Light window for right-handed neutrinos in the Left-Right model

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Introduction

Existence of neutrino masses implied by the discovery of neutrino oscillations (Super-Kamiokande & SNO).

Important questions:

- Dirac/Majorana nature of neutrinos,
- neutrino mass generation mechanism.

Introduction

Attractive explanation of neutrino masses (and their smallness) is the *seesaw mechanism*, where neutrinos are Majorana fermions.

Possible extension of SM is the *Left-Right symmetric model* (LRSM):

- restores parity,
- naturally embeds the seesaw mechanism.

Important consequence of Majorana neutrinos is *lepton number violation* (LNV), $\Delta L = 2$.

Left-right symmetric model

J. C. Pati, A. Salam, PRD **10** (1974); **11** (1975); R. N. Mohapatra, PRD **11** (1975)
G. Senjanović, R. N. Mohapatra, PRD **12** (1975); G. Senjanović, PRL **44** (1980) ...

Gauge group:

$$\mathcal{G}_{LR} = SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$\Rightarrow \quad W_{L,R} \quad Z_{L,R} \quad \gamma$$

Matter fields:

$$Q_{L,i} = \begin{pmatrix} u_L \\ d_L \end{pmatrix}_i \sim \left(\mathbf{2}, \mathbf{1}, \frac{1}{3}\right) \quad Q_{R,i} = \begin{pmatrix} u_R \\ d_R \end{pmatrix}_i \sim \left(\mathbf{1}, \mathbf{2}, \frac{1}{3}\right)$$

$$\psi_{L,i} = \begin{pmatrix} \nu_L \\ l_L \end{pmatrix}_i \sim (\mathbf{2}, \mathbf{1}, -1) \quad \psi_{R,i} = \begin{pmatrix} N_R \\ l_R \end{pmatrix}_i \sim (\mathbf{1}, \mathbf{2}, -1)$$

Left-right symmetric model

Scalar sector:

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \sim (\mathbf{2}, \mathbf{2}, 0)$$

$$\Delta_{L,R} = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}_{L,R} \sim (\mathbf{3}, \mathbf{1}, 2)\,, (\mathbf{1}, \mathbf{3}, 2)$$

Symmetry breaking pattern:

$$\mathcal{G}_{LR} \xrightarrow[\langle\Delta_L\rangle=0]{\langle\Delta_R\rangle\neq0} SU(2)_L \times U(1) \xrightarrow{\langle\Phi\rangle\neq0} U(1)_{\rm em}$$

$$Q_{\rm em} = I_{3L} + I_{3R} + \frac{B-L}{2}$$

Left-right symmetric model

Crucial ingredient — *Majorana nature of neutrinos.*

Smallness of neutrino mass is connected to the scale of new physics (M_{W_R}):

$$m_{\nu_l} \sim \frac{m_l^2}{M_{W_R}}.$$

Constraints

Constraints from low-energy experiments:

- $K^0 - \bar{K}^0$ and $B^0_{d,s} - \bar{B}^0_{d,s}$ oscillations

  Y. Zhang, H. An, X. Ji, R. N. Mohapatra, Nucl. Phys. B **802** (2008);

  S. Bertolini, A. Maiezza, F. Nesti, Phys. Rev. D **89** (2014)
- CP-violating processes (ε, ε')

  S. Bertolini, J. O. Eeg, A. Maiezza, F. Nesti, Phys. Rev. D **86** (2012);

  S. Bertolini, A. Maiezza, F. Nesti, Phys. Rev. D **88** (2013)
- nEDM

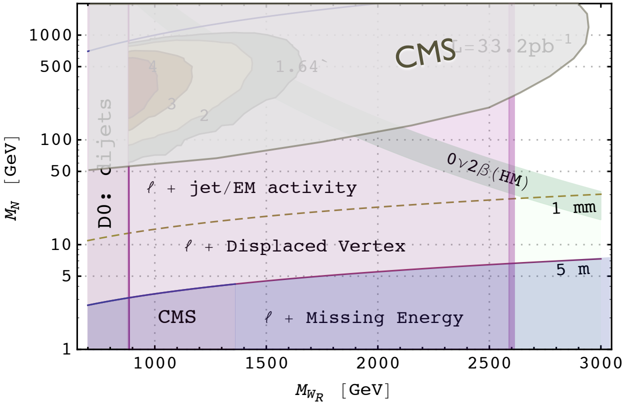
  A. Maiezza, M. Nemevšek, Phys. Rev. D **90** (2014)

$$\Rightarrow M_{W_R} \gtrsim 3 \text{ TeV}$$

Neutrino nautre is observable at LHC!

Constraints: Light window

M. Nemevšek, F. Nesti, G. Senjanović, Y. Zhang, Phys. Rev. D **83** (2011)



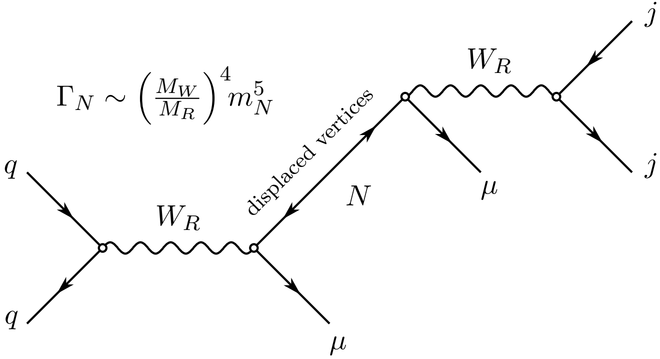
$$4\text{ TeV} \lesssim M_{W_R} \lesssim 7\text{ TeV} \quad \text{and} \quad 10\text{ GeV} \lesssim m_N \lesssim 400\text{ GeV}$$

Keung-Senjanović process

W.-Y. Keung, G. Senjanović, Phys. Rev. Lett. **50** (1983)

$$p\,p \to \mu^\pm \mu^\pm j j \quad \text{(LNV!)}$$

$$\Gamma_N \sim \left(\frac{M_W}{M_R}\right)^4 m_N^5$$



Keung-Senjanović process

Important features of Keung-Senjanović (KS) process:

- lepton number violation (not present in SM),
- *displaced vertices* (long-lived N) — helpful in eliminating the background,
- high-energy analogue to $0\nu2\beta$.

Although clean in principle, presents some real-world challenges:

- background
- detector effects (e. g. highly boosted products of N decay become collimated).

Monte Carlo simulation

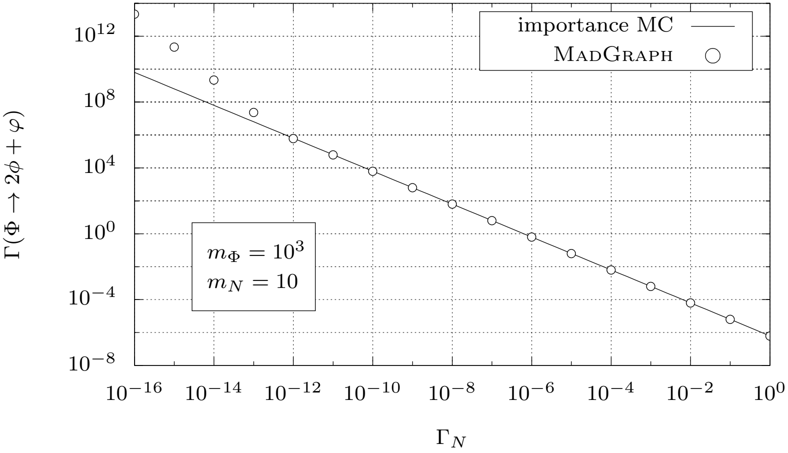
Simulation of signal and background involves several steps:

1. model definition (FeynRules),
2. event generation (MadGraph),
3. hadronization (Pythia),
4. detector simulation (Delphes),
5. analysis, cuts (MadAnalysis).

Narrow N resonance causes numerical instabilities in the event generation step!

Monte Carlo simulation: Narrow width problem

Simple test with scalars: $\Phi \to \phi N, N \to \phi\varphi$.



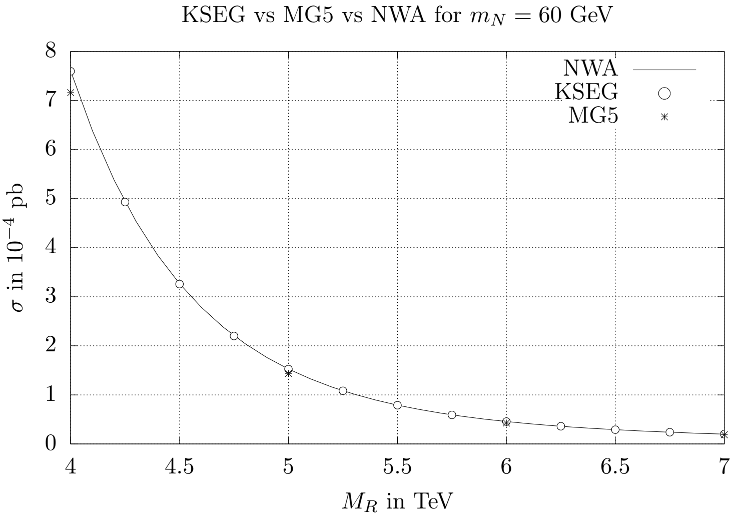
Monte Carlo simulation: Custom event generator

Solution – custom event generator (KSEG):

- recursive phase space decomposition (integration over resonances),
- importance sampling from Breit-Wigner distribution to eliminate narrow N peak,
- unweighted events output to LHE file (for further processing).

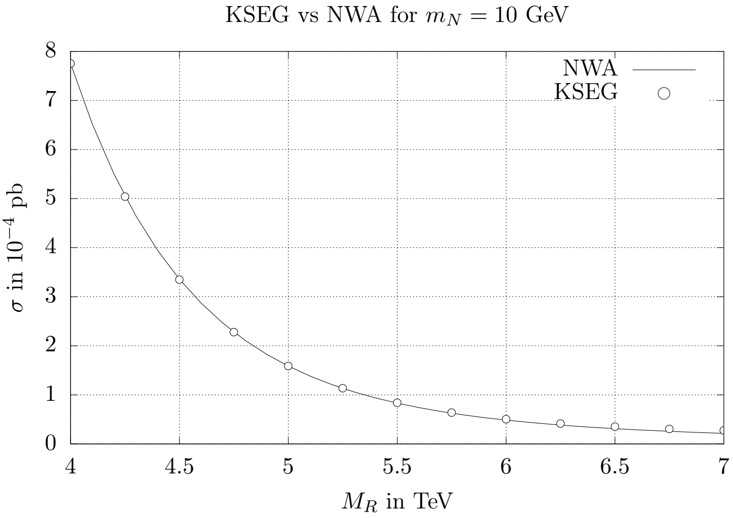
Monte Carlo simulation: Custom event generator

Cross-check using narrow width approximation:



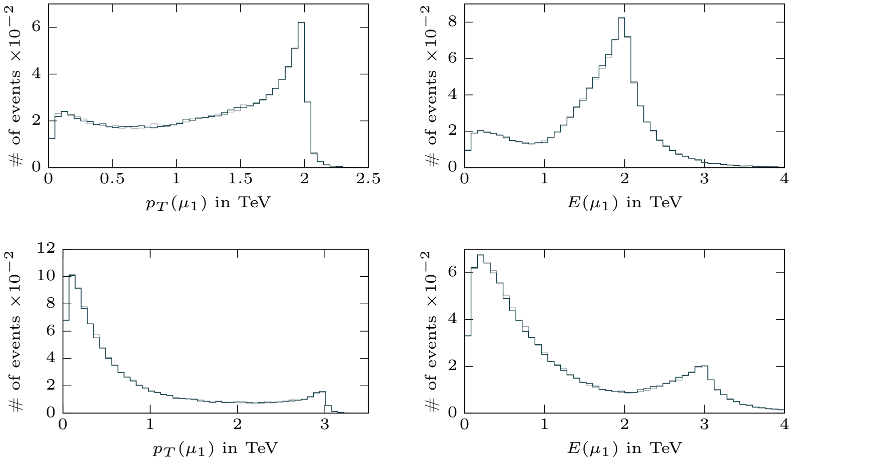
Monte Carlo simulation: Custom event generator

Cross-check using narrow width approximation:



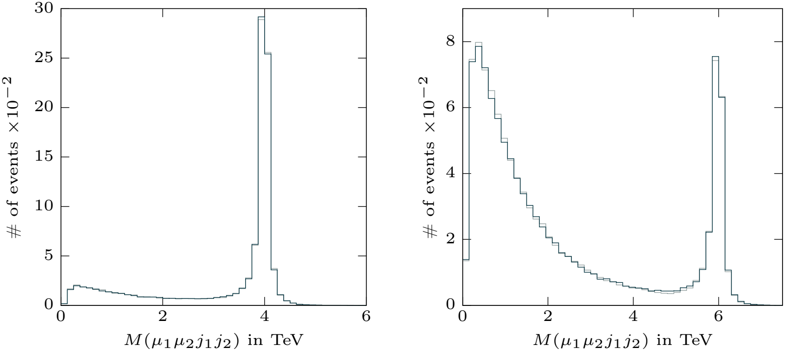
Monte Carlo simulation: Custom event generator

Transverse momentum and energy distributions (KSEG & MG5) of the prompt muon for $m_N = 80$ GeV and $M_R = 4$ TeV (upper panel) and $M_R = 6$ TeV (lower panel):



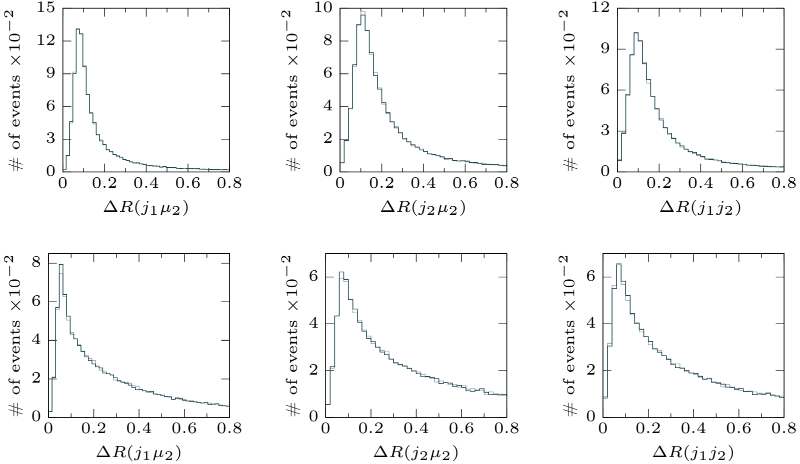
Monte Carlo simulation: Custom event generator

Invariant mass of the muons and jets for $m_N = 80$ GeV and $M_R = 4$ TeV (left) and $M_R = 6$ TeV (right):



Monte Carlo simulation: Custom event generator

ΔR of various pairs for $m_N = 80$ GeV and $M_R = 4$ TeV (upper panel) and $M_R = 6$ TeV (lower panel):



Outlook

MadGraph instability problem in Keung-Senjanović process is solved (for the relevant portion of parameter space).

Hadronization and detector simulation ongoing.

Things to be done:

1. consider background,
2. place/optimize cuts (displaced vertices interesting here),
3. sensitivity assessment, limits on the model,
4. prospects for future colliders.

Thank you!

Backup

Two kinds of LR symmetries, imposing restrictions on Yukawa matrices:

$$\mathcal{P}: \left\{ \begin{array}{c} Q_L \leftrightarrow Q_R \\ \Phi \to \Phi^\dagger \end{array} \right. \Rightarrow Y = Y^\dagger, \quad \mathcal{C}: \left\{ \begin{array}{c} Q_L \leftrightarrow (Q_R)^c \\ \Phi \to \Phi^T \end{array} \right. \Rightarrow Y = Y^T.$$

$\mathcal{C}$ has an advantage — it can be gauged (involves spinors with same final chirality).

A. Maiezza, M. Nemevšek, F. Nesti, G. Senjanović, Phys. Rev. D **82** (2010)