Prospect of the Electroweak Scale $\nu_R$ model in the Lifetime Frontier

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Chakdar, Ghosh, Hoang, Hung, Nandi, Phys.Rev. D95 (2017) no.1, 015014
Post Higgs LHC: where are we looking at?

95% of our analysis effort is dedicated to understanding five prompt objects.
New Physics at the LHC

The overwhelming majority of the work of the LHC experiments

New physics could be hiding here

$m_X$

$\mathcal{O}(mm)$

$C\mathcal{T}X$

Outer edge of detector

Stable

Slide: Beacham
Long Lived particles (LLPs)

For our purposes, LLP = BSM particles with a non-negligible lifetime that gives up all its energy or decays to SM somewhere in the detector acceptance.

• **LLPs in SM:**
  • muons (2 μs), π⁺ → μ⁺ν_μ (20 ns), b-quarks (ps)

• **LLPs in BSM:** variety of mechanisms can suppress decay width!
  • Small couplings, approximate symmetries, heavy mediators...
  • R-parity violating SUSY, Split SUSY, L-R Symmetric model....
  • Dedicated searches needed to look for LLPs....

LHCb, CMS, ATLAS, MilliQan, MoEDAL, FASER, MATHUSLA, SHiP
EW$\nu_R$ Model and Framework

• Neutrino mass is the only evidence of NP so far!
• Neutrino ($\nu$) masses $\rightarrow$ popular “Seesaw mechanism”
• In general Seesaw Mechanism:
  • $\nu_R \rightarrow SU(2)_L \times U(1)_Y$ singlet
  • RH neutrino mass at GUT scale! NOT directly testable at LHC

$$m_\nu \sim \frac{(m'^D_\nu)^2}{M_R} \leq 1 \text{eV}$$

• Stand scenes: L-R : $m_D \sim \Lambda_{\text{EW}}$, $M_R \sim M_{\text{WR}}$, GUT: $M_R \sim \Lambda_{\text{GUT}}$
• $\nu_R$’s are Sterile in standard scenarios
• What if $M_R \sim \Lambda_{\text{EW}}$? Can $\nu_R$’s be non-sterile?
EWνᵣ Model and mirror fermions

SM + Mirror Fermions + extended scalar sector
Gauge Group : SU(3)ₓSU(2)ₓU(1)

\[
\begin{align*}
  l_L &= (\nu_L^e) e_R \\
  q_L &= (u_L^d) d_R \\
  u_R, d_R
\end{align*}
\]

\[
\begin{align*}
  l_R^M &= (\nu_R^M e_L^M) \\
  q_R^M &= (u_R^M d_R^M) \\
  u_L^M, d_L^M
\end{align*}
\]
Particle content of EW$\nu_R$ model

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<thead>
<tr>
<th>Quarks</th>
<th>Mirror Quarks</th>
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<tbody>
<tr>
<td>$u$</td>
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<tr>
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Majorana and Dirac masses

- $\nu_R'$s are non-sterile, RH doublets couples to the same W

\[ \mathcal{L}_M = g_M (\tilde{l}_R^M, \tau_2) (i \tau_2 \tilde{\chi}) l_R^M + h.c. \]

- $\tilde{\chi} = \begin{pmatrix} \frac{1}{\sqrt{2}} \chi^+ & \chi^{++} \\ \chi^0 & -\frac{1}{\sqrt{2}} \chi^+ \end{pmatrix}$

\[ M_R = g_M v_M; <\chi^0> = v_M \sim \Lambda_{EW} \]

\[ \mathcal{L}_S = g_{SI} \bar{l}_L \phi_S l_R^M + h.c. \]

- $\phi_S (1, \frac{Y}{2} = 0)$

- Testable see-saw signals in the reach of the LHC!

- $m_{\nu}^D = g_{SI} v_S$ where $<\phi_S> = v_S$

- $m_\nu \leq 1eV \Rightarrow v_S \sim 10^{-5}-6eV$ with $g_{SI} \sim \mathcal{O}(1)$

- or $v_S \sim \Lambda_{EW}$ with $g_{SI} \sim \mathcal{O}(10^{-6})$
Mirror fermion decay

Yukawa interactions in terms of quark mass eigenstates

\[ L_S = \bar{q}_L^d U_L^{d\dagger} M_\phi^d U_R^{dM} q_R^{M,d} + h.c. \]

\[ = \bar{q}_L^d \tilde{M}_\phi^d q_R^{M,d} + h.c. \text{ where } M_\phi^d \text{ is mixing matrix} \]

\[
M_{\phi}^{d,u} = \begin{pmatrix}
g_{0S}^{d,u} \phi_{0S} & g_{1S}^{d,u} \phi_{3S} & g_{2S}^{d,u} \phi_{2S} \\
g_{2S}^{d,u} \phi_{3S} & g_{0S}^{d,u} \phi_{0S} & g_{1S}^{d,u} \phi_{1S} \\
g_{1S}^{d,u} \phi_{2S} & g_{2S}^{d,u} \phi_{1S} & g_{0S}^{d,u} \phi_{0S}
\end{pmatrix}
\]

Decay mode of the lightest mirror quark is \( q^M \rightarrow q + \phi_S \) or \( b + \phi_S \), with \( \phi_S \approx \text{miss } E_T \)

\[
\Gamma(q^M \rightarrow q + \phi_S) = \frac{g_{Sg}^2}{64\pi} m_{q^M} \left(1 - \frac{m_q^2}{m_{q^M}^2}\right) \left(1 + \frac{m_q}{m_{q^M}} - \frac{m_q^2}{2m_{q^M}^2}\right),
\]

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Mirror quarks Decay width

- Decay length can be substantially LARGE in this case
- Easily distinguishable from b-displaced vertices (~0.5mm)
LHC exclusion plot

For large BR mirror quark mass below about 600 GeV is excluded
If mirror quark to light quark BR < 50 %, NO bound on mirror quark mass
Bounds applicable only on mirror quarks decay at hard scattering point
Decay width could be small enough for hadronization → bounds don't apply!
Constraints from the lepton sector

- Constraints from $\mu \rightarrow e\gamma$, $\mu$ to $e$ conversion: $g_{sl} < 10^{-4}$
- Mirror fermions ↔ Axion-less solution to strong CP problem (Ref: arXiv:1712.09701)
- Constraints from the so-far absence of the neutron dipole moment: $\bar{\theta} < 10^{-10}$
- This framework has global Symmetry $U(1)_{SM} \times U(1)_{MF}$
- Corresponds to $\bar{\theta} \propto m_{\nu}$ in this framework
- Constraint on $\bar{\theta} \rightarrow$ Constraint on couplings $g_{sq} < g_{sl}$

$g_{sq} < g_{sl} < 10^{-4}$

- Lightest mirror fermions are LLPs
- Connection between Neutrino physics and QCD!
Mirror Meson formation

- Typical decay lengths >> Hadronization length
  \[ \sim O(\text{fermi}) \]

- Formation of QCD bound states

- Mirror mesons $\bar{q}^M q^M$ and hybrid mesons $\bar{q}^M q$ get formed first before decay
Mirror meson production & decays

Mirror meson production at 13 TeV LHC

\[ gg \rightarrow Q\bar{Q}^{(1S_0)} \]

Mirror-meson decay lengths:

\[ \text{Displaced Vertices} > O(cm) \text{ for } g_{Sq} < 10^{-4}. \]

Mirror meson decay length (\(\beta = 10^{-3}\))

- CMS's Silicon Strip Tracker radius
- \(m_{q^\mu} = 200 \text{ GeV}\)
- \(m_{q^\mu} = 400 \text{ GeV}\)
- \(m_{q^\mu} = 600 \text{ GeV}\)
- \(m_{q^\mu} = 1000 \text{ GeV}\)
Di-lepton Signals in Lepton Sector

Lepton-number violating signals at LHC

\[ q\bar{q} \rightarrow Z \rightarrow \nu_R \nu_R \]

\[ \nu_{R_i} \rightarrow e^M_{R_j} + W^+ \text{ followed by } e^M_{R_j} \rightarrow e_{Lk} + \phi_S \]

1. OSD Signals from production of \( e^M_R \pm \)

\[ pp \rightarrow e^M_+ e^M_- \rightarrow (e^+ \phi_S)(e^- \phi_S) \rightarrow e^+e^- + \psi_T. \]

2. SSD and OSD Signals from production and decays of \( e^M_R \pm \nu^M_R \)

\[ pp \rightarrow e^M_{R} \nu^M_{R} \]

\[ (e^+ \phi_S)(e^M_{R}W^+) \]

\[ e^\pm e^\mp qq'\phi_S\phi_S \text{ (SSD+2-jets + } \psi_T) \]

\[ (e^\pm \phi_S)(e^M_{R}W^+) \]

\[ (e^\pm \phi_S)(e^M_{R}W^\mp) \]

\[ e^\pm e^\mp e^\pm e^\mp \nu_L\phi_S\phi_S \text{ (3-leptons + } \psi_T) \]

\[ e^\pm e^\mp \nu_R\phi_S\phi_S \text{ (OSD+2-jets + } \psi_T) \]
**LLP Signals in Lepton Sector**

- Pair production $\nu_R$ of gives rise to more di-lepton signals

$$
pp \rightarrow \nu_R^M \nu_R^M \\
(e_R^{M\pm}W^\mp)(e_R^{M\pm}W^\mp) \leftrightarrow e^\pm e^\mp qq'q'\phi\phi_S (SSD+4-jets + \not{p_T})
$$

- The appearance of Like-sign dileptons!
- All Like-sign and opposite sign di-leptons signals @ displaced vertex or near the beam pipe $(g_{sl})$
Scalar Sector

Scalars

Singlet

$\phi_s, \langle \nu_s \rangle$
Dirac mass

Doublet

$\phi_2, \langle \nu_2 \rangle$
mass to SM

$\phi_2^M, \langle \nu_2^M \rangle$
mass to Mirror Fermions

Triplet

$\tilde{\chi}, \langle \chi^0 \rangle = \nu_M$
Majorana mass

$\xi, \langle \xi^0 \rangle = \nu_M$
Custodial symmetry
Singlet DM Prospect

• Imaginary part of Complex Singlet Scalar field $\varphi$ is investigated to be a feasible DM candidate

• This Nambu goldstone boson (0$^{-}$ state) comes into play due to the explicit breaking term of the U(1) symmetry present in the Higgs potential

• $\varphi$ gives the Dirac neutrino masses: $m_D^\nu = g_{sl} \nu_s$ in the see-saw formula: $m = m_D^2 / M_R \sim O (< eV)$

• $M_R$ are in EW Scale ($\sim 250$ GeV) and from $\mu \rightarrow e\gamma$, $\mu$ to $e$ conversion bound on the coupling $g_{sl} < 10^{-4} \leftrightarrow \nu_s \sim O(1 \text{ GeV})$

• The singlet connecting SM to Mirror world can be KeV scale DM candidate!

• Collider searches of DM promising through the Lifetime frontier due to the possibility of large displaced vertex ($e_R^M \rightarrow e + \varphi$)
Remarks

• Looking for NP shifting from theory driven ↔ signature driven search strategies

• LLPs predicted in many Theory models receiving resurgence in interest

• EW$\nu_R$ scenario links see-saw mechanism, strong CP and DM

• EW$\nu_R$ framework contains LLP signals with large displaced vertices (mm-cm) in quark and lepton sectors

• Promising signatures at LHC environment and LLP detectors due to characteristic signals and low bkds (Dedicated searches needed! )
THANK YOU!

Long Live the Lifetime Frontier!