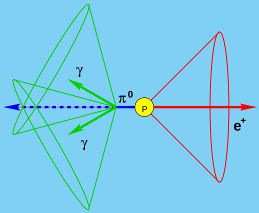
Gauge Theories for Baryon and Lepton Numbers.

Baryonic Dark Matter at the LHC



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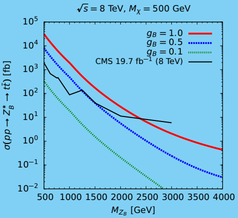


Michael Duerr
LHC Ski 2016
Obergurgl, 13 April 2016

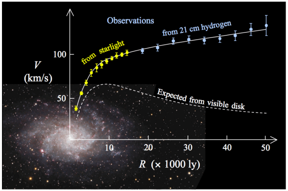
Based on.

- Phys. Rev. Lett. **110**, 231801 (2013) [arXiv:1304.0576 [hep-ph]]
- Phys. Lett. B **732** (2014) 101 [arXiv:1309.3970 [hep-ph]]
- Phys. Rev. D **91**, 095001 (2015) [arXiv:1409.8165 [hep-ph]]
- Phys. Rev. D **92**, 083521 (2015) [arXiv:1506.05107 [hep-ph]]
- Phys. Rev. D **93**, 023509 (2016) [arXiv:1508.01425 [hep-ph]]

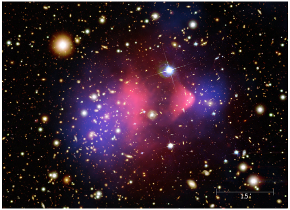
With Pavel Fileviez Pérez (MPIK/Caltech), Juri Smirnov (MPIK),
Mark B. Wise (Caltech)

Dark Matter in the Universe.

Rotation curves



Bullet cluster



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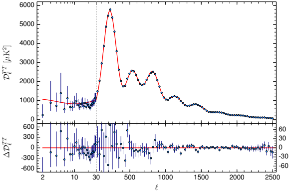
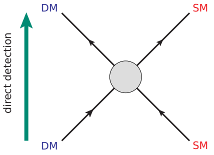
CMB



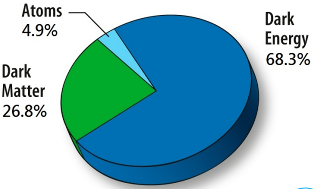
Planck Collaboration, arXiv:1502.01589 [astro-ph.CO]



thermal freeze-out (early Univ.)
indirect detection (now)

direct detection

production at colliders



The Standard Model of Particle Physics.

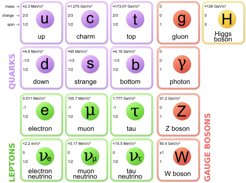


Figure: Wikipedia

- Standard Model gauge group:

$$G_{\mathrm{SM}} = SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

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

The Standard Model of Particle Physics.

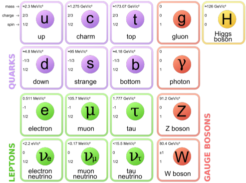


Figure: Wikipedia

- $U(1)'$ gauge extension of the SM:

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

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_B$	$U(1)_L$
Q_L	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$1/3$	0
u_R	$\mathbf{3}$	$\mathbf{1}$	$2/3$	$1/3$	0
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e_R	$\mathbf{1}$	$\mathbf{1}$	-1	0	1
H	$\mathbf{1}$	$\mathbf{2}$	$1/2$	0	0

Motivation: Baryon and Lepton Numbers.

B and *L* are accidental global symmetries in the SM

- Violation of *B*:
  - Baryon asymmetry of the Universe:

$$(n_B - n_{\bar{B}})/n_\gamma \sim 10^{-10}$$

  - Proton decay ($\Delta B = 1$, $\Delta L = \text{odd}$):

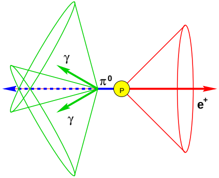
$$\tau_p \geq 10^{32-34}\,\text{years}$$

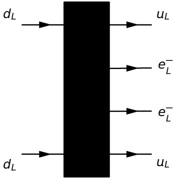
- Violation of *L*:
  - ν oscillation experiments:

$$\Delta L_e \neq 0,\ \Delta L_\mu \neq 0,\ \Delta L_\tau \neq 0$$

  - Total lepton number could be conserved (test with $0\nu\beta\beta$)

Figure: B. Viren, arXiv:hep-ex/9903029





The Great Desert.

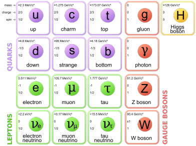


Figure: Wikipedia

Figure: Wikipedia

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

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

Low scale

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

High scale

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

Energy

The Great Desert.

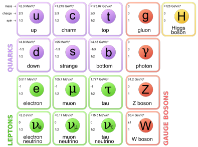


Figure: Wikipedia

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

Figure: Wikipedia

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

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

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

Energy

The Great Desert.

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

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

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

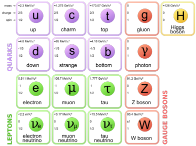


Figure: Wikipedia

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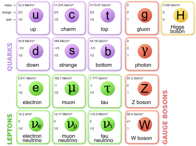

Figure: Wikipedia

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

Figure: Wikipedia

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

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

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The Great Desert.

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

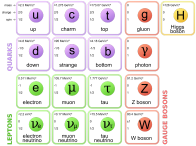


Figure: Wikipedia

Figure: Wikipedia

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

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

Low scale

Electroweak scale

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

High scale

e.g. GUT scale

($\Lambda_{GUT} \sim 10^{15}$ GeV)

Energy

Plan of the Talk.

Phenomenological aspects of
consistent gauge theories 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:

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

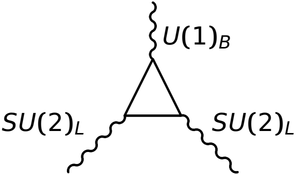
- Purely leptonic anomalies:

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

- 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:

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

> 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

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:

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)

2

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

- Mixed anomalies:

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

First Realistic Models are Ruled Out.

- Sequential/Mirror family: P. Fileviez Pérez, M. B. Wise, arXiv:1002.1754 [hep-ph]

  Ruled out: new quarks change gluon fusion Higgs production.

- Vector-like quarks: P. Fileviez Pérez, M. B. Wise, arXiv:1106.0343 [hep-ph]

  Ruled out: new charged leptons reduce BR of $H \to \gamma\gamma$ by a factor of 3.

- One family of leptoquarks: P. V. Dong, H. N. Long, arXiv:1010.3818 [hep-ph]

  $$F_L \sim (3,2,0,-1,-1),\, j_R \sim (3,1,\frac{1}{2},-1,-1),\, k_R \sim (3,1,-\frac{1}{2},-1,-1).$$

  Ruled out: stable charged fields.

New Solution: Vector-Like Lepto-Baryons.

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

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

MD, P. Fileviez Pérez, M. B. Wise, arXiv:1304.0576 [hep-ph]

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** tomorrow.

New 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

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New Solution: Vector-Like Lepto-Baryons.

Field	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_B$
Ψ_L	$\mathbf{1}$	$\mathbf{2}$	$\pm\frac{1}{2}$	B_1
Ψ_R	$\mathbf{1}$	$\mathbf{2}$	$\pm\frac{1}{2}$	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

Anomaly cancellation demands: $B_1 - B_2 = -3$,

MD, P. Fileviez Pérez, M. B. Wise, arXiv:1304.0576 [hep-ph]

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

Spontaneous Symmetry Breaking.

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

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

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

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

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

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

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

Baryonic Dark Matter.

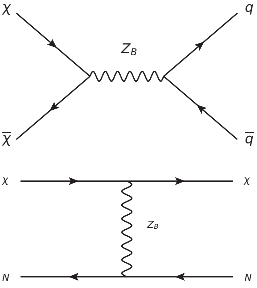
- Dirac DM, SM singlet-like: $\chi = \chi_R + \chi_L$
- Coupling to the new gauge boson:

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

DM annihilation and direct detection

- Model has only six free parameters:

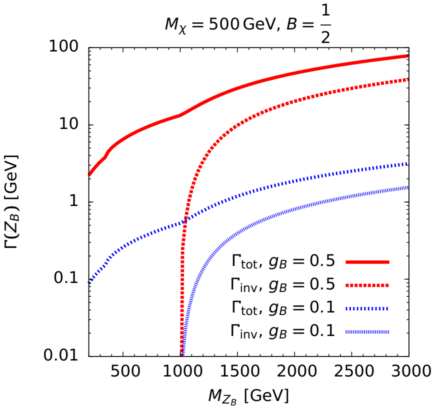
$$M_\chi, M_{Z_B}, g_B, B \equiv B_1 + B_2 \text{ and } M_{h_2}, \theta_B$$

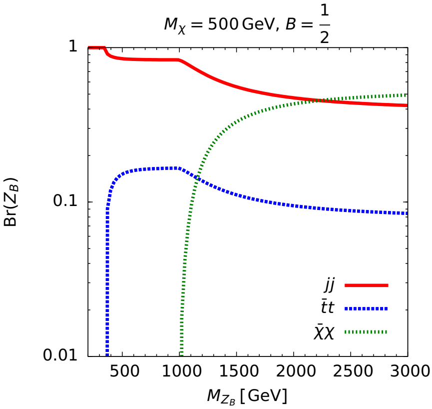


⟹ testable by combining LHC searches, DM direct detection, DM relic density constraints.

MD, P. Fileviez Pérez, arXiv:1309.3970 [hep-ph], arXiv:1409.8165 [hep-ph]

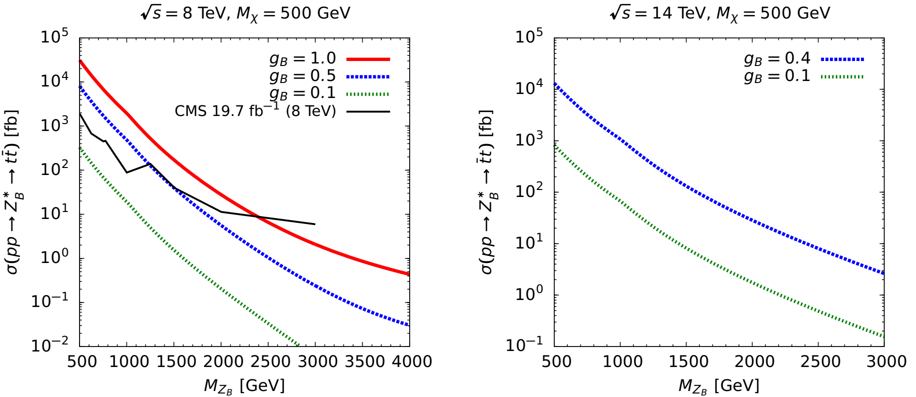
Decays of the new Gauge Boson Z_B.





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

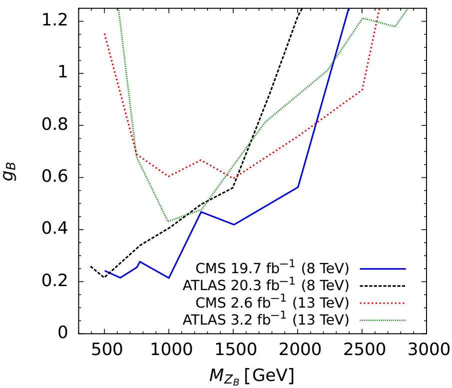
LHC Bounds: $pp \to Z_B^* \to t\bar{t}$



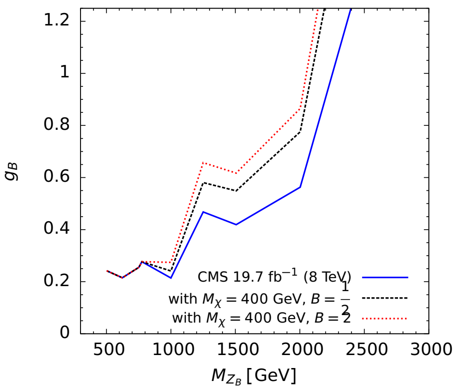
$$\sigma(\bar{q}q \to Z_B^* \to \bar{t}t)(\hat{s}) = \frac{g_B^4 \sqrt{\hat{s} - 4M_t^2}}{972\pi\sqrt{\hat{s}}} \frac{\left(2M_t^2 + \hat{s}\right)}{\left[(\hat{s} - M_{Z_B}^2)^2 + M_{Z_B}^2 \Gamma_{Z_B}^2\right]}$$

CMS: arXiv:1506.03062 [hep-ex]

Limits on Mass vs. Gauge Coupling.



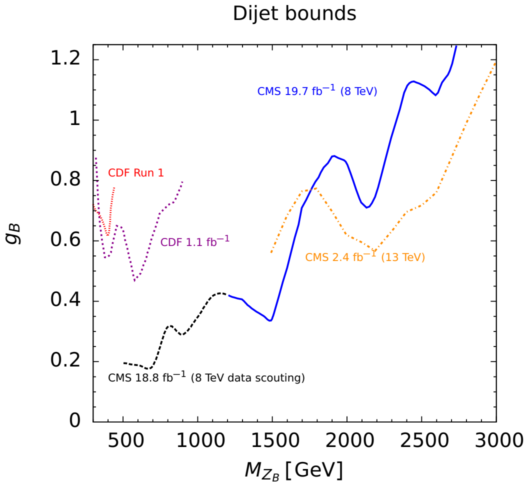
$\bar{t}t$ bounds



$\bar{t}t$ bounds with invisible width

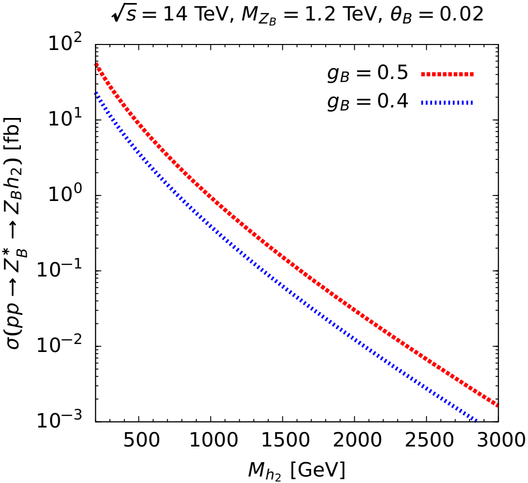
ATLAS: arXiv:1505.07018 [hep-ex], ATLAS-CONF-2016-14
CMS: arXiv:1506.03062 [hep-ex], CMS-PAS-2BG-15-002

Limits on Mass vs. Gauge Coupling.

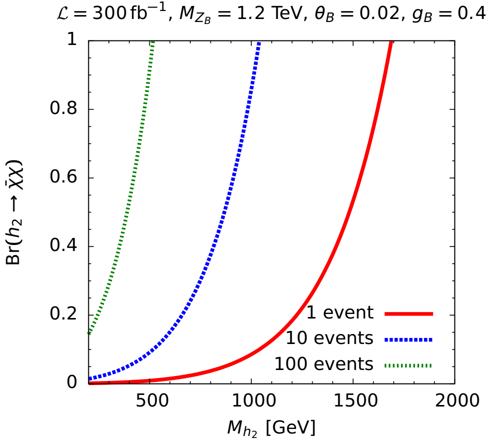


CDF: arXiv:hep-ex/9702004, arXiv:0812.4036 [hep-ex]
CMS: CMS-PAS-EXO-14-005, arXiv:1512.01530 [hep-ex]

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

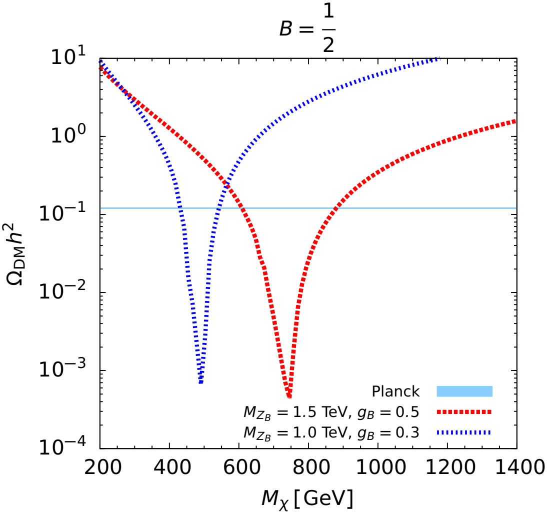


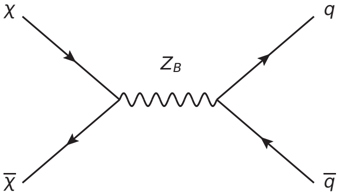
Signal: $\bar{t}t$ Plus Missing Energy.



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

Dark Matter Relic Density.





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

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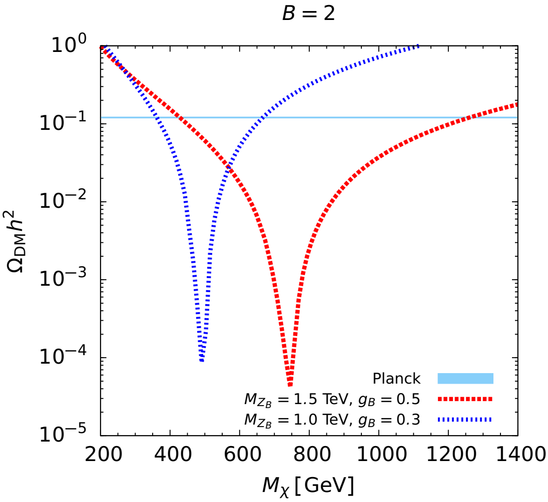
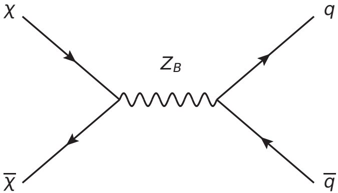
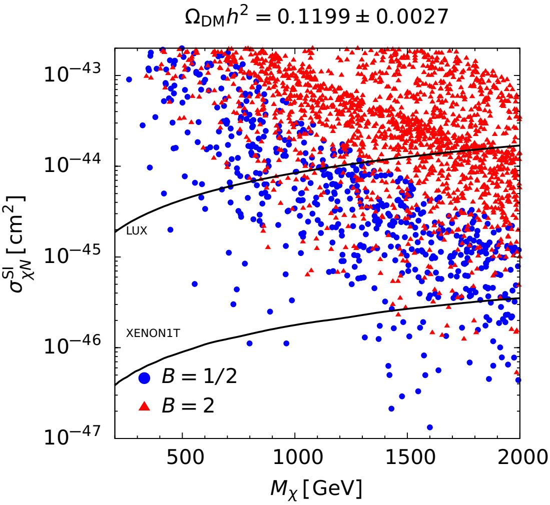
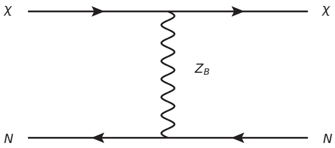




- Planck: $\Omega_{\mathrm{DM}} h^2 = 0.1199 \pm 0.0027$

Dark Matter Direct Detection.





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

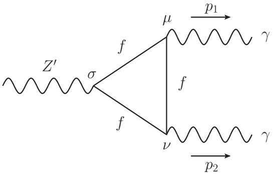
$$M_{Z_B} \in [0.5, 5.0]\ \mathrm{TeV}$$
$$g_B \in [0.1, 0.5]$$

Loop-Mediated Couplings to Photons.

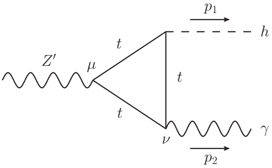
A $U(1)'$ extension of the Standard Model

- Effective couplings:

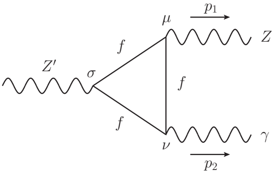
- $\delta\Gamma^{\mu\nu\sigma}_{Z'\gamma\gamma}$



- $\delta\Gamma^{\mu\nu}_{Z'h\gamma}$



- $\delta\Gamma^{\mu\nu\sigma}_{Z'Z\gamma}$



only possible if fermions f have axial coupling to the Z'

always possible if SM fermions are charged under the $U(1)'$

MD, P. Fileviez Pérez, J. Smirnov, arXiv:1506.05107 [hep-ph]

Recap: Baryonic Dark Matter.

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

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

- Condition from anomaly cancellation: $B_1 - B_2 = -3$.
- For $B_1 = -B_2 = -3/2$:

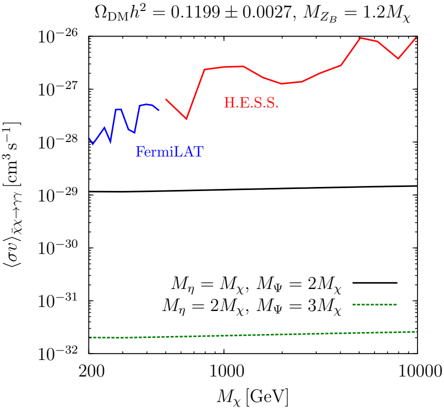
Majorana DM with axial coupling to the Z_B:

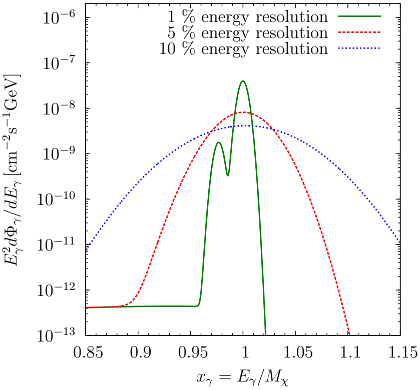
$$-\mathcal{L} \supset \frac{3}{2} g_B \bar{\chi} \gamma_\mu \gamma^5 \chi Z_B^\mu$$

MD, P. Fileviez Pérez, J. Smirnov, arXiv:1508.01425 [hep-ph]

Loop-Mediated Annihilation to Photons.

Majorana Dark Matter ($B_1 = -B_2$)





MD, P. Fileviez Pérez, J. Smirnov, arXiv:1508.01425 [hep-ph]

Summary.

Extensions of the Standard Model with gauged *B* (and *L*) provide a simple scenario for the DM of the Universe.

- Baryon (and lepton number) promoted to gauge symmetries that can be broken at the low scale
- No proton decay ⇒ no need for a desert
- Automatically stable fermionic DM candidate
- Gauge interaction mediates DM annihilation, direct detection and production at colliders
- Small number of free parameters ⇒ testable

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Thank you!

Backup Slides.

Symmetries of the Model.

- Symmetries of the Model:
  - $(B-L)_{\mathrm{SM}}$
  - Accidental η symmetry in the new sector:

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

$\Rightarrow$ 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,

$$\xi = \begin{cases} 2 & \text{for fermions,} \\ 1 & \text{for bosons.} \end{cases}$$

- $B - L$ asymmetry in the SM sector

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

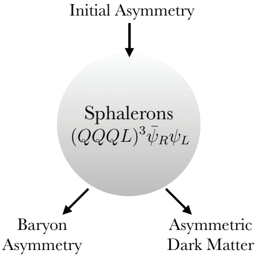
- η charge density

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

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

Baryon and Dark Matter Asymmetries.

$$B_f^{\mathrm{SM}} = \frac{32}{99}\Delta(B-L)_{\mathrm{SM}} + \frac{(15-14B_2)}{198}\Delta\eta,$$



Initial Asymmetry

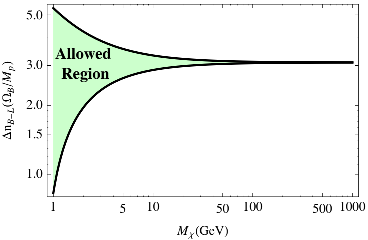
Sphalerons
$(QQQL)^3\bar{\psi}_R\psi_L$

Baryon
Asymmetry

Asymmetric
Dark Matter

$$|n_\chi - n_{\bar{\chi}}| \le n_{\mathrm{DM}}$$

$\Omega_\chi \le 5\ \Omega_B$



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

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

Gauging B and L in SUSY Setups.

- Lepto-baryon fields:

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

- Vector-like family:

P. Fileviez Pérez, M. B. Wise, arXiv:1106.0343 [hep-ph]

  - $U(1)_B$ and $U(1)_L$ breaking scale linked to SUSY breaking scale
  - Low B breaking renders the lightest neutralino unstable $\Rightarrow$ no DM candidate