From Majorana to Dirac in the Minimal Left-Right Model

Miha Nemevšek (ICTP, Trieste & JSI, Ljubljana)

with Fabrizio Nesti, Goran Senjanović, Vladimir Tello, Francesco Vissani

Portorož workshop 2013

What is the origin of neutrino mass...

...how to predict and test it?

And could LHC help?

“A model of leptons”

Weinberg ’67

single Higgs field

Higgs ’64

$$h \to v$$

$$m_W = g\,v$$

$$m_h = \sqrt{\lambda}\,v$$

$$m_f = y\,v$$

A complete theory of mass origin....

prediction $\Gamma_{h\to pp} \propto m_p^2$

test Br’s once $m_h \simeq 125~\mathrm{GeV}$ CMS, ATLAS ’12

...for *nearly* all elementary particles

Neutrino mass

SM fermions

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad \begin{matrix} u_R \\ d_R \end{matrix}$$

charged fermions Dirac particles

$$\mathcal{L}_{m_D} = y\, v\, \overline{f}_L f_R$$

$$L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad e_R$$

neutrinos massless

neutrinos neutral, can be Majorana

$$\mathcal{L}_{m_M} = m_M\, \nu_L^T \nu_L$$

Majorana '37

Effective approach

$$y_{eff} \frac{Lh\, Lh}{\Lambda} \Rightarrow m_M = y_{eff} \frac{v^2}{\Lambda}$$

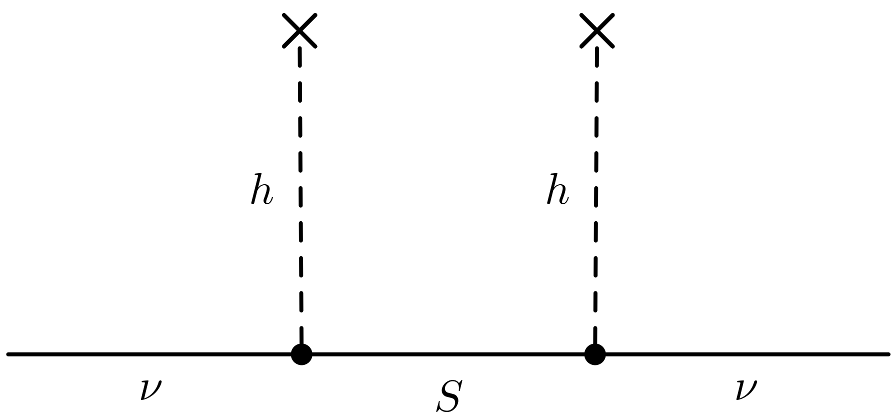
no dynamics, impossible to probe

Weinberg '79

See-saw

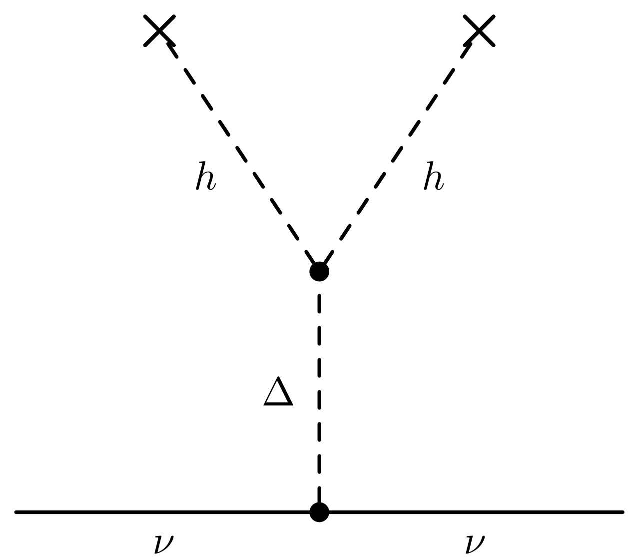
*naive UV completion

fermion singlets



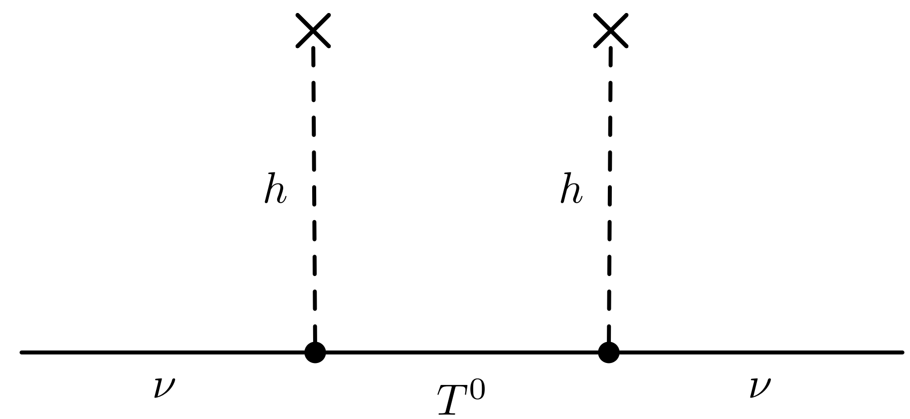
Minkowski ’77
Mohapatra, Senjanović ’80
Yanagida ’79, Glashow ’79
Gell-Mann, Ramond, Slansky ’79

boson triplet



Magg, Wetterich ’80
Lazarides, Shafi, Wetterich ’81
Mohapatra, Senjanović ’81

fermionic triplets



Foot, Lew, He, Joshi ’89

See-saw ambiguity

toy scenario - addition of fermion singlets *or* triplets

$$\mathcal{L}_m = M_D \overline{\nu}_L S + M_S S^T S$$

$$-{M_D}^T {M_S}^{-1} M_D = M_\nu = {V_L}^* m_\nu {V_L}^\dagger$$

$$M_D = i\sqrt{m_S}\, O\, \sqrt{m_\nu}\, {V_L}^\dagger$$

Casas, Ibarra '01

O *arbitrary*, disconnected from m_ν

Higgs couplings not predicted, measured at best

de Gouvea, Huang, Shalgar '10

Theory of see-saw

Glashow '79

Gell-Mann, Ramond, Slansky '79

$$SU(5) \ \ \& \ \ SO(10)$$

Minkowski '77

Mohapatra, Senjanović '79

$$SU(2)_L \otimes SU(2)_R$$

Yanagida '79

Grand Unified Theories

unification of forces

charge quantization

proton decay, monopoles

talks by di Luzio and Malinsky

Left-Right Symmetry

symmetric interactions

spontaneous parity breaking

new V+A dynamics

Family Symmetries

Left-Right Symmetry

Pati, Salam '74
Mohapatra, Pati '75

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

LR fermions

$$Q_{L,R} = \begin{pmatrix} u \\ d \end{pmatrix}_{L,R}$$

$$L_{L,R} = \begin{pmatrix} \nu \\ e \end{pmatrix}_{L,R}$$

LR parity *P* or *C*

RH neutrino automatic

L is gauged

Minimal LR model

Minkowski '77
Mohapatra, Senjanović '79

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

contains the SM Higgs

induces a vev $v_L \equiv \langle \Delta_L \rangle$

$v_R \equiv \langle \Delta_R \rangle$ breaks parity and *L*

gives mass to W_R and ν_R

Parity and Flavor: Quarks

$\mathcal{C}$ as LR parity: $f_L \leftrightarrow f_R^c, \quad \Phi \to \Phi^T, \quad \Delta_L \leftrightarrow \Delta_R^*$

$$\mathcal{L}_q = M_q \, \overline{Q}_L \, \Phi \, Q_R \Rightarrow {M_q}^T = M_q$$

$$\boxed{V_R^q = V_{\rm ckm}^*}$$

*up to extra phases

Parity fixes flavor of new gauge interactions

Stringent constraints, mainly kaon mixing

talk by Maiezza

Beal, Bander, Soni ’82,...

...Maiezza, MN, Nesti, Senjanović ’10

$M_{W_R} > 1.8 \text{ TeV}$

$M_{W_R} > 2.5 \text{ TeV}$

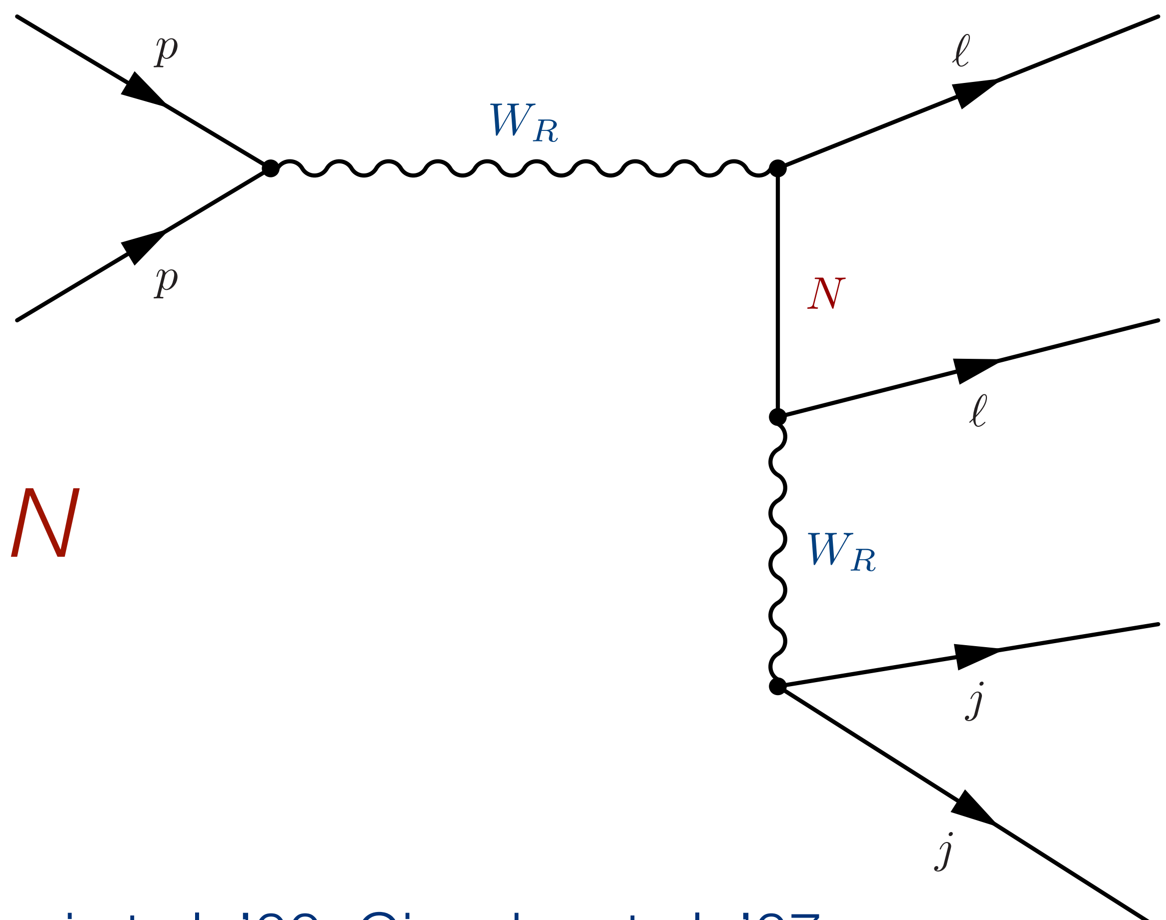
Guarantees production
at the LHC if W_R is light

see also: Blanke, Buras, Gemmler, Heidsieck ’11
Bertolini, Maiezza, Nesti, Eeg ’12

Neutrino at colliders

Keung, Senjanović ’83

same and opposite sign di-leptons and two jets, no missing energy



LNV and Majorana nature of *N* manifest at high energies

reach of ~5-6 TeV for W_R

Ferrari et al. ’00, Ginenko et al. ’07

Flavor studies

Das, Deppisch, Kittel, Valle ’12

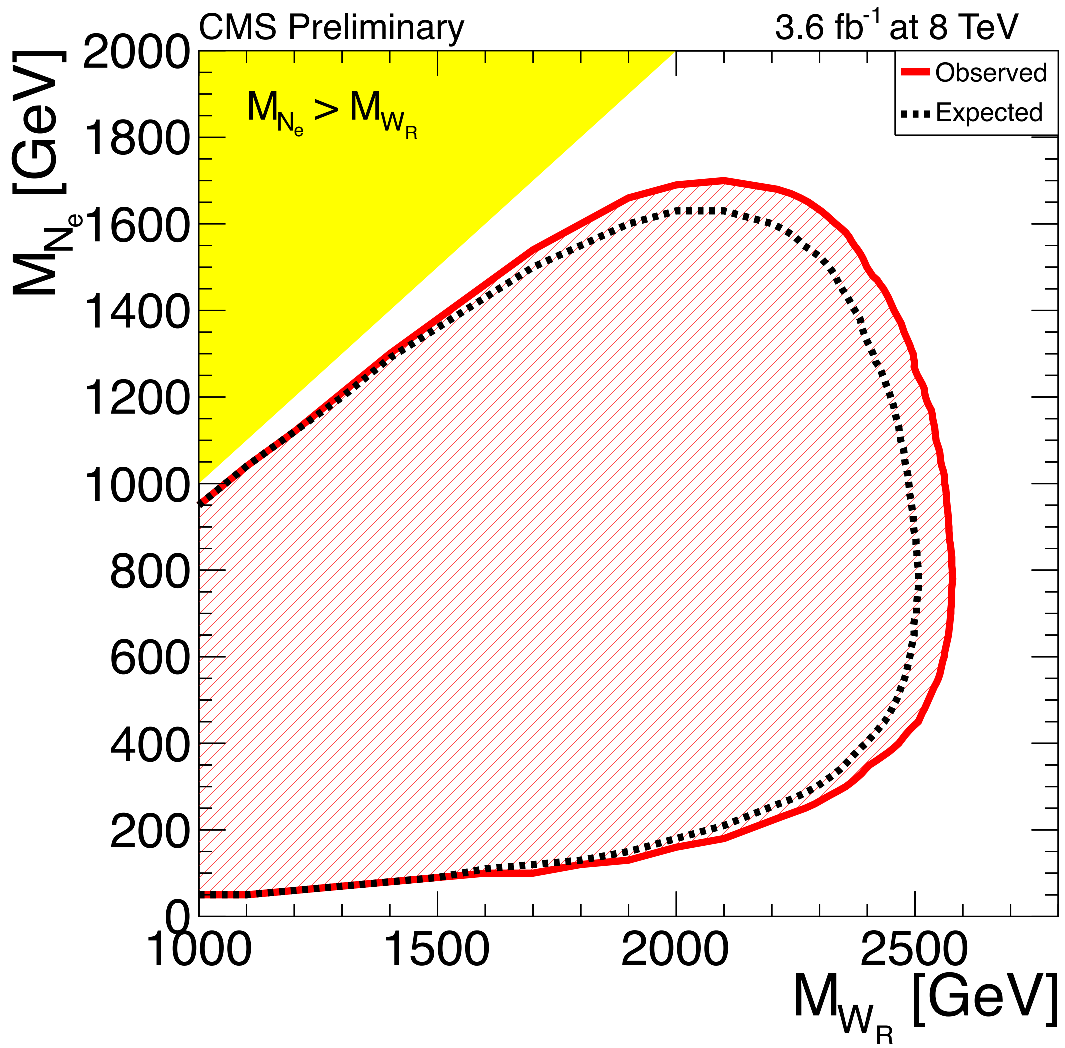
Aguilar-Saavedra, Joaquim ’12

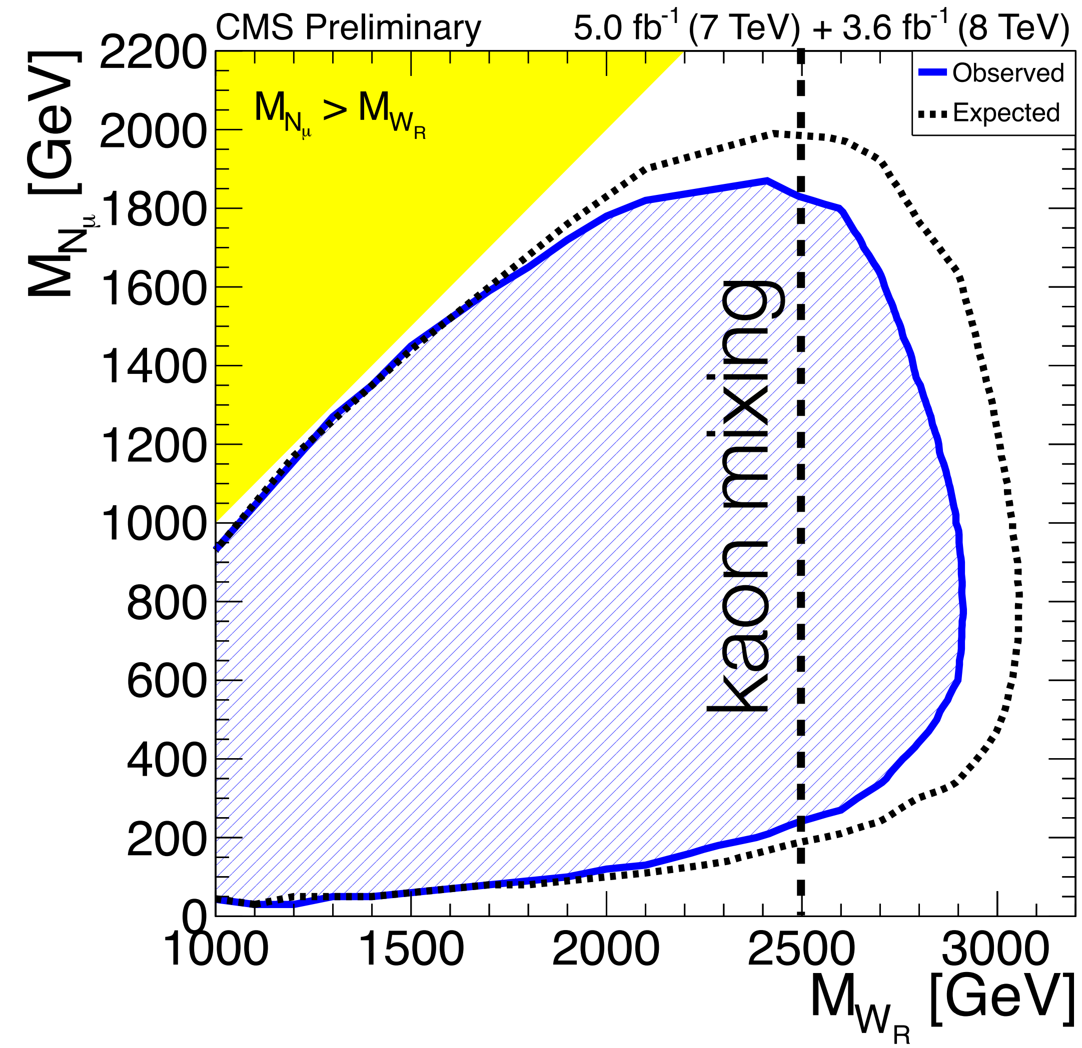
Multi-leptons

Chen, Dev ’12

Searches at the LHC

CMS PAS-EXO-12-017
CMS 1210.2402
ATLAS 1203.5420



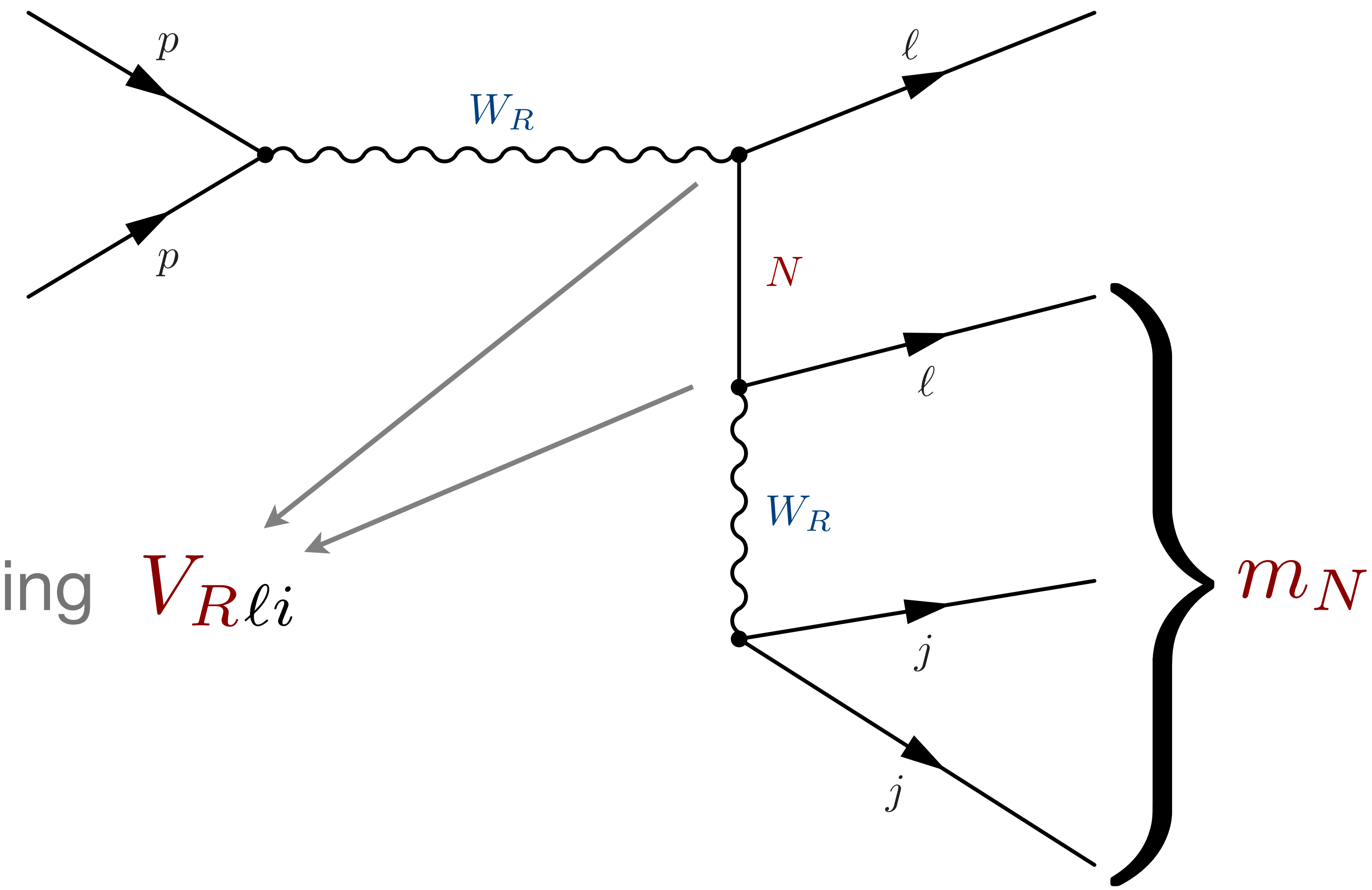


- Light *N*, missing energy $M_{W_R} > 3.3$ TeV — ATLAS 1209.4446, CMS 1302.2812
- di-jets $M_{W_R} > 2.3$ TeV — CMS-EXO-PAS-12-059
- t b $M_{W_R} > 2.1$ TeV — CMS-PAS-B2G-12-010

Keung, Senjanović '83

$$M_{W_R} = m^{\text{inv}}_{\ell\ell jj}$$

$$m_N = m^{\text{inv}}_{\ell jj}$$



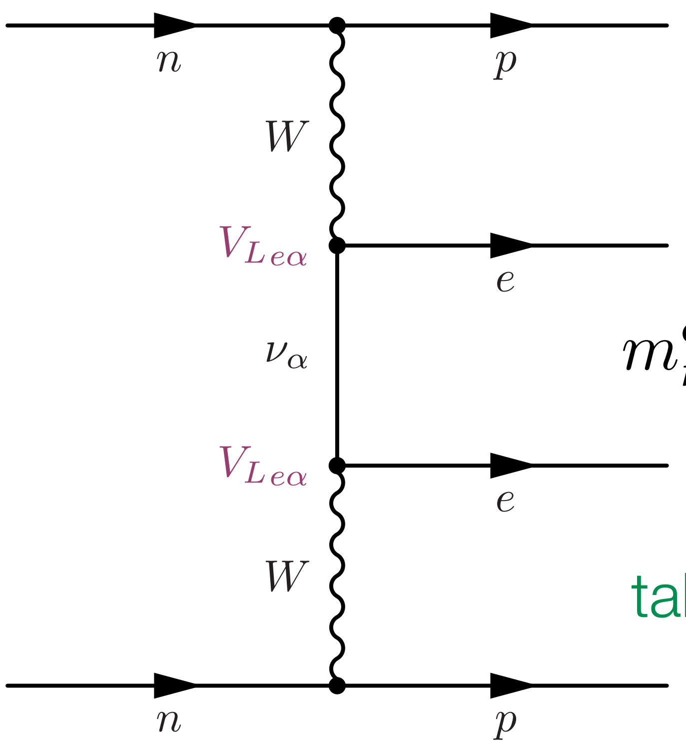
lepton flavor tagging $V_{R\ell i}$

Masses and mixings of *N* obtainable from colliders...

$$M_N = V_R m_N V_R{}^T$$

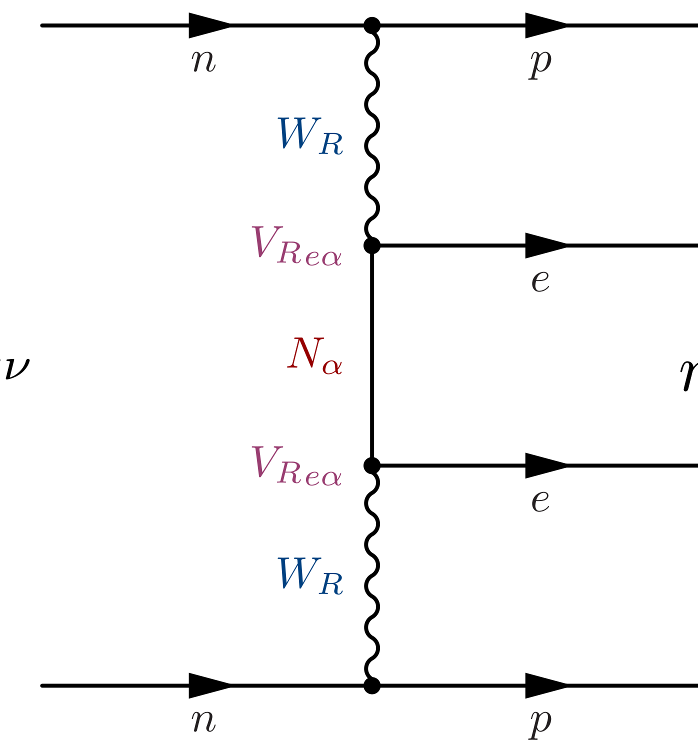
...are crucial to compute the Dirac couplings

Connecting to low energies



$$m_\nu^{ee} = \sum_\nu {V_L}^2 m_\nu$$

talk by Giunti

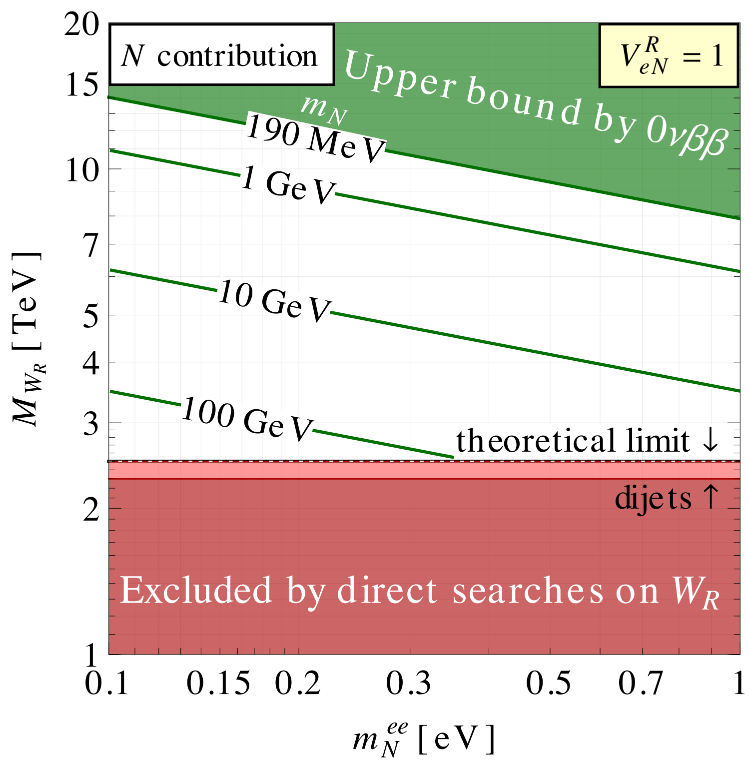


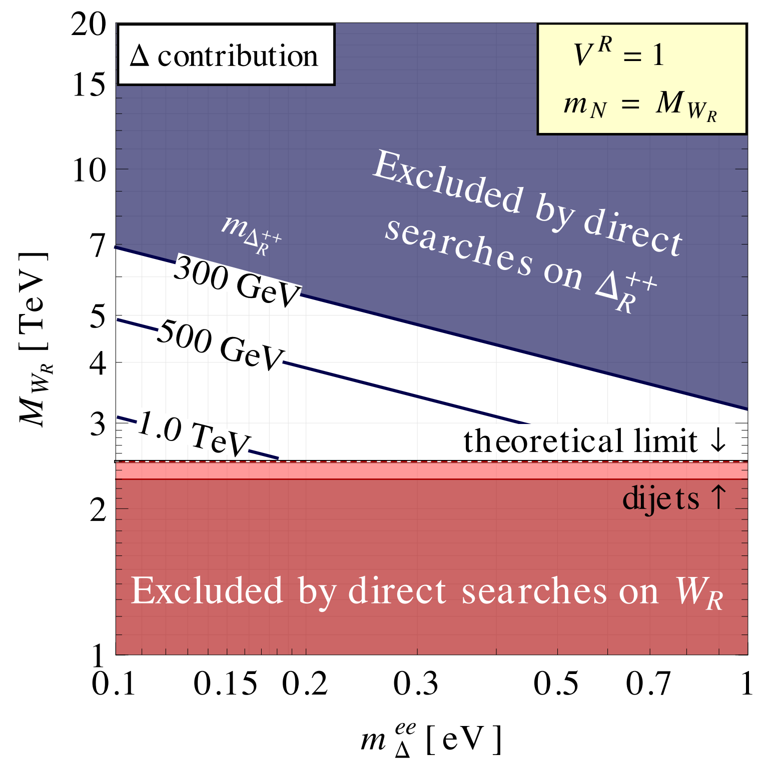
Mohapatra, Senjanović ’81

$$m_N^{ee} = p^2 \frac{M_{W_L}^4}{{M_{W_R}}^4} \sum_N \frac{{V_R}^2}{m_N}$$

- Δ_L negligible, Δ_R constrained by LFV

Tello, MN, Nesti, Senjanović, Vissani ’10





Tello, MN, Nesti, Senjanović ’11

Parity and Flavor: Leptons

See-saw in Left-Right

see also: Falcone '03
Akhmedov, Frigerio '05 and '06
Hosteins, Lavignac, Savoy '06

$$M_\nu = -{M_D}^T {M_N}^{-1} M_D + M_L$$

~to Quarks: Dirac mass matrices are symmetric

$$\mathcal{L}_\ell = M_\ell \, \overline{L}_L \, \Phi \, L_R \Rightarrow {M_\ell}^T = M_\ell$$

due to $\mathcal{C}$: $\quad M_L = \dfrac{v_L}{v_R} M_N$

$$M_\nu = -M_D {M_N}^{-1} M_D + \frac{v_L}{v_R} M_N$$

$$\boxed{M_D = M_N \sqrt{\frac{v_L}{v_R} - {M_N}^{-1} M_\nu}}$$

MN, Tello, Senjanović '12

Neutrino Higgs couplings

$$M_D = M_N \sqrt{\frac{v_L}{v_R} - M_N{}^{-1} M_\nu}$$

MN, Tello, Senjanović '12

M_ν from oscillations

M_N from colliders

talk by Giunti

$$M_D = 0 \quad \text{if} \quad M_\nu = \frac{v_L}{v_R} M_N$$

Higgs couplings unambiguously predicted as in the SM

no arbitrary complex orthogonal matrix (symmetricity fixes O)

discrete eightfold ambiguity due to the $\sqrt{}$

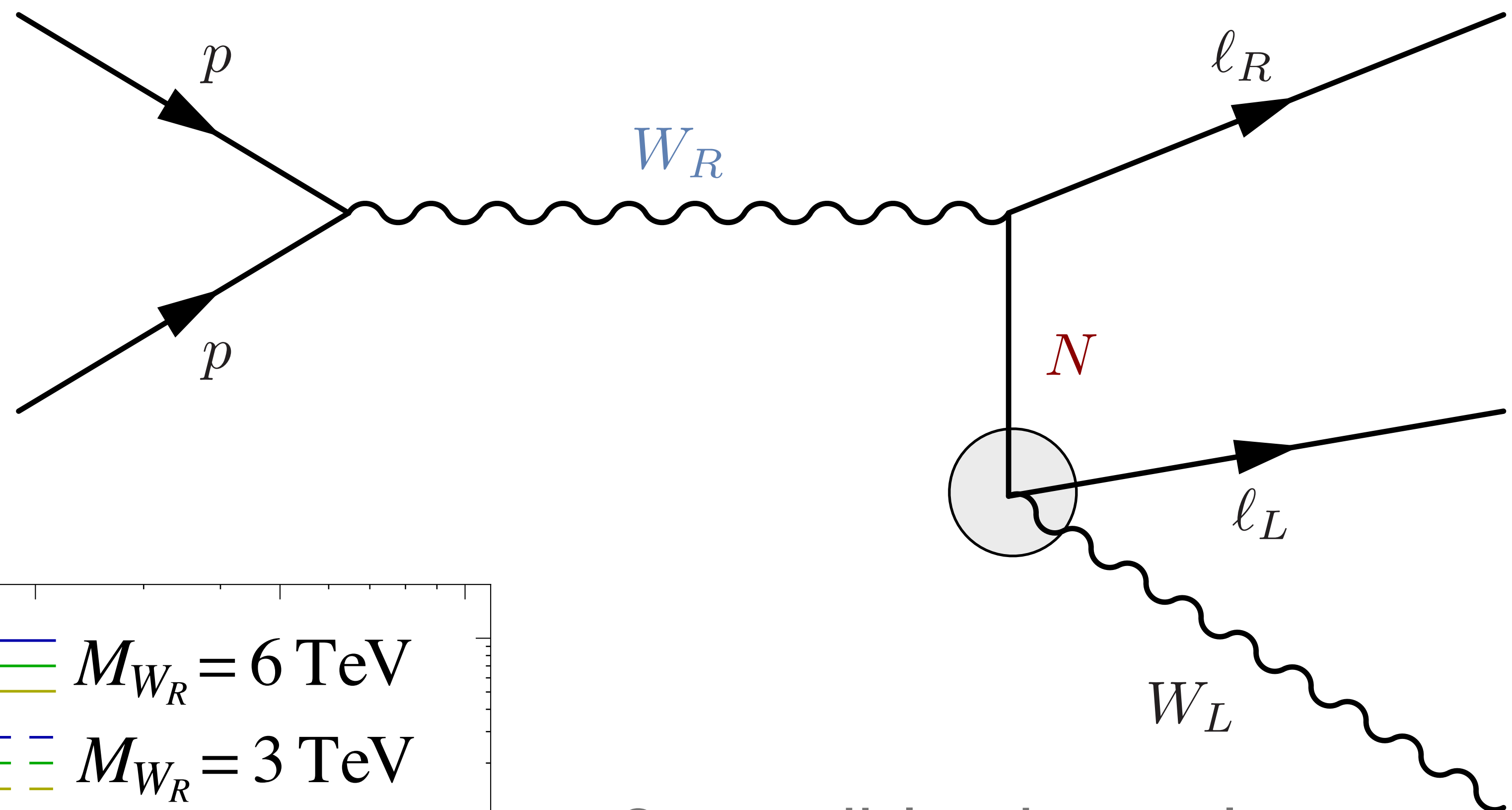
large values only in singular points or large cancellations

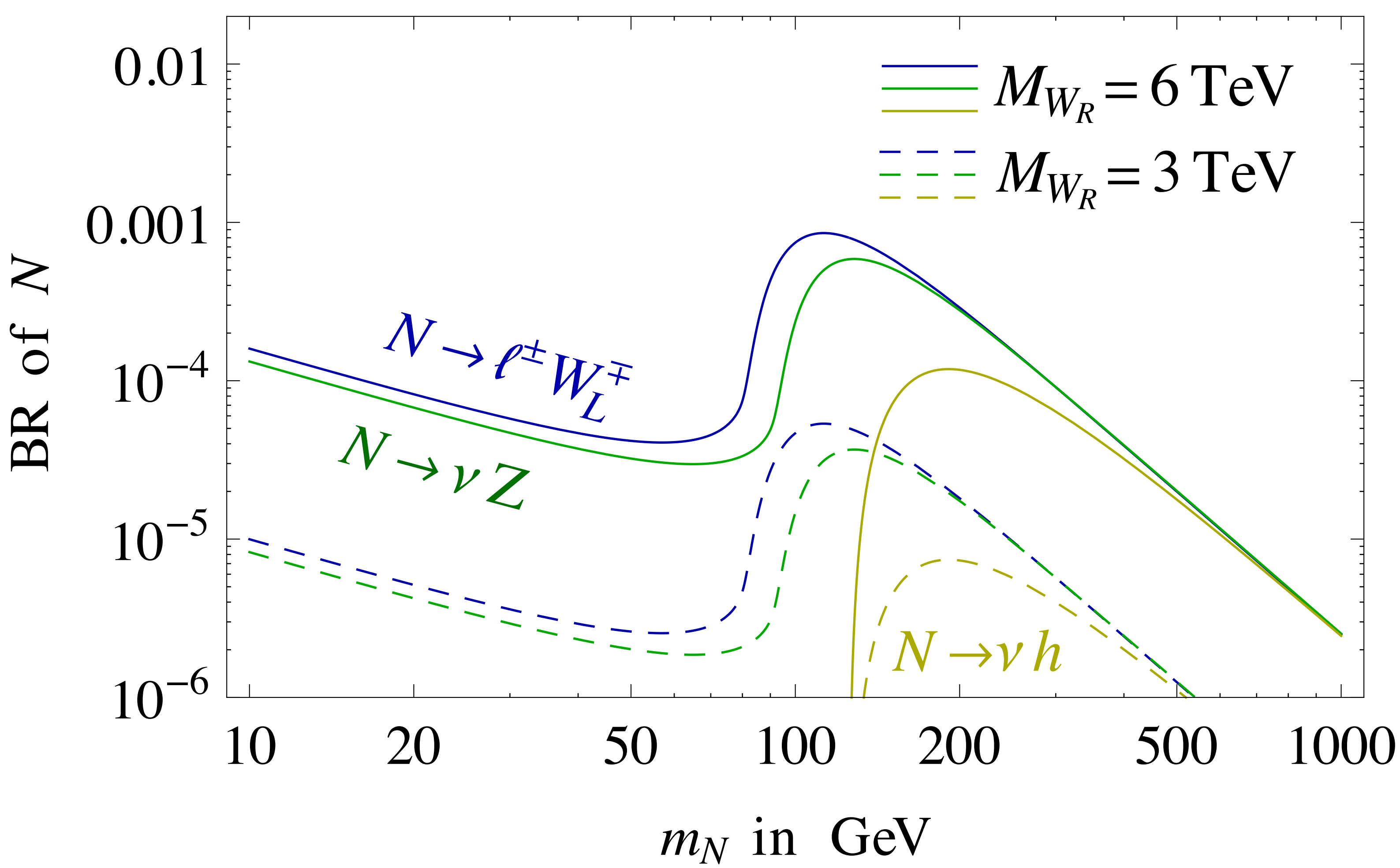
High energy probe

M_D at colliders

MN, Tello, Senjanović '12

Direct probe of Dirac mass





9 possible channels

allows to check the prediction for M_D

subdominant, high $\mathcal{L}$

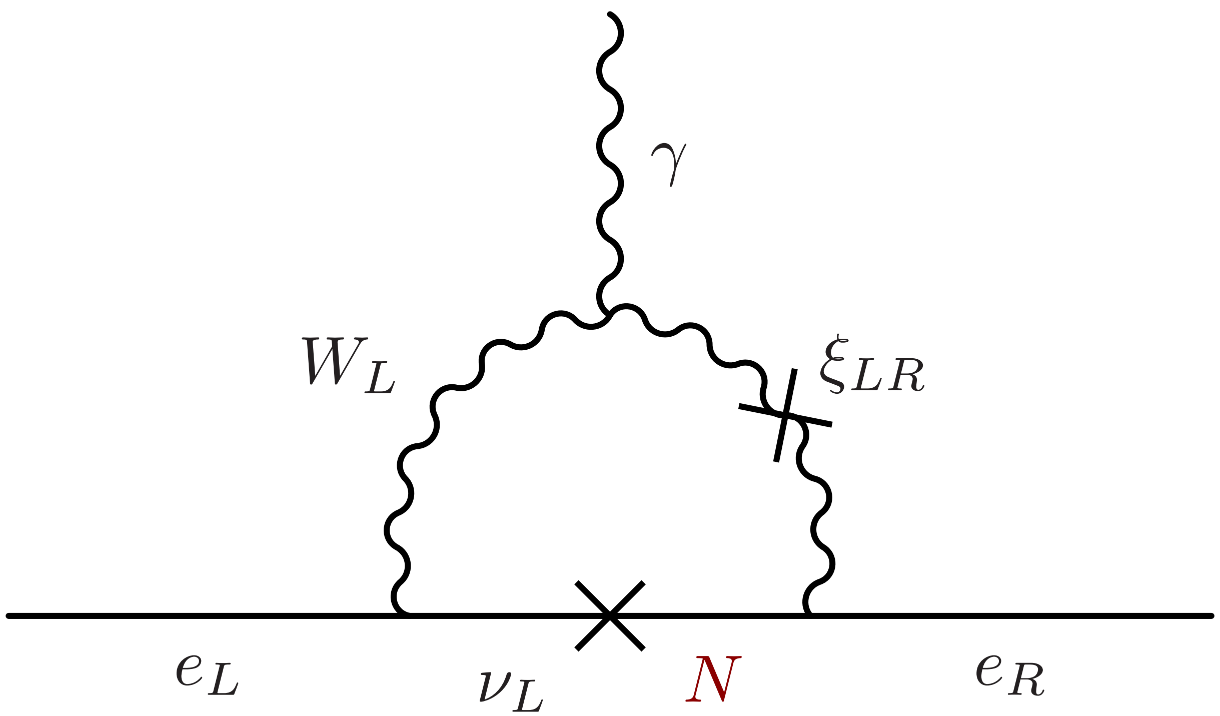
chiral couplings

Han, Luiz, Ruiz, Si '12

Low energies

Electron EDM

T-odd observable, sensitive to CP phases



extremely small in the SM (4 loops)

$d_e^{\rm SM} \lesssim 10^{-38}$ e cm   Pospelov, Ritz '05

current sensitivity   Hudson et al. '11

$d_e^{\rm exp} < 10^{-27}$ e cm

arises at one loop in LR   Chang, Nieves, Pal '86

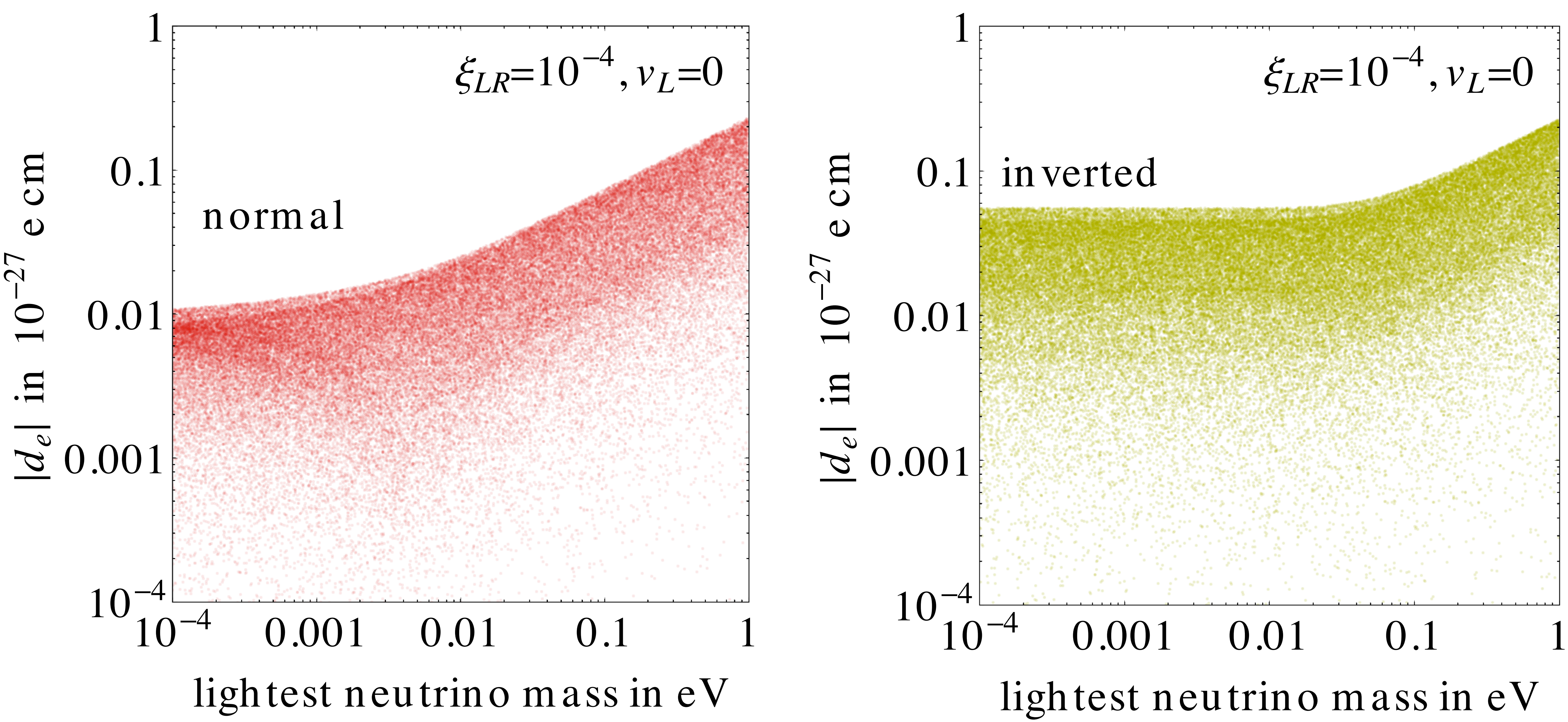
$$d_e = \frac{eG_F}{4\sqrt{2}\pi^2} \mathrm{Im}\left[\xi_{LR} V_R F(t) V_R{}^\dagger M_D\right]_{ee}$$

$$F(t) = (t^2 - 11t + 4 + (6t^2 \log t)/(t-1))/2(t-1)^2, t = (m_N/M_{W_L})^2$$

illustration: $V_R = V_L{}^* \Rightarrow M_D = i\, V_L{}^* \sqrt{m_N m_\nu} V_L{}^\dagger$

$m_{N_{1,2,3}} = 0.5, 2, 2.5\ \text{TeV}$

MN, Tello, Senjanović '12



CP-odd observable, sensitive to Majorana phases

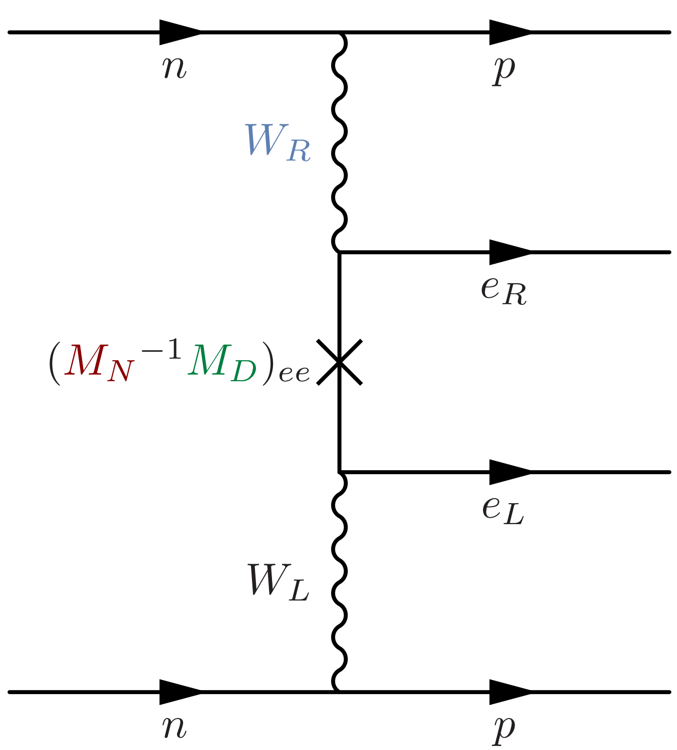
More on $0\nu2\beta$

Contributions through mixing

MN, Tello, Senjanović '12

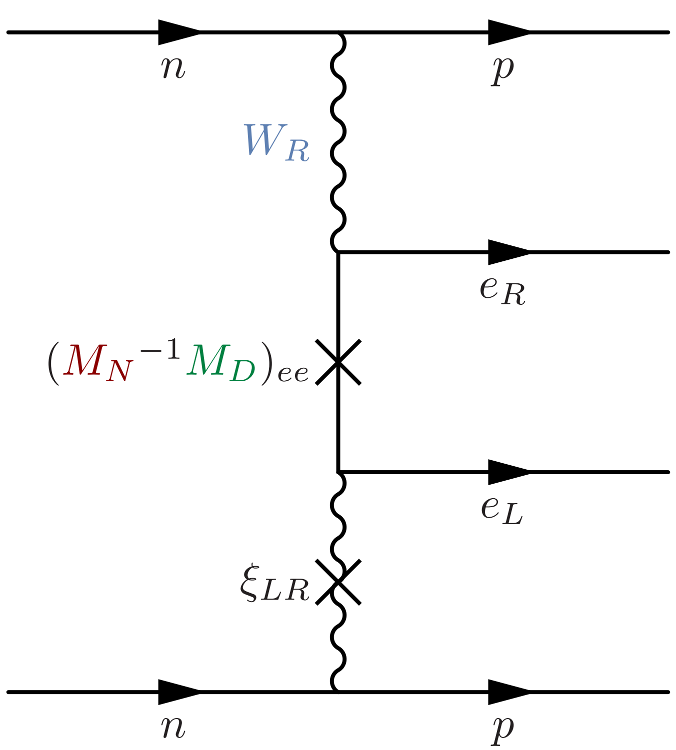
$$m_{\nu N}^{ee} = \left(\xi_{LR} + \eta \frac{M_{W_L}^2}{{M_{W_R}}^2}\right) p \left({M_N}^{-1} M_D\right)_{ee}$$

$p \sim 100$ MeV



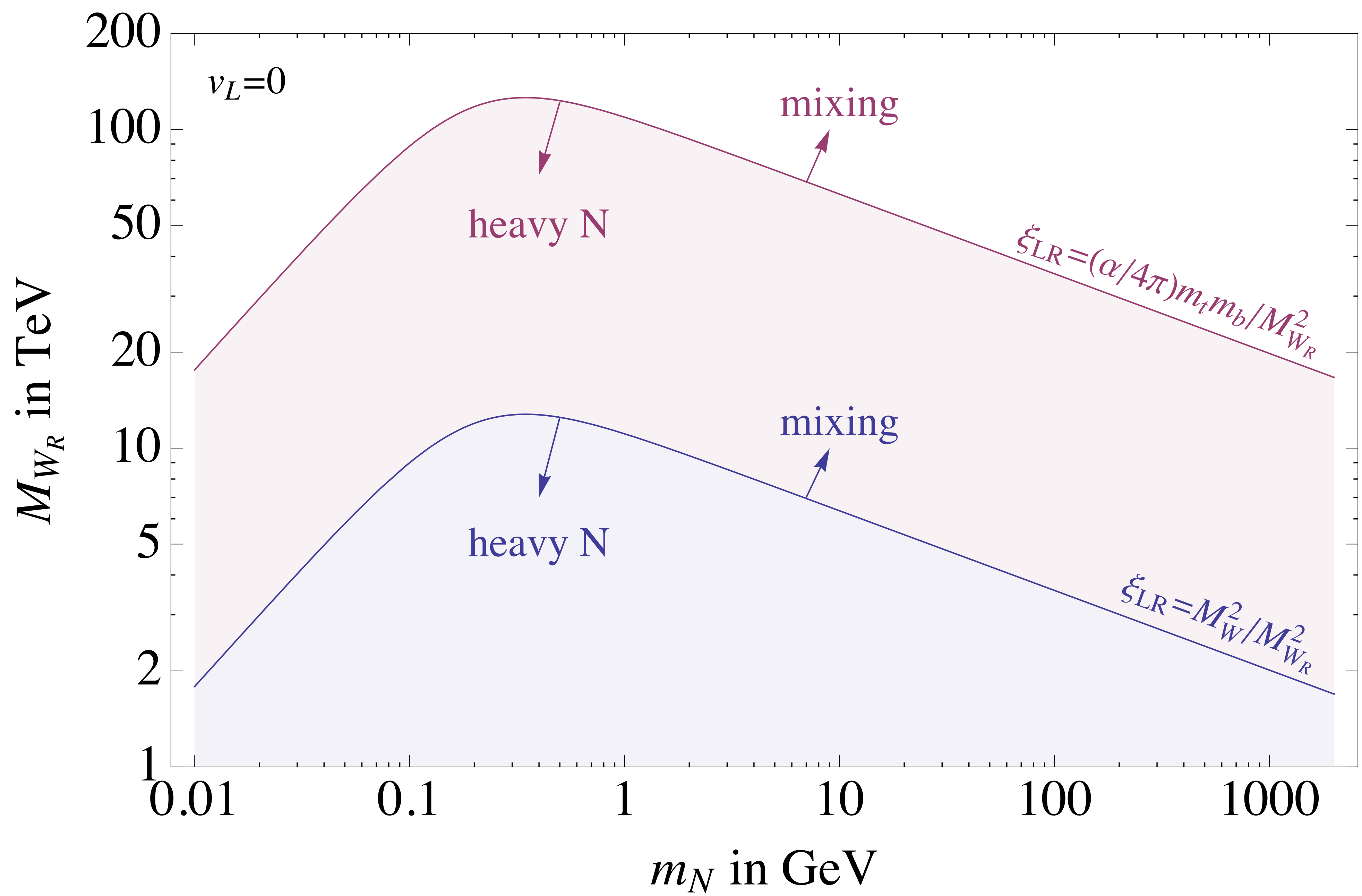
$\eta \sim 10^{-2}$

Doi, Kotani, Takasugi '85



see also: Chakrabortty, Devi, Goswami, Patra '11
Barry, Rodejohann '13

Dominant contribution to 0nu2b



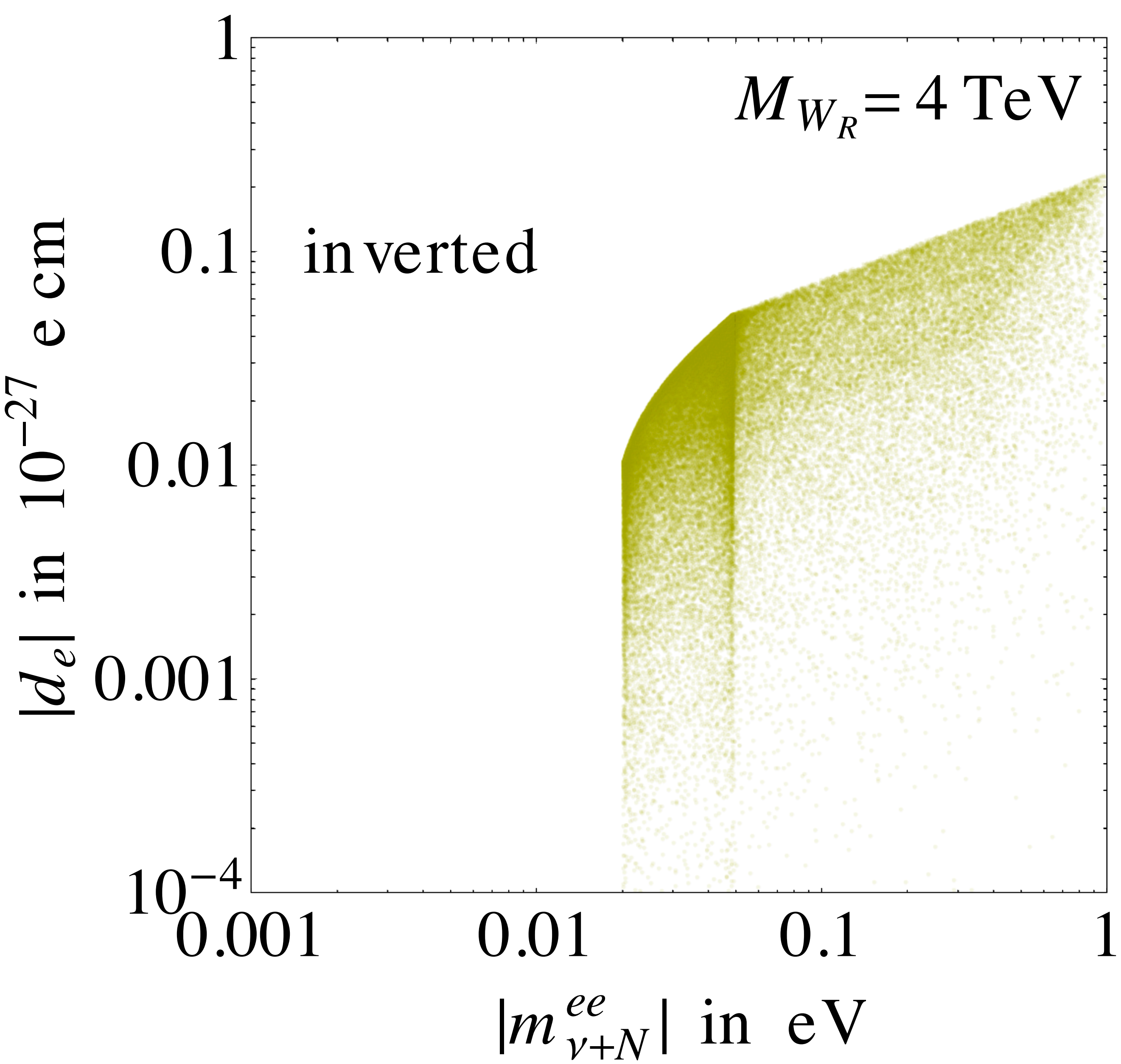
gauge boson mixing $$\frac{\alpha}{4\pi}\frac{m_t m_b}{{M_{W_R}}^2} \lesssim |\xi_{LR}| \lesssim \frac{M_{W_L}^2}{{M_{W_R}}^2}$$

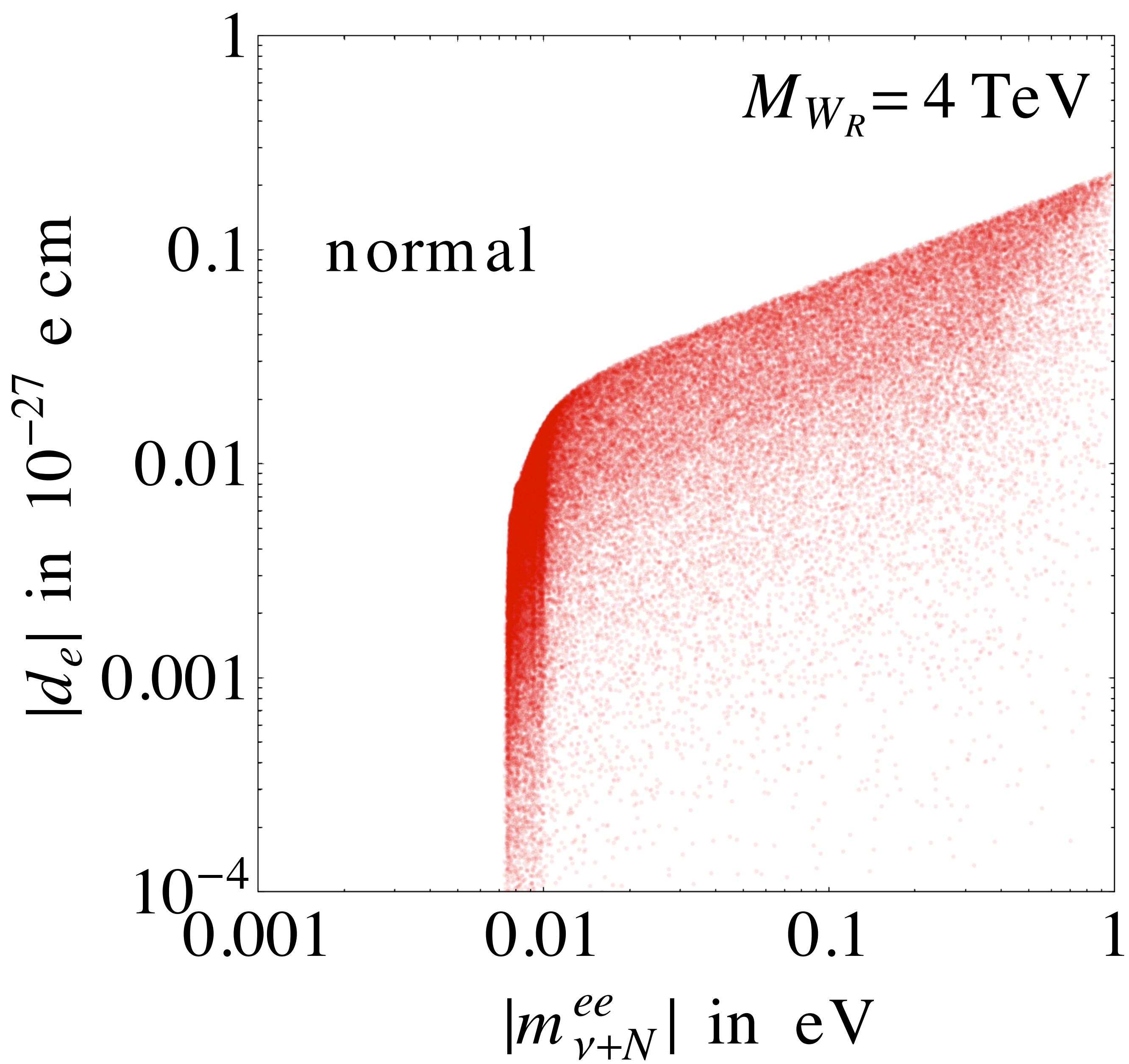
EDM vs. 0nu2b

MN, Tello, Senjanović '12

typically large contribution to 0nu2b if edm is seen

sensitive to Majorana CP phases





Conclusions

Complete theory of neutrino mass origin

see-saw can be disentangled in LR and M_D predicted from physical observables, LR parity is the key

Higgs coupling predicted from masses and mixings, similar to charged fermions in the SM

direct testable relations

heavy N decay with subdominant Br at the LHC

connects to electron EDM and 0nu2b

Thank you

On the size of M_D

"Isn't the TeV scale right-handed neutrino mass in contrast to the original see-saw paradigm?"

Neutrino Mass and Spontaneous Parity Nonconservation

Rabindra N. Mohapatra
Department of Physics, City College of New York, New York, New York 10031

and

Goran Senjanović
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742
(Received 10 December 1979)

In weak-interaction models with spontaneous parity nonconservation, based on the gauge group $SU(2)_L \otimes SU(2)_R \otimes U(1)$, we obtain the following formula for the neutrino mass: $m_{\nu_e} \simeq m_e^2/g m_{W_R}$, where W_R is the gauge boson which mediates right-handed weak interactions. This formula, valid for each lepton generation, relates the maximality of observed parity nonconservation at low energies to the smallness of neutrino masses.

The original work considered low scale masses with Dirac couplings similar to the electron mass.

Dirac mass of few eV radiatively stable

Branco, Senjanović '78

On fixing the O

$$M_D = i\sqrt{m_N}\,O\,\sqrt{m_\nu}\,{V_L}^\dagger$$

- complex orthogonal matrix: *n(n-1)/2* parameters

$$M_D = {M_D}^T$$

- symmetricity provides *n(n-1)/2* equations

2 x 2 example $$O = \begin{pmatrix} c_z & s_z \\ -s_z & c_z \end{pmatrix}$$

$$t_z = \frac{\sqrt{m_{N_2} m_{\nu_2}} V_L{}^*_{12} - \sqrt{m_{N_1} m_{\nu_1}} V_L{}^*_{21}}{\sqrt{m_{N_2} m_{\nu_1}} V_L{}^*_{11} + \sqrt{m_{N_1} m_{\nu_2}} V_L{}^*_{22}}$$

- can be generalized to 3 families and both see-saw contributions