On the Origin of Baryon and Lepton Number Violation

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think beyond the possible

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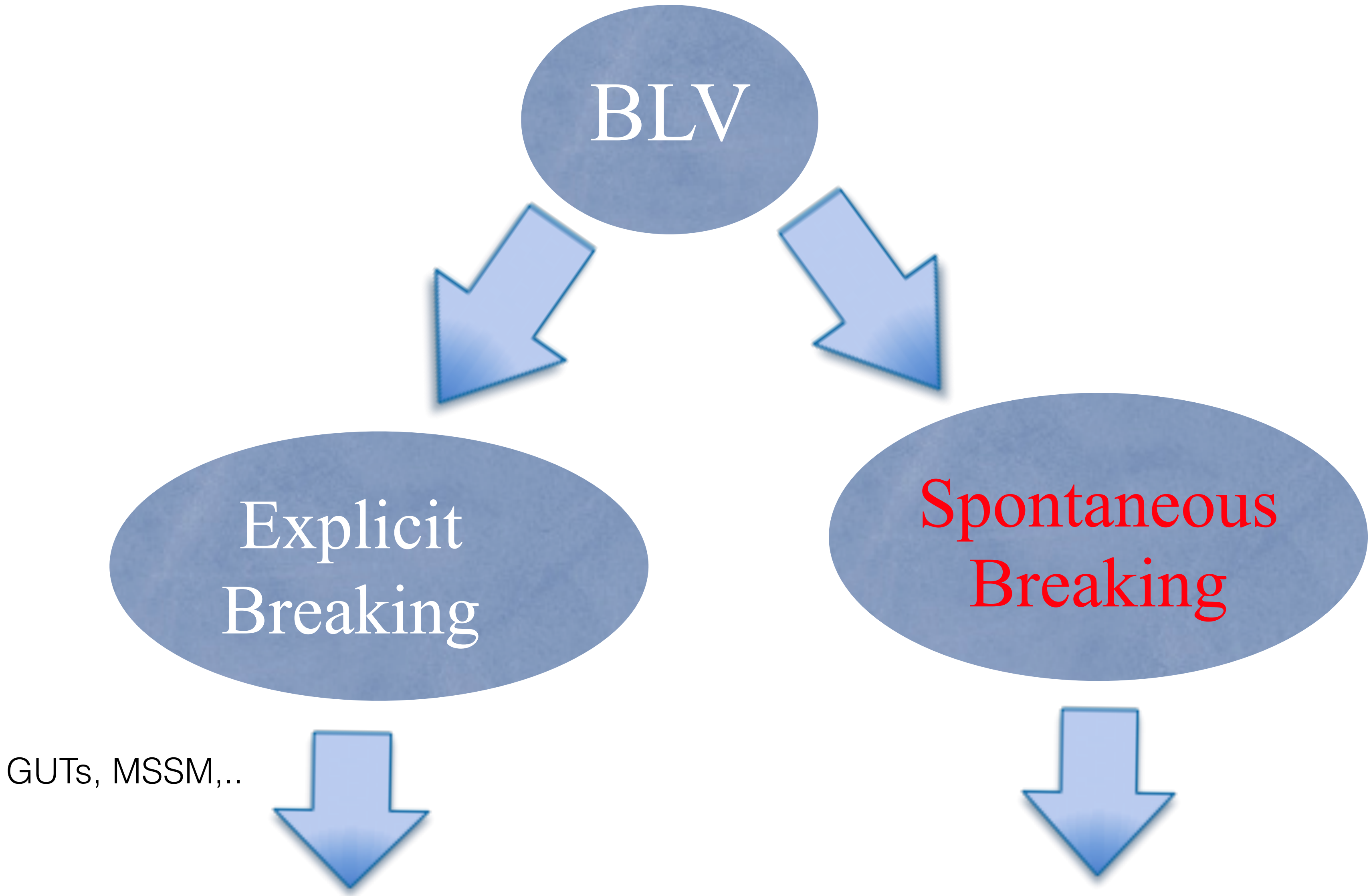
We need to understand the origin of B and L violation to explain :

- The origin of neutrino masses
- The Matter-Antimatter Asymmetry
- The Stability of the Proton
- New Exotic BLV processes
- The SM-EFT



- Proton decay
- Majorana neutrinos

- Stable proton
- Dirac or Majorana neutrinos
- Low B and/or L Scale
- Dark Matter

B and L Violating Effective Operators

S. Weinberg

$$\mathcal{L} \supset \frac{c_L}{\Lambda_L} \ell H \ell H$$

$$+ \frac{c_1}{\Lambda_B^2}(\overline{u^c}\gamma^\mu q)(\overline{e^c}\gamma_\mu q) + \frac{c_2}{\Lambda_B^2}(\overline{u^c}\gamma^\mu q)(\overline{d^c}\gamma_\mu \ell)$$

$$+ \frac{c_3}{\Lambda_B^2}(\overline{d^c}\gamma^\mu q)(\overline{u^c}\gamma_\mu \ell) + \frac{c_4}{\Lambda_B^2} qqq\ell + \frac{c_5}{\Lambda_B^2} u^c e^c u^c d^c + \ldots$$

What are the values for Λ_L and Λ_B?

Naive bounds: $\Lambda_L \lesssim 10^{14}$ GeV and $\Lambda_B \gtrsim 10^{15}$ GeV

These scales could be low and one can hope to test directly the origin of B and L violation !

Massive Neutrinos

What is the origin of neutrino masses ?

How do we test the theory of neutrino masses ?

Massive Neutrinos

- Majorana Fermions

B-L is broken !

$$\mathcal{L} \ni \frac{1}{2} \nu_L^T C M_M \nu_L + h.c.$$

- Dirac Fermions

B-L is conserved !

$$\mathcal{L} \ni M_D \bar{\nu}_L \nu_R + h.c.$$

Mechanisms for Majorana Neutrino Masses

$$\mathcal{L} \ni \frac{1}{2} \nu_L^T C M_M \nu_L + h.c.$$

- Type I Seesaw
- Type II Seesaw
- Type III Seesaw
- Zee's Model
- Colored Seesaw
- Babu-Zee Model
- Witten's Model

…

…

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

Canonical Seesaw

$$-\mathcal{L} \supset Y_\nu^D \bar{\ell}_L i\sigma_2 H^* \nu_R + \frac{1}{2} M_R \nu_R^T C \nu_R + h.c.$$

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

if $m_D \sim 10^2$ GeV → $M_R < 10^{14-15}$ GeV

In general we do not know the Seesaw Scale !

The simplest gauge theory predicting right-handed neutrinos is based on local B-L

$U(1)_{B-L}$: *Simplest Gauge Theory for Neutrino Masses*

- Right handed neutrinos predicted from anomaly cancellation
- Spontaneous B-L Breaking:

- Dirac Neutrinos:

$$S_{BL} \sim (1,1,0,n), \text{where } |\text{n}| > 2 \text{ and } \text{kn} \neq |2| \ (\text{k} \in \mathbb{Z})$$

- Majorana Neutrinos:

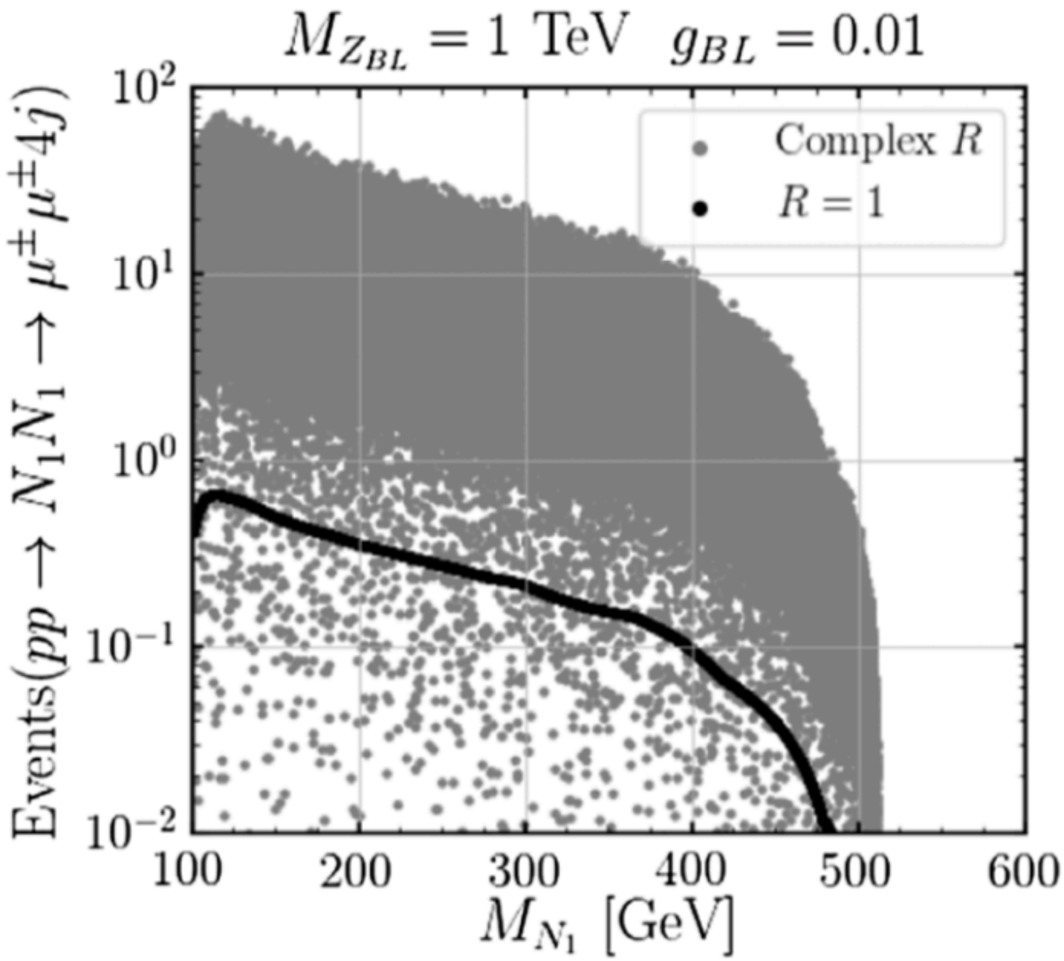
$$S_{BL} \sim (1,1,0,2) \quad \Rightarrow \quad \lambda_R \nu_R^T C \nu_R S_{BL} \ + \ \text{h.c.}$$

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

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

P. F. P., A.D. Plascencia, Phys.Rev.D 102 (2020) 1, 015010

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



See reviews: Deppisch, Dev, Pilaftsis, New J. Phys 17 (2015)
Cai, Han, Li, Ruiz, Front.in. Phys.6 (2018) 40

Spontaneous
Lepton Number Violation

Lepton Number as Local Gauge Symmetry

Realistic Theories:

P. F. P., M. B. Wise, JHEP1108, 068

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

P. F. P., S. Ohmer, H. H. Patel, Physics Letters B735, 283

P. F. P., Physics Reports 597

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

P. F. P., S. Ohmer, H. H. Patel

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	$-\frac{3}{2}$

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

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	$\frac{3}{2}$

P. F. P., S. Ohmer, H. H. Patel

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

$\Psi_L \sim (1,\ 2,\ 1/2,\ 3/2),$ $\Psi_R \sim (1,\ 2,\ 1/2,\ -3/2),$

$\Sigma_L \sim (1,\ 3,\ 0,\ -3/2),$ $\chi_L \sim (1,\ 1,\ 0,\ -3/2)\,.$

$$-\mathcal{L} \supset Y_\nu\ \bar{\ell}_L \tilde{H} \nu_R \ +\ y_\Psi \bar{\Psi}_L \Psi_R S_L \ +\ y_\Sigma \mathrm{Tr}(\Sigma_L \Sigma_L) S_L \ +\ y_\chi \chi_L \chi_L S_L \ +\ \text{h.c.}$$

New Higgs: $S_L \sim (1, 1, 0.3)$

$\Delta L = \pm 3$ → *Gauge Theory for Dirac Neutrinos !*

see also: M. Duerr, P. F. P., M. B. Wise, Phys. Rev. Lett.

Some Features:

Dark Matter: χ CDM Candidate from Anomaly Cancellation !

Leptophilic Gauge Boson: Z_L

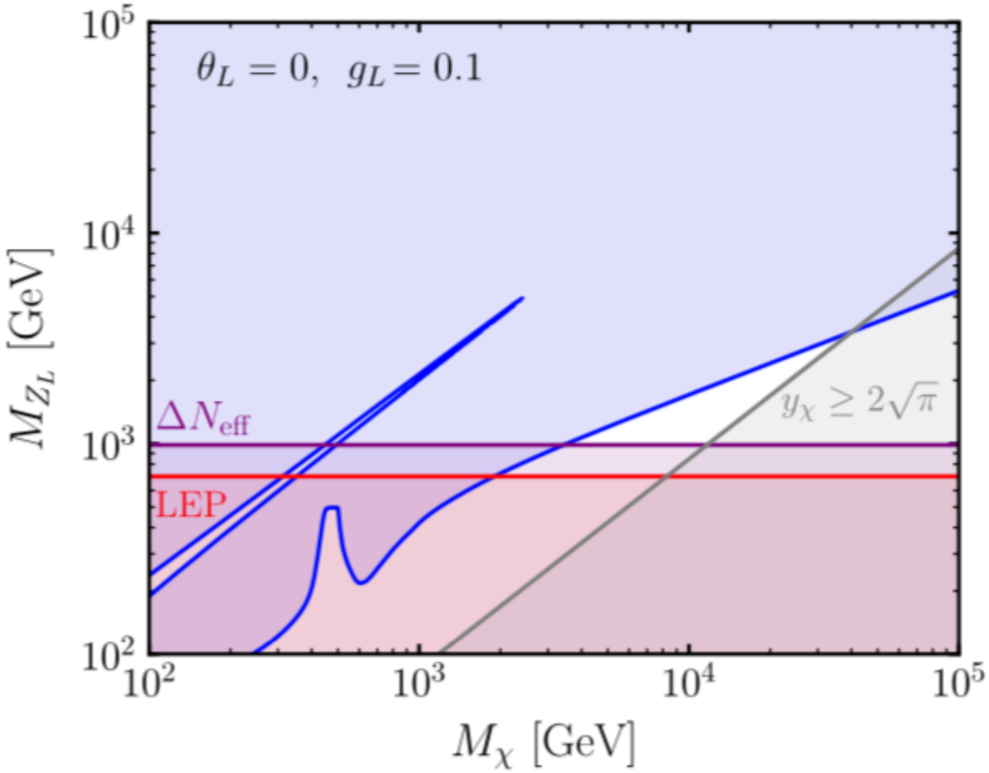
Symmetry Breaking:

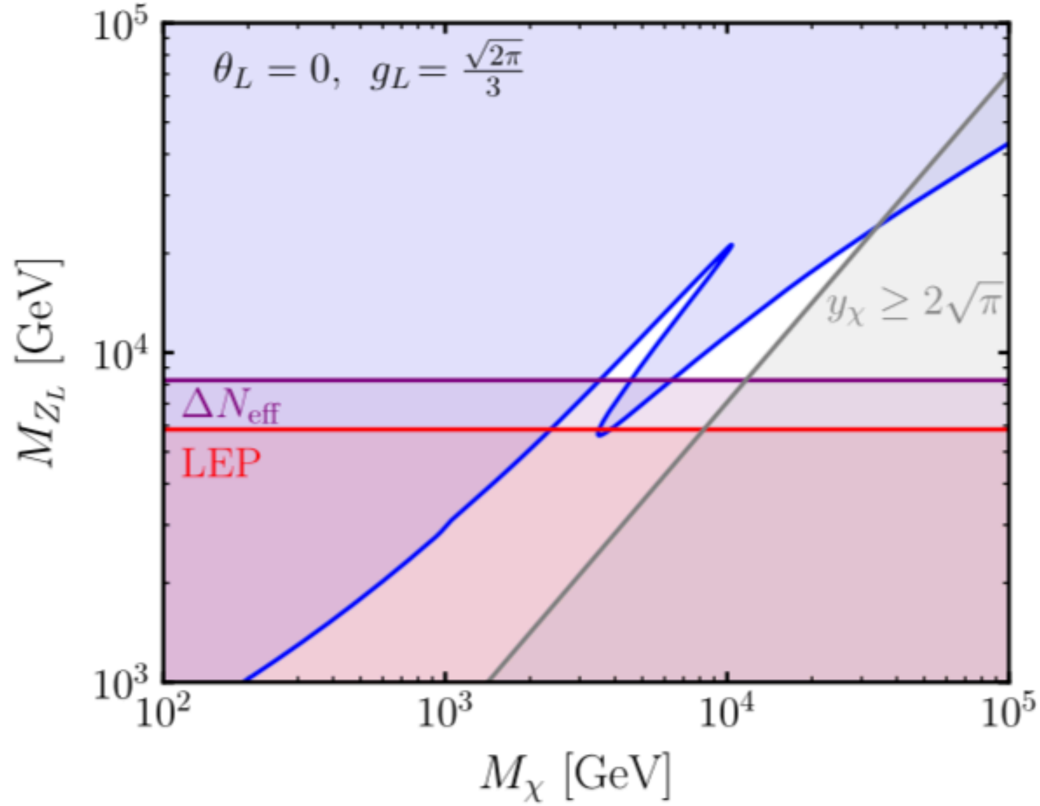
$$< S_L > \neq 0 \quad \Longrightarrow \quad U(1)_L \to \mathcal{Z}_2$$

$$\{\Psi_L \to -\Psi_L,\ \Psi_R \to -\Psi_R,\ \Sigma_L \to -\Sigma_L, \chi_L^0 \to -\chi_L^0\}.$$

P. F. P., C. Murgui, A.D. Plascencia, Phys. Rev. D100, 035041

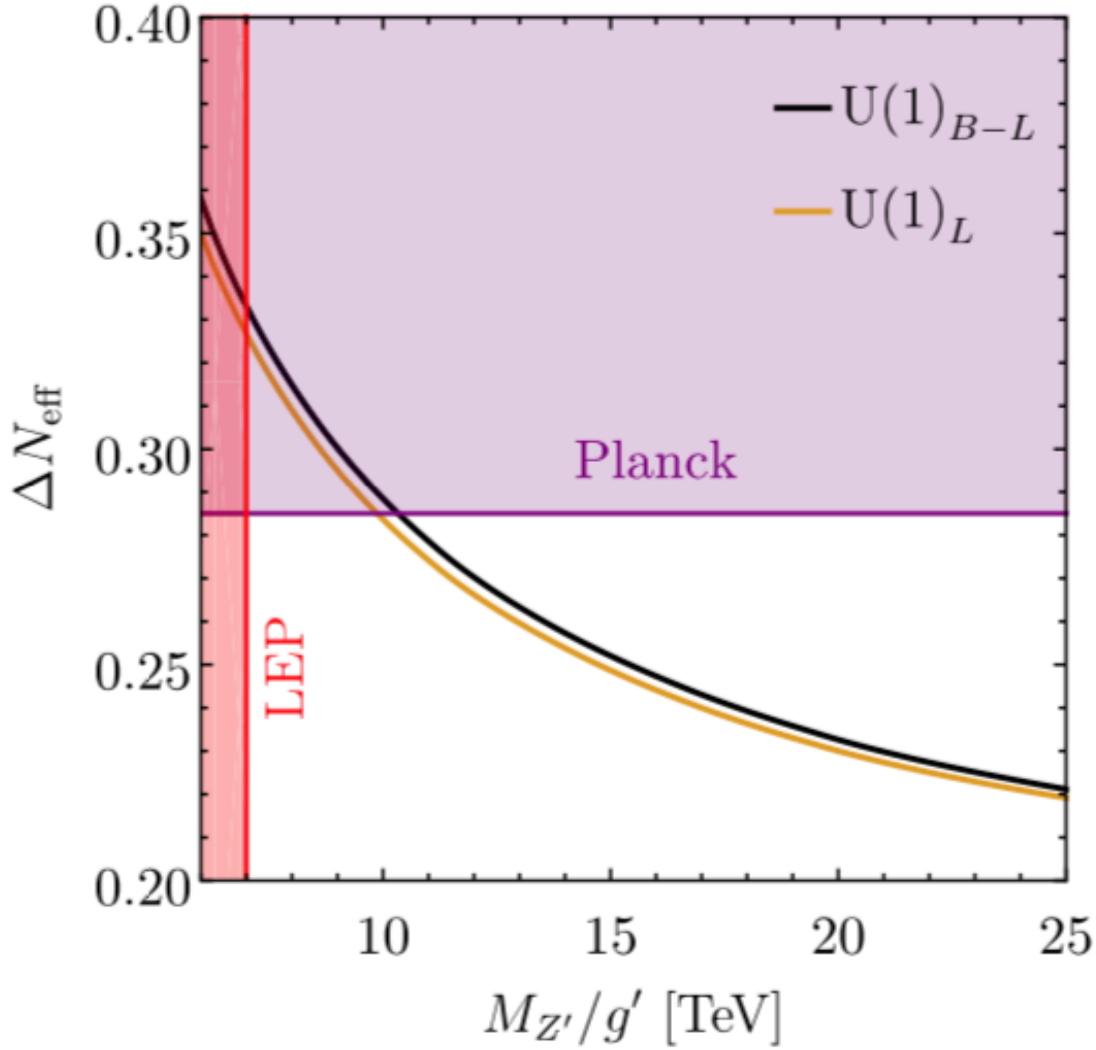
Leptophilic Dark Matter





The scale for Spontaneous L Violation must be below the multi-TeV scale !

Neff and Dirac Neutrinos



CMB-S4 $\rightarrow \Delta N_{eff} < 0.06$

Spontaneous Baryon Number Violation

P. Fileviez Perez

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

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

Fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_B$
$\Psi_L = \begin{pmatrix} \Psi_L^0 \\ \Psi_L^- \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	B_1
$\Psi_R = \begin{pmatrix} \Psi_R^0 \\ \Psi_R^- \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	B_2
η_R	$\mathbf{1}$	$\mathbf{1}$	-1	B_1
η_L	$\mathbf{1}$	$\mathbf{1}$	-1	B_2
χ_R	$\mathbf{1}$	$\mathbf{1}$	0	B_1
χ_L	$\mathbf{1}$	$\mathbf{1}$	0	B_2

$$B_2 - B_1 = 3$$

$$-\mathcal{L} \supset y_\Psi \bar{\Psi}_L \Psi_R S_B + \ldots$$

$$S_B \sim (1, 1, 0, -3)$$

$$\Delta B = \pm 3$$

Stable Proton !

Gauge Theory for Proton Stability !

Some Features:

Dark Matter: χ

CDM Candidate from Anomaly Cancellation

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

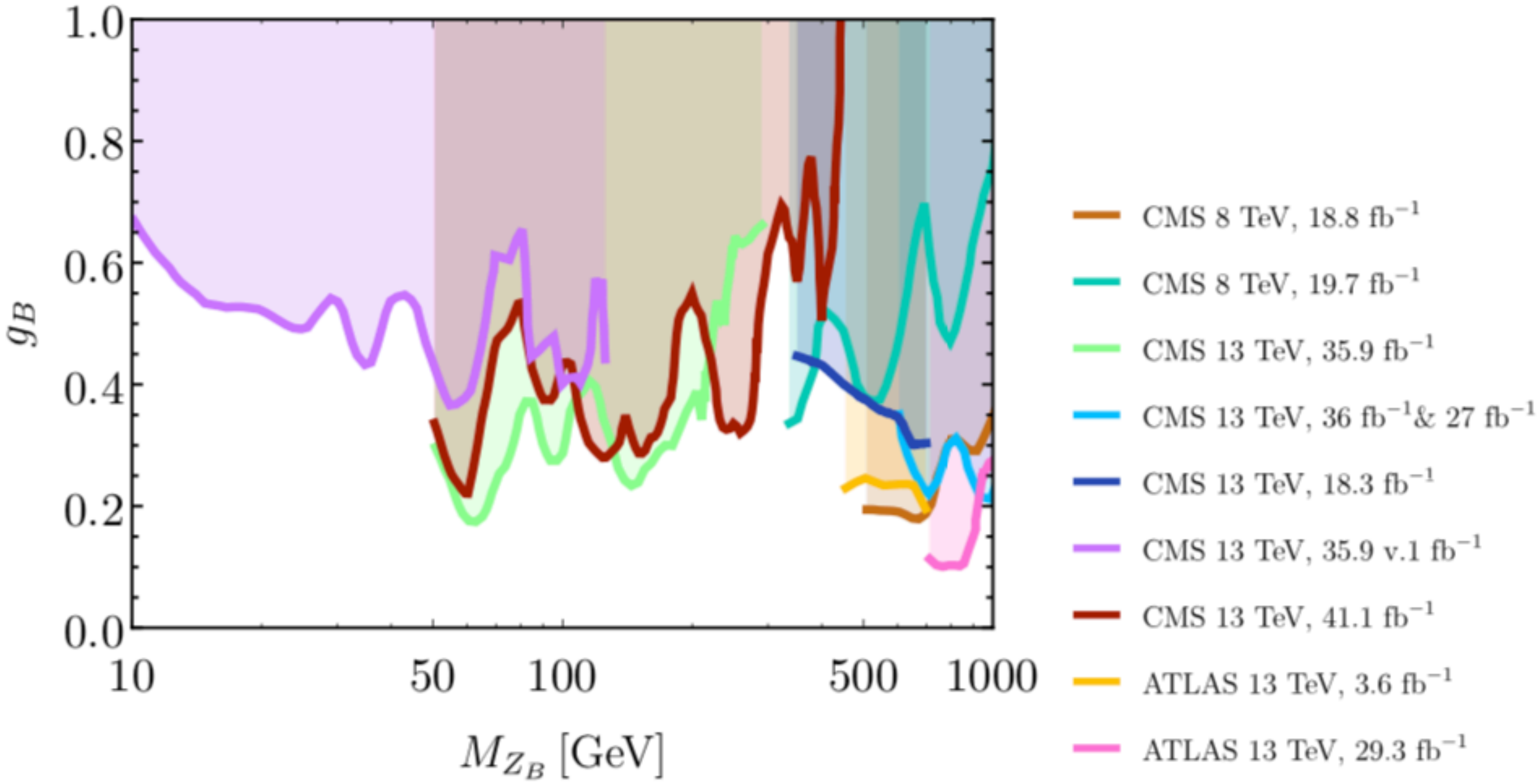
New Higgs Boson:

$$h_B \to \gamma\gamma,\ gg,\ \gamma Z,\ \gamma Z_B,\ ZZ,\ ZZ_B,\ Z_B Z_B,\ WW,\ \chi\chi,\ \overline{F_i}F_i,\ hh,\ \overline{f_i}f_i,$$

Signatures at the LHC: $pp \to Z_B h_B \to t\bar{t}\chi\chi \to t\bar{t}E_T^{miss}$

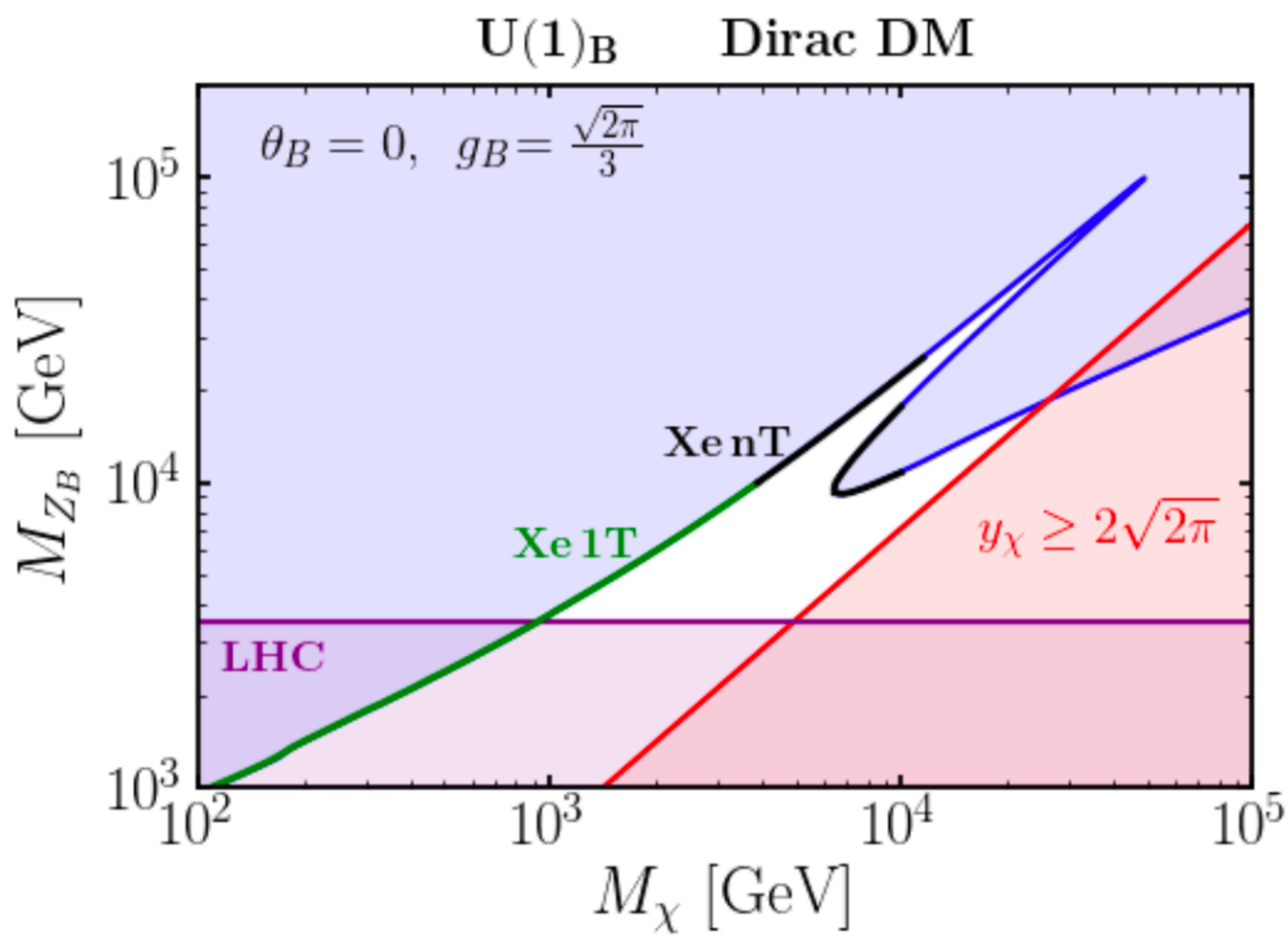
See: 2112.02103, 2103.13397, 2012.06599, 2008.09116, 2003.09426, …

Collider Bounds - Leptophobic Gauge Boson



P. F. P., A. D. Plascencia, Phys. Rev. D 105, 095021 (2022)

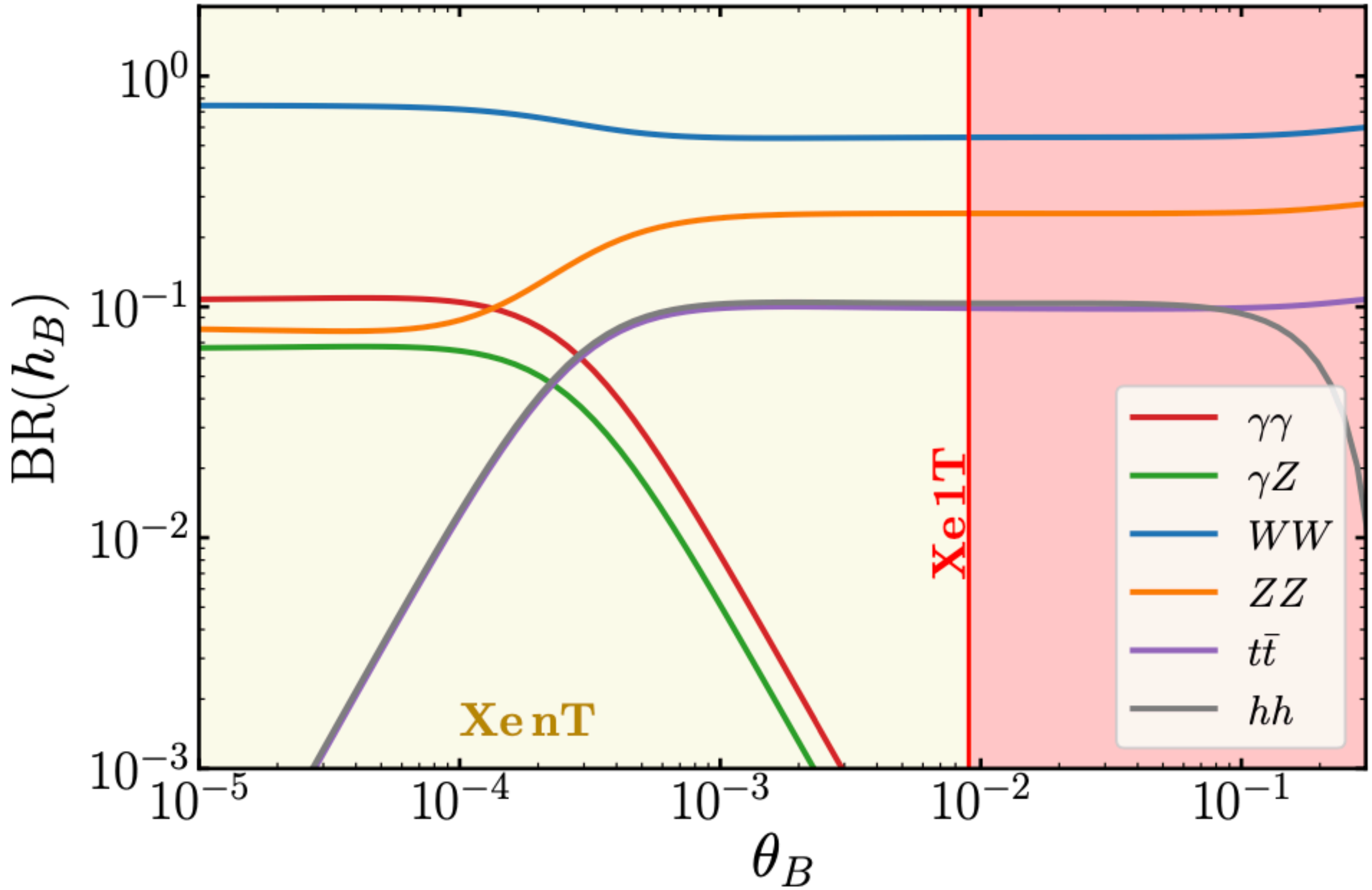
Dark Matter from Anomaly Cancellation



The scale for Spontaneous B Violation must be below the multi-TeV scale !

P. F. P., A. D. Plascencia, Phys. Rev. D 105, 095021 (2022)

Baryonic Higgs Decays



$g_B = 0.1$

$M_{h_B} = 400$ GeV

$M_{Z_B} = 1.14$ TeV

$M_\chi = 6.28$ TeV

$M_\eta = 6.7$ TeV

$M_\Psi = 7$ TeV

$\chi\bar{\chi} \to Z_B h_B$

$\Omega_{\mathrm{DM}} h^2 = 0.12$

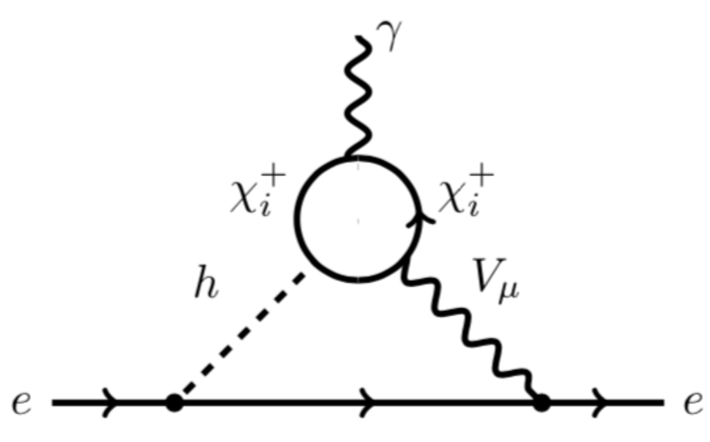
P. F. P., A. D. Plascencia, Phys. Rev. D 105, 095021 (2022)

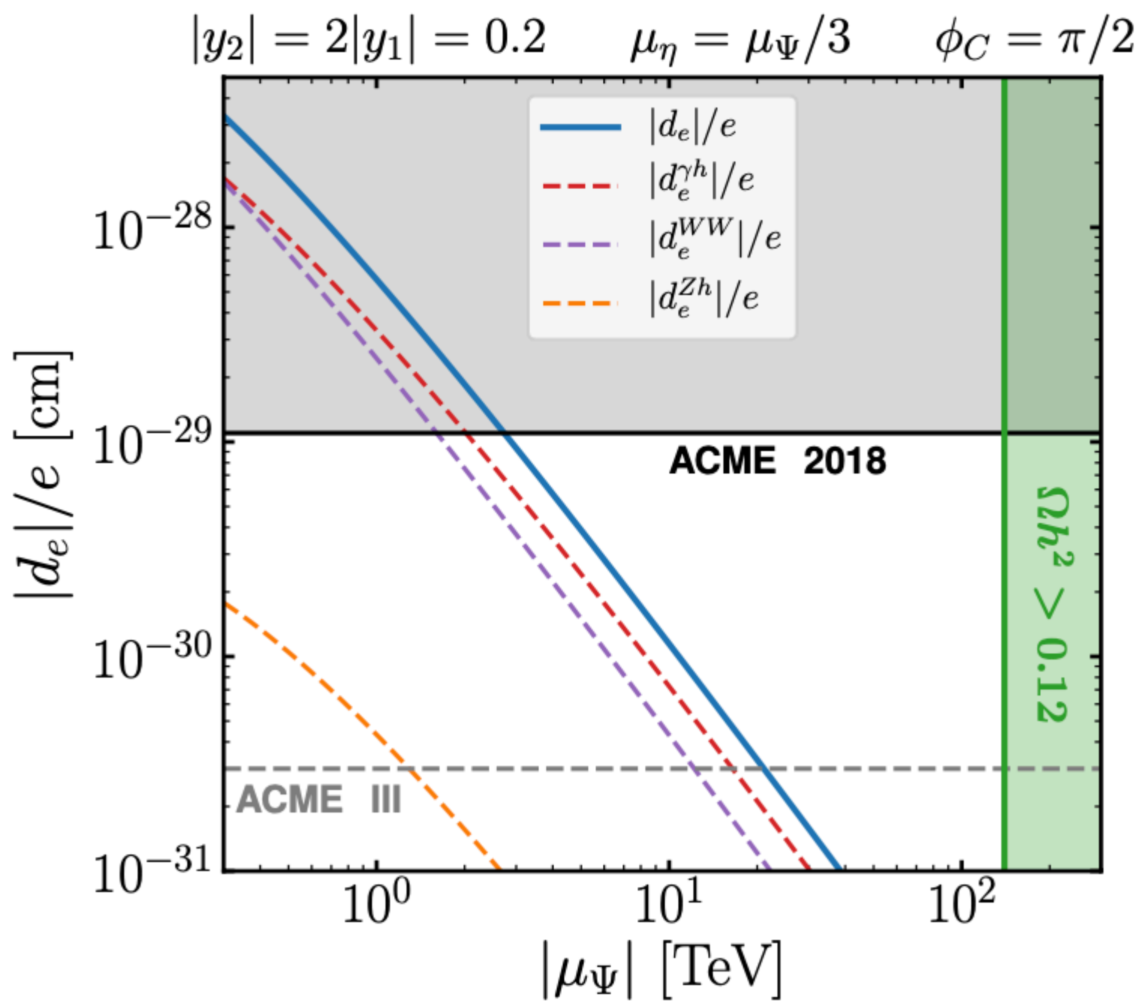
Predictions for EDMs

$$\phi_C = \arg(y_\eta y_\Psi^* y_1 y_2^*)$$

$$\frac{|d_e|}{e} < 1.1 \times 10^{-29} \text{ cm},$$

ACME exp
Nature 562, 355–360 (2018).

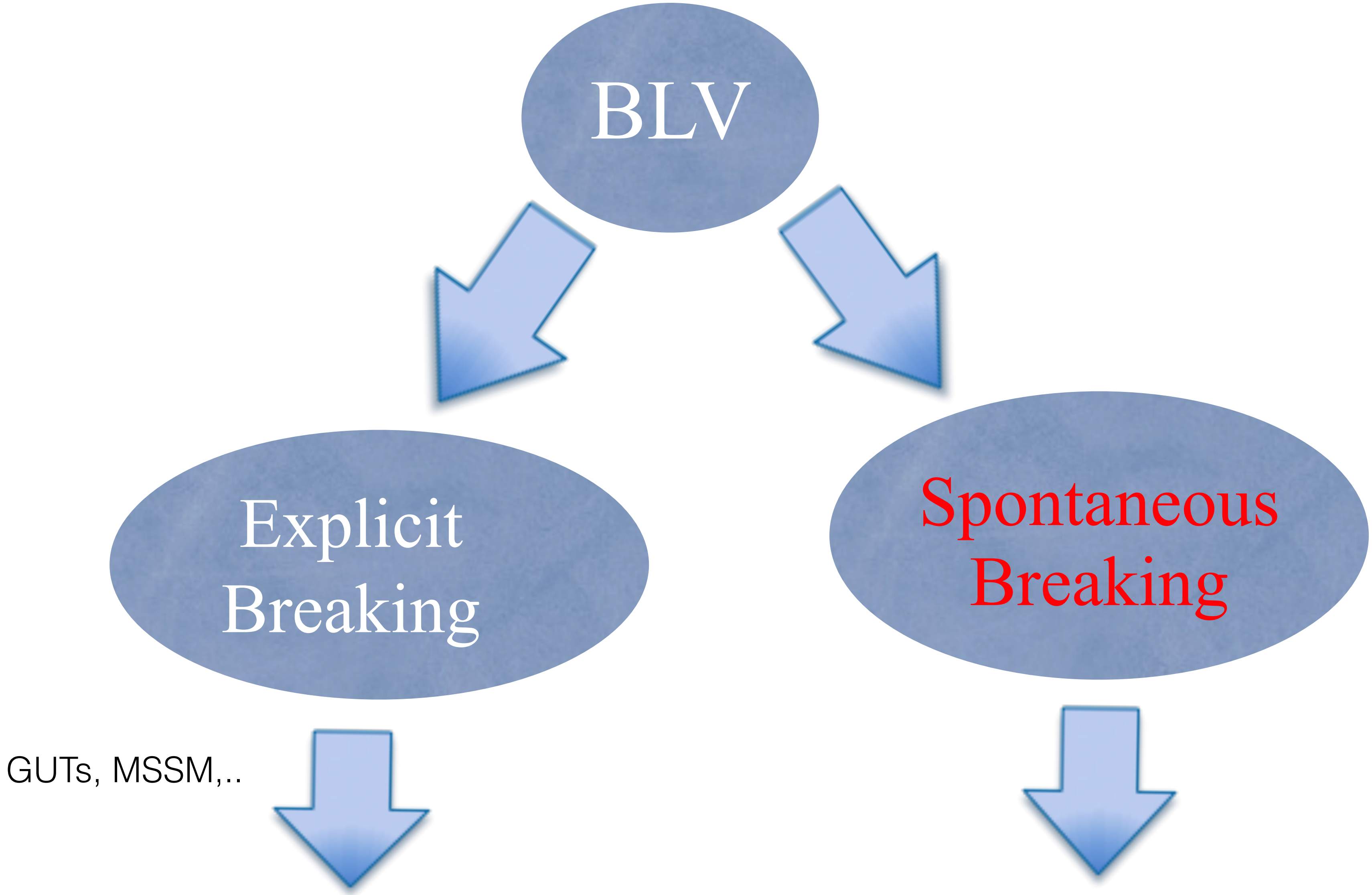




Spontaneous Baryon Number Violation

The minimal theories for Spontaneous B Breaking predict:

- Stable Proton
- Dark Matter candidate from Anomaly Cancellation
- The Symmetry Breaking Scale must be below the multi-TeV scale
- New sources for CP-violation
- Interesting correlation between the EDM and DM constraints
- Strong correlation between the Higgs decays and DM constraints
- Interesting signatures at colliders associated to DM



- Proton decay
- Majorana neutrinos

- Stable proton
- Dirac or Majorana neutrinos
- Low B and/or L Scale
- Dark Matter

THANK YOU !