

# Type II Seesaw Leptogenesis

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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, 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  $\phi$  with a global  $U(1)$  charge  $Q$ .

The charge density of  $\phi$  is,

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

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  $\phi$  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,

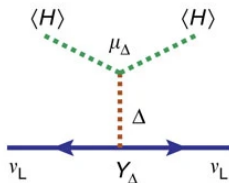
$$H = \begin{pmatrix} h^+ \\ h \end{pmatrix}, \quad \Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix},$$

Adds a neutrino yukawa coupling,

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

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

$$\mathcal{L}_\chi = \mu h^2 \Delta^{0*} + \frac{1}{M_P} \left( \lambda_5 |h|^2 h^2 \Delta^{0*} + \lambda'_5 |\Delta^0|^2 h^2 \Delta^{0*} \right) + h.c.$$



## Triplet Higgs Phenomenology

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

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

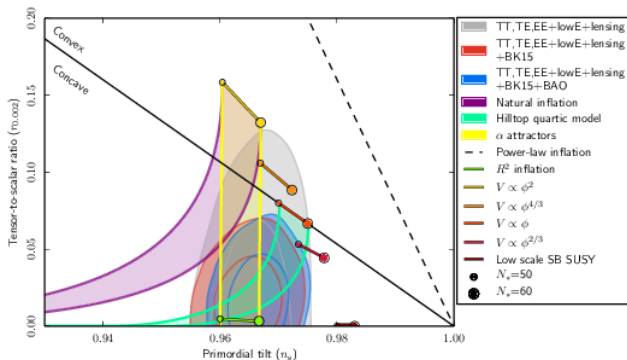
for  $m_\Delta \gg v_{EW}$ . Able to generate the observed  $m_\nu$  for  $\mathcal{O}(1) \text{ GeV} > \langle \Delta^0 \rangle \gtrsim 0.05 \text{ eV}$ , while ensuring  $y_\nu$  is perturbative.

- $m_\Delta \gtrsim 800 \text{ GeV}$  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  $\Delta^0$  to play a role in inflation.

# Inflation

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



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Starobinsky inflation, matches well with current observational 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  $m_S = \frac{\lambda_H M_p^2}{3\xi_H} \simeq 3 \cdot 10^{13}$  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  $\Delta$ ), 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.

## Inflationary Setting

Reparametrise in polar coordinates  $h \equiv \frac{1}{\sqrt{2}}\rho_H e^{i\eta}$ ,  $\Delta^0 \equiv \frac{1}{\sqrt{2}}\rho_\Delta e^{i\theta}$ , and

$$\rho_H = \varphi \sin \alpha, \quad \rho_\Delta = \varphi \cos \alpha, \quad \xi \equiv \xi_H \sin^2 \alpha + \xi_\Delta \cos^2 \alpha .$$

Giving the Lagrangian,

$$\begin{aligned} \frac{\mathcal{L}}{\sqrt{-g}} &= -\frac{1}{2}M_P^2 R - \frac{1}{2}\xi\varphi^2 R - \frac{1}{2}g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi \\ &\quad - \frac{1}{2}\varphi^2 \cos^2 \alpha g^{\mu\nu}\partial_\mu\theta\partial_\nu\theta - V(\varphi, \theta) , \end{aligned}$$

where

$$V(\varphi, \theta) = \frac{1}{2}m^2\varphi^2 + \frac{\lambda}{4}\varphi^4 + 2\varphi^3 \left( \tilde{\mu} + \frac{\tilde{\lambda}_5}{M_P}\varphi^2 \right) \cos \theta .$$

The inflationary trajectory is approximately fixed by,

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

and the Jordan frame inflaton is defined by  $\varphi$ .

## Assumptions

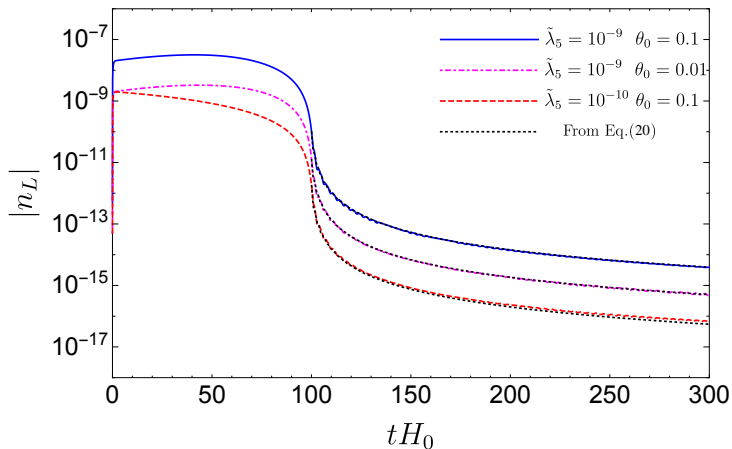
The inflaton is defined as  $\chi$  with potential,

$$U(\chi) = \frac{3}{4} m_S^2 M_P^2 \left( 1 - e^{-\sqrt{\frac{2}{3}}(\chi/M_P)} \right)^2 .$$

- Cubic term is suppressed relative to the Dim-5 term throughout inflation and reheating,
- Initial  $\theta_0 \neq 0$ ,
- The mixing angle  $\alpha$  is approximately constant,
- The Dim-5 term has a negligible effect on the inflationary trajectory.

Solve numerically and analytically to determine the generated  $\dot{\theta}$ .

# The Lepton Number Density



# Parameter Space

# Parameter Requirements

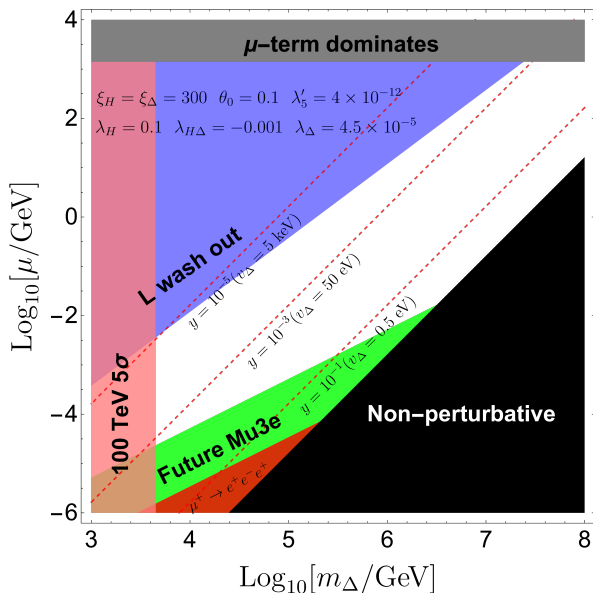
- Successful Leptogenesis -  $\eta_B \simeq \eta_B^{\text{obs}}$  ,
- Neutrino masses - At least one satisfying  $m_\nu \simeq y \frac{\mu v_{\text{ew}}^2}{2m_\Delta^2} \gtrsim 0.05 \text{ eV}$  ,
- Perturbative neutrino yukawa coupling -  $y \lesssim 1$  ,
- Avoiding lepton number washout effects:  
 $LL \leftrightarrow HH \Rightarrow m_\Delta < 10^{12} \text{ GeV}$ ,  
Combination of  $LL \leftrightarrow \Delta$  and  $HH \leftrightarrow \Delta \Rightarrow \langle \Delta^0 \rangle < 10 \text{ keV}$  ,
- LHC triplet Higgs mass constraints -  $m_\Delta \gtrsim 800 \text{ GeV}$ ,
- Triplet Higgs VEV -  $10 \text{ keV} > \langle \Delta^0 \rangle \gtrsim 0.05 \text{ eV}$  .

# 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 -  $\tilde{\mu} \lesssim \frac{m_S n_{L\text{reh}}}{4\varphi_{\text{reh}}^3}$  ,
- 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  $5\sigma$ ,
- $\nu_{\Delta} = 0.05$  eV - 10 keV, decays dominantly into Leptonic channel,
- Lepton violating interactions constrained by future Mu3e searches,
- Neutrinoless double beta decay,
- Vacuum Stability,
- Non-Gaussianities and Isocurvature Perturbations,
- Possible gravitational wave implications -  $r$  by LiteBIRD, Preheating, and First Order Phase Transition.

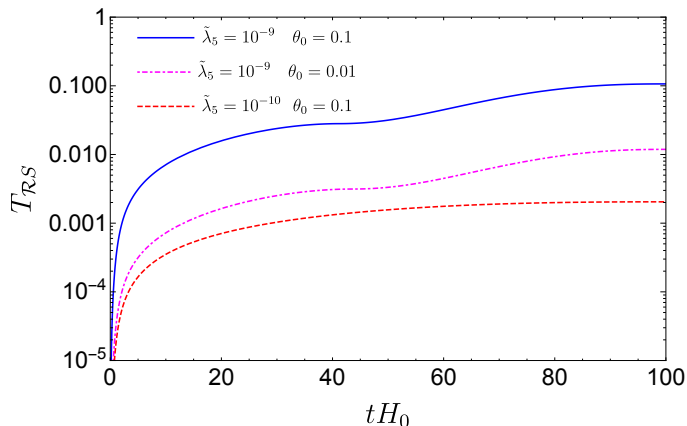
# Conclusion

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! :)

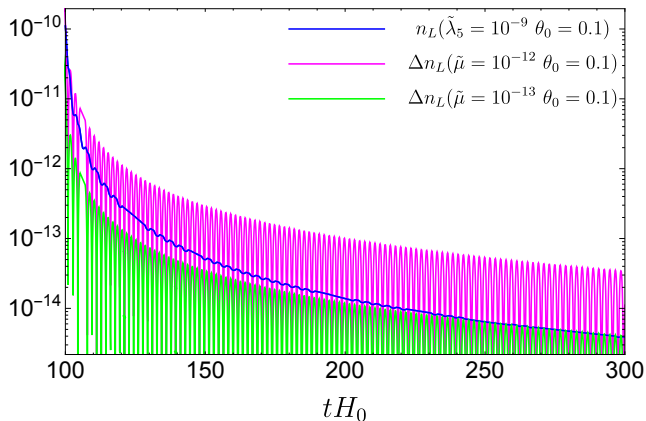
# Parameter Requirements - Isocurvature Perturbations



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

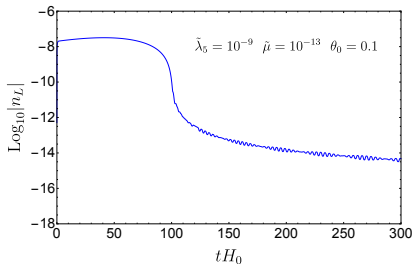
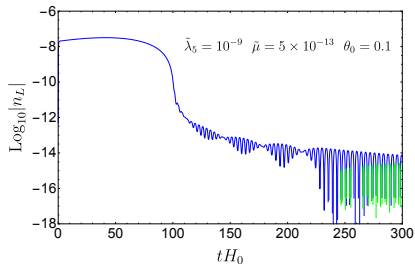
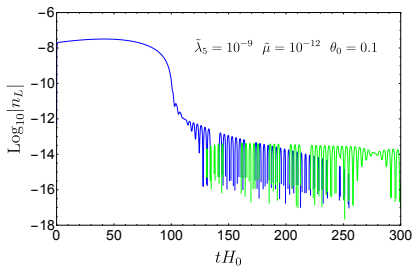
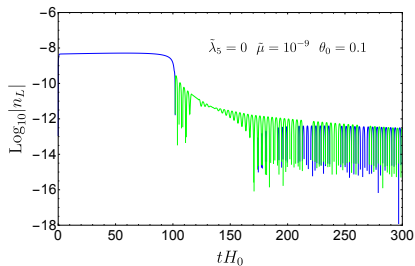
## Parameter Requirements -

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.

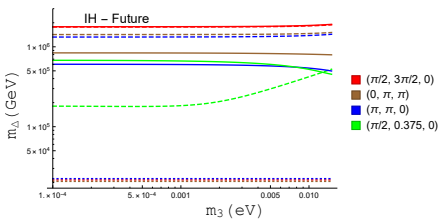
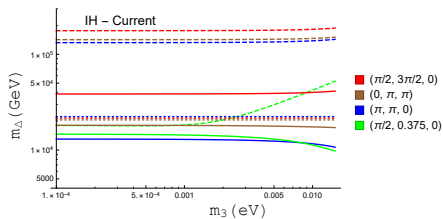
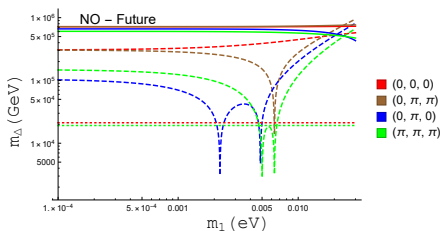
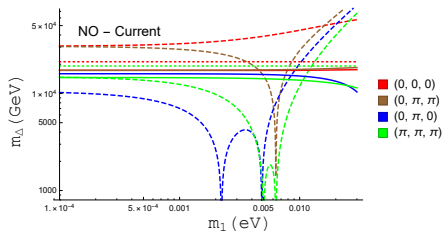
Experimentally important Lepton Flavour Violating decay processes:

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

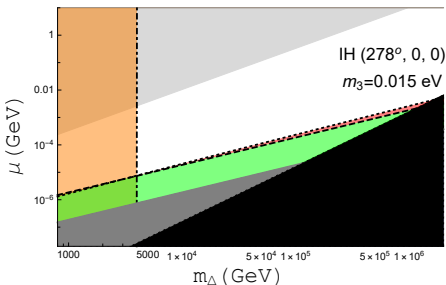
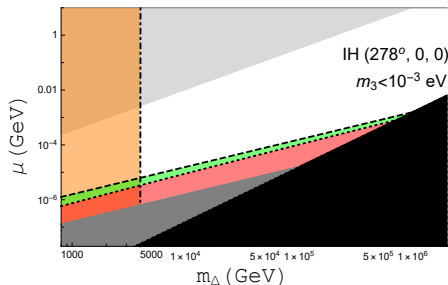
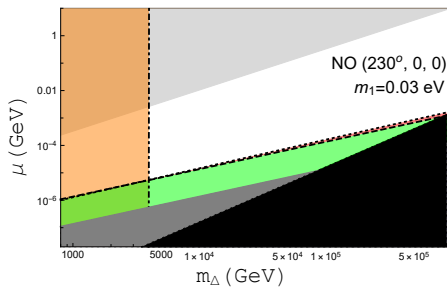
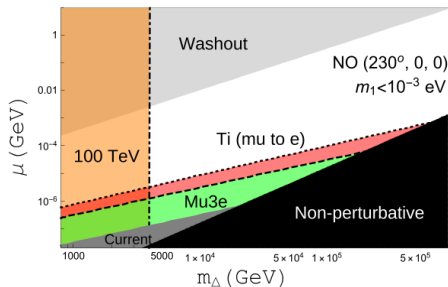
The branching ratios and conversion rate are each sensitive to the  $\mathcal{CP}$  phases in the neutrino sector -  $(\delta_{\mathcal{CP}}, \alpha_{21}, \alpha_{31})$  - mass ordering, and lightest neutrino mass.



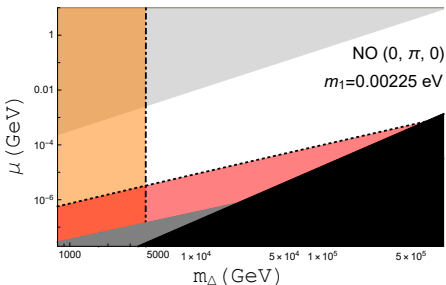
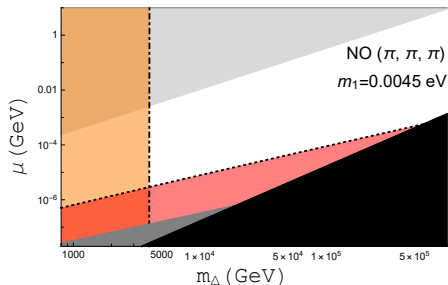
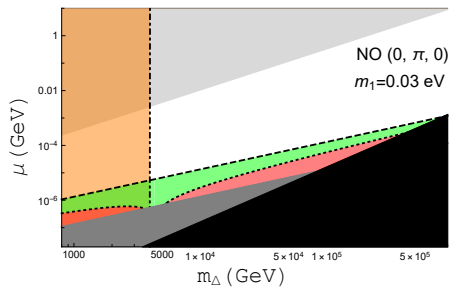
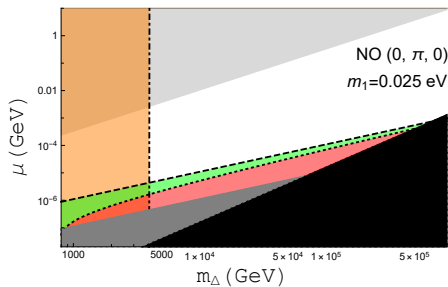
# Maximum Current and Future Sensitivities

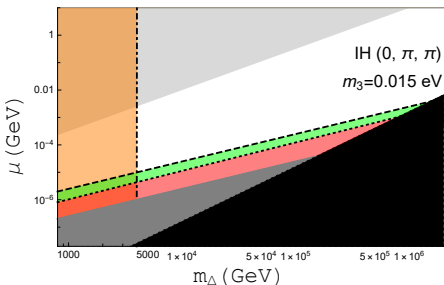
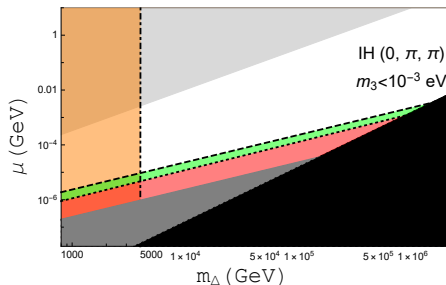
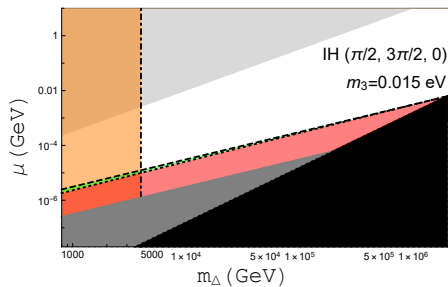
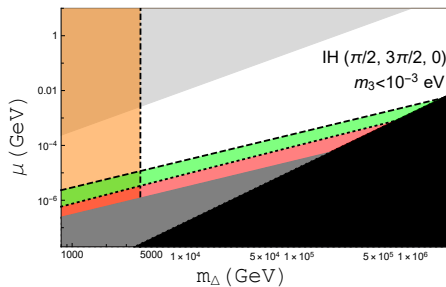


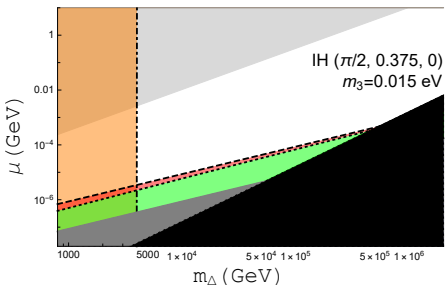
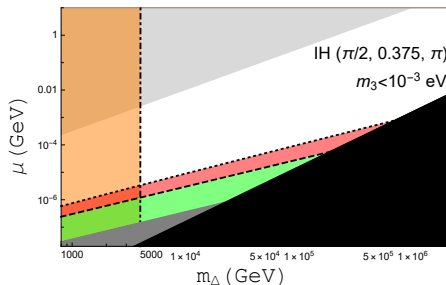
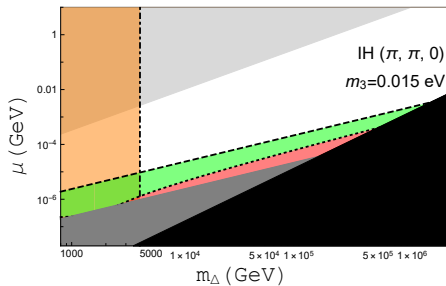
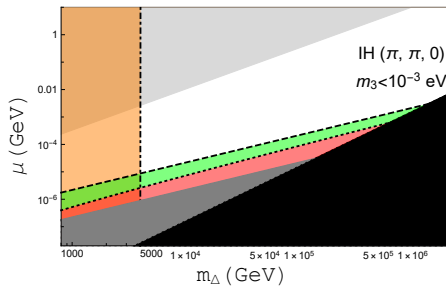
# Projected Constraints from BFP



# Suppression effects for NO scenario



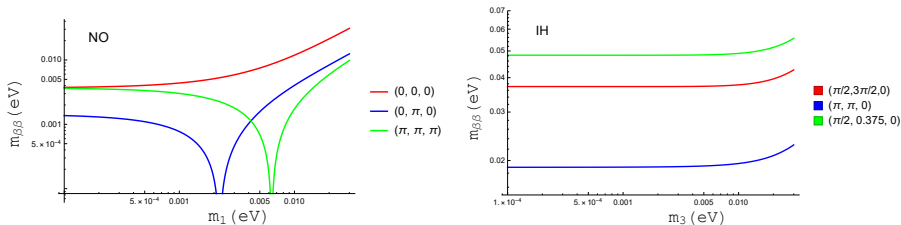




# Neutrinoless Double Beta Decay

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.