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

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MOTIVATIONS

- The Scotogenic Model is among the simplest extension of the SM to generate neutrino mass and solve the 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_i	N_i	H	Φ
$SU(2)_L$	2	1	2	2
$U(1)_Y$	$-\frac{1}{2}$	0	$\frac{1}{2}$	$\frac{1}{2}$
Z_2	+	-	+	-

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

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

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

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

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

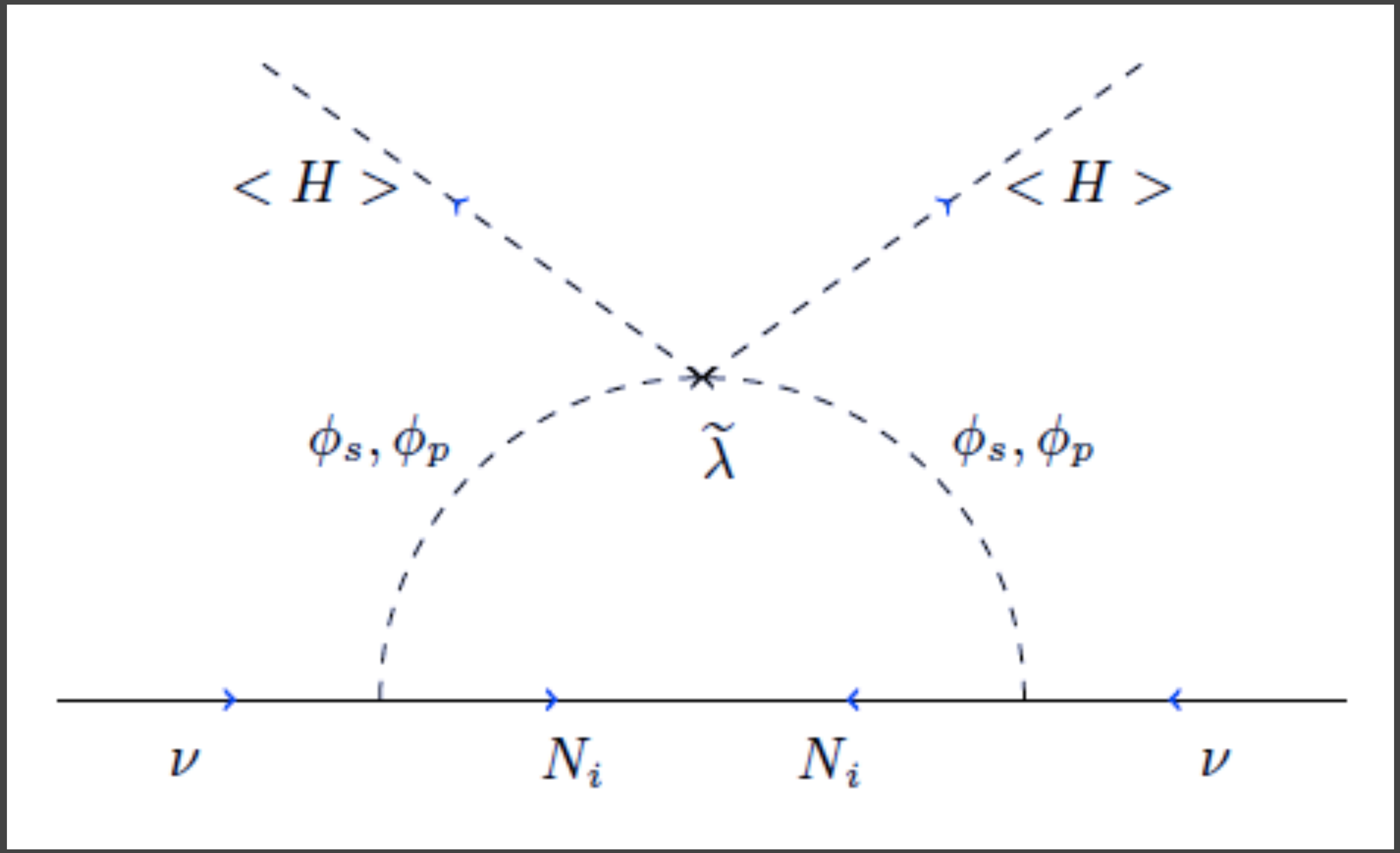
$$L_{int} = [-\lambda_1(H^\dagger H)(\Phi^\dagger\Phi) - \lambda_2|H^\dagger\Phi|^2 - \frac{\tilde{\lambda}}{2}[(H^\dagger\Phi)^2 + h.c.]$$
$$-(Y^{\alpha i}\overline{L_{\alpha_L}}\tilde{\Phi}N_i + h.c.)]$$

We the VEVs: $<H> = \frac{v}{\sqrt{2}}$ **, Where** $v = 246$ **GeV and** $<\Phi> = 0$

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

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 ν-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 $\bar{m}^2 = \frac{(m^2_{\phi_s} + m^2_{\phi_p})}{2}$

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

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:

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

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

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

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

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

Where, U is PMNS matrix

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

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

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

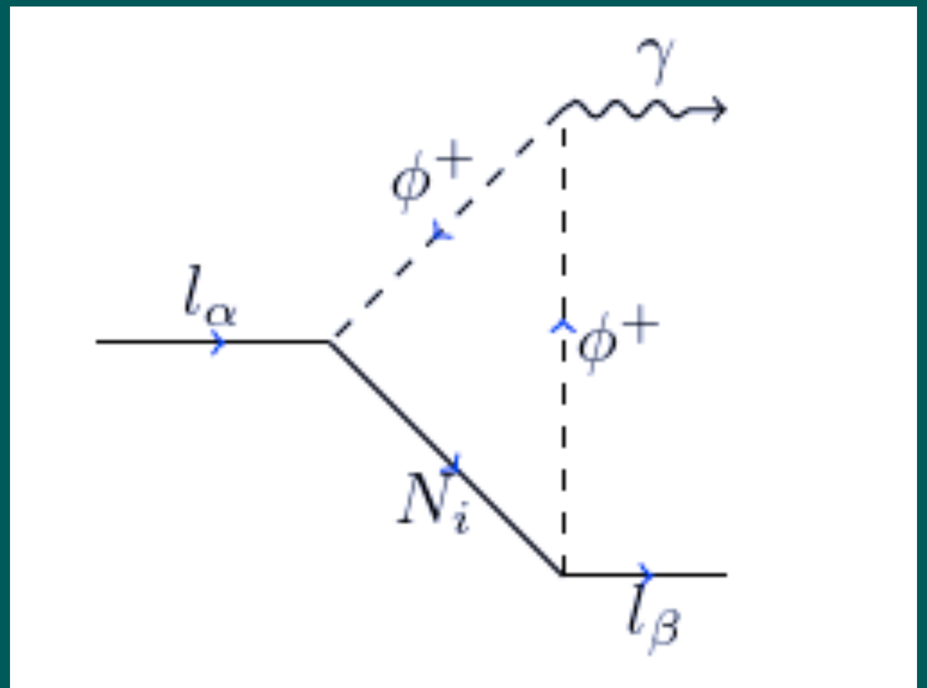
We get the Most general forms :

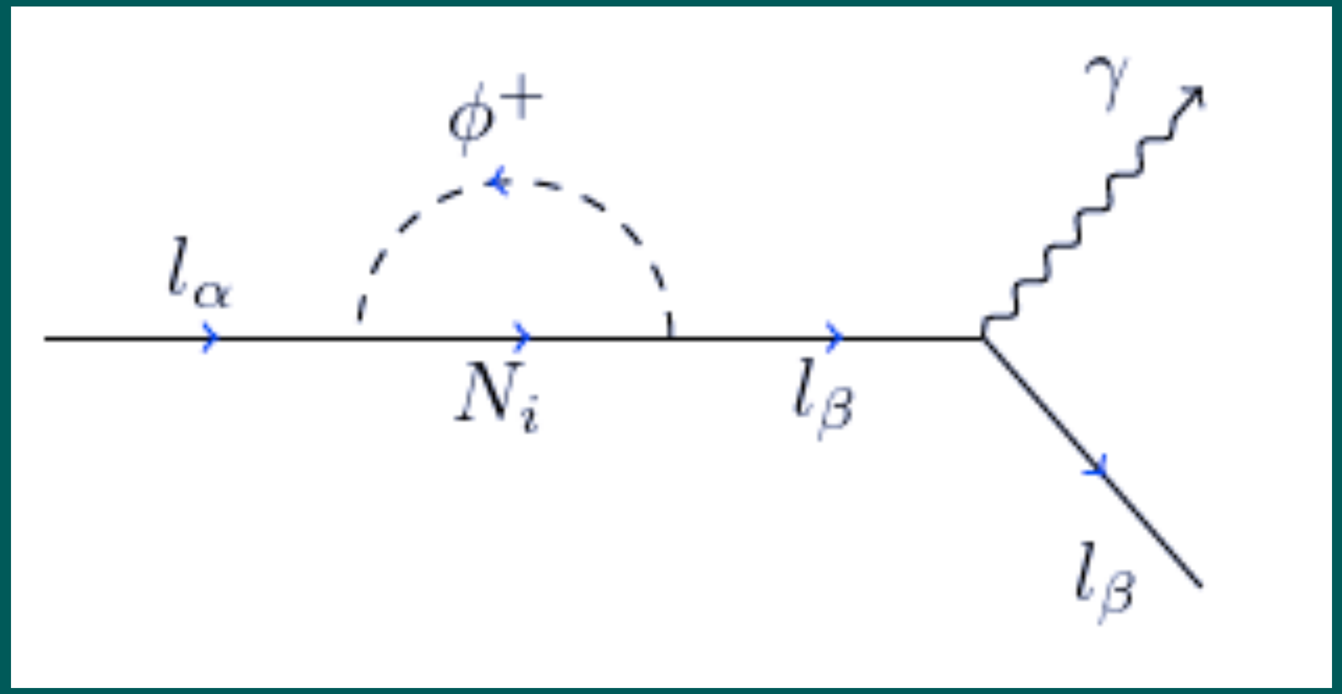
$$R^T = \frac{\sqrt{|\tilde{\lambda}| v}}{4\sqrt{2}\pi} \sqrt{\tilde{M}_\nu}^{-1} U^\dagger Y \sqrt{\mathscr{M}^{-1}}$$

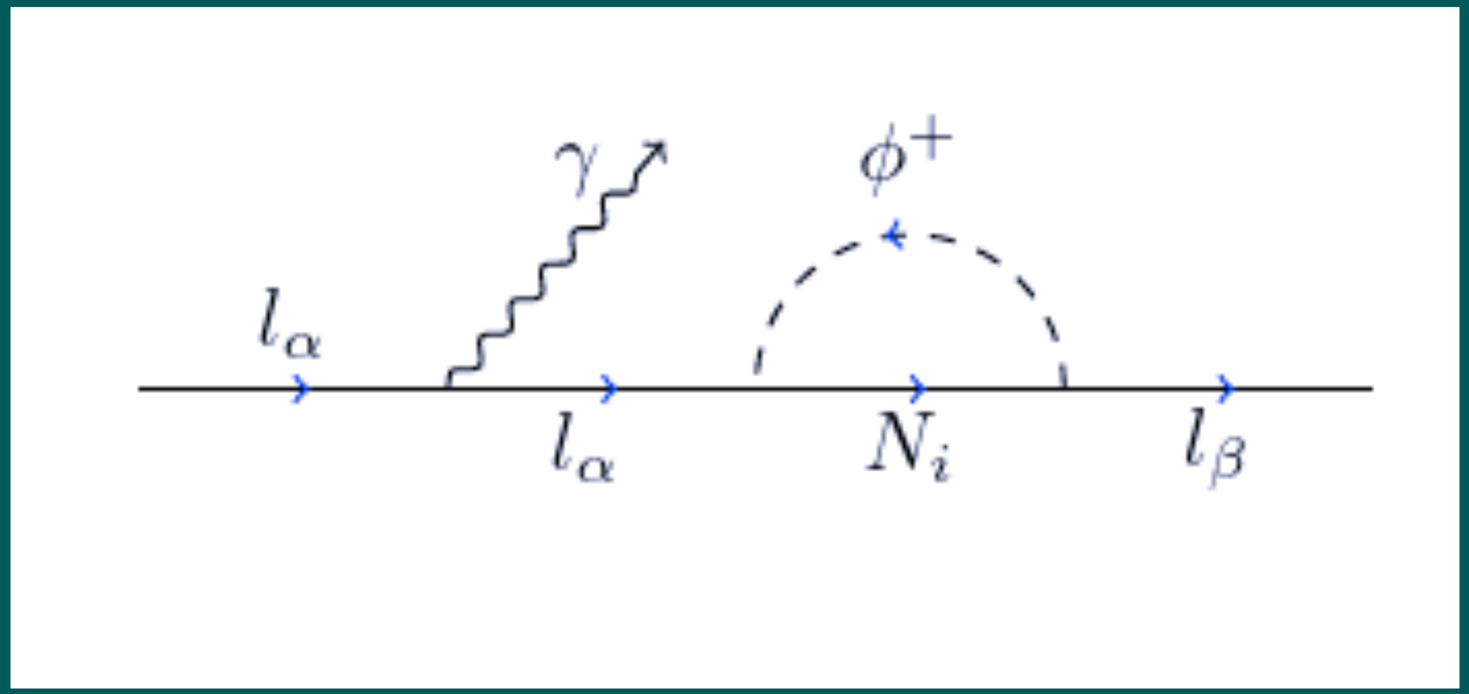
$$Y = \frac{4\sqrt{2}\pi}{\sqrt{|\tilde{\lambda}| v}} U \sqrt{\tilde{M}_\nu} R^T \sqrt{\mathscr{M}}$$

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 Z_2 symmetry.







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

Where,

$$F_2(z) = \frac{1 - 6z + 3z^2 + 2z^3 - 6z^2 \ln z}{6(1-z)^4}$$

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

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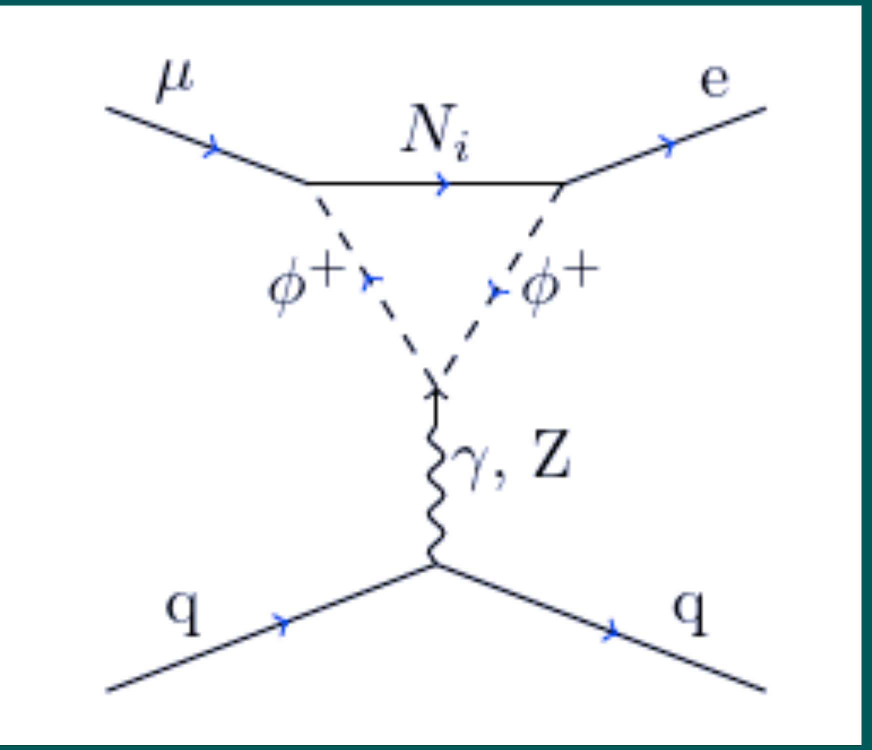
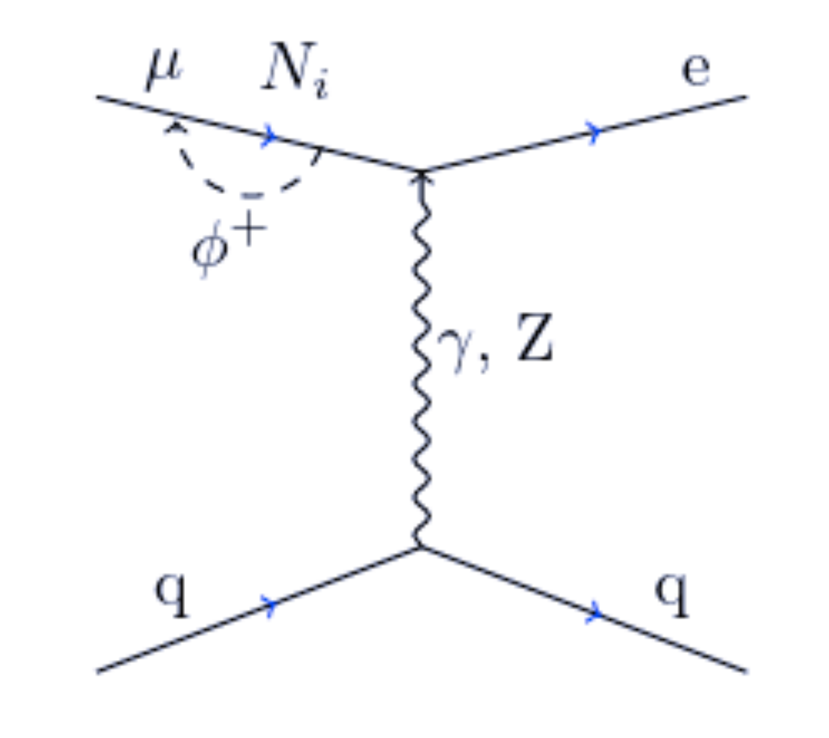
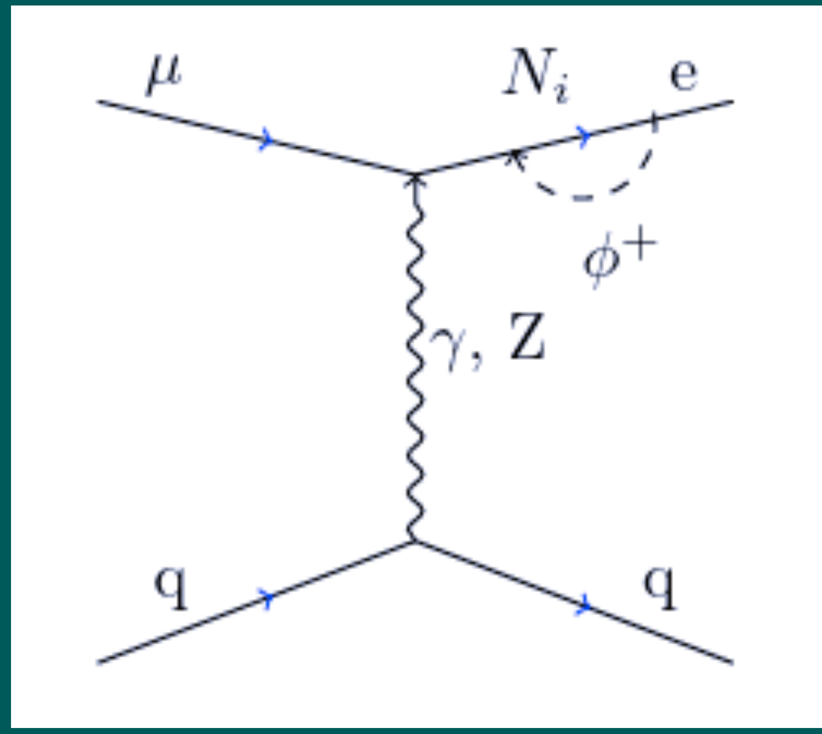






Being unable to detect some signal at the experiments , severe experimental bounds put over theoretical predictions

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

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

The Planck satellite set a limit on the cosmological content of dark matter: 0.1164 < Ωh^2< 0.1236 (3σ range).

Dark Matter

Scalar Dark Matter
ϕ_s and ϕ_p

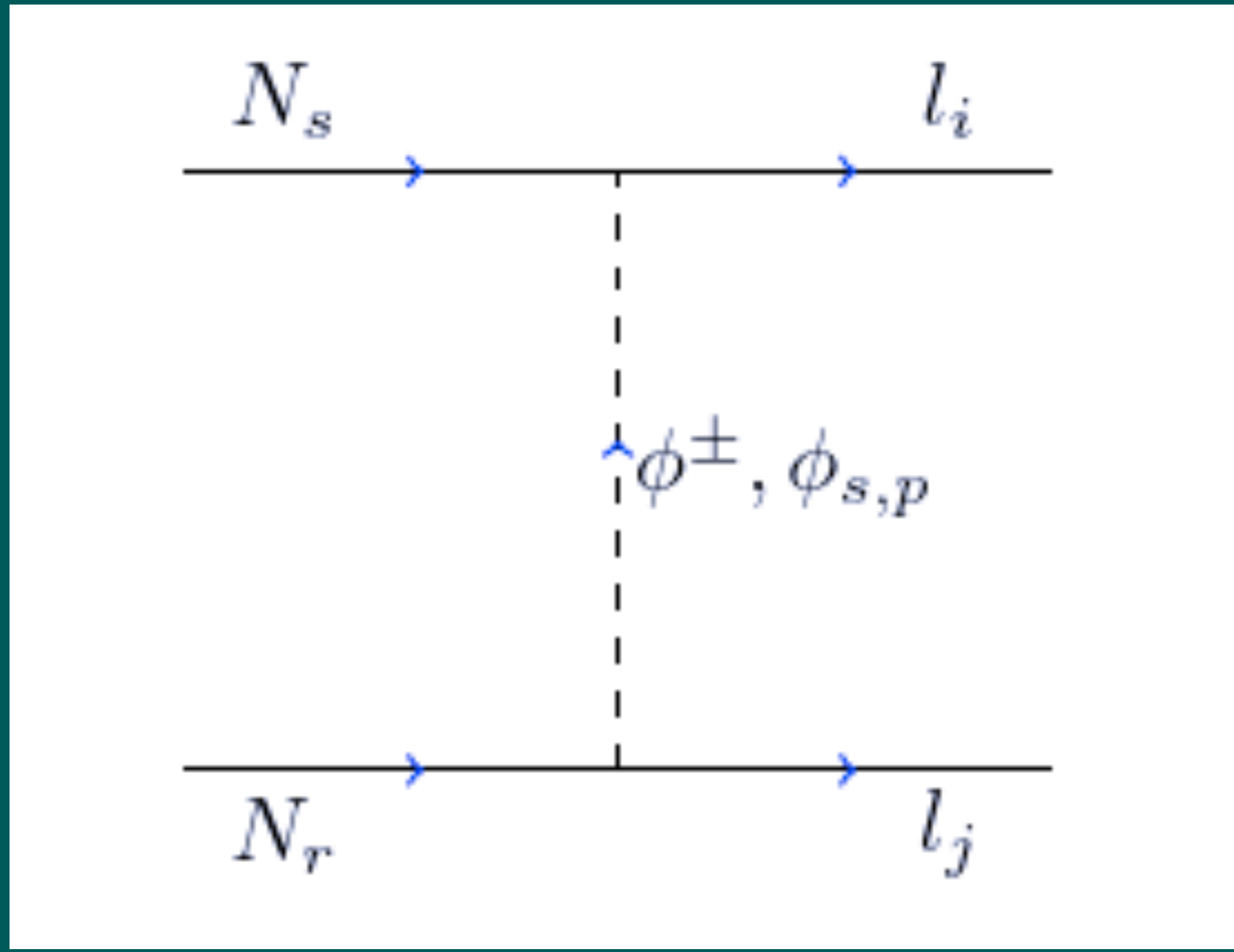
Fermion Dark Matter
The lightest of
N_i 's

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



Issues and Remedy

Can we have dark matter relic density satisfaction along with the LFV bounds in ν-mass model?

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

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

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

Taking $\sqrt{F_2}\sqrt{\mathscr{M}} R^* \sqrt{\tilde{M}_\nu} = X$ and the special choice $R = I$ $\rightarrow$ $X = \sqrt{C I}$

IFF : $F_{2_1}\mathscr{M}_{11}\tilde{M}_{\nu_{11}} = F_{2_2}\mathscr{M}_{22}\tilde{M}_{\nu_{22}} = F_{2_3}\mathscr{M}_{33}\tilde{M}_{\nu_{33}} = C$, Where C is some constant

The best outcome of this parameterisation is this: **We have only 3 parameters for whole physical phenomenology**

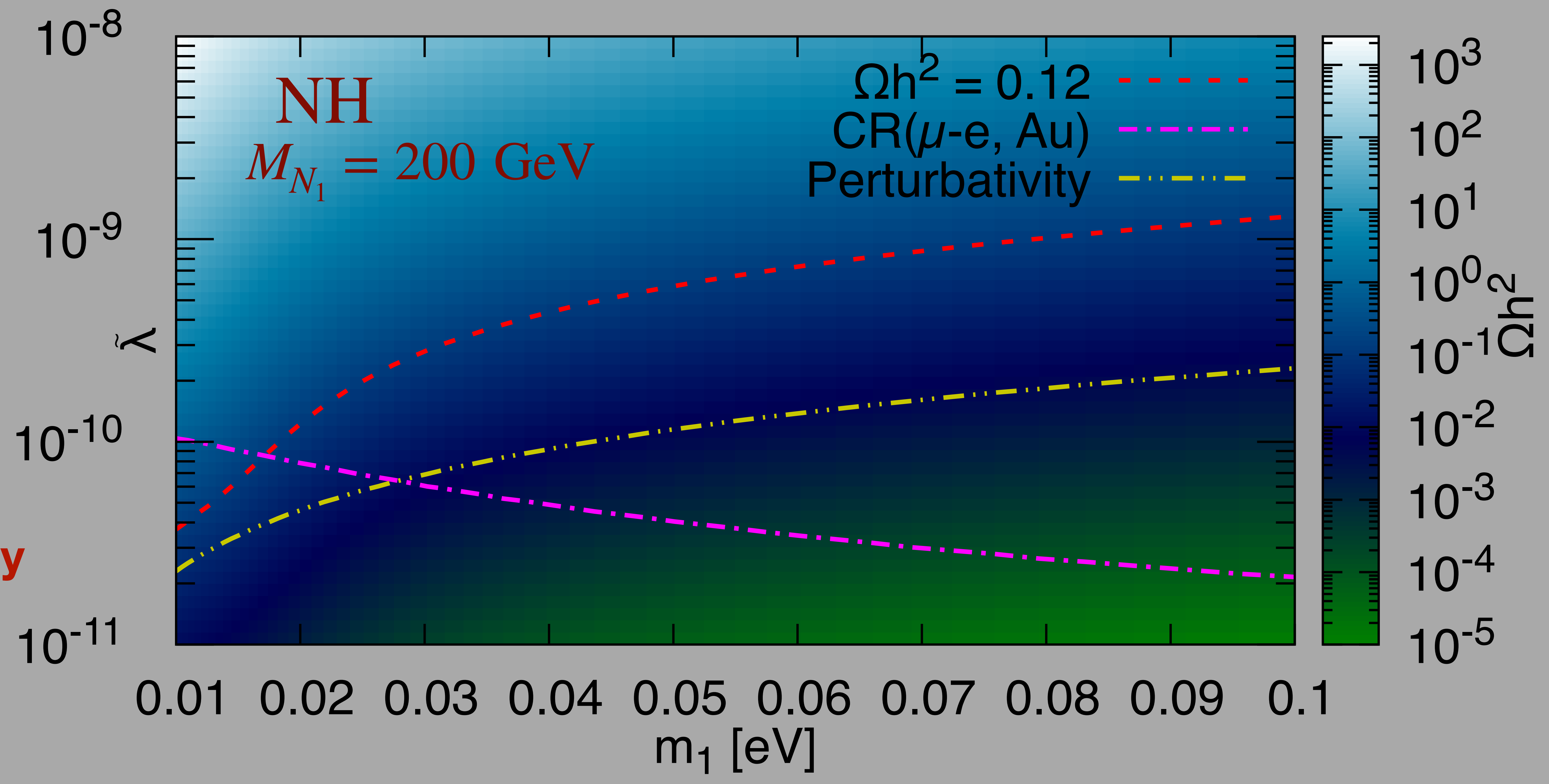
- The lightest N_i's mass: M_{N_i}
- The lightest physical neutrino mass m_i
- The value of $\tilde{\lambda}$

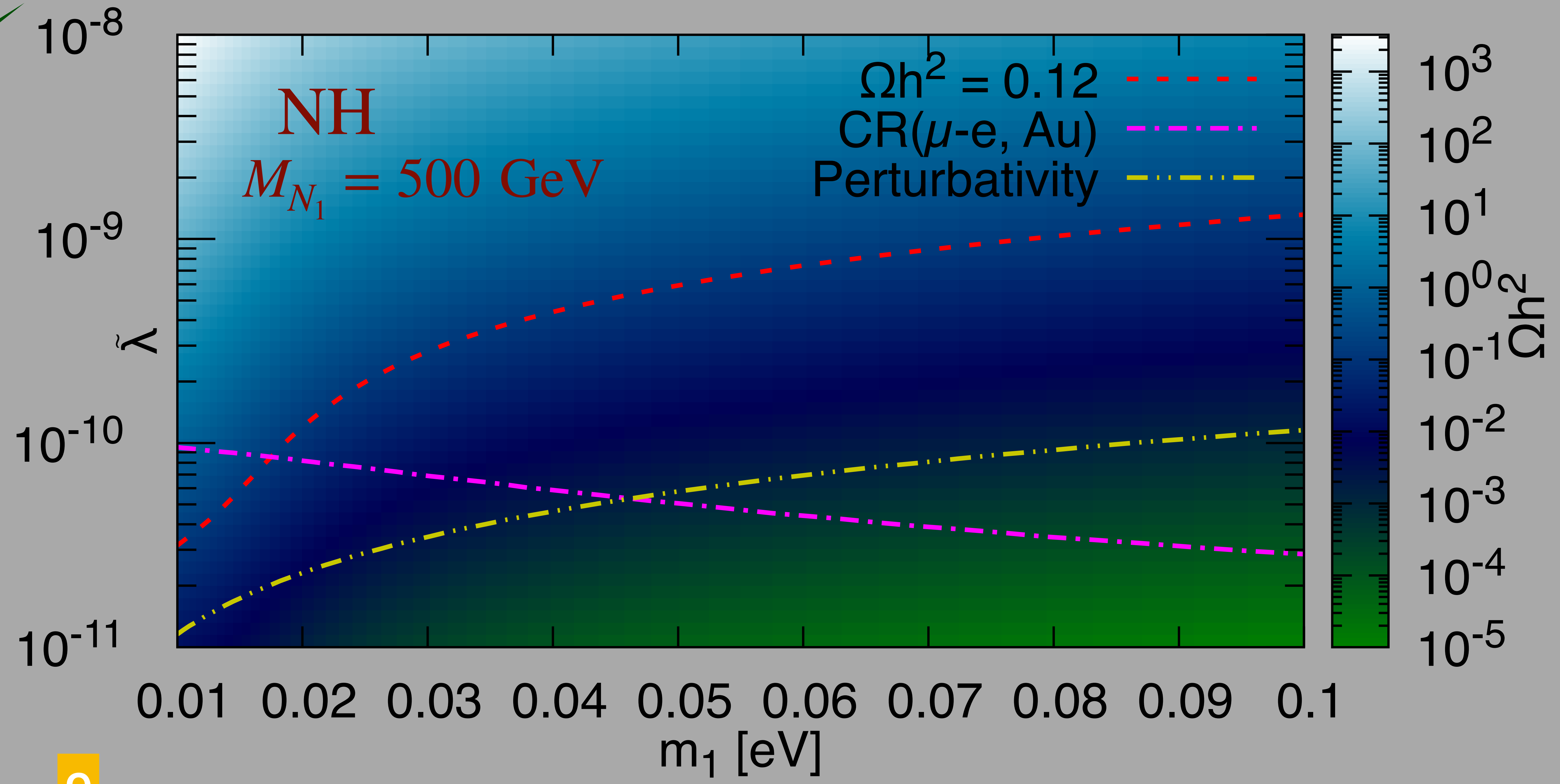
Exotic Parameter Space

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

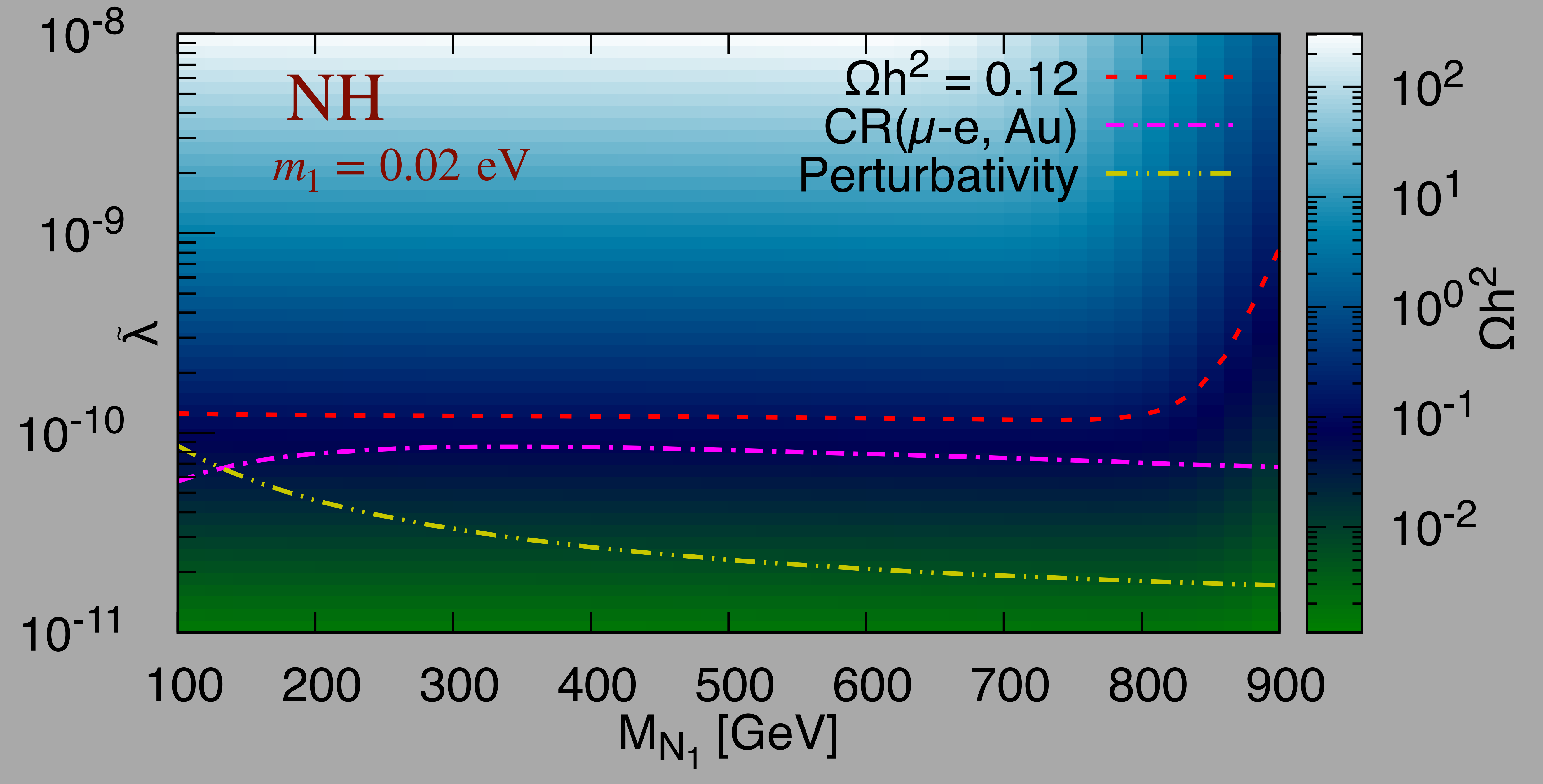
$\lambda_1 = 0.004$

$\lambda_2 = 0.005$

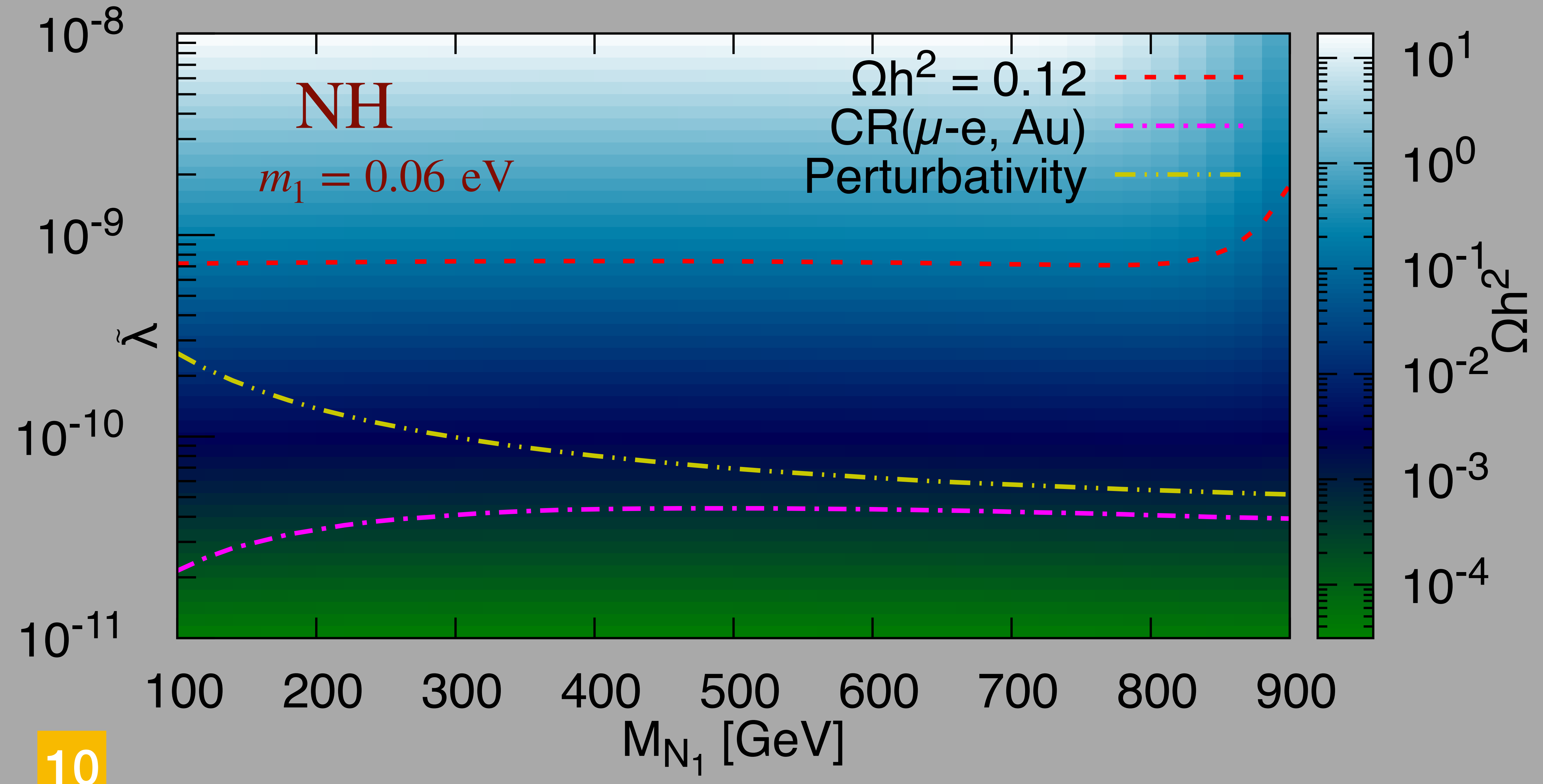
The constrained parameter space in $(M_{N_1} - \tilde{\lambda})$ plane is depicted as

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

$\lambda_1 = 0.004$

$\lambda_2 = 0.005$

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

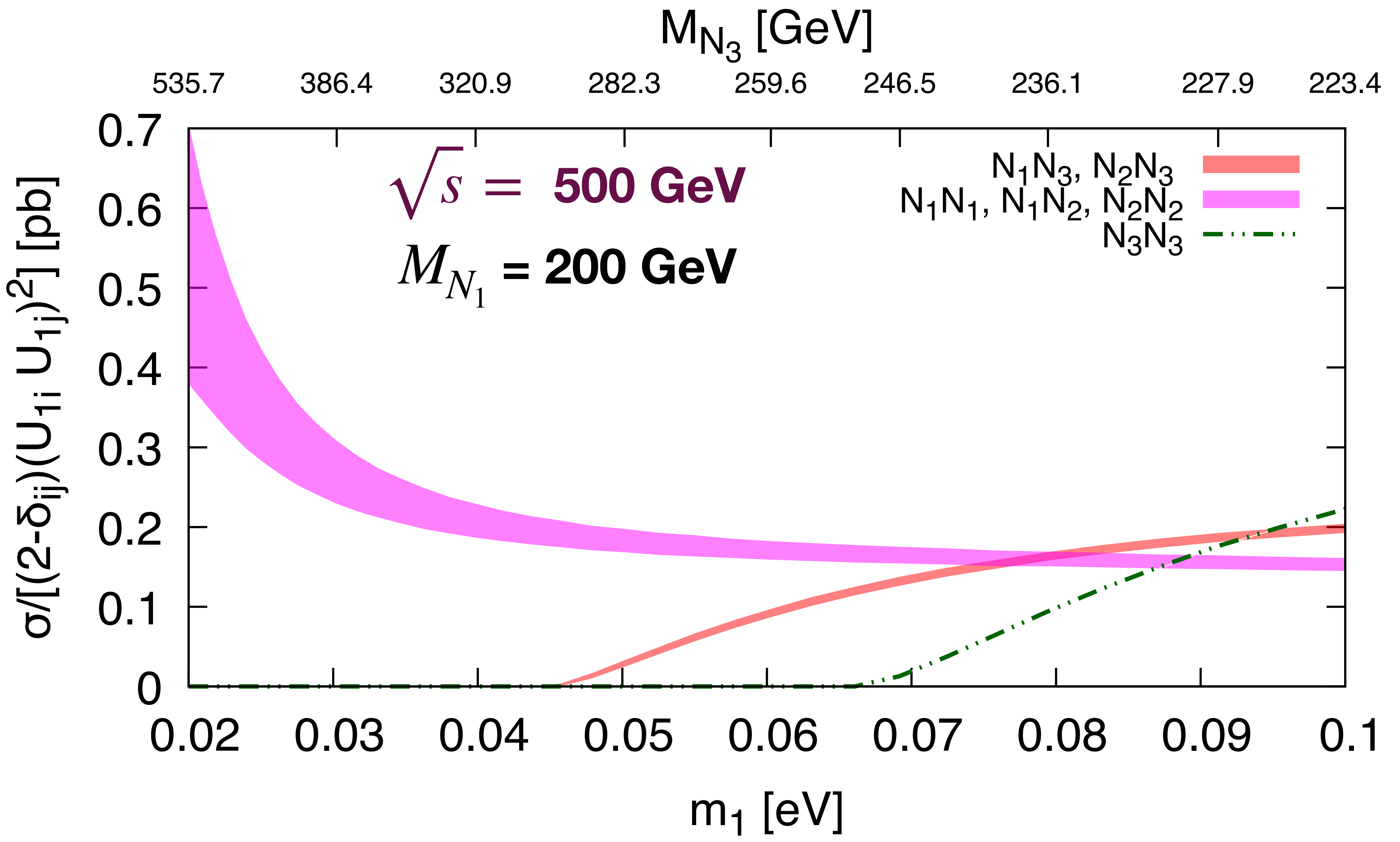
Collider Searches

Production Cross-Section :

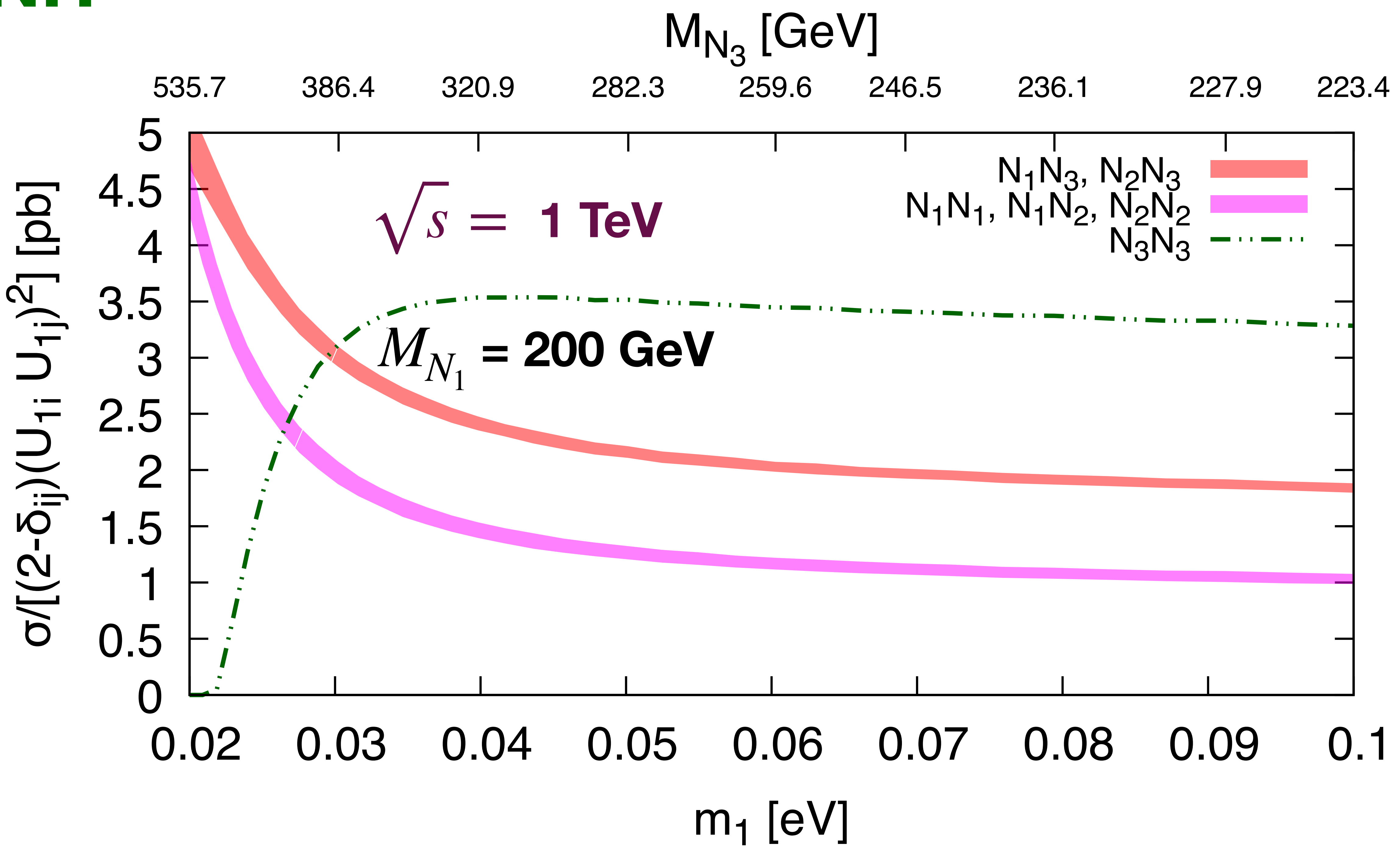
We have plotted the production cross-section of different processed at the colliders with varying the lightest neutrino mass.

$\tilde{\lambda}$ **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.

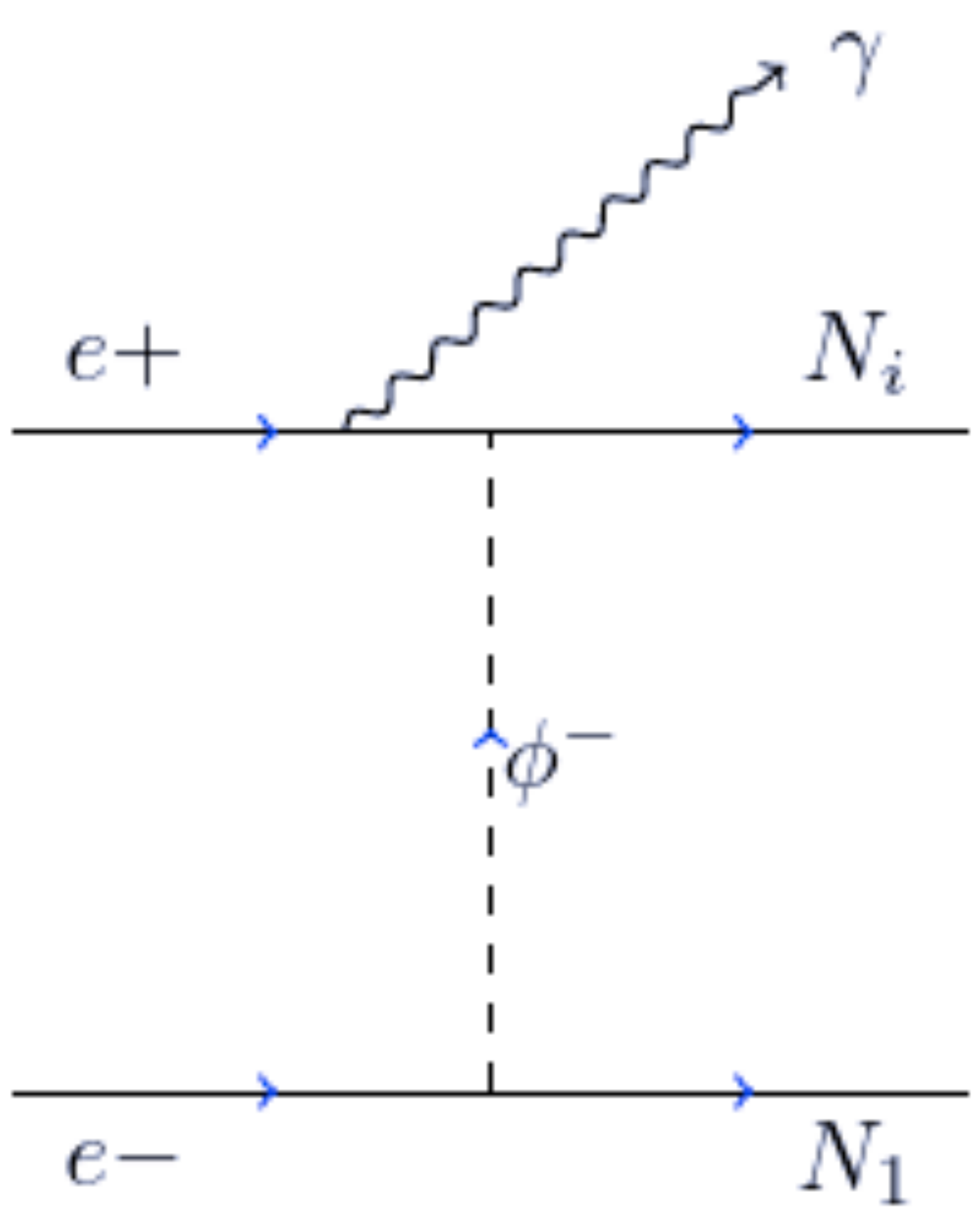


NH



Collider Signature Search

Signal 1 : Mono-Photon + Missing Energy



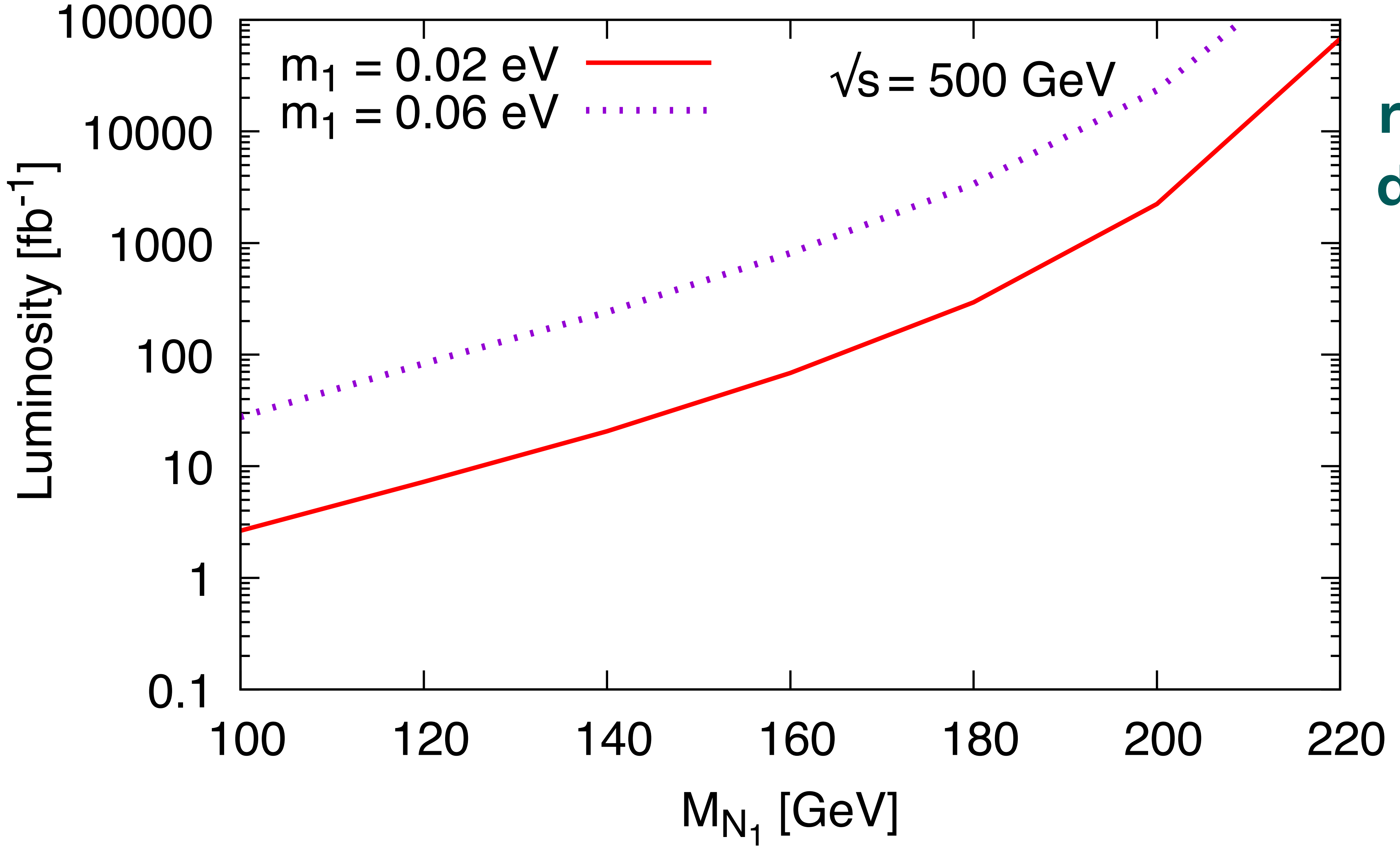
At collider , N_1 being dark matter goes into missing transverse energy.

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

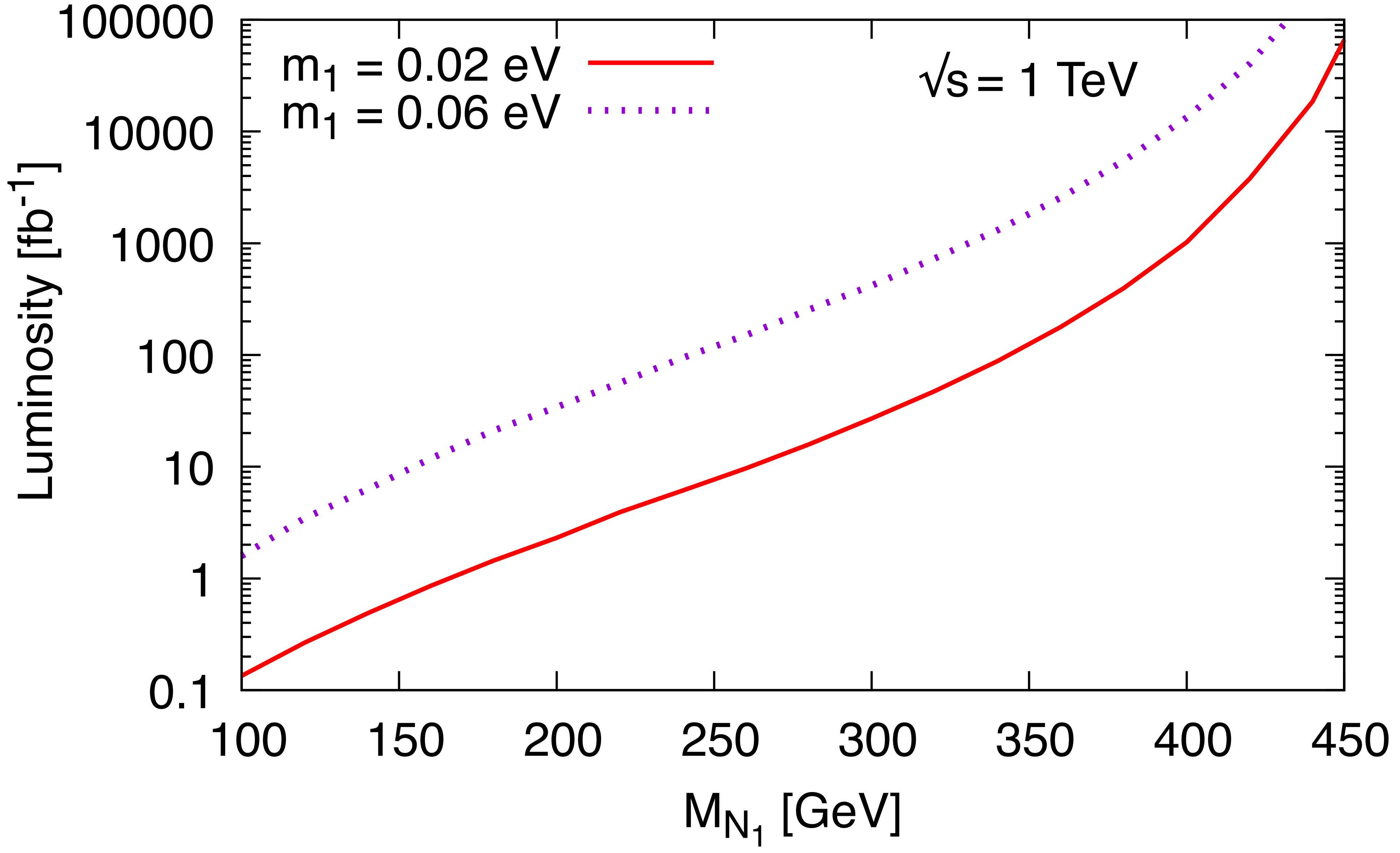
The SM background for this signal : 2ν+photon .

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

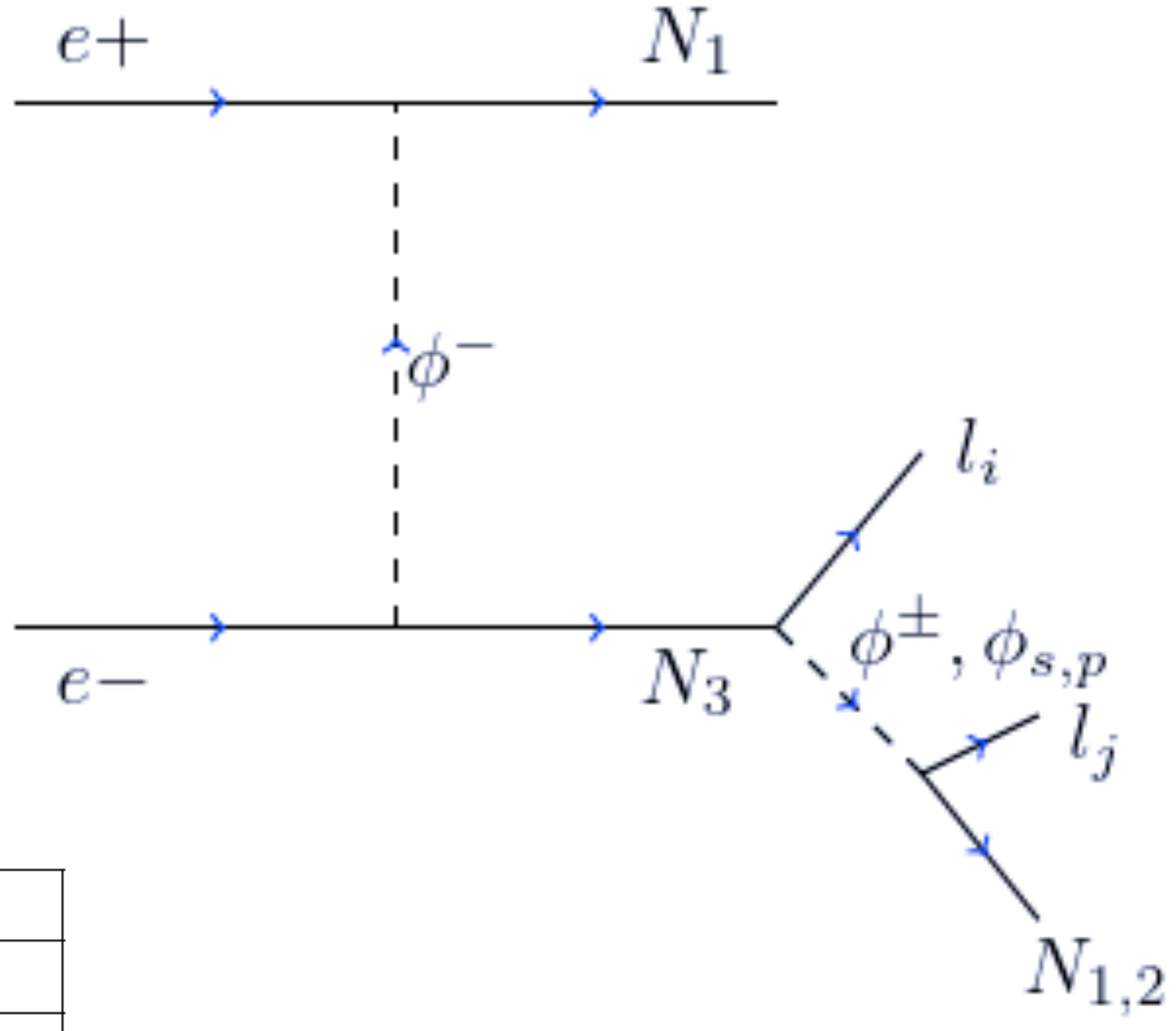


We have plotted the required luminosity for 5-σ detection For two different lightest neutrino mass values for varying Dark matter particle mass

$\tilde{\lambda}$ 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 + $\not{E}_T$ as signature.**

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

Benchmark Points :

<table>
<tr><th>BP1 (NH)</th><th>BP2 (NH)</th></tr>
<tr><td colspan="2">$\mu_\phi = 1$ TeV, $\lambda_1 = 0.004$, $\lambda_2 = 0.005$</td></tr>
<tr><td>$\widetilde{\lambda} = 1.24 \times 10^{-10}$, $M_{N_1} = 120$ GeV
$m_1 = 2.0 \times 10^{-11}$ GeV</td><td>$\widetilde{\lambda} = 7.32 \times 10^{-10}$, $M_{N_1} = 200$ GeV
$m_1 = 6.0 \times 10^{-11}$ GeV</td></tr>
<tr><td>$M_{N_2} = 130.07$ GeV, $M_{N_3} = 326.02$ GeV
$Y = \begin{pmatrix} 2.29 & -1.29 & 0.67 \\ 1.40 & 1.64 & -1.65 \\ 0.41 & 1.84 & 2.17 \end{pmatrix}$</td><td>$M_{N_2} = 201.94$ GeV, $M_{N_3} = 260.08$ GeV
$Y = \begin{pmatrix} 1.30 & -0.73 & 0.38 \\ 0.79 & 0.93 & -0.94 \\ 0.22 & 1 & 1.18 \end{pmatrix}$</td></tr>
</table>

Preliminary Cuts:

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

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

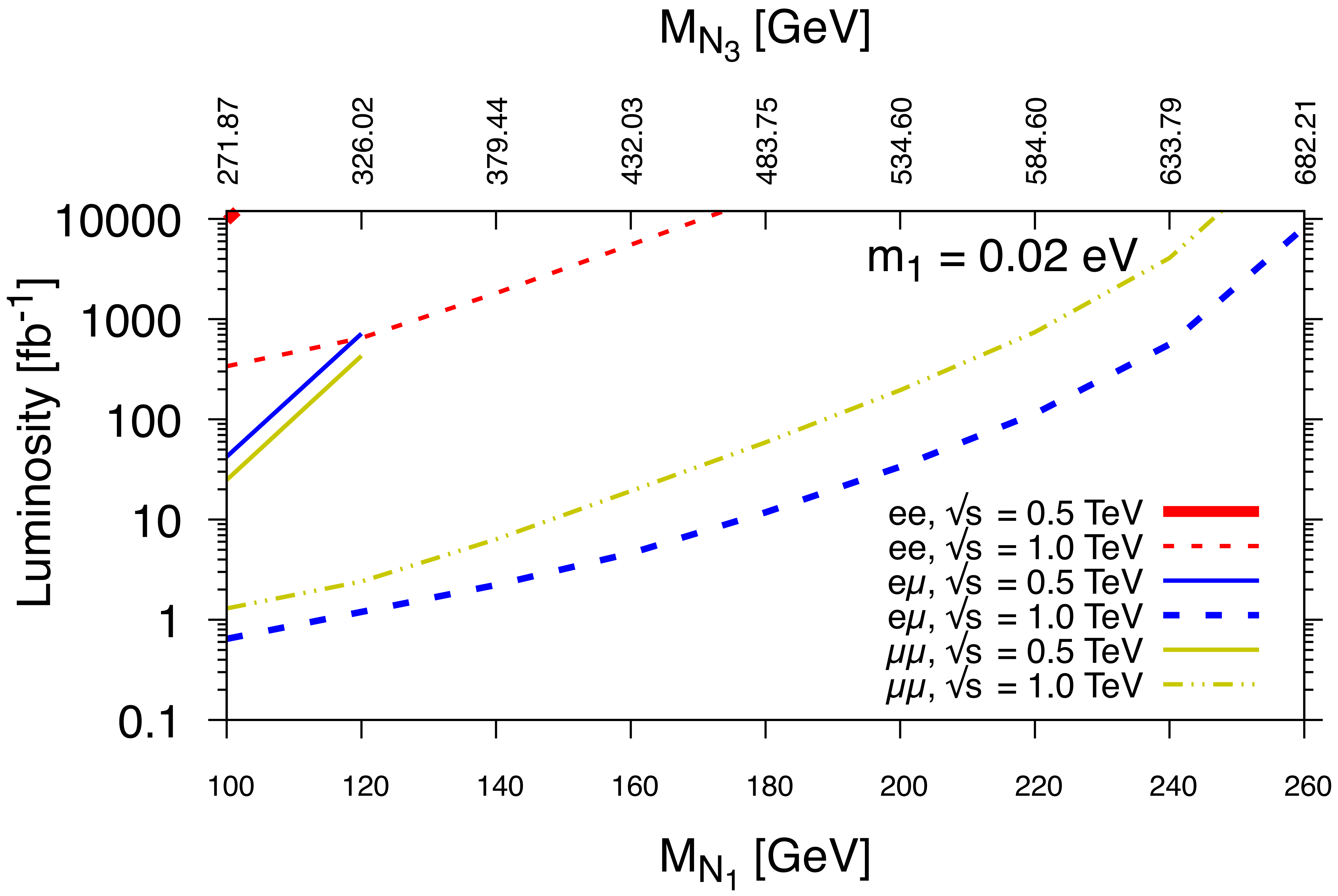
TABLE VI. Proposed cuts for signal OSD+$\not{E}_T$.

Cut Efficiency :

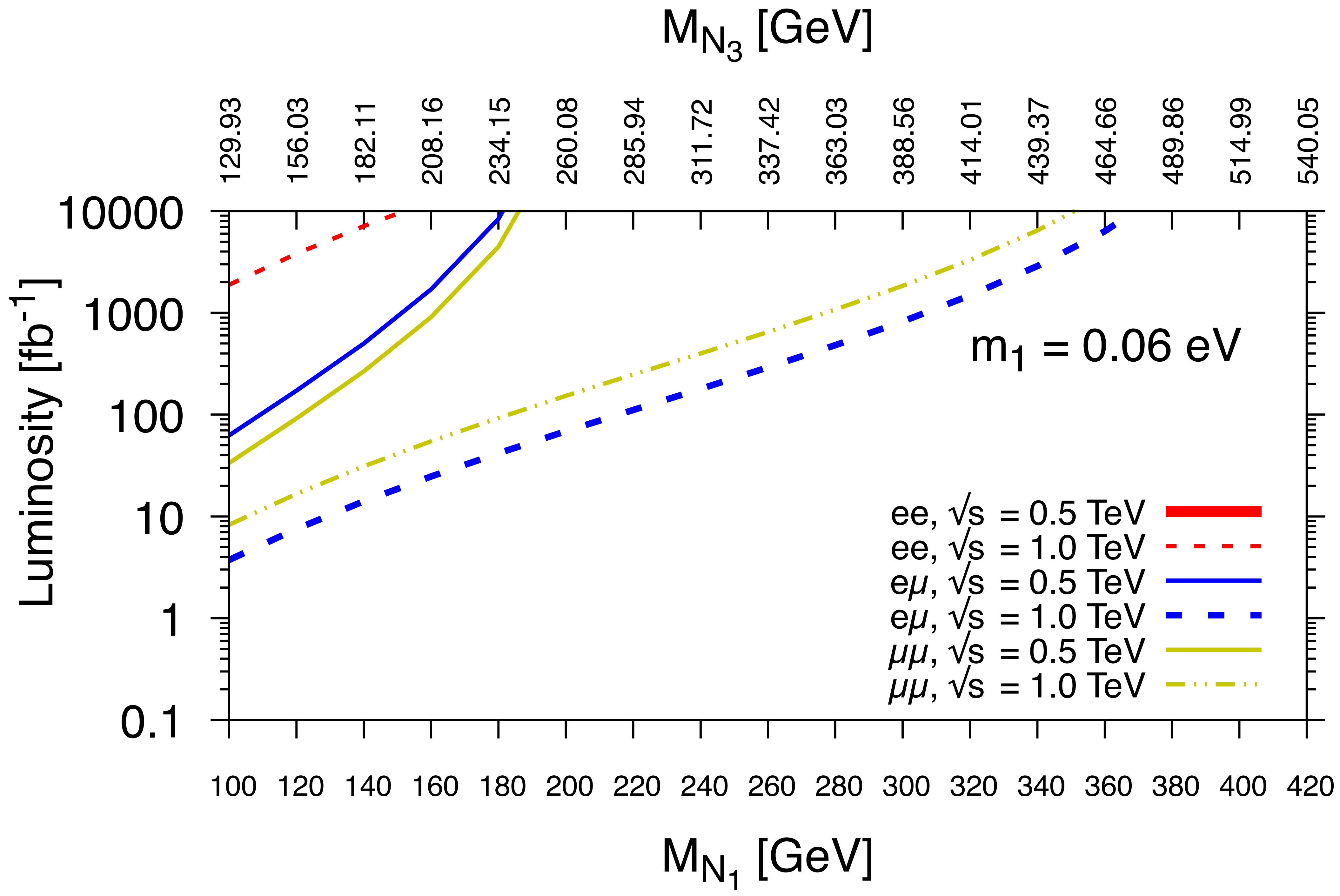
Cuts	BP1 (fb)	BP2 (fb)	Background (fb)
Preliminary	22.03	2.46	187.5
Reject $E_e > 300$ GeV	21	2.46	51.47
Reject $E_\mu > 300$ GeV	20.45	2.46	41.19
Reject $M_{e\mu} > 250$ GeV	20.45	2.46	33.31
Reject $\not{E}_T < 600$ GeV	18.55	2.45	16.56

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-σ 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

Theoretical constraints :

Vacuum stability conditions : $$\lambda, \lambda_\phi > 0, \;\; \lambda_1, \; \lambda_1 + \lambda_2 - |\tilde{\lambda}| > -2\sqrt{\lambda\lambda_\phi}$$

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

Experimental constraints :

Gauge boson decay widths : $$m_{\phi_s} + m_{\phi_p} > m_Z, \;\; m_{\phi^\pm} + m_{\phi_p} > m_W,$$ $$2m_{\phi^\pm} > m_Z, \;\; m_{\phi^\pm} + m_{\phi_s} > m_W$$

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

Mass Variations :

To See how the masses of other right handed neutrino varies, we have plotted them with varying the lightest neutrino mass

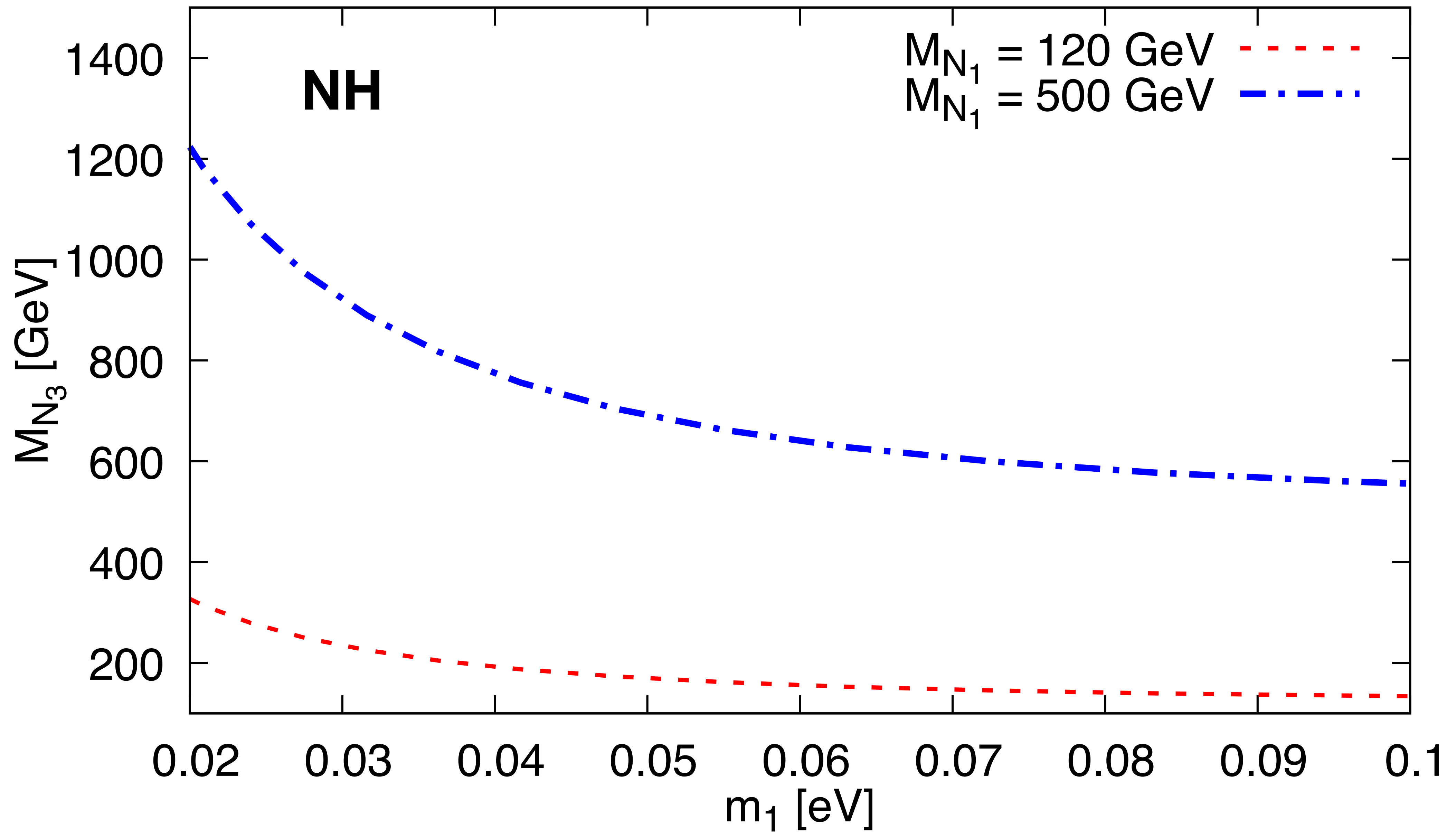
In the Normal Hierarchy, M_{N_2} is almost degenerate with M_{N_1}

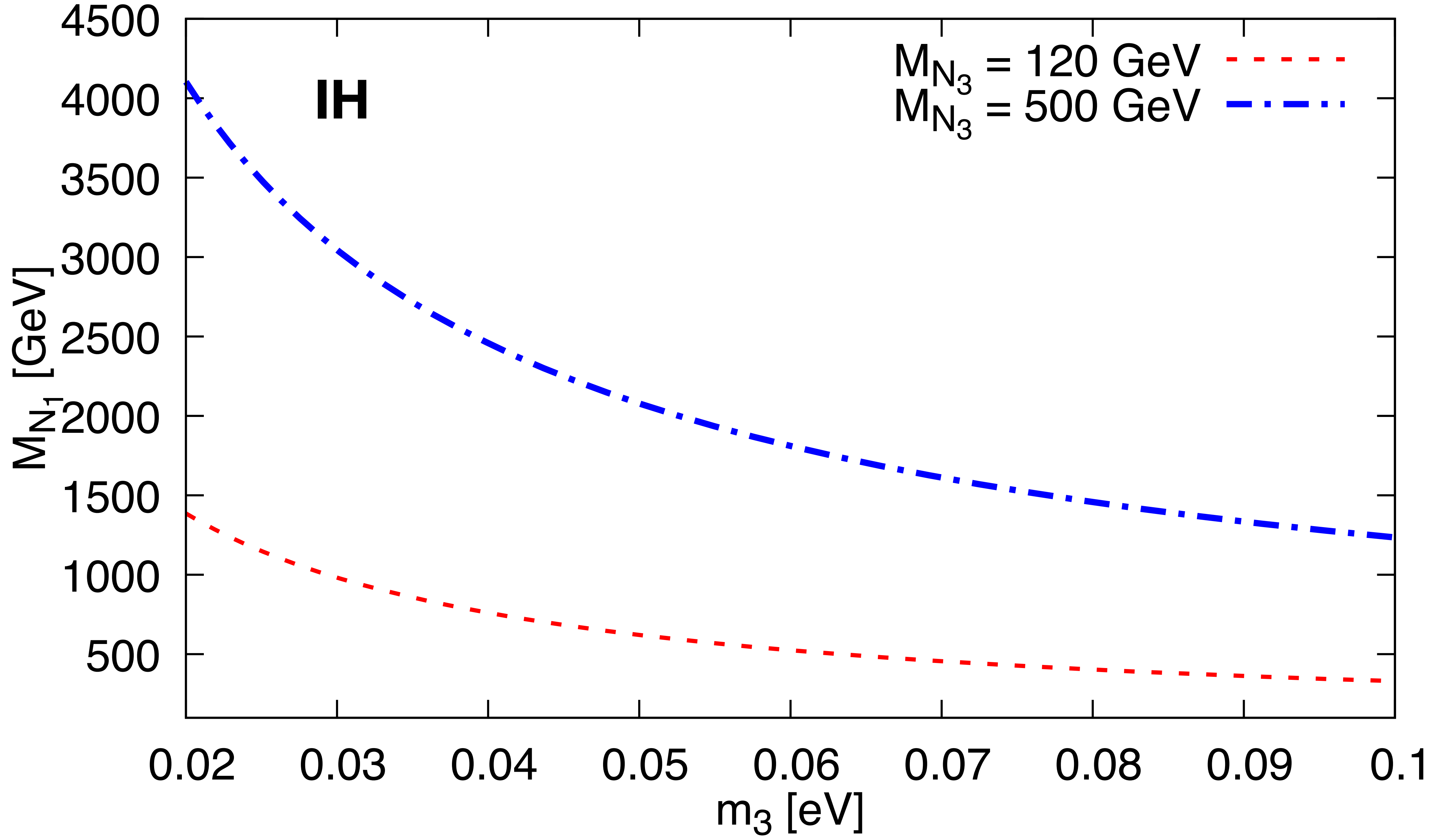
The value of M_{N_3} reduces with the increasing the lightest neutrino mass

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

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

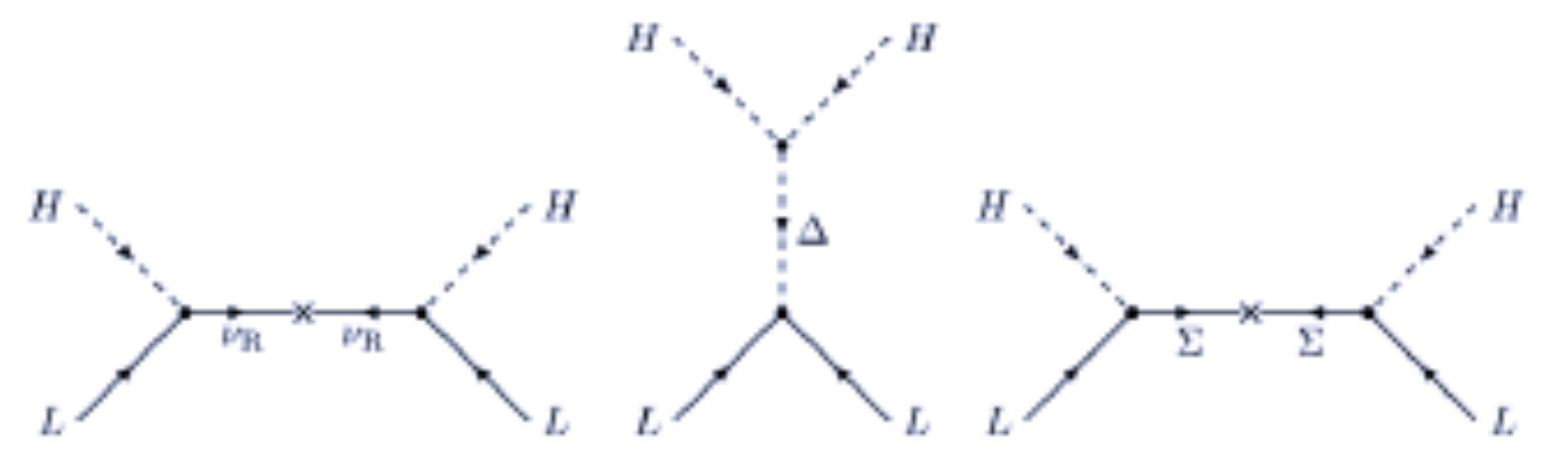
Weinberg Operator

$$\frac{LLHH}{\Lambda}, \quad m_\nu = \frac{v^2}{\Lambda}$$

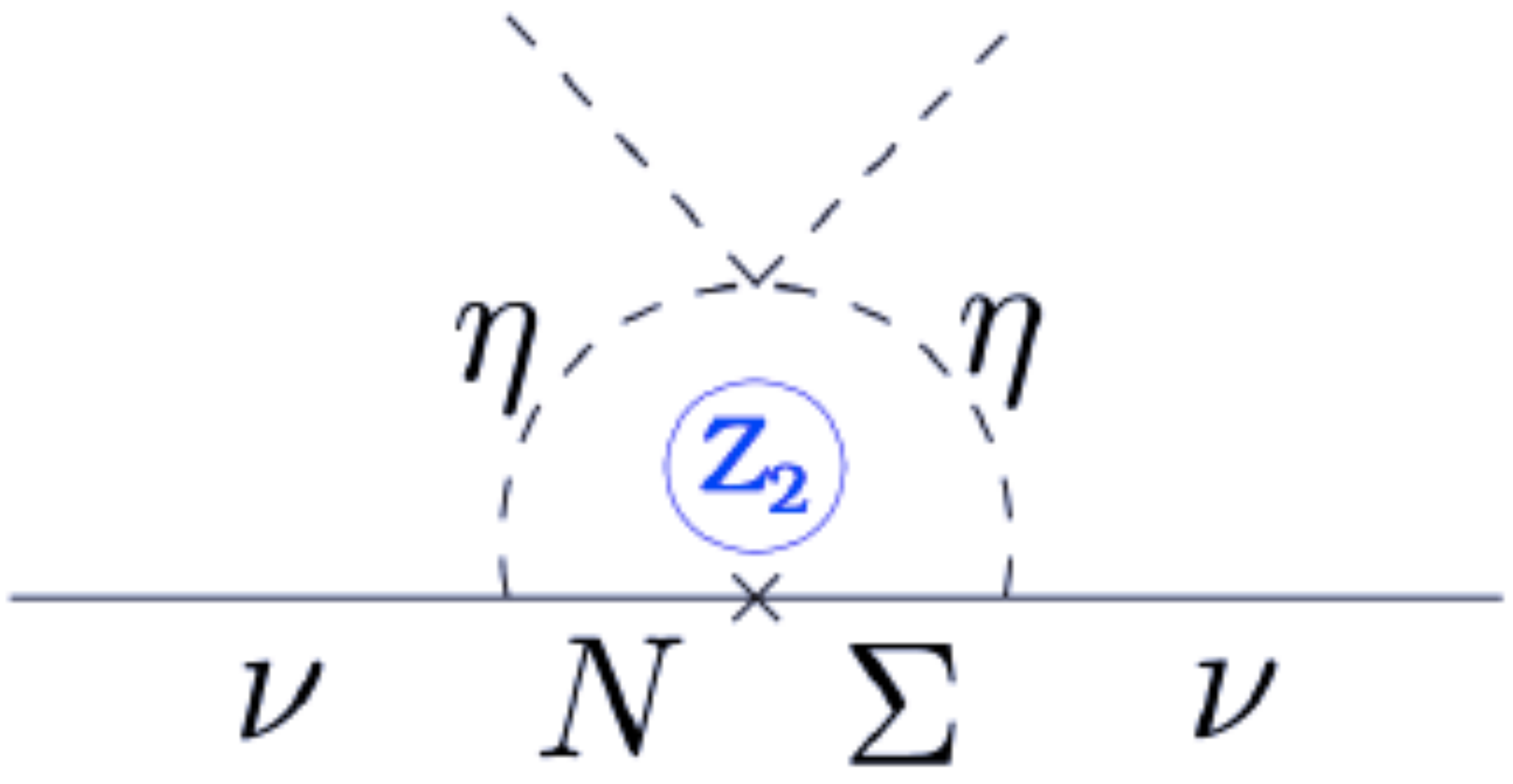
Gener^{d} Weinberg Operator

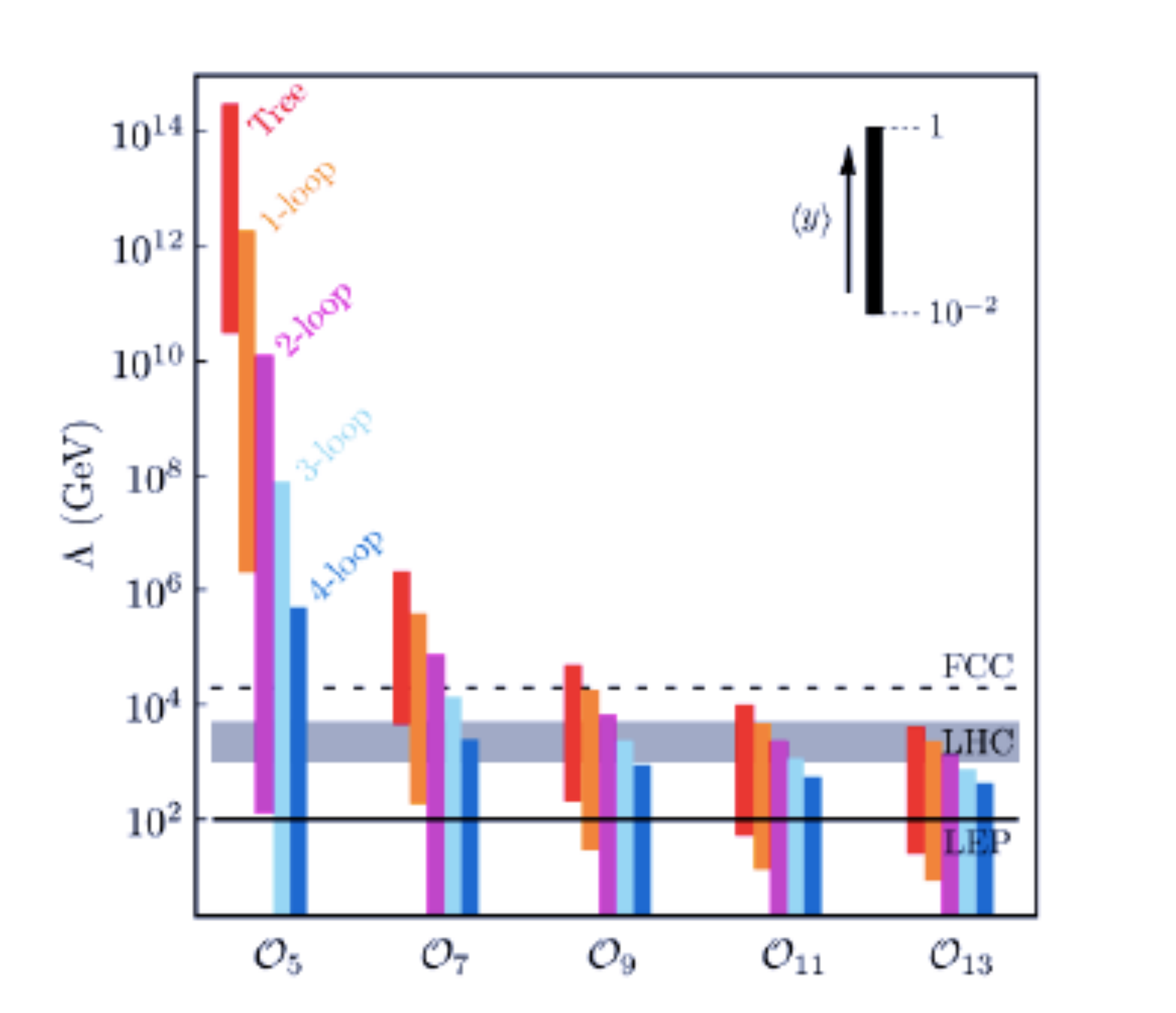
$$\frac{LLHH\left(H^\dagger H\right)^n}{\Lambda^{2n+1}}, \quad m_\nu \sim \epsilon \left(\frac{1}{16\pi^2}\right)^n \left(\frac{v}{\Lambda}\right)^{d-5} \frac{v^2}{\Lambda}$$

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