Baryonic Dark Matter

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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)

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Weak Interactions and Neutrinos

MPIK Heidelberg

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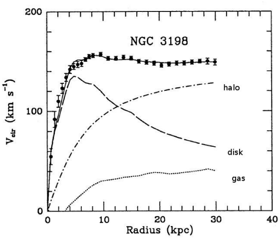
We need a stable dark matter particle!

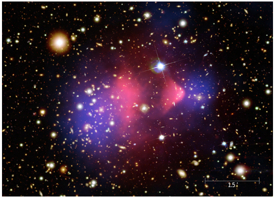
Rotation curves

Bullet cluster

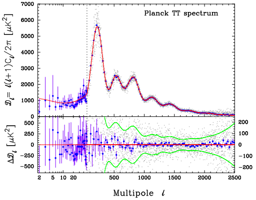
CMB



Begeman et al., MNRAS **249** (1991) 523



NASA



Planck Collaboration, arXiv:1303.5076 [astro-ph.CO]

The Great Desert

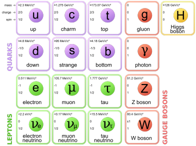


Figure: Wikipedia

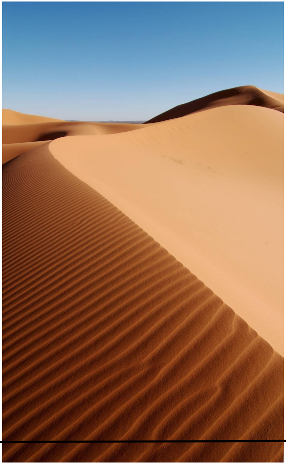


Figure: Wikipedia

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

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

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

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

Energy

The Great Desert

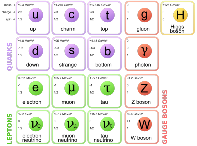


Figure: Wikipedia

Figure: Wikipedia

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

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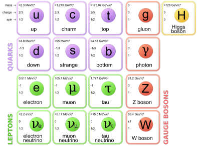

Figure: Wikipedia

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

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

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

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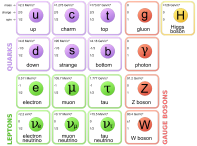

Figure: Wikipedia

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Figure: Wikipedia

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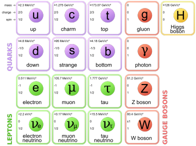

Figure: Wikipedia

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Low scale

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e.g. GUT scale

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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:

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

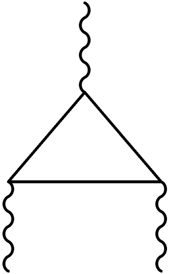
- Purely leptonic anomalies:

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

- Mixed anomalies:

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

Field	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_B$	$U(1)_L$
Q_L	**3**	**2**	$\frac{1}{6}$	$\frac{1}{3}$	0
u_R	**3**	**1**	$\frac{2}{3}$	$\frac{1}{3}$	0
d_R	**3**	**1**	$-\frac{1}{3}$	$\frac{1}{3}$	0
ℓ_L	**1**	**2**	$-\frac{1}{2}$	0	1
ν_R	**1**	**1**	0	0	1
e_R	**1**	**1**	-1	0	1
H	**1**	**2**	$\frac{1}{2}$	0	0



Baryonic and Leptonic Anomalies

- New gauge group:

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

- Purely leptonic anomalies:

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

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u_R	**3**	**1**	$\frac{2}{3}$	$\frac{1}{3}$	0
d_R	**3**	**1**	$-\frac{1}{3}$	$\frac{1}{3}$	0
ℓ_L	**1**	**2**	$-\frac{1}{2}$	0	1
ν_R	**1**	**1**	0	0	1
e_R	**1**	**1**	-1	0	1
H	**1**	**2**	$\frac{1}{2}$	0	0

SM + right-handed ν

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

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

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	**3**	**2**	$\frac{1}{6}$	$\frac{1}{3}$	0
					0
					0
					1
					1
					1
					0

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:

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

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

Solution: Vector-Like Lepto-Baryons

Field	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_B$	$U(1)_L$
Ψ_L	$\mathbf{1}$	$\mathbf{2}$	$\pm\frac{1}{2}$	B_1	L_1
Ψ_R	$\mathbf{1}$	$\mathbf{2}$	$\pm\frac{1}{2}$	B_2	L_2
η_R	$\mathbf{1}$	$\mathbf{1}$	± 1	B_1	L_1
η_L	$\mathbf{1}$	$\mathbf{1}$	± 1	B_2	L_2
χ_R	$\mathbf{1}$	$\mathbf{1}$	0	B_1	L_1
χ_L	$\mathbf{1}$	$\mathbf{1}$	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)

Other Solution for Anomaly Cancellation

$$\Psi_L \sim \left(\mathbf{1}, \mathbf{2}, \frac{1}{2}, \frac{3}{2}, \frac{3}{2}\right), \qquad \Psi_R \sim \left(\mathbf{1}, \mathbf{2}, \frac{1}{2}, -\frac{3}{2}, -\frac{3}{2}\right)$$

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

P. Fileviez Pérez, S. Ohmer, H. H. Patel, arXiv:1403.8029 [hep-ph]

S. Ohmer, H. H. Patel, arXiv:1506.00954 [hep-ph]

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

→ Talk by Sebastian Ohmer this morning

Solution: Vector-Like Lepto-Baryons

Field	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_B$	$U(1)_L$
Ψ_L	$\mathbf{1}$	$\mathbf{2}$	$\pm\frac{1}{2}$	B_1	L_1
Ψ_R	$\mathbf{1}$	$\mathbf{2}$	$\pm\frac{1}{2}$	B_2	L_2
η_R	$\mathbf{1}$	$\mathbf{1}$	± 1	B_1	L_1
η_L	$\mathbf{1}$	$\mathbf{1}$	± 1	B_2	L_2
χ_R	$\mathbf{1}$	$\mathbf{1}$	0	B_1	L_1
χ_L	$\mathbf{1}$	$\mathbf{1}$	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: $G_{\text{SM}} \otimes U(1)_B$
- 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 $B_1 \neq -B_2$):

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

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

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

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

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

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

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

Baryonic Dark Matter

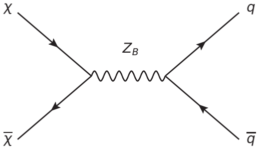
- Dirac DM, SM singlet-like: $\chi = \chi_R + \chi_L$
- Coupling to the new gauge boson:

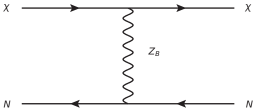
$$\mathcal{L} \supset g_B \overline{\chi} \gamma_\mu Z_B^\mu (B_2 P_L + B_1 P_R) \chi$$

Annihilation and direct detection!

- Model has six free parameters:

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

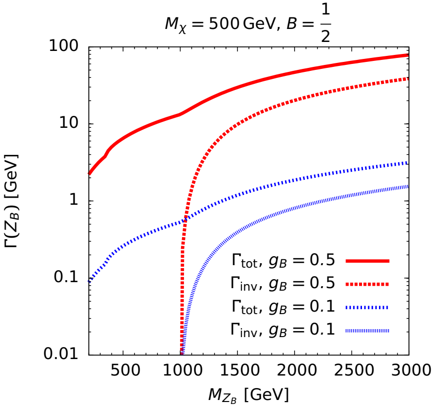


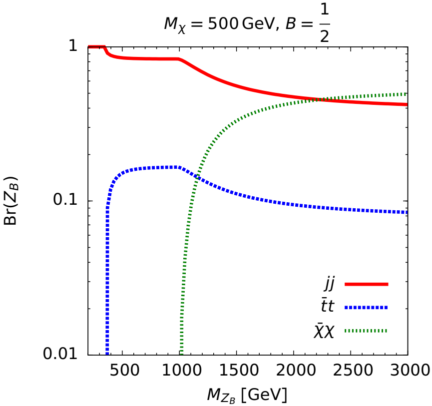


$\Longrightarrow$ testable by combining LHC, DM direct detection, DM relic density.

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

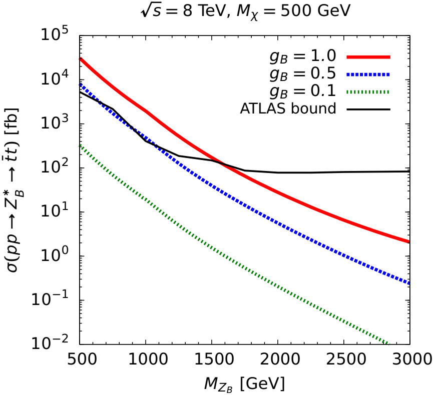
Decays of the new Gauge Boson Z_B

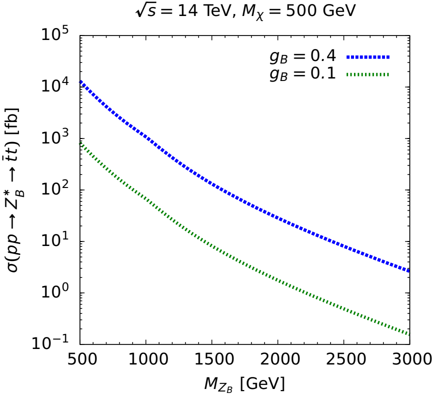




MD, P. Fileviez Pérez, arXiv:1409.8165 [hep-ph]

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

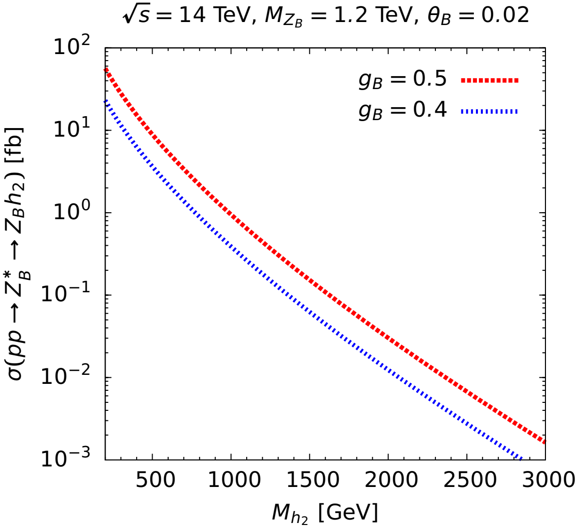




$$\sigma(\bar{q}q \to Z_B^* \to \bar{t}t)(\hat{s}) = \frac{g_B^4 \sqrt{\hat{s} - 4M_t^2}}{972\pi\sqrt{\hat{s}}} \frac{\left(2M_t^2 + \hat{s}\right)}{\left[(\hat{s} - M_{Z_B}^2)^2 + M_{Z_B}^2 \Gamma_{Z_B}^2\right]}$$

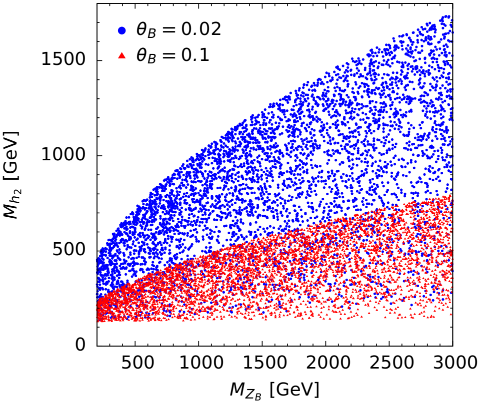
ATLAS-CONF-2013-052

Associated Production: $pp \to Z_B^* \to Z_B h_2$



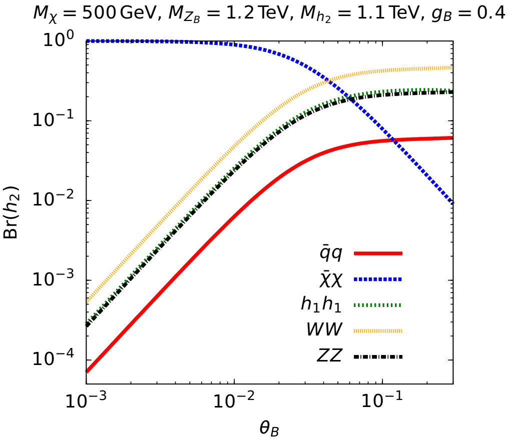
Mass of the Heavy Higgs h_2

$g_B = 0.4,\ \lambda_{HB} = 0.001 - 0.1$

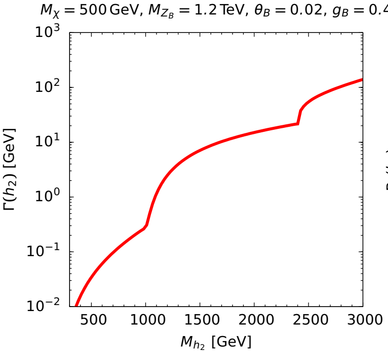


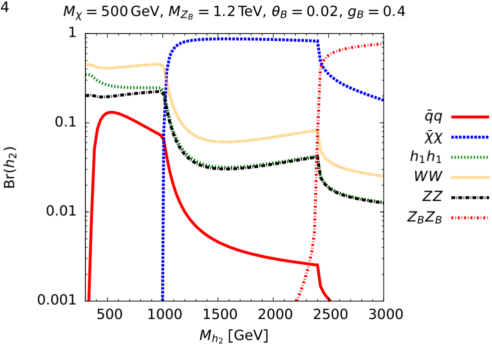
$$M_{h_2}^2 = M_{h_1}^2 + \frac{2}{3g_B}|\csc 2\theta_B|\ v_0\ M_{Z_B}\lambda_{HB}$$

Mixing Angle in the Higgs Sector

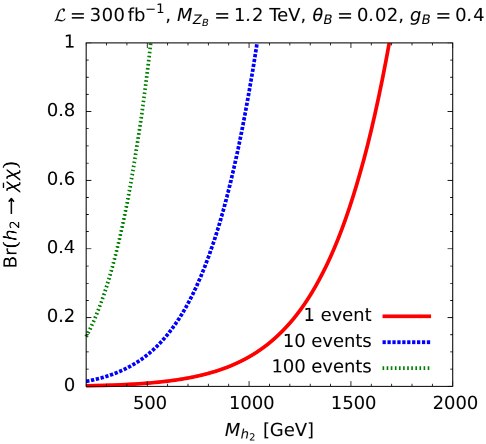


Decays of the new Heavy Higgs h_2



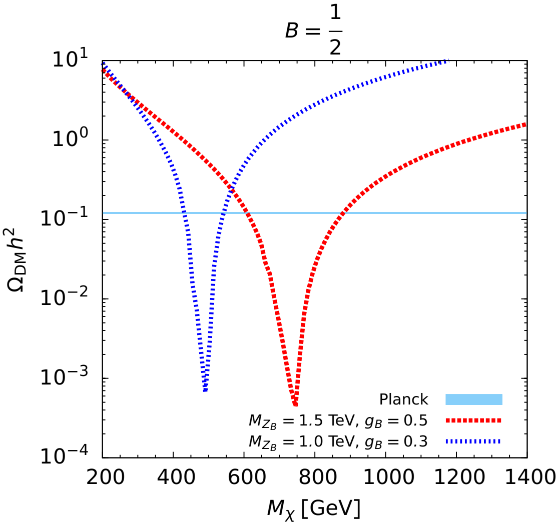


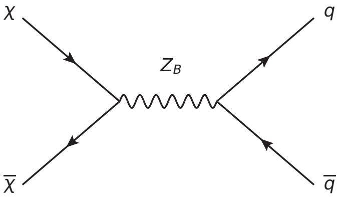
$\bar{t}t$ Plus Missing Energy



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

Dark Matter Relic Density





- Planck: $\Omega_{\mathrm{DM}} h^2 = 0.1199 \pm 0.0027$

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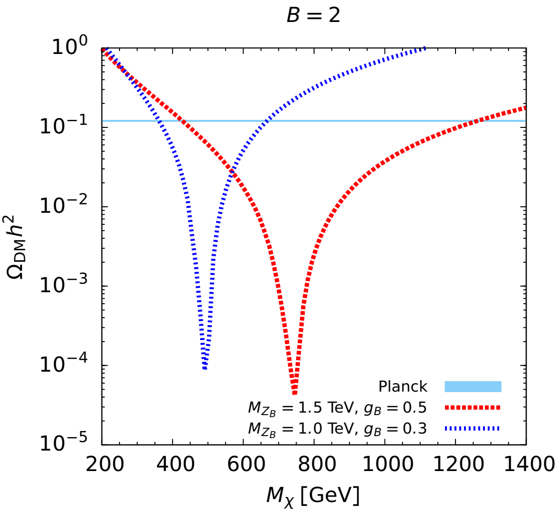

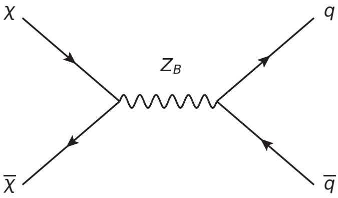

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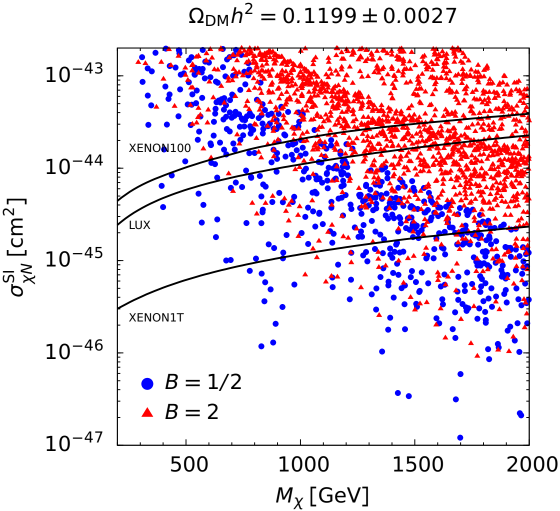
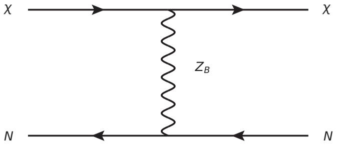
Dark Matter Direct Detection





- Planck: $\Omega_{\rm DM} h^2 = 0.1199 \pm 0.0027$

$$M_{Z_B} \in [0.5, 5.0] \text{ TeV}$$
$$g_B \in [0.1, 0.5]$$

Bound on the Symmetry Breaking Scale

- Unsuppressed terms the in annihilation cross section:

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

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

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

- For $x_f = 20$ and $B_1 + B_2 = 1/2$:

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

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

Summary

Baryonic Dark Matter:

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

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Thank you!

Backup slides

Gauging B and L in a SUSY Setup

- BLMSSM: J. M. Arnold, P. Fileviez Pérez, B. Fornal, S. Spinner, arXiv:1310.7052 [hep-ph]
  - $U(1)_B$ 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:
  - $(B-L)_{\mathrm{SM}}$
  - Accidental η symmetry in the new sector:

$$\Psi_{L,R} \to e^{i\eta}\Psi_{L,R},$$
$$\eta_{L,R} \to e^{i\eta}\eta_{L,R},$$
$$\chi_{L,R} \to e^{i\eta}\chi_{L,R}.$$

$\Rightarrow$ 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

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

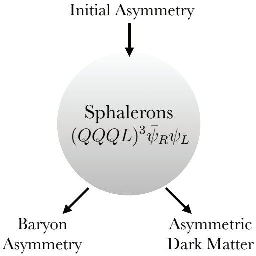
- η charge density

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

P. Fileviez Pérez, H. H. Patel, arXiv:1311.6472 [hep-ph]

Baryon and Dark Matter Asymmetries

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


Initial Asymmetry

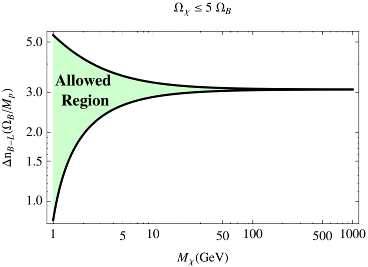
Sphalerons
$(QQQL)^3\bar{\psi}_R\psi_L$

Baryon Asymmetry

Asymmetric Dark Matter

$$3(3\mu_{u_L} + \mu_{e_L}) + \mu_{\Psi_L} - \mu_{\Psi_R} = 0.$$

$$|n_\chi - n_{\overline{\chi}}| \leq n_{\mathrm{DM}}$$



P. Fileviez Pérez, H. H. Patel, arXiv:1311.6472 [hep-ph]

Left–Right Symmetric Model

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

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

SM fields

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

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

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

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

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

- Promote gauge group

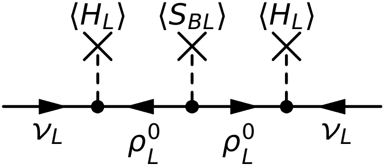
$$\Rightarrow SU(2)_L \otimes SU(2)_R \otimes U(1)_B \otimes U(1)_L$$

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

Anomaly Cancellation: Type III Seesaw

- Anomalies that need to be cancelled:

$$\mathcal{A}_1\left(SU(2)_L^2 \otimes U(1)_B\right) = 3/2$$
$$\mathcal{A}_2\left(SU(2)_L^2 \otimes U(1)_L\right) = 3/2$$
$$\mathcal{A}_3\left(SU(2)_R^2 \otimes U(1)_B\right) = -3/2$$
$$\mathcal{A}_4\left(SU(2)_R^2 \otimes U(1)_L\right) = -3/2$$



- 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)