FROM MAJORANA TO LHC (AND BACK)

Goran Senjanović
ICTP, Trieste

prepared for Planck11, Lisboa

Neutrino mass - the only established physics beyond SM

(if Majorana)

window to new physics

chance at LHC

Dirac '31

Dirac equation '28

anti particles

particle $\Rightarrow$ different antiparticle

for every fermion

neutrino = anti neutrino ?

Majorana '37

(neutron)

creation of electrons

- neutrino less double beta decay

Racah'37

- colliders - $p\,p$ (bar) collisions

Keung, GS '83

parity violation in weak interaction

Lee, Yang '56

(not well known: they argue it is eventually restored at high energies *)

talk by Yue Zhang

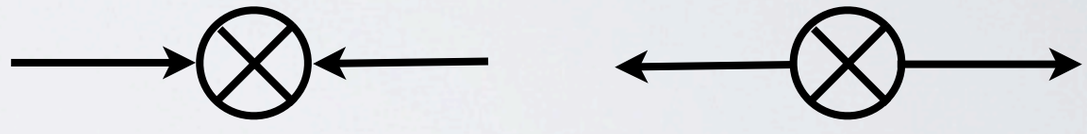
* mirror fermions

Martinez, Melfo, Nesti, GS, PRL '11
Melfo, Nemevsek, Nesti, Zhang, GS'11

Majorana Program:

neutrino mass

$$\nu_M = \nu_L + \nu_L^* \quad \Leftrightarrow \quad m_\nu^M (\nu_L \nu_L + h.c.)$$



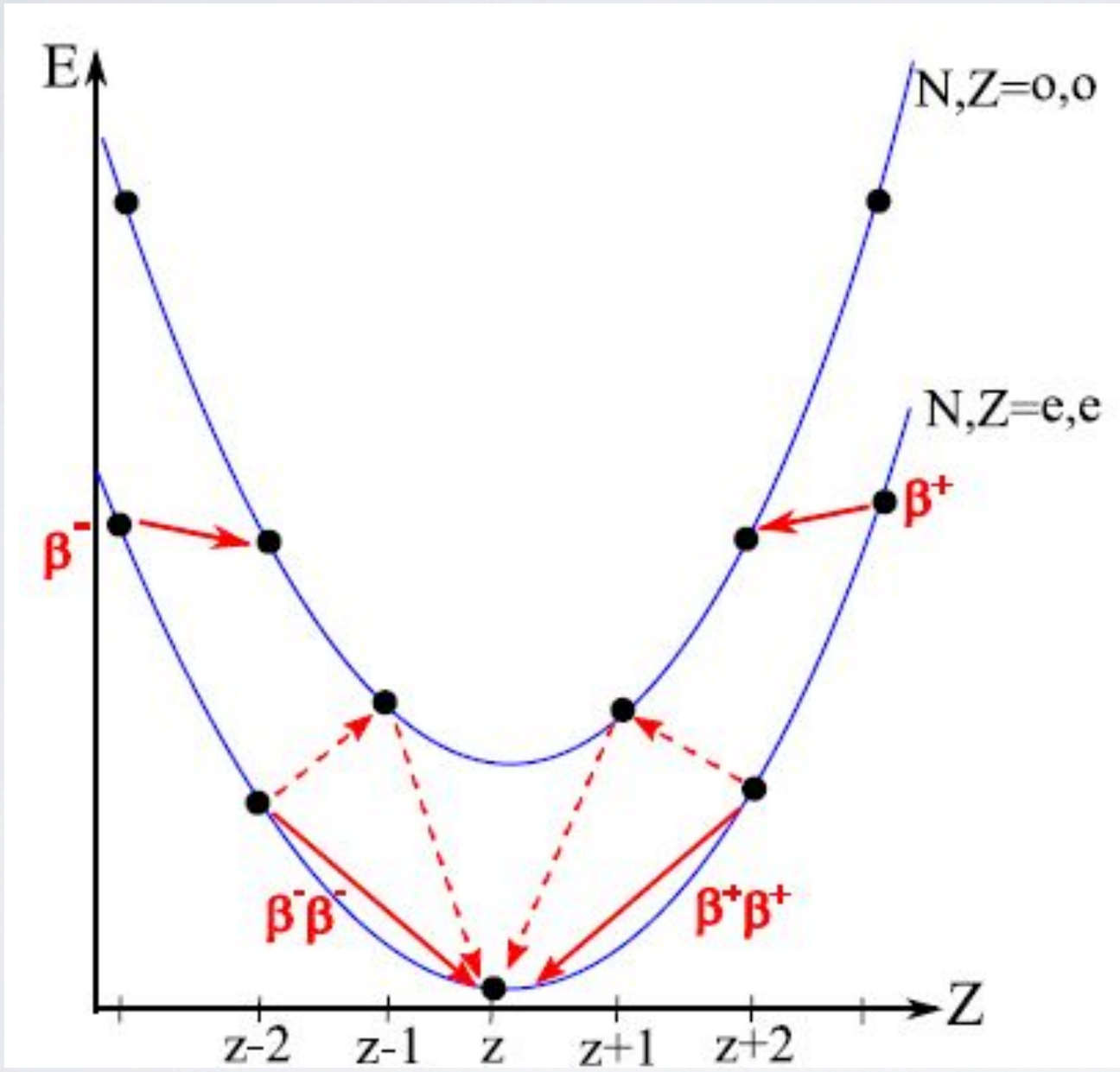
$$\Delta L = 2$$

lepton number violation

forbidden by SM symmetry → window to new physics

Double beta decay

N, Z = odd, odd

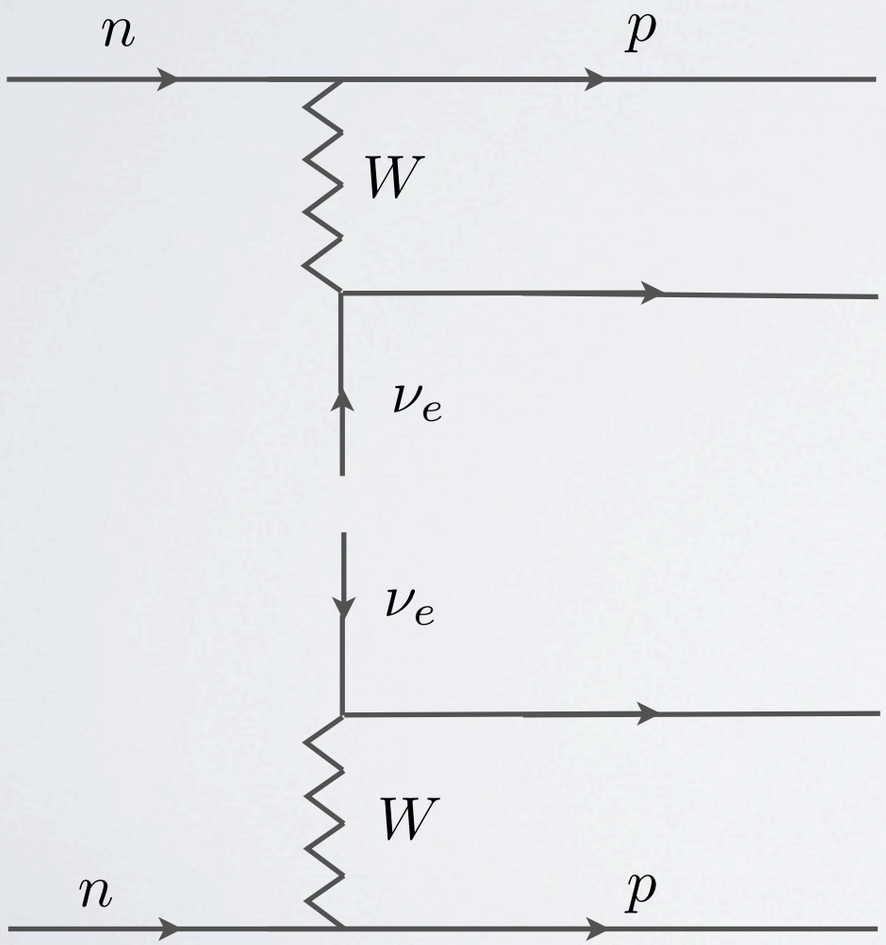


N, Z = even, even

Double-beta decay

$$^{76}_{32}Ge \not\to ^{76}_{33}As + e + \bar{\nu}$$ Ge lighter than As

$$^{76}_{32}Ge \to ^{76}_{34}Se + e + e + \bar{\nu}_e + \bar{\nu}_e$$ *Goepert-Mayer '35*



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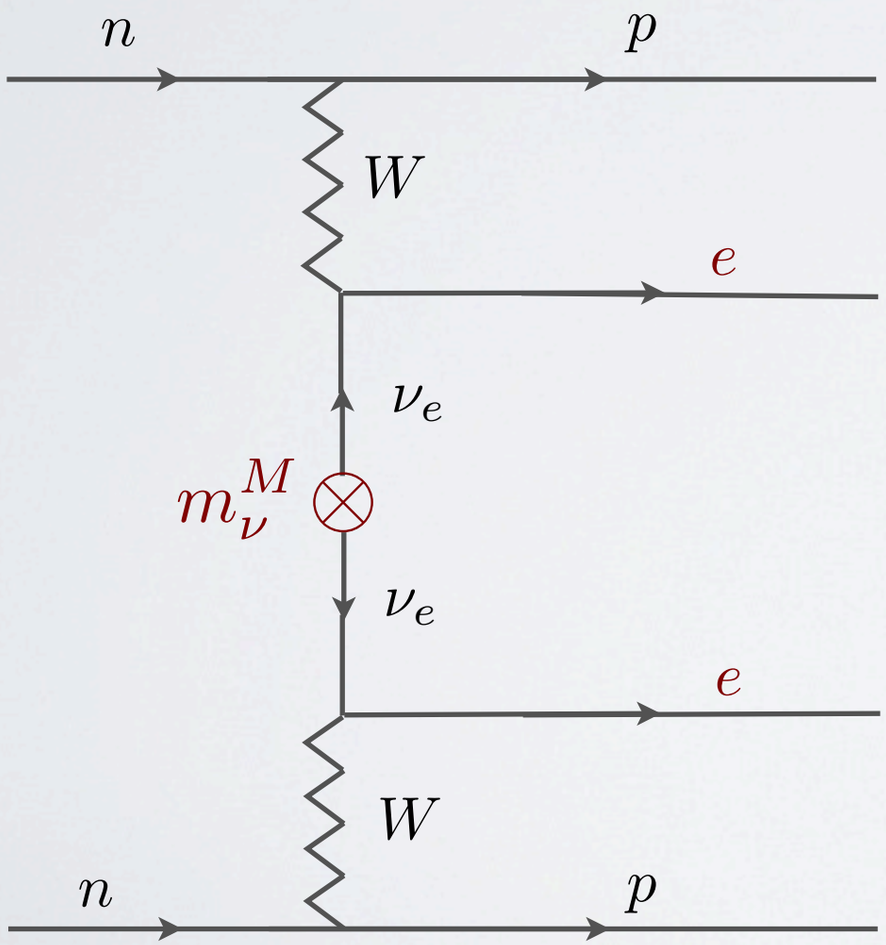

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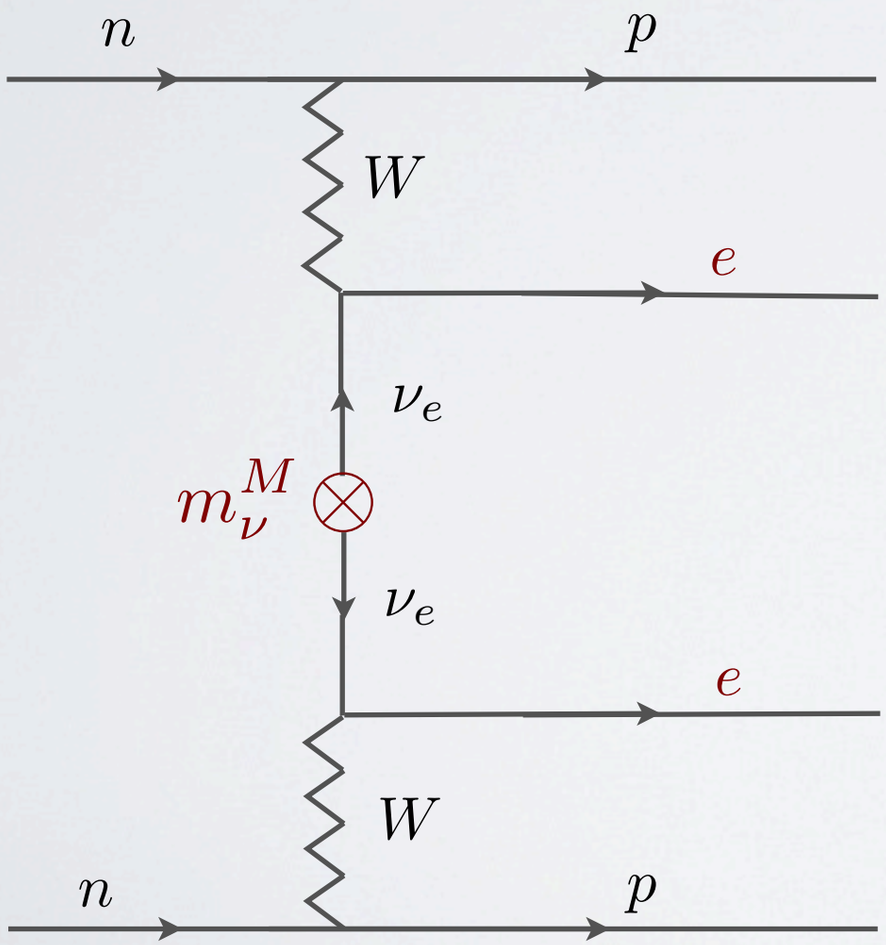
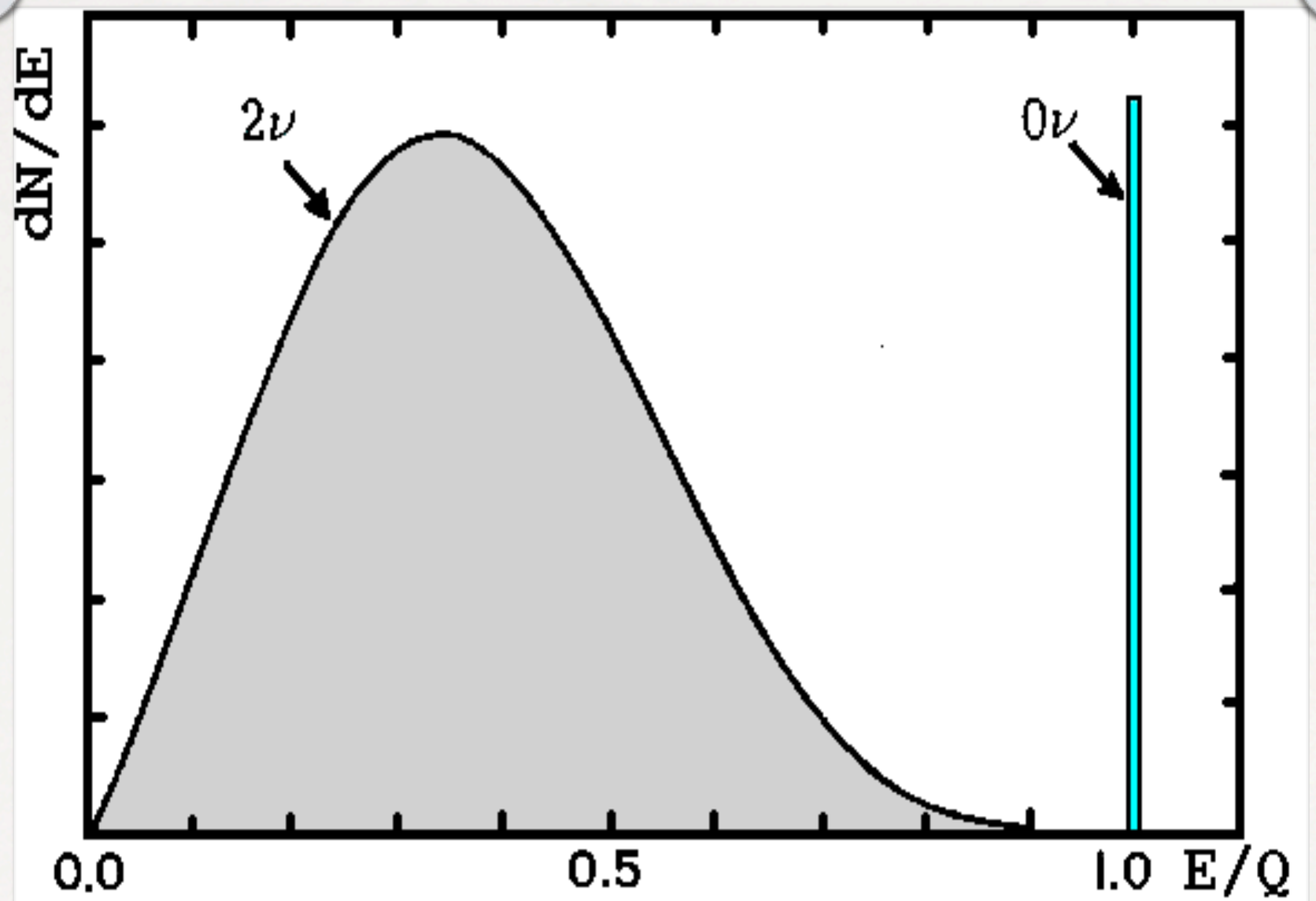


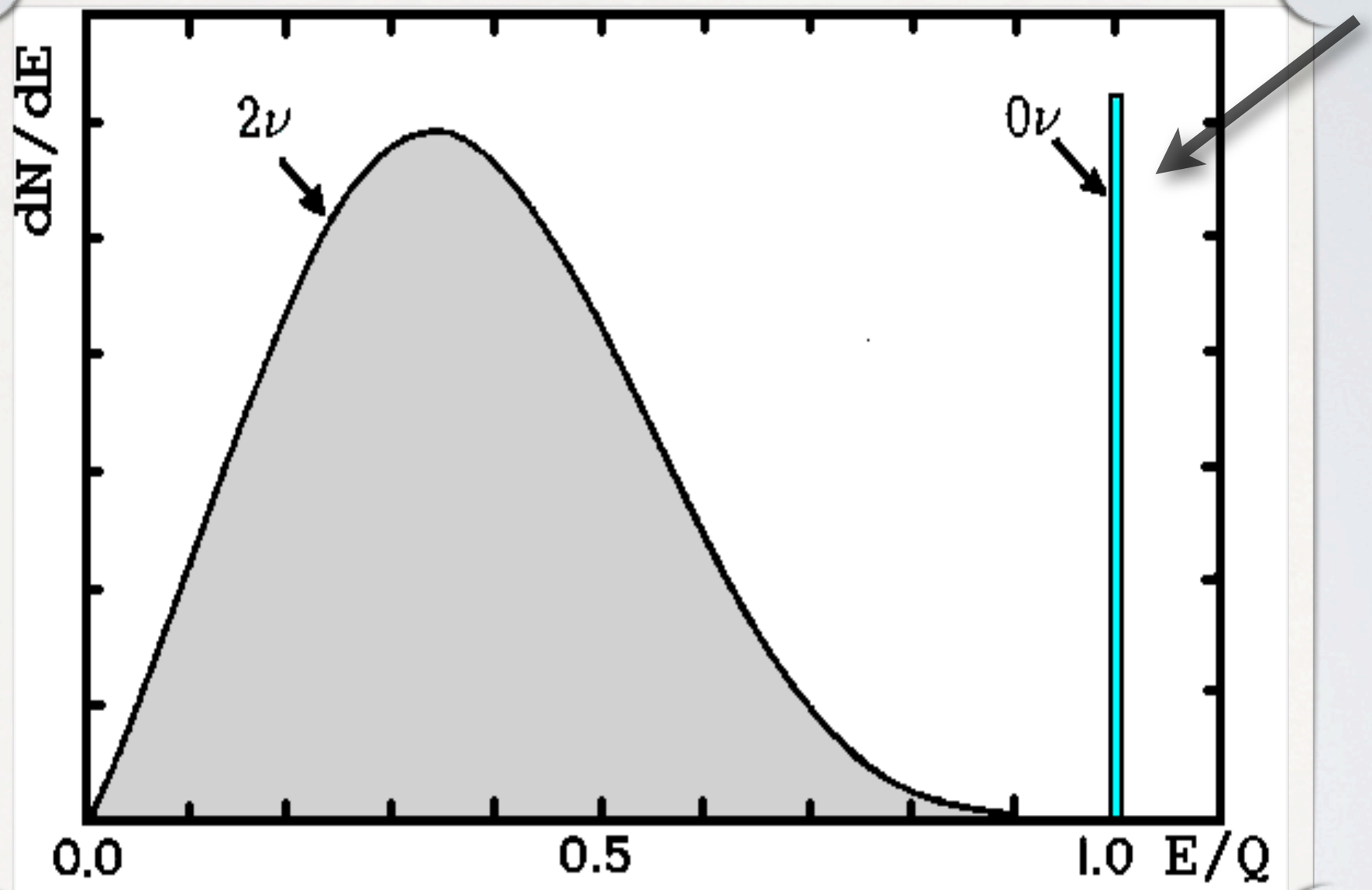
$$^{76}Ge \to ^{76}Se + e + e$$

proportional to neutrino mass

$$t_{1/2} \geq 10^{24}\, yr \implies m_\nu^M \lesssim 1\, eV$$

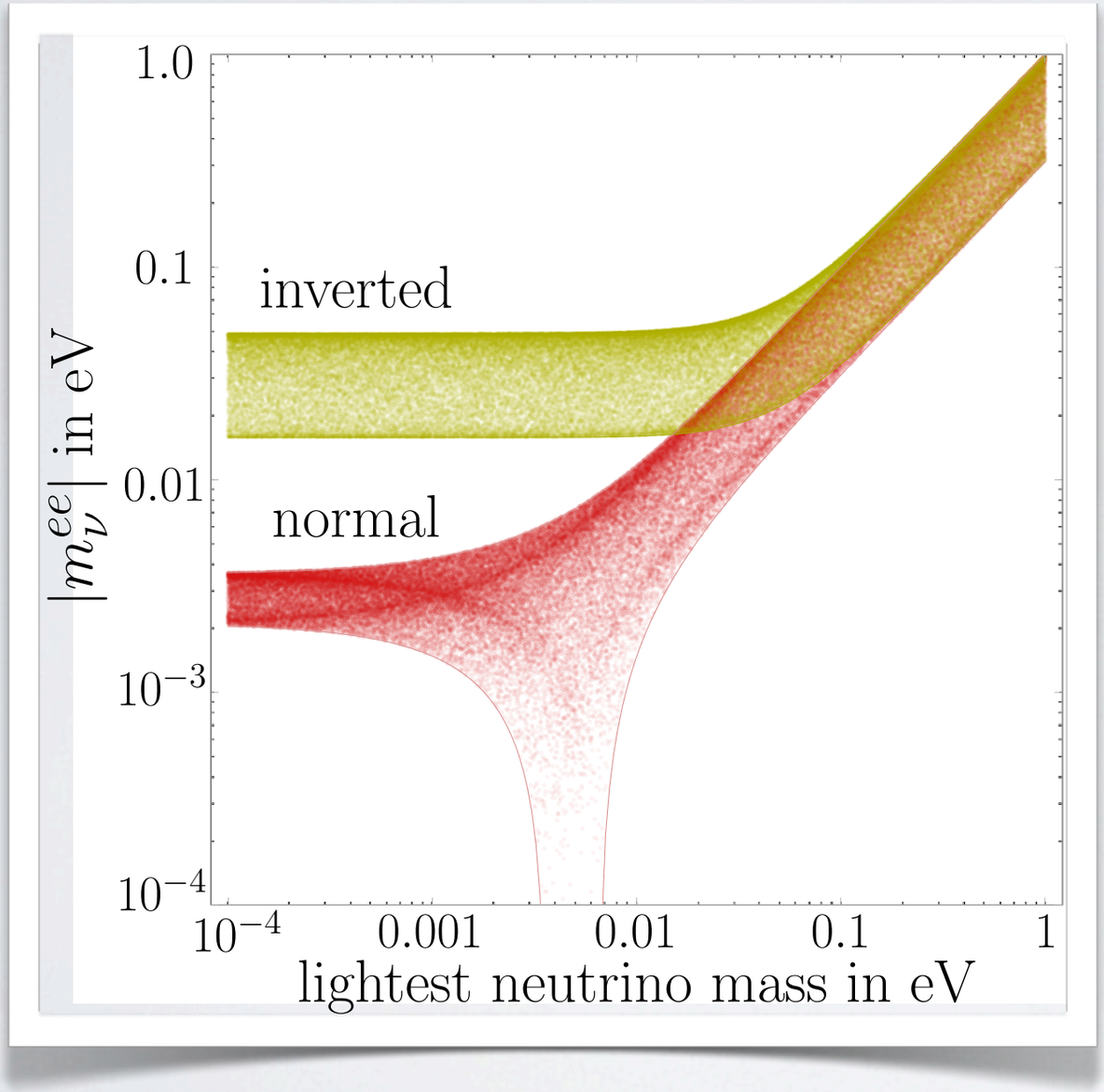


sum of electron energies



sum of electron energies

neutrino mass contribution



strong hierarchy dependence

inverted dominates

Vissani '02

Double beta versus cosmology ?

- Cosmology: $\Sigma m_\nu < 0.4$ - 1 eV WMAP

$\Sigma m_\nu \leq 0.17\, eV$ @ 95% CL *Seljak, Slosar, Mcdonald '06*

WMAP-7
HST
SDSS

SDSS

$\Sigma m_\nu \leq 0.44\, eV$ @ 95 % CL *Hannestad et al '10*

- HMBB experiment

claim: $m_\nu \simeq 0.4 eV$ *Klapdor '01-10*

CUORE 2012

MAJORANA

Super NEMO

GERDA - started LNGS

eventually order of magnitude better than HMBB

if confirmed (expect: **a few years)**

new physics necessary?

New Physics ?

Feinberg, Goldhaber '59

Pontecorvo '64

$n\,n\,p\,p\,e\,e$ d=9 operator

$$\mathcal{A}_\nu \propto \frac{G_F^2 m_\nu^{ee}}{p^2}$$

$p \simeq 100\ MeV$

neutrino virtuality

$$\mathcal{A}_{\mathcal{NP}} \propto \frac{G_F^2 M_W^4}{\Lambda^5}$$

$\Lambda \sim TeV$ → LHC

Neutrino mass:

theory?

STANDARD MODEL

$$\nu_L \nu_L$$ forbidden

- Why parity : $L \not\leftrightarrow R$ broken ?

> God may be left-handed, but not an invalid

L-R SYMMETRY

Lee, Yang dream

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$$

W_L W_R

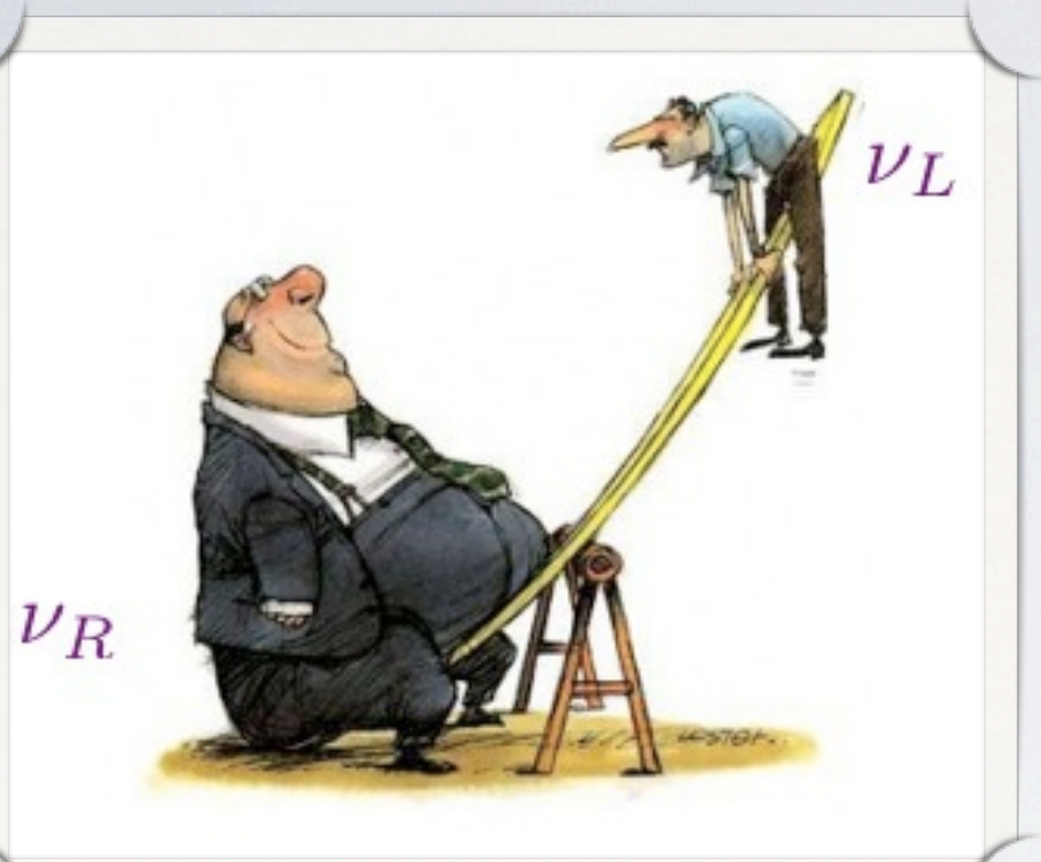
$$m_{W_R} \gg m_{W_L}$$

Pati Salam '74

Mohapatra GS '75

Curse: massive neutrinos

neutrino mass



Blessing: seesaw

$$m_{\nu_R} \propto M_{W_R}$$

Minkowski '77

Mohapatra, GS '79

Minimal model:

Theoretical limit

$$M_{W_R} \gtrsim 2500\,\mathrm{GeV}$$

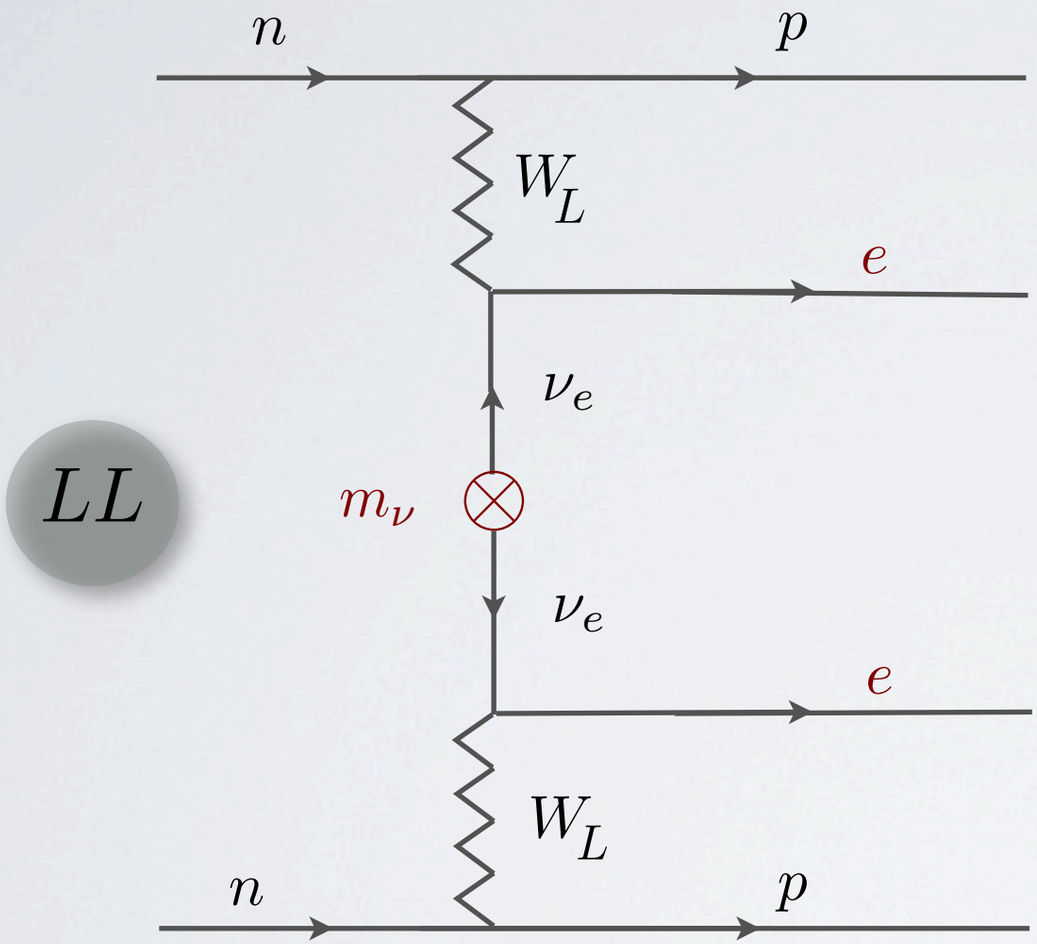
Beall, Bander, Soni '81

Zhang et al '07

Maiezza, Nemevsek, Nesti, GS '10

New source for $0\nu 2\beta$

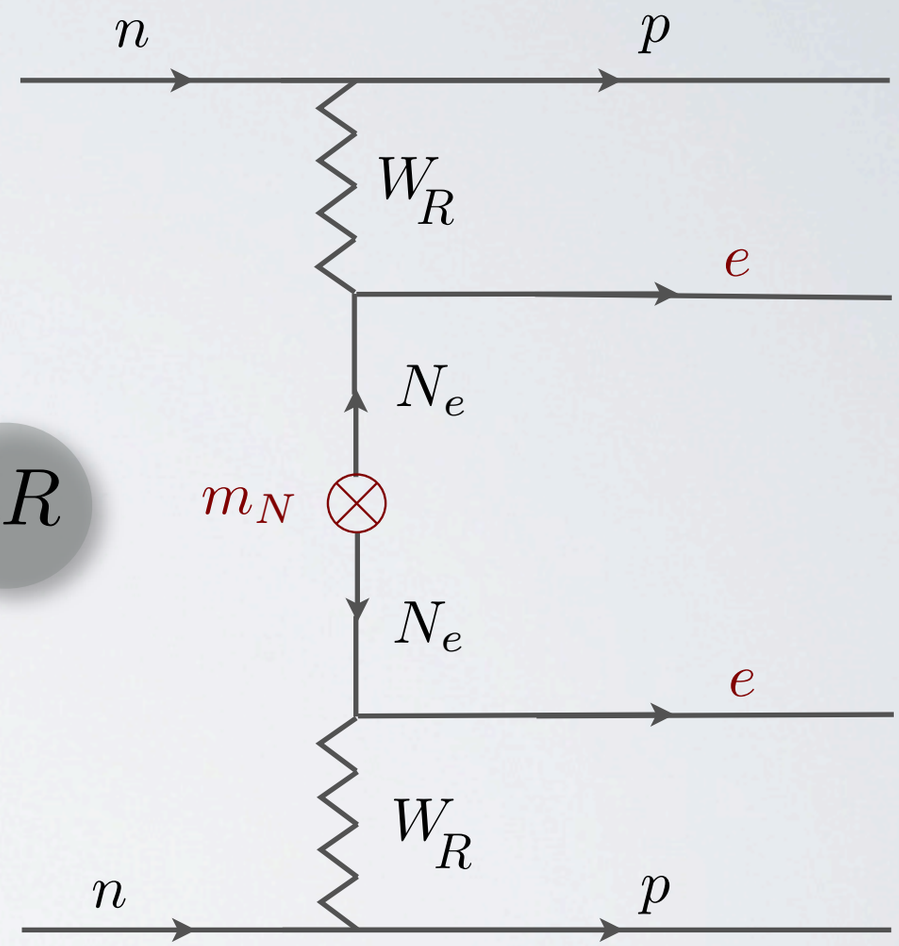
Mohapatra, GS '81



LL

$$LL \propto \frac{1}{M_{W_L}^4}\frac{m_\nu}{p^2}$$

$p \simeq 100 MeV$
$m_\nu \simeq 1\, eV$



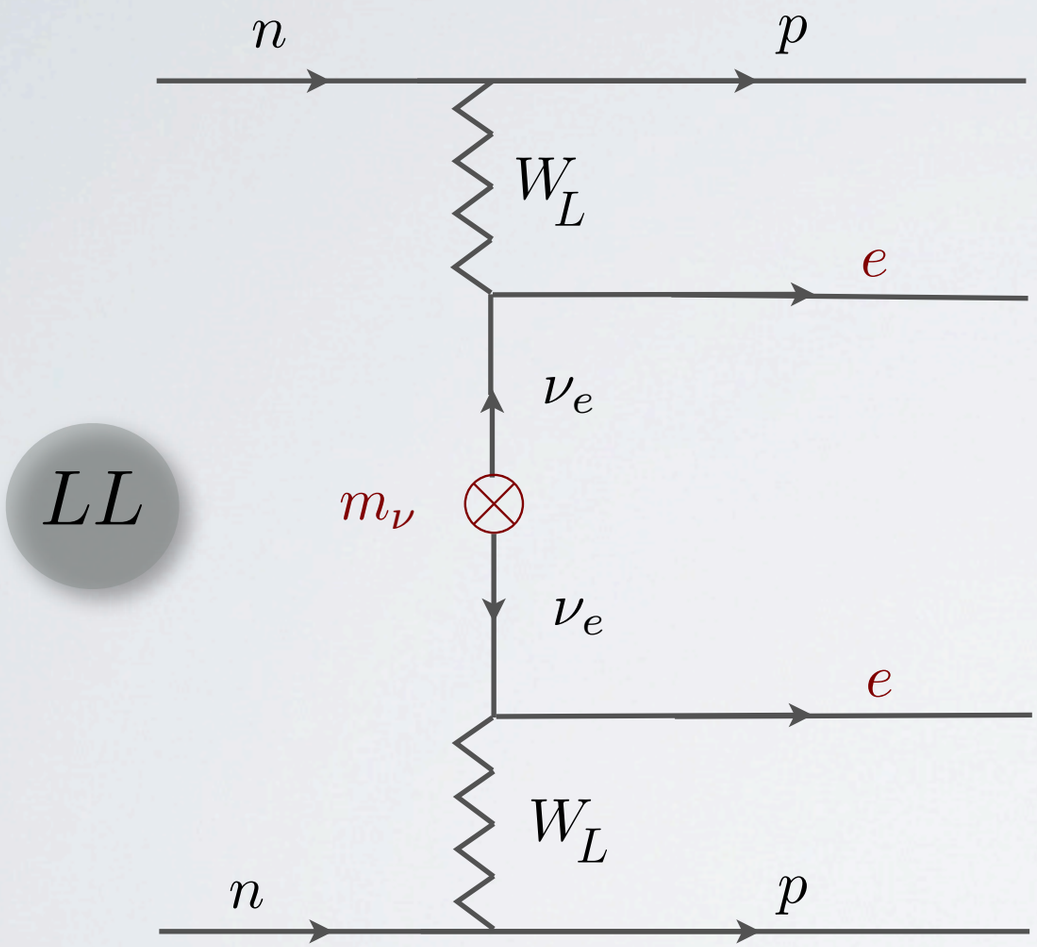
RR

$$RR \propto \frac{1}{M_{W_R}^4}\frac{1}{m_N}$$

$M_{W_R} \simeq m_N \simeq 10 M_{W_L}$

New source for $0\nu 2\beta$

Mohapatra, GS '81



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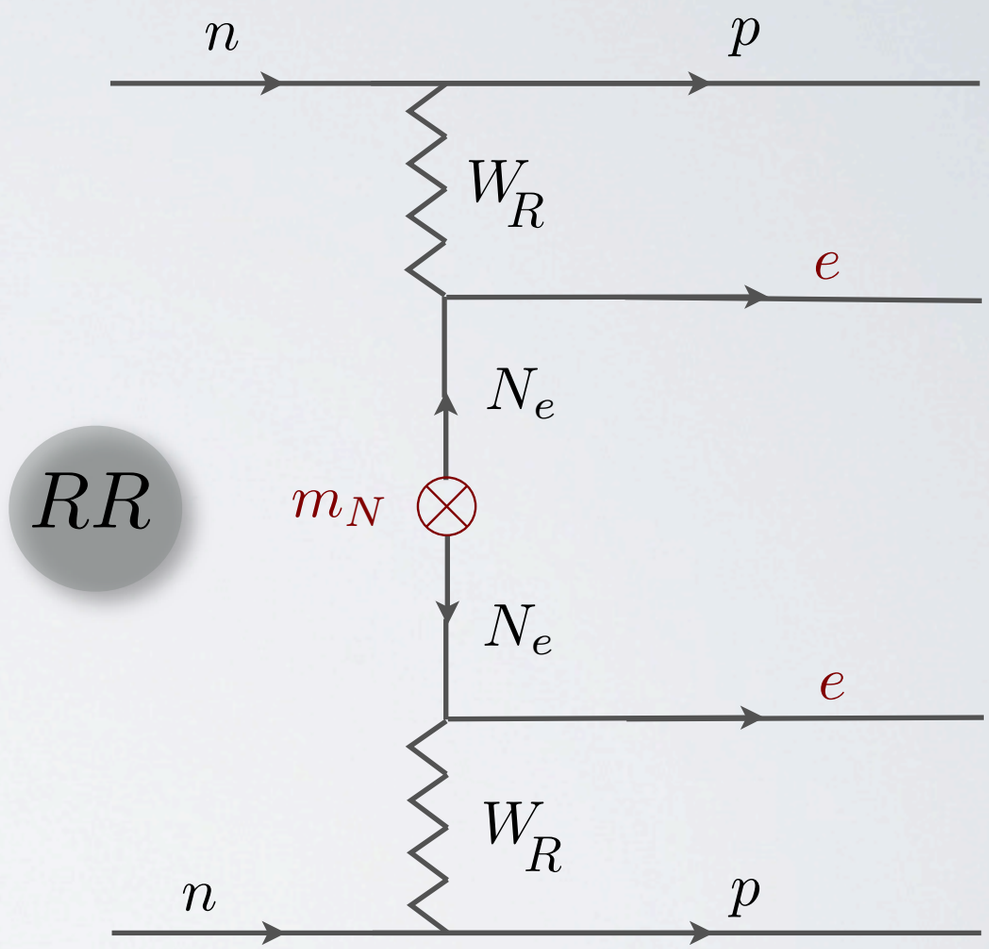

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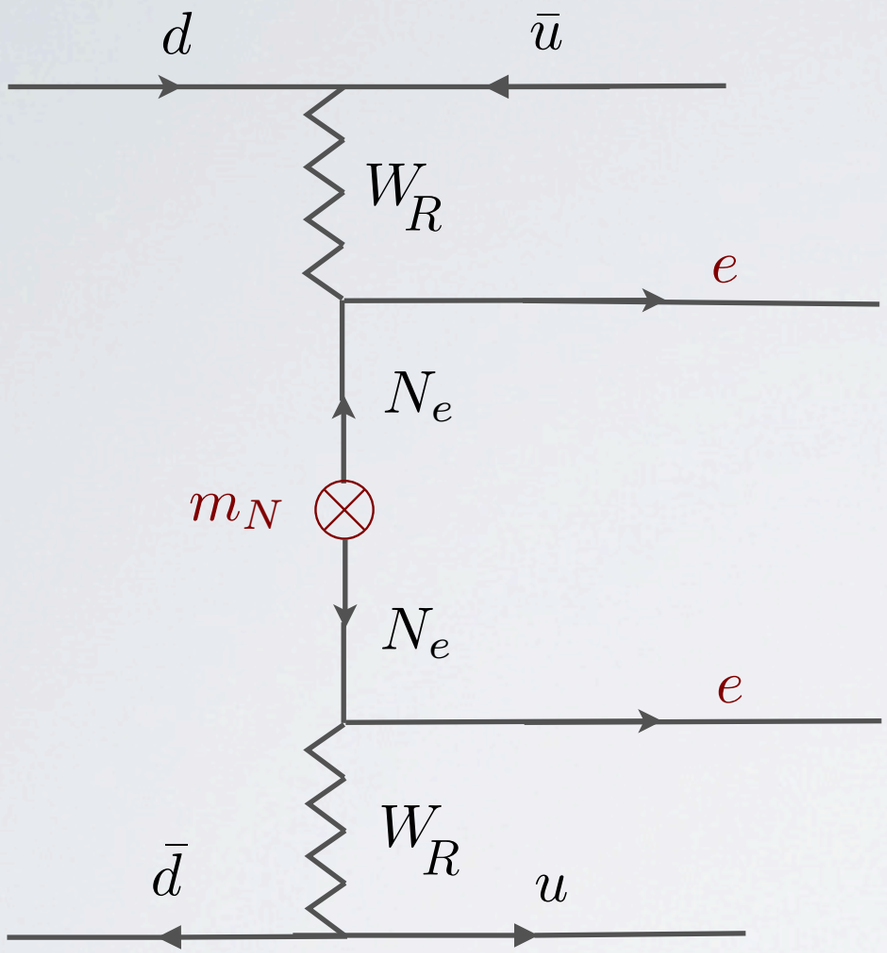
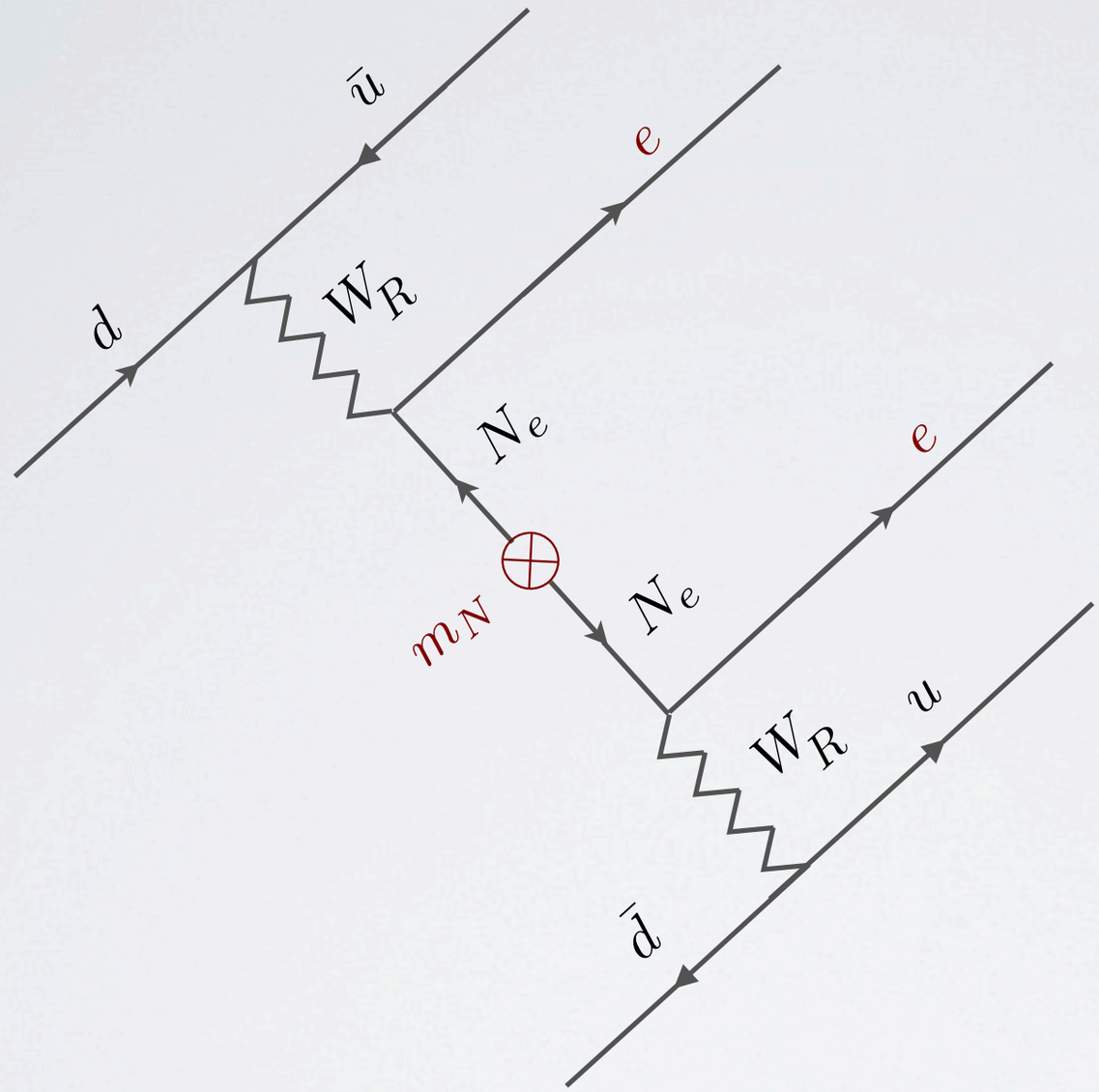


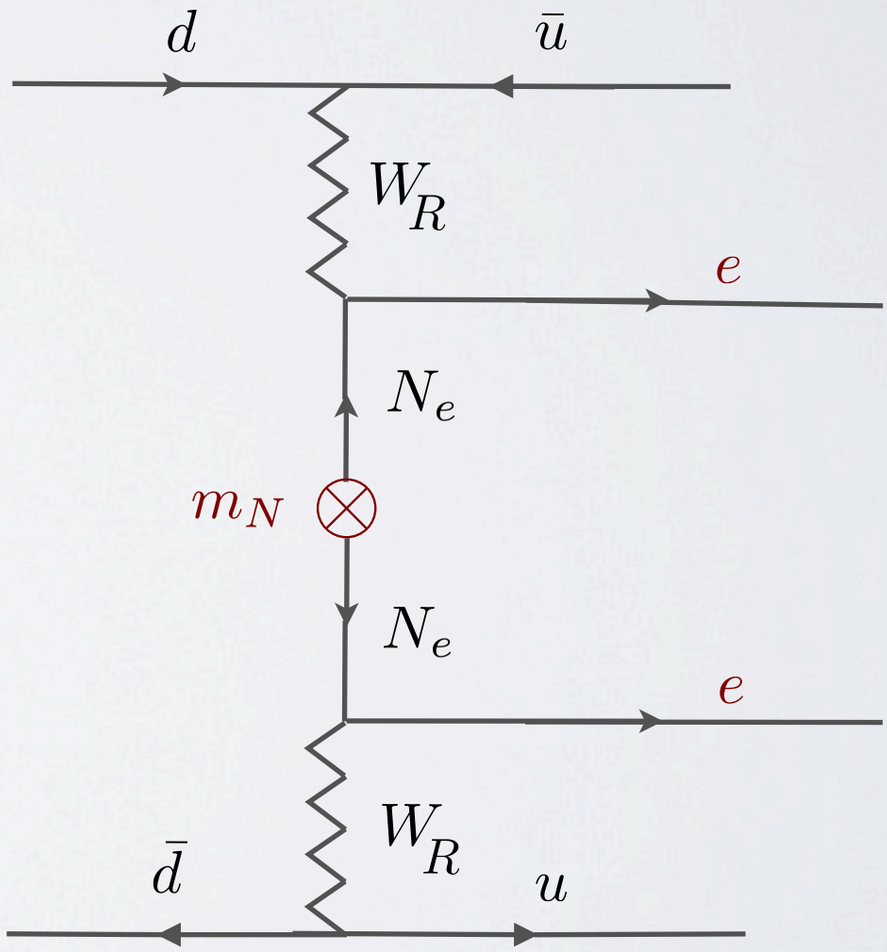
Tello, Nemevsek, Nesti, GS, Vissani, PRL'11

(if double beta claim **true)**
neutrino mass **small** (cosmology)

New Physics (W_R, N) @ TeV

LHC energies


$\bar{u}$
e
d
W_R
N_e
e
m_N
N_e
W_R
u
$\bar{d}$


d
$\bar{u}$
W_R
e
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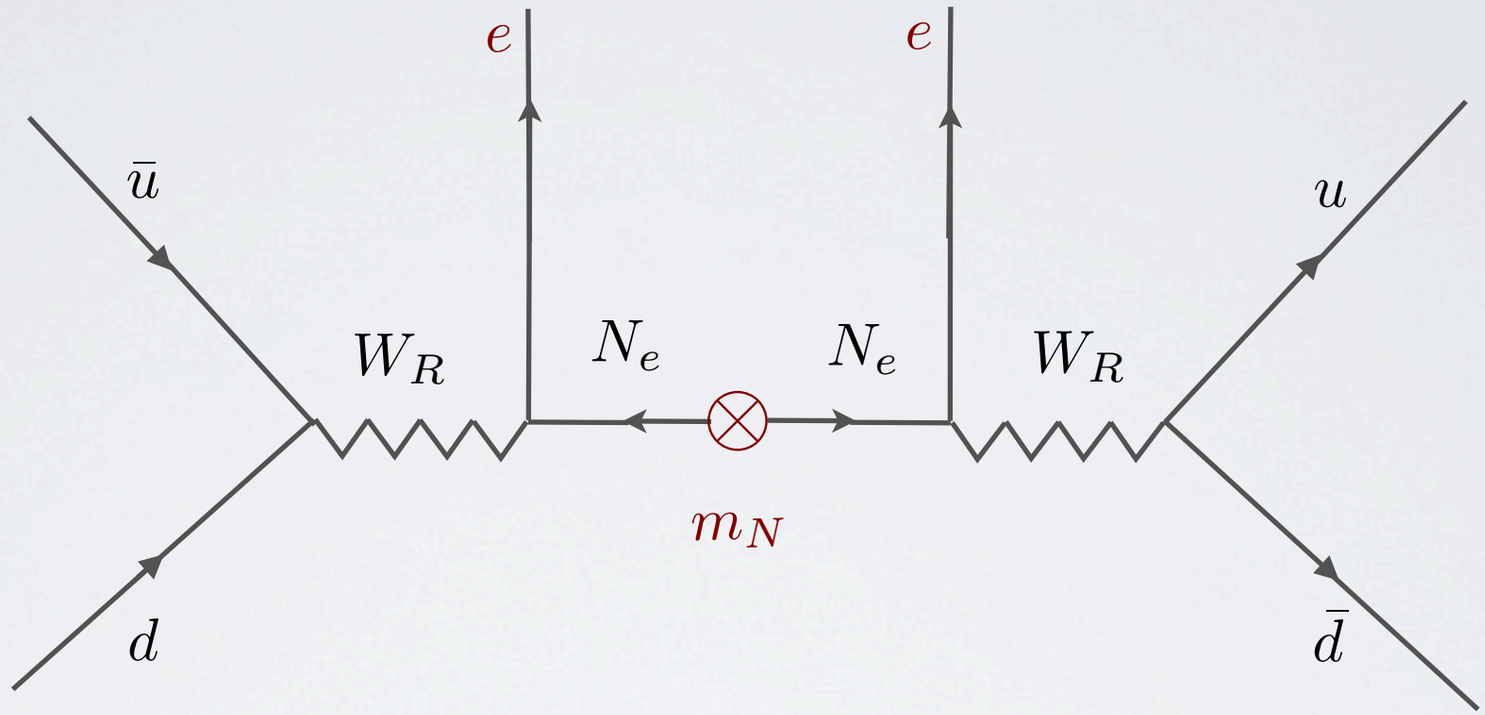
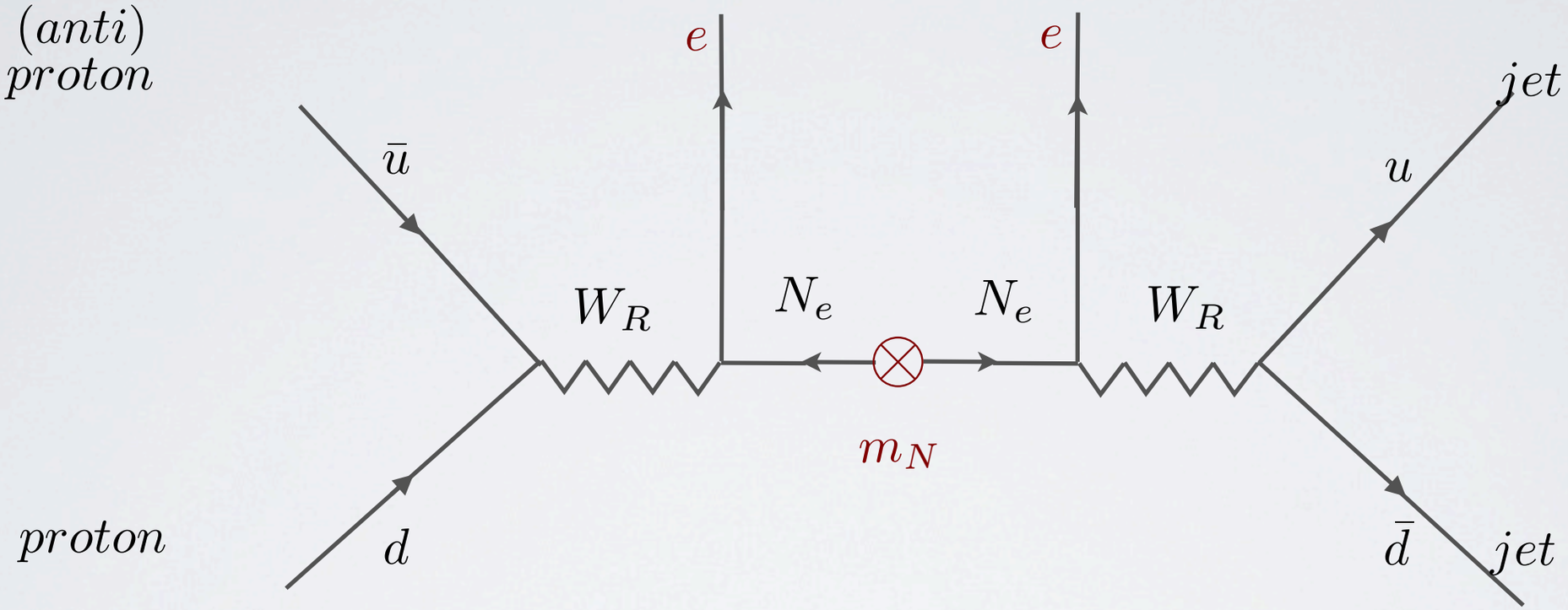
m_N
N_e
e
W_R
$\bar{d}$
u

direct probe of Majorana nature



direct probe of Majorana nature

W_R production @ colliders



- Parity restoration
- Lepton Number Violation: electrons (+ jets)

Keung, G.S. '83

both CMS and ATLAS:

dedicated study of W_R

@ 14 TeV:

W_R up to 4 TeV mass @ L= 30/fb

$100\,GeV \lesssim m_N \lesssim M_{W_R}$ up to 5.5 TeV mass @ L= 300/fb

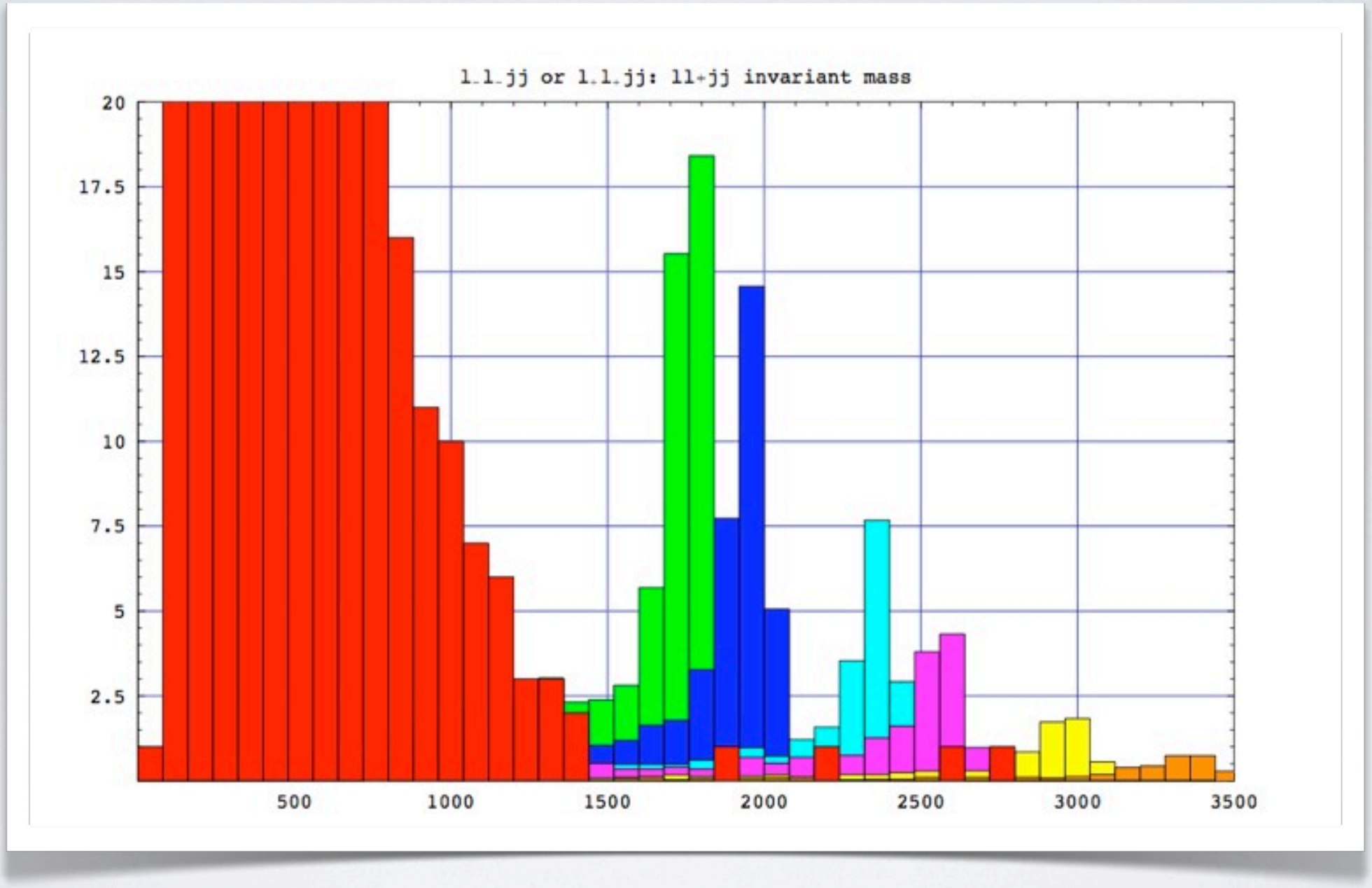
Ferrari '00

Gninenko et al '06

14 TeV LHC

Nesti

# of events as a function of energy (GeV) for $L = 10\ fb^{-1}$



red = background

peaks = mass of W_R

LHC @ E = 7 TeV

talk by Nemevsek

early data

$L = (33\text{-}34)\ pb^{-1}$

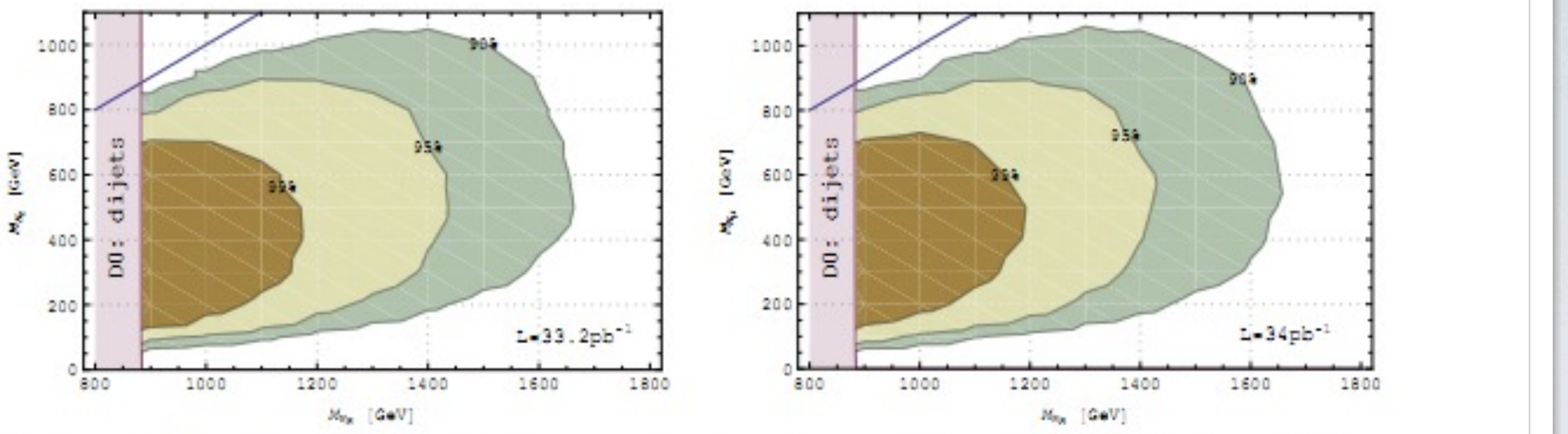


FIG. 1. Exclusion (90%, 95%, 99% CL) in the M_{W_R}–m_N plane from the $eejj$ (left) and $\mu\mu jj$ (right) channel. We assume no accidental cancelation in the RH lepton mixings. The 2σ lower bound ~1.4 TeV is valid over a range of RH neutrino masses of order several hundred GeV.

$$M_{W_R} \gtrsim 1400\, GeV$$

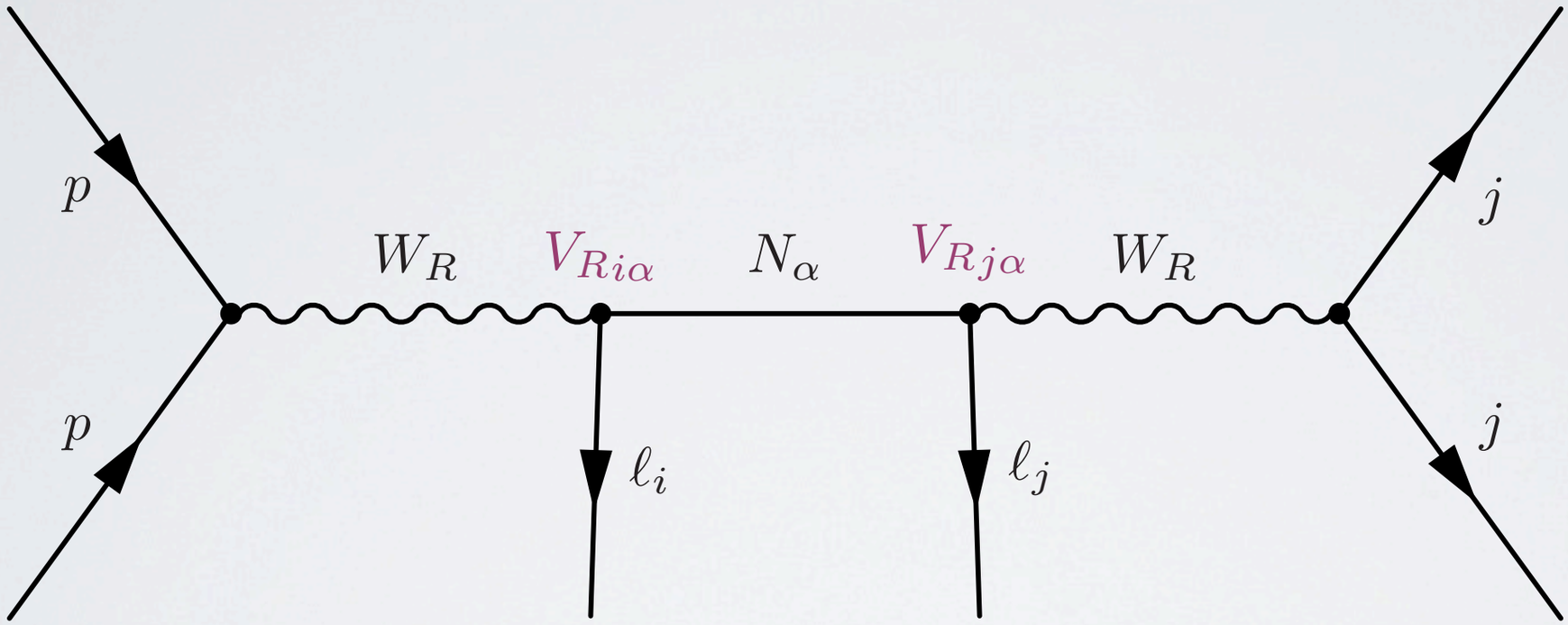
closing up on theory

Nemevsek, Nesti, GS, Zhang, '11

LHC

Tello, Nemevsek, Nesti, GS, Vissani, PRL'11

measure m_N and V_R



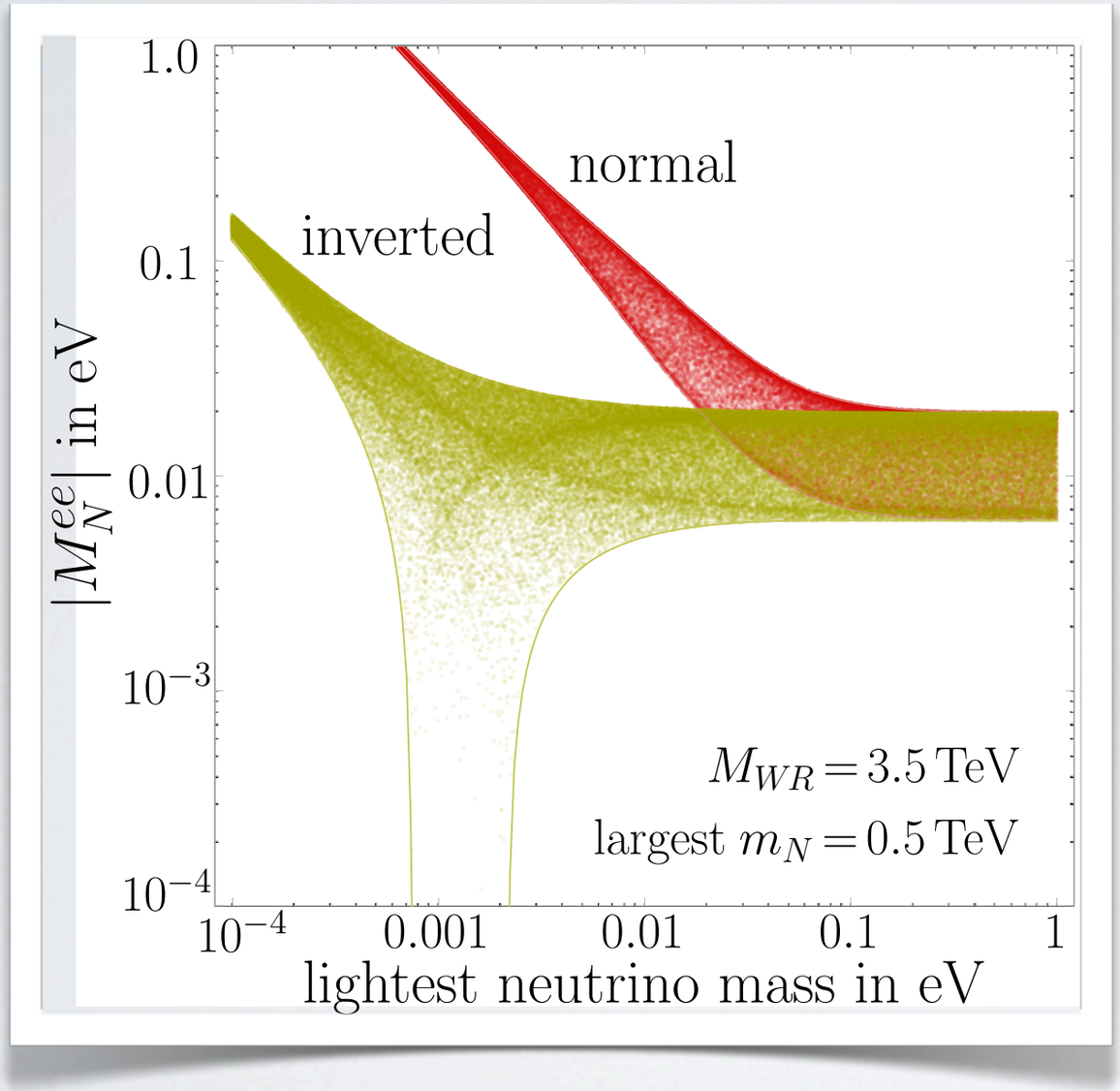
in order to illustrate:

$$V_R = V_L^* \qquad\qquad m_N/m_\nu = const$$

type II seesaw

$W_R - N$ contribution

Tello et al '11

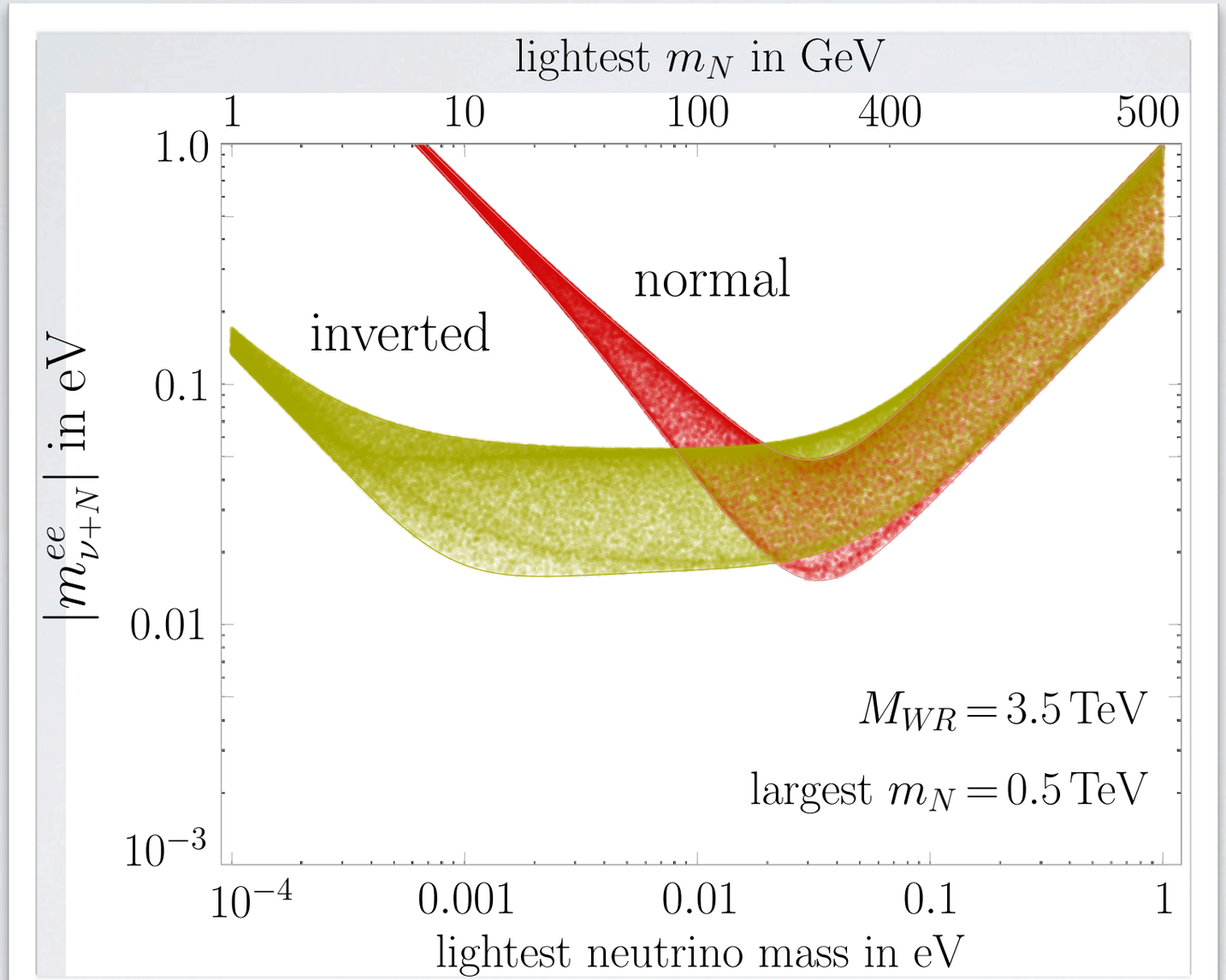


normal hierarchy dominates

opposite from m_ν

talk by Nemevsek

both Left and Right



non-vanishing

talk by Nemevsek

Model content: bidoublet $\phi \sim (h_{light}, H_{heavy})$, triplets Δ_L, Δ_R,

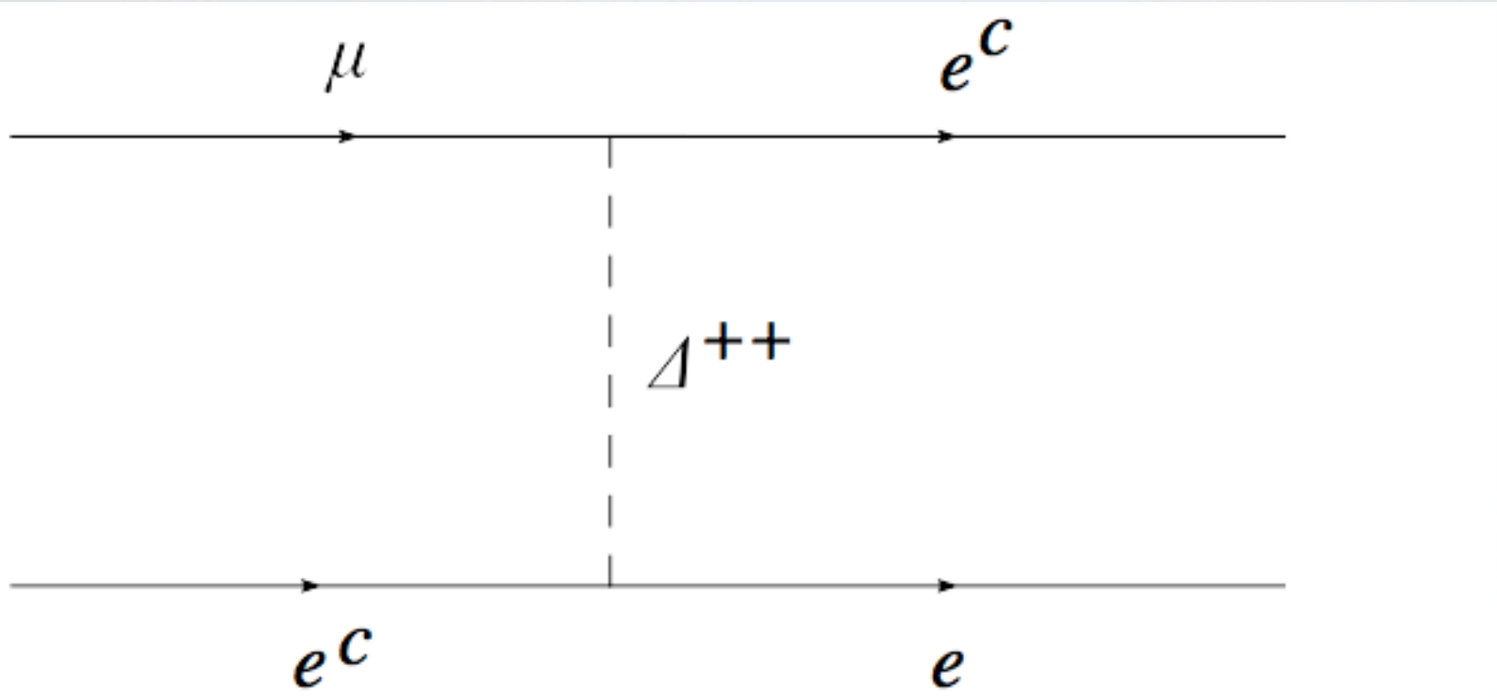
$$\langle \Delta_L \rangle = \begin{pmatrix} & \\ v_L & \end{pmatrix}, \qquad \langle \Delta_R \rangle = \begin{pmatrix} & \\ v_R & \end{pmatrix}, \qquad \langle \phi \rangle = \begin{pmatrix} v & \\ & v' \end{pmatrix}$$

$$v_L << v' < v << v_R$$

Mohapatra, GS '75, '81

Type II small Yukawa Dirac

LFV $\mu \to e\, e^c e$



$$B(\mu \to 3e) = \frac{|Y_{e\mu} Y_{ee}^*|^2}{4G_F^2} \left(\frac{1}{M_{\Delta_L}^4} + \frac{1}{M_{\Delta_R}^4} \right)$$

$$Y_\Delta = \frac{g_R}{M_{W_R}} V_R^T M_N V_R$$

Cirigliano et al '04

Tello '08

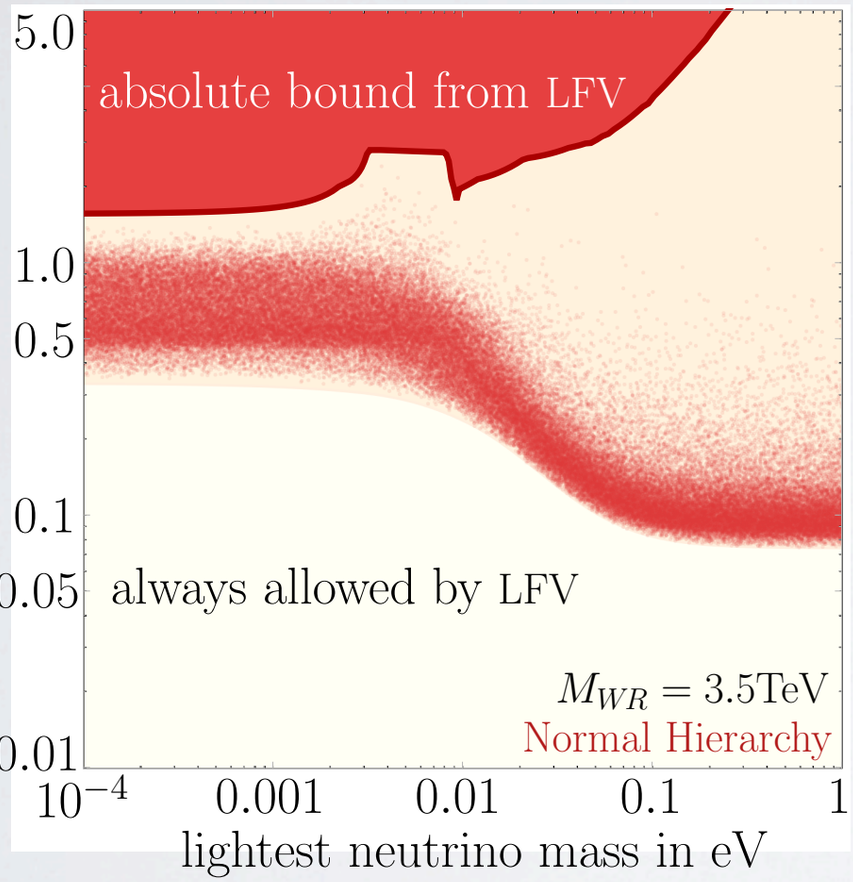
Loop induced

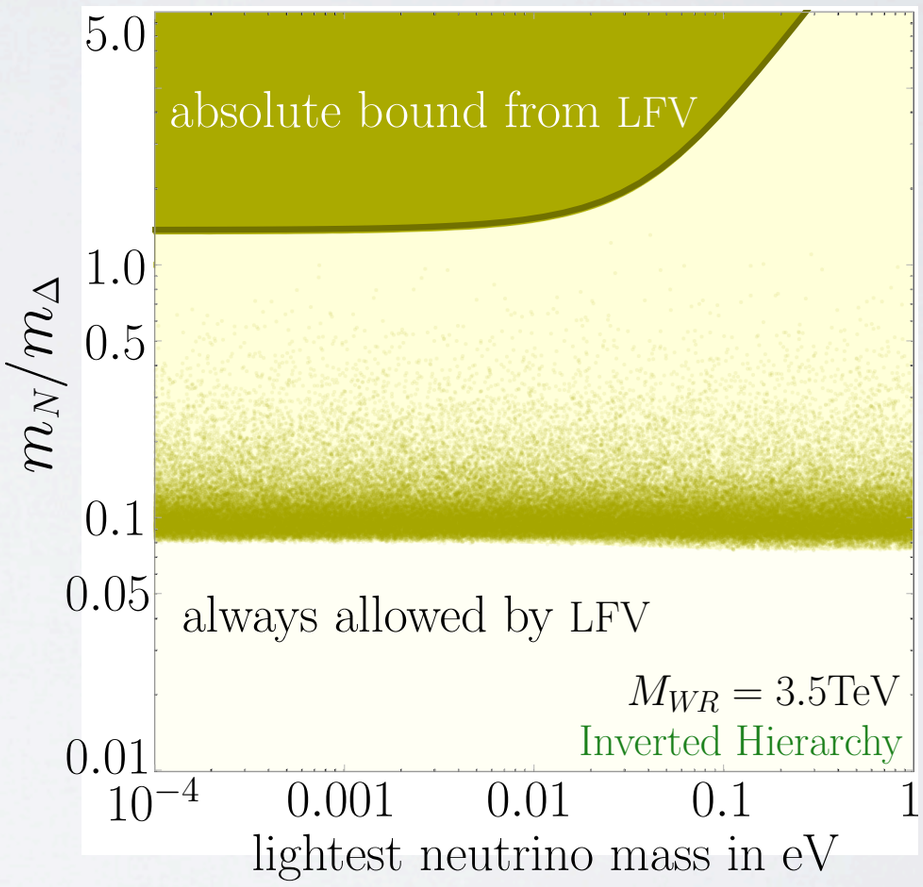
$\mu \to e\,\gamma$

$\mu \to e$ conversion in nuclei

Lepton Flavor Violation

talk by Nemevsek





$\mu \to e$ conversion in nuclei

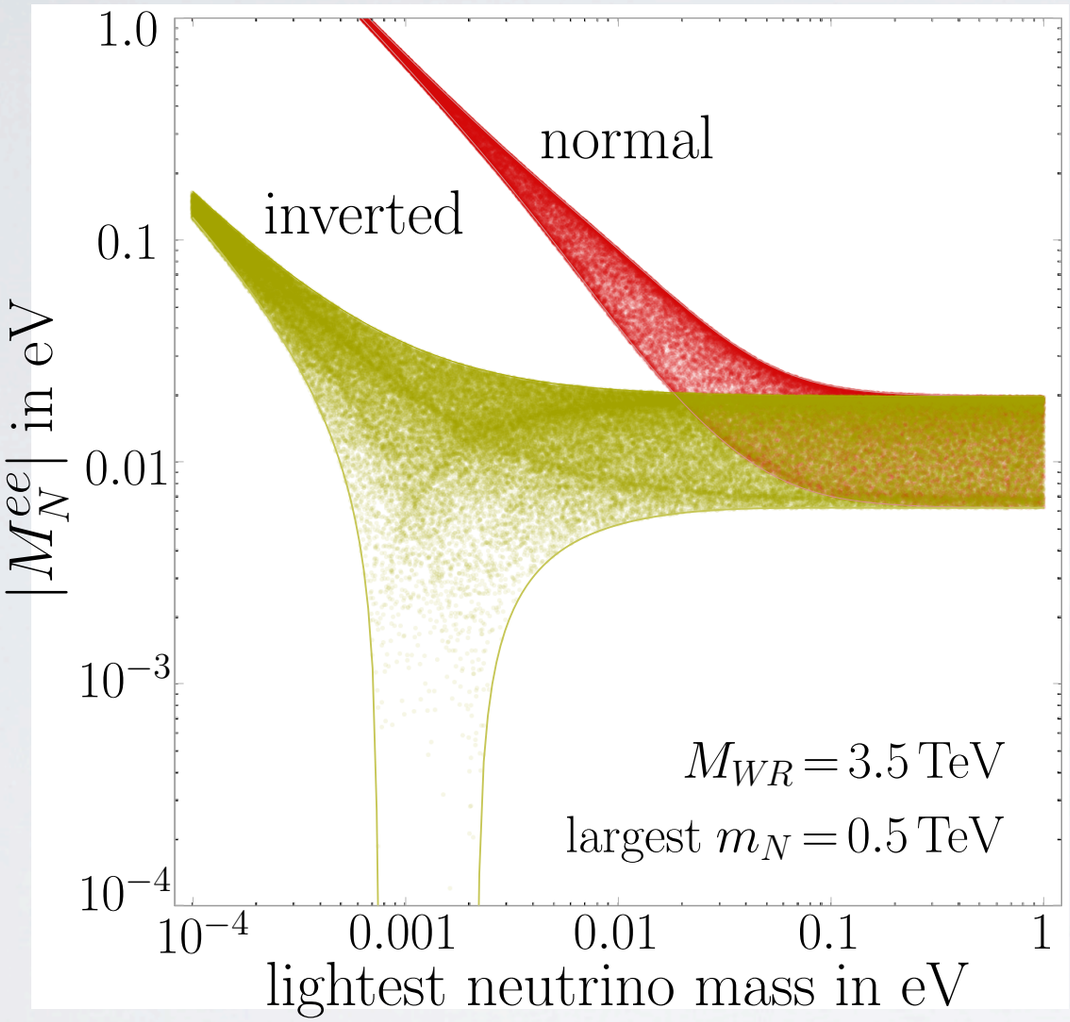
4-6 order of magnitude improvement ?

Fermilab, J/Park

probe leptonic CP from
spin correlations

Bajc, Nemevsek, GS '09

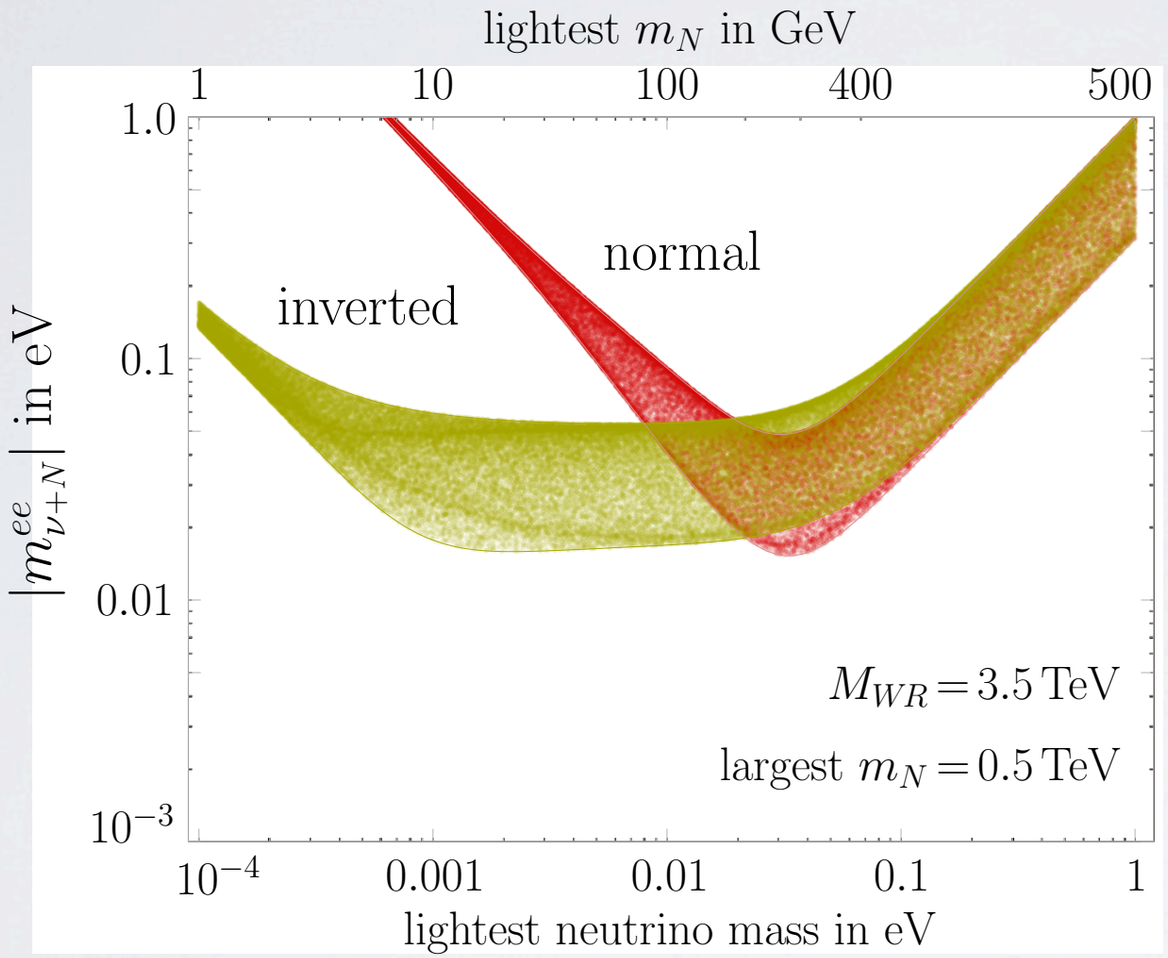
$W_R - N$ contribution



normal hierarchy dominates

opposite from m_ν

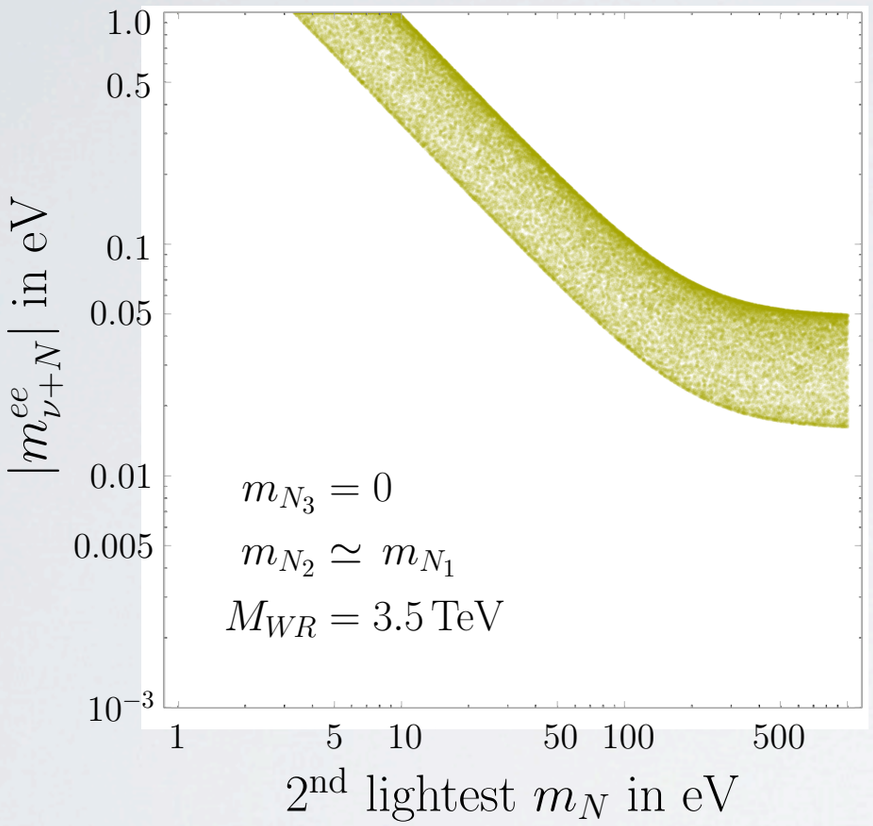
both Left and Right

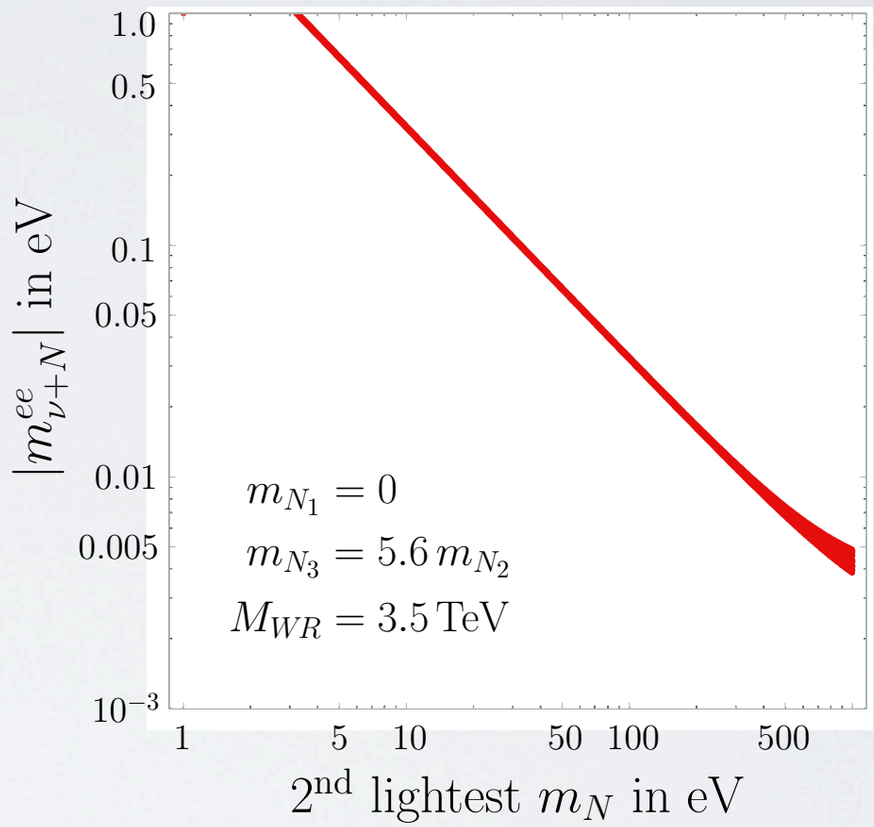


non-vanishing

Hannestad et al, '2010

BBN: $N_{eff} = 4$ ➔ three ν + N_1





IH

NH

Tello et al '2011

Message:

LHC

- can probe the origin of neutrino mass
- can resolve the mystery of L-R symmetry

STAY TUNED

Thank you