# Radiative Neutrino Mass with GeV Scale Majorana Dark Matter in Scotogenic Model

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06.12.2022

The Dark Side of the Universe DSU2022

# MOTIVATIONS

- The Scotogenic Model is among the simplest extension of the SM to generate neutrino mass and solve the Dark Matter (DM) problem.

- Neutrino mass generates radiatively with TeV Scale exotics and they are collider testable.

- Yukawa couplings are very important here, and are constrained from the DM relic density and LFV process observation bounds.

- We have searched for the maximum possible Yukawa couplings while satisfying the neutrino mass, LFVs and DM Relic density bounds simultaneously.

- For this purpose, we utilized a parameterization which reduces the effective parameters to only three and make our framework very predictive at the colliders.

# Model

$$L = L_{N_i} + L_H + L_\Phi + L_{int}$$

$$L_{N_i} = \frac{i}{2}\overline{N_i}\partial N_i + \frac{1}{2}(\text{M}_{N_i}\overline{N_i^c}N_i + h.c)$$

$$L_H = (D_\mu H)^\dagger(D^\mu H) - \mu^2 H^\dagger H + \lambda(H^\dagger H)^2$$

$$L_\Phi = (D_\mu \Phi)^\dagger(D^\mu \Phi) - \mu^2_{\ \phi}\Phi^\dagger\Phi - \lambda_\phi(\Phi^\dagger\Phi)^2$$

$$L_{int} = [-\lambda_1(H^\dagger H)(\Phi^\dagger\Phi) - \lambda_2|H^\dagger\Phi|^2 - \frac{\tilde{\lambda}}{2}[(H^\dagger\Phi)^2 + h.c.]$$

$$-(Y^{\alpha i}\overline{L_{\alpha_L}}\tilde{\Phi}N_i + h.c.)]$$

| | $L_i$ | $N_i$ | $H$ | $\Phi$ |
|---|---|---|---|---|
| $SU(2)_L$ | 2 | 1 | 2 | 2 |
| $U(1)_Y$ | $-\frac{1}{2}$ | 0 | $\frac{1}{2}$ | $\frac{1}{2}$ |
| $Z_2$ | + | - | + | - |

$$H = \begin{pmatrix} h^+ \\ \frac{v+h+i\eta}{\sqrt{2}} \end{pmatrix}, \quad \Phi = \begin{pmatrix} \phi^+ \\ \frac{\phi_s + i\phi_p}{\sqrt{2}} \end{pmatrix}$$

**Dark Matter**

**Scalar Dark Matter:**   **Fermion Dark Matter:**

$$\phi_s , \phi_p \qquad \text{Lightest } N_i$$

**We the VEVs:** $<H> = \frac{v}{\sqrt{2}}$ , **Where** $v = 246$ **GeV**   **and**   $<\Phi> = 0$   |   **We have taken Lightest RHN as DM**

$$m^2_{\phi_s} = \mu^2_\phi + \frac{1}{2}\left(\lambda_1 + \lambda_2 + \tilde{\lambda}\right)v^2 \qquad m^2_{\phi_p} = \mu^2_\phi + \frac{1}{2}\left(\lambda_1 + \lambda_2 - \tilde{\lambda}\right)v^2 \qquad m^2_{\phi^\pm} = \mu^2_\phi + \frac{1}{2}\lambda_1 v^2$$

# Neutrino Mass Generation

**The neutrino oscillation experiments performed over the last few decades provided imperative evidences for neutrino flavour oscillation, and hence non-zero neutrino masses and mixings.**
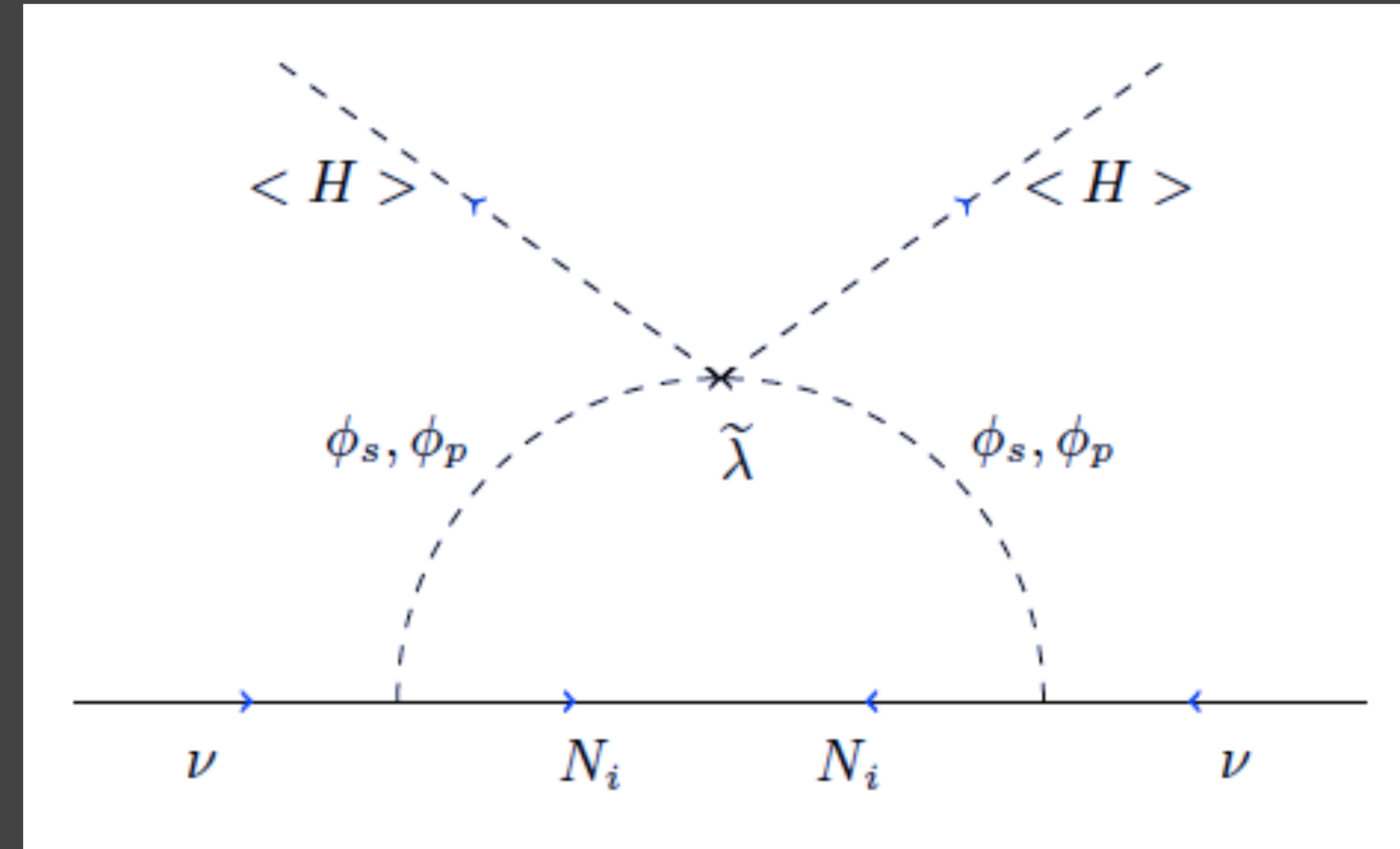
**Z2 symmetry prevents any Tree Level contribution in $\nu$-mass**

$$[M_\nu]^{\alpha\beta} = \sum_i \frac{Y^{\alpha i} Y^{\beta i} M_{N_i}}{32\pi^2} \left[ \frac{m^2_{\phi_s}}{m^2_{\phi_s} - M^2_{N_i}} \ln\left(\frac{m^2_{\phi_s}}{M^2_{N_i}}\right) - \frac{m^2_{\phi_p}}{m^2_{\phi_p} - M^2_{N_i}} \ln\left(\frac{m^2_{\phi_p}}{M^2_{N_i}}\right) \right]$$

**For**    $\tilde\lambda <<< 1$

$$[M_\nu]^{\alpha\beta} = \frac{|\tilde\lambda| v^2}{32\pi^2} \sum_i \frac{Y^{\alpha i} Y^{\beta i} M_{N_i}}{\bar m^2 - M^2_{N_i}} \left[ 1 - \frac{M^2_{N_i}}{\bar m^2 - M^2_{N_i}} \ln\left(\frac{\bar m^2}{M^2_{N_i}}\right) \right]$$

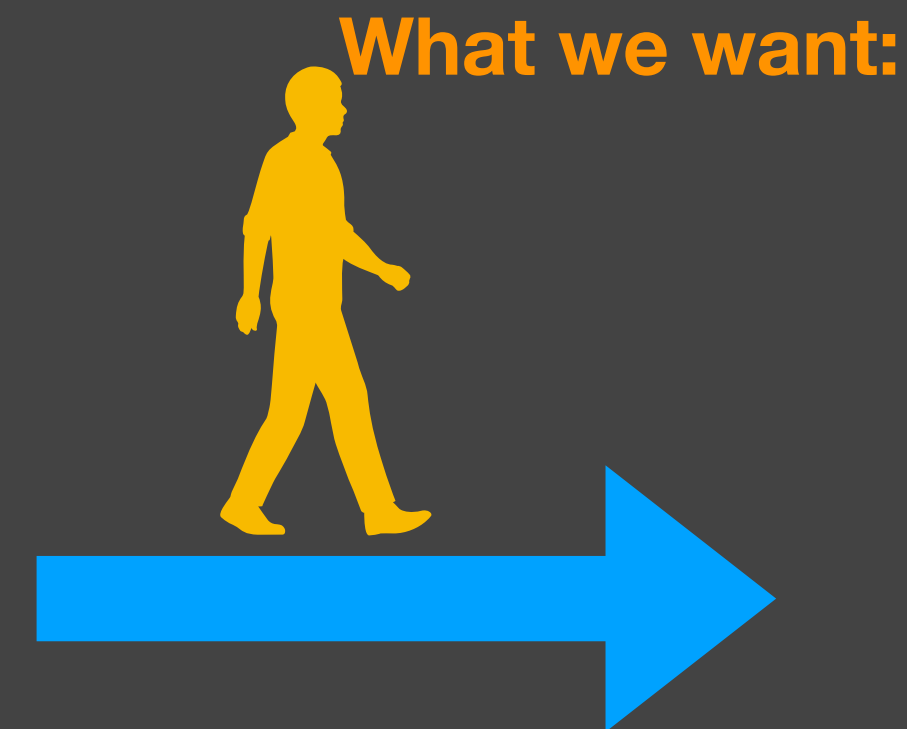**, Where**    $\bar m^2 = \dfrac{(m^2_{\phi_s} + m^2_{\phi_p})}{2}$

**The tininess of the neutrino mass can be achieved**

**Postulation of very small Yukawa couplings**

**Very massive particles in the loop**

**Tiny quadratic coupling $\tilde\lambda$**

**What we want:**

**Large Yukawa Couplings with TeV Scale Exotic Particles for greater detection prospects at the Colliders**

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# Parameterisation

**To make consistency of high energy theory to explain
the low energy neutrino oscillation experimental observations, the proper parameterisation is must**

**We can recast neutrino mass contribution from loop as:**

$$M_\nu \simeq \frac{|\tilde{\lambda}| v^2}{32\pi^2} \left( Y \mathcal{M}^{-1} Y^T \right)$$

$$[\mathcal{M}^{-1}]^{ij} = \delta^{ij} \frac{M_{N_i}}{\bar{m}^2 - M_{N_i}^2} \left[ 1 - \frac{M_{N_i}^2}{\bar{m}^2 - M_{N_i}^2} \ln\left( \frac{\bar{m}^2}{M_{N_i}^2} \right) \right]$$

**Diagonalization of $M_\nu$ to
a diagonal matrix $\tilde{M}_\nu$**

$$M_\nu = U \tilde{M}_\nu U^T$$

$$\tilde{M}_\nu = \text{diag}(m_1, m_2, m_3)$$

**Where, U is PMNS matrix**

$$\tilde{M}_\nu = \frac{|\tilde{\lambda}| v^2}{32\pi^2} U^\dagger Y \mathcal{M}^{-1} Y^T U^*$$

$$I_{3\times3} = R^T R$$

$R$ **is an orthogonal** $n \times 3$ **matrix and n is decided
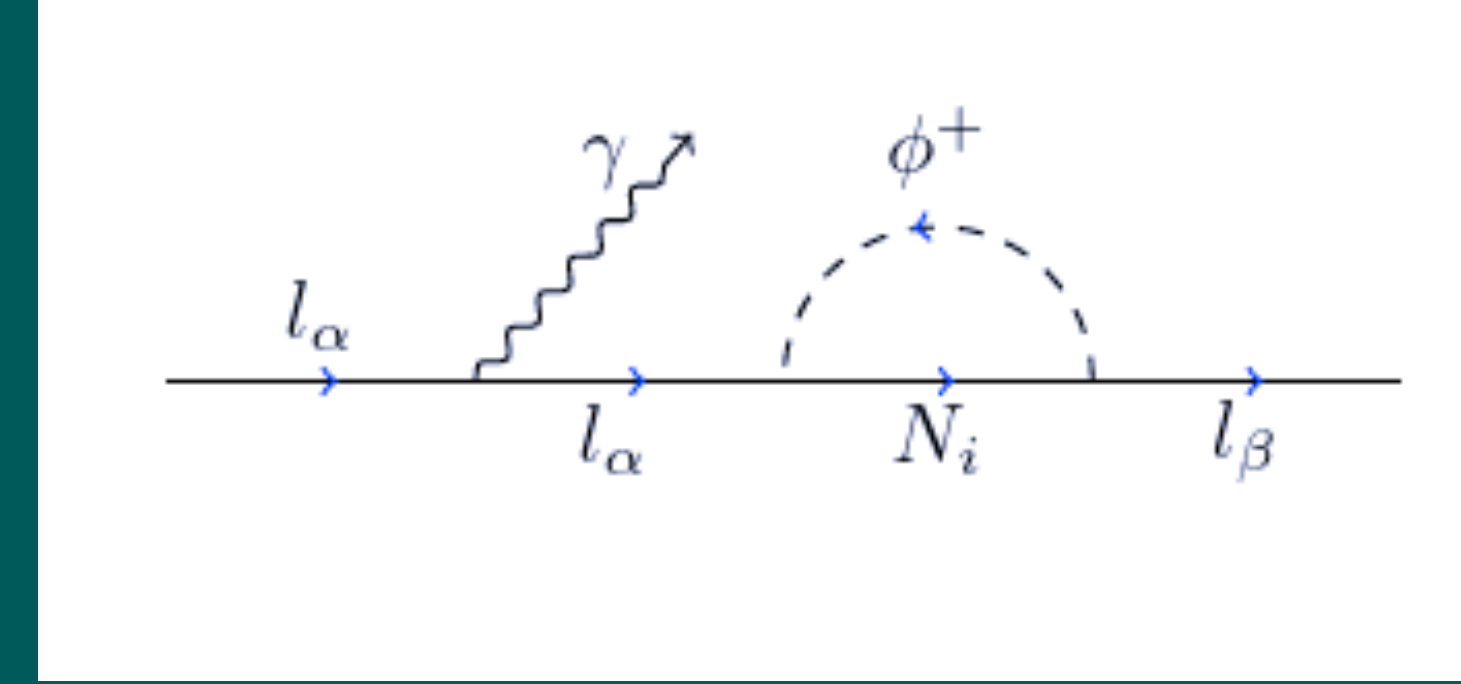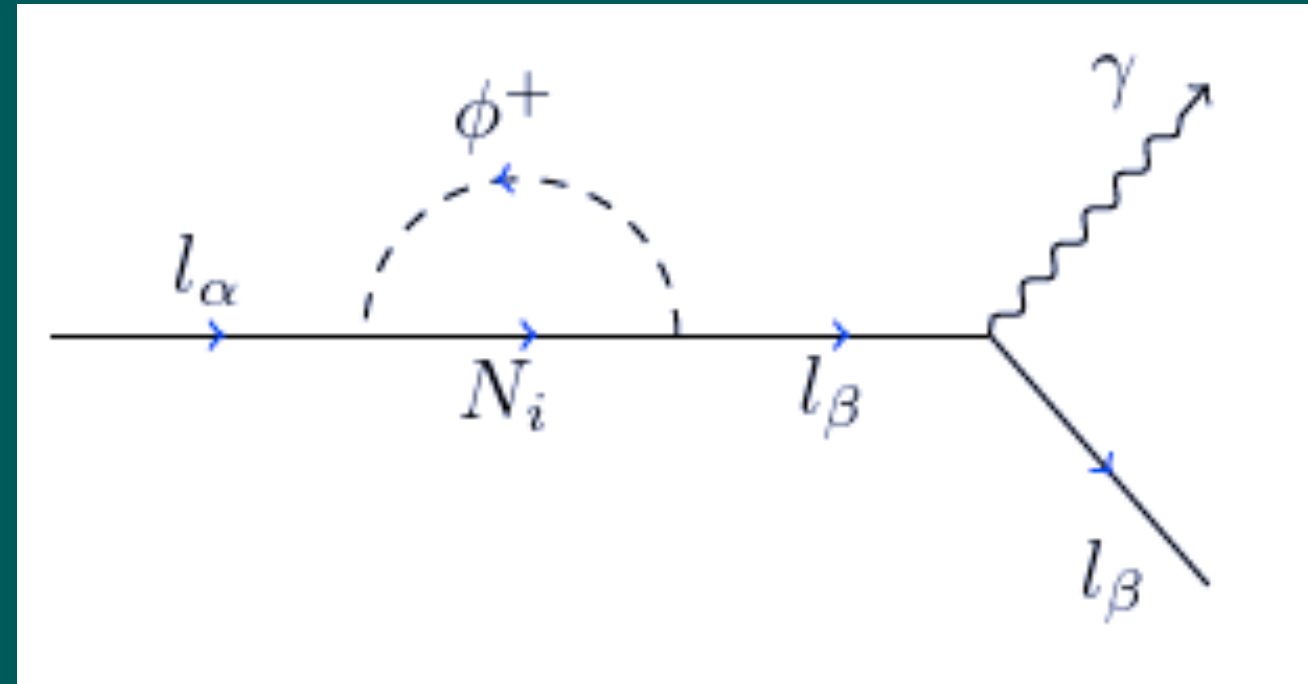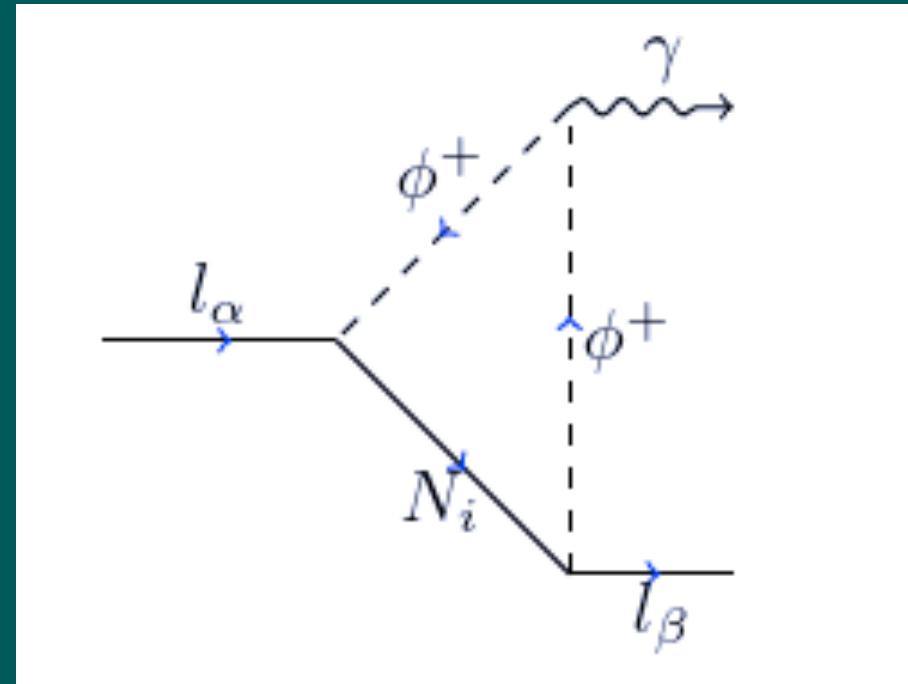with no .of Right handed neutrinos**

We get the Most general forms :

$$R^T = \frac{\sqrt{|\tilde{\lambda}|} v}{4\sqrt{2}\pi} \sqrt{\tilde{M}_\nu}^{-1} U^\dagger Y \sqrt{\mathcal{M}^{-1}}$$

$$Y = \frac{4\sqrt{2}\pi}{\sqrt{|\tilde{\lambda}|} v} U \sqrt{\tilde{M}_\nu} R^T \sqrt{\mathcal{M}}$$

# Lepton Flavour Violation and Conversion Rate

**LFV processes in the charged lepton sector arise at one loop level by exchange of new particles $\phi^{\pm}$ and $N_i$'s due to $\mathbb{Z}_2$ symmetry.**

$$\mathrm{BR}(l_\alpha \to l_\beta \gamma) = \frac{3\alpha_{em} v^4}{32\pi m_{\phi^{\pm}}^4} \left| \sum_{i=1}^{3} Y^{\alpha i} Y^{\beta i *} F_2 \left( \frac{M_{N_i}^2}{m_{\phi^{\pm}}^2} \right) \right|^2$$
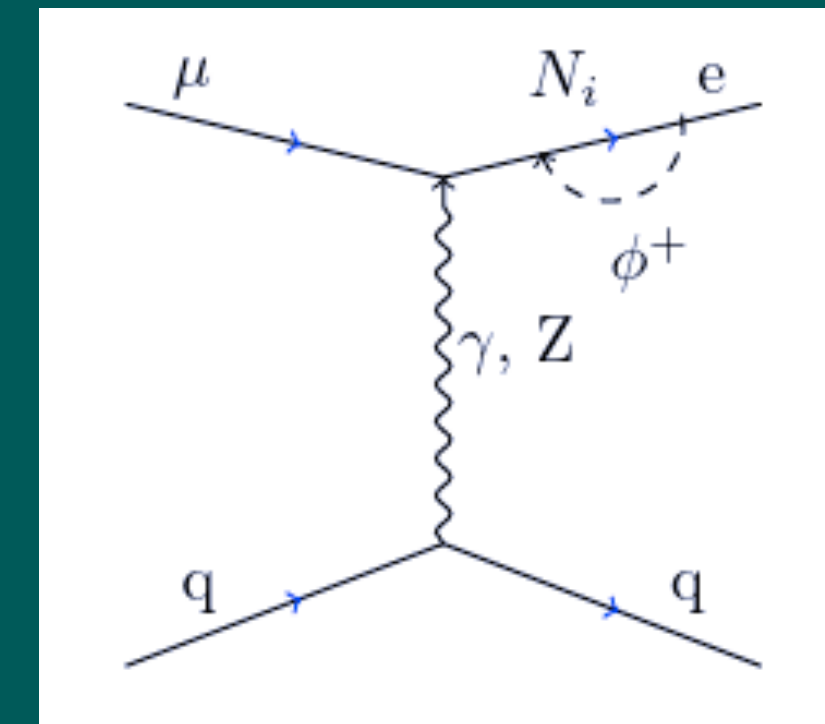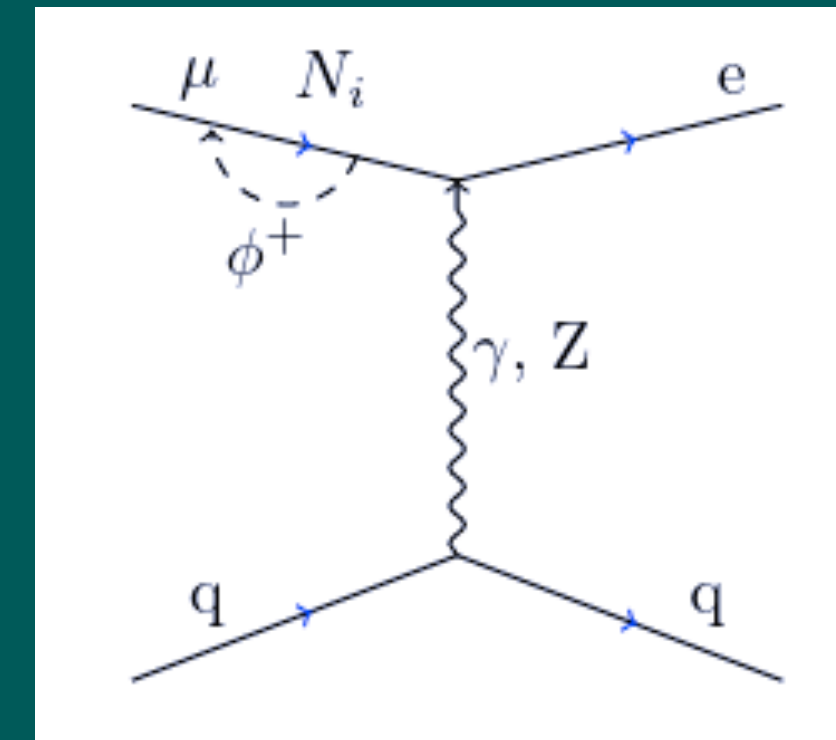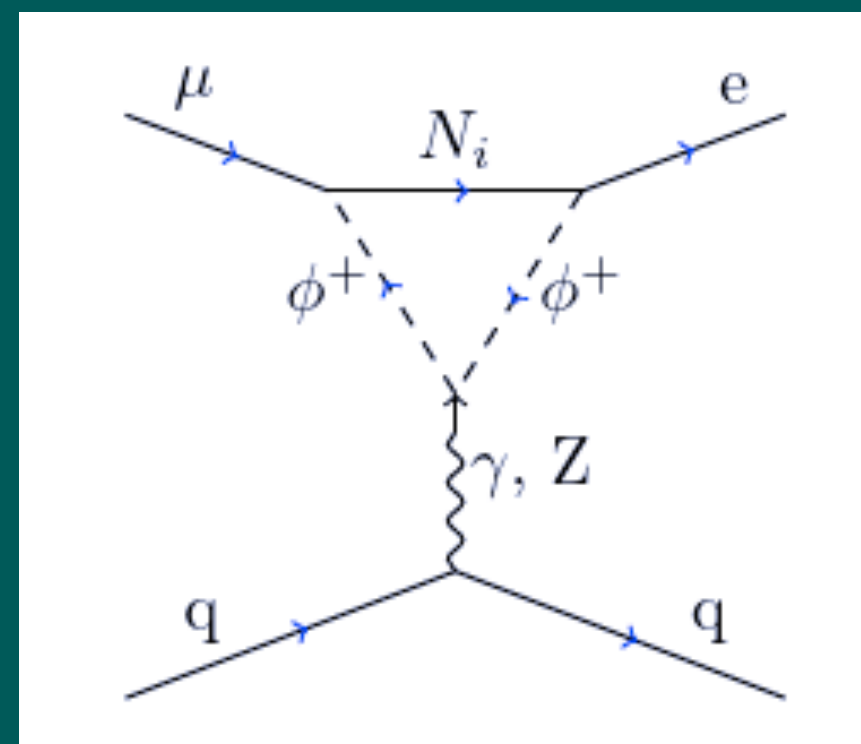
**Where,**
$$F_2(z) = \frac{1 - 6z + 3z^2 + 2z^3 - 6z^2 lnz}{6(1-z)^4}$$

**The Conversion of $(\mu - e)$ in nuclei Also take place through one loop processes**

**Being unable to detect some signal at the experiments , severe experimental bounds put over theoretical predictions**

**Among these experimental bounds, BR(μ → eγ) and CR(μ -e, Au) put the most severe limits on the parameter space of the model**
**( $4.2 \times 10^{-13}$ and $7.0 \times 10^{-13}$ )**

# Issues and Remedy

**The most severe problem is suppressing the LFV .**

**LFV BR is mainly controlled by off-diagonal parts of the multiplication of Yukawa couplings**

$$Y = \frac{4\sqrt{2}\pi}{\sqrt{|\tilde{\lambda}|}\, v} U \sqrt{\tilde{M}_\nu} R^T \sqrt{\mathscr{M}}$$

**The LFV bounds can be minimised by**

$$\mathrm{BR}(l_\alpha \to l_\beta \gamma) = \frac{3\alpha_{em} v^4}{32\pi m_{\phi^\pm}^4} \left| \sum_{i=1}^{3} Y^{\alpha i} Y^{\beta i*} F_2\left(\frac{M_{N_i}^2}{m_{\phi^\pm}^2}\right) \right|^2$$

$$U \left( \sqrt{\tilde{M}_\nu} R^T \sqrt{\mathscr{M}} \sqrt{F_2} \right) \left( \sqrt{F_2} \sqrt{\mathscr{M}} R^* \sqrt{\tilde{M}_\nu} \right) U^\dagger = I$$

**and the special choice**

**Taking** $\quad \sqrt{F_2}\sqrt{\mathscr{M}} R^* \sqrt{\tilde{M}_\nu} = X \qquad R = I \qquad \Longrightarrow \qquad X = \sqrt{C} I$

**IFF :** $\quad F_{21} \mathscr{M}_{11} \tilde{M}_{\nu 11} = F_{22} \mathscr{M}_{22} \tilde{M}_{\nu 22} = F_{23} \mathscr{M}_{33} \tilde{M}_{\nu 33} = C \qquad$ **, Where $C$ is some constant**

**The best outcome of this parameterisation is this:**

**We have only 3 parameters for whole physical phenomenology**

The lightest $N_i$'s mass: $M_{N_i}$

The lightest physical neutrino mass $m_i$

The value of $\tilde{\lambda}$

# Exotic Parameter Space

**The region below red dashed line is allowed by DM relic density**

**The points on the red line satisfy all the bounds ranging from Dark relic density, CR($\mu - e, Au$) and perturbativity**
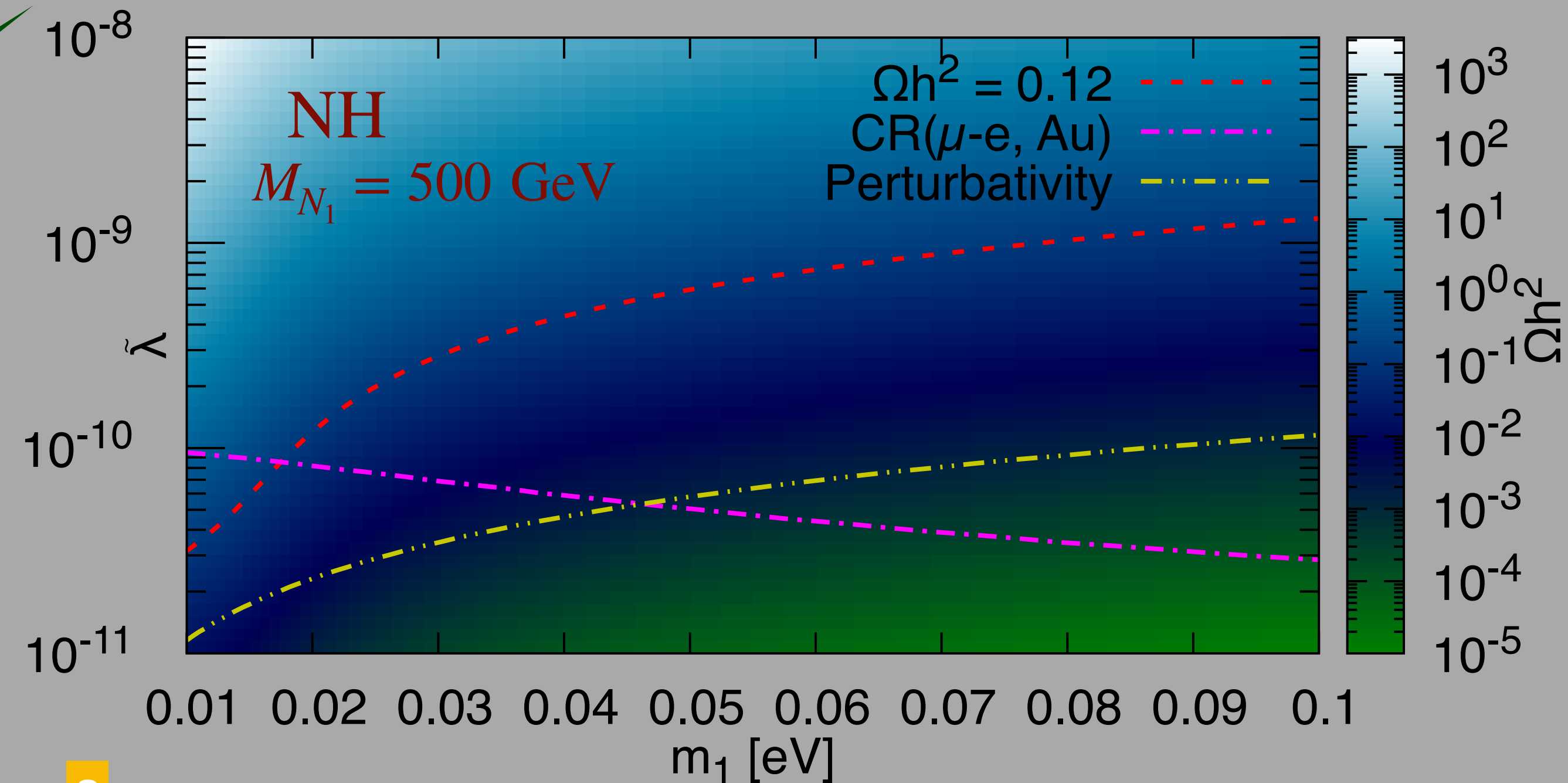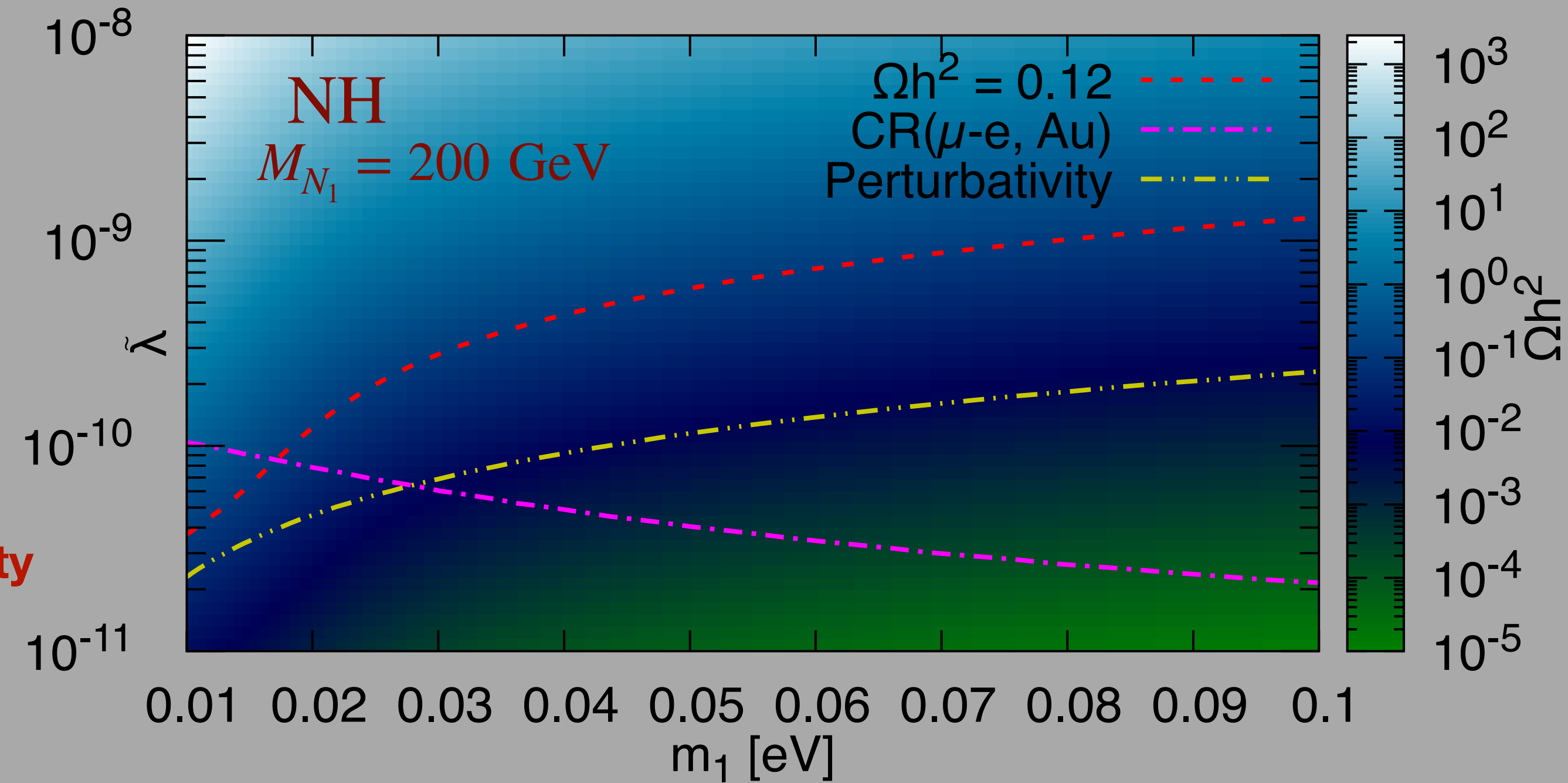
For these parameter scans in Normal Hierarchy,
We have fixed $M_{N_1}$ fixed and masses of $M_{N_2}, M_{N_3}$ calculated

The parameters for these scans:

$\mu_\phi = 1$ TeV

$\lambda_1 = 0.004$

$\lambda_2 = 0.005$



NH
$M_{N_1} = 200$ GeV

$\Omega h^2 = 0.12$
CR($\mu$-e, Au)
Perturbativity



NH
$M_{N_1} = 500$ GeV

$\Omega h^2 = 0.12$
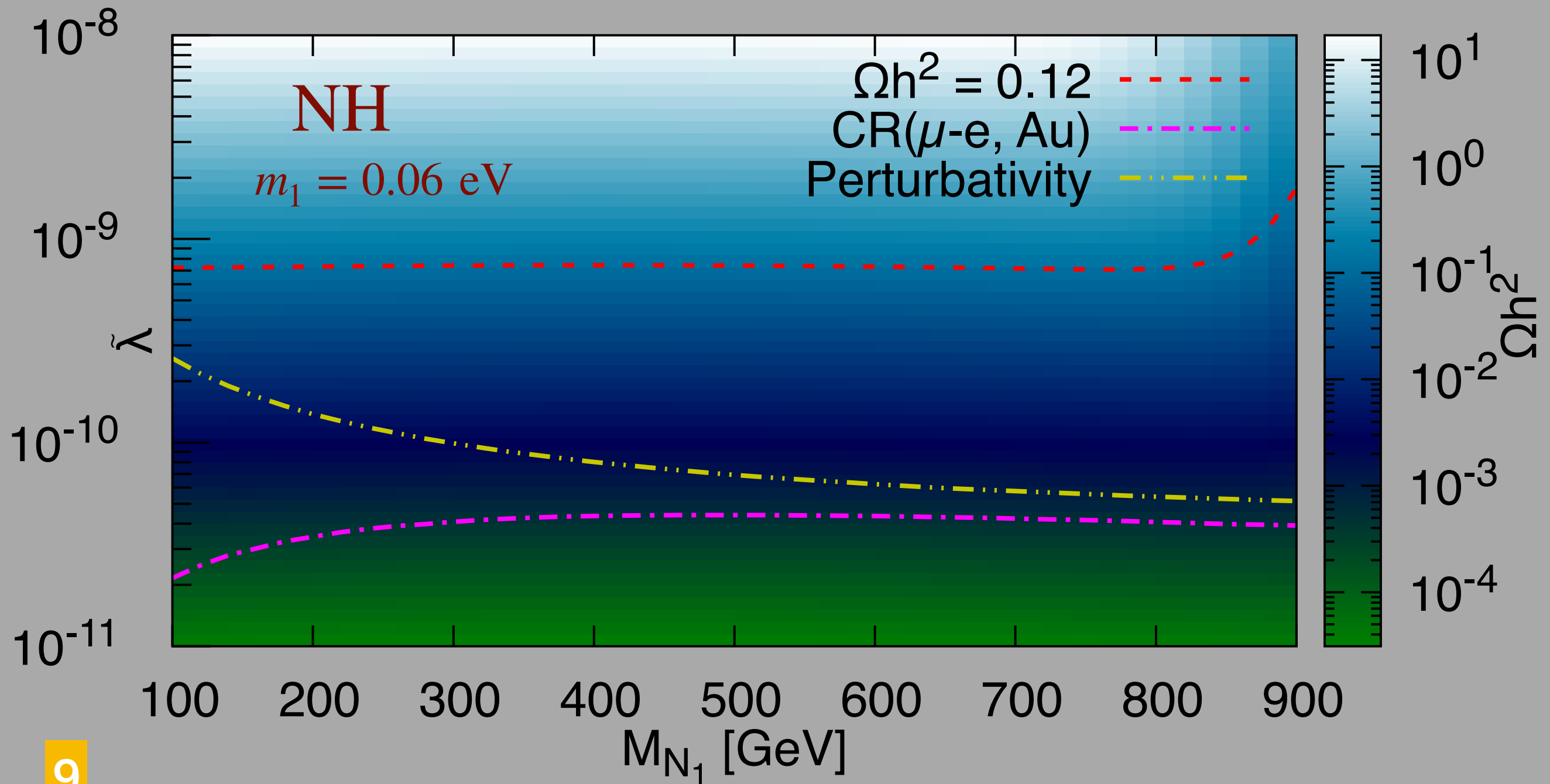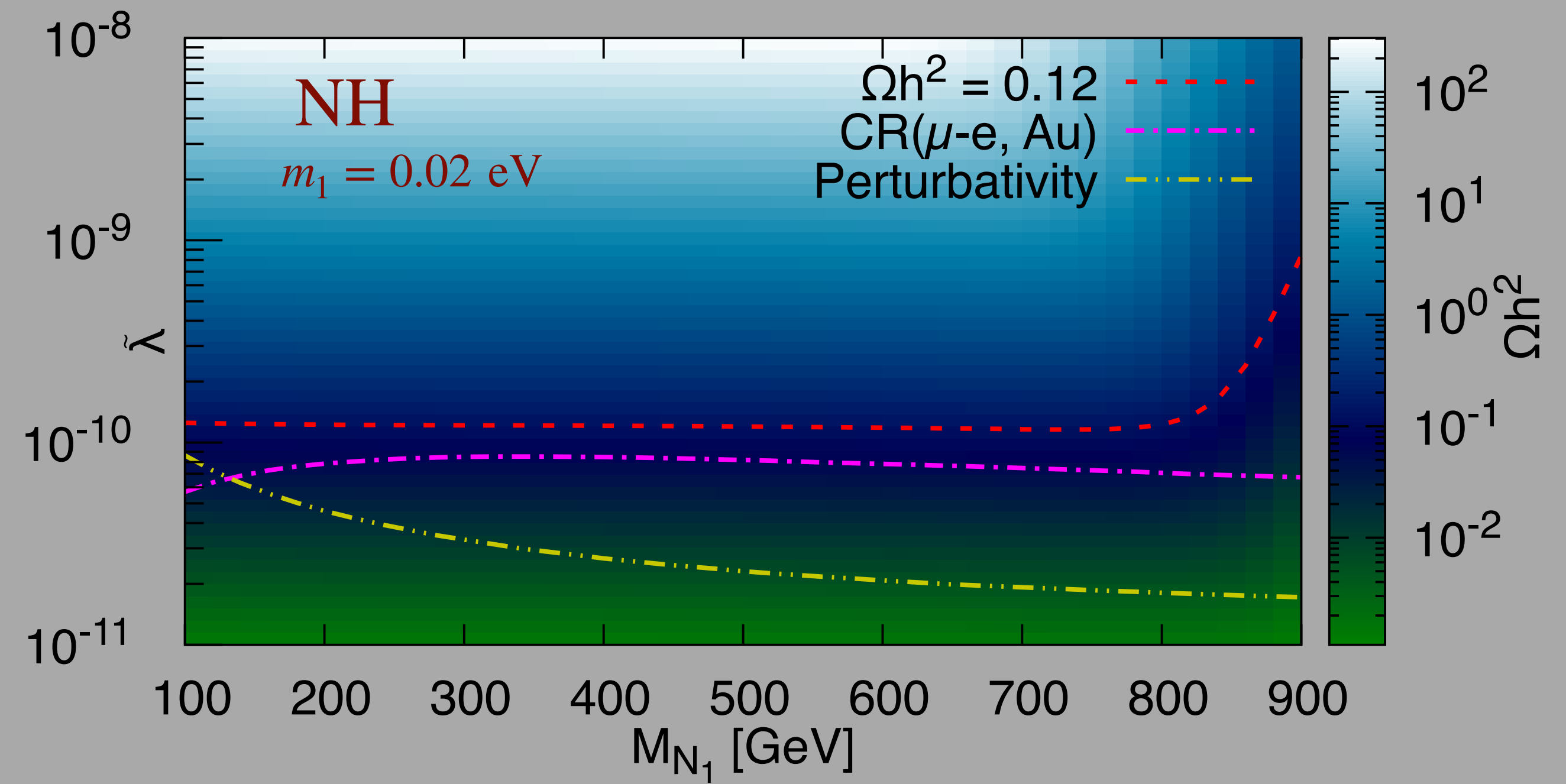CR($\mu$-e, Au)
Perturbativity

The constrained parameter space in $(M_{N_1} - \tilde{\lambda})$ plane is depicted as

Red dashed line points are the points satisfying the LFV as well as DM relic Density constraints simultaneously.

Here, We have considered only Normal Hierarchy, Because Inverted Hierarchy have not many points

With increasing the lightest neutrino mass, the value of required $\tilde{\lambda}$ also Increases.

The parameters for these scans:
$\mu_\phi = 1$ TeV
$\lambda_1 = 0.004$
$\lambda_2 = 0.005$



NH
$m_1 = 0.02$ eV
$\Omega h^2 = 0.12$
CR($\mu$-e, Au)
Perturbativity



NH
$m_1 = 0.06$ eV
$\Omega h^2 = 0.12$
CR($\mu$-e, Au)
Perturbativity

# Bench Mark Points

To search quantitatively, we have taken three Benchmark points:

| BP1 (NH) | BP2 (NH) | BP3 (IH) |
|---|---|---|
| | $\mu_\phi = 1$ TeV, $\lambda_1 = 0.004$, $\lambda_2 = 0.005$ | |
| $m_1 = 2.19 \times 10^{-11}$, $M_{N_1} = 200$ GeV $\widetilde{\lambda} = 1.5 \times 10^{-10}$ | $m_1 = 3.02 \times 10^{-11}$, $M_{N_1} = 500$ GeV $\widetilde{\lambda} = 2.84 \times 10^{-10}$ | $m_3 = 1.0 \times 10^{-10}$, $M_{N_3} = 200$ GeV $\widetilde{\lambda} = 3.68 \times 10^{-10}$ |
| $M_{N_2} = 214.14$ GeV, $M_{N_3} = 496.02$ GeV $Y = \begin{pmatrix} 1.74 & -0.98 & 0.5 \\ 1.07 & 1.24 & -1.25 \\ 0.32 & 1.46 & 1.73 \end{pmatrix}$ | $M_{N_2} = 517.89$ GeV, $M_{N_3} = 916$ GeV $Y = \begin{pmatrix} 1.05 & -0.59 & 0.31 \\ 0.65 & 0.76 & -0.76 \\ 0.21 & 0.95 & 1.12 \end{pmatrix}$ | $M_{N_1} = 542.06$ GeV, $M_{N_2} = 542.3$ GeV $Y = \begin{pmatrix} 2.68 & -1.51 & 0.78 \\ 1.64 & 1.92 & -1.93 \\ 0.39 & 1.79 & 2.11 \end{pmatrix}$ |

| Observables | Experimental limits | Estimate for BP1 | Estimate for BP2 | Estimate for BP3 |
|---|---|---|---|---|
| $\mathrm{BR}(\mu^+ \to e^+\gamma)$ | $4.2 \times 10^{-13}$ [27] | $1.03 \times 10^{-19}$ | $9.86 \times 10^{-22}$ | $3.84 \times 10^{-20}$ |
| $\mathrm{BR}(\tau^+ \to e^+\gamma)$ | $3.3 \times 10^{-8}$ [28] | $4.43 \times 10^{-20}$ | $3.76 \times 10^{-22}$ | $9.16 \times 10^{-23}$ |
| $\mathrm{BR}(\tau^+ \to \mu^+\gamma)$ | $4.4 \times 10^{-8}$ [28] | $7.46 \times 10^{-20}$ | $6.58 \times 10^{-22}$ | $7.48 \times 10^{-21}$ |
| $\mathrm{BR}(\mu^+ \to e^+e^-e^+)$ | $1.0 \times 10^{-12}$ [29] | $1.04 \times 10^{-12}$ | $7.75 \times 10^{-13}$ | $4.83 \times 10^{-10}$ |
| $\mathrm{BR}(\tau^+ \to e^+e^-e^+)$ | $2.7 \times 10^{-8}$ [30] | $3.48 \times 10^{-13}$ | $1.15 \times 10^{-13}$ | $1.21 \times 10^{-10}$ |
| $\mathrm{BR}(\tau^+ \to \mu^+\mu^-\mu^+)$ | $2.1 \times 10^{-8}$ [30] | $3.51 \times 10^{-11}$ | $4.49 \times 10^{-12}$ | $1.19 \times 10^{-9}$ |
| $\mathrm{CR}(\mu - e, Pb)$ | $4.6 \times 10^{-11}$ [31] | $1.62 \times 10^{-13}$ | $3.85 \times 10^{-14}$ | $5.99 \times 10^{-13}$ |
| $\mathrm{CR}(\mu - e, Ti)$ | $1.7 \times 10^{-12}$ [32] | $2.1 \times 10^{-13}$ | $4.99 \times 10^{-14}$ | $7.76 \times 10^{-13}$ |
| $\mathrm{CR}(\mu - e, Au)$ | $7.0 \times 10^{-13}$ [33] | $1.72 \times 10^{-13}$ | $4.09 \times 10^{-14}$ | $6.36 \times 10^{-13}$ |
| $\mathrm{CR}(\mu - e, Al)$ | $1.0 \times 10^{-16}$ [34, 35] | $1.16 \times 10^{-13}$ | $2.77 \times 10^{-14}$ | $4.31 \times 10^{-13}$ |
| $\Omega_{\mathrm{DM}}h^2$ | $0.118$ [36] | $0.118$ | $0.118$ | $0.118$ |

# Collider Searches:

**Production Cross-Section :**

We have plotted the production cross-section of different processed at the colliders with varying the lightest neutrino mass.

$\tilde{\lambda}$ **is varying in such a way to keep  DM relic density  satisfied.**

The mass of the lightest right handed neutrino $M_{N_1}$ is held fixed , But other RHN masses have been calculated.
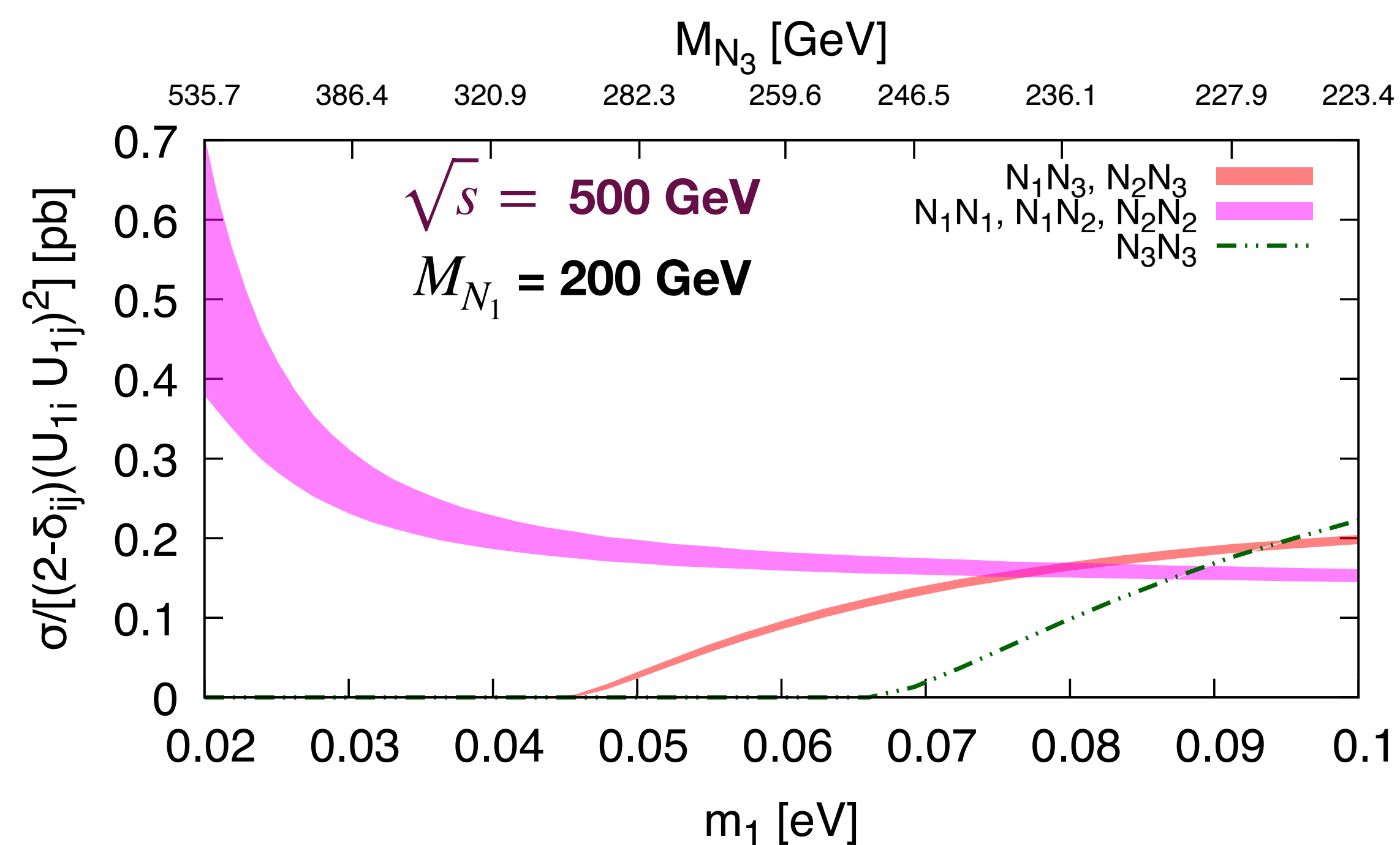


**NH**
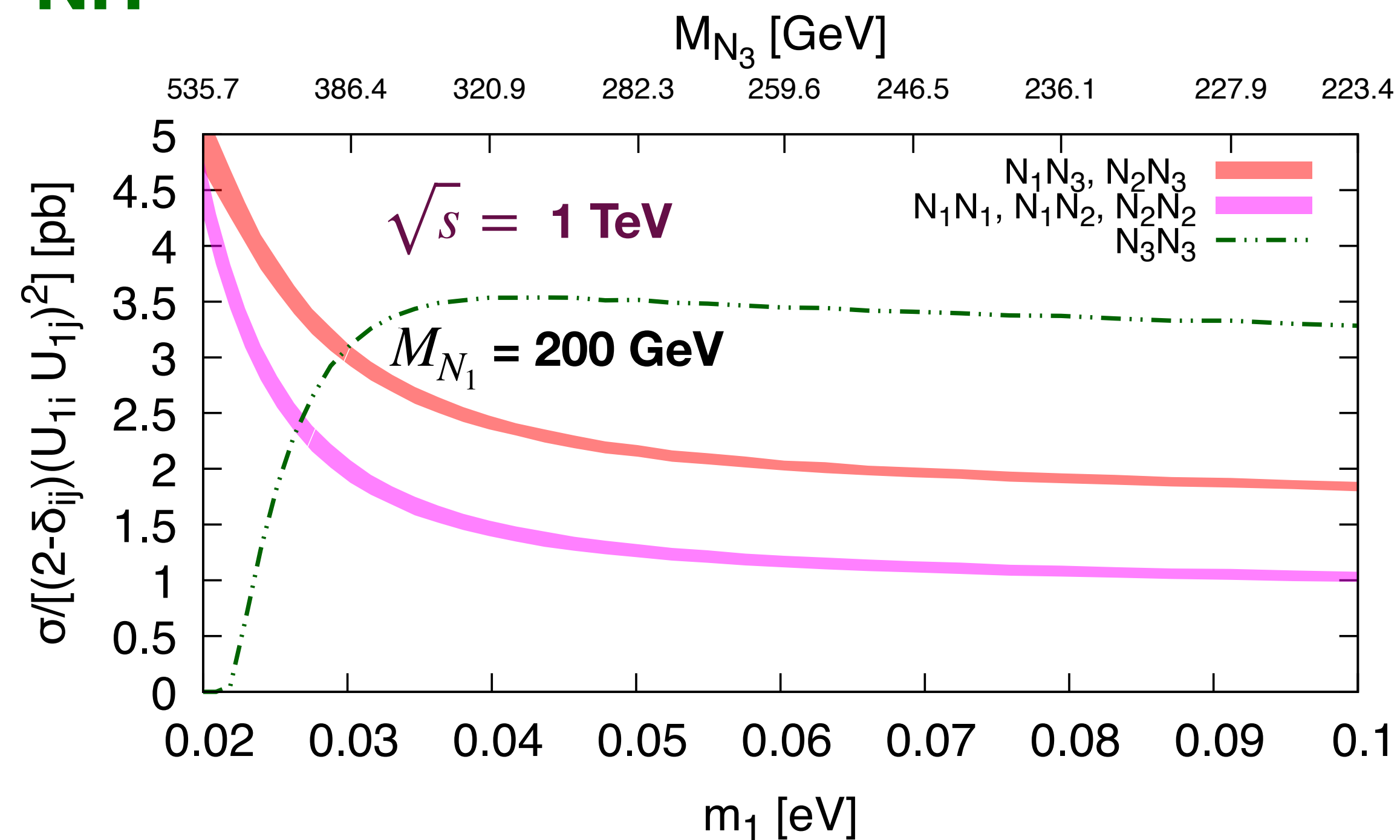
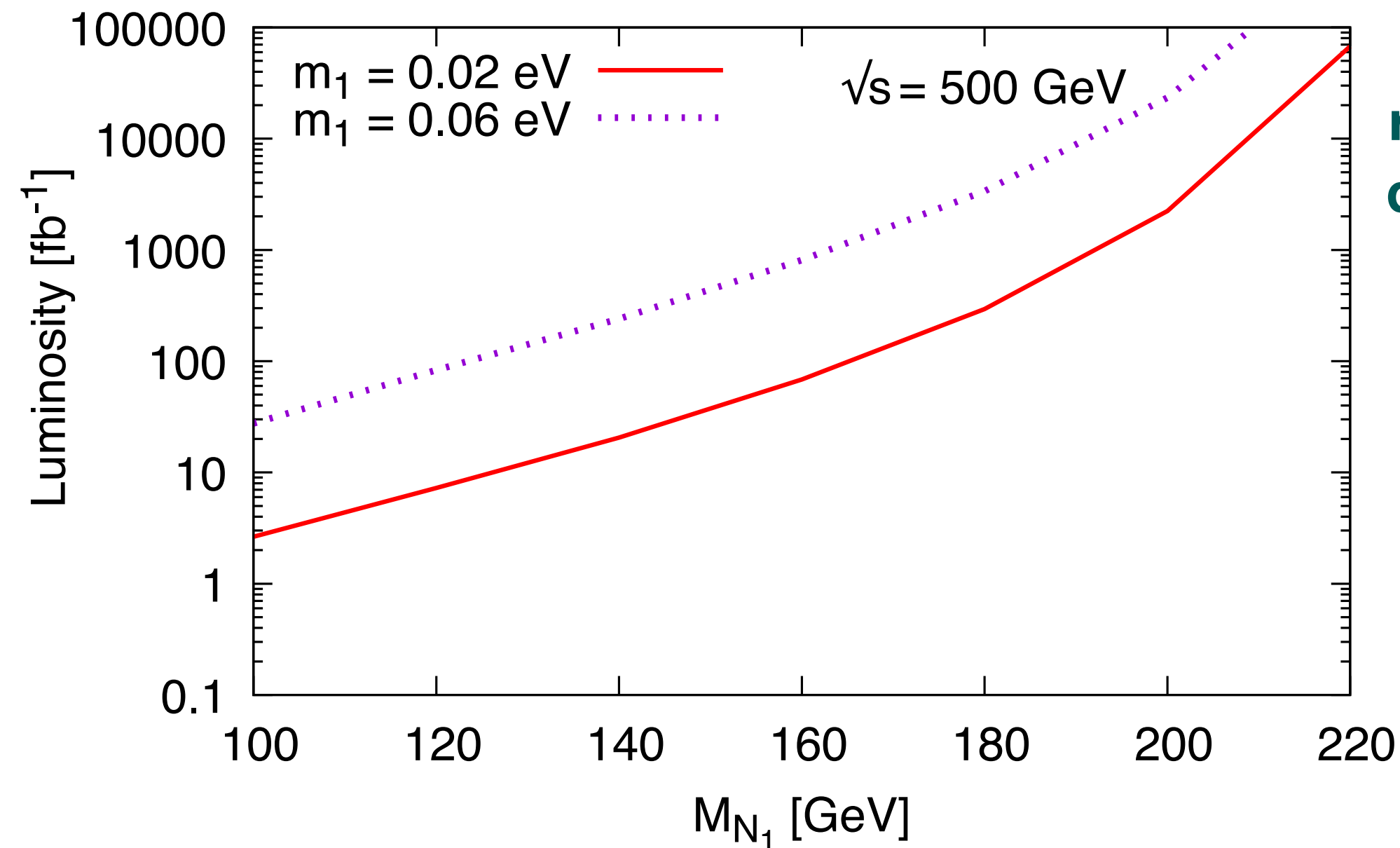# Collider Signature Search
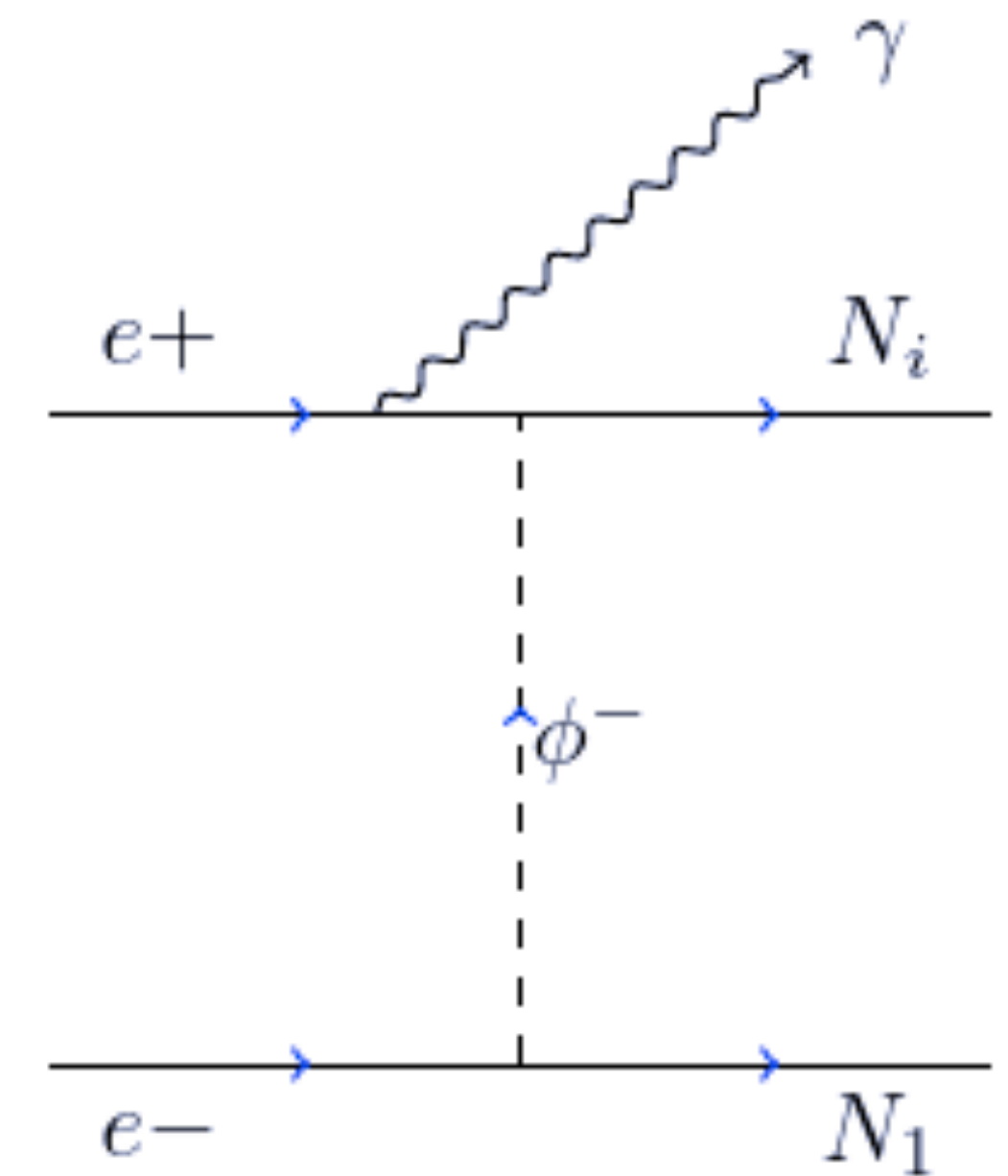
## Signal 1 : Mono-Photon + Missing Energy

At collider , $N_1$ being dark matter goes into missing transverse energy.

But we can have mono-photon from ISR as a signature at the colliders.

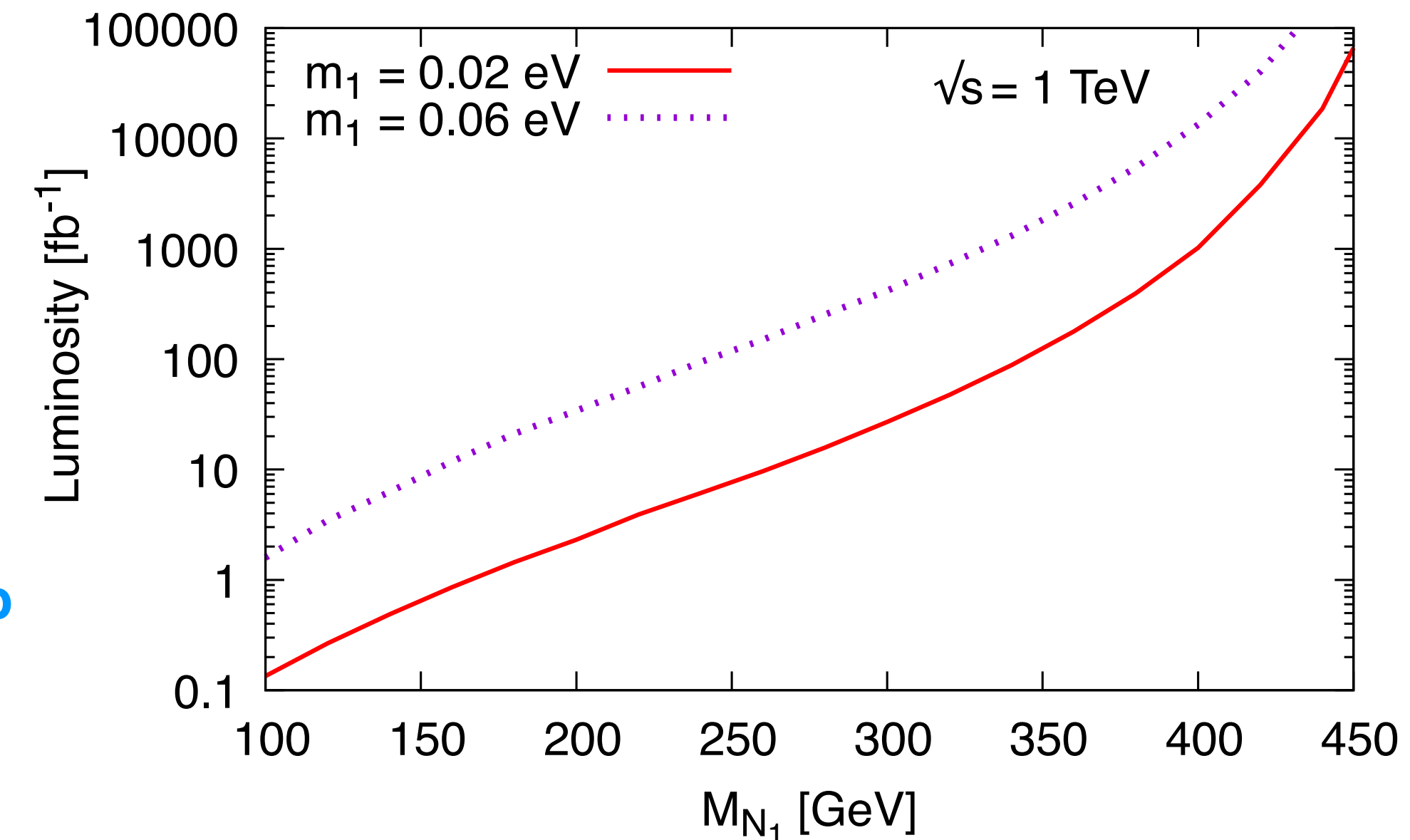In signal we take : $N_1N_1, N_1N_2, N_2N_2$  **Normal Hierarchy**

The SM background for this signal : $2\nu+$photon .

The required luminosity for s-$\sigma$ confidence: $L = \dfrac{\sigma_B}{\sigma_S^2}s^2$

We have plotted the required luminosity for 5-$\sigma$ detection For two different lightest neutrino mass values for varying Dark matter particle mass

$\tilde{\lambda}$ changed in order to keep DM relic density and LFV satisfied

# Signal 2 : Opposite Sign Di-Leptons + Missing Energy

- **At collider , $N_3$ produces with $N_1$.**

- **Heavier $N_3$ Decays into leptons and $N_{1,2}$.**

- **Provides Opposite Sign di-Leptons + $E_T$ as signature.**

**SM Background :** $l^{\pm}l^{\mp}\nu\bar{\nu}$, Leptonic decay of $(t\bar{t} \ + \ \tau\bar{\tau})$

## Benchmark Points :

| BP1 (NH) | | | BP2 (NH) | | |
|---|---|---|---|---|---|
| $\mu_\phi = 1$ TeV, $\lambda_1 = 0.004$, $\lambda_2 = 0.005$ | | | | | |
| $\widetilde{\lambda} = 1.24 \times 10^{-10}$, $M_{N_1} = 120$ GeV | | | $\widetilde{\lambda} = 7.32 \times 10^{-10}$, $M_{N_1} = 200$ GeV | | |
| $m_1 = 2.0 \times 10^{-11}$ GeV | | | $m_1 = 6.0 \times 10^{-11}$ GeV | | |
| $M_{N_2} = 130.07$ GeV, $M_{N_3} = 326.02$ GeV | | | $M_{N_2} = 201.94$ GeV, $M_{N_3} = 260.08$ GeV | | |
| $Y = \begin{pmatrix} 2.29 & -1.29 & 0.67 \\ 1.40 & 1.64 & -1.65 \\ 0.41 & 1.84 & 2.17 \end{pmatrix}$ | | | $Y = \begin{pmatrix} 1.30 & -0.73 & 0.38 \\ 0.79 & 0.93 & -0.94 \\ 0.22 & 1 & 1.18 \end{pmatrix}$ | | |

## Preliminary Cuts:

$$\min \mathrm{P}_{T_{l_1,l_2}} = 10 \text{ GeV}, \ |\eta_{l_1,l_2}| \leq 2.5, \ \min \Delta R_{l_1,l_2} = 0.4$$
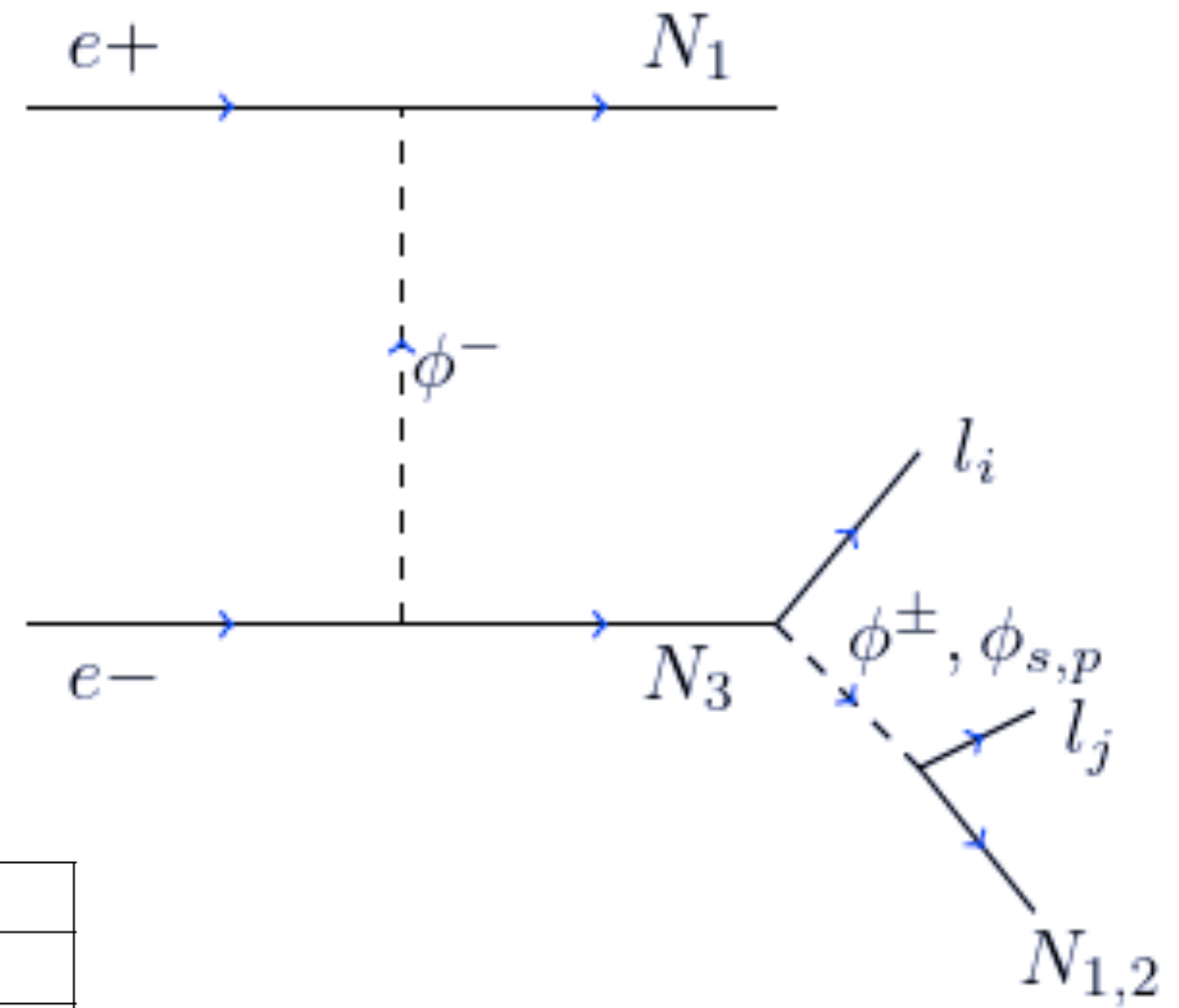
**Proposed Cuts :**

| Cuts | Signals | | | | | |
|------|---------|---|---|---|---|---|
| | $ee + \not{E}_T$ | | $e\mu + \not{E}_T$ | | $\mu\mu + \not{E}_T$ | |
| | $\sqrt{s} = 0.5$ TeV | $\sqrt{s} = 1.0$ TeV | $\sqrt{s} = 0.5$ TeV | $\sqrt{s} = 1.0$ TeV | $\sqrt{s} = 0.5$ TeV | $\sqrt{s} = 1.0$ TeV |
| Reject $E_{l_1} >$ [GeV] | 200 | 350 | 200 | 300 | 200 | 350 |
| Reject $E_{l_2} >$ [GeV] | 150 | 300 | 150 | 300 | 150 | 300 |
| Reject $M_{l_1 l_2} >$ [GeV] | 200 | 200 | 200 | 250 | 200 | 200 |
| Reject $\not{E}_T <$ [GeV] | 270 | 600 | 270 | 600 | 270 | 550 |

TABLE VI. Proposed cuts for signal OSD+$\not{E}_T$.

**Cut Efficiency :**

| Cuts | BP1 (fb) | BP2 (fb) | Background (fb) |
|------|----------|----------|-----------------|
| Preliminary | 22.03 | 2.46 | 187.5 |
| Reject $E_e > 300$ GeV | 21 | 2.46 | 51.47 |
| Reject $E_\mu > 300$ GeV | 20.45 | 2.46 | 41.19 |
| Reject $M_{e\mu} > 250$ GeV | 20.45 | 2.46 | 33.31 |
| Reject $\not{E}_T < 600$ GeV | 18.55 | 2.45 | 16.56 |

TABLE VII. Cut flow of cross-section for BPs and background regarding signal $e^{\pm}\mu^{\mp} + \not{E}_T$ at $\sqrt{s} = 1$ TeV.

**The required luminosity for 5-$\sigma$ confidence detection :**
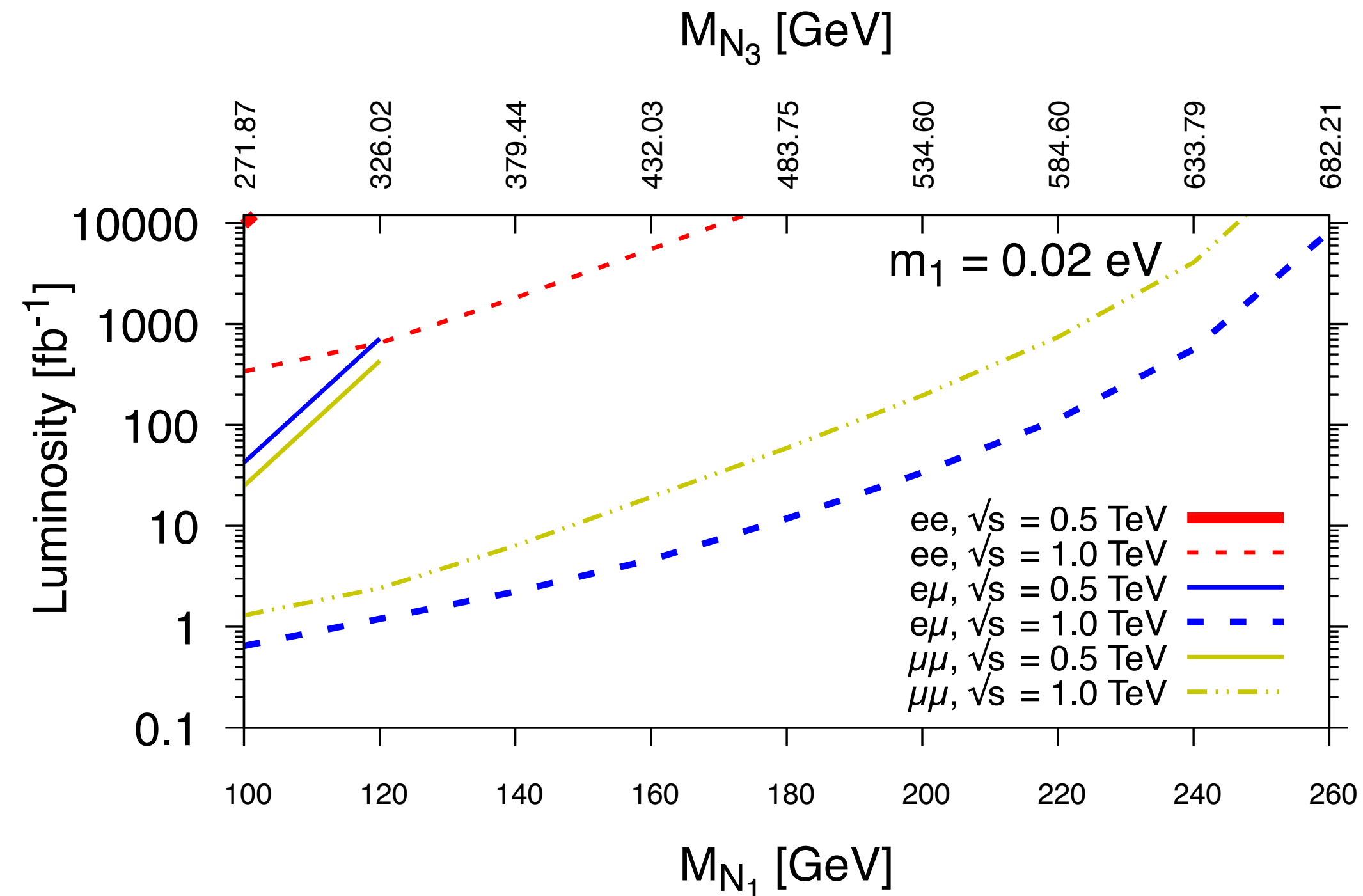


$\tilde{\lambda}$ **changed in order to keep DM relic density and LFV satisfied**
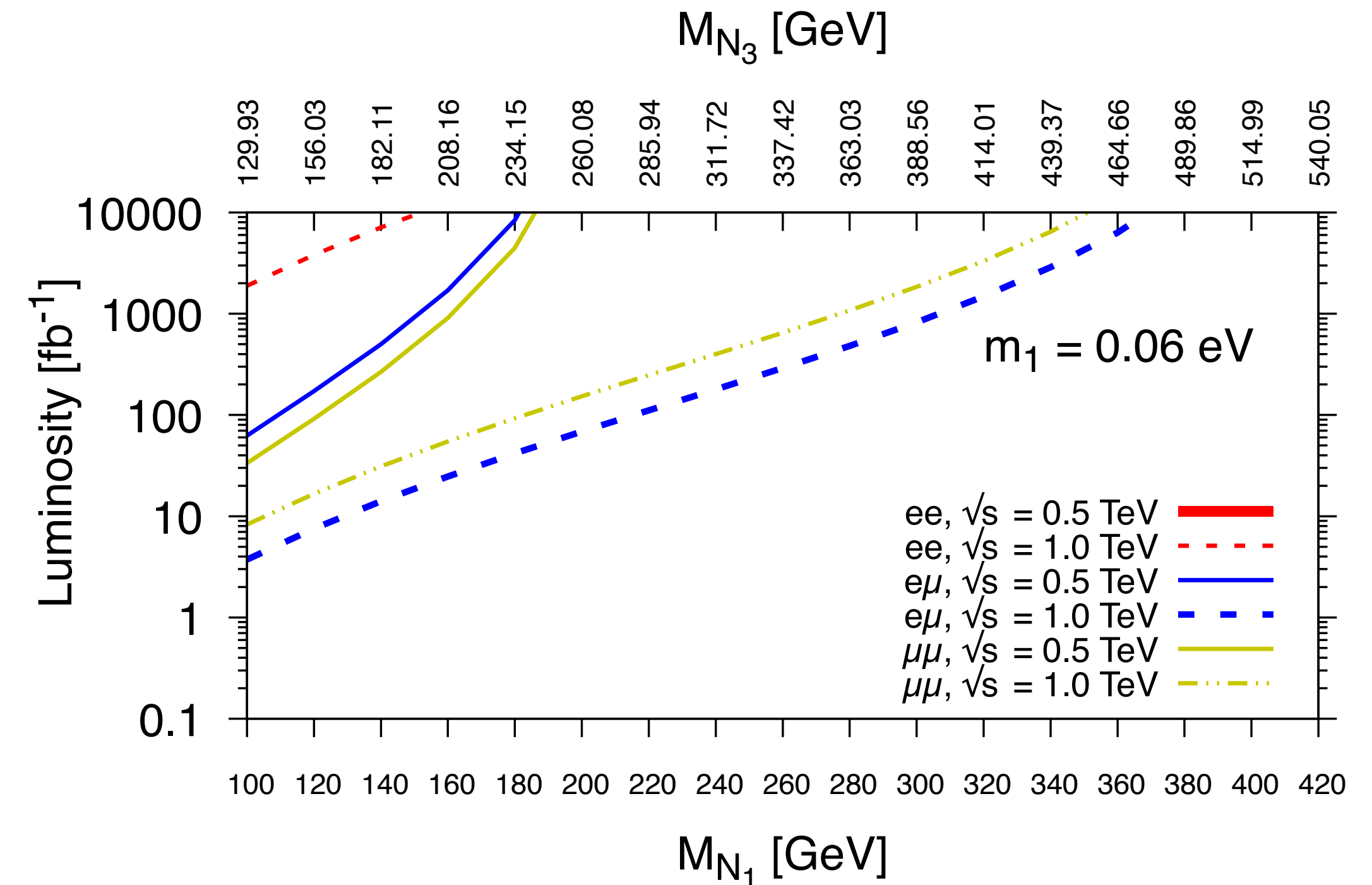
# Thanks for your time and valuable attention

# BackUp

# Model Constraints

**Vacuum stability conditions :**

$$\lambda, \lambda_\phi > 0, \quad \lambda_1, \ \lambda_1 + \lambda_2 - |\tilde{\lambda}| > -2\sqrt{\lambda \lambda_\phi}$$

**Perturbativity :**

$$\lambda, \lambda_\phi < 4\pi, \quad |\lambda_1 + \lambda_2| < 4\pi, \quad |\lambda_1 + \lambda_2 \mp \frac{\tilde{\lambda}}{2}| < 4\pi$$

**Experimental constraints :**

**Gauge boson decay widths :**

$$m_{\phi_s} + m_{\phi_p} > m_Z, \quad m_{\phi^\pm} + m_{\phi_p} > m_W,$$

$$2m_{\phi^\pm} > m_Z, \quad m_{\phi^\pm} + m_{\phi_s} > m_W$$

**LEP direct searches of Charginos and Neutralinos :** $\quad m_{\phi^\pm} > 113.5 \ \text{GeV}, \text{max}[m_{\phi_s}, m_{\phi_p}] > 100 \ \text{GeV}$

# Mass Variations :

To See how the masses of other right handed neutrino varies, we have plotted them with varying the lightest neutrino mass
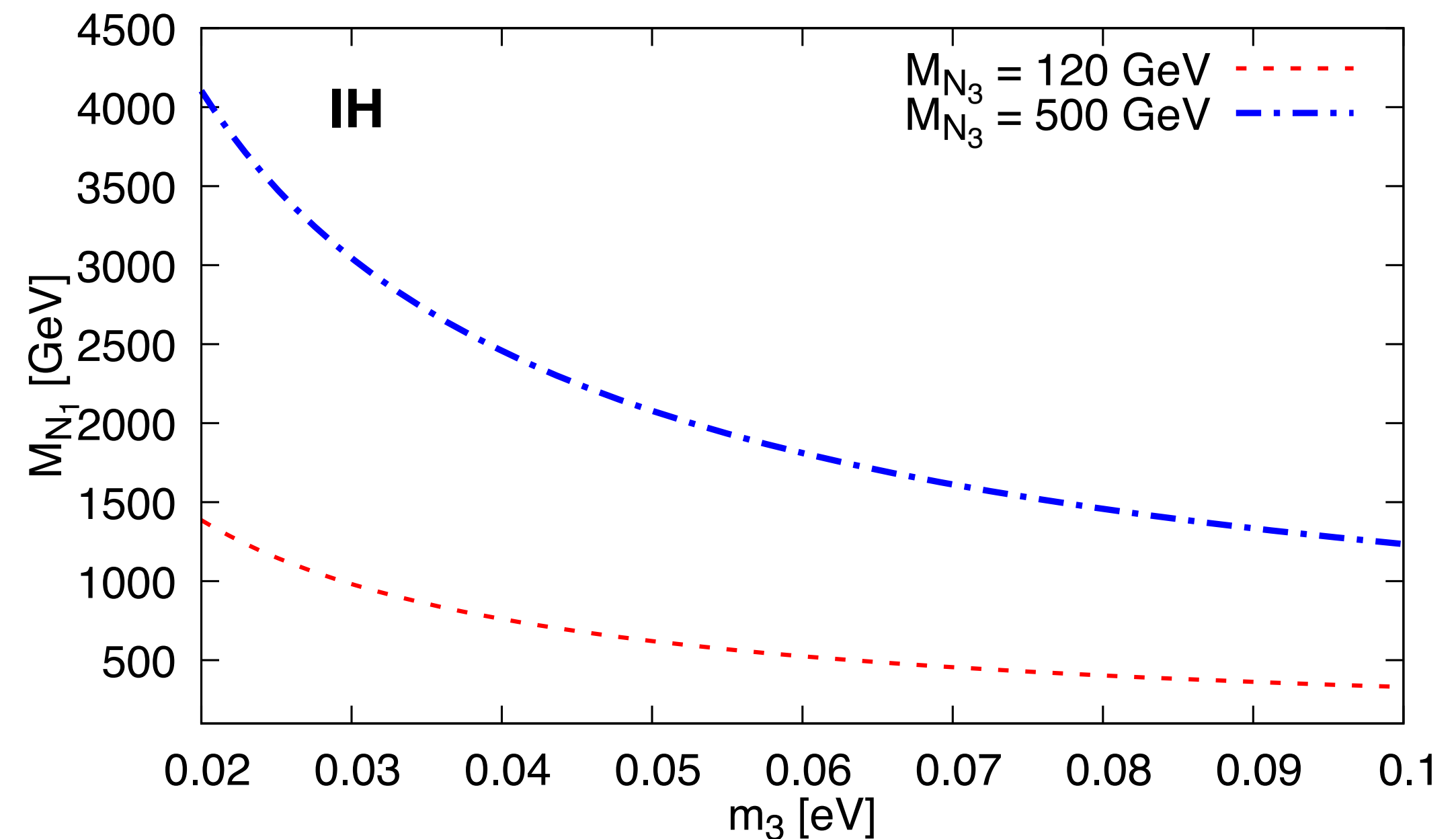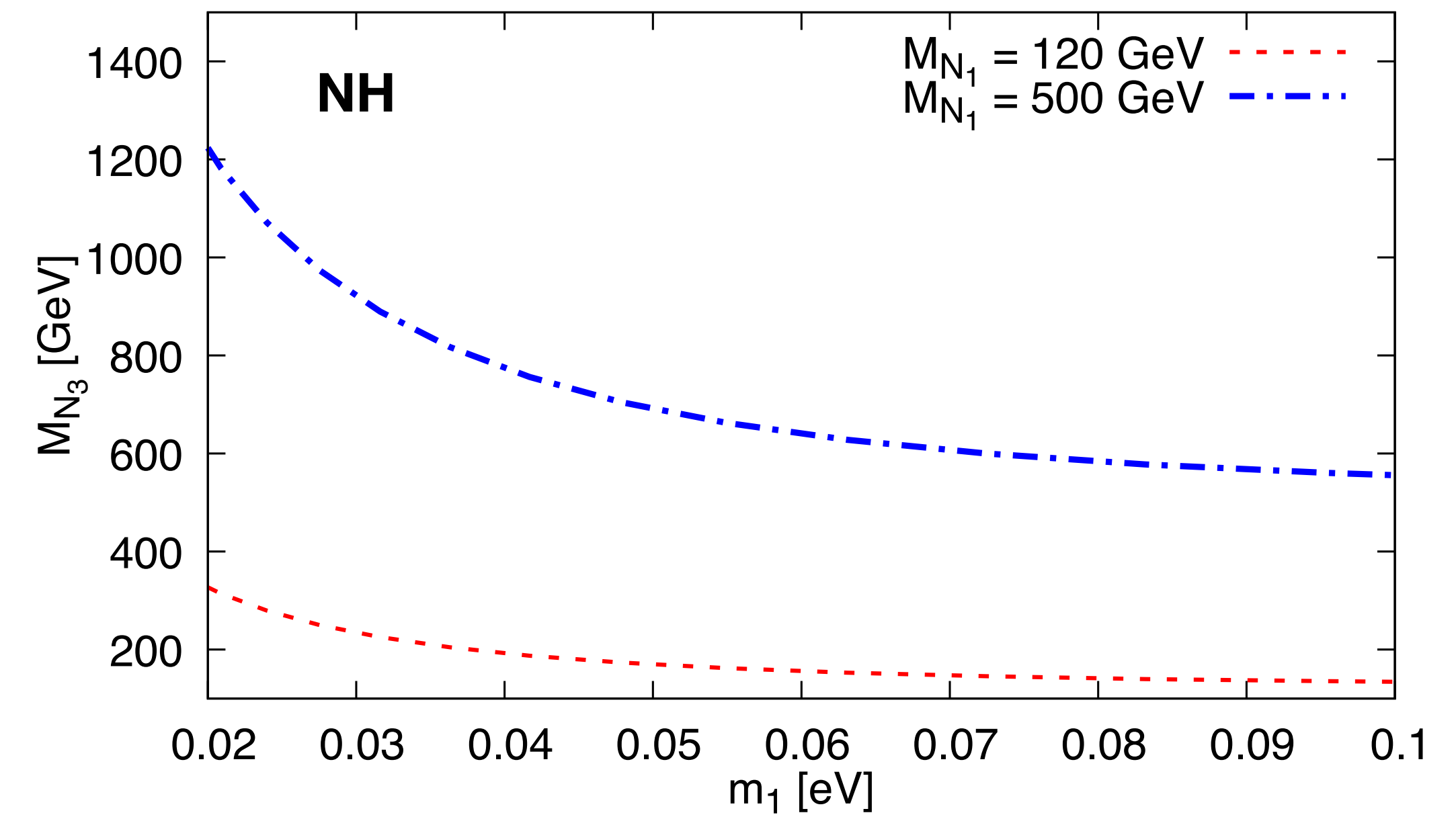
In the Normal Hierarchy, $M_{N_2}$ is almost degenerate with $M_{N_1}$

The value of $M_{N_3}$ reduces with the increasing the lightest neutrino mass

$$\tilde{\lambda} = 1 \times 10^{-9}$$

In the Inverted Hierarchy, $M_{N_2}$ is almost degenerate with $M_{N_3}$

The value of $M_{N_1}$ reduces with the increasing the lightest neutrino mass

# Motivation

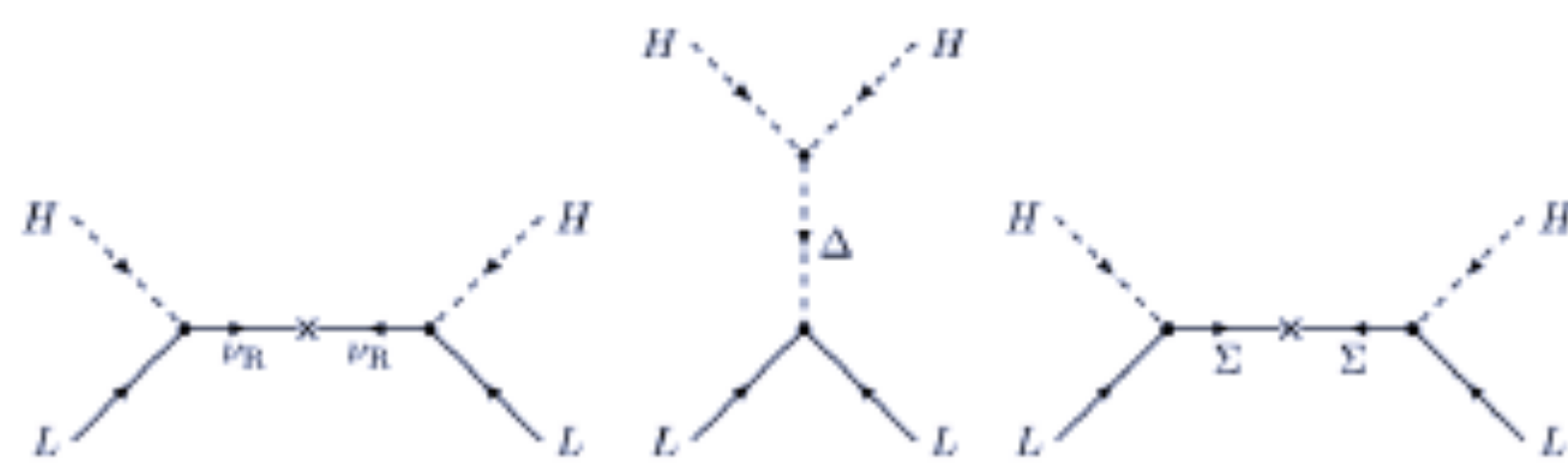- The tiny neutrino mass can be explained by d=5 Weinberg's operator

**Weinberg Operator**

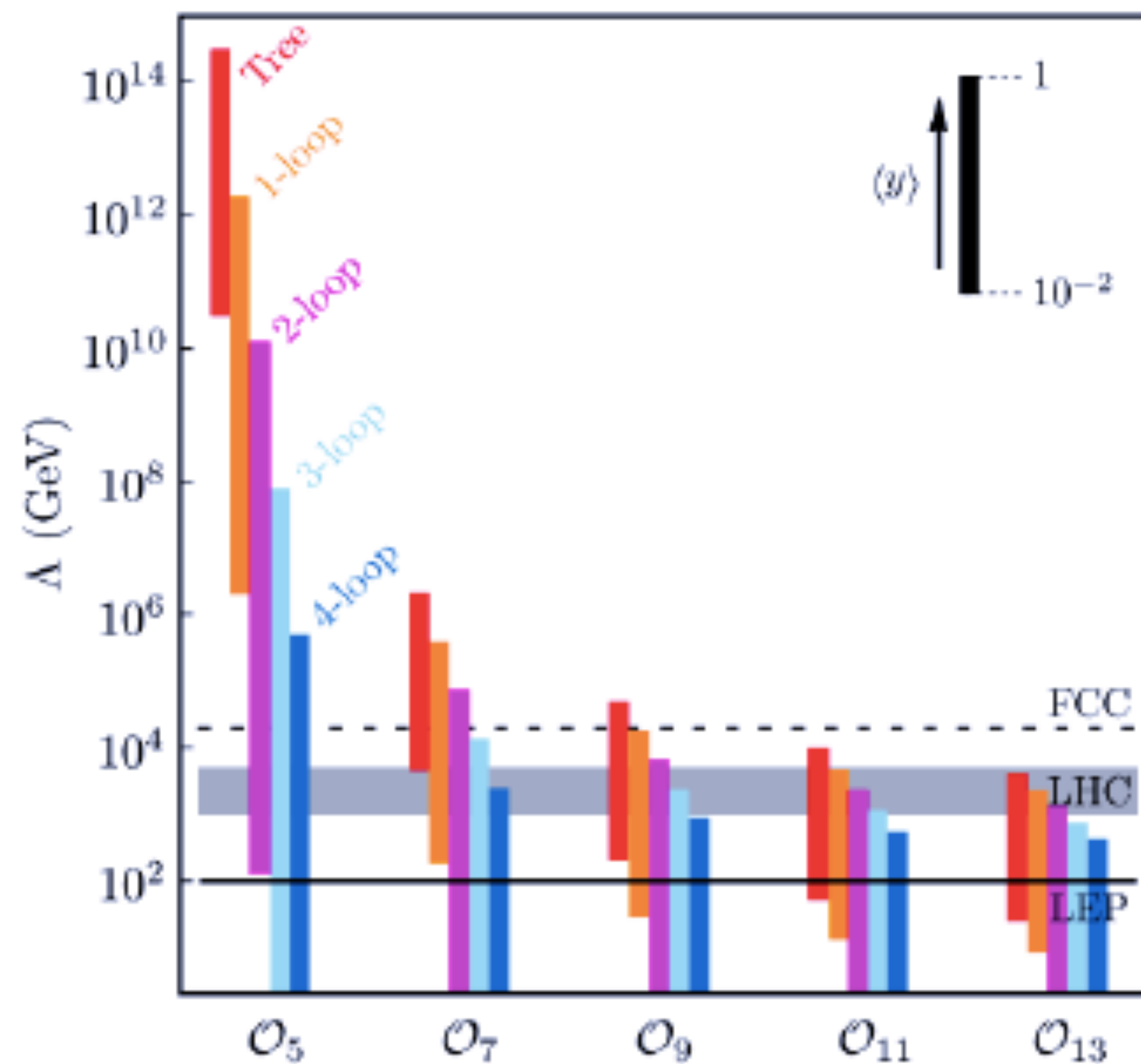$$\frac{LLHH}{\Lambda}, \quad m_\nu = \frac{v^2}{\Lambda}$$
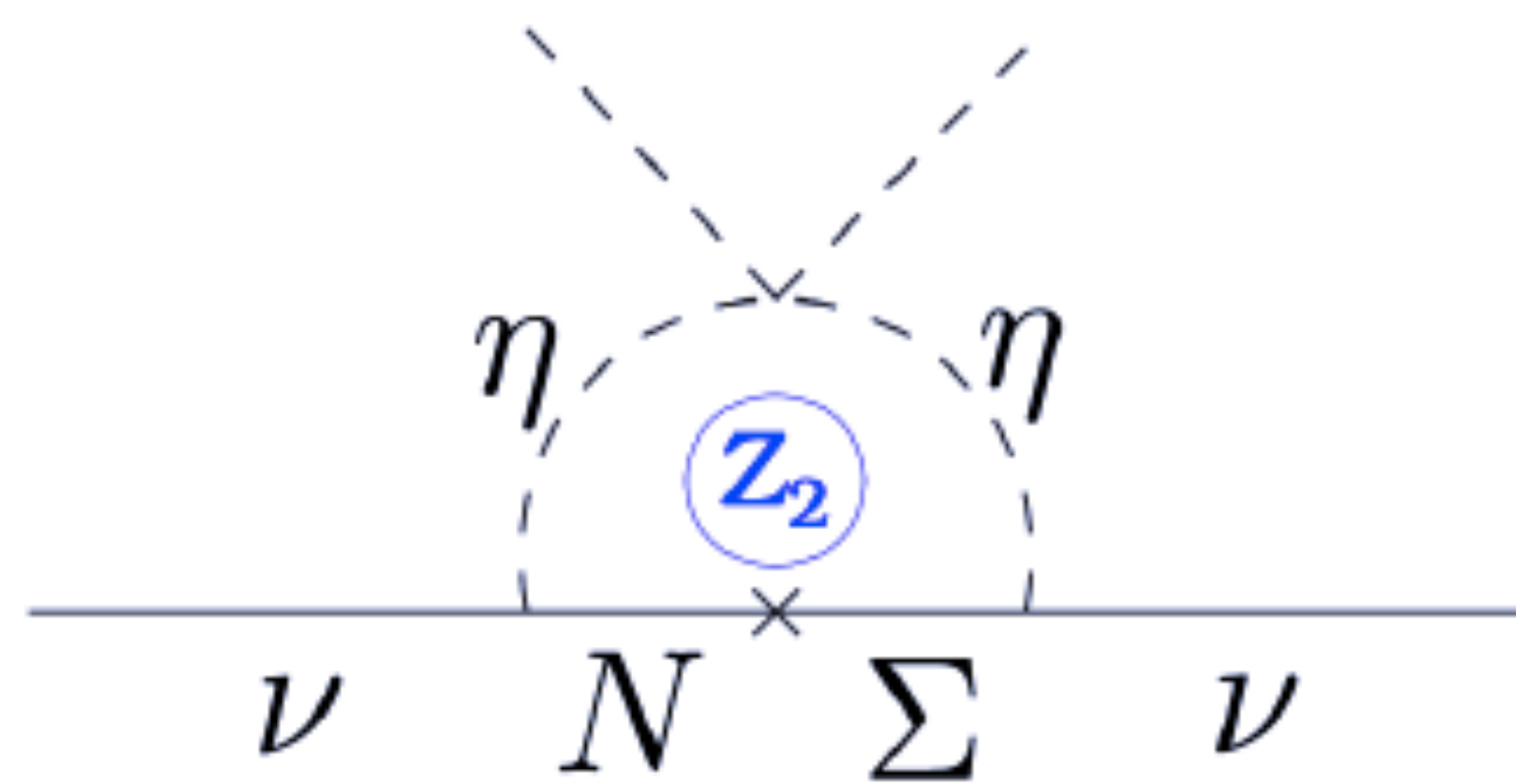
**Gener$^d$ Weinberg Operator**

$$\frac{LLHH(H^\dagger H)}{\Lambda^{2n+1}}, \quad m_\nu \sim \epsilon \left(\frac{1}{16\pi^2}\right)^n \left(\frac{v}{\Lambda}\right)^{d-5} \frac{v^2}{\Lambda}$$

Tree level realisations of Weinberg operator



Loop realisations of Weinberg operator





**Models without additional global Symmetry: Interesting collider Signatures**

**Models with additional global symmetries: Candidates for dark matter**

# Dark Matter Searches

**Dark matter is one of the most pressing evidence of inadequacy of the SM**

**Space observation data sets bound over dark matter relic density**

## Dark Matter

**Scalar Dark Matter**
$\phi_s$ and $\phi_p$

**Fermion Dark Matter**
The lightest of
$N_i$ 's

**We are considering the Lightest $N_i$ as the dark matter and it production through Freeze-out Mechanism**

**We need large Yukawa coupling to satisfy DM relic density with (co)-annihilation involving the heavy fermions.**

**Large Yukawa couplings (in general) lead to large LFV processes.**

## Annihilation diagrams