Majorons and Neutrino Masses in the Type 1 Seesaw Mechanism

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Overview

- One can explain the small neutrino masses by introducing 3 Majorana neutrinos with mass term

$$-\mathcal{L} \supset \frac{1}{2}\bar{\nu}_L^c M_M \nu_R + h.c \tag{1}$$

- Lepton number violation can be used to explained baryon assymetry in the universe through leptogenesis. Can be promoted to a symmetry that gets broken at a certain scale
- General mass Lagrangian considers both Dirac and Majorana masses

$$-\mathcal{L} \supset \frac{1}{2}\bar{\nu}_L^c M_N \nu_R + h.c; \quad \nu_R = (\nu_L^c, \nu_R) \tag{2}$$

- Mass matrix is non diagonal

$$M_N = \begin{pmatrix} 0 & M_D \\ M_D^T & M_M \end{pmatrix} \tag{3}$$

Weak eigenstates$\neq$ mass eigenstates

- If $M_M >> M_D$ the diagonal mass matrix becomes

$$M_N' = \begin{pmatrix} M_M & 0 \\ 0 & -M_M^{-1} M_D^T M_D \end{pmatrix} \tag{4}$$

- Type 1 Seesaw explains why measured mass values are so small. However, L gets broken by two units and M_M is put by hand.
- One can then promote L, or B-L, to an approximate global symmetry that becomes spontaneously broken at the Seesaw scale.
- Introduce scalar singlet φ with potential

$$V(\phi) = m_{\varphi}^2 \varphi^\dagger \varphi + \frac{\lambda_\varphi}{4}(\varphi^\dagger \varphi)^2 + V(\phi, \varphi) \tag{5}$$

- Hence, one can generate Majorana masses through Yukawa couplings

$$-\mathcal{L} \supset \frac{1}{2} y_{ij} \bar{\nu}_L^{c,i} \varphi \nu_R^j + h.c \tag{6}$$

- It is possible to parametrize φ around the new VEV as (Kibble parametrization)

$$\varphi = \frac{1}{\sqrt{2}}(f + A + iJ) \tag{7}$$

- Goldstone theorem $\rightarrow$ J gets massive. Referred to as the Majoron.
- If Seesaw scale = Peccei-Quinn scale, Majoron = Axion.

- After SSB, Majorana mass terms are obtained as well as Neutrino-Majoron interactions

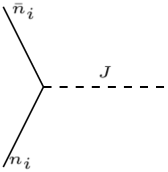
$$-\mathcal{L} \supset \frac{1}{2}(M_M)_{ij}\bar{\nu}_L^{c,i}\nu_R^j + \frac{1}{2\sqrt{2}}y_{ij}\bar{\nu}_L^{c,i}A\nu_R^j + \frac{i}{2\sqrt{2}}y_{ij}\bar{\nu}_L^{c,i}J\nu_R^j \tag{8}$$

- Rewrite Neutrino-J couplings in terms of the masses

$$\mathcal{L}_J = \frac{im_N}{2f}\bar{\nu}_L^c J\nu_R + h.c \tag{9}$$

In terms of the three massive neutrino eigenstates

$$\mathcal{L}_J = \frac{im_N}{2f}\bar{n}_i J n_i + h.c \tag{10}$$



- Majoron production at the LHC has not been largely studied.
- Three fundamental production mechanisms were studied.
  First one: W mediated production of a Majoron.

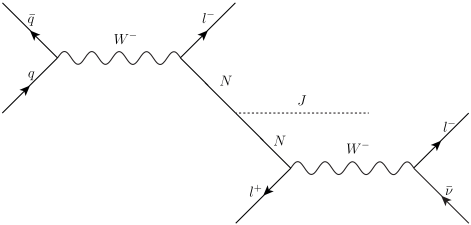


Figure: W mediated production of a J (W Channel)

- The second production mechanism emulates the signal from the $0\nu\beta\beta$ decay, and is obtained through indirect Vector Boson Fusion (VBF) processes

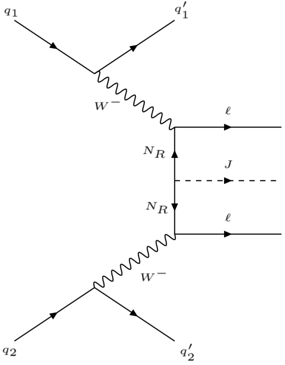


Figure: J production via VBF

- Third production mechanism → Drell-Yan

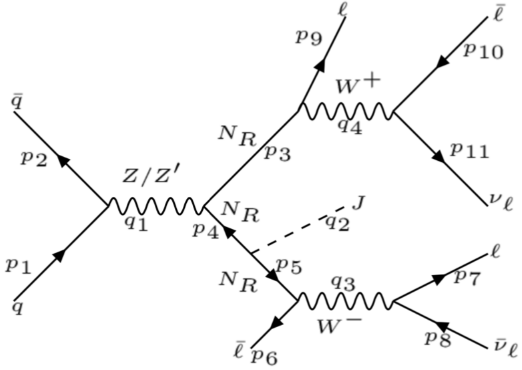


Figure: J production via DY process

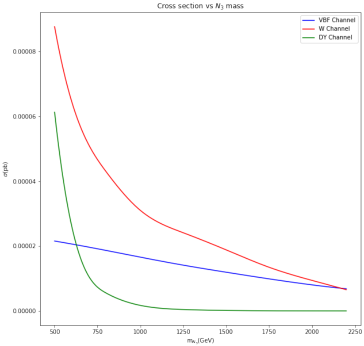


Figure: Behavior of the three different production cross sections as a function of N_3 mass for $f = 300GeV$ and $m_J = 100GeV$.

- Cross sections are too small for the process to be observed at the LHC
- This part of the work was carried with non decaying J
- Lower energy experiments can be a better probe to the parameter space

- Current focus: 2 loop couplings to photons

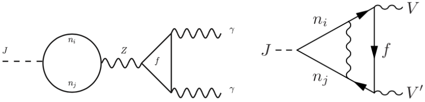


Figure: Example of 2 loop coupling to vector bosons

- Coupling at two loops is given by

$$g_{\gamma\gamma} = \frac{\alpha}{8\pi^3 v^2 f}\left\{ Tr(M_D M_D^\dagger) \sum_f N_c^f Q_f^2 T_3^f h\left(\frac{m_J^2}{4m_f^2}\right) + \sum_\ell (M_D M_D^\dagger)_{\ell\ell} h\left(\frac{m_J^2}{4m_f^2}\right)\right\} \tag{11}$$

- Partial decay width is given by

$$\Gamma(J \to \gamma\gamma) = \frac{|g_{\gamma\gamma}|^2 m_J^3}{64\pi} \tag{12}$$

Limits on the trace values

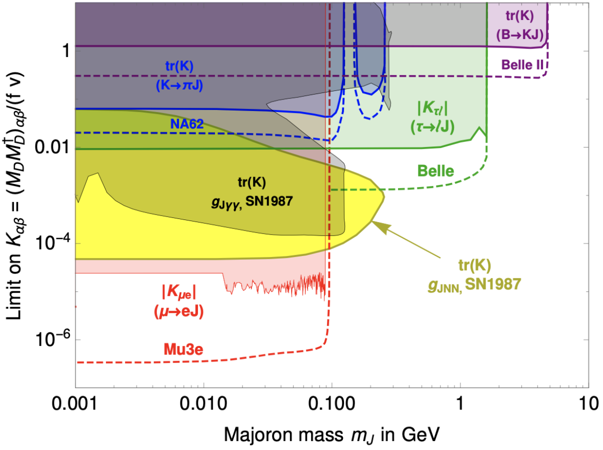


Figure: J. Heeck, H. Pattel Phys. Rev. D 100, 095015 (2019)

- Three free parameters $Tr(M_D M_D^\dagger), M_J, f$
- Two scenarios were considered to calculate the lifetime of the Majoron, namely large ($\tau \geq 1 \times 10^{17} s$) and short ($\tau \leq 1 s$) values . These calculations were performed by fixing one of the free parameters and allowing the other two to run in a certain range. $\rightarrow$ Heat maps were made.

Heat Maps: Fixed VEV and large τ

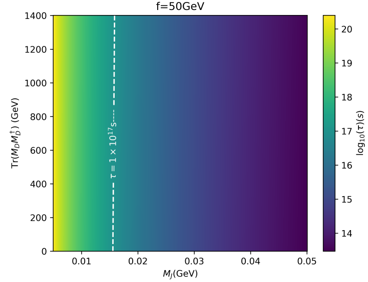
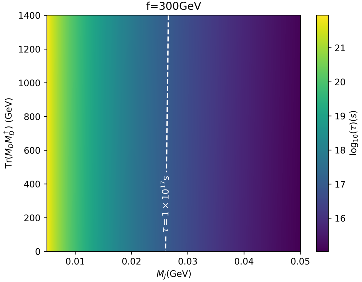


Figure: Majoron lifetime (in log scale) as a function of the mass and the trace for f=50GeV. Dashed line represent the age of the universe



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Heat Maps: Fixed VEV and large τ

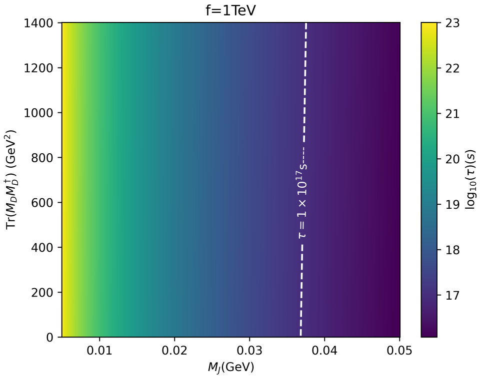


Figure: Majoron lifetime (in log scale) as a function of the mass and the trace for f=1TeV. Dashed lines represent the age of the universe.

- Increasing the VEV changes the mass values from around 16 MeV to 37 MeV.
- Highest τ value also increases with the VEV.

Heat Maps:Fixed Trace and large τ

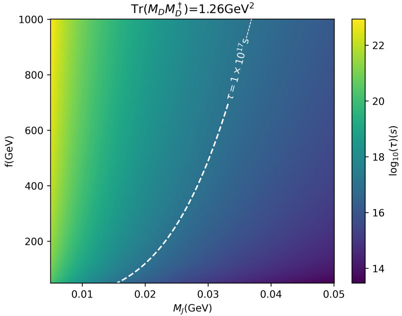


Figure: Majoron lifetime (in log scale) as a function of the mass and the vev for $Tr(M_D M_D^\dagger) = 1.26 GeV^2$. Dashed line represents the age of the universe.

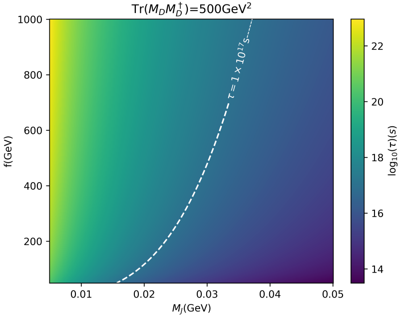


Figure: Majoron lifetime (in log scale) as a function of the mass and the vev for $Tr(M_D M_D^\dagger) = 500 GeV^2$. Dashed lines represents the age of the universe.

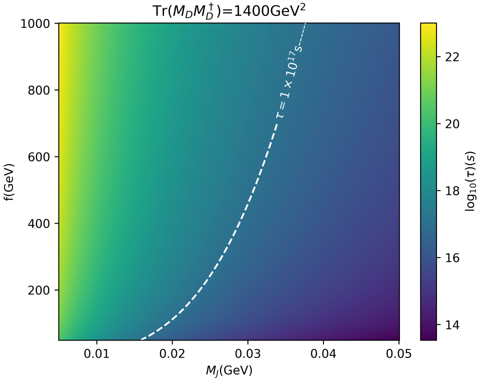


Figure: Majoron lifetime (in log scale) as a function of the mass and the vev for $Tr(M_D M_D^\dagger) = 1400 GeV^2$. Dashed line represents the age of the universe.

- Smallest τ can also be associated to higher mass values
- Broader mass spectrum independent of the trace value!
- Curves are smoother than in the fixed VEV scenario.

Heat Maps: Fixed VEV and short τ

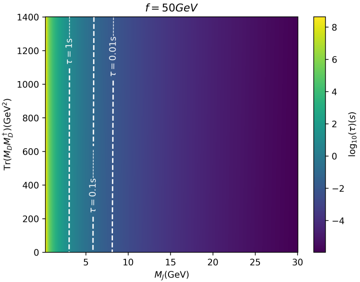


Figure: Majoron lifetime (in log scale) as a function of the mass and the trace for f=50GeV. Dashed lines represent $\tau \leq 1s$

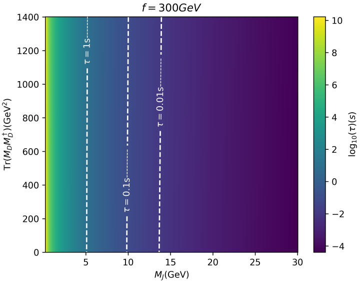


Figure: Majoron lifetime (in log scale) as a function of the mass and the trace for f=300GeV. Dashed lines represent $\tau \leq 1s$

Heat Maps: Fixed VEV and short τ

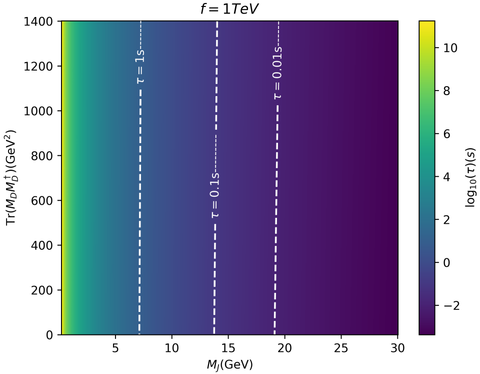
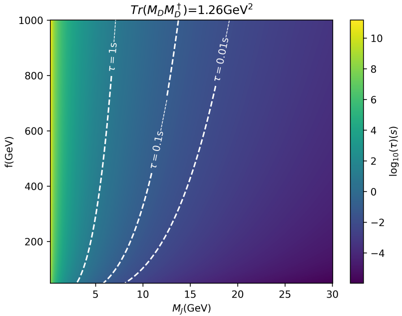


Figure: Majoron lifetime (in log scale) as a function of the mass and the trace for f=1TeV. Dashed lines represent $\tau \leq 1s$

- Increasing the VEV changes the range of mass values [0.5, 7] GeV to [7, 19] Gev
- Gap size inscreases with the mass in agreement with the structure of the Γ.
- Highest τ value also increases with the VEV.

Heat Maps:Fixed Trace and short τ



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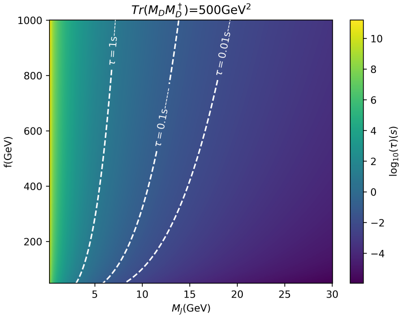

Figure: Majoron lifetime (in log scale) as a function of the mass and the vev for $(M_D M_D^\dagger) = 500 GeV^2$. Dashed lines represent $\tau \leq 1s$

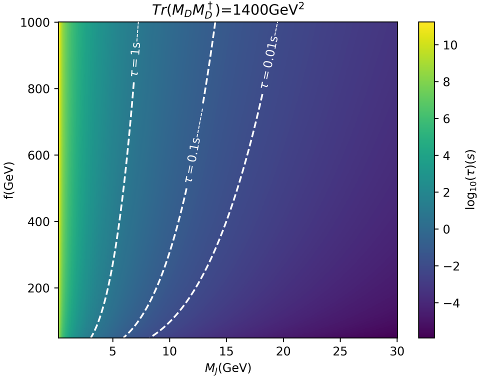

Figure: Majoron lifetime (in log scale) as a function of the mass and the vev for $(M_D M_D^\dagger) = 1400 GeV^2$. Dashed lines represent $\tau \leq 1s$

- Broader mass spectrum independent of the trace value! Just like for high τ values
- Which couple of variables can give us better control on the parameter space? $\rightarrow$ Correlations are needed!

Correlations

	$Tr(M_D M_D^\dagger)$	f	M_J
$Tr(M_D M_D^\dagger)$	1.000000e+00	2.373564e-15	-4.344185e-16
f	2.373564e-15	1.000000e+00	4.822399e-18
M_J	-4.344185e-16	4.822399e-18	1.000000e+00

- The most independent variables to perform this study are f and M_J! $\rightarrow$ Fix the trace

Conclusions

- Majoron is not expected to be found at collider experiments as the cross sections are too small.
- We have performed a premilinar study that gives us some mass values to scan the parameter space moving in regions that are still unconstrained.
- A set of independent variables to perform the scan has been found.
- Obtained $J \to \gamma\gamma$ coupling and mass values in the case of high τ could allow us to scan inside Mu3e sensitivity region.
- Higher mass values allow us to scan the rest of the parameter space.
- This study is a work in progress.