Explaining the $(g-2)_{e,\mu}$ anomalies with the "X_{17}-boson"

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Based on: JHEP 07 (2020) 235 with C. Hati, J. Orloff and A. M. Teixeira

6. Novembre 2020

Motivation – **LFUV** & other anomalies

SM: unique source of **L**epton **F**lavour **U**niversality **V**iolation – Higgs sector (Yukawa)

$$m_e \sim 511\,\text{keV}, \quad m_\mu \sim 105\,\text{MeV}, \quad m_\tau \sim 1.7\,\text{GeV}$$

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Deviations in $\boldsymbol{R_{D^{(*)}}} = \frac{\mathrm{BR}(B\to D^{(*)}\tau\nu)}{\mathrm{BR}(B\to D^{(*)}\ell\nu)}$ and $\boldsymbol{R_{K^{(*)}}} = \frac{\mathrm{BR}(B\to K^{(*)}\mu\mu)}{\mathrm{BR}(B\to K^{(*)}ee)}$ exceed $\boldsymbol{3\,\sigma}$

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If confirmed: **LFUV** should also be observed in other sectors!

⇒ Flavour **precision observables**

So far: $Z \to \ell\ell$, $W \to \ell\nu$ (LEP & ATLAS) in excellent agreement with SM

⇒ At low energies, *anomalous magnetic moments* powerful probes!

α_e and $(g-2)_{e,\mu}$

$$\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}} \sim (2.7 \pm 0.7) \times 10^{-9} \quad \Rightarrow \mathbf{3.7\,\sigma} \text{ discrepancy [2006.04822]}$$

NP Expectation for Δa_e $\begin{cases} \text{scaling of eff. dipole ops.: } \frac{\Delta a_e}{\Delta a_\mu} \sim \frac{m_e}{m_\mu} \sim 5 \times 10^{-3} \\ \text{MFV: } \frac{\Delta a_e}{\Delta a_\mu} \sim \frac{m_e^2}{m_\mu^2} \sim 2.5 \times 10^{-5} \end{cases}$

Recently improved measurement of α_e with Cs atoms (at $0.2\,\mathrm{ppb}$):

$\Rightarrow$ $\boldsymbol{\Delta a_e} \sim (-0.88 \pm 0.36) \times 10^{-12}$ vs $\boldsymbol{\Delta a_\mu} \sim (2.7 \pm 0.7) \times 10^{-9} \Rightarrow \frac{\Delta a_e}{\Delta a_\mu} \sim -3 \times 10^{-4}$

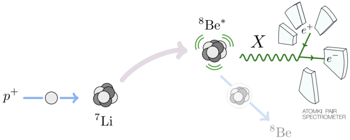
- $\mathbf{2.5\,\sigma}$ tension in electron has "*wrong*" sign **and** order of magnitude!

  $\Rightarrow$**Another** strong hint towards **LFUV** new physics!

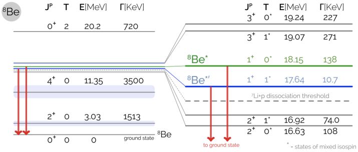
Most attempts to explain both $\Delta a_{\mu,e}$ require light new physics à la dark photon, axion, Z'...

Atomki experiment: a new light resonance?

In 2015, the ATOMKI collaboration claimed a $6.8\,\sigma$ excess in $^{8}\mathrm{Be}^* \to {}^{8}\mathrm{Be}\gamma(\to e^+e^-)$ transitions, compatible with a **resonance** [PRL 116 4, 042501]



- Create excited $^{8}\mathrm{Be}^*$ from a p-beam on $^{7}\mathrm{Li}$
- Nucleus de-excites emitting a γ
- Measure angular distribution of e^+e^- form internal pair creation



Figures from [1608.03591]

Atomki result: a new light resonance $m_X \sim 17\,\mathrm{MeV}$

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The result in particular:

- Measurement of **I**nternal **P**air **C**reation **C**orrelation
- Open circles "*control region*": asymmetric energy distribution
- Closed circles "*signal region*": symmetric energy distribution

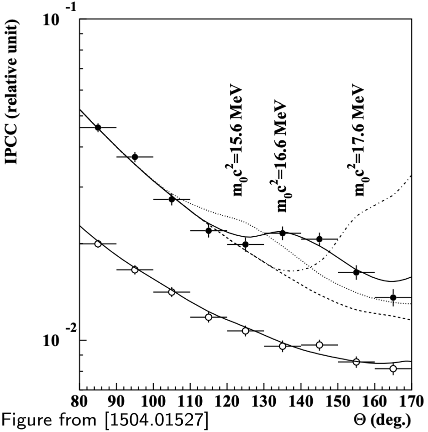

Figure from [1504.01527]

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⇒ Signal Consistent with the creation and subsequent decay of a *bosonic* **resonance** $m \sim 17\,\mathrm{MeV}$

$\rightsquigarrow X_{17}$

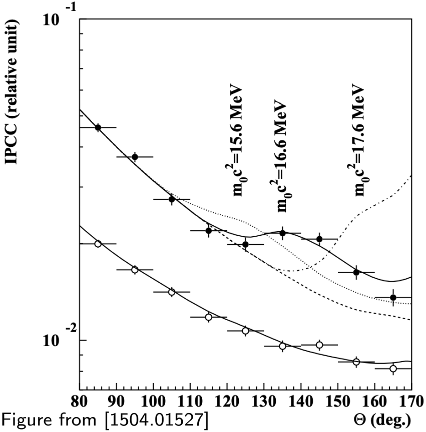

Figure from [1504.01527]

Requirements on X_{17}: nature & couplings to matter (I)

Possible Nuclear transitions in detail:

$$^{8}\mathrm{Be}^{*\prime}(j^{\pi}=1^{+},T=1^{*}) \to {}^{8}\mathrm{Be}^{0}(j^{\pi}=0^{+},T=0),\ \ E=17.64\,\mathrm{MeV}$$
$$^{8}\mathrm{Be}^{*}\ (j^{\pi}=1^{+},T=0^{*}) \to {}^{8}\mathrm{Be}^{0}(j^{\pi}=0^{+},T=0),\ \ E=18.15\,\mathrm{MeV} \quad \Leftarrow$$

Resonance observed in iso-spin **conserving** transition but absent in iso-spin violating one!

Possible candidates for $\boldsymbol{X_{17}}$:

- Light scalar resonance $\Rightarrow$ would violate angular momentum conservation in $1^{+} \to 0^{+}$ transition ✗
- Light pseudo-scalar: ok with angular momentum ✓, but minimal models for ALP already excluded in the required coupling range ✗ [1609.01669]
- Light vector: ok with angular momentum ✓, severe constraints on couplings (more details on next slides)
- Light axial vector: ok with angular momentum ✓, explored e.g. in [1612.01525]

Other exotic possibilities have been explored from open string QED mesons to "4 bare quarks" interpretations

Requirements on (vector) X_{17}: nature & couplings to matter (II)

Parametrise Z' neutral currents via effective couplings to fermions (ψ):

$$J^{\mu}_{Z'} = e\bar{\psi}_i\gamma^{\mu}(\varepsilon^{V}_{ij} + \gamma^5\varepsilon^{A}_{ij})\psi_j$$

Immediate constraint: on-shell $\boldsymbol{X_{17}} \equiv Z'$ must decay inside detector $\mathcal{O}(\mathrm{cm})$:

$$\Rightarrow |\varepsilon^{V}_{ee}| \gtrsim 1.3 \times 10^{-5}\sqrt{\mathrm{BR}(Z' \to e^+e^-)}$$

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A fit of the `ATOMKI` data results in:

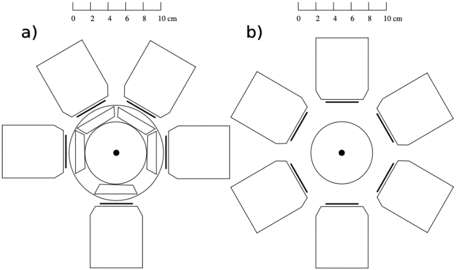
$$\frac{\Gamma(^8\mathrm{Be}^*\to {}^8\mathrm{Be}+Z')}{\Gamma(^8\mathrm{Be}^*\to {}^8\mathrm{Be}+\gamma)} \simeq (6\pm 1)\times 10^{-6} \quad \text{for} \quad m_{Z'}\simeq 17.01\pm 0.16\,\mathrm{MeV}$$

Conservative range: $|\varepsilon^V_n + \varepsilon^V_p| \simeq (2-15)\times 10^{-3}\sqrt{\mathrm{BR}(Z'\to e^+e^-)}^{\,-1}$

Cross-checks of the $^{8}\mathrm{Be}$ anomaly

Only the ATOMKI collaboration published results on such nuclear transitions...

- Original result 2015; since then new detector to re-investigate $^{8}\mathrm{Be}$ transition



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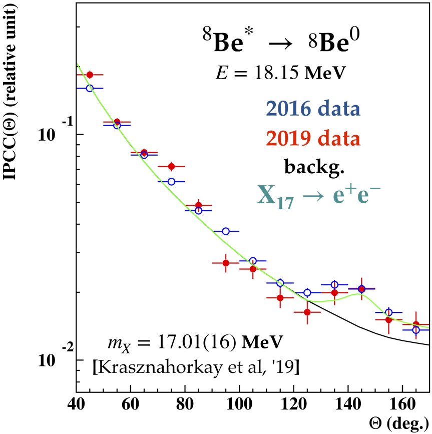

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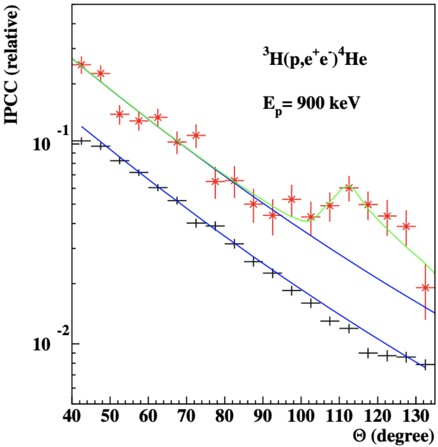

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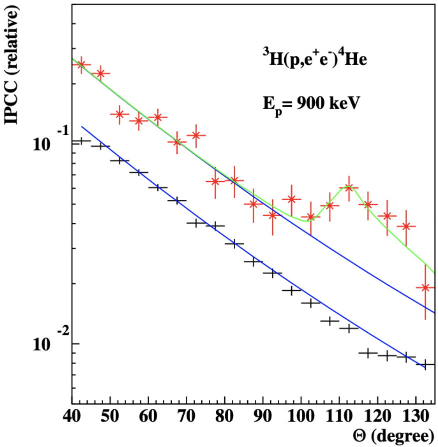

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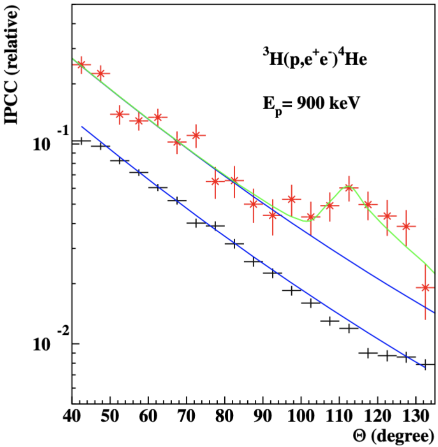
⇒ Has a **fifth force** been discovered?

- Plans to study similar transitions in ^{12}C for *conclusive* confirmation



Model independent constraints on (vector) $X_{17} \Rightarrow Z'$

New light vector from $U(1)$ extension of the SM with $J^{\mu}_{Z'} = e\bar{\psi}_i \gamma^{\mu}(\varepsilon^V_{ij} + \gamma^5 \varepsilon^A_{ij})\psi_j$

Recall from $^8\mathrm{Be}$ anomaly: $|\varepsilon^V_n + \varepsilon^V_p| \simeq (2-15)\times 10^{-3}$, $|\varepsilon^V_{ee}| \gtrsim 1.3 \times 10^{-5}$

Other constraints:

- KLOE-2 bound for $e^+e^- \to \gamma Z'(\to e^+e^-)$ leads to $\sqrt{\varepsilon^{V2}_{ee} + \varepsilon^{A2}_{ee}} \lesssim 2\times 10^{-3}$
- NA48/2 bound for $\pi^0 \to \gamma Z'$ leads to $|\varepsilon^V_p| \lesssim 1.2 \times 10^{-3}$
- NA64 **electron beam dump**: $\sqrt{|\varepsilon^V_{ee}|^2 + |\varepsilon^A_{ee}|^2} \gtrsim 6.8 \times 10^{-4} \sqrt{\mathrm{BR}(Z' \to e^+e^-)}^{-1}$
- **Neutrino scattering** (TEXONO & CHARM-II): $|\varepsilon^A_{\nu_e\nu_e}| \lesssim 1.2 \times 10^{-5}$ & $|\varepsilon^A_{\nu_\mu\nu_\mu}| \lesssim 12.2 \times 10^{-5}$
- **Atomic parity violation** (effective weak charge of Cs): $|\varepsilon^A_{ee}| \lesssim 2.6 \times 10^{-9}$

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$\Rightarrow$ Can we explain the $g-2$ anomalies (hinting at **LFUV**) with this light Z'?

A $U(1)_{B-L}$ model

- Extend SM by $U(1)_{B-L}$: Z' coupled to baryons and leptons
- New scalar singlet h_X: spontaneously breaks $U(1)_{B-L}$ below EW-scale

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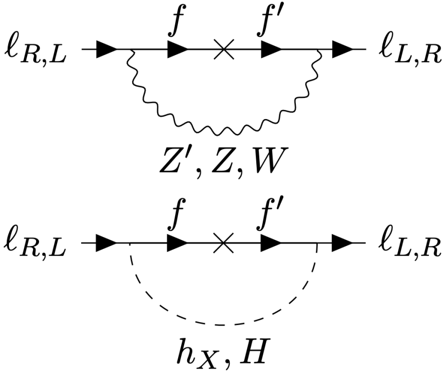
$$\mathcal{L}_{\text{Yuk.}} \supseteq -y_\ell^{ij} h_{\text{SM}} \bar{\ell}_L^i e_R^j + y_\nu^{ij} \tilde{h}_{\text{SM}} \bar{\ell}_L^i N_R^j - \frac{1}{2} y_M^{ij} h_X \bar{N}_R^{i\,c} N_R^j - \lambda_L^{ij} h_X \bar{\ell}_L^i L_R^j - M_L^{ij} \bar{L}_L^i L_R^j$$
$$- \lambda_E^{ij} h_X \bar{E}_L^i e_R^j - M_E^{ij} \bar{E}_L^i E_R^j - h^{ij} h_{\text{SM}} \bar{L}_L^i E_R^j + k^{ij} \tilde{h}_{\text{SM}} \bar{E}_L^i L_R^j$$

- Right-handed neutrinos N_R^j for anomaly cancellation $\Rightarrow$ type-I seesaw for free
- 3 vector-like doublet leptons $L_{L,R}$ to suppress $Z' - \nu\nu$ couplings
- 3 vector-like singlet leptons $E_{L,R}$ to suppress axial $Z' - \ell\ell$ couplings

New physics contributions to $g-2$

2 types of new contributions:

- γ can be attached to any charged line
- Dominant contributions by Z' and h_X
- Mass-insertion $\propto h_\alpha$ and $\propto k_\alpha$
- Since $m_{Z'} \simeq 17\,\mathrm{MeV}$, Z' contributions are too large



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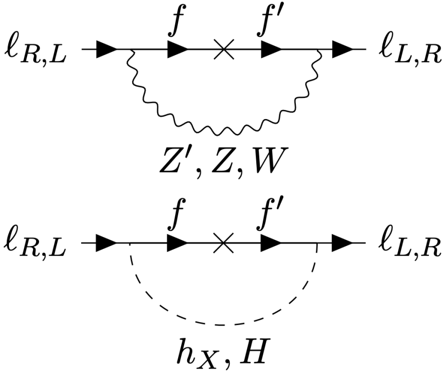

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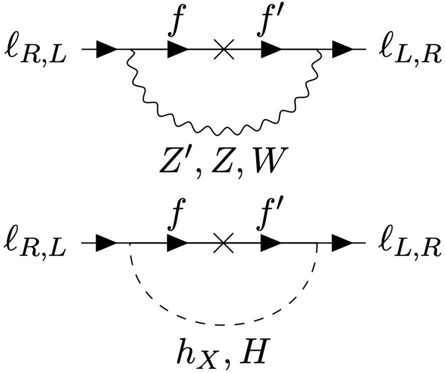
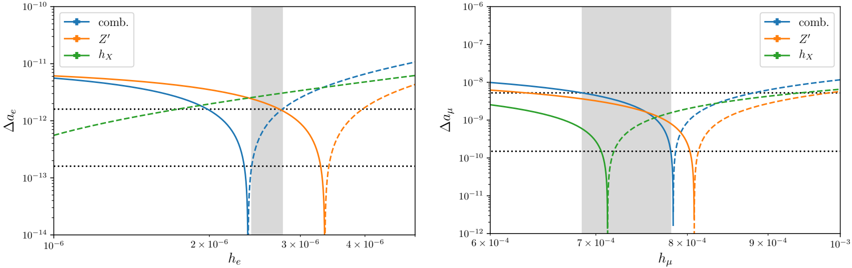
$\Rightarrow$ axial and pseudo-scalar couplings in $Z' - \ell L$ and $h_X - \ell L$ provide partial cancellation



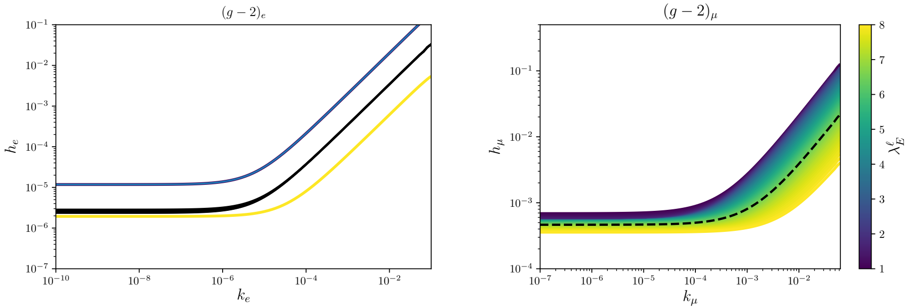
Cancellation of scalar/vector contributions leading to Δa_e, Δa_μ



- $M_E = M_L \simeq 90\,\text{GeV}$, $\lambda_L = \lambda_E = M_L/v_X (\simeq 6.4)$, $m_{h_X} \simeq 70\,\text{GeV}$, $\varepsilon_{B-L} = 2 \times 10^{-3}$, $\varepsilon = -8 \times 10^{-4}$, $k_e = k_\mu = 10^{-7}$
- Dashed lines: change of sign when pseudo-scalar contribution larger than scalar and/or axial larger than vector

$\Rightarrow$ Asymmetry in h and k provides "*effective*" **LFUV**

Remaining parameter space: impact from $\Delta a_e, \Delta a_\mu$



- Black line: $(g-2)_e$ explained ✓ coloured region: $(g-2)_\mu$ explained ✓✓
- λ_E^μ is still mostly free
- Curious hierarchy between h_ℓ & k_ℓ ($\Rightarrow$ could hint on residual Z_n-symmetry?)

Conclusion

- Exciting hints towards **LFUV** new physics in $(g-2)_{\mu,\, e}$
- Exciting hints of a **fifth force** discovered by `ATOMKI`

⇒ Parameter space to be probed soon (completely) by `NA64`

⇒ All 4 *anomalies* are explained in a single and very predictive model

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- Should measure parity non-conservation of μ's (`REDTOP`, muonic ARC), μ-scattering)

Model might also explain:

- N_R could be a dark matter candidate
- $R_{K^{(*)}}$ at very large hadronic recoil

Thank you!!!

Backup: Requirements on (vector) X_{17}: Nucleus & electron couplings I

Neutral current of fermions ψ_i can be parametrised with effective couplings:

$$J^{\mu}_{Z'} = e\bar{\psi}_i\gamma^{\mu}(\varepsilon^V_{ij} + \gamma^5\varepsilon^A_{ij})\psi_j$$

Most obvious constraint: on-shell $\boldsymbol{X_{17}} \equiv \boldsymbol{Z'}$ has to decay inside detector $\mathcal{O}(\mathrm{cm})$:

$$\Gamma(Z' \to e^+e^-) = (|\varepsilon^V_{ee}|^2 + |\varepsilon^A_{ee}|^2)\frac{\lambda^{\frac{1}{2}}(m_{Z'}, m_e, m_e)}{24\pi m_{Z'}}$$

... leading to $|\varepsilon^V_{ee}| \gtrsim 1.3 \times 10^{-5}\sqrt{\mathrm{BR}(Z' \to e^+e^-)}$

A fit of the `ATOMKI` data results in:

$$\frac{\Gamma(^8\mathrm{Be}^* \to {}^8\mathrm{Be} + Z')}{\Gamma(^8\mathrm{Be}^* \to {}^8\mathrm{Be} + \gamma)} \simeq (6 \pm 1) \times 10^{-6} \quad \text{for} \quad m_{Z'} \simeq 17.01 \pm 0.16\,\mathrm{MeV}$$

Baclup: Requirements on (vector) X_{17}: Nucleus & electron couplings II

With a vector resonance Z' the nuclear matrix elements cancel:

$$\frac{\Gamma(^8\mathrm{Be}^* \to {}^8\mathrm{Be} + Z')}{\Gamma(^8\mathrm{Be}^* \to {}^8\mathrm{Be} + \gamma)} \simeq (\varepsilon_p^V + \varepsilon_n^V)^2 \left[1 - \left(\frac{m_{Z'}}{18.15\,\mathrm{MeV}}\right)^2\right]^{\frac{3}{2}}$$

... leading to $|\varepsilon_p^V + \varepsilon_n^V| \simeq 1.2 \times 10^{-2} \sqrt{\mathrm{BR}(Z' \to e^+e^-)}^{-1}$

Including iso-spin mixing effects:

$$\frac{\Gamma(^8\mathrm{Be}^* \to {}^8\mathrm{Be} + Z')}{\Gamma(^8\mathrm{Be}^* \to {}^8\mathrm{Be} + \gamma)} \simeq |0.05(\varepsilon_p^V + \varepsilon_n^V) + 0.95(\varepsilon_p^V - \varepsilon_n^V)|^2 \left[1 - \left(\frac{m_{Z'}}{18.15\,\mathrm{MeV}}\right)^2\right]^{\frac{3}{2}}$$

... leads to $\sim 15\%$ modification and a heavier Z' leads to smaller width $\frac{\Gamma_{Z'}}{\Gamma_\gamma} \sim 0.5 \times 10^{-6}$

Conservative range: $|\varepsilon_n^V + \varepsilon_p^V| \simeq (2 - 15) \times 10^{-3} \sqrt{\mathrm{BR}(Z' \to e^+e^-)}^{-1}$

Backup: Minimal model ingredients

- New vector coming from gauge extension of SM – new $\boldsymbol{U(1)}$-gauge group
- We need a new scalar breaking $\boldsymbol{U(1)}$ and giving a mass around $\sim \mathbf{17}\,\mathrm{MeV}$
- We need couplings to **nucleons** (hadrons) and **electrons**

⇒ Could be a dark photon $\boldsymbol{A'}$?

"*Pure*" $\boldsymbol{A'}$-couplings due to kinetic mixing with photon: $\varepsilon_n^V = \varepsilon_\nu^V = 0\,, \quad \varepsilon_p^V = -\varepsilon_{ee}^V$

Recall from ${}^8\mathrm{Be}$ anomaly: $|\varepsilon_n^V + \varepsilon_p^V| \simeq (2-15)\times 10^{-3}\,,\ |\varepsilon_{ee}^V| \gtrsim 1.3\times 10^{-5}$

⇒ `KLOE-2` bound for $e^+e^- \to \gamma \boldsymbol{A'}(\to e^+e^-)$ leads to $\sqrt{\varepsilon_{ee}^{V2} + \varepsilon_{ee}^{A2}} \lesssim 2\times 10^{-3}$ ✗

Furthermore `NA48/2` bound for $\pi^0 \to \gamma \boldsymbol{A'}$ leads to $|\varepsilon_p^V| \lesssim 1.2\times 10^{-3}$ ✗✗

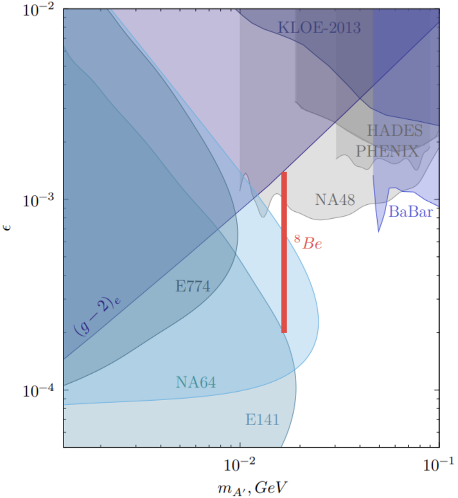
Protophobic scenario: proton couplings smaller than neutron, **dark photon** excluded!

Backup: Constraints: direct searches

Also NA64 (electron beam dump) is looking for light neutral vectors:

- Very recent result [1912.11389]
- Either $\varepsilon_{ee}^{V2} + \varepsilon_{ee}^{A2} < 1.1 \times 10^{-16}$ (negligible production)
- Or $\sqrt{|\varepsilon_{ee}^{V}|^2 + |\varepsilon_{ee}^{A}|^2} \gtrsim \frac{6.8\times10^{-4}}{\sqrt{\mathrm{BR}(Z'\to e^+e^-)}}$ (decay inside beam dump)

⇒ Globally allowed range:
$\sqrt{|\varepsilon_{ee}^{V}|^2 + |\varepsilon_{ee}^{A}|^2} \sim \frac{(0.68-2)\times10^{-3}}{\sqrt{\mathrm{BR}(Z'\to e^+e^-)}}$
(NA48/2 does not directly apply in *protophobic* case)



Backup: Constraints: (atomic) parity violation

Search for **parity** violating Møller scattering at `SLAC E158` yields a bound

$$|\varepsilon^V_{ee}\varepsilon^A_{ee}| \lesssim 1.1 \times 10^{-7}$$

Much more severe is *atomic* parity violation (effective weak charge) in Cs:

$$|\Delta Q_w| = |\frac{2\sqrt{2}}{G_F} 4\pi\alpha\varepsilon^A_{ee}[\varepsilon^V_{uu}(2Z+N) + \varepsilon^V_{dd}(Z+2N)]\frac{\mathcal{K}(m_{Z'})}{m^2_{Z'}}| \lesssim 0.71$$

At low energy, the nucleon couplings are $\varepsilon^V_p \simeq 2\,\varepsilon^V_{uu} + \varepsilon^V_{dd}$ and $\varepsilon^V_n \simeq \varepsilon^V_{uu} + 2\,\varepsilon^V_{dd}$

⇒ For $^8\mathrm{Be}$ nucleon couplings and $m_{Z'} \simeq 17\,\mathrm{MeV}$: upper bound $|\varepsilon^A_{ee}| \lesssim 2.6 \times 10^{-9}$

Backup: Constraints: neutrino-electron scattering

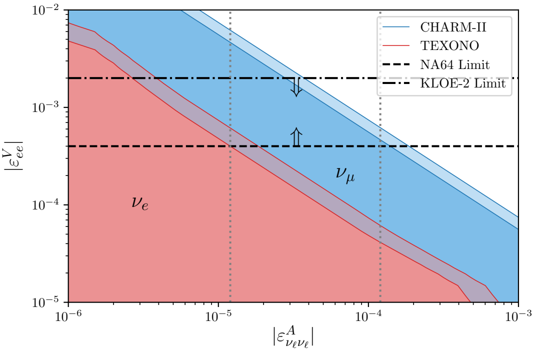
Neutrino-electron scattering provides very stringent constraints:

For **LFU** couplings and **Dirac ν**: $\sqrt{|\varepsilon^V_{ee}\varepsilon^V_{\nu_\ell\nu_\ell}|} < 7\times10^{-5}$ c.f. [1608.03591] and TEXONO data

For **Majorana ν** the vector coupling vanishes! $\Rightarrow$ new (**LFUV**) fit with **Majorana ν**:

- CHARM-II: SPS experiment $\nu_\mu - e$ scattering
- TEXONO: Reactor experiment $\nu_e - e$ scattering

$\Rightarrow$ Bound for lowest allowed $\varepsilon^V_{ee} \simeq 6.8\times10^{-4}$: $|\varepsilon^A_{\nu_e\nu_e}| \lesssim 1.2\times10^{-5}$ & $|\varepsilon^A_{\nu_\mu\nu_\mu}| \lesssim 12.2\times10^{-5}$



Model recipe

- Extend SM by $\boldsymbol{U(1)_{B-L}}$: Z' coupled to baryons and leptons
- New scalar singlet $\boldsymbol{h_X}$: spontaneously breaks $\boldsymbol{U(1)_{B-L}}$ somewhere below EW-scale

$\Rightarrow$ triangular gauge anomalies

$$\mathcal{A}\left[\boldsymbol{U(1)_{B-L}}(SU(2)_L)^2\right], \mathcal{A}\left[(\boldsymbol{U(1)_{B-L}})^3\right], \mathcal{A}\left[\boldsymbol{U(1)_{B-L}}(U(1)_Y)^2\right], \mathcal{A}\left[\mathrm{G.}^2 \times \boldsymbol{U(1)_{B-L}}\right]$$

... remaining $B - L = 3 \Rightarrow$ add 3 gens of sterile Majorana $\boldsymbol{N_R}$ with $\boldsymbol{Q^{B-L}} = -1$

$\Rightarrow$ with $\boldsymbol{Q^{B-L}} = +2$ for $\boldsymbol{h_X}$: dynamical type-I **seesaw** neutrino masses “for free”!

$$\mathcal{L}_{\mathsf{Yuk.}} \supseteq -y_\ell^{ij} h_{\mathsf{SM}} \bar{\ell}_L^i e_R^j + y_\nu^{ij} \tilde{h}_{\mathsf{SM}} \bar{\ell}_L^i \boldsymbol{N_R^j} - \frac{1}{2} y_M^{ij} \boldsymbol{h_X} \boldsymbol{\bar{N}_R^{i\,c}} \boldsymbol{N_R^j}$$

Coupling to nucleons now determined by photon kinetic mixing and $B - L$-current:

$$\varepsilon_n^V \propto g_{B-L}\,, \;\; m_{Z'}^2 \propto g_{B-L}^2 v_X^2 \Rightarrow \text{fixing vev of } \boldsymbol{h_X} \text{ to } v_X \simeq 14\,\mathrm{GeV}$$

Gauge boson mixing

$\boldsymbol{U(1)_{B-L}}$ is **kinetically** mixed with the $\boldsymbol{U(1)_Y}$:

$$\mathcal{L}_{\text{kin}}^{\text{gauge}} \supseteq -\frac{1}{4}\tilde{F}_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{4}\tilde{F}'_{\mu\nu}\tilde{F}'^{\mu\nu} + \frac{\epsilon_k}{2}\tilde{F}_{\mu\nu}\tilde{F}'^{\mu\nu}$$

⇝ consequently **mass mixing** between $\boldsymbol{U(1)_{B-L}}$-boson and W^3 with $\tan 2\theta' \simeq -2\frac{\epsilon_k}{\sqrt{1-\epsilon_k^2}}\sin\theta_w$

Diagonalising **kinetic** and **mass mixing** gives physical (gauge) couplings (at leading order):

$$D_\mu \simeq \partial_\mu + \ldots + i\frac{g}{\cos\theta_w}(T_{3\,f} - \sin^2\theta_w \boldsymbol{Q_f})Z_\mu + ie\boldsymbol{Q_f}A_\mu + ie(\varepsilon\boldsymbol{Q_f} + \varepsilon_{B-L}\boldsymbol{Q_f^{B-L}})Z'_\mu$$

$$\text{with } \varepsilon = \frac{\epsilon_k\cos\theta_w}{\sqrt{1-\epsilon_k^2}} \text{ and } \varepsilon_{B-L} = \frac{g_{B-L}}{e\sqrt{1-\epsilon_k^2}}$$

⇒ Nucleon couplings and mass: $\varepsilon_p^V = \varepsilon_{B-L} - \varepsilon\,,\ \varepsilon_n^V = \varepsilon_{B-L}\,,\ m_{Z'}^2 \simeq 4\varepsilon_{B-L}^2 v_X^2$

⇒ But also: $\varepsilon_{\nu\nu}^A = -\varepsilon_n^V$ neutrino coupling 10^2 too large! ✗✗✗

Vector-like leptons: Neutrino cancellation

Solution: Add 3 gens. of **vector-like lepton** *doublets* $L_{L,R} = \begin{pmatrix} L^0 \\ L^- \end{pmatrix}$ with $Q^{B-L} = +1$

- ◦ **VL**-fermions do not add further gauge anomalies
- ◦ Choice of charge to not spoil **LFU** SM-boson couplings

⇒ Mass mixing of ${L^0}_L$ with SM ν_ℓ will modify Z'-couplings

$$\mathcal{L}_{\text{Yuk.}} \supseteq -y_\ell^{ij} h_{\text{SM}} \bar{\ell}_L^i e_R^j + y_\nu^{ij} \tilde{h}_{\text{SM}} \bar{\ell}_L^i N_R^j - \frac{1}{2} y_M^{ij} h_X \bar{N}_R^{i\,c} N_R^j - \lambda_L^{ij} h_X \bar{\ell}_L^i {L^j}_R - M_L^{ij} {\bar{L}^i}_L {L^j}_R$$

- ◦ λ_L^{ij} needs to be (almost) diagonal to comply with **LFV** bounds: $\lambda_L^{ij} \to \lambda_{L\,\alpha}$
- ◦ M_L^{ij} can be chosen to be diagonal; **collider bounds:** mass scale $\sim 100\,\text{GeV}$

⇒ Z'-$\nu\nu$-couplings get modified: $\varepsilon_{\nu_\alpha \nu_\alpha} \simeq \varepsilon_{B-L} \left(1 - \frac{\lambda_{L\,\alpha}^2 v_X^2}{M_{L\,\alpha}^2}\right)$

⇒ $\lambda_{L\,\alpha}^2 v_X^2 \simeq M_{L\,\alpha}^2$ is fixed for each lepton generation α !

Vector-like leptons: atomic parity violation

The *charged* component of L_L mixes with the **left-handed** SM leptons

$\Rightarrow g^{\ell_\alpha \ell_\alpha}_{Z',L} \simeq -\varepsilon + \left(\frac{\lambda^2_{L\,\alpha} v_X^2}{M^2_{L\,\alpha}} - 1\right)\varepsilon_{B-L}$, but **right-handed** couplings unmodified

Solution: Add 3 gens. of charged **vector-like lepton** *singlets* $E_{L,R}$ with $Q^{B-L} = +1$

$$\mathcal{L}_{\text{Yuk.}} \supseteq - y_\ell^{ij} h_{\text{SM}} \bar{\ell}^i_L e^j_R + y_\nu^{ij} \tilde{h}_{\text{SM}} \bar{\ell}^i_L N^j_R - \frac{1}{2} y_M^{ij} h_X \bar{N}^{i\,c}_R N^j_R - \lambda_L^{ij} h_X \bar{\ell}^i_L L^j{}_R - M_L^{ij} \bar{L}^i{}_L L^j{}_R$$

$$- \lambda_E^{ij} h_X \bar{E}^i{}_L e^j_R - M_E^{ij} \bar{E}^i{}_L E^j{}_R - h^{ij} h_{\text{SM}} \bar{L}^i{}_L E^j{}_R + k^{ij} \tilde{h}_{\text{SM}} \bar{E}^i{}_L L^j{}_R$$

- $\Rightarrow \varepsilon^A_{\ell_\alpha \ell_\alpha} \simeq \frac{1}{2}\left(\frac{\lambda^2_{E\,\alpha} v_X^2}{M^2_{E\,\alpha}} - \frac{\lambda^2_{L\,\alpha} v_X^2}{M^2_{L\,\alpha}}\right)\varepsilon_{B-L} \Rightarrow \lambda_{E\,\alpha}$ is fixed for the 1. gen!
- $\Rightarrow \varepsilon^V_{\ell_\alpha \ell_\alpha} \simeq -\varepsilon + \frac{1}{2}\left(\frac{\lambda^2_{L\,\alpha} v_X^2}{M^2_{L\,\alpha}} + \frac{\lambda^2_{E\,\alpha} v_X^2}{M^2_{E\,\alpha}} - 2\right)\varepsilon_{B-L} \Rightarrow$ fixes $\varepsilon \simeq -(8-20)\times 10^{-4}$
- $\Rightarrow$ 2 new Yuk. matrices h^{ij} and k^{ij} (assumed to be diagonal): if different, their asymmetry will generate axial and pseudo-scalar couplings in $Z' - \ell L$ and $h_X - \ell L$ interactions

Backup: Gauge boson mixing

$$\begin{pmatrix} A^\mu \\ Z^\mu \\ Z'^\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_w & \sin\theta_w & 0 \\ -\sin\theta_w\cos\theta' & \cos\theta_w\cos\theta' & \sin\theta' \\ \sin\theta_w\sin\theta' & -\cos\theta_w\sin\theta' & \cos\theta' \end{pmatrix} \begin{pmatrix} B^\mu \\ W_3^\mu \\ B'^\mu \end{pmatrix}$$

$$\tan 2\theta' = \frac{2\,\varepsilon'\,g'\,\sqrt{g^2+g'^2}}{\varepsilon'^2\,g'^2 + 4\,m_{B'}^2/v^2 - g^2 - g'^2}$$

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

Backup: Charged lepton masses

$$\mathcal{L}^{\ell}_{\text{mass}} = \begin{pmatrix} \bar{e}_L & \bar{L}^-_L & \bar{E}_L \end{pmatrix} \begin{pmatrix} y\frac{v}{\sqrt{2}} & \lambda_L \frac{v_X}{\sqrt{2}} & 0 \\ 0 & M_L & h\frac{v}{\sqrt{2}} \\ \lambda_E \frac{v_X}{\sqrt{2}} & k\frac{v}{\sqrt{2}} & M_E \end{pmatrix} \begin{pmatrix} e_R \\ L^-_R \\ E_R \end{pmatrix}$$

$$U_L = \begin{pmatrix} 1 - \frac{\lambda_L^2 v_X^2}{4M_L^2} & \frac{\lambda_L v_X}{\sqrt{2}M_L} - \frac{\lambda_L^3 v_X^3}{4\sqrt{2}M_L^3} & \frac{(k\lambda_L M_E + h\lambda_L M_L + \lambda_E M_E y) v v_X}{2M_E^3} \\ \frac{\lambda_L^3 v_X^3}{4\sqrt{2}M_L^3} - \frac{\lambda_L v_X}{\sqrt{2}M_L} & 1 - \frac{\lambda_L^2 v_X^2}{4M_L^2} & \frac{(kM_E M_L + h(M_E^2 + M_L^2))v}{\sqrt{2}M_E^3} \\ \frac{(h\lambda_L M_E - \lambda_E M_L y) v v_X}{4M_E^3} & -\frac{(kM_E M_L + h(M_E^2 + M_L^2))v}{\sqrt{2}M_E^3} & 1 \end{pmatrix}$$

$$U_R = \begin{pmatrix} 1 - \frac{\lambda_E^2 v_X^2}{4M_E^2} & \frac{\lambda_L v v_X}{2M_L^2} - \frac{\lambda_E (kM_E M_L + h(M_E^2 + M_L^2)) v v_X}{2M_E^3 M_L} & \frac{\lambda_E v_X}{\sqrt{2}M_E} - \frac{\lambda_E^3 v_X^3}{4\sqrt{2}M_E^3} \\ \frac{(h\lambda_E M_L - \lambda_L M_E y) v v_X}{2M_E M_L^2} & 1 & \frac{(hM_E M_L + k(M_E^2 + M_L^2))v}{\sqrt{2}M_E^3} \\ \frac{\lambda_E^3 v_X^3}{4\sqrt{2}M_E^3} - \frac{\lambda_E v_X}{\sqrt{2}M_E} & -\frac{(hM_E M_L + k(M_E^2 + M_L^2))v}{\sqrt{2}M_E^3} & 1 - \frac{\lambda_E^2 v_X^2}{4M_E^2} \end{pmatrix}$$

Backup: Neutrino masses

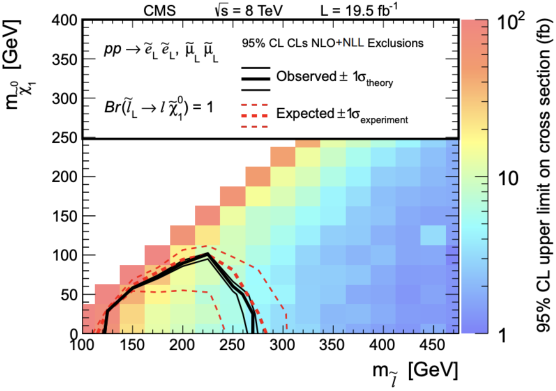
$$\mathcal{L}^{\nu}_{\text{mass}} = \begin{pmatrix} \nu^T & N^{c\,T} & L^{0\,T} & L^{0\,c\,T} \end{pmatrix}_L C^{-1} \begin{pmatrix} 0 & y_\nu \frac{v}{\sqrt{2}} & 0 & \lambda_L \frac{v_X}{\sqrt{2}} \\ y_\nu \frac{v}{\sqrt{2}} & y_M \frac{v_X}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & 0 & M_L \\ \lambda_L \frac{v_X}{\sqrt{2}} & 0 & M_L & 0 \end{pmatrix} \begin{pmatrix} \nu \\ N^c \\ L^0 \\ L^{0c} \end{pmatrix}_L$$

$$\tilde{U}_\nu = \begin{pmatrix} 1 - \frac{\lambda_L^2 v_X^2}{4M_L^2} - \frac{v^2 y_\nu^2}{2v_X^2 y_M^2} & \frac{v y_\nu}{v_X y_M} & \frac{\lambda_L v_X}{2M_L} & \frac{\lambda_L v_X}{2M_L} \\ -\frac{v y_\nu}{v_X y_M} & 1 - \frac{v^2 y_\nu^2}{2v_X^2 y_M^2} & 0 & 0 \\ -\frac{\lambda_L v_X}{\sqrt{2} M_L} & -\frac{\lambda_L v y_\nu}{\sqrt{2} M_L y_M} & \frac{1}{\sqrt{2}} - \frac{\lambda_L^2 v_X^2}{4\sqrt{2} M_L^2} & \frac{1}{\sqrt{2}} - \frac{\lambda_L^2 v_X^2}{4\sqrt{2} M_L^2} \\ 0 & 0 & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$$m_\nu \simeq -\frac{y_\nu^2 v^2}{v_X y_M}\,, \quad U_\nu = \tilde{U}_\nu\, \text{diag}(U_P, 1, 1, 1)$$

$$\mathcal{L}_{W^\pm} = -\frac{g}{\sqrt{2}} W^-_\mu \sum_{\alpha = e,\,\mu,\,\tau} \sum_{i=1}^{9} \sum_{j=1}^{12} \bar{\ell}_i\, (U_L^\dagger)_{i\,\alpha}\, \gamma^\mu\, P_L\, (U_\nu)_{\alpha\,j}\, \nu_j + \text{H.c.}\,,$$

Backup: Collider bounds



Recast searches for slepton/neutralino pair production: $\boldsymbol{h_X} \to \tilde{\chi}^0$, $\boldsymbol{E, L} \to \tilde{l}$

$\Rightarrow$ $m_{h_X} \gtrsim 50\,\mathrm{GeV}$ and **physical vector-like lepton** mass $\gtrsim 120\,\mathrm{GeV}$