Left-Right theory: From Majorana to Dirac via LHC

Miha Nemevšek (ICTP & SISSA Trieste & JSI, Ljubljana)

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

From Majorana to LHC: workshop
on the origin of neutrino mass

What is the origin of neutrino mass...

...how to predict and test it?

“A model of leptons”

Weinberg ’67

a single Higgs-Weinberg boson

Higgs ’64

$$h \to v$$

$$m_W = g\,v$$

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

$$m_f = y\,v$$

A complete theory of mass origin...

introduction by Goran

predictions

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

test Br’s once

$$m_h \simeq 125 \text{ GeV}$$

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

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

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

clear prediction $m_\nu = 0$

neutrinos can be Majorana

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

Majorana '37

Effective approach

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

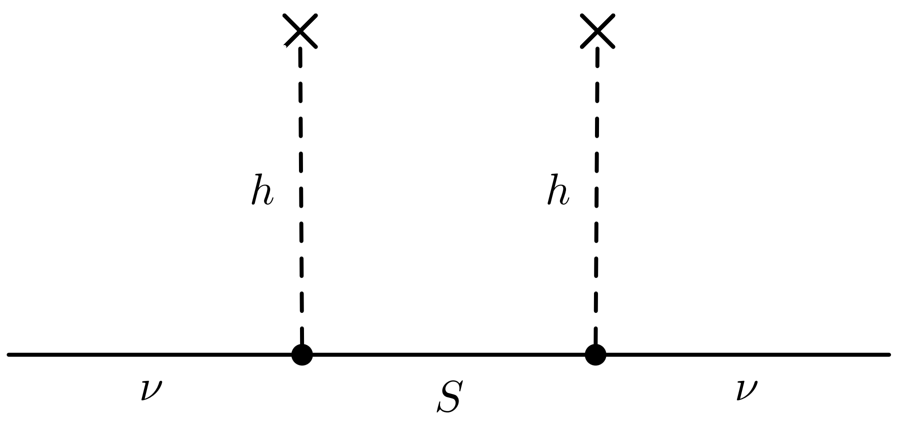
no dynamics, impossible to probe

Weinberg '79

See-saw

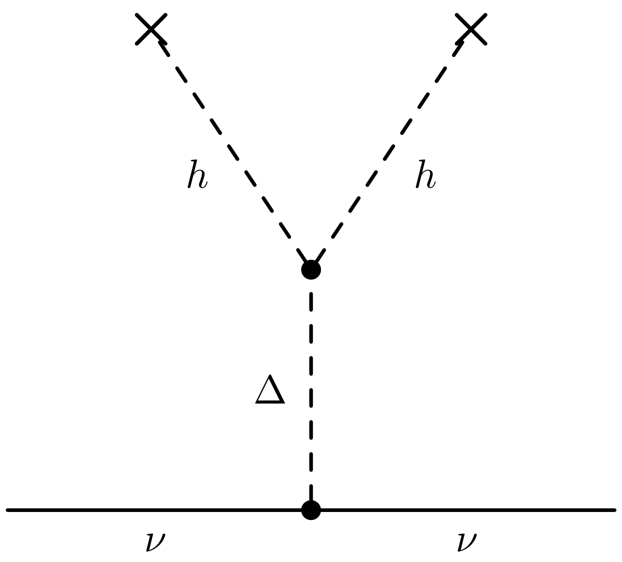
*naive UV completion

fermion singlets



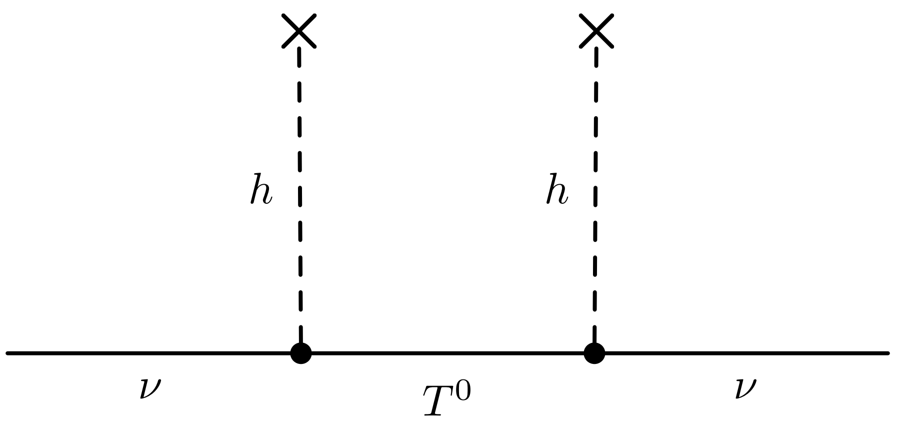
Minkowski '77
Mohapatra, Senjanović '80
Yanagida '79, Glashow '79
Gell-Mann, Ramond, Slansky '79

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

Theory of see-saw

Glashow '79

Gell-Mann, Ramond, Slansky '79

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

Grand Unified Theories

unification of forces

charge quantization

proton decay, monopoles

Minkowski '77

Mohapatra, Senjanović '79

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

Left-Right Symmetry

symmetric interactions

spontaneous parity breaking

new V+A dynamics

Yanagida '79

Family Symmetries

Left-Right Symmetry

Pati, Salam '74 @ ICTP
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 $\mathcal{P}$ or $\mathcal{C}$

RH neutrino automatic

L 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: $\quad f_L \leftrightarrow f_R^c, \quad \Phi \to \Phi^T, \quad \Delta_L \leftrightarrow \Delta_R^*$

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

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

*up to extra phases

Parity fixes flavor of new gauge interactions

Stringent constraints, *K* and *B* mixing

Beal, Bander, Soni ’82... *many* ...Maiezza, MN, Nesti, Senjanović ’10

$M_{W_R} > 1.8 \text{ TeV}$ $\qquad M_{W_R} > 2.5 \text{ TeV}$

Guarantees production at the LHC if W_R is light

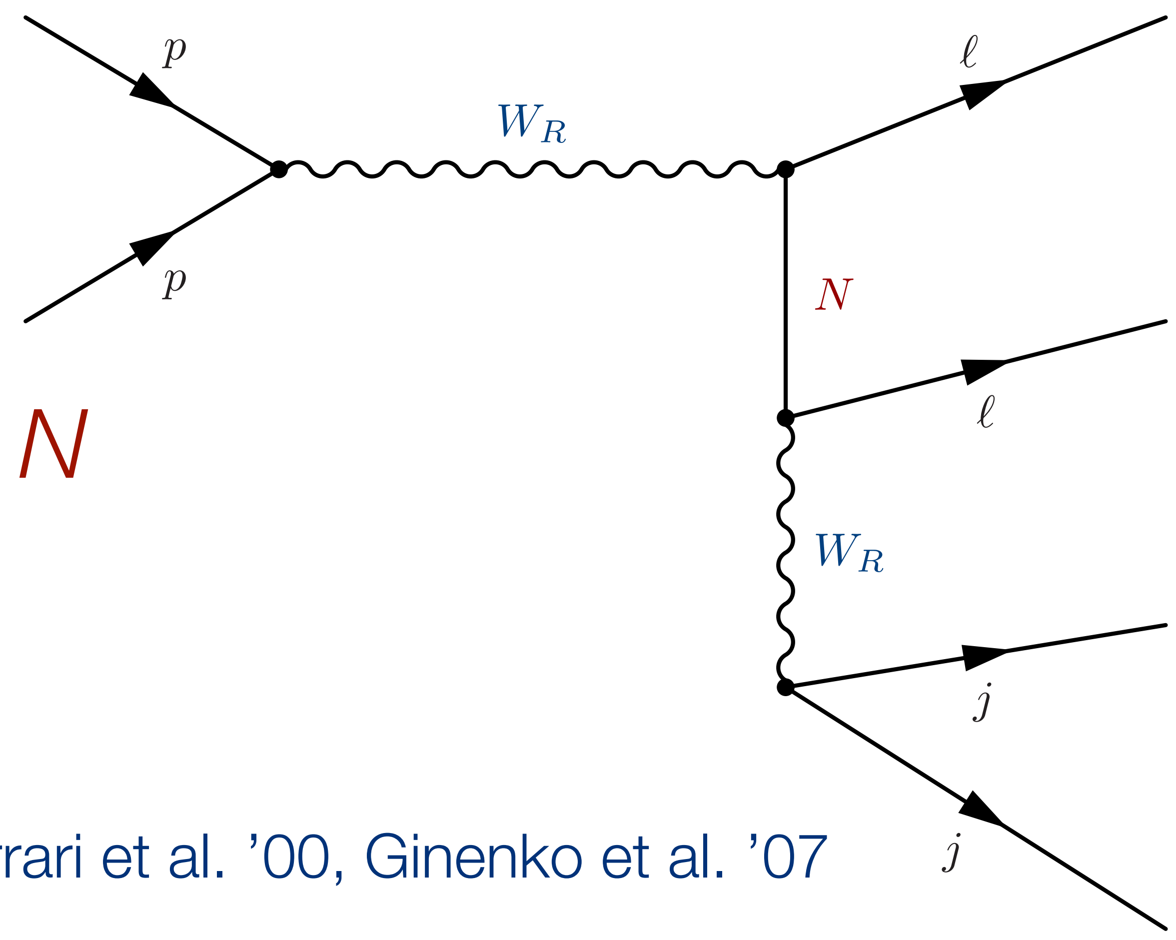
also Blanke, Buras, Gemmler, Heidsieck ’11
Bertolini, Maiezza, Nesti, Eeg ’12

Neutrino at colliders

Keung, Senjanović ’83

talks by del Aguila and Han

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

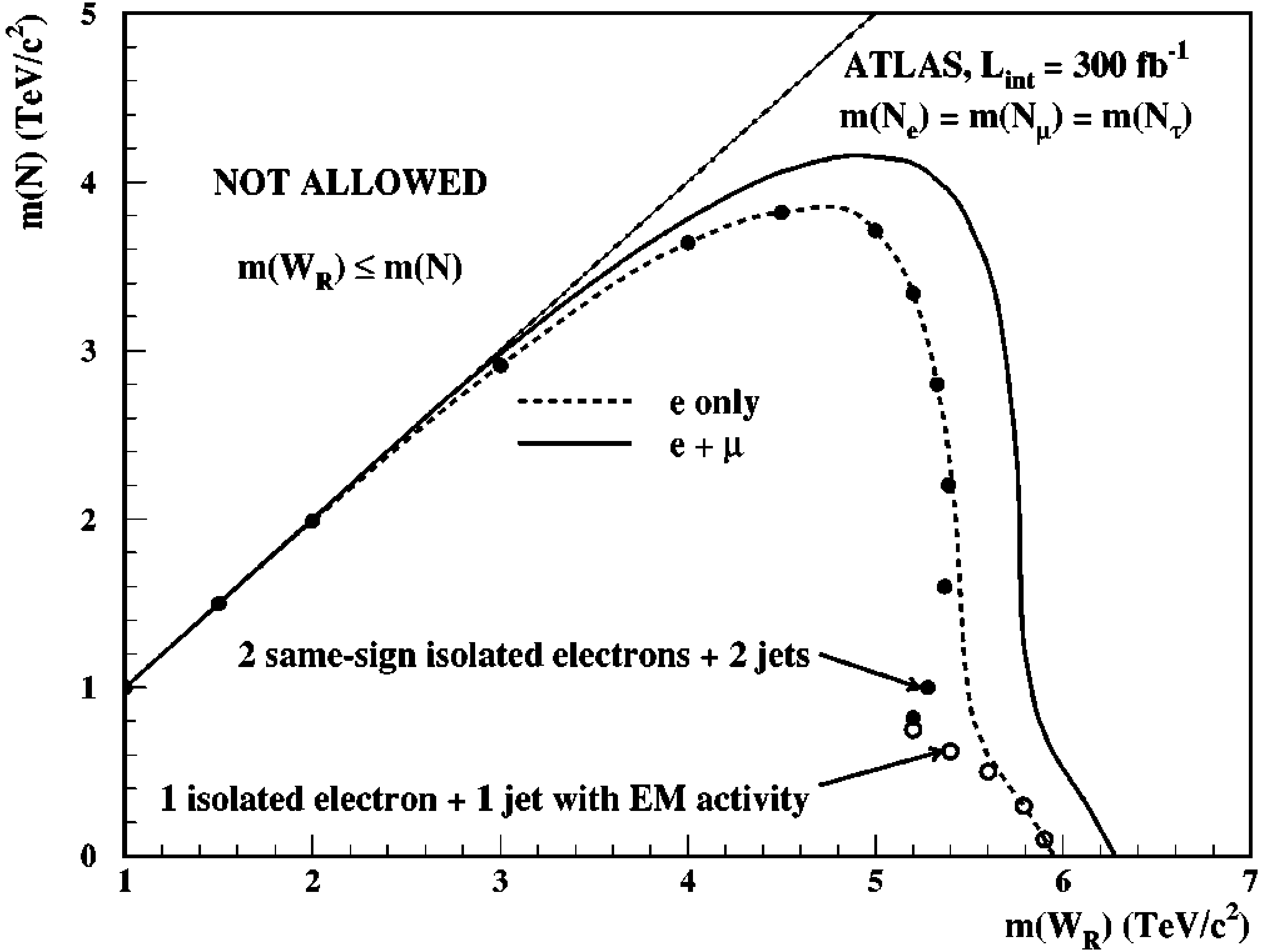
Aguilar-Saavedra, Joaquim ’12

Multi-leptons

Chen, Dev ’12

Realistic experimental study

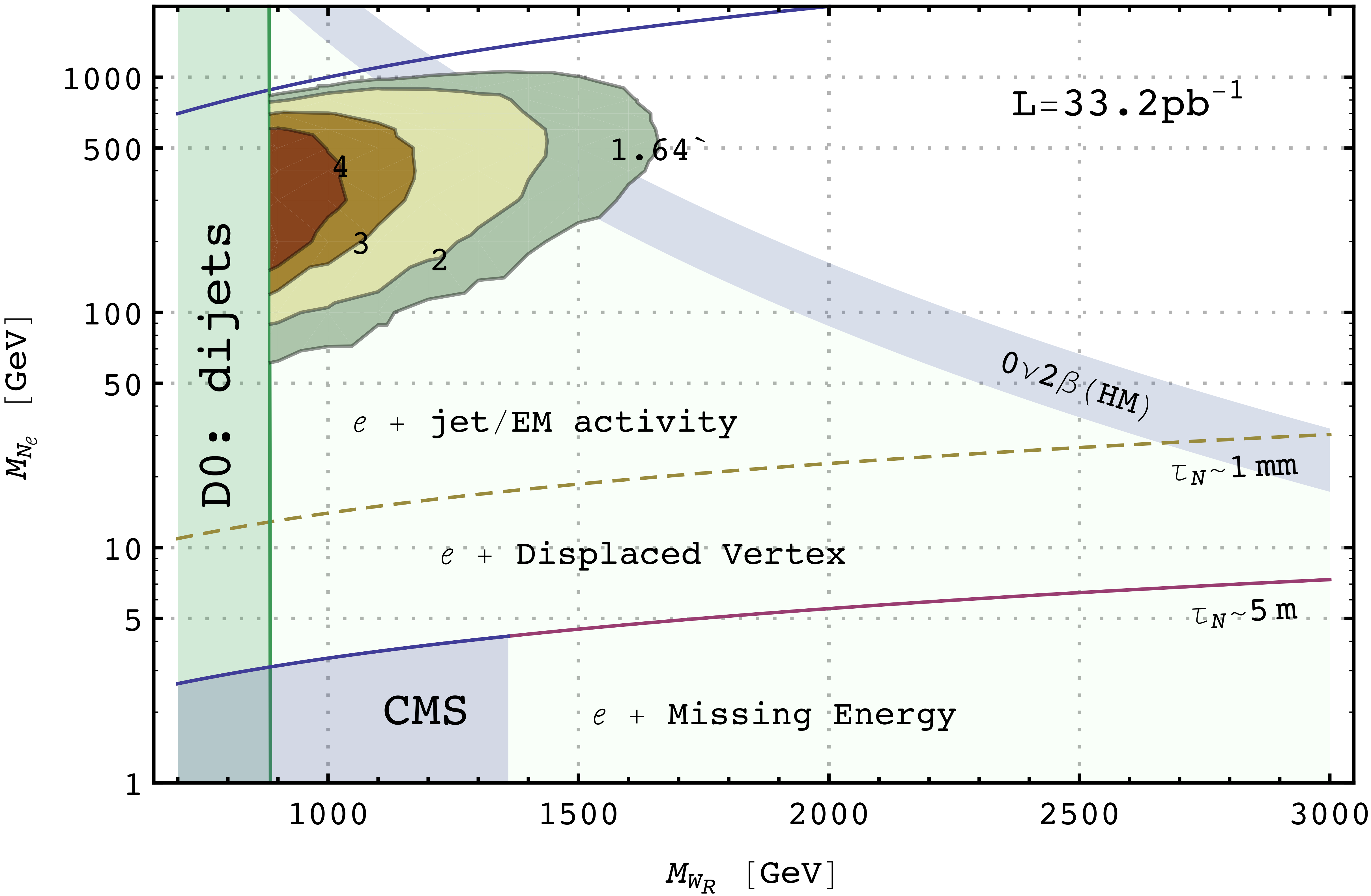
ATLAS group Ferrari et al. '00



Heavy *N* landscape

MN, Nesti, Senjanović, Zhang '11

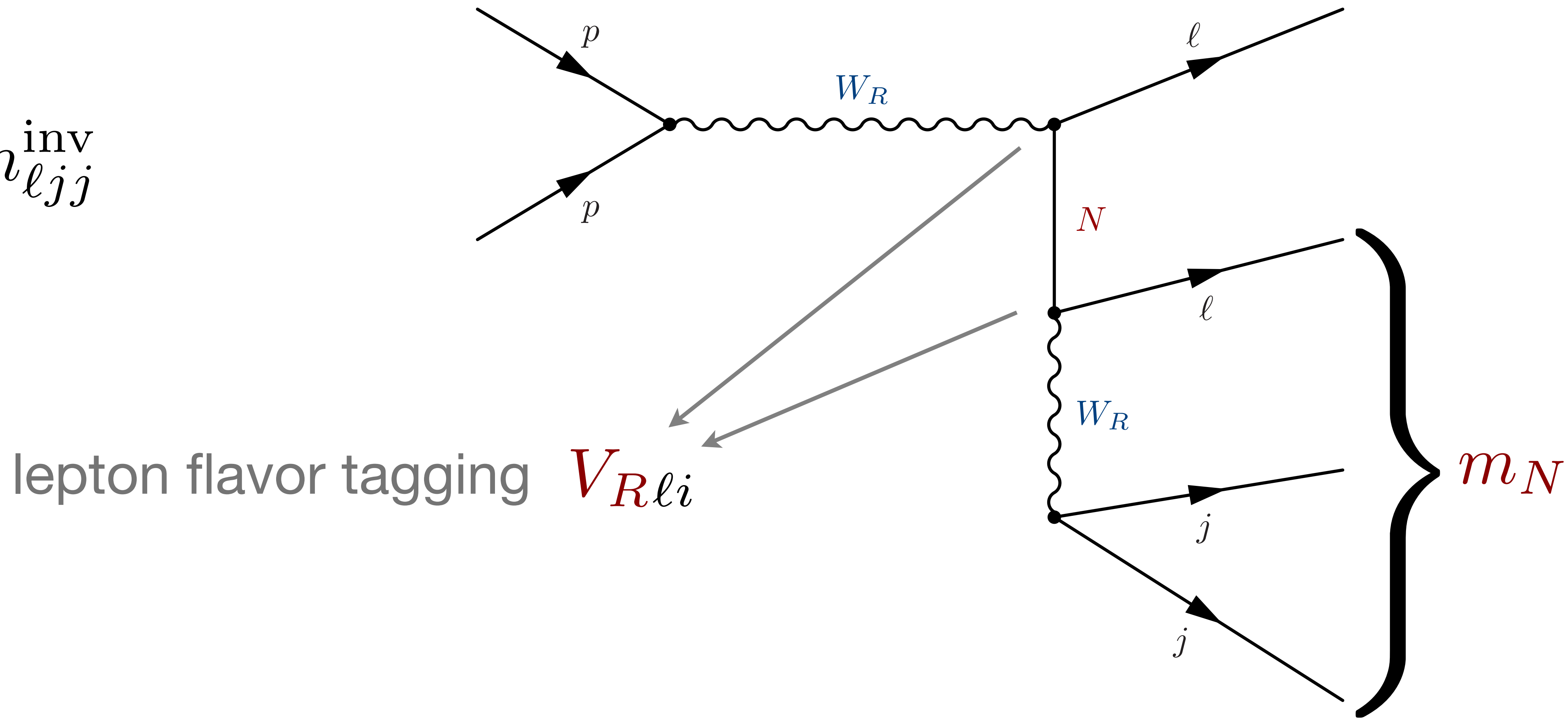
talks by Leonidopoulos and Savinov



Keung, Senjanović ’83

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

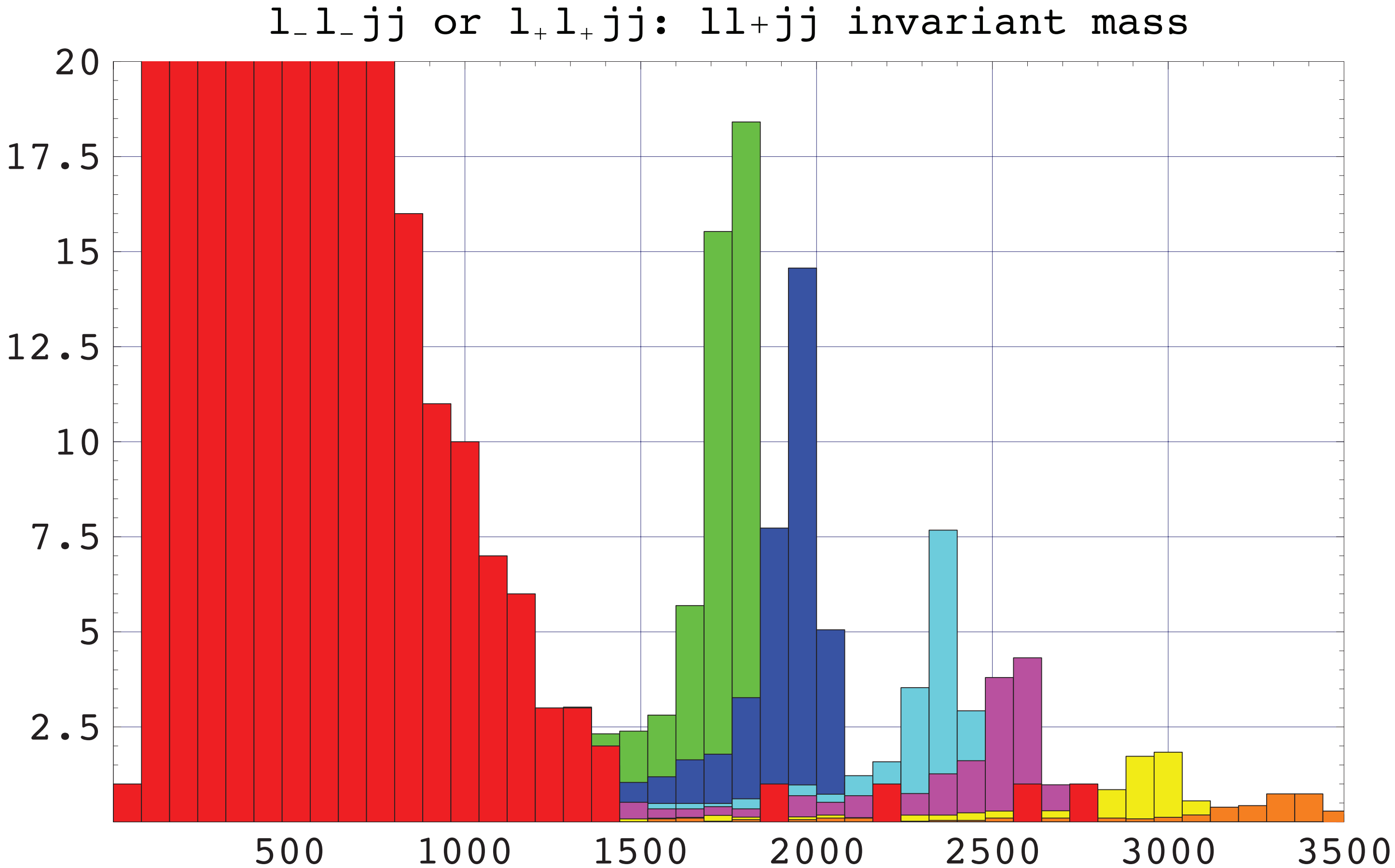
$$m_N = m^{\text{inv}}_{\ell jj}$$



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

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

...connect directly to low energies



Maiezza, MN, Nesti, Senjanović ’10

Pythia + PGS

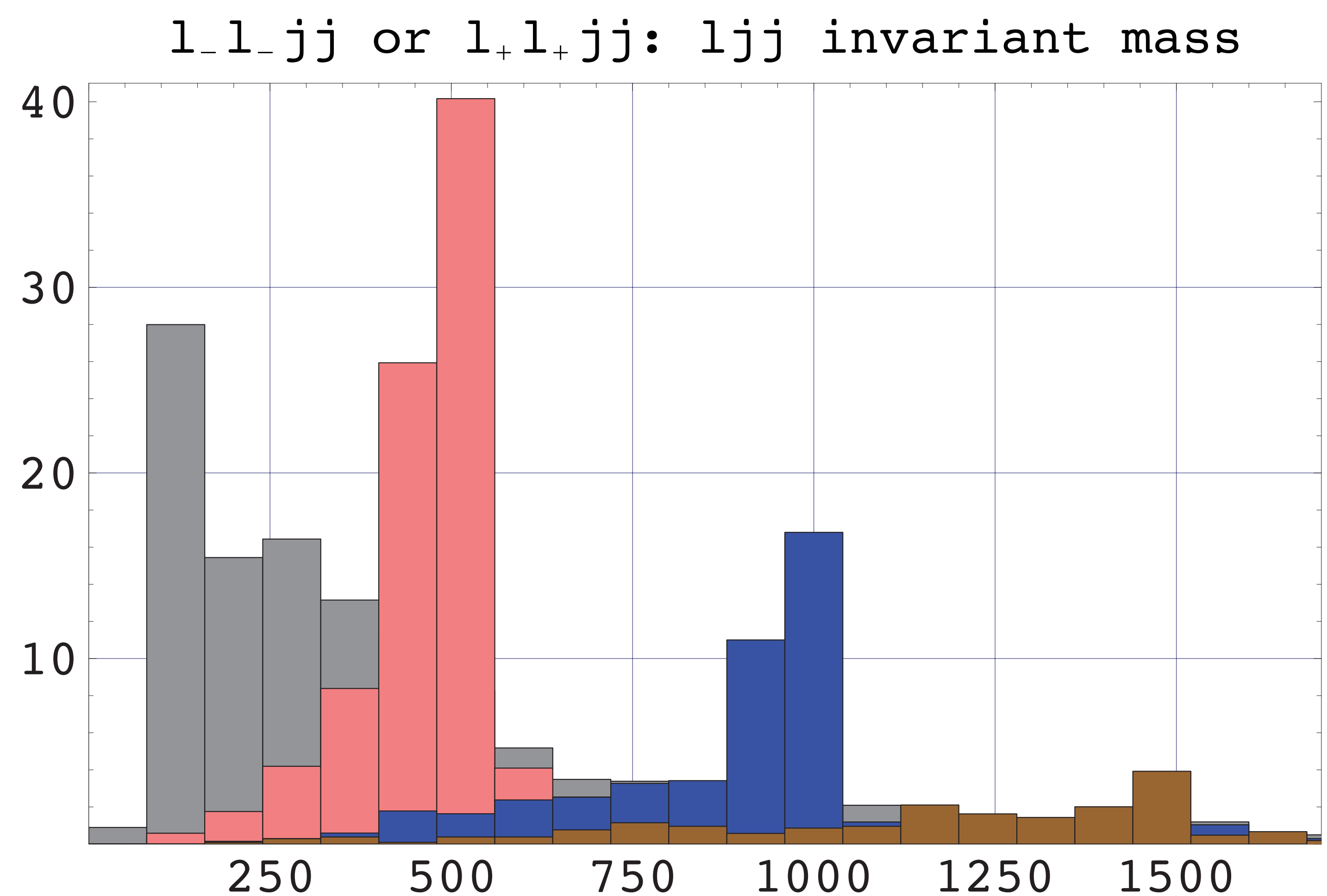
14 TeV LHC w 10/fb

di-lepton peak

six flavor channels
per three *N*s

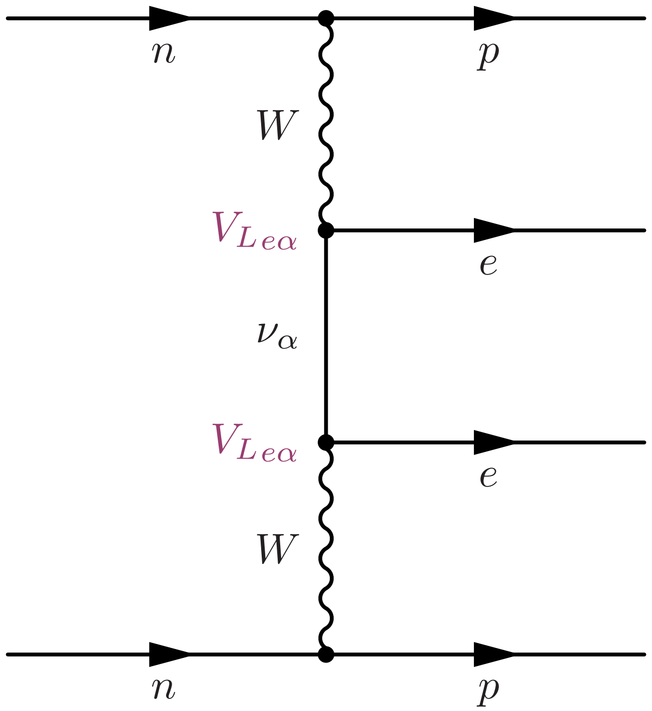
$$M_N = V_R m_N {V_R}^T$$

courtesy of Nesti

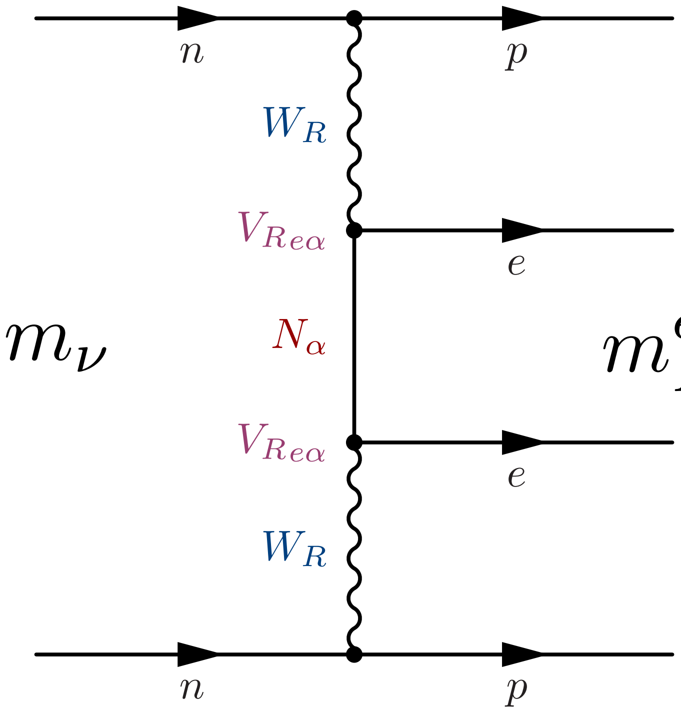


Connection to $0\nu 2\beta$

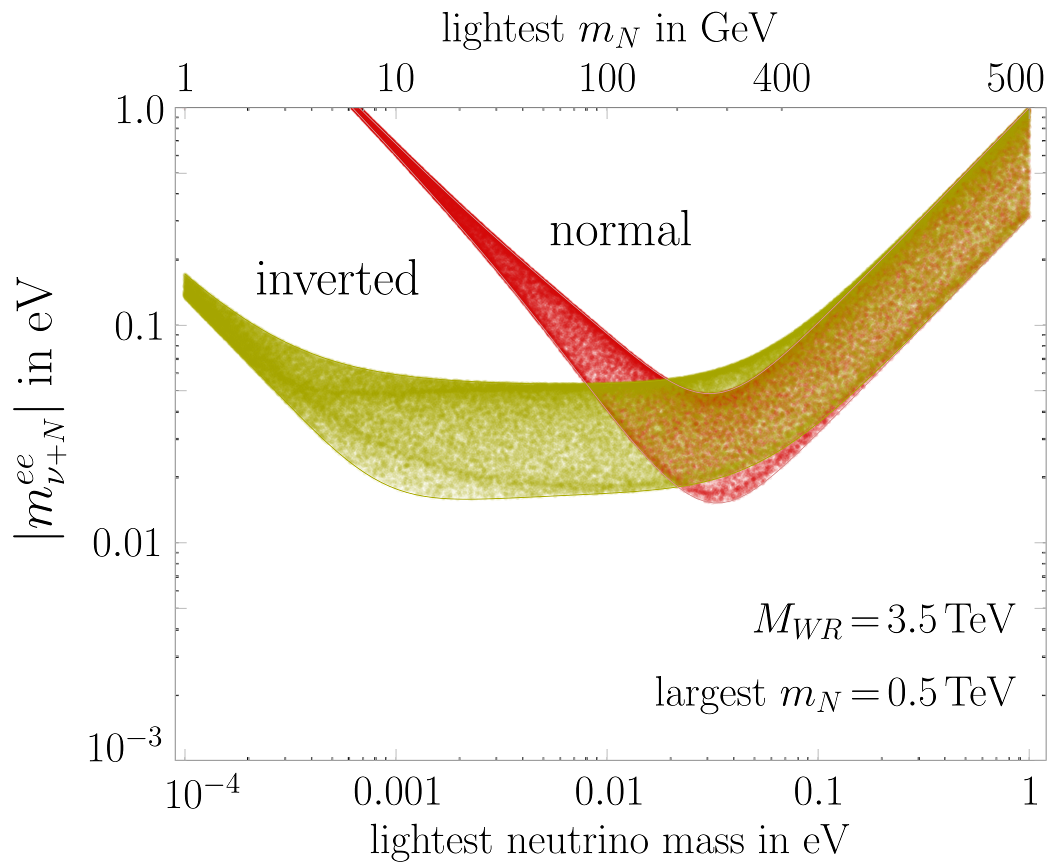
Mohapatra, Senjanović '79 and '81



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



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



Tello, MN, Nesti, Senjanović, Vissani '10

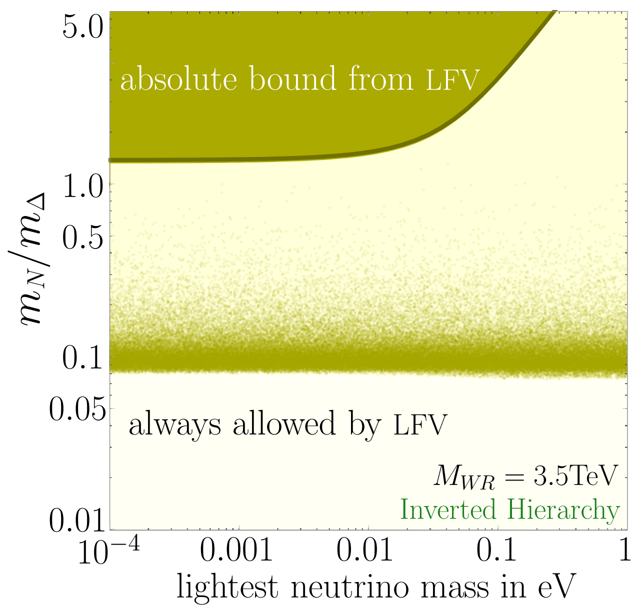
type II *illustration*

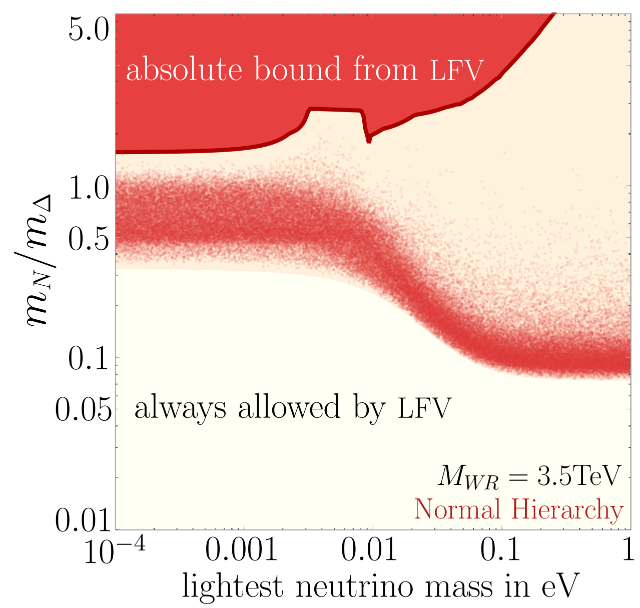
$$M_N \propto M_\nu$$

Connection to $0\nu2\beta$

- Δ_L negligible, Δ_R constrained by LFV

Tello, MN, Nesti, Senjanović, Vissani '10

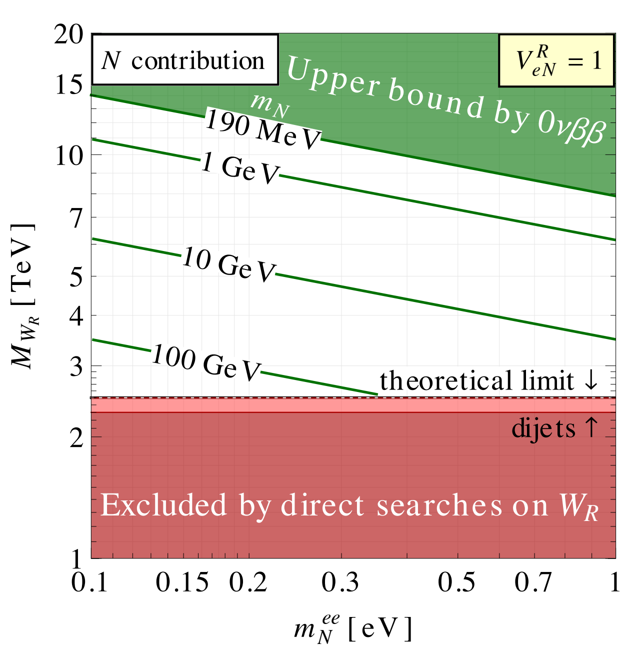


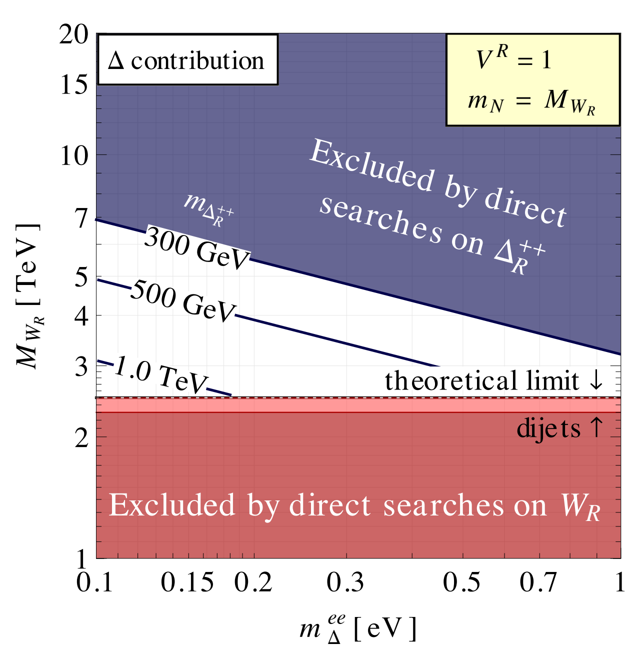


$$m_\Delta^{ee} \simeq 2\frac{{m_N}^2}{m_\Delta^2} m_N^{ee}$$

triplet sub-dominant

- LHC and $0\nu2\beta$ probe same scales





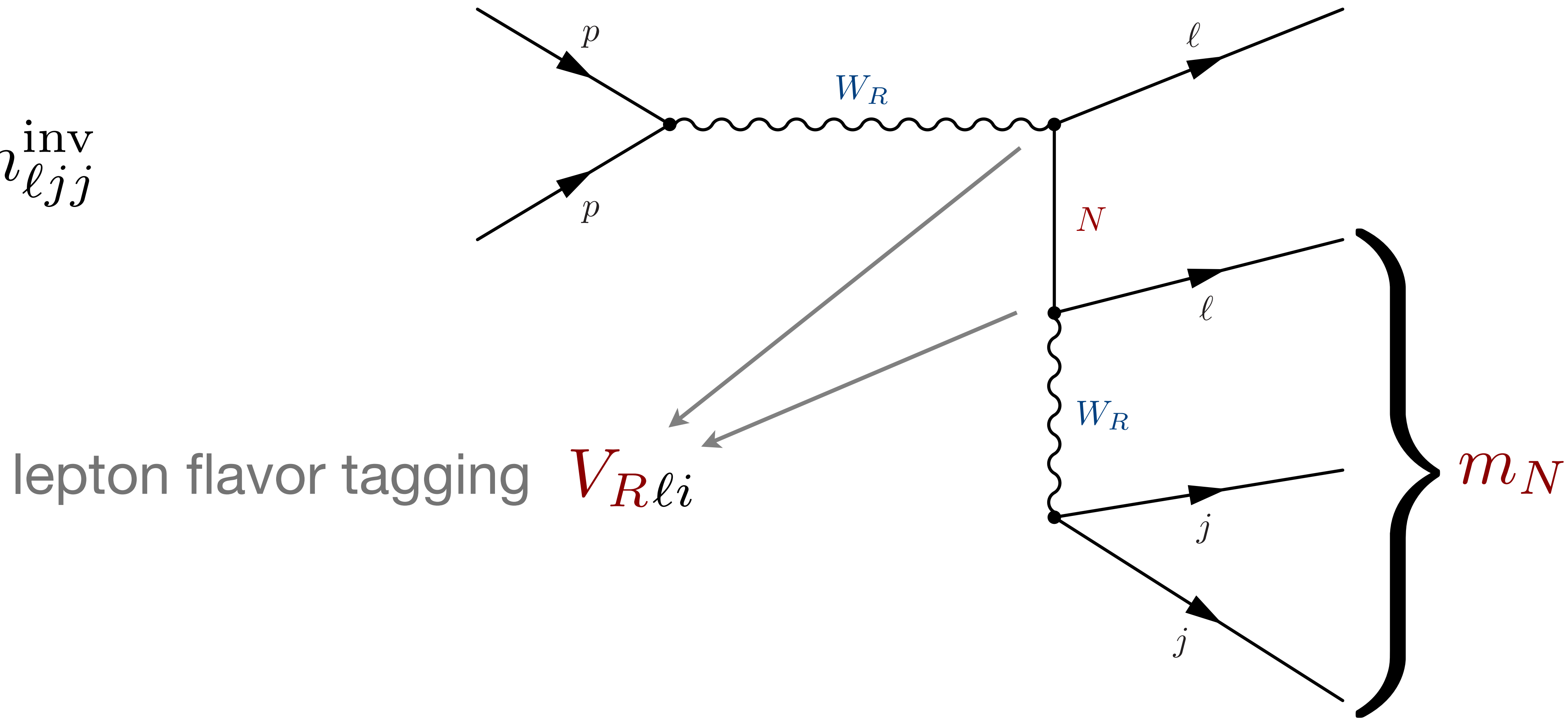
Tello, MN, Nesti, Senjanović '11

see talks on Thursday

Keung, Senjanović ’83

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

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



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

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

...are crucial to compute the Dirac couplings

Parity and Flavor: Leptons

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

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

~to Quarks: Dirac mass symmetric

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

due to $\mathcal{C}$: $M_L = \frac{v_L}{v_R} M_N$ (similar for $\mathcal{P}$)

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

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

MN, Tello, Senjanović '12

Neutrino Higgs couplings

colliders

oscillations, cosmology?

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

MN, Tello, Senjanović ’12

colliders, EDMs, $0\nu2\beta$, X-ray, ...

Unambiguously predicted as in the SM

no continuous parameters, discrete ambiguity

large only with extreme fine-tuning

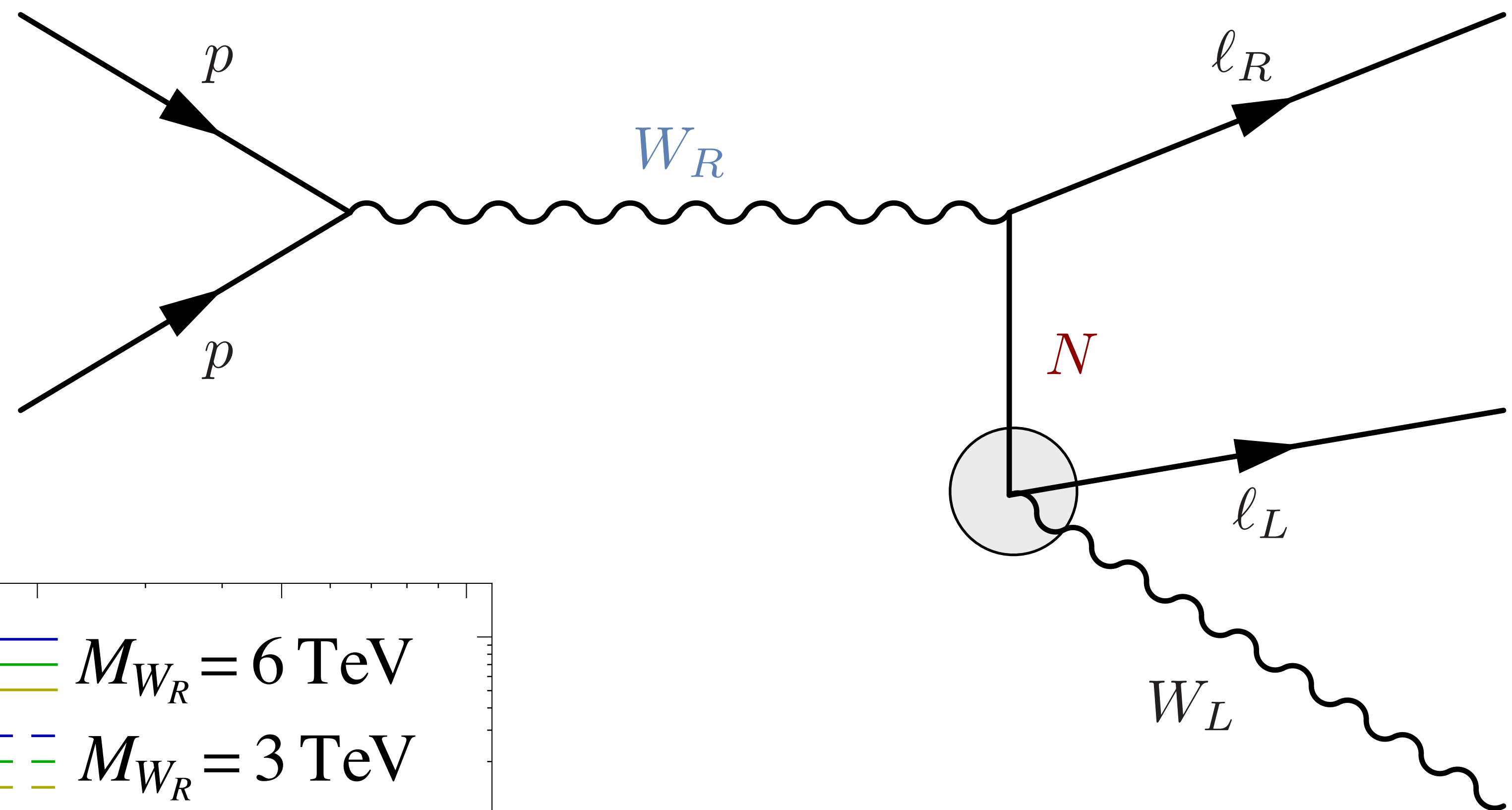
High energy probe

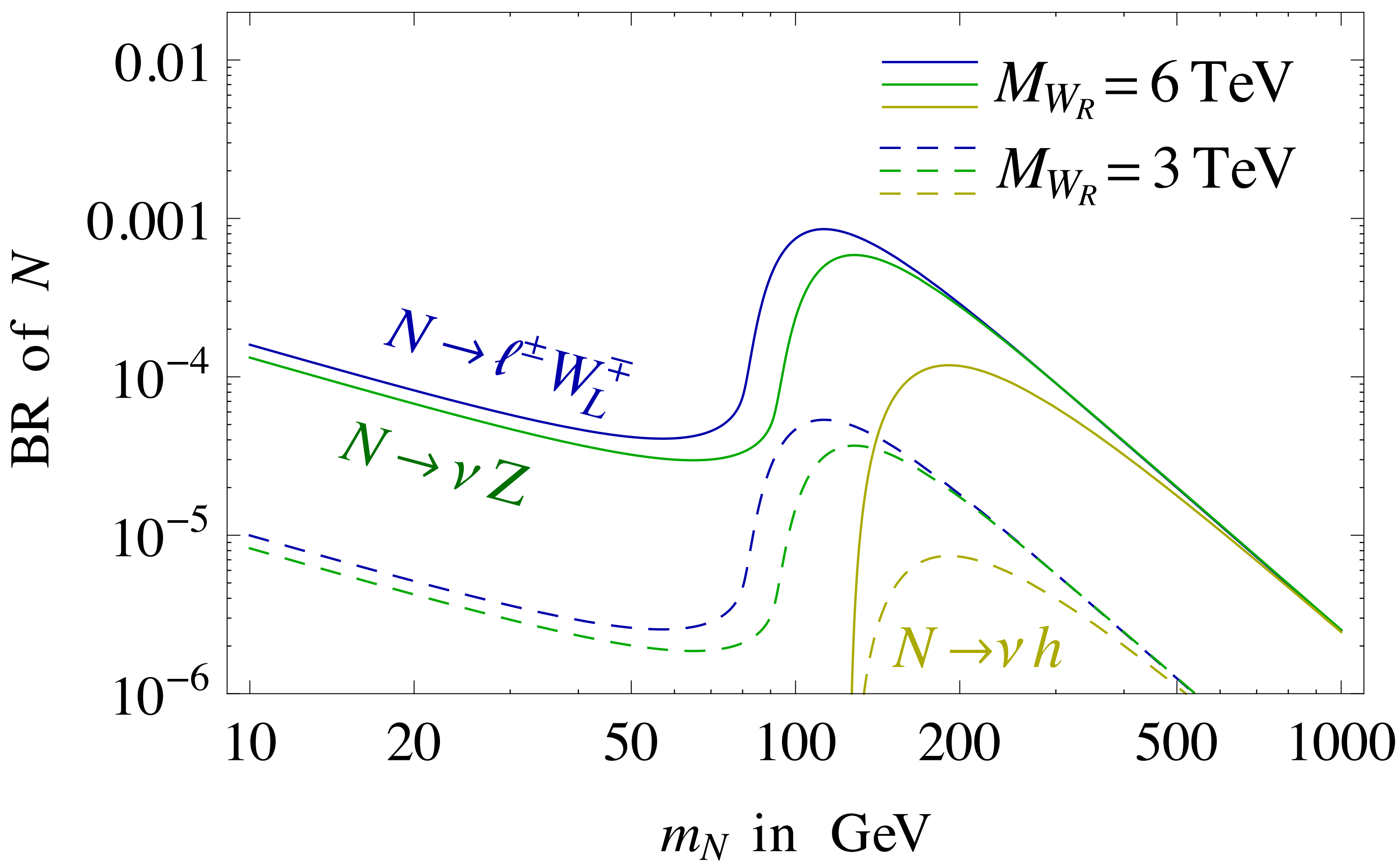
M_D at colliders

MN, Tello, Senjanović '12

A direct probe of predicted Dirac mass

~ Higgs in SM





subdominant, high $\mathcal{L}$

chirality Han, Luiz, Ruiz, Si '12

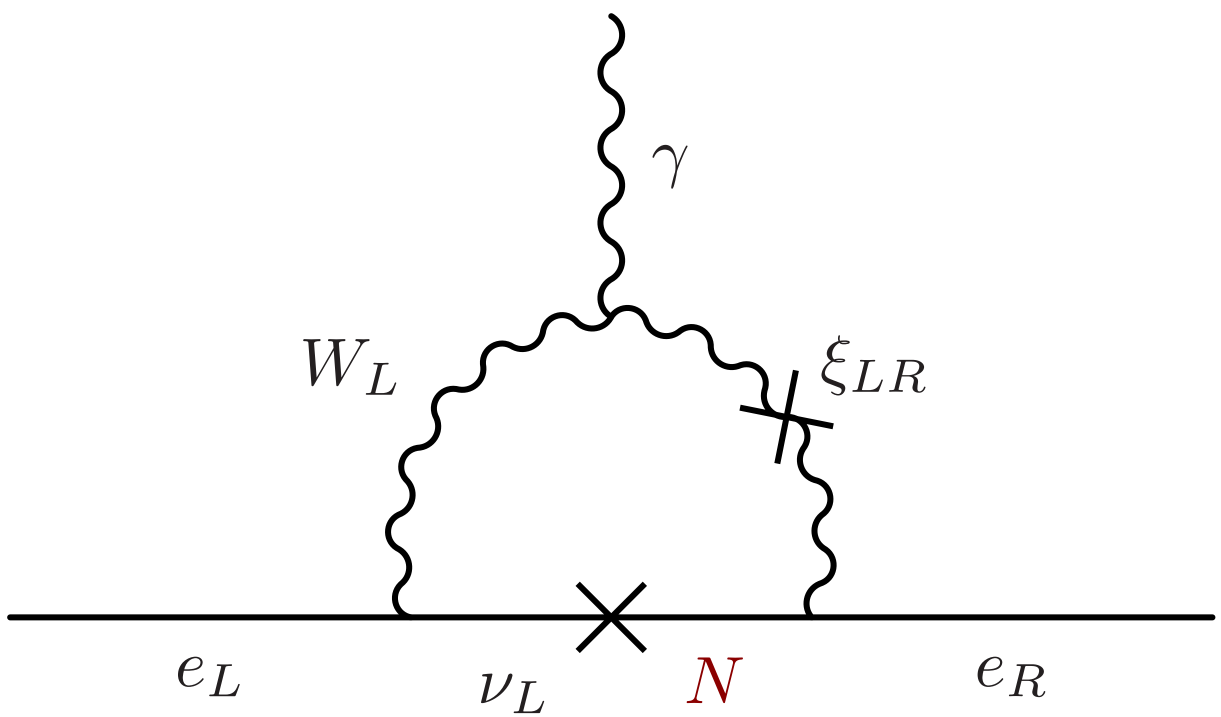
also Chen, Dev, Mohapatra '13

and talk by Dev

Low energies

Electron EDM

T-odd observable, sensitive to CP phases



extremely small in the SM (4 loops)

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

current sensitivity (YbF) Hudson et al. '11

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

@ one loop in LR Chang, Nieves, Pal '86

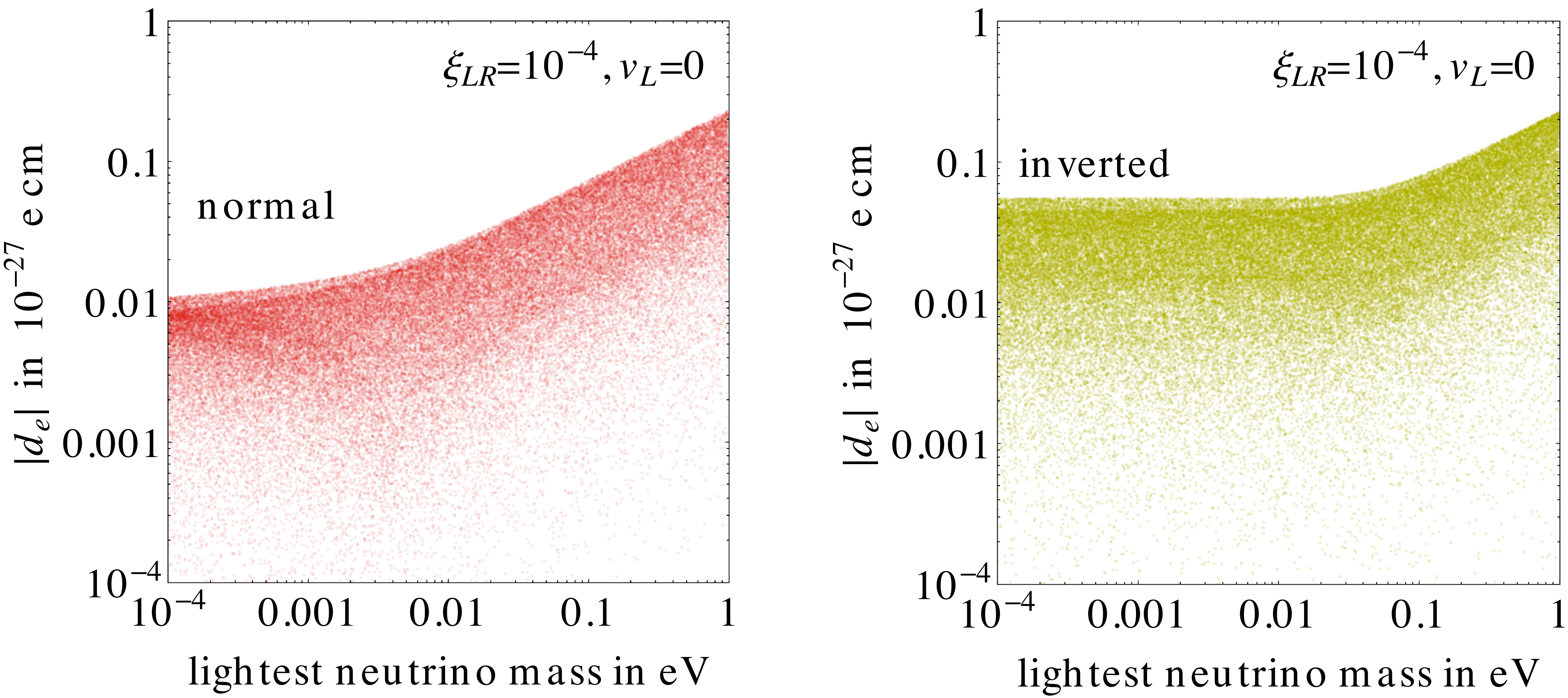
$$d_e = \frac{eG_F}{4\sqrt{2}\pi^2} \mathrm{Im}\left[\xi_{LR} V_R F(t) V_R{}^{\dagger} M_D\right]_{ee}$$

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

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

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

MN, Tello, Senjanović '12



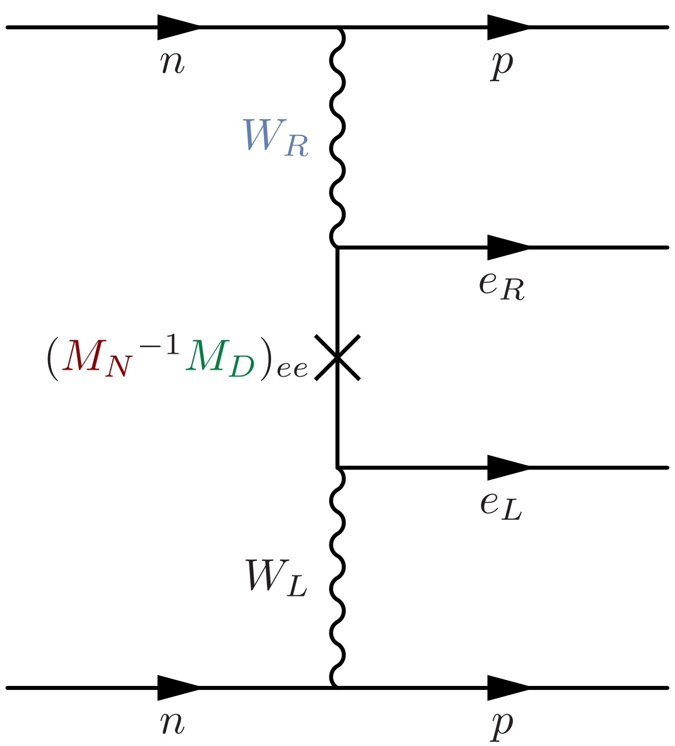
T-odd and sensitive to Majorana phases

More on $0\nu2\beta$

Contributions through mixing

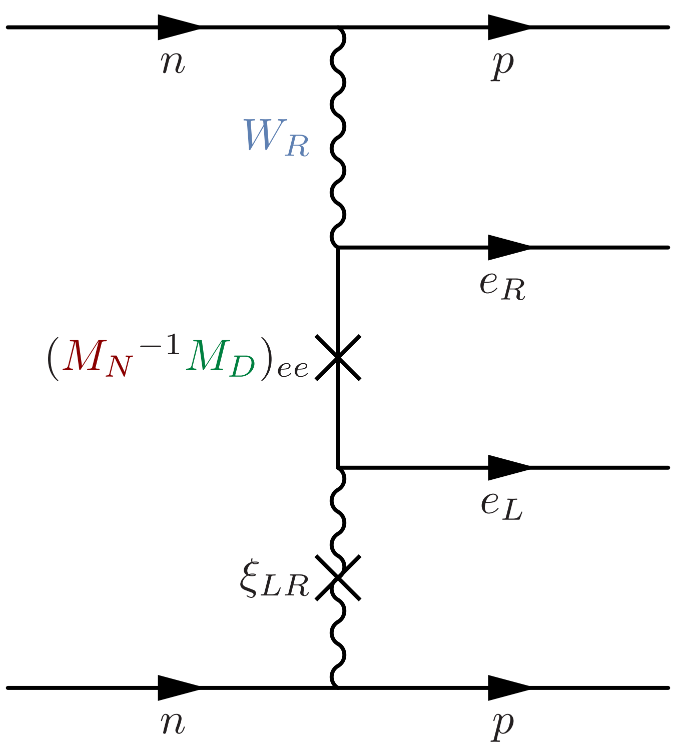
MN, Tello, Senjanović '12

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



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

Doi, Kotani, Takasugi '85

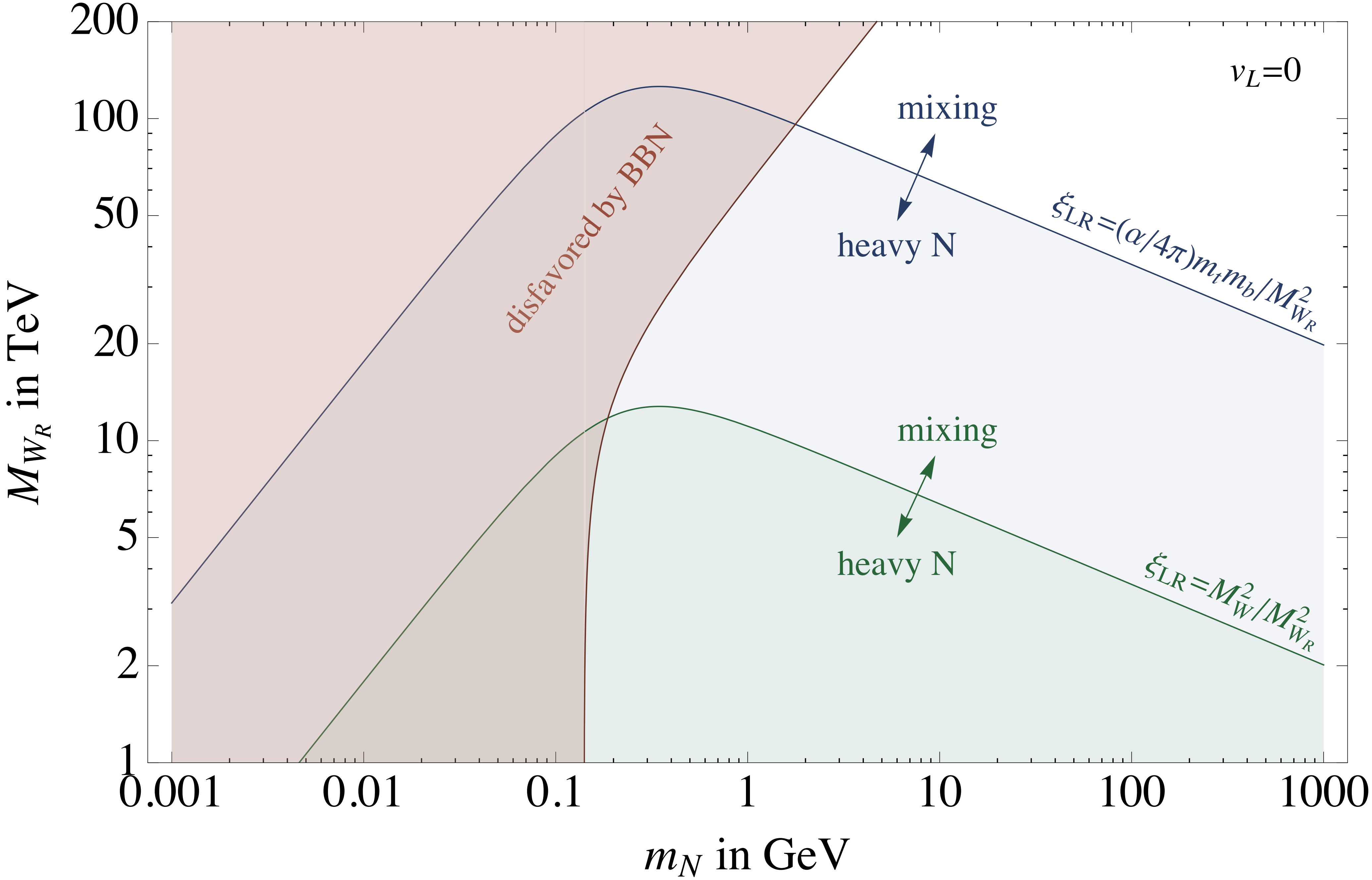


$p \sim 100\ \text{MeV}$

also

Chakrabortty, Devi, Goswami, Patra '11
Barry, Rodejohann '13, Huang, Lopez-Pavon '13

Dominant contribution to $0\nu 2\beta$



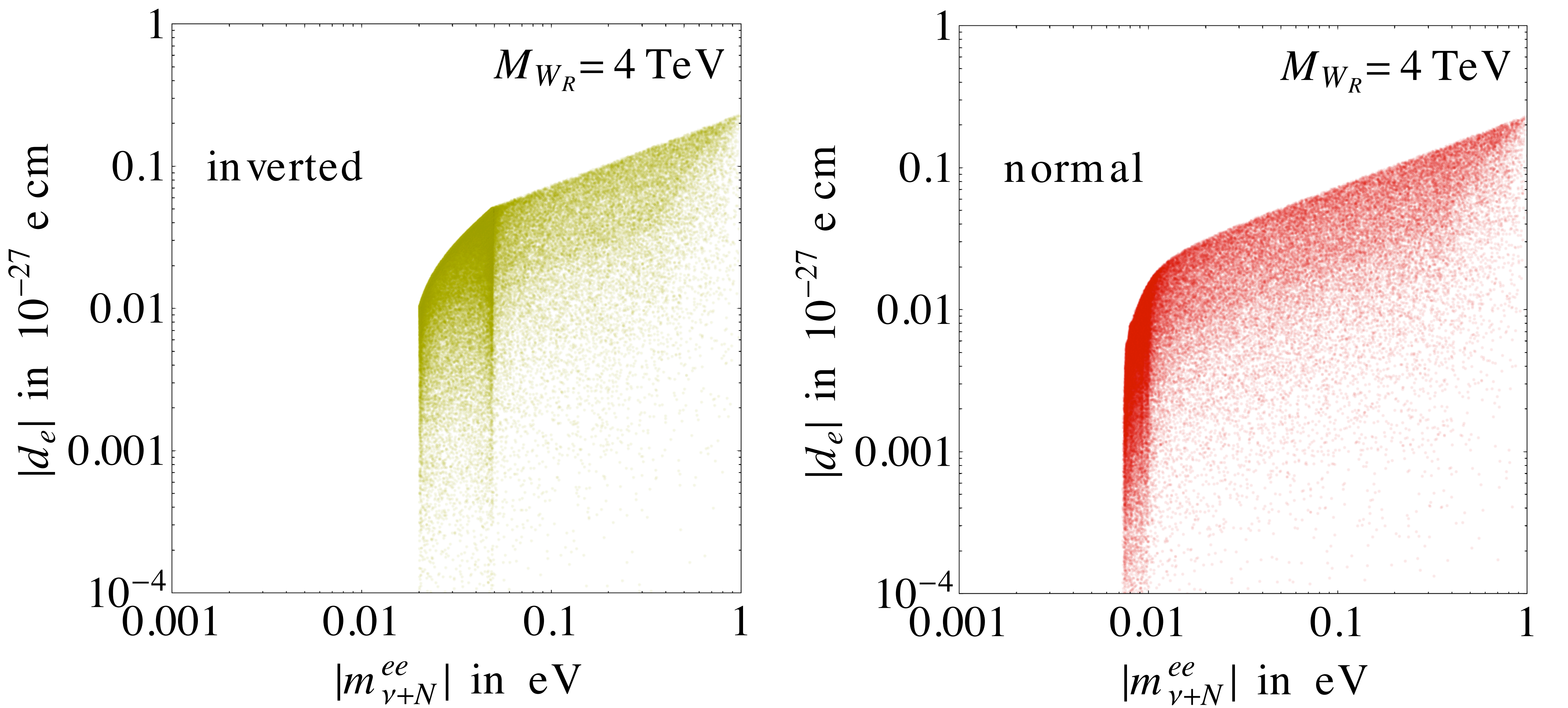
gauge boson mixing $$\frac{\alpha}{4\pi}\frac{m_t m_b}{{M_{W_R}}^2} \lesssim |\xi_{LR}| \lesssim \frac{M_{W_L}^2}{{M_{W_R}}^2}$$

EDM vs. $0\nu2\beta$

observed EDM $\rightsquigarrow 0\nu2\beta$

MN, Tello, Senjanović '12

sensitive to Majorana CP phases



Conclusions

Complete theory of neutrino mass origin

see-saw disentangled and Dirac mass predicted

Higgs couplings as in the SM

gives direct testable relations

heavy *N* decay at the LHC

connects electron EDM, $0\nu 2\beta$ and X-ray in wDM

see talk by Bezrukov

Thank you