Dark Matter and the Seesaw Scale

Clara Murgui
in collaboration with Pavel Fileviez Perez

IFIC, Universitat de Valencia-CSIC

PASCOS, June 5th 2018

References

This talk is based on:

- P. Fileviez Perez and C. M, Dark Matter and The Scale for Lepton Number Violation, arXiv:1803.07462 [hep-ph]

Motivation

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

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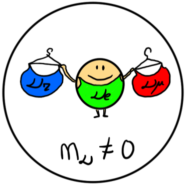


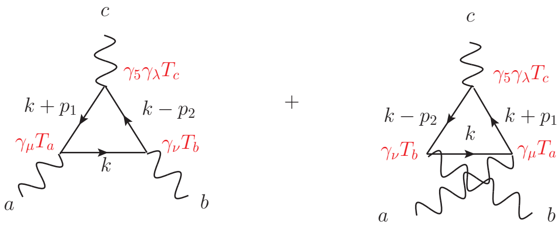
Motivation

- 

⇨ Extra: $U(1)_{B-L}$ global

Motivation

- Gauge anomalies:

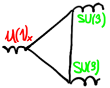


$$A^{abc} = \mathrm{Tr}\left[\{T_V^a, T_V^b\}, T_A^c\right]$$

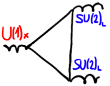
- In SM, a *magic* cancellation among representations and charges occurs!

Motivation

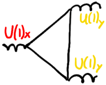
- Contributing diagrams when extra $U(1)_X$ gauged:



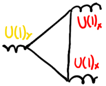
$$: A_1 \quad = \quad \sum_q X_{q_L} - \sum_q X_{q_R}$$



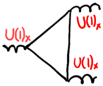
$$: A_2 \quad = \quad \sum_\ell X_{\ell_L} + 3 \sum_q X_{q_L}$$



$$: A_3 \quad = \quad \sum_{\ell,q} \left(Y^2_{\ell_L} X_{\ell_L} \; + \; 3 Y^2_{q_L} X_{q_L} \right) - \sum_{\ell,q} \left(Y^2_{\ell_R} X_{\ell_R} \; + \; 3 Y^2_{q_R} X_{q_R} \right)$$



$$: \quad A_4 \quad = \sum_{\ell,q} \left(Y_{\ell_L} X^2_{\ell_L} + 3 Y_{q_L} X^2_{q_L} \right) - \sum_{\ell,q} \left(Y_{\ell_R} X^2_{\ell_R} + 3 Y_{q_R} X^2_{q_R} \right)$$



$$: \quad A_5 \quad = \sum_{\ell,q} \left(X^3_{\ell_L} + 3 X^3_{q_L} \right) - \sum_{\ell,q} \left(X^3_{\ell_R} + 3 X^3_{q_R} \right)$$

$$A_6 = \sum_{\ell,q} \left(X_{\ell_L} + 3 X_{q_L} \right) - \sum_{\ell,q} \left(X_{\ell_R} + 3 X_{q_R} \right)$$

- Simplest solution $\rightarrow$ Addition of 3 ν_R

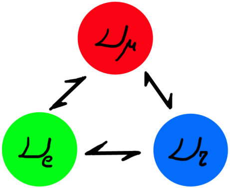
$$\boxed{M_\nu \neq 0}$$

Motivation

- 

  Extra: $U(1)_{B-L}$ global

- Connection



B-L

Breaking $U(1)_{B-L}$: Canonical Seesaw

Field content: $\quad SM \quad + \quad \underline{3\,\nu_R} \quad + \quad \underline{S_{BL}} \sim (1,1,0,2)$

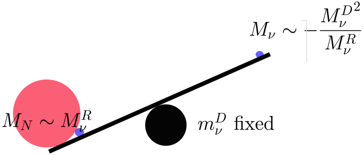
anomaly free theory

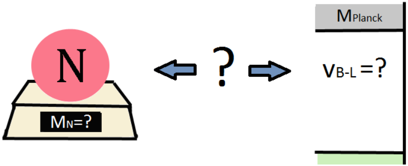
B-L breaking!

$$-\mathcal{L}_\nu^{\text{type-I}} = Y_\nu \bar{\ell}_L i\sigma_2 H^* \nu_R + \lambda_R \nu_R^T C \nu_R S_{BL} + \text{h.c.}$$

- Canonical See-saw:

$$\mathcal{M}_\nu^{\text{type-I}} = \begin{pmatrix} 0 & M_\nu^D \\ (M_\nu^D)^T & M_\nu^R \end{pmatrix}$$





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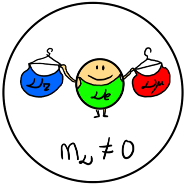

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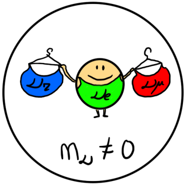
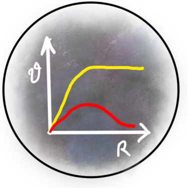




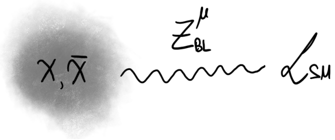
Vector-like fermions $\chi = \chi_L + \chi_R$ as DM

$$\chi_L \sim (1,1,0,n), \;\; \chi_R \sim (1,1,0,n)$$

$$\mathcal{L}_\nu^{DM} \supset i\overline{\chi}_L \gamma^\mu D_\mu \chi_L + i\overline{\chi}_R \gamma^\mu D_\mu \chi_R + (D_\mu S_{BL})^\dagger (D^\mu S_{BL}) - (M_\chi \bar{\chi}_L \chi_R + \text{h.c.}) \,,$$

- Relevant parameters:

$$n, \; g_{BL}, \; M_\chi, \; M_{h_2}, \; M_{N_i} \text{ and } M_{Z_{BL}}.$$



Relic Density

- Cosmological bound on the relic density:

$$\boxed{\Omega_{\mathrm{DM}} h^2 \sim \frac{1}{\langle \sigma v \rangle} \leq 0.1199 \pm 0.0027}$$

Ade *et al.* [Planck Collaboration], A&A, Volume 571, A16

- Relic density:

$$\Omega_{\mathrm{DM}} h^2 = \frac{1{,}07 \times 10^9 \mathrm{GeV}^{-1}}{M_{\mathrm{Pl}}} \left(\int_{x_f}^{\infty} \frac{g_*^{1/2}(x) \langle \sigma v \rangle (x)}{x^2} dx. \right)^{-1}$$

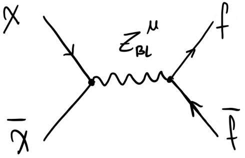
Gondolo, Gelmini, Nuclear Physics B 360(1)

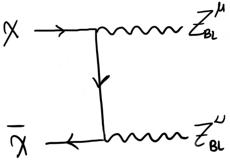
- Thermal averaged cross-section:

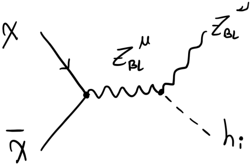
$$\langle \sigma v \rangle (x) = \frac{x}{8 M_\chi^5 K_2^2(x)} \int_{4M_\chi^2}^{\infty} \sigma \times (s - 4M_\chi^2) \sqrt{s}\, K_1 \left(\frac{x\sqrt{s}}{M_\chi} \right) ds,$$

Annihilation channels

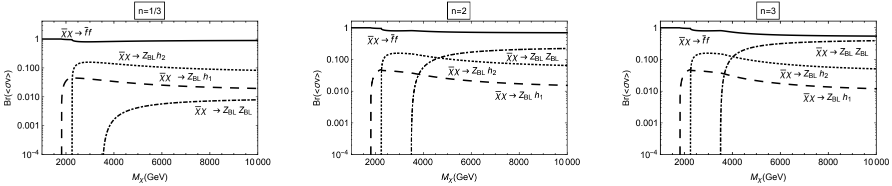
$$\mathcal{L}_{\nu}^{DM} \supset i\overline{\chi}_L \gamma^\mu D_\mu \chi_L + i\overline{\chi}_R \gamma^\mu D_\mu \chi_R + (D_\mu S_{BL})^\dagger (D^\mu S_{BL}) - (M_\chi \bar{\chi}_L \chi_R + \text{h.c.})\,,$$







- Branching ratios of $\langle \sigma v \rangle$ for above chanels:



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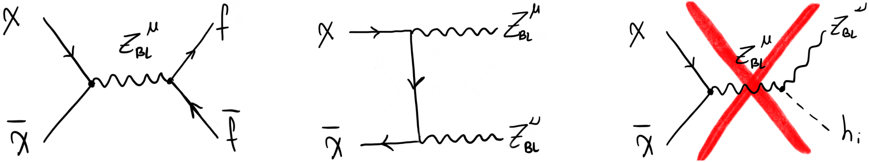

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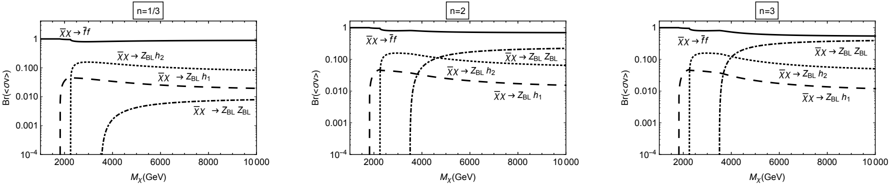

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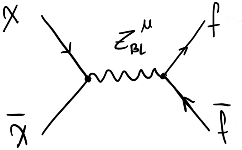
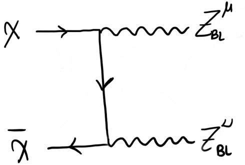


$$\sim g_{BL}^4\, n^2\, \frac{1}{\Lambda^2}$$



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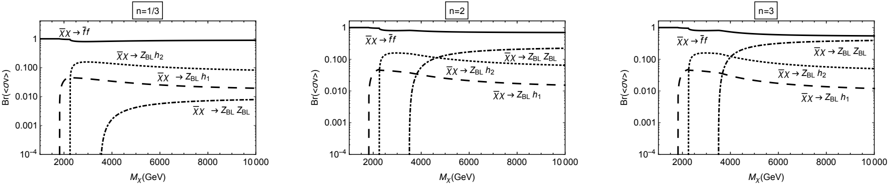
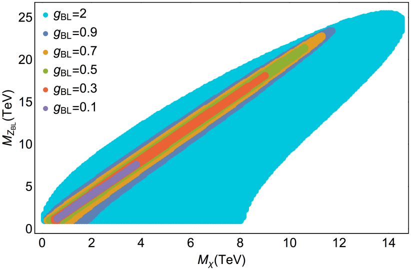
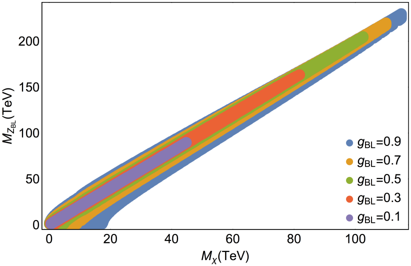


Phase Space allowed by Relic Density constraints

- In agreement with Relic Density constraint: $\Omega h^2 < 0.1199 \pm 0.0027$



$n = 1/3$



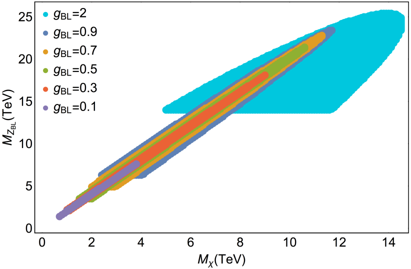
$n = 3$

Bounded below!

Collider bounds: LEP

- LEP:

$$\frac{M_{Z_{BL}}}{g_{BL}} > 7\ \text{TeV}$$



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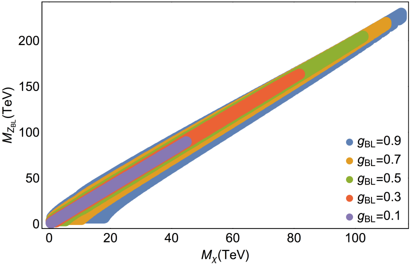
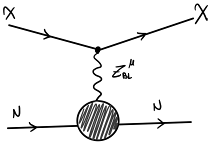
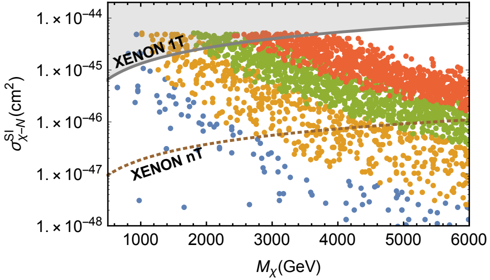


$n = 3$

Direct searches



$$\sigma^{\rm SI}_{\chi N} = \frac{M_N^2 M_\chi^2}{\pi(M_N + M_\chi)^2}\frac{g_{BL}^4}{M_{Z_{BL}}^4} n^2$$



Aprile *et al.* [XENON Collaboration] PhysRevLett.119.181301

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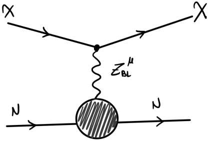

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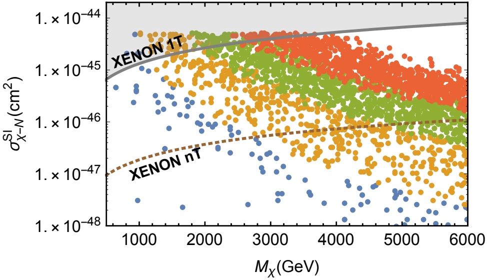

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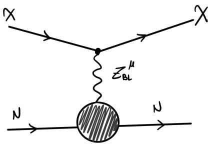

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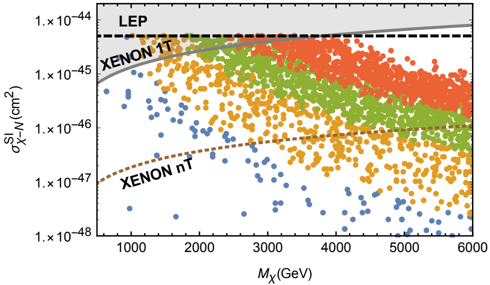
$$\sigma^{\rm SI}_{\chi N}({\rm cm}^2) = 12.4 \times 10^{-41} \left(\frac{\mu}{1{\rm GeV}}\right)^2 \left(\frac{1{\rm TeV}}{r_{BL}}\right)^4 n^2 \,{\rm cm}^2,$$



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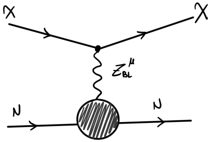
Direct searches: XENON-1T



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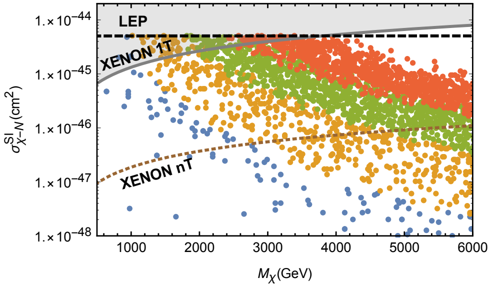

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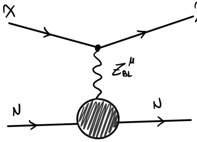

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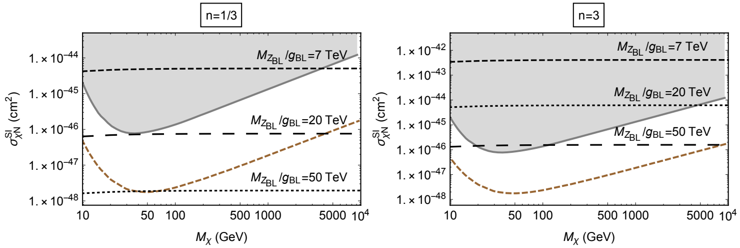

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Phase Space allowed by Relic Density constraints

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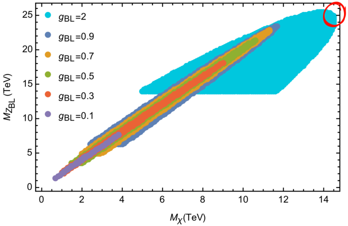
Upper bound !



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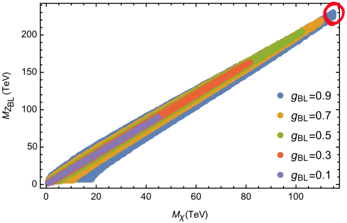

$n = 3$

Upper bound

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

Upper bound

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

$$\boxed{n < 1}$$

Upper bound

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

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

$\boxed{n < 1}$

$\boxed{n > 1}$

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

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

Upper bound

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

$\boxed{n < 1}$

$\boxed{n > 1}$

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

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

What if $n \to \infty$?!

Upper bound

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

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

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

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

Upper bound

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

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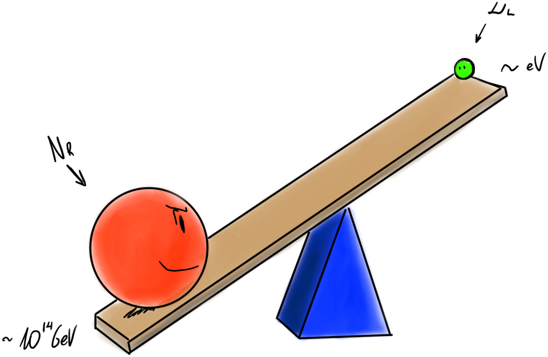
! $(\Gamma_{Z_{BL}}^{\mathrm{tot}})^2 \sim \Gamma^2(Z_{BL} \to \bar{\chi}\chi) \propto g_{BL}^4 n^2 \Lambda^2$

The Canonical Seesaw

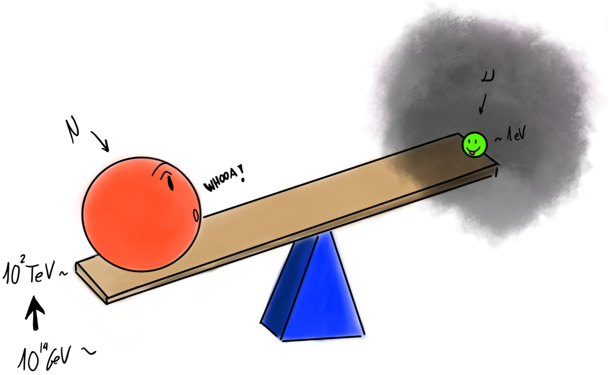
- In general, the upper bound for the $B-L$ breaking scale is the canonical seesaw scale, i.e. $v_{B-L} \leq 10^{14}$ GeV.



- The new theory could live anywhere up to the GUT scale...

The ~~Canonical~~ "Dark"Seesaw

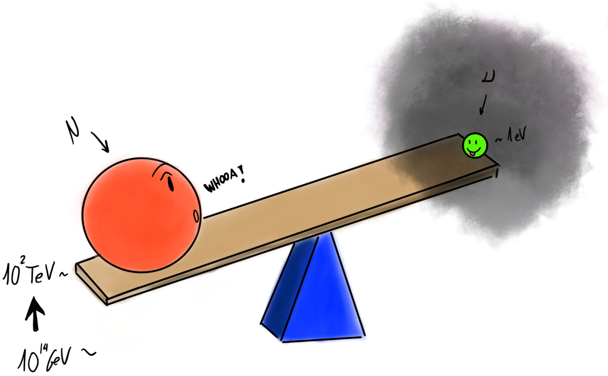
- The presence of Dark Matter in the game lowers considerably the upper bound to $v_{B-L} \lesssim 200$ TeV.



- Hope to see signals in a near future!!!

The ~~Canonical~~ "Dark" Seesaw

- The presence of Dark Matter in the game lowers considerably the upper bound to $v_{B-L} \lesssim 200$ TeV.



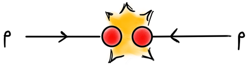
- Hope to see signals in a near future!!!

Consequences of a low B-L breaking scale

$$\text{Low B-L scale } (v_{BL} \ll) \left\{ M_{N_R} = \frac{\lambda_R}{\sqrt{2}} v_{BL} \right.$$

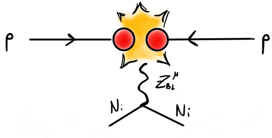
➡ Hope to see LNV signals at colliders!

Lepton Number Violation at the LHC



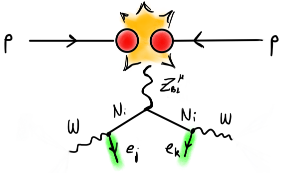
pp

Lepton Number Violation at the LHC



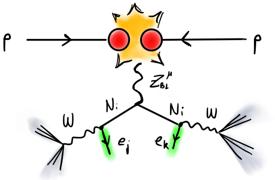
$pp \to Z_{BL}^{*} \to N_i N_i$

Lepton Number Violation at the LHC



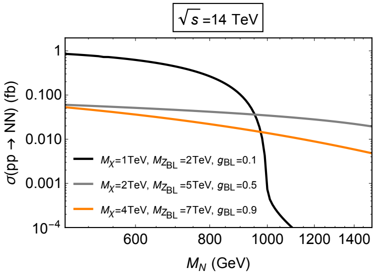
$$pp \to Z_{BL}^{*} \to N_i N_i \to e_j^{\pm} W^{\mp} e_k^{\pm} W^{\mp}$$

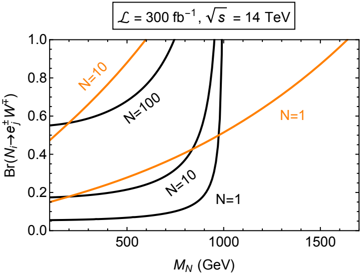
Lepton Number Violation at the LHC



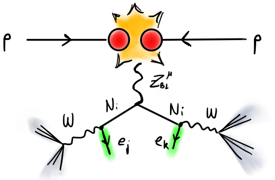
$$pp \to Z_{BL}^* \to N_i N_i \to e_j^{\pm} W^{\mp} e_k^{\pm} W^{\mp} \to e_j^{\pm} e_k^{\pm} 4j$$

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



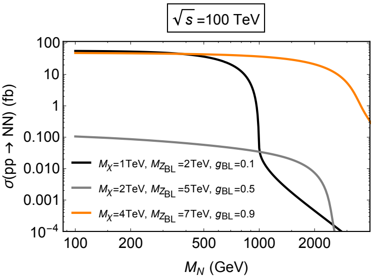


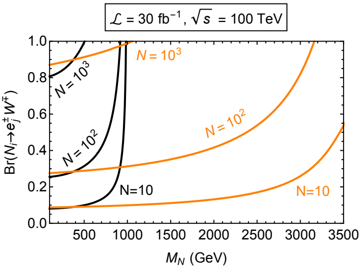
Lepton Number Violation at future colliders



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

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

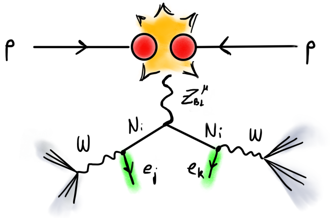




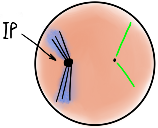
Consequences of a low B-L breaking scale

Low B-L scale $(v_{BL} \ll)$

$$M_{N_R} = \frac{\lambda_R}{\sqrt{2}} v_{BL}$$ ➡ Hope to see LNV signals at colliders!



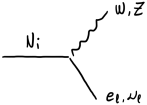
$$M_\nu = M_D^T M_R^{-1} M_D \sim \frac{Y_\nu^2 v_H^2}{M_{N_R}} \lesssim \mathrm{eV} \Rightarrow Y_\nu \text{ small}$$



➡ Displaced vertices!

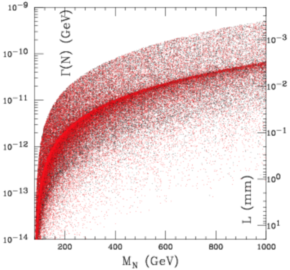
Displaced vertices

- Total decay width of N:

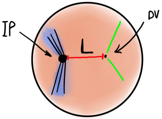


$$\Gamma_N^{\text{tot}} \sim |V_{\ell i}|^2 \frac{M_{N_i}^3}{M_W^2}$$

- Neutrino mixing: $|V_{\ell i}|^2 \propto M_\nu / M_{N_R}$, $\quad M_{\nu N} = \begin{pmatrix} 0 & M_\nu \\ M_\nu & M_{N_R} \end{pmatrix}$
- $\Gamma_{N_R} \propto \frac{M_\nu M_N^2}{M_W} \sim \frac{\mathbf{Y}_\nu \cancel{v_H} M_N^2}{v_H^{\cancel{2}}} \Rightarrow \tau_{N_R} \gg$ ➡ Long-lived particles



As an example: $M_N \sim 400$ GeV
$\Rightarrow L = (10^{-3} - 10^{-1})$mm



doi:10.1103/PhysRevD.80.073015

Summary

- We present a simple theory based on $U(1)_{B-L}$, which is the simplest and natural **connection between neutrino masses and dark matter**.
- This simple theory predicts an **upper bound** for the new $B-L$ scale of the order of 100 TeV.
- Therefore, there is hope to test te theory at colliders! Consequences of a **low $B-L$ scale**:
  - Low M_N: we have studied the main **lepton number violating signals** at the LHC and future colliders.
  - Tiny Y_ν: exotic signals of **displaced vertices** are expected.

Thanks for your attention!