Dirac Neutrinos from Gauged $B - L$ Symmetry

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The Standard Theory and Beyond in the LHC Era
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Outline

Outline

Neutrinos: Dirac or Majorana ?

- One of the most important open questions in neutrino physics: Whether neutrinos are Dirac or Majorana particles
- Answering this question: Essential to finding the underlying theory of neutrino masses and mixing
- No compelling evidence from experiments or cosmological observations in favor of either Dirac or Majorana nature of neutrino
- Neutrinoless double beta decay experiments: Dedicated ongoing experiments to determine the nature of neutrinos
- No $0\nu\beta\beta$ signal observed so far
- Current understanding: Dirac neutrinos as plausible as Majorana ones

Neutrinos: Dirac or Majorana ?

- Majorana Neutrinos: Well studied
  - Several mechanisms (e.g. seesaw) satisfactorily explain smallness of neutrino masses
- Dirac Neutrinos: Not as well studied
  - Few models capable of providing a natural explanation of smallness of neutrino masses
- We present a simple framework for Dirac neutrinos with naturally small masses based on gauged $B - L$ symmetry
- Gauged $B - L$ symmetry: Other new possibilities also discussed

$B - L$ Symmetry

- Historically Baryon number (B) and Lepton numbers (L_i) were introduced to explain the stability of proton and absence of lepton flavour changing processes
- In Standard Model (SM): Baryon and Lepton numbers turn out to be accidentally conserved classical symmetries
- The B and L currents are anomalous and only the combination $B - L$ is anomaly free
- Accidental Symmetries: Physics beyond standard model (BSM) need not conserve it
- Majorana mass term for neutrinos: $B - L$ symmetry broken by 2 units
- Addition of right handed neutrinos: Provides possibility of anomaly free gauged $B - L$ symmetry

Gauged $B - L$ Symmetry

- New $U(1)_x$ gauge symmetry: Need to cancel anomalies[1]
- Gauged $U(1)_{B-L}$ symmetry: Anomaly cancellation required
  - Triangular gauge anomalies :
    1) $\mathrm{Tr}\left(\mathrm{U}(1)_{\mathrm{B-L}}\left[\mathrm{SU}(2)_{\mathrm{L}}\right]^2\right)$
    2) $\mathrm{Tr}\left(\mathrm{U}(1)_{\mathrm{B-L}}\left[\mathrm{U}(1)_{\mathrm{Y}}\right]^2\right)$
    3) $\mathrm{Tr}\left(\mathrm{U}(1)_{\mathrm{B-L}}\right)^3$
  - Particle content of SM: First two anomalies are already zero
  - If the right handed neutrinos ν_{iR}; $i = 1, 2, 3$ transform as $\nu_{iR} \sim -1$ under $U(1)_{B-L}$, then $\sum U(1)^3_{B-L} = 0$
  - Gauge - gravitational anomalies also vanish as $-3(-1) = 3$
- Gauged $U(1)_{B-L}$ symmetry: One of the simplest and well studied models

[1]E. Ma, Phys. Rev. Lett. 89, 041801 (2002)

Majorana Neutrinos from Gauged $B-L$ Symmetry

- Add a singlet scalar χ transforming as $\chi \sim 2$ under $U(1)_{B-L}$
- The $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_{B-L}$ invariant Yukawa couplings for neutrinos is given by

$$-\mathcal{L}_Y^\nu = \sum_{i,j} y_{ij} \bar{L}_{iL} \hat{\Phi}^* \nu_{jR} + \frac{1}{2} \sum_{i,j} f_{ij} \bar{\nu}^c_{iR} \chi \nu_{jR} + \text{h.c.}$$

- The spontaneous symmetry breaking (SSB) of χ: Breaking of $B-L$ symmetry
- If $\langle \chi \rangle = u$: Right handed neutrinos get a Majorana mass $M_{ij} = \sqrt{2} f_{ij} u$
- If $u >> v$ then $M_R >> m_D$ leading to a natural implementation of Type I seesaw mechanism
- The gauged $B-L$ symmetry: Essential ingredient of Left-Right symmetric models
- Can be embedded in GUT groups e.g. $SO(10)$

Outline

Dirac Neutrinos from Gauged $B - L$ Symmetry

- Non standard $B - L$ charges: Let us add 3 right handed neutrinos transforming as $\nu_{iR} = (+5, -4, -4)$ under $B - L$ symmetry[2]
- No anomaly: Since $\nu_{iR} \sim (+5, -4, -4)$, therefore

$$\begin{aligned} -(+5)^3 - (-4)^3 - (-4)^3 &= +3 \\ -(5) - (-4) - (-4) &= +3 \end{aligned}$$

- The model is free from gauge as well as gauge-gravitational anomalies
- Now the standard-model Higgs doublet $(\phi^+, \phi^0)^T$ does not connect ν_L with ν_R
- Neutrinos are massless

[2] Ernest Ma, Rahul Srivastava, Phys. Lett. B, 741, 217-222 (2015)

Dirac Neutrinos from Gauged $B - L$ Symmetry

- Neutrino mass generation: Add three heavy Dirac singlet fermions $N_{L,R}$
- Let them transform as -1 under $B - L$
- They will not change the anomaly conditions: The model will remain anomaly free
- Also add singlet scalar χ_3 transforming as $+3$ under $B - L$
- Now for ν_{R2} and ν_{R3}, $(\bar{\nu}_L, \bar{N}_L)$ is linked to (ν_R, N_R) through the 6×5 mass matrix as follows

$$M_{\nu,N} = \begin{pmatrix} 0 & m_0 \\ m_3 & M \end{pmatrix}$$

where m_0 and M are 3×3 mass matrices and m_3 is 3×2. Also, m_0 originates from Yukawa coupling $\bar{\nu}_L N_R \phi$ and m_3 from $\bar{N}_L \nu_R \chi_3$

Dirac Neutrinos from Gauged $B-L$ Symmetry

- The invariant mass M is naturally large, so the Dirac seesaw yields a small neutrino mass $m_3 m_0/M$
- In the conventional $U(1)_{B-L}$ model, $\chi_2 \sim +2$ under $B-L$, is chosen to break the gauge symmetry, so that ν_R gets a Majorana mass
- Here, $\chi_3 \sim +3$ means that it is impossible to construct an operator of any dimension for a Majorana mass term
- Since $\nu_{R1} \sim +5$ does not connect with ν_L or N_L directly, there is one massless neutrino in this case
- The dimension-five operator $\bar{N}_L \nu_{R3} \chi_3^* \chi_3^* / \Lambda$ is allowed by $U(1)_{B-L}$ and would give it a small Dirac mass
- Alternatively, one can add a second scalar $\chi_6 \sim 6$ to the model to account for mass of ν_{R1}

Outline

The S_3 Group

- The previous discussion was aimed mainly at mass generation for Dirac neutrinos
- However, so far we haven't discussed how to obtain the observed mixing matrix
- $B - L$ symmetry alone does not provide any explanation for the currently observed PMNS mixing pattern
- In order to understand the leptonic family structure consistent with present neutrino oscillation data, we will make use of the non-Abelian discreet symmetry group S_3

The S_3 Group

- The S_3 group is the smallest non-Abelian discreet symmetry group and is the group of the permutation of three objects
- It consists of six elements and is also isomorphic to the symmetry group of the equilateral triangle
- It admits three irreducible representations 1, $1'$ and 2 with the tensor product rules

$$1 \otimes 1' = 1', \quad 1' \otimes 1' = 1, \quad 2 \otimes 1 = 2,$$
$$2 \otimes 1' = 2, \quad 2 \otimes 2 = 1 \oplus 1' \oplus 2$$

- In this talk we will use the complex representation of the S_3 group

The S_3 invariant lepton sector

- The $B-L$ charge and S_3 assignment of the fields for the lepton sector is as shown in Table

Fields	$B-L$	S_3	Fields	$B-L$	S_3
L^e	-1	$1'$	e_R	-1	$1'$
L^μ	-1	$1'$	μ_R	-1	$1'$
L^τ	-1	1	τ_R	-1	1
N_L^1	-1	$1'$	N_R^1	-1	$1'$
N_L^2	-1	$1'$	N_R^2	-1	$1'$
N_L^3	-1	1	N_R^3	-1	1
Φ	0	1	ν_R^e	5	$1'$
$\begin{pmatrix} \nu_R^\mu \\ \nu_R^\tau \end{pmatrix}$	-4	2	$\begin{pmatrix} \chi_2 \\ \chi_3 \end{pmatrix}$	3	2

Table : The $B-L$ and S_3 charge assignment for the fields

The S_3 invariant lepton sector

- The S_3 and $B-L$ invariant Yukawa $\mathcal{L}_Y$ interaction can be written as

$$\mathcal{L}_Y = \mathcal{L}_{L^\alpha l_R} + \mathcal{L}_{L^\alpha N_R} + \mathcal{L}_{N_L N_R} + \mathcal{L}_{N_L \nu_R}$$

- Where

$$\begin{aligned}
\mathcal{L}_{L^\alpha l_R} &= y'_e\, \bar{L}^e\, \Phi\, e_R + y'_{12}\, \bar{L}^e\, \Phi\, \mu_R + y'_{21}\, \bar{L}^\mu\, \Phi\, e_R + y'_\mu\, \bar{L}^\mu\, \Phi\, \mu_R \\
&+ y_\tau\, \bar{L}^\tau\, \Phi\, \tau_R \\
\mathcal{L}_{L^\alpha N_R} &= g'_{11}\, \bar{L}^e\, \hat{\Phi}^*\, N_R^1 + g'_{12}\, \bar{L}^e\, \hat{\Phi}^*\, N_R^2 + g'_{21}\, \bar{L}^\mu\, \hat{\Phi}^*\, N_R^1 \\
&+ g'_{22}\, \bar{L}^\mu\, \hat{\Phi}^*\, N_R^2 + g_{33}\, \bar{L}^\tau\, \hat{\Phi}^*\, N_R^3 \\
\mathcal{L}_{N_L N_R} &= M'_{11}\, \bar{N}_L^1\, N_R^1 + M'_{12}\, \bar{N}_L^1\, N_R^2 + M'_{21}\, \bar{N}_L^2\, N_R^1 + M'_{22}\, \bar{N}_L^2\, N_R^2 \\
&+ M_{33}\, \bar{N}_L^3\, N_R^3
\end{aligned}$$

The S_3 invariant lepton sector

- $$\begin{aligned}
\mathcal{L}_{N_L \nu_R} &= \frac{f'_{11}}{\Lambda} \left(\bar{N}_L^1 \, \nu_R^e\right) \otimes \left[\begin{pmatrix} \chi_3^* \\ \chi_2^* \end{pmatrix} \otimes \begin{pmatrix} \chi_3^* \\ \chi_2^* \end{pmatrix} \right]_1 \\
&+ \frac{f'_{21}}{\Lambda} \left(\bar{N}_L^2 \, \nu_R^e\right) \otimes \left[\begin{pmatrix} \chi_3^* \\ \chi_2^* \end{pmatrix} \otimes \begin{pmatrix} \chi_3^* \\ \chi_2^* \end{pmatrix} \right]_1 \\
&+ f'_{12} \, \bar{N}_L^1 \otimes \left[\begin{pmatrix} \nu_R^\mu \\ \nu_R^\tau \end{pmatrix} \otimes \begin{pmatrix} \chi_2 \\ \chi_3 \end{pmatrix} \right]_{1'} \\
&+ f'_{22} \, \bar{N}_L^2 \otimes \left[\begin{pmatrix} \nu_R^\mu \\ \nu_R^\tau \end{pmatrix} \otimes \begin{pmatrix} \chi_2 \\ \chi_3 \end{pmatrix} \right]_{1'} \\
&+ f_{33} \, \bar{N}_L^3 \otimes \left[\begin{pmatrix} \nu_R^\mu \\ \nu_R^\tau \end{pmatrix} \otimes \begin{pmatrix} \chi_2 \\ \chi_3 \end{pmatrix} \right]_1
\end{aligned}$$

- Here, y_α are the Yukawa couplings of the charged leptons whereas f_{ij}, g_{ij} and M_{ij} denote the dimensionless coupling constants between the leptons and the heavy fermions.

The S_3 invariant lepton sector

- After symmetry breaking the scalar fields get VEVs $\langle \phi^0 \rangle = v$, $\langle \chi_i \rangle = u_i$; $i = 2, 3$
- Then the mass matrices relevant to charged lepton is given by

$$\mathcal{M}_l = v \begin{pmatrix} y_e & y_{12} & 0 \\ 0 & y_\mu & 0 \\ 0 & 0 & y_\tau \end{pmatrix}$$

- This mass matrix can be readily diagonalized by bi-unitary transformation
- In the limit of $y_e << y_\mu$ we get

$$\begin{aligned} \theta^l_{12} &\approx \tan^{-1}\left(\frac{-y_{12}}{y_\mu}\right); \qquad m_e \approx v\, y_e \cos\theta^l_{12} \\ m_\mu &\approx v\left(y_\mu \cos\theta^l_{12} - y_{12}\sin\theta^l_{12}\right); \qquad m_\tau \approx v y_\tau \end{aligned}$$

- If $y_{12} = y_\mu$ then maximal mixing is achieved i.e. $\theta^l_{12} = -\frac{\pi}{4}$, with $m_\mu = \sqrt{2} v y_\mu$

The S_3 invariant lepton sector

- Also, the 6×6 mass matrix spanning $(\bar{\nu}_L^e, \bar{\nu}_L^\mu, \bar{\nu}_L^\tau, \bar{N}_L^1, \bar{N}_L^2, \bar{N}_L^3)$ and $(\nu_R^e, \nu_R^\mu, \nu_R^\tau, N_R^1, N_R^2, N_R^3)^{\mathrm{T}}$ of neutrinos and the heavy fermions is given by

$$\mathcal{M}_{\nu,N} = \begin{pmatrix} 0 & 0 & 0 & g_{11} v^* & g_{12} v^* & 0 \\ 0 & 0 & 0 & g_{21} v^* & g_{22} v^* & 0 \\ 0 & 0 & 0 & 0 & 0 & g_{33} v^* \\ 0 & f_{12} u_3 & -f_{12} u_2 & M_{11} & 0 & 0 \\ \frac{f_{21}}{\Lambda} u_2^* u_3^* & f_{22} u_3 & -f_{22} u_2 & M_{21} & M_{22} & 0 \\ 0 & f_{33} u_3 & f_{33} u_2 & 0 & 0 & M_3 \end{pmatrix}$$

- As remarked earlier, the mass terms M_{ij} between the heavy fermions can be naturally large, so we can block diagonalize the mass matrix assuming that $f_{ij}, g_{ij} << M_{ij}$

The S_3 invariant lepton sector

- The block diagonalized mass matrix of light neutrinos is given by

$$\mathcal{M}_\nu = m_{N_L \nu_R} \left(M_{N_L N_R}\right)^{-1} m_{L^\alpha N_R}$$
$$= v^* \begin{pmatrix} \frac{(g_{21} M_{11} - g_{11} M_{21}) f_{12} u_2}{M_{11} M_{22}} & \frac{(g_{22} M_{11} - g_{12} M_{21}) f_{12} u_2}{M_{11} M_{22}} & \frac{-f_{12} g_{33} u_3}{M_{33}} \\ \frac{(g_{21} M_{11} - g_{11} M_{21}) f_{22} u_2 + f_{21} g_{11} M_{22} u_6}{M_{11} M_{22}} & \frac{(g_{22} M_{11} - g_{12} M_{21}) f_{22} u_2 + f_{21} g_{12} M_{22} u_6}{M_{11} M_{22}} & \frac{-f_{22} g_{33} u_3}{M_{33}} \\ \frac{(g_{21} M_{11} - g_{11} M_{21}) f_{33} u_2}{M_{11} M_{22}} & \frac{(g_{22} M_{11} - g_{12} M_{21}) f_{33} u_2}{M_{11} M_{22}} & \frac{f_{33} g_{33} u_3}{M_{33}} \end{pmatrix}$$

  where we have written $u_6 = \frac{u_2^* u_3^*}{\Lambda}$
- Also, the 3×3 mass matrices $m_{L^\alpha N_R}$, $M_{N_L N_R}$ and $m_{N_L \nu_R}$ are obtained from the terms $\mathcal{L}_{L^\alpha N_R}$, $\mathcal{L}_{N_L N_R}$ and $\mathcal{L}_{N_L \nu_R}$ respectively
- This light neutrino mass matrix can be further diagonalized by the bi-unitary transformation
- The neutrino masses and the mixing angles so obtained will be dependent on the specific values of the coupling constants f_{ij}, g_{ij}, M_{ij} as well as the VEVs v, u_i; $i = 2, 3$

The S_3 invariant lepton sector

- In the simplifying case of $g_{ij} = g$ and $M_{ij} = M$ we get

$$\mathcal{M}_\nu = \frac{gv^*}{M} \begin{pmatrix} 0 & 0 & -f_{12}u_3 \\ f_{21}u_6 & f_{21}u_6 & -f_{22}u_3 \\ 0 & 0 & f_{33}u_3 \end{pmatrix}$$

- Diagonalizing the mass matrix we have

$$\begin{aligned} \theta^\nu_{12} &\approx 0; \quad \theta^\nu_{13} \approx \tan^{-1}\left(\frac{f_{12}}{f_{33}}\right); \quad \theta^\nu_{23} \approx \tan^{-1}\left(\frac{f_{22}}{\sqrt{f_{12}^2 + f_{33}^2}}\right) \\ m^\nu_1 &\approx 0; \qquad m^\nu_2 \approx \frac{\sqrt{2(f_{12}^2 + f_{33}^2)}f_{21}g|v|}{M\sqrt{f_{12}^2 + f_{22}^2 + f_{33}^2}}|u_6|; \\ m^\nu_3 &\approx \frac{\sqrt{f_{12}^2 + f_{22}^2 + f_{33}^2}\,g|v|}{M}|u_3| \end{aligned}$$

The S_3 invariant lepton sector

- Since, $u_6 << u_3$, we have a normal hierarchy pattern with two nearly massless neutrinos and one relatively heavy neutrino
- Moreover, the massless neutrino will also gain small mass, if any of the M_{ij}'s or g_{ij}'s are not equal to M or g respectively
- Also, if they deviate significantly from these values then one can possibly recover degenerate or inverted hierarchy patterns also
- Now, if U_l and U_ν are the mixing matrices of the charged leptons and neutrinos respectively, then the PMNS mixing matrix is given by

$$U_{\rm PMNS} = U_l^\dagger U_\nu$$

- Taking $y_{12} = y_\mu$, $f_{12} = -\frac{f_{33}}{2}$ and $f_{22} = \sqrt{f_{12}^2 + f_{33}^2}$ in we get $\theta_{23}^\nu = -\theta_{12}^l = \frac{\pi}{4}$ and $\theta_{13}^\nu = \tan^{-1}(-\frac{1}{2})$ which gives PMNS mixing angles consistent with present $3-\sigma$ limits of global fits obtained from experiments[3]

[3] Capozzi et.al. Phys. Rev. D, 89, 093018 (2014)

The Quark Sector

- In our minimal model with only one doublet scalar, the quark sector can be accommodated in a simple way if both the left handed quark doublets $Q_L^i = (u_L^i, d_L^i)^{\mathrm{T}}$, $i = 1, 2, 3$ and the right handed quark singlets u_R^i, d_R^i; $i = 1, 2, 3$ transform as 1 of S_3
- A better understanding of the quark sector can be obtained if, to our minimal model, we add more doublet scalars transforming non-trivially under S_3
- One such example for quark sector, albeit in context of a different model for lepton sector, has already been worked out[4]

[4]Shao-Long Chen, Michele Frigerio, Ernest Ma, Phys. Rev. D, 70, 073008 (2004)
Ernest Ma, Blazenka Melic, Phys. Lett. B, 725, 402-406 (2013)

Summary So Far

- Gauged $B - L$ symmetry is one of the simplest and most widely studied extension of SM
- Usually gauged $B - L$ symmetry is studied for the case of the three right handed neutrinos transforming as - 1 under $U(1)_{B-L}$
- Here we looked at the possibility of another anomaly-free solution for gauged $B - L$ interaction where the three right handed neutrinos transform as $(+\ 5$, - 4, - 4) under $U(1)_{B-L}$
- This lead us to Dirac neutrinos with naturally small masses
- We then imposed S_3 flavour symmetry to obtain realistic neutrino and charged-lepton mass matrices with a mixing pattern consistent with experiments

Outline

Enhanced Particle Content

- Dark Matter Candidate: Need to enhance the particle content
- Two more singlet scalars: χ_2 with $B - L = 2$ and χ_6 with $B - L = -6$
- Addition of χ_6: All neutrinos can have tree level mass
- For simplicity will not impose S_3 flavour symmetry: Only one χ_3 sufficient
- The important new terms in the Lagrangian are

$$\bar{N}_L \nu_{R1} \chi_6, \quad \chi_2 N_L N_L, \quad \chi_2 N_R N_R, \quad \chi_2^3 \chi_6, \quad \chi_3^2 \chi_6$$

$B-L$ Broken to Z_3

- $B-L$ is broken by $\langle\chi_3\rangle = u_3$ as well as $\langle\chi_6\rangle = u_6$: All neutrinos are massive
- No VEV for χ_2 i.e. $\langle\chi_2\rangle = 0$
- If χ_2 is absent: Residual global L symmetry with $L=1$ for ν, l, N and $L=0$ for $\chi_{3,6}$
- Including χ_2: The residual symmetry is only Z_3
- All leptons and χ_2 transform as $\omega = \exp(2\pi i/3)$ under Z_3 with $\chi_{3,6} \sim 1$
- Note that Z_3 is also sufficient to guarantee that all the neutrinos remain Dirac
- This is one of the few examples of a lepton symmetry which is not Z_2 (for Majorana neutrinos), nor $U(1)$ (for Dirac neutrinos)

Long Lived Dark Matter

- χ_2 candidate for long lived complex scalar dark matter
- No stabilizing symmetry for dark matter
- However, χ_2 has very small coupling to the neutrinos through the Yukawa terms due to the mixing between N_i and ν_i
- Implies that χ_2 can have long enough lifetime to be a suitable dark matter candidate
- Consider for simplicity the coupling of χ_2 to just one N, with the interaction

$$\mathcal{L}_{int} = \frac{1}{2} f_L \chi_2 N_L N_L + \frac{1}{2} f_R \chi_2 N_R N_R + H.c.$$

- Lets denote the $\nu_L - N_L$ mixing by $\zeta_0 = m_0/m_N$ and $\nu_R - N_R$ mixing by $\zeta_3 = m_3/m_N$

Long Lived Dark Matter

- The decay rate of χ_2 is

$$\Gamma(\chi_2 \to \bar{\nu}\bar{\nu}) = \frac{m_\chi}{32\pi}(f_L^2\zeta_0^4 + f_R^2\zeta_3^4)$$

- Setting the half life of χ_2 equal to the age of the Universe (13.75×10^9 years), and assuming $m_\chi = 100$ GeV, $f_L = f_R$ and $\zeta_0 = \zeta_3$, we have $f\zeta^2 = 8.75 \times 10^{-22}$
- This implies that

$$\sqrt{f}\zeta << 3 \times 10^{-11}$$

would guarantee the stability of χ_2 to the present day, and allow it to be a dark-matter candidate

- Sets the scale of M_N at about 10^{13} GeV: Also the usual mass scale for the heavy Majorana singlet neutrinos in the canonical seesaw mechanism

Outline

The Z' Boson

- Gauged $B-L$: Corresponding Z' boson
- Scale of $B-L$ breaking: Bounded from below by experimental constraints
- Production at LHC: Predominantly through its coupling with quarks
- Decay: Predominantly decays into quarks and leptons
- Conventional $B-L$ scenario: Branching fractions to quarks, charged leptons, and neutrinos are $1/4$, $3/8$, and $3/8$ respectively
- New ν_R charges: Large partial widths to neutrinos
- Assuming that Z' decays also into χ_2: Branching fractions into quarks, charged leptons, neutrinos and χ_2 are $1/18$, $1/12$, $5/6$, and $1/36$ respectively
- This means Z' has an 86% invisible width

Collider Constraints on Z' Mass and Couplings

- Conventional $B-L$ Scenario: Using the production of Z' via $u\bar{u}$ and $d\bar{d}$ initial states at the LHC and its decay into e^-e^+ or $\mu^-\mu^+$ as signature, the current bound on $m_{Z'}$ assuming $g' = g$, i.e. the $SU(2)_L$ gauge coupling of the SM, is about 3 TeV, based on recent LHC data[5]

- However, because the branching fraction into l^-l^+ is reduced by a factor of 2/9 in our $B-L$ model, this bound is reduced to about 2.5 TeV, again for $g' = g$

[5] ATLAS Collaboration, Phys. Rev. D, 90, 052005 (2014)
CMS Collaboration, JHEP, 1504, 025 (2015)

Constraints on Z' from Direct Dark Matter Searches

- χ_2 interacts with nuclei through Z': Significant constraint from dark-matter direct-search experiments
- The cross section per nucleon is given by

$$\sigma_0 = \frac{1}{\pi}\left(\frac{m_\chi m_n}{m_\chi + A m_n}\right)^2 \left(\frac{2g'^2}{m_{Z'}^2}\right)^2,$$

  where A is the number of nucleons in the target and m_n is the nucleon mass
- Taking $m_\chi = 100$ GeV gives $\sigma_0 < 1.25 \times 10^{-45}\ \mathrm{cm}^2$ from the recent LUX data[6]
- Implies $m_{Z'}/g' > 16.2$ TeV

[6] LUX Collaboration, Phys. Rev. Lett. 112, 091303 (2014)

Constraints on Z' from Direct Dark Matter Searches

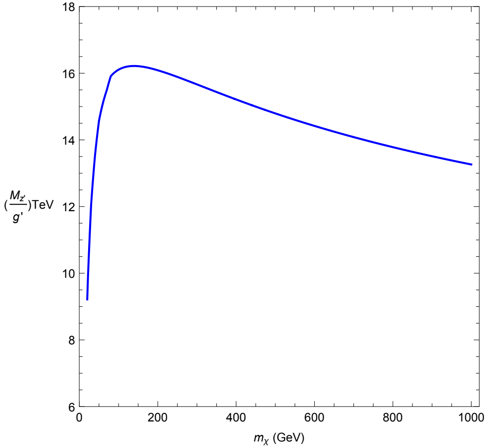

Figure : Lower bound on $m_{Z'}/g'$ versus m_χ from LUX data

Constraints on Z' from Direct Dark Matter Searches

- If $g' = g$, then $m_{Z'} > 10.6$ TeV
- This limit is thus much more severe than the LHC bound of 2.5 TeV
- If $g' < g$, then both the LHC and LUX bounds on $m_{Z'}$ are relaxed
- It also means that it is unlikely that Z' would be discovered at the LHC even with the 14 TeV run

Outline

Inverse Seesaw Mechanism

- Other possibilities: Depends on particle content [7]
- Another possible outcome can be obtained with the choice of two complex scalar fields $\chi_2 \sim 2$ and $\chi_6 \sim 6$ under $U(1)_{B-L}$
- In this case, ν_L is not connected to $\nu_{R2,R3} \sim -4$
- It is connected however to $N_{L,R}$ through the mass matrix spanning $(\bar{\nu}_L, \bar{N}_R^c, \bar{N}_L)$ as follows:

$$M_{\nu,N} = \begin{pmatrix} 0 & m_0 & 0 \\ m_0 & m_2' & M \\ 0 & M & m_2 \end{pmatrix}$$

  where m_2 and m_2' come from the Yukawa couplings with χ_2 .
- This leads to an inverse seesaw, i.e. $m_\nu \simeq m_0^2 m_2 / M^2$

[7] Ernest Ma, Rahul Srivastava, Phys. Lett. B, 741, 217-222 (2015)

Inverse Seesaw Mechanism

- In the case of $\nu_{R1} \sim +5$, the corresponding mass matrix spanning $(\bar{\nu}_L, \bar{N}_R^c, \bar{N}_L, \bar{\nu}_{R1}^c)$ is given by

$$M_{\nu,N} = \begin{pmatrix} 0 & m_0 & 0 & 0 \\ m_0 & m_2' & M & 0 \\ 0 & M & m_2 & m_6 \\ 0 & 0 & m_6 & 0 \end{pmatrix}$$

  where m_6 comes from the Yukawa coupling with χ_6
- Thus ν_{R1} also gets an inverse seesaw mass $\simeq m_6^2 m_2' / M^2$
- In this scheme, ν_L and ν_{R1} get small masses via inverse seesaw mechanism. Also, $N_{1,2,3}$ become heavy pseudo-Dirac fermions.
- However, $\nu_{R2,R3}$ remain massless
- They can be given mass by adding extra scalars e.g. by adding a third scalar $\chi_8 \sim 8$ under $B - L$

Outline

Conclusions

- The idea that $B - L$ should be a gauge symmetry has been around for some time
- However most of the work on gauged $B - L$ symmetry has been done for the case of the three right handed neutrinos transforming as - 1 under $U(1)_{B-L}$
- In this work we looked at the possibility of the simple anomaly-free solution for gauged $B - L$ interaction with the three right handed neutrinos transforming as (+ 5, - 4, - 4) under $U(1)_{B-L}$
- We showed how these assignments can be used to obtain seesaw Dirac neutrino masses, as well as inverse seesaw Majorana neutrino masses
- We then showed that imposition of S_3 flavour symmetry to the first case can lead to realistic neutrino and charged-lepton mass matrices with a mixing pattern consistent with experiments

Conclusions

- We also looked at the possibility of a long lived scalar dark matter
- The dark matter transforms as ω under Z_3. It is thus an example of Z_3 dark matter
- It is not absolutely stable and decays slowly to two anti-neutrinos with a lifetime much greater than that of the Universe
- The dark matter has significant elastic interactions with nuclei through Z' and Higgs exchange and can be detected in direct-search experiments
- We also looked at the discover potential of the Z' boson at LHC
- Dark matter direct-search experiments constrain $m_{Z'}/g'$ to be very large, thus making it impossible to discover Z' at the LHC even with the current run

Thank You