Long-Lived Neutrinos in the Left-Right Symmetric Model

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May 16, 2018
Talk Outline

- Left-Right Model
- Keung-Senjanović (KS) Process
- Monte Carlo for KS
- Results
- Conclusion
Left-Right 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:

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

\[ \Rightarrow W_{L,R} \quad Z_{L,R} \quad \gamma \]

Matter fields:

\[ Q_{L,i} = \begin{pmatrix} u_L \\ d_L \end{pmatrix}_i \sim \begin{pmatrix} 2 \\ 1 \\ \frac{1}{3} \end{pmatrix} \quad Q_{R,i} = \begin{pmatrix} u_R \\ d_R \end{pmatrix}_i \sim \begin{pmatrix} 1 \\ 2 \\ \frac{1}{3} \end{pmatrix} \]

\[ \psi_{L,i} = \begin{pmatrix} \nu_L \\ l_L \end{pmatrix}_i \sim \begin{pmatrix} 2 \\ 1 \\ -1 \end{pmatrix} \quad \psi_{R,i} = \begin{pmatrix} N_R \\ l_R \end{pmatrix}_i \sim \begin{pmatrix} 1 \\ 2 \\ -1 \end{pmatrix} \]
Left-Right Model

Scalar sector:

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

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

Symmetry breaking pattern:

\[ G_{LR} \xrightarrow{\langle \Delta_R \rangle \neq 0 \langle \Delta_L \rangle = 0} SU(2)_L \times U(1) \xrightarrow{\langle \Phi \rangle \neq 0} U(1)_{em} \]

\[ Q_{em} = I_{3L} + I_{3R} + \frac{B - L}{2} \]
Left-Right Model


In the LR model, there is no ambiguity of $M_D$.

$$M_D = \sqrt{\frac{v_L}{v_R} - \frac{1}{M_N} M_\nu}$$

⇒ Connection between low energy ($M_\nu$) and high energy ($M_N$) phenomena.

Crucial ingredient — *Majorana nature of neutrinos.*
⇒ Lepton Number Violation
Left-Right Model: Constraints

Constraints from low-energy experiments:

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

- CP-violating processes (\( \varepsilon, \varepsilon' \))
  

- \( nEDM \)
  

Also: KS search from CMS and ATLAS, \( W_R \to jj \)

\[ \Rightarrow M_{W_R} \gtrsim 3.7 \text{ TeV} \]
Keung-Senjanović Process


Important features of Keung-Senjanović (KS) process:

- lepton number violation (not present in SM),

- displaced vertices: \( \Gamma \sim \left( \frac{M_W}{M_R} \right)^4 m_N^5 \Rightarrow \) possibly long-lived \( N \)

- high-energy analogue to \( 0\nu2\beta \).
Final states ranging from:

- **standard KS region**: $m_N \gtrsim 150 - 200$ GeV, invariant masses $m_{lljj}^{\text{inv}}$ and $m_{ljj}^{\text{inv}}$ can reconstruct $m_N$ and $M_R$;

- **merged region**: small mass of $N$ makes it difficult to reconstruct $m_N$ using $j_N$ invariant mass, $M_R$ can be identified from $m_{ljj}^{\text{inv}}$;

- **displaced region**: merged neutrino jet appears at a visibly displaced distance from the primary vertex;

- **invisible region**: jet appears outside the detector and manifests itself as a missing energy.
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!
Low $N$ masses ($\leq 10$ GeV for $M_R \gtrsim 3$ TeV) are problematic for 
MadGraph (understandable for a general purpose event generator).

Robust event generator for the whole parameter space was needed.

Well known solutions exist. Procedure:

1. decompose the phase space into two-body ones,
2. choose the appropriate integration variables/phase space mappings,
3. sample the integration variables according to the suitable 
distributions,
4. evaluate the amplitudes.
General/adaptive integrators may not be able to probe the narrow Breit-Wigner peaks (if not eliminated beforehand).

Sample the problematic variables according to Breit-Wigner distribution.

In case of multiple peaks, use a basis of functions\(^1\)

\[
f = \sum_i f_i \quad f_i = \frac{|\mathcal{M}_i|^2}{\sum_j |\mathcal{M}_j|^2} |\mathcal{M}_{\text{tot}}|^2 \quad \mathcal{M}_{\text{tot}} = \sum_i \mathcal{M}_i
\]

In general, each \(f_i\) has a different peaking structure.

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\(^1\)F. Maltoni, T. Stelzer, JHEP 0302 (2003) 027
Possible numerical difficulties in propagators (cancellation of $p^2$ and $m^2 \sim m^2\Gamma^2$):

$$\frac{1}{(p^2 - m^2)^2 + m^2\Gamma^2}$$

Solution: Use $p^2$ as the integration variable (change the integration variables in the phase space).

Minor technical complication: Use $p^2$ for evaluation of the chosen diagram (basis function $f_i$), calculate from external momenta in others.
Using these techniques, we developed a custom event generator for KS process (KSEG).

KSEG does the following:

- calculates the $W_R$ and $N$ widths,
- calculates the cross section for a given set of processes,
- produces unweighted events and outputs them to an LHE file.

Model file, event generator and modified DELPHES and MadAnalysis sources can be found on the web:

https://sites.google.com/site/leftrighthep
Jet Displacement

Simple DELPHES module: minimum displacement among the tracks associated with the jet which have $p_T > 20$ GeV.

Delphes visualization:
Sensitivity Assessment

Choice of measure: $S/\sqrt{S + B}$

Different *multivariate* approaches:
Cuts, Neural Networks, Decision Trees, Binning (new), …

Sensitivity measure for binning approach:

$$\sqrt{\sum_{i \in \text{bins}} \frac{s_i^2}{s_i + b_i}}$$

Variables used:
1. prompt lepton $p_T$
2. jet displacement $d_T$
3. number of leptons
4. number of jets
5. number of same-sign leptons
6. invariant mass of $W_R$ products
Master Plot

- Standard KS (eejj) exclusion, 2σ CL (CMS)
- Dijet exclusion (ATLAS)
- $m_N > M_{W_R}$
- Standard + displaced KS (eejj + ej) reach ($L = 300/\text{fb}$)
- $\sigma$ (CL)
- $\nu$ (CL)
- $\beta$ (CL)
- $d(t) [\text{mm}]$
We developed a dedicated event generator for the KS process, modified some of the existing tools to fit our needs, and used some simple tools of our own (binning, neural nets), showed that jet displacement is a good discrimination variable for the low $N$ mass, analyzed the invisible region by recasting the current search for $W'$ in the $l\not{E}_T$ signature.

$\Rightarrow$ KS process can reach a sensitivity up to 7–8 TeV for RH neutrino masses down to $\sim 20$ GeV.
Discrete LR Symmetries

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

\[ \mathcal{P} : \begin{cases} Q_L \leftrightarrow Q_R \\ \Phi \rightarrow \Phi^\dagger \end{cases} \Rightarrow Y = Y^\dagger, \quad \mathcal{C} : \begin{cases} Q_L \leftrightarrow (Q_R)^c \\ \Phi \rightarrow \Phi^T \end{cases} \Rightarrow Y = Y^T. \]

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


Also,

\[ M_L = \frac{v_L}{v_R} M_N, \]
\[ M_R = M_D^T. \]
Casas-Ibarra Ambiguity


But, Dirac couplings for neutrinos is not unambiguously defined.

\[ M_D = i\sqrt{m_N}O\sqrt{m_\nu}V_L^\dagger \]

- \( m_\nu \) – light neutrino mass,
- \( m_N \) – heavy neutrino mass,
- \( O \) – arbitrary orthogonal complex matrix,
- \( V_L \) – light neutrino mixing matrix.

⇒ Not predictive by itself!

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

- restores parity,
- naturally embeds the seesaw mechanism.
Multichannel MC


Solution is the multichannel Monte Carlo, where

\[ g(\vec{x}) = \sum_{i=1}^{n} \alpha_i g_i(\vec{x}), \quad \int d\vec{x} g_i(\vec{x}) = 1, \quad \sum_{i=1}^{n} \alpha_i = 1. \]

\( g_i(\vec{x}) \) – one peaking structure,
\( \alpha_i \) – weight (probability) for a channel.

Weights can be optimized during the integration.

\[ \alpha_{i}^{\text{new}} \propto \alpha_i \sqrt{W_i(\alpha)} \quad W_i(\alpha) = \left\langle \frac{g_i(\vec{x})}{g(\vec{x})} w(\vec{x})^2 \right\rangle \]
MadGraph vs KSEG

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

Percentage of secondary leptons passing the isolation requirements:

\[ W_R \to eN \to e\bar{e}jj \]

\[ W_R \to \mu N \to \mu\bar{\mu}jj \]