Revisiting type-II seesaw: 
the high-energy and high-precision frontier tests

Yongchao Zhang
Washington University in St. Louis

November 9, 2018

NuTheories: Beyond the 3 × 3 Paradigm at Current and Near-Future Facilities
PITT PACC, University of Pittsburgh

based on
Outline

- Type-II seesaw
- MOLLER sensitivity to $H^{±±}_{L,R}$
  - sensitivity of MOLLER
  - prospect of $H^{±±}_{L}$ in type-II seesaw
  - prospect of $H^{±±}_{R}$ in LRSM
- Displaced vertex searches of $H^{±±}_{L,R}$
  - current prompt same-sign dilepton constraints and the Heavy Stable Charged Particle searches
  - DV prospects of $H^{±±}_{L}$ at HL-LHC, FCC-hh and ILC
  - DV prospects of $H^{±±}_{R}$ at HL-LHC, FCC-hh and ILC
- Conclusion
type-II seesaw
One of the simplest seesaw frameworks to generate the tiny neutrino masses...

\[ \mathcal{L} = - (f_L)_{\alpha\beta} \psi_L^\dagger \psi_L \psi_L + \mu H^T i\sigma_2 \Delta_L^\dagger H + \text{H.c.}, \]

with the left-handed triplet \[ \Delta_L = \begin{pmatrix} \delta_L^+ / \sqrt{2} & \delta_L^{++} \\ \delta_0 & -\delta_L^- / \sqrt{2} \end{pmatrix}. \]

Neutrino masses are given by

\[ m_\nu = \sqrt{2} f_L v_L = U \hat{m}_\nu U^\dagger \quad \text{(with the VEV } \langle \delta_0 \rangle = v_L / \sqrt{2}) \]

The coupling matrix \( f_L \) is fixed by neutrino oscillation data, up to the unknown lightest neutrino mass \( m_0 \), the neutrino mass hierarchy, and the Dirac & Majorana CP violating phases.
Important couplings of $H_L^{\pm\pm} = \delta_L^{\pm\pm}$

- **Gauge couplings to $\gamma/Z$ bosons:**
  production at hadron/lepton colliders

- **Gauge interaction** $H_L^{\pm\pm} W^\mp W^\mp (\propto v_L)$:
  inducing decay $H_L^{\pm\pm} \rightarrow W^\pm(*) W^\pm(*)$

- **Gauge interaction** $H_L^{\pm\pm} H^\mp W^\mp$:
  production at hadron/lepton colliders
  inducing decay $H_L^{\pm\pm} \rightarrow H^{(*)} W^{(*)}$

- **Scalar interaction** $H_L^{\pm\pm} H^\mp H^\mp$:
  inducing decay $H_L^{\pm\pm} \rightarrow H^{(*)} H^{(*)}$

- **Yukawa couplings** $(f_L)_{\alpha\beta} H_L^{\pm\pm} \ell^\mp_{\alpha} \ell^\mp_{\beta}$:
  - $\alpha\beta = ee$: $e^- e^- \text{ scattering (MOLLER experiment, high-precision test)}$
  - $\alpha \neq \beta$: low-energy LFV processes (e.g. $\mu \rightarrow e\gamma$)
  - inducing decay $H_L^{\pm\pm} \rightarrow \ell^\pm_{\alpha} \ell^\pm_{\beta}$ (potentially LFV)
  - production at hadron/lepton colliders [Dev, Mohapatra & YCZ, 1803.11167]
Long-lived $H_L^{\pm\pm}$

- Decay through the Yukawa couplings (suppressed by $m_\nu^2/\nu^2_L$)

$$\Gamma(H_L^{\pm\pm} \rightarrow \ell^\pm_\alpha \ell^\pm_\beta) = \frac{M_{H_L^{\pm\pm}}}{8\pi(1 + \delta_{\alpha\beta})} \frac{|(m_\nu)_{\alpha\beta}|^2}{\nu^2_L},$$

- Decay through the gauge interactions (suppressed by $\nu^2_L$ and potentially the phase-space)

$$\Gamma(H_L^{\pm\pm} \rightarrow W^\pm W^\pm) = \frac{G_F^2 \nu^2_L M^3_{H_L^{\pm\pm}}}{2\pi} \sqrt{1 - 4x_W(1 - 4x_W + 12x^2_W)},$$

(with $x_W \equiv m_W^2/M_{H_L^{\pm\pm}}^2$)

Four-body decay for off-shell $W$-boson pairs

$$H_L^{\pm\pm} \rightarrow W^{\pm\ast} W^{\pm\ast} \rightarrow f \bar{f}' f'' \bar{f}''',$$
Neglecting the following decay modes

- $H_L \rightarrow H^\pm(\ast) W^\pm(\ast)$:
  - The mass splitting $\Delta M = M_{H^\pm} - M_{H^\mp} > 60$ GeV is disfavored by current electroweak precision data; [Aoki, Kanemura, Kikuchi & Yagyu ’12]
  - For $M_{H^\pm} - M_{H^\mp} \lesssim 1$ GeV, this channel is negligible.

- $H_L \rightarrow H^\pm(\ast) H^\pm(\ast)$:
  - Depending on the triplet scalar coupling;
  - Due to electroweak precision constraints, both $H^\pm$ are expected to be off-shell.

Figure: From Melfo, Nemevšek, Nesti, Senjanović & Zhang ’11

⇒ Displaced searches of $H_L^{\pm\pm}$ at LHC and future lepton/hadron colliders (high-energy frontier)
Proper lifetime of $H_L^{±±}$

$$\Gamma_{\text{total}}(H_L^{±±}) = \Gamma(H_L^{±±} \rightarrow \ell_\alpha \ell_\beta) + \Gamma(H_L^{±±} \rightarrow W^±(*) W^±(*)) .$$

Assuming lightest neutrino mass $m_0 = 0$.

$$\nu_L |f_L|_{\text{max}} \approx \begin{cases} 0.027 \text{ eV} , & \text{for NH with } m_1 = 0 , \\ 0.048 \text{ eV} , & \text{for IH with } m_3 = 0 . \end{cases}$$
$H_L^{\pm\pm} \odot$ MOLLER experiment
MOLLER experiment

(Measurement Of a Lepton Lepton Electroweak Reaction)

MOLLER Collaboration, 1411.4088; https://moller.jlab.org/moller_root/
Parity-violating asymmetry

MOLLER Collaboration, 1411.4088; https://moller.jlab.org/moller_root/

Scattering of longitudinally polarized electrons off unpolarized electrons, using the upgraded 11 GeV beam in Hall A at JLab

\[ A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = mE \frac{G_F}{\sqrt{2\pi\alpha}} \frac{2y(1-y)}{1 + y^4 + (1-y)^4} Q^e_W, \]

\(E(E')\) : incident beam (scattered electron) energy; \(y = 1 - E'/E\);
\(Q^e_W = 1 - 4 \sin^2 \theta_W\) (tree level)
Precision measurement of the weak mixing angle

MOLLER Collaboration, 1411.4088; https://moller.jlab.org/moller_root/

Primary Goal:
Precision measurement of $A_{PV}$ to the level of 0.7 ppb ($A^{SM}_{PV} \approx 33$ ppb);
An overall fractional accuracy of 2.4% for $Q^e_W$. 
\[
\Lambda \over \sqrt{|g_{RR}^2 - g_{LL}^2|} = \frac{1}{\sqrt{2}G_F |\Delta Q^e_W|} \simeq 7.5 \text{ TeV},
\]
Sensitivity to doubly-charged scalar

\[ M_{PV} \sim \frac{|(f_{L})_{ee}|^2}{2M_{H_L}^2} (\bar{e}_L \gamma^\mu e_L)(\bar{e}_L \gamma^\mu e_L) + (L \leftrightarrow R). \]

Keeping only the left-handed part: \(|g_{LL}|^2 = |(f_{L})_{ee}|^2 / 2 \& g_{RR} = 0: \]

\[ \frac{M_{H_L}^{\pm\pm}}{|(f_{L})_{ee}|} \gtrsim 3.7 \text{ TeV} \quad \text{(at the 95\% C.L.)} \]
Sensitivity to doubly-charged scalar

SLAC E158 Collaboration, hep-ex/050409
Neutrino oscillation data within their $2\sigma$ ranges;
Lightest neutrino mass $m_0 \in [0, 0.05]$ eV;
Dirac and Majorana phases $\in [0, 2\pi]$.

$$\delta A_{\nu V} \approx 0.3 \text{ eV} \times \left( \frac{M_{H_L^{\pm\pm}}}{1 \text{ TeV}} \right)^{-1}$$
LFV constraints

<table>
<thead>
<tr>
<th>process</th>
<th>current data</th>
<th>constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^- \rightarrow e^- e^+ e^-$</td>
<td>$&lt; 1.0 \times 10^{-12}$</td>
<td>$M_{H_L}^{\pm \pm} / \sqrt{</td>
</tr>
<tr>
<td>$\mu^- \rightarrow e^- \gamma$</td>
<td>$&lt; 4.2 \times 10^{-13}$</td>
<td>$M_{H_L}^{\pm \pm} / \sqrt{</td>
</tr>
</tbody>
</table>

If an anomalous $\delta A_{PV}$ could be observed by MOLLER, the simplest type-II seesaw has to be extended to accommodate the deviation, like the left-right models.
type-II seesaw extended to be left-right symmetric
A right-handed triplet is introduced to break the $SU(2)_R$ gauge symmetry

$$
\Delta_R = \begin{pmatrix}
\delta_R^+ / \sqrt{2} & \delta_R^{++} \\
\delta_R^0 & -\delta_R^+/\sqrt{2}
\end{pmatrix}
$$

The right-handed Yukawa interaction

$$
\mathcal{L}_Y = - (f_R)_{\alpha\beta} \psi_{R\alpha}^T Ci\sigma_2 \Delta_R \psi_{R\beta} + \text{ H.c.},
$$

Neutrino masses

$$
m_\nu \simeq -m_D M_N^{-1} m_D^T + \sqrt{2} f_L v_L,
$$

Assuming type-II dominance, and parity-symmetry dictates $f_L = f_R$
The LFV constraints apply equally to $f_R$. 
The LFV constraints apply equally to $f_R$. 
• Parity-restoration scale $\neq SU(20_R)$ scale;
• $\Delta_L$ could decouple from the TeV-scale physics avoiding fine-tuning in the scalar potential and/or unacceptably large neutrino masses;
• The couplings $f_L \neq f_R$ and $f_R$ is not directly relevant to neutrino oscillation data;
• $(f_R)_{ee}$ could be viewed as a free parameter.
Neutrinoless double-beta decay ($0\nu\beta\beta$)

\[ \eta \delta_R = m_p \left( \frac{g_R}{g_L} \right)^4 \left( \frac{m_W}{M_{W_R}} \right)^4 \frac{\sqrt{2}(f_{R ee} \nu_R)}{M_{H_R^{\pm \pm}}^2} \]
The MOLLER experiment could probe a sizable parameter space, beyond the current low and high-energy constraints.
Displaced vertex searches of $H_L^{\pm\pm}$ at colliders
Same-sign dilepton constraints on $H_{L}^{\pm\pm}$

- LEP
- Tevatron
- LHC7
- LHC8
- LHC13

- OPAL, hep-ex/0111059; DELPHI, hep-ex/0303026; L3, hep-ex/0309076;
- CDF, hep-ex/0406073; 0808.2161; D0, 0803.1534; 1106.4250;
- ATLAS, ATLAS-CONF-2011-127; 1412.0237; 1710.09748;
- CMS, CMS-PAS-HIG-11-007; CMS-PAS-HIG-14-039; CMS-PAS-HIG-16-036
Lower limit on $H_L^{\pm\pm}$ mass in the limit of small $v_L$

Predominant decay mode $H_L^{\pm\pm} \rightarrow \ell_\alpha^\pm \ell_\beta^\pm$
Lower limit on $H_L^{\pm\pm}$ mass ($m_0 = 0$)

Predominant decay mode $H_L^{\pm\pm} \to \ell_{\alpha}^{\pm\pm} \ell_{\beta}^{\pm\pm}, W^{\pm(*)} W^{\pm(*)}$

Dashed lines: central values of neutrino oscillation data;
Colorful bands: $3\sigma$ uncertainties
Lower limit on $H_L^{\pm\pm}$ mass ($m_0 = 0.05$ eV)

Predominant decay mode $H_L^{\pm\pm} \rightarrow \ell_\alpha^{\pm}\ell_\beta^{\pm}$, $W^{\pm(*)} W^{\pm(*)}$

Dashed lines: central values of neutrino oscillation data;
Colorful bands: 3$\sigma$ uncertainties
Heavy Stable Charged particle (HSCP) searches

12.9 fb$^{-1}$ (13 TeV)

Type-II seesaw at the frontiers

Nov 9, 2018
Long-lived $H_L^{±±}$ decays outside either the inner silicon tracker or the whole detector.

We use conservatively only the “tracker-only” analysis.

The decay length $43 \text{ mm} < bc\tau_0(H_L^{±±}) < 1100 \text{ mm}$.
Dominant background: low-mass Drell-Yan processes $pp \rightarrow e^+e^-, \mu^+\mu^-$, with the charges of the electron or muon misidentified (and the electron misidentified as a muon or vice versa), depending largely on $m_{\ell\ell'}$ and $r_{vtx}$.

The dileptons from Drell-Yan processes tend to be back-to-back, which could be easily distinguished from the four-body process $pp \rightarrow H_L^{++} H_L^{--} \rightarrow \ell^+_\alpha \ell^\pm_\beta \ell^\mp_\gamma \ell^-_\delta$. 
**DV prospects of \( H_L^{\pm\pm} \)**

- **HL-LHC** 14 TeV, 3000 fb\(^{-1}\); **FCC-hh** 100 TeV, 30 ab\(^{-1}\); **ILC** 1 TeV, 1 ab\(^{-1}\);
- \( K \)-factor for HL-LHC & FCC-hh taken conservatively to be 1.2 and 1 for ILC;
- Counting only the decays \( H_L^{\pm\pm} \to e^\pm e^\pm, e^\pm \mu^\pm, \mu^\pm \mu^\pm \);
- Decay length \( 1 \text{ mm} < b c \tau_0 (H_L^{\pm\pm}) < 1 (3) \text{ m} \);
- Basic cuts \( p_T(\ell) > 25 (10) \text{ GeV}, |\eta(\ell)| < 2.5, \Delta\phi(\ell\ell') > 0.4 \), requiring at least one displaced \( H_L^{\pm\pm} \) to be reconstructed.
Assuming at least 100 events for the DV sensitivities.

The low-energy high-precision LFV measurements (such as $\mu \rightarrow eee$ and $\mu \rightarrow e\gamma$), the prompt same-sign dilepton searches of $H_{L}^{\pm\pm}$ and the DV searches of $H_{L}^{\pm\pm}$ are largely complementary to each other in the type-II seesaw.
...for $H_{R}^{\pm\pm}$ in LRSM
Proper lifetime of $H^\pm_\pm$

\[ \Gamma_{total}(H^\pm_\pm) = \Gamma(H^\pm_\pm \rightarrow \ell_\alpha \ell_\beta) + \Gamma(H^\pm_\pm \rightarrow W^*_R W^*_R). \]

Assuming lightest neutrino mass $m_0 = 0$.

Assuming $f_L = f_R, g_L = g_R$ and $v_R = 5\sqrt{2}$ TeV.

$H^\pm_\pm \rightarrow W^*_R W^*_R$ highly suppressed by $W_R$ mass.
Same-sign dilepton constraints on $H_R^{\pm\pm}$

To some extent weaker than the $H_L^{\pm\pm}$ limits

OPAL, hep-ex/0111059; DELPHI, hep-ex/0303026; L3, hep-ex/0309076;
CDF, hep-ex/0406073; 0808.2161; D0, 0803.1534; 1106.4250;
ATLAS, ATLAS-CONF-2011-127; 1412.0237; 1710.09748;
CMS, CMS-PAS-HIG-11-007; CMS-PAS-HIG-14-039; CMS-PAS-HIG-16-036
Predominant decay mode $H_R^{\pm\pm} \rightarrow \ell^\pm \ell^\pm$
Lower limit on $H_{\pm\pm}^R$ mass ($m_0 = 0$)

$H_{\pm\pm}^R \rightarrow \ell_\alpha^\pm \ell_\beta^\pm, \ W_R^+ W_R^- $ 

Dashed lines: central values of neutrino oscillation data; 
Colorful bands: 3$\sigma$ uncertainties
Lower limit on $H_R^{±±}$ mass ($m_0 = 0.05$ eV)

\[ H_R^{±±} \rightarrow \ell_α^{±} \ell_β^{±}, \ W_R^{±*} W_R^{±*} \]

Dashed lines: central values of neutrino oscillation data;
Colorful bands: $3\sigma$ uncertainties
Long-lived $H_{R}^{\pm\pm}$ decays outside either the inner silicon tracker or the whole detector.

We use conservatively only the “tracker-only” analysis.

The decay length $43 \text{ mm} < b c \tau_0 (H_{R}^{\pm\pm}) < 1100 \text{ mm}$.

Very different from the $H_{L}^{\pm\pm}$ case
Counting only the decays $H_{L}^{\pm\pm} \rightarrow e^\pm e^\pm, e^\pm \mu^\pm, \mu^\pm \mu^\pm$;
Setting $g_R = g_L$ and the right-handed scale $\nu_R = 5\sqrt{2}$ TeV.
Assuming at least 100 events for the DV sensitivities.

The low-energy high-precision LFV measurements (such as $\mu \rightarrow eee$, $\mu \rightarrow e\gamma$ and $0\nu\beta\beta$), the prompt same-sign dilepton searches of $H_{R}^{\pm\pm}$ and the DV searches of $H_{R}^{\pm\pm}$ are largely complementary to each other in the LRSM.
Considering the simple scenario \( H_R^{\pm\pm} \to e^\pm e^\pm, W_R^{\pm\ast} W_R^{\pm\ast} \).

We do not have the LFV constraints e.g. \( \mu \to e\gamma \), and MOLLER pops out...

The low-energy high-precision LFV measurements (MOLLER and 0\( \nu \beta \beta \)), the prompt same-sign dilepton searches of \( H_R^{\pm\pm} \) and the DV searches of \( H_R^{\pm\pm} \) are largely complementary to each other in the LRSM.
The MOLLER experiment is sensitive to doubly-charged scalars up to the scale of $\sim 10$ TeV.

In the minimal type-II seesaw, the LFV constraints (e.g. $\mu \rightarrow e\gamma$) are stronger; however, in parity-violating MOLLER could go beyond the $0\nu\beta\beta$ limits.

In type-II seesaw $H_{L}^{\pm\pm}$ might be long-lived in a sizable parameter space, depending on the Yukawa couplings $f_L$ (or equivalently $\nu_L$); in LRSM, $H_R$ could also long-lived, for small $f_R$ and TeV-scale $\nu_R$.

A broad region of the parameter space could be probed at HL-LHC, ILC (FCC-hh): $10^{-10} \lesssim |f_{L,R}| \lesssim 10^{-6}$ and $m_Z/2 < M_{H^{\pm\pm}} \lesssim 200 \ (500)$ GeV.

The low-energy high-precision and high-energy experiments are largely complementary to each other in the (in)direct searches of $H^{\pm\pm}$.

Thank you for your attention!