(T_i^3 - s_W^2 Q_i\right) \left(U_{L,R}^\dagger\right)_{1i} \left(U_{L,R}\right)_{i1}$$

$$\mathcal{M}_\ell^{\text{diag}} = U_L^\dagger \mathcal{M}_\ell U_R$$

The mixing is not constrained by Z-pole measurements!

Adding VLLs

$$\mathcal{M}_\ell = \begin{pmatrix} y_l \frac{v}{\sqrt{2}} & \lambda_L \frac{w}{\sqrt{2}} & 0 \\ 0 & M_L & h \frac{v}{\sqrt{2}} \\ \lambda_E \frac{w}{\sqrt{2}} & k \frac{v}{\sqrt{2}} & M_E \end{pmatrix}$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & y_\nu \frac{v}{\sqrt{2}} & 0 & \lambda_L \frac{w}{\sqrt{2}} \\ y_\nu \frac{v}{\sqrt{2}} & y_M \frac{w}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & 0 & M_L \\ \lambda_L \frac{w}{\sqrt{2}} & 0 & M_L & 0 \end{pmatrix}$$

$$\mathcal{M}_\ell^{\text{diag}} = U_L^\dagger \mathcal{M}_\ell U_R$$

$$\mathcal{M}_\nu^{\text{diag}} = U_\nu^T \mathcal{M}_\nu U_\nu$$

Adding VLLs

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & y_\nu \frac{v}{\sqrt{2}} & 0 & \lambda_L \frac{w}{\sqrt{2}} \\ y_\nu \frac{v}{\sqrt{2}} & y_M \frac{w}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & 0 & M_L \\ \lambda_L \frac{w}{\sqrt{2}} & 0 & M_L & 0 \end{pmatrix}$$

$$\mathcal{M}_\nu^{\text{diag}} = U_\nu^T \mathcal{M}_\nu U_\nu$$

Adding VLLs

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & y_\nu \frac{v}{\sqrt{2}} & 0 & \lambda_L \frac{w}{\sqrt{2}} \\ y_\nu \frac{v}{\sqrt{2}} & y_M \frac{w}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & 0 & M_L \\ \lambda_L \frac{w}{\sqrt{2}} & 0 & M_L & 0 \end{pmatrix}$$

$$\mathcal{M}_\nu^{\text{diag}} = U_\nu^T \mathcal{M}_\nu U_\nu$$

Adding VLLs

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & y_\nu \frac{v}{\sqrt{2}} & 0 & \lambda_L \frac{w}{\sqrt{2}} \\ y_\nu \frac{v}{\sqrt{2}} & y_M \frac{w}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & 0 & M_L \\ \lambda_L \frac{w}{\sqrt{2}} & 0 & M_L & 0 \end{pmatrix}$$

$$U_\nu = \begin{pmatrix} -\frac{1}{\sqrt{1+\Lambda_L^2}} & 0 & -\frac{1}{\sqrt{2}}\frac{\Lambda_L}{\sqrt{1+\Lambda_L^2}} & \frac{1}{\sqrt{2}}\frac{\Lambda_L}{\sqrt{1+\Lambda_L^2}} \\ 0 & 1 & 0 & 0 \\ \frac{\Lambda_L}{\sqrt{1+\Lambda_L^2}} & 0 & -\frac{1}{\sqrt{2}}\frac{1}{\sqrt{1+\Lambda_L^2}} & \frac{1}{\sqrt{2}}\frac{1}{\sqrt{1+\Lambda_L^2}} \\ 0 & 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$$\mathcal{M}_\nu^{\text{diag}} = U_\nu^T \mathcal{M}_\nu U_\nu$$

Adding VLLs

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & y_\nu \frac{v}{\sqrt{2}} & 0 & \lambda_{\rm L} \frac{w}{\sqrt{2}} \\ y_\nu \frac{v}{\sqrt{2}} & y_M \frac{w}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & 0 & M_{\rm L} \\ \lambda_{\rm L} \frac{w}{\sqrt{2}} & 0 & M_{\rm L} & 0 \end{pmatrix}$$

$$U_\nu = \begin{pmatrix} -\frac{1}{\sqrt{1+\Lambda_{\rm L}^2}} & 0 & -\frac{1}{\sqrt{2}} \frac{\Lambda_{\rm L}}{\sqrt{1+\Lambda_{\rm L}^2}} & \frac{1}{\sqrt{2}} \frac{\Lambda_{\rm L}}{\sqrt{1+\Lambda_{\rm L}^2}} \\ 0 & 1 & 0 & 0 \\ \frac{\Lambda_{\rm L}}{\sqrt{1+\Lambda_{\rm L}^2}} & 0 & -\frac{1}{\sqrt{2}} \frac{1}{\sqrt{1+\Lambda_{\rm L}^2}} & \frac{1}{\sqrt{2}} \frac{1}{\sqrt{1+\Lambda_{\rm L}^2}} \\ 0 & 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$$\mathcal{M}_\nu^{\rm diag} = U_\nu^T \mathcal{M}_\nu U_\nu$$

$$\varepsilon^A_{\nu_1\nu_1} = \varepsilon_{B-L} \left(\frac{1-\Lambda_{\rm L}^2}{1+\Lambda_{\rm L}^2} \right)$$

Adding VLLs

$$\varepsilon^{A}_{\nu_1\nu_1} = \varepsilon_{B-L}\left(\frac{1-\Lambda_{\mathrm{L}}^2}{1+\Lambda_{\mathrm{L}}^2}\right)$$

$$\Lambda_{\mathrm{L}} = 1 - \delta_{\mathrm{L}}$$

$$\delta_{\mathrm{L}} \ll 1$$

$$\frac{\varepsilon^{A}_{\nu_1\nu_1}}{\varepsilon_{B-L}} = \delta_{\mathrm{L}} + \mathcal{O}\left(\delta_{\mathrm{L}}^2\right) \ll 1$$

Adding VLLs

$$\varepsilon^{A}_{\nu_1\nu_1} = \varepsilon_{B-L}\left(\frac{1-\Lambda_{\rm L}^2}{1+\Lambda_{\rm L}^2}\right) \longrightarrow \boxed{\Lambda_{\rm L} = 1 - \delta_{\rm L}} \qquad \delta_{\rm L} \ll 1$$

$$\varepsilon^{A}_{\ell_1^{\pm}\ell_1^{\mp}} \simeq \frac{1}{2}\varepsilon_{B-L}\left(\frac{\Lambda_{\rm E}^2-1}{1+\Lambda_{\rm E}^2}\right) \longrightarrow \boxed{\Lambda_{\rm E} = 1 - \delta_{\rm E}} \qquad \delta_{\rm E} \ll 1$$

Adding VLLs: large mixing / unity charge

$$\Lambda_L = 1 - \delta_L$$

$$\delta_L \ll 1$$

$$\Lambda_E = 1 - \delta_E$$

$$\delta_E \ll 1$$

Adding VLLs: large mixing / unity charge

$$\Lambda_L = 1 - \delta_L$$

$$\delta_L \ll 1$$

$$\Lambda_E = 1 - \delta_E$$

$$\delta_E \ll 1$$

Higgs couplings modifiers

Adding VLLs: large mixing / unity charge

$$\Lambda_{\rm L} = 1 - \delta_{\rm L}$$

$$\delta_{\rm L} \ll 1$$

$$\Lambda_{\rm E} = 1 - \delta_{\rm E}$$

$$\delta_{\rm E} \ll 1$$

Higgs couplings modifiers

$$-\mathcal{L} \supset \frac{m_\ell}{v} \kappa_\ell \, h \, \overline{\ell^\pm_{\rm L}} \ell^\pm_{\rm R} + \text{H.c.}$$

$$\kappa_\ell = |(U_{\rm L})_{11}|^2 \, |(U_{\rm R})_{11}|^2 = \frac{1}{1+\Lambda_{\rm L}^2} \frac{1}{1+\Lambda_{\rm E}^2}$$

$$\kappa_\ell = \frac{1}{4} + \mathcal{O}(\delta_{\rm L}, \delta_{\rm E})$$

Adding VLLs: large mixing / unity charge

$$\Lambda_\mathrm{L} = 1 - \delta_\mathrm{L}$$

$$\delta_\mathrm{L} \ll 1$$

$$\Lambda_\mathrm{E} = 1 - \delta_\mathrm{E}$$

$$\delta_\mathrm{E} \ll 1$$

Higgs couplings modifiers

$$-\mathcal{L} \supset \frac{m_\ell}{v} \kappa_\ell \, h \, \overline{\ell^\pm_\mathrm{L}} \ell^\pm_\mathrm{R} + \mathrm{H.c.}$$

$$\kappa_\ell = |(U_\mathrm{L})_{11}|^2 \, |(U_\mathrm{R})_{11}|^2 = \frac{1}{1+\Lambda_\mathrm{L}^2} \frac{1}{1+\Lambda_\mathrm{E}^2}$$

$$\kappa_\ell = \frac{1}{4} + \mathcal{O}\left(\delta_\mathrm{L}, \delta_\mathrm{E}\right)$$

Non-unitarity on neutrinos

Adding VLLs: large mixing / unity charge

$$\Lambda_{\rm L} = 1 - \delta_{\rm L}$$

$$\delta_{\rm L} \ll 1$$

$$\Lambda_{\rm E} = 1 - \delta_{\rm E}$$

$$\delta_{\rm E} \ll 1$$

Higgs couplings modifiers

$$-\mathcal{L} \supset \frac{m_\ell}{v} \kappa_\ell \, h \, \overline{\ell_{\rm L}^{\pm}} \ell_{\rm R}^{\pm} + \text{H.c.}$$

$$\kappa_\ell = |(U_{\rm L})_{11}|^2 \, |(U_{\rm R})_{11}|^2 = \frac{1}{1+\Lambda_{\rm L}^2} \frac{1}{1+\Lambda_{\rm E}^2}$$

$$\kappa_\ell = \frac{1}{4} + \mathcal{O}(\delta_{\rm L}, \delta_{\rm E})$$

Non-unitarity on neutrinos

$$\delta_e = 1 - |\,(U_\nu)_{11}\,|^2 \lesssim 0.04$$

$$\Rightarrow \quad \Lambda_{\rm L}^2 \lesssim 1/24$$

Adding VLLs

	Fields	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	Q_{B-L}	
Vanilla $B-L$	$q_{iL} = (u_{iL}, d_{iL})^T$	**3**	**2**	$1/6$	$1/3$	Vanilla $B-L$ + VLLs
	u_{iR}	**3**	**1**	$2/3$	$1/3$	
	d_{iR}	**3**	**1**	$-1/3$	$1/3$	
	$l_{iL} = (\nu_{iL}, e_{iL})^T$	**1**	**2**	$-1/2$	-1	
	e_{iR}	**1**	**1**	-1	-1	
	N_{iR}	**1**	**1**	0	-1	
	Φ	**1**	**2**	$1/2$	0	
	S	**1**	**1**	0	2	
	$L_{iL,R} = (\mathcal{N}_{iL,R}, \mathcal{E}_{iL,R})^T$	**1**	**2**	$-1/2$	1	
	$E_{iL,R}$	**1**	**1**	-1	1	

Adding VLLs

	Fields	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	Q_{B-L}	
Vanilla $B-L$	$q_{iL} = (u_{iL}, d_{iL})^T$	**3**	**2**	$1/6$	$1/3$	Vanilla $B-L$ + VLLs
	u_{iR}	**3**	**1**	$2/3$	$1/3$	
	d_{iR}	**3**	**1**	$-1/3$	$1/3$	
	$l_{iL} = (\nu_{iL}, e_{iL})^T$	**1**	**2**	$-1/2$	-1	
	e_{iR}	**1**	**1**	-1	-1	
	N_{iR}	**1**	**1**	0	-1	
	Φ	**1**	**2**	$1/2$	0	
	S	**1**	**1**	0	$Q^{B-L}_{\text{VLL}} + 1$	
	$L_{iL,R} = (\mathcal{N}_{iL,R}, \mathcal{E}_{iL,R})^T$	**1**	**2**	$-1/2$	Q^{B-L}_{VLL}	
	$E_{iL,R}$	**1**	**1**	-1	Q^{B-L}_{VLL}	

Adding VLLs

$$\varepsilon^{A}_{\nu_1\nu_1} = \varepsilon_{B-L}\left(\frac{1-\Lambda_{\mathrm{L}}^2}{1+\Lambda_{\mathrm{L}}^2}\right)$$

$$\varepsilon^{A}_{\ell_1^{\pm}\ell_1^{\mp}} \simeq \frac{1}{2}\,\varepsilon_{B-L}\left(\frac{\Lambda_{\mathrm{E}}^2-1}{1+\Lambda_{\mathrm{E}}^2}\right)$$

Adding VLLs

$$\varepsilon^A_{\nu_1\nu_1} = \varepsilon_{B-L}\left(\frac{1-\Lambda^2_{\mathrm{L}}}{1+\Lambda^2_{\mathrm{L}}}\right) \longrightarrow \boxed{\varepsilon^A_{\nu_1\nu_1} = \varepsilon_{B-L}\left(\frac{1-Q^{B-L}_{\mathrm{VLL}}\Lambda^2_{\mathrm{L}}}{1+\Lambda^2_{\mathrm{L}}}\right)}$$

$$\varepsilon^A_{\ell_1^\pm\ell_1^\mp} \simeq \frac{1}{2}\varepsilon_{B-L}\left(\frac{\Lambda^2_{\mathrm{E}}-1}{1+\Lambda^2_{\mathrm{E}}}\right) \longrightarrow \boxed{\varepsilon^A_{\ell_1^\pm\ell_1^\mp} \simeq \frac{1}{2}\varepsilon_{B-L}\left(\frac{Q^{B-L}_{\mathrm{VLL}}\Lambda^2_{\mathrm{E}}-1}{1+\Lambda^2_{\mathrm{E}}}\right)}$$

Adding VLLs: small mixing / large charges

$$\varepsilon^{A}_{\nu_1\nu_1} = \varepsilon_{B-L}\left(\frac{1-\Lambda_{\mathrm{L}}^2}{1+\Lambda_{\mathrm{L}}^2}\right) \longrightarrow \boxed{\varepsilon^{A}_{\nu_1\nu_1} = \varepsilon_{B-L}\left(\frac{1-Q_{\mathrm{VLL}}^{B-L}\Lambda_{\mathrm{L}}^2}{1+\Lambda_{\mathrm{L}}^2}\right)}$$

$$\varepsilon^{A}_{\ell_1^{\pm}\ell_1^{\mp}} \simeq \frac{1}{2}\varepsilon_{B-L}\left(\frac{\Lambda_{\mathrm{E}}^2-1}{1+\Lambda_{\mathrm{E}}^2}\right) \longrightarrow \boxed{\varepsilon^{A}_{\ell_1^{\pm}\ell_1^{\mp}} \simeq \frac{1}{2}\varepsilon_{B-L}\left(\frac{Q_{\mathrm{VLL}}^{B-L}\Lambda_{\mathrm{E}}^2-1}{1+\Lambda_{\mathrm{E}}^2}\right)}$$

Adding VLLs: small mixing / large charges

$$\varepsilon^{A}_{\nu_1\nu_1} = \varepsilon_{B-L}\left(\frac{1-\Lambda_{\mathrm{L}}^2}{1+\Lambda_{\mathrm{L}}^2}\right) \longrightarrow \boxed{\varepsilon^{A}_{\nu_1\nu_1} = \varepsilon_{B-L}\left(\frac{1-Q^{B-L}_{\mathrm{VLL}}\Lambda_{\mathrm{L}}^2}{1+\Lambda_{\mathrm{L}}^2}\right)} \qquad Q^{B-L}_{\mathrm{VLL}}\Lambda_{\mathrm{L}}^2 \simeq 1$$

$$\varepsilon^{A}_{\ell_1^{\pm}\ell_1^{\mp}} \simeq \frac{1}{2}\,\varepsilon_{B-L}\left(\frac{\Lambda_{\mathrm{E}}^2-1}{1+\Lambda_{\mathrm{E}}^2}\right) \longrightarrow \boxed{\varepsilon^{A}_{\ell_1^{\pm}\ell_1^{\mp}} \simeq \frac{1}{2}\,\varepsilon_{B-L}\left(\frac{Q^{B-L}_{\mathrm{VLL}}\Lambda_{\mathrm{E}}^2-1}{1+\Lambda_{\mathrm{E}}^2}\right)}$$

Adding VLLs: small mixing / large charges

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$$\delta_e = 1 - |\,(U_\nu)_{11}\,|^2 \lesssim 0.04$$

$$\Rightarrow \quad \Lambda^2_{\rm L} \lesssim 1/24$$

Adding VLLs: small mixing / large charges

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Adding VLLs: small mixing / large charges

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$$\delta_e = 1 - |\,(U_\nu)_{11}\,|^2 \lesssim 0.04$$

$$\Rightarrow \quad \Lambda^2_{\rm L} \lesssim 1/24 \qquad\qquad \Lambda_{\rm L} \simeq \Lambda_{\rm E} < \sqrt{1/24} \simeq 0.2$$

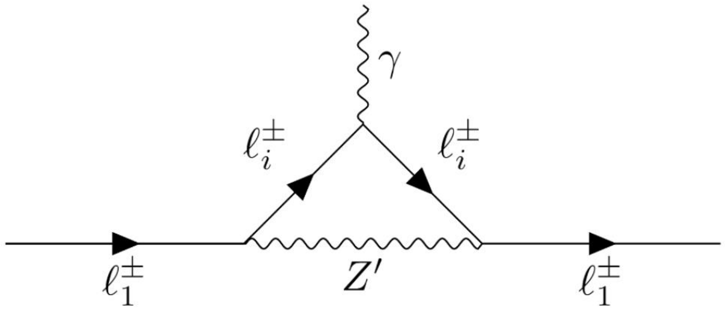
$$\longrightarrow \quad Q^{B-L}_{\rm VLL} > 24$$

Adding VLLs: small mixing / large charges

Muon anomalous magnetic moment

Adding VLLs: small mixing / large charges

Muon anomalous magnetic moment



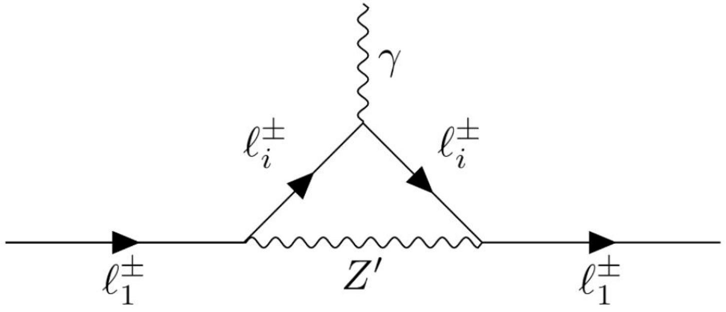
$$\Delta a_\mu^{Z'} \simeq \mathcal{A}_\mu + \mathcal{A}_{\rm VLL} = -\frac{m_\mu^2 e^2}{8\pi^2 m_{Z'}^2}\left(\mathcal{C}_\mu \varepsilon^2 + \mathcal{C}_{\rm VLL}\,\varepsilon_{B-L}^2 Q_{\rm VLL}^{B-L}\right)$$

$$\mathcal{C}_\mu = 2\,F_{Z'}\left(\frac{m_\mu^2}{m_{Z'}^2}\right) - G_{Z'}\left(\frac{m_\mu^2}{m_{Z'}^2}\right) \simeq 0.321$$

$$\mathcal{C}_{\rm VLL} = F_{Z'}\left(\frac{M_{\rm L}^2}{m_{Z'}^2}\right) + F_{Z'}\left(\frac{M_{\rm E}^2}{m_{Z'}^2}\right) \simeq 2\lim_{x\to\infty} F_{Z'}(x) = \frac{5}{6}$$

Adding VLLs: small mixing / large charges

Muon anomalous magnetic moment



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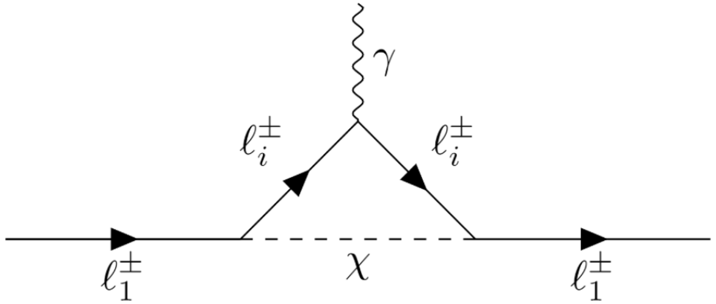
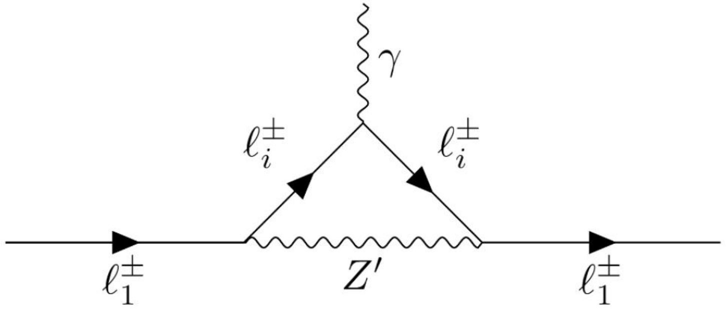


$$\Delta a_\mu^{\chi} \simeq \mathcal{A}_{\rm L} + \mathcal{A}_{\rm E} = \frac{m_\mu^2 e^2}{4\pi^2 m_{Z'}^2}\varepsilon_{B-L}^2\left(\mathcal{C}_{\rm L}\Lambda_{\rm L}^2 + \mathcal{C}_{\rm E}\Lambda_{\rm E}^2\right)$$

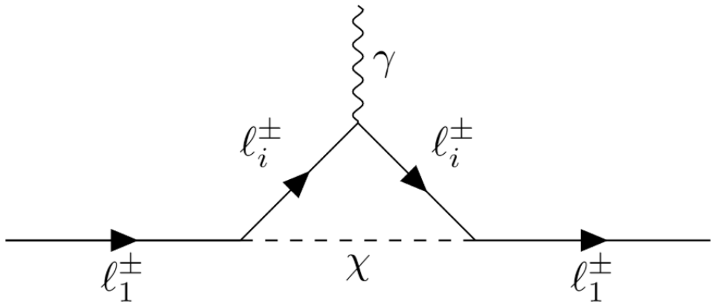
$$\mathcal{C}_{\rm L,E} = \frac{M_{\rm L,E}^2}{m_\chi^2} F_\chi\left(\frac{M_{\rm L,E}^2}{m_\chi^2}\right) \simeq \lim_{x\to\infty} x\, F_\chi(x) = \frac{1}{6}$$

Adding VLLs: small mixing / large charges

Muon anomalous magnetic moment



$$\Delta a_\mu^{Z'} \simeq \mathcal{A}_\mu + \mathcal{A}_{\mathrm{VLL}} = -\frac{m_\mu^2 e^2}{8\pi^2 m_{Z'}^2}\left(\mathcal{C}_\mu \varepsilon^2 + \mathcal{C}_{\mathrm{VLL}}\, \varepsilon_{B-L}^2 Q_{\mathrm{VLL}}^{B-L}\right)$$



$$\Delta a_\mu^{\chi} \simeq \mathcal{A}_{\mathrm{L}} + \mathcal{A}_{\mathrm{E}} = \frac{m_\mu^2 e^2}{4\pi^2 m_{Z'}^2}\varepsilon_{B-L}^2 \left(\mathcal{C}_{\mathrm{L}} \Lambda_{\mathrm{L}}^2 + \mathcal{C}_{\mathrm{E}} \Lambda_{\mathrm{E}}^2\right)$$

Adding VLLs: small mixing / large charges

Muon anomalous magnetic moment

$$Q^{B-L}_{\mathrm{VLL}} = 24\,, \quad \Lambda_{\mathrm{L}} = \Lambda_{\mathrm{E}} = \frac{1}{\sqrt{24}}\,, \quad \varepsilon = -1.5 \times 10^{-3}\,, \quad \varepsilon_{B-L} = 2 \times 10^{-3}$$

Adding VLLs: small mixing / large charges

Muon anomalous magnetic moment

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$$\mathcal{A}_{\mu} \simeq -3.26 \times 10^{-8}\,, \quad \mathcal{A}_{\text{VLL}} \simeq -3.61 \times 10^{-6}\,, \quad \mathcal{A}_{\text{L,E}} \simeq 2.51 \times 10^{-9}$$

Adding VLLs: small mixing / large charges

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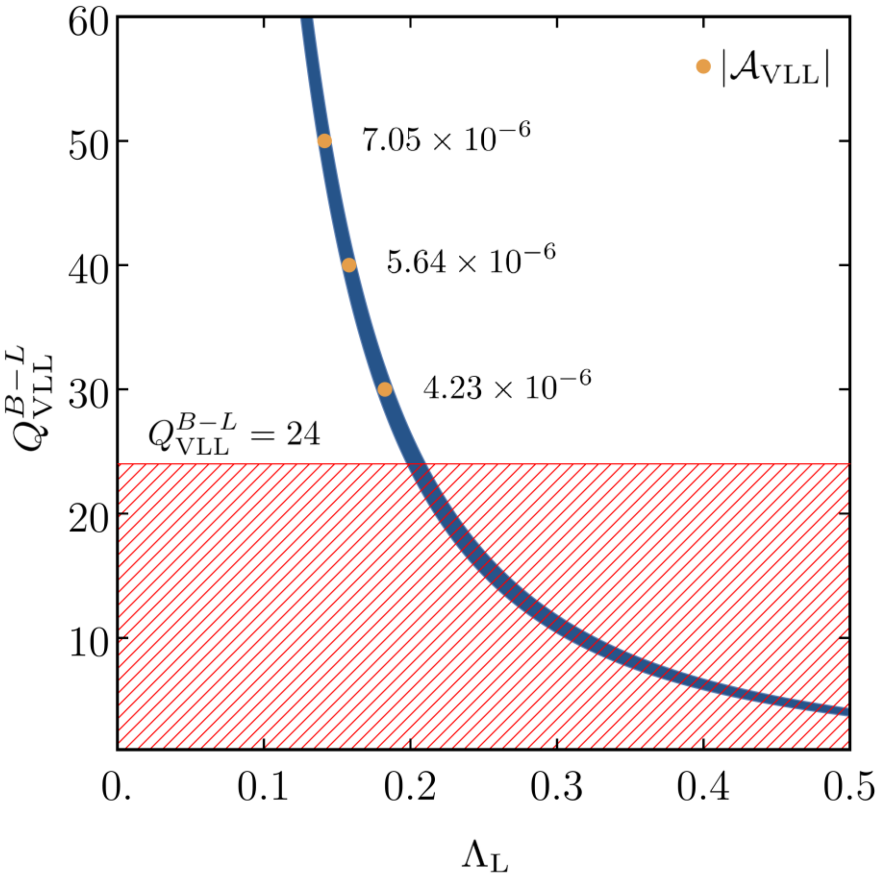
$$\Rightarrow \quad \Delta a_{\mu} \simeq -3.64\times 10^{-6}$$

Adding VLLs: small mixing / large charges

Muon anomalous magnetic moment



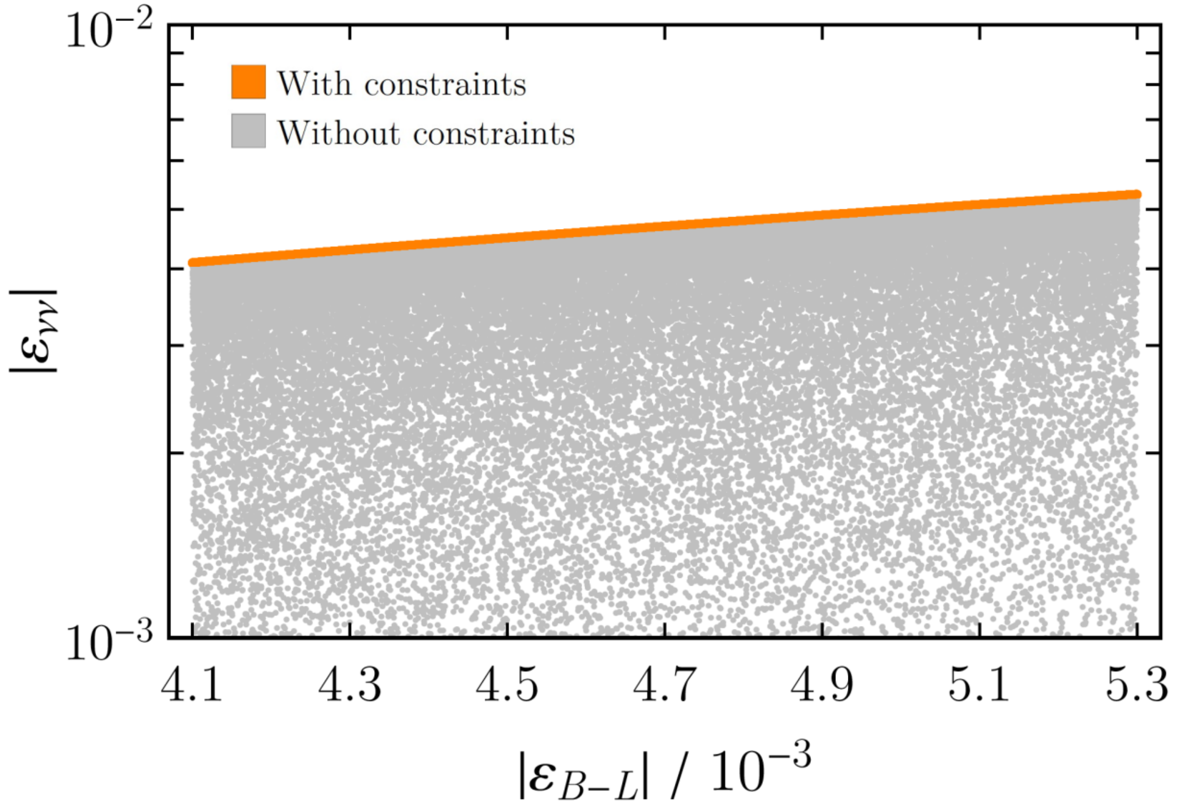
Dominant contribution to muon's *g-2* in the region of neutrino coupling suppression, considering

$$\varepsilon_{B-L} = 2 \times 10^{-3}$$

Long story short

- ✓ The B-L solution was one of the first solutions to the ATOMKI anomalies
- ✓ The vanilla scenario does not account for the neutrino coupling suppression
- ✓ Adding VLLs with B-L charge of 1 allows for that suppression, but requires large mixing
- ✓ Large mixing is in tension with experimental data (Higgs couplings, non-unitarity constraints on the neutrino sector)
- ✓ Large B-L charges allow for small mixing
- ✓ However, large charges lead to large and negative muon's g-2!

Backup slides



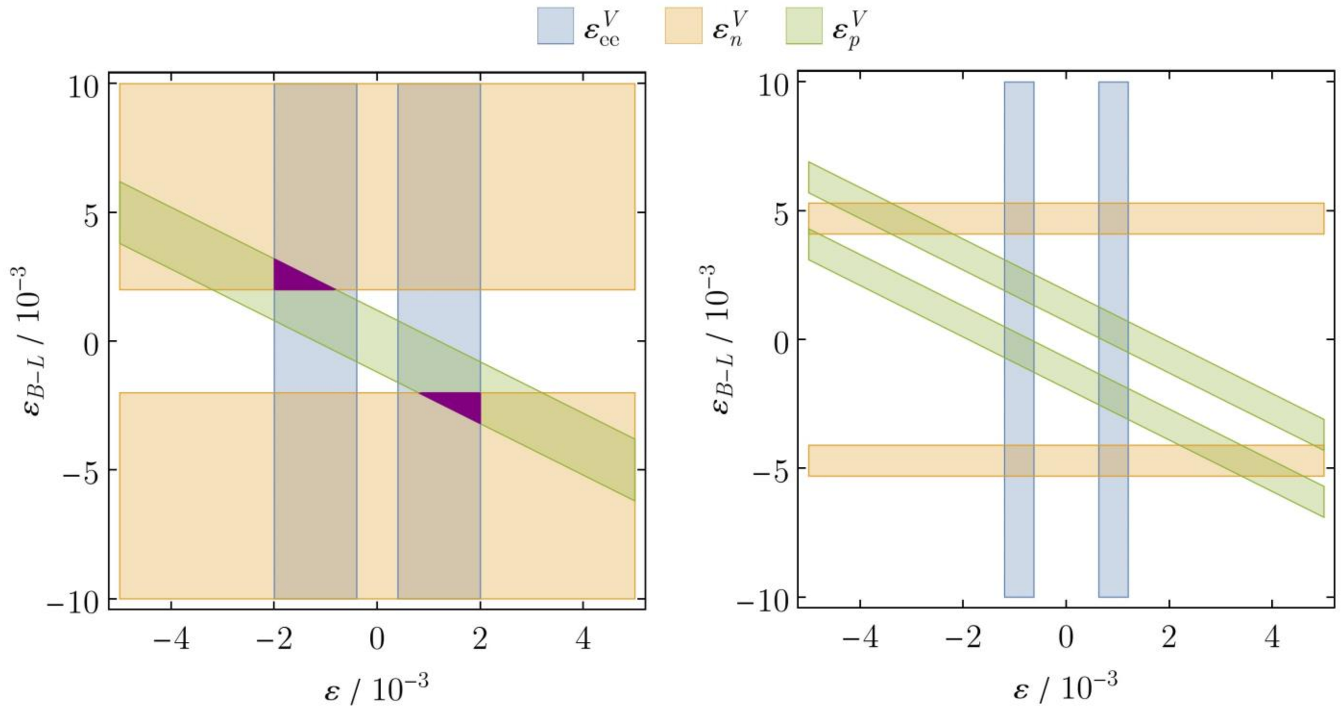
Numerical study for the large mixing scenario

Backup slides

Perturbativity problems in the small mixing scenario

$$Q_{\mathrm{VLL}}^{B-L} \simeq \frac{1}{\Lambda_{\mathrm{L}}^2} \simeq (57-95)\left(\frac{M_{\mathrm{L}}}{130\ \mathrm{GeV}}\right)^2\left(\frac{\sqrt{4\pi}}{\lambda_{\mathrm{L}}}\right)^2$$

Tension in the allowed regions for the couplings in the small mixing scenario



Backup slides

Small mixing in the scalar sector $\lambda_1 \simeq m_h^2/v^2$ $\lambda_2 \simeq m_\chi^2/w^2$

Unitarity bound

$$\frac{3}{2}\frac{m_h^2}{v^2} + \frac{m_\chi^2}{w^2} + \sqrt{\left(\frac{3}{2}\frac{m_h^2}{v^2} + \frac{m_\chi^2}{w^2}\right)^2 + \left(\frac{m_\chi^2}{w^2}\right)^2} \leq 8\pi\,, \quad w^{-2} = \frac{4e^2\varepsilon_{B-L}^2}{m_{Z'}^2}$$

Mass bound

$$\varepsilon_{B-L} = 2\times 10^{-3} \longrightarrow \boxed{m_\chi \lesssim 45\ \text{GeV}}$$

Backup slides

Loop functions

$$F_{Z'}(x) = \frac{5x^4 - 14x^3 + 39x^2 - 38x + 8 - 18x^2 \log x}{12(1-x)^4}$$

$$G_{Z'}(x) = -\frac{x^3 + 3x - 4 - 6x \log x}{2(1-x)^3}$$

$$F_{\chi}(x) = \frac{x^3 - 6x^2 + 3x + 2 + 6x \log x}{6(1-x)^4}$$