Baryon Number.

A Key to Physics Beyond the Standard Model

DESY

Michael Duerr
Seminar I.N.F.N. Firenze
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Thanks to my collaborators.

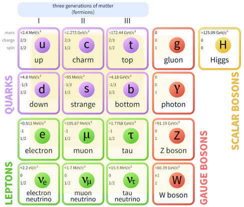
This talk is based on

arXiv:1304.0576 [hep-ph], arXiv:1306.0568 [hep-ph],
arXiv:1309.3970 [hep-ph], arXiv:1409.8165 [hep-ph],
arXiv:1508.01425 [hep-ph], arXiv:1604.05319 [hep-ph],
arXiv:1704.03811 [hep-ph], arXiv:1712.01841 [hep-ph]

together with

Pavel Fileviez Pérez (Case Western), Manfred Lindner (MPIK Heidelberg), Kai Schmidt-Hoberg (DESY Hamburg), Juri Smirnov (INFN and University Firenze), James Unwin (U. of Illinois at Chicago), Mark B. Wise (Caltech)

The Standard Model of particle physics.



> 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	**3**	**2**	1/6	1/3	0
u_R	**3**	**1**	2/3	1/3	0
d_R	**3**	**1**	−1/3	1/3	0
ℓ_L	**1**	**2**	−1/2	0	1
e_R	**1**	**1**	−1	0	1
H	**1**	**2**	1/2	0	0

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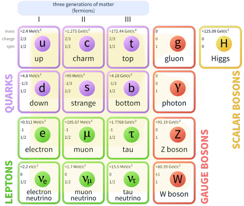

> B: accidental global symmetry of the renormalizable couplings (broken by non-perturbative quantum effects)

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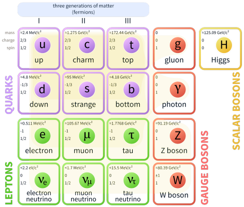

> stable proton and no n–$\bar{n}$ oscillations in the renormalizable SM. But the SM is incomplete . . .

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_B$	$U(1)_L$
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Grand Unified Theories (GUTs).

- Embed the SM into some larger symmetry group, e.g.,

$$SU(5) \supseteq SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

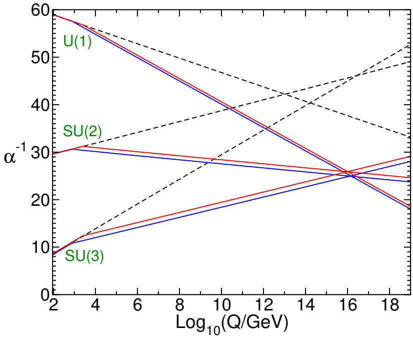
[Georgi and Glashow 1974]

- SM families fit nicely into multiplets

$$\overline{5} = \begin{pmatrix} d^{c1} \\ d^{c2} \\ d^{c3} \\ e^- \\ -\nu_e \end{pmatrix}_L \qquad 10 = \begin{pmatrix} 0 & u^{c3} & -u^{c2} & u_1 & d_1 \\ -u^{c3} & 0 & u^{c1} & u_2 & d_2 \\ u^{c2} & -u^{c1} & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^+ \\ -d_1 & -d_2 & -d_3 & -e^+ & 0 \end{pmatrix}_L \qquad 24 = \left(\begin{array}{ccc|cc} G_{11} - \frac{2B}{\sqrt{30}} & G_{12} & G_{13} & X_1 & Y_1 \\ G_{21} & G_{22} - \frac{2B}{\sqrt{30}} & G_{23} & X_2 & Y_2 \\ G_{31} & G_{32} & G_{33} - \frac{2B}{\sqrt{30}} & X_3 & Y_3 \\ \hline X^1 & X^2 & X^3 & \frac{W^3}{\sqrt{2}} + \frac{3B}{\sqrt{30}} & W^+ \\ Y^1 & Y^2 & Y^3 & W^- & -\frac{W^3}{\sqrt{2}} + \frac{3B}{\sqrt{30}} \end{array}\right)$$

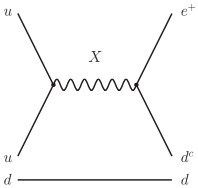
- since quarks and leptons are in the same multiplet
  → one cannot define baryon number
- proton decay ($\Delta B = 1$, $\Delta L =$ odd) due to new gauge interactions via gauge bosons X, Y

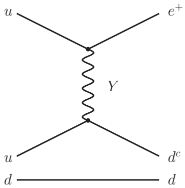
Proton Decay in GUTs.



[S. Martin, arXiv:hep-ph/9709356]

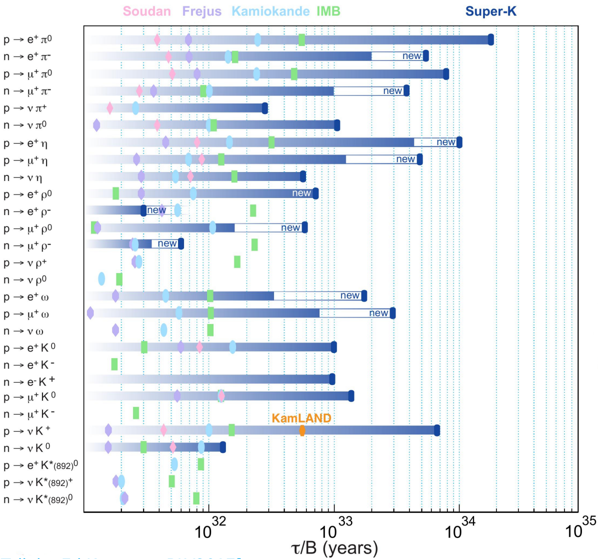
- New gauge bosons X, Y directly mediate proton decay

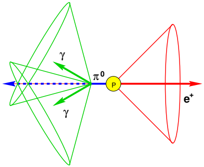


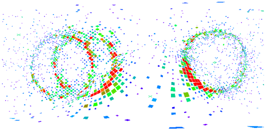


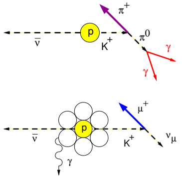
- Lifetime estimate $\tau = \dfrac{M_{X,Y}^4}{\alpha_{\mathrm{GUT}}^2 M_p^5}$ (dimension-6 operator)
- Additional proton decay diagrams (dimension-5 operators) in SUSY GUTs . . .

Experimental results on proton decay.









[Talk by Ed Kearns at BLV2017]

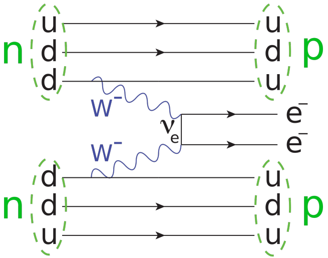
[Figures: B. Viren, arXiv:hep-ex/9903029]

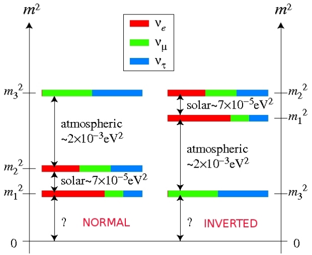
Side remark: lepton number.

- Lepton number L conserved at the renormalizable level in the Standard Model as well
- What do we know about violation of L?
  - ν oscillation experiments:

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

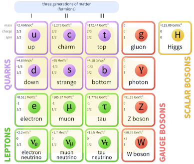
  - $\Delta L = 2$: Majorana neutrino masses (test with $0\nu\beta\beta$)





[Figure: Mohapatra et al., arXiv:hep-ph/0412099]

The desert of particle physics.



Low scale

Electroweak scale

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

[Figure: Wikipedia]

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

[Weinberg, PRL **43** (1979) 1566]

High scale

e.g. GUT scale

($\Lambda \gtrsim 10^{15}$ GeV)

Energy

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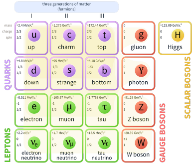

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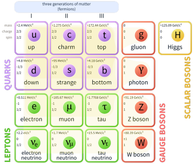

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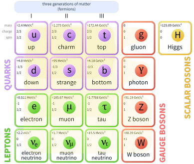

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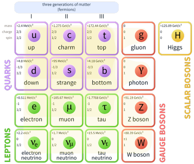

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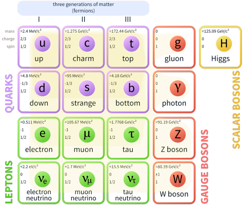

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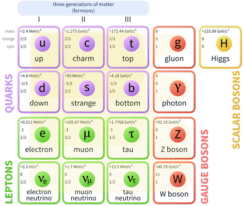

> Extension of the SM gauge group:

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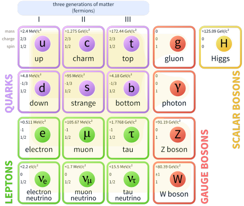

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Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_B$	$U(1)_L$
Q_L					0
u_R					0
d_R					0
ℓ_L					1
e_R	**1**	**1**	-1	0	1
H	**1**	**2**	1/2	0	0

Gauge theories for B (and L)

How to define a realistic theory where B (and L) are local gauge symmetries that can be broken at the low (TeV) scale?

Some history.

The idea of a conservation law for baryon number was formulated very early to explain the stability of matter

- Weyl (1929), Stueckelberg (1938): analogy to the electron
- A footnote in E.P. Wigner, *Invariance in Physical Theory*, Proc. Am. Philos. Soc. **93** (1949) 521

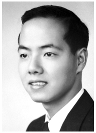
[9] It is conceivable, for instance, that a conservation law for the number of heavy particles (protons and neutrons) is responsible for the stability of the protons in the same way as the conservation law for charges is responsible for the stability of the electron. Without the conservation law in question, the proton could disintegrate, under emission of a light quantum, into a positron, just as the electron could disintegrate, were it not for the conservation law for the electric charge, into a light quantum and a neutrino.

Some history.

Phys. Rev. **98**, 1501 (1955)

PHYSICAL REVIEW VOLUME 98, NUMBER 5 JUNE 1, 1955

Conservation of Heavy Particles and Generalized Gauge Transformations



T. D. LEE, *Columbia University, New York, New York*

AND

C. N. YANG, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 2, 1955)

The possibility of a heavy-particle gauge transformation is discussed.

THE conservation laws of nature fall into two distinct categories: those that are related to invariance under space-time displacements and rotations, and those that are not. In the former category there are the conservation laws of momentum, energy, and angular momentum. In the latter category we find the conservation laws of electric charge, of heavy particles, and the approximate conservation laws of isotopic spin, and perhaps others.[1] We notice that the best known within this second category, the conservation of electric charge, is related to invariance under gauge transformations,[2] which expresses the nonmeasurability of the phase of the complex wave function of

charge" of $-\eta$. The force between two massive bodies therefore would contain a contribution from the Coulomb-like repulsion between such "heavy-particle charges." The total force including the gravitational attraction is:

$$\text{Force} = -G(M_1M_2/R^2) + \eta^2(A_1A_2/R^2). \qquad (2)$$

Here M_1, M_2, A_1, and A_2 are the inertia masses and mass numbers of the two bodies. There should also be a magnetic-dipole-like interaction between individual nuclei because the nucleons are in constant motion in a nucleus. But in a macroscopic object the nuclear

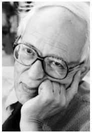
- heavy particle (= neutrons and protons) gauge transformation:

$$\psi_N \to e^{i\alpha}\psi_N,\ \psi_P \to e^{i\alpha}\psi_P$$

- massless vector boson: gauge coupling must be tiny ($\alpha_B \lesssim 10^{-45}$)

Some history.

Phys. Rev. D **8**, 1844 (1973)



PHYSICAL REVIEW D VOLUME 8, NUMBER 6 15 SEPTEMBER 1973

Remark on Baryon Conservation*

A. Pais
Rockefeller University, New York, New York 10021
(Received 27 March 1973)

The Higgs mechanism can serve to implement baryon conservation via an extension of the local weak-electromagnetic gauge group by a local factor U(1) without conflict with the Eötvös experiments.

(1) Charge conservation and baryon conservation are believed to be equally absolute.[1] The former law emerges in the dynamical context of a strict local gauge invariance. On the other hand, no convincing dynamical framework has been found so far for baryon conservation. To be sure, one may postulate a local gauge invariance for this purpose, in straight analogy to the electromagnetic case. This implies the existence of a neutral

(2) As is well known, the Abelian nature of the electromagnetic gauge group precludes any insight into the problem of why charge is quantized.[7] In simplest terms, if we treat electromagnetism as a separate phenomenon, then the equality of the positron and the proton (bare) charge is to be put in by hand (after which the ratio is stable under renormalization). In the recent attempts to formulate a renormalizable unified field theory of weak

> Use the Higgs mechanism to break *B*!

Some history.

- Early discussions of gauging B (and L): anomaly cancellation, introduction of new fermions, properties of the gauge boson ...
  - 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 (sequential/mirror family with $B = \pm 1$)
  - P. Fileviez Pérez, M. B. Wise, PRD **82**, 011901 (2010)

    Ruled out: new chiral quarks get mass from SM Higgs

    $\Rightarrow$ change gluon fusion Higgs production + Landau poles
- This talk will focus on the following models:
  - P. Fileviez Pérez, M. B. Wise, JHEP **08** (2011) 068
  - MD, P. Fileviez Pérez, M. B. Wise, PRL **110** (2013) 231801
  - P. Fileviez Pérez, S. Ohmer, H. H. Patel, Phys. Rev. D **90** (2014) 037701

Features of these models.

- Framework for the spontaneous breaking of local baryon number at the low scale in agreement with experiments.
- Proton is stable (or long-lived) → think about the possibility of low-scale unification.
- Vector-like fermions F with baryon number to cancel anomalies (with or without color).
- Cold dark matter candidate χ: lightest neutral field in the new sector.
- Leptophobic gauge boson coupling to SM quarks and new fermions: $Z_B \to \bar{q}q, \chi\chi, \bar{F}F$
- New Higgs Boson $h_B \to \bar{q}q, Z_B Z_B, \bar{F}F$
- Connection between the DM and baryon asymmetries.

Outline.

> Local baryon number

> Dark matter with baryon number

> Baryon asymmetry

> Collider signatures

> Protecting the axion with local baryon number

> Summary

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Anomaly cancellation.

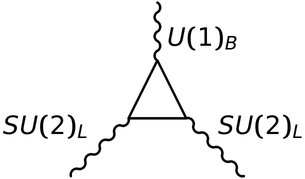
> New gauge group:

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

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

> Baryonic anomalies:

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



Standard Model

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

> New fermions needed to cancel non-trivial anomalies
> $\mathcal{A}_1 = 0 \Rightarrow$ simplest solution: colorless fields

How many new fermion multiplets?

> Two fermion multiplets

$$\Psi_L \sim (1, N, Y_1, B_1) \text{ and } \Psi_R \sim (1, M, Y_2, B_2)$$

- $\mathcal{A}_5 \left(U(1)_B\right) = 0$ requires $B_1 = MB_2/N$
- Then $\mathcal{A}_6 \left(U(1)_B^3\right) = 0$ requires $M = N$ and $B_1 = B_2$
- $\mathcal{A}_2 \left(SU(2)^2 \otimes U(1)_B\right)$ cannot be canceled
- No solution with two new fermion multiplets

[Fileviez Pérez, Ohmer, Patel, arXiv:1403.8029]

How many new fermion multiplets?

- Three fermion multiplets

$$\Phi_L \sim (1, N, Y, B_1), \Phi_R \sim (1, N, Y, B_2), \text{ and } \chi_L \sim (1, M, 0, B_3)$$

  - Anomaly cancellation requires

$$M = 2N, Y^2 = N^2/4, B_1 = -B_2 = -B_3 = 3/N^3$$

  - χ_L: fermions with fractional electric charge that cannot decay to SM particles
  - more general assignments lead to same conclusion
  - consistent with anomaly cancellation but in conflict with cosmology

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Anomaly cancellation ≠ phenomenologically viable model

Solution with four fermion multiplets.

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

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

[Fileviez Pérez, Ohmer, Patel, arXiv:1403.8029]

[Ohmer, Patel, arXiv:1506.00954]

- No fractional charges in the particle spectrum
- particle content allows for vector-like masses
- Majorana dark matter candidate

A very general solution.

All anomalies can be cancelled with the following setup:

Field	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_B$
Ψ_L	$\mathbf{N}$	$\mathbf{2}$	Y_1	B_1
Ψ_R	$\mathbf{N}$	$\mathbf{2}$	Y_1	B_2
η_R	$\mathbf{N}$	$\mathbf{1}$	Y_2	B_1
η_L	$\mathbf{N}$	$\mathbf{1}$	Y_2	B_2
χ_R	$\mathbf{N}$	$\mathbf{1}$	Y_3	B_1
χ_L	$\mathbf{N}$	$\mathbf{1}$	Y_3	B_2

Anomaly cancellation demands: $B_1 - B_2 = -3/(N n_F)$,
$Y_2 = Y_1 \mp 1/2$ and $Y_3 = Y_1 \pm 1/2$

[Fileviez Pérez, Wise, arXiv:1106.0343 [hep-ph]]

[MD, Fileviez Pérez, Wise, arXiv:1304.0576 [hep-ph]]

Possible scenarios.

Guidelines:

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

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  - Scenario II: $Y_1 = -5/6$, $Y_2 = -4/3$, $Y_3 = -1/3$
  - Scenario III: $Y_1 = 7/6$, $Y_2 = 5/3$, $Y_3 = 2/3$

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  $n_F = 3$: dimension-9 operator for proton decay $\Rightarrow$
  suppressed, even if cutoff of the theory not very large

- $N = 8$: interesting but non-minimal

Simplest scenario.

Consider only uncolored fields:

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, Fileviez Pérez, Wise, arXiv:1304.0576]

[MD, Fileviez Pérez, arXiv:1309.3970]

What about lepton number.

> 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's

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

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

Simplest scenario: lepto-baryons.

Assign lepton number to the same fields that cancel the baryonic anomalies

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: $B_1 - B_2 = -3,\ L_1 - L_2 = -3$

[MD, Fileviez Pérez, Wise, arXiv:1304.0576]

Simplest scenario: lepto-baryons.

Assign lepton number to the same fields that cancel the baryonic anomalies

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, Fileviez Pérez, Wise, arXiv:1304.0576]

Spontaneous symmetry breaking.

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

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

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

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

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

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

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

Outline.

- > Local baryon number
- > Dark matter with baryon number
- > Baryon asymmetry
- > Collider signatures
- > Protecting the axion with local baryon number
- > Summary

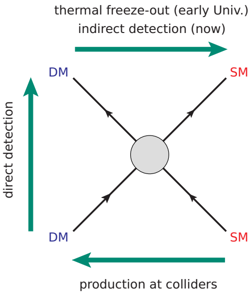
Dark matter with baryon number.

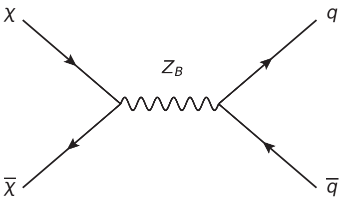
- Dirac DM, SM singlet-like: $\chi = \chi_R + \chi_L$
- Coupling to the new gauge boson:

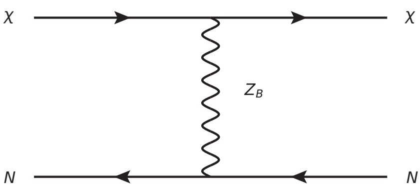
$$\mathcal{L} \supset g_B \overline{\chi} \gamma_\mu Z_B^\mu (B_2 P_L + B_1 P_R) \chi$$

DM annihilation and direct detection

- Model has only six free parameters:
$M_\chi, M_{Z_B}, g_B, B \equiv B_1 + B_2$ and M_{h_2}, θ_B

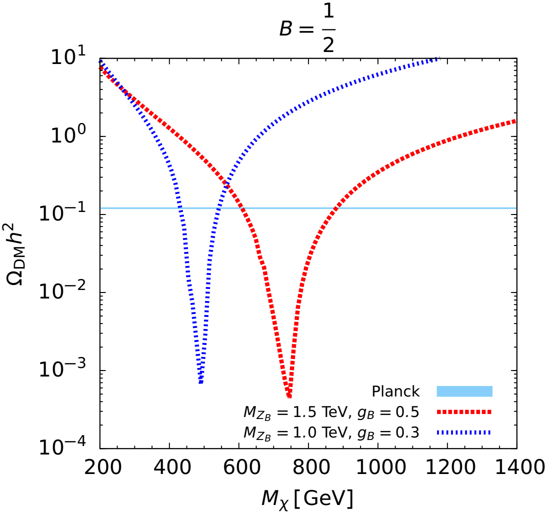


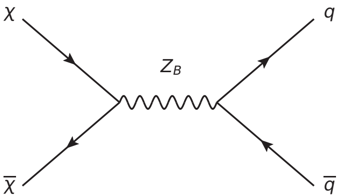




[MD, Fileviez Pérez, arXiv:1309.3970, arXiv:1409.8165]

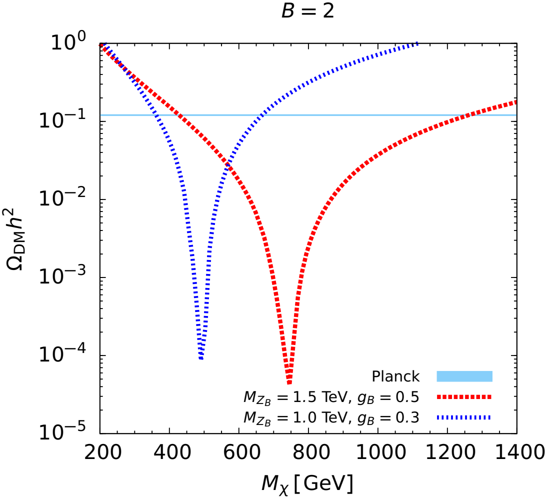
Dark matter relic density.

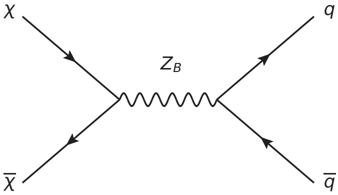




> Planck: $\Omega_{DM} h^2 = 0.1199 \pm 0.0027$

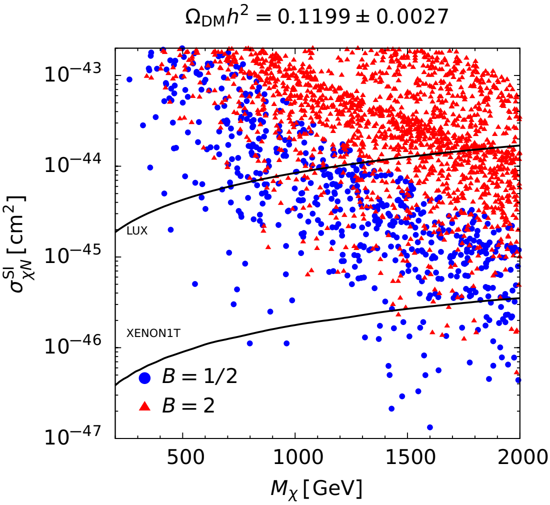
Dark matter relic density.

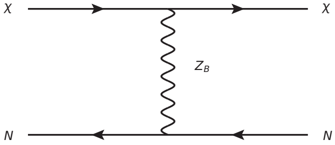




> Planck: $\Omega_{\mathrm{DM}} h^2 = 0.1199 \pm 0.0027$

Dark matter direct detection.





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

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

Scalar dark matter.

- Scalar DM can arise in these models as well.
- If vector-like colored fermions (Q', u', d') cancel the anomalies, they should decay.
- Introduce new scalar field X with baryon number $B_X = 1/3 - B_{Q'_R}$:

$$-\mathcal{L} \supset \lambda_1 X \overline{Q_L} Q'_R + \lambda_2 X \overline{u_R} u'_L + \lambda_3 X \overline{d_R} d'_L + \text{h.c.}$$

- Possible annihilation channels:

$$XX^\dagger \to Z_B^* \to \bar{q}q \text{ or } XX^\dagger \to H^* \to \text{SM SM}$$

- viable DM candidate in part of the parameter space

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Baryon asymmetry and dark matter.

> 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

> Relevant interactions:

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

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

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

- η charge density

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

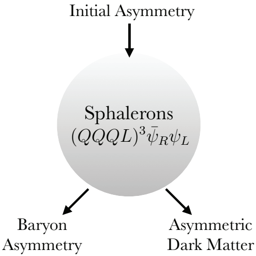
- Baryon asymmetry

$$B_f^{\text{SM}} = \frac{n_q - n_{\bar{q}}}{s} = \frac{15}{4\pi^2 g_* T}3\left(\mu_{u_L} + \mu_{u_R} + \mu_{d_L} + \mu_{d_R}\right).$$

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

Baryon and dark matter asymmetries.

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



Consistent picture for baryogenesis!

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

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

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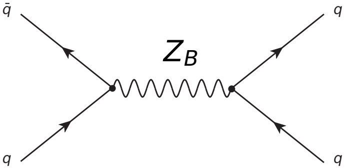
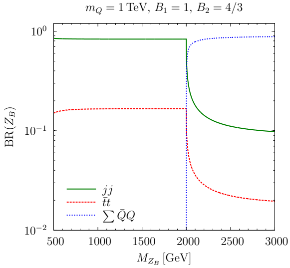
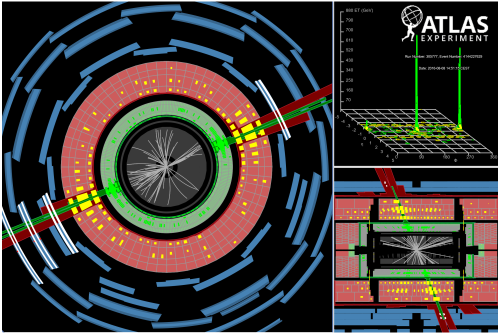
Dijet searches.

> Since the leptophobic gauge boson Z_B is produced from quarks, it can decay back to quarks → dijet searches

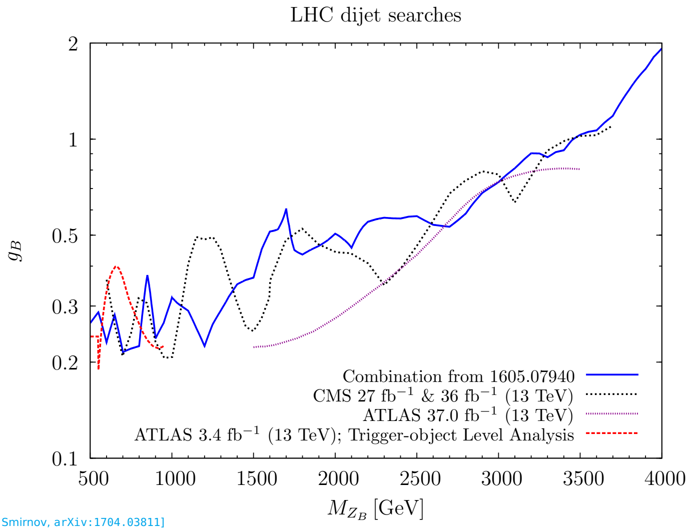






ATLAS highest-mass dijet event (Event 4144227629, Run 305777)

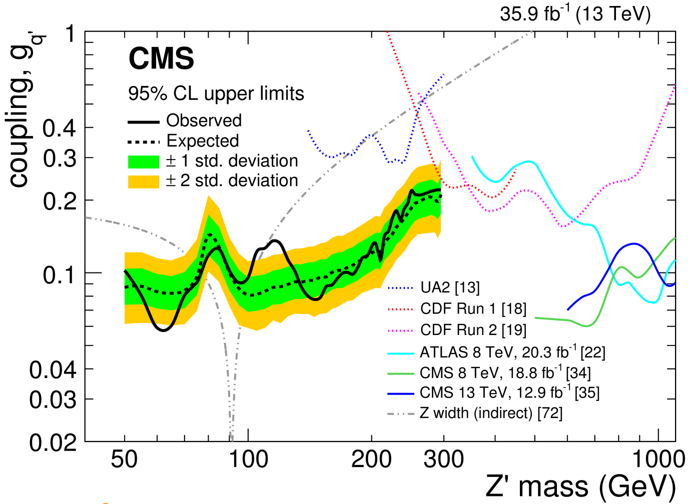
Limits on mass vs. gauge coupling.



[MD, Fileviez Pérez, Smirnov, arXiv:1704.03811]

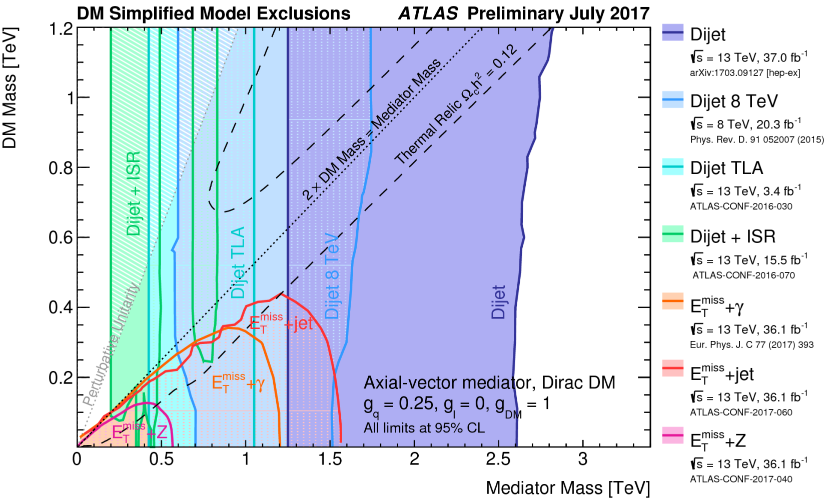
Low-mass region.

> New CMS search with ISR jet (CMS-PAS-EXO-17-001)



$\mathcal{L} \supset g_q Z'_\mu \bar{q}\gamma_\mu q \Rightarrow g_B = 3g_q$

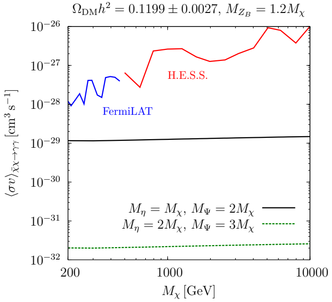
Dijet vs. Monojet searches.



What about the additional fermions?

> Majorana DM ($B_1 = -B_2$):

loop-mediated DM annihilation to photons



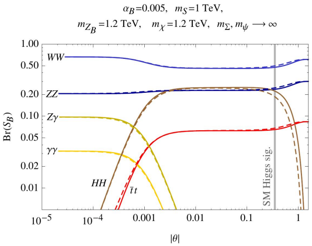
[MD, Fileviez Pérez, Smirnov, arXiv:1508.01425]

> Decays of S_B:

> For $\theta \to 0$, the branching fractions of the fermion-loop-mediated decays of S_B may provide clues about the fermion content of the model at the LHC

> Model with $SU(2)$ triplet:

$$\Gamma_{WW} : \Gamma_{ZZ} : \Gamma_{Z\gamma} : \Gamma_{\gamma\gamma} = 20 : 7 : 3 : 1$$



[Ohmer, Patel, arXiv:1506.00954]

> Vector-like model:

$$\Gamma_{WW} : \Gamma_{ZZ} : \Gamma_{Z\gamma} : \Gamma_{\gamma\gamma} = 2 : 1 : 10^{-3} : 1$$

Baryonic Higgs at the LHC.

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

MD, P. Fileviez Pérez, J. Smirnov, arXiv:1704.03811 [hep-ph]

Cancel the anomalies with vector-like quarks.

- Use three copies (analogy to the SM families) ⇒ $B_1 - B_2 = -1/3$

- Scenario I: $Y_1 = 1/6$, $Y_2 = 2/3$, $Y_3 = -1/3$
- Scenario II: $Y_1 = -5/6$, $Y_2 = -4/3$, $Y_3 = -1/3$
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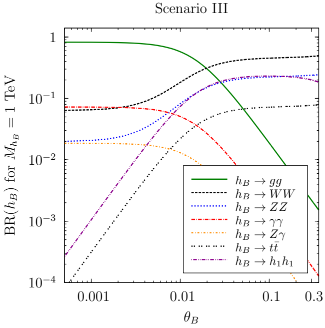

BR into photons large compared to SM Higgs, colored new fermions in the loop.

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

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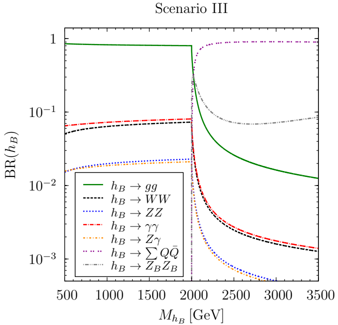
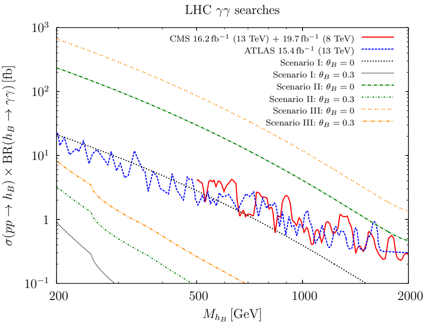


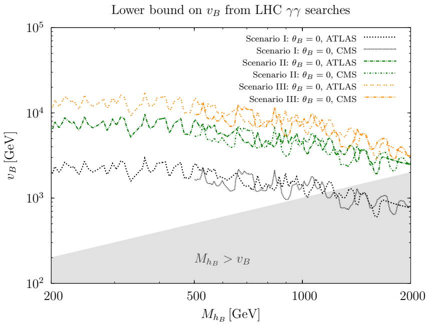
BR into photons large compared to SM Higgs, colored new fermions in the loop.

Baryonic Higgs at the LHC.

MD, P. Fileviez Pérez, J. Smirnov, `arXiv:1704.03811 [hep-ph]`

Di-photon channel can severely constrain the baryonic scale.





Dominant production via gluon fusion with colored new fermions in the loop.

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The strong CP problem.

> QCD Lagrangian is expected to contain CP-violating term:

$$\mathcal{L}_{\mathrm{QCD}} \supset -\bar{\theta}\frac{\alpha_S}{8\pi}\mathrm{Tr}\, G_{\mu\nu}\tilde{G}^{\mu\nu}$$

> Implies non-vanishing neutron EDM [Crewther et al., 1979]

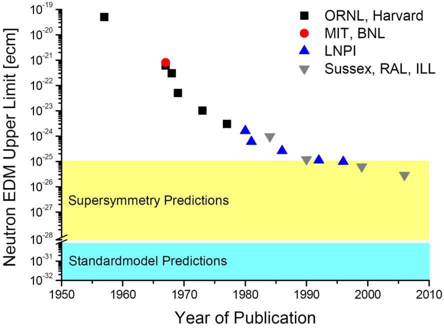
$$d_n \simeq 5.2 \times 10^{-16}\bar{\theta}\, e\,\mathrm{cm}$$

> Current experimental limit [Pendlebury et al., 2015]

$$d_n < 3.0 \times 10^{-26} e\,\mathrm{cm}$$

> Why so small?

$$\bar{\theta} \lesssim \bar{\theta}_{\mathrm{lim}} \simeq 10^{-10} e\,\mathrm{cm}$$



strong CP problem

The Peccei–Quinn mechanism.

[Peccei–Quinn, 1977]

- Introduction of a spontaneously broken global symmetry $U(1)_{\mathrm{PQ}}$ can solve the strong CP problem
- The axion is the corresponding Nambu–Goldstone boson

$$\mathcal{L}_{\mathrm{QCD}} \supset \left(\frac{a}{f_a} - \bar{\theta}\right) \frac{\alpha_S}{8\pi} \mathrm{Tr}\, G_{\mu\nu} \tilde{G}^{\mu\nu}$$

- Invisible axion models ($f_a \gg v_H$): axion is very light, very weakly coupled, very long-lived
  - Kim–Shifman–Vainshtein–Zakharov (KSVZ): SM singlet axion field, pair of heavy quarks Q_L, Q_R that transform non-trivially under $SU(3)_C$ and chirally under $U(1)_{\mathrm{PQ}}$
  - Dine–Fischler–Srednicki–Zhitnitsky (DFSZ): two or more Higgs doublets H_i carry PQ charge, SM singlet axion field, SM quarks (and leptons) carry PQ charge

Searches for the QCD Axion.

> for the QCD axion:

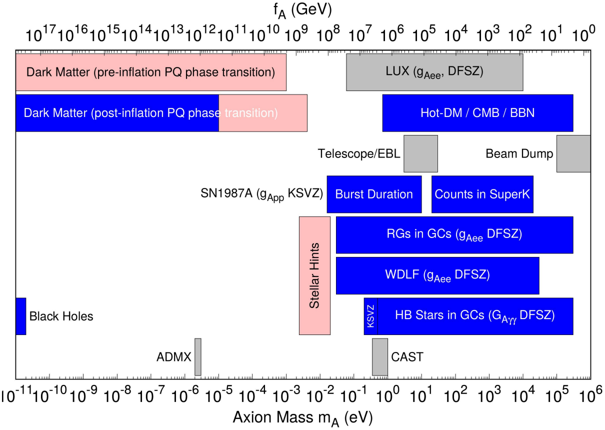
$$m_a \sim 6\,\mu\text{eV}\left(\frac{9\times 10^{11}\,\text{GeV}}{f_a}\right)$$

> all couplings $\propto 1/f_a$

> post-inflationary PQ symmetry breaking:

$$\Omega_a h^2 \simeq 0.12\left(\frac{30\,\mu\text{eV}}{m_a}\right)^{\frac{7}{6}}$$

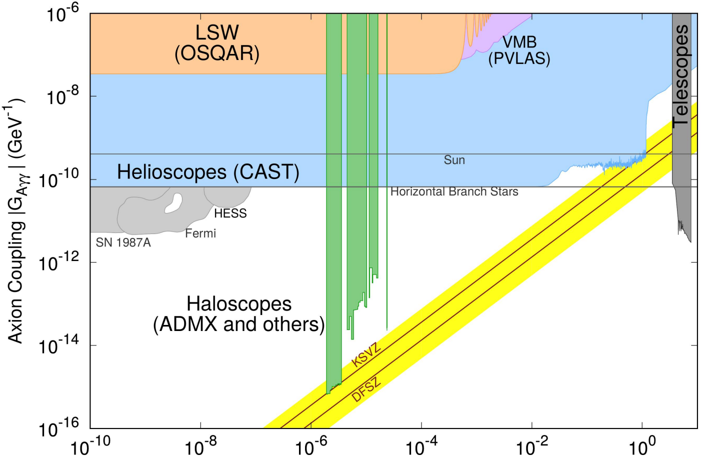
PDG 2017



> pre-inflationary PQ symmetry breaking: $\Omega_a h^2 \simeq 0.12\left(\frac{f_a}{9\times 10^{11}\,\text{GeV}}\right)^{\frac{7}{6}} F\theta_i^2$

Searches for axion-like particles (ALPS).

PDG 2017



> for axion-like particles coupling is independent of mass

Quality of the Peccei–Quinn Solution.

- If PQ symmetry explicitly broken by sources other than the QCD chiral anomaly, then generically $\bar{\theta} \neq 0$
- Continuous global symmetries are expected to be explicitly broken by Planck-scale physics
- Planck-scale breaking of the PQ symmetry via an operator of mass dimension D leads to

$$\bar{\theta} \simeq g_{\mathrm{Pl}} \frac{M_{\mathrm{Pl}}^2}{m_a^2} \left(\frac{f_a}{M_{\mathrm{Pl}}} \right)^{D-2}$$

- Unless Planck-suppressed operators with mass dimension $D \lesssim 9$ are absent, then $\bar{\theta} > \bar{\theta}_{\mathrm{lim}}$ for $g_{\mathrm{Pl}} = \mathcal{O}(1)$ and $f_a \sim \mathcal{O}(10^{11}\,\mathrm{GeV})$
- Possible solutions: impose discrete symmetries, or embed $U(1)_{\mathrm{PQ}}$ into a local symmetry or GUT
- Caveat: the couplings g_{Pl} might be very small

[Barr, Seckel, PRD **46** (1922) 539; Holman et al., PLB **282** (1992) 132; Kamionkowski, March-Russell, PLB **282** (1992) 137]

A gauged $U(1)_{\mathrm{PQ}}$.

- Relevant ingredient of the PQ mechanism: QCD chiral anomaly is main source of explicit $U(1)_{\mathrm{PQ}}$ breaking

$$\mathcal{A}_{\mathrm{U(1)_{PQ}\times SU(3)^2}} \neq 0$$

- Thus this symmetry cannot be gauge symmetry by itself
- Assume two sectors, PQ and PQ′, that are decoupled except for gauge interactions: gauge anomalies can be cancelled between the sectors, and both global exotics symmetries $U(1)_{\mathrm{PQ}}$ and $U(1)'_{\mathrm{PQ}}$ are anomalous:

$$\mathcal{A}_{\mathrm{U(1)_{PQ}\times SU(3)^2}} = -\mathcal{A}_{\mathrm{U(1)'_{PQ}\times SU(3)^2}} \neq 0$$

- Both exotics symmetries are suitable for implementing the PQ mechanism

[See discussion in: Fukuda et al., arXiv:1703.01112]

A Gauged $U(1)_{\mathrm{PQ}}$

- One combination is anomaly free and thus can be a gauged PQ symmetry, $U(1)_{\mathrm{gPQ}}$, and a second combination is anomalous, $U(1)_{\mathrm{aPQ}}$, and can play the role of the symmetry for the PQ mechanism
- In reality there will be interactions between the sectors (scalar operators!): they may respect the gauge symmetry but break the anomalous combination:

$$\mathcal{L} = \frac{1}{M_{\mathrm{Pl}}^{d_{\mathcal{O}_1}+d_{\mathcal{O}_2}-4}} \mathcal{O}_1 \mathcal{O}_2$$

- Cross-sector symmetry breaking can be suppressed by an appropriate gauge charge assignment
- Physical axion is admixture of the two Goldstone bosons, orthogonal admixture eaten by the Z' gauge boson
- effective axion decay constant $f_a = \dfrac{ff'}{\sqrt{f^2 + f'^2}}$

DESY

erc European Research Council Established by the European Commission

Example: the Barr–Seckel model.

[Barr, Seckel, PRD **46** (1992) 539]

- Two KSVZ axion models: in each sector the PQ symmetry is spontaneously broken by the VEVs of complex scalars ϕ and ϕ'
- Scalars couple to vector-like quarks (N_f and N'_f flavors) in each sector:

$$\mathcal{L} = y\phi Q\bar{Q} + \text{h.c.} \quad \text{and} \quad \mathcal{L}' = y'\phi' Q'\bar{Q}' + \text{h.c.}$$

- Couplings of the axion candidates in each sector:

$$\mathcal{L} = \frac{g_s^2}{32\pi^2}\left(\frac{N_f\tilde{a}}{f_a} + \frac{N'_f\tilde{b}}{f_b}\right)G\tilde{G}$$

- A linear combination of the two PQ symmetries is anomaly-free (charge assignments $\phi(q)$ and $\phi'(q')$ -> gauge symmetry $U(1)_{\text{gPQ}}$
- Interaction terms between the two sectors break the anomalous combination $U(1)_{\text{aPQ}}$:

$$\mathcal{L} = \frac{1}{M_{\text{Pl}}^{|q|+|q'|-4}}\phi^{|q'|}\phi'^{|q|}$$

- For $|q| + |q'| \geq 10$: acceptable $U(1)_{\text{aPQ}}$ as a result of $U(1)_{\text{gPQ}}$

Protecting the axion with baryon number.

[MD, K. Schmidt-Hoberg, J. Unwin, arXiv:1712.01841]

- Can this be implemented with gauged baryon number?
- Setup:
  - at least two pairs of fermion exotics / two accidental PQ symmetries
  - at least one exotic fermion pair must transform non-trivially under $SU(2)_L$ to cancel $SU(2)_L^2 \times U(1)_B$ anomaly
  - not all exotic fermions can transform in same $SU(2)$ representation (simultaneous cancellation of $SU(2)_L^2 \times U(1)_B$ and $SU(3)^2 \times U(1)_B$
  - vector-like under SM gauge group to allow simple mass terms
- n fermion pairs in λ_i-dimensional representation of $SU(2)_L$

$$\lambda_{1L} = (\mathbf{3}, \boldsymbol{\lambda_1}, Y_1, B_1), \qquad \lambda_{1R} = (\mathbf{3}, \boldsymbol{\lambda_1}, Y_1, B'_1),$$
$$\vdots \qquad\qquad\qquad\qquad \vdots$$
$$\lambda_{nL} = (\mathbf{3}, \boldsymbol{\lambda_n}, Y_n, B_n), \qquad \lambda_{nR} = (\mathbf{3}, \boldsymbol{\lambda_n}, Y_n, B'_n),$$

- Anomaly cancellation requires $\sum_{i=1}^{n} \lambda_i (B_i - B'_i) = 0$

Operators violating the PQ symmetry.

- Dominant operators leading to a deviation of $\bar{\theta}$ from zero: operators involving only scalars with high-scale VEVs
- Operators involving fields that do not obtain VEVs are expected to be subdominant. [B. Dobrescu 1996]
- Leading scalar operator violating the PQ symmetry occurs at mass dimension $D \leq \sum_{i=1}^{n} \lambda_i$
- Scalars carry charges Δ_1 and Δ_2
- Inequality is saturated, if the following are coprime:

$$\sum_{B_i - B_i' = \Delta_1} \lambda_i \quad \text{and} \quad \sum_{B_i - B_i' = \Delta_2} \lambda_i$$

A simple solution.

- With fermions in fundamental and adjoint of $SU(2)$, several exotic fermions are needed to provide adequate protection (operator dimension increases with number of exotic fermions)
- Possible solution:

$$\begin{aligned} T_L^1 &= (\mathbf{3}, \mathbf{3}, -2, 1/3), & T_R^1 &= (\mathbf{3}, \mathbf{3}, -2, 5/12), \\ T_L^2 &= (\mathbf{3}, \mathbf{3}, 0, 0), & T_R^2 &= (\mathbf{3}, \mathbf{3}, 0, 1/12), \\ T_L^3 &= (\mathbf{3}, \mathbf{3}, 0, 1/6), & T_R^3 &= (\mathbf{3}, \mathbf{3}, 0, 1/4), \\ S_L &= (\mathbf{3}, \mathbf{1}, -2, 1/2), & S_R &= (\mathbf{3}, \mathbf{1}, -2, -1/4). \end{aligned}$$

- Mass terms with two SM singlet scalars:

$$\Phi_S = (\mathbf{1}, \mathbf{1}, 0, 3/4), \quad \Phi_T = (\mathbf{1}, \mathbf{1}, 0, -1/12).$$

$$\mathcal{L} \supset \Phi_T \left(\kappa_1 \overline{T_L^1} T_R^1 + \kappa_2 \overline{T_L^2} T_R^2 + \kappa_3 \overline{T_L^3} T_R^3 \right) + \kappa_S \Phi_S \overline{S_L} S_R + \kappa_\times \Phi_T^\dagger \overline{T_L^3} T_R^2 + \text{h.c.}$$

- Leading PQ violating operator at dimension 10: $\mathcal{O} \sim \Phi_S \Phi_T^9$
- Viable with pre-inflationary PQ symmetry breaking

Outline.

> Local baryon number
> Dark matter with baryon number
> Baryon asymmetry
> Collider signatures
> Protecting the axion with local baryon number
> Summary

Summary.

- I presented simple theories for the spontaneous breaking of baryon number (and lepton number).
- Features include:
  - No proton decay even though B can be broken at the low scale.
  - DM stability as an automatic consequence of the gauge symmetry.
  - Leptophobic Z_B that can be searched for at colliders.
- Additionally, I showed that a PQ symmetry can be protected from M_{Pl} operators by $U(1)_B$ gauge invariance
  - a well motivated example of a $U(1)_{\mathrm{PQ}}$ arising from a gauge symmetry
  - chiral fermions needed for anomaly cancellation can implement a KSVZ sector
  - aesthetically pleasing connection between the QCD sector and baryon number

Backup slides.

Baryonic dark matter.

Condition from anomaly cancellation: $B_1 - B_2 = -3$
$\Rightarrow$ two options:

$B_1 \neq -B_2$

- Dirac DM, SM singlet-like:

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

- Coupling to the Z_B:

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

- six free parameters (plus extra fermion masses):

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

[MD, Fileviez Pérez, arXiv:1309.3970, arXiv:1409.8165]

$B_1 = -B_2 = -3/2$:

- Majorana DM with axial coupling to the Z_B:

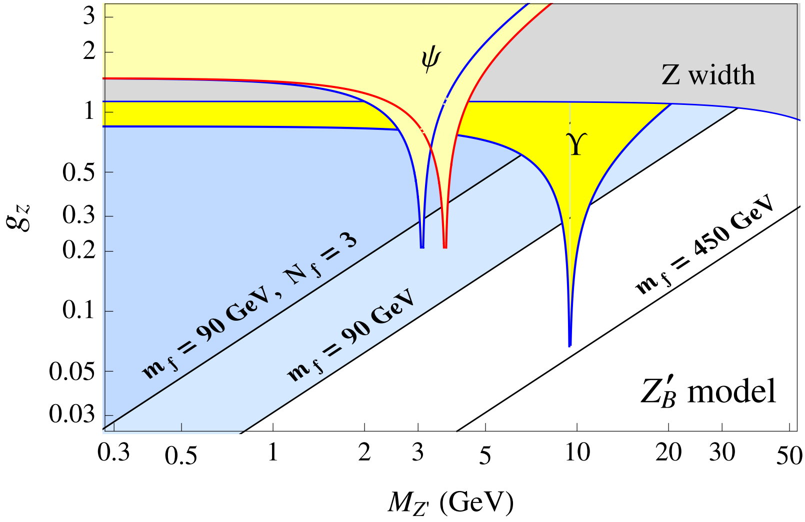
$$-\mathcal{L} \supset \frac{3}{2} g_B \bar{\chi} \gamma_\mu \gamma^5 \chi Z_B^\mu$$

- five free parameters (plus extra fermion masses):

$$M_\chi, M_{Z_B}, g_B, \text{ and } M_{h_2}, \theta_B$$

[MD, Fileviez Pérez, Smirnov, arXiv:1508.01425]

Even lower-mass region.



[Dobrescu, Frugiuele, arXiv:1404.3947]

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

Left–right symmetric model.

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

SM fields

$$Q_L \sim (\mathbf{2}, \mathbf{1}, 1/3)$$
$$Q_R \sim (\mathbf{1}, \mathbf{2}, 1/3)$$
$$\ell_L \sim (\mathbf{2}, \mathbf{1}, -1)$$
$$\ell_R \sim (\mathbf{1}, \mathbf{2}, -1)$$

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

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

- Promote gauge group to

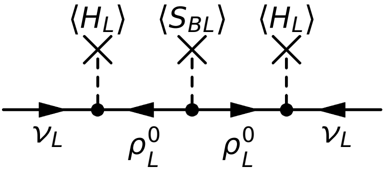
$$SU(2)_L \otimes SU(2)_R \otimes U(1)_B \otimes U(1)_L$$

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]

Towards low-scale unification.

- Step 1: Unification of gauge interactions at the low scale

P. Fileviez Pérez, S. Ohmer, arXiv:1405.1199

  - Fields in minimal theory for B and L allow for unification at the low scale (proton is stable!)

- Step 2: Find UV completion and embed baryon number into a non-abelian gauge symmetry

P. Fileviez Pérez, S. Ohmer, arXiv:1612.07165

  - If quarks and leptons live in the same multiplets, B and L cannot be defined
  - With extra matter one can have multiplets with definite baryon number, one of the generators can be identified with baryon number
  - Color and baryon number can be unified in $SU(4)_C$

similar to Pati, Salam, Phys. Rev. D **10** (1974) 275
Fileviez Pérez, Wise, arXiv:1307.6213
Fornal, Rajaraman, Tait, arXiv:1506.06131

Gauge coupling unification.

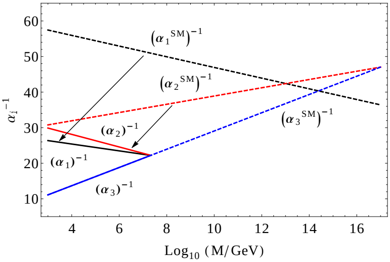
> Running of gauge couplings (@ 1-loop):

$$k_i \alpha_i^{-1}(M) = \alpha_i^{-1}(M_Z) - \frac{B_i}{2\pi} \log(M/M_Z)$$

$$B_i = b_i^{\mathrm{SM}} + \Theta(M - M_F) n_F b_i^{\mathrm{new}} \frac{\log(M/M_F)}{\log(M/M_Z)}$$

> k_i: normalization
> M_F: mass scale of the new fermions (here: 500 GeV)
> n_F: number of new fermion copies

P. Fileviez Pérez, S. Ohmer, arXiv:1405.1199 [hep-ph]



> Model with $SU(2)$ triplet:

n_F	unification scale [TeV]	k_1
1	1.24×10^9	2.05
2	4.96×10^6	2.67
4	2.14×10^4	3.62
5	4.58×10^3	3.99

Gauge coupling unification.

- Running of gauge couplings (@ 1-loop):

$$k_i \alpha_i^{-1}(M) = \alpha_i^{-1}(M_Z) - \frac{B_i}{2\pi} \log(M/M_Z)$$

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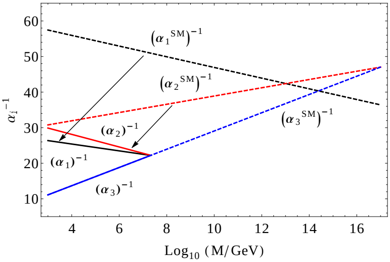
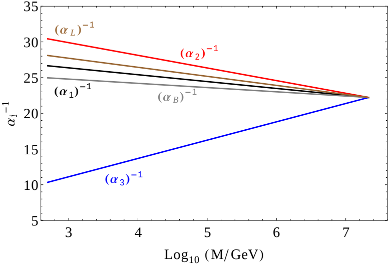
P. Fileviez Pérez, S. Ohmer, arXiv:1405.1199 [hep-ph]





Unification of gauge interactions possible with small α_B (and α_L) at the low scale.

Baryon number as the fourth color.

- Embed $\mathrm{SM} \otimes U(1)_B$ into $SU(4)_C \otimes SU(3)_L \otimes SU(3)_R$

  P. Fileviez Pérez, S. Ohmer, arXiv:1612.07165

  - SM fermions

$$Q = \begin{pmatrix} d_r & u_r & D_r \\ d_b & u_b & D_b \\ d_g & u_g & D_g \\ \Psi_d & \Psi_u & \Psi_D \end{pmatrix} \sim (4, \bar{3}, 1)$$

$$Q^c = \begin{pmatrix} d^c_{\bar{r}} & d^c_{\bar{b}} & d^c_{\bar{g}} & \eta^c_d \\ u^c_{\bar{r}} & u^c_{\bar{b}} & u^c_{\bar{g}} & \eta^c_u \\ D^c_{\bar{r}} & D^c_{\bar{b}} & D^c_{\bar{g}} & \eta^c_D \end{pmatrix} \sim (\bar{4}, 1, 3)$$

$$L = \begin{pmatrix} N_1 & E^+ & \nu \\ E^- & N_2 & e^- \\ \nu^c & e^+ & N_3 \end{pmatrix} \sim (1, 3, \bar{3})$$

$$\boxed{SU(4)_C \otimes SU(3)_L \otimes SU(3)_R} \xrightarrow{\langle \Sigma \rangle \neq 0} \boxed{SU(3)_C \otimes SU(3)_L \otimes SU(3)_R \otimes U(1)_B}$$

$$\xrightarrow{\langle \Phi_{33} \rangle \neq 0} \boxed{SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \otimes U(1)_B} \xrightarrow{\langle \Phi_{23} \rangle \neq 0} \boxed{SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_B}$$

  - extra fermions (anomalies)

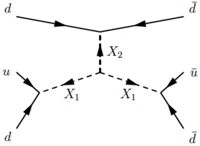
    $\Psi^c \sim (1, 3, 1)$ and $\eta \sim (1, 1, \bar{3})$

- Possible embedding into $SU(4)_C \otimes SU(4)_L \otimes SU(4)_R$ (plus Z_3 symmetry)

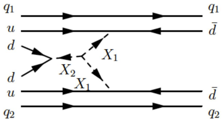
More B-violating processes.

> $\Delta B = 2$

> n–$\bar{n}$ oscillation



> dinucleon decay



> $\Delta B = 3$: effective operators containing SM fields arise at $d = 15$

> triple nucleon decay

$$ppp \to e^+ + \pi^+ + \pi^+$$
$$ppn \to e^+ + \pi^+$$
$$pnn \to e^+ + \pi^0$$
$$nnn \to \bar{\nu} + \pi^0$$

> three-nucleon systems in nature: Tritium (^{3}H) and Helium-3 (^{3}He)
> unstable and undergo β-decay with short lifetimes
> potential decays: $^3\mathrm{H} \to e^+ + \pi^0$ and $^3\mathrm{He} \to e^+ + \pi^+$

> limits can be obtained from triple nucleon decay in oxygen in water detectors: $\lambda \sim 10^2$ GeV
[Babu et al., arXiv:hep-ph/0306003]

The baryon asymmetry of the Universe.

> Baryon asymmetry of the Universe:

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

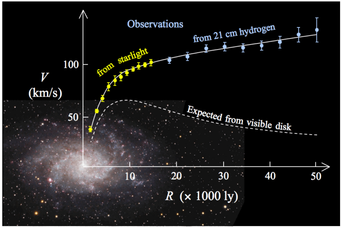
> Necessary ingredients for baryon asymmetry in the Universe: Sakharov Conditions

1. B violation
2. Departure from thermal equilibrium
3. Violation of C and CP

[Sakharov, 1967]

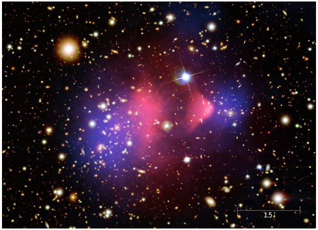
Dark matter in the Universe.

> Rotation curves



[Figure: Wikipedia]

> Bullet cluster



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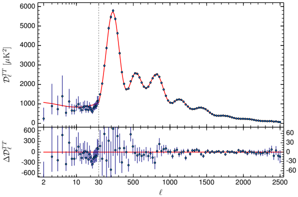
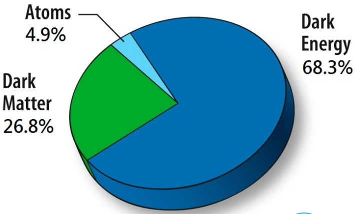
> CMB

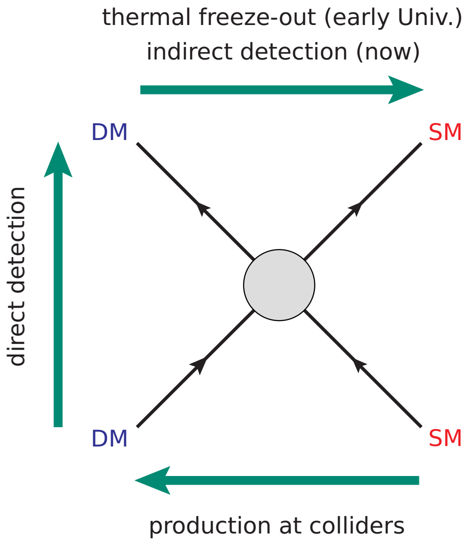


[Planck Collaboration, arXiv:1502.01589]

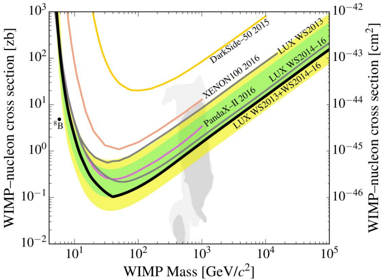
> Content of the Universe



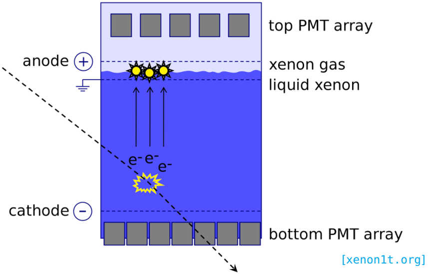
DM–SM interaction.



Direct detection experiments.



[LUX Collaboration, arXiv:1608.07648]



[xenon1t.org]

- Detect recoil energy of dark matter scattering off nuclei in underground experiments.
- Scattering rate

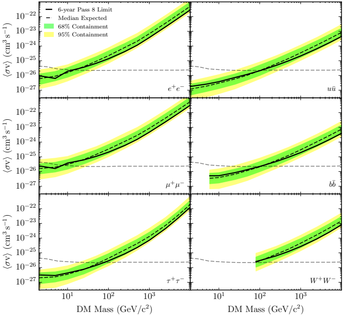
$$\frac{dR}{dE_{\rm nr}} = \frac{\rho_0}{m_{\rm DM} m_N} \int_{v_{\rm min}}^{\infty} dv\, v\, f(v, v_{\rm E}) \frac{d\sigma}{dE_{\rm nr}}$$

- It is possible to compare DD experiments by only specifying DM mass and scattering cross section with nucleons (e.g., for spin-independent scattering); no explicit model necessary.

Indirect detection experiments.

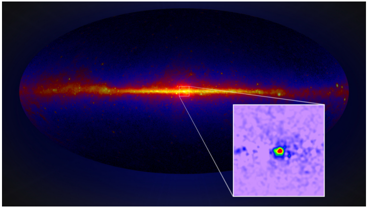
- Satellites, balloons, and ground-based telescopes can look for the SM products from DM annihilation that happens today.
- Most promising in regions of high DM density, such as the galactic center or dwarf spheroidals.

- Cross section limits from dwarf spheroidals:



[Fermi-LAT Collaboration, arXiv:1503.02641]

- Galactic center excess:



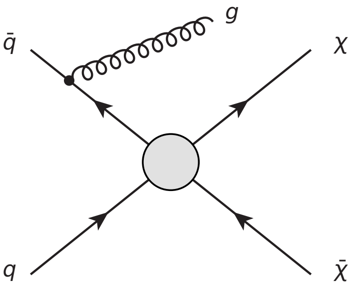
[Credit: NASA/T. Linden, U. Chicago]

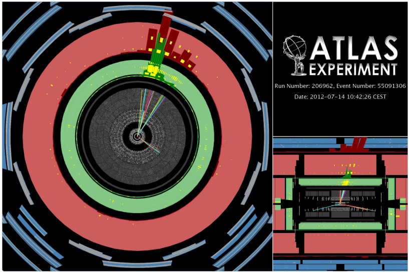
DM at the LHC: mono-X searches.

- No chance to see *pp* → DM DM directly at the LHC: DM particles escape the detector
- Solution: tag DM event with some recoiling SM particle

  mono-X + MET (missing transverse energy) searches

- Collider searches alone cannot establish DM stability on cosmological time scales





Variant with protection to higher order.

- Three pairs of fermion exotics in higher $SU(2)$ representations and corresponding scalars Φ_1 and Φ_2:

$$\begin{aligned}
F_L^1 &= (\mathbf{3}, \mathbf{4}, -2/3, -1/3), & F_R^1 &= (\mathbf{3}, \mathbf{4}, -2/3, 1/6), \\
F_L^2 &= (\mathbf{3}, \mathbf{4}, 2/3, 1/3), & F_R^2 &= (\mathbf{3}, \mathbf{4}, 2/3, 1/21), \\
T_L &= (\mathbf{3}, \mathbf{3}, 5/3, 5/42), & T_R &= (\mathbf{3}, \mathbf{3}, 5/3, -1/6), \\
\Phi_1 &= (\mathbf{1}, \mathbf{1}, 0, -1/2), & \Phi_2 &= (\mathbf{1}, \mathbf{1}, 0, 2/7).
\end{aligned}$$

- Leading PQ violating scalar operator at mass dimension 11:

$$\Phi_1^4 \Phi_2^7$$