Can LHC Test the See-Saw Mechanism?

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2 Cancellation of Neutrino Masses and Underlying Symmetries

3 Signals at Colliders

4 Conclusions
The See-Saw Mechanism

Standard Model (or MSSM) + right-handed neutrinos $\nu_R$

- Singlets under all gauge groups
  $\leadsto$ Very large Majorana masses $m_R$ possible

- Yukawa couplings to Higgs and lepton doublets
  $\leadsto$ Electroweak-scale Dirac masses $m_D$
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Mass eigenstates:

- Very light Majorana neutrinos, $m_\nu = -m_D m_R^{-1} m_D^T$
- Very heavy ones with masses $\sim m_R$
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Mass eigenstates:

- Very light Majorana neutrinos, $m_\nu = -m_D m_R^{-1} m_D^T$
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- Experimental limit: $m_\nu \lesssim 0.1$ eV
- Common assumption: $O(1)$ Yukawa couplings
  $\Rightarrow m_R \gtrsim 10^{14}$ GeV
  $\Rightarrow$ Mechanism not directly testable
Electroweak-Scale Singlets

What if $m_R \sim 100$ GeV?

$m_D \sim 10^{-4}$ GeV = 100 keV $\sim m_e$

$\sim$ Not totally unreasonable

$\Rightarrow$ RH neutrinos may be within reach of LHC and ILC
Electroweak-Scale Singlets

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  - $m_D \sim 10^{-4}$ GeV = 100 keV $\sim m_e$
  - Not totally unreasonable
  - $\Rightarrow$ RH neutrinos may be within reach of LHC and ILC

- Yukawa couplings tiny $\Rightarrow$ irrelevant for colliders

- Gauge interactions via mixing, e.g.
  \[
  \alpha \, V = \frac{m_D}{m_R} \sim \frac{10^{-4} \text{GeV}}{100 \text{ GeV}} = 10^{-6}
  \]

- Observation at colliders needs $V \gtrsim 0.01$
  - $\Rightarrow$ no way?
2. Cancellation of Neutrino Masses and Underlying Symmetries
Less Naive Point of View

- Contributions from different singlets to $m_\nu$ can cancel

- 3 singlets: $m_\nu = 0$ if and only if
  
  $m_D$ has rank 1, $m_D = m \begin{pmatrix} y_1 & y_2 & y_3 \\ \alpha y_1 & \alpha y_2 & \alpha y_3 \\ \beta y_1 & \beta y_2 & \beta y_3 \end{pmatrix}$

  $\frac{y_1^2}{M_1} + \frac{y_2^2}{M_2} + \frac{y_3^2}{M_3} = 0$

Contributions from different singlets to $m_\nu$ can cancel

3 singlets: $m_\nu = 0$ if and only if

$\begin{align*}
\text{m}_D \text{ has rank 1, } m_D &= m \begin{pmatrix}
y_1 & y_2 & y_3 \\
\alpha y_1 & \alpha y_2 & \alpha y_3 \\
\beta y_1 & \beta y_2 & \beta y_3 
\end{pmatrix} \\
\frac{y_1^2}{M_1} + \frac{y_2^2}{M_2} + \frac{y_3^2}{M_3} &= 0
\end{align*}$


Size of Yukawa couplings arbitrary $\Rightarrow$ large mixing allowed

Experimental limit: $V \lesssim 0.1$
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3 singlets: $m_\nu = 0$ if and only if

$m_D$ has rank 1, $m_D = m \left( \begin{array}{ccc} y_1 & y_2 & y_3 \\ \alpha y_1 & \alpha y_2 & \alpha y_3 \\ \beta y_1 & \beta y_2 & \beta y_3 \end{array} \right)$

$\frac{y_1^2}{M_1} + \frac{y_2^2}{M_2} + \frac{y_3^2}{M_3} = 0$


Size of Yukawa couplings arbitrary $\Rightarrow$ large mixing allowed

Experimental limit: $V \lesssim 0.1$

Cancellation at least at the level $10^{-8} \Rightarrow$ severe fine-tuning
$\Rightarrow$ Symmetry motivation?
Lepton Number Conservation

Most straightforward: conserved lepton number


\[
L(\nu_L) = 1, \quad L(\nu^1_R) = 1, \quad L(\nu^2_R) = -1, \quad L(\nu^3_R) = 0
\]

\[
\Rightarrow m_R = \begin{pmatrix}
0 & M & 0 \\
M & 0 & 0 \\
0 & 0 & M_3
\end{pmatrix}, \quad m_D = m \begin{pmatrix}
a & 0 & 0 \\
b & 0 & 0 \\
c & 0 & 0
\end{pmatrix}
\]

- \(\nu^1_R, \nu^2_R\) form a Dirac neutrino with mass \(M\)
- \(\nu^3_R\) is decoupled
Lepton Number Conservation

Most straightforward: **conserved lepton number**

\[ L(\nu_L) = 1, \ L(\nu^1_R) = 1, \ L(\nu^2_R) = -1, \ L(\nu^3_R) = 0 \]

\[ \Rightarrow \begin{pmatrix} 0 & M & 0 \\ M & 0 & 0 \\ 0 & 0 & M_3 \end{pmatrix}, \quad m_D = m \begin{pmatrix} a & 0 & 0 \\ b & 0 & 0 \\ c & 0 & 0 \end{pmatrix} \]

- \( \nu^1_R, \nu^2_R \) form a Dirac neutrino with mass \( M \)
- \( \nu^3_R \) is decoupled

Are there symmetries realizing the cancellation without \( L \) conservation?
Cancellation Without $L$ Conservation?

2 or 3 singlets with equal masses involved in cancellation

$\Rightarrow L$ conservation $\rightsquigarrow$ try $M_1 \neq M_2$

- Suppose singlets $\nu^1_R$ and $\nu^2_R$ participate in cancellation
- Some symmetry $\rightsquigarrow m_\nu = 0$ at scale $M_2$
- Symmetry broken below $M_2$
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- Symmetry broken below $M_2$
- **Running** of contributions from $\nu^1_R$ and $\nu^2_R$ different

Antusch, J.K., Lindner, Ratz, PLB 538 (2002); Antusch, J.K., Lindner, Ratz, Schmidt, JHEP 03 (2005)

$\Rightarrow$ Cancellation unstable

$$m_\nu \sim 100 \text{ keV } \ln \frac{M_2}{M_1} \text{ at } M_1$$
Cancellation Without $L$ Conservation?

2 or 3 singlets with equal masses involved in cancellation
⇒ $L$ conservation $\iff$ try $M_1 \neq M_2$

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⇒ Cancellation unstable

$$m_\nu \sim 100 \text{ keV} \ln \frac{M_2}{M_1} \text{ at } M_1$$

⇒ Singlets must be degenerate
⇒ Lepton number must be conserved
Perturbations Leading to Non-Zero Neutrino Masses

\[ m_R = \begin{pmatrix} 0 & M & 0 \\ M & 0 & 0 \\ 0 & 0 & M_3 \end{pmatrix}, \quad m_D = m \begin{pmatrix} a & 0 & 0 \\ b & 0 & 0 \\ c & 0 & 0 \end{pmatrix} \]
Perturbations Leading to Non-Zero Neutrino Masses

\[ m_R = \begin{pmatrix} \epsilon_1 M & M & \epsilon_{13} M \\ M & \epsilon_2 M & \epsilon_{23} M \\ \epsilon_{13} M & \epsilon_{23} M & M_3 \end{pmatrix}, \quad m_D = m \begin{pmatrix} a & \delta_a & \epsilon_a \\ b & \delta_b & \epsilon_b \\ c & \delta_c & \epsilon_c \end{pmatrix} \]

\[ \epsilon_2, \delta_{a,b,c} \lesssim 10^{-10} \text{ for } \max(a, b, c) \sim 1, \quad \frac{m}{M} \sim 0.1 \]
Perturbations Leading to Non-Zero Neutrino Masses

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\[ \epsilon_2, \delta_{a,b,c} \lesssim 10^{-10} \text{ for } \max(a, b, c) \sim 1, \quad \frac{m}{M} \sim 0.1 \]

- Most general case: more parameters than observables
- Restricted cases, e.g. assuming similar size for all \( \epsilon, \delta \):

\[ m_\nu \approx \frac{m^2}{M} \left[ \epsilon_2 vv^T - (vv_\delta^T + v_\delta v^T) \right] \]

- Strong mass hierarchy
- Leading-order Yukawa couplings determined by observables
- Examples studied in leptogenesis context

Raidal, Strumia, Turzyński, PLB 609 (2005); Pilaftsis, Underwood, PRD 72 (2005)
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Lepton Number Violation

$q \bar{q} \rightarrow l_\alpha^- l_\beta^- + \text{jets}$

- $m_\nu = 0$ due to symmetry $\Rightarrow L$ conservation $\Rightarrow$ leading-order cross-section vanishes
- $L$-violating perturbations $\Rightarrow m_\nu \neq 0 \Rightarrow$ tiny $\Rightarrow$ Unobservable without fine-tuning
Lepton Flavour Violation

\[ q \bar{q} \rightarrow l^-_\alpha l^+_\beta + \text{jets} \quad (\alpha \neq \beta) \]

- \( L \) conservation \( \Rightarrow \) no cancellation possible
- Strong constraints from searches for LFV decays, especially \( \mu \rightarrow e\gamma \) \( \Rightarrow \) best candidate: \( \mu^-\tau^+ \)

\( \Rightarrow \) Observable in principle

Probably not at LHC

del Aguila, Aguilar-Saavedra, Pittau, hep-ph/0703261
Testing the See-Saw Mechanism

- $m_\nu$ small due to cancellation, not due to see-saw
- Colliders probe leading-order Yukawa couplings, not perturbations giving $m_\nu \neq 0$
- General case: no relation to neutrino masses and mixings

$\rightsquigarrow$ **Decoupling** of collider physics and neutrino mass generation
Testing the See-Saw Mechanism

- $m_\nu$ small due to cancellation, not due to see-saw
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$\leadsto$ Decoupling of collider physics and neutrino mass generation

Restricted cases:
- Strong neutrino mass hierarchy
- Leading-order Yukawas related to $m_\nu$
- Correlations between LFV amplitudes
- Possible verification: measure $V$ directly at $e^+e^-$ collider
Conclusions

- Considered type-I see-saw scenario with light singlets
- **Not** considered: Right-handed neutrinos with additional interactions
- Naive expectation: Yukawa couplings tiny $\Rightarrow$ unobservable
- Sizable couplings $\Rightarrow$ cancellation needed for small $m_\nu$
- Requires either fine-tuning or lepton number conservation
- Small neutrino masses due to tiny perturbations
- Colliders: lepton number violation not observable in untuned scenario
- Lepton **flavour** violation possibly observable
- Neutrino mass generation and collider physics decoupled in general
- Connection possible in constrained setups