Testing minimal seesaw models at hadron colliders

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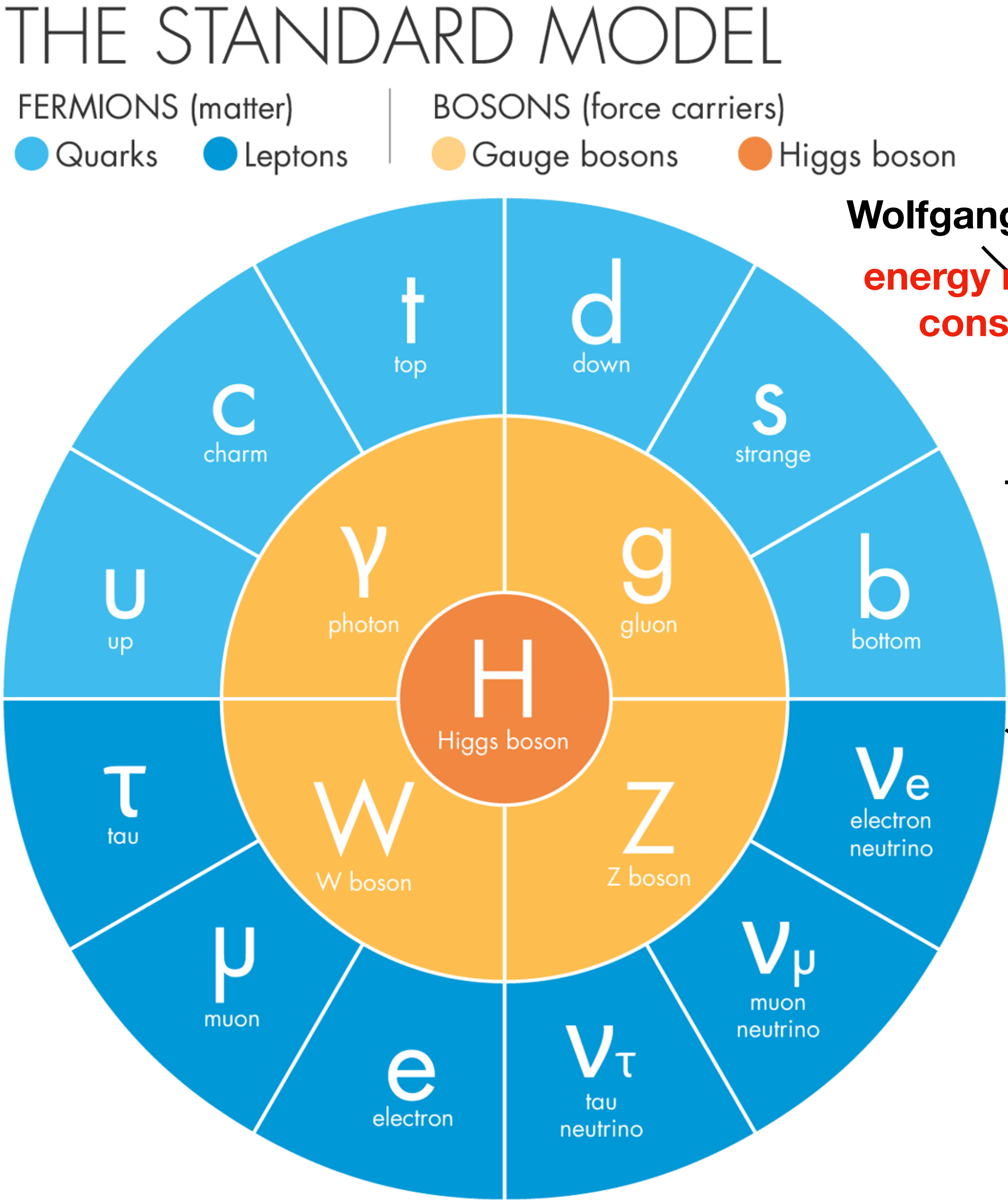
Neutrinos at the High Energy Frontier

AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS
Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts Amherst



Wolfgang Pauli, Enrico Fermi

energy momentum conservation

'Little neutral one' going to be the most attractive key now a days

more care needed amongst many open questions of the SM

Quick Historical

Homestake experiment site
at Homestake gold mine in Lead, South Dakota

Raymond Davis Jr.
(1914-2006)

John Bahcall
(1934-2005)

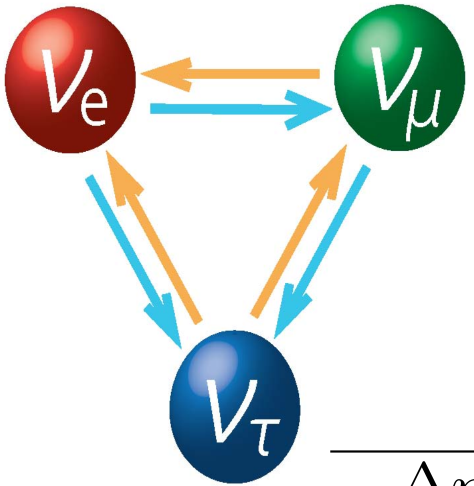
Development of the neutrino oscillation experiments

↓

Kamiokande, Japan; SAGE, former Soviet Union; GALLEX, Italy;
Super Kamiokande, Japan; Sudbury Neutrino Observatory, Canada

Some Results

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



Neutrino oscillation data

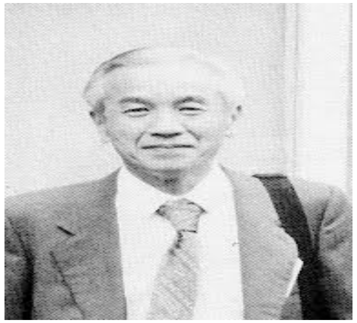
Δm^2_{21}	$7.6 \times 10^{-5}\mathrm{eV}^2$	SNO
$\lvert\Delta m_{31}\rvert^2$	$2.4 \times 10^{-3}\mathrm{eV}^2$	Super – K
$\sin^2 2\theta_{12}$	0.87	KamLAND, SNO
$\sin^2 2\theta_{23}$	0.999	T2K
	0.90	MINOS
$\sin^2 2\theta_{13}$	0.084	DayaBay2015
	0.1	RENO
	0.09	DoubleChooz

All the MYSTERIES are not solved

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

Bruno Pontecorvo

Ziro Maki



Masami Nakagawa

Shoichi Sakata

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

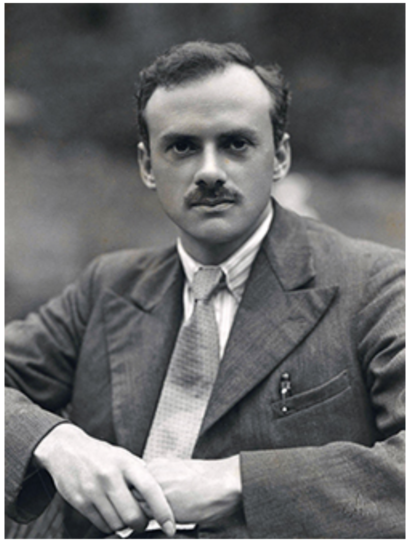
We are looking for $\delta \neq 0$? Can we measure ρ and ϕ ?

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

Testing the UNITARITY of U_{PMNS}

Type of neutrino mass still unknown

Ettore Majorana , (1906- ?)



Paul Dirac, FRS (1902-1984)

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

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

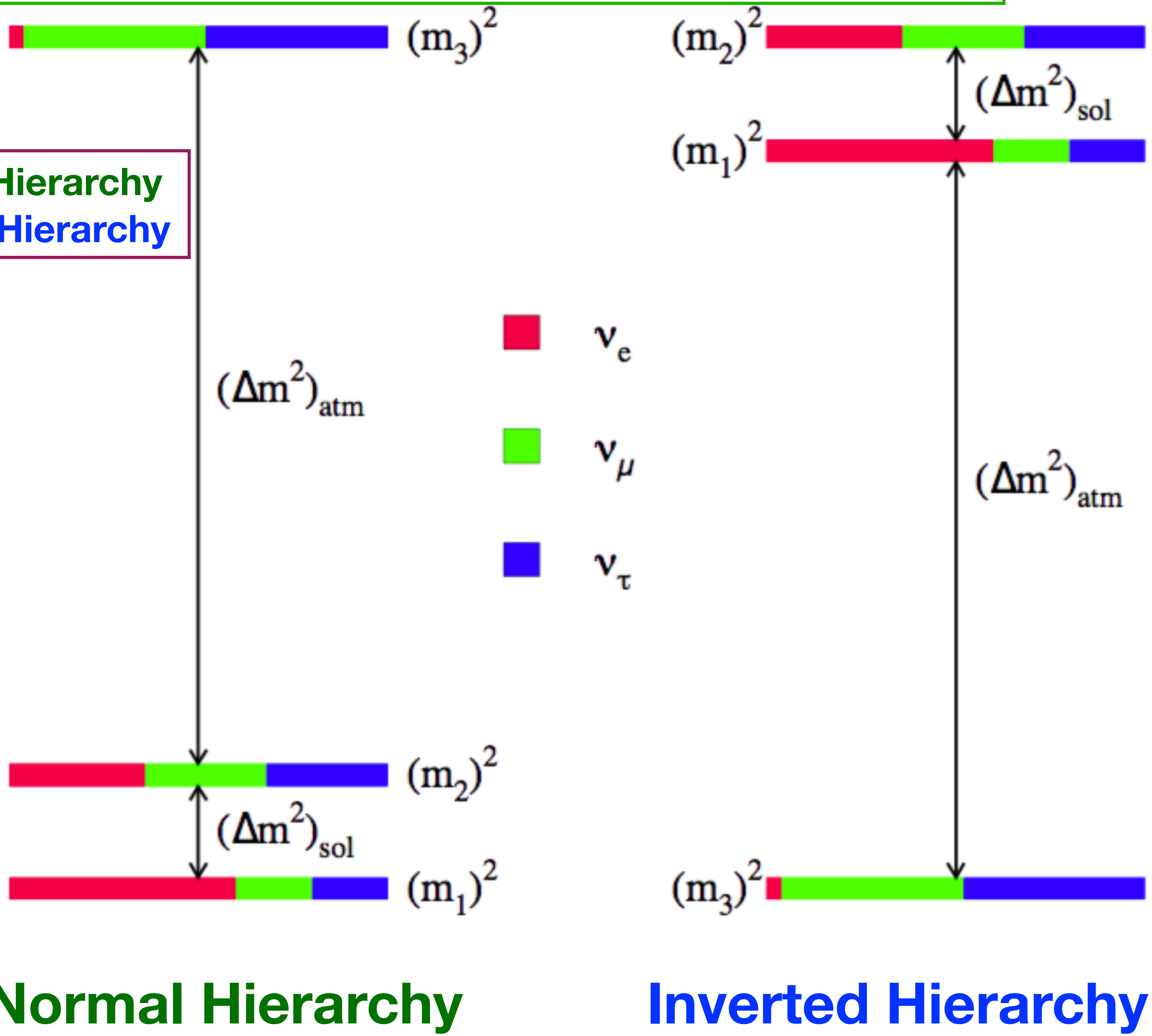
Fermion Number Violating

Fermion Number Conserving

Can be tested in neutrinoless double beta decay and collider experiments

Lightest mass eigenstate: Not fixed yet

$m_1 < m_2 < m_3$: Normal Hierarchy
$m_3 < m_1 < m_2$: Inverted Hierarchy



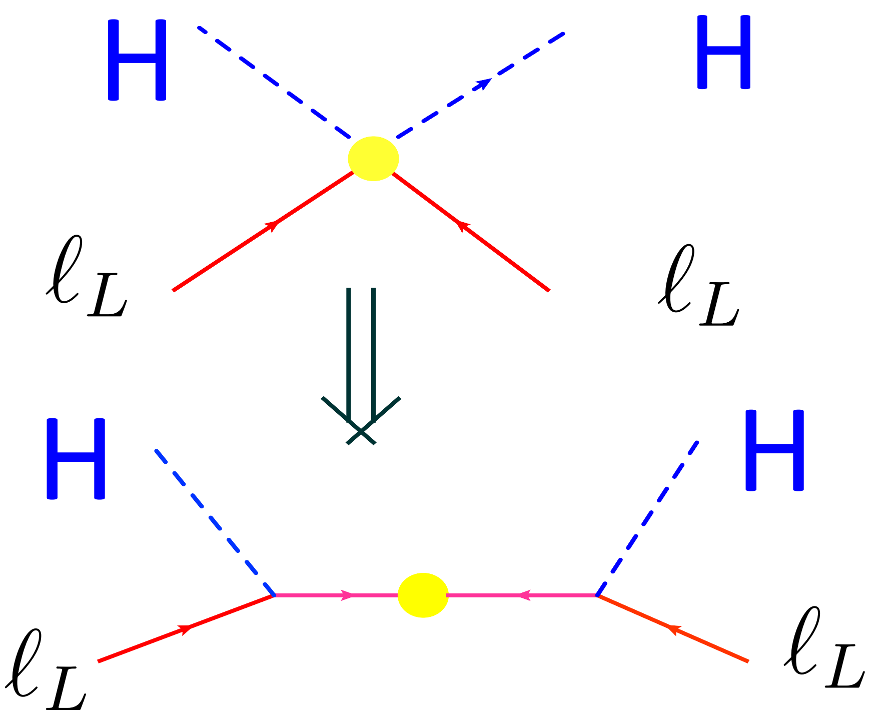
Birth of (a) new idea/ s : generation of neutrino mass

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

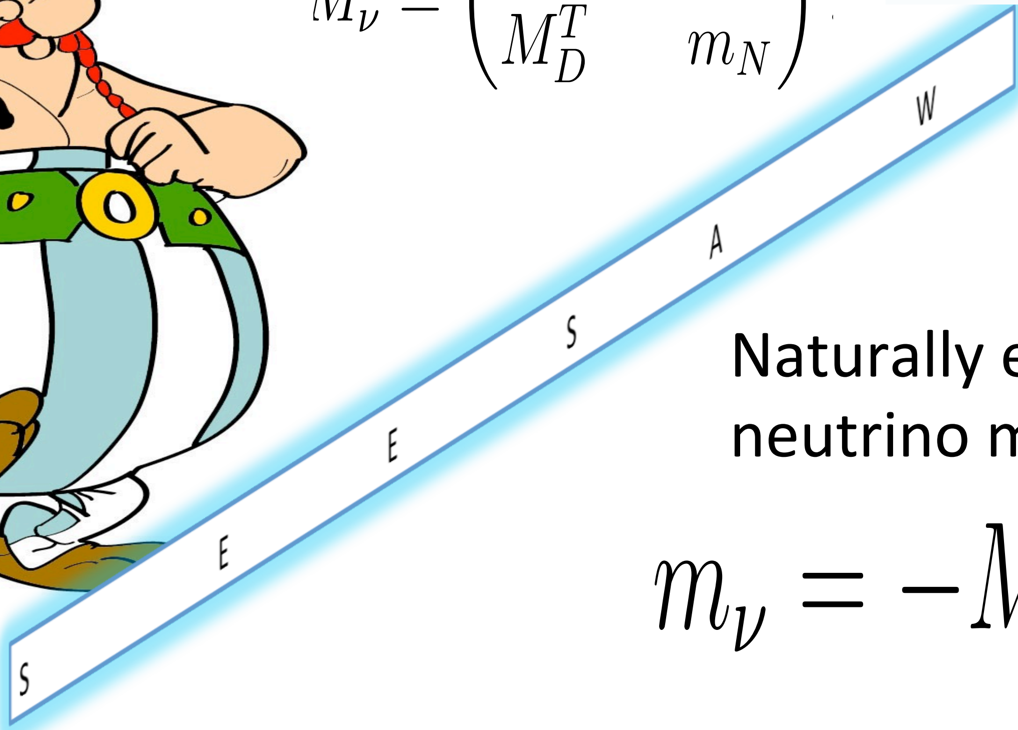
Gell-Mann, Glashow, Minkowski, Mohapatra, Ramond, Senjanovic, Slansky, Yanagida

	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

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

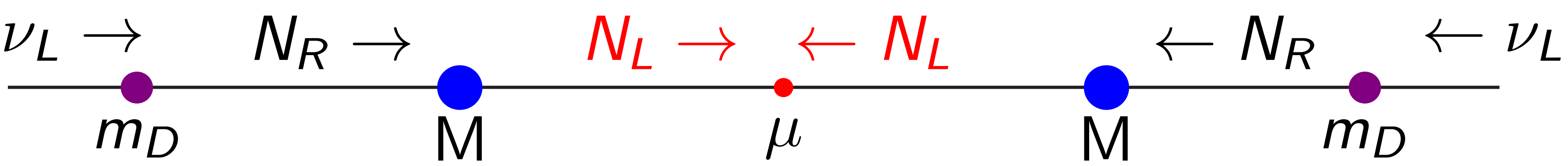
Inverse Seesaw Mechanism : Mohapatra(1986), Mohapatra & Valle (1986)

	SU(2)	$U(1)_Y$
ℓ_L	$\mathbf{2}$	$-1/2$
H	$\mathbf{2}$	$-1/2$
N_R^j	$\mathbf{1}$	0
N_L^j	$\mathbf{1}$	0

Relevant Part of the Lagrangian

$$\mathcal{L}_{mass} \supset -\mu_{ij}\overline{((N_L)^c)^i} N_L^j - m_{ij}\overline{N_R^i} N_L^j - Y_{D_{ij}}\overline{\ell_L^i} H N_R^j + H.c.$$

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



$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$$

$$m_\nu = (m_D \mathbf{M}^{-1}) \mu (m_D \mathbf{M}^{-1})^T$$

$$\mu \backsim \mathcal{O}(m_\nu)$$

$$m_D \mathbf{M}^{-1} \sim \mathcal{O}(1)$$

Light- heavy mixing could be large and Heavy neutrino can be produced at LHC

Phenomenological Constraints on $\mathcal{N}$ and $\mathcal{R}$

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

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

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

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

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

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

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

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

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
$\Delta m_{12}^2 = m_2^2 - m_1^2$	$7.6 \times 10^{-5}\text{eV}^2$
$\Delta m_{23}^2 = \lvert m_3^2 - m_2^2 \rvert$	$2.4 \times 10^{-3}\text{eV}^2$

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

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

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

we assume degenerate case

$$M_N = m_N^1 = m_N^2$$

Light neutrino mass matrix for **type-I** seesaw can be simplified

$$m_\nu = \frac{1}{M_N} m_D m_D^T = U_{\rm MNS}^* D_{\rm NH/IH} U_{\rm MNS}^\dagger$$

$$m_D = \sqrt{M_N} U_{\rm MNS}^* \sqrt{D_{\rm NH/IH}}\, O$$

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

How can we write O

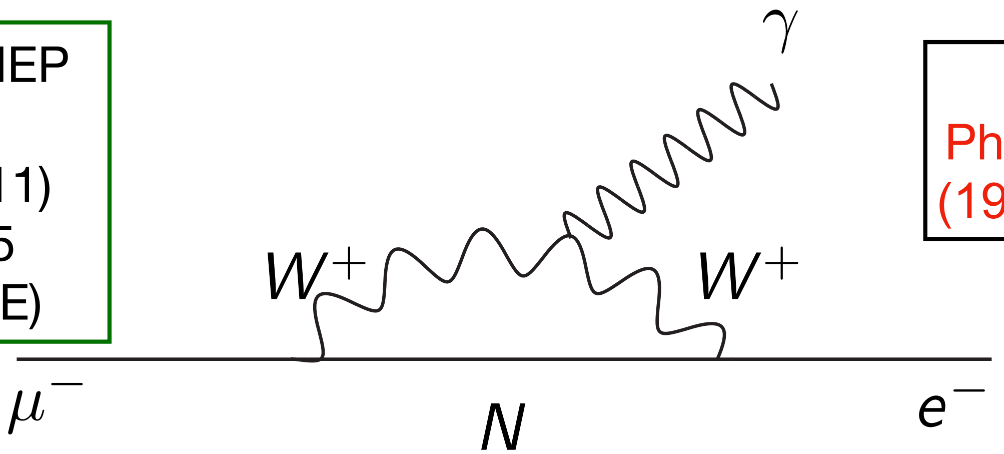
Application Casas- Ibarra Conjecture

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

X and Y 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).

$\mu \to e\gamma$	$\mathcal{B}(<4.2\times10^{-13})$	EPJ C 76, (2016) no.8, 434
$\tau \to e\gamma$	$\mathcal{B}\ (<4.5\times10^{8})$	PLB 666, (2008)16-22
$\tau \to \mu\gamma$	$\mathcal{B}\ (<12.0\times10^{-8})$	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

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

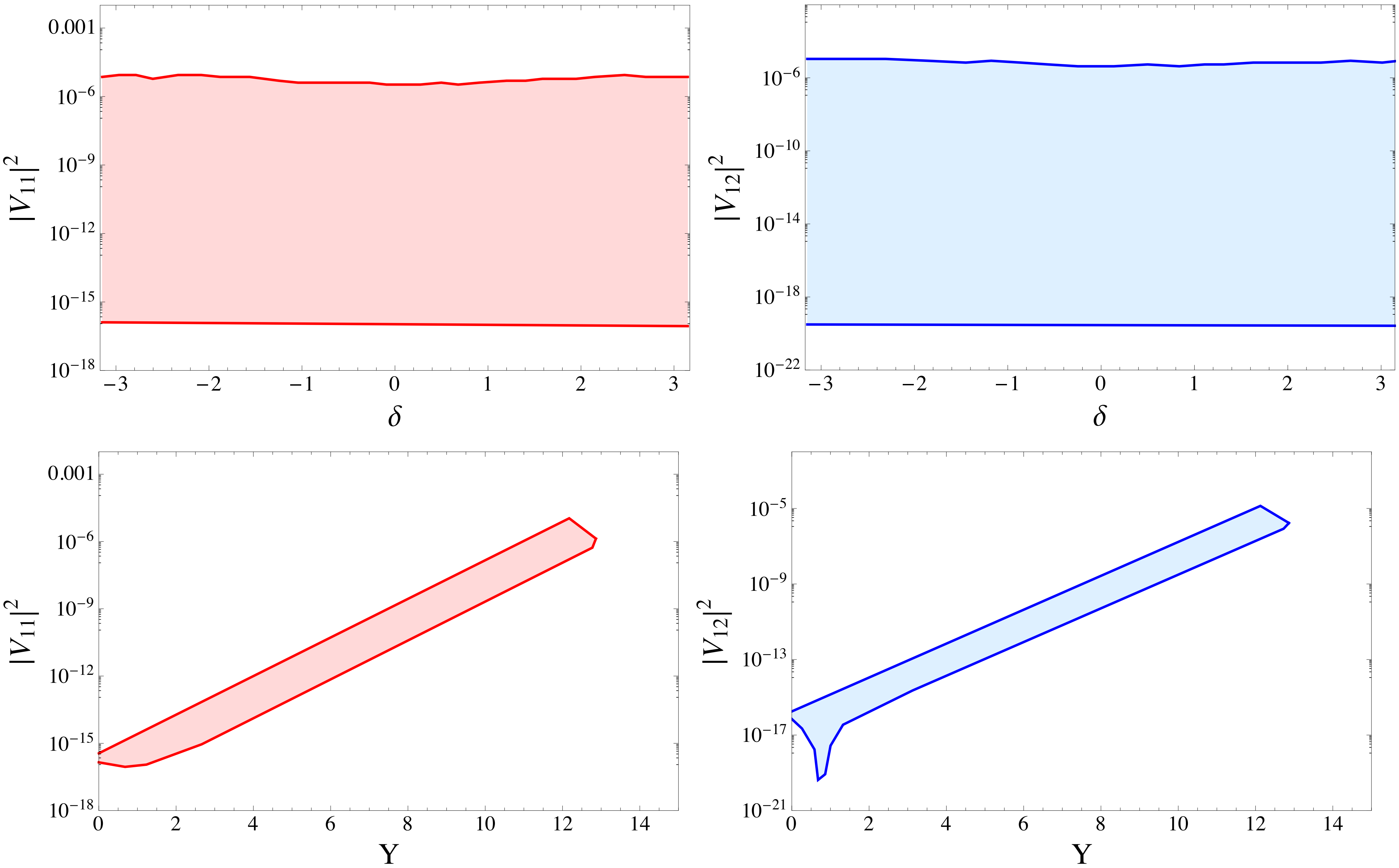
Now we perform a scan for the parameter set $\{\delta, \rho, Y\}$ and identify an allowed region for which $\epsilon(\delta, \rho, Y)$ satisfies the experimental constraints

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

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

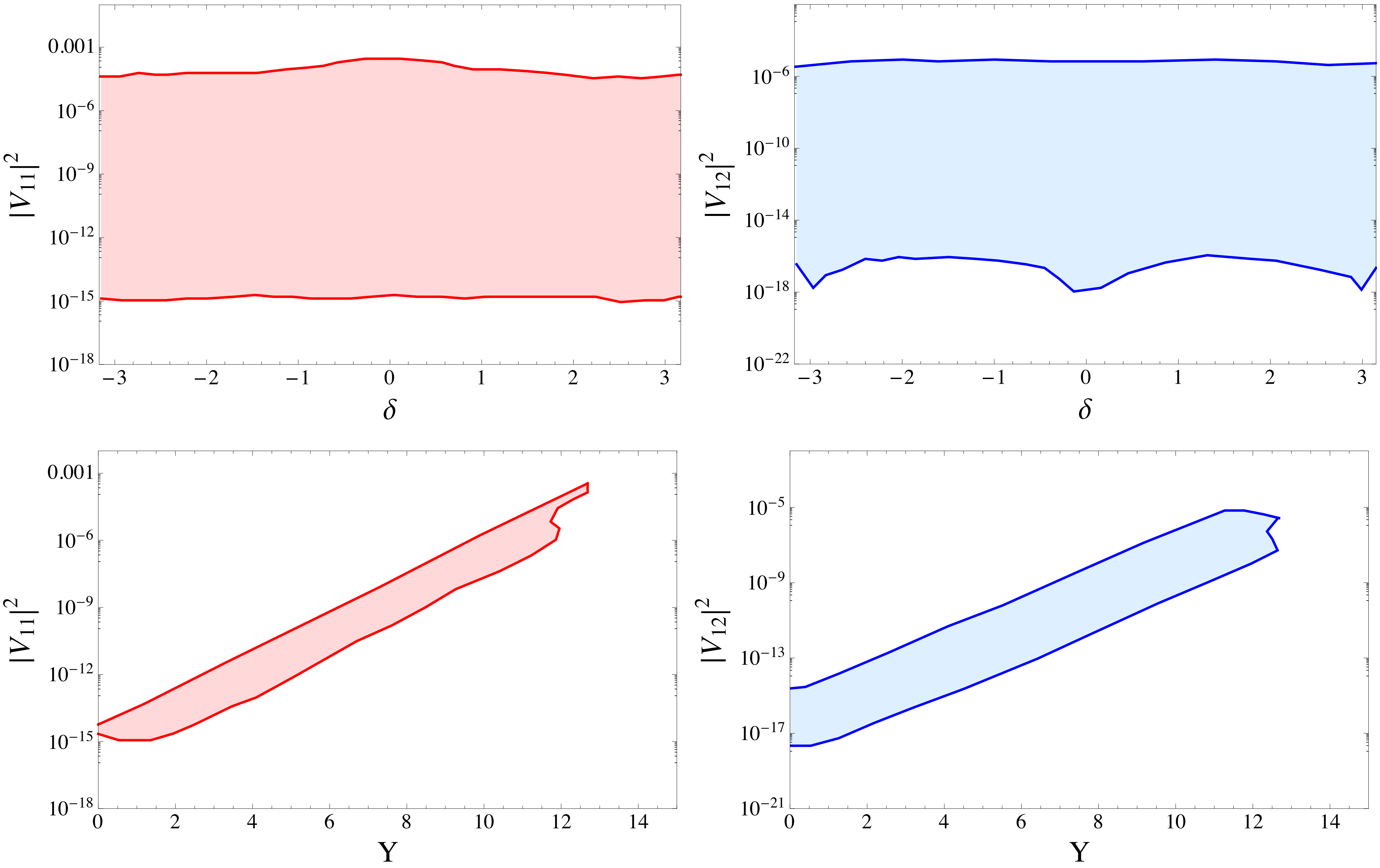
NH Case

Das, Okada: arXiv:1702.04688

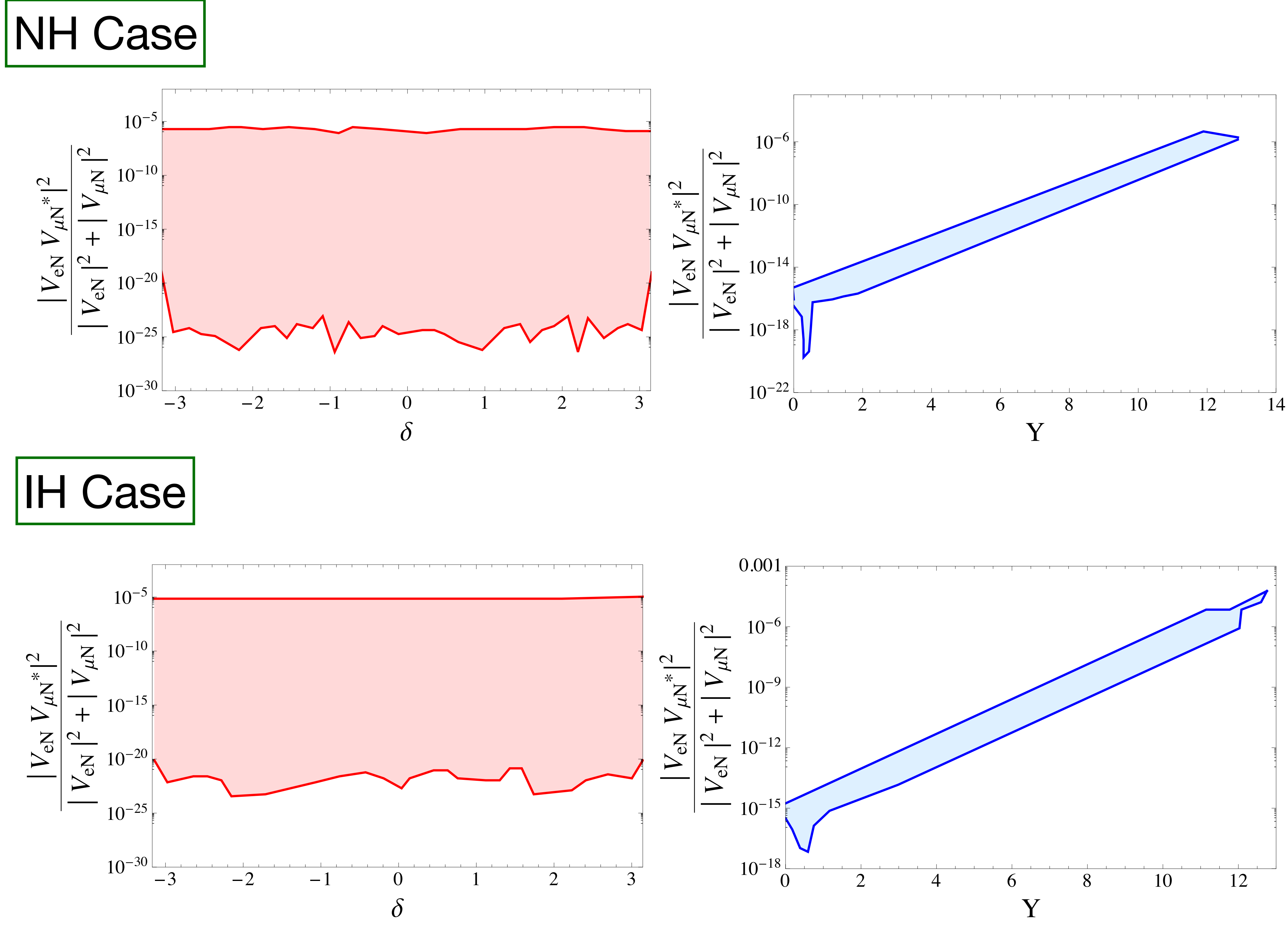


Mixing parameters vary between 10^{-5}-10^{-20}, similar behavior is obtained for the other elements

IH Case



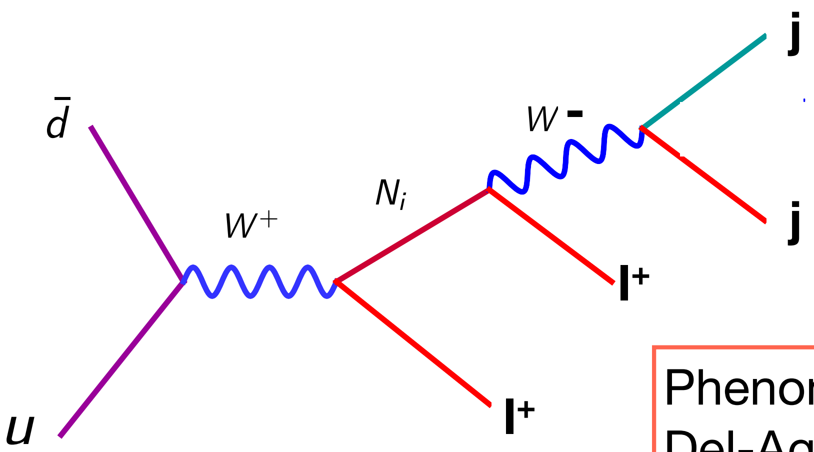
Mixing parameters vary between 10^{-5}-10^{-19}, similar behavior is obtained for the other elements



NH Case
IH Case
|V_eN V_μN*|^2 / (|V_eN|^2 + |V_μN|^2)
δ
Y
10^-5
10^-10
10^-15
10^-20
10^-25
10^-30
10^-6
10^-14
10^-18
10^-22
0.001
10^-9
10^-12
10^-15

Implication in collider physics

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

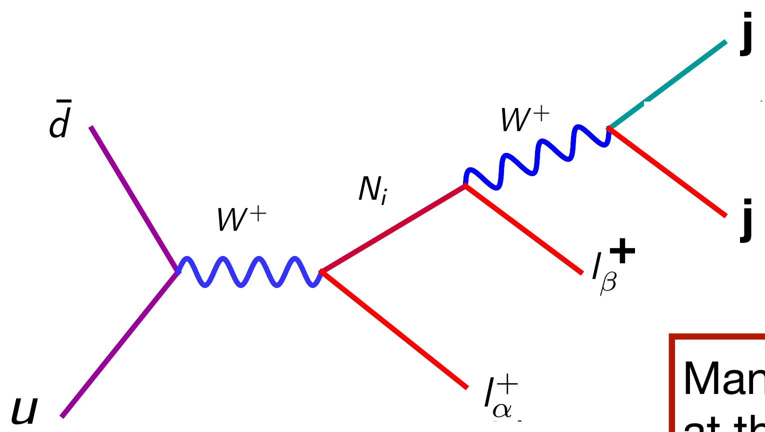


$$\sigma(q\bar{q}' \to \ell_\alpha N_i) = \sigma_{LHC}|\mathcal{R}_{11(22)}|^2$$

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.

$$\text{N} \longrightarrow \ell\,\text{W, W} \longrightarrow \text{jj}$$

BR(m_N) >= 50% Leading



$$\sigma(q\bar{q}' \to \ell_\alpha N_i) = \sigma_{LHC}|\mathcal{R}_{12(21)}|^2$$

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.

Light neutrino mass matrix for **inverse seesaw** can be simplified

$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$$

$$m_\nu = (m_D \mathbf{M}^{-1}) \mu (m_D \mathbf{M}^{-1})^T$$

We assume degenerate heavy neutrinos

$$M \to \begin{pmatrix} M & 0 \\ 0 & M \end{pmatrix}$$

$$\mu \to \begin{pmatrix} \mu & 0 \\ 0 & \mu \end{pmatrix}$$

$$m_\nu = \mathcal{R} \mu \mathcal{R}^T = U^*_{MNS} D_{NH/IH} U^\dagger_{MNS}$$

$$D_{NH} = \mathrm{diag}\left(0, \sqrt{\Delta m^2_{12}}, \sqrt{\Delta m^2_{12} + \Delta m^2_{23}}\right) \qquad D_{IH} = \mathrm{diag}\left(\sqrt{\Delta m^2_{23} - \Delta m^2_{12}}, \sqrt{\Delta m^2_{23}}, 0\right)$$

Two typical cases :

a) Flavor non-diagonal (FND)

$\mu \sim \mu \mathbf{1}$ $\quad m_D \sim \mathrm{nondiag}(\mathrm{m_D})$

FND : 2 generations $\quad N_{R_j}, N_{L_j}; j = 1, 2$

$$m_\nu = \frac{\mu}{M^2} m_D m_D = U^*_{MNS} D_{NH/IH} U^\dagger_{MNS}$$

$$m_D = \frac{M}{\sqrt{\mu}} U^*_{MNS} \sqrt{D_{NH/IH}}$$

b) Flavor diagonal (FD)

$m_D \sim m_D \mathbf{1}$

μ has Flavor structure

$$m_\nu = \left(\frac{m_D}{M}\right)^2 \mu = U^*_{MNS} D_{NH/IH} U^\dagger_{MNS}$$

we use

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

FND

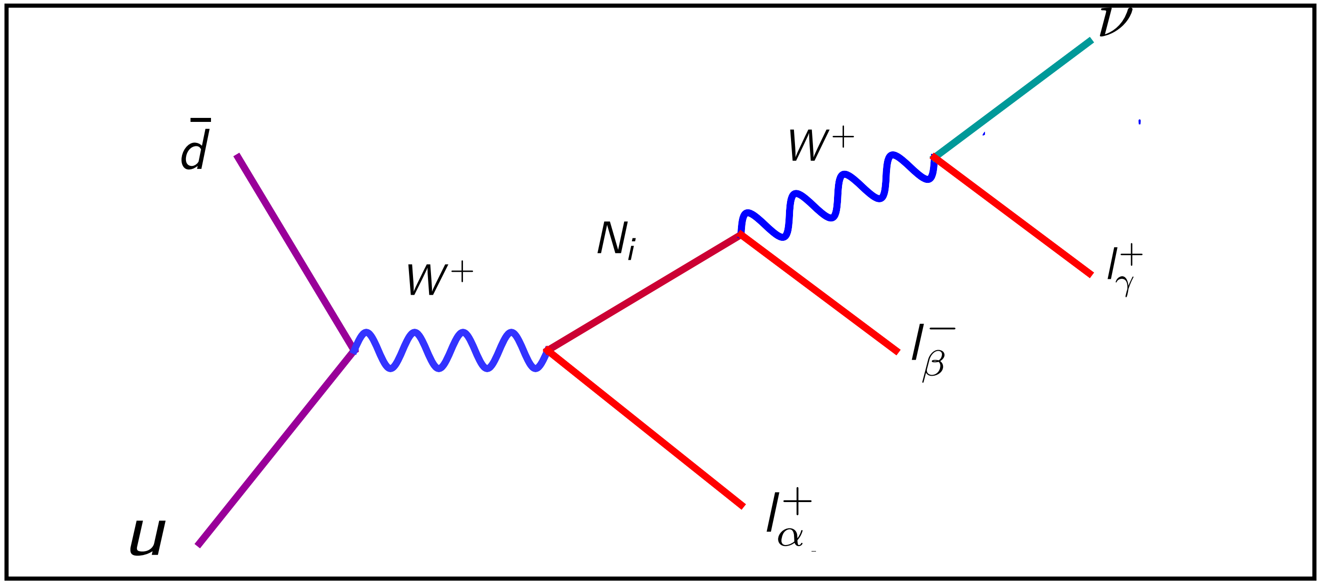
$$\epsilon = \frac{1}{M^2} m_D m_D^T = \frac{1}{\mu} U_{MNS} D_{NH/IH} U_{MNS}^T$$

$$\mu_{min_{NH}} = 525\text{eV}$$

$$\mu_{min_{IH}} = 329\text{eV}$$

FD

$$\epsilon = \left(\frac{m_D}{M}\right)^2 \mathbf{1} = 0.01225(\mathbf{1})$$



$$l^- = e, \mu$$

Mass of the heavy neutrino: 100 GeV, $\sqrt{s} = 14$ TeV

General Parameterization

Casas-Ibarra, NPB 618(2001)171-204

$$\mathcal{R}(\delta,\rho,x,y) = \frac{1}{\sqrt{\mu}} U^*_{MNS} \sqrt{D_{NH/IH}} O \qquad O = \begin{pmatrix} cos(x+iy) & sin(x+iy) \\ -sin(x+iy) & cos(x+iy) \end{pmatrix}$$

$$\mathcal{R}^*\mathcal{R}^T(\delta,\rho,y) = \frac{1}{\mu} U_{MNS} \sqrt{D_{NH/IH}} O^* O^T \sqrt{D_{NH/IH}}^T U^\dagger_{MNS}$$

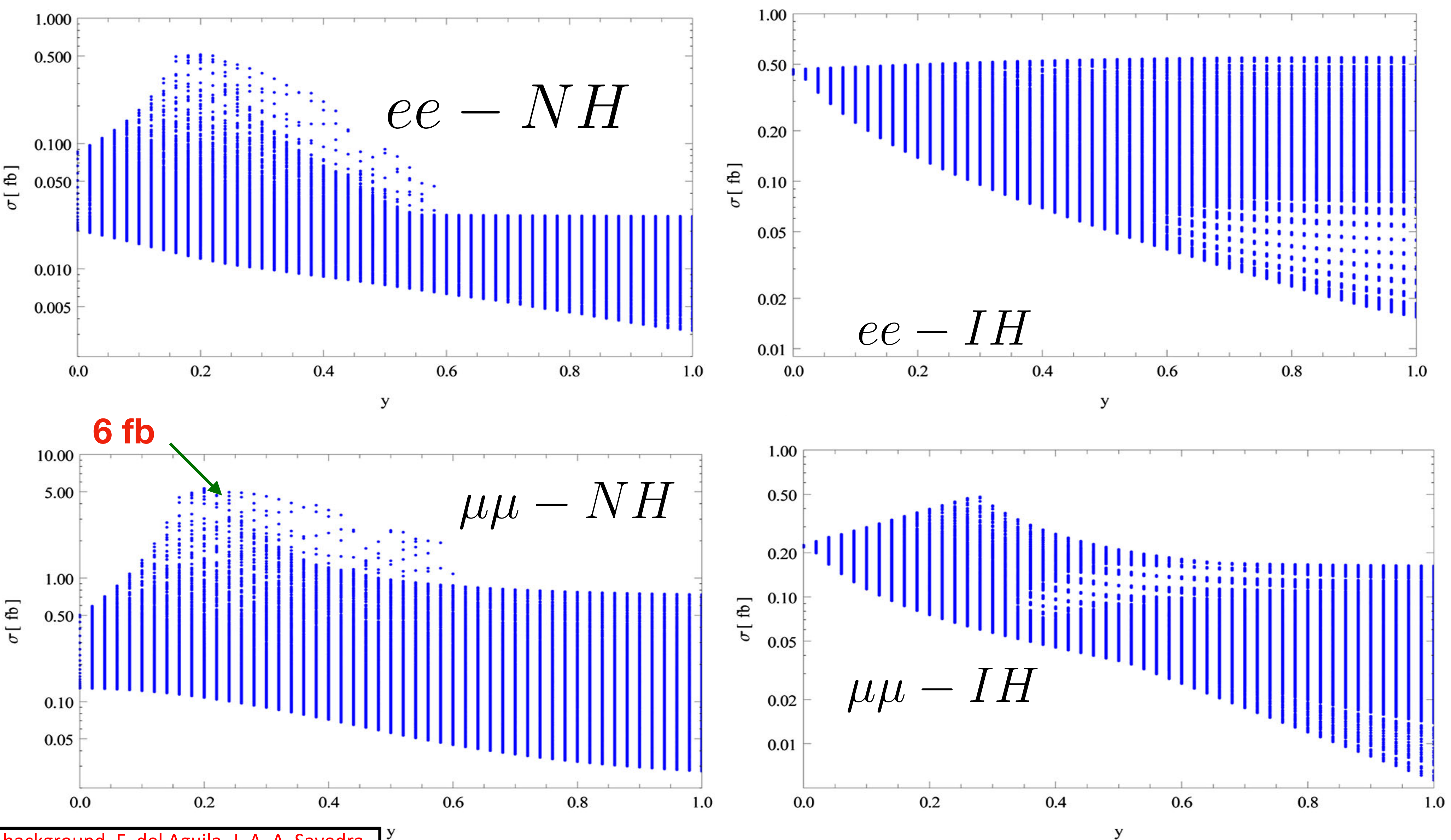
$$O^* O^T(y) = \begin{pmatrix} cosh^2 y + sinh^2 y & -2i cosh y sinh y \\ 2i cosh y sinh y & cosh^2 y + sinh^2 y \end{pmatrix}$$

Das, Okada: arXiv:1207.3734

$$\mathcal{N}\mathcal{N}^\dagger \simeq \mathbf{1} - \mathcal{R}^*\mathcal{R}^{\mathbf{T}}$$

$\mathcal{R}^*\mathcal{R}^T$ is constrained by the LFV and LEP data

- The Dirac phase (δ) can be measured in future.
- Majorana phase (ρ) and y are independent of the oscillation data



SM background, F. del Aguila, J. A. A. Savedra
NPB 813 (2009) 22-90, PLB 672 (2009) 158-165

$\sqrt{s}$ = 14 TeV,M= 100 GeV, Luminosity = 30 fb^{-1}

$\mu\mu$ -NH: 12 σ Other cases around 2 σ

FND: Cross section is enhanced by the general parameterization

	ee	$\mu\mu$
NH	15.5	178.5
IH	17.3	14.3
SMBG	116.4	45.6

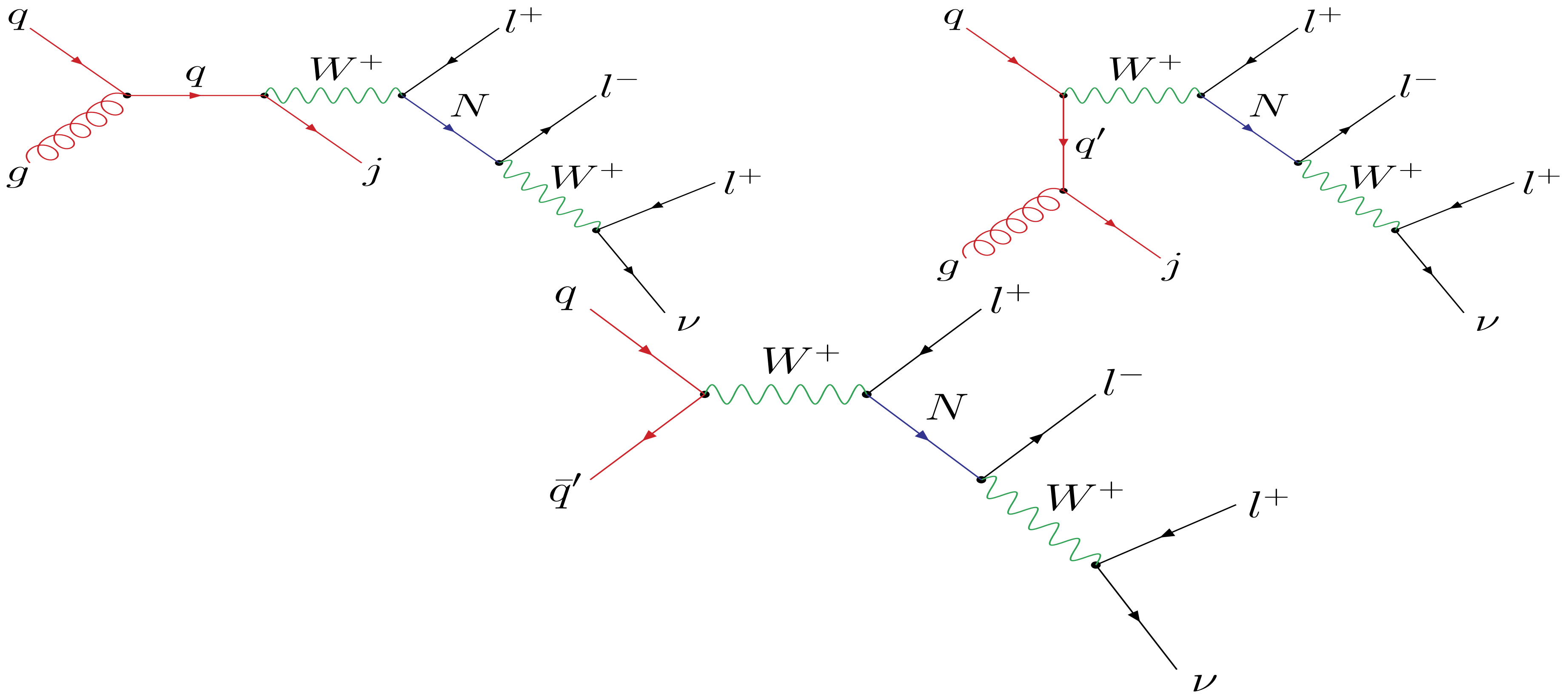
Production of the heavy neutrino

AD, PSB Dev, N Okada: PLB 735(2014)364-370

• We consider the two benchmark cases : a) Single Flavor (SF) and b) Flavor Diagonal (FD)

• SF: One heavy neutrino couples with one flavor.
Signal Example: $pp \to N\mu$, $N \to W\mu$, $W \to \ell_\alpha \nu_\alpha$

• FD: Two degenerate heavy neutrinos couple with two lepton flavors individually. The cross section is twice larger than that of the SF case.



CMS search for the tri-lepton+ MET (matches with our signal state)

CMS Criteria

PHYSICAL REVIEW D **90**, 032006 (2014)

(i) The transverse momentum of each lepton: $p_T^\ell > 10$ GeV.
(ii) The transverse momentum of at least one lepton: $p_T^{\ell,\text{leading}} > 20$ GeV.
(iii) The jet transverse momentum: $p_T^j > 30$ GeV.
(iv) The pseudo-rapidity of leptons: $|\eta^\ell| < 2.4$ and of jets: $|\eta^j| < 2.5$.
(v) The lepton-lepton separation: $\Delta R_{\ell\ell} > 0.1$ and the lepton-jet separation: $\Delta R_{\ell j} > 0.3$.
(vi) The invariant mass of each OSSF lepton pair: a) $m_{\ell^+\ell^-} < 75$ GeV and b) $m_{\ell^+\ell^-} > 105$ GeV.
(vii) The scalar sum of the jet transverse momenta: $H_T < 200$ GeV.
(viii) The missing transverse energy: $\not{E}_T < 50$ GeV.

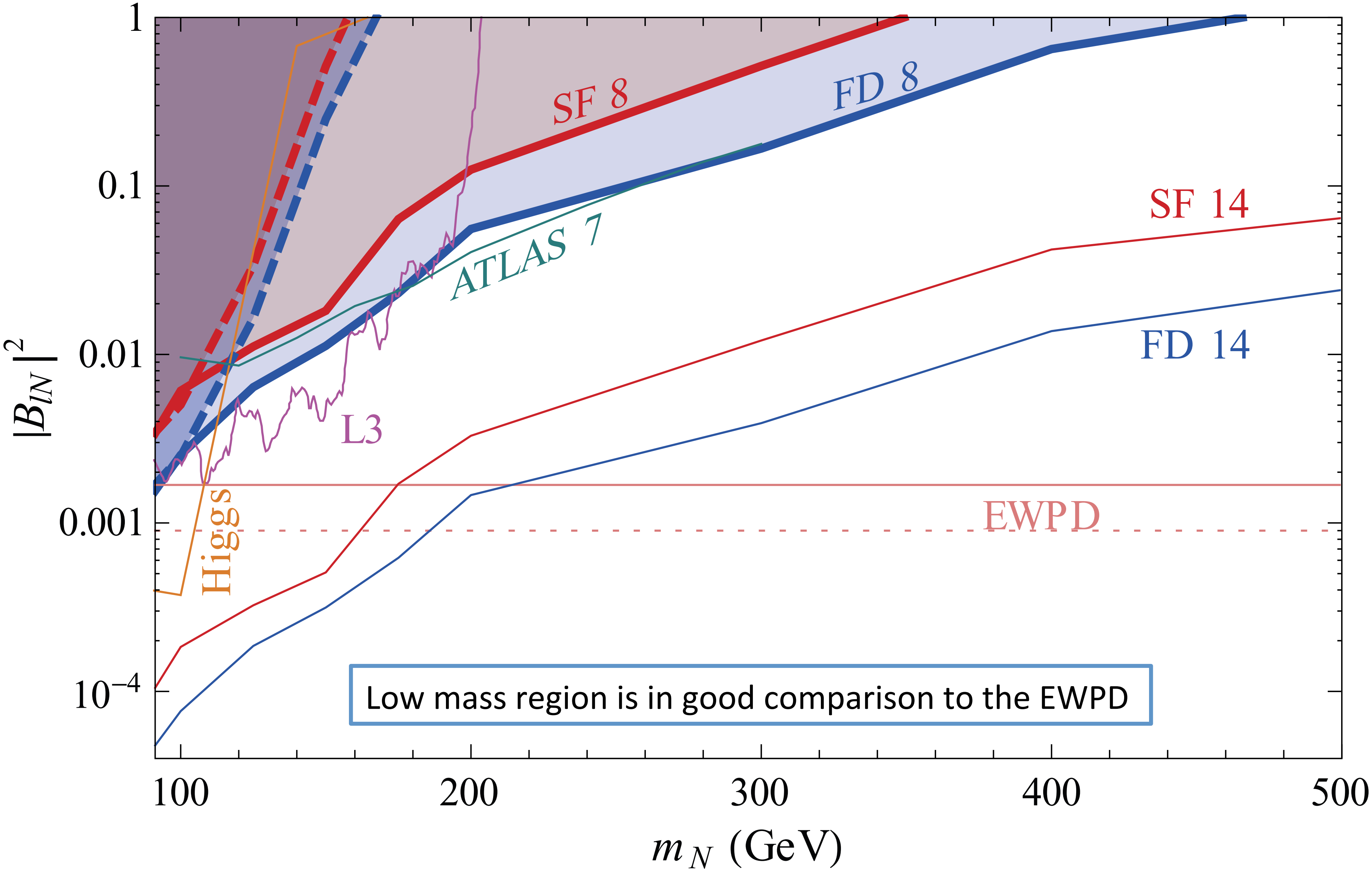
•Case I : $m_{\ell^+\ell^-} < 75$: CMS has observed 510 events with the SM background expectation 560±87 events . Upper limit of $510 - (560 - 87) = 37$ events.

•Case II: $m_{\ell^+\ell^-} > 105$: CMS has observed 178 events with the SM background expectation 200±35 events. Upper limit of $178 - (200 - 35) = 13$ events.

• These set a 95 % CL on the mixing parameter as a function of the heavy neutrino mass.

• The upper bound in FD case is twice stronger than that in the SF case as it was expected.

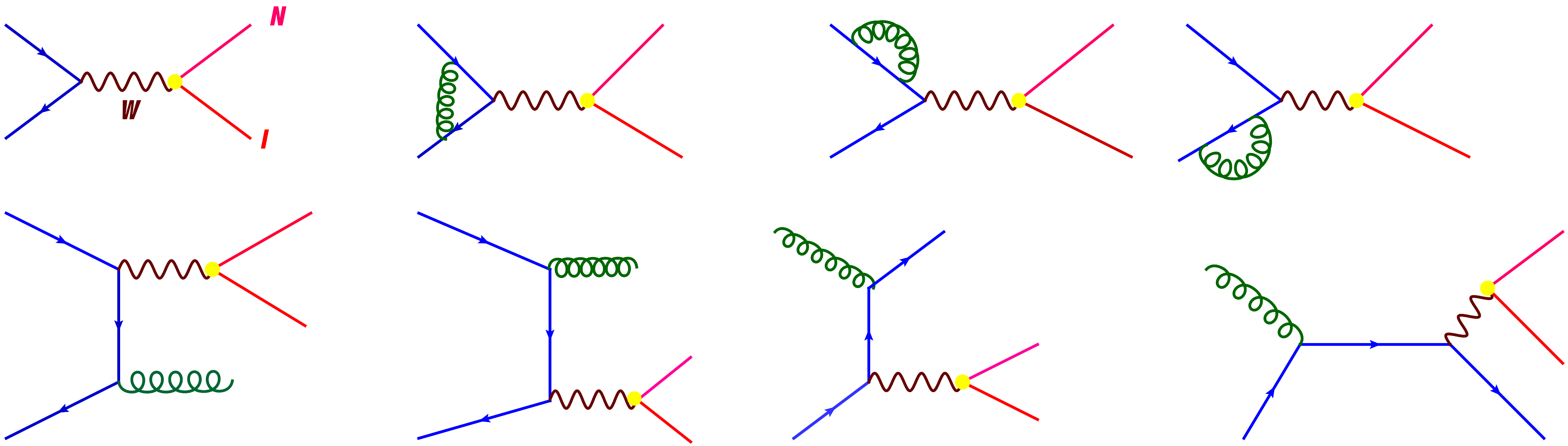
Upper bound on the Mixing angle from tri-lepton-lepton search from the pseudo-Dirac heavy neutrino (inverse seesaw)



m_N=100 GeV -200 GeV will be good to study

see also, arXiv:1510.04790

Production of heavy neutrino at the NLO-QCD order



AD, P Konar, S Majhi: JHEP 1606(2016) 019

$$\mu_F^{\rm NLO} = \mu_R^{\rm NLO} = \xi * m_N$$

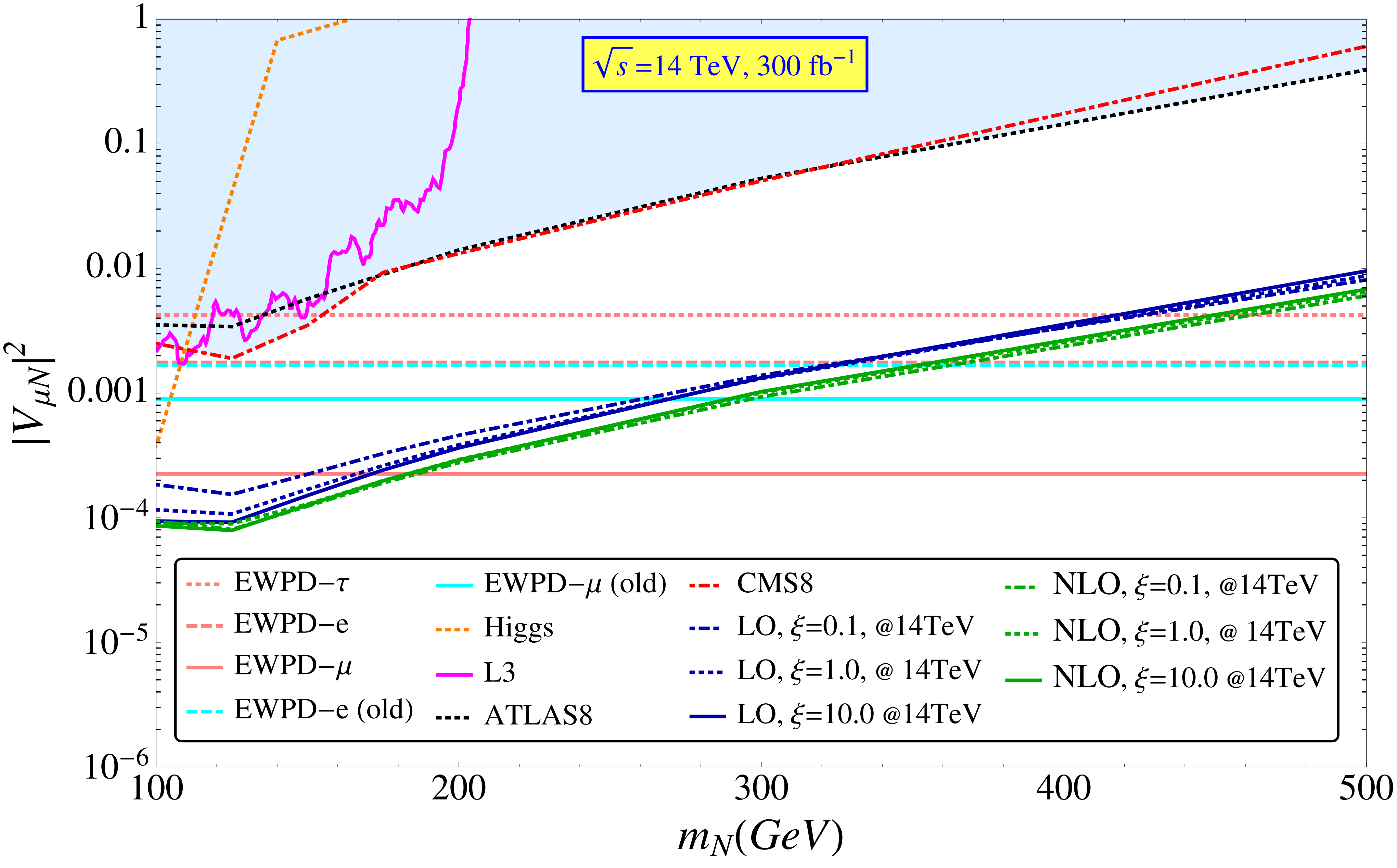
$$\mu_F^{\rm NLO} = m_N, \mu_R^{\rm NLO} = \xi * m_N$$

$$\mu_F^{\rm NLO} = \xi * m_N, \mu_R^{\rm NLO} = m_N.$$

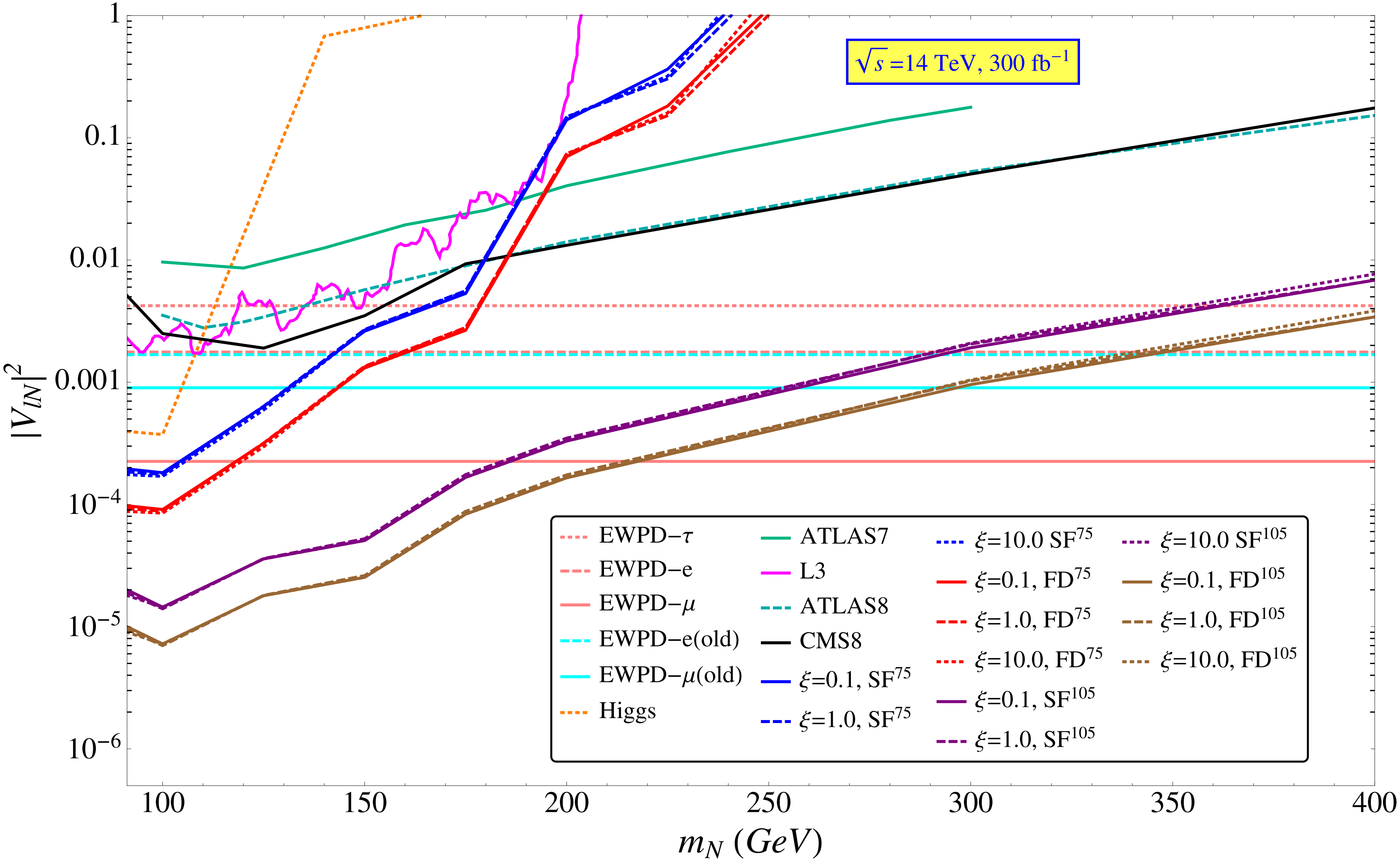
$$0.1 \leq \xi \leq 10$$

Majorana heavy neutrino can display distinct same sign dilepton mode plus dijet
Pseudo-Dirac heavy neutrino can display trilepton mode

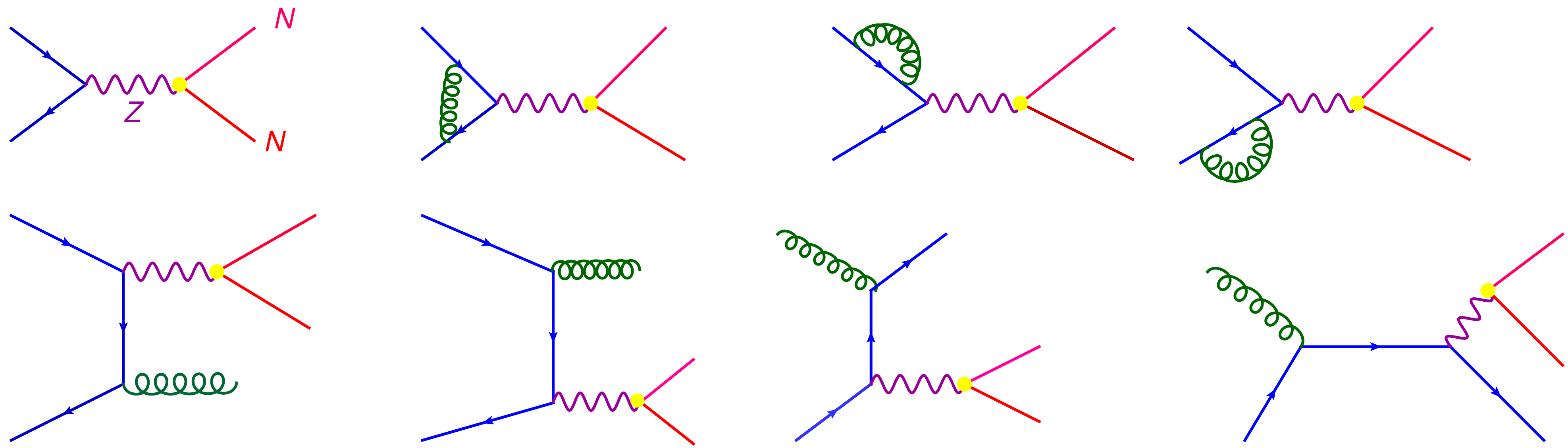
Prospective bounds on the mixing angle as a function of the Majorana heavy neutrino mass



Prospective bounds on the mixing angle as a function of the pseudo-Dirac heavy neutrino mass



Production of heavy neutrino pair at the NLO-QCD order



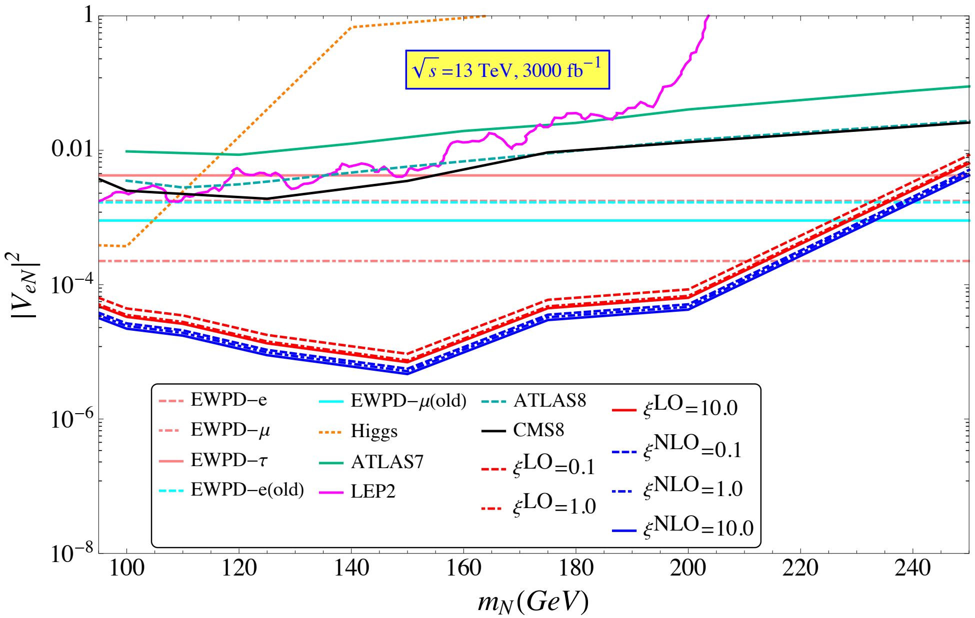
AD : arXiv:1701.04946,
more to come in the updated version

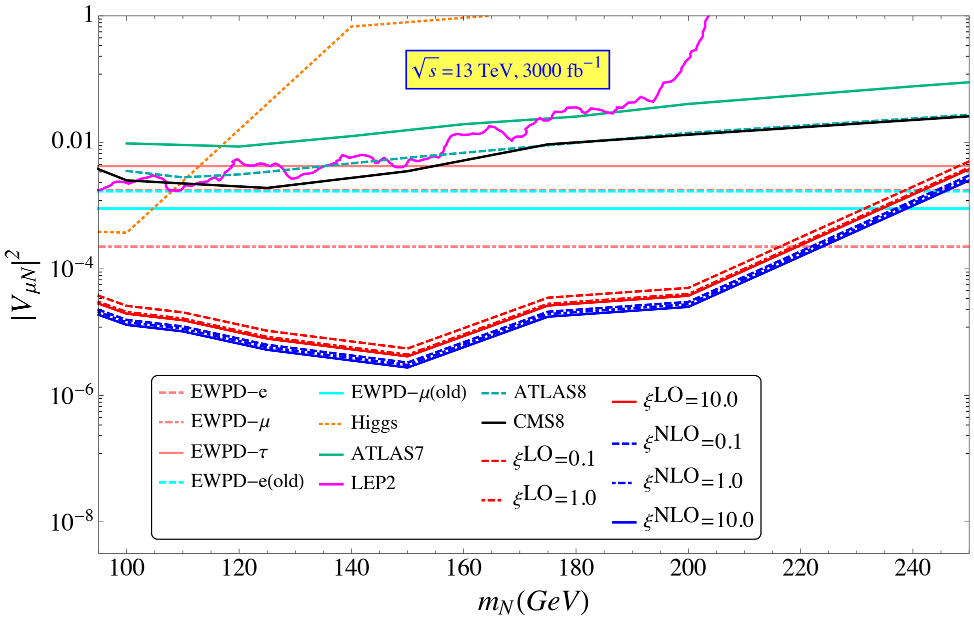
$$0.1 \leq \xi \leq 10$$

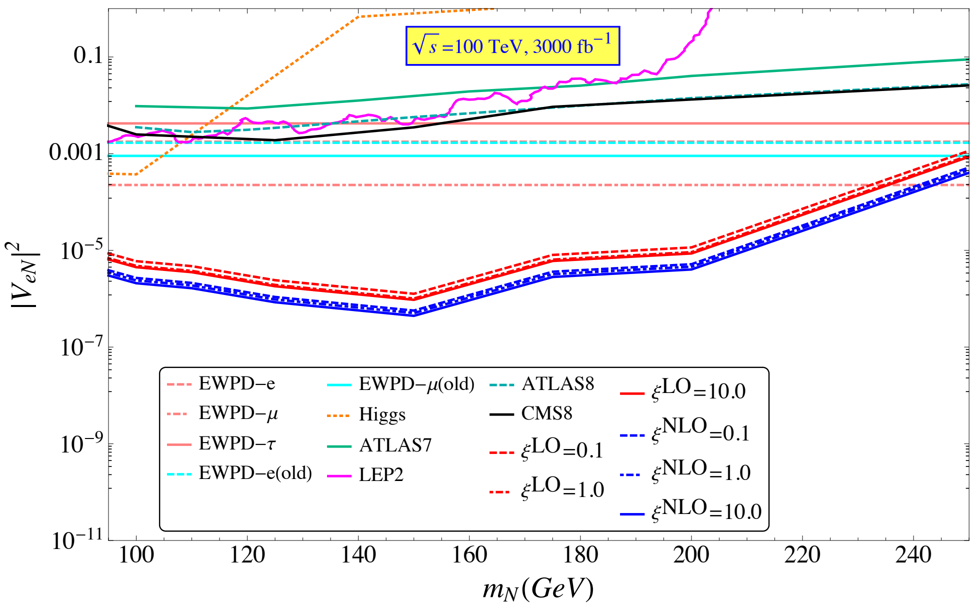
$$\mu_F^{\rm NLO} = \mu_R^{\rm NLO} = \xi * m_N$$
$$\mu_F^{\rm NLO} = m_N, \mu_R^{\rm NLO} = \xi * m_N$$
$$\mu_F^{\rm NLO} = \xi * m_N, \mu_R^{\rm NLO} = m_N.$$

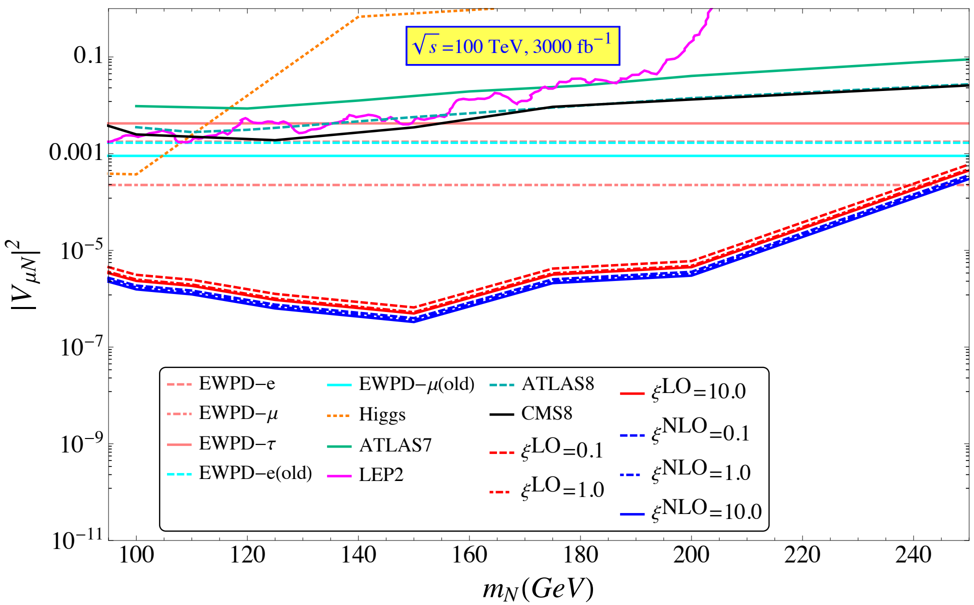
Majorana heavy neutrinos can display distinct same sign dilepton mode plus W, W can decay into leptons / jets
Pseudo-Dirac heavy neutrinos can decay opposite sign dileptons plus W, W can decay into leptons/ jets
However, heavy neutrinos can decay into Z but that is not the dominant mode

Prospective bounds on the mixing angle as a function of the Majorana heavy neutrino mass



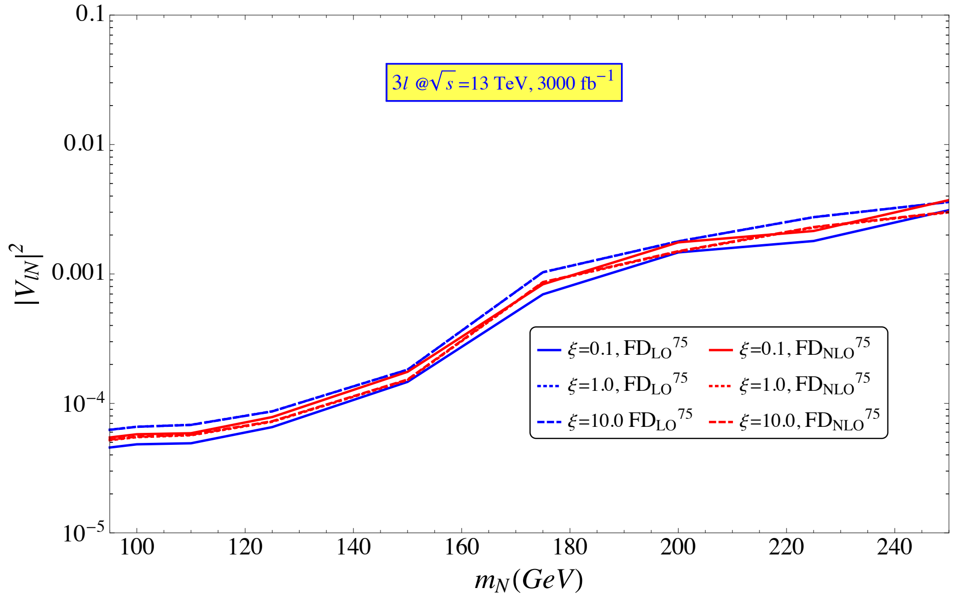


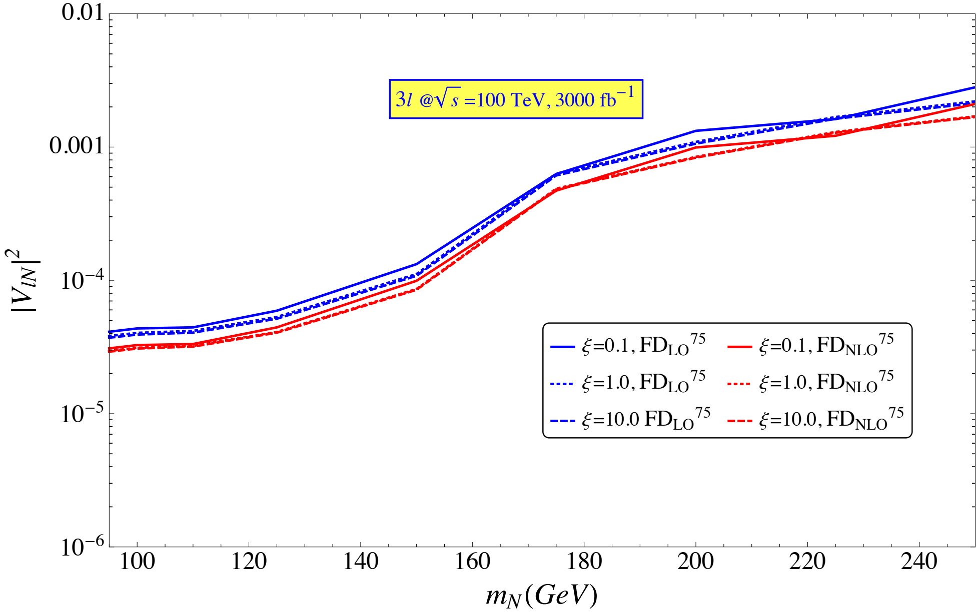


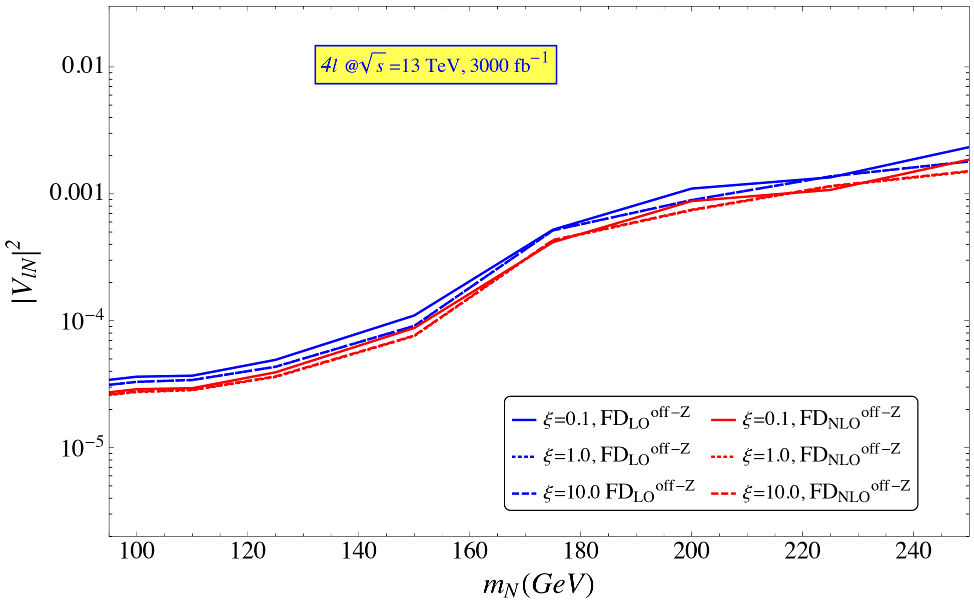


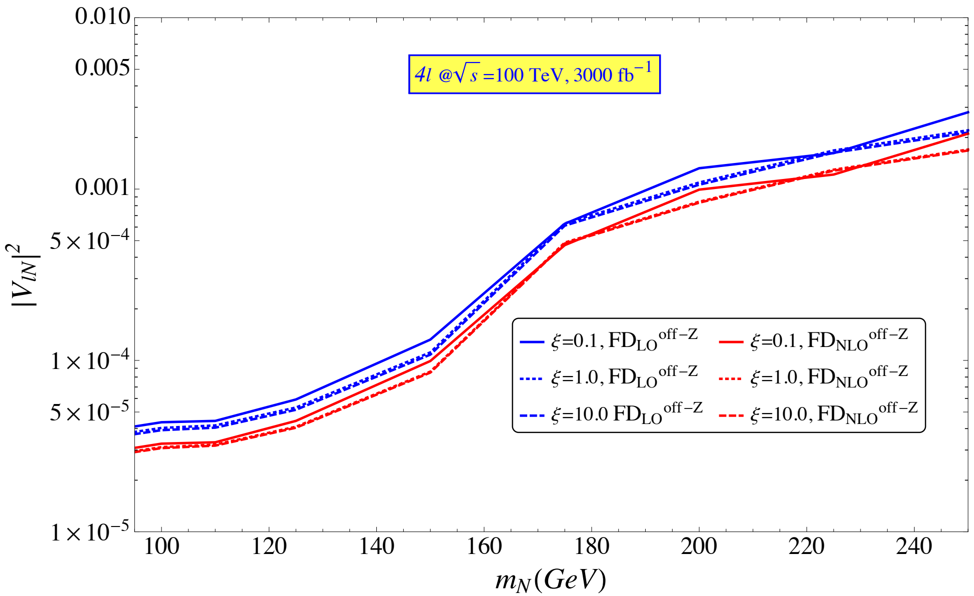
m_N=100 GeV -200 GeV will be good to study

Prospective bounds on the mixing angle as a function of the pseudo-Dirac heavy neutrino (FD case) mass









m_N=100 GeV -200 GeV will be good to study

Yukawa Interaction

Antusch, Atre, Chen, Deppisch, Dev, Drewes, Franceschini, Gao, Kamon, Kim, Mohapatra, Fischer, Han, Pascoli, Pilaftsis, Senjanovic

$$\mathcal{L}_Y \supset -Y_{D_{\ell m}} \bar{L}_\ell \phi N_m + \text{H.c.}$$

$SU(2)_L$ lepton doublet

$SU(2)_L$ Higgs doublet

$\langle \phi^0 \rangle = v$ $\quad M_D = vY_D \quad Y_D = VM_N/v$, which is also suppressed by V

Mixing

$N \rightarrow \ell^- W^+, \nu_\ell Z, \nu_\ell h$

SM Higgs boson, physical remnant of ϕ

Decay Widths

$$\Gamma(N \rightarrow \ell^- W^+) = \frac{g^2 |V_{\ell N}|^2}{64\pi} \frac{M_N^3}{M_W^2} \left(1 - \frac{M_W^2}{M_N^2}\right)^2 \left(1 + \frac{2M_W^2}{M_N^2}\right)$$

$$\Gamma(N \rightarrow \nu_\ell Z) = \frac{g^2 |V_{\ell N}|^2}{128\pi} \frac{M_N^3}{M_W^2} \left(1 - \frac{M_Z^2}{M_N^2}\right)^2 \left(1 + \frac{2M_Z^2}{M_N^2}\right)$$

$$\Gamma(N_1 \rightarrow \nu_\ell h) = \frac{|V_{\ell N}|^2}{128\pi} \frac{M_N^3}{M_W^2} \left(1 - \frac{M_h^2}{M_N^2}\right)^2$$

Das, Okada; Das, Konar, Majhi; Deppisch, Dev, Pilaftsis: Review arXiv:1502.06541

$M_N < M_W$

All three body decays

$N \to \ell^- W^+$ → **leptons**

$$\Gamma(N \to \ell_1^- \ell_2^+ \nu_{\ell_2}) \simeq \frac{|V_{\ell_1 N}|^2 G_F^2 M_N^5}{192\pi^3}$$

$$\Gamma(N \to \nu_{\ell_1} \ell_2^+ \ell_2^-) \simeq \frac{|V_{\ell_1 N}|^2 G_F^2 M_N^5}{96\pi^3}(g_L g_R + g_L^2 + g_R^2)$$

Gorbunov and Shaposhnikov: arXiv:0705.1729
Atre, Han, Pascoli and Zhang: arXiv: 0901.3589
Dib and Kim : arXiv: 1509.05981

$N \to \nu_\ell Z$ → **leptons**

$$\Gamma(N \to \nu_\ell \ell^+ \ell^-) \simeq \frac{|V_{\ell N}|^2 G_F^2 M_N^5}{96\pi^3}(g_L g_R + g_L^2 + g_R^2 + 1 + 2g_L)$$

$$\Gamma(N \to \nu_{\ell_1} \nu_{\ell_2} \bar{\nu}_{\ell_2}) \simeq \frac{|V_{\ell_1 N}|^2 G_F^2 M_N^5}{96\pi^3}$$

$N \to \ell^- W^+$ → **hadrons**

$$\Gamma(N \to \ell^- jj) \simeq 3\frac{|V_{\ell N}|^2 G_F^2 M_N^5}{192\pi^3}$$

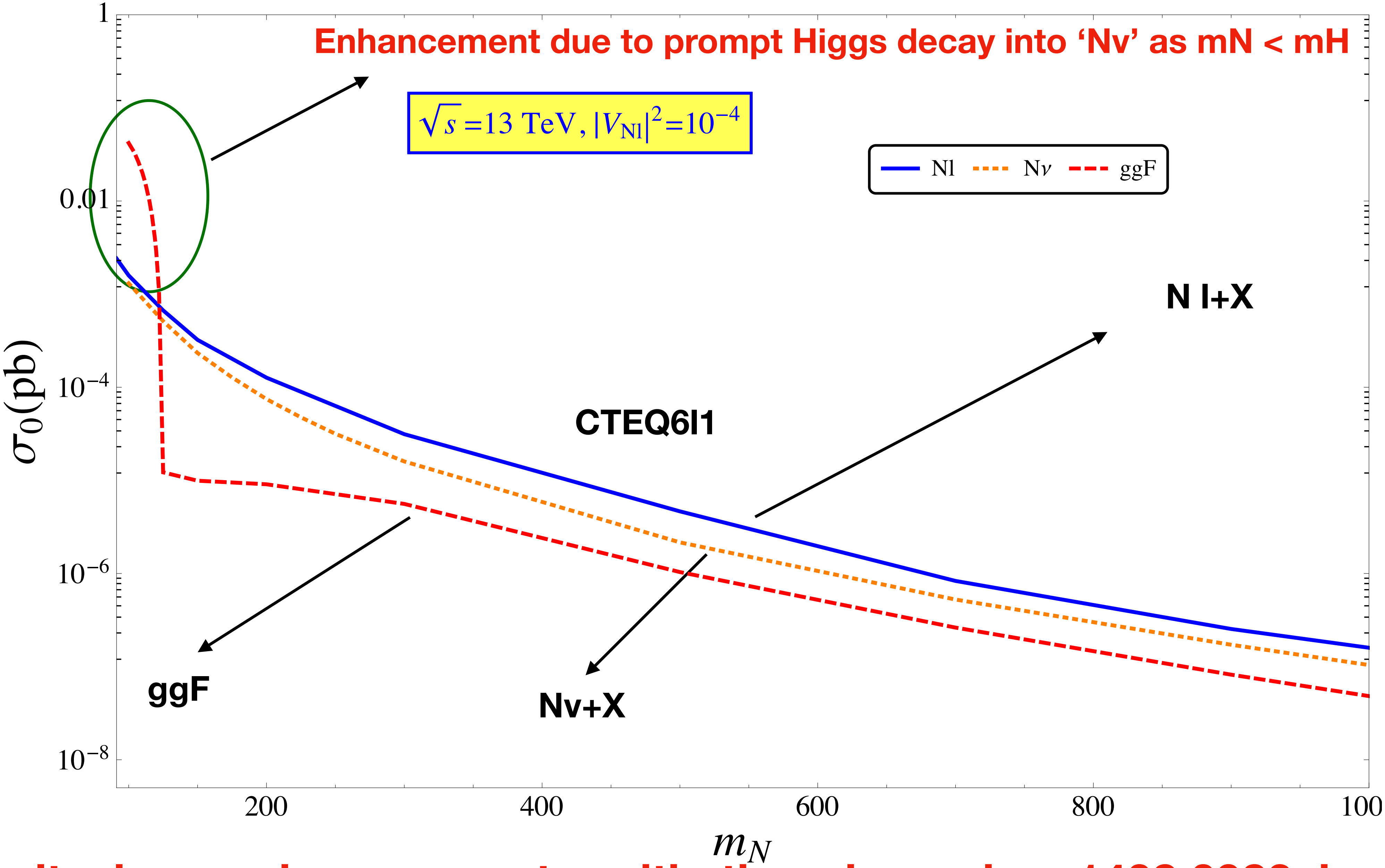
Das, Dev, Kim: arXiv:1704.0880
Das, Gao, Kamon: arXiv:1704.00881

$N \to \nu_\ell Z$ → **hadrons**

$$\Gamma(N \to \nu_\ell jj) \simeq 3\frac{|V_{\ell N}|^2 G_F^2 M_N^5}{96\pi^3}(g_L g_R + g_L^2 + g_R^2)$$

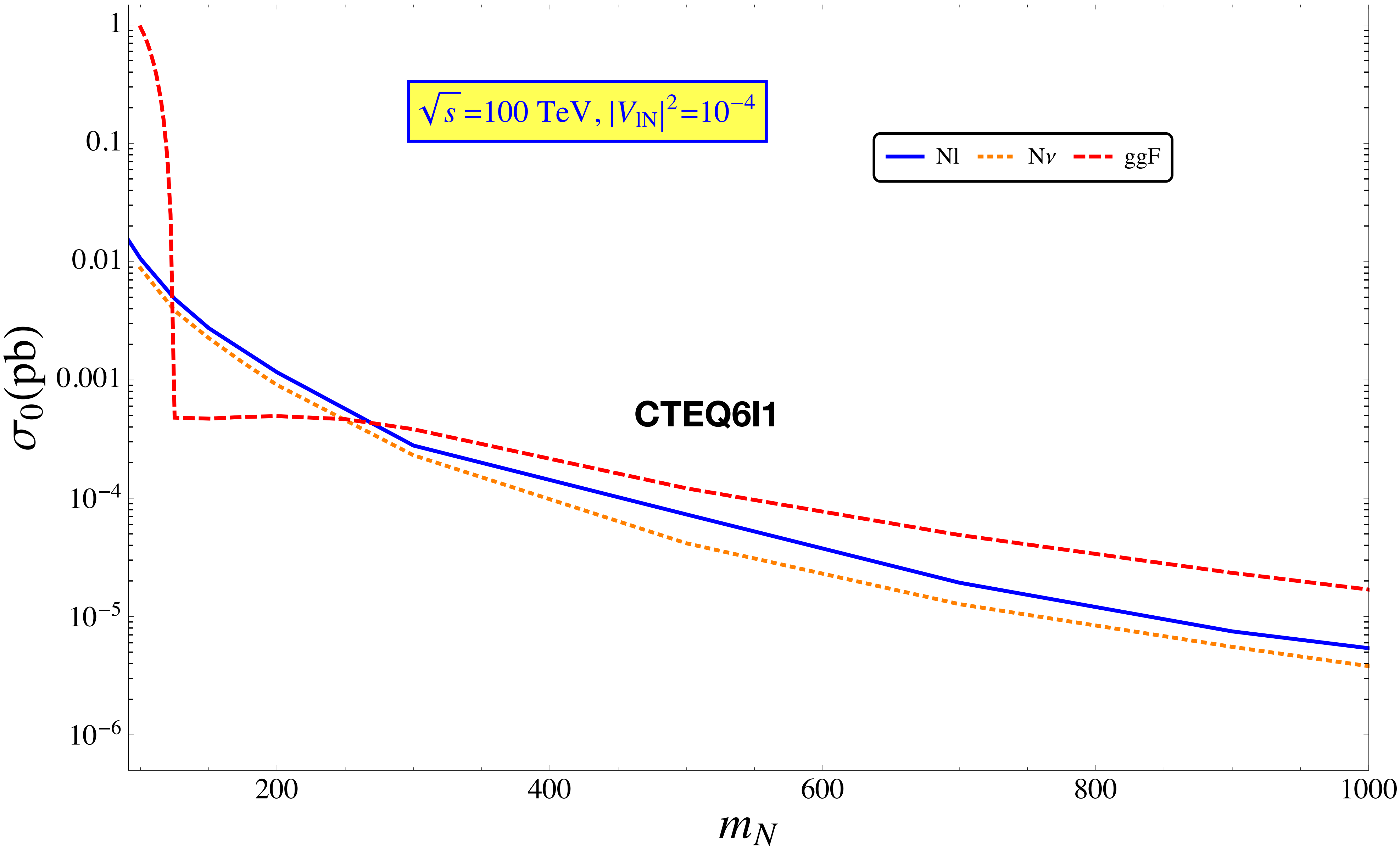
$$g_L = -\tfrac{1}{2} + \sin^2\theta_w, \; g_R = \sin^2\theta_w$$

Production cross section of the heavy neutrinos in from different initial states



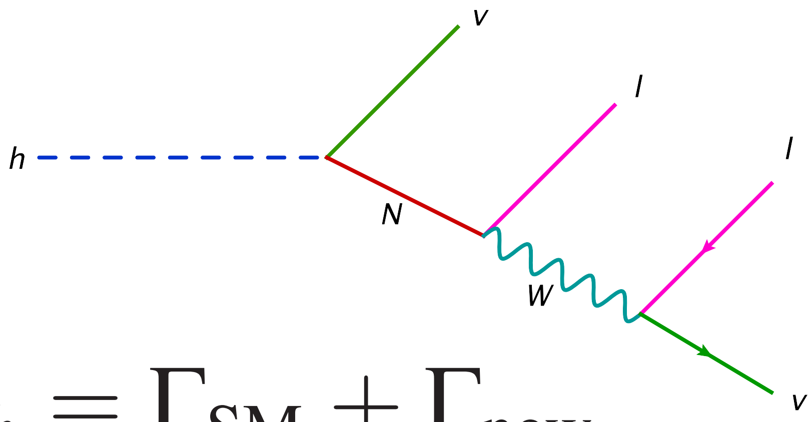
Results in good agreements with the pioneering 1408.0983 by Hessler, Ibarra, Molinaro and Vogl

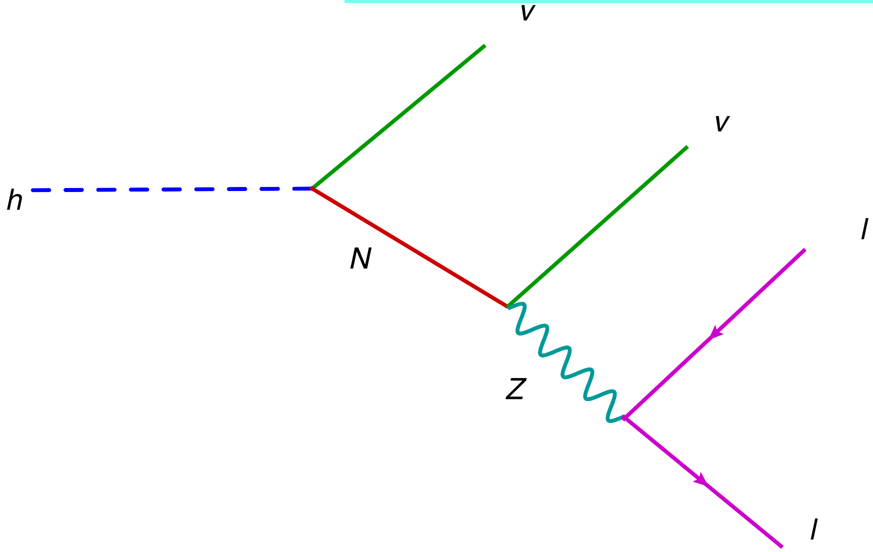
Production cross section of the heavy neutrinos in from different initial states



Heavy Neutrino Production from Higgs Decay

Dev, Franceschini, Mohapatra: PRD86,093010(2012)@8TeV LHC





$$\Gamma_h = \Gamma_{\rm SM} + \Gamma_{\rm new}$$

$$\Gamma_{\rm SM} \simeq 4.1 \text{ MeV for } M_h = 125 \text{ GeV} \qquad \Gamma_{\rm new} = \frac{Y_D^2 M_h}{8\pi}\left(1 - \frac{M_N^2}{M_h^2}\right)^2$$

$$h \to WW^* \to 2\ell 2\nu \qquad h \to \nu N \to 2\ell 2\nu$$

Region	Mass range
1	$M_N < M_W$
2	$M_W < M_N < M_Z$
3	$M_Z < M_N < M_h$
4	$M_N > M_h$

$e\bar{e}$ Same as the previous slide except $|\eta^{\ell_{1,2}}| < 2.47$

$\mu\bar{e}(e\bar{\mu})$ $|\eta^e| < 2.47, \ |\eta^\mu| < 2.4$ $m_{e\mu} > 10$ GeV and $\not{E}_T > 20$ GeV

The transverse mass cut is common in the three cases

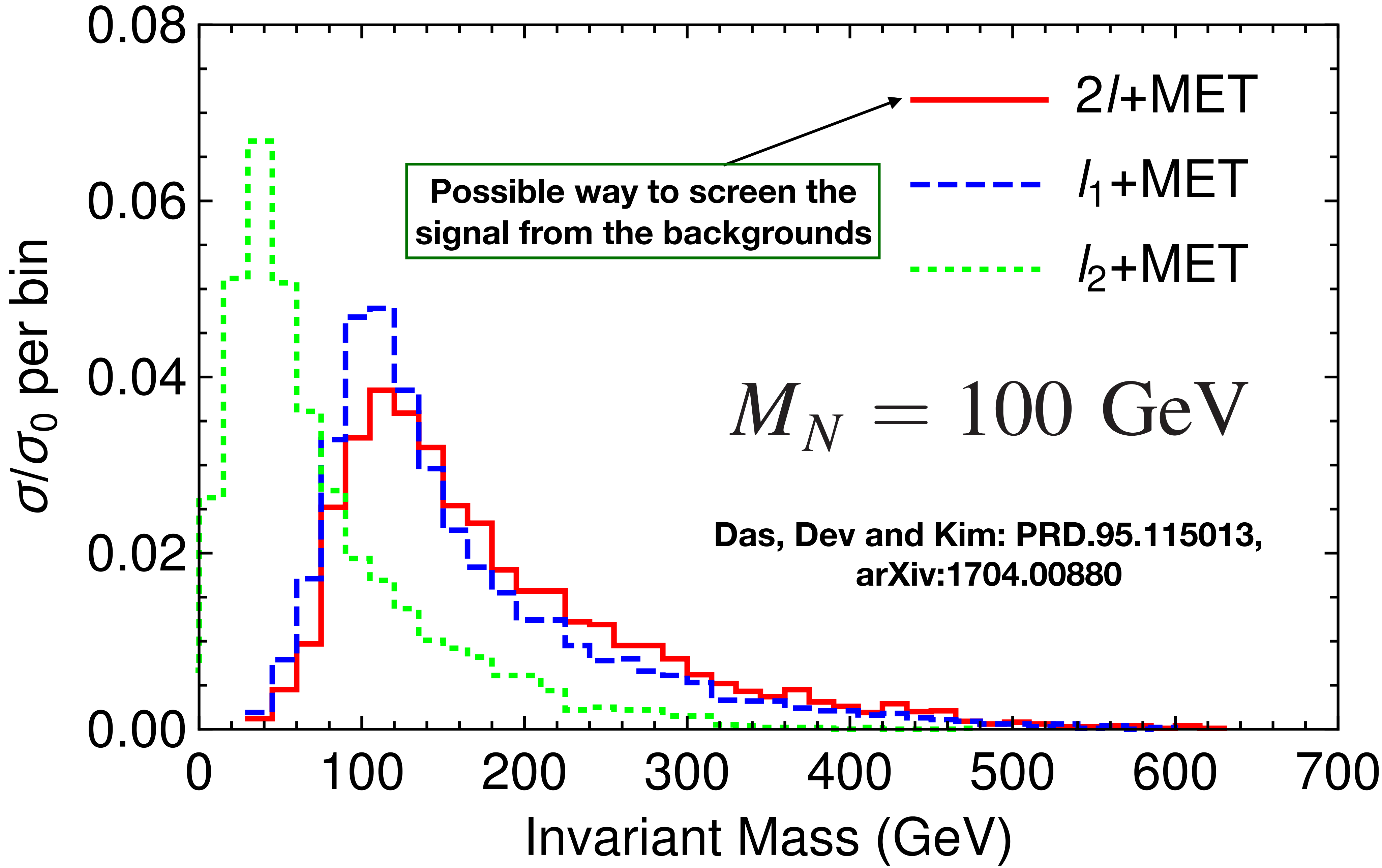
$$m_T\colon \tfrac{3}{4}M_h < m_T < M_h.$$

$$m_T = \sqrt{(E^{\ell\ell} + p_T^{\nu\nu})^2 - |\vec{p_T}^{\ell\ell} + \vec{p_T}^{\nu\nu}|^2} \qquad E_T^{\ell\ell} = \sqrt{(p_T^{\ell\ell})^2 + (m_{\ell\ell})^2}$$

$\vec{p_T}^{\nu\nu}(\vec{p_T}^{\ell\ell})$ = **Vector sum of the neutrino (lepton) transverse momenta**

$p_T^{\nu\nu}(p_T^{\ell\ell})$ **is the magnitude**

For more detailed analysis of the backgrounds and separation techniques, see Refs. [111-114] of arXiv:1704.0880.



0.08
0.06
0.04
0.02
0.00
σ/σ_0 per bin
0
100
200
300
400
500
600
700
Invariant Mass (GeV)
2l+MET
l_1+MET
l_2+MET
Possible way to screen the signal from the backgrounds
$M_N = 100$ GeV
Das, Dev and Kim: PRD.95.115013, arXiv:1704.00880

$pp \to h \to \nu N \to 2\ell 2\nu$. $\ell = e, \mu$

Final States: OSSF $\mu\bar{\mu}\nu\bar{\nu}$ and $e\bar{e}\nu\bar{\nu}$

OSOF $\mu\bar{e}\nu\bar{\nu}$ and $e\bar{\mu}\nu\bar{\nu}$

We consider all sorts of charge combinations as Higgs can decay into heavy and anti-heavy neutrinos for Dirac type heavy neutrino or for a Majorana type case the heavy neutrino can decay into both positively and negatively charged leptons

Selection Cuts **ATLAS Phys. Rev. D 92, 012006**

$\mu\bar{\mu}$ $p_T^{\ell_2,\text{sub-leading}} > 10$ GeV $p_T^{\ell_1,\text{leading}} > 22$ GeV. $p_T^j > 25$ GeV

$|\eta^{\ell_{1,2}}| < 2.4$ $|\eta^j| < 2.4$ $\Delta R_{\ell\ell} > 0.3$ $\Delta R_{\ell j} > 0.3$ $\Delta R_{jj} > 0.3$

$m_{\ell\ell} > 12$ GeV $\not{E}_T > 40$ GeV

Dilepton transverse momentum is away from the MET $\Delta\phi^{\ell\ell,\text{MET}} > \frac{\pi}{2}$

$p_T^{\ell\ell} > 30$ GeV

Limits on the mixing angle

After applying the cuts from ATLAS we calculate the yield

$$\mathcal{N}(M_N, |V_{\ell N}|^2) = L \cdot \sigma_h^{\rm SM} \left[\epsilon^{\rm SM} \frac{\Gamma(h \to WW^* \to \ell\bar{\ell}\nu\bar{\nu})}{\Gamma_{\rm SM} + \Gamma_{\rm New}} + \sum_{j,k} \epsilon_{jk} \frac{\Gamma(h \to \bar{\nu}N + \text{c.c.} \to \ell_j \bar{\ell}_k \nu\bar{\nu})}{\Gamma_{\rm SM} + \Gamma_{\rm New}} \right]$$

L **= Integrated luminosity** $\sigma_h^{\rm SM}(pp \to h)$ **= SM Higgs production cross section**

$\epsilon_{\rm SM}$, ϵ_{jk} **= efficiencies for the decays mediated by SM and in presence of heavy neutrino, respectively**

jk → e and μ

Efficiencies → **Calculated using cuts of ATLAS**

$\Gamma(h \to WW^* \to \ell\bar{\ell}\nu\bar{\nu})$, $\Gamma_{\rm SM}$ S. Heinemeyer *et al.* (LHC Higgs Cross Section Working Group), arXiv:1307.1347.

$\sigma_h^{\rm SM}$ **8 TeV** https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt8TeV.

14 TeV, 100 TeV https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HiggsEuropeanStrategy.

$$|V_{\ell N}|^2 \xrightarrow{\textbf{Maximal values}} \mathcal{N}(M_N, |V_{\ell N}|^2) < \mathcal{N}_{\rm expt}$$

$\mathcal{N}_{\rm expt} = 169$

↓

G. Aad *et al.* (ATLAS Collaboration), Phys. Rev. D **92**, 012006 (2015).

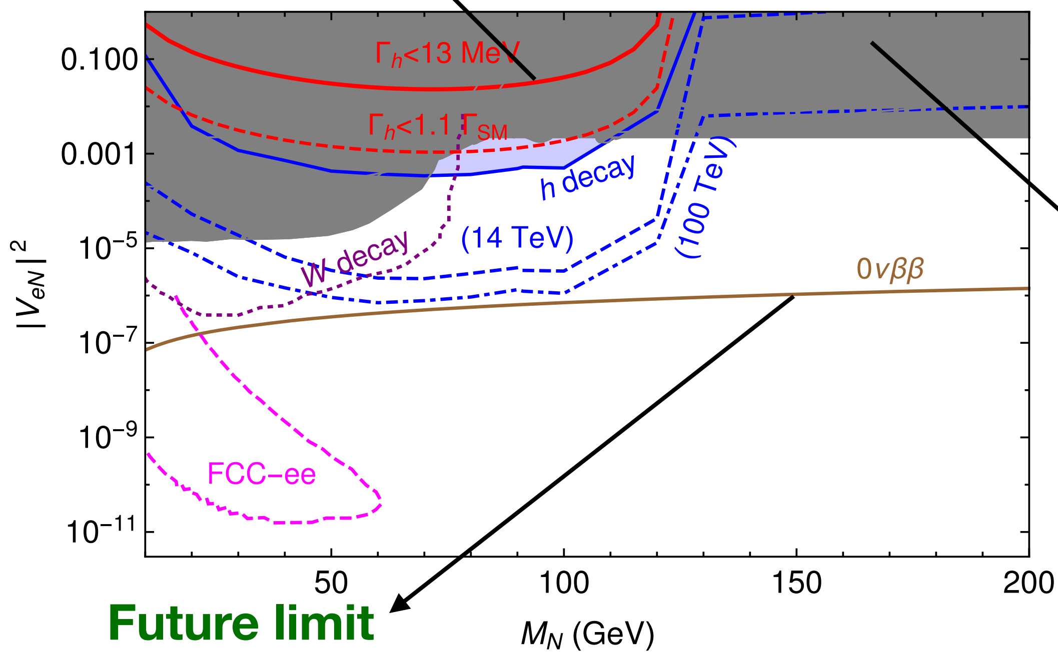
for $M_h = 125$ GeV at $\sqrt{s} = 8$ TeV with $L = 20.3\ \mathrm{fb}^{-1}$

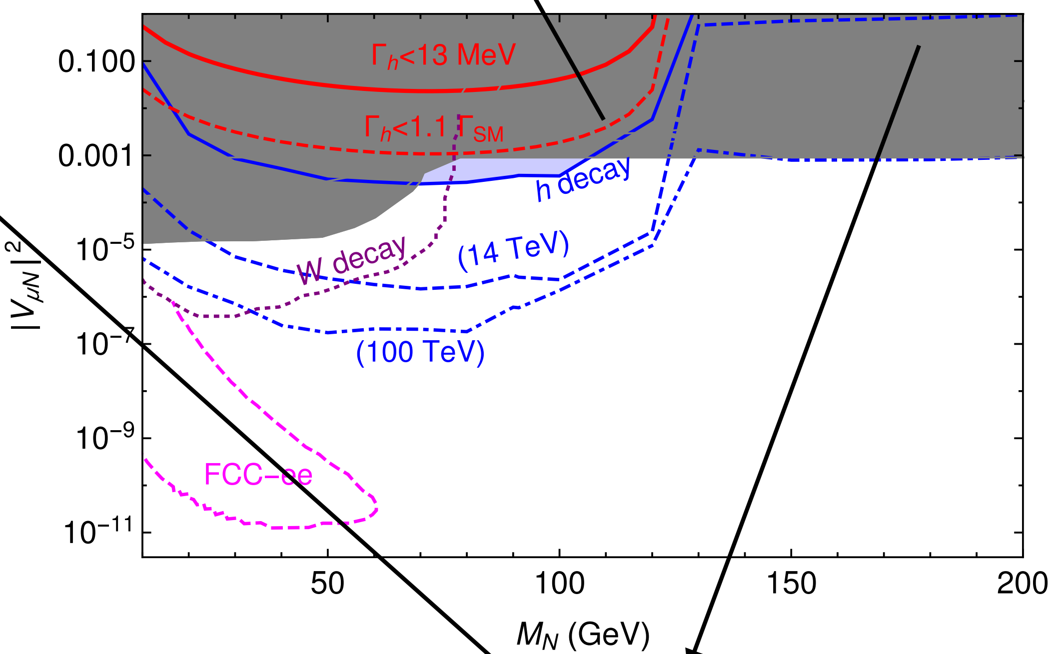
Assuming the same $\mathcal{N}_{\rm expt}$ for $\sqrt{s} = 14$ and 100 TeV colliders, but with an integrated luminosity of 3000 fb^{-1},

we also show the corresponding future limits

CMS, JHEP 09 (2016) 051: 7&8 TeV combined H ⟶ W W*, upper limit on Yukawa as well as mixing

Future sensitivity @100 can go down to 10%precise result at 100 TeV pp collider: arXiv:1606.09408

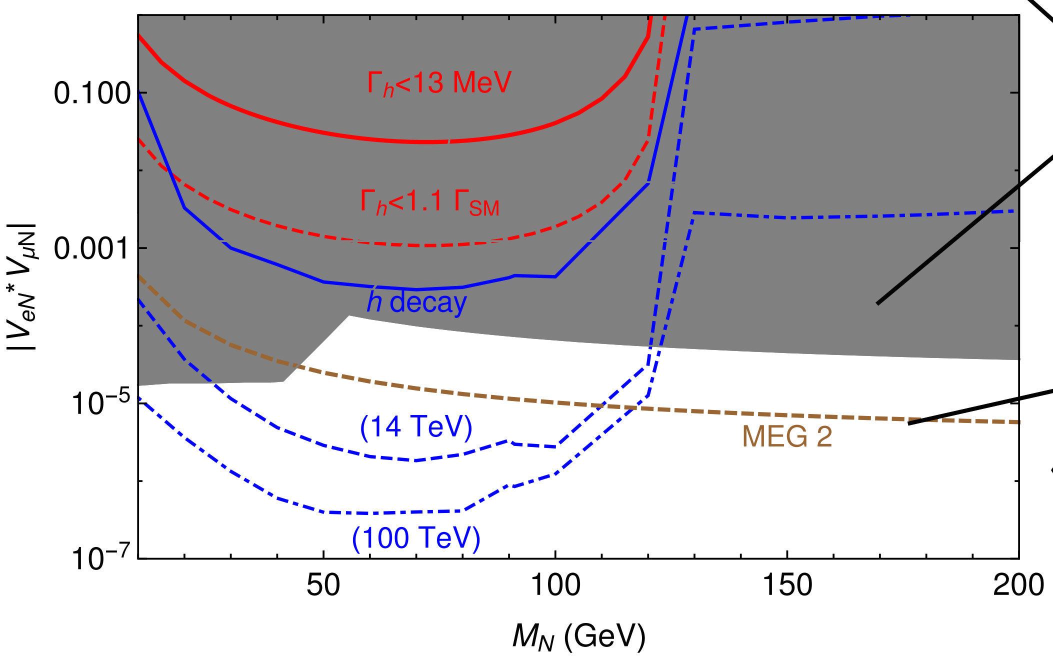




Future limit considering Majorana heavy neutrinos only

Excluded by LEP LHC,EWPD,

LFV limits from CMS is also included in the lower panel



$\mu \to e\gamma$

~ future branching ratio O(10^{-15})

FCC-ee : Limits from Z decay

W-decay @LHC

Future limits

Heavy neutrino production from $\ell \nu jj$

W boson produced in the Higgs decay to $\nu N \to \nu \ell W$

$$\ell \nu jj$$

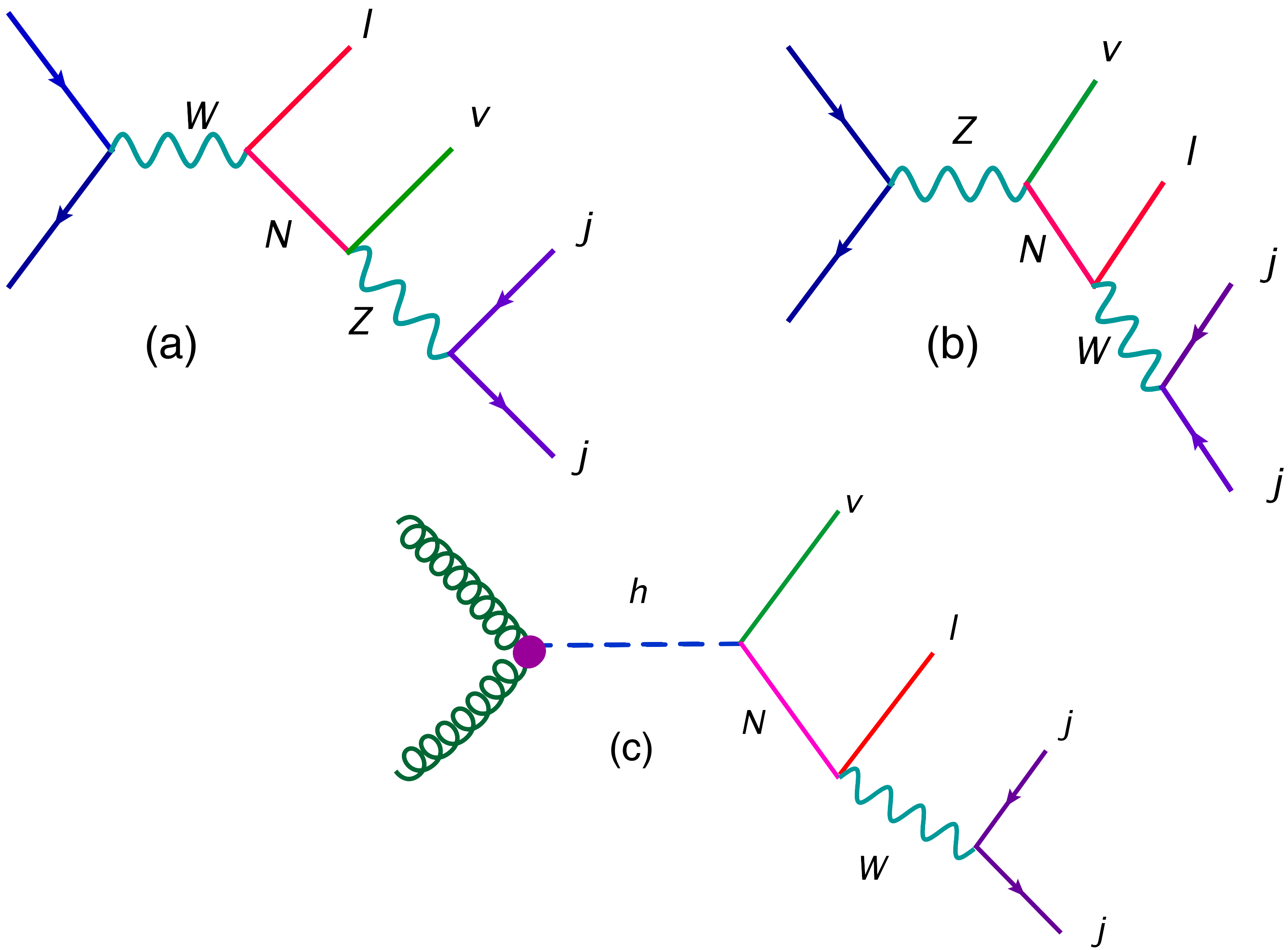
W $\longrightarrow$ Br(lv) : 22%, $\ell = e, \mu$

W $\longrightarrow$ Br(jj) : 67% $\longrightarrow$ **Chance of a gain due to > 3 times Br. into leptons**

Large irreducible backgrounds WW and WZ.

Practically, the purely leptonic modes are more clean turning out the signal sensitivity better than those with the jets, however, reconstruction is easier due to one neutrino in the final state.

Apart from the Higgs decay, the heavy neutrino can display the same final states through the CC and NC interactions. Finally after the decays of the W, Z bosons hadronically, we can get same final states.



Selection cuts

$$\sqrt{s} = 8\ \text{TeV}$$

$$p_T^{\ell} > 20\ \text{GeV} \qquad p_T^{j_{1,2}} > 30\ \text{GeV}$$

$$|\eta_{\ell}| < 2.5 \qquad |\eta^{j_{1,2}}| < 2.5$$

$$\Delta R_{\ell j} > 0.3$$

$$\Delta R_{jj} > 0.4.$$

$$m_i - 20 < m_i < m_i + 20, \quad m_i = M_N, m_W \ \text{or} \ m_Z$$

↑ Depending upon the process

$$\sqrt{s} = 14\ \text{TeV}$$

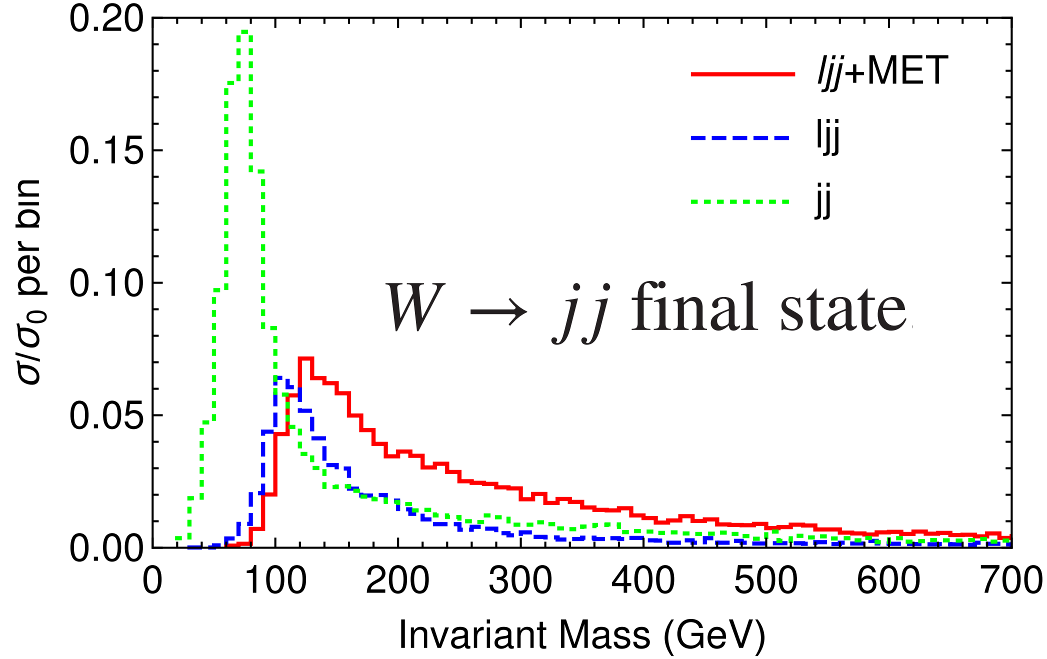
$$p_T^{\ell} > 30\ \text{GeV and } p_T^{j_{1,2}} > 32\ \text{GeV}$$

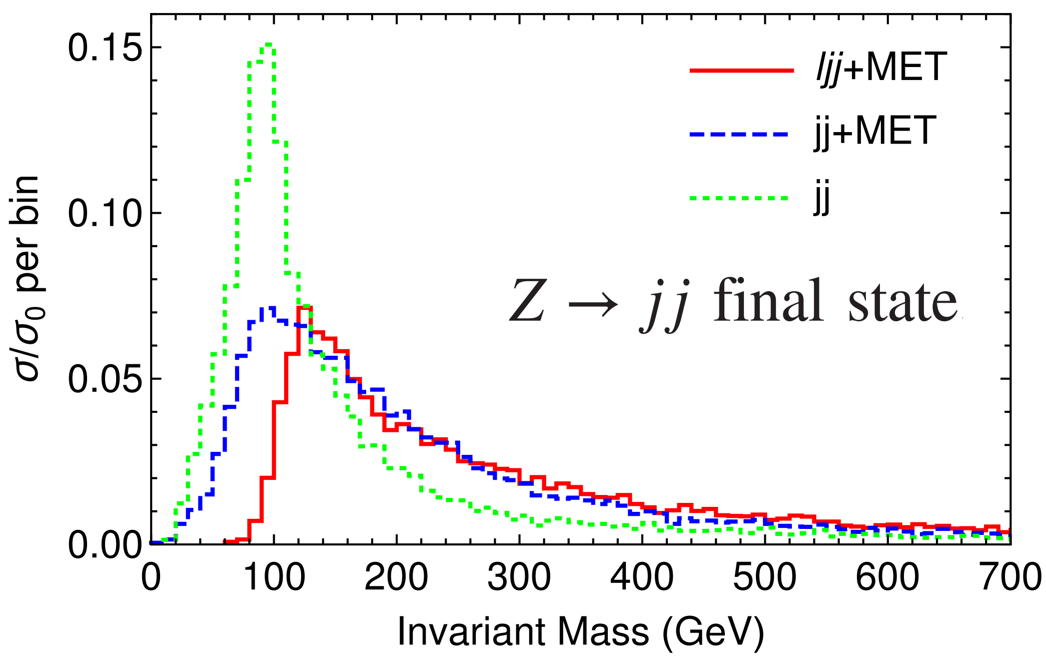
$$\sqrt{s} = 100\ \text{TeV}$$

$$p_T^{\ell} > 53\ \text{GeV} \quad \text{and} \quad p_T^{j_{1,2}} > 35\ \text{GeV}$$

Other cuts remain the same

$M_N = 100$ GeV



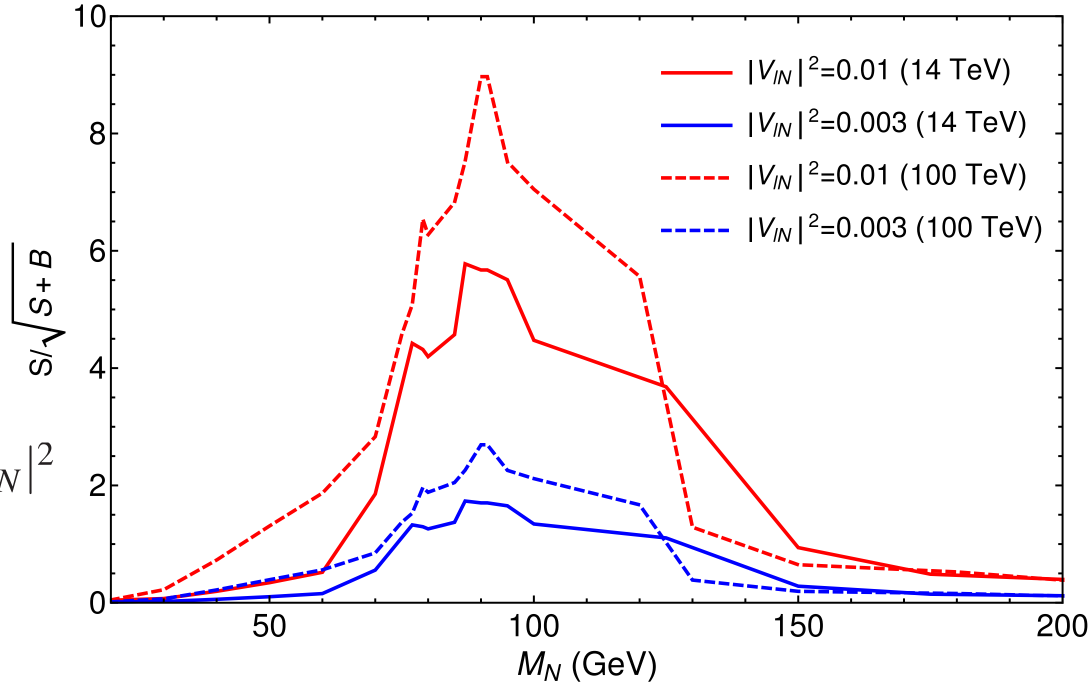


Significance

$\sqrt{s} = 14$ **TeV**

$\sqrt{s} = 100$ TeV

Two different choices of $|V_{\ell N}|^2$



Conclusions

Neutrinos are NOT massless particles which ensures the necessary extension of the SM

Many BSM scenarios can include the possibilities of neutrino mass. Amongst them type-I and inverse seesaw models are the simplest ones which include right handed SM gauge singlet heavy neutrinos. We have studied the various channels to produce such heavy neutrinos at the high energy colliders, such as LHC and 100 TeV pp collider comparing the bounds on the mixing angles.

The bounds on the mixing angle coming from the LFV, LEP experiments are very strong so that the production of such heavy neutrinos from the type-I seesaw could be challenging. However, at the low mass such as 100 GeV that could be testable using Casas-Ibarra conjecture.

Due to small lepton number violation parameter, on the other hand, the inverse seesaw scenario is still hopeful to us at the colliders. Even the Casas-Ibarra conjecture can help in testing the LFV modes at the LHC.

Recently discovered Higgs can be used as a handle to study the properties of the heavy neutrinos where the heavy neutrino can show leptonic or hadronic decays through the SM gauge bosons. Even, the Higgs+ISR can improve the situation (Das, Gao, Kamon: arXiv:1704.00881 [hep-ph]).

Thank you