Bounds on heavy Majorana neutrinos in type-I seesaw and implications for collider searches

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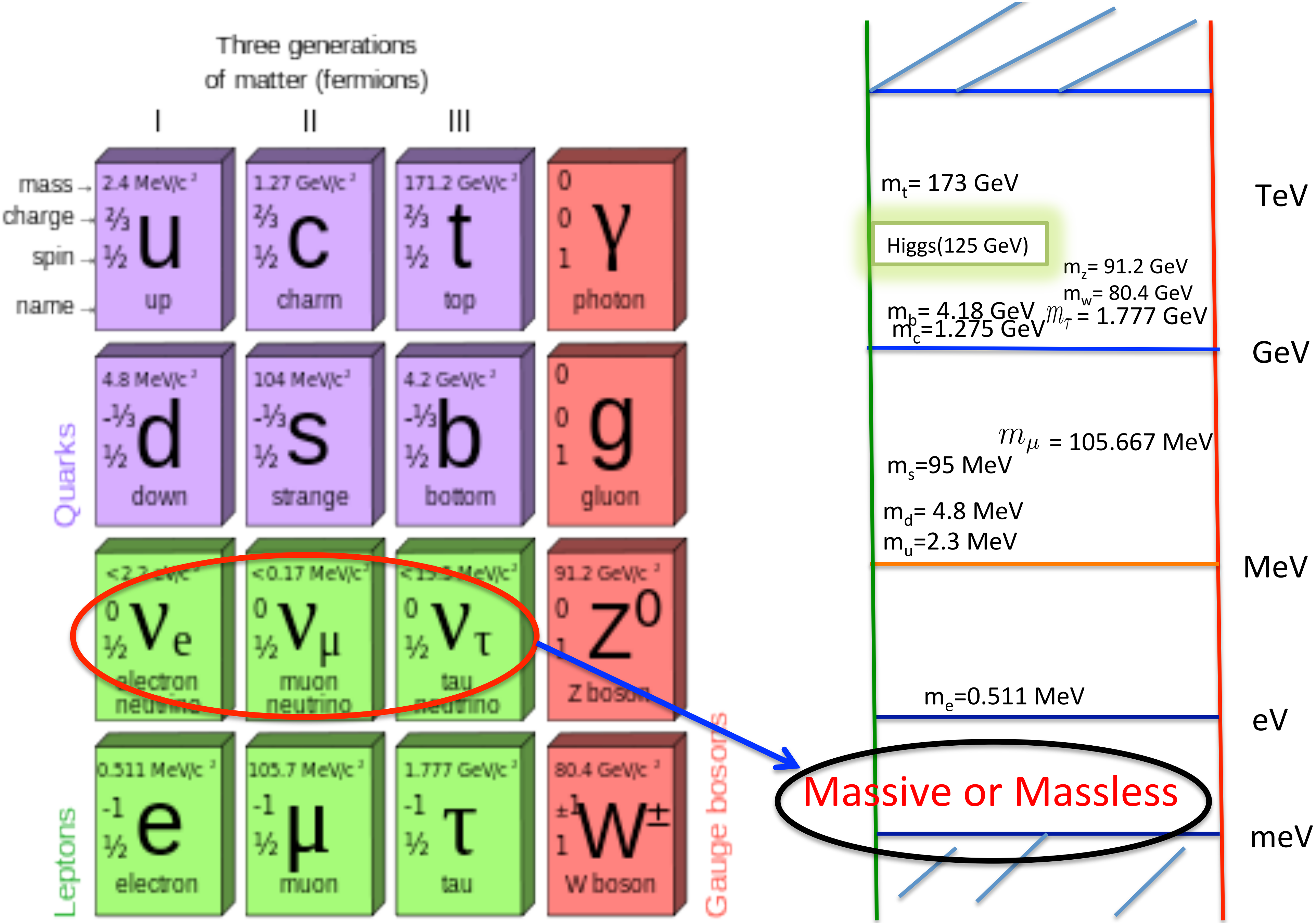
21 June, 2017 @WIN2017, UC Irvine

INTRODUCTION



First evidence of the existence of the solar neutrino : Homestake / Ray-Davis Experiment

VOLUME 20, NUMBER 21 PHYSICAL REVIEW LETTERS 20 MAY 1968

SEARCH FOR NEUTRINOS FROM THE SUN*

Raymond Davis, Jr., Don S. Harmer,† and Kenneth C. Hoffman
Brookhaven National Laboratory, Upton, New York 11973
(Received 16 April 1968)

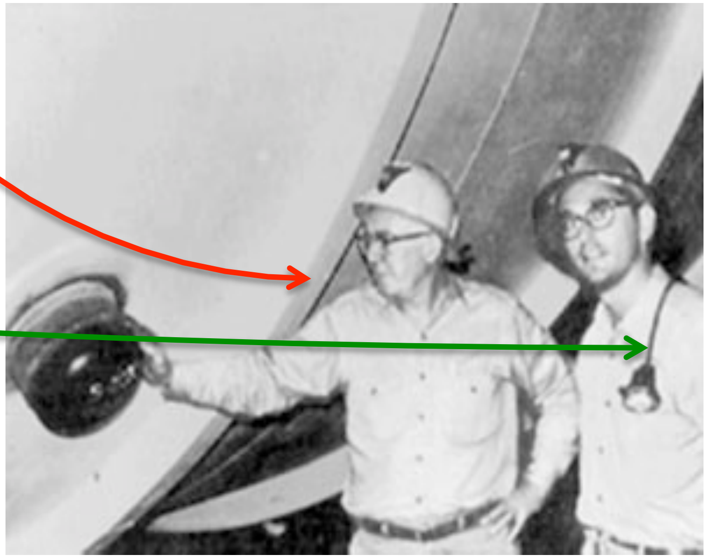
A search was made for solar neutrinos with a detector based upon the reaction $Cl^{37}(\nu, e^-)Ar^{37}$. The upper limit of the product of the neutrino flux and the cross sections for all sources of neutrinos was 3×10^{-36} sec^{-1} per Cl^{37} atom. It was concluded specifically that the flux of neutrinos from B^8 decay in the sun was equal to or less than 2×10^6 cm^{-2} sec^{-1} at the earth, and that less than 9% of the sun's energy is produced by the carbon-nitrogen cycle.

THE RATE OF THE PROTON-PROTON REACTION*

JOHN N. BAHCALL AND ROBERT M. MAY†
California Institute of Technology, Pasadena
Received January 31, 1968

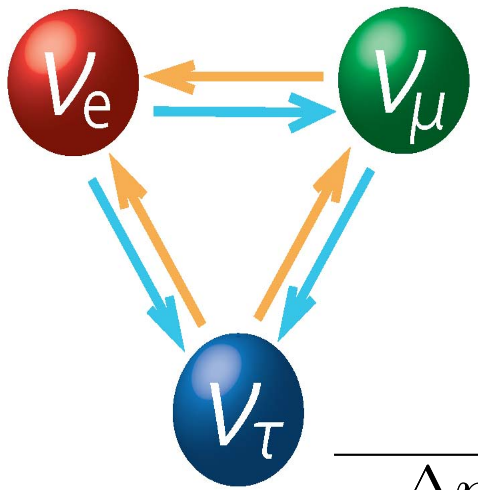
THE RATE OF THE PROTON-PROTON REACTION AND SOME RELATED REACTIONS

JOHN N. BAHCALL* AND ROBERT M. MAY†
California Institute of Technology, Pasadena, California
Received July 3, 1968



More developments

Super- Kamiokande, Sudbury Neutrino Observatory 1999 ,
Neutrino oscillation between mass and flavor eigenstates



Neutrinos are very special

Nobel Prize in 2015

Neutrino oscillation data

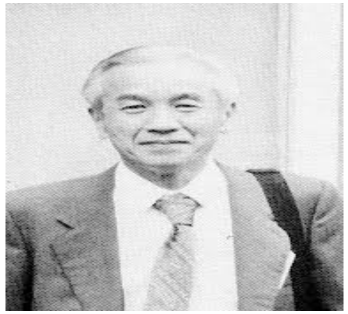
Δm^2_{21}	$7.6 \times 10^{-5}\mathrm{eV}^2$	SNO
$\lvert\Delta m_{31}\rvert^2$	$2.4 \times 10^{-3}\mathrm{eV}^2$	Super – K
$\sin^2 2\theta_{12}$	0.87	KamLAND, SNO
$\sin^2 2\theta_{23}$	0.999	T2K
	0.90	MINOS
$\sin^2 2\theta_{13}$	0.084	DayaBay2015
	0.1	RENO
	0.09	DoubleChooz

Yet to be fixed

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Bruno Pontecorvo

Ziro Maki



Masami Nakagawa

Shoichi Sakata

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times diag\left(1, e^{i\rho}, e^{i\phi}\right)$$

We are looking for

$\delta \neq 0$? Can we measure ρ and ϕ ?

$-\frac{\pi}{2}$

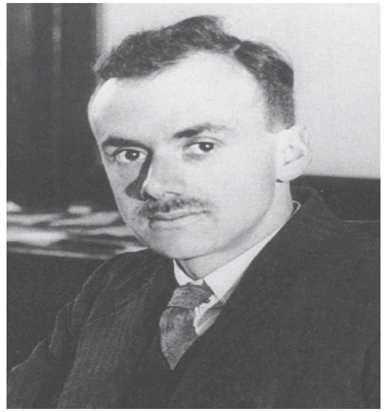
Testing the UNITARITY of U_{PMNS}

Neutrino Mass : What Type

Ettore Majorana , (1906- ?)

$$m_\nu \overline{\nu_L^c} \nu_L \text{ + H. c.}$$

Fermion Number Violating



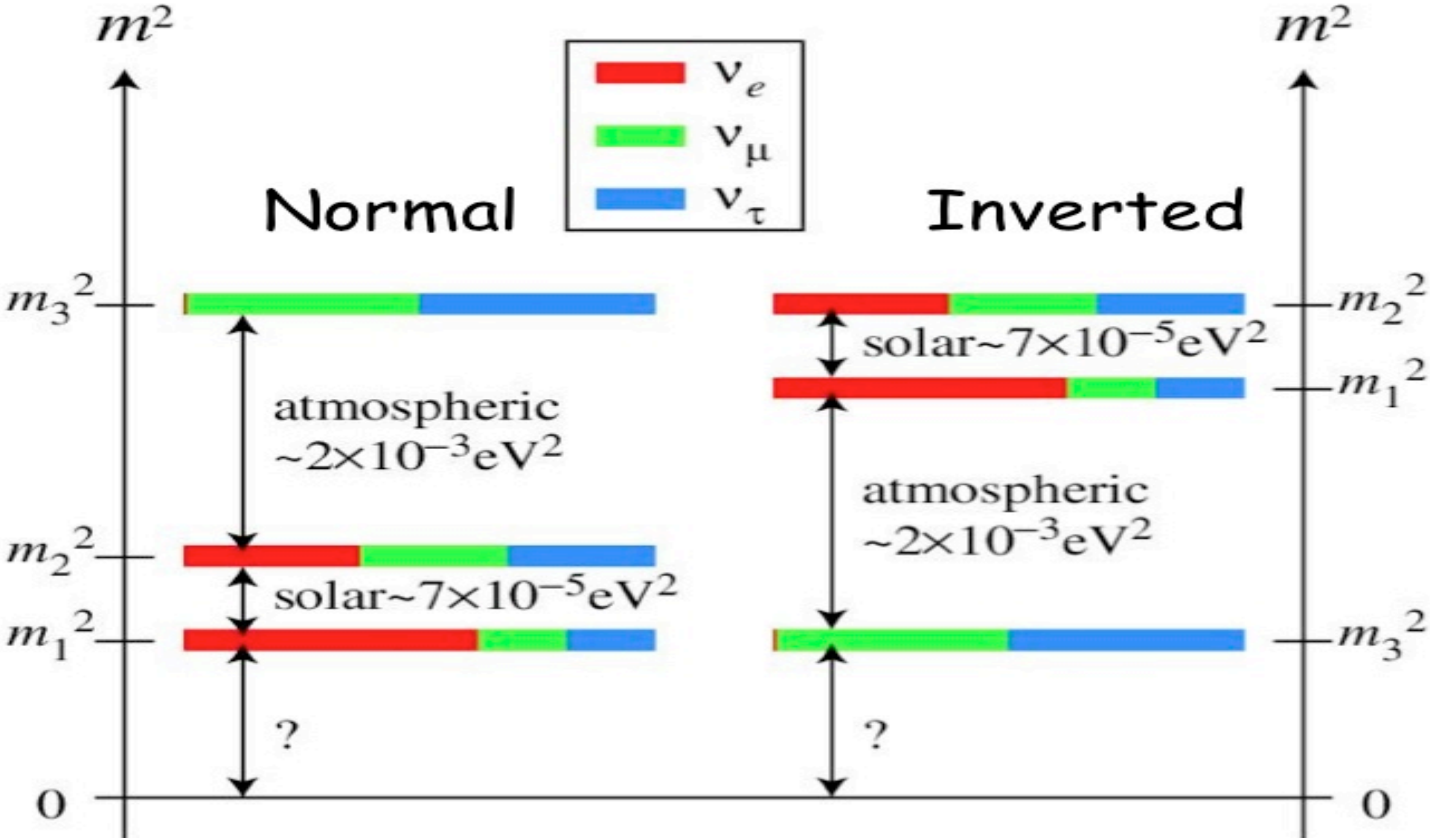
Paul Dirac, FRS (1902-1984)

$$m_\nu \overline{\nu_R} \nu_L \text{ + H. c.}$$

Fermion Number Conserving

Can be tested in neutrinoless double beta decay and collider experiments

Neutrino Mass Hierarchy : **Unknown**



Can be fixed by the neutrino oscillation experiments？

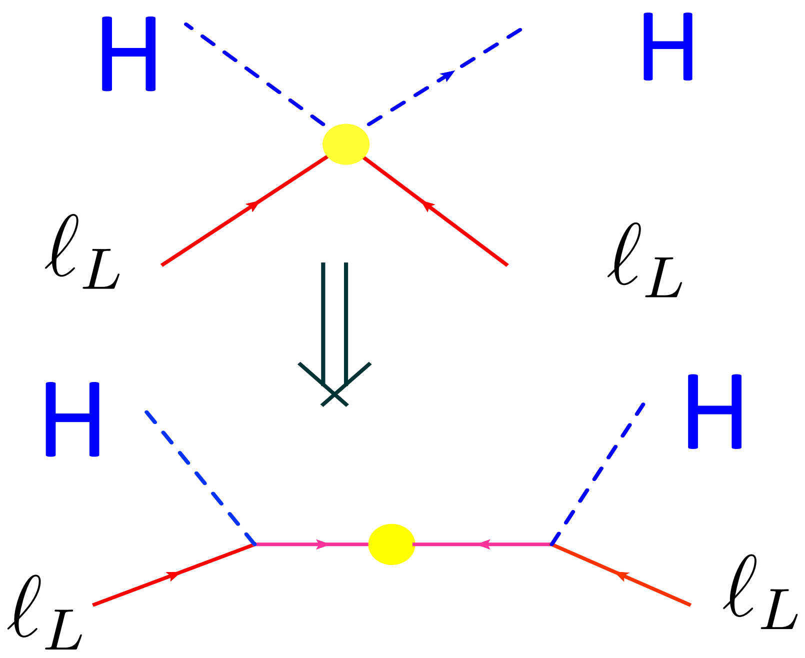
Birth of (a) new idea/ s : generation of neutrino mass

Weinberg Operator in SM (d=5), PRL 43, 1566(1979)

$$\frac{\overline{\ell_L} H \overline{\ell_L^c}^T H}{M}$$

within the Standard Model

The dimension 5 operator can be realized in the following ways



Majorana mass term is generated by the breaking of the lepton numbers by 2 units.

Seesaw Mechanism

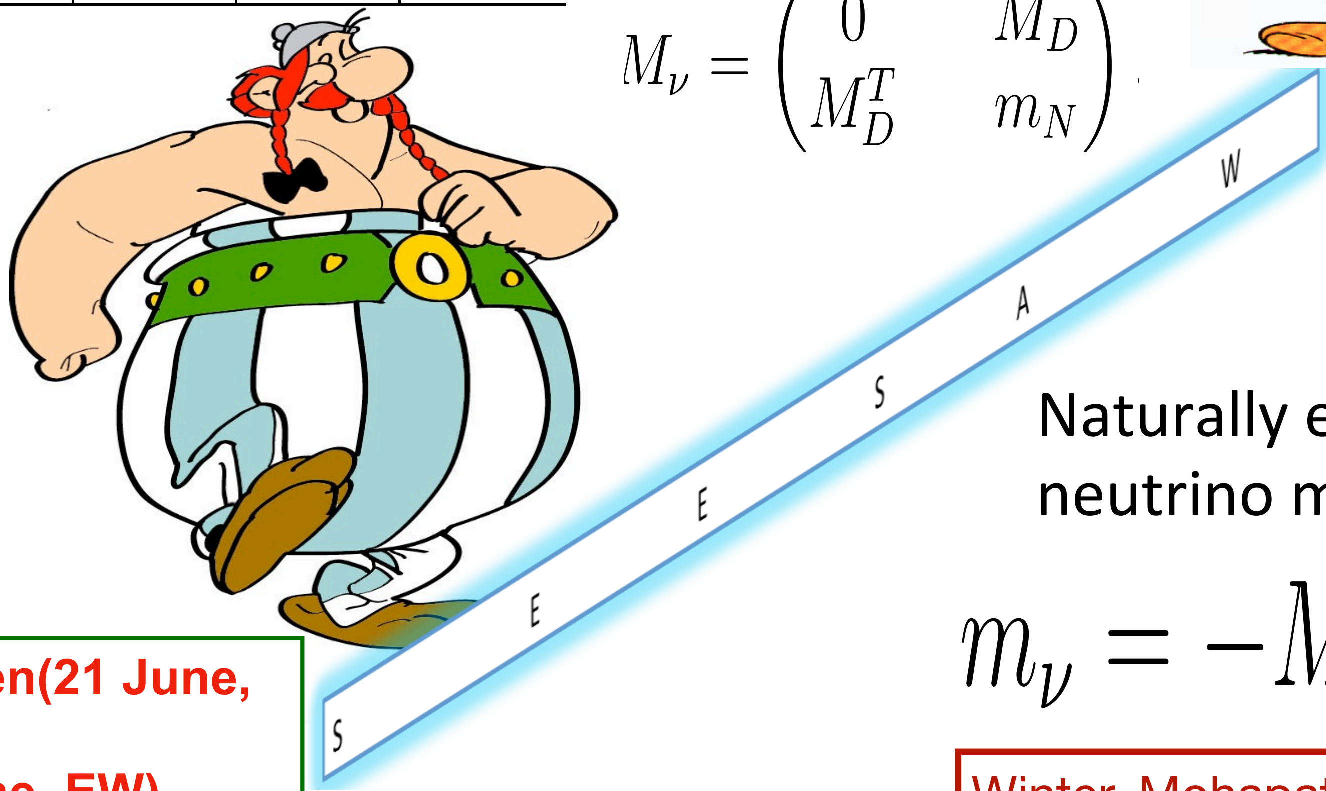
Gell-Mann, Glashow, Minkowski, Mohapatra, Ramond, Senjanovic, Slansky, Yanagida

	SU(3)	SU(2)	$\mathrm{U}(1)_Y$
$\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	1	**2**	$-\frac{1}{2}$
e_R	1	1	-1
$H = \begin{pmatrix} H^0 \\ H^- \end{pmatrix}$	1	**2**	$-\frac{1}{2}$
N_R	1	1	0

$$\mathcal{L} \supset -Y_D^{\alpha\beta}\overline{\ell_L^\alpha} H N_R^\beta - \frac{1}{2} m_N^{\alpha\beta} \overline{N_R^{\alpha C}} N_R^\beta + H.c..$$

$$M_D = \frac{Y_D v}{\sqrt{2}}$$

$$M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & m_N \end{pmatrix}.$$



Naturally explains the small neutrino mass

$$m_\nu = -M_D m_N^{-1} M_D^T.$$

Rasmussen(21 June, Neutrino), Das(20June, EW)

Winter, Mohapatra: WIN2017, Plenary

Phenomenological Constraints on $\mathcal{N}$

$$\nu \simeq \mathcal{N}\nu_m + \mathcal{R}N_m$$

$$\left(1-\tfrac{1}{2}\epsilon\right)U_{\rm MNS} \qquad\qquad m_D m_N^{-1}$$

$$\boxed{\epsilon = \mathcal{R}^*\mathcal{R}^T}$$

$$\boxed{U_{\rm MNS}^T m_\nu U_{\rm MNS} = {\rm diag}(m_1, m_2, m_3)}$$

In the presence of ϵ, the mixing matrix $\mathcal{N}$ is not unitary, namely $\mathcal{N}^\dagger\mathcal{N} \neq 1$

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} W_\mu \overline{\ell_\alpha}\gamma^\mu P_L \left(\mathcal{N}_{\alpha j}\nu_{m_j} + \mathcal{R}_{\alpha j}N_{m_j}\right) + {\rm H.c.}$$

$$\mathcal{L}_{NC} = -\frac{g}{2\cos\theta_{\rm W}} Z_\mu \Big[\overline{\nu_{m_i}}\gamma^\mu P_L(\mathcal{N}^\dagger\mathcal{N})_{ij}\nu_{m_j} + \overline{N_{m_i}}\gamma^\mu P_L(\mathcal{R}^\dagger\mathcal{R})_{ij}N_{m_j} + \left\{\overline{\nu_{m_i}}\gamma^\mu P_L(\mathcal{N}^\dagger\mathcal{R})_{ij}N_{m_j} + {\rm H.c.}\right\}\Big]$$

Nonunitarity: JHEP 10 (2006) 084
JHEP 12(2007) 061

Fixing the Matrices $\mathcal{N}$ and $\mathcal{R}$

- We consider the two generations of heavy neutrinos

$$U_{MNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$\times diag(1, e^{i\rho}, 1)$$

- We fix the parameters by the following neutrino oscillation data

$\sin^2\theta_{12}$	0.87
$\sin^2\theta_{23}$	1.00
$\sin^2\theta_{13}$	0.092
$\Delta m^2_{12} = m^2_2 - m^2_1$	$7.6 \times 10^{-5}\mathrm{eV}^2$
$\Delta m^2_{23} = \lvert m^2_3 - m^2_2\rvert$	$2.4 \times 10^{-3}\mathrm{eV}^2$

For the minimal scenario we consider the Normal Hierarchy(NH) and Inverted Hierarchy(IH) cases as

$$\boxed{D_{\rm NH} = {\rm diag}\left(0, \sqrt{\Delta m^2_{12}}, \sqrt{\Delta m^2_{12} + \Delta m^2_{23}}\right)}$$

$$\boxed{D_{\rm IH} = {\rm diag}\left(\sqrt{\Delta m^2_{23} - \Delta m^2_{12}}, \sqrt{\Delta m^2_{23}}, 0\right)}$$

we assume degenerate case

$$\boxed{M_N = m_N^1 = m_N^2}$$

Light neutrino mass matrix can be simplified

$$m_\nu = \frac{1}{M_N} m_D m_D^T = U^*_{\rm MNS} D_{\rm NH/IH} U^\dagger_{\rm MNS} \qquad m_D = \sqrt{M_N} U^*_{\rm MNS} \sqrt{D_{\rm NH/IH}}\, O$$

$$\sqrt{D_{\rm NH}} = \begin{pmatrix} 0 & 0 \\ (\Delta m^2_{12})^{\frac{1}{4}} & 0 \\ 0 & (\Delta m^2_{23} + \Delta m^2_{12})^{\frac{1}{4}} \end{pmatrix}, \quad \sqrt{D_{\rm IH}} = \begin{pmatrix} (\Delta m^2_{23} - \Delta m^2_{12})^{\frac{1}{4}} & 0 \\ 0 & (\Delta m^2_{23})^{\frac{1}{4}} \\ 0 & 0 \end{pmatrix}$$

How can we write O

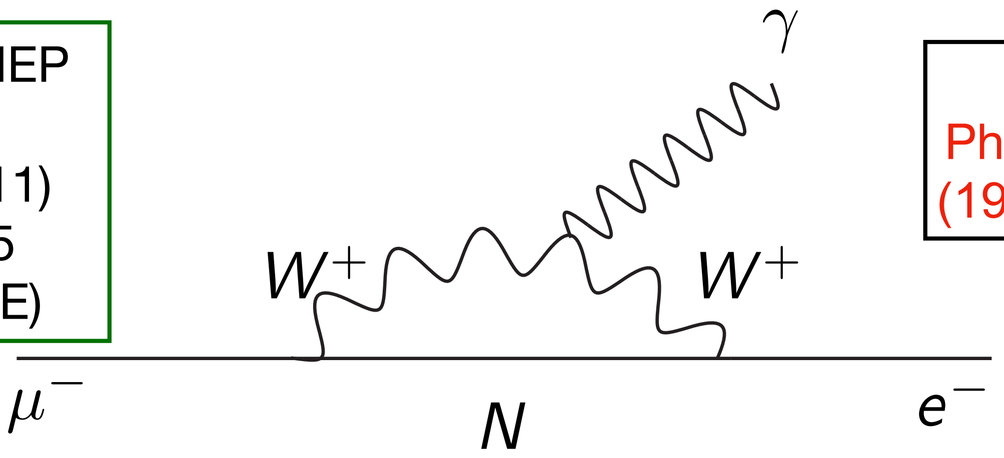
Application Casas- Ibarra Conjecture

$$O = \begin{pmatrix} \cos(X+iY) & \sin(X+iY) \\ -\sin(X+iY) & \cos(X+iY) \end{pmatrix} = \begin{pmatrix} \cosh Y & i\sinh Y \\ -i\sinh Y & \cosh Y \end{pmatrix} \begin{pmatrix} \cos X & \sin X \\ -\sin X & \cos X \end{pmatrix}$$

$\boxed{X \text{ and } Y \text{ are real parameters}}$

Due to non unitarity, the elements of N are highly constrained by the precession experiments of the W, Z decays and the LFV processes

Phenomenologies: JHEP 09 (2010) 108
PRD 84, 013005 (2011)
JHEP 08 (2012) 125
JHEP 09 (2013) 023(E)



Lee and Shrock: Phys. Rev. D16, 1444 (1977).

$\mu \to e\gamma$	$\mathcal{B}(< 4.2 \times 10^{-13})$	EPJ C 76, (2016) no.8, 434
$\tau \to e\gamma$	$\mathcal{B}\ (< 4.5 \times 10^{8})$	PLB 666, (2008)16-22
$\tau \to \mu\gamma$	$\mathcal{B}\ (< 12.0 \times 10^{-8})$	PLB 666, (2008)16-22

$$|\mathcal{N}\mathcal{N}^\dagger| = \begin{pmatrix} 0.994 \pm 0.00625 & 1.288 \times 10^{-5} & 8.76356 \times 10^{-3} \\ 1.288 \times 10^{-5} & 0.995 \pm 0.00625 & 1.046 \times 10^{-2} \\ 8.76356 \times 10^{-3} & 1.046 \times 10^{-2} & 0.995 \pm 0.00625 \end{pmatrix}$$

$$\mathcal{N}\mathcal{N}^\dagger \simeq \mathbf{1} - \epsilon$$

$$\tau \to e\gamma$$

$$|\epsilon| = \begin{pmatrix} 0.006 \pm 0.00625 & < 1.288 \times 10^{-5} & < 8.76356 \times 10^{-3} \\ < 1.288 \times 10^{-5} & 0.005 \pm 0.00625 & < 1.046 \times 10^{-2} \\ < 8.76356 \times 10^{-3} & < 1.046 \times 10^{-2} & 0.005 \pm 0.00625 \end{pmatrix}$$

$$\tau \to \mu\gamma$$

$$\mu \to e\gamma$$

$$\epsilon(\delta, \rho, Y) \;=\; (\mathcal{R}^* \mathcal{R}^T)_{\mathrm{NH/IH}} = \frac{1}{M_N^2} m_D m_D^T \;=\; \frac{1}{m_N} U_{\mathrm{MNS}} \sqrt{D_{\mathrm{NH/IH}}}\, O^* O^T \sqrt{D_{\mathrm{NH/IH}}}\, U_{\mathrm{MNS}}^\dagger$$

$\epsilon(\delta, \rho, Y)$ is independent of X since

$$O^* O^T = \begin{pmatrix} \cosh^2 Y + \sinh^2 Y & -2i \cosh Y \ \sinh Y \\ 2i \cosh Y \ \sinh Y & \cosh^2 Y + \sinh^2 Y \end{pmatrix}$$

Now we perform a scan for the parameter set $\{\delta, \rho, Y\}$ and identify an allowed region for which $\epsilon(\delta, \rho, Y)$ satisfies the experimental constraints

$$M_N = 100 \ \text{GeV}$$

$-\pi \leq \delta, \rho \leq \pi$ with the interval of $\frac{\pi}{20}$ and $0 \leq y \leq 14$ with the interval of 0.01875

Production of the heavy neutrino at the LHC

Through the Charged Current interaction

$$q\bar{q}' \to \ell N_i \ (u\bar{d} \to \ell_\alpha^+ N_i \text{ and } \bar{u}d \to \ell_\alpha^- \overline{N_i})$$

$$\sigma(q\bar{q}' \to \ell_\alpha N_i) = \sigma_{LHC} |\mathcal{R}_{\alpha i}|^2$$

Phenomenological works by Atre, Antusch, Chen, Das et. al., Del-Aguila, Dev et. al., Fischer, Han, Mohapatra et. al., Okada et. al. Savedraa et.al.

Mixing-squared

Put bounds on the mixing angle to constrain the production cross section

$$N \longrightarrow \ell W,\ W \longrightarrow jj$$

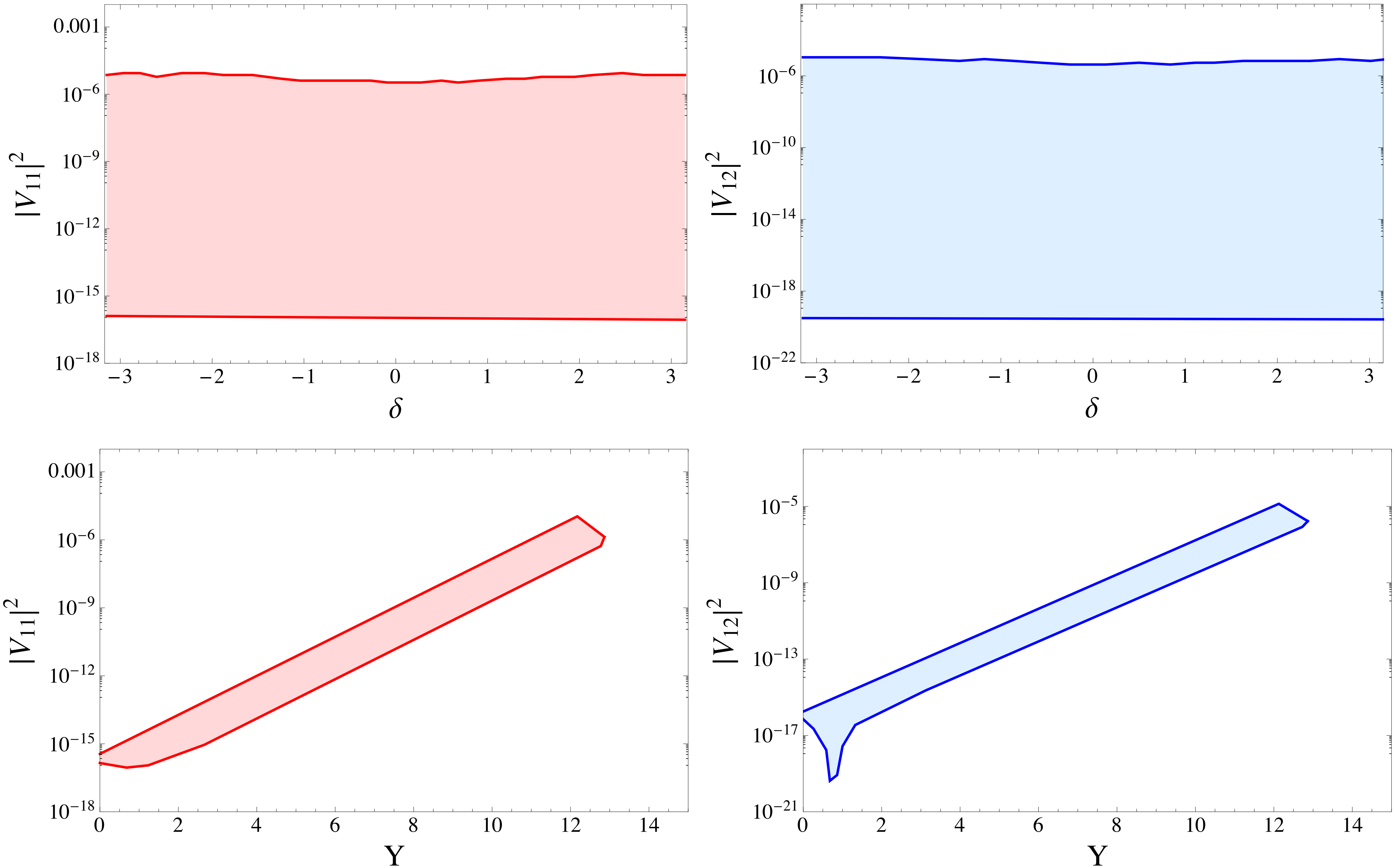
BR(m_N) >= 50% Leading

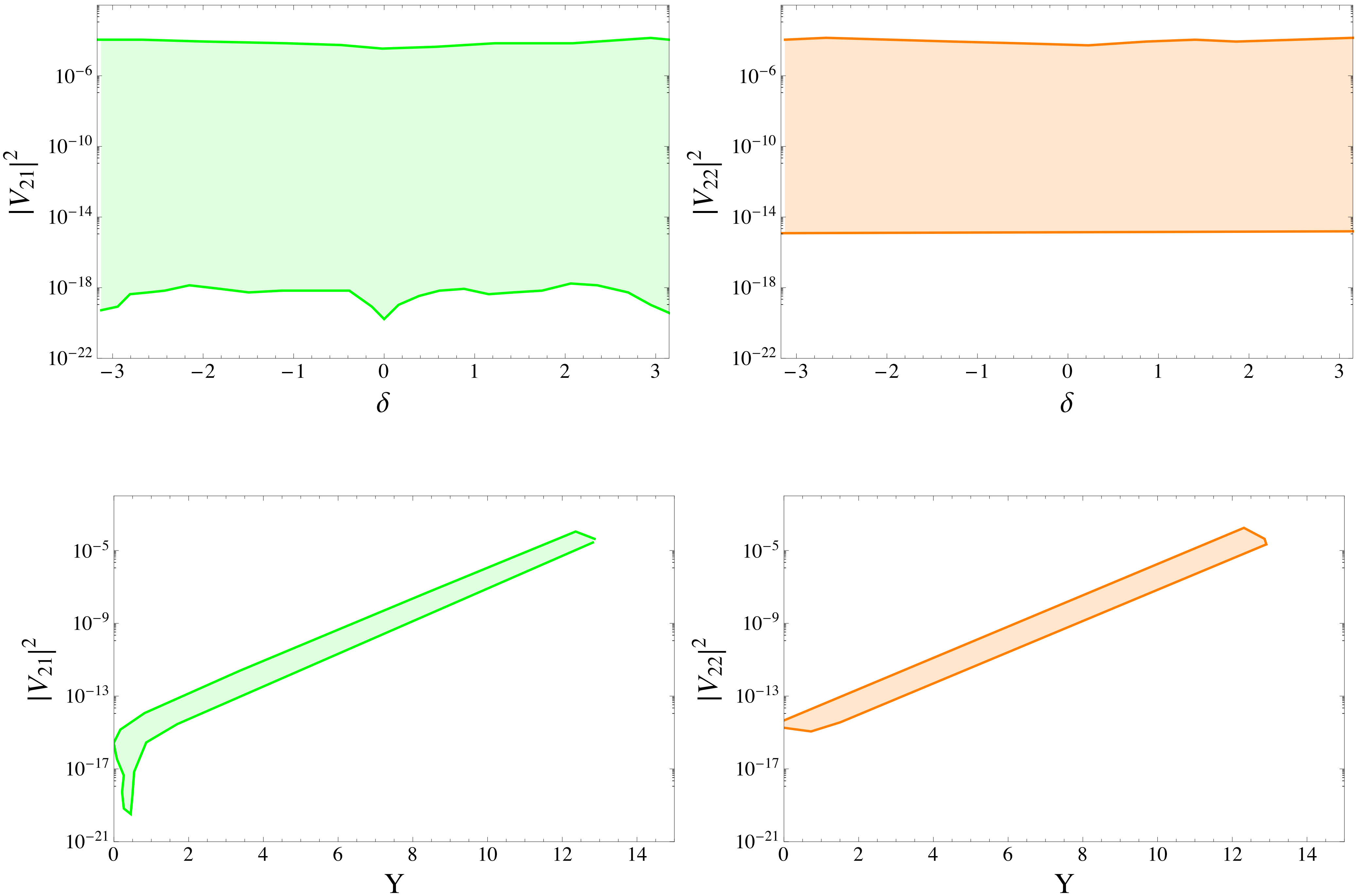
Many modes/ many ways to produce the heavy neutrinos at the colliders but (very small) mixings can spoil the game of search, but still we should hope for the best.

NH Case

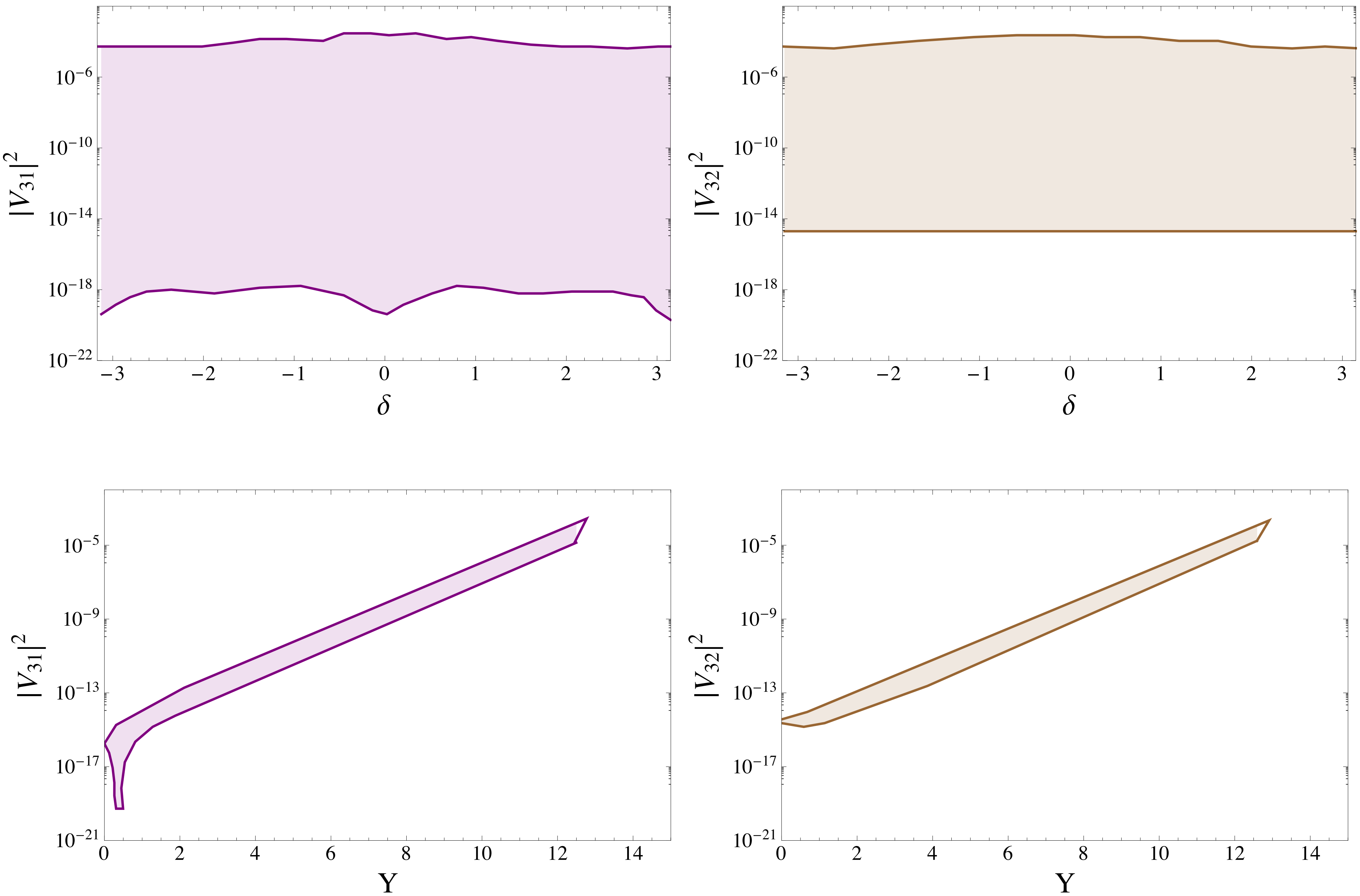
Das, Okada: arXiv:1702.04688 for type-I seesaw and

Das, Okada: arXiv:1207.3734 for the Inverse Seesaw case



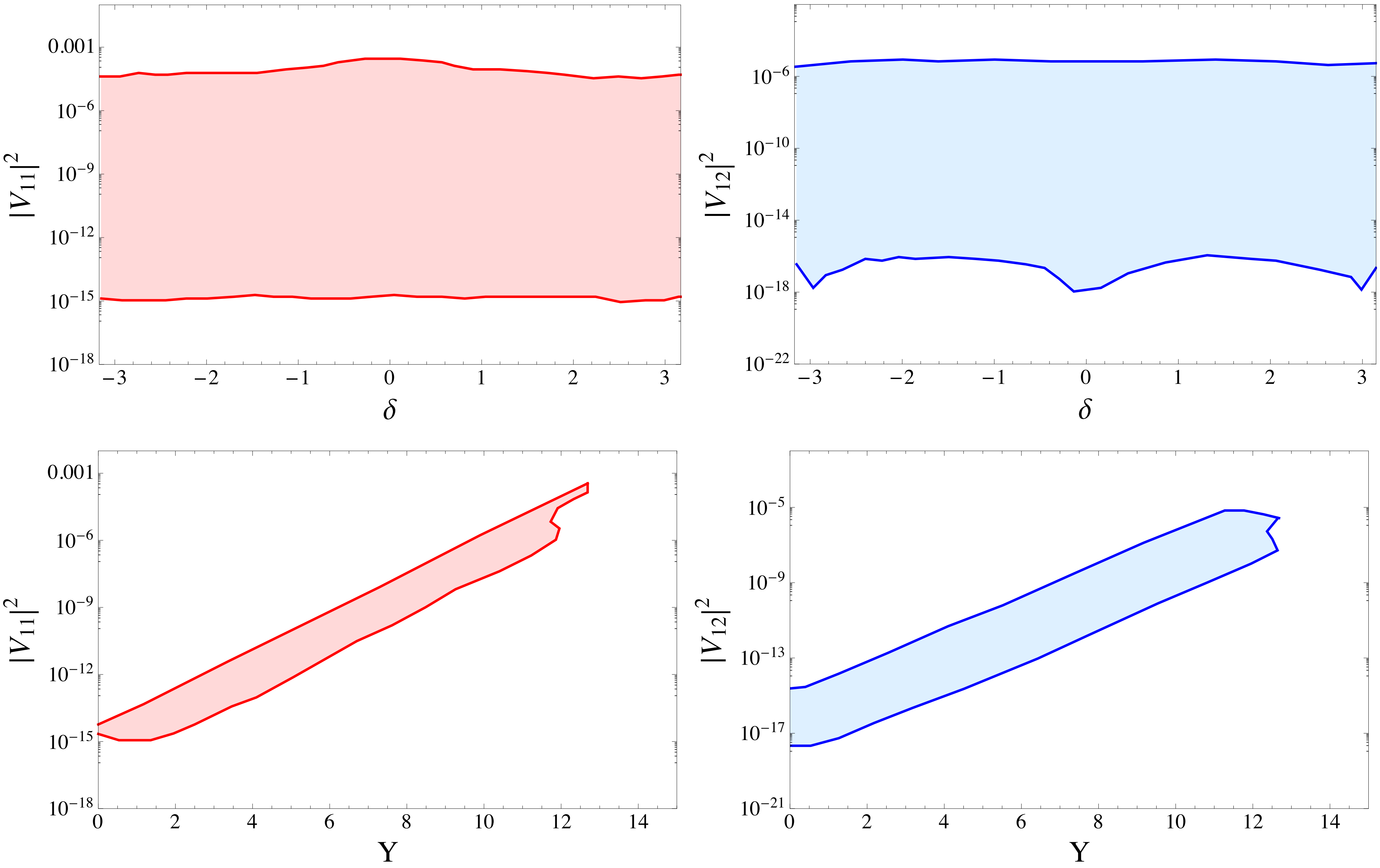


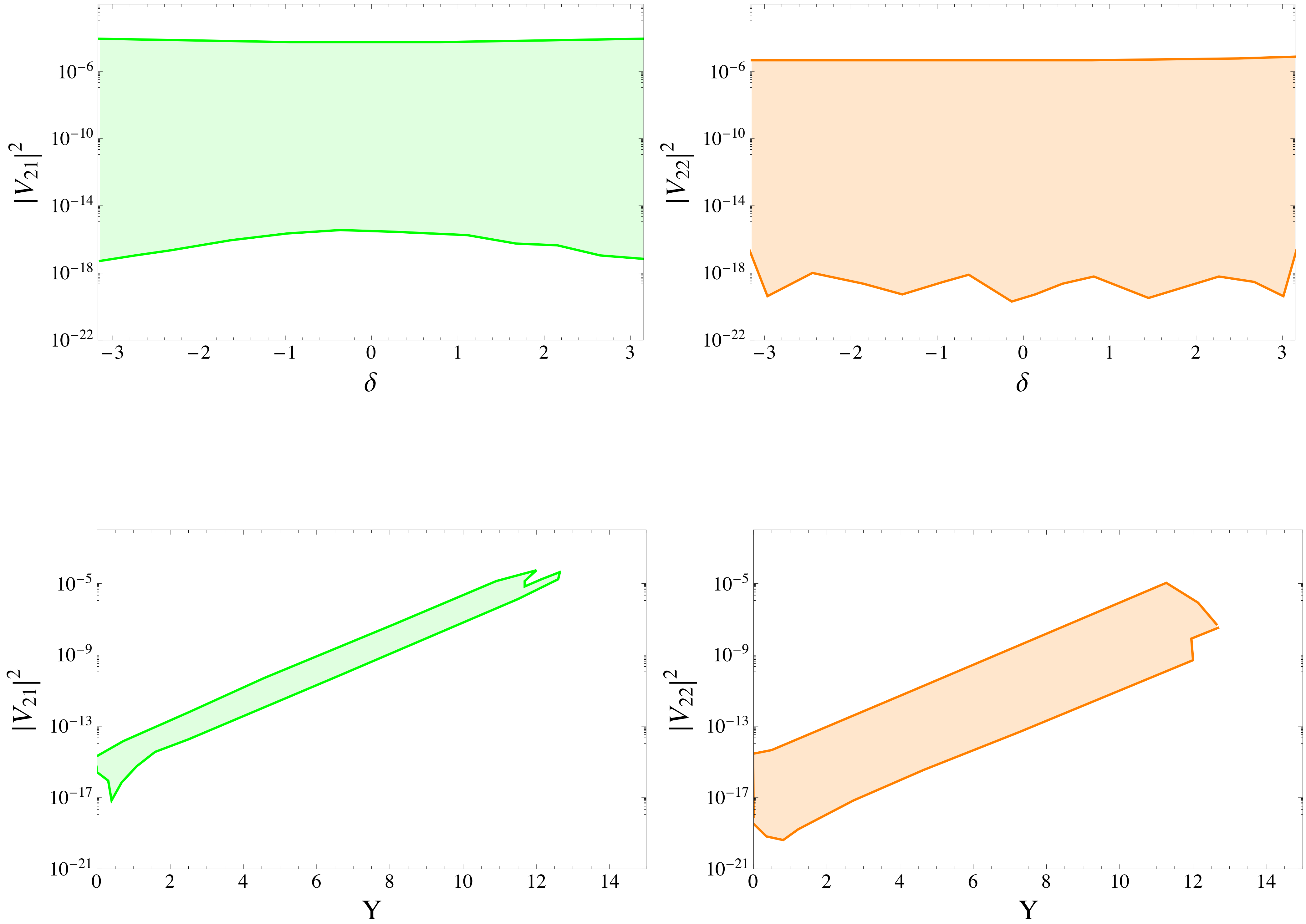
$|V_{21}|^2$
δ
$|V_{22}|^2$
δ
$|V_{21}|^2$
Y
$|V_{22}|^2$
Y



$|V_{31}|^2$
10^{-6}
10^{-10}
10^{-14}
10^{-18}
10^{-22}
-3 -2 -1 0 1 2 3
δ
$|V_{32}|^2$
10^{-6}
10^{-10}
10^{-14}
10^{-18}
10^{-22}
-3 -2 -1 0 1 2 3
δ
$|V_{31}|^2$
10^{-5}
10^{-9}
10^{-13}
10^{-17}
10^{-21}
0 2 4 6 8 10 12 14
Y
$|V_{32}|^2$
10^{-5}
10^{-9}
10^{-13}
10^{-17}
10^{-21}
0 2 4 6 8 10 12 14
Y

IH Case





$|V_{21}|^2$
10^{-6}
10^{-10}
10^{-14}
10^{-18}
10^{-22}
−3
−2
−1
0
1
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3
δ
$|V_{22}|^2$
10^{-6}
10^{-10}
10^{-14}
10^{-18}
10^{-22}
−3
−2
−1
0
1
2
3
δ
$|V_{21}|^2$
10^{-5}
10^{-9}
10^{-13}
10^{-17}
10^{-21}
0
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4
6
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12
14
Y
$|V_{22}|^2$
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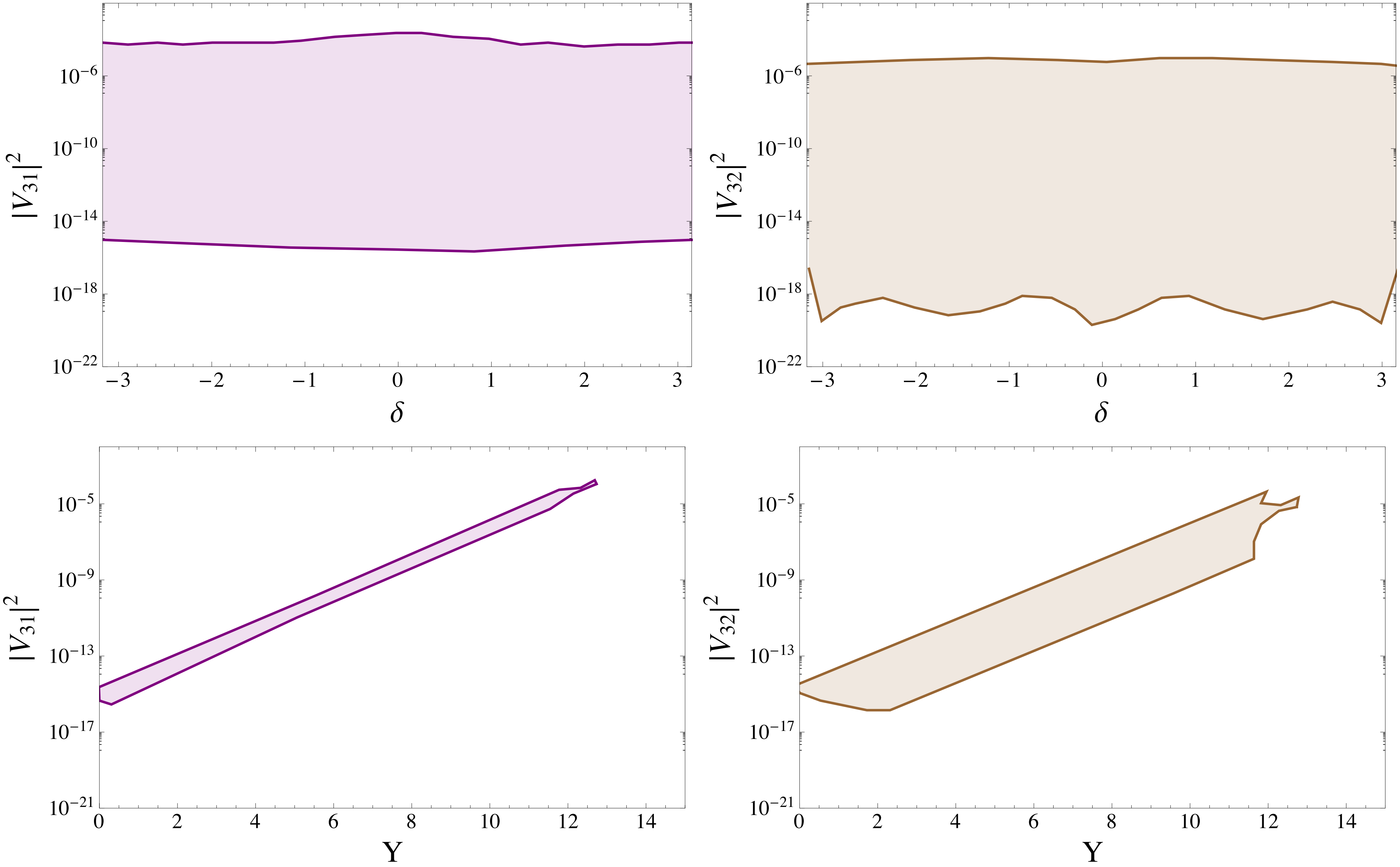
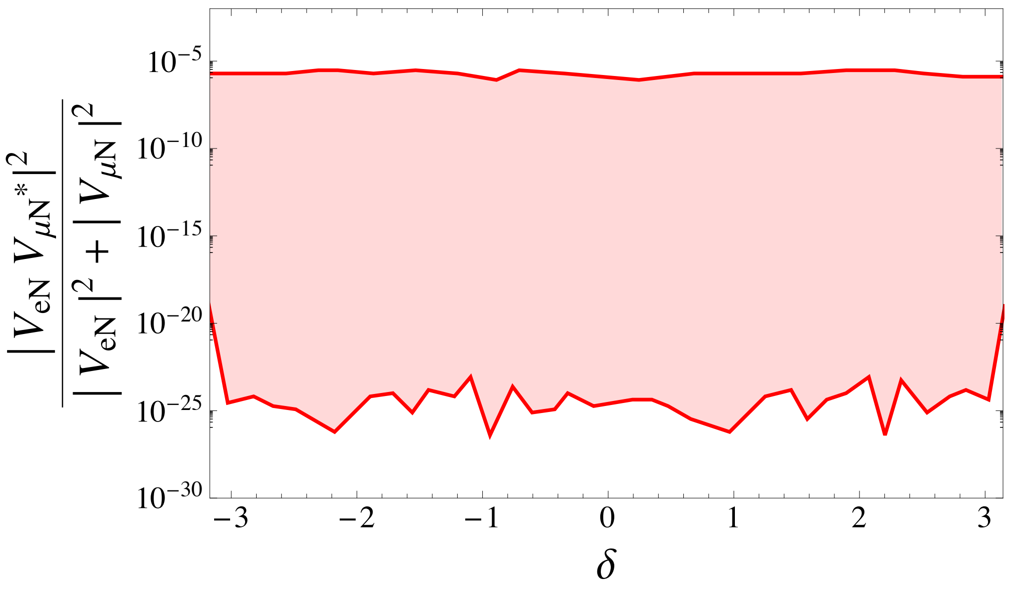
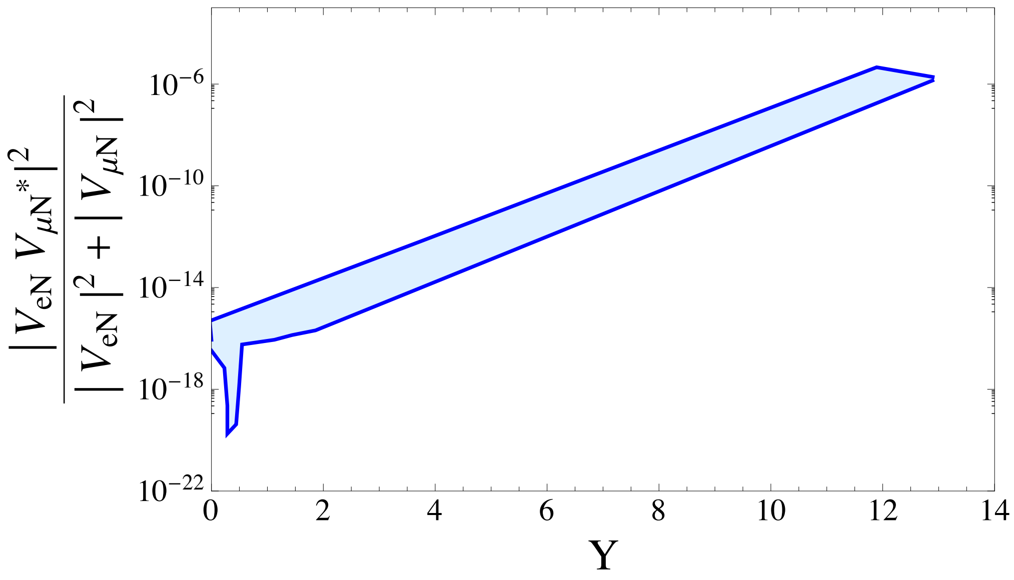
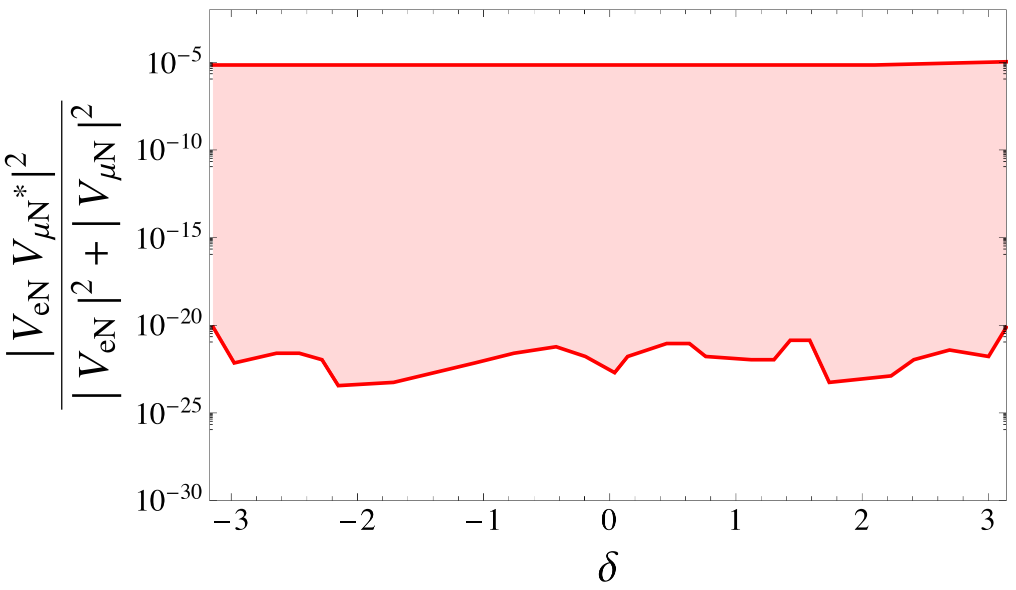

$|V_{31}|^2$
δ
$|V_{32}|^2$
δ
$|V_{31}|^2$
Y
$|V_{32}|^2$
Y

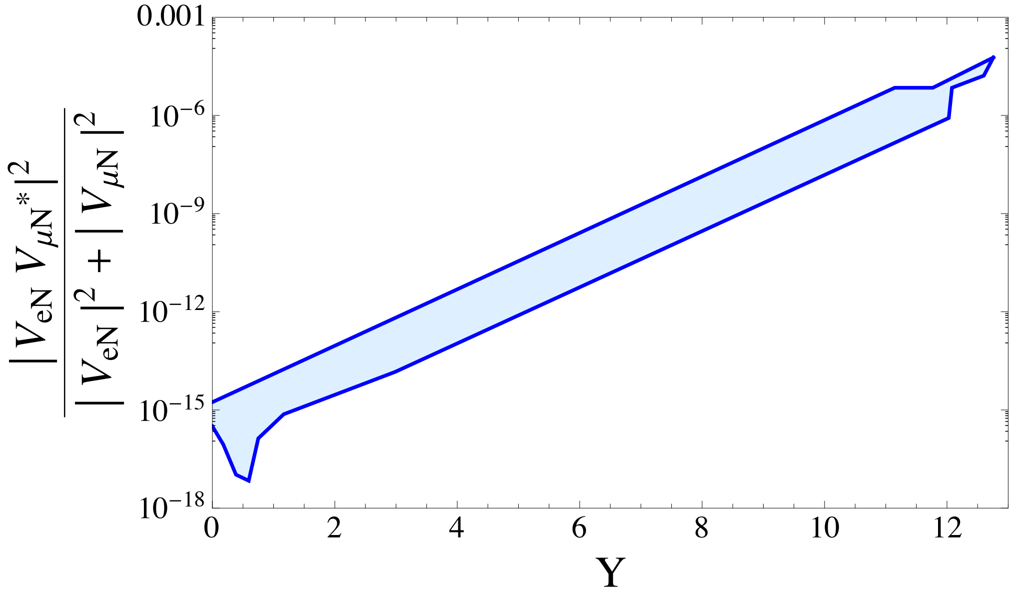
NH Case





IH Case





Current Limits

$$M_N = 100 \text{ GeV}.$$

Experiments	Mixning angles	Upper Bounds
EWPD-e[62–64]	$\lvert V_{eN}\rvert^2$	1.7×10^{-3}
EWPD-μ[62–64]	$\lvert V_{\mu N}\rvert^2$	9.0×10^{-3}
EWPD-τ[62–64]	$\lvert V_{\tau N}\rvert^2$	4.2×10^{-3}
L3[65]	$\lvert V_{\ell N}\rvert^2,\ \ell = e, \mu$	2.2×10^{-3}
Higgs-LHC[66]	$\lvert V_{\ell N}\rvert^2,\ \ell = e, \mu$	3.4×10^{-3}
LHC-e(ATLAS, 8 TeV)[67]	$\lvert V_{eN}\rvert^2$	4.1×10^{-2}
LHC-μ(ATLAS, 8 TeV)[67]	$\lvert V_{\mu N}\rvert^2$	1.9×10^{-3}
LHC-e(CMS, 8 TeV)[68]	$\lvert V_{eN}\rvert^2$	1.1×10^{-2}
LHC-μ(CMS, 8 TeV)[68]	$\lvert V_{eN}\rvert^2$	4.6×10^{-3}
LHC-e, μ(CMS, 8 TeV)[68]	$\frac{\lvert V_{eN} V^*_{\mu N}\rvert^2}{\lvert V_{eN}\rvert^2 + \lvert V_{\mu N}\rvert^2}$	2.4×10^{-3}

References from arXiv:1702.04668

Remains unaltered with the mass of the N

Relaxed with the mass of N

In our case the parameter regions will remain the same even with the higher values of the heavy neutrino mass, e. g., 1TeV and even high enough, however, the mixing angle squared raises up to O(10^{-4}).

Conclusions

We have studied the minimal type-I seesaw scenario and the current experimental bounds on the mixing between the degenerate heavy Majorana neutrinos and SM neutrinos using the general Dirac Yukawa parameters in the light of Cases-Ibarra conjecture.

To constrain the analysis we use neutrino oscillation data, LFV and LEP results. Hence we obtain indirect limits on the light-heavy mixing angle which are stronger than the current experimental bounds.

We have noticed that the parameter regions of the mixing angles remain unaltered with the change in mass even make it high enough.

Thank You