Neutrinos and the LHC

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ICTP, Trieste

with Maiezza, Nesti, Senjanović, Tello, Vissani and Zhang

NuFact '11, CERN

LHC a neutrino machine?

Neutrino mass is an experimentally established fact for BSM physics.

CERN colloquium by Senjanović

- *Might as well be @ TeV (hierarchy)*
- *A phenomenological hint may already be here*

Neutrino mass and BSM

Facts

$$\Delta m^2_{S,A} \,\&\, \theta_{A,S,13}$$

- *At least two massive light neutrinos*

Questions

- *Mass scale & hierarchy*
- *CP phases*
- *Dirac or Majorana*

- *LHC may play a crucial role*
- *Low-high energy interplay becomes important*

The theory of neutrino mass?

Origin of m_ν

- *Standard Model* ν_L *only,* $m_\nu = 0$
- *Effective theory* $\mathcal{O}_W = y\frac{\ell h \ell h}{\Lambda} \Rightarrow m_\nu = \frac{y^2 v^2}{\Lambda}$

High scale

- *Typical in GUTs*
- *Indirect, LHC of little use*

TeV

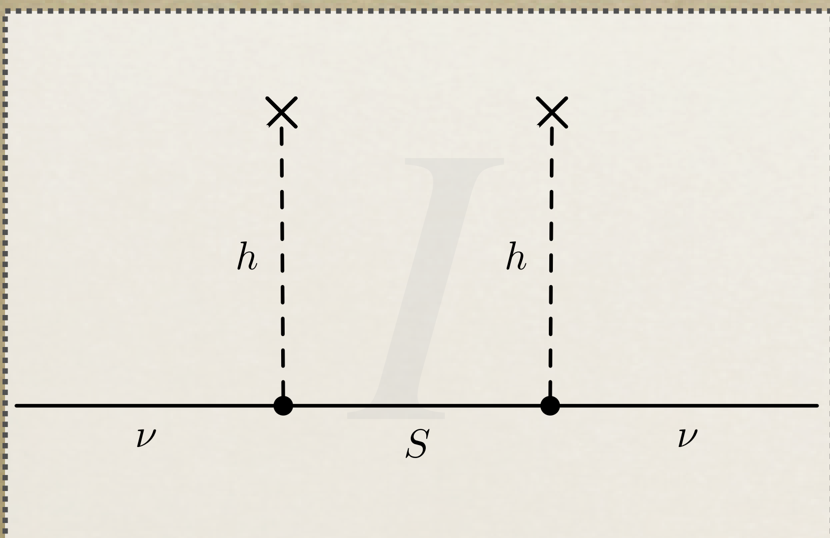
- *Theory: GUT remnant*
- *Phenomenological*

Neutrinos @ LHC

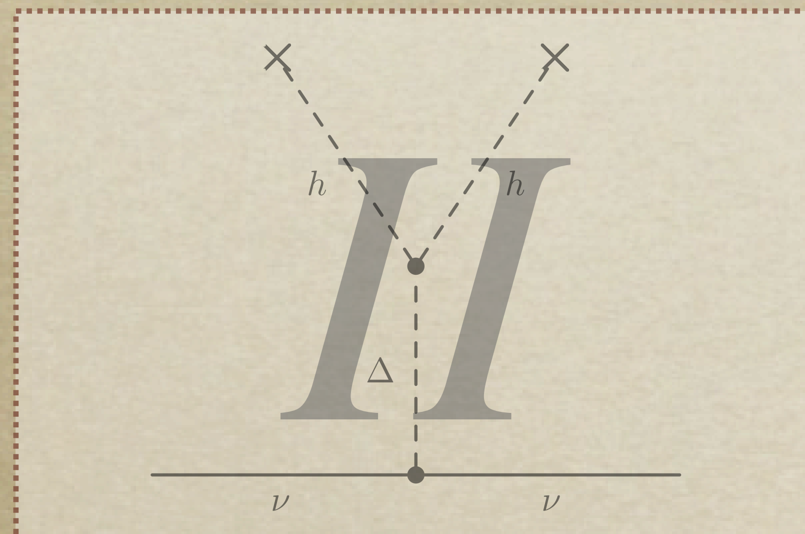
UV completions of $\mathcal{O}_W$

- *Renormalizable theory = seesaw scenarios*

Fermionic singlet



Bosonic triplet



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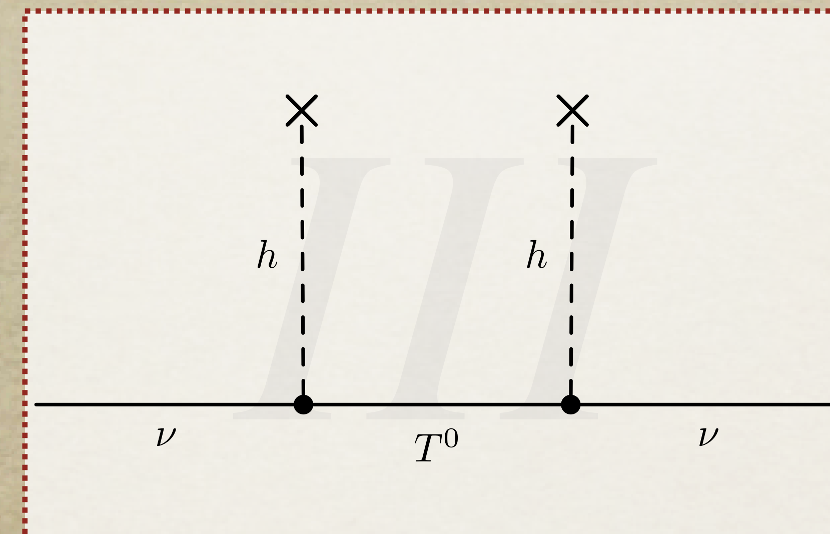


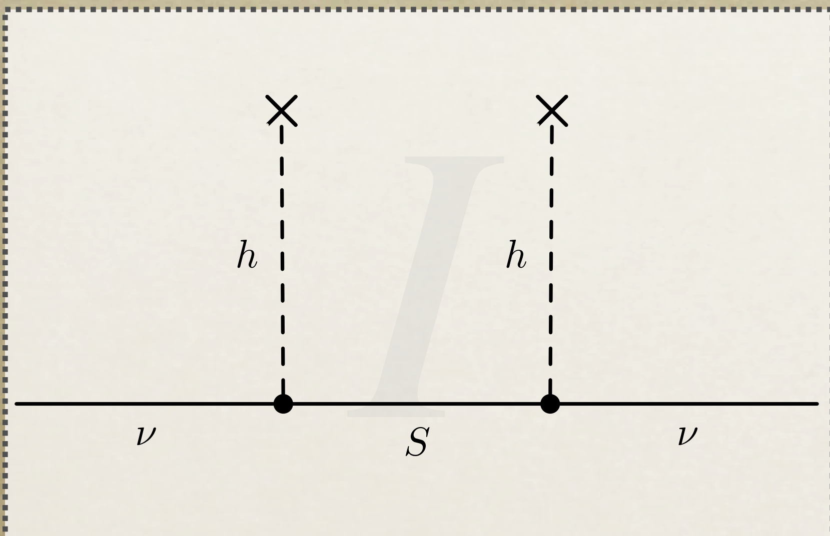
Type I+III

- *Triplet predicted at TeV by a minimal SU(5) with* 24_F
- *Neutrino mass matrix through decays*
- *Oscillations-collider connection*

Bajc, Senjanović '06
Bajc, MN, Senjanović '07

UV completions of $\mathcal{O}_W$

Fermionic singlet



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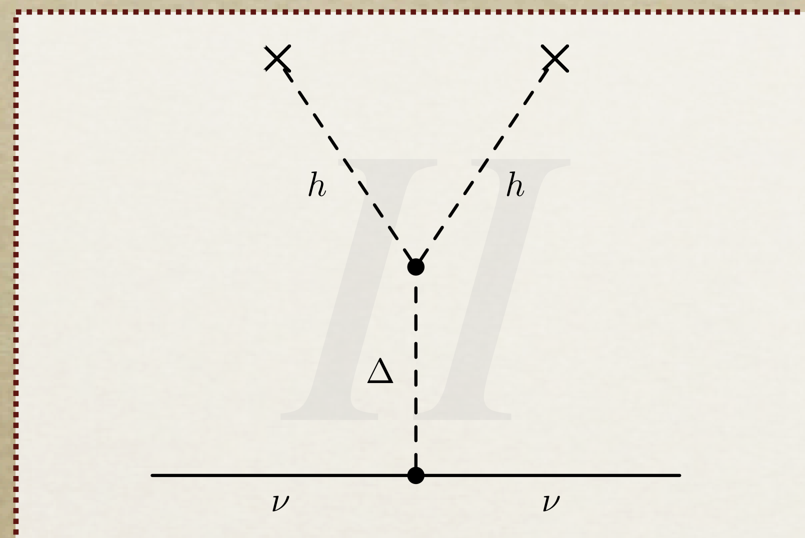

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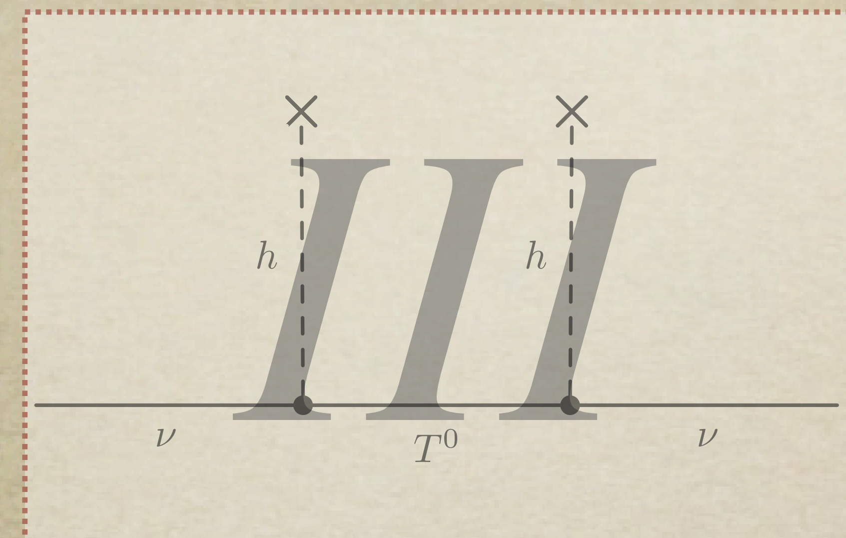

Type I+II

- *Predicted by a minimal LR symmetric theory*
- *Singlet is gauged, type I required by anomalies*
- *Triplet breaks the LR symmetry - type II*
- *May need to be light* $\hookrightarrow$

Left-Right symmetry

Talk by Senjanović

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, W_L \leftrightarrow \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}, W_R$$

- *Parity restoration at high scales* — *Pati, Salam '74*; *Mohapatra, Pati '75*
- *Spontaneously broken* — *Mohapatra, Senjanović '75*
- *Origin of the seesaw mechanism* — *Minkowski '77*; *Senjanović '79*; *Senjanović, Mohapatra '80*

Minimal LR Model

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

- *LR symmetric Higgs sector, parity invariant* $\mathcal{L}$

$$\Phi(2,2,0),\ \Delta_L(3,1,2),\ \Delta_R(1,3,2)$$

- *First stage @ TeV*

$$\langle \Delta_R \rangle = \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}$$

$$\langle \Delta_L \rangle \equiv v_L = 0$$

- *Second stage @ 100 GeV*

$$\langle \Phi \rangle = \begin{pmatrix} v_1 & 0 \\ 0 & v_2 e^{i\alpha} \end{pmatrix}$$

$$v_L = \lambda v^2 / v_R$$

- *Breaks* $SU(2)_R$ *and Lepton number*

$$M_{W_R} = g\, v_R, \quad m_N = y\, v_R$$

$$M_W \propto v \equiv \sqrt{v_1^2 + v_2^2}, \quad m_D \propto v$$

Mass spectra

$$\mathcal{L}_Y = \bar{\ell}_L(Y_\Phi\,\Phi + \tilde{Y}_\Phi\,\tilde{\Phi})\ell_R + \ell_L^T\,Y_{\Delta_L}\Delta_L\ell_L + \ell_R^T\,Y_{\Delta_R}\Delta_R\ell_R + \text{h.c.}$$

- *Dirac terms*
- *Majorana terms*

$$M_D = v_1\,Y_\Phi + v_2\,\mathrm{e}^{-i\alpha}\,\tilde{Y}_\Phi,$$
$$M_\ell = v_2\,\mathrm{e}^{i\alpha}\,Y_\Phi + v_1\,\tilde{Y}_\Phi$$

$$\mathcal{C}: \quad Y_\Phi = {Y_\Phi}^T,$$

$$M_{\nu_R} = v_R\,Y_{\Delta_R}$$
$$M_{\nu_L} = v_L\,Y_{\Delta_L} - M_D^T\,M_{\nu_R}^{-1}\,M_D$$

$$Y_{\Delta_{L,R}} = {Y_{\Delta_{R,L}}}^*$$

- *Mass eigenstate basis*

$$M_\ell = U_{\ell L}\,m_\ell\,U_{\ell R}^\dagger,\;\; M_{\nu_L} = U_{\nu L}^*\,m_\nu\,U_{\nu L}^\dagger,\;\; M_{\nu_R} = U_{\nu R}^*\,m_N\,U_{\nu R}^\dagger$$

$$\mathcal{C}: U_{\ell L} = U_{\ell R}^*$$

The Interactions

- *New Gauge:* $\mathcal{L}_{cc} = \frac{g}{\sqrt{2}} \left(\bar{\nu}_L {V_L}^\dagger \not{W} \ell_L + \bar{\nu}_R {V_R}^\dagger \not{W}_R \ell_R \right)$
- *New Scalar:* $\mathcal{L}_{\Delta^{++}} = e_R^T \, Y \, \Delta_R^{++} \, e_R$

$$Y = \frac{g}{M_{W_R}} {V_R}^* m_N {V_R}^\dagger$$

- *Flavor fixed in type II:* ${V_R}^* = V_L$
  - *Remember; two angles, one limit, no phases*

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- *Flavor fixed in type II:*
    - *Remember; two … limit, no phases*

Example only!

- *LHC could eventually measure these*

Bounds on the LR scale

- *Theoretical bounds since '81* — Beall et al. '81...Zhang et al. '07
- *A recent detailed study, including CP violation* — Maiezza, Nesti, MN, Senjanović '10

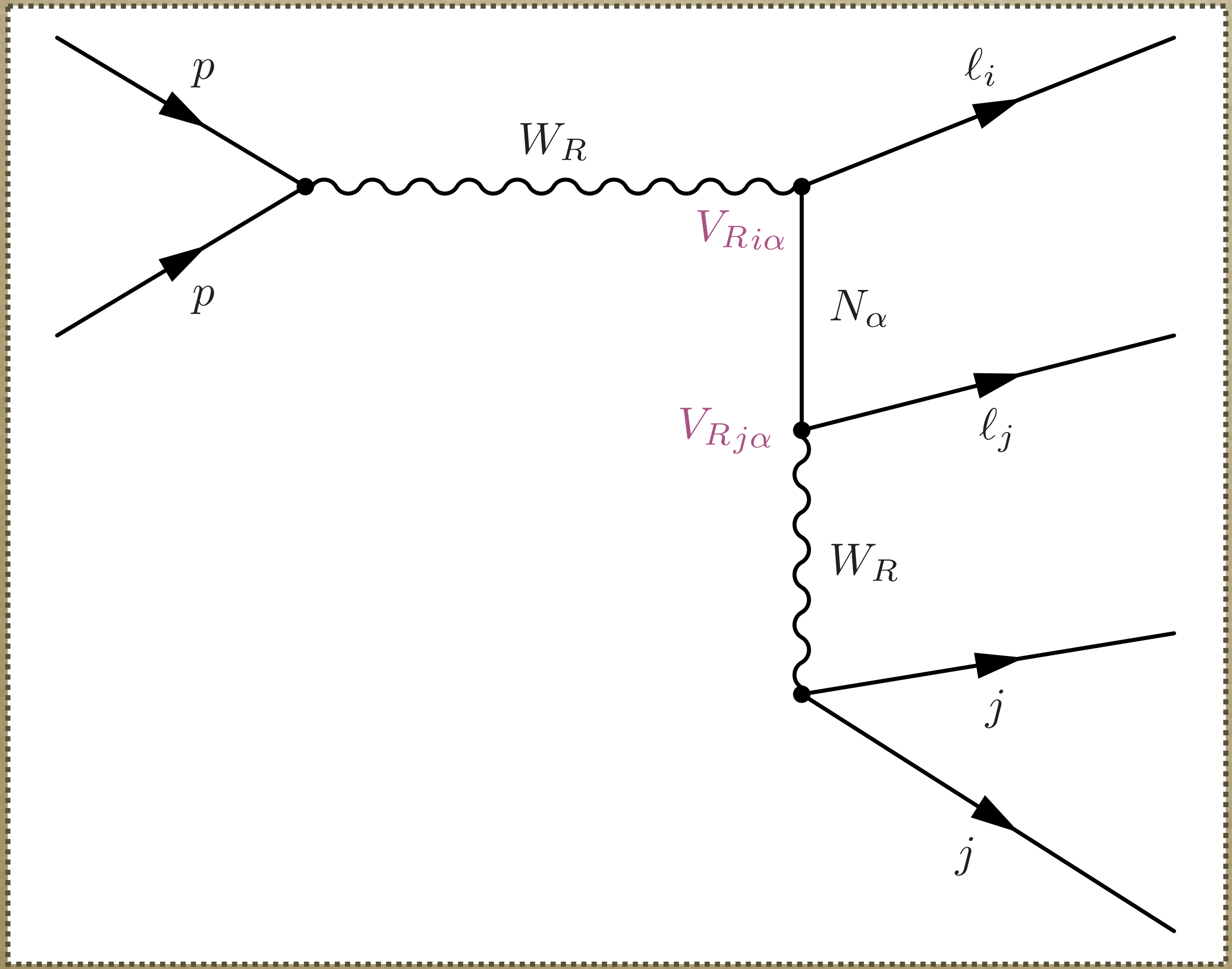
$$\mathcal{C} : M_{W_R} > 2.5\,\mathrm{TeV} \qquad \mathcal{P} : M_{W_R} > 3.2 - 4.2\,\mathrm{TeV}$$

- *Direct searches*
  - *Dijets* $M_{W_R} > 1.51$ TeV — CMS 1107.4771
  - *Light neutrino* $M_{W_R} > 2.27$ TeV — CMS PAS EXO-11-024

LHC is here!

Left-Right @ LHC

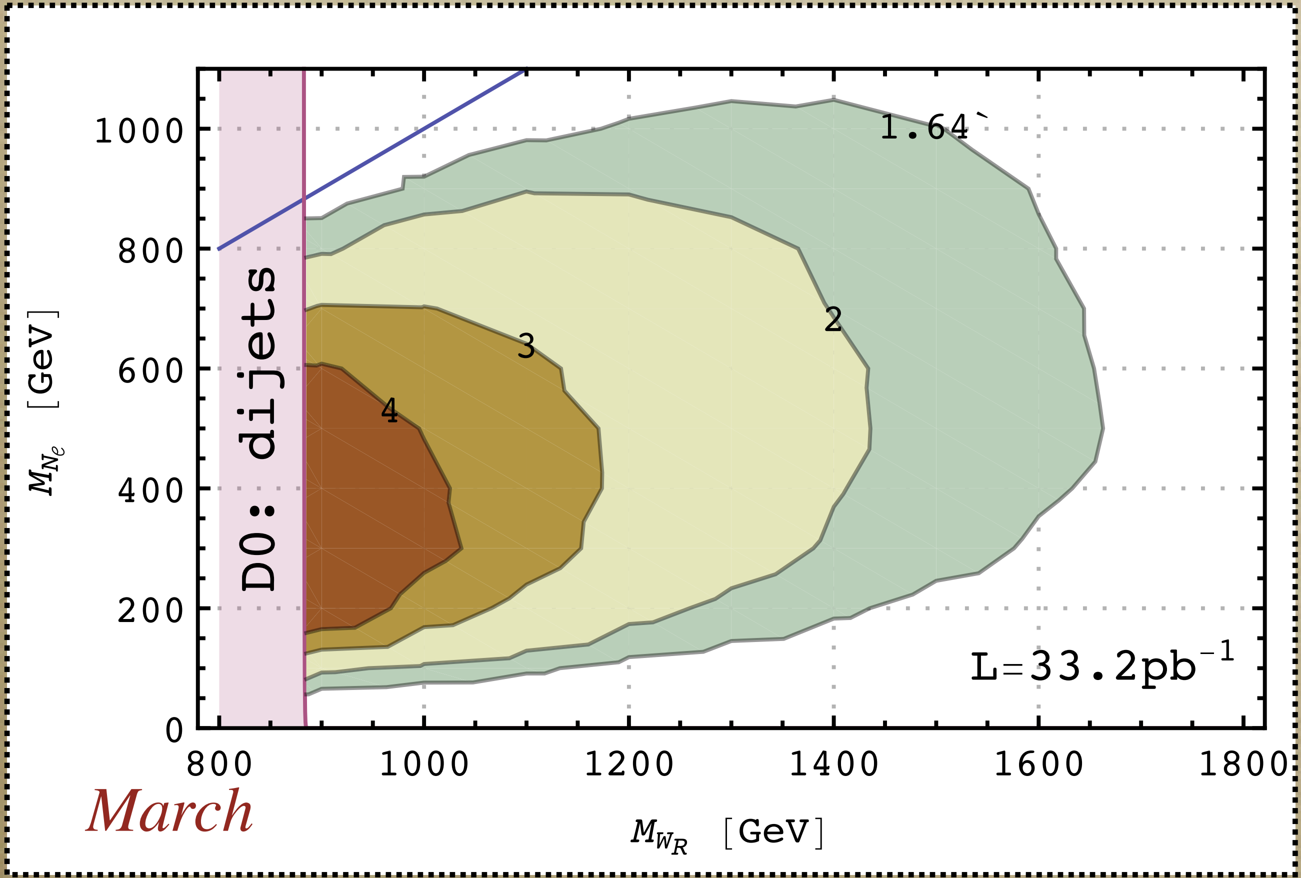
- *Most interesting channel: l l j j* — *Keung, Senjanović '83*
- *LNV at colliders*

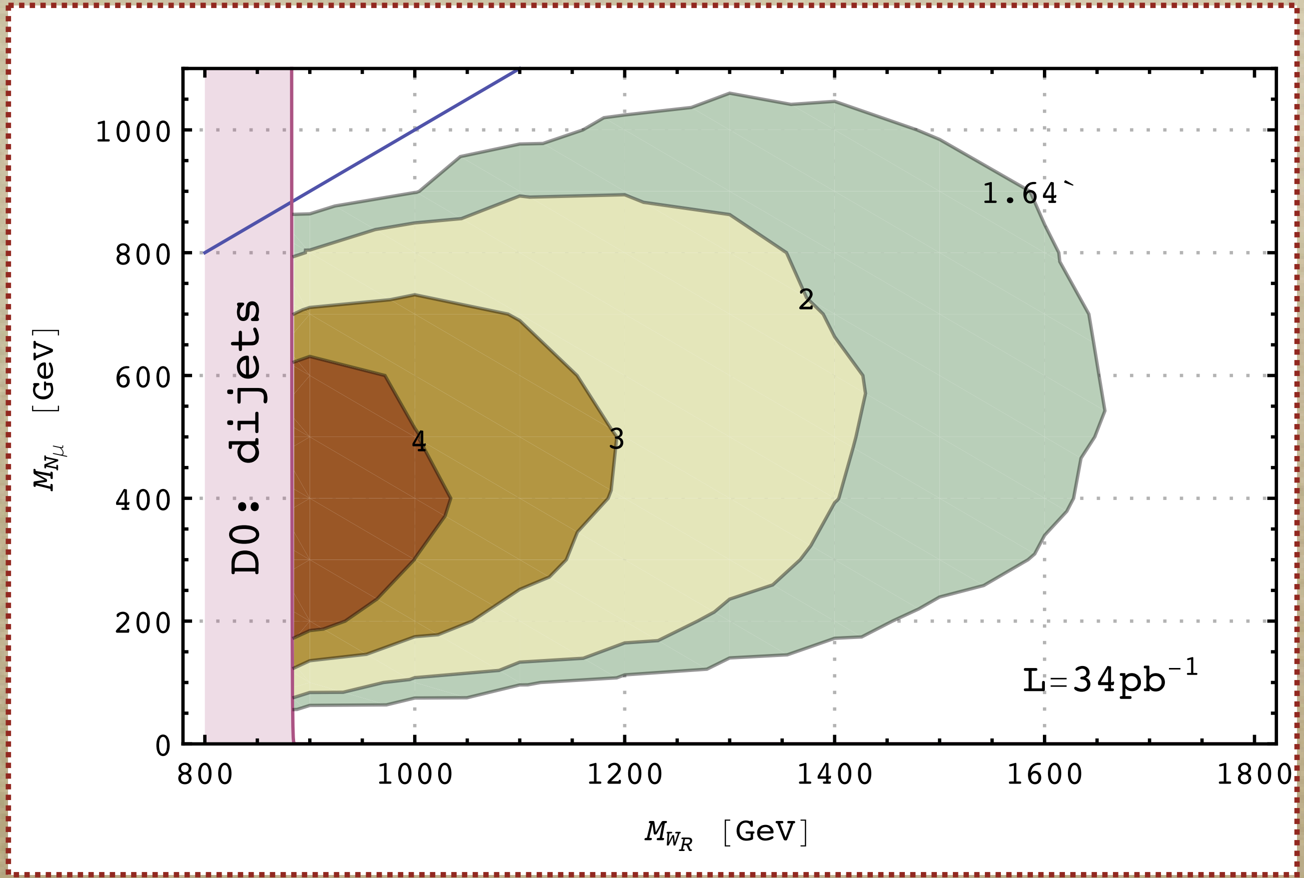


- *Gauge production: s-channel, W nearly on-shell*
- *Clean, no missing energy*
- *Reconstructs W and N masses*
- *Information on the flavor*

Limits from the LHC

MN, Nesti, Senjanović, Zhang '11



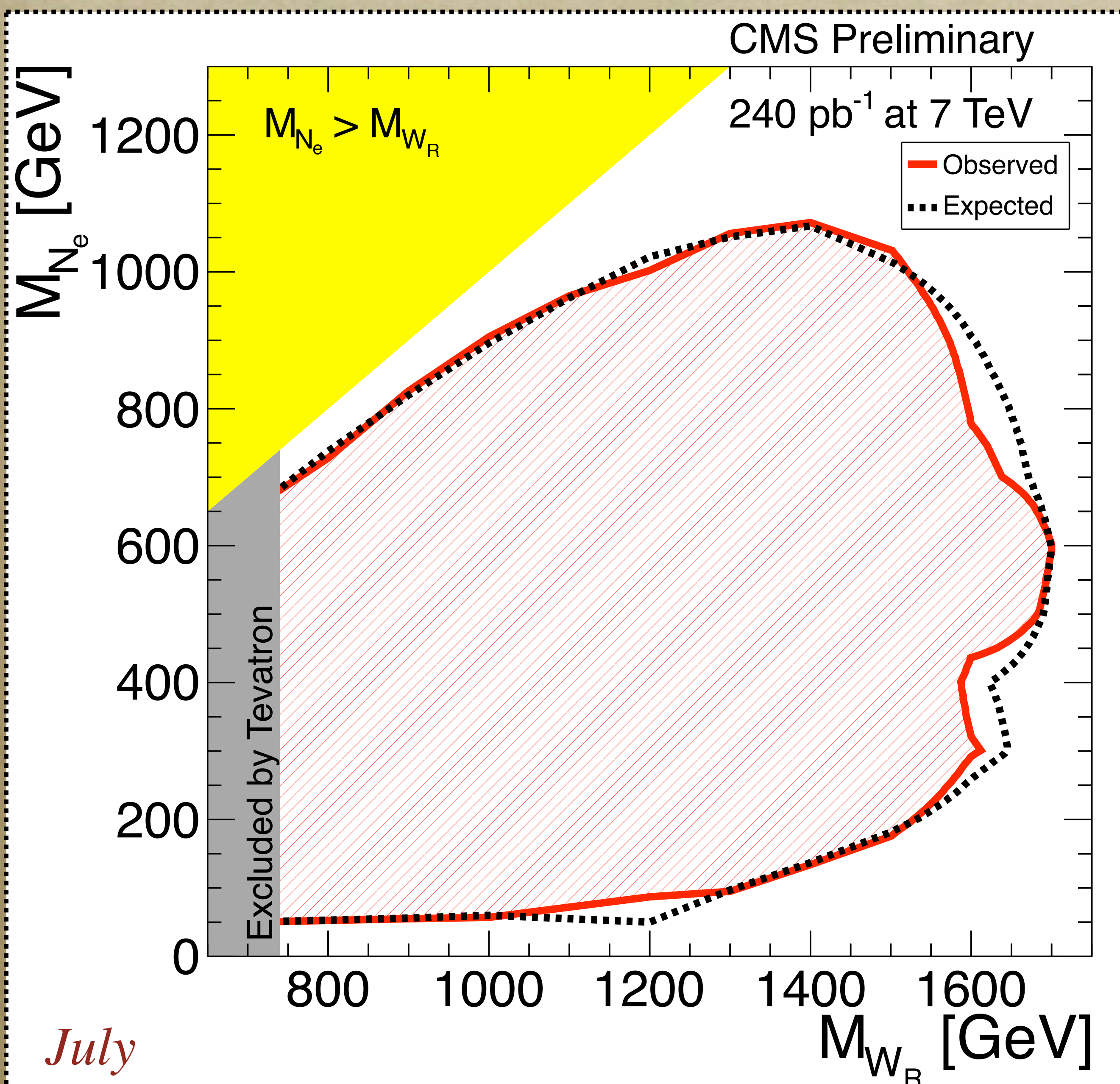


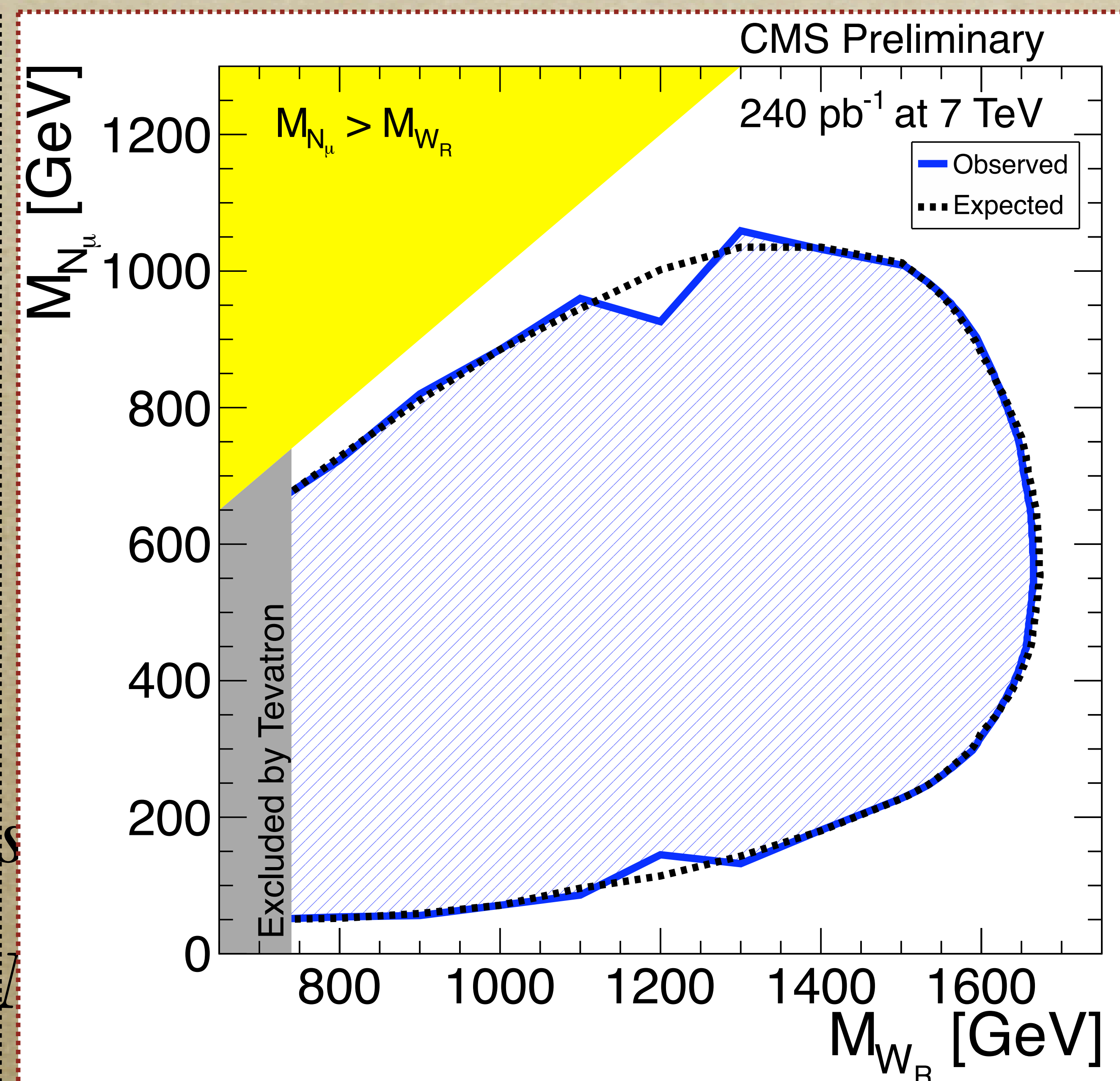
- *High N inaccessible due to jets, low N due to isolation*
- *This year:* $\mathcal{L} = 0.1(1)\,\mathrm{fb}^{-1} : M_{W_R} > 1.6(2.2)\,\mathrm{TeV}$
- *Electron and muon channel essentially the same*

Limits from the LHC

CMS PAS EXO-11-002

MN, Nesti, Senjanović, Zhang '11





- *Electron and muon channel essentially the same*

Low/high energy interplay

- *Majorana mass term dominance*

$$M_{\nu_R} = v_R\, Y \qquad\qquad M_{\nu_L} = v_L\, Y^*$$

- *Implications for masses and mixings*

$$m_N \propto m_\nu \qquad\qquad U_{\nu R} = U^*_{\nu L} \Rightarrow V_R = V_L^*$$

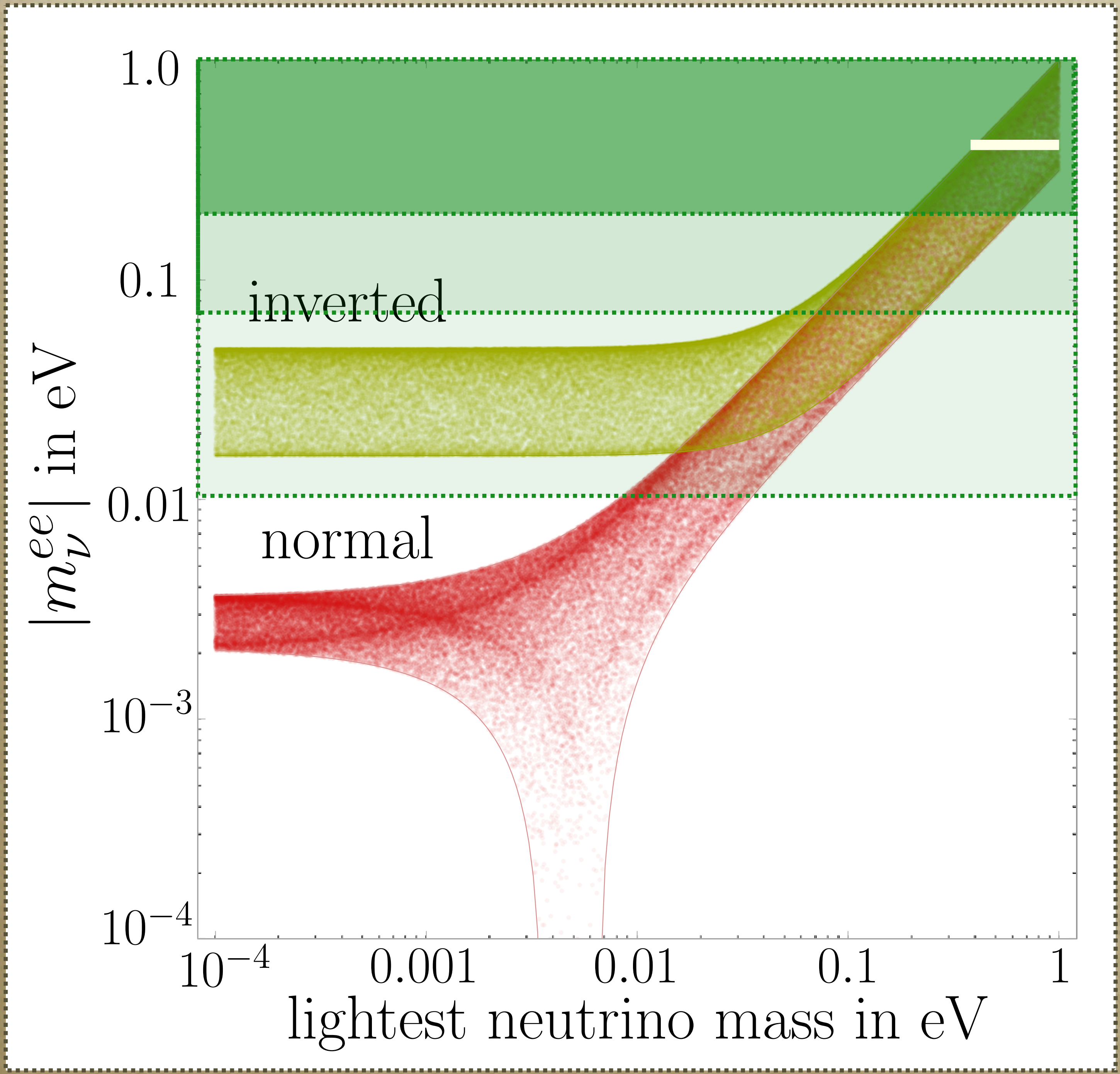
$$\frac{{m_{N_2}}^2 - {m_{N_1}}^2}{{m_{N_3}}^2 - {m_{N_1}}^2} = \frac{{m_{\nu_2}}^2 - {m_{\nu_1}}^2}{{m_{\nu_3}}^2 - {m_{\nu_1}}^2} \simeq \pm 0.03$$

- *Hierarchy probe @ LHC*

$$m_{\mathrm{cosm}} = \sqrt{\Delta m_A^2}\,\frac{\sum_i m_{N_i}}{\sqrt{|{m_{N_3}}^2 - m_{N_2}^2|}},$$

- *Cosmo-oscillations -LHC link*

$0\nu2\beta$ and cosmology



- *Majorana mass implies*

  $0\nu2\beta$ Talk by Lopez-Pavon

- *Gerda, Cuore, Majorana,...*

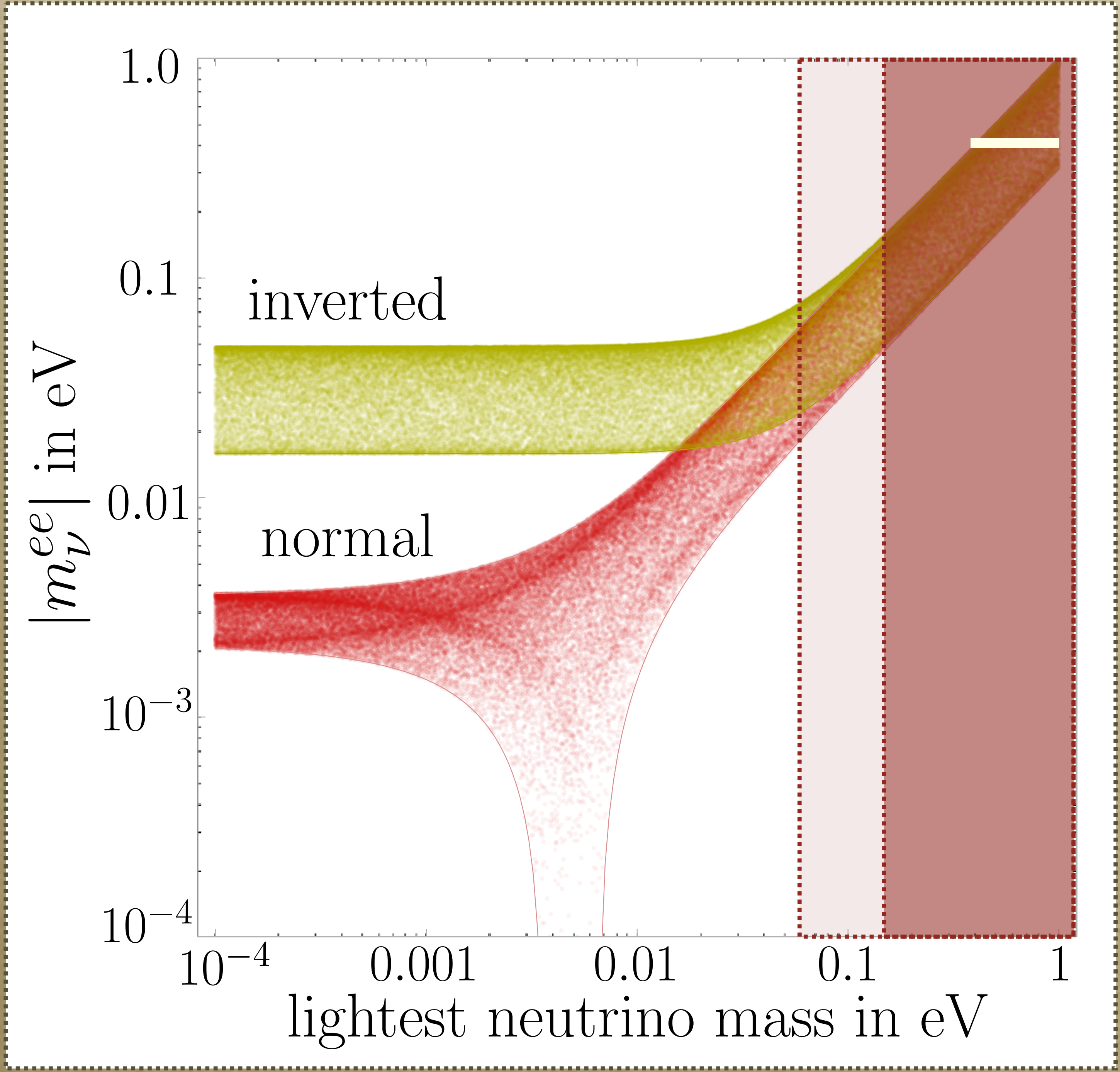
  Review by Rodejohann '11

- *Claim of observation*

$$|m_\nu^{ee}| \simeq 0.4 \text{ eV}$$

Klapdor-Kleingrothaus '06, '09

$0\nu 2\beta$ and cosmology



- *Cosmological bounds*

$$\sum m_\nu < 0.17 \text{ eV}$$

Seljak et al. '06

- *WMAP alone*

$$\sum m_\nu < 0.44 \text{ eV}$$

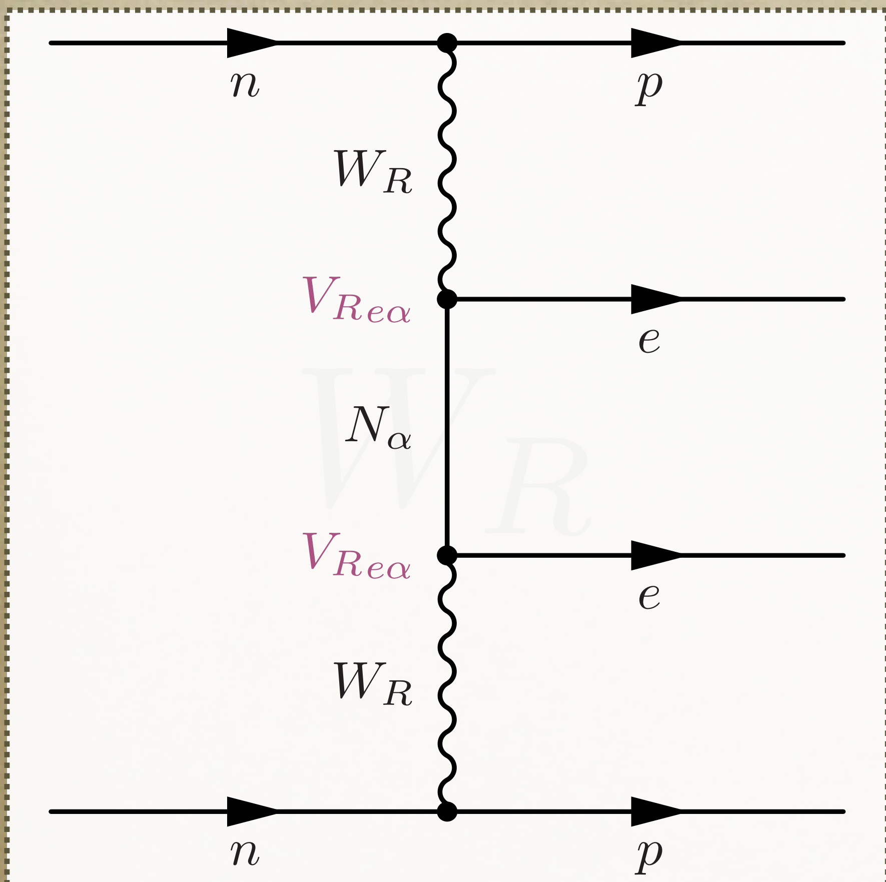
Hannestad et al. '10

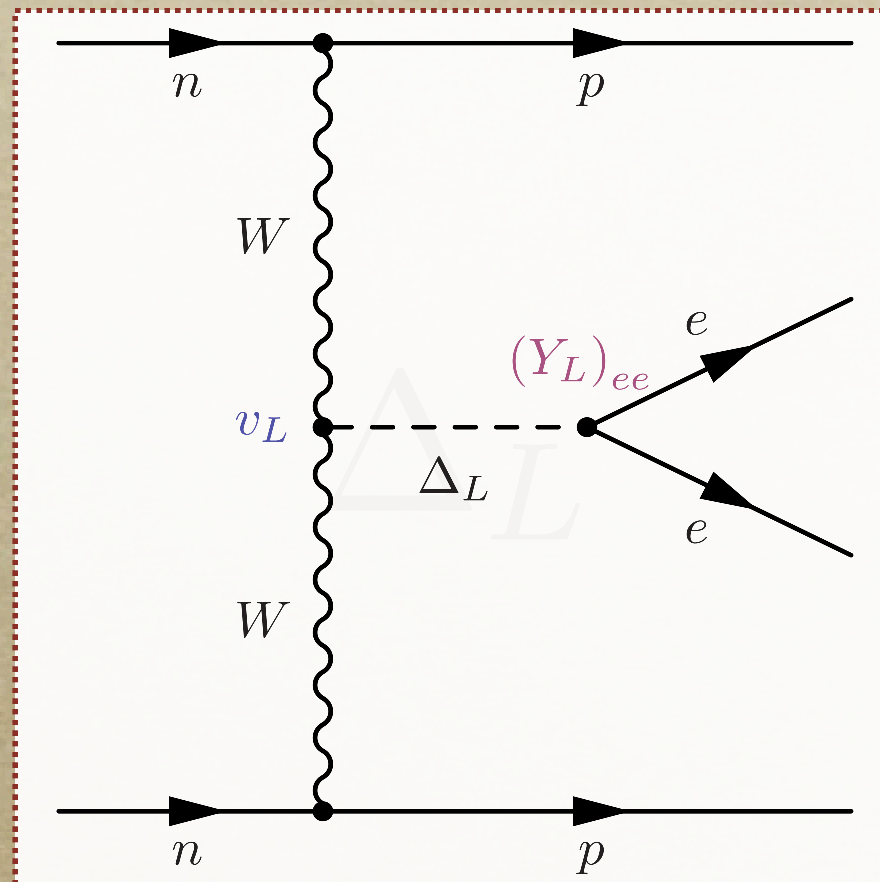
- *If confirmed, a hint for NP*

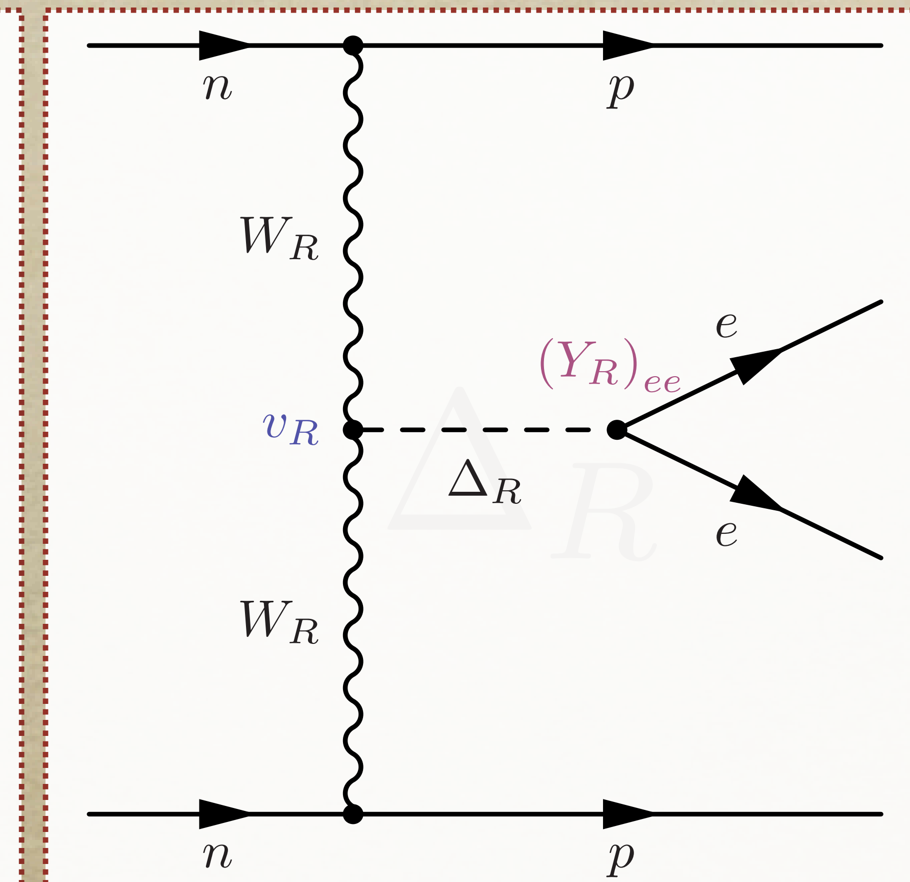
Vissani '02

New Diagrams for $0\nu 2\beta$

Mohapatra, Senjanović '81







$\propto 1/m_N$ $\propto m_\nu$ $\propto m_N$

- *Large?*
- *Tiny*
- *Subdominant?*

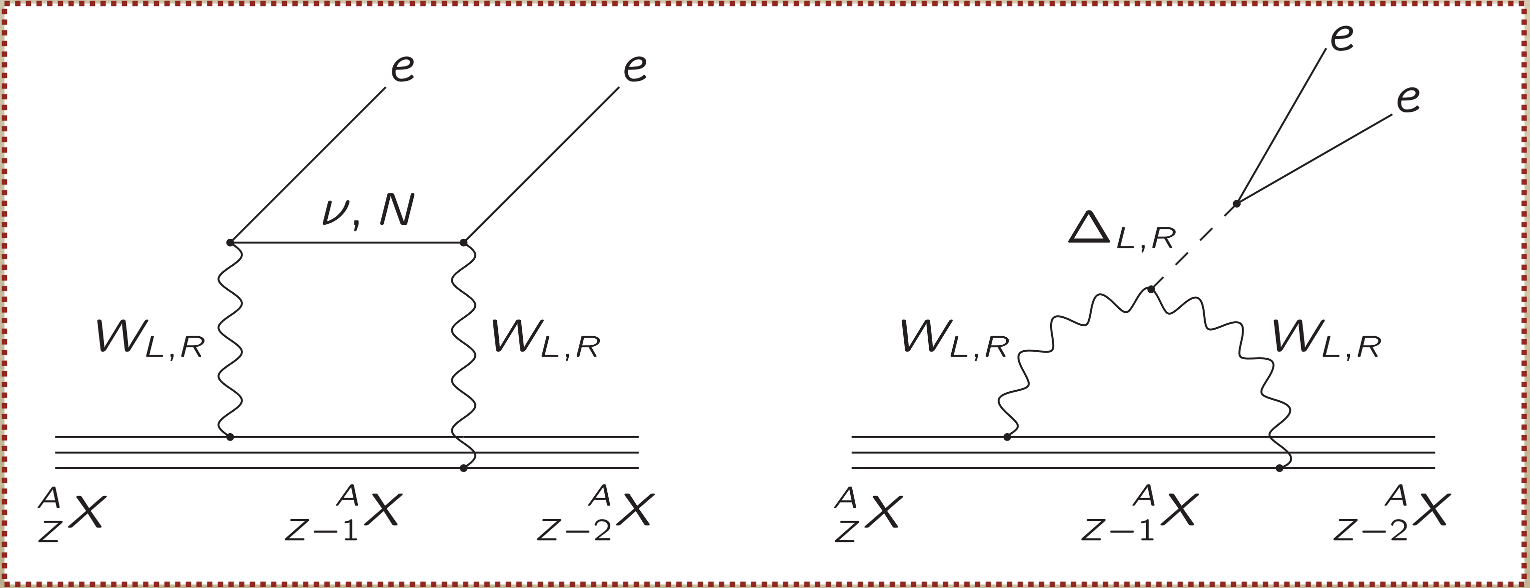
- *In agreement with cosmology?*

$0\nu2\beta$: the new contribution

- *LR mixings small*

$$\sin\xi < M_W/M_{W_R} < 10^{-3}$$

$$m_D \simeq 0$$

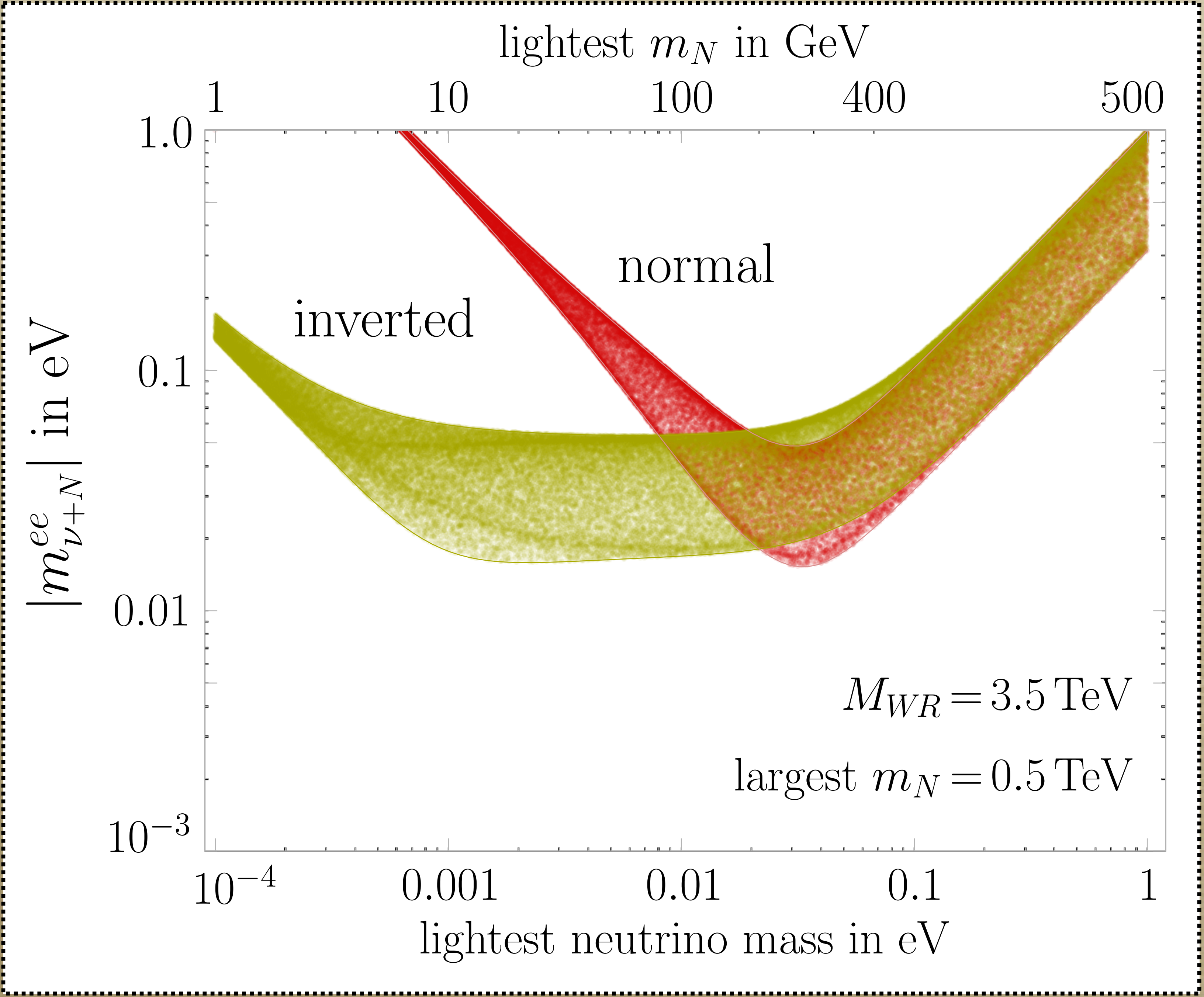


$$\mathcal{H}_{\rm NP} = G_F^2 {V_R}_{ej}^2 \left[\frac{1}{m_{Nj}} + \frac{2\, m_{Nj}}{m_\Delta^2} \right] \frac{M_W^4}{M_{W_R}^4} J_{R\mu} J_R^\mu \, \overline{e_R} e_R^c$$

- *Type II:* ${V_R}^* = V_L$
- Δ_L *suppressed:* $m_\nu / m_\Delta \ll 1$
- *LFV:* $m_N / m_{\Delta_R} < 1$
- *The gauge contribution is dominant*

$0\nu2\beta$: the total contribution

- *LHC accessible regime*



$$|m_{\nu+N}{}^{ee}|^2 \equiv |m_\nu{}^{ee}|^2 + |m_N{}^{ee}|^2$$

- Interference small
- Reversed role of hierarchies
- No tension with cosmology
- A light $m_N < M_{W_R}$
- No cancellations

$0\nu 2\beta$: the total contribution

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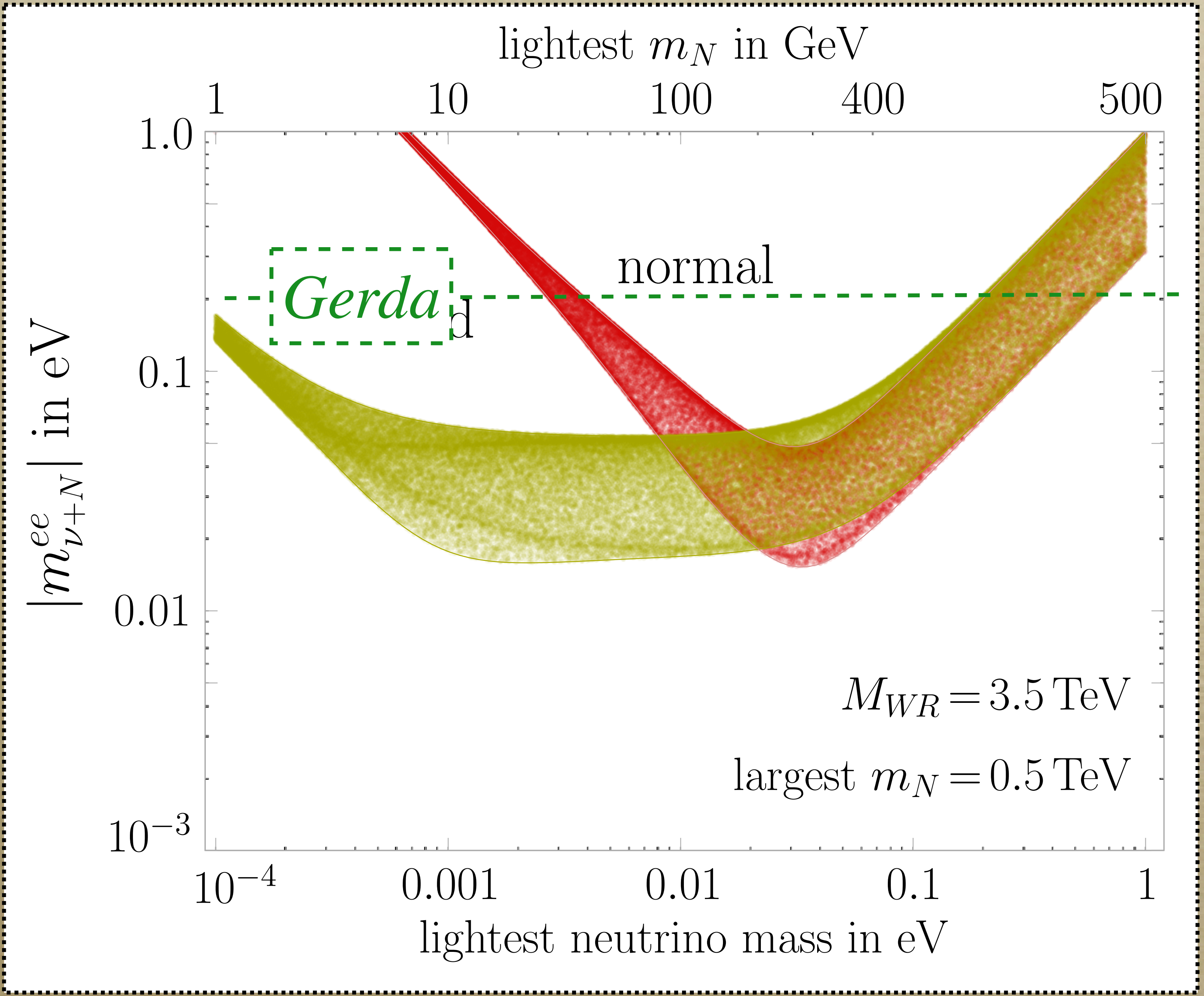

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LHC and $0\nu2\beta$

- *Suppose NP is a must for* $0\nu2\beta$; $\theta_{13} \simeq 0$ $\alpha = 2(\varphi_2 - \varphi_1)$

$$|M_{\nu+N}{}^{ee}|^2 = |m_{\nu_1}\cos^2\theta_{12} + m_{\nu_2} e^{i\alpha}\sin^2\theta_{12}|^2 + \left| p^2 \frac{M_W^4}{M_{W_R}^4}\left(\frac{1}{m_{N_1}}\cos^2\theta_{12} + \frac{1}{m_{N_2}} e^{i\alpha}\sin^2\theta_{12}\right)\right|^2$$

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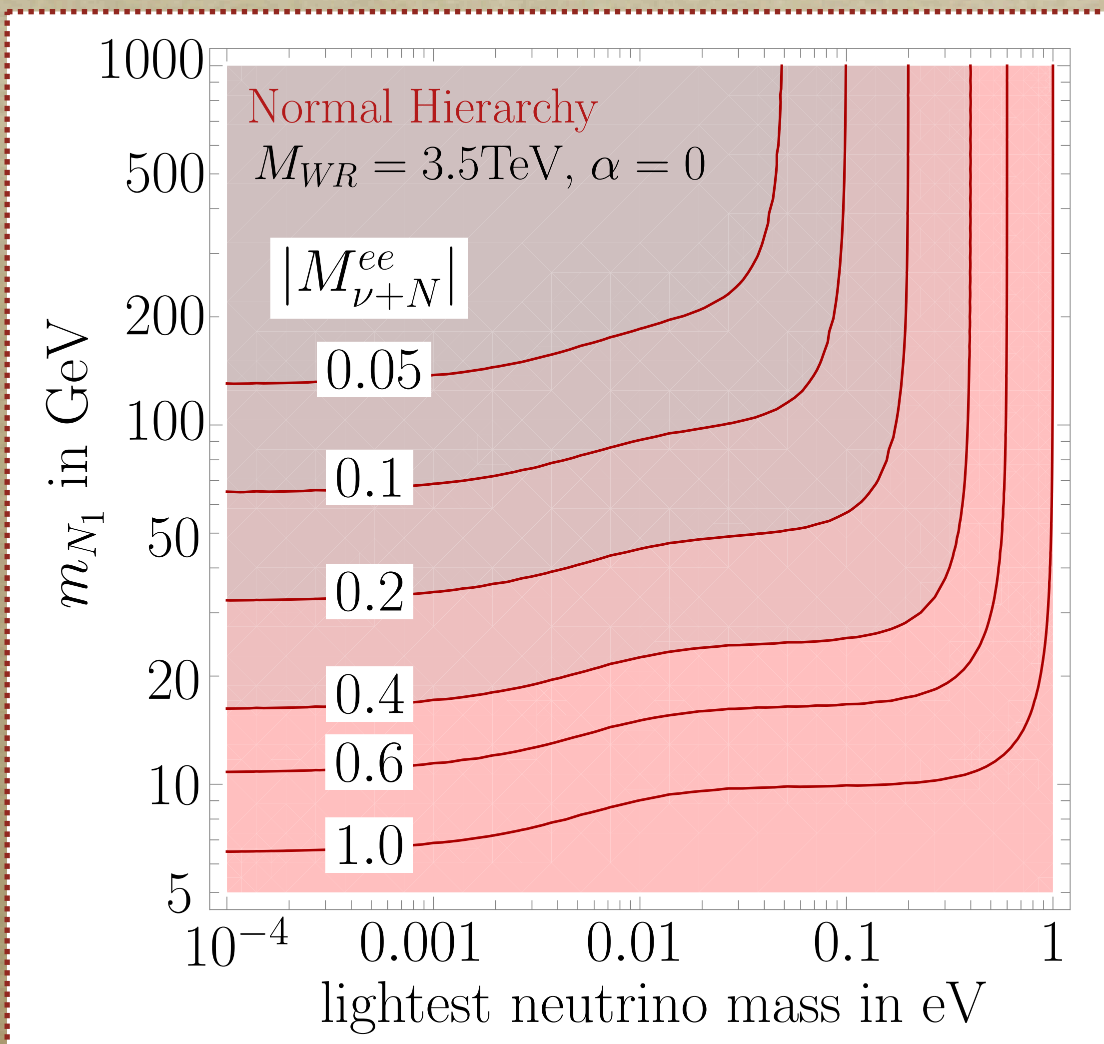

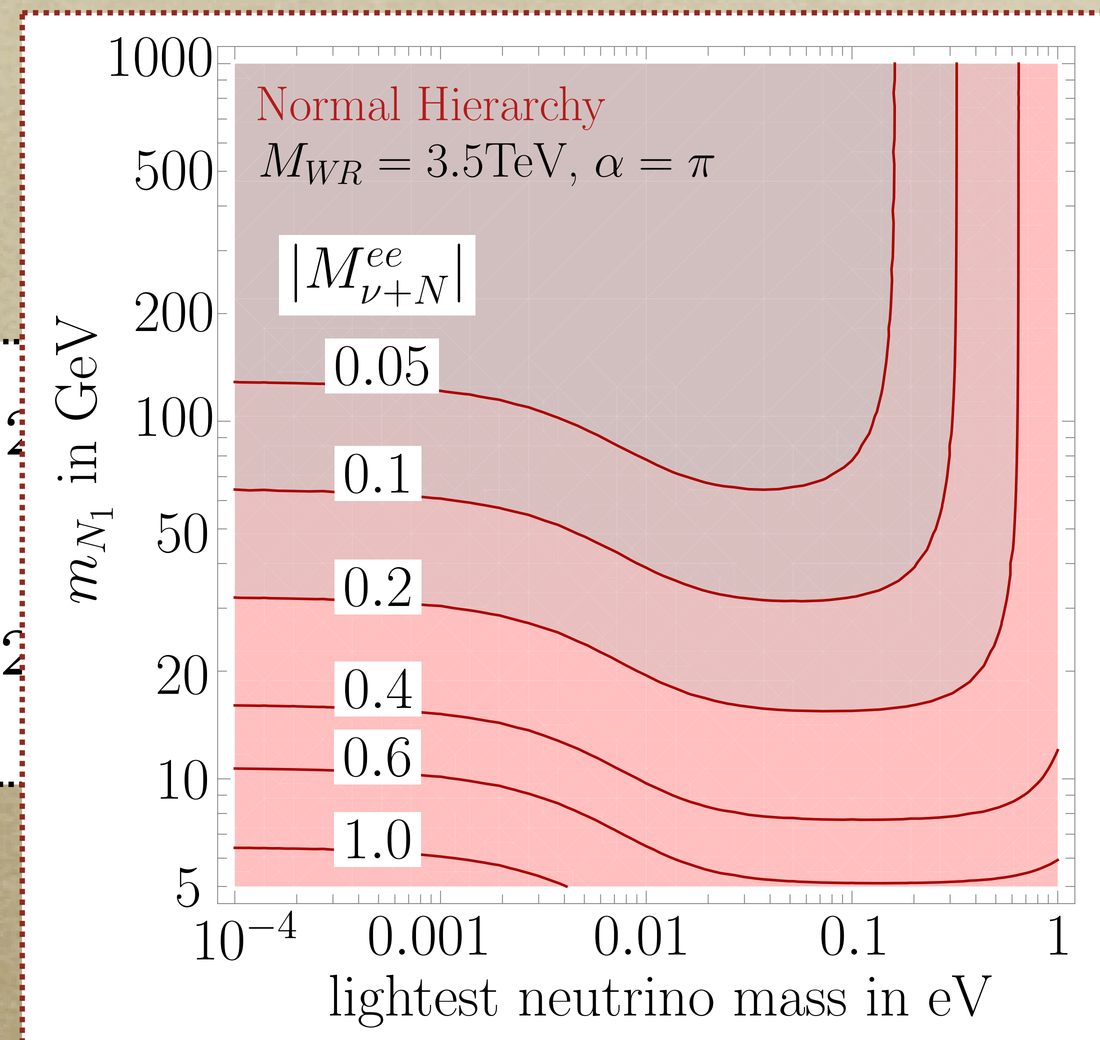

- *LHC:*

$jj : m_N \gtrsim 50\ \text{GeV}$ $\qquad \not{p} : m_N \lesssim 20\ \text{GeV}$

$j\ell : m_N \gtrsim 20\ \text{GeV}$ $\qquad \not{E} : m_N \lesssim 3 - 7\ \text{GeV}$

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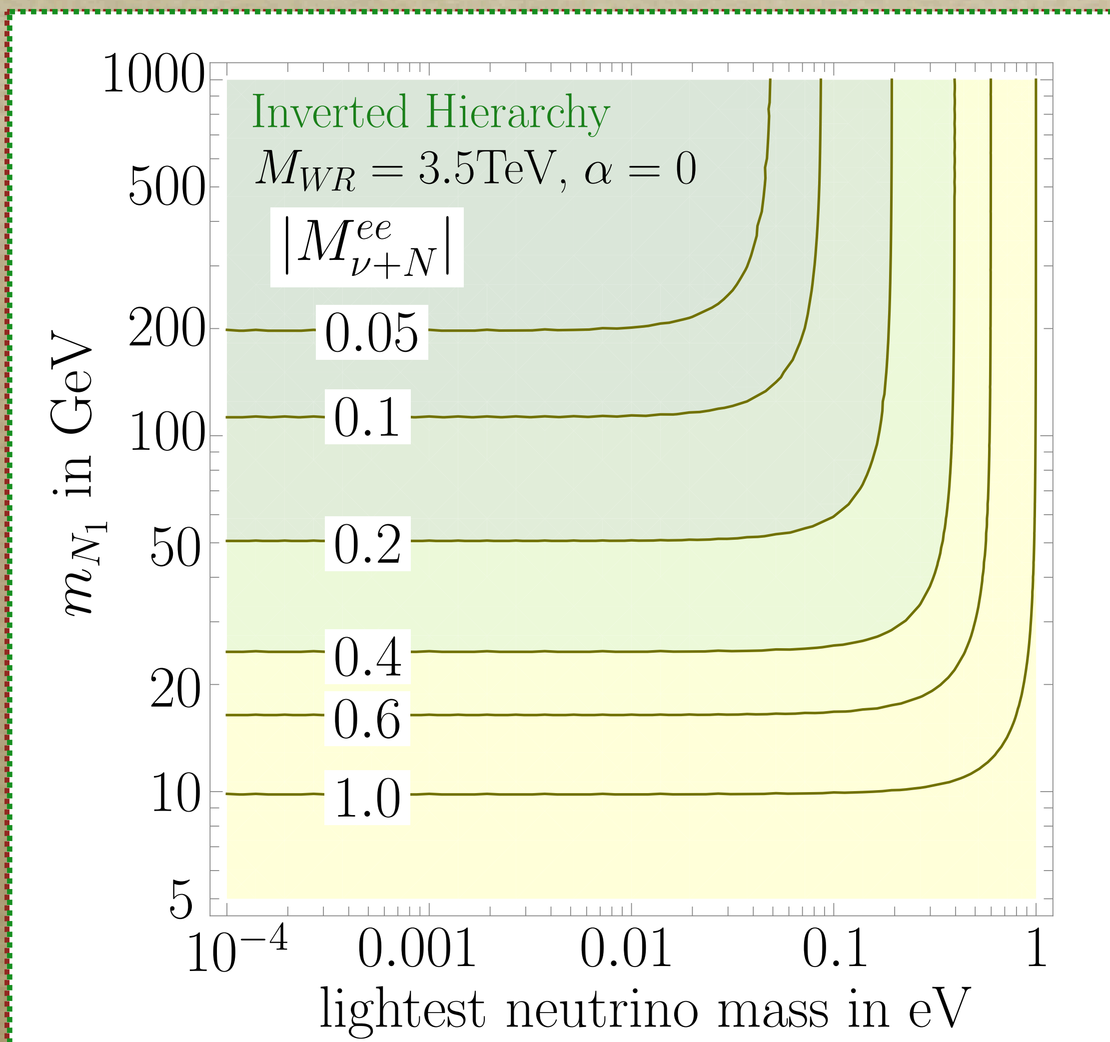
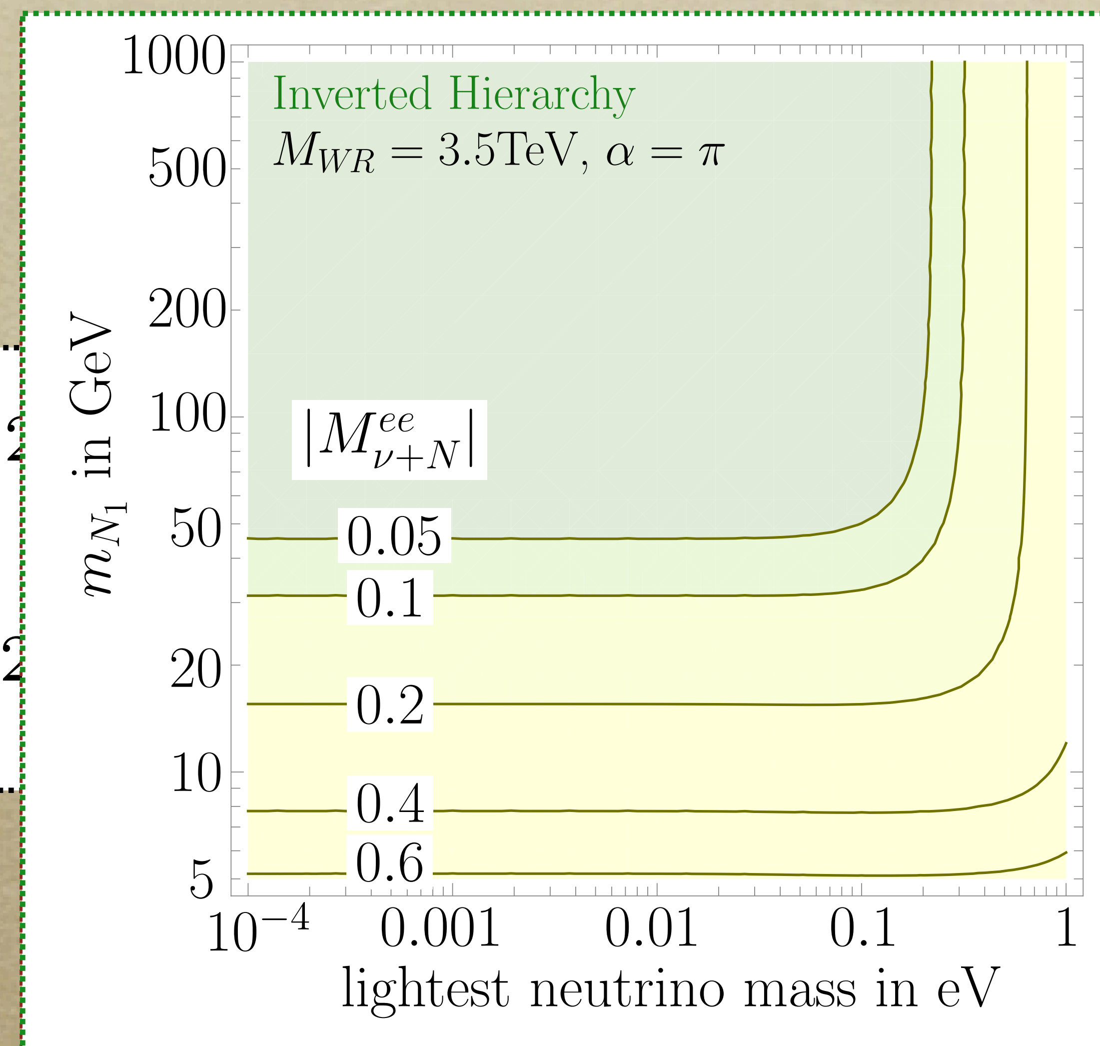


θ_{12}

θ_{12}



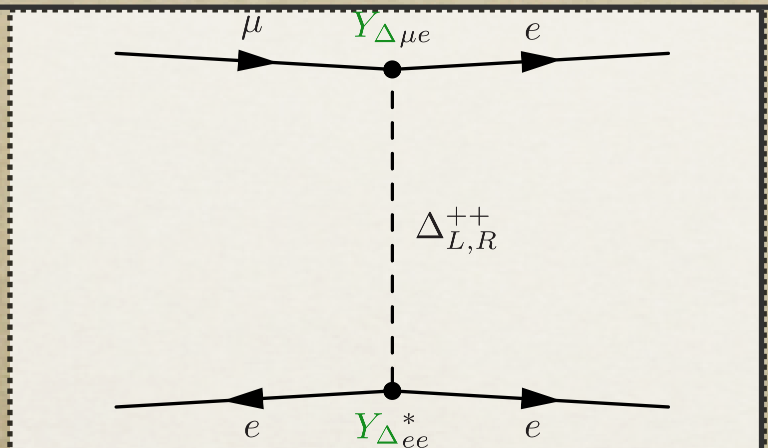
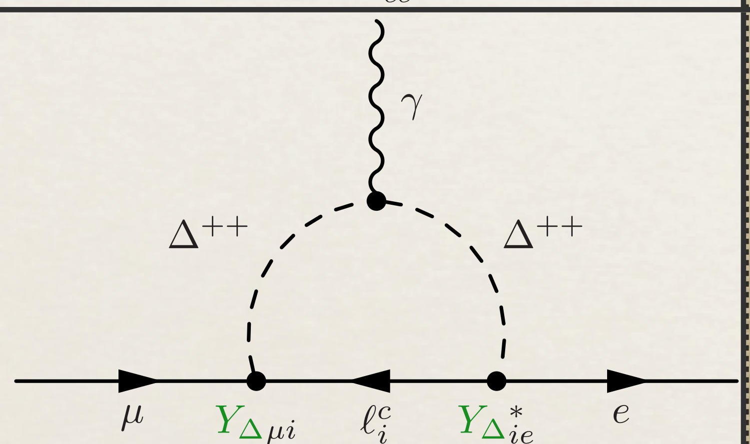
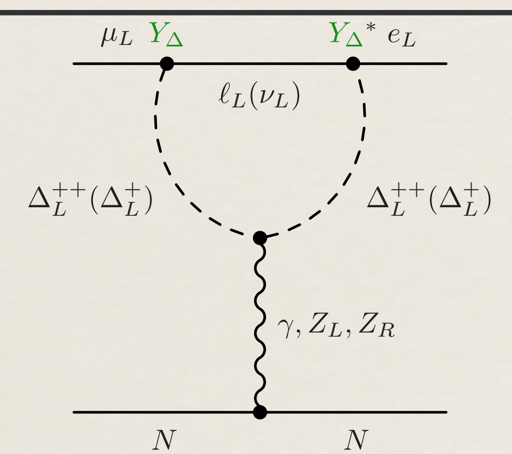
- *LHC:*
  - $jj : m_N \gtrsim 50\ \text{GeV}$
  - $j\ell : m_N \gtrsim 20\ \text{GeV}$
  - $\not{\ell} : m_N \lesssim 20\ \text{GeV}$
  - $\not{E} : m_N \lesssim 3 - 7\ \text{GeV}$

Lepton Flavor Violation

- *LFV rates computable: type II (or LHC)*

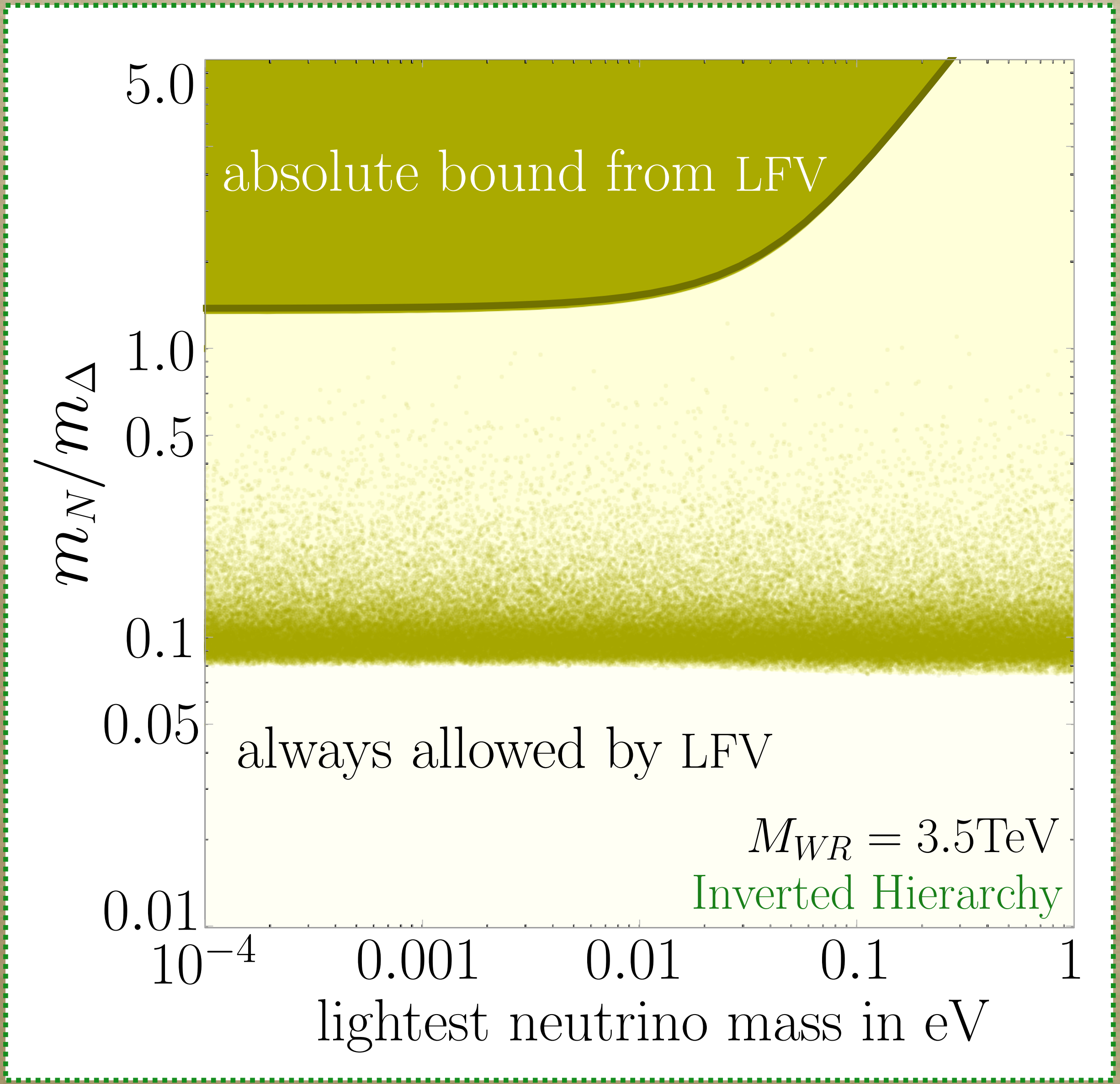
Cirigliano et al '04

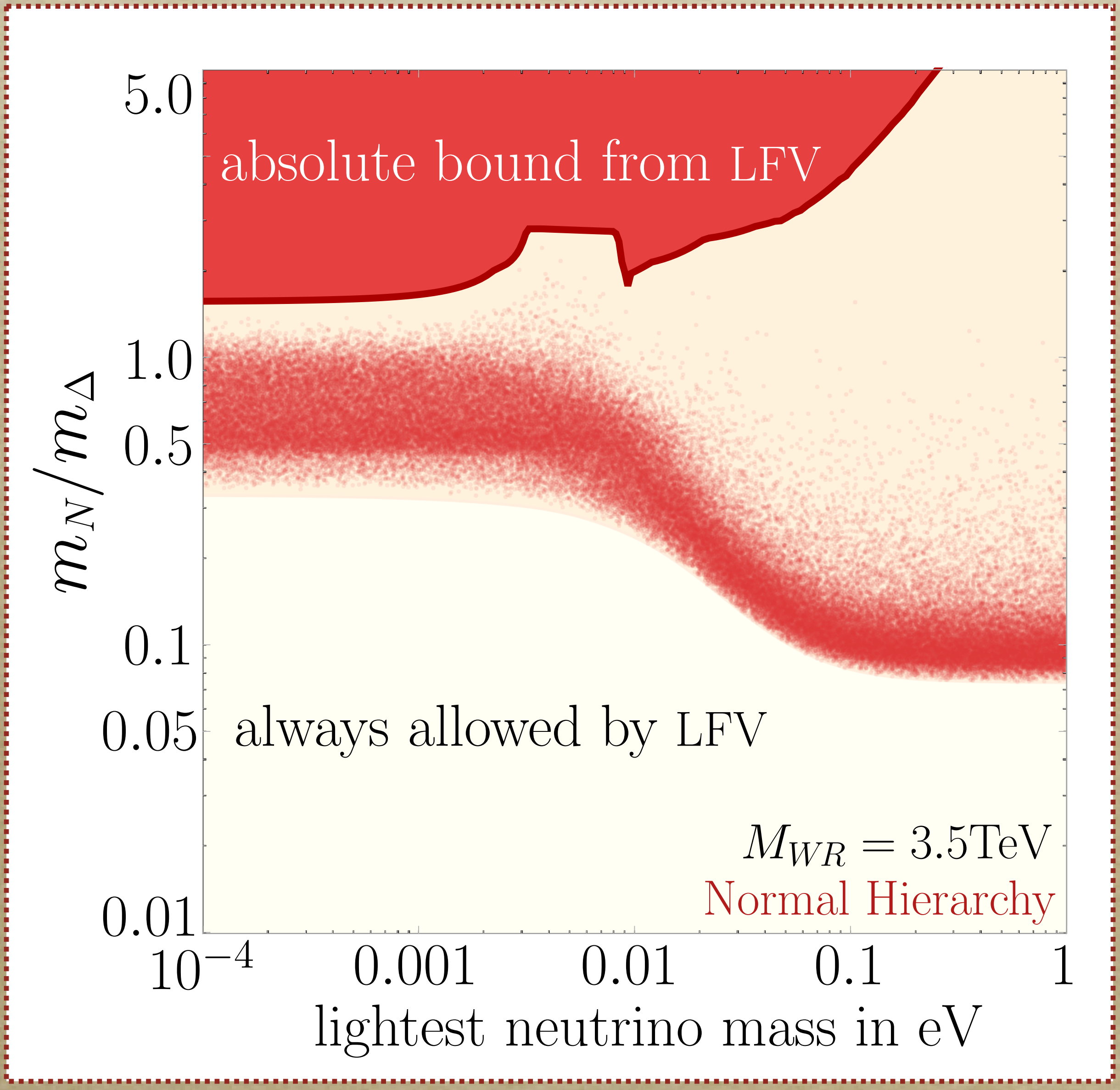
Raidal, Santamaria '97

$\ell \to 3\ell$	*tree*		$V_L\, m_N / m_\Delta\, V_L^T$
$\ell \to \ell' \gamma$	*loop*		$V_L\, m_N / m_\Delta\, V_L^\dagger$
$\mu\,\mathrm{N} - e\,\mathrm{N}$	*log*		$V_L\, m_N / m_\Delta\, V_L^\dagger$

Combined LFV constraints

- *Muonic and tau channels* — *Tello, MN, Senjanović, Vissani '10*
- *Varying PMNS constrains* $m_N/m_\Delta < 1$





Role of θ_{13}

- *Flavor structure in muon-electron transitions*

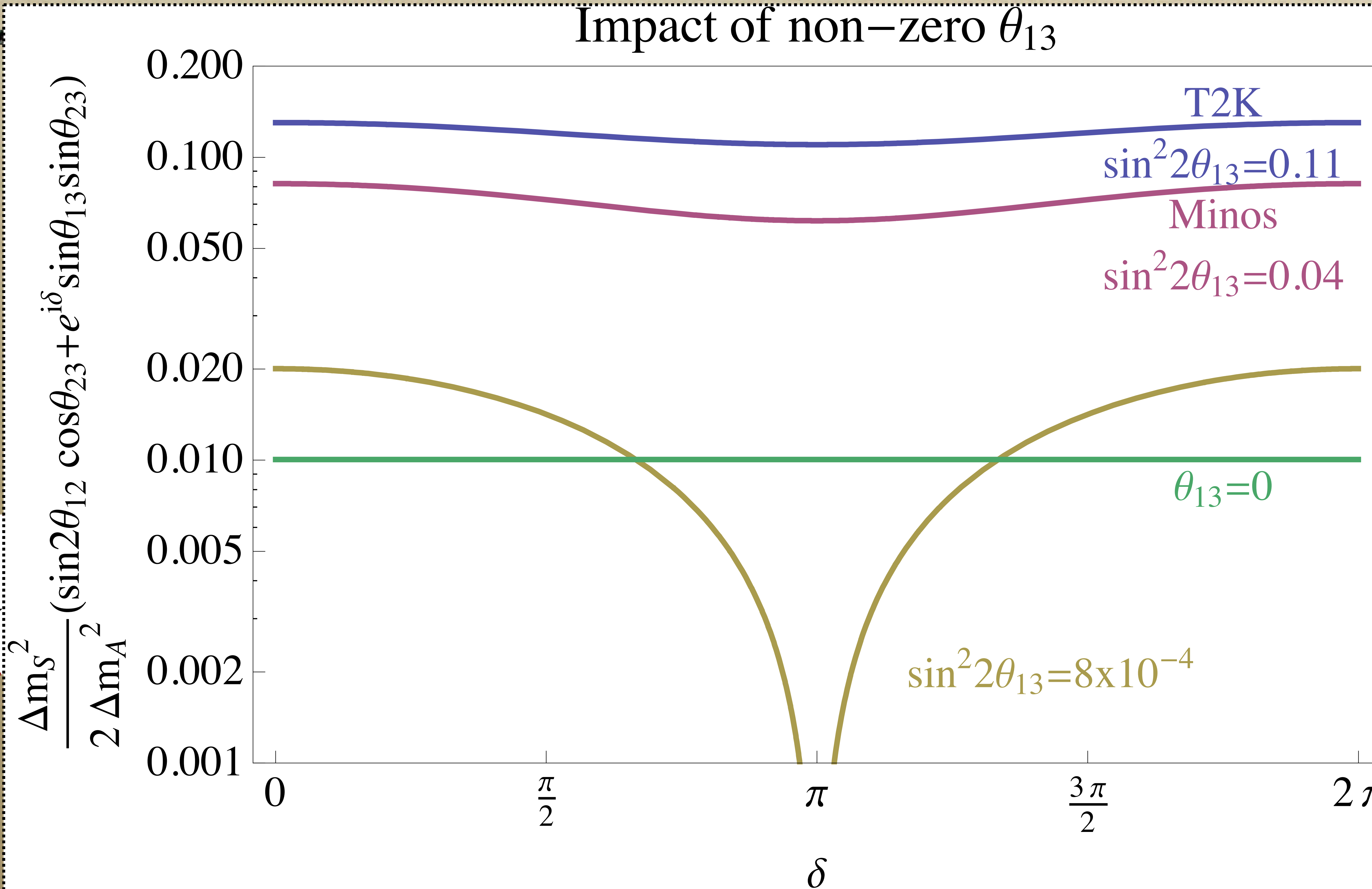
$$\mathcal{A}(\mu \to 3e) \propto \left(-m_{N_1} + \exp^{i\alpha} m_{N_2}\right) \sin 2\theta_{12} \cos \theta_{23} \left(m_{N_1} \cos^2 \theta_{12} + \exp^{i\alpha} m_{N_2} \sin^2 \theta_{12}\right) / m^2_{\Delta^{++}}$$

- $\mu \to 3e$ *insensitive to* θ_{13}

$$\mathcal{A}(\mu \to e) \propto \frac{\Delta m^2_{N_{13}}}{m^2_{\Delta^{++}}} \left(\frac{\Delta m^2_S}{2\Delta m^2_A} \sin 2\theta_{12} \cos \theta_{23} + e^{i\delta} \sin \theta_{13} \sin \theta_{23} \right)$$

- $\mu - e$ *conversion and* $\mu \to e\gamma$ *depend a lot*

Role of θ_{13}



Conclusions

- $0\nu 2\beta$ *signal may require new physics at TeV*
- *Left-Right symmetry @ LHC a natural example*
    - *no tension with cosmology, precision data or LFV*
    - *links oscillations, cosmology and the LHC*
- *Exclusions with fairly low luminosity and 7 TeV*
- *LHC may observe LNV and in turn connect it to low energy rates, both LNV and LFV*