Gauge Theories for Baryon and Lepton Numbers

IMPRS-PTFS Seminar, 7 November 2013

Based on arXiv:1304.0576 [hep-ph],
arXiv:1306.0568 [hep-ph],
arXiv:1309.3970 [hep-ph].

With P. Fileviez Pérez (MPIK), M. Lindner (MPIK),
M. B. Wise (Caltech).

Michael Duerr

Max-Planck-Institut für Kernphysik, Heidelberg

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FOR PRECISION TESTS
OF FUNDAMENTAL
SYMMETRIES

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Outline

- Introduction
- Gauging Baryon and Lepton Numbers
- Fermionic Leptoquarks
- Summary

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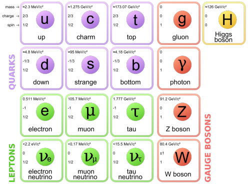
The Standard Model of Particle Physics



Wikipedia

- Standard Model gauge group:

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

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

Standard Model Features

- Renormalizable SM couplings conserve *B* and *L*, e.g.,

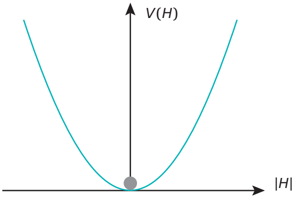
$$\mathcal{L}_{\text{SM}} \supset \overline{\ell_L} \not{D} \ell_L + Y_Q \overline{Q_L} H d_R$$

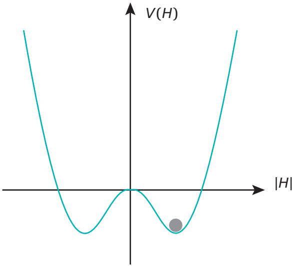
- Yukawa couplings of massless charged leptons:

$$\mathcal{L}_Y = -Y_l \overline{\ell_L} H e_R + \text{h.c.}$$

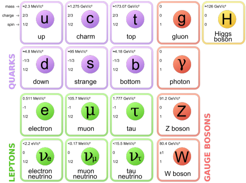
- Spontaneous symmetry breaking $SU(2)_L \otimes U(1)_Y \xrightarrow{\langle H^0 \rangle = v/\sqrt{2}} U(1)_{\text{em}}$:

$$\mathcal{L}_Y \to -\frac{v}{\sqrt{2}} Y_l \overline{e_L} e_R + \text{h.c.}$$





The Standard Model of Particle Physics



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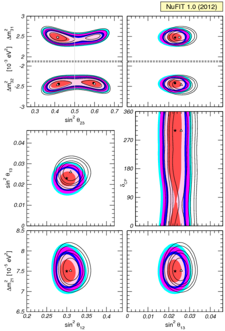
Q_L	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$1/3$	0
u_R	$\mathbf{3}$	$\mathbf{1}$	$2/3$	$1/3$	0
d_R	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	$1/3$	0
ℓ_L	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	0	1
e_R					1
H					0

No right-handed neutrinos:
neutrinos massless in the SM!

Neutrinos Have Mass



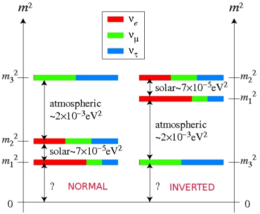
M. C. Gonzalez-Garcia et al., arXiv:1209.3023 [hep-ph]

Neutrino oscillations

$$\nu_i = \sum_\alpha U^*_{i\alpha}\nu_\alpha$$

$$\nu_i(t) = e^{-i(Et-p_ix)}\nu_i$$

$$P_{\alpha\to\beta} = \sin^2(2\theta)\sin^2(1.27\frac{\Delta m^2}{\mathrm{ev}^2}\frac{L/\mathrm{km}}{E/\mathrm{GeV}})$$



R. N. Mohapatra et al., arXiv:hep-ph/0412099

▸ Oszillation parameters

- Is lepton number conserved in Nature? → $0\nu\beta\beta$ experiments

?
$\Longleftrightarrow$

- Weinberg:

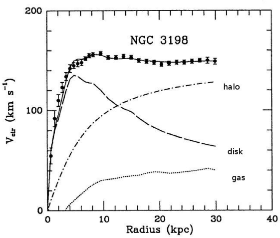
$$\mathcal{O}_5 = \frac{c_5}{\Lambda_L}LLHH$$

Hints for DM

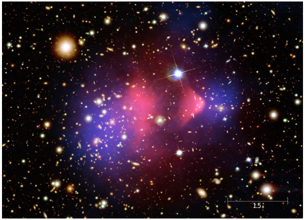
Galaxy rotation curves

Bullet cluster

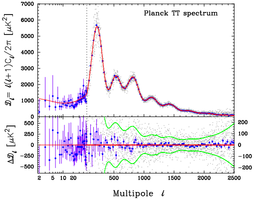
CMB



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



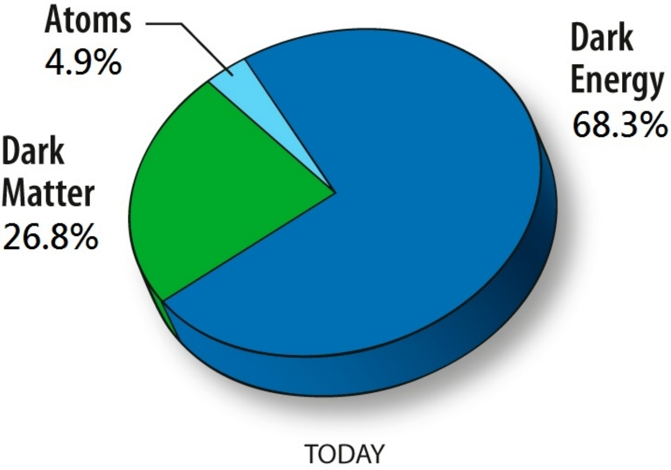
NASA



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

Consistent hints on all scales.

Content of the Universe



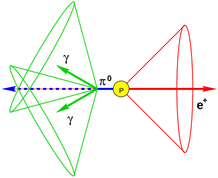
Wikipedia

What about Baryon Number?

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

- Violation of *B*:
    - Matter–antimatter asymmetry of the Universe.
    - Proton decay ($\Delta B = 1$, $\Delta L = \text{odd}$):

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



B. Viren, arXiv:hep-ex/9903029

- Add non-renormalizable operators to the SM, e.g.,

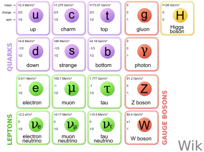
$$\mathcal{O}_6 = \frac{c_6}{\Lambda_B^2} QQQL$$

- The scale Λ_B must be large:

$$\Lambda_B \geq 10^{15}\ \text{GeV}$$

The Big Desert

S. Weinberg, Phys. Rev. Lett. **49** (1979) 1566

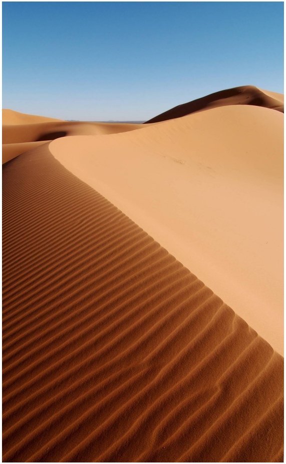


Wikipedia

Low scale

Electroweak scale

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



Wikipedia

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

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

High scale

e.g. GUT scale

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

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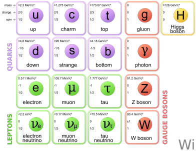
S. Weinberg, Phys. Rev. Lett. **49** (1979) 1566

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



Wikipedia

Low scale

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Wikipedia

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

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

High scale

e.g. GUT scale

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

Aim of this Talk

Define a consistent gauge theory
for baryon and lepton numbers
that can be broken at a low scale.

- Neutrino masses
- Baryogenesis?
- Dark matter
- Signals at the LHC

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B and *L* in the Standard Model

- SM: B and L are accidental symmetries, not free of anomalies.

  $\Rightarrow$ we need additional fermions for anomaly cancellation.

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_B$	$U(1)_L$
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
ℓ_L	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	0	1
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

- B and L may be gauged to obtain the gauge group:

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

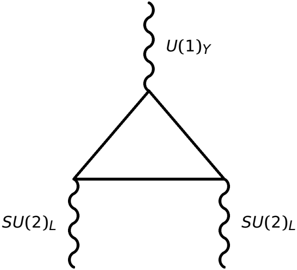
Standard Model Anomalies

Example: $SU(2)_L^2 \otimes U(1)_Y$

$$\mathcal{A} = \mathrm{Tr}\left(t^a t^b Y\right) = \frac{1}{2}\delta^{ab} \cdot \sum_i Y_i$$

$$\sum_i Y_i = -\frac{1}{2} + 3 \cdot \frac{1}{6} = 0$$

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_B$	$U(1)_L$
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



Standard Model Anomalies

Another example: $U(1)_Y^3$

$$\mathcal{A} = \mathrm{Tr}\left(Y^3\right) = \sum_i Y_i^3$$

$$\sum_i Y_i^3 = 2\left(-\frac{1}{2}\right)^3 - (-1)^3 + 3\left[2\left(\frac{1}{6}\right)^3 - \left(\frac{2}{3}\right)^3 - \left(-\frac{1}{3}\right)^3\right] = 0$$

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_B$	$U(1)_L$
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
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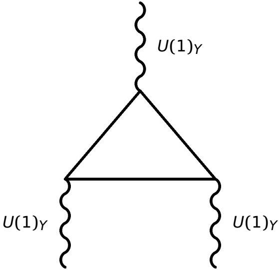


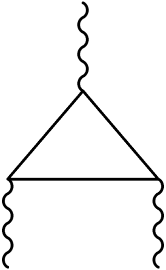
Baryonic and Leptonic Anomalies

- 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:

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

Baryonic and Leptonic Anomalies

- 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:

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

SM + right-handed ν

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

Possible Solutions

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

  Ruled out: new quarks change gluon fusion production; Landau poles of the new Yukawas near the weak scale.

- Vector-Like fermions: 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.

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New Solution: Vectorlike Leptoquarks

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_B$	$U(1)_L$
Ψ_L	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	$-\frac{3}{2}$	$-\frac{3}{2}$
Ψ_R	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	$+\frac{3}{2}$	$+\frac{3}{2}$
η_R	$\mathbf{1}$	$\mathbf{1}$	-1	$-\frac{3}{2}$	$-\frac{3}{2}$
η_L	$\mathbf{1}$	$\mathbf{1}$	-1	$+\frac{3}{2}$	$+\frac{3}{2}$
χ_R	$\mathbf{1}$	$\mathbf{1}$	0	$-\frac{3}{2}$	$-\frac{3}{2}$
χ_L	$\mathbf{1}$	$\mathbf{1}$	0	$+\frac{3}{2}$	$+\frac{3}{2}$

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

Interactions

- Responsible for the new fermion masses:

$$
\begin{aligned}
-\mathcal{L} \supset\; & h_1 \overline{\Psi}_L H \eta_R + h_2 \overline{\Psi}_L \tilde{H} \chi_R + h_3 \overline{\Psi}_R H \eta_L + h_4 \overline{\Psi}_R \tilde{H} \chi_L \\
& + \lambda_1 \overline{\Psi}_L \Psi_R S_{BL} + \lambda_2 \overline{\eta}_R \eta_L S_{BL} + \lambda_3 \overline{\chi}_R \chi_L S_{BL} \\
& + a_1 \chi_L \chi_L S_{BL} + a_2 \chi_R \chi_R S_{BL}^\dagger + \text{h.c.}
\end{aligned}
$$

  with $S_{BL} \sim (1, 1, 0, -3, -3)$
- Neutrino masses:

$$
-\mathcal{L}_\nu = Y_\nu \bar{\ell}_L \tilde{H} \nu_R + \frac{\lambda_R}{2} \nu_R \nu_R S_L + \text{h.c.}
$$

  with $S_L \sim (1, 1, 0, 0, -2)$

Further Aspects

- Symmetry breaking:
  - S_{BL} breaks $U(1)_B$ and $U(1)_L$ ($\Delta B = \pm 3$, $\Delta L = \pm 3$),
  - S_L contributes to breaking of $U(1)_L$ ($\Delta L = \pm 2$).

→ no proton decay

- Fermionic sector:
  - 4 neutral and 4 charged new chiral fermions after symmetry breaking.
  - No coupling to the SM fermions → no new source of flavor violation.
  - Lightest new fermion automatically stable → DM candidate.

Simple Example: Baryon Number Only

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

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

- New Higgs for spontaneous breaking of baryon number: $S_B \sim (\mathbf{1}, \mathbf{1}, 0, -3)$
- Condition from anomaly cancellation: $B_1 - B_2 = -3$.

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

Spontaneous Symmetry Breaking

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

$$-\mathcal{L} \supset \lambda_1 \bar{\Psi}_L \Psi_R S_B + \lambda_2 \bar{\eta}_R \eta_L S_B + \lambda_3 \bar{\chi}_R \chi_L S_B + \text{h.c.}$$

- $\langle S_B \rangle \neq 0$:

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

- Remnant Z_2 stabilizes the DM candidate:

$$\Psi_{L,R} \to -\Psi_{L,R},\ \ \eta_{L,R} \to -\eta_{L,R}, \text{and } \chi_{L,R} \to -\chi_{L,R}$$

Dark Matter

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

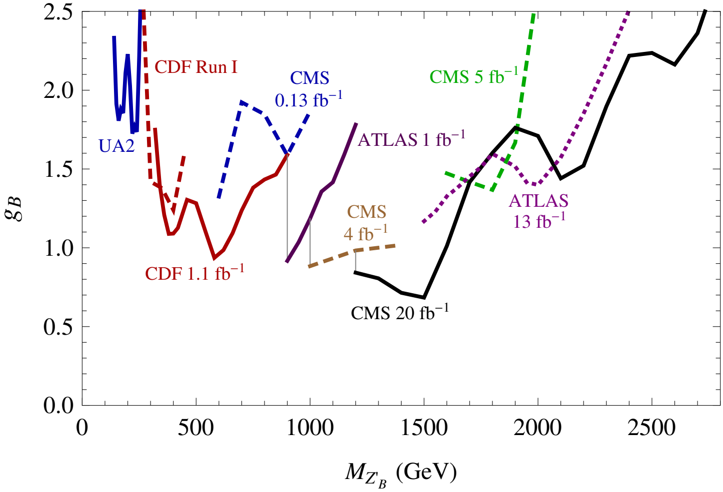
$$\mathcal{L} \supset g_B \overline{\chi} \gamma_\mu Z_B^\mu (B_2 P_L + B_1 P_R) \chi$$

- Model has only four free parameters:

$$M_\chi, M_{Z_B}, g_B, \text{ and } B_1 + B_2$$

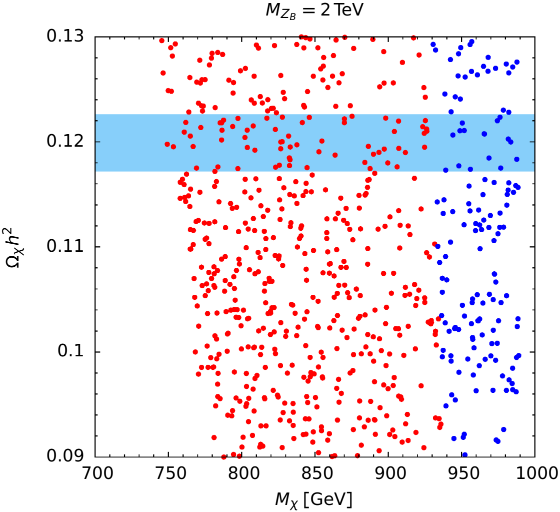
$\Longrightarrow$ fully testable by combining LHC, DM direct detection, DM relic density.

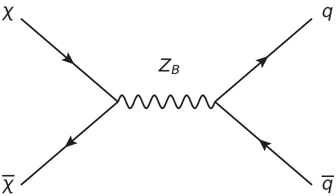
New Gauge Boson at the LHC



B. A. Dobrescu, F. Yu, arXiv:1306.2629 [hep-ph]

Dark Matter Relic Density

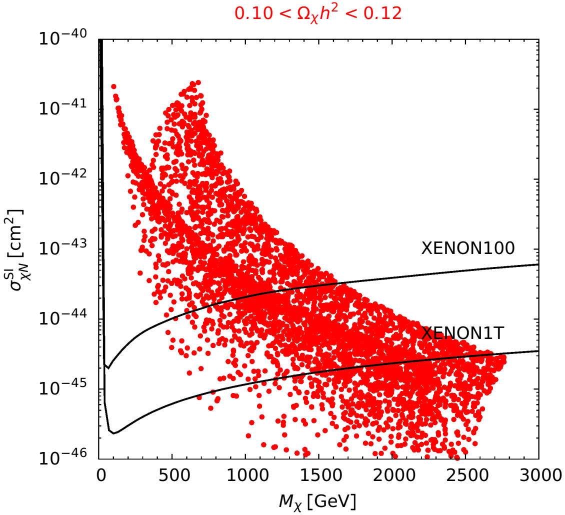




- Planck: $\Omega_{\text{DM}} h^2 = 0.1199 \pm 0.0027$

$g_B \in [0.10, 0.25]$
$g_B \in [0.25, 0.50]$

Dark Matter Direct Detection



Left–right symmetric model

SM fields

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

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

- 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

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

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

Anomaly Cancellation

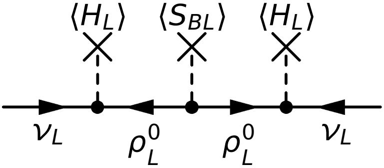
- Anomalies that need to be cancelled:

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

- Simplest solution: type III seesaw fields

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

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



M. Duerr, P. Fileviez Pérez, M. Lindner, arXiv:1306.0568 [hep-ph]

Outline

- Introduction
- Gauging Baryon and Lepton Numbers
- Fermionic Leptoquarks
- Summary

Summary

Simple extension of the SM:

- *B* and *L* are gauge symmetries broken at a low scale
- no proton decay ⇒ no need for a desert
- Neutrino masses
- Fermionic DM candidate
- Testable at the LHC

Summary

Simple extension of the SM:

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Thank you!

Backup slides

Neutrino parameters

- Pontecorvo–Maki–Nakagawa–Sakata mixing matrix

$s_{ij} = \sin\theta_{ij}$
$c_{ij} = \cos\theta_{ij}$
α, β: Majorana phases
δ: Dirac phase

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \operatorname{diag}\left(1, e^{i\frac{\alpha}{2}}, e^{i(\frac{\beta}{2}+\delta)}\right)$$

- Oszillation parameters ($\Delta m_{ij}^2 = m_i^2 - m_j^2$)

$\sin^2\theta_{12}$	$\sin^2\theta_{23}$		$\sin^2\theta_{13}$
$0.302^{+0.013}_{-0.012}$	$0.413^{+0.037}_{-0.025} \oplus 0.594^{+0.021}_{-0.022}$		$0.0227^{+0.0023}_{-0.0024}$
$\delta_{\mathrm{CP}}/°$	$\Delta m_{21}^2\,[10^{-5}\,\mathrm{eV}^2]$	$\Delta m_{31}^2\,[10^{-3}\,\mathrm{eV}^2]$ (NO)	$\Delta m_{32}^2\,[10^{-3}\,\mathrm{eV}^2]$ (IO)
300^{+66}_{-138}	$7.50^{+0.18}_{-0.19}$	$+2.473^{+0.070}_{-0.067}$	$-2.427^{+0.042}_{-0.065}$

M. C. Gonzalez-Garcia et al., `arXiv:1209.3023 [hep-ph]`

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