Type II Seesaw Leptogenesis

Neil D. Barrie

NDB, C. Han, H. Murayama, Phys. Rev. Lett. 128 (2022) 14, 141801; arxiv:2106.03381
NDB, C. Han, H. Murayama, JHEP 05 (2022) 160; arxiv:2204.08202
NDB, S. T. Petcov, JHEP 01 (2023) 001; arxiv:2210.02110

The Neutrino Masses and Seesaw Mechanisms

The origin of the observed non-zero neutrino masses remains unknown.

The types of Seesaw Mechanism, extend the SM by:

I At least two right-handed neutrinos,

II A $SU(2)_L$ triplet scalar,

III At least two $SU(2)_L$ fermion triplets.

None of these models, or mixtures, have been experimentally observed.

Matter-antimatter Asymmetry

Unknowns of neutrino sector could explain observed baryon asymmetry,

$$\eta = \frac{n_b - n_{\bar{b}}}{s} \simeq 8.5 \times 10^{-11}$$

- Equilibrium sphalerons can transfer an asymmetry from the leptons to baryons.
- Thermal Leptogenesis possible in Type I and III Seesaw Mechanisms.
- Type II Seesaw requires additional triplet scalar or RH neutrino.
- Consider other mechanisms for Leptogenesis:
  Affleck-Dine mechanism

Affleck-Dine Mechanism

Consider a complex field ϕ with a global $U(1)$ charge Q.

The charge density of ϕ is,

$$n_\phi = j^0 = 2Q\mathrm{Im}[\phi^\dagger \dot{\phi}] = Q\phi_r^2\dot{\theta} \ ,$$

where $\phi = \frac{1}{\sqrt{2}}\phi_r e^{i\theta}$.

Required ingredients:

- A scalar that is charged under some mixture of the global $U(1)_L$ or $U(1)_B$ symmetries,
- A small term in the Lagrangian that breaks this symmetry,
- A displaced vacuum value during the early universe.

Affleck-Dine Mechanism

Standard Case:

- Originally explored in the context of SUSY,
- Scalar superpartners carry B and L,
- Flat directions in scalar potential,
- Scalars displaced from potential minimum during inflationary epoch,
- Motion in complex phase via B and L violating interactions.

We want to instead consider ϕ to be the Triplet Higgs, giving,

- A minimal framework that does not require Supersymmetry, or new particles beyond the Triplet Higgs.
- A natural way to transfer the asymmetry from scalar to SM fermions.

The Type II Seesaw Mechanism

SM Higgs doublet and Triplet Higgs,

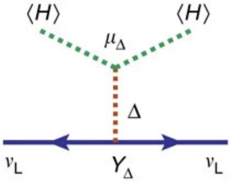
$$H = \begin{pmatrix} h^+ \\ h \end{pmatrix}, \quad \Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix} ,$$

Adds a neutrino yukawa coupling,

$$\mathcal{L}_{\rm yukawa} = -\frac{1}{2} y_{ij} \bar{L}_i^c \Delta L_j + h.c.$$

Making Δ doubly charged under $U(1)_L$ with lepton violation terms,

$$\mathcal{L}_{\not{L}} = \mu h^2 {\Delta^0}^* + \frac{1}{M_P}\left(\lambda_5 |h|^2 h^2 {\Delta^0}^* + \lambda_5' |\Delta^0|^2 h^2 {\Delta^0}^*\right) + h.c.$$



Nature Commun. 5 (2014) 5153

Triplet Higgs Phenomenology

- The neutral component of the triplet has a non-zero vev,

  $$\langle \Delta^0 \rangle \simeq \frac{\mu v_{\rm EW}^2}{2 m_\Delta^2} \ ,$$

  for $m_\Delta \gg v_{\rm EW}$. Able to generate the observed m_ν for $\mathcal{O}(1)\ {\rm GeV} > \langle \Delta^0 \rangle \gtrsim 0.05$ eV, while ensuring y_ν is perturbative.

- $m_\Delta \gtrsim 800$ GeV from searches for the doubly-charged Higgs.

- Lepton Flavour violating interactions.

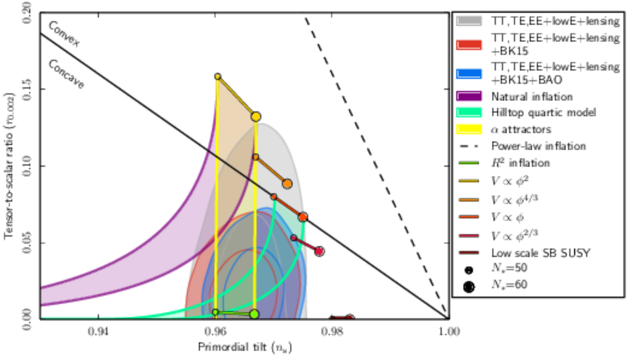
- Neutrinoless double beta decay,

- Vacuum stability.

To fulfill the third Affleck-Dine mechanism criteria we can take the Δ^0 to play a role in inflation.

Inflation

- Explains homogeneity, flatness, and primordial perturbations.
- Scalar field with a very flat potential, satisfying slow roll parameters.



Astron.Astrophys. 641 (2020) A10

Starobinsky inflation, matches well with current observional constraints.

Higgs Inflation

- The SM Higgs has been considered as a possible inflaton candidate,
- The Higgs potential is too steep to be consistent with observation,
- Require flattening by non-minimal coupling to gravity,

$$M_p^2 \left(1 + \frac{\xi_H |H|^2}{M_p^2}\right) R \ ,$$

- Gives the Starobinsky potential in Einstein frame,

$$U(\chi) = \frac{3}{4} m_S^2 M_p^2 (1 - e^{-\sqrt{2/3}\chi/M_p})^2 \ ,$$

where $m_S = \frac{\lambda_H M_p^2}{3\xi_H^2} \simeq 3 \cdot 10^{13}$ GeV, fitting observations.

Model Framework

Simple extension of the SM motivated by the unknown origins of Inflation, Baryogenesis, and the neutrino masses.

Explain by addition of a Triplet Higgs to SM,

- Two-field inflation (H and Δ), with Starobinsky-like observables,
- Lepton number phase motion, n_L, induced during inflationary phase,
- Baryon asymmetry via sphaleron redistribution,
- Neutrino masses via triplet higgs vacuum expectation value,
- Rich phenomenological implications.

Model Framework

Lagrangian:

$$\begin{aligned}\frac{\mathcal{L}}{\sqrt{-g}} &= -\frac{1}{2}M_P^2 R - (\xi_H|H|^2 + \xi_\Delta|\Delta|^2)R - g^{\mu\nu}(D_\mu H)^\dagger(D_\nu H) \\ &\quad -g^{\mu\nu}(D_\mu\Delta)^\dagger(D_\nu\Delta) - V(H,\Delta) + \mathcal{L}_{\mathrm{Yukawa}},\end{aligned}$$

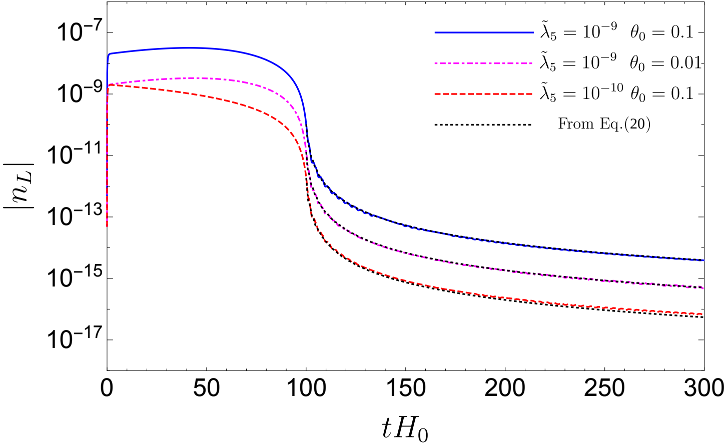
where in the unitary gauge,

$$\begin{aligned}V(h,\Delta^0) &= -m_H^2|h|^2 + m_\Delta^2|\Delta^0|^2 + \lambda_H|h|^4 + \lambda_\Delta|\Delta^0|^4 + \lambda_{H\Delta}|h|^2|\Delta^0|^2 \\ &\quad -\mu h^2\Delta^{0*} - \frac{1}{M_P}\left(\lambda_5|h|^2h^2\Delta^{0*} + \lambda_5'|\Delta^0|^2h^2\Delta^{0*}\right) + \dots\,,\end{aligned}$$

The inflationary trajectory is approximately fixed by,

$$\frac{\rho_H}{\rho_\Delta} \equiv \tan\alpha \simeq \sqrt{\frac{2\lambda_\Delta\xi_H - \lambda_{H\Delta}\xi_\Delta}{2\lambda_H\xi_\Delta - \lambda_{H\Delta}\xi_H}}\,.$$

The Lepton Number Density



Parameter Space

Parameter Requirements

- Successful Leptogenesis - $\eta_B \simeq \eta_B^{\mathrm{obs}}$,
- Neutrino masses - At least one satisfying $m_\nu \simeq y\frac{\mu v_{ew}^2}{2m_\Delta^2} \gtrsim 0.05$ eV ,
- Perturbative neutrino yukawa coupling - $y \lesssim 1$,
- Avoiding lepton number washout effects:

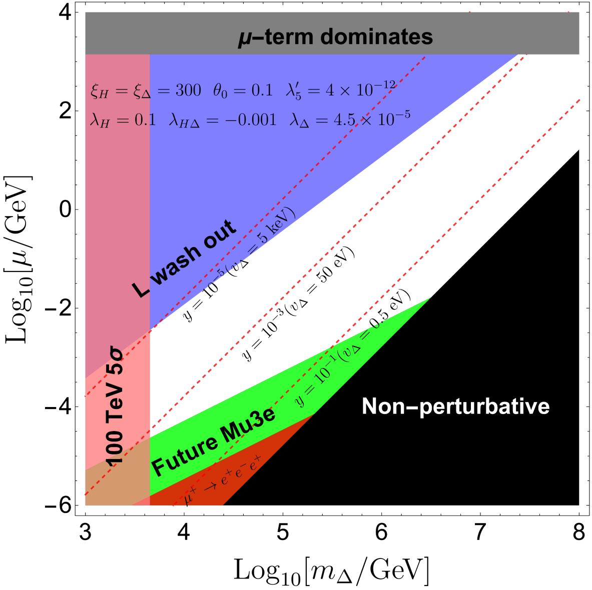
  $LL \leftrightarrow HH \Rightarrow m_\Delta < 10^{12}$ GeV,

  Combination of $LL \leftrightarrow \Delta$ and $HH \leftrightarrow \Delta \Rightarrow \langle \Delta^0 \rangle < 10\ \mathrm{keV}$,
- LHC triplet Higgs mass constraints - $m_\Delta \gtrsim 800$ GeV,
- Triplet Higgs VEV - $10\ \mathrm{keV} > \langle \Delta^0 \rangle \gtrsim 0.05$ eV .

Parameter Requirements

- Inflationary observables - n_s, r, N_e, $\frac{\lambda}{\xi^2} \simeq 5 \cdot 10^{-10}$; consistent with Starobinsky inflation predictions,
- Avoid unitarity violation during preheating - $\lambda\xi^2 < 300$,
- Sub-dominance of $\tilde{\lambda}_5$ term - $\frac{\tilde{\lambda}_5}{\xi^2} \ll 6 \cdot 10^{-11}\sqrt{\xi}e^{-\frac{\chi_0}{\sqrt{6}M_p}}$,
- Asymmetry conservation during oscillatory epoch - $\tilde{\mu} \lesssim \frac{m_S n_{L\mathrm{reh}}}{4\varphi^3_{\mathrm{reh}}}$,
- Isocurvature Perturbations,
- No stable Q-ball formation.

Allowed Parameter Space



Summary of Phenomenological Implications

- 100 TeV collider searches, probe up to $\sim$ 4 TeV at 5σ,
- v_Δ= 0.05 eV - 10 keV, decays dominantly into Leptonic channel,
- Lepton violating interactions constrained by future Mu3e searches,
- Neutrinoless double beta decay,
- Vacuum Stability,
- Non-Gaussianties and Isocurvature Perturbations,
- Possible gravitational wave implications - r by LiteBIRD, Preheating, and First Order Phase Transition.

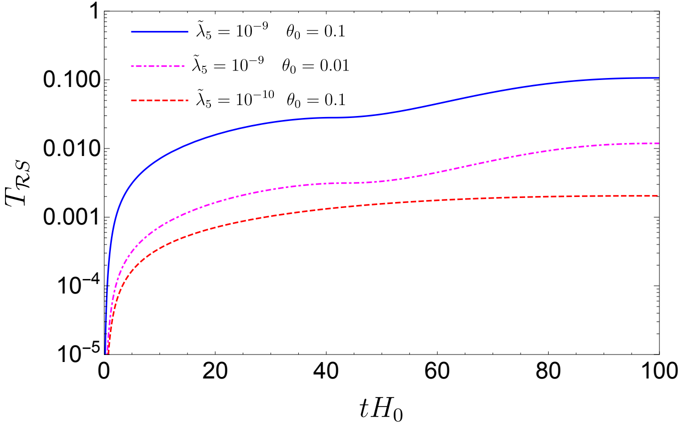
Conclusion

Simple extension of the SM by the triplet Higgs of the Type II Seesaw Mechanism, unified solution to multiple unknowns.

- Successful Type II Seesaw Leptogenesis scenario,
- Explains the observed neutrino masses,
- Inflationary measurements consistent with observations,
- Unique phenomenology to be probed at future experiments.

Thank You! :)

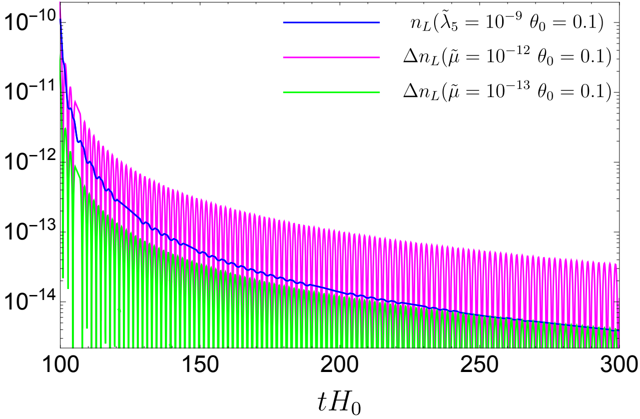
Parameter Requirements - Isocurvature Perturbations



The evolution of $T_{\mathcal{R}S}$ during inflation for different input parameters. The input parameters are fixed to $\xi = 300$ and $\lambda = 4.5 \cdot 10^{-5}$, with initial conditions $\chi_0 = 6.0 M_p$, $\dot{\chi}_0 = 0$, and $\dot{\theta}_0 = 0$ chosen.

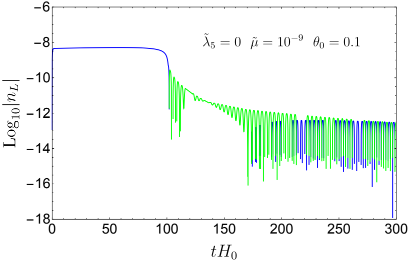
Parameter Requirements -

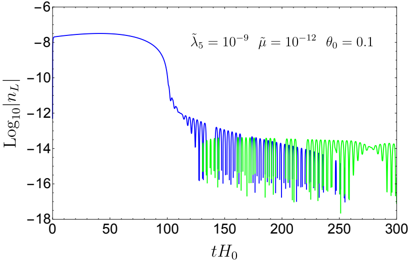
We must ensure that $\Delta n_L \lesssim n_L$ before reheating completed,

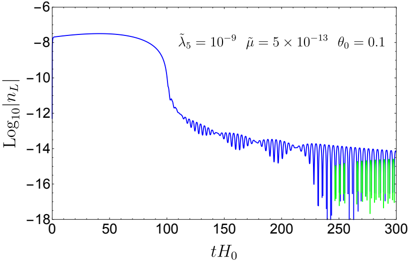


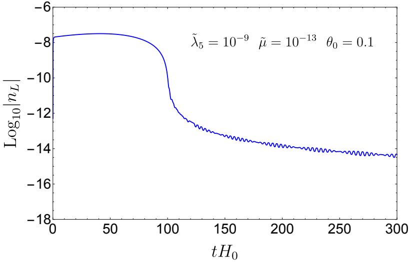
For these example parameters we require $\tilde{\mu} \lesssim 10^{-13} M_p$.

Parameter Requirements - $\tilde{\mu}$ upper bound









Lepton Flavour Violation Tests of Type II Seesaw Leptogenesis

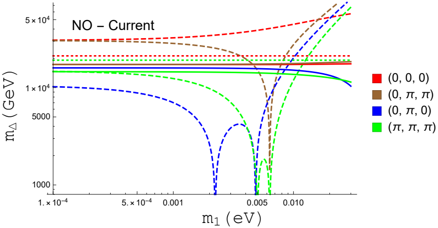
The charged components of the triplet Higgs leads to Lepton Flavour Violating decays.

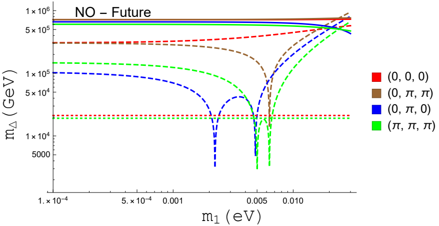
Experimentally important Lepton Flavour Violating decay processes:

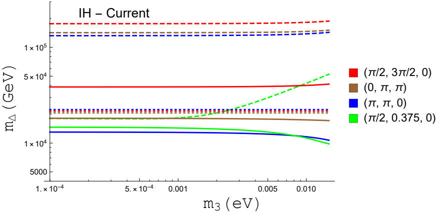
- $\mu \rightarrow e\gamma$,
- $\mu \rightarrow 3e$,
- μ to e conversion in nuclei.

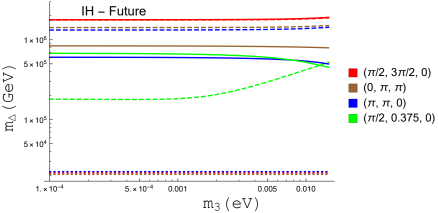
The branching ratios and conversion rate are each sensitive to the $\mathcal{CP}$ phases in the neutrino sector - ($\delta_{\mathcal{CP}}$, α_{21}, α_{31}) - mass ordering, and lightest neutrino mass.

Maximum Current and Future Sensitivities

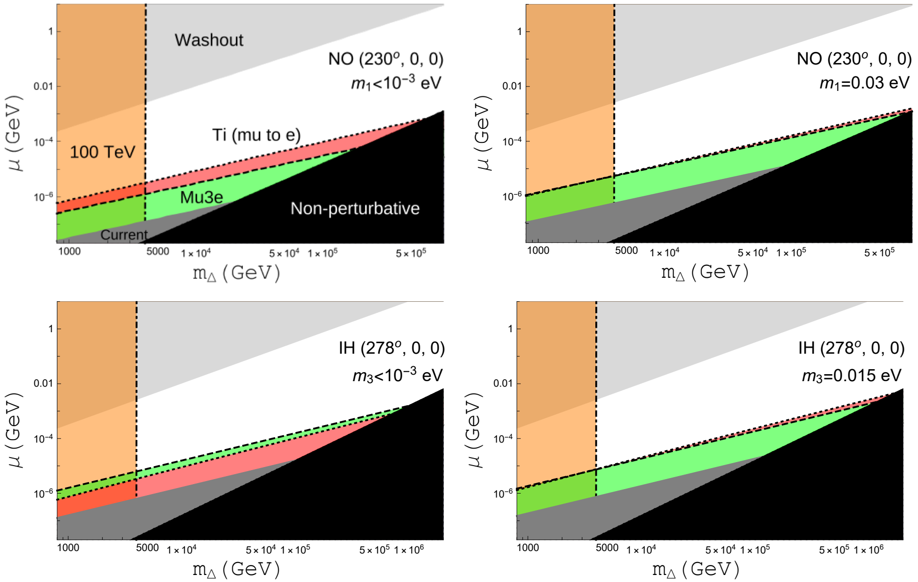




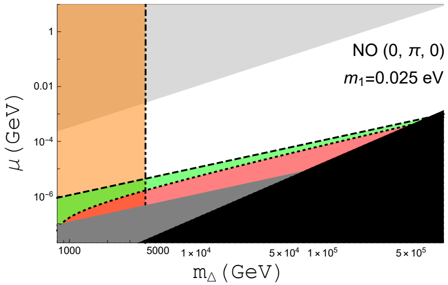


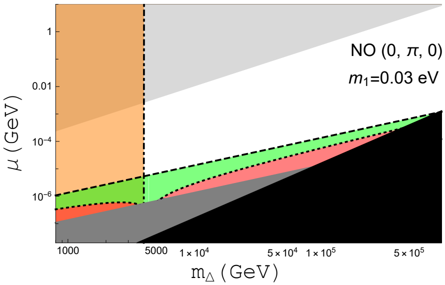


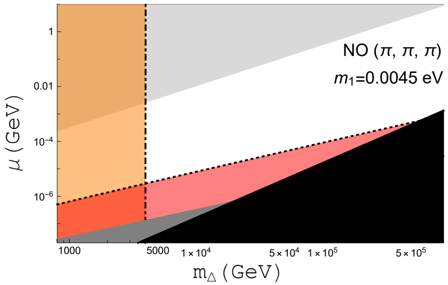
Projected Constraints from BFP

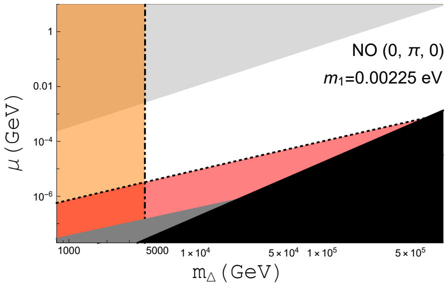


Suppression effects for NO scenario









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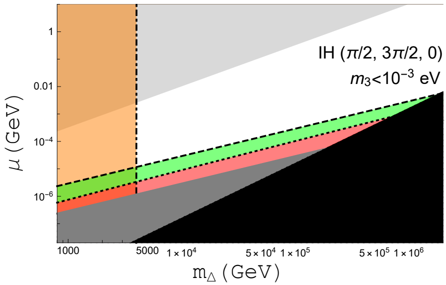
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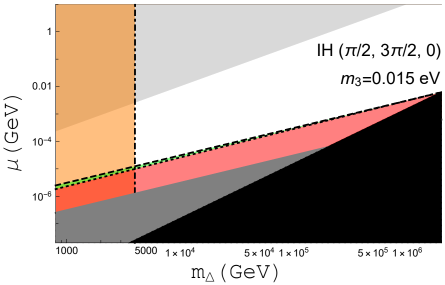
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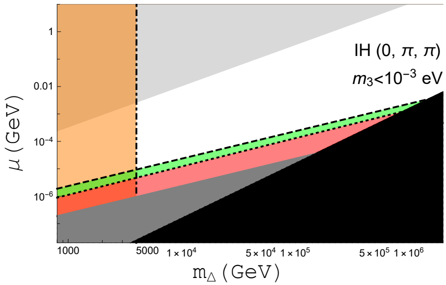
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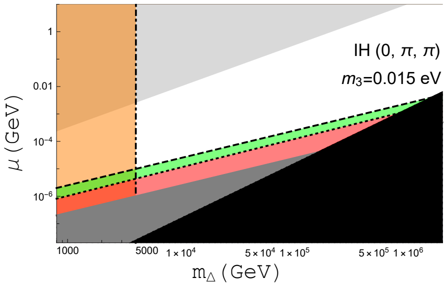
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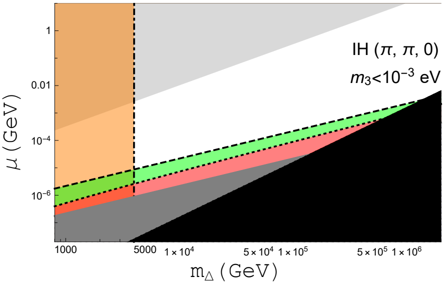
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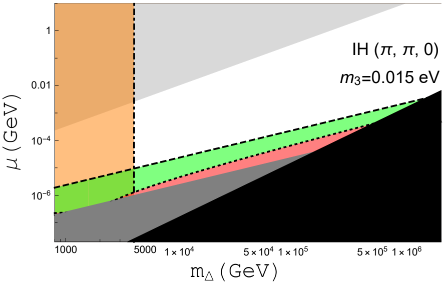
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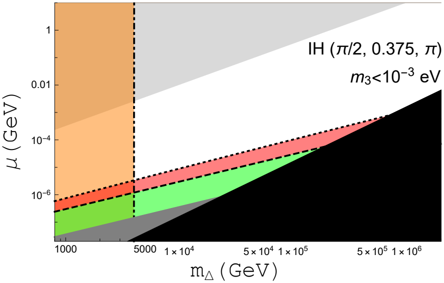
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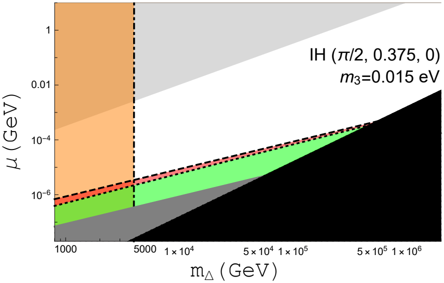
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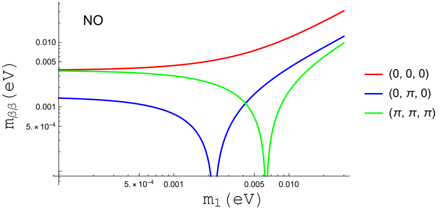
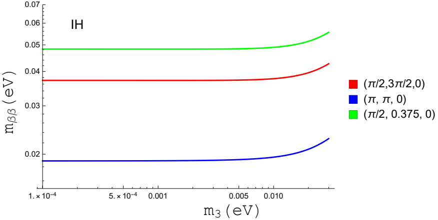
Neutrinoless Double Beta Decay

Neutrinoless double beta decay is a process predicted in models that contain Majorana mass terms for the neutrinos.

In the Type II Seesaw mechanism, the generated neutrino masses generated are of the Majorana type.





Provides a complementary test to the projected LFV experimental limits.