Exploring the Neutrino-Dark Matter Connection

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in collaboration with Pavel Fileviez Perez and Alexis Plascencia
CWRU, Cleveland, OH, USA

Planck 2019, 3-7 June 2019

References

This talk is based on:

- P. Fileviez Perez and C. M., Dark Matter and The Seesaw Scale, Phys. Rev. D **98** (2018) no.5, 055008 arXiv:1803.07462 [hep-ph],
- P. Fileviez Perez, A. D. Plascencia and C. M. Neutrino-Dark Matter Connections in Gauge Theories, arXiv:1905.06344 [hep-ph].

Introduction

- The Standard Model rocks as an EFT at low energies.
- However, clear evidence calling for new physics beyond:

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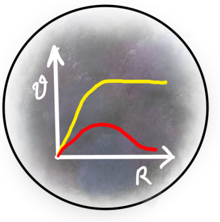

Introduction

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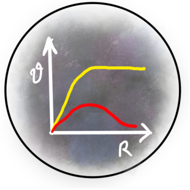
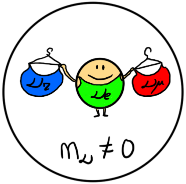
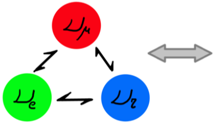
- However, clear evidence calling for new physics beyond:





Neutrino masses

-  $M_\nu \neq 0$ $\leftrightarrow$ $3\,\nu_R$

- We do not have any clue about their nature!

LN Conserved

- Neutrinos are **Dirac**

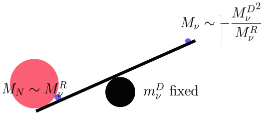
$$\mathcal{L}_\nu^D \supset Y_\nu \bar{\ell}_L \tilde{H} \nu_R + \text{h.c.}$$

$$m_\nu \leq 0.1 \text{ eV} \Rightarrow Y_\nu \leq 10^{-12}$$

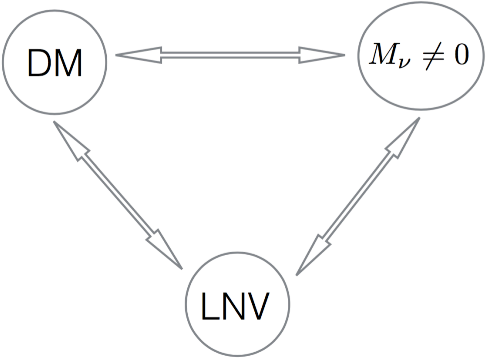
LN Violated

- Neutrinos might be **Majorana**

$$\mathcal{L}_\nu^M \supset Y_\nu \bar{\ell}_L \tilde{H} \nu_R + \frac{1}{2} \nu_R^T C M_R \nu_R + \text{ h.c.}$$



Aim



The Simplest Theories for Neutrino Masses

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Extra symmetries:

$U(1)_{B-L}$, $U(1)_B$, $U(1)_L$ global

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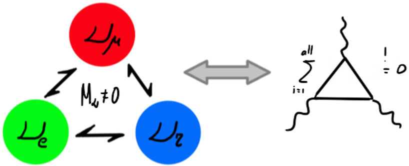
- Connection:



The Simplest Theories for Neutrino Masses

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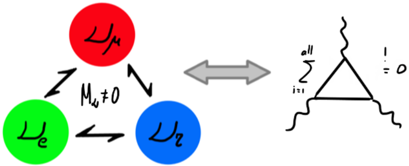


- Dark Matter candidate: $\chi_L, \chi_R \sim (1,1,0,n_\chi) \to \chi = \chi_L + \chi_R$

Gauging $U(1)_{B-L}$

and leaving it unbroken

$U(1)_{B-L}$ unbroken

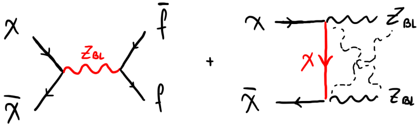
Interaction with Z_{BL} Dirac mass term

$$\mathcal{L}_{U(1)_{B-L}} \supset \underline{i\bar{\chi}_L \not{D}\chi_L + i\bar{\chi}_R \not{D}\chi_R} - (Y_\nu \bar{\ell}_L i\sigma_2 H^* \nu_R + \underline{M_\chi \bar{\chi}_L \chi_R} + \text{h.c.})$$
$$-\frac{1}{2}\underbrace{(M_{Z_{BL}} Z^\mu_{BL} + \partial^\mu \sigma)(M_{Z_{BL}} Z_{BL\mu} + \partial_\mu \sigma)}_{\text{Stuckelberg mechanism}}$$

↳ mass term allowed!

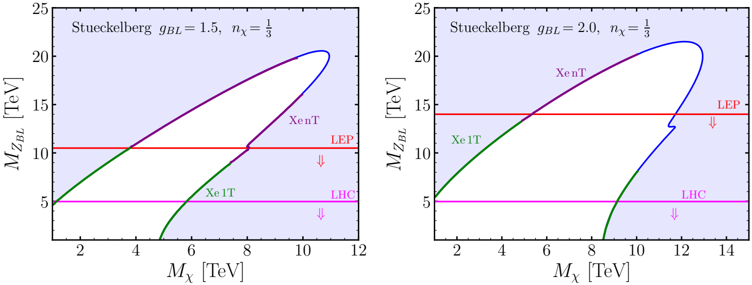
- Relevant parameters: $\boxed{M_\chi, \;\; M_{Z_{BL}}, \;\; g_{BL}, \;\; n_\chi}$ $\quad (n_\chi \neq 1)$

- Annihilation channels:



$U(1)_{\text{B-L}}$ unbroken

- Parameter space allowed by the correct relic abundance:



$\Omega h^2 > 0.12$ $\Omega h^2 < 0.12$ $\Omega h^2 = 0.12$

Light Relics

- $\Delta N_{\rm eff} = N_{\rm eff} - N_{\rm eff}^{\rm SM} = N_{\nu_R}\left(\frac{T_{\nu_R}}{T_{\nu_L}}\right)^4 = N_{\nu_R}\left(\frac{g(T_{\nu_L}^{\rm dec})}{g(T_{\nu_R}^{\rm dec})}\right)^{\frac{4}{3}}$

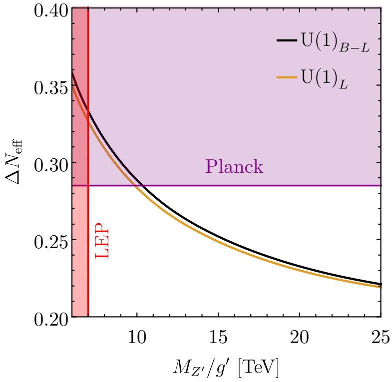
- Decoupling temperature:

$$\Gamma(T_{\nu_R}^{\rm dec}) = H(T_{\nu_R}^{\rm dec})$$

- Bounds from Planck:

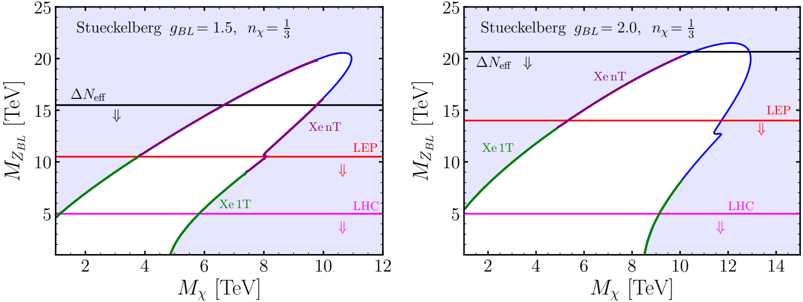
$$\begin{aligned} N_{\rm eff} &= 2.99^{+0.34}_{-0.33} \\ &\Rightarrow \Delta N_{\rm eff} < 0.285 \end{aligned}$$

- $\Rightarrow \frac{M_{Z_{BL}}}{g_{BL}} > 10.33$ TeV

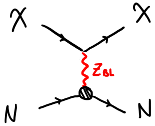


- Projected bounds from CMB-S4: $\Delta N_{\rm eff} \leq 0.06$ at 95 CL!!

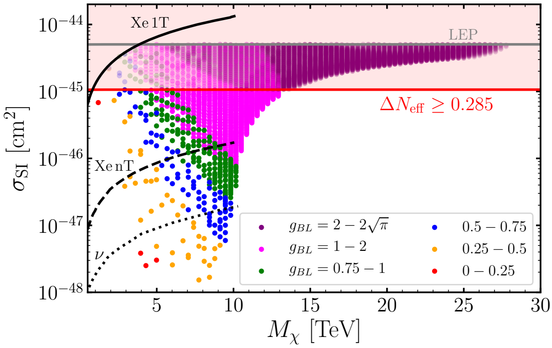
$U(1)_{\text{B-L}}$ unbroken



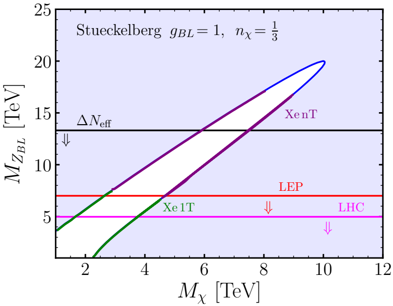
Direct Detection

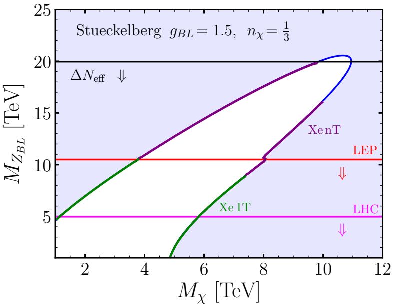


$$\sigma_{\rm SI} = \frac{M_N^2 M_{\rm DM}^2}{\pi (M_N + M_{\rm DM})^2} \frac{n^2 g_{BL}^4}{M_{Z_{BL}}^4},$$

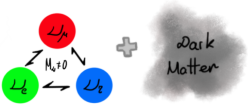


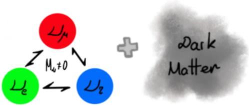
$U(1)_{\text{B-L}}$ unbroken





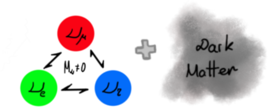
- Upper bound around 20 TeV!


Dark Matter



$\mathcal{U}(1)_{B-L}$ } ν Dirac $m_\nu \leq 0.1$ eV

Very strong bounds from N_{eff} ⇒ CMB-S4 will probe these theories!



$\Rightarrow \Lambda_{LN} \lesssim \mathcal{O}(10)\,\text{TeV}$

$U(1)_{B-L}$ } ν Dirac $\quad m_\nu \lesssim 0.1$ eV

Very strong bounds from N_{eff} $\Rightarrow$ CMB-S4 will probe these theories!

Gauging $U(1)_{B-L}$

and breaking it by 2 units

$U(1)_{\text{B-L}}$ broken by 2 units

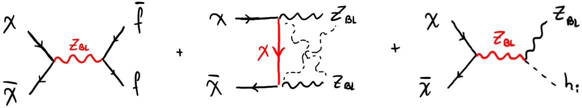
SSB $\quad S_{BL} \sim (1,0,0,2)$

$$\mathcal{L}_{U(1)_{\text{B-L}}} \supset i\bar{\chi}_L \not{D} \chi_L + i\bar{\chi}_R \not{D} \chi_R + (D_\mu S_{BL})^\dagger (D^\mu S_{BL})$$
$$-(Y_\nu \bar{\ell}_L i\sigma_2 H^* \nu_R + M_\chi \bar{\chi}_L \chi_R + y_R \nu_R^T C \nu_R S_{BL} + \text{h.c.})$$

Majorana mass term

- Relevant parameters: $\boxed{M_\chi,\ M_{Z_{BL}},\ g_{BL},\ n_\chi,\ M_N,\ M_{h_2},\ \theta_{BL}}$
  $(n_\chi \neq 1, 3)$

- Annihilation channels:



$U(1)_{B-L}$ broken by 2 units

$$\mathcal{L}_{U(1)_{\text{B-L}}} \supset i\bar{\chi}_L \not{D}\chi_L + i\bar{\chi}_R \not{D}\chi_R + (D_\mu S_{BL})^\dagger (D^\mu S_{BL}) \\ -(Y_\nu \bar{\ell}_L i\sigma_2 H^* \nu_R + M_\chi \bar{\chi}_L \chi_R + y_R \nu_R^T C \nu_R S_{BL} + \text{h.c.})$$

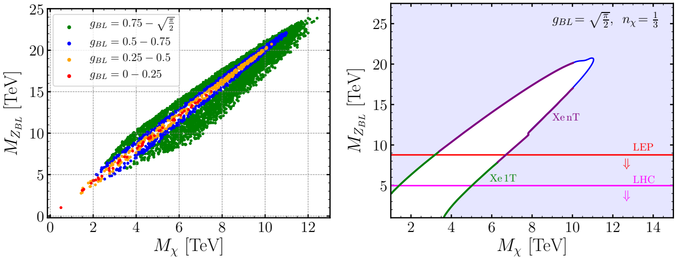
- Relevant parameters: $\boxed{M_\chi,\ \ M_{Z_{BL}},\ \ g_{BL},\ \ n_\chi,\ \ M_{h_2},\ \ \theta_{BL}}$
  $(n_\chi \neq 1, 3)$

- Perturbativity sets an upper bound on g_{BL}:

$$\mathcal{L} \supset g_{BL}^2 (2)^2 S_{BL}^\dagger S_{BL} Z_{BL\mu} Z_{BL}^\mu \Rightarrow g_{BL} \leq \sqrt{\frac{\pi}{2}}$$

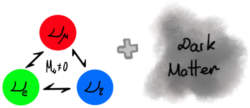
$U(1)_{B-L}$ broken by 2 units

- For $n_\chi = 1/3$, $\theta_{BL} = 0$, $M_{h_2} = M_N = 1$ TeV:



$\Omega h^2 > 0.12$ $\Omega h^2 < 0.12$ $\Omega h^2 = 0.12$

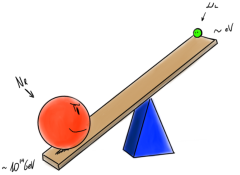
- Upper bound around 20 TeV!

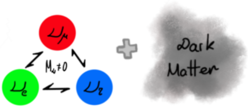


$U(1)_{B-L}$ } ν Dirac $m_\nu \leq 0.1$ eV

Very strong bounds from N_{eff} $\Rightarrow$ CMB-S4 will probe these theories!

$U(\cancel{1})_{B-L}$ ($\Delta B\text{-}L = 2$) } ν Majorana





$$\Lambda_{LN} \lesssim \mathcal{O}(10)\,\text{TeV}$$

$U(1)_{B-L}$ } ν Dirac $\quad m_\nu \lesssim 0.1$ eV

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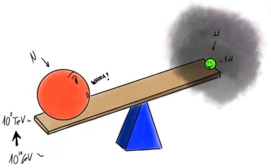

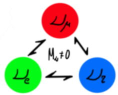

+ Dark Matter ⇒ $\Lambda_{LN} \lesssim \mathcal{O}(10)$ TeV

$U(1)_{B-L}$ } ν Dirac $m_\nu \lesssim 0.1$ eV

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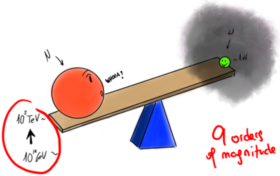
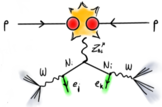


9 orders of magnitude!

LNV signals @ LHC

Displaced vertices



The Simplest Theories for Neutrino Masses

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Extra symmetries:

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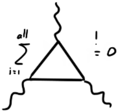
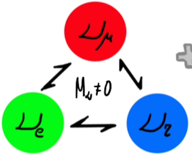
- Connection:





Gauging $U(1)_L$

and breaking it by 3 units

$U(1)_L$ broken by 3 units

SSB $S_L \sim (1,0,0,3)$ χ gets mass from SSB!

$$\mathcal{L}_{U(1)_L} \supset \quad i\bar{\chi}_L \not{D} \chi_L + (D_\mu S_L)^\dagger (D^\mu S_L) - \left(\frac{\lambda_\chi}{\sqrt{2}} \chi_L^T C \chi_L S_L + \text{h.c.} \right)$$

$$\xrightarrow{\text{After SSB}} \frac{3}{2} g_L \bar{\chi} \gamma_\mu \gamma^5 \chi Z_L^\mu - g_L \bar{f} \gamma_\mu f Z_L^\mu - \lambda_i \bar{\chi} \chi h_i - \frac{1}{2} M_\chi \chi^T C \chi$$

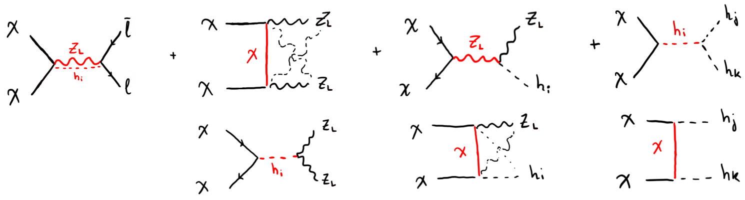
P. Fileviez Perez and M. B. Wise, JHEP **1108** (2011) 068.

M. Duerr, P. Fileviez Perez and M. B. Wise, Phys. Rev. Lett. **110** (2013) 231801

P. Fileviez Perez, S. Ohmer and H. H. Patel, Phys. Lett. B **735** (2014) 283

- Relevant parameters: $\boxed{M_\chi, \quad M_{Z_L}, \quad g_L, \quad M_{h_2}, \quad \theta_L}$

- Annihilation channels:



$U(1)_L$ broken by 3 units

$$\mathcal{L}_{U(1)_L} \frac{3}{2} g_L \bar{\chi}\gamma_\mu \gamma^5 \chi Z_L^\mu - g_L \bar{f}\gamma_\mu f Z_L^\mu - \lambda_i \bar{\chi}\chi h_i - \frac{1}{2} M_\chi \chi^T C \chi$$

- Relevant parameters: $\boxed{M_\chi, \;\; M_{Z_L}, \;\; g_L, \;\; M_{h_2}, \;\; \theta_L}$

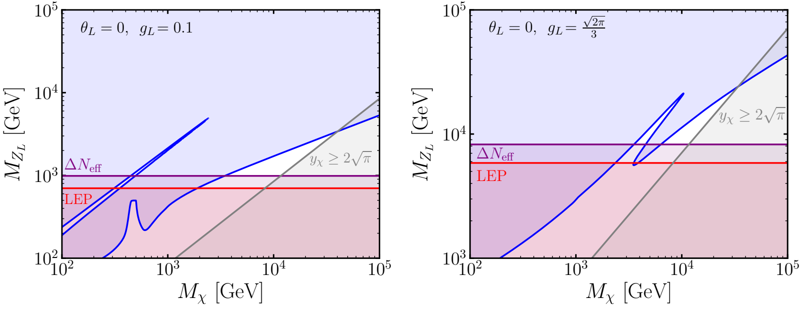
- Perturbativity sets an upper bound on g_L:

$$\mathcal{L} \supset g_L^2 (3)^2 S_L^\dagger S_L Z_{L\mu} Z_L^\mu \Rightarrow g_L \leq \frac{\sqrt{2\pi}}{3}$$

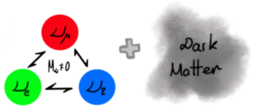
...and also on the λ_χ:

$$\lambda_\chi \leq 2\sqrt{\pi} \quad \Rightarrow \quad 3 g_L \frac{M_\chi}{M_{Z_L}} \leq 2\sqrt{\pi}$$

$U(1)_L$ broken by 3 units



Upper bound $\sim$ [1 TeV, 10 TeV]



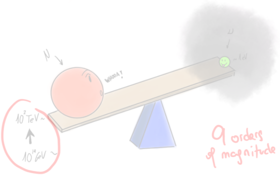
$\Rightarrow \Lambda_{LN} \lesssim \mathcal{O}(10)\,\mathrm{TeV}$

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

$\cancel{U(1)}_L$ $\Delta L = 3$ $\Big\}$ ν Dirac $\quad m_\nu \lesssim 0.1$ eV

Very strong bounds from N_{eff} $\Rightarrow$ CMB-S4 will probe these theories!

$\cancel{U(1)}_{B-L}$ $\Delta B\text{-}L = 2$ $\}$ ν Majorana $\rightarrow$ predicts DM ???



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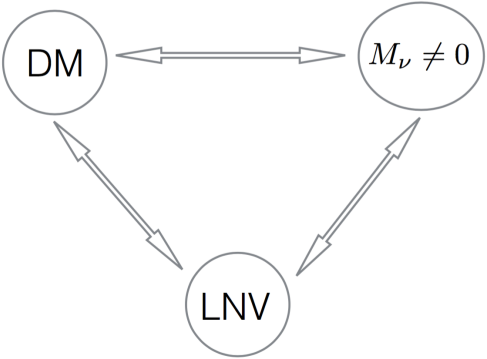
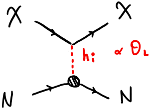

DM
$M_\nu \neq 0$
LNV

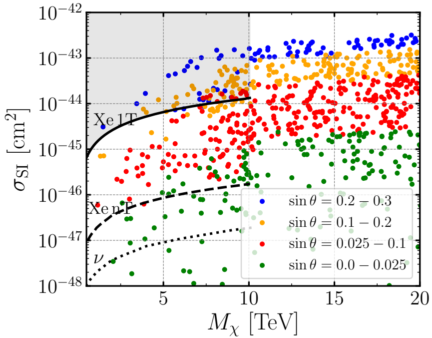
Thanks for your attention!

Back up slides

$U(1)_L$ broken by 3 units



$$\sigma^{\rm SI}_{\chi N}(h_i) = \frac{72 G_F}{\sqrt{2} 4\pi} \sin^2\theta_B \cos^2\theta_B M_N^4 \frac{g_L^2 M_\chi^2}{M_{Z_L}^2} \left(\frac{1}{M_{h_1}^2} - \frac{1}{M_{h_2}^2} \right)^2 f_N^2$$



$U(1)_L$ theories

Fermionic representations in the model proposed in Ref. 1403.8029:

Fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_L$
$\Psi_L = \begin{pmatrix} \Psi_L^+ \\ \Psi_L^0 \end{pmatrix}$	1	2	$\frac{1}{2}$	$\frac{3}{2}$
$\Psi_R = \begin{pmatrix} \Psi_R^+ \\ \Psi_R^0 \end{pmatrix}$	1	2	$\frac{1}{2}$	$-\frac{3}{2}$
$\Sigma_L = \frac{1}{\sqrt{2}} \begin{pmatrix} \Sigma_L^0 & \sqrt{2}\Sigma_L^+ \\ \sqrt{2}\Sigma_L^- & -\Sigma_L^0 \end{pmatrix}$	1	3	0	$-\frac{3}{2}$
χ_L^0	1	1	0	$-\frac{3}{2}$

$U(1)_L$ theories

Fermionic representations in the model proposed in Ref. 1304.0576:

Fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_L$
$\Psi_L = \begin{pmatrix} \Psi_L^0 \\ \Psi_L^- \end{pmatrix}$	1	2	$-\frac{1}{2}$	$-\frac{3}{2}$
$\Psi_R = \begin{pmatrix} \Psi_R^0 \\ \Psi_R^- \end{pmatrix}$	1	2	$-\frac{1}{2}$	$\frac{3}{2}$
η_R^-	1	1	-1	$-\frac{3}{2}$
η_L^-	1	1	-1	$\frac{3}{2}$
χ_R^0	1	1	0	$-\frac{3}{2}$
χ_L^0	1	1	0	$\frac{3}{2}$

Upper bound $U(1)_{BL}$

$$\sigma(\bar{\chi}\chi \to \bar{f}f) \quad \propto \quad \frac{g_{BL}^4 n^2}{\Gamma_{Z_{BL}}^2} \underbrace{\rightarrow}_{\Gamma_{Z_{BL}}^2 \sim g_{BL}^4 \Lambda^2} n^2 \frac{1}{\Lambda^2}$$

$$\sigma(\bar{\chi}\chi \to Z_{BL} Z_{BL}) \quad \propto \quad g_{BL}^4 n^4 \frac{1}{\Lambda^2}$$

Upper bound $U(1)_{BL}$

$$\sigma(\bar{\chi}\chi \to \bar{f}f) \quad \propto \quad n^2 \frac{1}{\Lambda^2}$$

$$\sigma(\bar{\chi}\chi \to Z_{BL}Z_{BL}) \quad \propto \quad g_{BL}^4 n^4 \frac{1}{\Lambda^2}$$

$$\boxed{n < 1}$$

$$(\mathcal{L}_K \supset g_{BL}\bar{\ell}\gamma_\mu Z^\mu_{BL}\ell)$$

Perturbative bound $\Rightarrow g_{BL} < \sqrt{2\pi}$

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$(\mathcal{L}_K \supset g_{BL}\bar{\ell}\gamma_\mu Z_{BL}^\mu \ell)$

Perturbative bound $\Rightarrow g_{BL} < \sqrt{2\pi}$

$\boxed{n > 1}$

$(\mathcal{L}_K \supset n\, g_{BL}\, \bar{\chi}\gamma_\mu Z_{BL}^\mu \chi)$

Perturbative bound $\Rightarrow n\, g_{BL} < \sqrt{2\pi}$

Upper bound $U(1)_{BL}$

$$\sigma(\bar{\chi}\chi \to \bar{f}f) \quad \propto \quad n^2 \frac{1}{\Lambda^2}$$
$$\sigma(\bar{\chi}\chi \to Z_{BL}Z_{BL}) \quad \propto \quad \tilde{\mathbf{n}}^4 \frac{1}{\Lambda^2}$$

$\boxed{n < 1}$

$(\mathcal{L}_K \supset g_{BL}\bar{\ell}\gamma_\mu Z^\mu_{BL}\ell)$

Perturbative bound $\Rightarrow g_{BL} < \sqrt{2\pi}$

$\boxed{n > 1}$

$(\mathcal{L}_K \supset n\, g_{BL}\, \bar{\chi}\gamma_\mu Z^\mu_{BL}\chi)$

Perturbative bound $\Rightarrow \underbrace{n\, g_{BL}}_{\tilde{\mathbf{n}}} < \sqrt{2\pi}$

Upper bound $U(1)_{BL}$

$$\sigma(\bar{\chi}\chi \to \bar{f}f) \propto n^2 \frac{1}{\Lambda^2}$$
$$\sigma(\bar{\chi}\chi \to Z_{BL}Z_{BL}) \propto \tilde{\mathbf{n}}^4 \frac{1}{\Lambda^2}$$

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$(\mathcal{L}_K \supset g_{BL}\bar{\ell}\gamma_\mu Z^\mu_{BL}\ell)$

Perturbative bound $\Rightarrow g_{BL} < \sqrt{2\pi}$

$\boxed{n > 1}$

$(\mathcal{L}_K \supset n\, g_{BL}\, \bar{\chi}\gamma_\mu Z^\mu_{BL}\chi)$

Perturbative bound $\Rightarrow \underbrace{n\, g_{BL}}_{\tilde{\mathbf{n}}} < \sqrt{2\pi}$

What if $n \to \infty$?!

Upper bound $U(1)_{BL}$

In the hypothetical (non "pheno-interesting") case of $n \to \infty$:

$$\sigma(\bar{\chi}\chi \to \bar{f}f) \quad \propto \quad \frac{g_{BL}^4 n^2}{\Gamma_{Z_{BL}}^2}$$

$$\sigma(\bar{\chi}\chi \to Z_{BL}Z_{BL}) \quad \propto \quad \tilde{\mathbf{n}}^4 \frac{1}{\Lambda^2}$$

! $(\Gamma_{Z_{BL}}^{\text{tot}})^2 \sim \Gamma^2(Z_{BL} \to \bar{\chi}\chi) \propto g_{BL}^4 n^2 \Lambda^2$

Upper bound

In the hypothetical (non ”pheno-interesting”) case of $n \to \infty$:

$$\sigma(\bar{\chi}\chi \to \bar{f}f) \quad \propto \quad \frac{g_{BL}^4 n^2}{\Gamma_{Z_{BL}}^2} \to \frac{1}{\Lambda^2}$$

$$\sigma(\bar{\chi}\chi \to Z_{BL} Z_{BL}) \quad \propto \quad \tilde{\mathbf{n}}^4 \frac{1}{\Lambda^2}$$

❗ $(\Gamma_{Z_{BL}}^{\text{tot}})^2 \sim \Gamma^2(Z_{BL} \to \bar{\chi}\chi) \propto g_{BL}^4 n^2 \Lambda^2$

😍😍😍😍

Upper bound

In the hypothetical (non "pheno-interesting") case of $n \to \infty$:

$$
\begin{aligned}
\color{red}{\sigma(\bar{\chi}\chi \to \bar{f}f)} &\propto \frac{g_{BL}^4 n^2}{\Gamma_{Z_{BL}}^2} \to \frac{1}{\Lambda^2} \\
\sigma(\bar{\chi}\chi \to Z_{BL} Z_{BL}) &\propto \tilde{\mathbf{n}}^4 \frac{1}{\Lambda^2}
\end{aligned}
$$

❗ $(\Gamma_{Z_{BL}}^{\text{tot}})^2 \sim \Gamma^2(Z_{BL} \to \bar{\chi}\chi) \propto g_{BL}^4 n^2 \Lambda^2$

😍😍😍😍

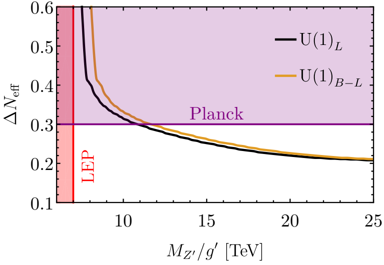
$N_{\rm eff}$

$$\Gamma_i(T) = n_{\nu_R}(T)\langle\sigma(\bar{\nu}_R\nu_R \to \text{SM SM})v\rangle$$

$$= \frac{g_{\nu_R}}{8\pi^4 n_{\nu_R}}\int_0^\infty p^2 dp \int_0^\infty k^2 dk \int_{-1}^{1} d\cos\theta \frac{1-\cos\theta}{(e^{k/T}+1)(e^{p/T}+1)}\sigma_i(s)$$

In the limit $s \ll M_{Z_L}$,

$$\Gamma_N(T) = \frac{49\pi^5 T^5}{194400\xi(3)}\left(\frac{g'}{M_{Z'}}\right)^4 \sum_f n_f^2.$$



New Higgs stuff

$$V(H, S_{new}) = -\mu_H^2 H^\dagger H - \mu_{new}^2 S_{new}^\dagger S_{new} + \lambda_H (H^\dagger H)^2 \\ + \lambda_{new} (S_{new}^\dagger S_{new})^2 + \lambda_{Hnew} (H^\dagger H)(S_{new}^\dagger S_{new}),$$

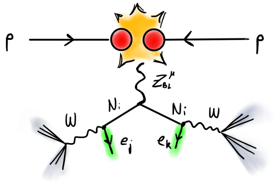
$$S_{new} = \frac{1}{\sqrt{2}} (s_{new} + v_{new}), \qquad H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ h + v_H \end{pmatrix},$$

$$h_1 = h \cos\theta_{new} - s_{new} \sin\theta_{new}, \\ h_2 = s_{new} \cos\theta_{new} + h \sin\theta_{new},$$

$$\tan 2\theta_{new} = \frac{\lambda_{Hnew}\, v_H v_{new}}{\lambda_{BL} v_{new}^2 - \lambda_H v_H^2}.$$

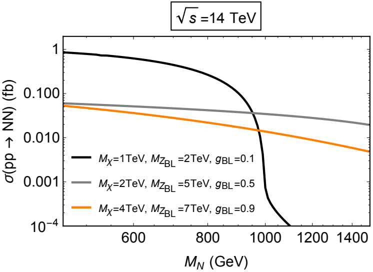
$$M_{Z_{new}} = n_{new} g_{new} v_{new}, \qquad (M_N = \sqrt{2}\, y_R v_{BL})$$

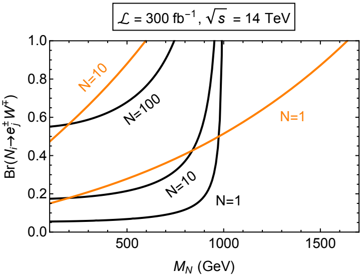
Lepton Number Violation at the LHC



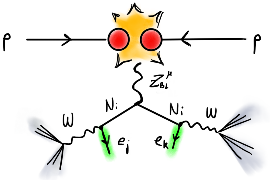
$$pp \to Z^*_{BL} \to N_i N_i \to e^{\pm}_j W^{\mp} e^{\pm}_k W^{\mp} \to e^{\pm}_j e^{\pm}_k 4j$$

$$N_{e^{\pm}_j e^{\pm}_k 4j} = 2\mathcal{L}\sigma(pp \to N_i N_i)\mathrm{Br}(N_i \to e^{\pm}_j W^{\mp})\mathrm{Br}(N_i \to e^{\pm}_k W^{\mp})\mathrm{Br}(W \to jj)^2$$



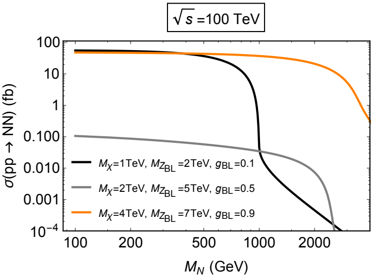


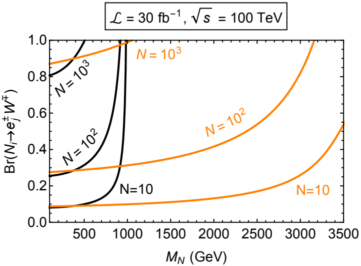
Lepton Number Violation at future colliders



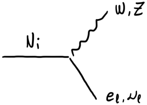
$$pp \to Z^*_{BL} \to N_i N_i \to e_j^{\pm} W^{\mp} e_k^{\pm} W^{\mp} \to e_j^{\pm} e_k^{\pm} 4j$$

$$N_{e_j^{\pm} e_k^{\pm} 4j} = 2\mathcal{L}\sigma(pp \to N_i N_i)\mathrm{Br}(N_i \to e_j^{\pm} W^{\mp})\mathrm{Br}(N_i \to e_k^{\pm} W^{\mp})\mathrm{Br}(W \to jj)^2$$





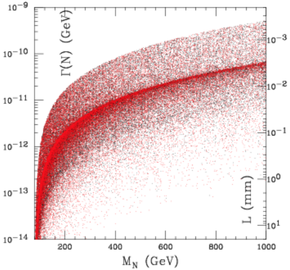
Displaced vertices

- Total decay width of N: 

$\Gamma_N^{\text{tot}} \sim |V_{\ell i}|^2 \frac{M_{N_i}^3}{M_W^2}$

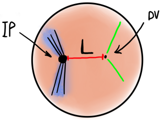
- Neutrino mixing: $|V_{\ell i}|^2 \propto M_\nu / M_{N_R}$, $\quad M_{\nu N} = \begin{pmatrix} 0 & M_\nu \\ M_\nu & M_{N_R} \end{pmatrix}$

- $\Gamma_{N_R} \propto \frac{M_\nu M_N^2}{M_W} \sim \frac{\color{red}{\mathbf{Y}_\nu} \cancel{v_H} M_N^2}{\cancel{v_H^2}} \Rightarrow \tau_{N_R} \gg$ Long-lived particles



As an example: $M_N \sim 400$ GeV

$\Rightarrow L = (10^{-3} - 10^{-1})$mm



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