Neutrinos, *Dark Matter* *and* *The New Physics Scale*

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CASE WESTERN RESERVE UNIVERSITY EST. 1826
think beyond the possible

IPA2018, Cincinnati, October 2018

Collaborators

Michael Duerr (Oxford)

Elliot Golias (CWRU)

Ruihao Li (CWRU)

Clara Murgui (IFIC)

Sebastian Ohmer (MPIK)

Juri Smirnov (CP3-Origins)

Mark B. Wise (Caltech)

The Standard Model provides a good "explanation" for most of the current experimental results in particle physics and it is one of the most successful theories of nature !

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Some Questions

What is the origin of Neutrino Masses ?

Why the SM interactions are so different ?

Why the fermion masses are so different ?

Why the Higgs boson is light?

How can we explain the Dark Matter in the Universe ?

How can we explain the matter-antimatter asymmetry ?

Is there New Physics at the TeV Scale ?

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Is there New Physics at the TeV Scale ?

Let us ignore the Standard Fine Tuning arguments and discuss some other possibilities which motivate the existence of New Physics at the TeV Scale

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Neutrinos are Massive !

What is the origin of Neutrino Masses ?

How do we test the theory of Neutrino Masses ?

Massive Neutrinos

NuFit Collaboration

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 0.83$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.271 \to 0.345$
$\theta_{12}/^\circ$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$31.38 \to 35.99$
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.385 \to 0.635$	$0.587^{+0.020}_{-0.024}$	$0.393 \to 0.640$	$0.385 \to 0.638$
$\theta_{23}/^\circ$	$41.6^{+1.5}_{-1.2}$	$38.4 \to 52.8$	$50.0^{+1.1}_{-1.4}$	$38.8 \to 53.1$	$38.4 \to 53.0$
$\sin^2\theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.01934 \to 0.02392$	$0.02179^{+0.00076}_{-0.00076}$	$0.01953 \to 0.02408$	$0.01934 \to 0.02397$
$\theta_{13}/^\circ$	$8.46^{+0.15}_{-0.15}$	$7.99 \to 8.90$	$8.49^{+0.15}_{-0.15}$	$8.03 \to 8.93$	$7.99 \to 8.91$
$\delta_{CP}/^\circ$	261^{+51}_{-59}	$0 \to 360$	277^{+40}_{-46}	$145 \to 391$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.03 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.524^{+0.039}_{-0.040}$	$+2.407 \to +2.643$	$-2.514^{+0.038}_{-0.041}$	$-2.635 \to -2.399$	$\begin{bmatrix} +2.407 \to +2.643 \\ -2.629 \to -2.405 \end{bmatrix}$

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Massive Neutrinos

- Dirac Fermions — *B-L Conservation !*

$$-\mathcal{L}_D = Y_\nu^D \ \bar{\ell}_L i\sigma_2 H^* \nu_R + \text{h.c.}$$

- Majorana Fermions — *B-L Violation !*

Many Ideas !

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Dirac Neutrinos

B-L Conservation !

$$-\mathcal{L}_D = Y_\nu^D \ \bar{\ell}_L i\sigma_2 H^* \nu_R + \text{h.c.}$$

$Y_\nu^D \lesssim 10^{-12}$ ⇒ $M_\nu \lesssim 0.1 \text{ eV}$

$3\nu_R$ ⇒ $U(1)_{B-L}$ Local Anomaly Free Symmetry

a) Unbroken B-L: Stueckelberg Mechanism — Feldman, P.F.P., Nath

b) Broken B-L: $S_{BL} \sim (1,1,0,n_{BL}), |n_{BL}| > 2.$

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(Minkowski, Mohapatra, Senjanovic, Glashow, Yanagida, Gell-Mann, Ramond, Slansky)

Majorana Neutrinos

$$-\mathcal{L}_M = Y_\nu^D \ \bar{\ell}_L i\sigma_2 H^* \nu_R + \frac{1}{2} M_R \nu_R^T C \nu_R + \text{h.c.}$$ (Canonical Seesaw)

$\Rightarrow$ $$M_\nu = m_D M_R^{-1} m_D^T$$

if $m_D \sim 10^2 \text{GeV}$ $\Rightarrow$ $M_R \lesssim 10^{14-15} \text{GeV}$ (Seesaw Scale)

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

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

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

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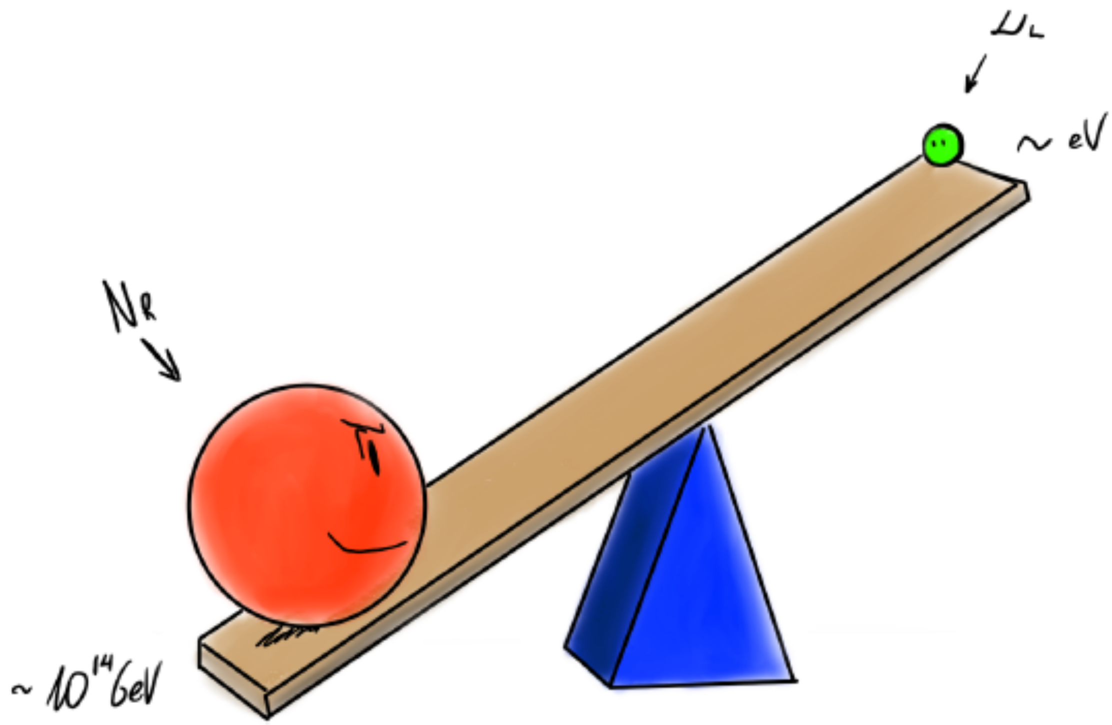
The Canonical Seesaw

- 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.



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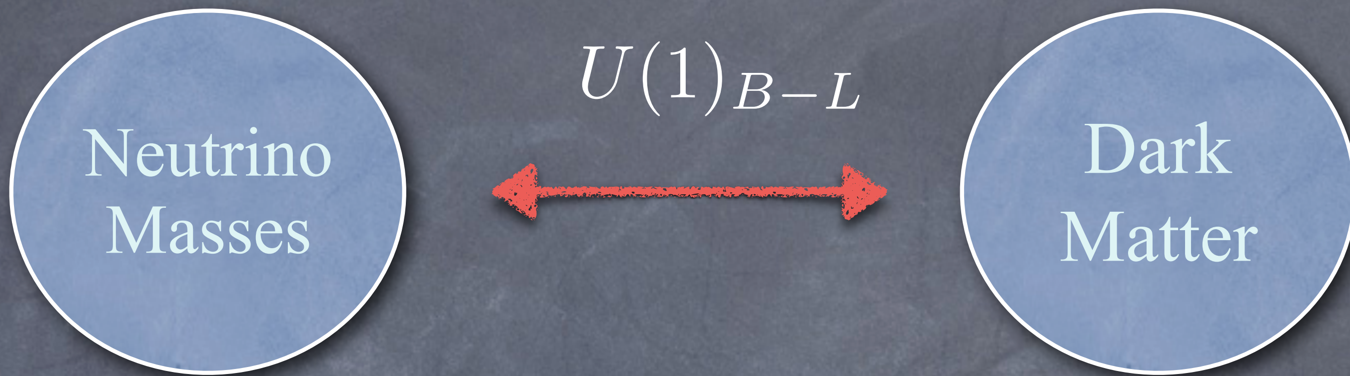
How do we test the theory of Neutrino Masses ?

How do we test the theory of Neutrino Masses ?

Dark Matter and Seesaw Scale

P. F. P., C. Murgui, Phys.Rev. D98 (2018) 055008

Seesaw Scale and Dark Matter



$$\mathcal{L}_\nu^{DM} \supset -\frac{1}{4} F_{\mu\nu}^{BL} F_{\alpha\beta}^{BL} g^{\alpha\mu} g^{\beta\nu} + i\overline{\chi}_L \gamma^\mu D_\mu \chi_L + i\overline{\chi}_R \gamma^\mu D_\mu \chi_R + (D_\mu S_{BL})^\dagger (D^\mu S_{BL})$$
$$- \left(Y_\nu \, \bar{\ell}_L i\sigma_2 H^* \nu_R \; + \; \lambda_R \, \nu_R^T C \nu_R S_{BL} + M_\chi \bar{\chi}_L \chi_R + \text{h.c.} \right),$$

$$M_R = \sqrt{2}\lambda_R v_{BL} \qquad M_{Z_{BL}} = 2 g_{BL} v_{BL}$$

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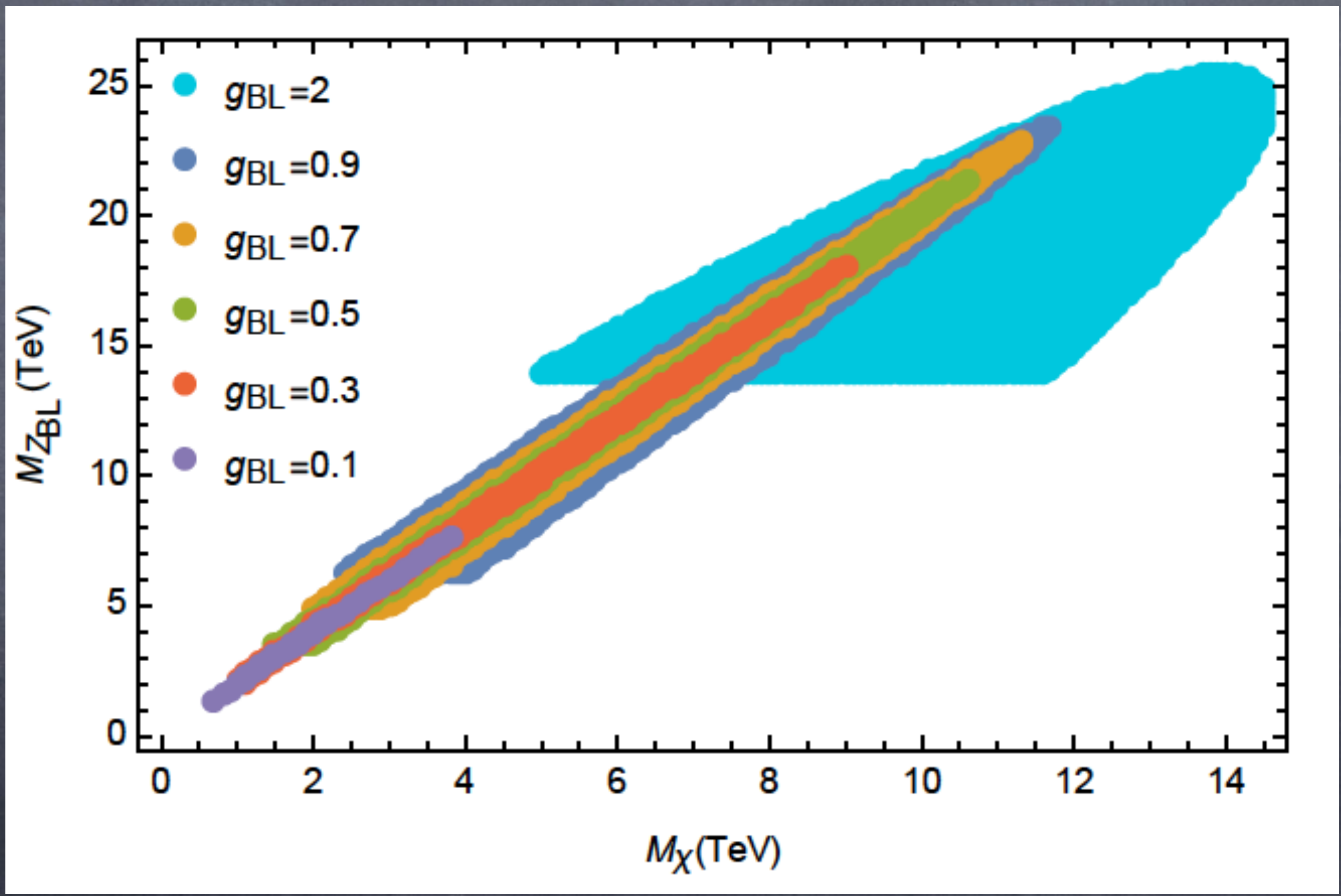
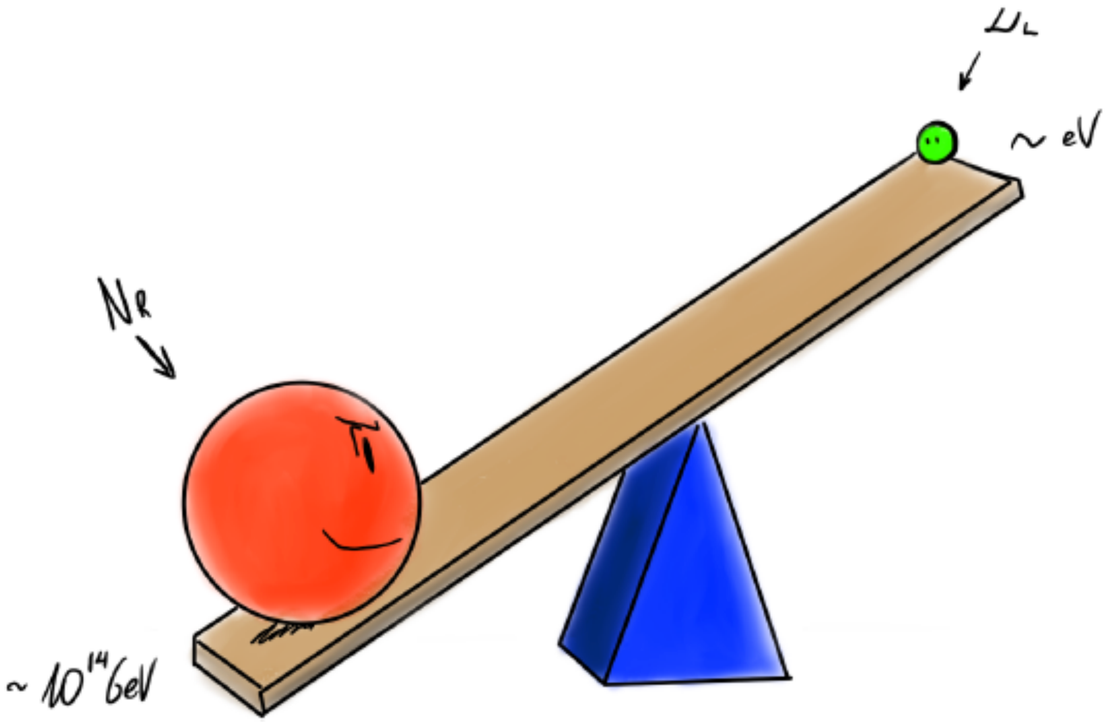
Seesaw Scale and Dark Matter

$n = 1/3$ when $\Omega_{DM} h^2 \leq 0.1199 \pm 0.0027$



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.



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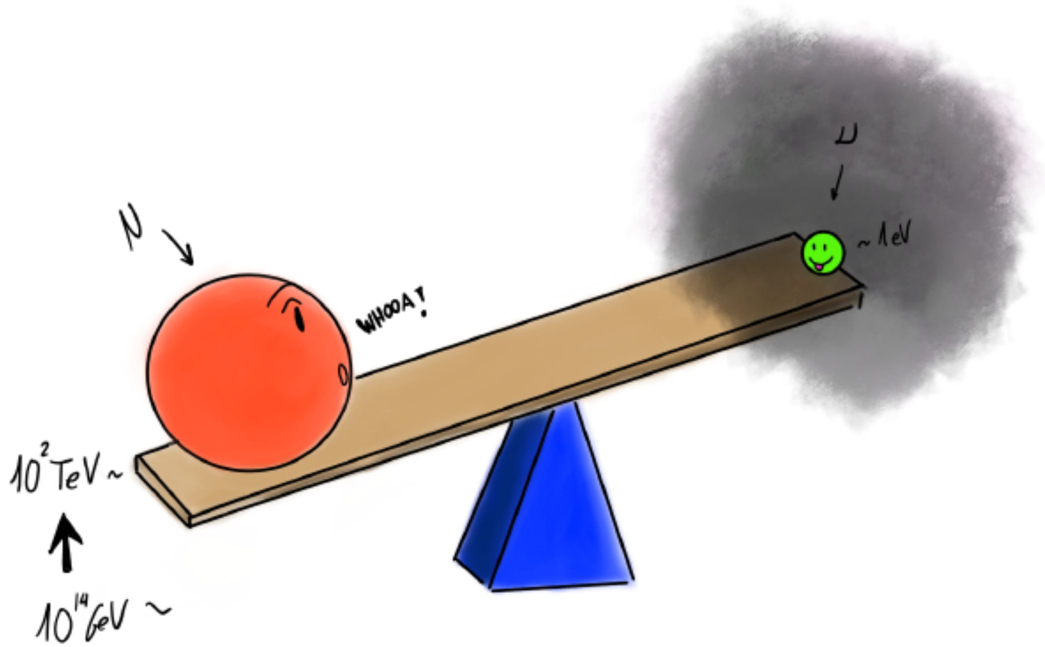
Seesaw Scale and Dark Matter

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!!!

P. F. P., C. Murgui, Phys.Rev. D98 (2018) 055008

Seesaw Scale and Dark Matter

The upper bound on B-L Seesaw Scale is in the multi-TeV region

Therefore there is a hope to test the origin of neutrinos masses at Colliders !

LNV Signatures at LHC

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

P. F. P., T. Han, T. Li

See also M. Duerr, P.F.P., J. Smirnov

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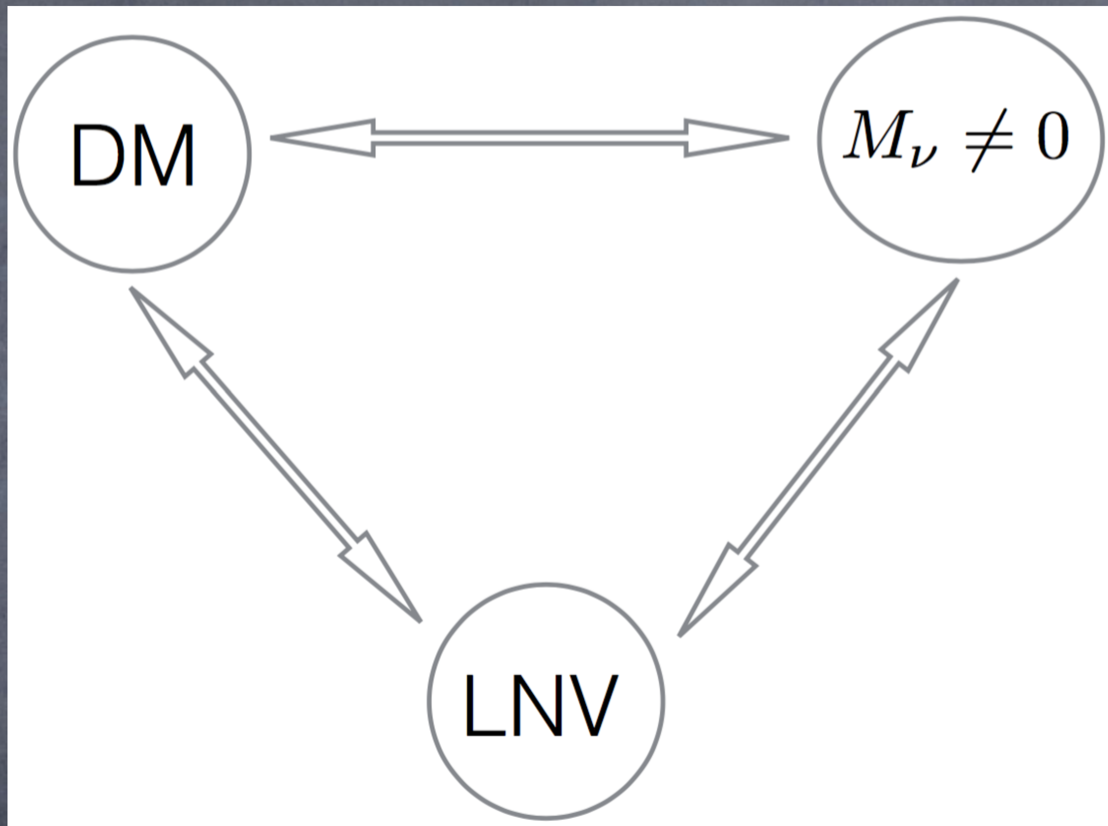
P. F. P., C. Murgui, Phys.Rev. D98 (2018) 055008

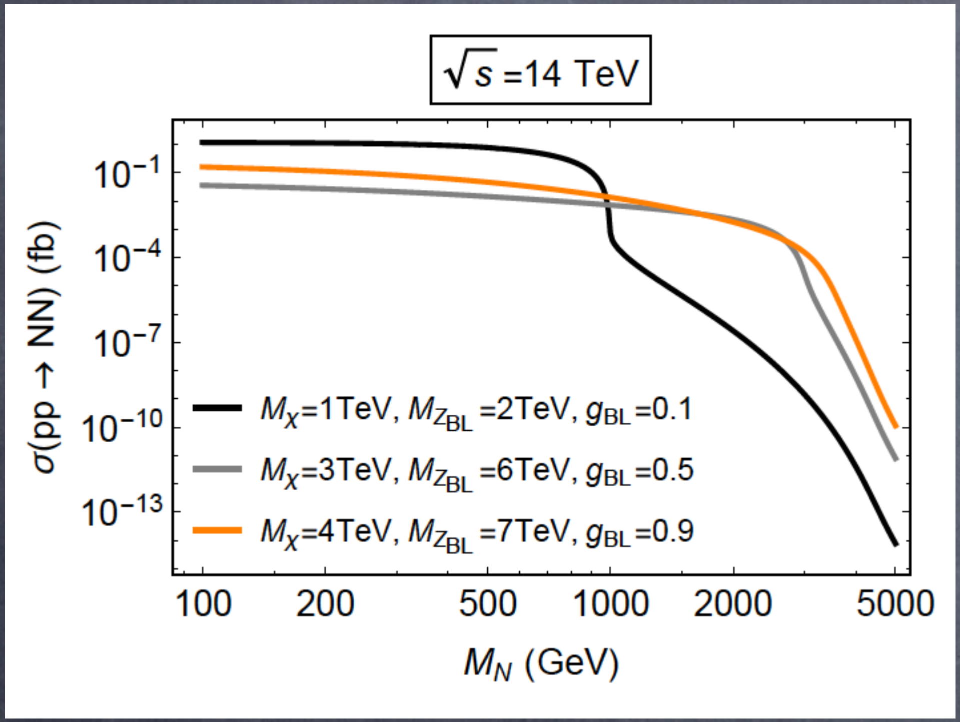


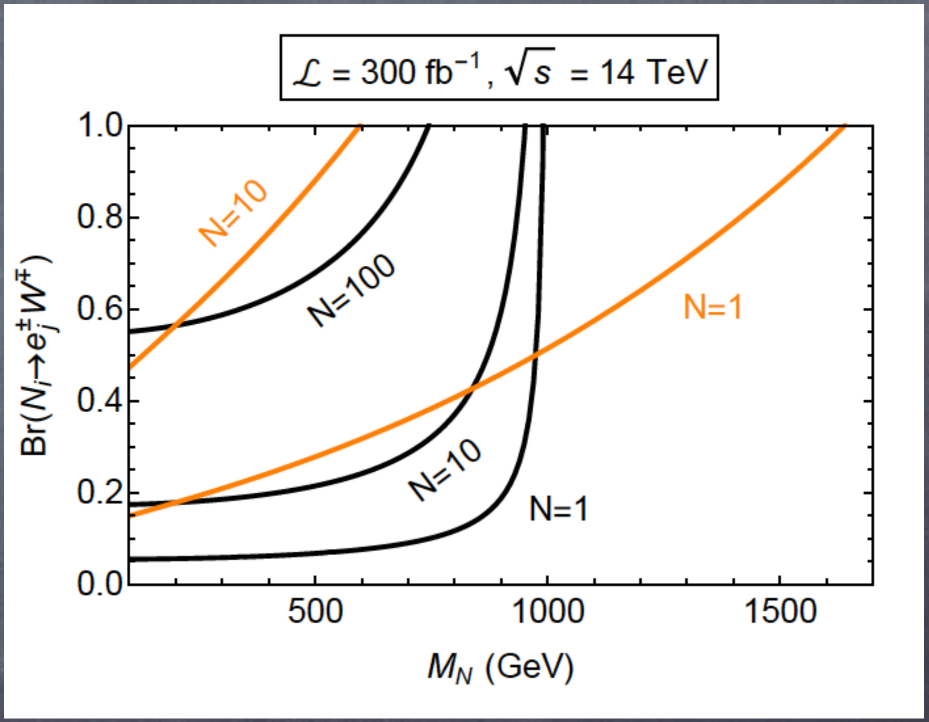
One can expect lepton number violating and DM signatures at the LHC

P. F. P., C. Murgui, Phys.Rev. D98 (2018) 055008

Testability at the LHC

$$pp \to Z^*_{BL} \to N_i N_i \to e^\pm_j W^\mp e^\pm_k W^\mp \to e^\pm_j e^\pm_k 4j.$$





The LHC could see these events in the near future !

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Spontaneous Baryon Number Violation

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Baryon Number Violation in BSM

Explicit Breaking

for example in GUTs: $M_{GUT} > 10^{15}\mathrm{GeV}$

Spontaneous Breaking

➡ *Baryon Number as a Local Gauge Symmetry*

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Baryon Number as a Local Gauge Symmetry

A. Pais, 1973

S. Rajpoot, 1988

R. Foot, G. C. Joshi, H. Lew, 1989

C. Carone, H. Murayama,1995

P. F. P., M. B. Wise, PRD82 (2010)011901; JHEP1108(2011)068

M. Duerr, P. F. P., M. B. Wise, Physical Review Letters 110 (2013) 231801

P. F. P., S. Ohmer, H. H. Patel, Phys. Rev. D90 (2014)3,037701

P.F.P., Physics Reports 597 (2015)

P. F. P., M. B. Wise

Breaking B and L at the TeV scale !

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_B \otimes U(1)_L$$

where $U(1)_B$ and $\mathrm{U}(1)_{\mathrm{L}}$ can be broken at the TeV Scale !

$$B(\text{quark}) = 1/3 \qquad L(\text{lepton}) = 1$$

How to define an anomaly free theory ?

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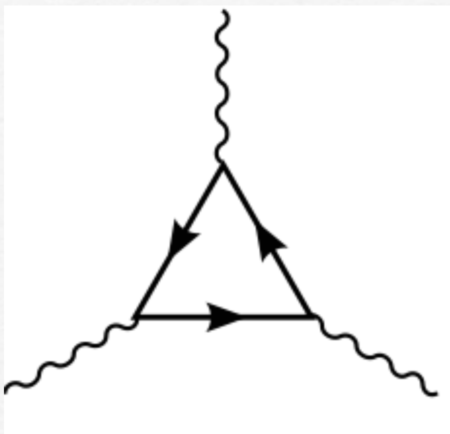
Anomaly Cancellation

Baryonic Anomalies:



$$\mathcal{A}_1\left(SU(3)^2\otimes U(1)_B\right),\ \mathcal{A}_2\left(SU(2)^2\otimes U(1)_B\right),$$
$$\mathcal{A}_3\left(U(1)_Y^2\otimes U(1)_B\right),\ \mathcal{A}_4\left(U(1)_Y\otimes U(1)_B^2\right),$$
$$\mathcal{A}_5\left(U(1)_B\right),\ \mathcal{A}_6\left(U(1)_B^3\right),$$

In the SM: $\mathcal{A}_2 = -\mathcal{A}_3 = 3/2$

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Different Solutions for Anomaly free theories:

- ~~Sequential Family~~
- ~~Mirror family~~
- Vector-like Fermions

P. F. P., M. B. Wise, PRD82 (2010)011901; JHEP1108(2011)068

M. Duerr, P. F. P., M. B. Wise, Phys. Rev. Lett. 110 (2013) 231801

P. F. P., S. Ohmer, H. H. Patel, Phys. Rev. D90 (2014)3,037701

P.F.P., Physics Reports 597 (2015)

M. Duerr, **P. F. P.**, M. B. Wise, Phys. Rev. Lett.

One can define an anomaly free theory using the Fermionic Lepto-baryons:

Example:

$$\Psi_L \sim (1, 2, -1/2, B_1) \qquad \Psi_R \sim (1, 2, -1/2, B_2)$$

$$\eta_R \sim (1, 1, -1, B_1) \qquad \eta_L \sim (1, 1, -1, B_2)$$

$$\chi_R \sim (1, 1, 0, B_1) \qquad \chi_L \sim (1, 1, 0, B_2)$$

$$\Rightarrow \qquad B_1 - B_2 = -3$$

They can have vector-like masses and cancel all anomalies !

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M. Duerr, P. F. P., M. B. Wise, Phys. Rev. Lett.

Generation of Mass:

$$\mathcal{L} \supset \lambda_\Psi \overline{\Psi}_L \Psi_R S_{BL} \; + \lambda_\eta \overline{\eta}_R \eta_L S_{BL} + \lambda_\chi \overline{\chi}_R \chi_L S_{BL} + \text{h.c.}$$

New Higgs: $S_{BL} \sim (1, 1, 0, -3, -3)$

$\Delta B = \pm 3$ → **Stable Proton !** → **NO DESERT !**

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M. Duerr, **P. F. P.**, M. B. Wise, Phys. Rev. Lett.

Some Features:

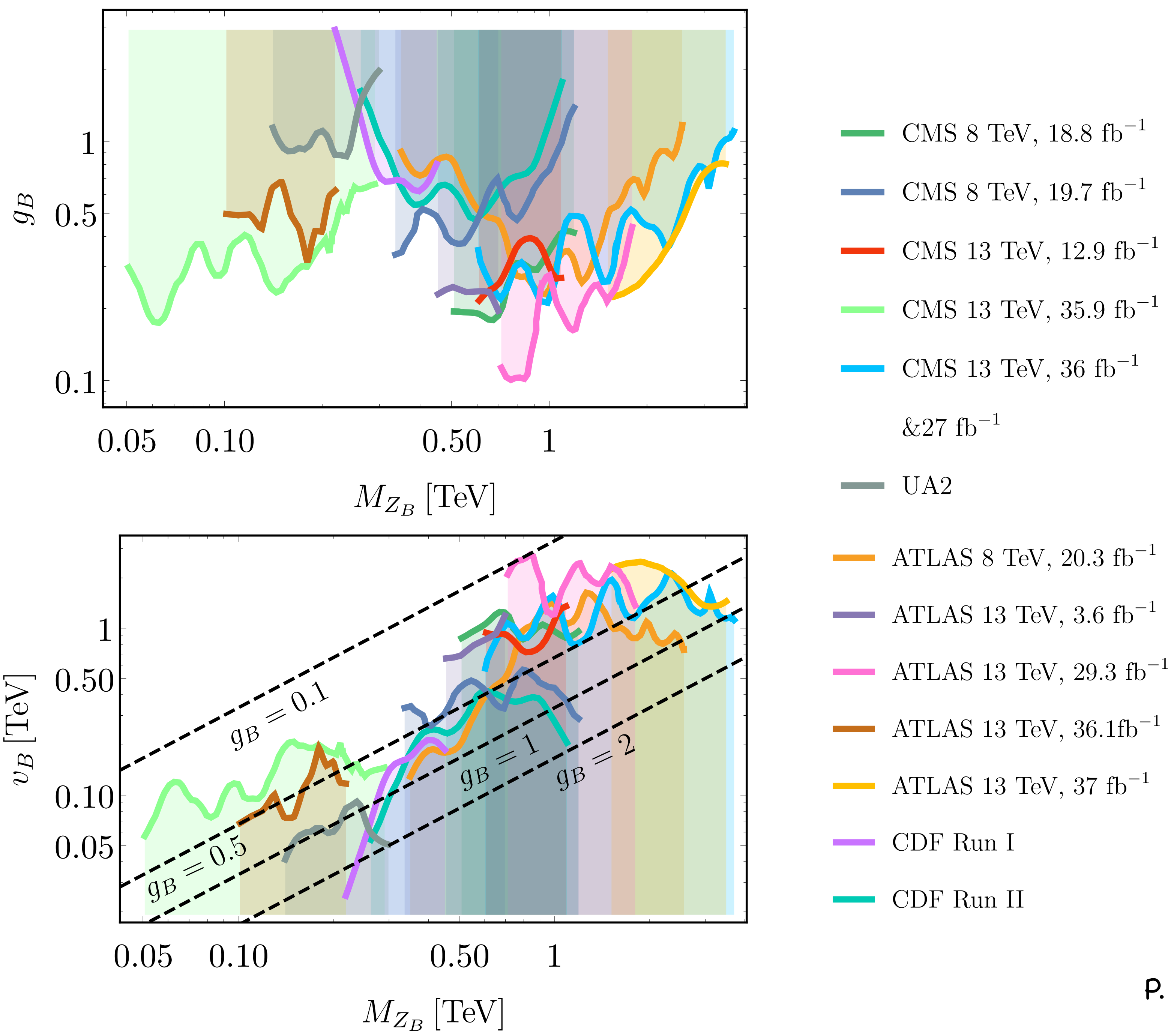
Dark Matter: $\chi = \chi_L + \chi_R$ cold dark matter candidate !

Leptophobic Gauge Boson: $Z_B \to \bar{q}q, \bar{\chi}\chi$

New Higgs Boson: $h_2 \to \bar{q}q, WW, ZZ, hh, \bar{\chi}\chi$

Missing Energy at the LHC: $pp \to Z_B h_2 \to \bar{t}t\bar{\chi}\chi \to \bar{t}tE_T^{\text{miss}}$

P. F. P., E. Golias, R. Li, C. Murgui, 2018



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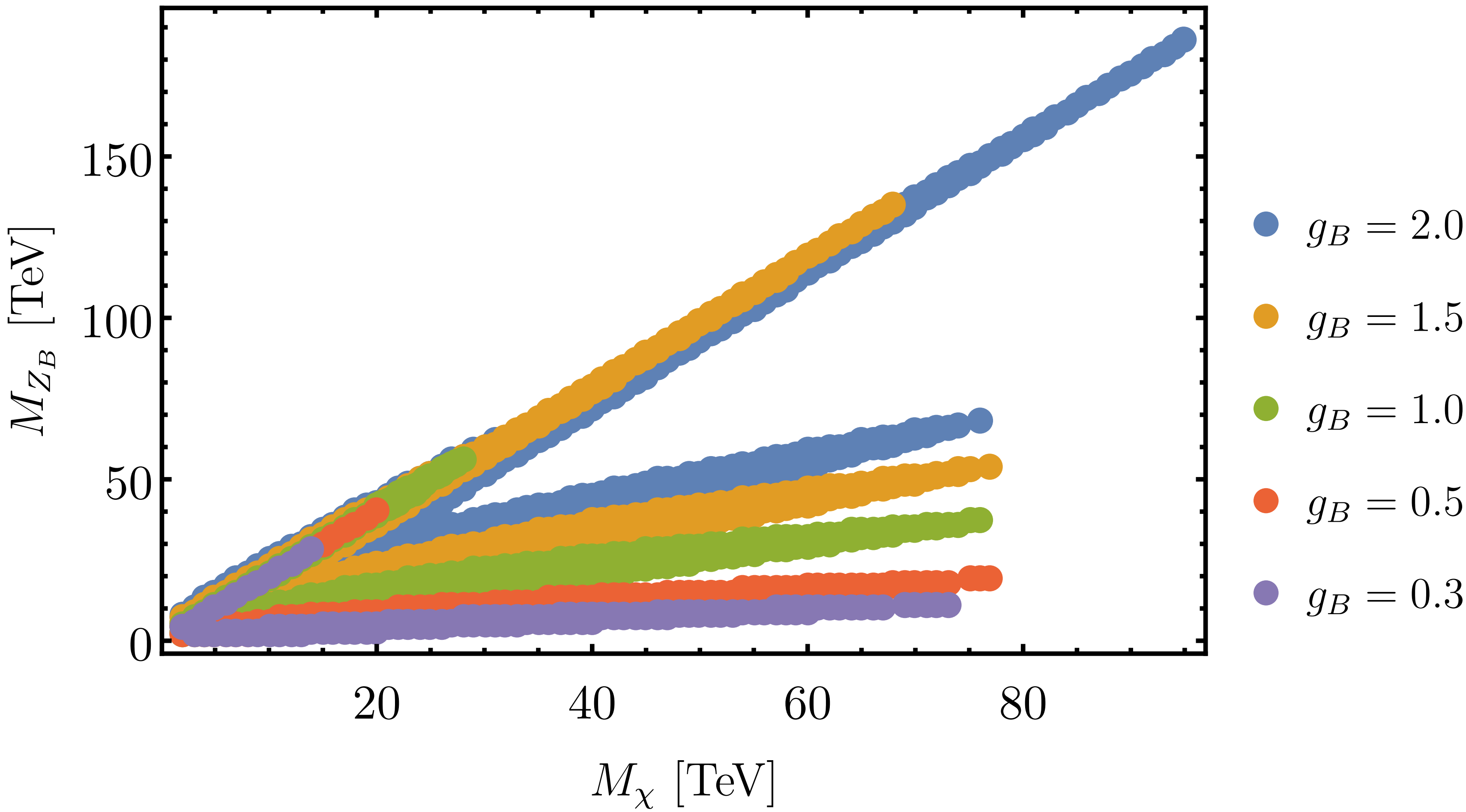
P. F. P., E. Golias, R. Li, C. Murgui, 2018

$$\Omega_{DM} h^2 \ \leq \ 0.12.$$

$$\bar{\chi}\chi \to \bar{q}q, WW, ZZ, h_1 h_1, Z_B Z_B, Z_B h_2, Z_B h_1, h_2 h_2, h_1 h_2.$$



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Spontaneous Baryon Number Violation

The scale for baryon number violation must be low in agreement with cosmology and one could test the spontaneous breaking of baryon number at colliders

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Summary

The testability of the theory of neutrino masses is crucial to complete our understanding of the origin of fermion masses !

The Seesaw Scale must be in the multi-TeV scale in the simplest theories based on B-L if there is a relation between DM and the origin of neutrino masses. One can hope to test this mechanism at current or future colliders.

The simplest theories for spontaneous baryon number violation predicts new physics at the multi-TeV scale in agreement with cosmology. This theory predicts the proton stability, it is a good theory for dark matter and one could change the way we think about unification of forces.

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Thank You !