Perturbativity constraints on $U(1)_{B-L}$ and Left-Right Models

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Outline

- Introduction & Motivation
- Theoretical Constraints
- Bounds in $U(1)_{B-L}$ model
- Bounds in Minimal LRSM
- Conclusions
The Standard Model (SM) has been highly successful but needs extension to include new physics such as tiny neutrino masses, DM and baryon asymmetry.
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Many TeV scale extensions introduce extended gauge groups like extra $U(1)'s$ or $SU(2) \times U(1)$.

Our results apply to a subclass of these gauge extensions of SM, where the generators of the extra gauge groups contribute to the electric charge.
In such cases, there are upper and lower limits on the gauge couplings by requiring perturbativity up to GUT scale.
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We’ll specifically focus on $U(1)_{B-L}$ & minimal LRSM, and discuss the implications for gauge boson searches.
Theoretical Constraint on Gauge Couplings

Consider a SM extension: $SU(2)_L \times U(1)_X \times U(1)_Z$ such that:

$$Q = I_{3L} + I_X + \frac{Q_Z}{2}$$
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- Then requiring that coupling $g_Z$ is perturbative at breaking scale,

  $$\Rightarrow \quad r_g \equiv \frac{g_X}{g_L} > \tan \theta_W \left(1 - \frac{4\pi}{g_Z^2} \frac{\alpha_{EM}}{\cos^2 \theta_W}\right)^{-1/2}$$
\( U(1)_{B-L} \) model

- Particle content of the \( SU(2)_L \times U(1)_{I_3R} \times U(1)_{B-L} \) model:

|       | \( SU(2)_L \) | \( U(1)_{I_3R} \) | \( U(1)_{B-L} \) |
|-------|---------------|-------------------|-----------------|
| \( Q \) | 2             | 0                 | \( \frac{1}{3} \) |
| \( u_R \) | 1             | \( \frac{1}{2} \) | \( \frac{1}{3} \) |
| \( d_R \) | 1             | \( -\frac{1}{2} \) | \( \frac{1}{3} \) |
| \( L \) | 2             | 0                 | \( -1 \)         |
| \( N \) | 1             | \( \frac{1}{2} \) | \( -1 \)         |
| \( e_R \) | 1             | \( -\frac{1}{2} \) | \( -1 \)         |
| \( H \) | 2             | \( -\frac{1}{2} \) | 0               |
| \( \Delta_R \) | 1             | \( -1 \)       | 2               |
$U(1)_{B-L}$ model

- Particle content of the $SU(2)_L \times U(1)_{I3R} \times U(1)_{B-L}$ model:

|       | $SU(2)_L$ | $U(1)_{I3R}$ | $U(1)_{B-L}$ |
|-------|-----------|--------------|--------------|
| $Q$   | 2         | 0            | $\frac{1}{3}$ |
| $u_R$ | 1         | $\frac{1}{2}$ | $\frac{1}{3}$ |
| $d_R$ | 1         | $-\frac{1}{2}$ | $\frac{1}{3}$ |
| $L$   | 2         | 0            | $-1$         |
| $N$   | 1         | $\frac{1}{2}$ | $-1$         |
| $e_R$ | 1         | $-\frac{1}{2}$ | $-1$         |
| $H$   | 2         | $-\frac{1}{2}$ | 0            |
| $\Delta_R$ | 1         | $-1$ | 2 |

- The RGEs for the gauge couplings of the two $U(1)$‘s are respectively

$$16\pi^2 \beta(g_{I3R}) = \frac{9}{2} g_{I3R}^3, \quad 16\pi^2 \beta(g_{BL}) = 3 g_{BL}^3.$$
$SU(2)_L \times U(1)_{I3R} \times U(1)_{B-L}$ (Gauge Couplings)
$SU(2)_L \times U(1)_{I3R} \times U(1)_{B-L}$ (Gauge Couplings)
$SU(2)_L \times U(1)_{I3R} \times U(1)_{B-L}$ (Gauge Couplings)

$0.398 < g_R < 0.768; \quad 0.416 < g_{BL} < 0.931$, with $0.631 < r_g < 1.218$

at $v_R = 5$ TeV
$SU(2)_L \times U(1)_{I3R} \times U(1)_{B-L}$ ($Z_R$ searches)

\[ r_g = \frac{g_R}{g_L} \]

\[ v_R = 5 \text{ TeV} \]

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(ATLAS-CONF-2016-045)

(CMS-PAS-EXO-16-031)
\( SU(2)_L \times U(1)_{I3R} \times U(1)_{B-L} \) (\( Z_R \) searches)

\[
rg = g_R/g_L
\]

\( \nu_R = 5 \text{ TeV} \)

\( M_{Z_R} = 5 \text{ TeV} \)

(\text{ATLAS-CONF-2016-045})

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$SU(2)_L \times U(1)_{I3R} \times U(1)_{B-L}$ ($Z_R$ searches)

| collider  | $M_{Z_R}$ [TeV] | $v_R$ [TeV] |
|-----------|-----------------|-------------|
| LHC13     | [3.6, 4.2]      | [3.02, 3.57]|
| HL-LHC    | [6.0, 6.6]      | [4.60, 5.82]|
| FCC-hh    | [27.9, 31.8]    | [19.9, 26.8]|

$Z_R$ mass [TeV]

$rg = g_R/g_L$

$r_g = g_R/g_L$

$M_{Z_R} = 5$ TeV

$v_R = 5$ TeV

50 TeV

20 TeV

10 TeV

$U(1)_{B-L}$ model

perturbative limit

FCC–hh

HL–LHC

LHC13
Particle content of the minimal LRSM based on the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$:

|       | $SU(2)_L$ | $SU(2)_R$ | $U(1)_{B-L}$ |
|-------|-----------|-----------|--------------|
| $Q_L$ | 2         | 1         | $\frac{1}{3}$ |
| $Q_R$ | 1         | 2         | $\frac{1}{3}$ |
| $\psi_L$ | 2   | 1         | $-1$          |
| $\psi_R$ | 1   | 2         | $-1$          |
| $\Phi$ | 2         | 2         | 0             |
| $\Delta_R$ | 1 | 3         | 2             |
The RGEs for the gauge couplings in the minimal LRSM are \(^1\)

\[
16\pi^2 \beta(g_L) = -3 g_L^3 ,
\]

\[
16\pi^2 \beta(g_R) = -\frac{7}{3} g_R^3 ,
\]

\[
16\pi^2 \beta(g_{BL}) = \frac{11}{3} g_{BL}^3
\]

\(^1\)I. Z. Rothstein, Nucl. Phys. B358, 181 (1991)
\( SU(2)_L \times SU(2)_R \times U(1)_{B-L} \) (Gauge Couplings)
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$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ (Gauge Couplings)

\[ 0.406 < g_R < \sqrt{4\pi}; \quad 0.369 < g_{BL} < 0.857, \quad \text{with} \quad 0.648 < r_g < 5.65 \]

at $v_R = 10$ TeV
$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ (Scalar sector)
$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ (Scalar sector)

$r_g = 1.1$, $v_R = 6$ TeV

$r_g = 1.1$, $v_R = 12$ TeV
$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ ($Z_R$ and $W_R$ searches)

$(ATLAS-CONF-2016-045)$
$(CMS-PAS-EXO-16-031)$
$(arXiv: 1809.11105)$
$(arXiv: 1803.11116)$
\[ SU(2)_L \times SU(2)_R \times U(1)_{B-L} \ (Z_R \text{ and } W_R \text{ searches}) \]

| \(W_R\) mass [TeV] | \(Z_R\) mass [TeV] |
|---------------------|---------------------|
| Perturbative limit (gauge) | Perturbative limit (scalar) |
| \(v_R = 5\) TeV | \(v_R = 5\) TeV |
| \(50\) TeV | \(50\) TeV |
| \(20\) TeV | \(20\) TeV |
| \(10\) TeV | \(10\) TeV |

\(r_g = g_R/g_L\)

LHC13
HL–LHC
FCC–hh

(ATLAS-CONF-2016-045)
(CMS-PAS-EXO-16-031)
(arXiv: 1809.11105)
(arXiv: 1803.11116)
$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ ($Z_R$ and $W_R$ searches)

\begin{align*}
W_R \text{ mass [TeV]} & \quad v_R = 5 \text{ TeV} & \quad v_R = 5 \text{ TeV} \\
50 \text{ TeV} & \quad 20 \text{ TeV} & \quad 10 \text{ TeV} \\
2.0 & \quad 1.5 & \quad 1.0 \quad 0.5
\end{align*}

\begin{align*}
Z_R \text{ mass [TeV]} & \quad v_R = 5 \text{ TeV} & \quad v_R = 5 \text{ TeV} \\
50 \text{ TeV} & \quad 20 \text{ TeV} & \quad 10 \text{ TeV} \\
2.0 & \quad 1.5 & \quad 1.0 \quad 0.5
\end{align*}

| collider  | $W_R$ searches | $Z_R$ searches |
|-----------|----------------|----------------|
|           | $M_{W_R}$ [TeV] | $v_R$ [TeV] | $M_{Z_R}$ [TeV] | $v_R$ [TeV] |
| LHC13     | –              | –              | –              | –              |
| HL-LHC    | [6.09, 6.47]   | [10.3, 14.8]   | –              | –              |
| FCC-hh    | [35.6, 42.2]   | [38.3, 87.5]   | [27.9, 35.4]   | [21.8, 26.8]   |
$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ ($\nu_R$ bound)
$SU(2)_L \times SU(2)_R \times U(1)_{B-L} (\nu_R \text{ bound})$

\[
r_g = \frac{g_R}{g_L}
\]

**W_R searches**
- Perturbative limit (gauge)
- Perturbative limit (scalar)
- $M_{W_R} = 5 \text{ TeV}$
- FCC-hh
- HL-LHC
- LHC13

\[
\nu_R \text{ [TeV]}
\]

**Z_R searches**
- Perturbative limit (gauge)
- Perturbative limit (scalar)
- $M_{Z_R} = 5 \text{ TeV}$
- FCC-hh
- HL-LHC
- LHC13
There are strong limits on the gauge couplings from the requirement to be perturbative till the GUT scale.
Conclusions

- There are strong limits on the gauge couplings from the requirement to be perturbative till the GUT scale.
- For $U(1)_{B-L}$ model, we found that it can be probed(almost) at HL-LHC for $\nu_R$ at 5 TeV.
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For $U(1)_{B-L}$ model, we found that it can be probed(almost) at HL-LHC for $v_R$ at 5 TeV.

For minimal LRSM, we found $W_R$ and $Z_R$ couldn’t have been seen at LHC13.
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- For $U(1)_{B-L}$ model, we found that it can be probed (almost) at HL-LHC for $\nu_R$ at 5 TeV.
- For minimal LRSM, we found $W_R$ and $Z_R$ couldn’t have been seen at LHC13.
- In case, $Z_R$ is found in HL-LHC run then couldn’t be from minimal LRSM.
Conclusions

- There are strong limits on the gauge couplings from the requirement to be perturbative till the GUT scale.
- For $U(1)_{B-L}$ model, we found that it can be probed (almost) at HL-LHC for $v_R$ at 5 TeV.
- For minimal LRSM, we found $W_R$ and $Z_R$ couldn’t have been seen at LHC13.
- In case, $Z_R$ is found in HL-LHC run then couldn’t be from minimal LRSM.
  - The results can be generalized to other gauge group extensions.

Thank you! Questions?