

# Baryonic Dark Matter

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MAX-PLANCK-GESELLSCHAFT

Based on:

MD, P. Fileviez Pérez, M. B. Wise, PRL **110**, 231801 (2013)

MD, P. Fileviez Pérez, PLB **732** (2014) 101

MD, P. Fileviez Pérez, PRD **91**, 095001 (2015)

**PHENO 2015**

University of Pittsburgh

5 May 2015



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# The Great Desert

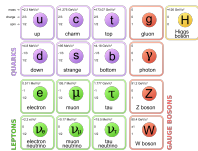
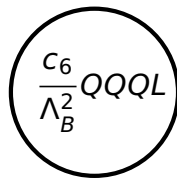


Figure: Wikipedia

Low scale  
Electroweak scale  
( $\Lambda_{EW} \sim 10^2$  GeV)



Figure: Wikipedia

S. Weinberg, PRL **43** (1979) 1566

High scale  
e.g. GUT scale  
( $\Lambda_{GUT} \sim 10^{15}$  GeV)

Energy →

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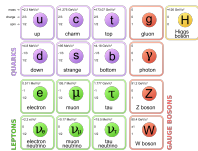
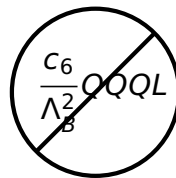


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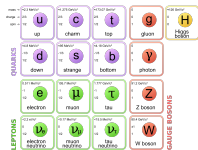


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Figure: Wikipedia

$$\frac{C_5}{\Lambda_L} LLHH$$

$$\frac{C_6}{\Lambda_B^2} QQQL$$

S. Weinberg, PRL 43 (1979) 1566

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e.g. GUT scale  
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Energy  $\rightarrow$

# The Great Desert

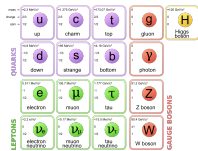
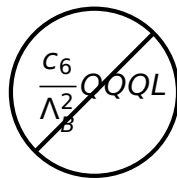


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S. Weinberg, PRL 43 (1979) 1566

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Energy →

# The Great Desert

$$\frac{c_5}{\Lambda_L} LLHH$$

up	charm	top	gluon	Higgs boson
down	strange	bottom	photon	
electron	muon	tau	Z boson	
electron neutrino	muon neutrino	tau neutrino	W boson	

Figure: Wikipedia

Low scale  
Electroweak scale  
( $\Lambda_{EW} \sim 10^2$  GeV)



Figure: Wikipedia

~~$$\frac{c_6}{\Lambda_B^2} QQQL$$~~

S. Weinberg, PRL 43 (1979) 1566

High scale  
e.g. GUT scale  
( $\Lambda_{GUT} \sim 10^{15}$  GeV)

Energy

# What I will talk about today

Phenomenological aspects of a  
consistent gauge theory for  
baryon and lepton numbers  
that can be broken at the low scale.

# Baryonic and Leptonic Anomalies

- ▶ New gauge group:

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

- ▶ Purely baryonic anomalies:

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

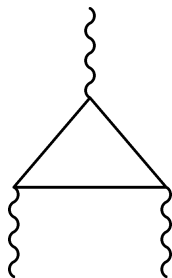
- ▶ Purely leptonic anomalies:

$$\mathcal{A}_7 (SU(3)^2 \otimes U(1)_L), \mathcal{A}_8 (SU(2)^2 \otimes U(1)_L), \mathcal{A}_9 (U(1)_Y^2 \otimes U(1)_L), \\ \mathcal{A}_{10} (U(1)_Y \otimes U(1)_L^2), \mathcal{A}_{11} (U(1)_L), \mathcal{A}_{12} (U(1)_L^3).$$

- ▶ Mixed anomalies:

$$\mathcal{A}_{13} (U(1)_B^2 \otimes U(1)_L), \mathcal{A}_{14} (U(1)_L^2 \otimes U(1)_B), \\ \mathcal{A}_{15} (U(1)_Y \otimes U(1)_L \otimes U(1)_B).$$

Field	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_B$	$U(1)_L$
$Q_L$	<b>3</b>	<b>2</b>	$\frac{1}{6}$	$\frac{1}{3}$	0
$u_R$	<b>3</b>	<b>1</b>	$\frac{2}{3}$	$\frac{1}{3}$	0
$d_R$	<b>3</b>	<b>1</b>	$-\frac{1}{3}$	$\frac{1}{3}$	0
$\ell_L$	<b>1</b>	<b>2</b>	$-\frac{1}{2}$	0	1
$\nu_R$	<b>1</b>	<b>1</b>	0	0	1
$e_R$	<b>1</b>	<b>1</b>	-1	0	1
$H$	<b>1</b>	<b>2</b>	$\frac{1}{2}$	0	0





# Baryonic and Leptonic Anomalies

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- ▶ Purely baryonic anomalies:

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

- ▶ Purely leptonic anomalies:

$$\mathcal{A}_7 (SU(3)^2 \otimes U(1)_L), \mathcal{A}_8 (SU(2)^2 \otimes U(1)_L), \mathcal{A}_9 (U(1)_Y^2 \otimes U(1)_L), \\ \mathcal{A}_{10} (U(1)_Y \otimes U(1)_L^2), \mathcal{A}_{11} (U(1)_L), \mathcal{A}_{12} (U(1)_L^3).$$

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Field	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_B$	$U(1)_L$
$Q_L$	<b>3</b>	<b>2</b>	$\frac{1}{6}$	$\frac{1}{3}$	0
$u_R$	<b>3</b>	<b>1</b>	$\frac{2}{3}$	$\frac{1}{3}$	0
$d_R$	<b>3</b>	<b>1</b>	$-\frac{1}{3}$	$\frac{1}{3}$	0
$\ell_L$	<b>1</b>	<b>2</b>	$-\frac{1}{2}$	0	1
$\nu_R$	<b>1</b>	<b>1</b>	0	0	1
$e_R$	<b>1</b>	<b>1</b>	-1	0	1
$H$	<b>1</b>	<b>2</b>	$\frac{1}{2}$	0	0

SM + right-handed  $\nu$ 's

$$\mathcal{A}_2 = -\mathcal{A}_3 = \frac{3}{2}, \\ \mathcal{A}_8 = -\mathcal{A}_9 = \frac{3}{2}$$

# Baryonic and Leptonic Anomalies

- ▶ New gauge group:

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

Field	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_B$	$U(1)_L$
$Q_L$	<b>3</b>	<b>2</b>	$\frac{1}{6}$	$\frac{1}{3}$	0
$u_R$	<b>3</b>	<b>1</b>	$\frac{2}{3}$	$\frac{1}{3}$	0
$d_R$	<b>3</b>	<b>1</b>	$-\frac{1}{3}$	$\frac{1}{3}$	0
$e_R$	<b>1</b>	<b>1</b>	-1	0	-1
$\nu_R$	<b>1</b>	<b>1</b>	0	0	-1

## Some History

- ▶ Early attempts to gauge  $B$  and  $L$ 
  - ▶ A. Pais, PRD **8**, 1844 (1973)
  - ▶ S. Rajpoot, Int. J. Theor. Phys. **27**, 689 (1988)
  - ▶ R. Foot, G. C. Joshi, H. Lew, PRD **40**, 2487 (1989)
  - ▶ C. D. Carone, H. Murayama, PRD **52**, 484 (1995)
  - ▶ H. Georgi, S. L. Glashow, PLB **387**, 341 (1996)
- ▶ First realistic model
  - ▶ P. Fileviez Pérez, M.B. Wise, PRD **82**, 011901 (2010)

- ▶ Mixed anomalies:

$$\mathcal{A}_{13} (U(1)_B^2 \otimes U(1)_L), \quad \mathcal{A}_{14} (U(1)_L^2 \otimes U(1)_B),$$

$$\mathcal{A}_{15} (U(1)_Y \otimes U(1)_L \otimes U(1)_B).$$

$$\mathcal{A}_8 = -\mathcal{A}_9 = \frac{4}{2}$$

## Solution: Vector-Like Lepto-Baryons

Field	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_B$	$U(1)_L$
$\Psi_L$	<b>1</b>	<b>2</b>	$\pm\frac{1}{2}$	$B_1$	$L_1$
$\Psi_R$	<b>1</b>	<b>2</b>	$\pm\frac{1}{2}$	$B_2$	$L_2$
$\eta_R$	<b>1</b>	<b>1</b>	$\pm 1$	$B_1$	$L_1$
$\eta_L$	<b>1</b>	<b>1</b>	$\pm 1$	$B_2$	$L_2$
$\chi_R$	<b>1</b>	<b>1</b>	0	$B_1$	$L_1$
$\chi_L$	<b>1</b>	<b>1</b>	0	$B_2$	$L_2$

Anomaly cancellation demands:  $B_1 - B_2 = L_1 - L_2 = -3$

MD, P. Fileviez Perez, M. B. Wise, arXiv:1304.0576 [hep-ph] (PRL)

## Simple Version: Baryon Number Only

- ▶ Gauge group:  $G_{SM} \otimes U(1)_B$
- ▶ Additional fields for an anomaly-free theory:

$$\begin{aligned} \Psi_L &\sim (\mathbf{1}, \mathbf{2}, -1/2, B_1), & \Psi_R &\sim (\mathbf{1}, \mathbf{2}, -1/2, B_2), \\ \eta_R &\sim (\mathbf{1}, \mathbf{1}, -1, B_1), & \eta_L &\sim (\mathbf{1}, \mathbf{1}, -1, B_2), \\ \chi_R &\sim (\mathbf{1}, \mathbf{1}, 0, B_1), & \chi_L &\sim (\mathbf{1}, \mathbf{1}, 0, B_2), \end{aligned}$$

- ▶ New Higgs for spontaneous breaking of  $B$ :  $S_B$
- ▶ Condition from anomaly cancellation:  $B_1 - B_2 = -3$ .

MD, P. Fileviez Pérez, arXiv:1309.3970 [hep-ph] (PLB)

# Spontaneous Symmetry Breaking

- ▶ Relevant interactions of the new fields (for  $B_1 \neq -B_2$ ):

$$-\mathcal{L} \supset h_1 \bar{\Psi}_L H \eta_R + h_2 \bar{\Psi}_L \tilde{H} \chi_R + h_3 \bar{\Psi}_R H \eta_L + h_4 \bar{\Psi}_R \tilde{H} \chi_L \\ + \lambda_1 \bar{\Psi}_L \Psi_R S_B + \lambda_2 \bar{\eta}_R \eta_L S_B + \lambda_3 \bar{\chi}_R \chi_L S_B + \text{h.c.}$$

$$S_B \sim (\mathbf{1}, \mathbf{1}, 0, B_1 - B_2)$$

- ▶  $\langle S_B \rangle \neq 0$  generates vector-like masses:

$$-\mathcal{L} \supset M_\Psi \bar{\Psi}_L \Psi_R + M_\eta \bar{\eta}_R \eta_L + M_\chi \bar{\chi}_R \chi_L + \text{h.c.}$$

$$S_B \sim (\mathbf{1}, \mathbf{1}, 0, -3) \rightarrow \Delta B = 3 \Rightarrow \text{no proton decay!}$$

- ▶ Remnant  $\mathcal{Z}_2$  stabilizes lightest new fermion.

# Baryonic Dark Matter

- ▶ Dirac DM, SM singlet-like:  $\chi = \chi_R + \chi_L$
- ▶ Coupling to the new gauge boson:

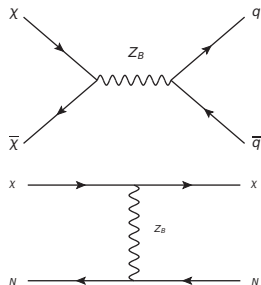
$$\mathcal{L} \supset g_B \bar{\chi} \gamma_\mu Z_B^\mu (B_2 P_L + B_1 P_R) \chi$$

Annihilation and direct detection!

- ▶ Model has six free parameters:

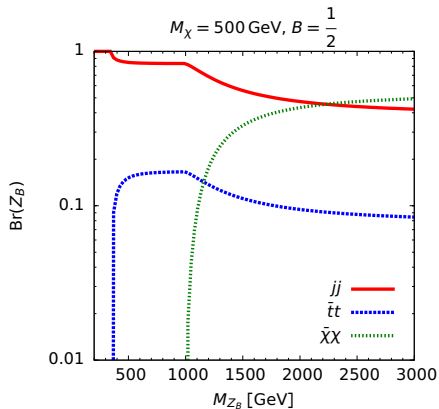
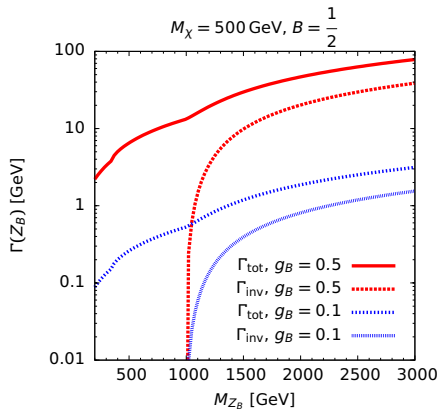
$$M_\chi, M_{Z_B}, g_B, B \equiv B_1 + B_2 \text{ and } M_{h_2}, \theta_B$$

$\Rightarrow$  testable by combining LHC, DM direct detection, DM relic density.



MD, P. Fileviez Pérez, arXiv:1409.8165 [hep-ph] (PRD)

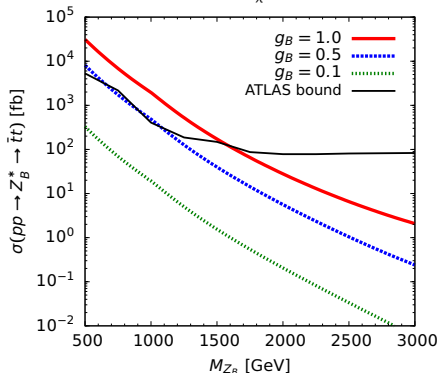
# Decays of the new Gauge Boson $Z_B$



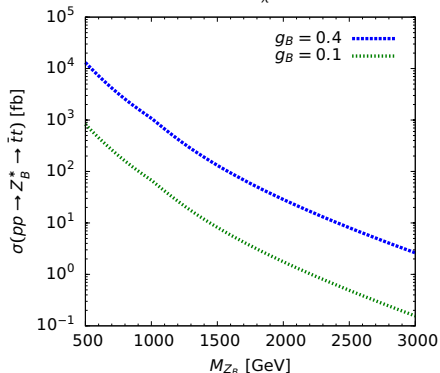
MD, P. Fileviez Pérez, [arXiv:1409.8165](https://arxiv.org/abs/1409.8165) [hep-ph] (PRD)

# LHC Bounds: $pp \rightarrow Z_B^* \rightarrow \bar{t}t$

$\sqrt{s} = 8 \text{ TeV}, M_\chi = 500 \text{ GeV}$



$\sqrt{s} = 14 \text{ TeV}, M_\chi = 500 \text{ GeV}$

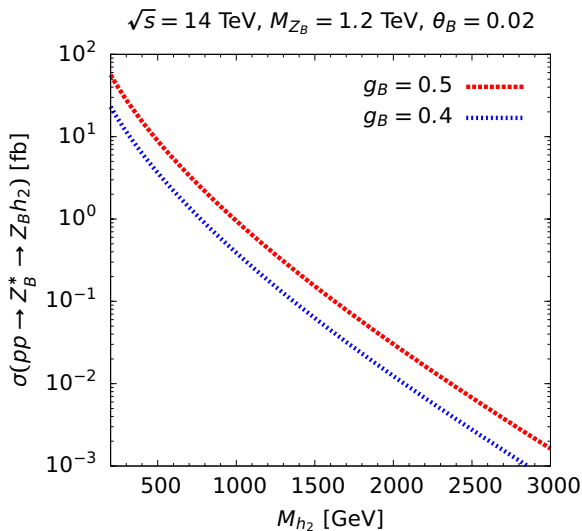


$$\sigma(\bar{q}q \rightarrow Z_B^* \rightarrow \bar{t}t)(\hat{s}) = \frac{g_B^4 \sqrt{\hat{s} - 4M_t^2}}{972\pi\sqrt{\hat{s}}} \frac{(2M_t^2 + \hat{s})}{\left[ (\hat{s} - M_{Z_B}^2)^2 + M_{Z_B}^2 \Gamma_{Z_B}^2 \right]}$$

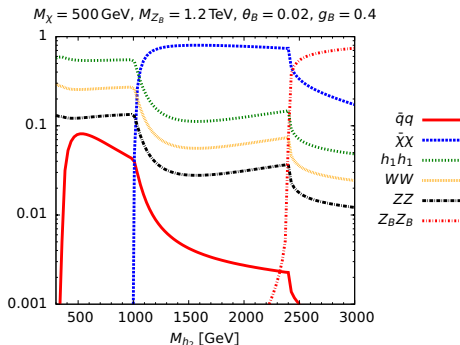
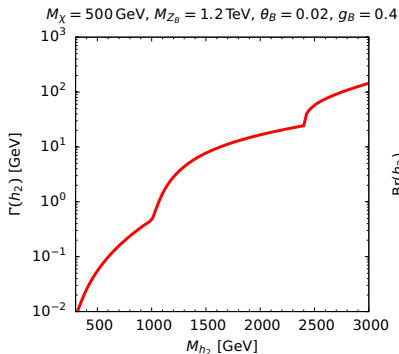
ATLAS-CONF-2013-052



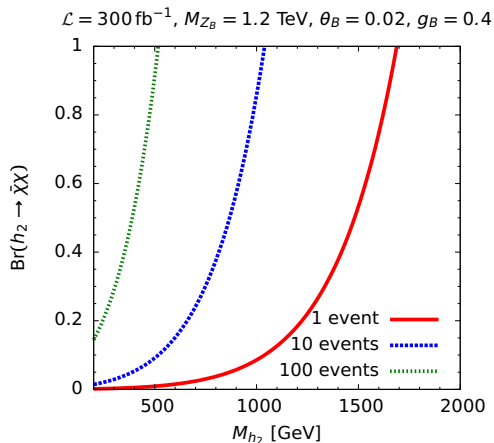
# Associated Production: $pp \rightarrow Z_B^* \rightarrow Z_B h_2$



# Decays of the new Heavy Higgs $h_2$

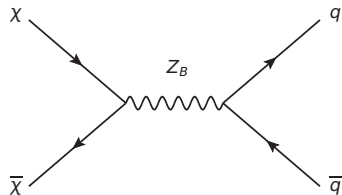
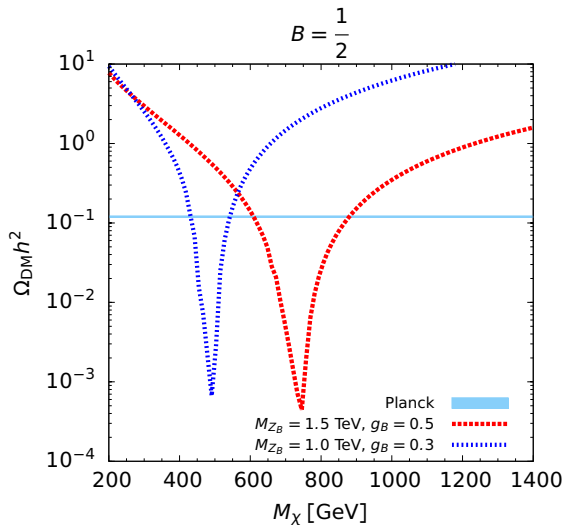


# $\bar{t}t$ Plus Missing Energy



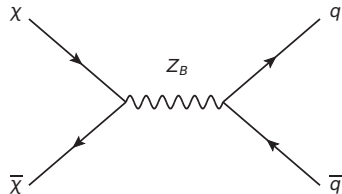
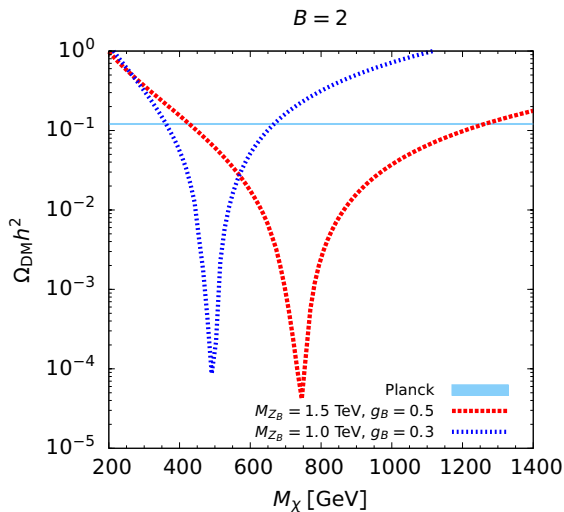
$$N(\bar{t}tE_T^{\text{miss}}) = \mathcal{L} \times \sigma(pp \rightarrow Z_B h_2) \times \text{Br}(Z_B \rightarrow \bar{t}t) \times \text{Br}(h_2 \rightarrow \bar{\chi}\chi)$$

# Dark Matter Relic Density



► Planck:  $\Omega_{\text{DM}} h^2 = 0.1199 \pm 0.0027$

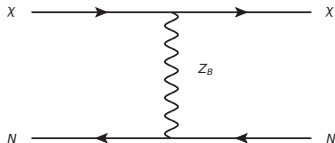
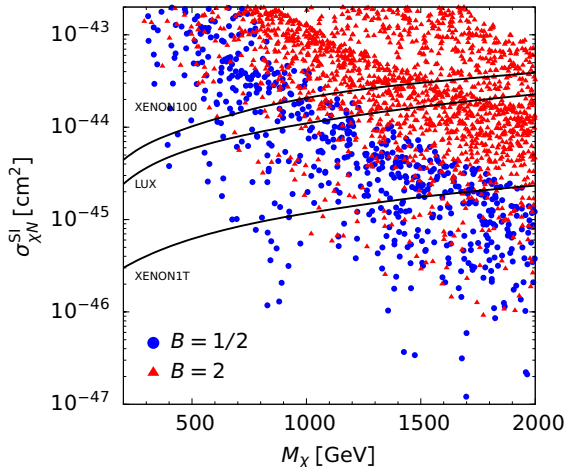
# Dark Matter Relic Density



► Planck:  $\Omega_{\text{DM}} h^2 = 0.1199 \pm 0.0027$

# Dark Matter Direct Detection

$$\Omega_{\text{DM}} h^2 = 0.1199 \pm 0.0027$$



► Planck:  $\Omega_{\text{DM}} h^2 = 0.1199 \pm 0.0027$

$$M_{Z_B} \in [0.5, 5.0] \text{ TeV}$$

$$g_B \in [0.1, 0.5]$$

## Bound on the Symmetry Breaking Scale

- ▶ Unsuppressed terms in the annihilation cross section:

$$\sum_q \sigma v(\bar{\chi}\chi \rightarrow Z_B^* \rightarrow \bar{q}q) = \frac{g_B^4 M_\chi^2}{2\pi} \frac{(B_1 + B_2)^2}{\left[ (4M_\chi^2 - M_{Z_B}^2)^2 + M_{Z_B}^2 \Gamma_{Z_B}^2 \right]}$$

- ▶ Using  $\Omega_{\text{DM}} h^2 \leq 0.12$  and  $M_\chi = \lambda_\chi v_B / \sqrt{2}$  and  $M_{Z_B} = 3g_B v_B$ , one obtains

$$v_B^2 \leq \frac{g_B^4 \lambda_\chi^2 (B_1 + B_2)^2 \cdot 1.77 \times 10^9 \text{ GeV}^2}{\pi \left[ (2\lambda_\chi^2 - 9g_B^2)^2 + \frac{9}{4\pi^2} g_B^8 \right] \chi_f}$$

- ▶ For  $\chi_f = 20$  and  $B_1 + B_2 = 1/2$ :

$$M_{Z_B} \leq 35.3 \text{ TeV} \text{ and } M_\chi \leq 17.7 \text{ TeV}$$

# Summary

## Baryonic Dark Matter:

- ▶  $B$  (and  $L$ ) are gauge symmetries that can be broken at the low scale
- ▶ no proton decay  $\Rightarrow$  no need for a desert
- ▶ Fermionic DM candidate
- ▶ Testable at the LHC



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# Thank you!



# Backup slides

## Other Solution for Anomaly Cancellation

$$\Psi_L \sim (\mathbf{1}, \mathbf{2}, \frac{1}{2}, \frac{3}{2}, \frac{3}{2}),$$

$$\Psi_R \sim (\mathbf{1}, \mathbf{2}, \frac{1}{2}, -\frac{3}{2}, -\frac{3}{2})$$

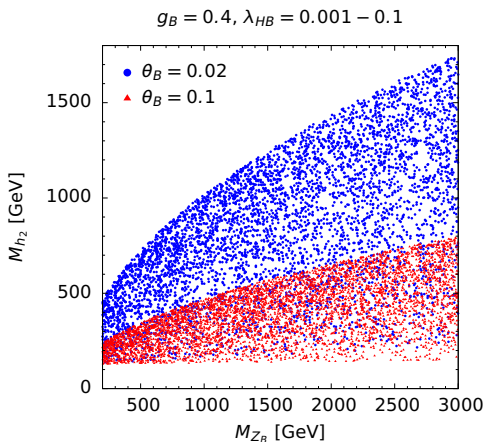
$$\Sigma_L \sim (\mathbf{1}, \mathbf{3}, 0, -\frac{3}{2}, -\frac{3}{2}),$$

$$\chi_L \sim (\mathbf{1}, \mathbf{1}, 0, -\frac{3}{2}, -\frac{3}{2})$$

P. Fileviez Pérez, S. Ohmer, H. H. Patel, [arXiv:1403.8029](https://arxiv.org/abs/1403.8029) [hep-ph]

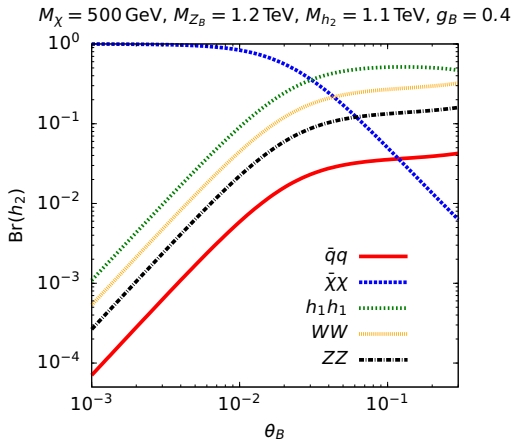
- ▶ Less representations
- ▶ Same degrees of freedom after symmetry breaking
- ▶ Majorana dark matter

# Mass of the Heavy Higgs $h_2$



$$M_{h_2}^2 = M_{h_1}^2 + \frac{2}{3g_B} |\csc 2\theta_B| v_0 M_{Z_B} \lambda_{HB}$$

# Mixing Angle in the Higgs Sector



# Gauging $B$ and $L$ in a SUSY Setup

## ▶ BLMSSM:

J. M. Arnold, P. Fileviez Pérez, B. Fornal, S. Spinner, [arXiv:1310.7052 \[hep-ph\]](https://arxiv.org/abs/1310.7052)

- ▶  $U(1)_B$  and  $U(1)_L$  breaking scale linked to SUSY breaking scale
- ▶ R-parity must be spontaneously broken
- ▶ Stable DM candidate

# Symmetries of the Model

- ▶ Symmetries of the Model:

- ▶  $(B - L)_{\text{SM}}$

- ▶ Accidental  $\eta$  symmetry in the new sector:

$$\Psi_{L,R} \rightarrow e^{i\eta} \Psi_{L,R},$$

$$\eta_{L,R} \rightarrow e^{i\eta} \eta_{L,R},$$

$$\chi_{L,R} \rightarrow e^{i\eta} \chi_{L,R}.$$

⇒ DM stability

- ▶ Total baryon number  $B_T$  (above symmetry-breaking scale)

Assume that scale for baryon number breaking is low, close to the EW scale.

# Baryon and Dark Matter Asymmetries

- ▶ For  $\mu \ll T$ :

$$\frac{\Delta n}{s} = \frac{n_+ - n_-}{s} = \frac{15g}{2\pi^2 g_* \xi} \frac{\mu}{T}$$

$g$ : internal degrees of freedom,  
 $s$ : entropy density,  
 $g_*$ : total number of relativistic  
degrees of freedom,  
 $\xi = 2$  for fermions,  
 $\xi = 1$  for bosons

- ▶  $B - L$  asymmetry in the SM sector

$$\Delta(B - L)_{\text{SM}} = \frac{45}{4\pi^2 g_* T} (\mu_{u_L} + \mu_{u_R} + \mu_{d_L} + \mu_{d_R} - \mu_{\nu_L} - \mu_{e_L} - \mu_{e_R}),$$

- ▶  $\eta$  charge density

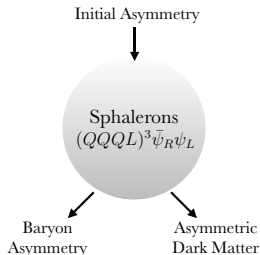
$$\Delta\eta = \frac{15}{4\pi^2 g_* T} (2\mu_{\psi_L} + 2\mu_{\psi_R} + \mu_{\chi_L} + \mu_{\chi_R} + \mu_{\eta_L} + \mu_{\eta_R}).$$

P. Fileviez Pérez, H. H. Patel, [arXiv:1311.6472](https://arxiv.org/abs/1311.6472) [hep-ph]



# Baryon and Dark Matter Asymmetries

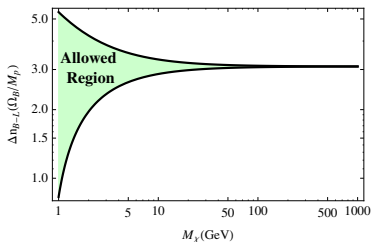
$$B_f^{\text{SM}} \equiv \frac{15}{4\pi^2 g_* T} (12\mu_{u_L}) = \frac{32}{99} \Delta(B-L)_{\text{SM}} + \frac{(15 - 14B_2)}{198} \Delta\eta,$$



$$3(3\mu_{u_L} + \mu_{e_L}) + \mu_{\psi_L} - \mu_{\psi_R} = 0.$$

$$|n_\chi - n_{\bar{\chi}}| \leq n_{\text{DM}}$$

$$\Omega_\chi \leq 5 \Omega_B$$



P. Fileviez Pérez, H. H. Patel, [arXiv:1311.6472 \[hep-ph\]](https://arxiv.org/abs/1311.6472)

# Left-Right Symmetric Model

$$G_{LR} = SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$

SM fields

- ▶ Connects neutrino masses and spontaneous parity violation.
- ▶ Standard version uses hybrid version of type I and type II seesaw mechanism for neutrino masses.

$$Q_L \sim (\mathbf{2}, \mathbf{1}, 1/3)$$

$$Q_R \sim (\mathbf{1}, \mathbf{2}, 1/3)$$

$$\ell_L \sim (\mathbf{2}, \mathbf{1}, -1)$$

$$\ell_R \sim (\mathbf{1}, \mathbf{2}, -1)$$

Pati, Salam, PRD **10** (1974) 275, Mohapatra, Pati, PRD **11** (1975) 2558, Senjanovic, Mohapatra, PRD **12** (1975) 1502

- ▶ Promote gauge group

$$\Rightarrow SU(2)_L \otimes SU(2)_R \otimes U(1)_B \otimes U(1)_L$$

He, Rajpoot, PRD **41** (1990) 1636

# Anomaly Cancellation: Type III Seesaw

- ▶ Anomalies that need to be cancelled:

$$\mathcal{A}_1 (SU(2)_L^2 \otimes U(1)_B) = 3/2$$

$$\mathcal{A}_2 (SU(2)_L^2 \otimes U(1)_L) = 3/2$$

$$\mathcal{A}_3 (SU(2)_R^2 \otimes U(1)_B) = -3/2$$

$$\mathcal{A}_4 (SU(2)_R^2 \otimes U(1)_L) = -3/2$$

- ▶ Simplest solution: type III seesaw fields

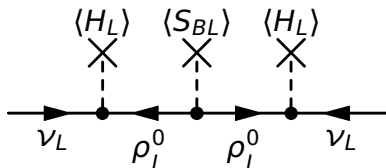
$$\rho_L \sim (\mathbf{3}, \mathbf{1}, -3/4, -3/4),$$

$$\rho_R \sim (\mathbf{1}, \mathbf{3}, -3/4, -3/4)$$

- ▶ Neutrino mass matrix:

$$\mathcal{M}_\nu^{3+2} = \begin{pmatrix} 0 & 0 & 0 & m_D^1 & m_D^2 \\ 0 & m_1 & 0 & m_D^3 & m_D^4 \\ 0 & 0 & m_2 & m_D^5 & m_D^6 \\ m_D^1 & m_D^3 & m_D^5 & 0 & 0 \\ m_D^2 & m_D^4 & m_D^6 & 0 & 0 \end{pmatrix}.$$

- ▶ Two light sterile neutrinos.



MD, P. Fileviez Pérez, M. Lindner, arXiv:1306.0568 [hep-ph] (PRD)