ATOMKI NUCLEAR ANOMALIES AND (B-L)

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CFTP Centro de Física Teórica de Partículas

Based on [JHEP 04 (2024) 003]

Workshop on the Standard Model and Beyond
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Bernardo Gonçalves (CFTP-IST/CFTC)

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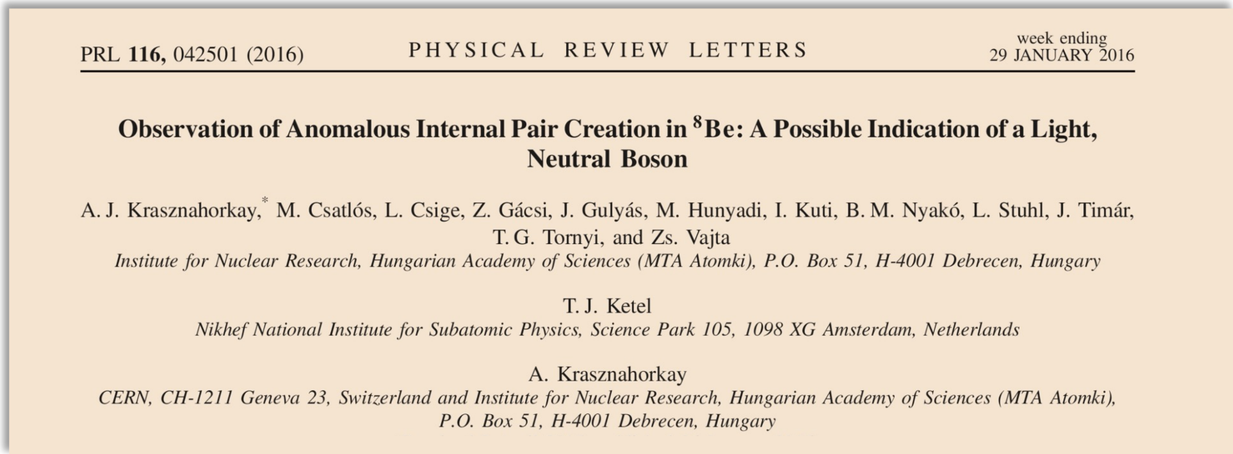
The ATOMKI Anomaly(ies) : Brief overview



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
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T. J. Ketel
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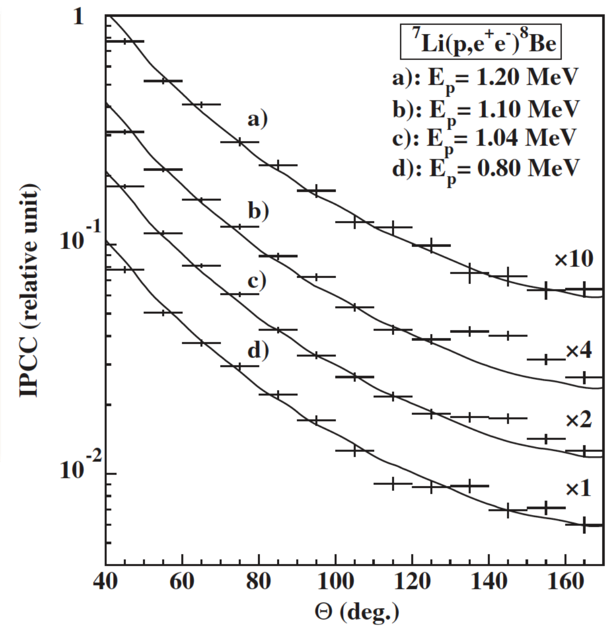
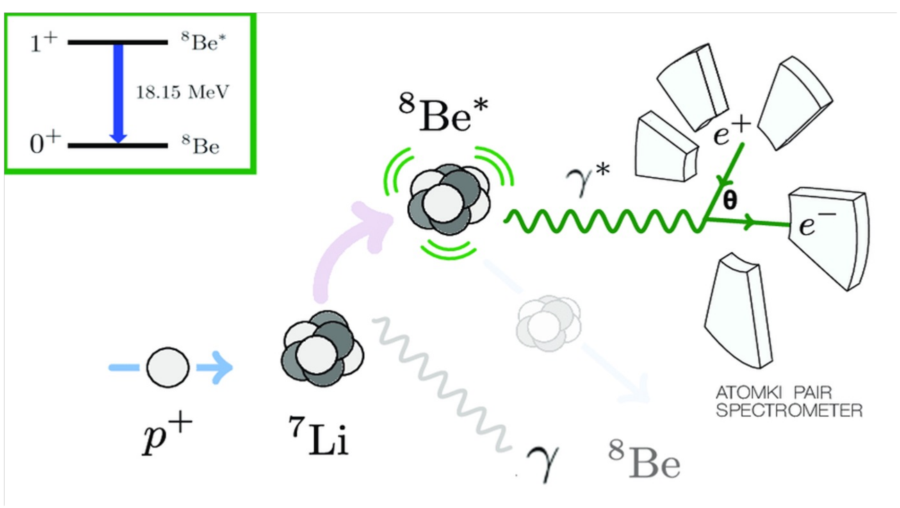
CERN, CH-1211 Geneva 23, Switzerland and Institute for Nuclear Research, Hungarian Academy of Sciences (MTA Atomki), P.O. Box 51, H-4001 Debrecen, Hungary



$$p + {}^7\mathrm{Li} \longrightarrow {}^8\mathrm{Be}^*(18.15\mathrm{MeV}) \longrightarrow {}^8\mathrm{Be} + e^+e^-$$



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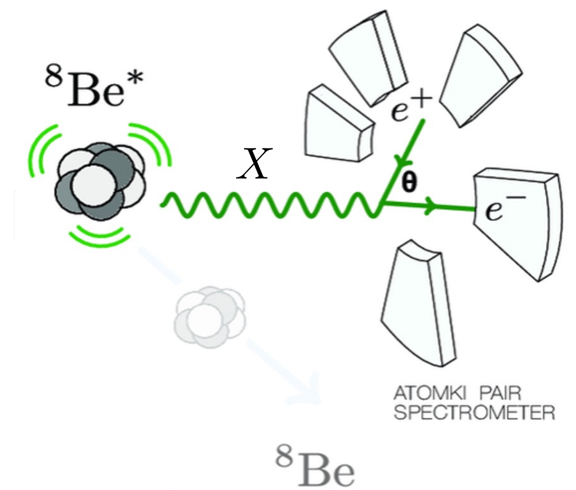

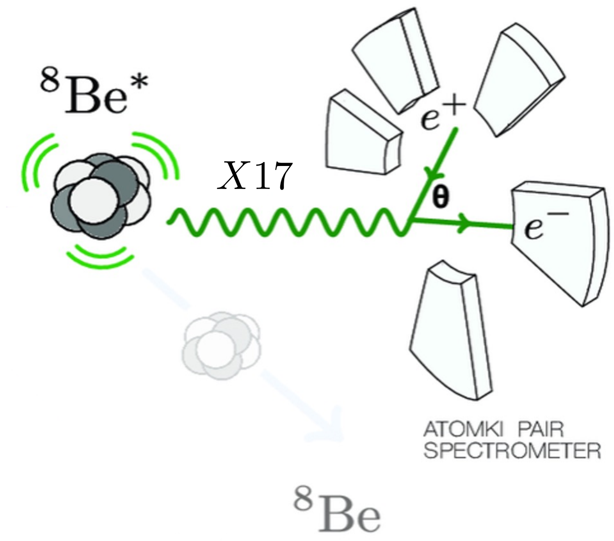

our knowledge, no nuclear physics related description of such deviation can be made. The deviation between the experimental and theoretical angular correlations is significant and can be described by assuming the creation and subsequent decay of a $J^\pi = 1^+$ boson with mass $m_0c^2 = 16.70 \pm 0.35(\text{stat}) \pm 0.5(\text{syst})$ MeV. The branching ratio of the e^+e^- decay of such a boson to the γ decay of the 18.15 MeV level of ^{8}Be is found to be 5.8×10^{-6} for the best fit.

$$m_X c^2 = 16.70 \pm 0.35(\text{ stat }) \pm 0.5(\text{ syst })\text{MeV}$$

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]

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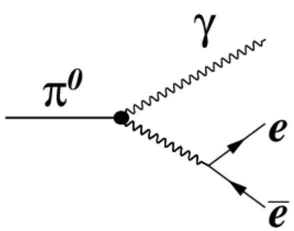
(Received 3 May 2016; published 11 August 2016)

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

ATOMKI: $|\varepsilon_u + \varepsilon_d| \approx 3.7 \times 10^{-3}$



$$\pi^0 \to X\gamma$$

$$N_\pi \equiv (\varepsilon_u q_u - \varepsilon_d q_d)^2$$

NA48/2: $|2\varepsilon_u + \varepsilon_d| < \varepsilon_{\max} = 8 \times 10^{-4}$

$$-0.067 < \frac{\varepsilon_p}{\varepsilon_n} < 0.078$$

"Protophobic" X17

The ATOMKI Anomaly(ies) : Brief overview

PHYSICAL REVIEW C **104**, 044003 (2021)

New anomaly observed in ^{4}He supports the existence of the hypothetical X17 particle

A. J. Krasznahorkay,[1,*] M. Csatlós,[1] L. Csige,[1] J. Gulyás,[1] A. Krasznahorkay,[1,†] B. M. Nyakó,[1] I. Rajta,[1] J. Timár,[1] I. Vajda,[1] and N. J. Sas[2]
[1]*Institute for Nuclear Research (ATOMKI), P.O. Box 51, H-4001 Debrecen, Hungary*
[2]*University of Debrecen, 4010 Debrecen, PO Box 105, Hungary*

(Received 27 October 2019; revised 30 June 2021; accepted 6 October 2021; published 18 October 2021)

Angular correlation spectra of e^+e^- pairs produced in the ^{3}H$(p, e^+e^-)^4$He nuclear reaction have been studied at $E_p = 510, 610$, and 900 keV proton energies. The main features of the spectra can be understood by taking into account the internal and external pair creations following the proton capture by ^{3}H. However, these processes cannot account for an observed peak around 115° in the angular correlation spectra. This anomalous excess of e^+e^- pairs can be described by the creation and subsequent decay of a light particle during the direct capture process. The derived mass of the particle is $m_X c^2 = 16.94 \pm 0.12(\text{stat}) \pm 0.21(\text{syst})$ MeV. According to the mass this is likely the same X17 particle, which we recently suggested [Phys. Rev. Lett. **116**, 042501 (2016)] for describing the anomaly observed in the decay of ^{8}Be.

DOI: 10.1103/PhysRevC.104.044003

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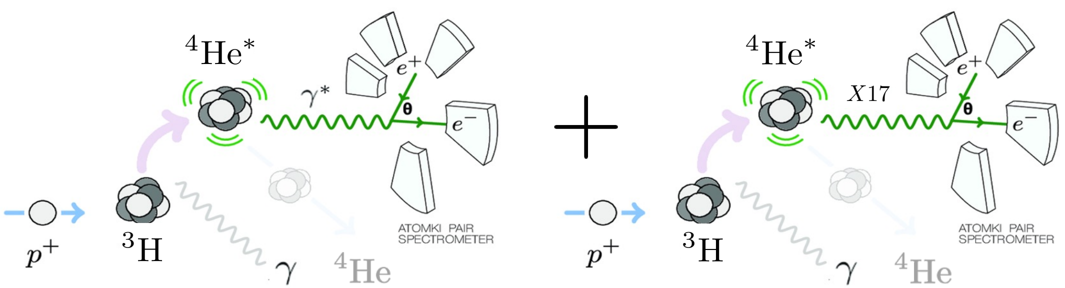
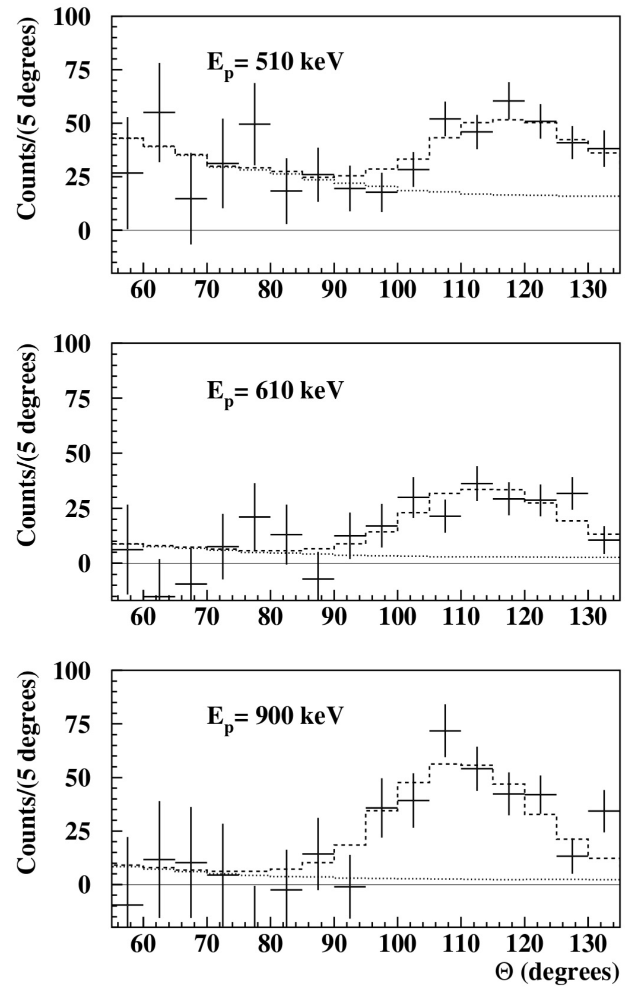
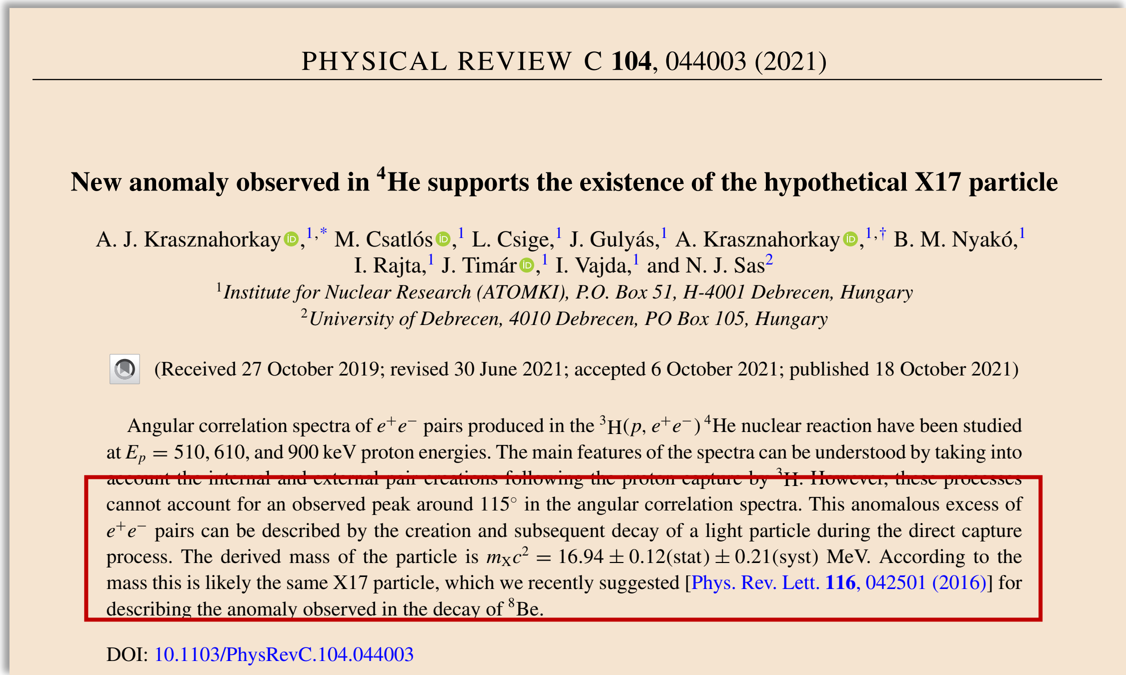




$$m_X c^2 = 16.94 \pm 0.12_{\text{stat}} \pm 0.21_{\text{syst}} \text{ MeV}$$

Consistent with the ^{8}Be result !!

The ATOMKI Anomaly(ies) : Brief overview


PHYSICAL REVIEW C **104**, 044003 (2021)

New anomaly observed in ^{4}He supports the existence of the hypothetical X17 particle

A. J. Krasznahorkay,[1,*] M. Csatlós,[1] L. Csige,[1] J. Gulyás,[1] A. Krasznahorkay,[1,†] B. M. Nyakó,[1] I. Rajta,[1] J. Timár,[1] I. Vajda,[1] and N. J. Sas[2]
[1]Institute for Nuclear Research (ATOMKI), P.O. Box 51, H-4001 Debrecen, Hungary
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DOI: 10.1103/PhysRevC.104.044003

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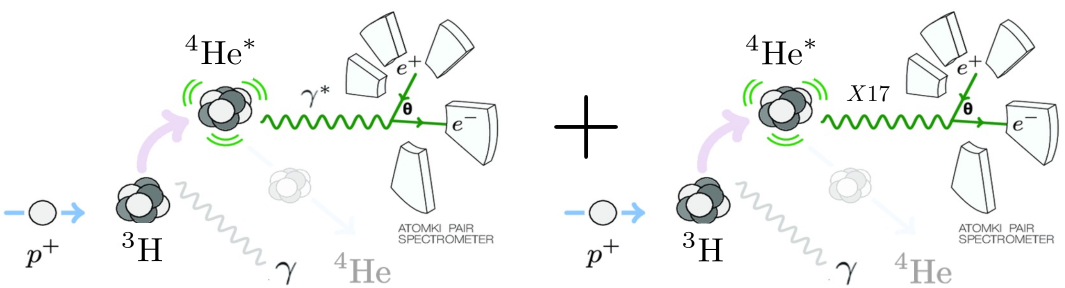
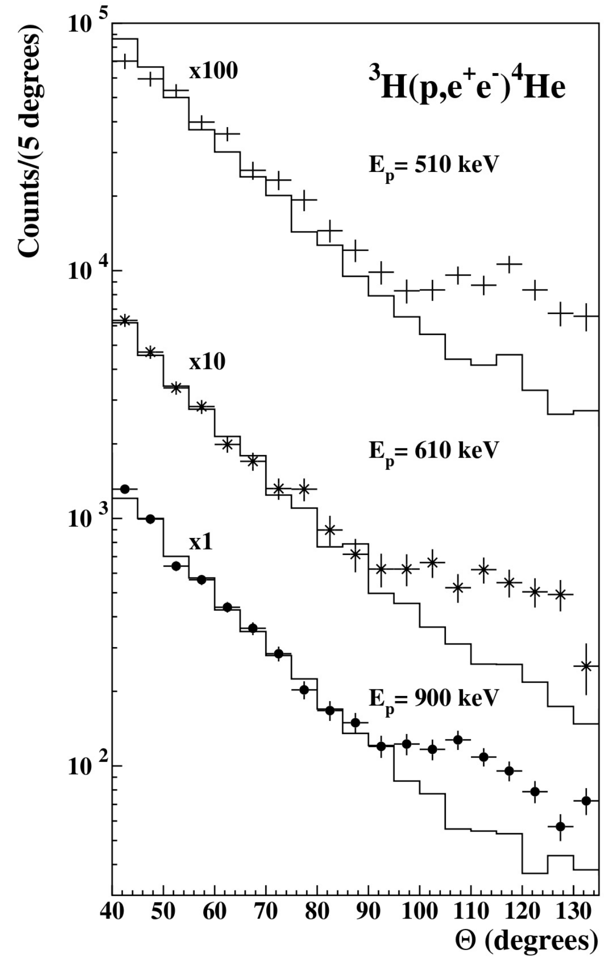




$$m_Xc^2 = 16.94 \pm 0.12_{\text{stat}} \pm 0.21_{\text{syst}}\ \text{MeV}$$

Consistent with the ^{8}Be result !!

The ATOMKI Anomaly(ies) : Brief overview

PHYSICAL REVIEW D **102,** 036016 (2020)

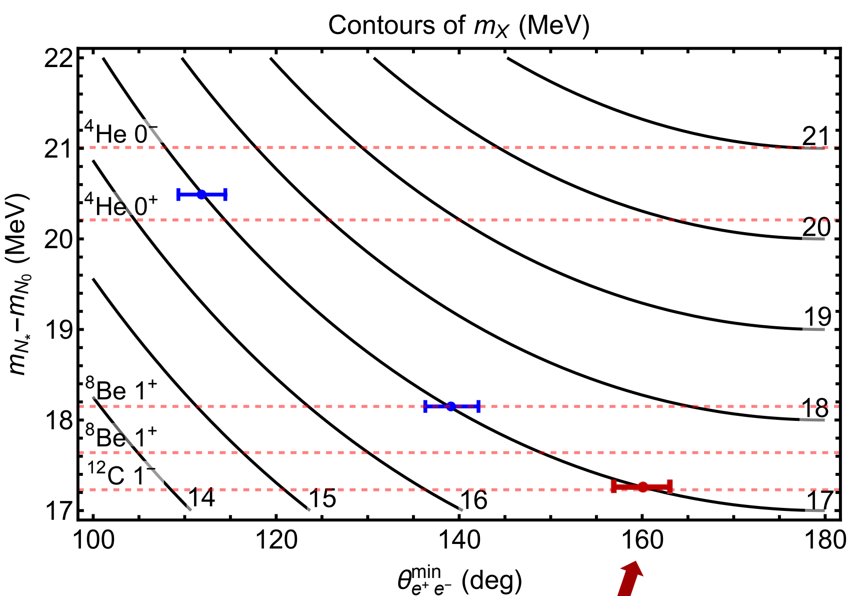
Dynamical evidence for a fifth force explanation of the ATOMKI nuclear anomalies

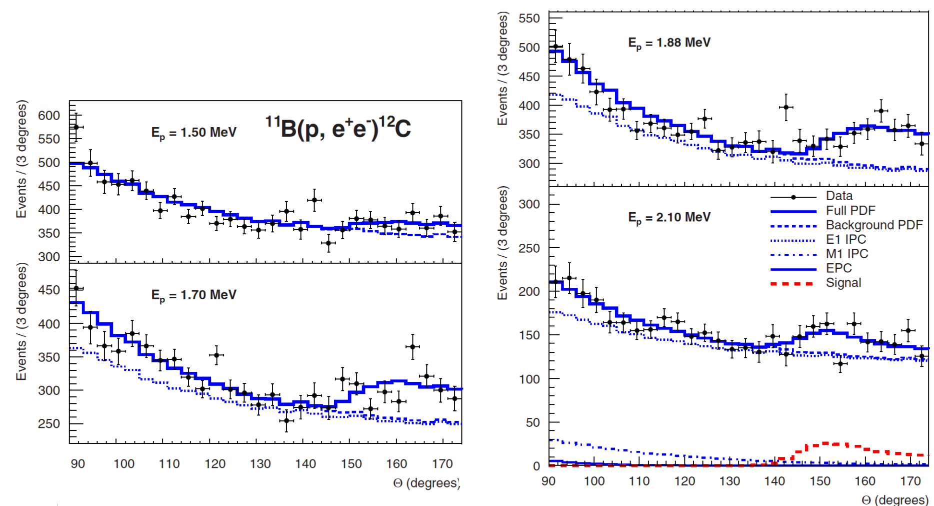
Jonathan L. Feng,* Tim M. P. Tait,† and Christopher B. Verhaaren‡
Department of Physics and Astronomy, University of California, Irvine, California 92697-4575, USA

PHYSICAL REVIEW C **106**, L061601 (2022)

New anomaly observed in ^{12}C supports the existence and the vector character of the hypothetical X17 boson

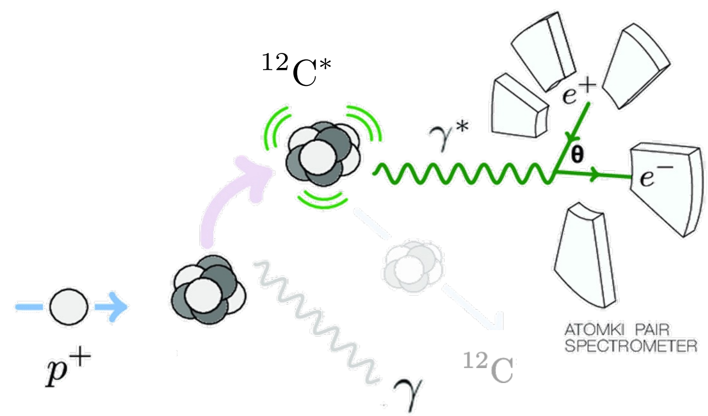
A. J. Krasznahorkay,* A. Krasznahorkay,† M. Begala, M. Csatlós, L. Csige, J. Gulyás, A. Krakó, J. Timár, I. Rajta, and I. Vajda
Institute for Nuclear Research (ATOMKI), P.O. Box 51, H-4001 Debrecen, Hungary
N. J. Sas
University of Debrecen, Faculty of Science and Technology, Physics Institute, 4010 Debrecen, PO Box 105, Hungary





$$\theta^{min}_{e^+e^-} \simeq 2\sin^{-1}\left(\frac{m_X}{m_{N_*}-m_{N_0}}\right)$$

$$\theta^{min}_{e^+e^-}(^{12}\mathrm{C}) \simeq 160^\circ$$



Feng et. all predict that for ^{12}C the should be seen at an angle close to 160° for X(17).

The ATOMKI Anomaly(ies) : Protophobic

Confirmation (?) with a similar experiment at VNU.

universe MDPI

Article

Checking the ^{8}Be Anomaly with a Two-Arm Electron Positron Pair Spectrometer

Tran The Anh [1], Tran Dinh Trong [2,*], Attila J. Krasznahorkay [3], Attila Krasznahorkay [3], József Molnár [3], Zoltán Pintye [3], Nguyen Ai Viet [1], Nguyen The Nghia [1,*], Do Thi Khanh Linh [4], Bui Thi Hoa [1], Le Xuan Chung [4] and Nguyen Tuan Anh [5]

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Published: 1 April 2024

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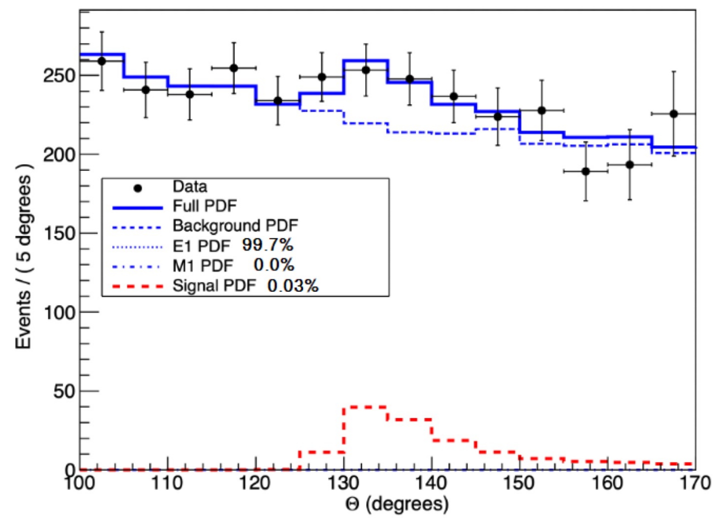
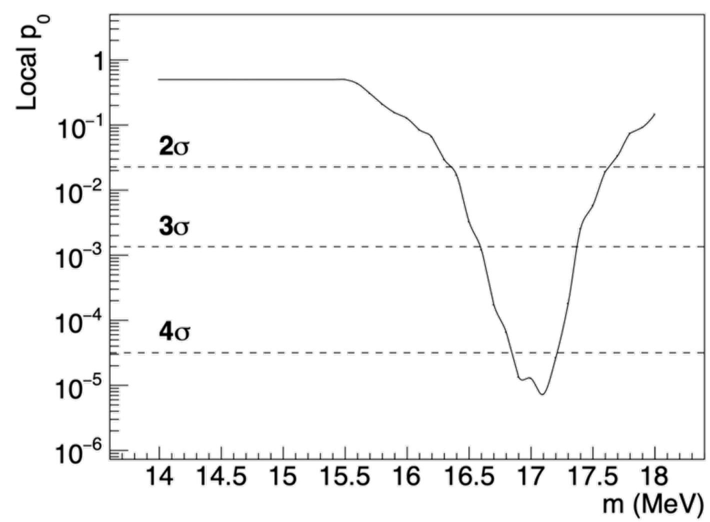
* Correspondence: tdtrong@iop.vast.vn (T.D.T.); nguyenthenghia@hus.edu.vn (N.T.N.)

4. Summary

We successfully built a two-arm e^+e^- spectrometer in Hanoi. The spectrometer was tested and calibrated using the 17.6 MeV M1 transition excited in the ^{7}Li(p,e^+e^-)^{8}Be reaction. We have obtained a nice agreement between the experimentally determined acceptance of the spectrometer and the one coming from our simulation. The angular correlation of the e^+e^- pairs measured for the 17.6 MeV transition (E_p = 441keV) agrees well with the simulated one dominated by the M1 transition, and no anomaly was observed for this. However, a significant anomaly (>4σ) was observed for E_p = 1225 keV, which is the off-resonance region above the E_p = 1040 keV resonance, at around 135°, in agreement with the ATOMKI results published in 2016 [1]. The mass of the hypothetical particle from this result was obtained to be 16.66 ± 0.47 (statistical) ±0.35 (systematic) MeV. In the future, we plan to upgrade the spectrometer to obtain a wider angular acceptance.



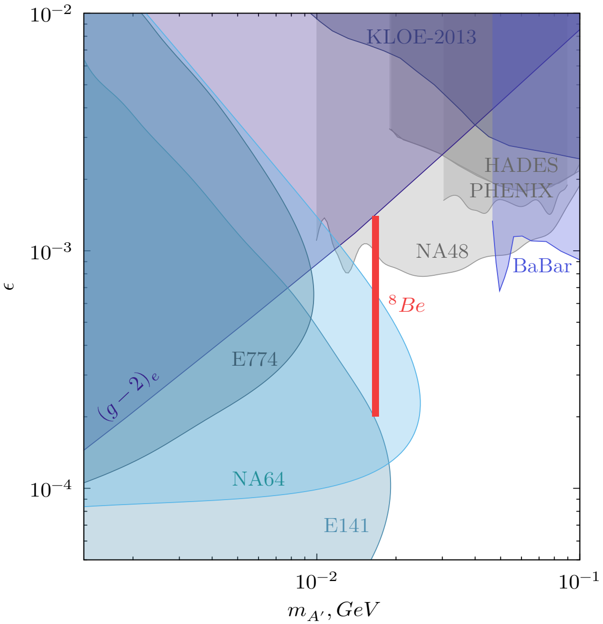
$$m_X = 16.7 \pm 0.47\ \text{(statistical) (MeV)}$$



The ATOMKI Anomaly(ies) : Constraints

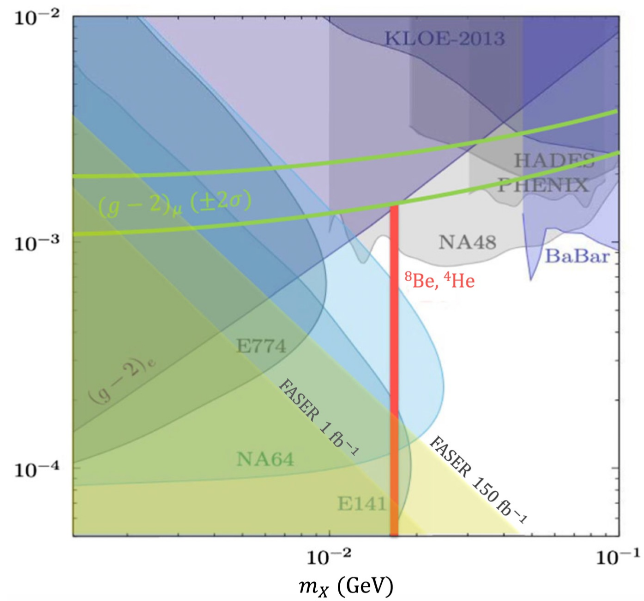
Protophobic vector boson X

NA64 collab.,PRD 101 (2020) 071101



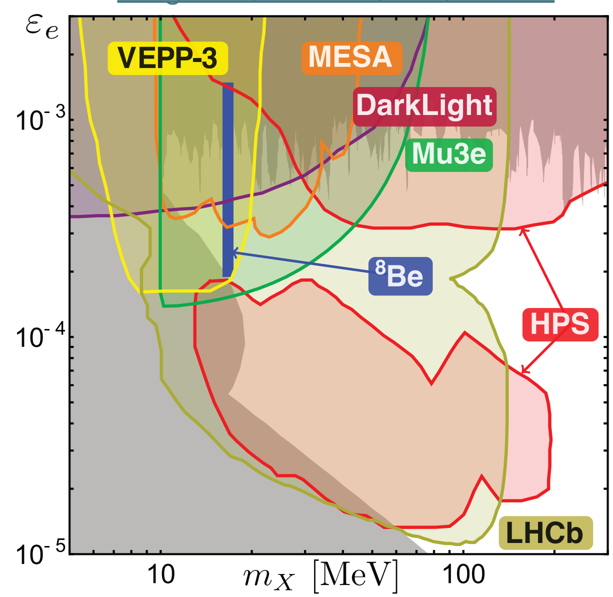
Protophobic vector boson X

Alves et. al., Eur.Phys.J.C 83 (2023) 3



Protophobic vector boson X

Feng et al., PRL 117 (2016) 071803



Very nice seminar at EPFL by M. Raggi. Available here

Feng et all., PRD 102 (2020) 036016

N_*	$J_*^{P_*}$	Scalar X	Pseudoscalar X	Vector X	Axial Vector X
^{8}Be(18.15)	1^+	…	$\mathcal{O}_{4P}^{(0)}$ (27)	$\mathcal{O}_{5P}^{(1)}$ (37)	$\mathcal{O}_{3S}^{(1)}$ (29), $\mathcal{O}_{5D}^{(1)}$ (34)
^{12}C(17.23)	1^-	$\mathcal{O}_{4P}^{(0)}$ (27)	…	$\mathcal{O}_{3S}^{(1)}$ (29), $\mathcal{O}_{5D}^{(1)}$ (34)	$\mathcal{O}_{5P}^{(1)}$ (37)
^{4}He(21.01)	0^-	…	$\mathcal{O}_{3S}^{(0)}$ (39)	…	$\mathcal{O}_{4P}^{(1)}$ (40)
^{4}He(20.21)	0^+	$\mathcal{O}_{3S}^{(0)}$ (39)	…	$\mathcal{O}_{4P}^{(1)}$ (40)	…

EFT for Nuclear Transitions

$$\mathcal{L}_I = \sum_i c_i \mathcal{O}_i$$

The ATOMKI Anomaly(ies) : Constraints

Protophobic vector boson X

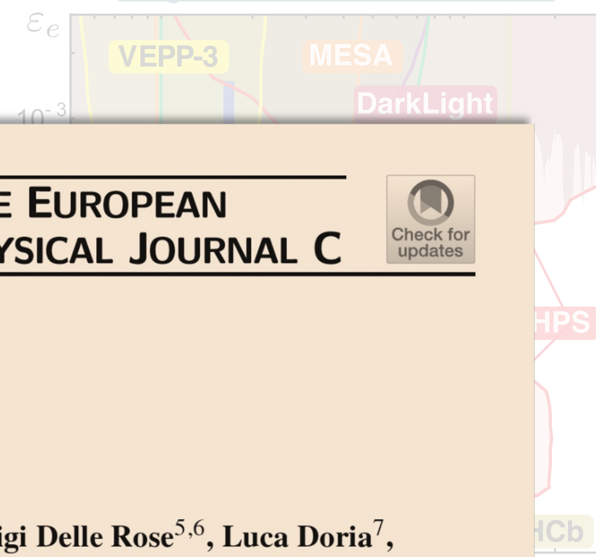
NA64 collab.,PRD 101 (2020) 071101

Protophobic vector boson X

Alves et. al., Eur.Phys.J.C 83 (2023) 3

Protophobic vector boson X

Feng et al., PRL 117 (2016) 071803



Eur. Phys. J. C (2023) 83:230
https://doi.org/10.1140/epjc/s10052-023-11271-x

THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Review

Shedding light on X17: community report

Daniele S. M. Alves[1], Daniele Barducci[2,3], Gianluca Cavoto[2,3], Luc Darmé[4], Luigi Delle Rose[5,6], Luca Doria[7], Jonathan L. Feng[8], André Frankenthal[9], Ashot Gasparian[10], Evgueni Goudzovski[11], Carlo Gustavino[3], Shaaban Khalil[12], Venelin Kozhuharov[13], Attila J. Krasznahorkay[14], Tommaso Marchi[15], Manuel Meucci[2,3], Gerald A. Miller[16], Stefano Moretti[17], Marco Nardecchia[2,3], Enrico Nardi[18], Hugo Natal da Luz[19], Giovanni Organtini[2,3], Angela Papa[20], Ann-Kathrin Perrevoort[21], Vlasios Petousis[19], Gabriele Piperno[2], Mauro Raggi[2,3,a], Francesco Renga[3], Patrick Schwendimann[20], Rudolf Sýkora[19], Claudio Toni[2,3], Paolo Valente[3], Cecilia Voena[3], Cheuk-Yin Wong[22], Xilin Zhang[23]

Feng e

N_*	$J_*^{P_*}$	Scalar X	Pseudoscalar X	Vector X	Axial Vector X
^{8}Be(18.15)	1^+	…	$\mathcal{O}_{4P}^{(0)}$ (27)	$\mathcal{O}_{5P}^{(1)}$ (37)	$\mathcal{O}_{3S}^{(1)}$ (29), $\mathcal{O}_{5D}^{(1)}$ (34)
^{12}C(17.23)	1^-	$\mathcal{O}_{4P}^{(0)}$ (27)	…	$\mathcal{O}_{3S}^{(1)}$ (29), $\mathcal{O}_{5D}^{(1)}$ (34)	$\mathcal{O}_{5P}^{(1)}$ (37)
^{4}He(21.01)	0^-	…	$\mathcal{O}_{3S}^{(0)}$ (39)	…	$\mathcal{O}_{4P}^{(1)}$ (40)
^{4}He(20.21)	0^+	$\mathcal{O}_{3S}^{(0)}$ (39)	…	$\mathcal{O}_{4P}^{(1)}$ (40)	…

EFT for Nuclear Transitions

$$\mathcal{L}_I = \sum_i c_i \mathcal{O}_i$$

➢ **VECTOR (V) AND AXIAL-VECTOR (A) Z′ COUPLINGS TO FERMIONS:**

General form: $\bar{f}\,\not{D}\,f \longrightarrow \mathcal{L} \supset e\overline{f_a}\gamma^\mu\left(\varepsilon^V_{ab} + \gamma^5\varepsilon^A_{ab}\right)f_b Z'_\mu$

Couplings	Experimental range
ε^V_n	$2\times10^{-3}\ [4.1\times10^{-3}] \lesssim \lvert\varepsilon^V_n\rvert \lesssim 15\times10^{-3}\ [5.3\times10^{-3}]$
ε^V_p	$[0.7\times10^{-3}] \lesssim \lvert\varepsilon^V_p\rvert \lesssim 1.2\times10^{-3}\ [1.9\times10^{-3}]$
ε^V_{ee}	$0.4\times10^{-3}\ [0.63\times10^{-3}] \lesssim \lvert\varepsilon^V_{ee}\rvert \lesssim 2\times10^{-3}\ [1.2\times10^{-3}]$
ε^A_{ee}	$\lvert\varepsilon^A_{ee}\rvert \lesssim 2.6\times10^{-9}$
$\varepsilon^A_{\nu_e\nu_e}$	$\lvert\varepsilon^A_{\nu_e\nu_e}\rvert \lesssim 1.2\times10^{-5}\ [(3.5-4.5)\times10^{-6}]$
$\varepsilon^A_{\nu_\mu\nu_\mu}$	$\lvert\varepsilon^A_{\nu_\mu\nu_\mu}\rvert \lesssim 12.2\times10^{-5}$

Hati, Kriewald, Orloff & Teixeira JHEP 07 (2020) 235

Denton and Gehrlein, PRD 108 (2023) 1, 015009

What kind of **models** can accomodate these results?

The ATOMKI Anomaly(ies) : some (models)

PHYSICAL REVIEW D **96,** 115024 (2017)

Explanation of the 17 MeV Atomki anomaly in a $U(1)'$-extended two Higgs doublet model

Luigi Delle Rose,[1,2] Shaaban Khalil,[3] and Stefano Moretti[1,2]

Available online at www.sciencedirect.com

ScienceDirect

Nuclear Physics B 919 (2017) 209–217

www.elsevier.com/locate/nuclphysb

Realistic model for a fifth force explaining anomaly in $^8Be^* \to {}^8Be\, e^+e^-$ decay

Pei-Hong Gu [a], Xiao-Gang He [a,b,c,*]

JHEP — Published for SISSA by Springer

Atomki anomaly in gauged $U(1)_R$ symmetric model

Osamu Seto[a,b] and Takashi Shimomura[c]

JHEP — Published for SISSA by Springer

Anomalies in ^{8}Be nuclear transitions and $(g-2)_{e,\mu}$: towards a minimal combined explanation

C. Hati,[a] J. Kriewald,[b] J. Orloff[b] and A.M. Teixeira[b]

Chinese Journal of Physics 71 (2021) 506–517

Contents lists available at ScienceDirect

Chinese Journal of Physics

journal homepage: www.sciencedirect.com/journal/chinese-journal-of-physics

A Family-nonuniversal $U(1)'$ Model for Excited Beryllium Decays

Beyhan Puliçe [*]

Department of Physics, İzmir Institute of Technology, İzmir, TR35430, Turkey

Feng et all., PRD 95 (2017) 035017

Prepared for submission to JHEP HRI-RECAPP-2024-02

A 17 MeV pseudoscalar and the LSND, MiniBooNE and ATOMKI anomalies[1]

Waleed Abdallah,[a] Raj Gandhi,[b] Tathgata Ghosh,[b] Najimuddin Khan,[c] Samiran Roy,[d] and Subhojit Roy[e]

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]

JHEP — Published for SISSA by Springer

Explaining Atomki anomaly and muon $g-2$ in $U(1)_X$ extended flavour violating two Higgs doublet model

Takaaki Nomura[a] and Prasenjit Sanyal[b,c]

The ATOMKI Anomaly(ies) : some (models)

PHYSICAL REVIEW D 96, 115024 (2017)

Explanation of the 17 MeV Atomki anomaly in a $U(1)'$-extended two Higgs doublet model

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Realistic model for a fifth force explaining anomaly in $^8Be^* \to {}^8Be\, e^+e^-$ decay

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JHEP Published for SISSA by Springer

Atomki anomaly in gauged $U(1)_R$ symmetric model

Osamu Seto[a,b] and Takashi Shimomura[c]

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Anomalies in ^{8}Be nuclear transitions and $(g-2)_{e,\mu}$: towards a minimal combined explanation

C. Hati,[a] J. Kriewald,[a] J. Orloff[b] and A.M. Teixeira[b]

MOST OBVIOUS CHOICE: GAUGED $U(1)_{B-L}$…

Feng et all., PRD 95 (2017) 035017

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A Family-nonuniversal $U(1)'$ Model for Excited Beryllium Decays

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A 17 MeV pseudoscalar and the LSND, MiniBooNE and ATOMKI anomalies[1]

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PHYSICAL REVIEW D 95, 035017 (2017)

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

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JHEP Published for SISSA by Springer

Explaining Atomki anomaly and muon $g-2$ in $U(1)_X$ extended flavour violating two Higgs doublet model

Takaaki Nomura[a] and Prasenjit Sanyal[b,c]

Vanilla B-L : SM + 3 RH N_R's + 1 complex scalar S

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

(Gauge) Lagrangian: $\mathcal{L} \supset -\frac{1}{4}\tilde{F}_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{4}\tilde{F}'_{\mu\nu}\tilde{F}'^{\mu\nu} + \frac{\epsilon_k}{2}\tilde{F}_{\mu\nu}\tilde{F}'^{\mu\nu}$

Kinetic mixing parameter ϵ_k constrained to be small by Z-pole measurements

Covariant derivative: $\tilde{D}_\mu = \partial_\mu + \cdots + ig'Y_f\tilde{B}_\mu + ig_{B-L}Q_f^{B-L}\tilde{B}'_\mu$

Which can be brought to its final convenient form in terms of gauge boson mass eigenstates
(see e.g. Hati, Kriewald, Orloff & Teixeira JHEP 07 (2020) 235)

Bring to the canonical form

Redefinition of the gauge fields:

$$\tilde{B}_\mu = B_\mu + \frac{\epsilon_k}{\sqrt{1-\epsilon_k^2}} B'_\mu \ , \ \tilde{B}'_\mu = \frac{1}{\sqrt{1-\epsilon_k^2}} B'_\mu$$

Redefinition of couling constants:

$$\varepsilon' = \frac{\epsilon_k}{\sqrt{1-\epsilon_k^2}}, \quad \varepsilon'_{B-L} = \frac{g_{B-L}}{\sqrt{1-\epsilon_k^2}}$$

$$D_\mu = \partial_\mu + \cdots + igT_{3f}W_{3\mu} + ig'Y_f B_\mu + i\left(\varepsilon' g' Y_f + \varepsilon'_{B-L} Q_f^{B-L}\right) B'_\mu$$

➢ **GAUGE BOSON MASSES:** $\mathcal{L}_{\text{mass}}^{\text{gauge}} \supseteq (D_\mu \langle\Phi\rangle)^\dagger (D^\mu \langle\Phi\rangle) + (D_\mu \langle S\rangle)^\dagger (D^\mu \langle S\rangle)$

vacuum → more later…

$$\langle\Phi\rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}, \ \langle S\rangle = w/\sqrt{2}$$

→ B′ mass term: $m_{B'}^2 = 4\varepsilon'^2_{B-L} w^2$

Physical gauge boson masses

$$M_A = 0, \quad M_{Z,Z'} = \frac{g}{\cos\theta_w} \frac{v}{2} \left[\frac{1}{2}\left(\frac{\varepsilon'^2 + 4m_{B'}^2/v^2}{g^2 + g'^2} + 1\right) \mp \frac{g' \cos\theta_w \varepsilon'}{g \sin 2\theta'}\right]^{\frac{1}{2}}$$

Vanilla (B-L) model : general structure

Small kinetic mixing ($\epsilon_k \ll 1$) $\longrightarrow$ $M_Z^2 \simeq \frac{g^2 + g'^2}{4} v^2, \quad M_{Z'}^2 \simeq m_{B'}^2, \quad \tan 2\theta' \simeq -2\varepsilon' \sin\theta_w$

Covariant derivative in terms of physical gauge bosons

$$D_\mu \supset \partial_\mu + i\frac{g}{\cos\theta_w}(T_{3f} - \sin^2\theta_W Q_f) Z_\mu + ieQ_f A_\mu + ie\left(\varepsilon Q_f + \varepsilon_{B-L} Q_f^{B-L}\right) Z'_\mu$$

$$\varepsilon = \varepsilon' \cos\theta_w \quad , \quad e\,\varepsilon_{B-L} = \varepsilon'_{B-L}$$

- **SCALAR SECTOR:** $V_{\text{Higgs}} = \mu^2 |\Phi|^2 + m^2 |S|^2 + \frac{\lambda_1}{2}|\Phi|^4 + \frac{\lambda_2}{2}|S|^4 + \lambda_3 |\Phi|^2 |S|^2$

- In the limit of small kinetic mixing: $\langle S \rangle = w/\sqrt{2}$ $\longrightarrow$ $m_{Z'} \simeq 2e|\varepsilon_{B-L}|w = 17\,\text{MeV}$

Two CP-even scalars h and χ with masses $m_{h,\chi}$ with $m_h = 125\,\text{GeV}$

- In terms of scalar masses and mixing:

$$\lambda_1 = \frac{1}{v^2}(c_\alpha^2 m_h^2 + s_\alpha^2 m_\chi^2), \quad \lambda_2 = \frac{1}{w^2}(s_\alpha^2 m_h^2 + c_\alpha^2 m_\chi^2), \quad \lambda_3 = \frac{1}{vw}(m_h^2 - m_\chi^2) s_\alpha c_\alpha$$

Vanilla (B-L) model : general structure

- Boundness from below and perturbative unitarity constraints :

  Coimbra, Sampaio & Santos, Eur.Phys.J.C 73 (2013) 2428

$$0 < \lambda_{1,2} \leq 8\pi \;\;,\quad -\sqrt{\lambda_1\lambda_2} < \lambda_3 \leq 8\pi \;\;,\quad |a_\pm| = \left|\frac{3}{2}\lambda_1 + \lambda_2 \pm \sqrt{\left(\frac{3}{2}\lambda_1 + \lambda_2\right)^2 + \lambda_2^2}\right| \leq 8\pi$$

$c_\alpha = 1$ ⟶ $\lambda_1 \simeq m_h^2/v^2\,,\; \lambda_2 \simeq m_\chi^2/w^2$

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

Lowest allowed value: $\varepsilon_{B-L} = 2\times 10^{-3}$ ⟶ $m_\chi \lesssim \begin{cases} 45\text{GeV}, c_\alpha = 1.0 \\ 34\text{GeV}, c_\alpha = 0.97 \end{cases} < m_h/2$ ⟶ $h \to \chi\chi\,,\; Z'Z'$ are allowed

➢ VECTOR (V) AND AXIAL-VECTOR (A) Z′ COUPLINGS TO FERMIONS:

General form: $\bar{f}\,\not{D} f$ ⟶ $\mathcal{L} \supset e\overline{f_a}\gamma^\mu\left(\varepsilon_{ab}^V + \gamma^5\varepsilon_{ab}^A\right) f_b Z'_\mu$

Vanilla (B-L) model vs ATOMKI

Couplings	Vanilla $B-L$	Experimental range
ε_n^V	ε_{B-L}	$2\times10^{-3}\,[4.1\times10^{-3}] \lesssim \lvert\varepsilon_n^V\rvert \lesssim 15\times10^{-3}\,[5.3\times10^{-3}]$
ε_p^V	$\varepsilon+\varepsilon_{B-L}$	$[0.7\times10^{-3}] \lesssim \lvert\varepsilon_p^V\rvert \lesssim 1.2\times10^{-3}\,[1.9\times10^{-3}]$
ε_{ee}^V	$-(\varepsilon+\varepsilon_{B-L})$	$0.4\times10^{-3}\,[0.63\times10^{-3}] \lesssim \lvert\varepsilon_{ee}^V\rvert \lesssim 2\times10^{-3}\,[1.2\times10^{-3}]$
ε_{ee}^A	0	$\lvert\varepsilon_{ee}^A\rvert \lesssim 2.6\times10^{-9}$
$\varepsilon_{\nu_e\nu_e}^A$	ε_{B-L}	$\lvert\varepsilon_{\nu_e\nu_e}^A\rvert \lesssim 1.2\times10^{-5}\,[(3.5-4.5)\times10^{-6}]$
$\varepsilon_{\nu_\mu\nu_\mu}^A$	ε_{B-L}	$\lvert\varepsilon_{\nu_\mu\nu_\mu}^A\rvert \lesssim 12.2\times10^{-5}$

Hati, Kriewald, Orloff & Teixeira JHEP 07 (2020) 235

Denton and Gehrlein, PRD 108 (2023) 1, 015009

HOW DO WE SUPPRESS THE Z′ COUPLINGS TO NEUTRINOS?

SOLUTION: ADD VECTOR-LIKE LEPTONS!

Feng et. all, PRD 95 (2017) 3, 035017

Hati, Kriewald, Orloff & Teixeira JHEP 07 (2020) 235

(B-L) + VLLs model : general structure

(B-L) + VLLs: Vanilla (B-L) + 3 Doublet VLL pairs + 3 charged singlet VLL pairs

	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	
$i = 1, 2, 3$ ←	$L_{iL,R} = (\mathcal{N}_{iL,R}, \mathcal{E}_{iL,R})^T$	**1**	**2**	$-1/2$	1	
	$E_{iL,R}$	**1**	**1**	-1	1	

Lepton Yukawa and mass terms

$$\mathcal{L}_{\rm lepton} = -y_l^{ij}\overline{l_{i\,L}}\Phi e_{j_R} - y_\nu^{ij}\bar{l}_{i\,L}\tilde{\Phi}N_{j_R} - \frac{1}{2}y_M^{ij}S\bar{N}^c_{iR}N_{j_R} - \lambda_L^{ij}S^*\bar{l}_{i\,L}L_{j_R} - \lambda_E^{ij}S\overline{E_{i\,L}}e_{jR}$$

$$-M_L^{ij}\overline{L_i}L_{j_R} - M_E^{ij}\overline{E_{i\,L}}E_{j_R} - h^{ij}\overline{L_i}\Phi E_{j_R} - k^{ij}\overline{E_{i\,L}}\Phi^\dagger L_{j_R} + \text{ H.c.}\,, i,j = 1,2,3$$

For simplicity, all Yukawa and mass matrices are considered **real and diagonal.**

(B-L) + VLLs model : general structure

- **Charged- and neutral-lepton mass matrix (after SSB):**

$$\mathcal{L}_{\text{c.l.}} = \overline{\psi^\ell_{\text{L}}}\mathcal{M}_\ell \psi^\ell_{\text{R}} + \text{ H.c.}\,, \quad \psi^\ell_{\text{L,R}} = (e_{\text{L,R}}, \quad \mathcal{E}_{\text{L,R}}, \quad E_{\text{L,R}})^T$$

$$\mathcal{L}_{\text{n.l.}} = \overline{\psi^{\nu c}_{\text{L}}}\mathcal{M}_\nu \psi^\nu_{\text{L}} + \text{ H.c.}\,, \quad \psi^\nu_{\text{L}} = (\nu, \quad N^c, \quad \mathcal{N}, \quad \mathcal{N}^c)^T_{\text{L}}$$

Mass matrices

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

Each entry is a 3×3 diagonal matrix with distinct $y^i_{l,\nu,M}, \lambda^i_{\text{L,E}}, M^i_{\text{L,E}}, k_i$ and h_i elements.

- **Mass-eigenstate basis:** $\mathcal{M}_\ell^{\text{diag}} = U_{\text{L}}^\dagger \mathcal{M}_\ell U_{\text{R}} \;,\; \mathcal{M}_\nu^{\text{diag}} = U_\nu^T \mathcal{M}_\nu U_\nu$

Three (four) charged (neutral) leptons ℓ_a (ν_a) for each family.

(B-L) + VLLs model : general structure

➢ **Z′ couplings to (physical) fermions:** $\mathcal{L} \supset e\overline{f_a}\gamma^\mu\left(\varepsilon^V_{ab} + \gamma^5\varepsilon^A_{ab}\right) f_b Z'_\mu$

Couplings	Vanila (B − L) + VLLs
ε^V_n	ε_{B-L}
ε^V_p	$\varepsilon + \varepsilon_{B-L}$
$\varepsilon^{V(A)}_{\ell_a\ell_b}$	$\frac{1}{2}\sum_{i=1}^{3}(\varepsilon Q_i + \varepsilon_{B-L}Q_i^{B-L})\left[\left(U_{\rm R}^\dagger\right)_{ai}(U_{\rm R})_{ib} \pm \left(U_{\rm L}^\dagger\right)_{ai}(U_{\rm L})_{ib}\right]$
$\varepsilon^{V(A)}_{\nu_a\nu_b}$	$\pm\frac{1}{2}\sum_{i=1}^{12}\varepsilon_{B-L}Q_i^{B-L}[(U_\nu^*)_{ia}(U_\nu)_{ib} \mp (U_\nu)_{ia}(U_\nu^*)_{ib}]$

$Q_i^{B-L} = \{-1,+1,+1\}$
$Q_i = \{-1,-1,-1\}$

$Q_i^{B-L} = \{-1,-1,+1,+1\}$

Comparing with what we have seen before:

Couplings	Experimental range
ε^V_n	$2\times10^{-3}\,[4.1\times10^{-3}] \lesssim \left\|\varepsilon^V_n\right\| \lesssim 15\times10^{-3}\,[5.3\times10^{-3}]$
ε^V_p	$[0.7\times10^{-3}] \lesssim \left\|\varepsilon^V_p\right\| \lesssim 1.2\times10^{-3}\,[1.9\times10^{-3}]$
ε^V_{ee}	$0.4\times10^{-3}\,[0.63\times10^{-3}] \lesssim \left\|\varepsilon^V_{ee}\right\| \lesssim 2\times10^{-3}\,[1.2\times10^{-3}]$
ε^A_{ee}	$\left\|\varepsilon^A_{ee}\right\| \lesssim 2.6\times10^{-9}$
$\varepsilon^A_{\nu_e\nu_e}$	$\left\|\varepsilon^A_{\nu_e\nu_e}\right\| \lesssim 1.2\times10^{-5}\,[(3.5-4.5)\times10^{-6}]$
$\varepsilon^A_{\nu_\mu\nu_\mu}$	$\left\|\varepsilon^A_{\nu_\mu\nu_\mu}\right\| \lesssim 12.2\times10^{-5}$

CAN $\varepsilon_{\nu\nu}$ BE NATURALLY SUPPRESSED?

(B-L) + VLLs model : $\varepsilon^A_{\nu_1\nu_1}$ supression (?)

➢ **Z' couplings to neutrinos:**

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & y_\nu \frac{v}{\sqrt{2}} & 0 & \lambda_L \frac{w}{\sqrt{2}} \\ y_\nu \frac{v}{\sqrt{2}} & y_M \frac{w}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & 0 & M_L \\ \lambda_L \frac{w}{\sqrt{2}} & 0 & M_L & 0 \end{pmatrix} \xrightarrow[\Lambda_L \equiv \frac{\lambda_L w}{\sqrt{2} M_L}]{\frac{y_\nu v}{y_M w}, \frac{y_\nu v}{\lambda_L w}, \frac{y_\nu v}{M_L} \ll 1} U_\nu \simeq \begin{pmatrix} -\frac{1}{\sqrt{1+\Lambda_L^2}} & 0 & -\frac{1}{\sqrt{2}}\frac{\Lambda_L}{\sqrt{1+\Lambda_L^2}} & \frac{1}{\sqrt{2}}\frac{\Lambda_L}{\sqrt{1+\Lambda_L^2}} \\ 0 & 1 & 0 & 0 \\ \frac{\Lambda_L}{\sqrt{1+\Lambda_L^2}} & 0 & -\frac{1}{\sqrt{2}}\frac{1}{\sqrt{1+\Lambda_L^2}} & \frac{1}{\sqrt{2}}\frac{1}{\sqrt{1+\Lambda_L^2}} \\ 0 & 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

THE A-V COUPLING TO NEUTRINOS IS NOW: $\varepsilon^A_{\nu_1\nu_1} \simeq \varepsilon_{B-L}\left(\frac{1-\Lambda_L^2}{1+\Lambda_L^2}\right)$

Couplings	Vanilla $B-L+$ VLLs	Experimental range
ε^V_n	ε_{B-L}	$2\times10^{-3}\left[4.1\times10^{-3}\right] \lesssim \lvert\varepsilon^V_n\rvert \lesssim 15\times10^{-3}\left[5.3\times10^{-3}\right]$
$\varepsilon^A_{\nu_1\nu_1}$	$\varepsilon_{B-L}\left(\frac{1-\Lambda_L^2}{1+\Lambda_L^2}\right)$	$\lvert\varepsilon^A_{\nu_e\nu_e}\rvert \lesssim 1.2\times10^{-5}\ [3.5-4.5]\times10^{-6}$

CONCLUSION: To suppress $\varepsilon^A_{\nu\nu}$ we must have: $\Lambda_L \equiv \frac{\lambda_L w}{\sqrt{2}M_L} \simeq 1$

$$\xrightarrow[\delta_L \ll 1]{\Lambda_L = 1-\delta_L} \frac{\varepsilon^A_{\nu_1\nu_1}}{\varepsilon^V_n} \simeq \delta_L \lesssim 10^{-3}$$

There is no reason for this "tunning"...

(still, let us turn a blind eye on this detail)

(B-L) + VLLs model : $\varepsilon^A_{\nu_1\nu_1}$ supression (?)

- **Z' couplings to charged leptons:**

$$\mathcal{M}_\ell = \begin{pmatrix} y_l \frac{v}{\sqrt{2}} & \lambda_\mathrm{L}\frac{w}{\sqrt{2}} & 0 \\ 0 & M_\mathrm{L} & h\frac{v}{\sqrt{2}} \\ \lambda_\mathrm{E}\frac{w}{\sqrt{2}} & k\frac{v}{\sqrt{2}} & M_\mathrm{E} \end{pmatrix} \xrightarrow[\frac{y_l v}{\lambda_{\mathrm{L,E}} w},\ \frac{y_l v}{M_{\mathrm{L,E}}} \ll 1]{h = k = 0}$$

Coupling	Experimental range
ε^A_{ee}	$\left\lvert\varepsilon^A_{ee}\right\rvert \lesssim 2.6 \times 10^{-9}$

With respect to the coupling with the neutron:

$$\delta_\mathrm{E} = \Lambda_\mathrm{E} - 1 \ll 1 \longrightarrow \left\lvert \frac{\varepsilon^A_{\ell_1^\pm \ell_1^\mp}}{\varepsilon^V_n} \right\rvert \simeq \delta_\mathrm{E}/2 \lesssim 10^{-6}$$!!!

BOTTOM-LINE CONCLUSION: $\Lambda_{\mathrm{L,E}} \equiv \dfrac{\lambda_{\mathrm{L,E}} w}{\sqrt{2} M_{\mathrm{L,E}}} \simeq 1$

Let's just accept this and move on…

Ferreira, Gonçalves & FRJ, *JHEP* 04 (2024) 003

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

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

$$\Lambda_{\mathrm{L,E}} \equiv \frac{\lambda_{\mathrm{L,E}} w}{\sqrt{2} M_{\mathrm{L,E}}} \qquad \delta_\mathrm{L} = \Lambda_\mathrm{L} - 1 \ll 1$$

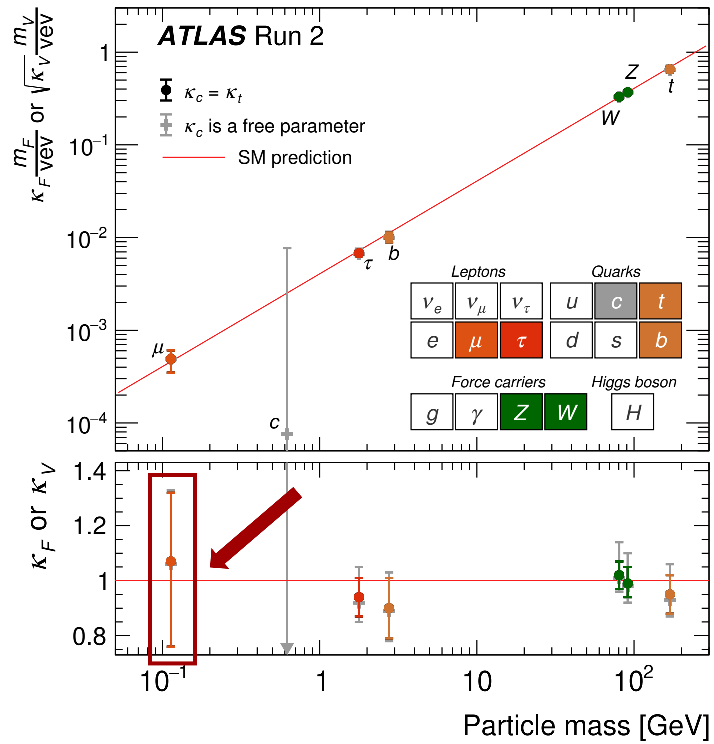
The A-V Z' couplings to charged leptons are:

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

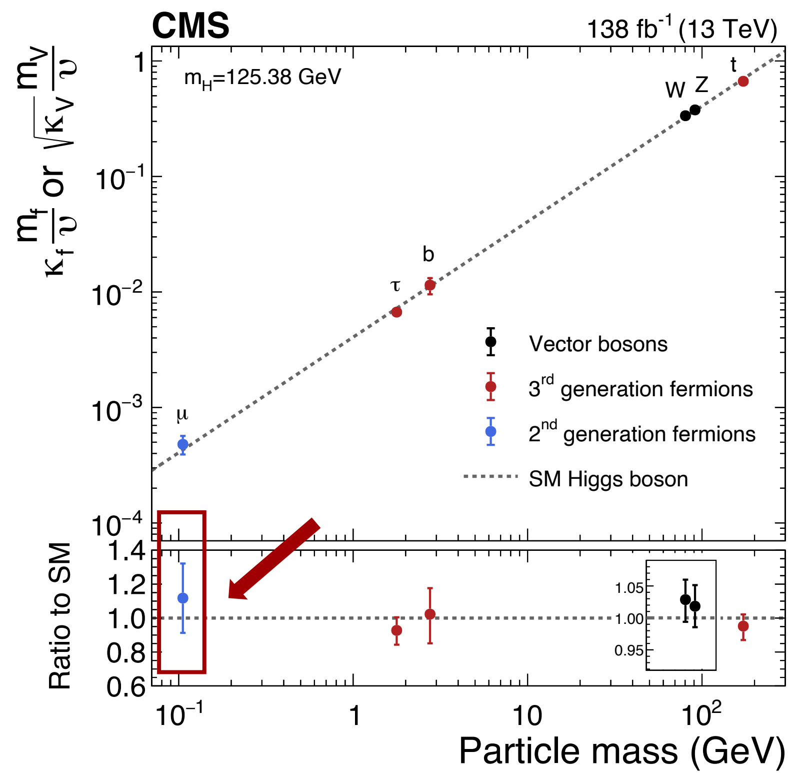
(B-L) + VLLs model : a real problem

Ferreira, Gonçalves & FRJ, *JHEP* 04 (2024) 003

➤ Charged-lepton couplings with the Higgs



ATLAS Collaboration, Nature 607 (2022) 7917, 52-59



CMS Collaboration, Nature 607 (2022) 7917, 60-68

Coupling modifiers : $-\mathcal{L} \supset \frac{m_\ell}{v}\kappa_\ell h \overline{\ell_L^\pm}\ell_R^\pm + \text{H.c.}$

$$\kappa_\ell = |(U_L)_{11}|^2|(U_R)_{11}|^2 = \frac{1}{1+\Lambda_L^2}\frac{1}{1+\Lambda_E^2} \xrightarrow[\Lambda_{L,E} = 1+\delta_{L,E}]{} \kappa_\ell = \frac{1}{4} + \mathcal{O}(\delta_L, \delta_E)$$

!!!

(B-L) + VLLs model : The full picture

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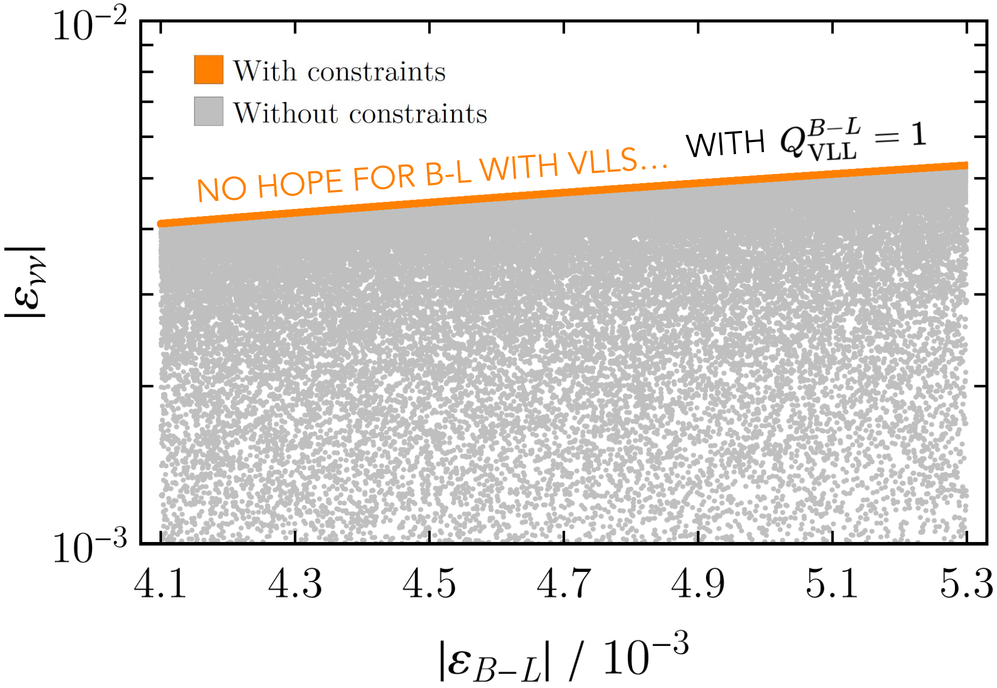
➢ Full numerical analysis:

- $M_{\mathrm{L,E}} \in [100\,\mathrm{GeV}, 1\,\mathrm{TeV}]$
- $m_\chi \in [10, 62.5]$ GeV with c_α free
- Lepton mixing angles $\in [0, \pi/2]$
- Vary $4.1 \times 10^{-3} \lesssim \varepsilon_{B-L} \lesssim 5.3 \times 10^{-3}$
- All Yukawa couplings $< \sqrt{4\pi}$
- Boundness from below and $a_\pm$



Compute the couplings

$$\varepsilon^{V(A)}_{\nu_a\nu_b} = \pm\frac{1}{2}\sum_{i=1}^{12}\varepsilon_{B-L}Q_i^{B-L}[(U_\nu^*)_{ia}(U_\nu)_{ib} \mp (U_\nu)_{ia}(U_\nu^*)_{ib}]$$

$$\varepsilon^{V(A)}_{\ell_a\ell_b} = \frac{1}{2}\sum_{i=1}^{3}(\varepsilon Q_i + \varepsilon_{B-L}Q_i^{B-L})\left[\left(U_\mathrm{R}^\dagger\right)_{ai}(U_\mathrm{R})_{ib} \pm \left(U_\mathrm{L}^\dagger\right)_{ai}(U_\mathrm{L})_{ib}\right]$$

Numerical results confirm the analytical findings.

APPLY CONSTRAINTS: (S,T,U), invisible Higgs decays, coupling modifiers, neutrino non-unitarity constraints.

(B-L) + VLLs model : possible wayout (?)

WHAT IF $Q^{B-L}_{\rm VLL} \neq 1$ **?**

Denton and Gehrlein, PRD 108 (2023) 1, 015009

$$\varepsilon^{A}_{\nu_1\nu_1} = \varepsilon_{B-L}\left(\frac{1 - Q^{B-L}_{\rm VL}\Lambda^2_{\rm L}}{1+\Lambda^2_{\rm L}}\right)$$

→ Neutrino coupling suppression for $Q^{B-L}_{\rm VLL}\Lambda^2_{\rm L} \simeq 1$

This implies: $Q^{B-L}_{\rm VLL} \gtrsim \dfrac{1}{\Lambda^2_{\rm L}} \simeq (57-95)\left(\dfrac{M_{\rm L}}{130{\rm GeV}}\right)^2\left(\dfrac{\sqrt{4\pi}}{\lambda_{\rm L}}\right)^2$ → $Q^{B-L}_{\rm VLL} \gtrsim 57$

Ferreira, Gonçalves & FRJ, *JHEP* 04 (2024) 003

(once more, let us turn a blind eye on this ugly requirement)

With $Q^{B-L}_{\rm VLL}\Lambda^2_{\rm L} \simeq 1$: $\varepsilon^{A}_{\ell'_1\ell^{\mp}_1} \simeq \dfrac{1}{2}\varepsilon_{B-L}\left(\dfrac{Q^{B-L}_{\rm VLL}\Lambda^2_{\rm E} - 1}{1+\Lambda^2_{\rm E}}\right)$, $\varepsilon^{V}_{\ell^{\pm}_1\ell^{\mp}_1} \simeq -\varepsilon$

Couplings	Experimental range	
ε^V_n	$2\times10^{-3}\,[4.1\times10^{-3}] \lesssim \lvert\varepsilon^V_n\rvert \lesssim 15\times10^{-3}\,[5.3\times10^{-3}]$	ε_{B-L}
ε^V_p	$[0.7\times10^{-3}] \lesssim \lvert\varepsilon^V_p\rvert \lesssim 1.2\times10^{-3}\,[1.9\times10^{-3}]$	$\varepsilon+\varepsilon_{B-L}$
ε^V_{ee}	$0.4\times10^{-3}\,[0.63\times10^{-3}] \lesssim \lvert\varepsilon^V_{ee}\rvert \lesssim 2\times10^{-3}\,[1.2\times10^{-3}]$	$-\varepsilon$
ε^A_{ee}	$\lvert\varepsilon^A_{ee}\rvert \lesssim 2.6\times10^{-9}$	→ $Q^{B-L}_{\rm VLL}\Lambda^2_{\rm E} \simeq 1$
$\varepsilon^A_{\nu_e\nu_e}$	$\lvert\varepsilon^A_{\nu_e\nu_e}\rvert \lesssim 1.2\times10^{-5}\,[(3.5-4.5)\times10^{-6}]$	} $Q^{B-L}_{\rm VLL}\Lambda^2_{\rm L} \simeq 1$
$\varepsilon^A_{\nu_\mu\nu_\mu}$	$\lvert\varepsilon^A_{\nu_\mu\nu_\mu}\rvert \lesssim 12.2\times10^{-5}$	

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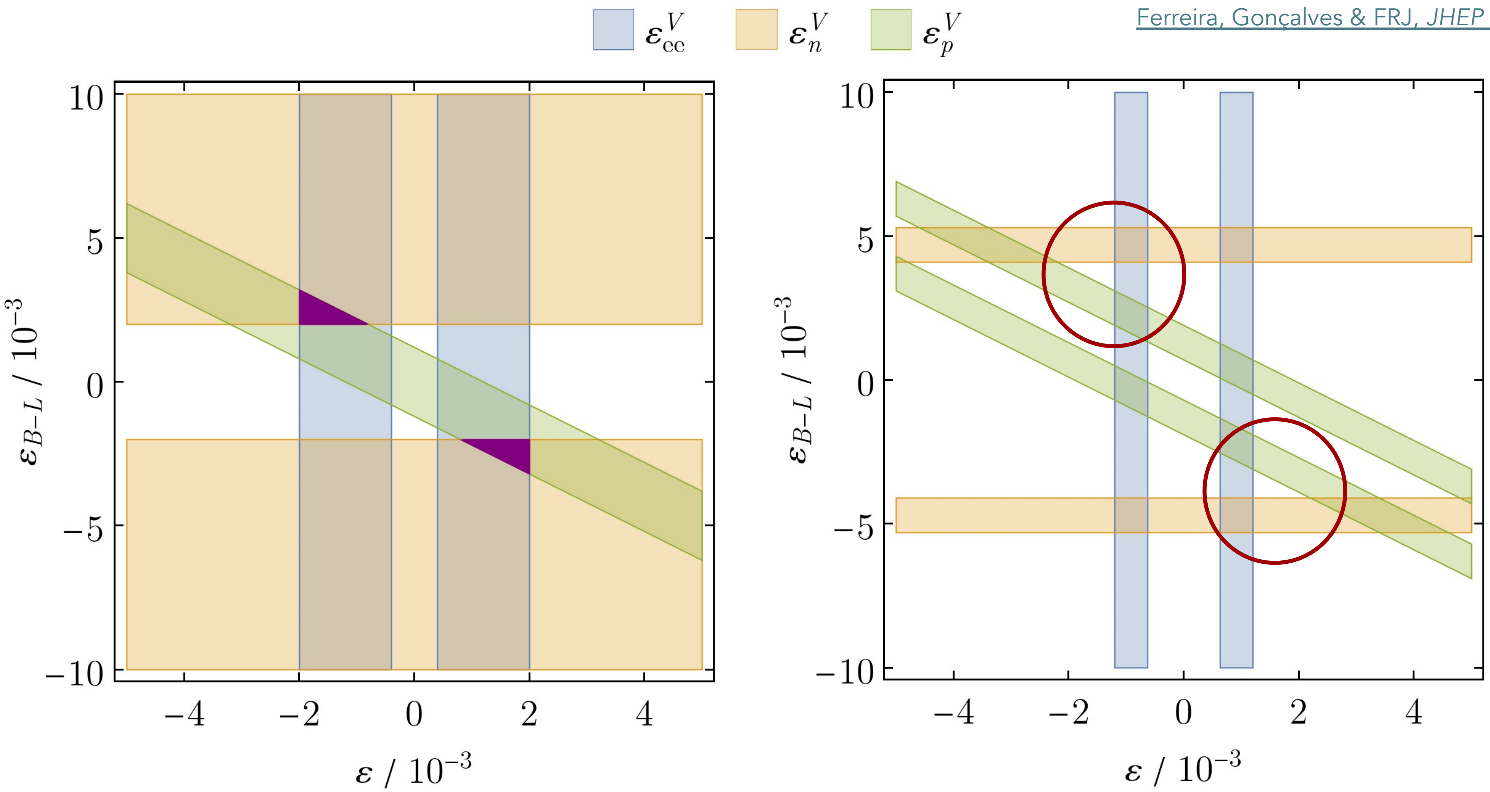

There appears to be some tension, but...

There is a more serious problem than that.

$$(g-2)_\mu$$

(B-L) + VLLs model : the real problem

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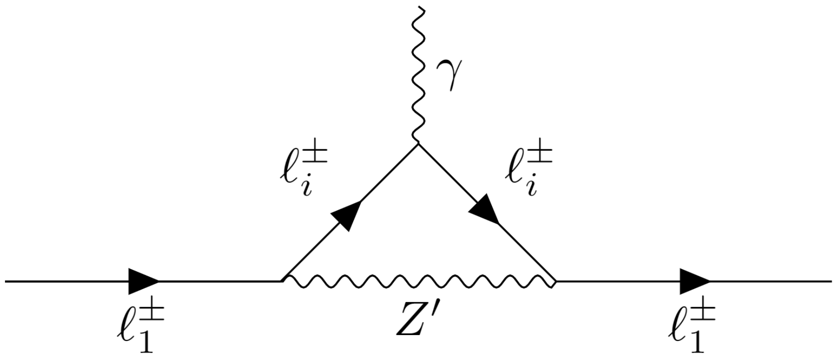
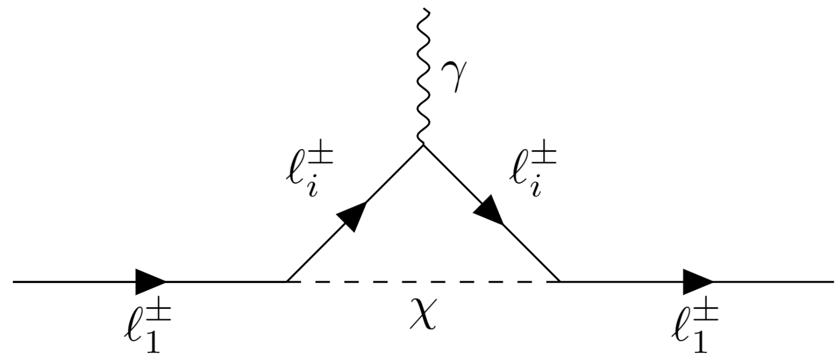
➢ **Two new contributions to the (g-2)$_\mu$:** $\Delta a_\mu = \Delta a_\mu^{Z'} + \Delta a_\mu^{\chi}$

$$\Delta a_\mu^{Z'} \simeq \mathcal{A}_\mu + \mathcal{A}_{\rm VLL}$$



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

$$\Delta a_\mu^{\chi} \simeq \mathcal{A}_{\rm L} + \mathcal{A}_{\rm E}$$



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

$m_{Z'} = 17\,\mathrm{MeV}$ ↓ $M_{\rm E,L} \gg m_{Z'}$

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

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

$m_\chi \lesssim 22\,\mathrm{GeV}$ ↓ $M_{\rm E,L} \gg m_\chi$

$$\mathcal{C}_{\rm L,E} = \frac{M_{\rm L,E}^2}{m_\chi^2} F_\chi\left(\frac{M_{\rm L,E}^2}{m_\chi^2}\right)$$

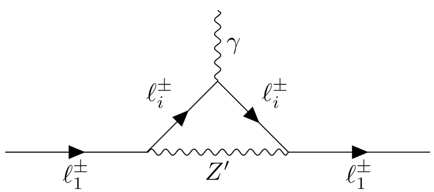
$$\mathcal{C}_{\rm L,E} \simeq \lim_{x\to\infty} x F_\chi(x) = \frac{1}{6}$$

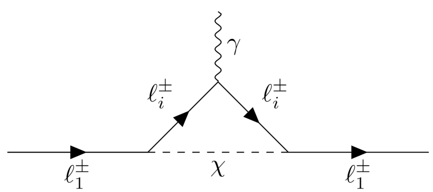
(B-L) + VLLs model : final veredict

➢ BENCHMARK:

$$Q_{\rm VLL}^{B-L} = 24, \quad \Lambda_{\rm L} = \Lambda_{\rm E} = \frac{1}{\sqrt{24}}$$

$$\varepsilon = -1.5 \times 10^{-3}, \quad \varepsilon_{B-L} = 2 \times 10^{-3}$$





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

$\mathcal{A}_{\rm VLL} \simeq -3.61 \times 10^{-6}$

$$\Delta a_\mu = a_\mu({\rm Exp}) - a_\mu({\rm SM}) = (251 \pm 59) \times 10^{-11}$$

B. Abi *et al.* (Muon g−2 Collaboration), PRL 126, 141801

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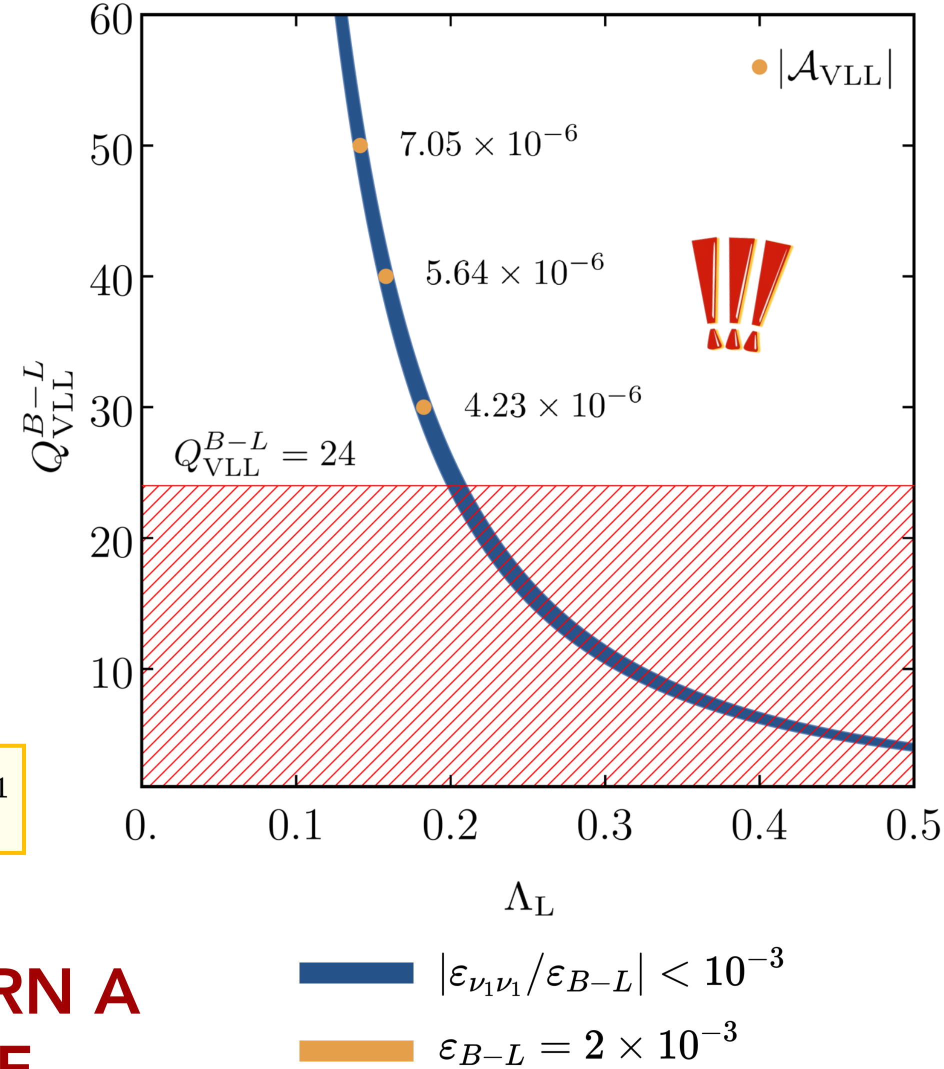

THERE IS NO WAY TO TURN A BLIND EYE ON THIS ONE...

CONCLUSIONS

- **ATOMKI anomalies:** evidence of **new physics** (?)

  - **High** statistical significance **$\gtrsim 6\ \sigma$**
  - **Different** detector configurations were used
  - **New X17 particle** imply remarkable fits
  - Different nuclei **^{8}Be - ^{4}He -^{12}C** anomalies
  - ^{12}C anomaly **predicted and confirmed**
  - Independent **confirmation** from VNU (?)

  - No confirmation of the X17 existence from **experiments of different nature**
  - **Strong constraints** on the parameter space from particle physics experiments

- **VANILLA B-L:** doesn't work!
- **B-L + VLLs** leads to problems (Higgs couplings, muon g-2, neutrino constraints)
- **If confirmed** we will have to bring up the right model…

Ευχαριστώ!