Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

Physik Department T70
Technical University of Munich

A recette for combined explanation of anomalies in ^{8}Be nuclear transitions and $(g-2)_{e,\mu}$


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SEARCHES FOR NEW PHYSICS | NEWS

Rekindled Atomki anomaly merits closer scrutiny

20 December 2019

Atomki's new high-resolution $LaBr_3$ spectrometer, which will record gamma–gamma pairs from excited nuclei. Credit: Atomki

Chandan Hati

Based on *JHEP* 07 (2020) 235

in collaboration with

Jonathan Kriewald, Jean Orloff and Ana M. Teixeira

c.hati@tum.de

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Physics beyond the Standard Model (BSM): direction

The only laboratory evidence of BSM physics so far:

neutrino oscillations => neutrino masses

Other strong motivations: observed baryon asymmetry of the Universe, dark matter, dark energy

A number of theoretical caveats/motivations:

hierarchy problem, unification of interactions, gravity, parity violation, …

Hundreds of theoretical candidates for BSM physics to address neutrino masses and other theoretical motivations: how to proceed?

Guidance from multi-frontier experimental searches

A challenge: lack of any direction from the direct collider searches so far

A particularly interesting alternative is to look for deviations from the SM @ rare processes with no or small SM backgrounds (high intensity frontier)

Charged lepton observables @ high intensity frontier

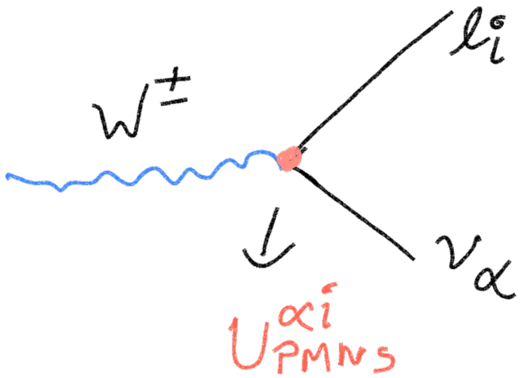
- **lepton moments: *(g-2)* and EDMs**
- **charged lepton flavour violation (cLFV)**
- **lepton number violation (LNV)**
- **lepton flavour universality violation (LFUV)**
- **…**

Whats's so special about leptonic observables?

Purely SM:

- strictly massless neutrinos
- conservation of total lepton number and lepton flavours
- leptonic EDMs at 4-loop level $d_e^{\text{CKM}} \leq 10^{-38}\, e\, cm$

What if the SM is extended minimally to only include massive Dirac neutrinos?

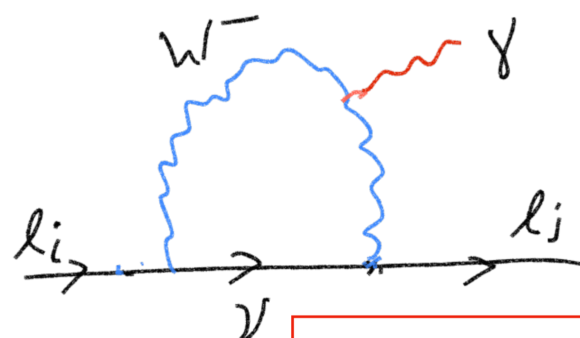


$$\mathscr{L}_{\text{CC}}^{\text{lepton}} = U_{\text{PMNS}}\, W_\mu^- \bar{\ell}_L \gamma^\mu \nu_L + \text{h.c.}$$

$$(\nu_e, \nu_\mu, \nu_\tau) \overset{U_{\text{PMNS}}}{\longleftrightarrow} (\nu_1, \nu_2, \nu_3)$$

$$|\nu_\alpha\rangle = U^*_{\alpha i} |\nu_i\rangle$$

no LNV, finite but extremely tiny cLFV



$$\text{BR}(\mu \to e\gamma) \propto \left| \sum U^*_{\mu i} U_{ei} \frac{m^2_{\nu_i}}{M_W^2} \right|^2 \sim 10^{-54}$$

Cheng and Li'77; Petcov'77;
Marciano and Sanda'77; Shrock and Lee ...

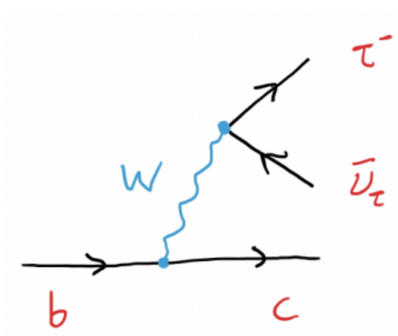
EDM at 2-loop level, but still tiny $d_e^{\text{lep}} \leq 10^{-35}\, e\, cm$

Therefore any signal from the current or upcoming experiments will be a clear indication of some nontrivial NP

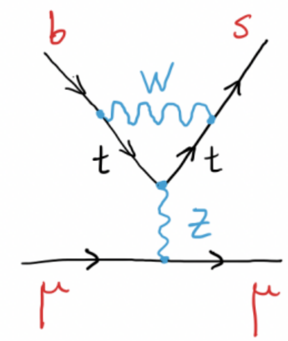
Observables involving charged leptons

Charged lepton sector is currently hosting several lingering tensions with the SM!

★ Lepton flavour universality violation in CC and NC *B*-decays



~15% of a SM tree-level effect



~20% of a SM loop effect

- explainable separately by invoking heavy NP: scalar LQ, RPV SUSY, heavy Z', ….
- only select few scenarios can explain them combined: vector LQ, combinations of scale LQ

see many interesting talks@
Anomalies 2020

★ Long-standing tension in $(g-2)_\mu$

explainable by many NP candidates!

★ Emerging anomaly in $(g-2)_e$

less-trivial to explain when combined with $(g-2)_\mu$

★ Anomalous internal pair creation in ^{8}Be transitions

requires light NP ~ 17 MeV

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Muon and electron magnetic dipole moment

Muon (g-2):

lingering tension between SM and experiment!

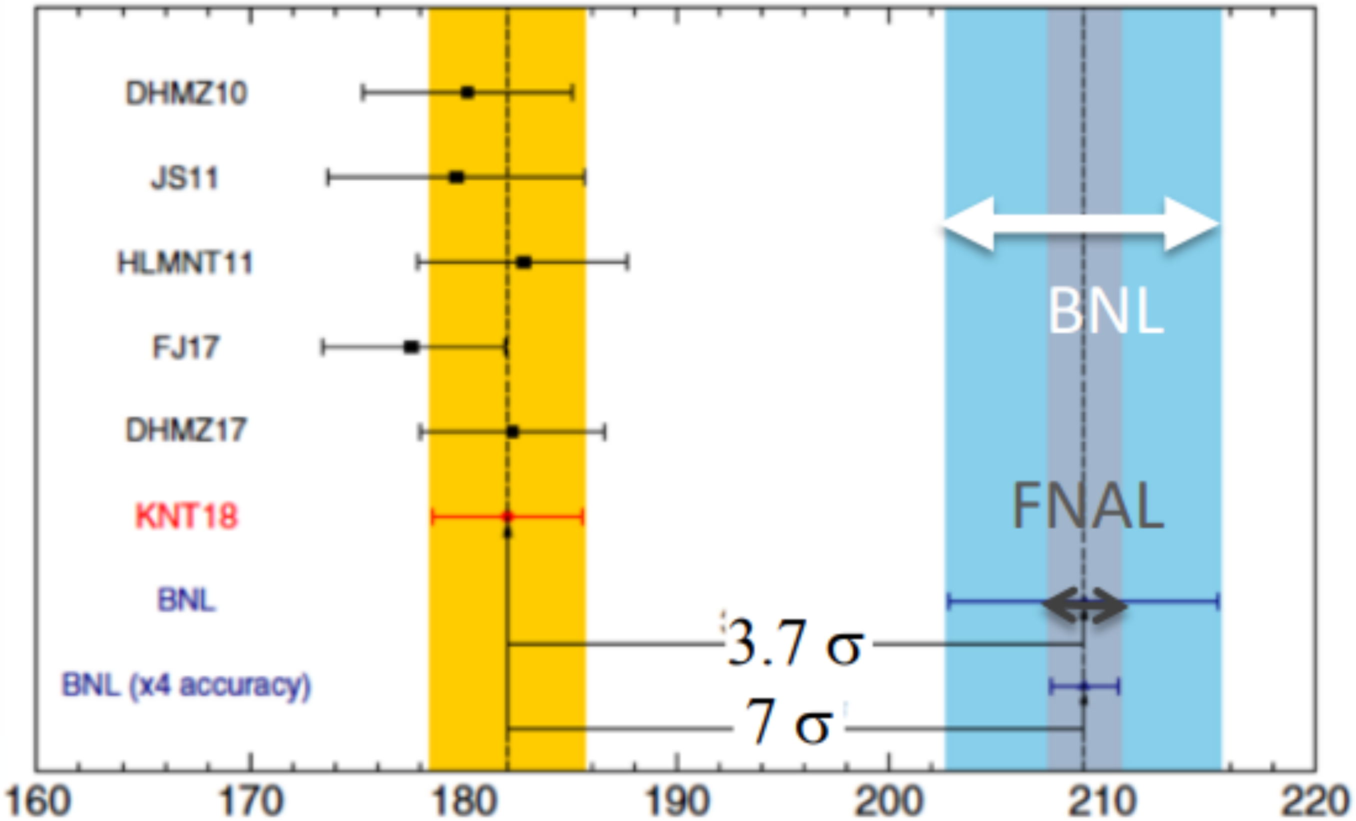
$$\Delta a_\mu := a_\mu^{\textbf{exp}} - a_\mu^{\textbf{SM}} = 279(76) \times 10^{-11}$$

$$a_\mu^{\textbf{BNL}} = 116\,592\,089(63) \times 10^{-11}$$

$$a_\mu^{\textbf{SM}} = 116\,591\,810(43) \times 10^{-11}$$

the latest consensus value

current tension @ 3.7σ



upcoming experimental results from Fermilab/JPARC will update the current deadlock

Electron (g-2): interesting development with new measurement of α using Cs

Parker et. al. Science (2018)

$$a_e^{\textbf{SM}}\big|_{\alpha_{\textbf{Cs}}} \; 1\,159\,652\,181.61(23) \times 10^{-12}$$

$$\Delta a_e := a_e^{\textbf{exp}} - a_e^{\textbf{SM}} = -0.88(36) \times 10^{-12}$$

current tension @ 2.5σ

Another developing anomaly ?

Minimal scenarios: explaining $(g-2)_\mu$ and $(g-2)_e$ simultaneously

$$\Delta a_\mu := a_\mu^{\textbf{exp}} - a_\mu^{\textbf{SM}} = 279(76) \times 10^{-11}$$

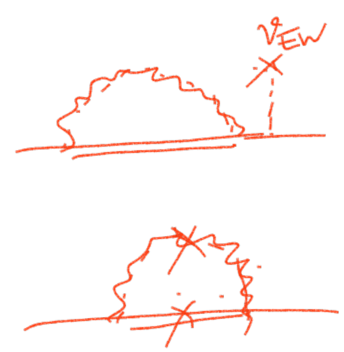
$$\Delta a_e := a_e^{\textbf{exp}} - a_e^{\textbf{SM}} = -0.88(36) \times 10^{-12}$$

Heavy NP EFT: $$\mathcal{H}_{\text{eff}} = c_R^{\ell_f \ell_i}\, \bar{\ell}_f \sigma_{\mu\nu} P_R \ell_i F^{\mu\nu} + \text{h.c.}$$

$$a_{\ell_i} \sim -\frac{2 m_{\ell_i}}{e} \left(c_R^{\ell_i \ell_i} + c_R^{\ell_i \ell_i *} \right)$$

$$\text{Br}[\mu \to e\gamma] \sim \frac{m_\mu^3}{4\pi \Gamma_\mu} \left(|c_R^{e\mu}|^2 + |c_R^{\mu e}|^2 \right)$$

NP with universal coupling:



$$\frac{\Delta a_\mu}{\Delta a_e} \sim \frac{m_\mu^2}{m_e^2}$$

$$\frac{\Delta a_\mu}{\Delta a_e} \sim \frac{m_\mu}{m_e}$$

Neither compatible with the observed behaviour

Giudice et al JHEP 2012
Crivellin et al. PRD 2018
Calibbi et al JHEP 2020
++

Ingredients to achieve a simultaneous explanation:

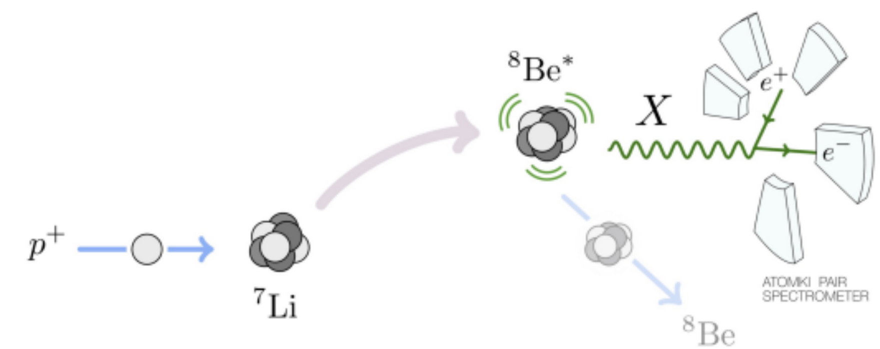
breaking the universality of the flavour structure of NP

some type of cancellation among different contributions

Vector-like leptons together with nontrivial NP seems to be a plausible option!

Anomalies in nuclear transitions of: ^{8}Be and ^{4}He

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



In 2016, the ATOMKI collaboration reported to have seen a "6.8σ" excess in ^{8}Be* → ^{8}Be γ (→ e$^+$e$^-$) transition, compatible with a resonance

Krasznahorkay et al PRL 2016

2019 reinvestigation @ " 5σ "

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

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

Resonance observed in isospin conserving transition
but absent in isospin violating one!

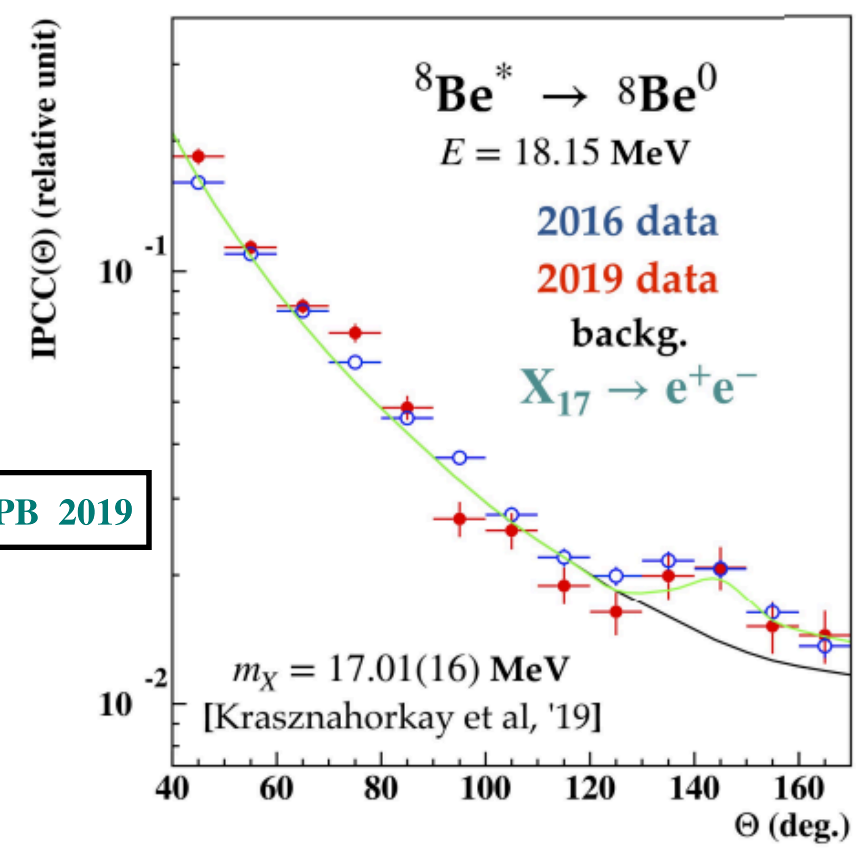
Best fit for the isospin conserving transition:

Krasznahorkay et al APPB 2019

$$m_X = 17.01(16)\,\mathrm{MeV}$$

$$\Gamma_X/\Gamma_\gamma = 6(1) \times 10^{-6}$$

***Isospin mixing can affect these fit values



Similar anomaly in e^+e^- angular correlation of ^{4}He ($0^- \to 0^+$, 21.01 MeV decay) @ 7.2 σ

Anomaly in ^{8}Be nuclear transition: suspects

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

Possible candidates for X_{17}:

★ Light scalar resonance ⇒ would violate angular momentum conservation in $1^+ \to 0^+$ transition

★ Light pseudo-scalar: minimal models already excluded in the required coupling range
can be partially circumvented in the presence of additional non-photonic couplings

Doebrich et al. JHEP 2016
Ellwanger et al. JHEP 2016

★ Light vector: severe constraints on couplings for the relevant mass range
(more details on next slides)

Feng et al. PRL 2016; PRD 2017; 2020

★ Light axial vector: possible, requires ab-initio computation for the relevant form factors

Kozaczuk et al PRD 2017

○ Other exotic possibilities explored range from open string QED mesons to “4 bare quarks” interpretation

Couplings of the new vector boson for ^{8}Be

A new Z' NC can be parametrised with effective couplings: $J^\mu_{Z'} = e\bar{\psi}_i\gamma^\mu(\varepsilon^V_{ij} + \gamma^5\varepsilon^A_{ij})\psi_j$

in the simple case of purely vector quark current; the isospin conserving limit gives

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

$$\varepsilon^V_p \simeq 2\,\varepsilon^V_{uu} + \varepsilon^V_{dd}$$
$$\varepsilon^V_n \simeq \varepsilon^V_{uu} + 2\,\varepsilon^V_{dd}$$

including isospin mixing effects à la Feng et.al. leads to about 15% modification in allowed ranges

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

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

the null results for the mostly isotriplet excited state require a kinematic suppression in the presence of isospin mixing => a larger preferred mass for the Z' to achieve the required phase space suppression

for a mass 17.5 MeV the normalised branching fraction fit can be as low as $\Gamma_{Z'}/\Gamma_\gamma = 0.5 \times 10^{-6}$

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

Couplings of the new vector boson for ^{8}Be

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

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

← from normalised branching fraction fit

Z' should be sufficiently short lived for its decay to occur inside the Atomki spectrometer ~ $\mathcal{O}$(cm)

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

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

Atomic parity violation in Caesium

$$|\varepsilon^A_{ee}| \lesssim 2.6 \times 10^{-9}$$

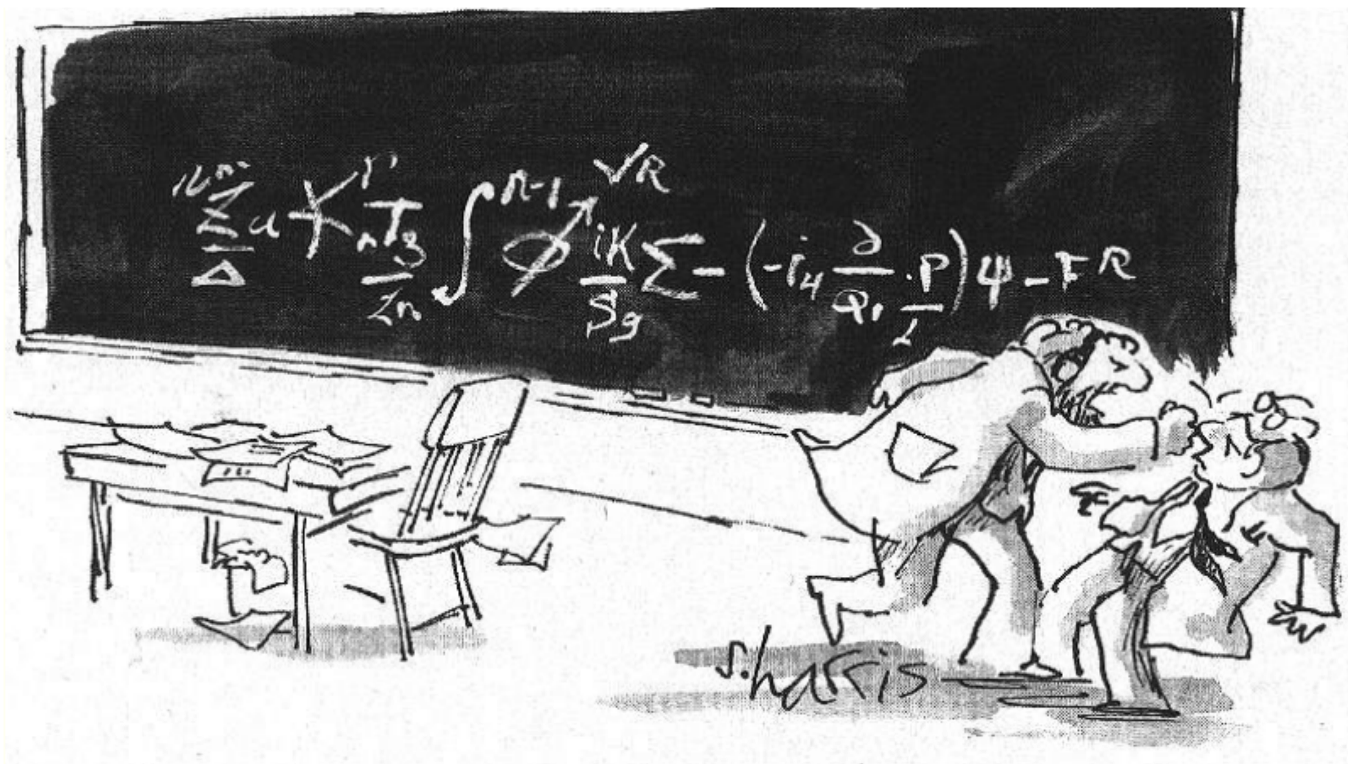
Can pure dark photon work as a solution?

NO, couplings due to kinetic mixing with photon: $\varepsilon^V_n = \varepsilon^V_\nu = 0\,, \quad \varepsilon^V_p = -\,\varepsilon^V_{ee}$

NA48/2 bound for $\pi^0 \to \gamma A'$ leads to $|\varepsilon^V_p| \lesssim 1.2 \times 10^{-3}$ ✗

"protophobic" scenarios are preferred

After the experiments: which new physics model ?



"YOU WANT PROOF? I'LL GIVE YOU PROOF!"

A "prototype" extension of the SM: $U(1)_{B-L}$

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
$Q = (u_L, d_L)^T$	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	$\frac{1}{3}$
$\ell = (\nu_L, e_L)^T$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	-1
u_R	$\mathbf{3}$	$\mathbf{1}$	$\frac{2}{3}$	$\frac{1}{3}$
d_R	$\mathbf{3}$	$\mathbf{1}$	$-\frac{1}{3}$	$\frac{1}{3}$
e_R	$\mathbf{1}$	$\mathbf{1}$	-1	-1
$h_{\rm SM}$	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	0
N_R	$\mathbf{1}$	$\mathbf{1}$	0	-1
$L_{L,R} = \left(L^0_{L,R}, L^-_{L,R}\right)^T$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	1
$E_{L,R}$	$\mathbf{1}$	$\mathbf{1}$	-1	1
h_X	$\mathbf{1}$	$\mathbf{1}$	0	2

New scalar singlet h_X: spontaneously breaks $U(1)_{B-L}$ below the EW scale giving a 17 MeV Z'

3 gen $\times$ N_R: cancel the triangular gauge anomalies

3 gen $\times$ (isodoublet + isosinglet) vector-like lepton: provides non-universality to new charged lepton NC

also plays an essential role in cancelling the NC interaction of neutrinos to Z'

A "prototype" extension of the SM: $U(1)_{B-L}$

Natural type-I seesaw mass

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

Field	$\text{SU}(3)_c$	$\text{SU}(2)_L$	$\text{U}(1)_Y$	$\text{U}(1)_{B-L}$
$Q = (u_L, d_L)^T$	**3**	**2**	$\frac{1}{6}$	$\frac{1}{3}$
$\ell = (\nu_L, e_L)^T$	**1**	**2**	$-\frac{1}{2}$	-1
u_R	**3**	**1**	$\frac{2}{3}$	$\frac{1}{3}$
d_R	**3**	**1**	$-\frac{1}{3}$	$\frac{1}{3}$
e_R	**1**	**1**	-1	-1
h_{SM}	**1**	**2**	$\frac{1}{2}$	0
N_R	**1**	**1**	0	-1
$L_{L,R} = \left(L^0_{L,R}, L^-_{L,R}\right)^T$	**1**	**2**	$-\frac{1}{2}$	1
$E_{L,R}$	**1**	**1**	-1	1
h_X	**1**	**1**	0	2

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

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

=> mass mixing between $U(1)_{B-L}$ 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):

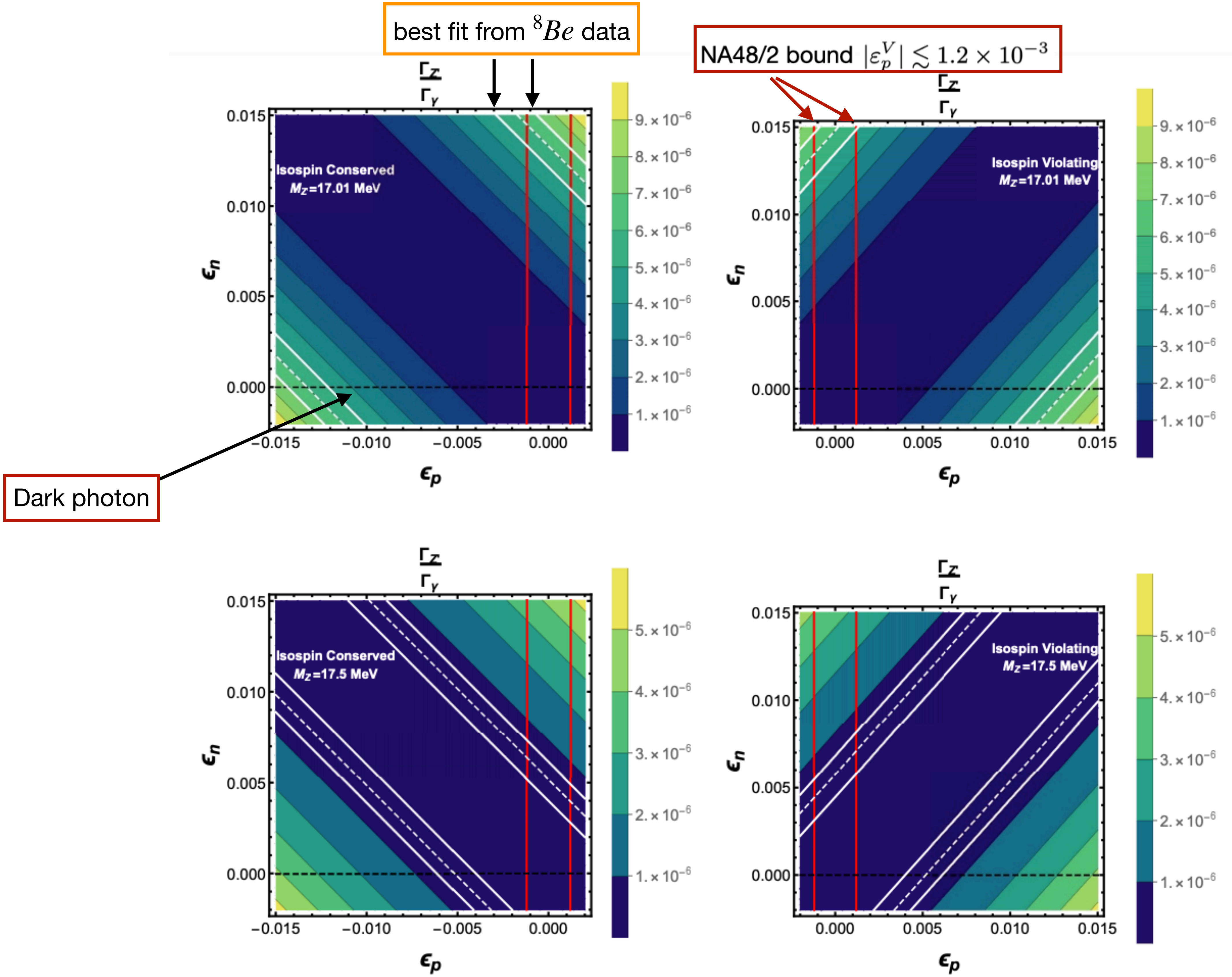
$$D_\mu \simeq \partial_\mu + \ldots + i\frac{g}{\cos\theta_w}(T_{3\,f} - \sin^2\theta_w Q_f)Z_\mu + ieQ_f A_\mu + ie(\varepsilon Q_f + \varepsilon_{B-L} Q_f^{B-L})Z'_\mu$$

with $\varepsilon = \frac{\epsilon_k \cos\theta_w}{\sqrt{1-\epsilon_k^2}}$ 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 too large ✗✗✗ more in a few slides

^{8}Be data and coupling to nucleons



$$2 \times 10^{-3} \lesssim |\varepsilon_n^V| \lesssim 15 \times 10^{-3}$$

$$|\varepsilon_p^V| \lesssim 1.2 \times 10^{-3}$$

CH, Kriewald, Orloff, Teixeira JHEP 2020

^8Be data and coupling to leptons

Direct searches: negative results @ electron beam dump NA64

negligible production

$$\varepsilon_{ee}^{V2} + \varepsilon_{ee}^{A2} < 1.1 \times 10^{-16}$$

or

decay inside the beam dump

$$\sqrt{|\varepsilon_{ee}^{V}|^2 + |\varepsilon_{ee}^{A}|^2} \gtrsim \frac{6.8\times10^{-4}}{\sqrt{\mathrm{BR}(Z' \to e^+ e^-)}}$$

Tight constraints from neutrino-electron scattering:

For LFU couplings and Dirac ν:

$$\sqrt{|\varepsilon_{ee}^{V}\varepsilon_{\nu_\ell\nu_\ell}^{V}|} < 7 \times 10^{-5}$$

Feng et al. PRD 2017

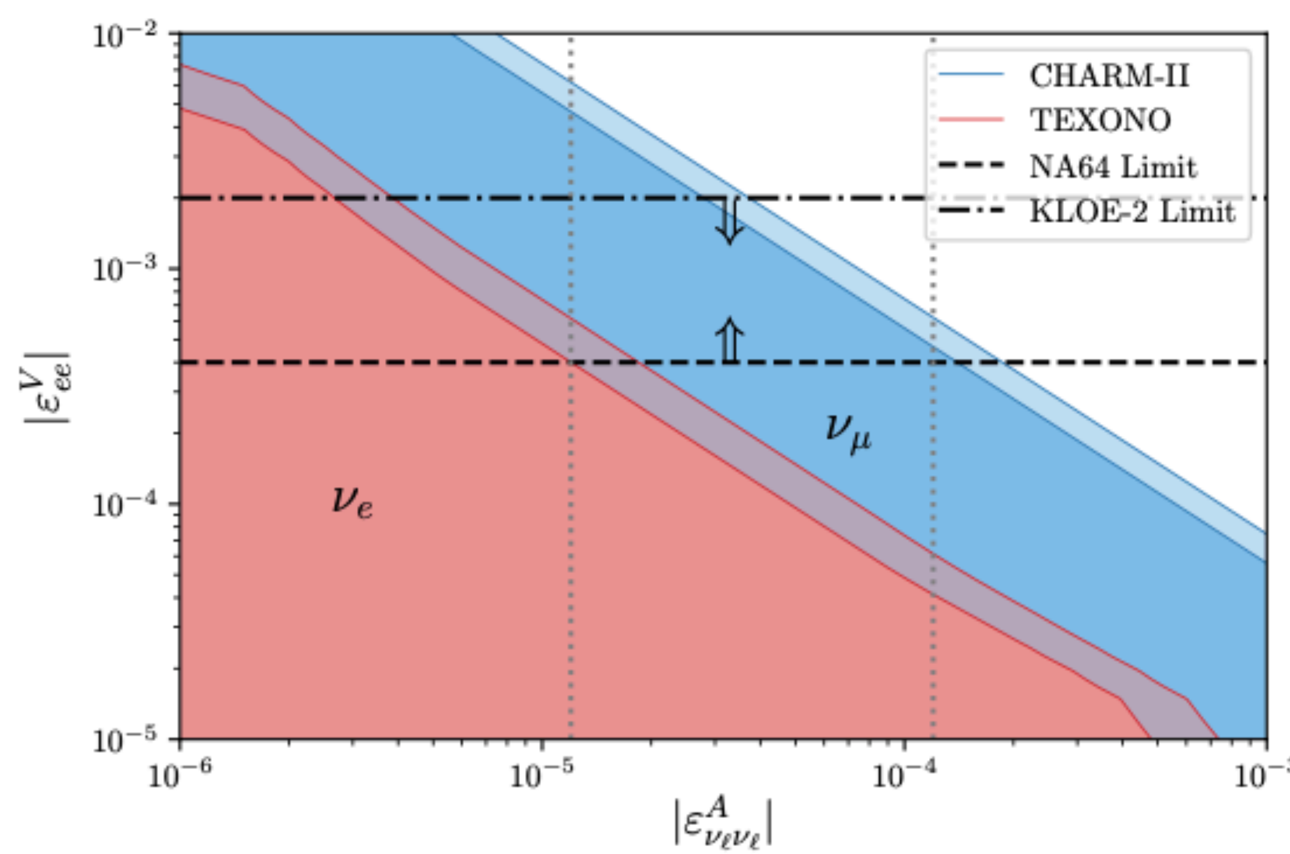
For Majorana ν the vector current is vanishing

requires new fit !

CHARM-II => $\nu_\mu - e$ scattering

TEXONO => $\nu_e - e$ scattering

$$|\varepsilon_{\nu_e\nu_e}^{A}| \lesssim 1.2 \times 10^{-5} \;\&$$
$$|\varepsilon_{\nu_\mu\nu_\mu}^{A}| \lesssim 12.2 \times 10^{-5}$$



But, we have seen that with SM fermion content $\varepsilon_{\nu\nu}^{A} = -\varepsilon_{n}^{V}$

CH, Kriewald, Orloff, Teixeira JHEP 2020

Isodoublet vector-like leptons

Solution: Add 3 gens. of vector-like lepton doublets

mass mixing of L^0 with ν_L can arrange cancellations to give an acceptably small $\epsilon^A_{\nu\nu}$

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

- 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 $\sim 100\,\text{GeV}$

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

$\Rightarrow$ $\lambda^2_{L\,\alpha} v_X^2 \simeq M^2_{L\,\alpha}$ is fixed for each lepton generation α !

But now the charged component of L mixes with left-handed SM charged leptons, but the right handed couplings remain unmodified

$$g^{\ell_\alpha \ell_\alpha}_{Z',\,L} \simeq -\varepsilon + \left(\frac{\lambda^2_{L\,\alpha} v_X^2}{M^2_{L\,\alpha}} - 1\right)\varepsilon_{B-L} \qquad \varepsilon^V_n = \varepsilon_{B-L}$$

in conflict with

Atomic parity violation in Caesium $|\varepsilon^A_{ee}| \lesssim 2.6 \times 10^{-9}$

Isosinglet vector-like leptons

Solution: Add 3 gens. of vector-like lepton isosinglets

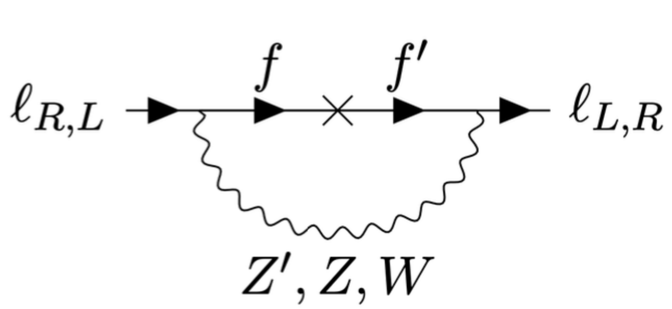
$$\mathcal{L}_{\text{Yuk.}} \supseteq - y_\ell^{ij} h_{\text{SM}} \bar{\ell}_L^i e_R^j + y_\nu^{ij} \tilde{h}_{\text{SM}} \bar{\ell}_L^i \boldsymbol{N_R^j} - \frac{1}{2} y_M^{ij} \boldsymbol{h_X} \boldsymbol{\bar{N}_R^{i\,c} N_R^j} - \boldsymbol{\lambda_L^{ij}} \boldsymbol{h_X} \bar{\ell}_L^i \boldsymbol{L^j}_{\boldsymbol{R}}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

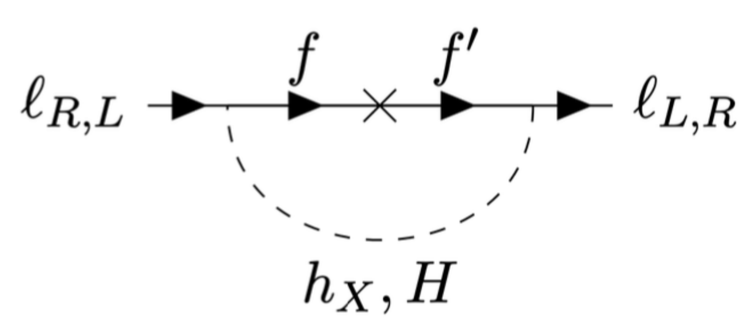
$$- \boldsymbol{\lambda_E^{ij}} \boldsymbol{h_X} \boldsymbol{\bar{E}^i}_{\boldsymbol{L}} e_R^j - \boldsymbol{M_E^{ij}} \boldsymbol{\bar{E}^i}_{\boldsymbol{L}} \boldsymbol{E^j}_{\boldsymbol{R}} - \boldsymbol{h^{ij}} h_{\text{SM}} \boldsymbol{\bar{L}^i}_{\boldsymbol{L}} \boldsymbol{E^j}_{\boldsymbol{R}} + \boldsymbol{k^{ij}} \tilde{h}_{\text{SM}} \boldsymbol{\bar{E}^i}_{\boldsymbol{L}} \boldsymbol{L^j}_{\boldsymbol{R}}$$

$\Rightarrow \varepsilon^A_{\ell_\alpha \ell_\alpha} \simeq \frac{1}{2} \left(\frac{\boldsymbol{\lambda^2_{E\,\alpha}} v_X^2}{\boldsymbol{M^2_{E\,\alpha}}} - \frac{\boldsymbol{\lambda^2_{L\,\alpha}} v_X^2}{\boldsymbol{M^2_{L\,\alpha}}} \right) \varepsilon_{B-L} \Rightarrow \boldsymbol{\lambda_{E\,\alpha}}$ is fixed for the 1. gen!

$\Rightarrow \varepsilon^V_{\ell_\alpha \ell_\alpha} \simeq -\varepsilon + \frac{1}{2} \left(\frac{\boldsymbol{\lambda^2_{L\,\alpha}} v_X^2}{\boldsymbol{M^2_{L\,\alpha}}} + \frac{\boldsymbol{\lambda^2_{E\,\alpha}} v_X^2}{\boldsymbol{M^2_{E\,\alpha}}} - 2 \right) \varepsilon_{B-L} \Rightarrow$ fixes $\varepsilon \simeq -(8 - 20) \times 10^{-4}$

$\Rightarrow$ 2 new Yuk. matrices $\boldsymbol{h^{ij}}$ and $\boldsymbol{k^{ij}}$ (assumed to be diagonal): if different, their asymmetry will generate axial and pseudo-scalar couplings in $\boldsymbol{Z'} - \ell \boldsymbol{L}$ and $\boldsymbol{h_X} - \ell \boldsymbol{L}$ interactions



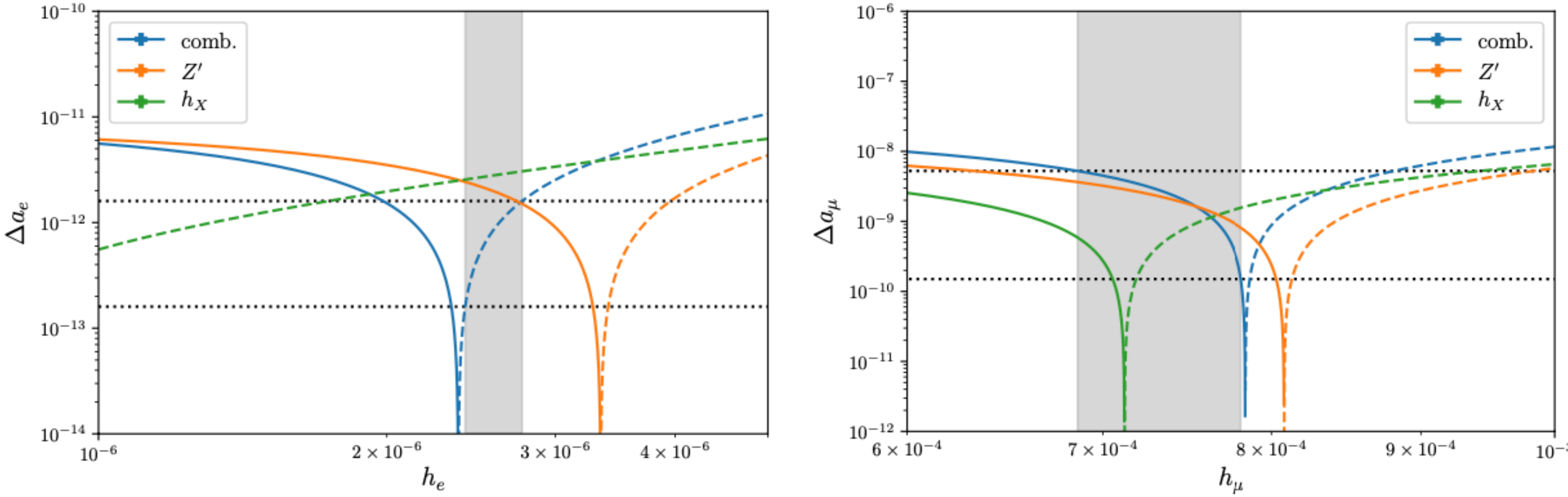


- Dominant contributions by $\boldsymbol{Z'}$ and $\boldsymbol{h_X}$
- Mass-insertion $\propto \boldsymbol{h_\alpha}$ and $\propto \boldsymbol{k_\alpha}$

- Loop-functions for scalar/pseudo-scalar and vector/axial couplings have opposite sign

Explaining $(g-2)_\mu$ and $(g-2)_e$ simultaneously

CH, Kriewald, Orloff, Teixeira JHEP 2020



- $\boldsymbol{M_E} = \boldsymbol{M_L} \simeq 90\,\text{GeV}$, $\boldsymbol{\lambda_L} = \boldsymbol{\lambda_E} = \boldsymbol{M_L}/v_X (\simeq 6.4)$, $m_{h_X} \simeq 70\,\text{GeV}$, $\varepsilon_{B-L} = 2\times10^{-3}$, $\varepsilon = -8\times10^{-4}$, $\boldsymbol{k_e} = \boldsymbol{k_\mu} = 10^{-7}$

Dashed lines: change of sign when pseudo-scalar contribution larger than scalar and/or axial larger than vector

Parameter space and predictability of the model

To explain ^8Be:

$$2\times10^{-3}\lesssim|\varepsilon_n^V|\lesssim 15\times10^{-3}\,,$$
$$|\varepsilon_p^V|\lesssim 1.2\times10^{-3}\,,$$
$$0.68\times10^{-3}\lesssim|\varepsilon_{ee}^V|\lesssim 2\times10^{-3}\,,$$
$$|\varepsilon_{ee}^A|\lesssim 2.6\times10^{-9}\,,$$
$$|\varepsilon_{\nu_e\nu_e}^A|\lesssim 7.8\times10^{-6}\,,$$
$$|\varepsilon_{\nu_\mu\nu_\mu}^A|\lesssim 8.4\times10^{-5}\,.$$

$$v_X\lesssim 14\ \mathrm{GeV} \qquad m_{Z'}\approx m_{B'}=2\,e\,|\varepsilon_{B-L}|\,v_X$$

$$\varepsilon_{B-L}=0.002 \qquad |\varepsilon_n^V|=|\varepsilon_{B-L}|$$

$$-0.002\lesssim\varepsilon\lesssim-0.0008 \qquad |\varepsilon_p^V|=|\varepsilon+\varepsilon_{B-L}|$$

$$\left|1-\frac{\lambda_L^2 v_X^2}{M_L^2}\right|\lesssim 0.01 \qquad \left|\frac{\lambda_E^2\,v_X^2}{M_E^2}-\frac{\lambda_L^2\,v_X^2}{M_L^2}\right|\lesssim 2.6\times10^{-6}$$

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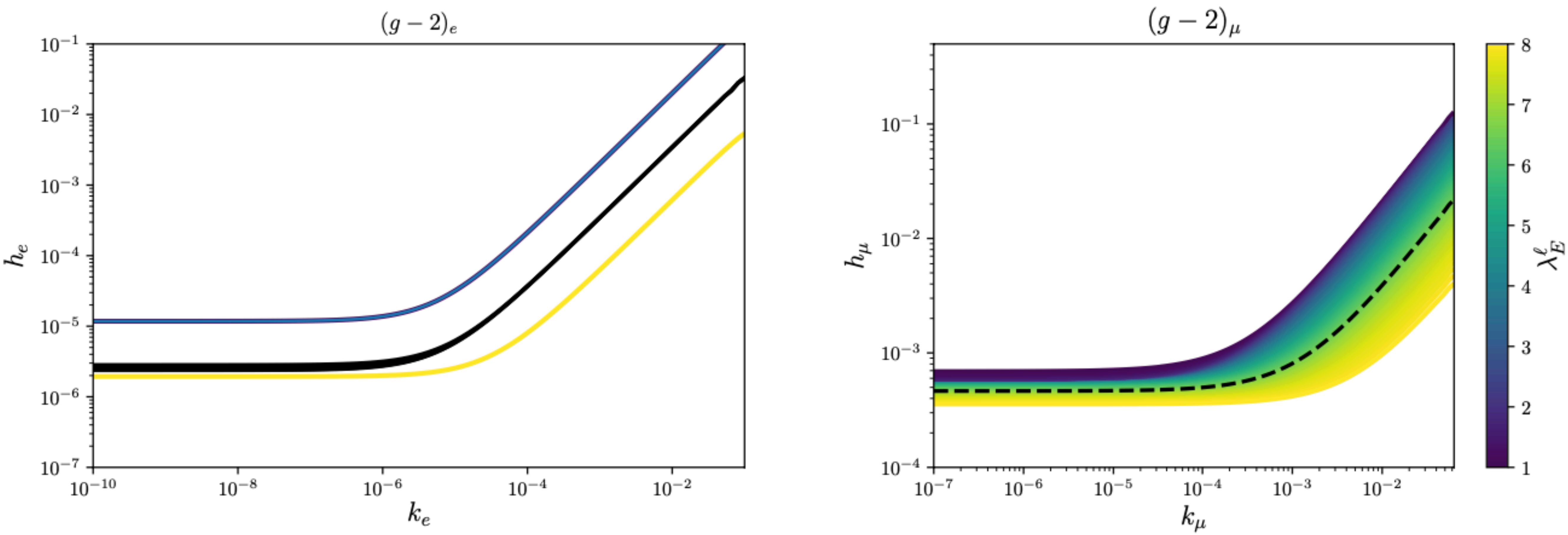


- Black line: $(g-2)_e$ explained ✓ coloured region: $(g-2)_\mu$ explained ✓✓

Concluding remarks

Currently many “tensions” with SM hosted in lepton-related observables

We have discussed three of such tensions in detail in the context of a simple prototype $U(1)_{B-L}$ extension

Light vector candidates to explain ^{8}Be is an exciting new physics possibility

Potential to address the lepton anomalous magnetic moments in simple NP extensions

Constrained parameter space: experimental bounds, ^{8}Be & $\Delta a_\mu \Rightarrow$ “predict” Δa_e

Exciting near-future @ “experimental” front!

FNAL update on $(g-2)_\mu$ expected soon!

NA64 is getting ready to hunt down the X17 boson at the CERN SPS 2009.02756

Thank you for your attention!

Backup-I

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

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

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

Backup-II

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

$$M_\ell^{\text{diag}} = U_L^\dagger M_\ell U_R$$

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

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

Backup-III

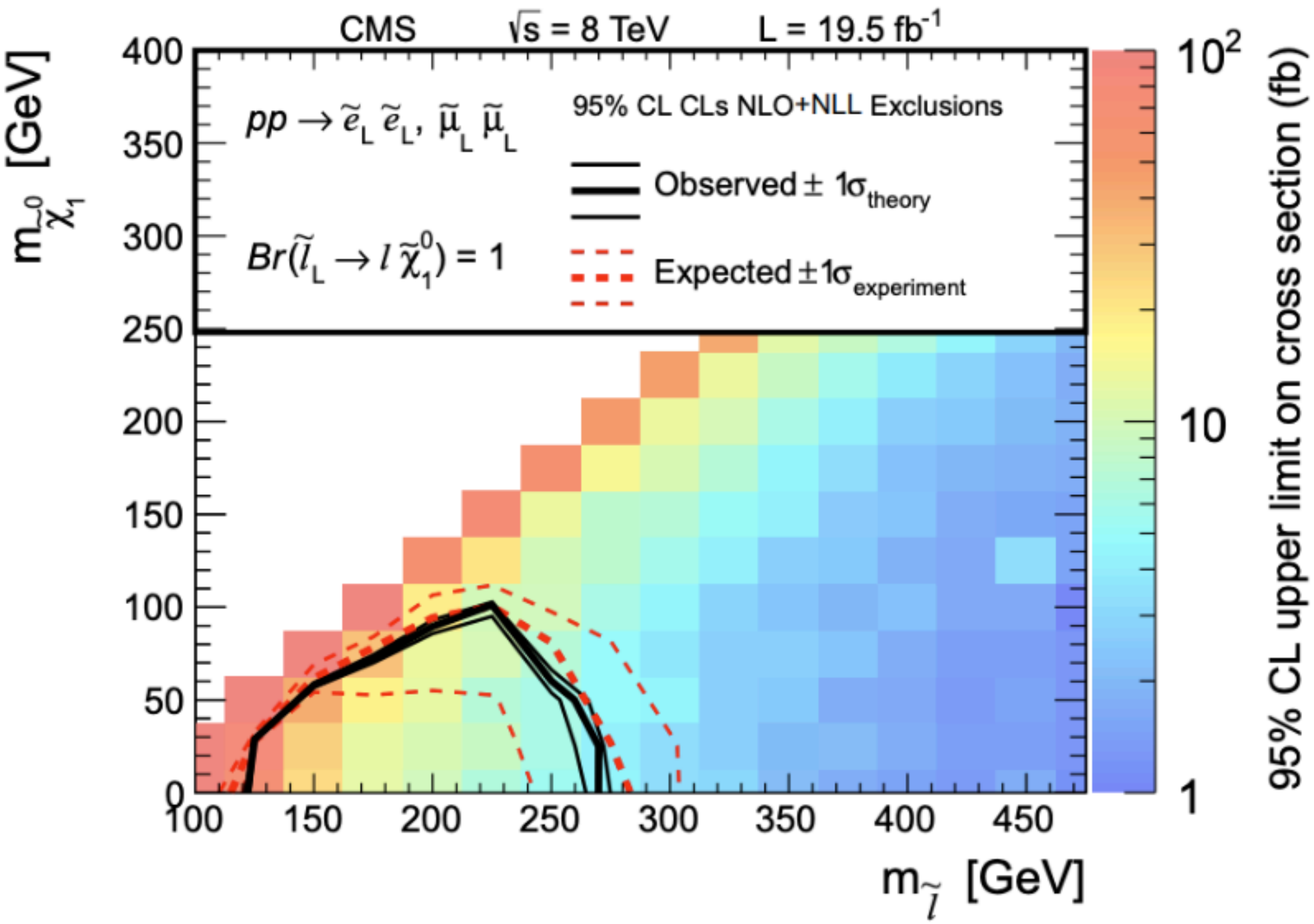
$$\mathcal{L}^{\nu}_{\rm mass} = \left(\nu^T \; N^{c\,T} \; L^{0\,T} \; L^{0\,c\,T}\right)_L C^{-1} \cdot M_\nu \cdot \begin{pmatrix} \nu \\ N^c \\ L^0 \\ L^{0\,c} \end{pmatrix}_L$$

$$= \left(\nu^T \; N^{c\,T} \; L^{0\,T} \; L^{0\,c\,T}\right)_L C^{-1} \begin{pmatrix} 0 & y_\nu \frac{v}{\sqrt{2}} & 0 & \lambda_L \frac{v_X}{\sqrt{2}} \\ y_\nu \frac{v}{\sqrt{2}} & y_M \frac{v_X}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & 0 & M_L \\ \lambda_L \frac{v_X}{\sqrt{2}} & 0 & M_L & 0 \end{pmatrix} \begin{pmatrix} \nu \\ N^c \\ L^0 \\ L^{0c} \end{pmatrix}_L$$

$$M_\nu^{\rm diag} = \tilde{U}_\nu^T \, M_\nu \, \tilde{U}_\nu \,,$$

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

Backup-IV



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