Can LHC Test the See-Saw Mechanism?

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Based on
J.K., A.Yu. Smirnov, `arXiv:0705.3221 [hep-ph]`

Outline

1. Introduction
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 ν_R

- Singlets under all gauge groups
  $\rightsquigarrow$ Very large Majorana masses m_R possible
- Yukawa couplings to Higgs and lepton doublets
  $\rightsquigarrow$ Electroweak-scale Dirac masses m_D

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- Very light Majorana neutrinos, $m_\nu = -m_\mathrm{D} {m_\mathrm{R}}^{-1} {m_\mathrm{D}}^T$
- Very heavy ones with masses $\sim m_\mathrm{R}$

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- Experimental limit: $m_\nu \lesssim 0.1$ eV
- Common assumption: $\mathcal{O}(1)$ Yukawa couplings
  $\Rightarrow m_\mathrm{R} \gtrsim 10^{14}$ GeV
  $\Rightarrow$ Mechanism not directly testable

Electroweak-Scale Singlets

- What if $m_{\mathrm{R}} \sim 100\,\mathrm{GeV}$?
  $m_{\mathrm{D}} \sim 10^{-4}\,\mathrm{GeV} = 100\,\mathrm{keV} \sim m_e$
  $\rightsquigarrow$ Not totally unreasonable
  $\Rightarrow$ RH neutrinos may be within reach of LHC and ILC

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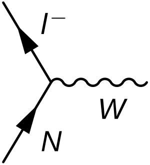
  $\rightsquigarrow$ Not totally unreasonable
  $\Rightarrow$ RH neutrinos may be within reach of LHC and ILC
- Yukawa couplings tiny $\Rightarrow$ irrelevant for colliders
- Gauge interactions via mixing, e.g.



$$\propto V = m_\mathrm{D} {m_\mathrm{R}}^{-1} \sim \frac{10^{-4}\,\mathrm{GeV}}{100\,\mathrm{GeV}} = 10^{-6}$$

- Observation at colliders needs $V \gtrsim 0.01$
  Han, Zhang, PRL **97** (2006); del Aguila, Aguilar-Saavedra, Pittau, J. Phys. Conf. Ser. **53** (2006); Bray, Lee, Pilaftsis, `hep-ph/0702294`
  $\Rightarrow$ no way?

Less Naive Point of View

- Contributions from different singlets to m_ν can cancel

  Buchmüller, Wyler, PLB **249** (1990); Pilaftsis, Z. Phys. **C55** (1992)

- 3 singlets: $m_\nu = 0$ if and only if
  - m_D has rank 1, $m_\mathrm{D} = m \begin{pmatrix} y_1 & y_2 & y_3 \\ \alpha y_1 & \alpha y_2 & \alpha y_3 \\ \beta y_1 & \beta y_2 & \beta y_3 \end{pmatrix}$
  - $\dfrac{y_1^2}{M_1} + \dfrac{y_2^2}{M_2} + \dfrac{y_3^2}{M_3} = 0$

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- Size of Yukawa couplings arbitrary ⇒ large mixing allowed
- Experimental limit: $V \lesssim 0.1$
- Cancellation at least at the level 10^{-8} ⇒ severe fine-tuning
  $\rightsquigarrow$ Symmetry motivation?

Lepton Number Conservation

Most straightforward: conserved lepton number

Wyler, Wolfenstein, NPB **218** (1983); Bernabéu, Santamaria, Vidal, Mendez, Valle, PLB **187** (1987); Tommasini, Barenboim, Bernabéu, Jarlskog, NPB **444** (1995); Pilaftsis, PRL **95** (2005); Pilaftsis, Underwood, PRD **72** (2005);

$$L(\nu_\mathrm{L}) = 1,\ L(\nu_\mathrm{R}^1) = 1,\ L(\nu_\mathrm{R}^2) = -1,\ L(\nu_\mathrm{R}^3) = 0$$

$$\Rightarrow\ m_\mathrm{R} = \begin{pmatrix} 0 & M & 0 \\ M & 0 & 0 \\ 0 & 0 & M_3 \end{pmatrix},\ m_\mathrm{D} = m\begin{pmatrix} a & 0 & 0 \\ b & 0 & 0 \\ c & 0 & 0 \end{pmatrix}$$

- $\nu_\mathrm{R}^1, \nu_\mathrm{R}^2$ form a Dirac neutrino with mass M
- ν_R^3 is decoupled

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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 ν_R^1 and ν_R^2 participate in cancellation
- Some symmetry $\rightsquigarrow m_\nu = 0$ at scale M_2
- Symmetry broken below M_2

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

  $\Rightarrow$ Cancellation unstable

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

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

$\Rightarrow$ Singlets must be degenerate
$\Rightarrow$ Lepton number must be conserved

Perturbations Leading to Non-Zero Neutrino Masses

$$m_R = \begin{pmatrix} 0 & M & 0 \\ M & 0 & 0 \\ 0 & 0 & M_3 \end{pmatrix} \,, \; m_D = m \begin{pmatrix} a & 0 & 0 \\ b & 0 & 0 \\ c & 0 & 0 \end{pmatrix}$$

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

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

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

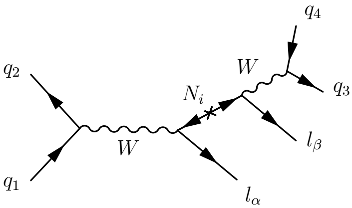
- Most general case: more parameters than observables
- Restricted cases, e.g. assuming similar size for all ϵ, δ:

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

  - 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)

Lepton Number Violation

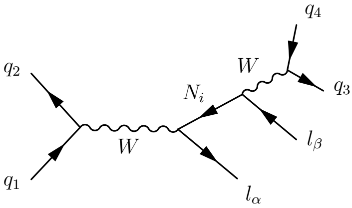


$q\bar{q} \to l_\alpha^- l_\beta^- +$ jets

- $m_\nu = 0$ 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



$$q\bar{q} \to l_\alpha^- l_\beta^+ + \text{jets} \quad (\alpha \neq \beta)$$

- L conservation ⇒ no cancellation possible
- Strong constraints from searches for LFV decays, especially $\mu \to e\gamma$ ⇒ best candidate: $\mu^-\tau^+$

⇒ Observable in principle

Probably not at LHC

del Aguila, Aguilar-Saavedra, Pittau, `hep-ph/0703261`

Testing the See-Saw Mechanism

- m_ν 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

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$\rightsquigarrow$ Decoupling of collider physics and neutrino mass generation

Restricted cases:

- Strong neutrino mass hierarchy
- Leading-order Yukawas related to m_ν
- 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 ⇒ unobservable
- Sizable couplings ⇒ cancellation needed for small m_ν
- 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