Long-Lived Neutrinos in the Left-Right Symmetric Model

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based on arXiv:1801.05813

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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:

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

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

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 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:

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

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

Left-Right Model

M. Nemevšek, G. Senjanović, V. Tello, Phys. Rev. Lett. **110** (2013)

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

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

$\Rightarrow$ Connection between low energy (M_ν) and high energy (M_N) phenomena.

Crucial ingredient — *Majorana nature of neutrinos.*
$\Rightarrow$ 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

  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

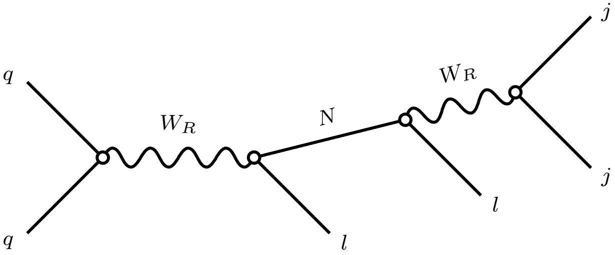
  A. Maiezza, M. Nemevšek, Phys. Rev. D **90** (2014)

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

$$\Rightarrow M_{W_R} \gtrsim 3.7 \text{ TeV}$$

Keung-Senjanović Process

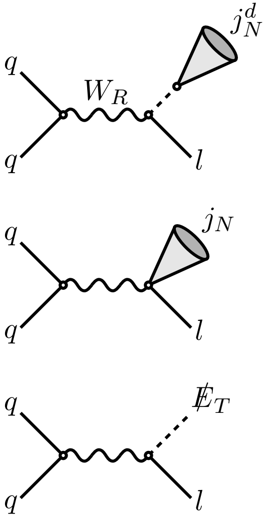
W.-Y. Keung, G. Senjanović, Phys. Rev. Lett. **50** (1983)



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 $0\nu 2\beta$.

Keung-Senjanović Process



Final states ranging from:

- *standard KS region*: $m_N \gtrsim 150 - 200$ GeV, invariant masses m_{lljj}^{inv} and m_{ljj}^{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 idetified from $m_{lj_N}^{\text{inv}}$;
- *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.

Monte Carlo: General Framework

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!

Custom Event Generator: Motivation

Low N masses (≤ 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.

Importance Sampling

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]

$$f = \sum_i f_i \qquad f_i = \frac{|\mathcal{M}_i|^2}{\sum_j |\mathcal{M}_j|^2} |\mathcal{M}_{\text{tot}}|^2 \qquad \mathcal{M}_{\text{tot}} = \sum_i \mathcal{M}_i$$

In general, each f_i has a different peaking structure.

[1] F. Maltoni, T. Stelzer, JHEP 0302 (2003) 027

Amplitude Evaluation

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.

KSEG

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.

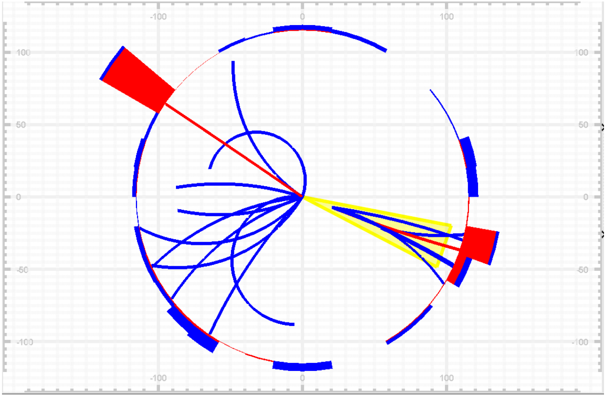
Model file, event generator and modified DELPHES and MADANALYSIS sources can be found on the web:

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), ...

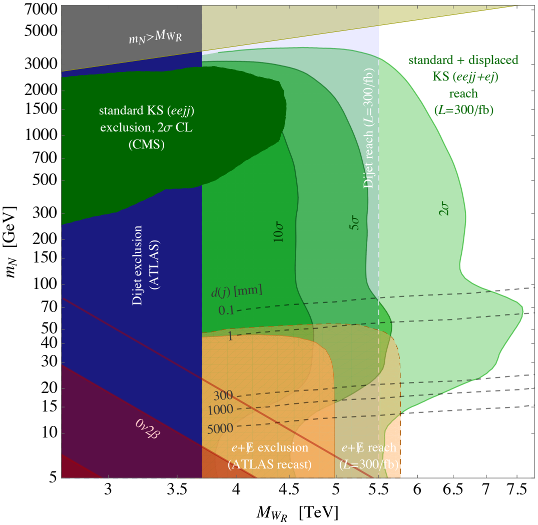
Sensitivity measure for binning approach:

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

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


$m_N > M_{W_R}$
standard + displaced
KS (eejj+ej)
reach
(L=300/fb)
standard KS (eejj)
exclusion, 2σ CL
(CMS)
Dijet reach (L=300/fb)
Dijet exclusion
(ATLAS)
10σ
5σ
2σ
d(j) [mm]
0.1
1
300
1000
5000
0ν2β
e+E̸ exclusion
(ATLAS recast)
e+E̸ reach
(L=300/fb)
m_N [GeV]
M_{W_R} [TeV]
7000
5000
3000
2000
1500
1000
700
500
300
200
150
100
70
50
40
30
20
15
10
5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5

Conclusion

- 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 $l\not{E}$ 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:

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

$\mathcal{C}$ 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)

Also,

$$M_L = \frac{v_L}{v_R} M_N,$$
$$M_R = M_D^T.$$

Casas-Ibarra Ambiguity

J. A. Casas, A. Ibarra, Nucl. Phys. B **618** (2001)

But, Dirac couplings for neutrinos is not unambiguously defined.

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

m_ν	–	light neutrino mass,
m_N	–	heavy neutrino mass,
O	–	arbitrary orthogonal complex matrix,
V_L	–	light neutrino mixing matrix.

$\Rightarrow$ Not predicitve by itself!

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

- restores parity,
- naturally embeds the seesaw mechanism.

Multichannel MC

R. Kleiss, R. Pittau, Comput. Phys. Commun. **83** (1994)

Solution is the multichannel Monte Carlo, where

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

$g_i(\vec{x})$ – one peaking structure,

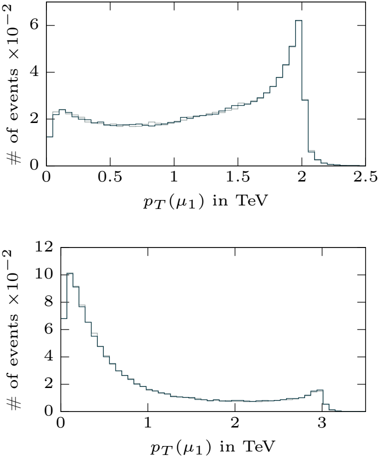
α_i – weight (probability) for a channel.

Weights can be optimized during the integration.

$$\alpha_i^{\mathrm{new}} \propto \alpha_i \sqrt{W_i(\alpha)} \qquad W_i(\alpha) = \left\langle \frac{g_i(\vec{x})}{g(\vec{x})} w(\vec{x})^2 \right\rangle$$

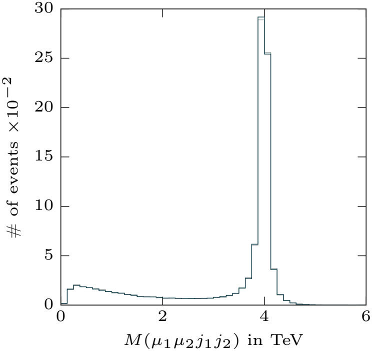
MadGraph vs KSEG

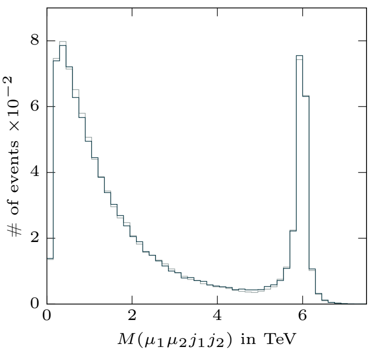
Transverse momentum and energy distributions (KSEG & MG5) of the prompt muon for $m_N = 80$ GeV and $M_R = 4$ TeV (upper panel) and $M_R = 6$ TeV (lower panel):



MadGraph vs KSEG

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: