LHC Test of the See-Saw

Jörn Kersten

The Abdus Salam ICTP, Trieste

Based on
J.K., A.Yu. Smirnov, Phys. Rev. **D76** (2007), 073005
[arXiv:0705.3221]

Outline

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

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

Mass eigenstates:

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

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

Mass eigenstates:

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

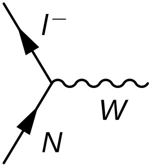
- Experimental limit: $m_\nu \lesssim 0.1$ eV
- Common assumption: $\mathcal{O}(1)$ Yukawa couplings
  $\Rightarrow m_R \gtrsim 10^{14}$ GeV
  $\Rightarrow$ Mechanism not directly testable

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

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
- 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, $m_D = m \begin{pmatrix} y_1 & y_2 & y_3 \\ \alpha y_1 & \alpha y_2 & \alpha y_3 \\ \beta y_1 & \beta y_2 & \beta y_3 \end{pmatrix}$
  - $\dfrac{y_1^2}{M_1} + \dfrac{y_2^2}{M_2} + \dfrac{y_3^2}{M_3} = 0$

  Buchmüller, Greub, NPB **363** (1991); Ingelman, Rathsman, Z. Phys. **C60** (1993); Heusch, Minkowski, NPB **416** (1994)

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, $m_D = m \begin{pmatrix} y_1 & y_2 & y_3 \\ \alpha y_1 & \alpha y_2 & \alpha y_3 \\ \beta y_1 & \beta y_2 & \beta y_3 \end{pmatrix}$
  - $\dfrac{y_1^2}{M_1} + \dfrac{y_2^2}{M_2} + \dfrac{y_3^2}{M_3} = 0$

  Buchmüller, Greub, NPB **363** (1991); Ingelman, Rathsman, Z. Phys. **C60** (1993); Heusch, Minkowski, NPB **416** (1994)
- Size of Yukawa couplings arbitrary $\Rightarrow$ large mixing allowed
- Experimental limit: $V \lesssim 0.1$

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, $m_\mathrm{D} = m \begin{pmatrix} y_1 & y_2 & y_3 \\ \alpha y_1 & \alpha y_2 & \alpha y_3 \\ \beta y_1 & \beta y_2 & \beta y_3 \end{pmatrix}$
  - $\frac{y_1^2}{M_1} + \frac{y_2^2}{M_2} + \frac{y_3^2}{M_3} = 0$

  Buchmüller, Greub, NPB **363** (1991); Ingelman, Rathsman, Z. Phys. **C60** (1993); Heusch, Minkowski, NPB **416** (1994)
- 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
  $\rightsquigarrow$ 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

Are there symmetries realizing the cancellation without L conservation?

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)

$$L(\nu_L) = 1,\ L(\nu_R^1) = 1,\ L(\nu_R^2) = -1,\ L(\nu_R^3) = 0$$

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

- ν_R^1, ν_R^2 form a Dirac neutrino with mass M
- ν_R^3 is decoupled

Are there symmetries realizing the cancellation without L conservation?

No, lepton number must be conserved

Perturbations Leading to Non-Zero Neutrino Masses

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

Perturbations Leading to Non-Zero Neutrino Masses

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

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

Perturbations Leading to Non-Zero Neutrino Masses

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

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

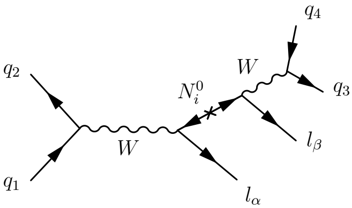
- Most general case: more parameters than observables
- Restricted cases, e.g. assuming similar size for all ϵ, δ:

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

- 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

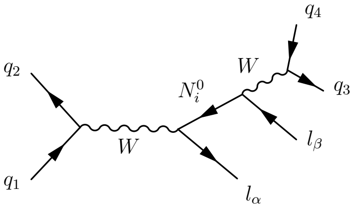


$q\bar{q} \to l_\alpha^- l_\beta^- + \text{jets}$

- $m_\nu = 0$ 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



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

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

$\Rightarrow$ Observable in principle

Probably not at LHC

Del Aguila, Aguilar-Saavedra, Pittau, JHEP **10** (2007)

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

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

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

Different Scenarios

Production by gauge interactions $\Rightarrow$ No large Yukawas needed

- Low-Scale Left-Right Symmetry
  $q\bar{q} \rightarrow W_R \rightarrow N\, l^- \rightarrow l^- l^- +$ jets
  Keung, Senjanović, PRL **50** (1983)
- Type-II See-Saw: Neutrino masses from Higgs triplet Δ
  $q\bar{q} \rightarrow \gamma, Z \rightarrow \Delta^{++}\Delta^{--}$
  Gunion, Vega, Wudka, PRD **42** (1990)
  $\Gamma(\Delta^{++} \rightarrow l^+_\alpha l^+_\beta) \propto |(m_\nu)_{\alpha\beta}|^2$
  May even probe Majorana phases
  Garayoa, Schwetz, `arXiv:0712.1453`; Kadastik, Raidal, Rebane, `arXiv:0712.3912`; Akeroyd, Aoki, Sugiyama, `arXiv:0712.4019`
- Type-III See-Saw: Neutrino masses from triplet neutrino T
  $q\bar{q} \rightarrow W^- \rightarrow T^- T^0 \rightarrow l^- l^- +$ jets
  Bajc, Senjanović, JHEP **08** (2007)
- Others
  Hung, PLB **649** (2007); Graesser, PRD **76** (2007); ...

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_ν
- Requires either fine-tuning or lepton number conservation
- 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