TEV SCALE MODELS OF NEW PHYSICS
AT THE LHC

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In this talk, I present two well motivated models of new physics to solve some of the drawbacks of the SM

Predictions of the models can be tested at the LHC

MODEL 1: TOP $SU(5)$ MODEL $\Rightarrow$ new vector bosons

MODEL 2: LEFT-RIGHT SYMMETRIC MIRROR MODEL $\Rightarrow$ new fermions

MODEL 3: PARALLEL UNIVERSE, DARK MATTER AND INVISIBLE HIGGS DECAYS $\Rightarrow$ new Higgs-like boson
MODEL 1 : Top $SU(5)$ model


MOTIVATION

- Remedy the non-unification of gauge couplings in SM.
- Has lepto-quark and di-quark gauge bosons at the TeV scale.
- Has baryon and lepton number violating interactions at the LHC.
- Potential for generating baryon asymmetry of the universe.
MODEL 1 : Top $SU(5)$ model

- Our gauge symmetry is non-supersymmetric $SU(5) \times SM'$ where $SM' = SU(3)'_C \times SU(2)'_L \times U(1)'_Y$.

- First two families of the SM fermions are charged under $SM'$ and singlet under the $SU(5)$.

- The third family is charged under $SU(5)$ and singlet under $SM'$.

- The symmetry is broken to SM at TeV scale.

- Have lepto-quark and di-quark gage bosons, X and Y at the TeV scale coupling only to 3rd family.
The lepto-quark and di-quark gauge bosons, X and Y: $Q_X = +4/3, Q_Y = +1/3$ decays as

- $X \Rightarrow \bar{b}\tau^+, tt$; $Y \Rightarrow \bar{b}\nu_\tau, tb, \bar{t}\tau^+$. 

The decays of X and Y violate both baryon number and lepton number.

- X can be observed as a resonance in $\bar{b}\tau^+$ and $tt$ mode
- Y can be observed as a resonance in $\bar{t}\tau^+$ and $tb$ mode.
Lepto-quark gauge bosons X and Y can be pair produced at the LHC via QCD strong interaction.

\[ pp \to X\bar{X} \Rightarrow (\bar{b}^+\tau)(b^-\tau); (tt)(\bar{t}\bar{t}); (\bar{b}^+\tau)(\bar{t}\bar{t}). \]

Similarly for \( Y\bar{Y} \) production

From \( X\bar{X} \) productions \( \Rightarrow \) Resonance peaks in \( (b\tau) \) and \( (tt) \).

For \( Y\bar{Y} \) productions, \( \Rightarrow \) Resonance peaks in \( (\bar{t}\tau^+) \) and \((tb)\).

Dominant SM background for \( (\bar{b}^+\tau)(b^-\tau) \) final state

\[ pp \Rightarrow 2b2\tau, 4b, 2j2b, 4j, t\bar{t} \]

Similarly for the other final states.
In this section, we analyze the invariant mass distribution for the $b\tau^-$ channel at 8 TeV LHC. The graph illustrates the distribution of the invariant mass $M_{b\tau^-}$, showing the signature of a resonance. The data is analyzed in two modes: $2b^+\tau^-$ and $2b^-\tau^-$. The SM prediction for $2b^+\tau^-$ is also included for comparison. The distribution peaks at around 800 GeV, indicating a significant signal in this mass range. This resonance could be indicative of new physics, requiring further investigation.
X resonance in the $b\tau^-$ mode at 14 LHC

- Invariant mass distribution for the $b\tau^-$ channel for 14 TeV LHC
X resonance in the $tt$ mode at 8 TeV LHC

Invariant mass distribution for the $tt$ channel for $M_X = 800$ GeV at 8 TeV
X resonance in the $tt$ mode at 14 TeV LHC

Invariant mass distribution for the $tt$ channel for $M_X = 1000$ GeV at 14 TeV.
LHC SEARCH SO FAR

CMS COLLABORATION: Search for $b\tau$ resonance: 7 TeV LHC, $4.8 fb^{-1}$ (PRL) $\Rightarrow M_X > 760$ GeV (95% CL); 8 TeV LHC, $19.7 fb^{-1}$ $\Rightarrow M_{scalar} > 740$ GeV.

ATLAS COLLABORATION: Search for $b\tau$ resonance: 7 TeV LHC, $4.7 fb^{-1}$ $\Rightarrow M_{scalar} > 534$ GeV (95% CL).

NOTE: Observation of Resonances at both $X \rightarrow b\tau$ and $tt$ are needed to establish bayon and lepton number violation.

LHC REACH at $5\sigma$

8 TeV LHC, $30 fb^{-1}$ $\Rightarrow M \simeq 800$ GeV.

14 TeV LHC, $100 fb^{-1}$ $\Rightarrow M \simeq 1.5$ TeV.
LHC sensitivity to the $X$ and $Y$ gauge bosons

For the sensitivity analysis we define

$$\sigma_s \geq \frac{N}{L} \left[ N + 2 \sqrt{L\sigma_b} \right],$$

(0.1)

<table>
<thead>
<tr>
<th>Final States</th>
<th>$\sqrt{s} = 8$ TeV</th>
<th>$\sqrt{s} = 14$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b\ b\ MET$</td>
<td>$L(fb^{-1})$</td>
<td>$M_Y$(GeV)</td>
</tr>
<tr>
<td>10</td>
<td>737</td>
<td>30</td>
</tr>
<tr>
<td>20</td>
<td>772</td>
<td>100</td>
</tr>
<tr>
<td>30</td>
<td>793</td>
<td>300</td>
</tr>
<tr>
<td>$bt\tau^- ME_T$</td>
<td>20</td>
<td>770</td>
</tr>
<tr>
<td>$+b\bar{t}\tau^+ ME_T$</td>
<td>30</td>
<td>795</td>
</tr>
</tbody>
</table>
MODEL 2: LEFT-RIGHT (L-R) SYMMETRIC MIRROR MODEL


MOTIVATION

- Explain parity violation at low energy.
- Solve strong CP problem.
- Generate tiny neutrino masses
- Can have mirror fermions at the TeV scale and be explored at the LHC.
USUAL L-R SYMMETRIC MODEL

Gauge Symmetry: $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$.

FERMIONS: For every left handed doublet, there is a right handed doublet

\[
\begin{pmatrix}
\nu \\
e
\end{pmatrix}_L \Rightarrow \begin{pmatrix}
\nu \\
e
\end{pmatrix}_R
\]

\[
\begin{pmatrix}
u \\
d
\end{pmatrix}_L \Rightarrow \begin{pmatrix}
u \\
d
\end{pmatrix}_R
\]

(0.2)

HIGGSES: Under $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

$(2, 1, 1) + (1, 2, 1) + (1, 2, 2)$
MODEL 2: LEFT-RIGHT SYMMETRIC MIRROR MODEL

Gauge Symmetry: $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{Y'} \times Z_2$

FERMIONS: Ordinary sector: blue, mirror sector: red with hat.

$l_L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L \sim (1, 2, 1, -1)$, $e_R \sim (1, 1, 1, -2)$, $\nu_R \sim (1, 1, 1, 0)$;

$\hat{l}_R = \begin{pmatrix} \hat{\nu} \\ \hat{e} \end{pmatrix}_R \sim (1, 1, 2, -1)$, $\hat{e}_L \sim (1, 1, 1, -2)$, $\hat{\nu}_L \sim (1, 1, 1, 0)$;

$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L \sim (3, 2, 1, \frac{1}{3})$, $u_R \sim (3, 1, 1, \frac{4}{3})$, $d_R \sim (3, 1, 1, -\frac{2}{3})$;

$\hat{Q}_R = \begin{pmatrix} \hat{u} \\ \hat{d} \end{pmatrix}_R \sim (3, 1, 2, \frac{1}{3})$, $\hat{u}_L \sim (3, 1, 1, \frac{4}{3})$, $\hat{d}_L \sim (1, 1, 1, -\frac{2}{3})$;

$Q = T_{3L} + T_{3R} + \frac{Y'}{2}$.

- $Z_2$: SM and RH singlet $\nu$'s: even
- Mirror fermions and LH singlet $\nu$'s: odd
MODEL 2: LEFT-RIGHT SYMMETRIC MIRROR MODEL

- **HIGGSES:** Under $SU(2)_L \times SU(2)_R \times U(1)_{Y'}$
  $(2, 1, 1) + (1, 2, 1) + (2, 2, 1) \Rightarrow Z_2$ even

- **Additional Higgs:** $\chi(1, 1, 0) \Rightarrow Z_2$ odd $\rightarrow$ needed for the mixing between the ordinary fermions and mirror fermions.

- **SYMMETRY BREAKING:**
  - $SU(2)_L \times SU(2)_R \times U(1)_{Y'} \times Z_2 \rightarrow SU(2)_L \times SU(2)_R \times U(1)_{Y'} \rightarrow SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$
  - $Z_2$ is broken spontaneously by $<V_\chi> \simeq 10^7$ GeV, and also softly.
  - $\chi$ mixes ordinary fermions with mirror fermions.
  - $L_{mix} = h_u \bar{u}_R \hat{u}_L \chi + h_d \bar{d}_R \hat{d}_L \chi + h_e \bar{e}_R \hat{e}_L \chi + h.c.$
NEUTRINO MASSES

- Four $\nu$'s per family (one light, 3 very heavy)

- Dirac masses: $m = f_{\nu} V / \sqrt{2}$, $m' = f_{\nu} \hat{V} / \sqrt{2}$, $M_{\nu\hat{\nu}} = \bar{\nu}_R \nu_L$

- Majorana masses, $M : \nu_R \nu_R, \nu_L \nu_L$

Assuming $M_{\nu\hat{\nu}} \simeq M \simeq \hat{V} \Rightarrow ((m_{\nu})_{\text{light}} \simeq m^2 / M$;

- all other $\nu$'s are heavy

To get $(m_{\nu})_{\text{light}} \simeq 10^{-2}$ eV $\Rightarrow M \simeq \hat{V} \simeq 10^7$ GeV

[with $f_{\nu} \simeq 10^{-4}$]
MIRROR PARTICLE MASSES

- Only first mirror family is light

\[
\frac{m_{\hat{u}}}{m_u} \approx \frac{m_{\hat{d}}}{m_d} \approx \frac{m_{\hat{e}}}{m_e} \approx \frac{\nu'}{v}
\]

- With \( \hat{V} \approx 10^7 \) GeV
  \[\Rightarrow m_{\hat{u}}, m_{\hat{d}} \Rightarrow \text{few hundred GeV - TeV range}\]

DOMINANT DECAY MODES

\( \hat{u} \Rightarrow uz, dW \)
\( \hat{d} \Rightarrow dz, uW \)
MODEL 2 : LEFT-RIGHT SYMMETRIC MIRROR MODEL

- $pp \Rightarrow \bar{q}q \Rightarrow (qZ)(\bar{q}Z) : 2$ jets + $2$ $Z$ final states

- $pp \Rightarrow \bar{q}q \Rightarrow (qZ)(\bar{q}'W) : 2$ jets + $Z + W$ final states

- Resonance in $(qZ)$, $(qW)$ modes
2 jets+Z-boson+W boson signature after $\Delta \phi$ cut

Center-of-mass energy 14 TeV

$\frac{d\sigma}{dM}$ [fb/GeV]

SM Background
$m_{q'}=400$ GeV
$m_{q'}=600$ GeV
MODEL 2 : LEFT-RIGHT SYMMETRIC MIRROR MODEL

Reach at the LHC in ZZ channel in 99% CL

![Graph showing Luminosity vs. Mq for pp collision at 8 and 14 TeV]
MODEL 2: LEFT-RIGHT SYMMETRIC MIRROR MODEL

Reach at the LHC in ZW channel in 99% CL
Presented two well motivated TeV scale models of new physics.

**MODEL 1: TOP $SU(5)$ MODEL**
- Has di-quark and lepto-quark gauge bosons, violating both baryon and lepton number.
- Resonances in $(b\tau), (tt)$ and $(tb)$ channels.
- Reach: 14 TeV LHC, $100fb^{-1} \sim 1.5$ TeV. (Current LHC limit $\Rightarrow M > 760$ GeV (CMS Collaboration).

**MODEL 2: LEFT-RIGHT SYMMETRIC MIRROR MODEL**
- Has mirror fermions (1st family at TeV scale)
- Resonances at $(u Z), (d Z), (u W), (d W)$ channels.
- Reach at 14 TeV LHC, $100fb^{-1}$ luminosity, $\Rightarrow \sim 800$ GeV.
- Current LHC limit: Analysis in progress by ATLAS Collaboration.