Baryonic Dark Matter at the Large Hadron Collider.

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Motivation: Baryon and Lepton Numbers.

> Global symmetries of the Standard Model

Baryon and lepton numbers are accidental global symmetries of the renormalizable couplings in the Standard Model of particle physics.

> Violation of baryon number

> The baryon asymmetry of the Universe tells us that baryon number should be broken:

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

> The long lifetime of the proton tells us that processes that violate baryon number by one and lepton number by an odd number must be very suppressed:

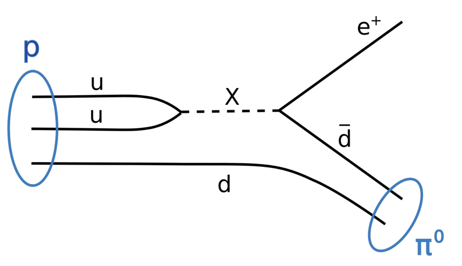
$$\tau_p \geq 10^{32-34} \text{ years}$$

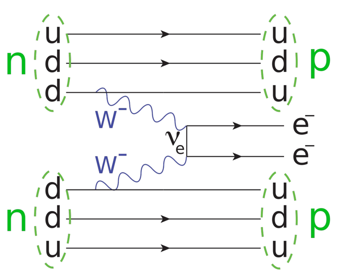
> Violation of lepton number

> Neutrino oscillations violate lepton flavor number:

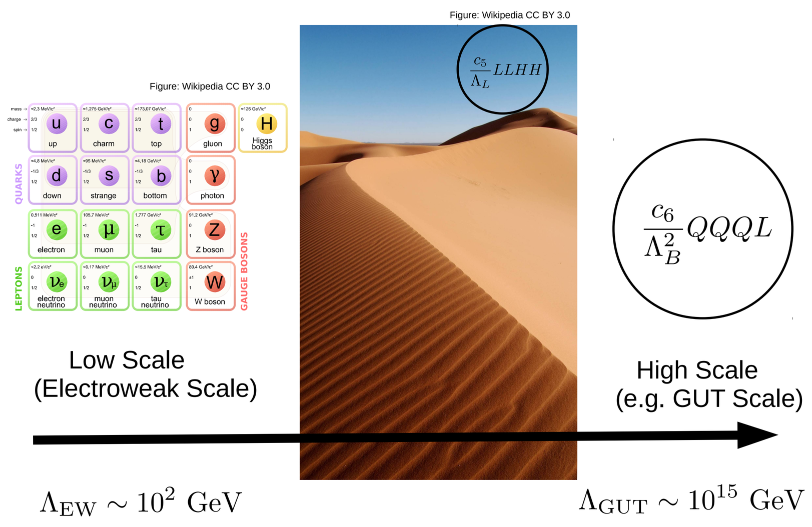
$$\Delta L_e \neq 0,\ \Delta L_\mu \neq 0,\ \Delta L_\tau \neq 0$$

> Total lepton number could be conserved in Nature, one promising test are the searches for neutrinoless double beta decay.





The Great Desert of Particle Physics.



> Proton Decay and the Great Desert

The Standard Model of particle physics lives at the low scale, the electroweak scale. Higher-dimensional operators that induce proton decay arise at dimension 6 and therefore have to live at the high scale to be in agreement with the long lifetime of the proton.

This leads to the Great Desert between the electroweak scale and some high scale where one can understand the origin of the proton decay operators, e.g. the GUT scale.

Lepton number violation arises at dimension 5, the so-called Weinberg operator. Realising this operator at a high scale can nicely explain the smallness of neutrino masses, the so-called seesaw mechanism.

> Basic idea of the project

Define a consistent gauge theory for baryon (and lepton) number(s) that can be broken at the low scale without introducing dangerous baryon number violating operators and study the implications.

Gauging Baryon and Lepton Numbers.

> New gauge group

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

> Anomaly cancellation

To consistently gauge baryon and lepton numbers, all relevant gauge anomalies must be cancelled. The mixed anomalies arise because fields carrying both baryon and lepton number will be introduced.

> 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

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

> With the SM particle content + right-handed neutrinos (see below for their quantum numbers) not all of the above anomalies vanish and therefore new particles need to be introduced to consistently gauge baryon and lepton numbers:

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

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

A Simple Solution.

> General Solution

All anomalies are cancelled when introducing a vector-like family of lepto-baryons, i.e., particles carrying both baryon and lepton numbers.

Field	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_B$	$U(1)_L$
Ψ_L	**N**	**2**	Y_1	B_1	L_1
Ψ_R	**N**	**2**	Y_1	B_2	L_2
η_R	**N**	**1**	Y_2	B_1	L_1
η_L	**N**	**1**	Y_2	B_2	L_2
χ_R	**N**	**1**	Y_3	B_1	L_1
χ_L	**N**	**1**	Y_3	B_2	L_2

The new fields can have different representations under QCD, and the U(1) quantum numbers have to fulfill some conditions:

$$\{Y_1, Y_2, Y_3\} = \{a, a \pm \frac{1}{2}, a \mp \frac{1}{2}\},\ B_1 - B_2 = -\frac{3}{N},\ L_1 - L_2 = -\frac{3}{N}$$

> Possible Scenarios

It is not sufficient to only cancel the anomalies, but one needs to also write down a working model. This means that all fields should obtain masses in agreement with experiment, and no stable charged fields should be introduced. A guideline for viable models can be:

> new fields should have direct coupling to SM fields, or
> the lightest new particle is neutral and stable.

> $N = 1:$ Use $Y_1 = \pm\frac{1}{2},\ Y_2 = \pm 1,\ Y_3 = 0.$

If the lightest new field is neutral, it can be a DM candidate. This is the model that I will focus on.

> $N = 3:$ Use $Y_1 = \pm\frac{1}{6},\ Y_2 = \pm\frac{2}{3},\ Y_3 = \pm\frac{1}{3}.$

In this setup, the new scalar breaking B and L generates dimension seven proton decay operators.

> $N = 8:$
Extra colored fields, e.g., color octet scalars, are needed to couple the new fermions to the SM fermions.

Baryonic Dark Matter.

> Simplified version considering only baryon number

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

> Spontaneous symmetry breaking

For $B_1 \neq -B_2$, the relevant interactions of the new fermions are

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

The baryon number of the new Higgs is unambiguously fixed by the requirement of anomaly cancellation:

$$S_B \sim (\mathbf{1}, \mathbf{1}, 0, B_1 - B_2) = (\mathbf{1}, \mathbf{1}, 0, -3)$$

After obtaining a VEV and breaking the baryonic symmetry, the new Higgs generates vector-like masses for the new fermions

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

and induces only $\Delta B = 3$ processes such that proton decay never occurs. A remnant $\mathcal{Z}_2$ stabilizes the lightest new fermion.

> Dark matter sector of the model

For definiteness, I study the case of a Dirac fermion DM that is a SM singlet:

$$\chi = \chi_R + \chi_L$$

The coupling to the new gauge boson associated with baryon number dominates DM annihilation and DM direct detection in the interesting regions of parameter space:

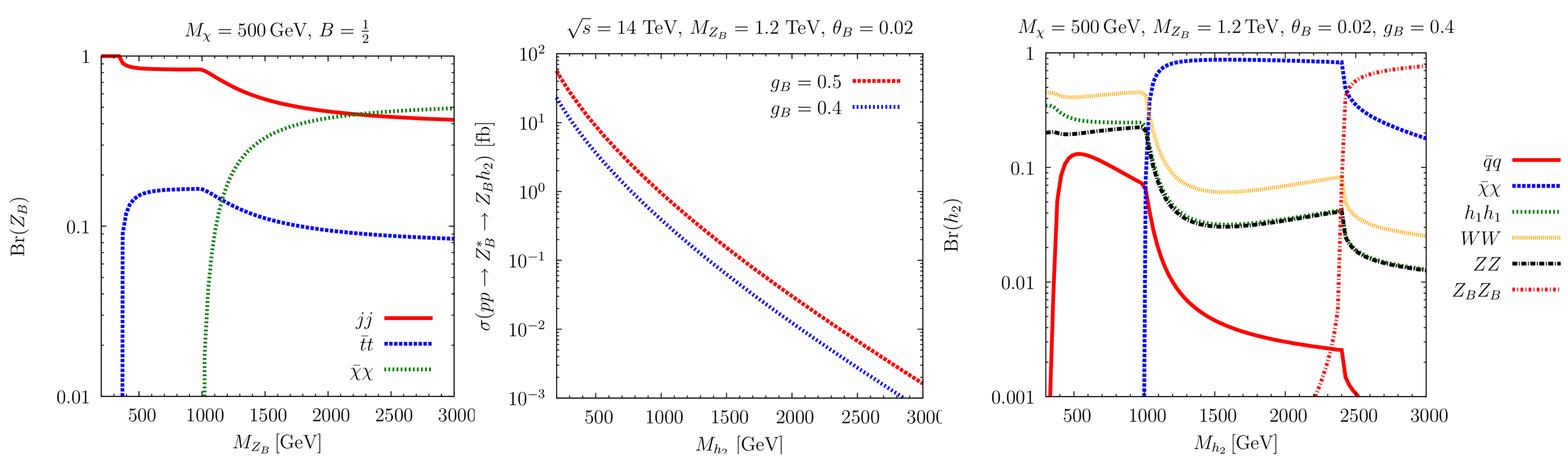
$$\mathcal{L} \supset g_B \overline{\chi} \gamma_\mu Z_B^\mu (B_2 P_L + B_1 P_R) \chi$$

> Free parameters

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

The model has only six free parameters and thus can be tested by combining LHC searches, DM direct detection and DM relic density constraints.

Searching for Baryonic Dark Matter at the Large Hadron Collider.



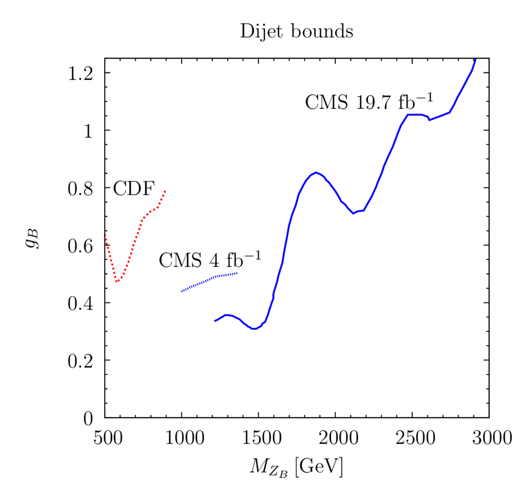
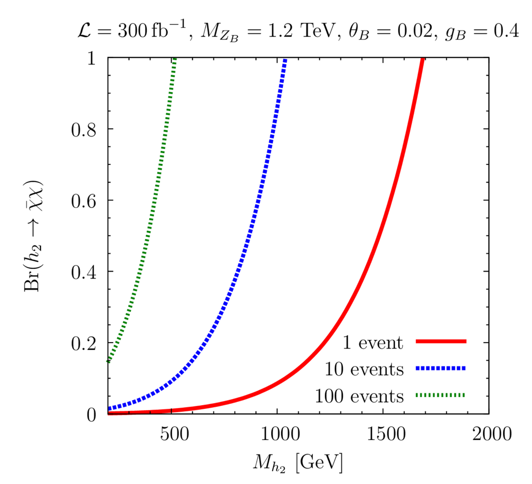


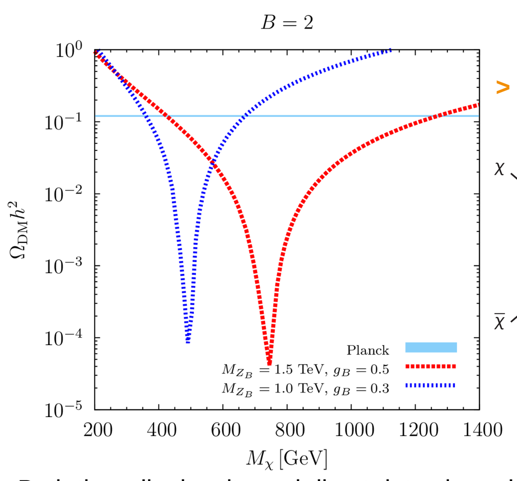
Figure from arXiv:1506.00954

A way to test this model at the collider is the search for the leptophobic gauge boson and the additional Higgs breaking baryon number. The leptophobic gauge boson can be produced through its couplings to quarks, and the only unsuppressed production channel for the new Higgs is associated production with the Z_B.
Dijet searches give the most significant bounds on the mass and coupling of the Z_B.
The connection to DM can be established if both have significant invisible decay branching ratios. A possibly interesting DM signal at the LHC is a top quark pair together with missing energy (see right):

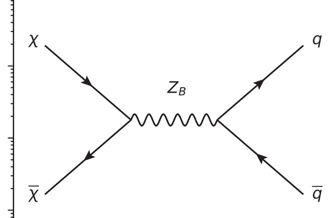


$$N(\bar{t}tE_{\rm T}^{\rm miss}) = \mathcal{L} \times \sigma(pp \to Z_B h_2) \times \mathrm{Br}(Z_B \to \bar{t}t) \times \mathrm{Br}(h_2 \to \bar{\chi}\chi)$$

DM Relic Density and Direct Detection.

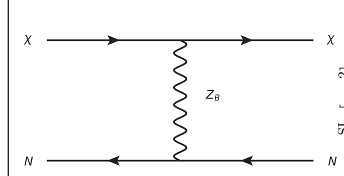


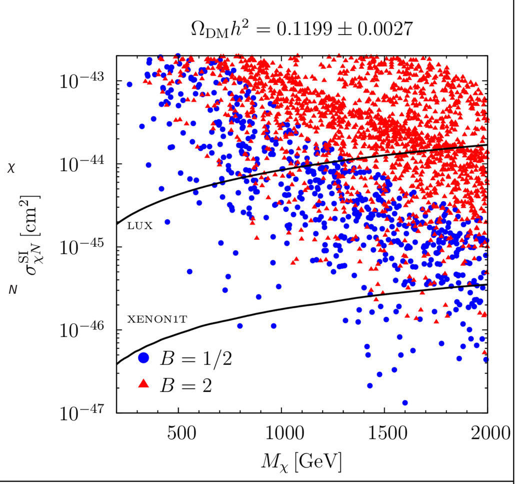
> DM relic density



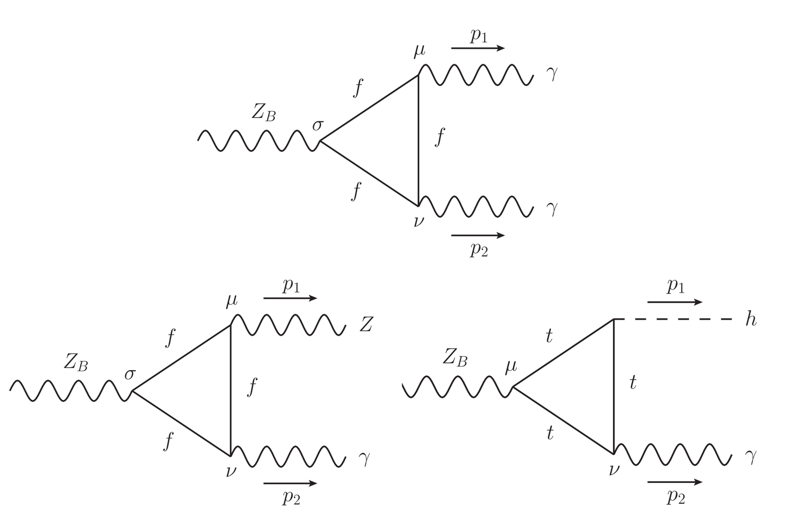
Both the relic density and direct detection rely on the coupling to the new gauge boson. Depending on the parameters, the correct relic density can be set without relying on the resonance. Current direct detection experiments cut into the parameter space of the model, but leave viable models with DM masses larger than ~ 500 GeV. Future direct detection experiments such as XENON1T will allow for DM masses larger than ~ 800 GeV.

> DM direct detection





Gamma-Ray Lines from Baryonic Dark Matter.



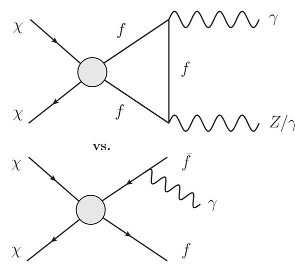
> Effective loop-mediated couplings to photons

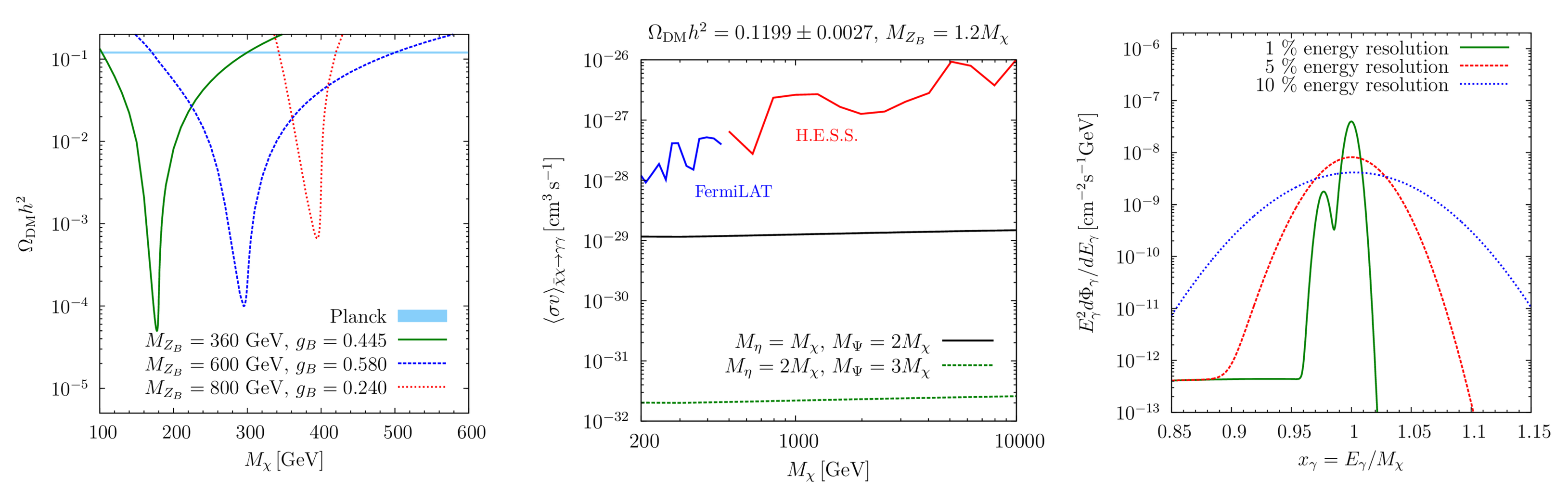
The effective coupling of the leptophobic gauge boson to two photons is only possible if the fermions in the loop have axial couplings to the gauge boson. The other two effective couplings are possible whenever SM fermions are charged under the new gauge group.

> Tree-level processes vs. loop processes

Possible effective interactions of a Majorana DM charged under new gauge symmetry and the corresponding strength of the gamma-ray lines from DM annihilation:

Operator	$\gamma\gamma$	$Z\gamma$	$h\gamma$
$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{f}\gamma_\mu\gamma^5 f$	OK	OK	suppressed
$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{f}\gamma_\mu f$	–	OK	suppressed





> Baryonic dark matter with a Majorana dark matter candidate

For the choice

$$B_1 = -B_2 = -\frac{3}{2}$$

the Baryonic Dark Matter model contains a Majorana DM candidate with axial couplings to the new leptophobic gauge boson.

> Couplings that generate the relevant effective operators

> Coupling of the DM to the new gauge boson:

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

> Coupling of the SM quarks to the new gauge boson:

$$-\mathcal{L} \supset \frac{1}{3} g_B \bar{q}\gamma^\mu q Z_B^\mu$$

> Coupling of the additional new fermoins to the new gauge boson:

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

> Relic density

The dominant annihilation channel in the Majorana case is also the s-channel exchange of a leptophobic gauge boson. The velocity suppression is not too strong in the early Universe and the right relic density can easily be achieved.

> Annihilation into gamma-ray lines

For the annihilation into gamma-ray lines, two more parameters are relevant for the model – the masses of the additional fermions introduced for anomaly cancellation. The annihilation cross section is given by

$$\sigma(\bar{\chi}\chi \to \gamma\gamma) = \frac{81\alpha^2}{32\pi^3}\frac{g_B^4 M_\chi^2}{M_{Z_B}^2\left(M_{Z_B}^2 + \Gamma_{Z_B}^2\right)}\frac{\left[M_\Psi^2 C_0(s; M_\Psi) - M_\eta^2 C_0(s; M_\eta)\right]^2}{\sqrt{1 - 4M_\chi^2/s}}$$

> Photon spectrum

The continuum photon emission is suppressed, such that the gamma-ray lines can be easily visible over the continuum background.

Summary.

I have discussed a simple extension of the Standard Model where baryon and lepton numbers are gauge symmetries broken at the low scale. These models have an interesting DM phenomenology, and I discussed how to search for the new particles in DM direct and indirect detection experiments, as well as at the LHC.

Interestingly, DM stability is an automatic consequence of the gauge symmetry and does not have to be introduced by hand. Even though baryon number is broken at the low scale, non-renormalizable operators that induce proton decay do not occur.

Based on.

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HELMHOLTZ
GEMEINSCHAFT

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