# Searches for heavy neutral leptons: beyond simplified scenarios


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In collab. with A. Abada, X. Marcano and P. Escribano

# Outline of the talk

- Collider searches of Heavy Neutral Leptons (HNL) (*1 HNL + single mixing hypothesis*)
- How to reinterpret the bounds on $|V_{\ell N}|^2$ in two cases:
    - One HNL mixing with 3 active flavors $(e\,,\mu\,,\tau)$
    - Two HNLs interfering in the LNC/LNV processes $(W^+ \to \ell_1^+ \ell_2^\pm q\bar{q}')$

# Neutrino window to new physics

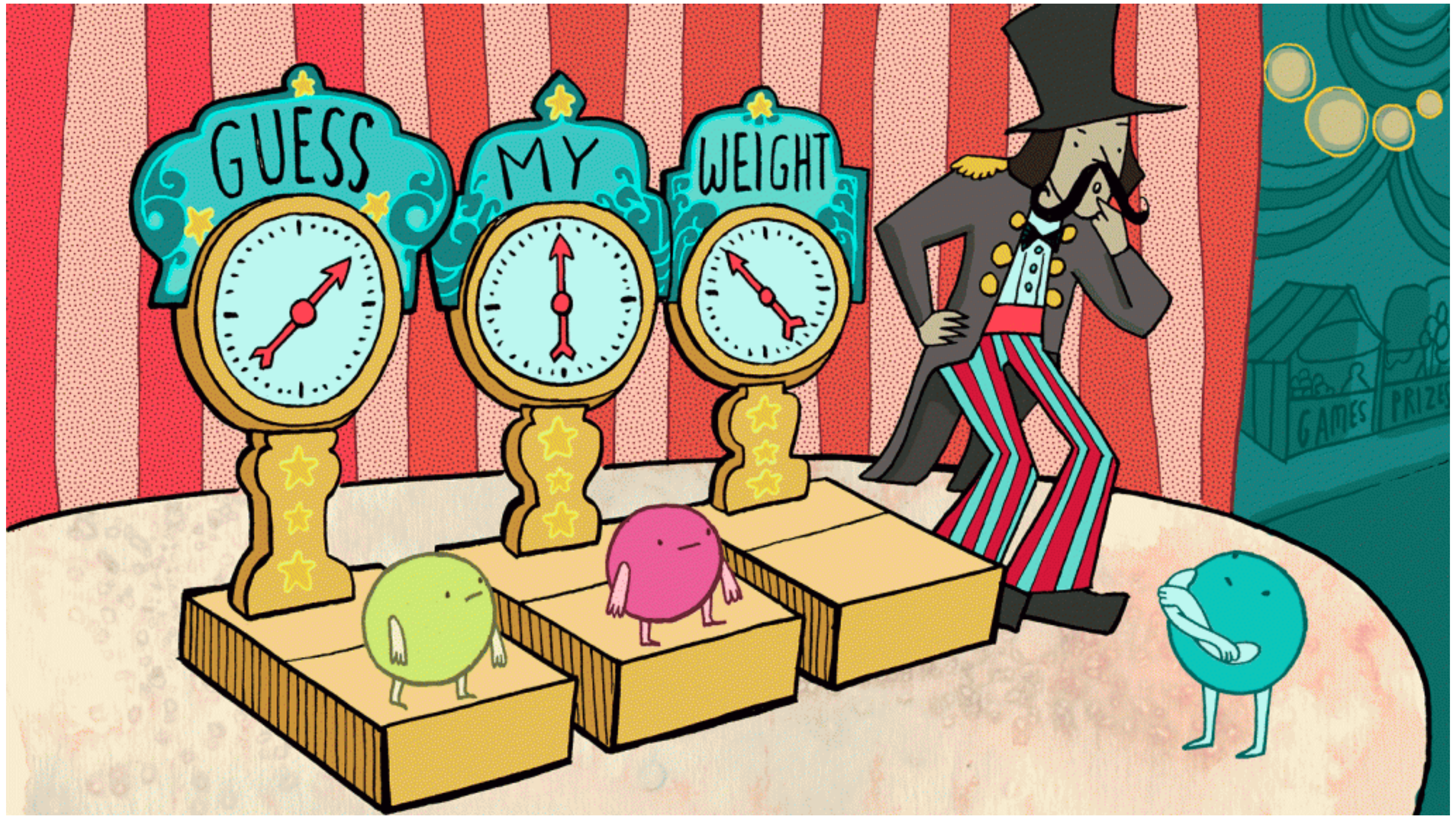
Neutrino oscillations establish that at least **two** of the SM neutrinos have masses $\neq 0$

$$\theta_{12} \simeq 33^\circ \quad \theta_{23} \simeq 49^\circ \quad \theta_{13} \simeq 8^\circ$$

$$\Delta m^2_{12} \simeq 7 \times 10^{-5}\ \text{eV}^2$$

$$\Delta m^2_{3\ell} \simeq \pm 2.5 \times 10^{-3}\ \text{eV}^2$$

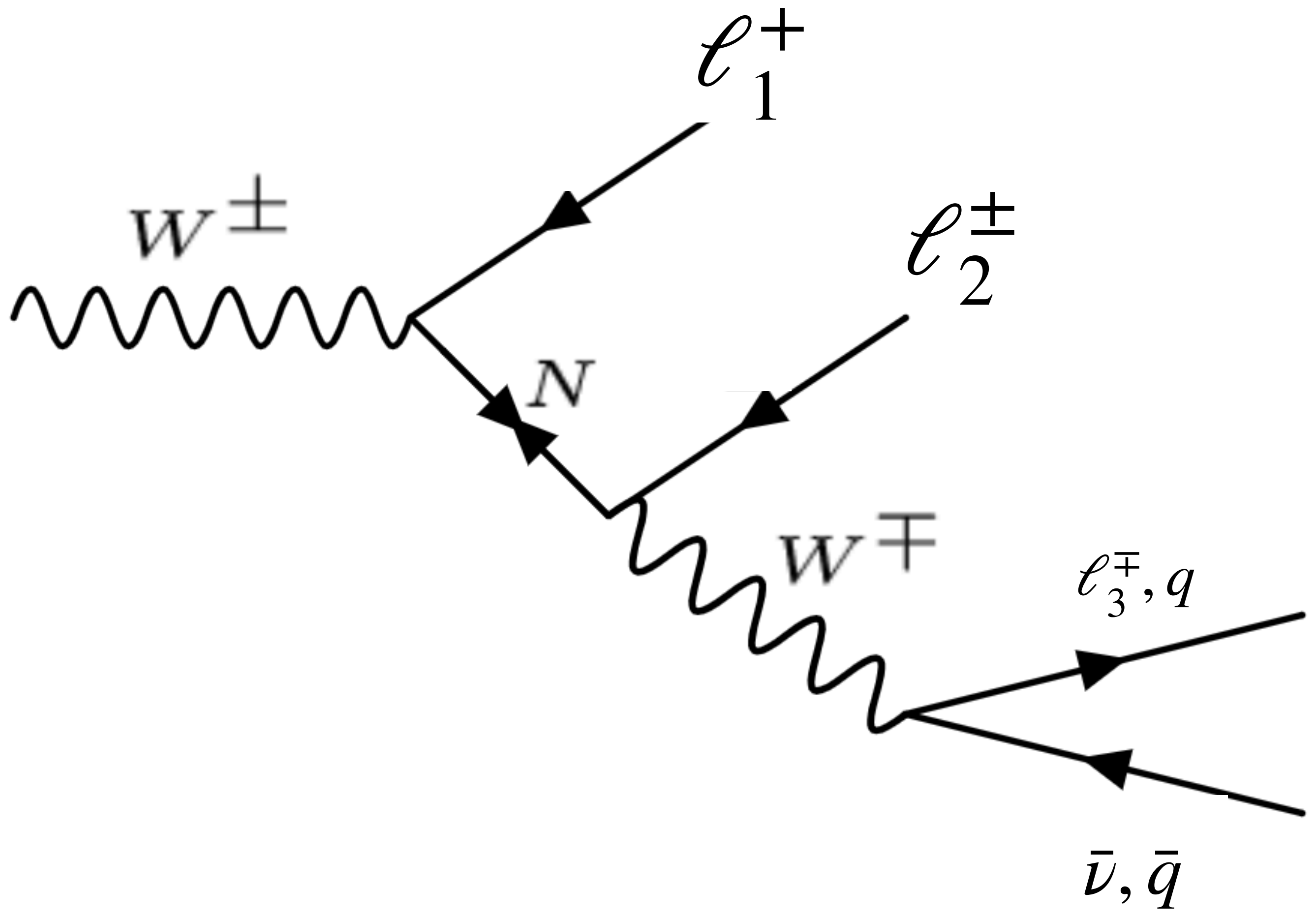
see [2111.03086]




New neutral fermions are common byproducts of $\nu$ mass generation.

The case with **2 HNLs** is the minimal phenomenologically viable when embedding a seesaw.

# HNL collider searches

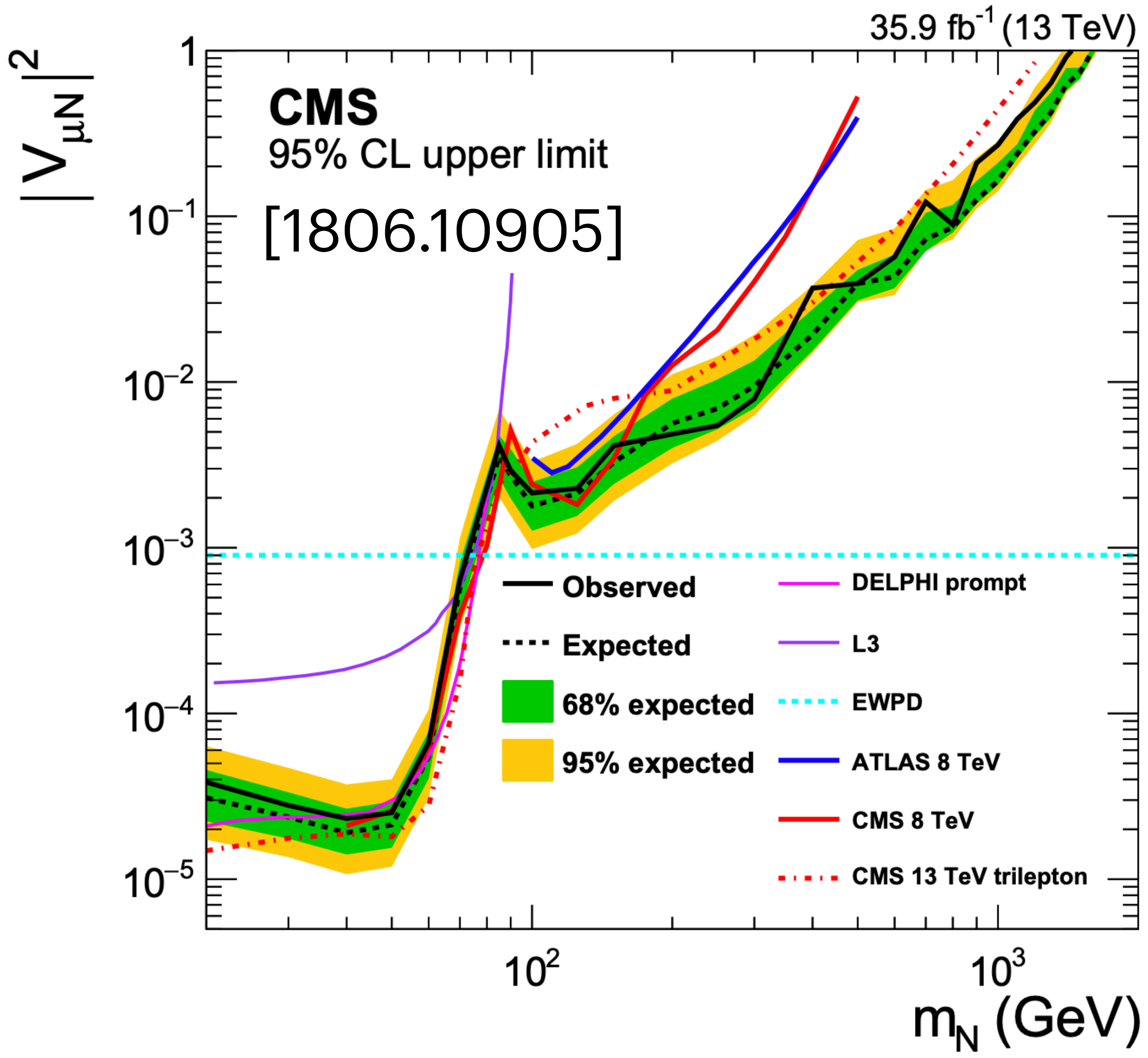



## 3 leptons + ME

| | | | |
|---|---|---|---|
| CMS [1802.02965] | LNV, LFV or LFC | $pp \to \ell_1^+ \ell_2^+ \ell_3^- + \mathrm{ME}\ (1,2,3 = \mu, e)$ | $[1,1200]\,\mathrm{GeV}$ |
| ATLAS [1905.09787] | LNV, LFC | $pp \to \ell^+ \ell^+ \ell'^- + \mathrm{ME}\ (\ell^{(')} = \mu, e)$ | $[5,50]\,\mathrm{GeV}$ |

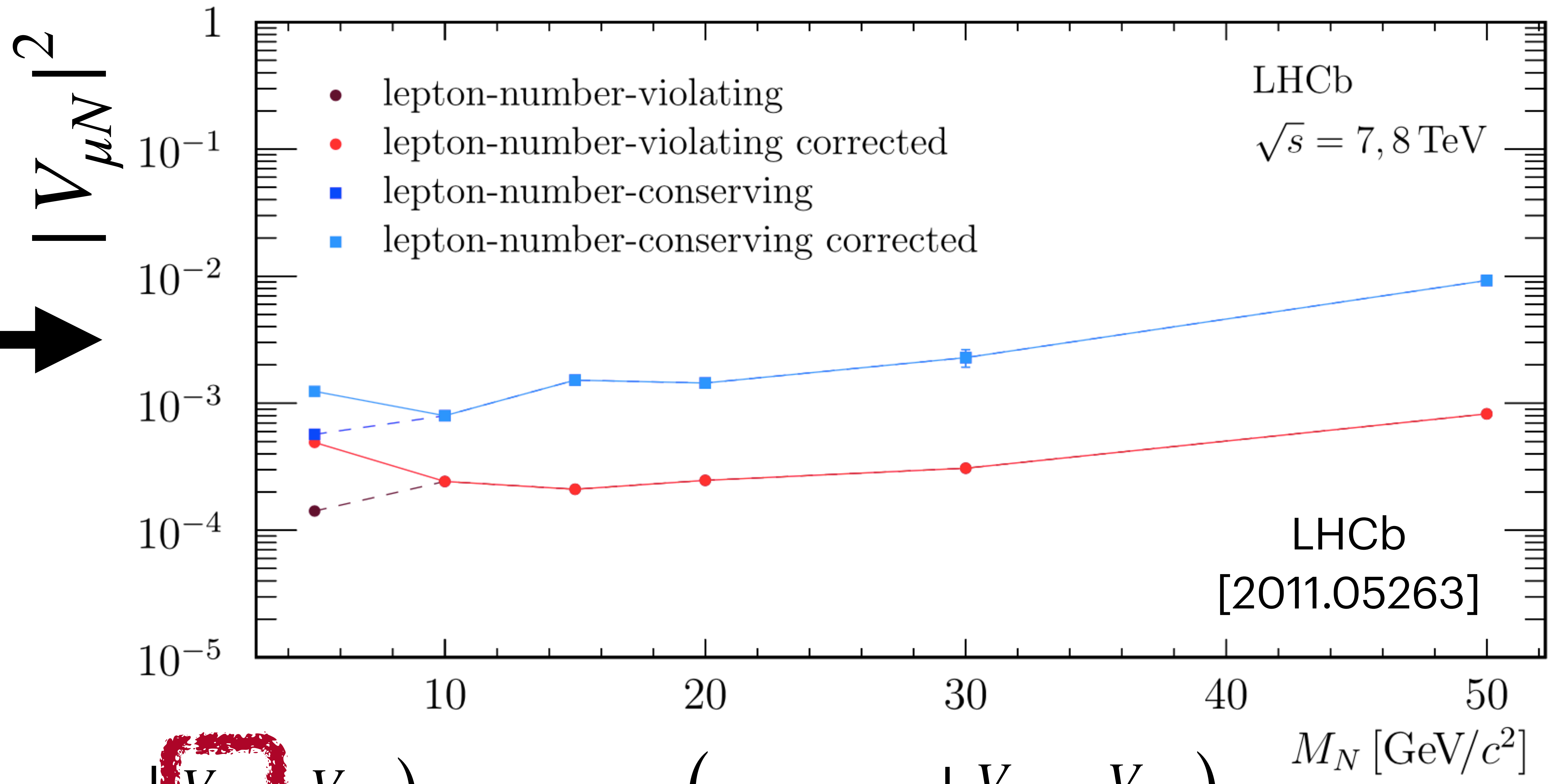
## 2 leptons + jets

| | | | |
|---|---|---|---|
| ATLAS [1506.06020] | LNV, LFC | $pp \to \ell_1^\pm \ell_2^\pm j \quad (1,2 = \mu, e)$ | $[100,500]\,\mathrm{GeV}$ |
| CMS [1806.10905] | LNV, LFV or LFC | $pp \to \ell^\pm \ell^\pm j \quad (\ell = \mu, e)$ | $[20,1600]\,\mathrm{GeV}$ |
| LHCb [2011.05263] | LNC or LNV, LFC | $pp \to \mu^+ \mu^\pm j$ | $[5,50]\,\mathrm{GeV}$ |



Experimental searches generally assume **one** generic HNL and **single mixing hypothesis** $(V_{\alpha N})$

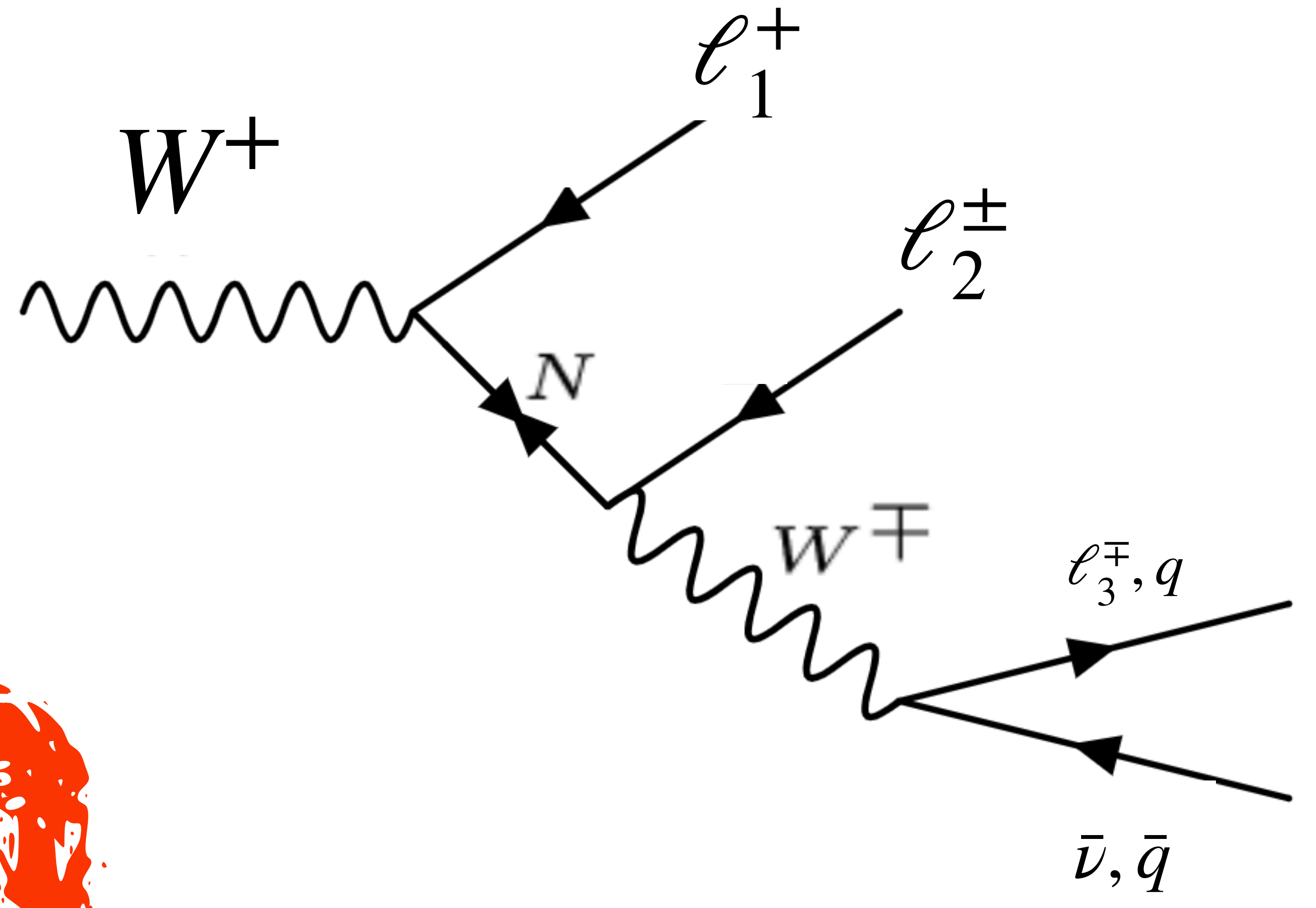
$$V = \begin{pmatrix} \tilde{V}_{PMNS} & \begin{matrix} V_{eN_1} & V_{eN_2} \\ V_{\mu N_1} & V_{\mu N_2} \\ V_{\tau N_1} & V_{\tau N_2} \end{matrix} \\ & \end{pmatrix}$$




Relax these assumptions:

$$V = \begin{pmatrix} \tilde{V}_{PMNS} & \begin{matrix} V_{eN_1} & V_{eN_2} \\ V_{\mu N_1} & V_{\mu N_2} \\ V_{\tau N_1} & V_{\tau N_2} \end{matrix} \\ & \end{pmatrix} \quad \text{or} \quad V = \begin{pmatrix} \tilde{V}_{PMNS} & \begin{matrix} V_{eN_1} & V_{eN_2} \\ V_{\mu N_1} & V_{\mu N_2} \\ V_{\tau N_1} & V_{\tau N_2} \end{matrix} \\ & \end{pmatrix}$$

# HNL collider searches

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See [Tastet et al. 2107.12980]

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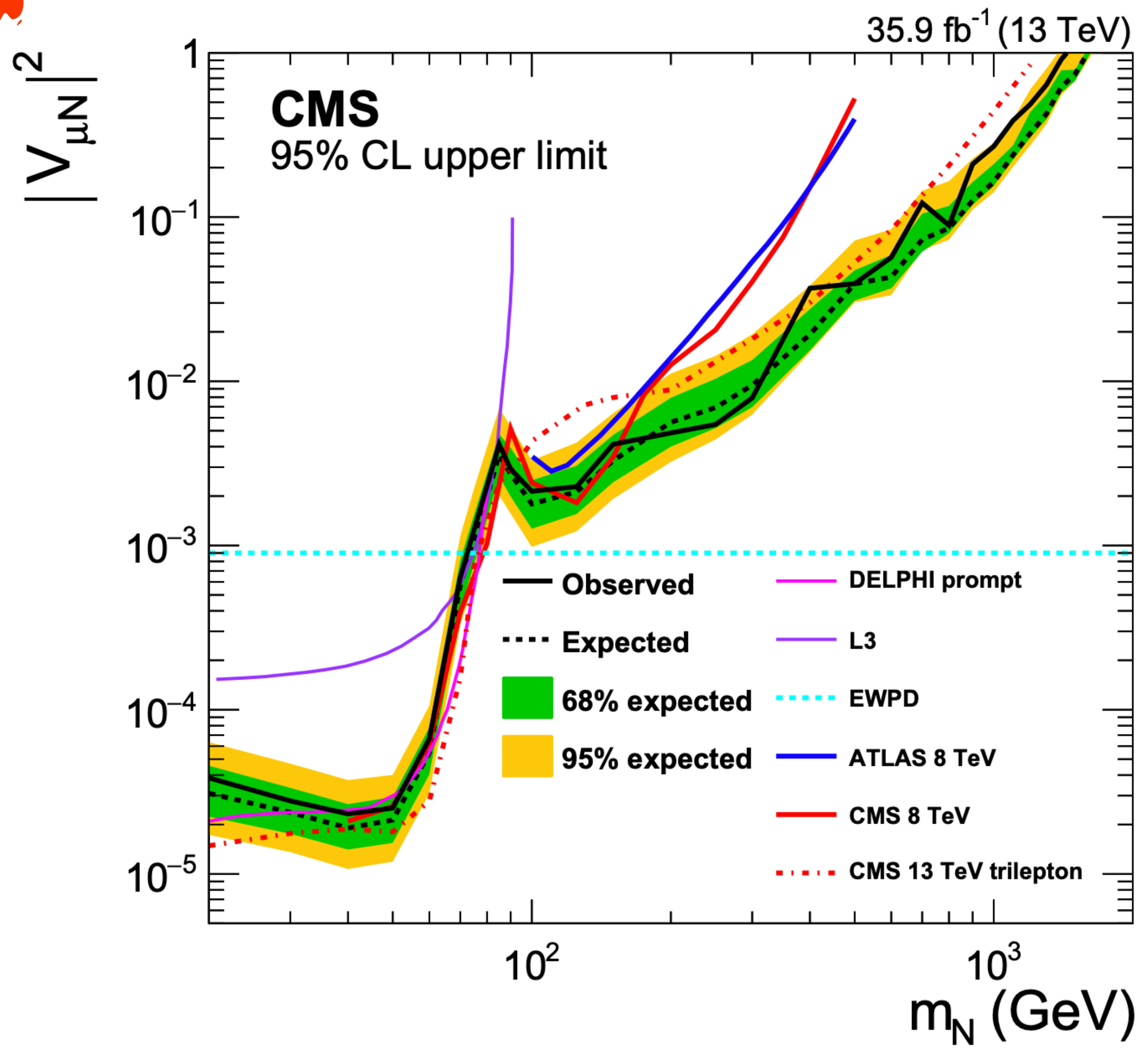

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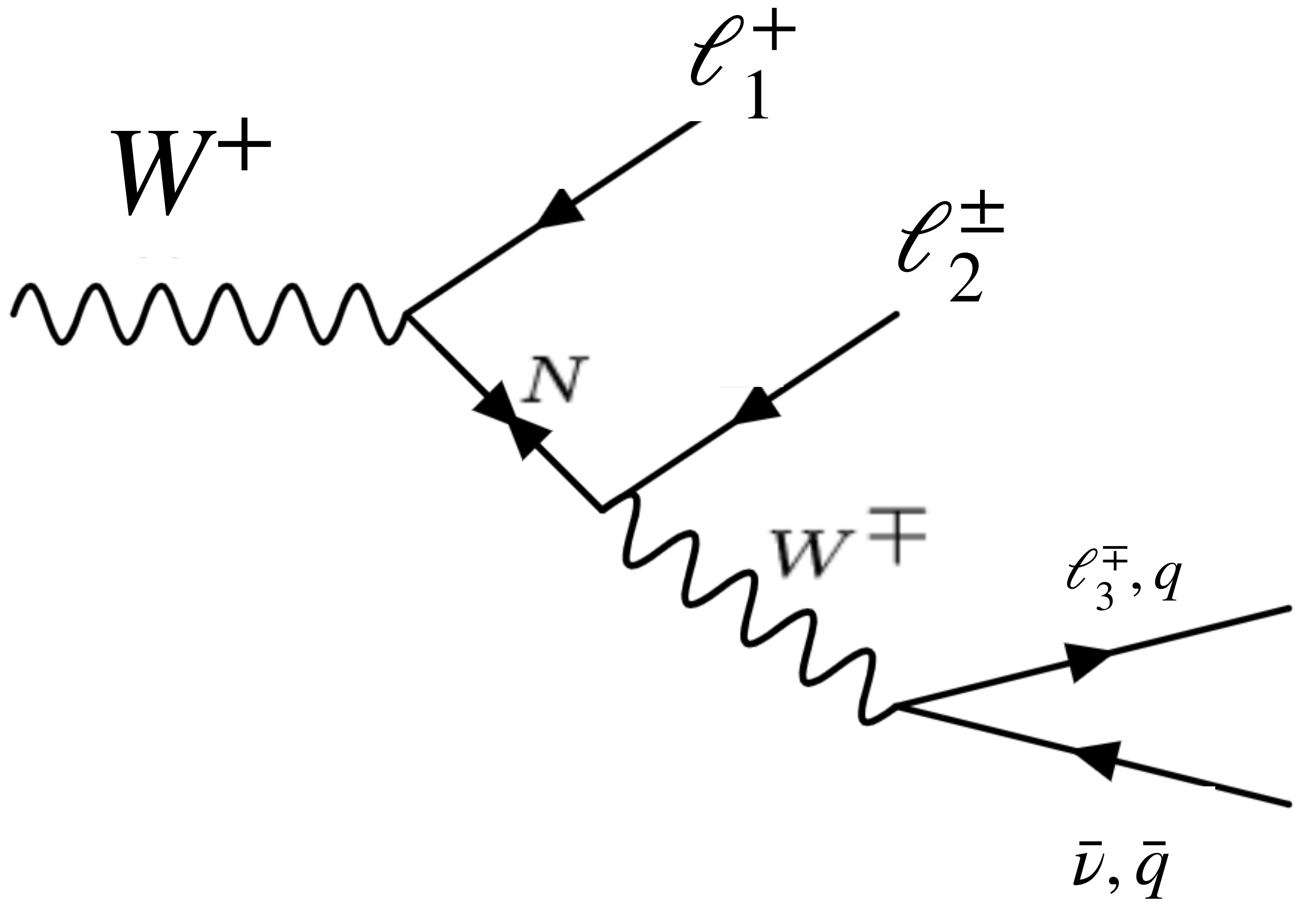


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## 2 leptons + jets

| | | | |
|---|---|---|---|
| ATLAS [illegible] | LNV, LFC | $pp \to \ell_1^\pm \ell_2^\pm j \quad (1,2 = \mu, e)$ | $[100,500]\,\mathrm{GeV}$ |
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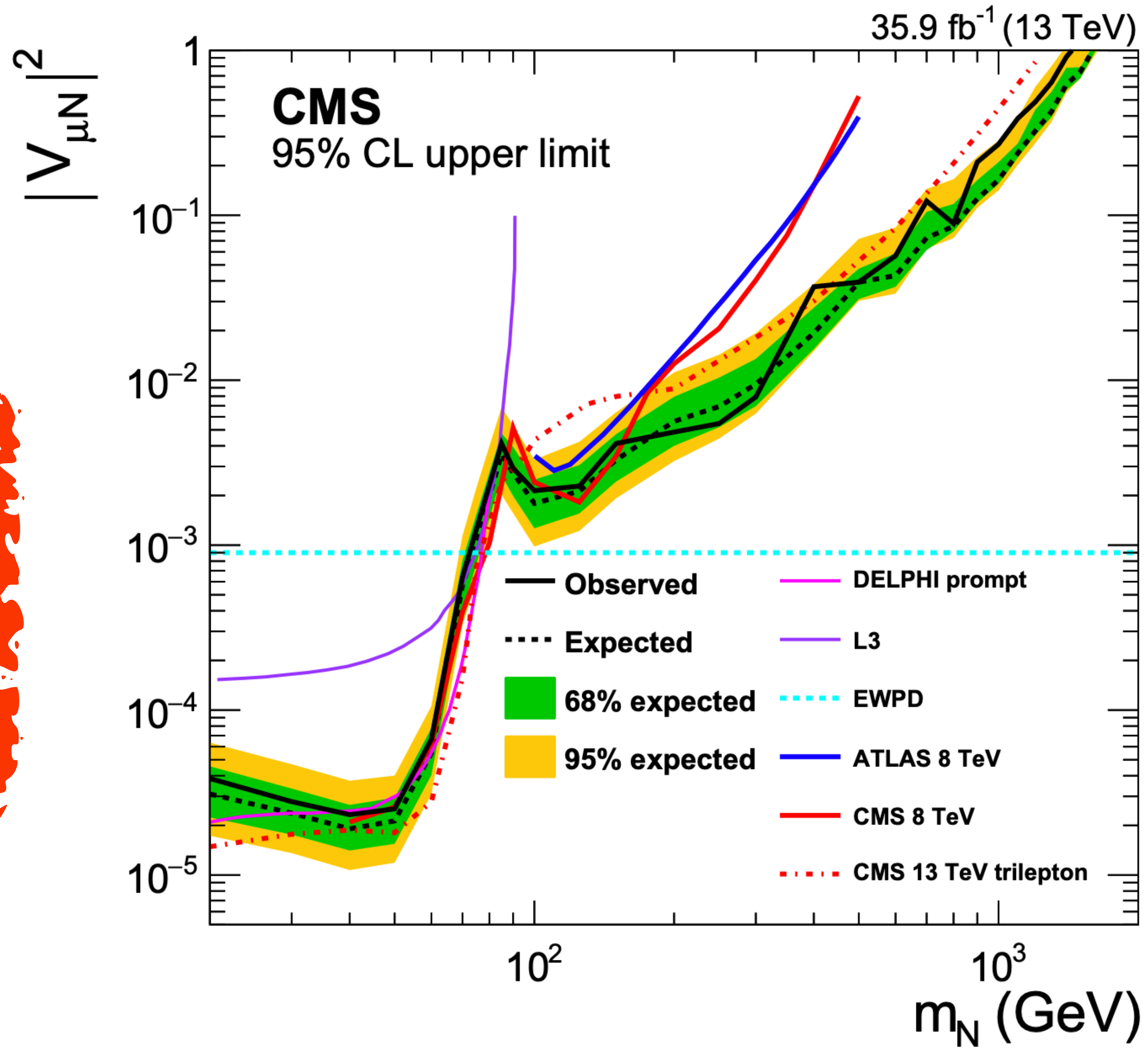
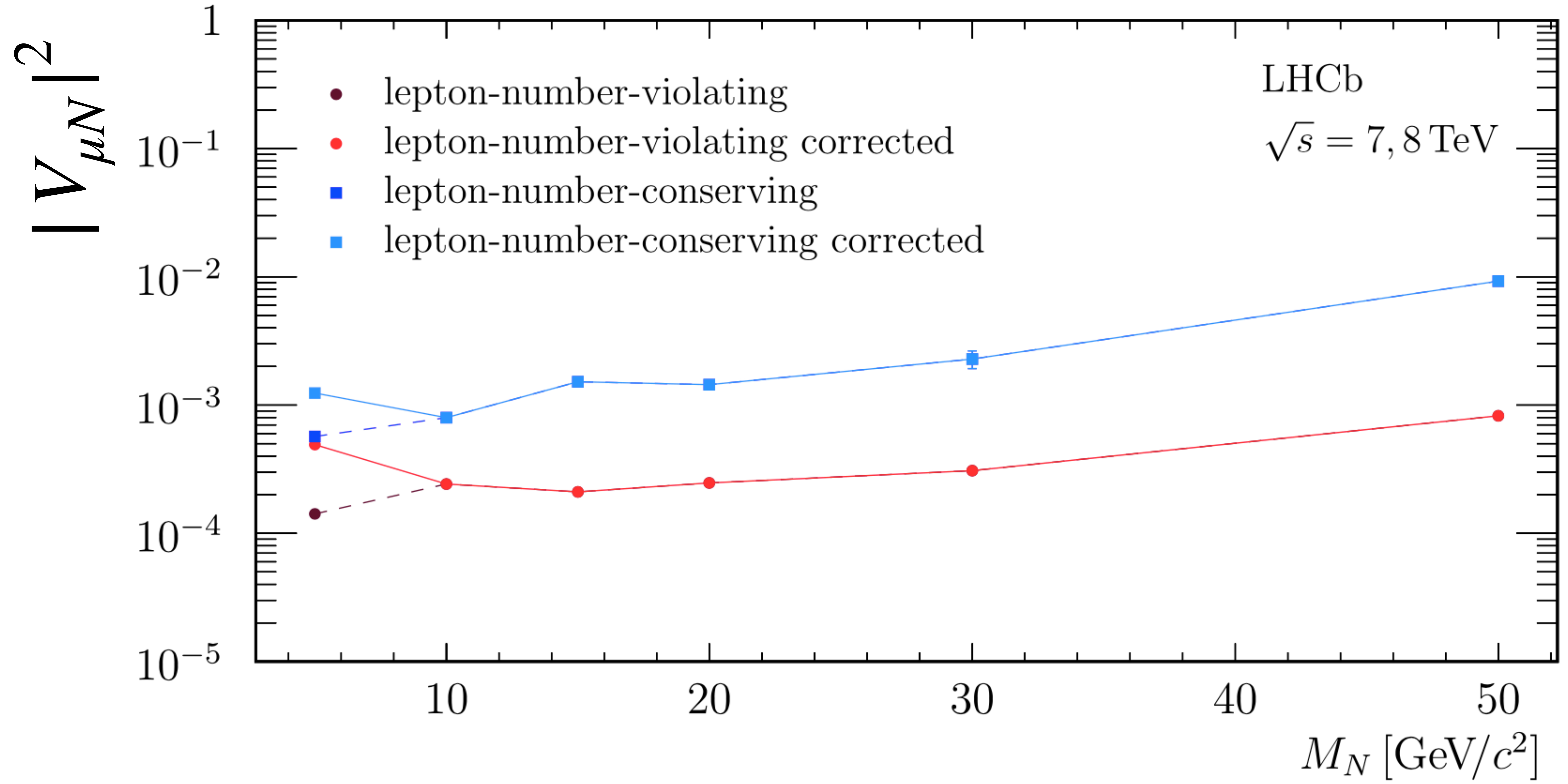
Short-lived HNL

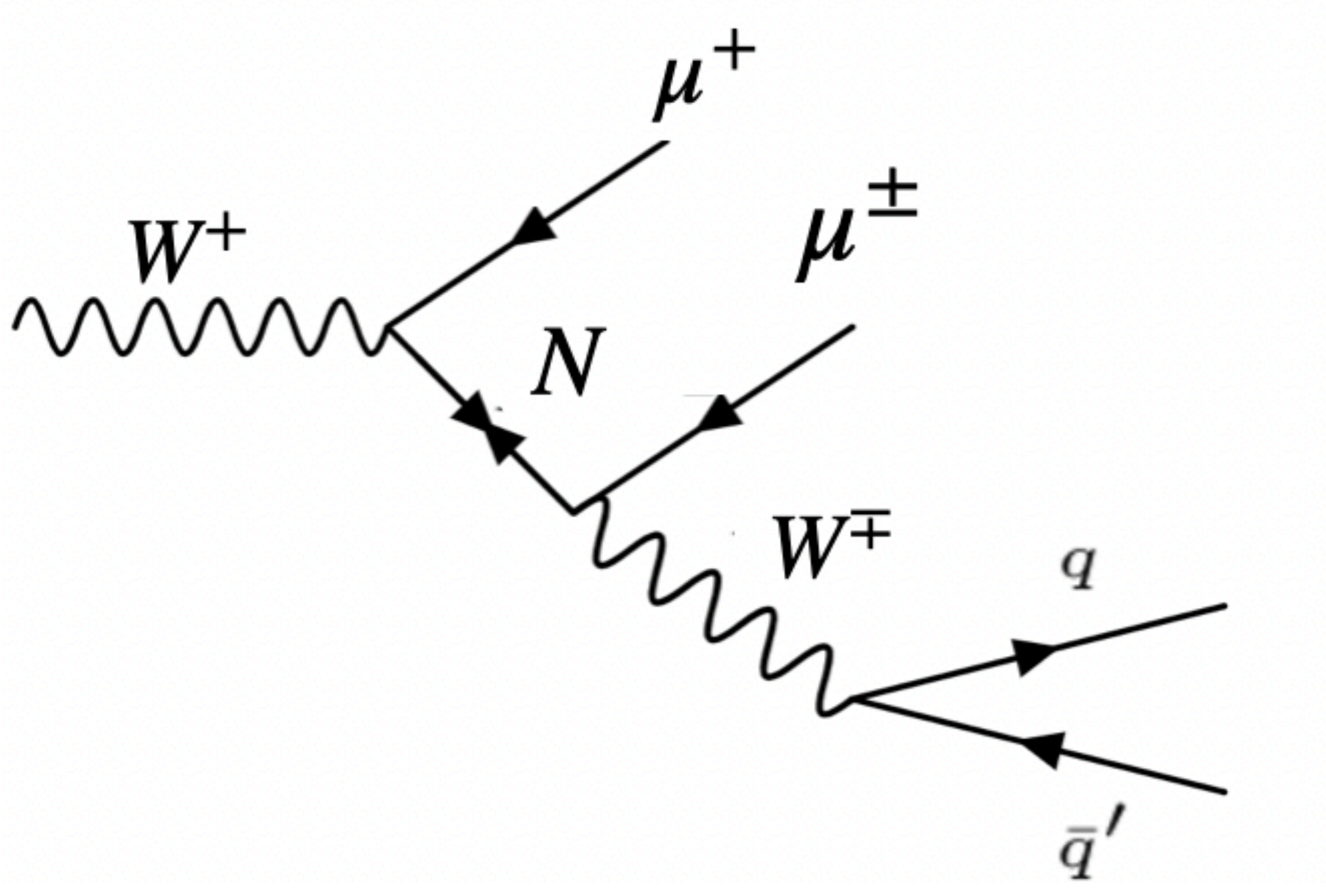


# 2 leptons + jets: generic mixing pattern (1HNL)

$$V = \left(\begin{array}{c|cc} & V_{eN_1} & V_{eN_2} \\ \tilde{V}_{PMNS} & V_{\mu N_1} & V_{\mu N_2} \\ & V_{\tau N_1} & V_{\tau N_2} \\ \hline & & \end{array}\right)$$

# 2 leptons + jets: generic mixing pattern (1HNL)



# 2 leptons + jets: generic mixing pattern (1HNL)

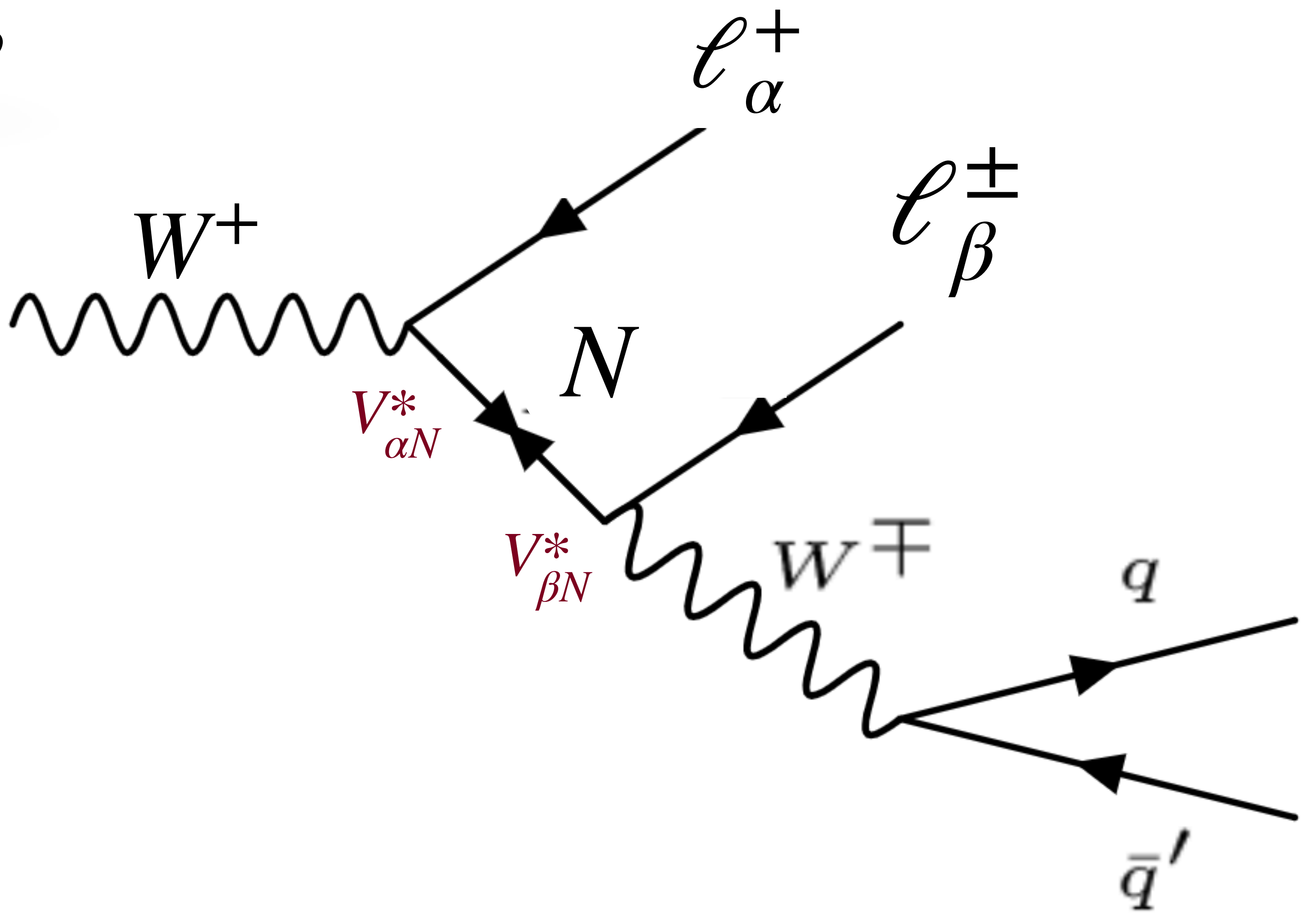
$$\Gamma(W^+ \to \ell_\alpha^+ \ell_\beta^\pm q\bar{q}') = \Gamma(W^+ \to \ell_\alpha^+ N) \times \mathrm{Br}(\mathrm{N} \to \ell_\beta^\pm \mathrm{q}\bar{\mathrm{q}}') \propto |\mathrm{V}_{\alpha \mathrm{N}}|^2 \times \mathrm{Br}(\mathrm{N} \to \ell_\beta^\pm \mathrm{q}\bar{\mathrm{q}}')$$

$$\frac{\Gamma(N \to \ell_\beta^\pm q\bar{q}')}{\Gamma_N}$$

- Single mixing ($\alpha = \beta$): $\Gamma_N^{\mathrm{Sing}} = |V_{\alpha N}|^2 \tilde{\Gamma}_N^\alpha$
- Generic mixing: $\Gamma_N^{\mathrm{Gen}} = |V_{eN}|^2 \tilde{\Gamma}_N^e + |V_{\mu N}|^2 \tilde{\Gamma}_N^\mu + |V_{\tau N}|^2 \tilde{\Gamma}_N^\tau$,

$$V = \begin{pmatrix} & & V_{eN_1} & V_{eN_2} \\ \tilde{V}_{PMNS} & & V_{\mu N_1} & V_{\mu N_2} \\ & & V_{\tau N_1} & V_{\tau N_2} \\ \hline & & & \end{pmatrix}$$

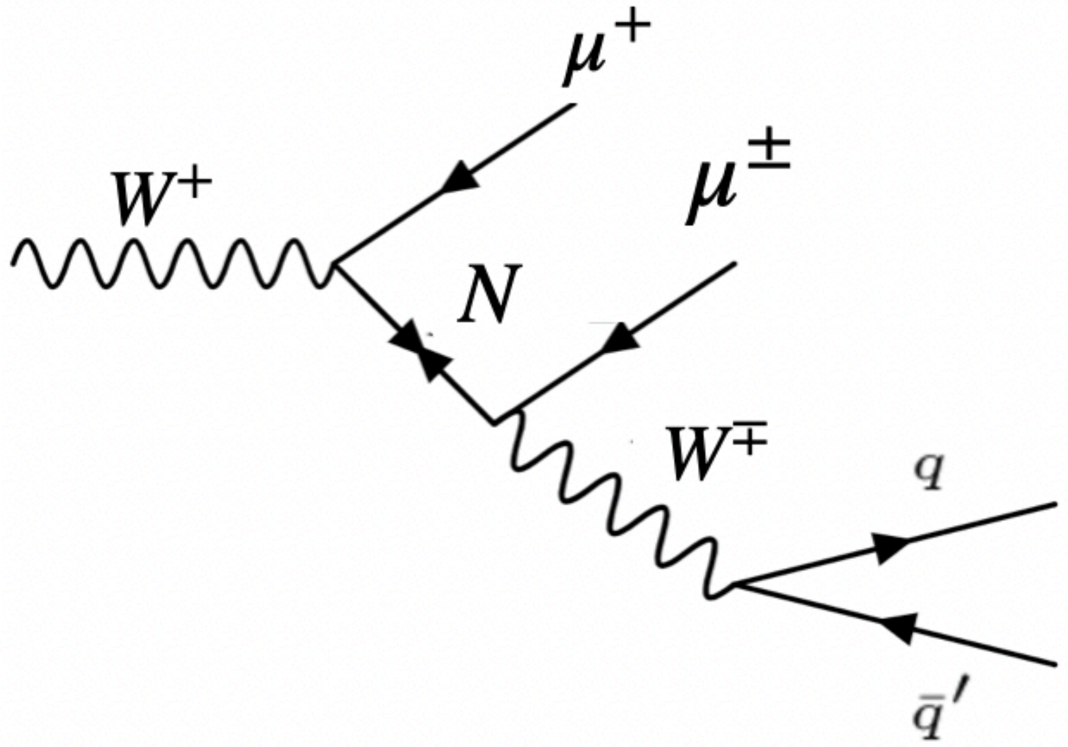
$$|V_{\mu N_1}|^2_{\mathrm{Gen}} = |V_{\mu N_1}|^2_{\mathrm{Sing}} \frac{\Gamma_N^{\mathrm{Gen}}}{\Gamma_N^{\mathrm{Sing}}}$$

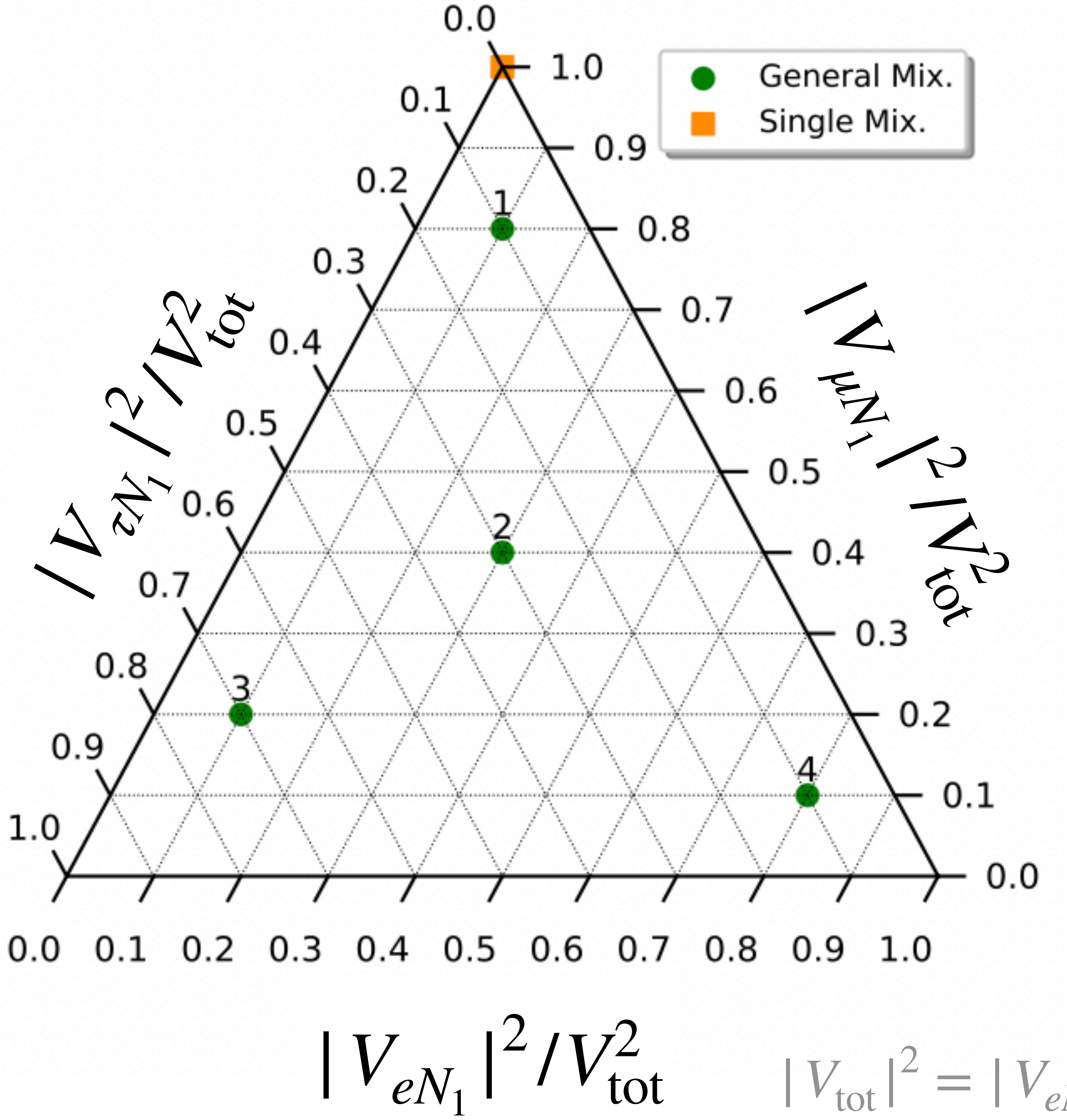


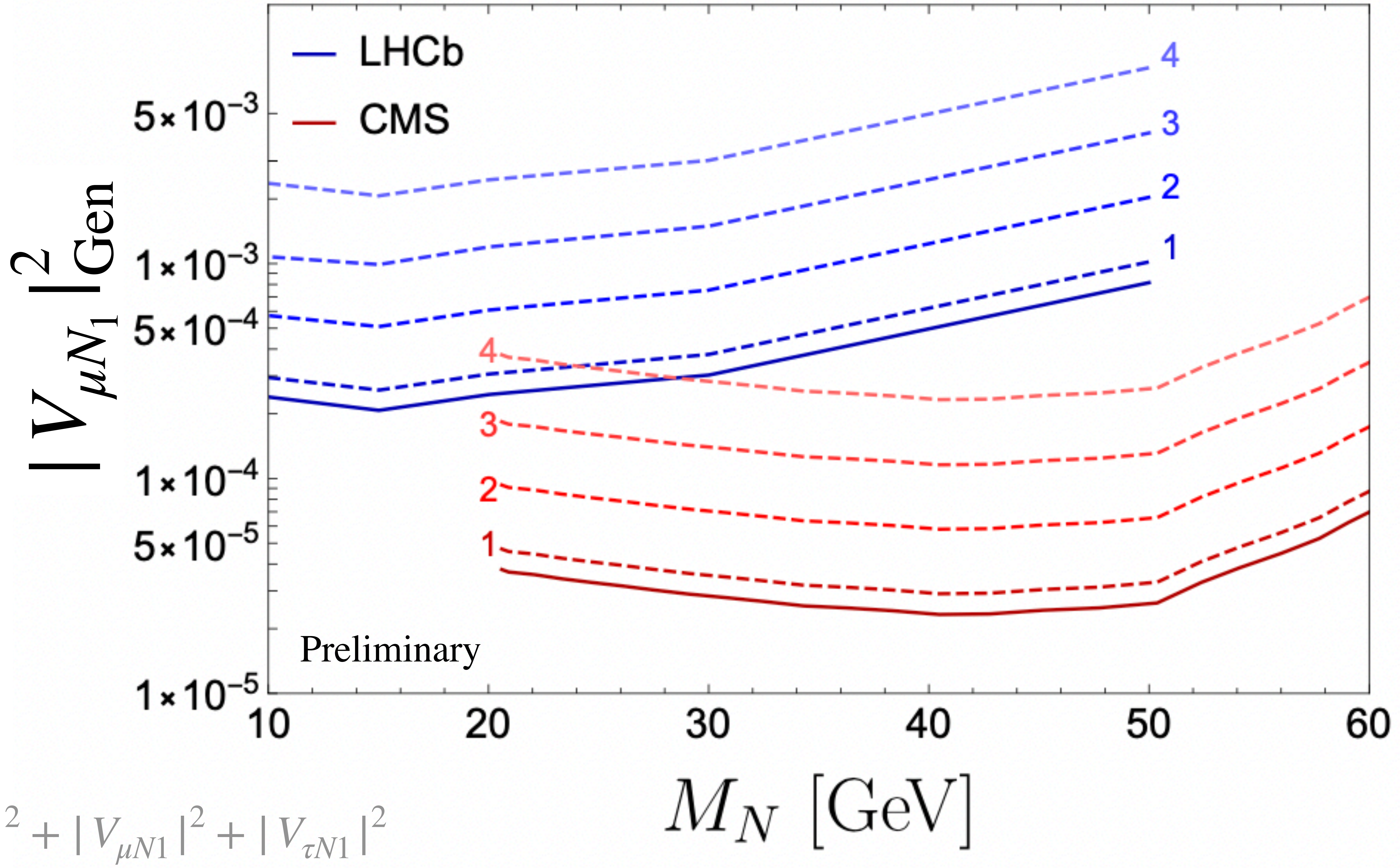
# 2 leptons + jets: generic mixing pattern (1HNL)

$$|V_{\mu N_1}|^2_{\text{Gen}} = |V_{\mu N_1}|^2_{\text{Sing}} \frac{\Gamma_N^{\text{Gen}}}{\Gamma_N^{\text{Sing}}}$$

$$V = \begin{pmatrix} \tilde{V}_{PMNS} & V_{eN_1} & V_{eN_2} \\ & V_{\mu N_1} & V_{\mu N_2} \\ & V_{\tau N_1} & V_{\tau N_2} \end{pmatrix}$$



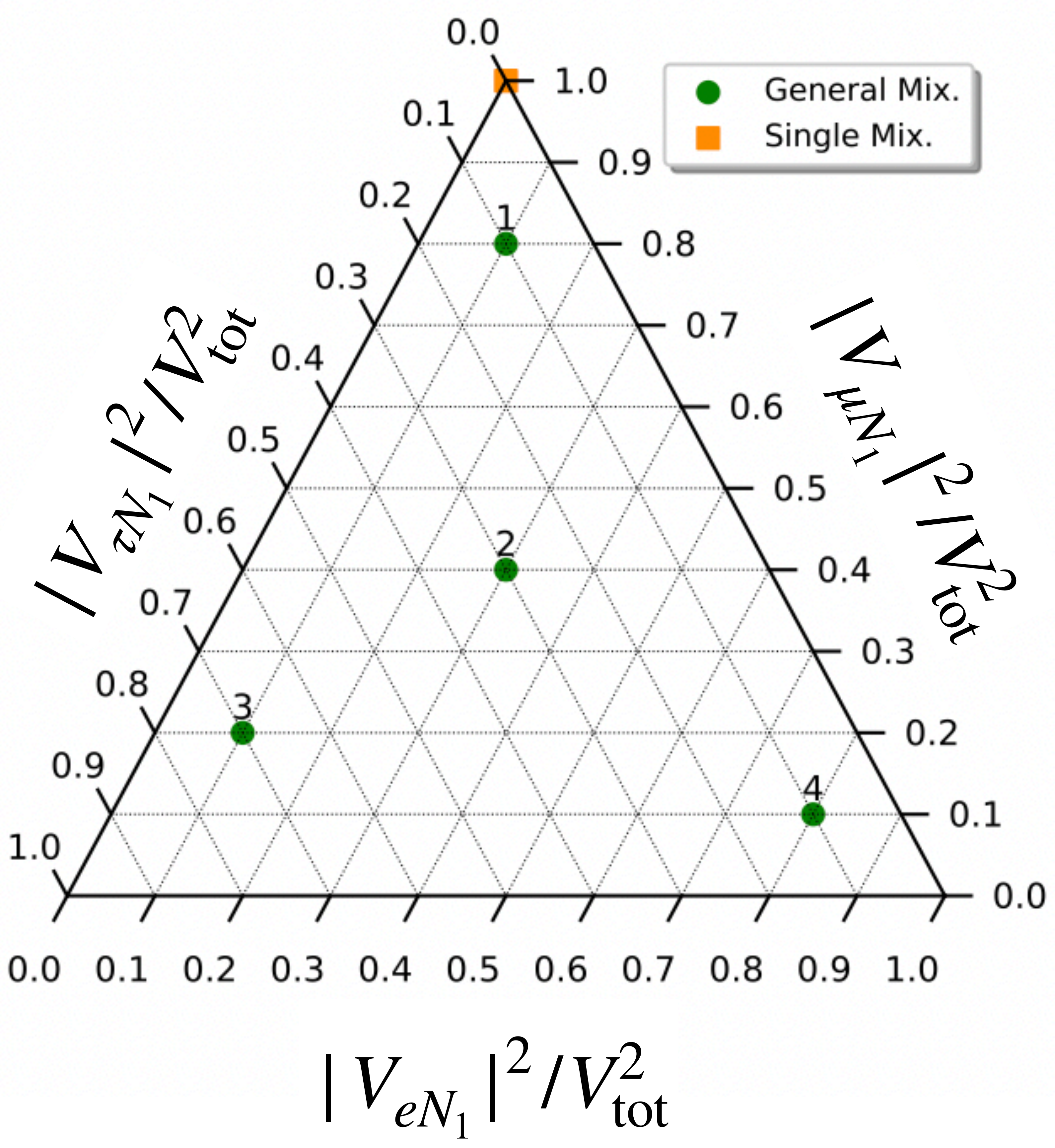



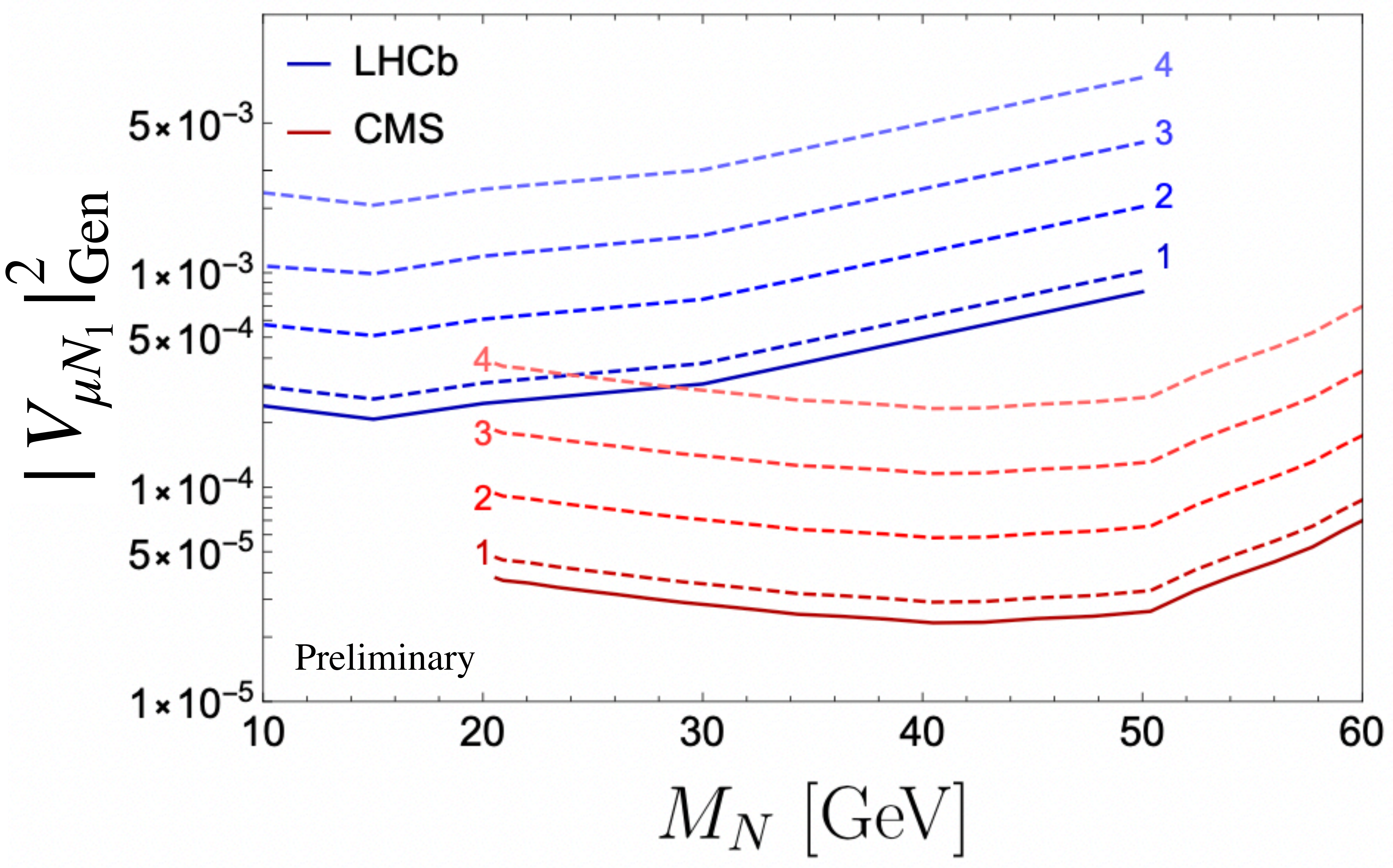




$|V_{\text{tot}}|^2 = |V_{eN1}|^2 + |V_{\mu N1}|^2 + |V_{\tau N1}|^2$

# 2 leptons + jets: generic mixing pattern (1HNL)

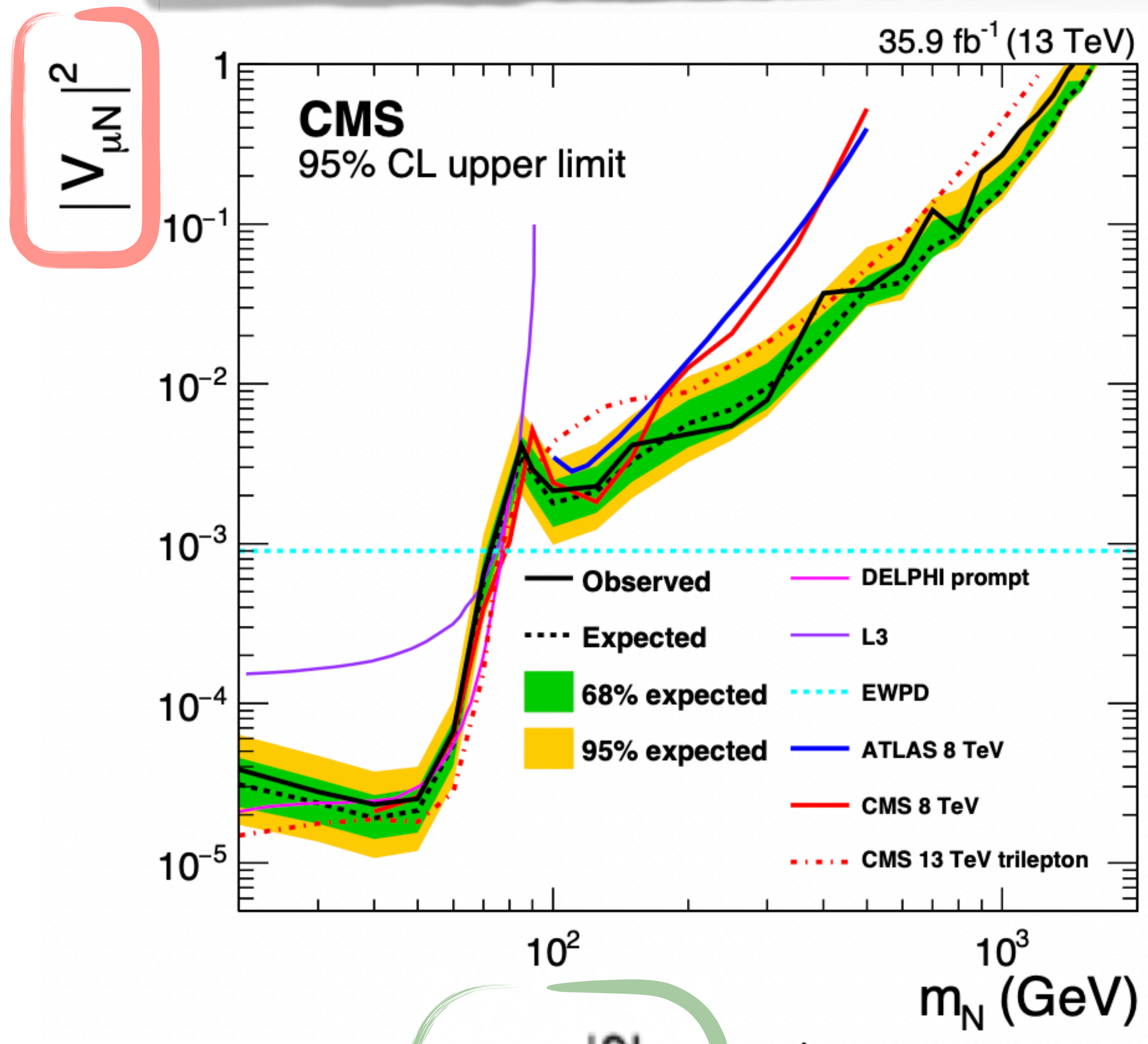
Fixing ( $M_N$ , $V^2_{tot}$ ) and scanning the parameter space in the ternary plot, check which points are allowed after the rescaling of the bound.

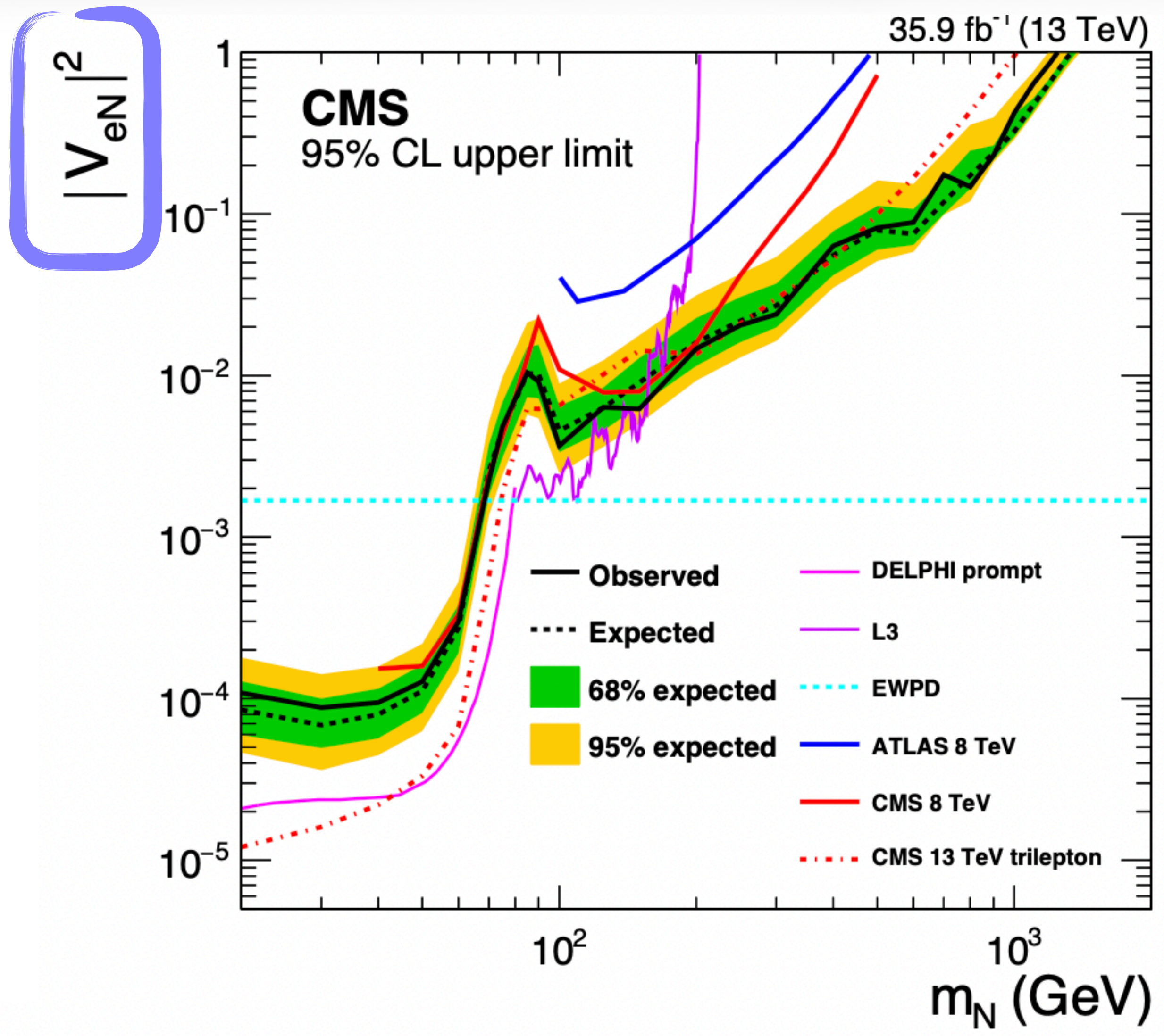


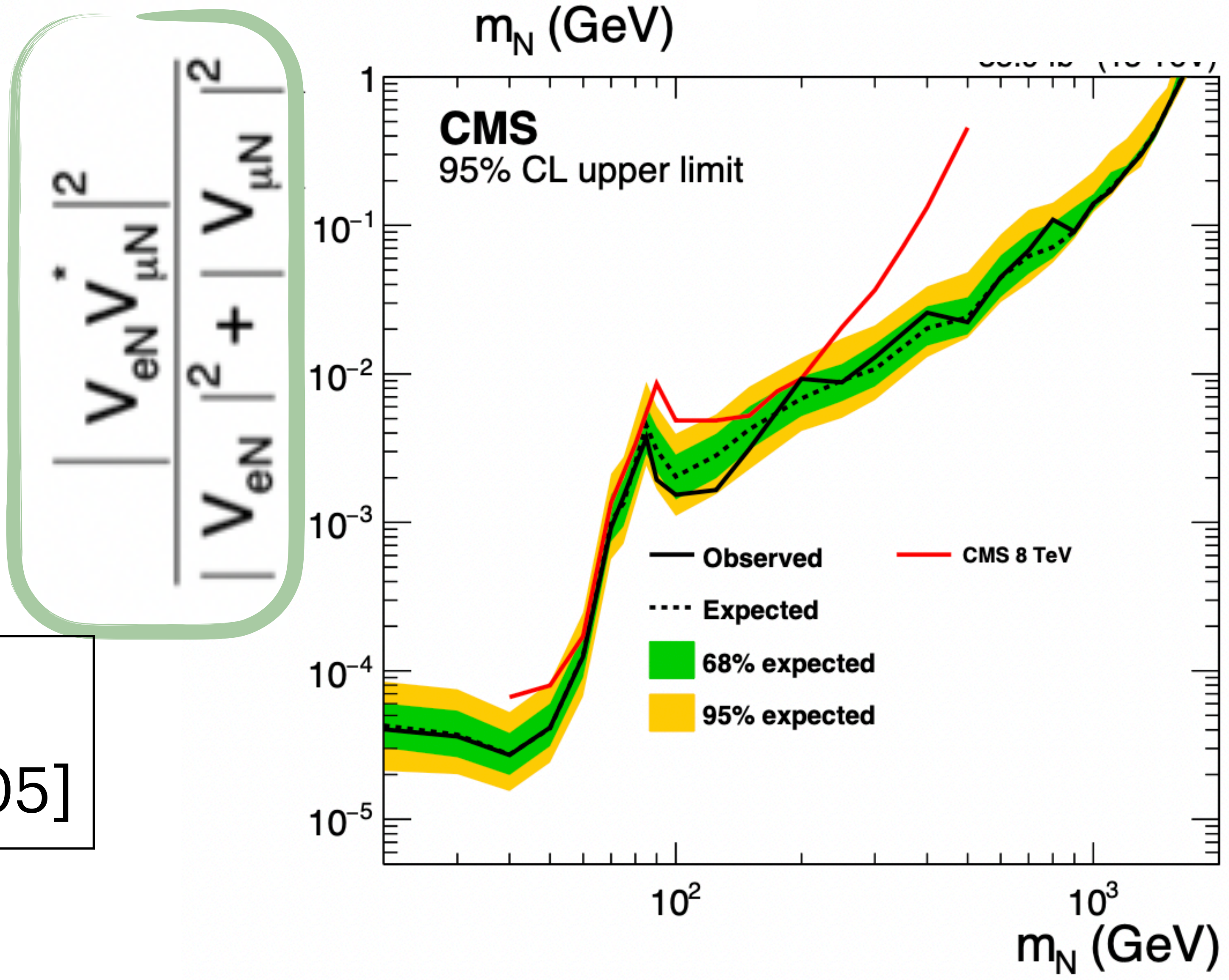



# 2 leptons + jets: generic mixing pattern (1HNL)

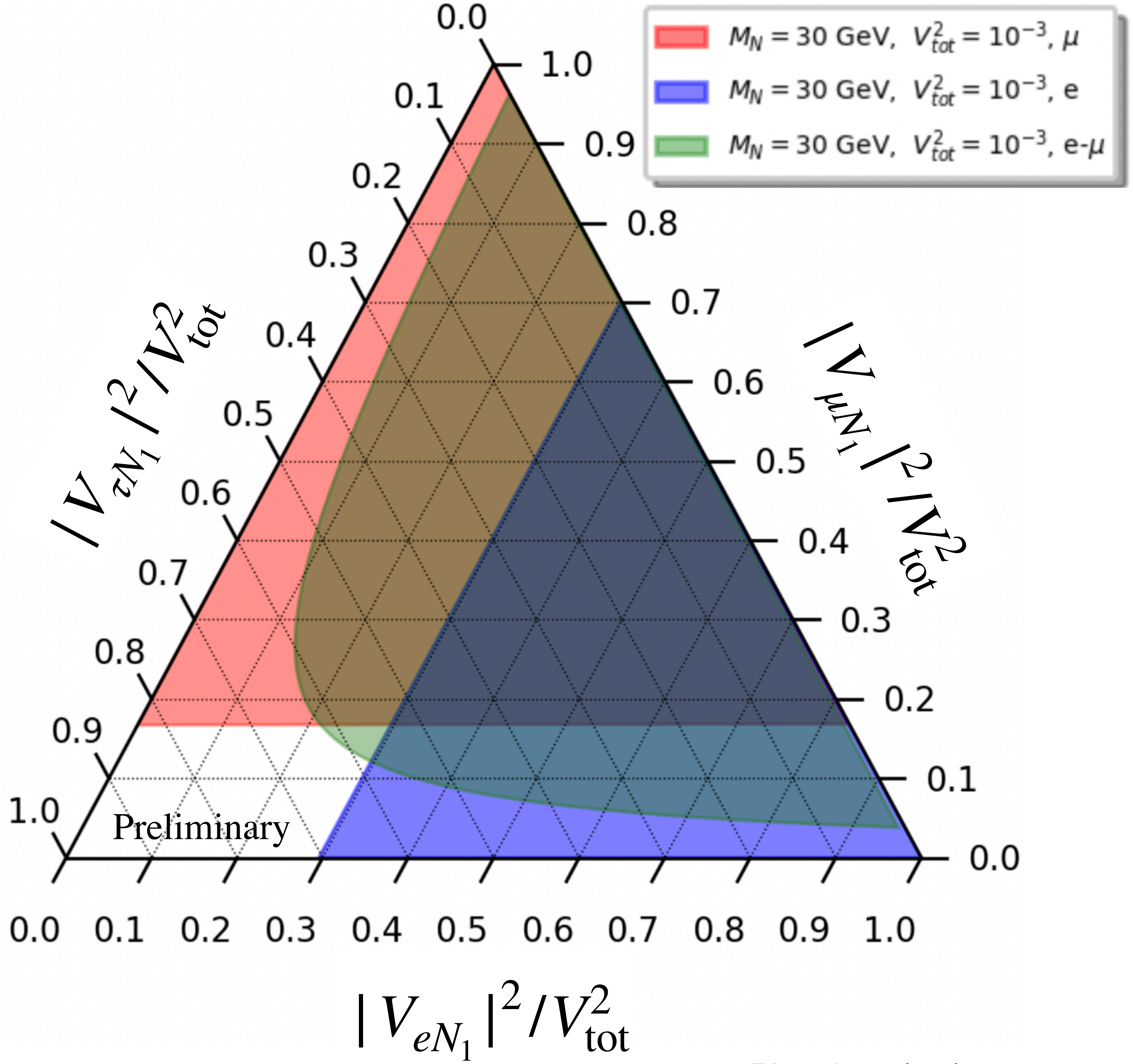
Fixing ( $M_N$ , $V^2_{\text{tot}}$ ), and combining the searches on ( $e$ , $\mu$ , $e-\mu$ ):




CMS [1806.10905]



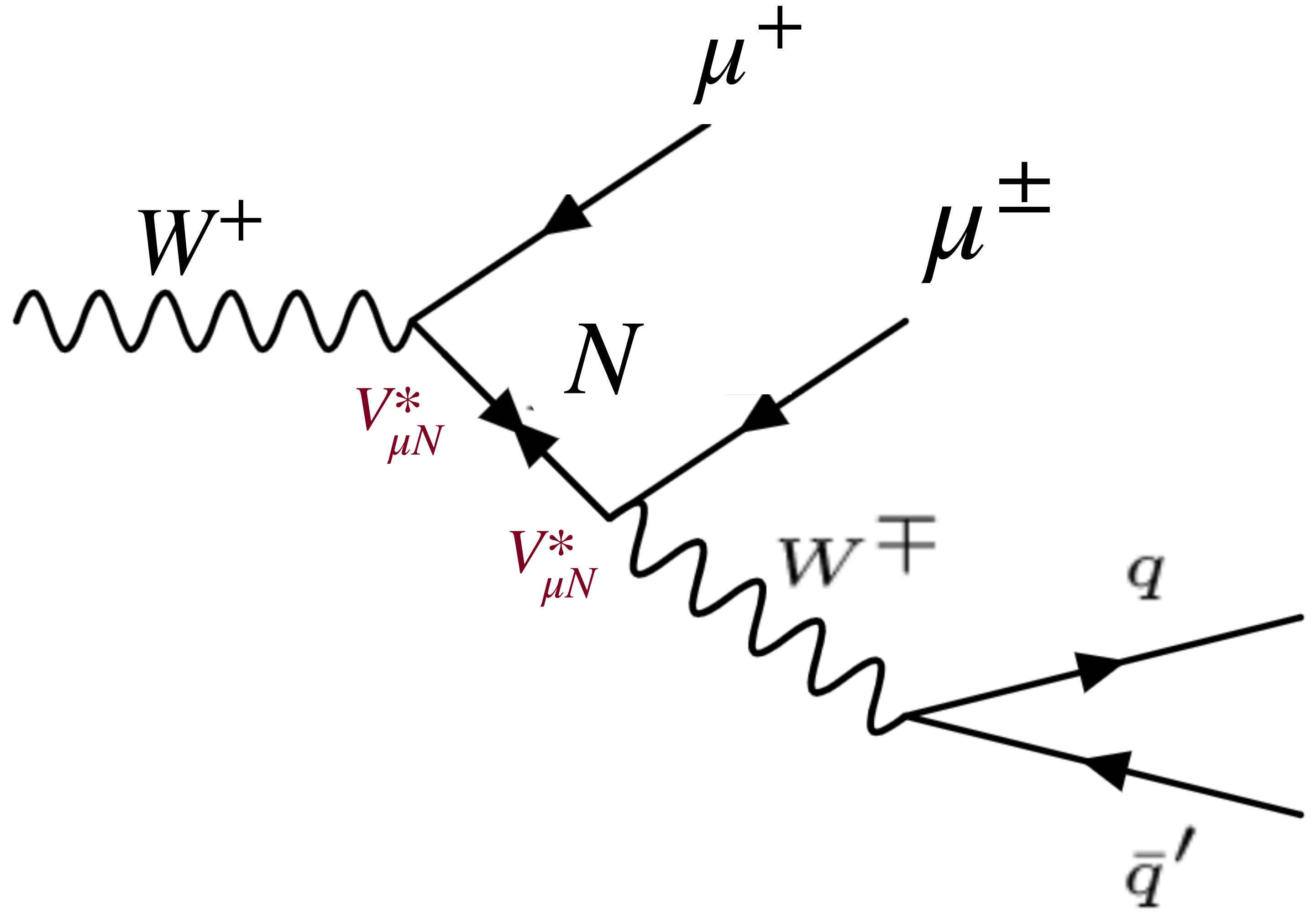
# 2 leptons + jets: 2 HNLs (single mixing)

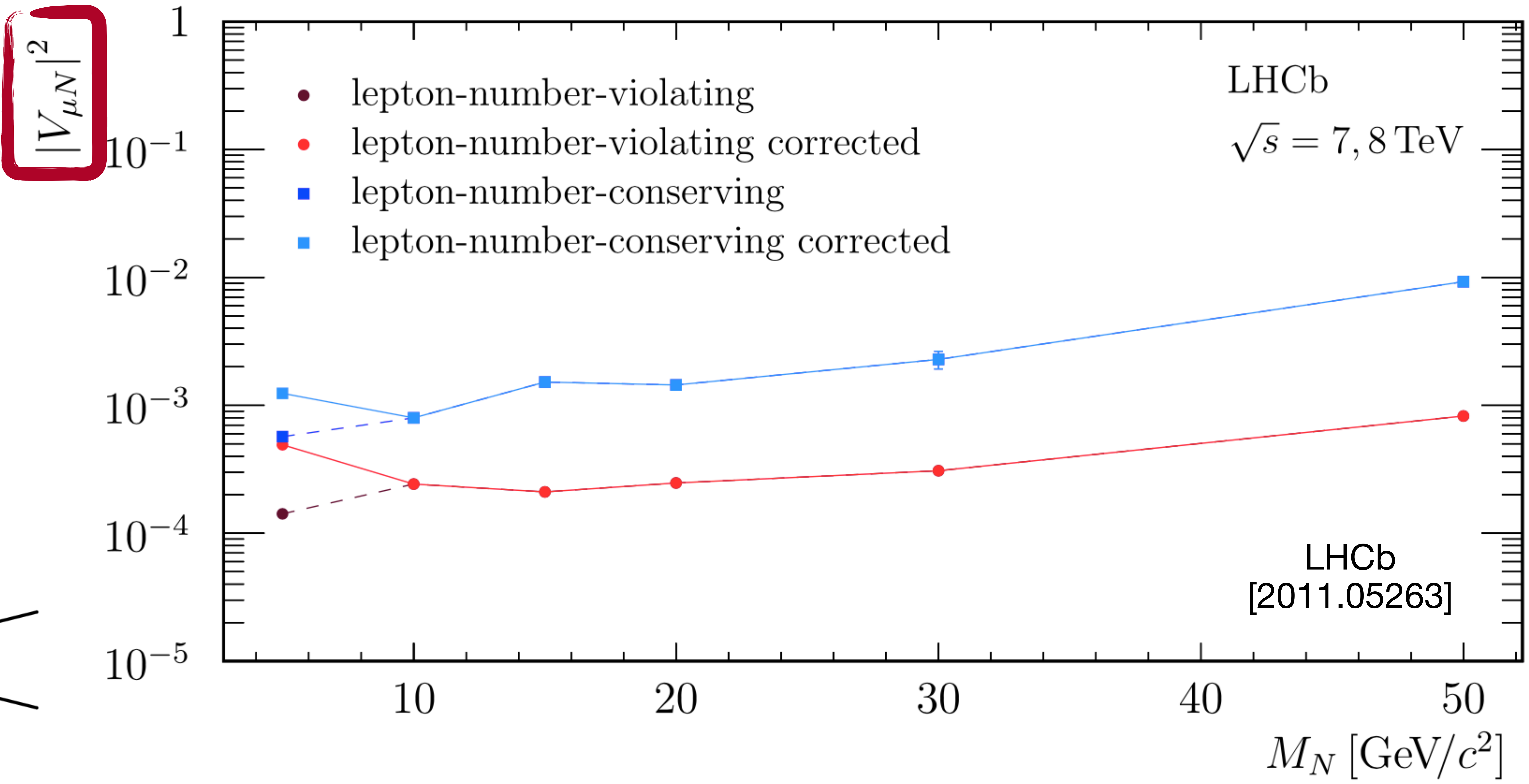
$$V = \left(\begin{array}{ccc|cc} & & & V_{eN_1} & V_{eN_2} \\ & \tilde{V}_{PMNS} & & V_{\mu N_1} & V_{\mu N_2} \\ & & & V_{\tau N_1} & V_{\tau N_2} \\ \hline & & & & \end{array}\right)$$

# 2 leptons + jets: 2 HNLs (single mixing)

$$V = \begin{pmatrix} \tilde{V}_{PMNS} & \begin{matrix} V_{eN_1} & V_{eN_2} \\ V_{\mu N_1} & V_{\mu N_2} \\ V_{\tau N_1} & V_{\tau N_2} \end{matrix} \\ \cdots & \cdots \end{pmatrix}$$

$$|V_{\mu N_1}|^2 + |V_{\mu N_2}|^2$$ , **OK if NO Interference!**



# 2 leptons + jets: 2 HNLs Interfering

Defining $V_{\ell_\alpha N_j} = |V_{\ell_\alpha N_j}| e^{i\phi_{\alpha j}}$, and assuming $|V_{\ell N_1}|^2 \simeq |V_{\ell N_2}|^2, M_1 \simeq M_2 \equiv M, \Delta M_{12} \neq 0, \; \Gamma_1 \simeq \Gamma_2 \equiv \Gamma$

$$\Gamma(W^+ \to \ell_\alpha^+ \ell_\beta^\pm q\bar{q}')|_{N_1 \& N_2} = \Gamma(W^+ \to \ell_\alpha^+ \ell_\beta^\pm q\bar{q}')|_{N_1} \times 2\, \mathscr{K}(y, \delta\phi^\pm)$$

!

$$\mathscr{K}(y, \delta\phi^\pm) = \left(1 + \cos\delta\phi^\pm \frac{1}{1+y^2} - \sin\delta\phi^\pm \frac{y}{1+y^2}\right)$$

$$y \equiv \frac{\Delta M_{12}}{\Gamma}, \qquad \delta\phi^\pm = \left(\phi_{\alpha 2} - \phi_{\alpha 1}\right) \pm \left(\phi_{\beta 2} - \phi_{\beta 1}\right),$$

$$\delta\phi^- = 0 \quad \text{for} \;\; \alpha = \beta$$

# 2 leptons +jets: 2 HNLs (single mixing)

$$|V_{\mu N_1}|^2_{2N} = |V_{\mu N}|^2_{1N}/[2\mathscr{K}(y,\delta\phi)]$$

$$\mathscr{K}(y,\delta\phi^{\pm}) = \left(1 + \cos\delta\phi^{\pm}\frac{1}{1+y^2} - \sin\delta\phi^{\pm}\frac{y}{1+y^2}\right)$$

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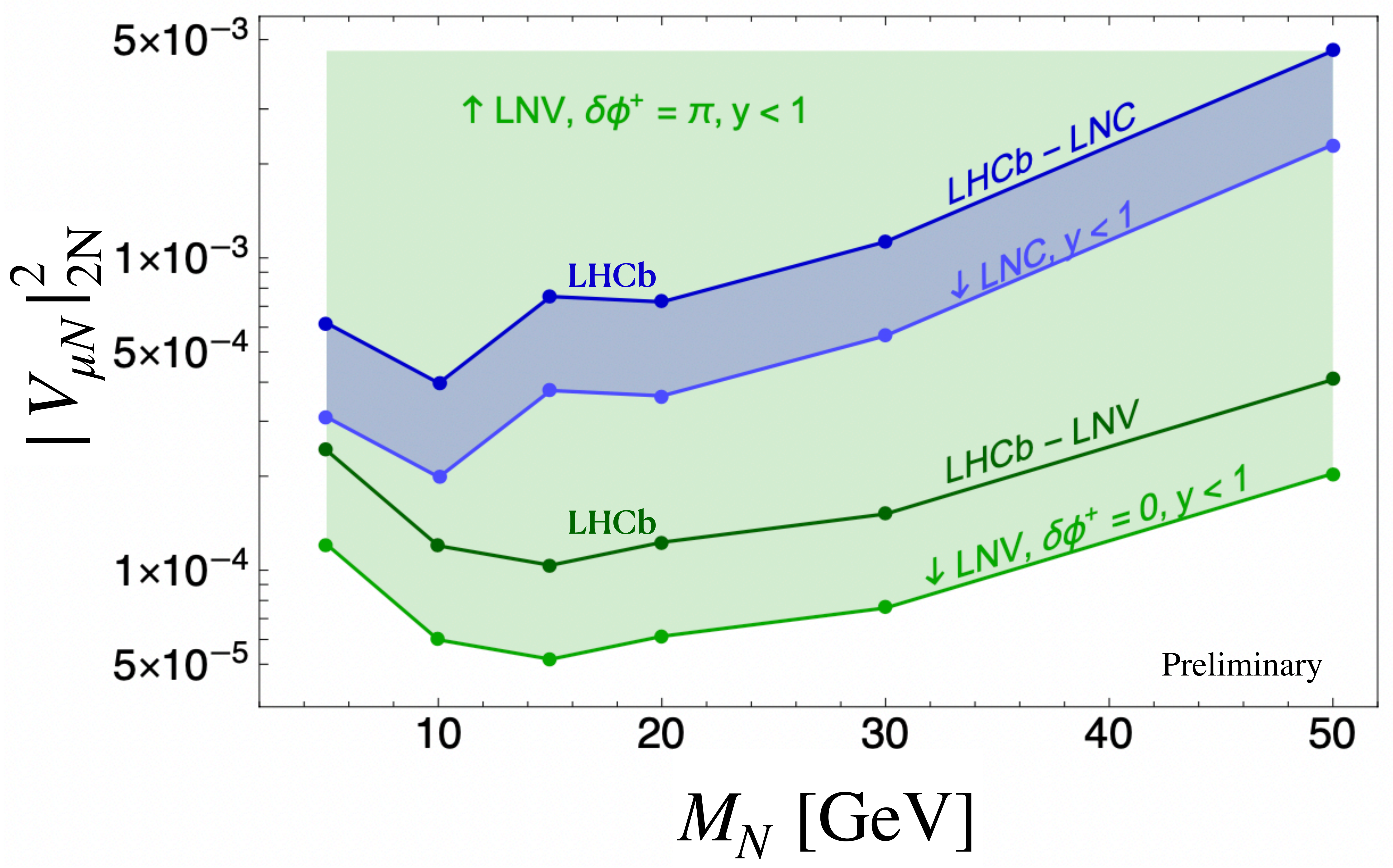


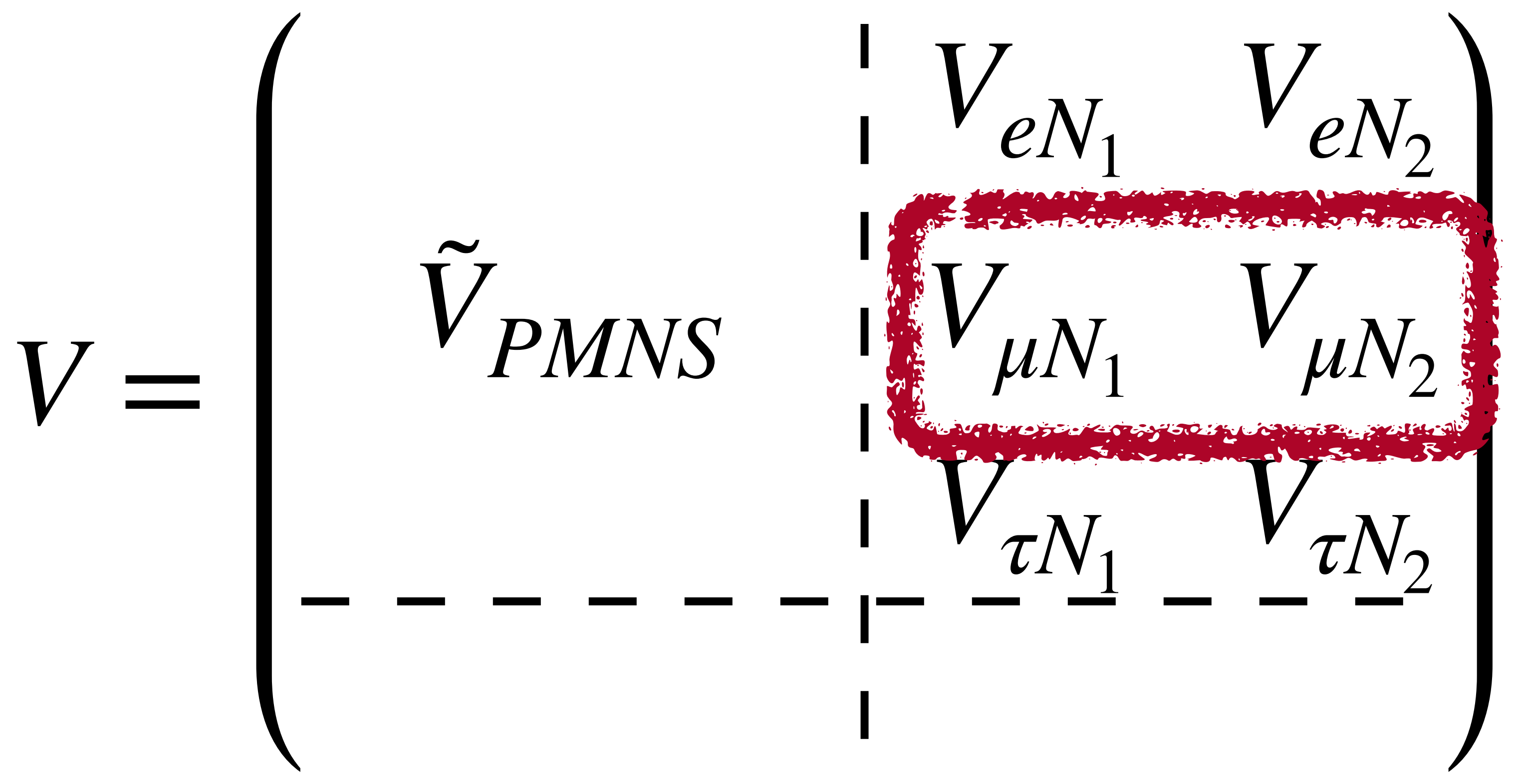

# 2 leptons +jets: 2 HNLs (single mixing)

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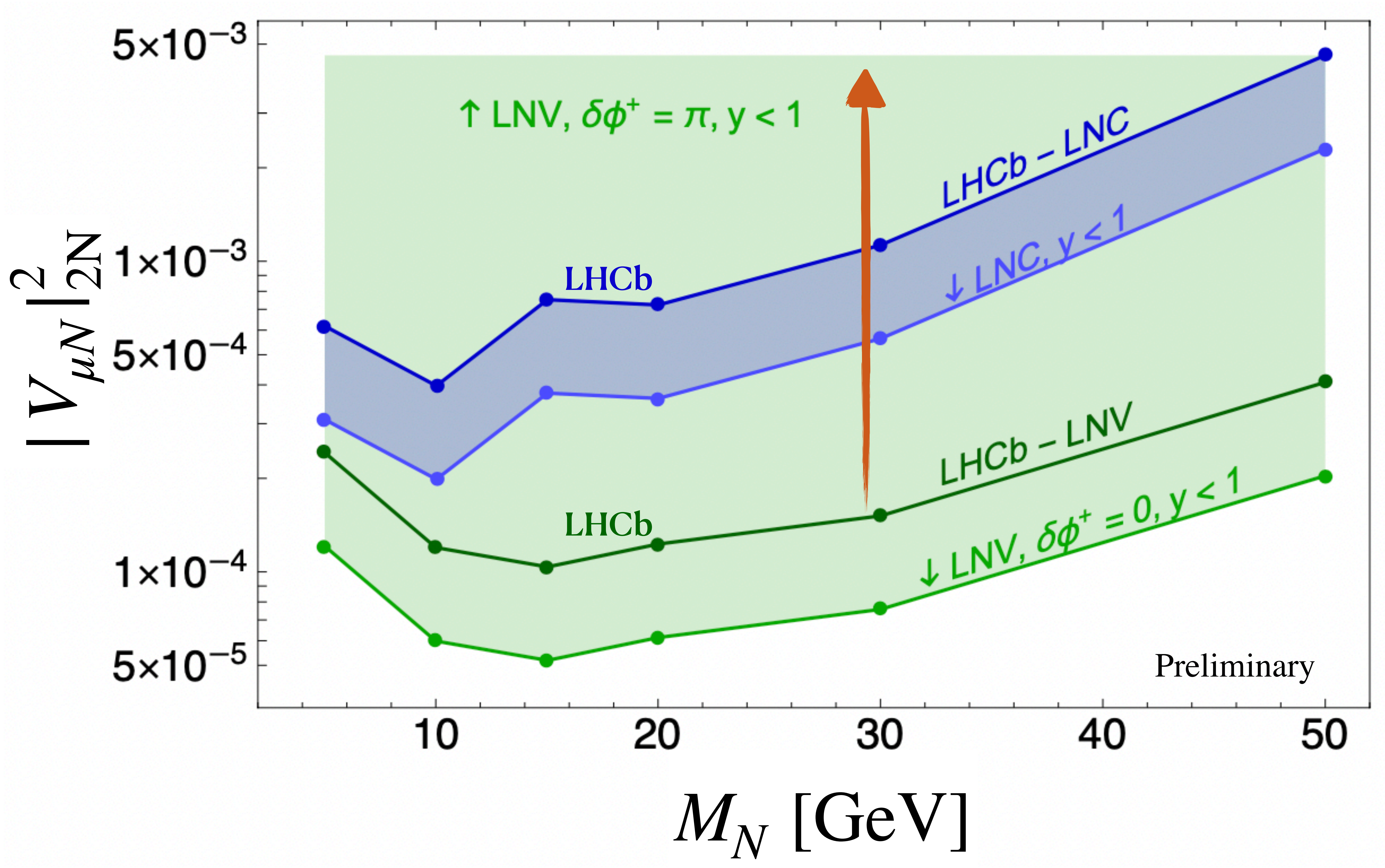


$$y \equiv \frac{\Delta M_{12}}{\Gamma}, \quad \delta\phi^\pm = (\phi_{\alpha 2} - \phi_{\alpha 1}) \pm (\phi_{\beta 2} - \phi_{\beta 1})$$

It is possible to relax the LNV bound.
($N_1, N_2$ PseudoDirac Pair -> LNV forbidden)

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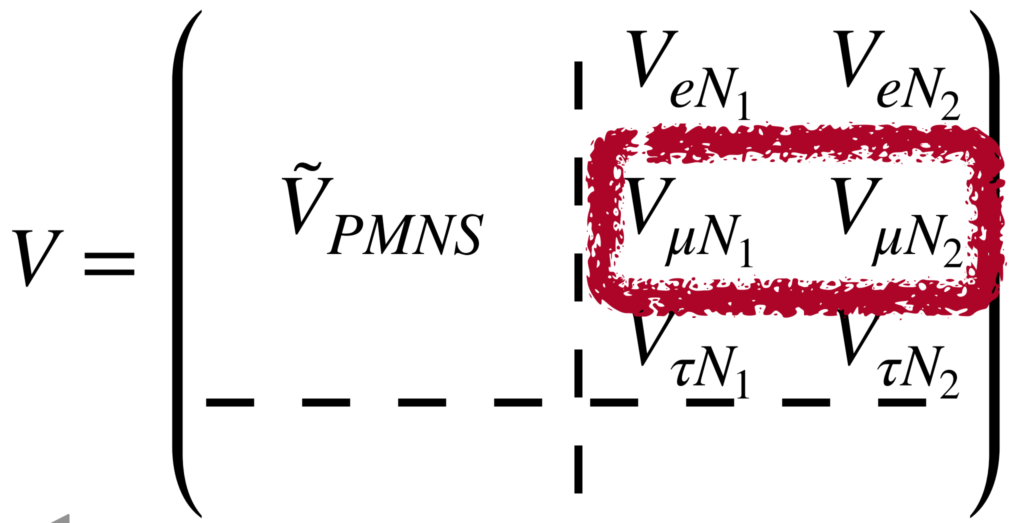


$$|V_{\mu N_1}|^2_{2\mathrm{N}} = |V_{\mu N}|^2_{1\mathrm{N}} / [2\mathcal{K}(y, \delta\phi)]$$

$$\mathcal{K}(y, \delta\phi^{\pm}) = \left(1 + \cos\delta\phi^{\pm}\frac{1}{1+y^2} - \sin\delta\phi^{\pm}\frac{y}{1+y^2}\right)$$

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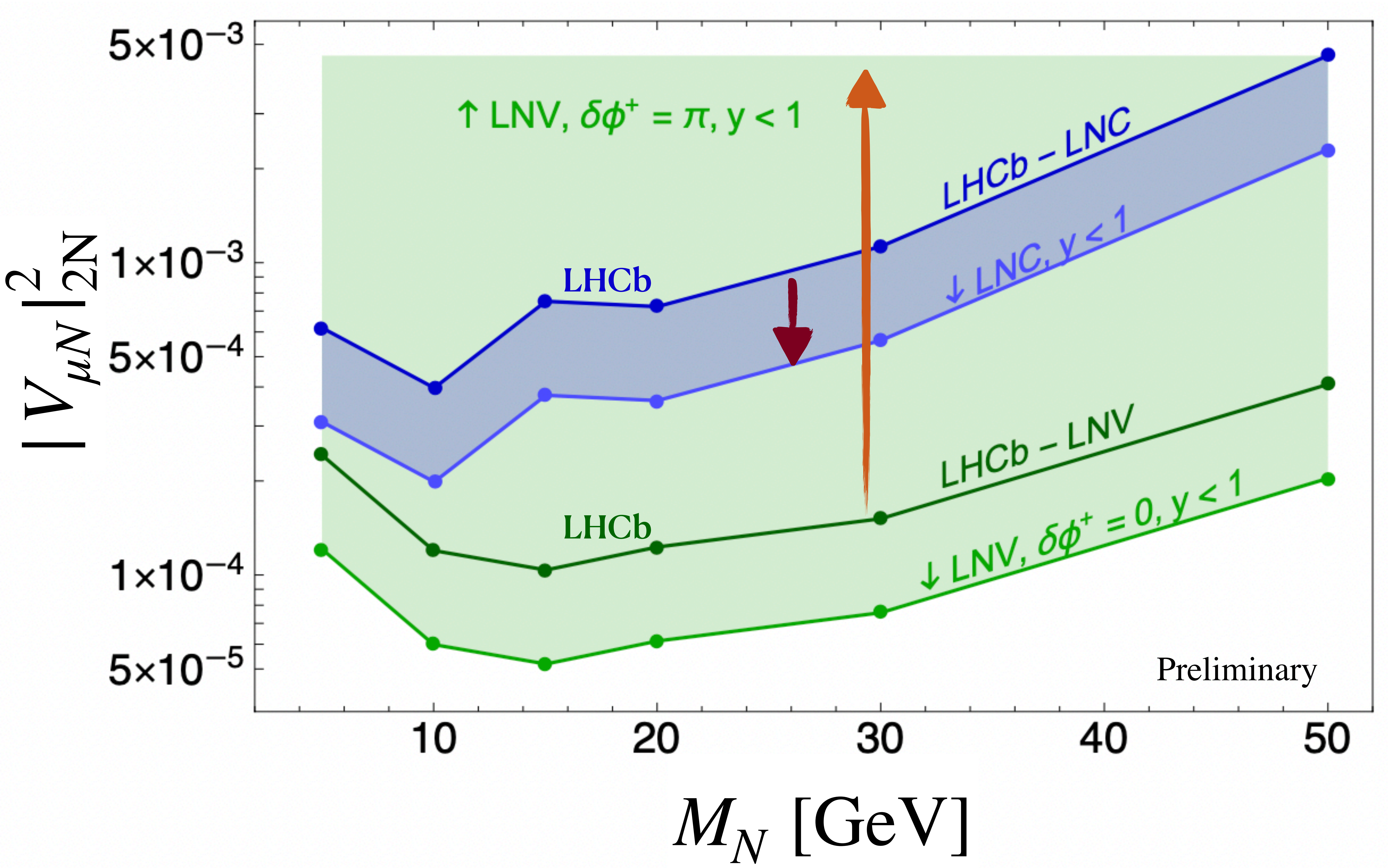
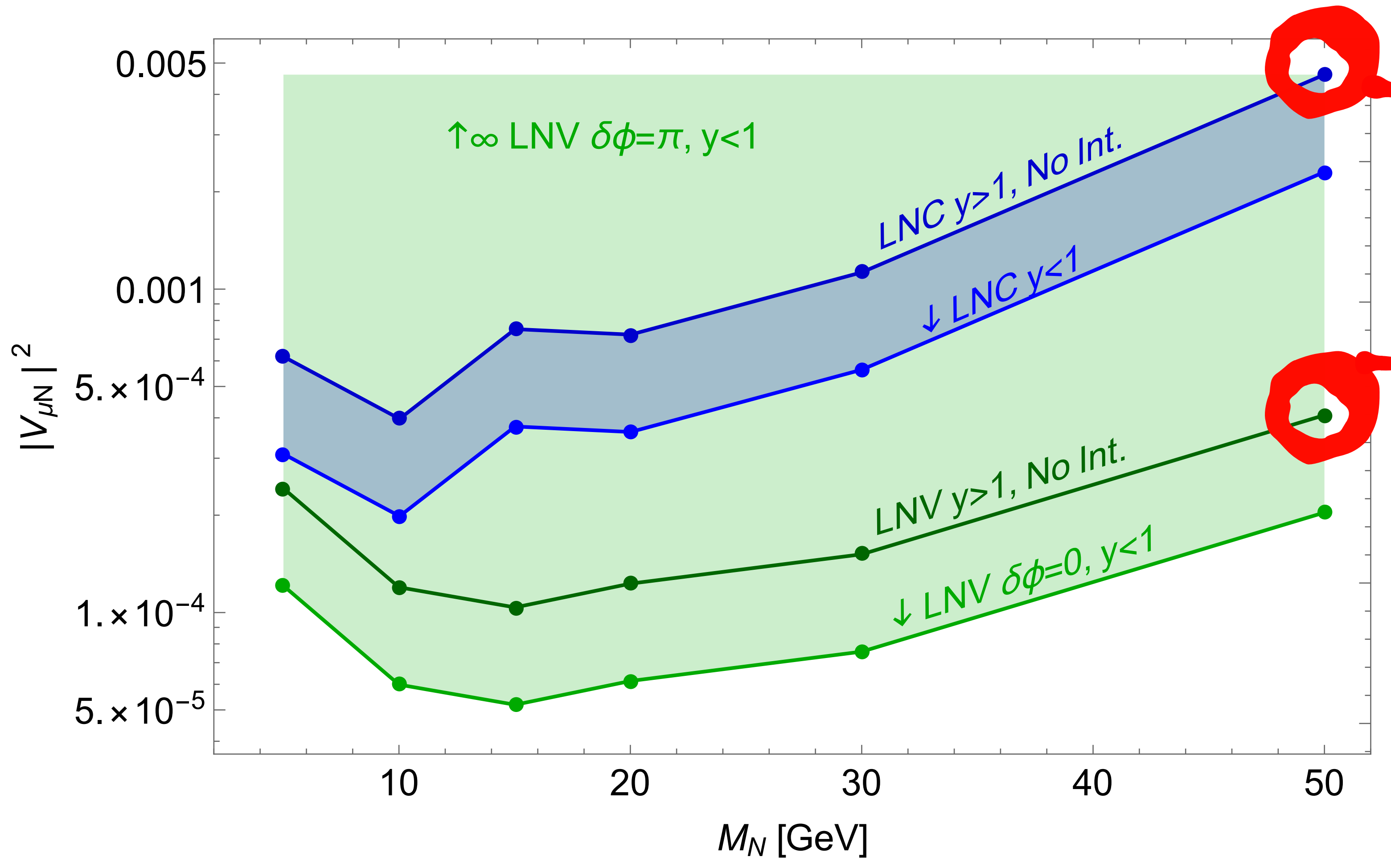


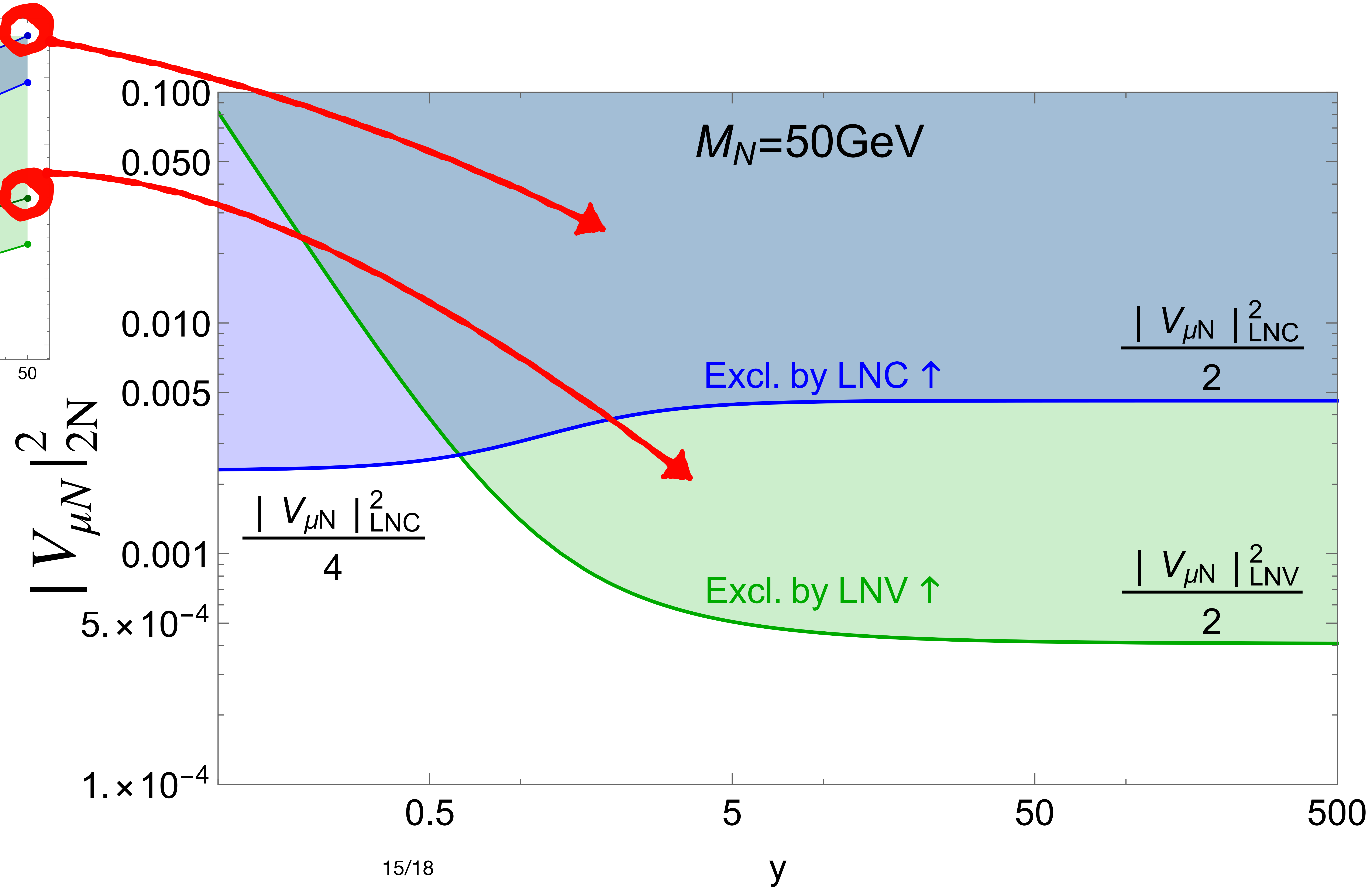

It is possible to relax the LNV bound.
($N_1, N_2$ PseudoDirac Pair -> LNV forbidden)

However, for $y < 1$ LNC bound stronger

# Combining LNV & LNC, What is the maximum allowed value for $|V_{\mu N}|^2$ ?

We can maximise LNC and LNV bounds over $[y, \delta\phi]$.



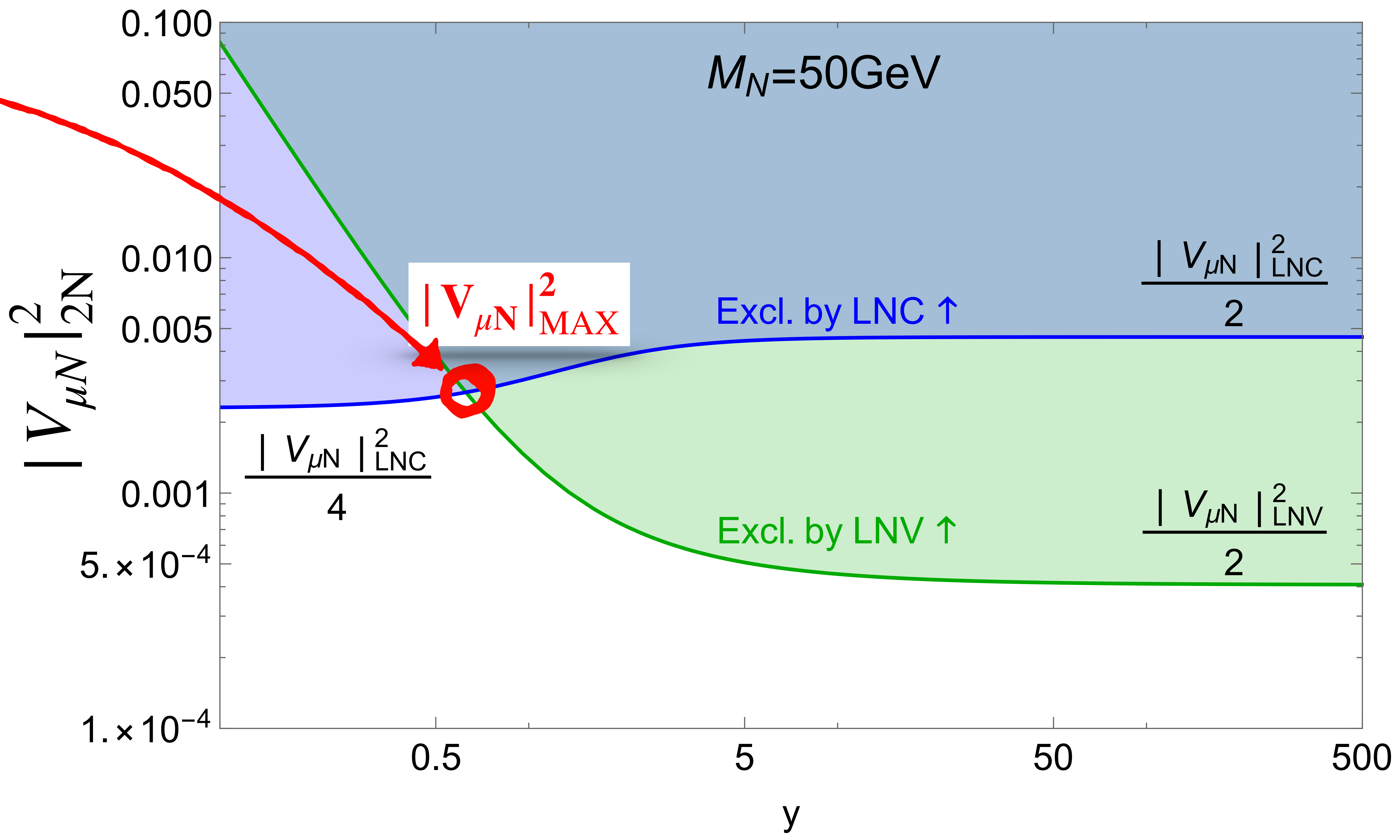



# How to get a conservative bound?

We can maximise LNC and LNV bounds over $[y, \delta\phi]$.

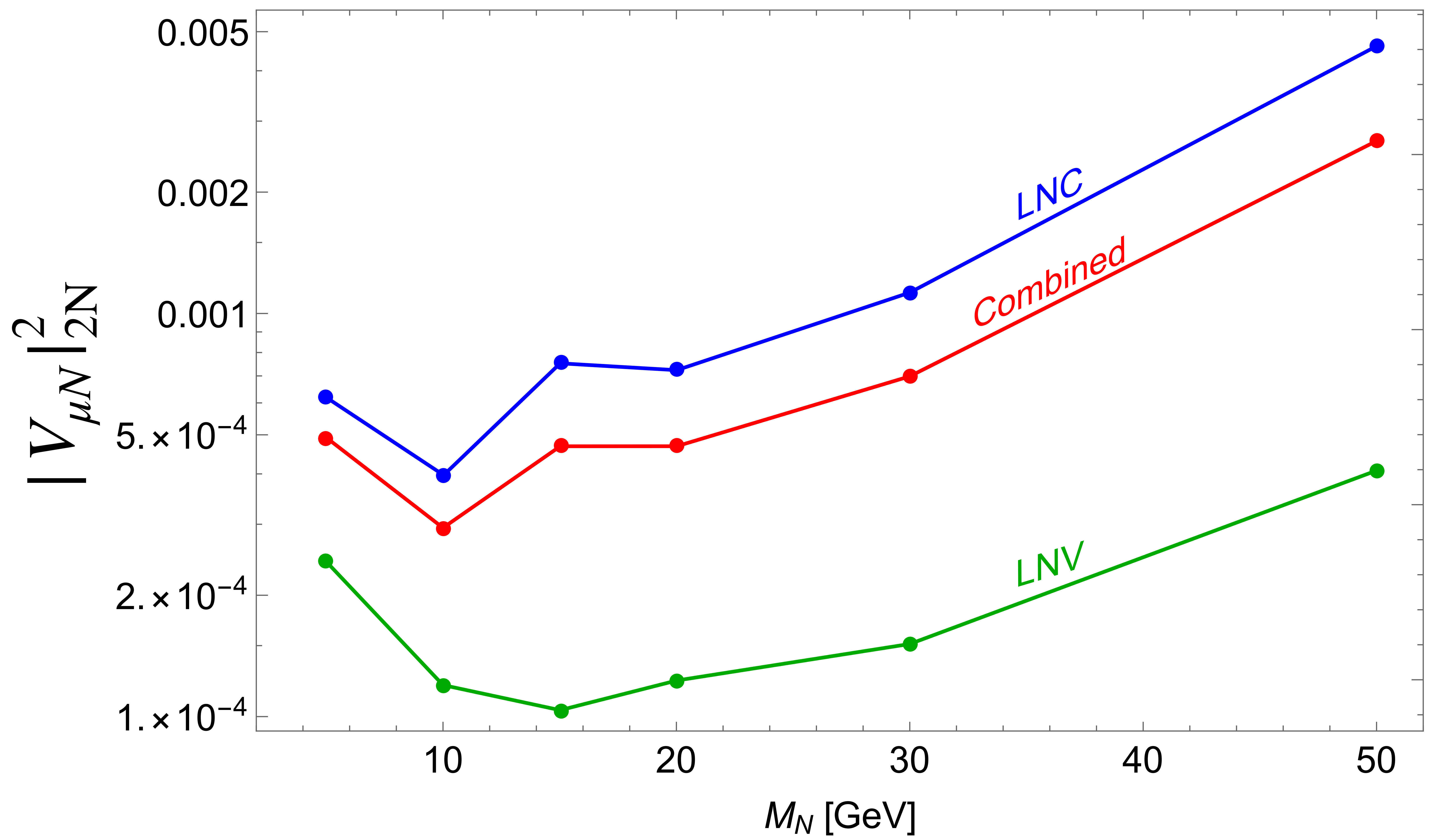
*Combined* conservative bound.

Impossible to relax the bound above this value, even with interferences.



# Combined bound with interferences

Identifying $|\mathbf{V}_{\mu\mathbf{N}}|^2_{\mathrm{MAX}}$ for each $M_N$, we get:



# Conclusions

- Bounds on HNLs in the simplified scenarios are often over-constraining if naively applied to realistic models;
- Actual bounds are model and benchmark dependent, and must be recast;
- It is crucial for experiments to perform BOTH LNV & LNC searches to get combined bounds.

# Thank you!

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Curie grant No 860881-HIDDeN

# Backup

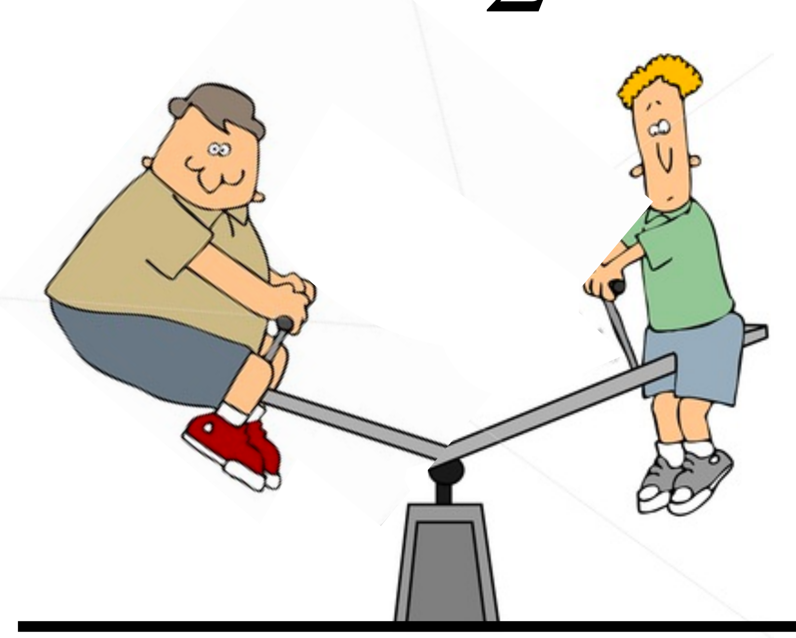
# Outlook: Inferring details on Low-Scale SeeSaw

Our approximations are justified in the L-S ss

Degeneracy $N_4$ & $N_5$ : $M_4 \simeq M_5\,,\ \Gamma_4 \simeq \Gamma_5$

$$\mathscr{L}_{LS} = -\, m_D\, \bar{\nu}_R\, \nu_L - M\, \overline{\nu_R^c}\, \nu_s - \frac{1}{2}\mu_S\, \bar{\nu}_s\, \nu_s^c - \frac{1}{2}\mu_R\, \bar{\nu}_R\, \nu_R^c + \mathrm{h.c.}$$

$$\nu = \begin{pmatrix} \nu_L \\ \nu_R^c \\ \nu_s^c \end{pmatrix} \qquad M_{LS} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & \mu_R & M \\ 0 & M & \mu_S \end{pmatrix}$$



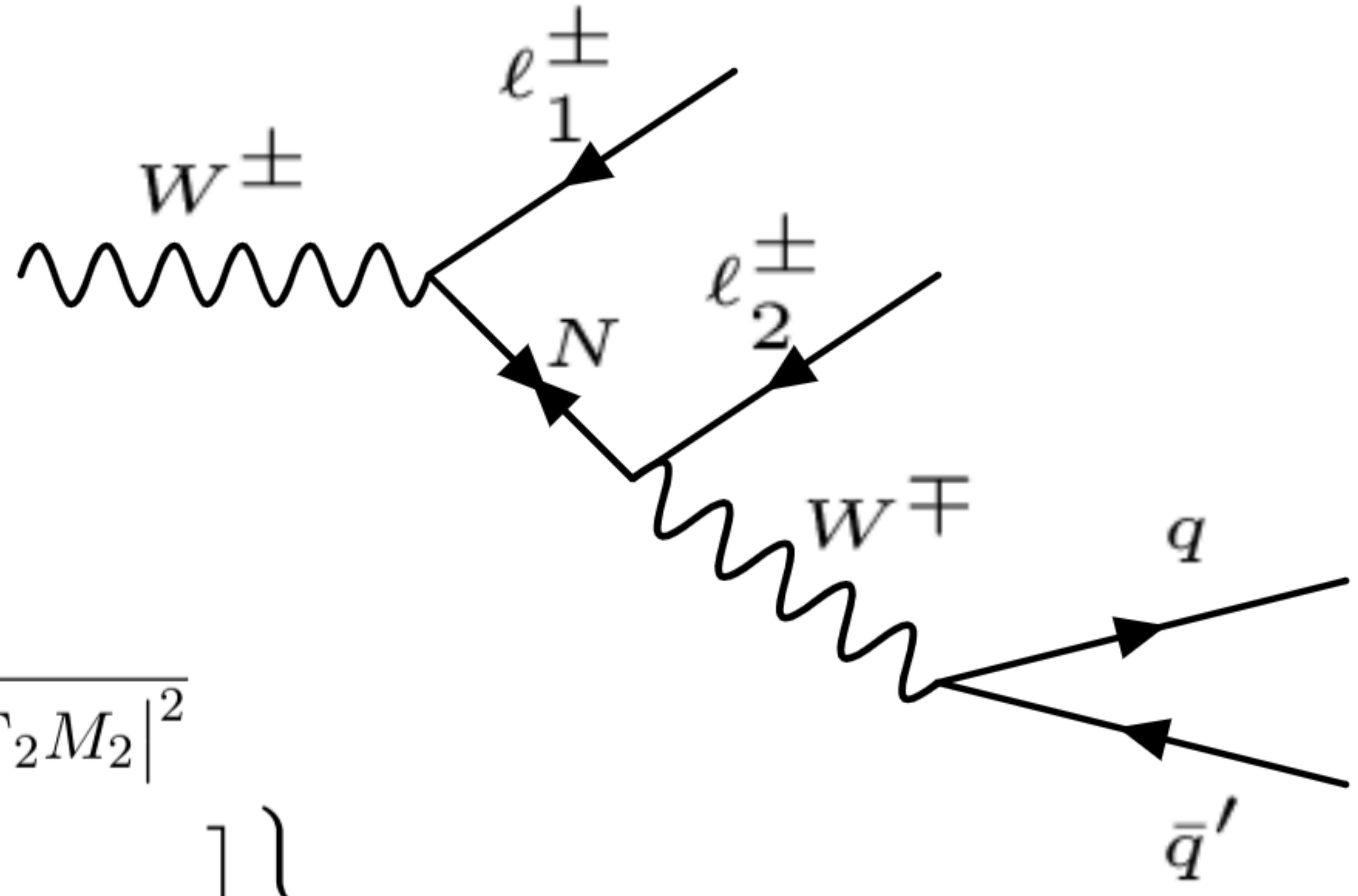
in the see-saw limit

$$M_{\mathrm{light}} \approx \mu\, \frac{m_D^2}{M^2}$$

$$M_{N_4, N_5} \approx \pm M + \mathcal{O}(\mu)$$

$N_4, N_5$ almost degenerate and with opposite CP phases $\rightarrow$ $\Delta M \ll M\,,\ \delta\phi_V = \pi$ ✓

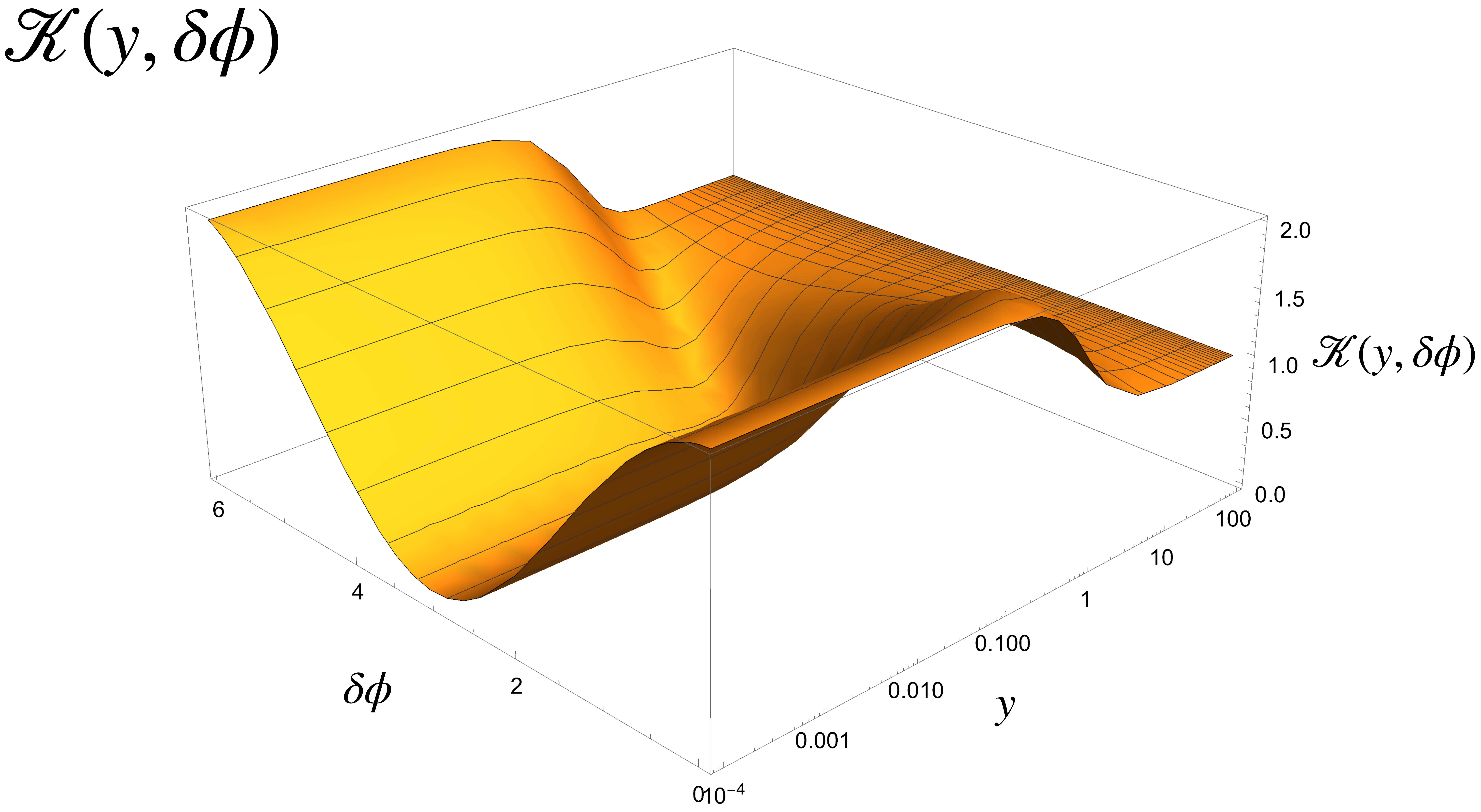
LNV & LNC searches can test LowScale SS models



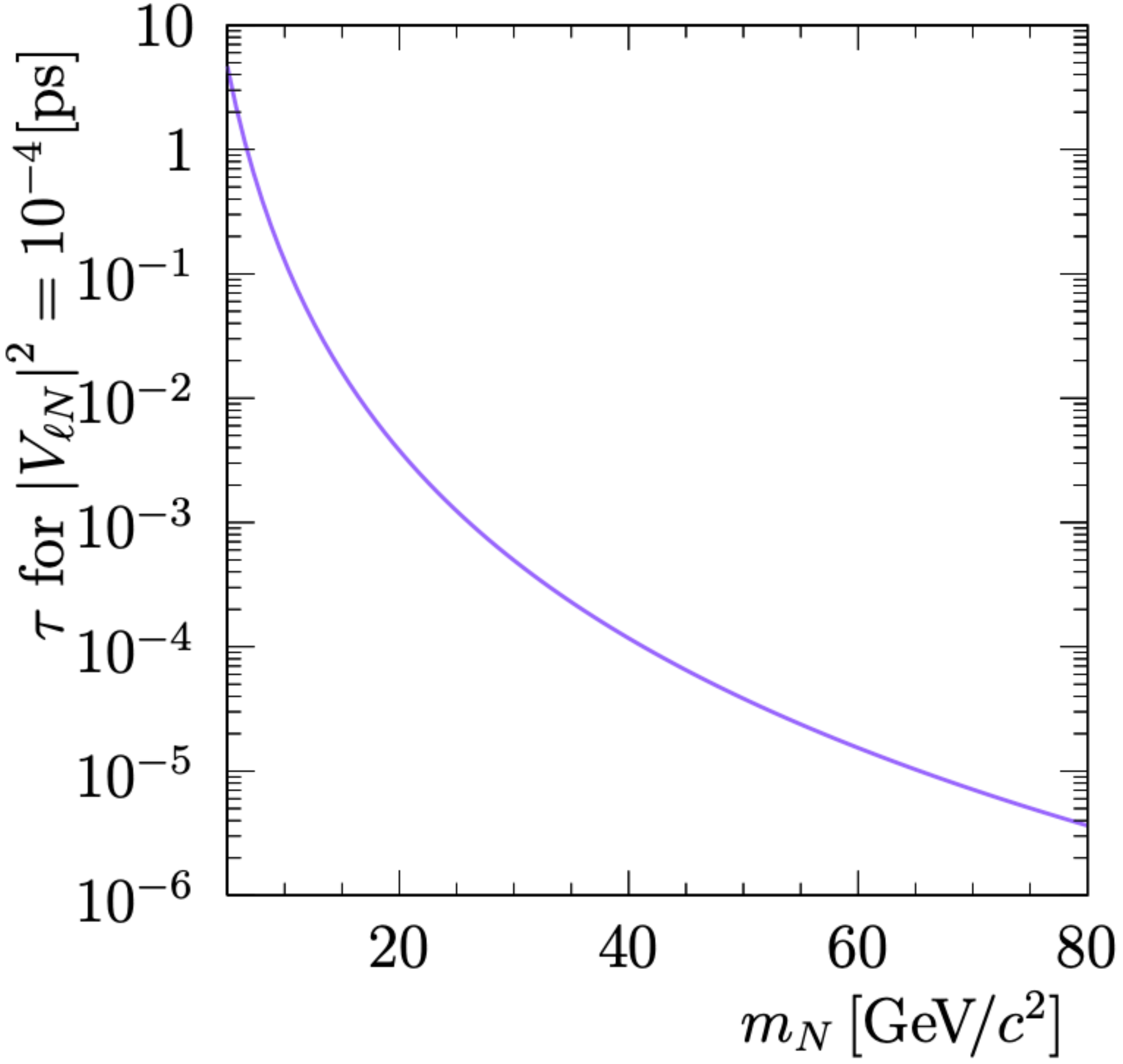

$$\overline{|M|}^2 = \frac{1}{16}\left[\frac{g^3}{2\sqrt{2}M_W^2}\right]^2 16\,(p_{\ell_2}\cdot p_q)\,(2E_{\ell_1}E_{q'} + p_{\ell_1}\cdot p_{q'})\Bigg\{ |U_{\ell_1 N_1}|^2\,|U_{\ell_2 N_1}|^2\,\frac{M_1^2}{\left|p_N^2 - M_1^2 + i\Gamma_1 M_1\right|^2} + |U_{\ell_1 N_2}|^2\,|U_{\ell_2 N_2}|^2\,\frac{M_2^2}{\left|p_N^2 - M_2^2 + i\Gamma_2 M_2\right|^2} + 2\,\mathrm{Re}\left[|U_{\ell_1 N_1}|\,|U_{\ell_1 N_2}|\,|U_{\ell_2 N_1}|\,|U_{\ell_2 N_2}|\,e^{i\delta\phi}\frac{M_1 M_2}{(p_N^2 - M_1^2 + i\Gamma_1 M_1)(p_N^2 - M_2^2 - i\Gamma_2 M_2)}\right]\Bigg\}$$

$$\overline{|M|}^2 \simeq \left[\frac{g^3}{2\sqrt{2}M_W^2}\right]^2 \pi\,(p_{\ell_2}\cdot p_q)\,(2E_{\ell_1}E_{q'} + p_{\ell_1}\cdot p_{q'})\,\delta\left(p_N^2 - M^2\right)\frac{M}{\Gamma}\,|U_{\ell_1 N_1}|^2\,|U_{\ell_2 N_1}|^2\Bigg\{ 1 + \xi^2 + 4\xi\left[2\cos\delta\phi\frac{M^2\Gamma^2}{(\Delta M^2)^2 + 4\Gamma^2 M^2} - \sin\delta\phi\frac{M\Gamma\Delta M^2}{(\Delta M^2)^2 + 4\Gamma^2 M^2}\right]\Bigg\}$$

with $\xi = |U_{\ell_1 N_2}|\,|U_{\ell_2 N_2}|\,/\,|U_{\ell_1 N_1}|\,|U_{\ell_2 N_1}|$


$\mathscr{K}(y, \delta\phi)$
2.0
1.5
1.0
0.5
0.0
$\mathscr{K}(y, \delta\phi)$
6
4
2
0
$\delta\phi$
$10^{-4}$
0.001
0.010
0.100
1
10
100
$y$

# N lifetime




LHCb
[2011.05263]