Neutrino Paradigm and LHC

Goran Senjanović
ICTP, Trieste

La Sapienza, March 30, 2012

Neutrino Mass

only new established physics beyond SM

if Majorana

➘ window

new physics

how serious a chance at LHC ?

Effective operators and New Physics

SM degrees of freedom

two operators stand out

$$\mathcal{L}_\nu = Y^\nu_{eff} \frac{\ell\ell H H}{\Lambda_\nu}$$

$$\mathcal{L}_p = Y^p_{eff} \frac{qqq\ell}{\Lambda_p^2}$$

$$\Rightarrow Y^\nu_{eff} \frac{v^2}{\Lambda_\nu} \nu\nu$$ Majorana mass

Weinberg '79

Wilczek, Zee '79

$Y_{eff} \simeq 1$ ➡ $\Lambda_\nu \lesssim 10^{14}\, GeV$ $\Lambda_p \gtrsim 10^{15}\, GeV$

Grand Unification?

suggestive: $\Lambda_\nu \lesssim \Lambda_p \simeq M_{GUT}$

SO(10) tailor made

minimal supersymmetric version:

$\theta_{\rm atm} \simeq 45^o \Leftrightarrow \theta_{ub} \simeq 0$

Bajc, GS, Vissani '02

Goh, Mohapatra, Ng '03

....

GS: RNC '11

$\theta_{13} \simeq 10^o$

$\Downarrow$

T2K, Daya Bay

No LHC

Fermi theory

$$G_F = \frac{1}{\Lambda^2}$$

$$\Lambda \simeq 300\, GeV$$

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} \qquad g \simeq 0.6$$

$$M_W \simeq 80\, GeV$$

True scale can be (much) smaller

$$G_N = \frac{1}{M_P^2}$$

$$M_P \simeq 10^{19}\, GeV$$

$$G_N = \frac{g^2}{\Lambda_F^2} \qquad g \ll 1$$

$$\Lambda_F \simeq TeV$$

$$\Uparrow \quad g = (\Lambda_F R)^{-n/2}$$

ADD '98

large extra dimensions

Talk:

- a case for LHC as a neutrino machine
- case study of a (the?) theory
- seesaw at LHC

crucial role:

neutrinoless double beta decay

Dirac '31

Dirac equation

anti particles

particle $\Rightarrow$ different antiparticle

for every fermion

not necessarily, says Majorana

Ettore Majorana March 26 1938

took a boat from Palermo to Napoli -
never seen afterwards

only 32

"A slightly uncertain destination"

beautiful novel,
physics remarkably correct

neutrino = anti neutrino ?

Majorana '37

neutron

Lepton Number Violation:

`creation of electrons'

- neutrino less double beta decay

Racah'37

Furry '38

- colliders - LHC

Keung, GS '83

Parity violation in weak interaction

Lee, Yang '56

not well known:
they argue it is a
hidden symmetry *

* mirror fermions

SO(2N) unified
thoeries

Gell-Mann, Ramond, Slansky '79

GS, Wilczek, Zee '84

Bagger, Dimopoulos '84

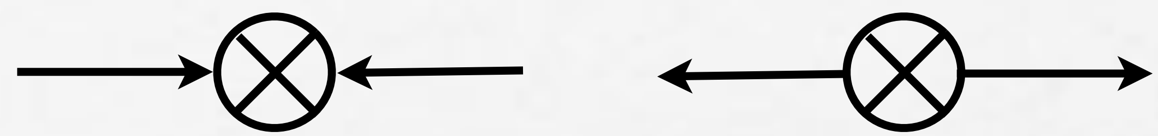
Martinez, Melfo, Nesti, GS '11

Melfo, Nemevsek, Nesti, GS, Zhang '11

Majorana Program:

neutrino mass

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



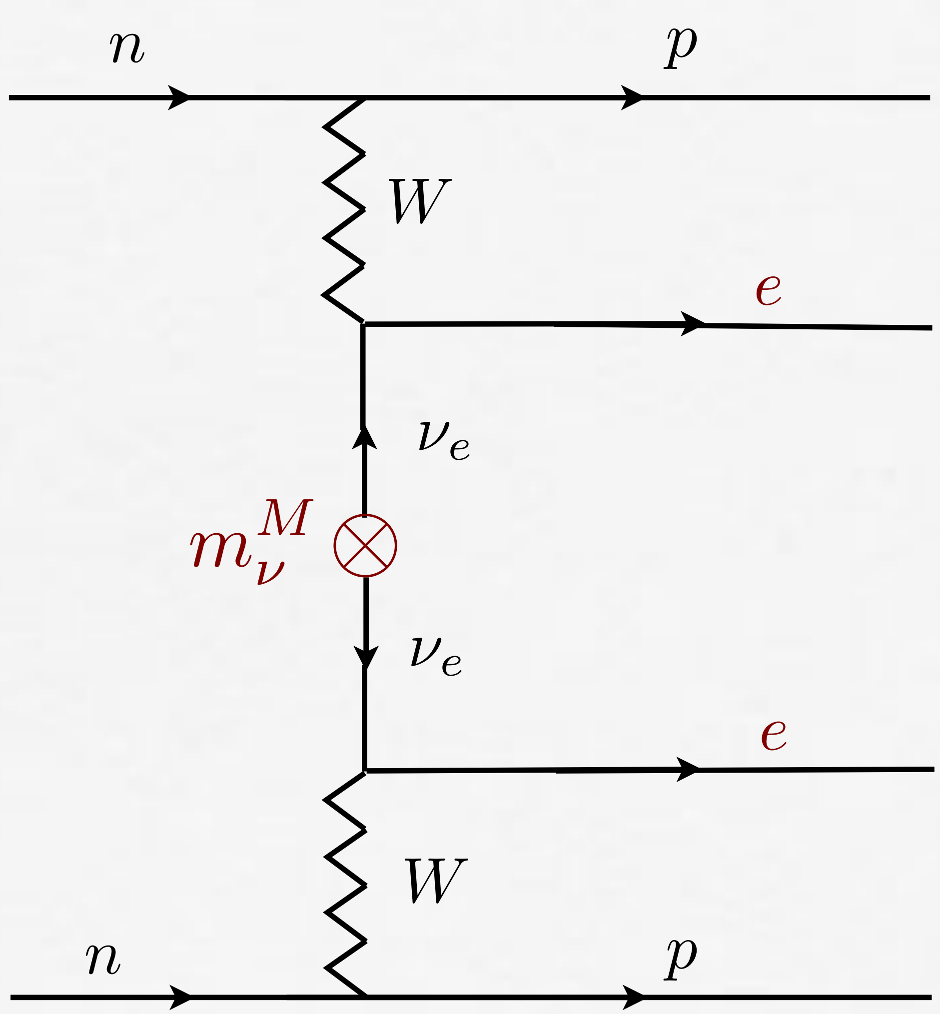
$$\Delta L = 2$$

lepton number violation

Neutrinoless Double-beta decay

Goepert-Mayer '35

$$^{76}_{32}Ge \not\to ^{76}_{33}As + e + \bar{\nu} \quad \Rightarrow \quad ^{76}_{32}Ge \to ^{76}_{34}Se + e + e + \bar{\nu} + \bar{\nu}$$



$$^{76}_{32}Ge \to ^{76}_{34}Se + e + e$$

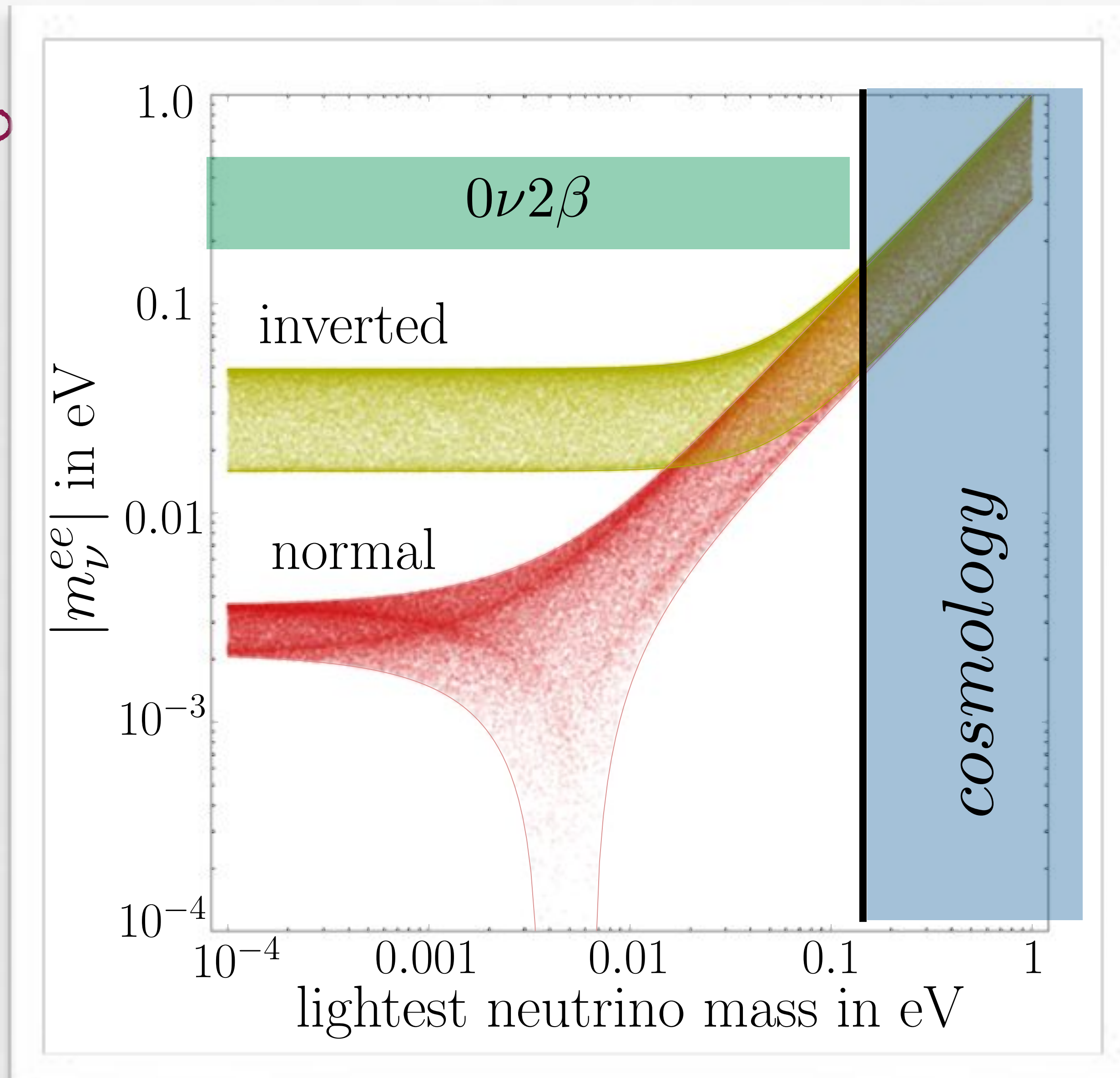
proportional to neutrino mass

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

Neutrino mass contribution

Klapdor '01-10

HM



		central value
Δm^2_{12}	$=$	$(7.58 \pm 0.21)\, 10^{-5}\, \mathrm{eV}^2$
$\vert\Delta m^2_{23}\vert$	$=$	$(2.40 \pm 0.15)\, 10^{-3}\, \mathrm{eV}^2$
$\tan^2\theta_{12}$	$=$	0.484 ± 0.048
$\sin^2 2\theta_{23}$	$=$	1.02 ± 0.04
$\sin^2 2\theta_{13}$	$=$	0.07 ± 0.04

Seljak et al '06

Hannestad et al '10

Vissani '99

0.09 ± 0.02

Experiments

Experiment	Isotope	Mass of Isotope [kg]	Sensitivity $T_{1/2}^{0\nu}$ [yrs]	Sensitivity $\langle m_\nu \rangle$, meV	Status	Start
GERDA	^{76}Ge	18	3×10^{25}	~ 200	running!	2011
		40	2×10^{26}	~ 70	in progress	$\sim$ 2012
		1000	6×10^{27}	10-40	R&D	$\sim$ 2015
CUORE	^{130}Te	200	$(6.5 \div 2.1) \times 10^{26}$	20-90	in progress	$\sim$ 2013
MAJORANA	^{76}Ge	30-60	$(1 \div 2) \times 10^{26}$	70-200	in progress	$\sim$ 2013
		1000	6×10^{27}	10-40	R&D	$\sim$ 2015
EXO	^{136}Xe	200	6.4×10^{25}	100-200	in progress	$\sim$ 2011
		1000	8×10^{26}	30-60	R&D	$\sim$ 2015
SuperNEMO	^{82}Se	100-200	$(1 - 2) \times 10^{26}$	40-100	R&D	$\sim$ 2013-2015
KamLAND-Zen	^{136}Xe	400	4×10^{26}	40-80	in progress	$\sim$ 2011
		1000	10^{27}	25-50	R&D	$\sim$ 2013-2015
SNO+	^{150}Nd	56	4.5×10^{24}	100-300	in progress	$\sim$ 2012
		500	3×10^{25}	40-120	R&D	$\sim$ 2015

Rodejohann'11

GERDA started

if confirmed

new physics necessary?

$$\mathcal{A}_\nu \propto \frac{G_F^2 m_\nu^{ee}}{p^2} \simeq G_F^2 \; 10^{-8} \, GeV^{-1}$$

Feinberg, Goldhaber '59

Pontecorvo '64

$(p \simeq 100 \, MeV)$

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

$\Lambda \sim TeV$ **LHC**

Neutrino mass: theory

Standard Model

$$SU(2)_L \times U(1)$$

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad e_R \qquad \text{no } \nu_R$$

L-R asymmetry

neutrino massless

L-R symmetry

Lee, Yang dream

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad e_R \qquad \begin{matrix} u_R \\ d_R \end{matrix}$$

$$W_L$$

L-R symmetry

Lee, Yang dream

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad \begin{pmatrix} \nu_R \\ e_R \end{pmatrix} \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

W_L $\qquad$ W_R

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

$E \gg m_{W_R}$ parity restored?

Pati, Salam '74

Mohapatra, GS '75

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

$$Q = T_L^3 + T_R^3 + \frac{B-L}{2}$$

- hypercharge Y:

traded for

gauge B-L

- RH neutrinos:

LR symmetry & no B-L anomaly

Minimal model:

theoretical limit

$M_{W_R} \gtrsim 2.5\,\mathrm{TeV}$ (LR=C)

$M_{W_R} \gtrsim 4\,TeV$ (LR=P)

Maiezza, Nemevsek, Nesti, GS '10

rare processes:

$K_L - K_S$ mass difference...

Beall, Bander, Soni '81

Mohapatra, GS, Tran '83

Ecker, Grimus '85

...

Zhang, An, Ji, Mohapatra '07

experiment is catching up !

Neutral gauge boson

Z_{LR}

$$\frac{M_{Z_{LR}}}{M_{W_R}} = \frac{\sqrt{2} g_R/g_L}{\sqrt{(g_R/g_L)^2 - \tan^2\theta_W}} \cdot \quad = 1.7 \text{ for } g_L = g_R$$

very hard to see at LHC

indirectly at ILC

Curse: neutrino mass

- neutrino massive -

just like the electron

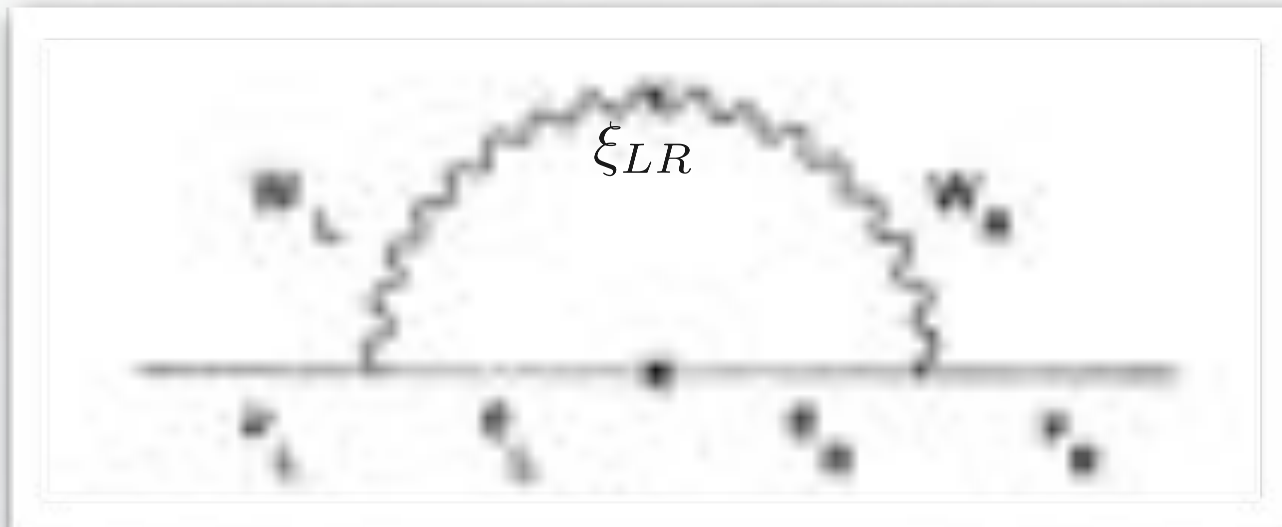
- naive expectation:

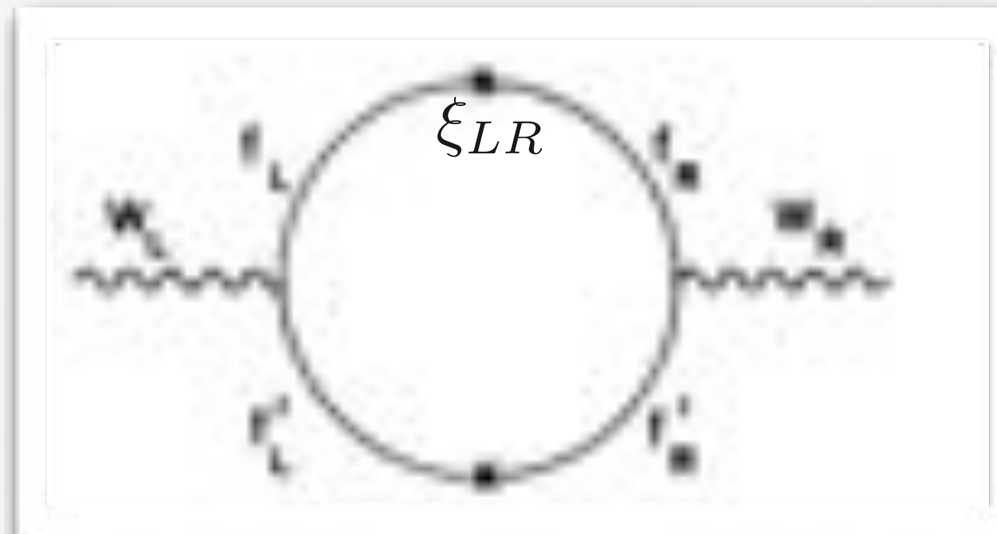
$$m_\nu \simeq m_e$$ (if Dirac particles)

more subtle

radiative stability

Branco, GS '77





$$m_D \gtrsim \frac{\alpha_W}{4\pi}\, \xi_{LR}\, m_\ell$$

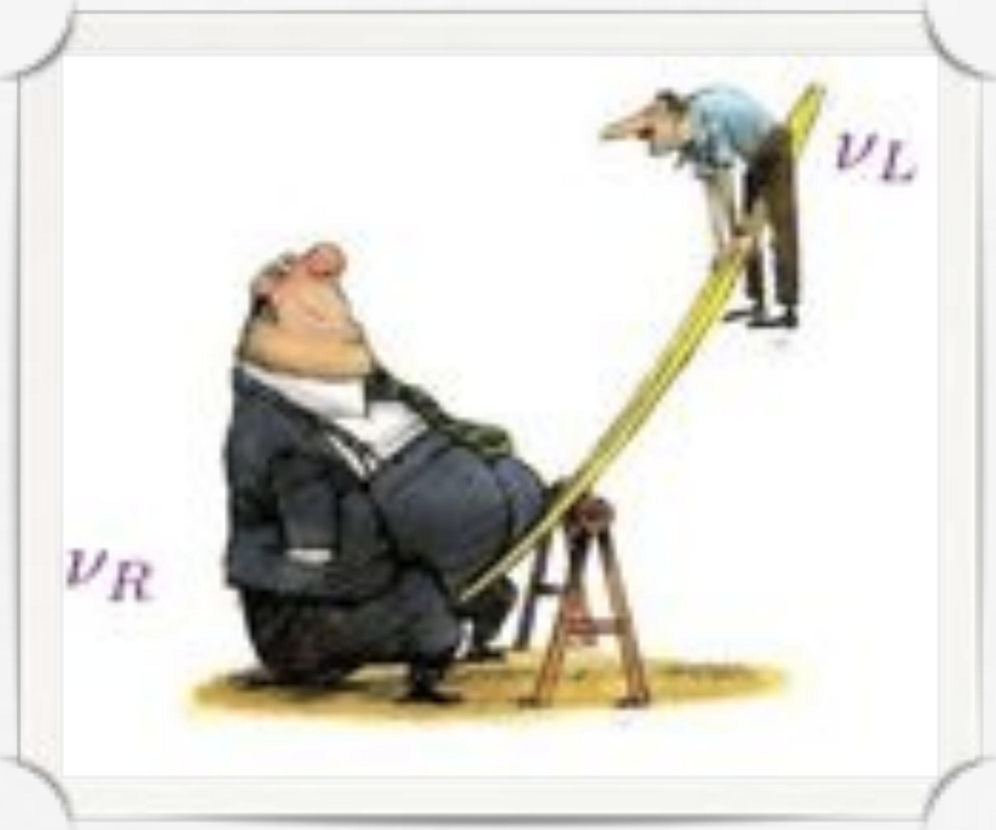
$$\gtrsim 1 - 10\, eV$$

$$\xi_{LR} \gtrsim \frac{\alpha_W}{4\pi}\, \frac{m_t m_b}{M_{W_R}^2}$$

$$\gtrsim 10^{-6}$$

for W_R in a few TeV region

Blessing: neutrino mass



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

$$\begin{matrix} \nu_L \\ \nu_R \end{matrix} \begin{pmatrix} 0 & m_D \\ m_D & M_{\nu_R} \end{pmatrix}$$

Minkowski '77

Mohapatra, GS '79

$$m_\nu = m_D^T \frac{1}{M_{\nu_R}} m_D$$

neutrino mass related to P violation

Glashow '79

Gell-Mann et al '79

Yanagida '79

seesaw

$$m_\nu \simeq \frac{m_D^2}{m_N}$$

$$m_D \gtrsim 10\,eV \qquad\qquad m_\nu \lesssim 10^{-1}\,eV$$

⇓

$$m_N \gtrsim keV$$

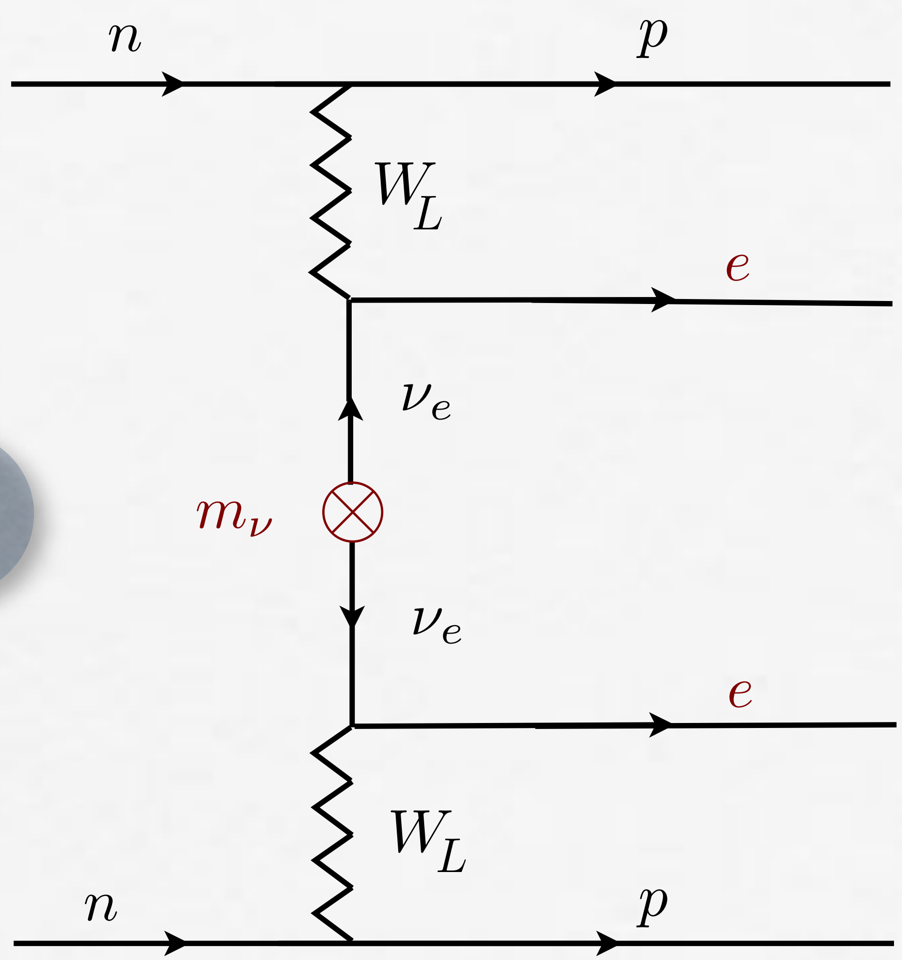
the bigger N mass, the better

$$m_N \gtrsim 100\,GeV \quad \Rightarrow \; m_D \gtrsim 100\,keV$$

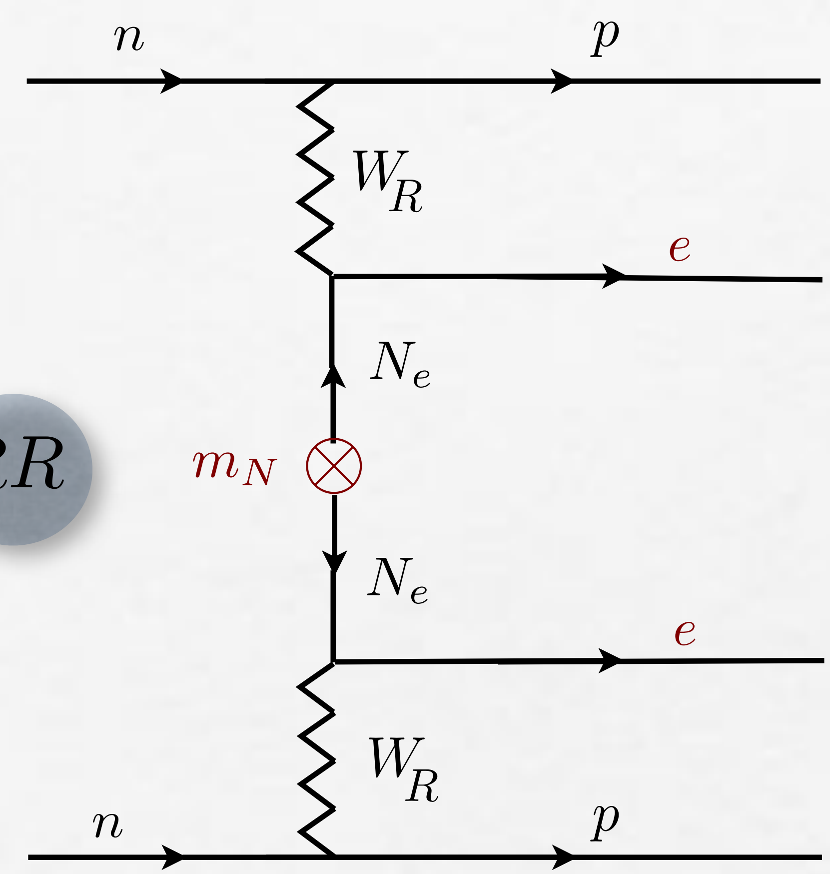
New source for $0\nu 2\beta$

Mohapatra, GS '81

LL



RR



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

N = right-handed neutrino

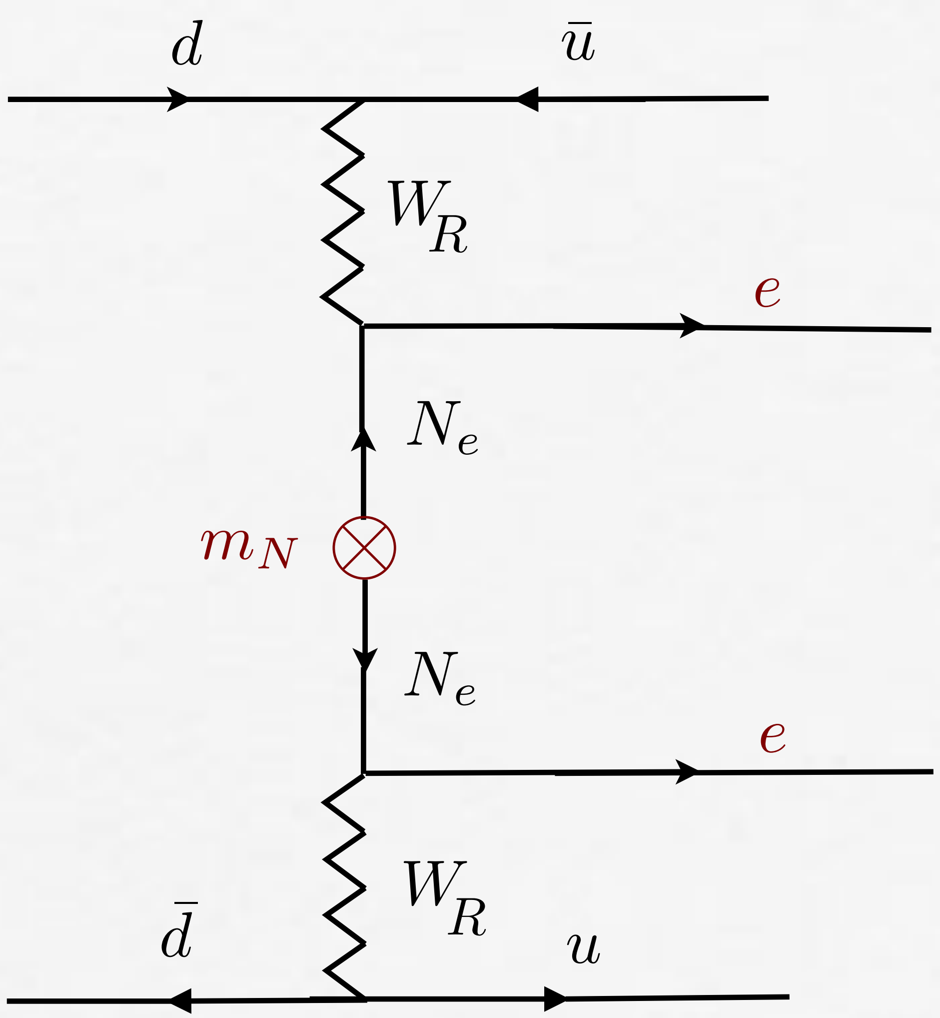
$$RR \propto \frac{1}{M_{W_R}^4} \frac{1}{m_N}$$

$p \simeq 100 MeV$

$m_\nu \simeq 1\, eV$

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

LHC connection?



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

Nemevsek, Nesti, GS, Tello 1112.3061 [hep-ph]

If neutrino mass **small**

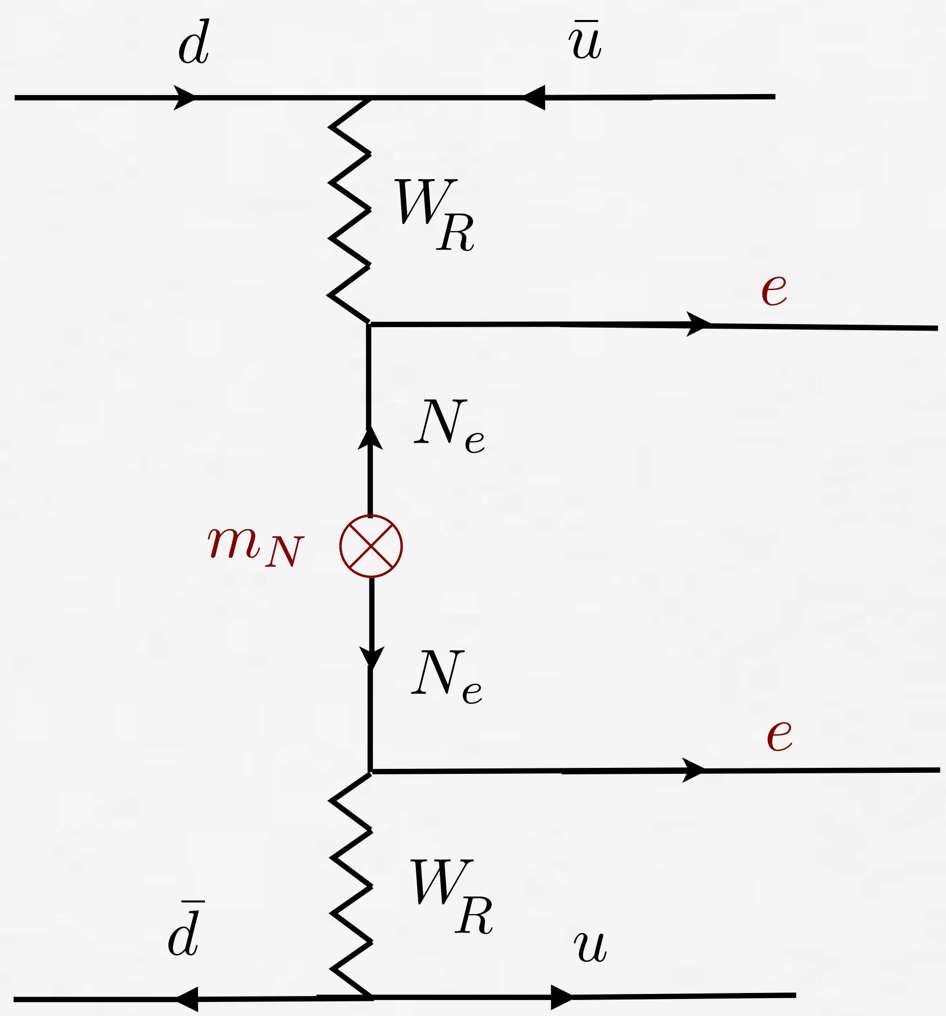
⬇

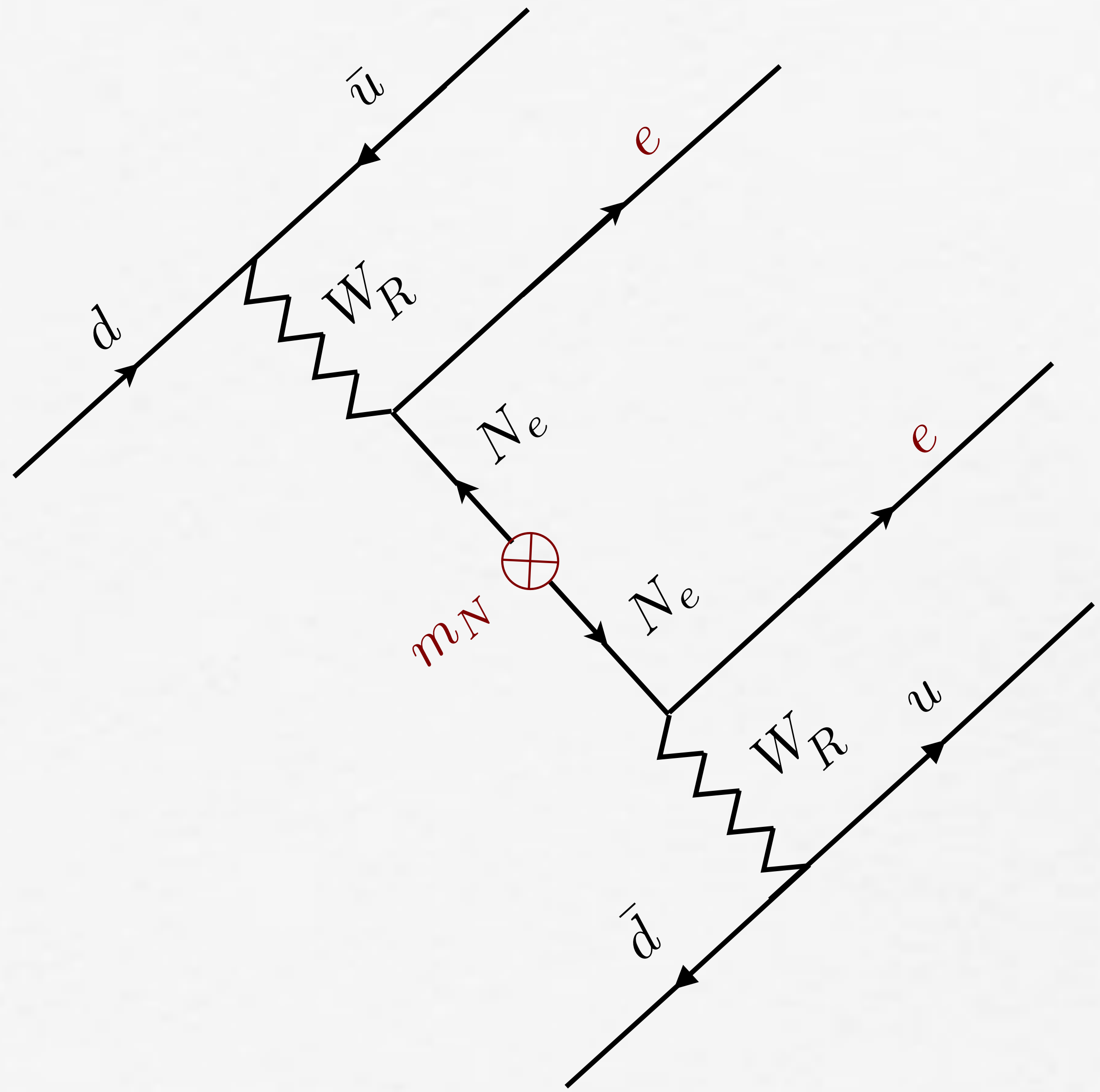
$(W_R$, N) @ TeV

connection with LHC?

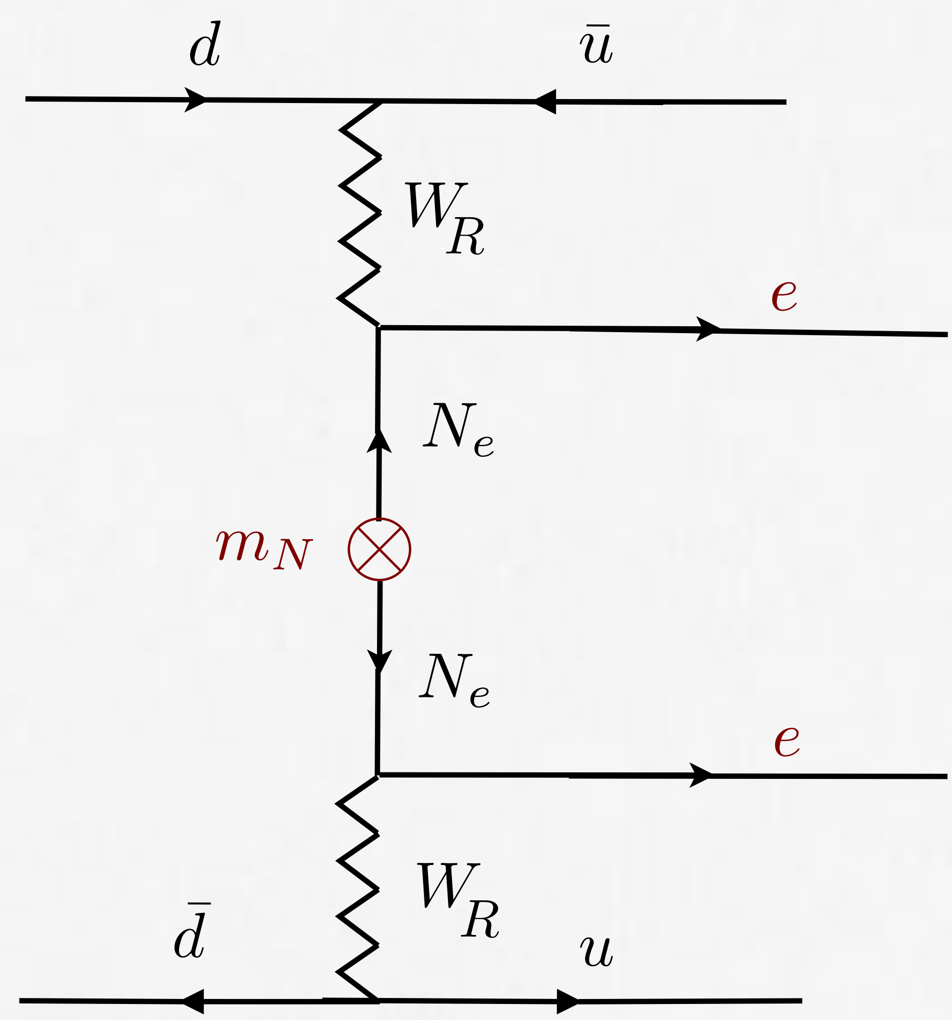
Keung, G.S. '83

rotation in a plane

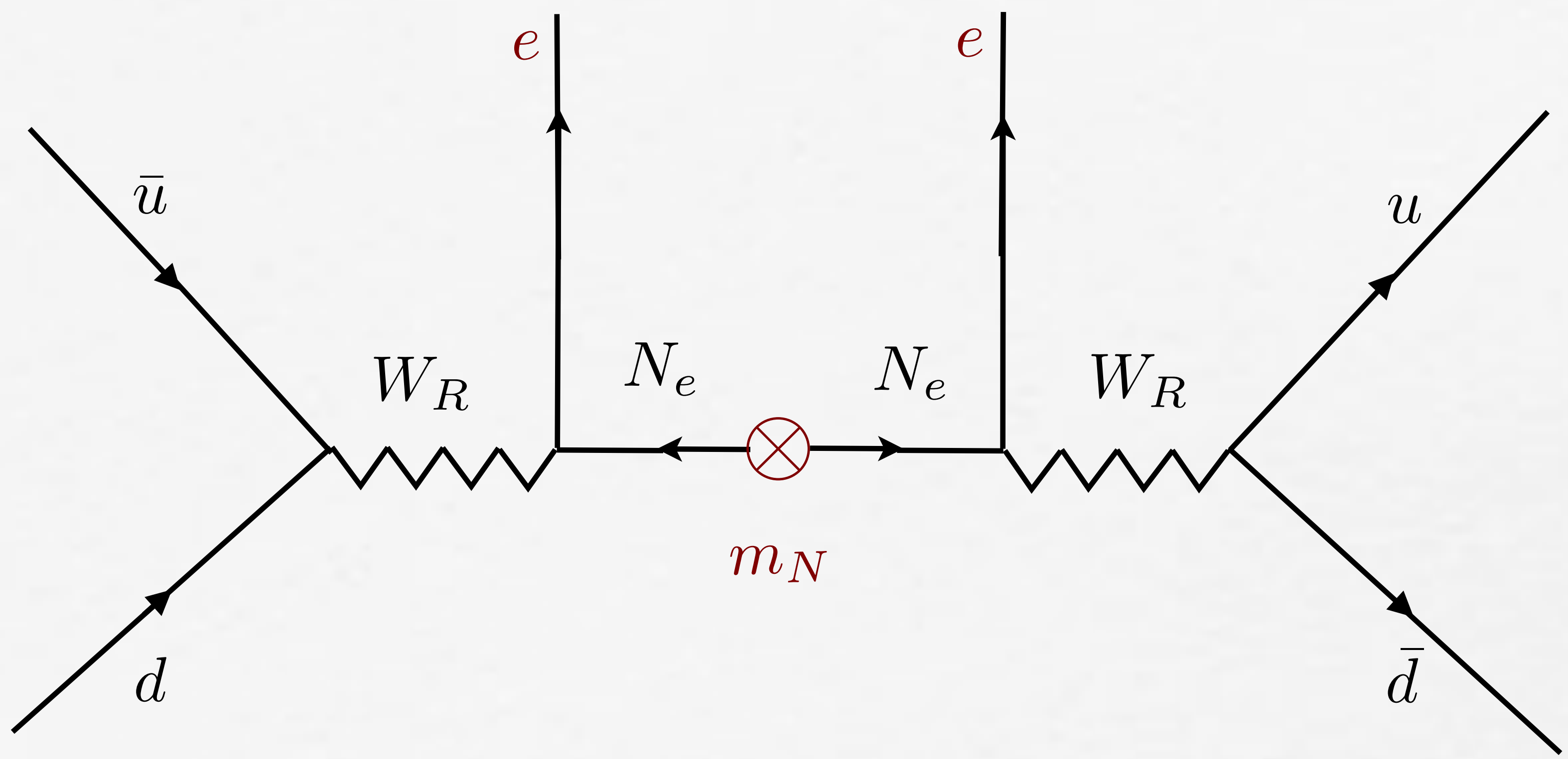




$\bar{u}$
e
d
W_R
N_e
e
m_N
N_e
u
W_R
$\bar{d}$



d
ū
W_R
e
N_e
m_N
N_e
e
W_R
d̄
u

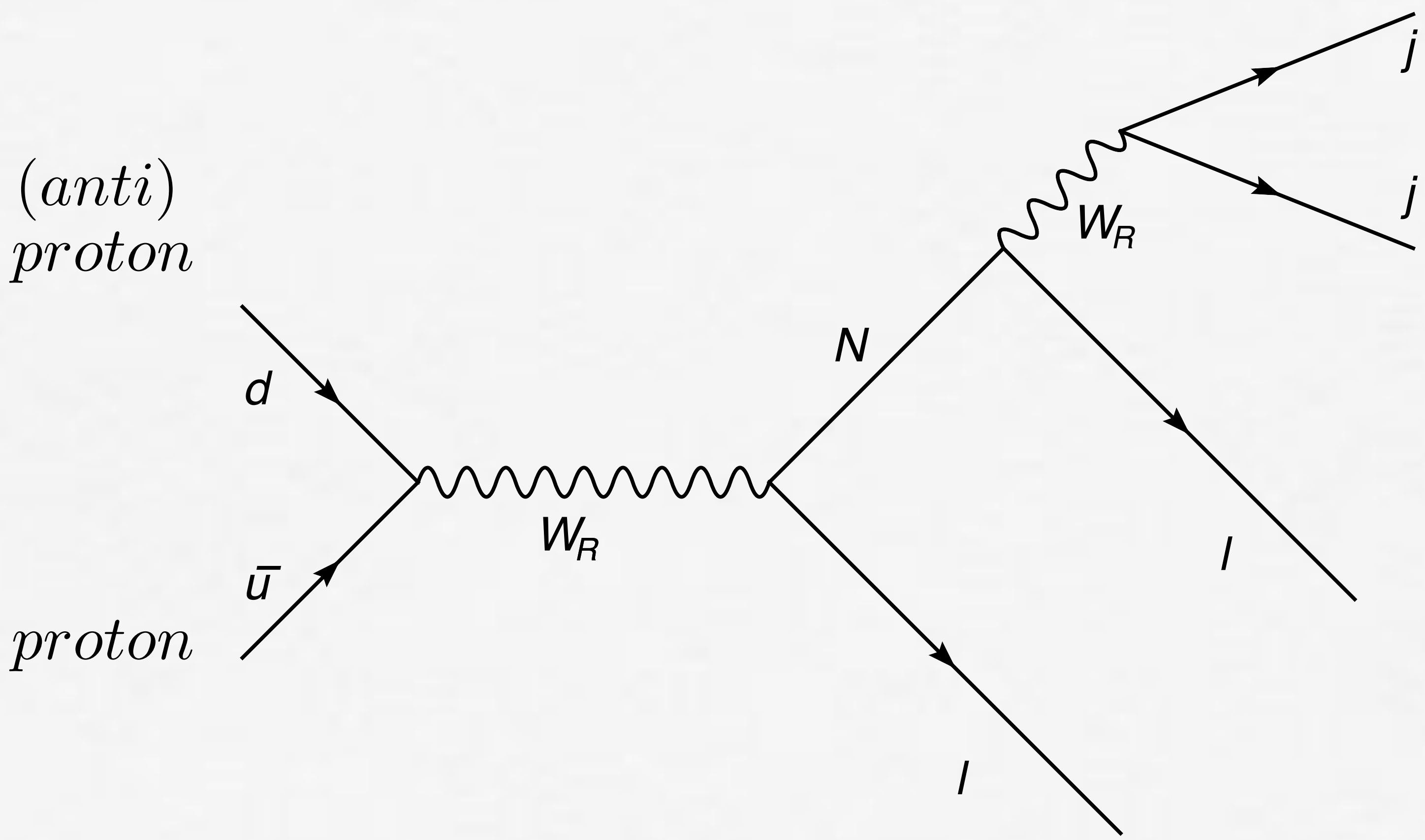


e
e
$\bar{u}$
u
W_R
N_e
N_e
W_R
m_N
d
$\bar{d}$

production @ colliders

Keung, G.S. '83

- direct probe of Majorana nature:

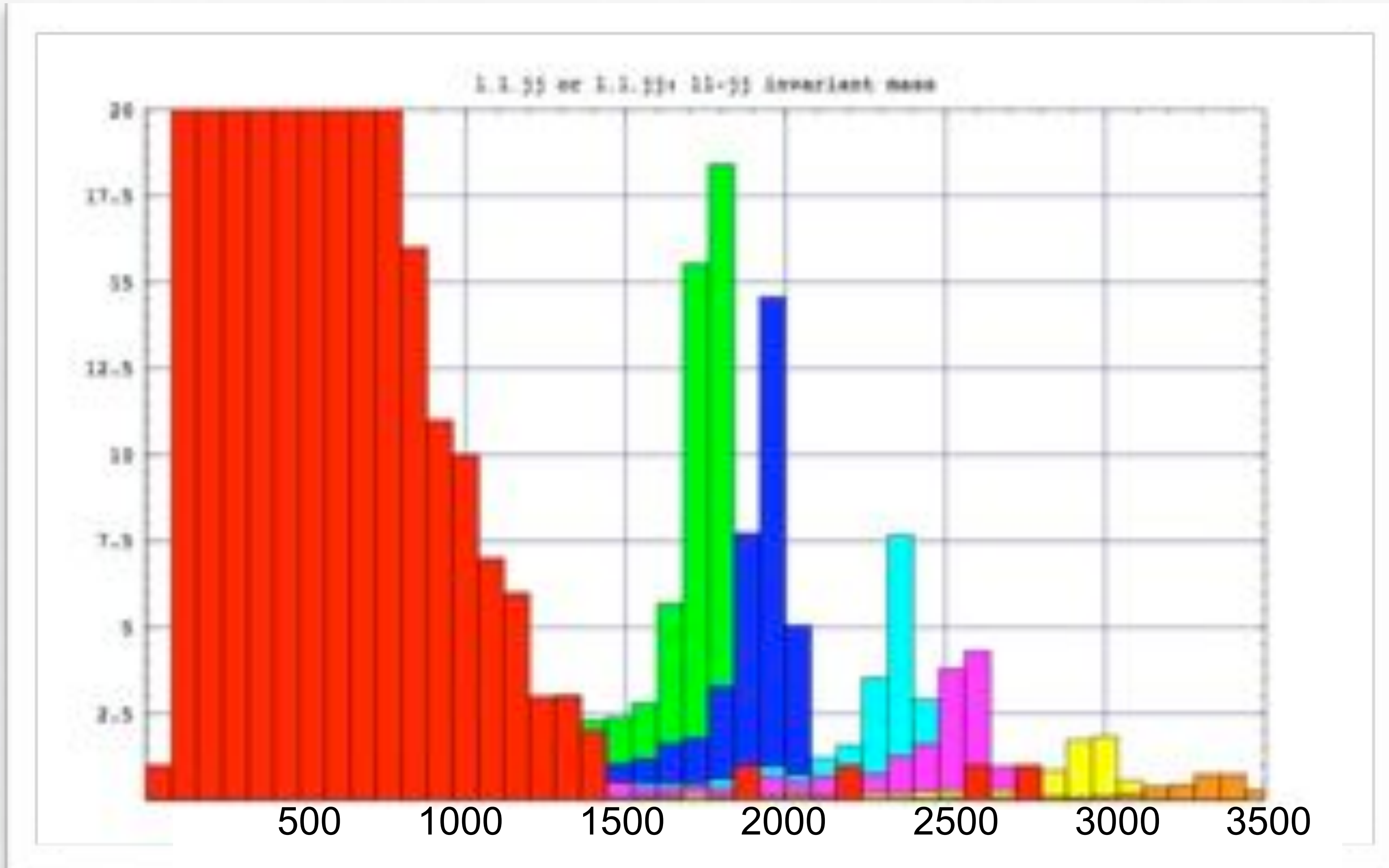


- 50% electrons -
- 50 % positrons

- Parity restoration
- Lepton Number Violation: same sign leptons

14 TeV LHC   L=10/fb

Nesti



red = background

peaks = mass of W_R (GeV)

no background above 1.5 TeV

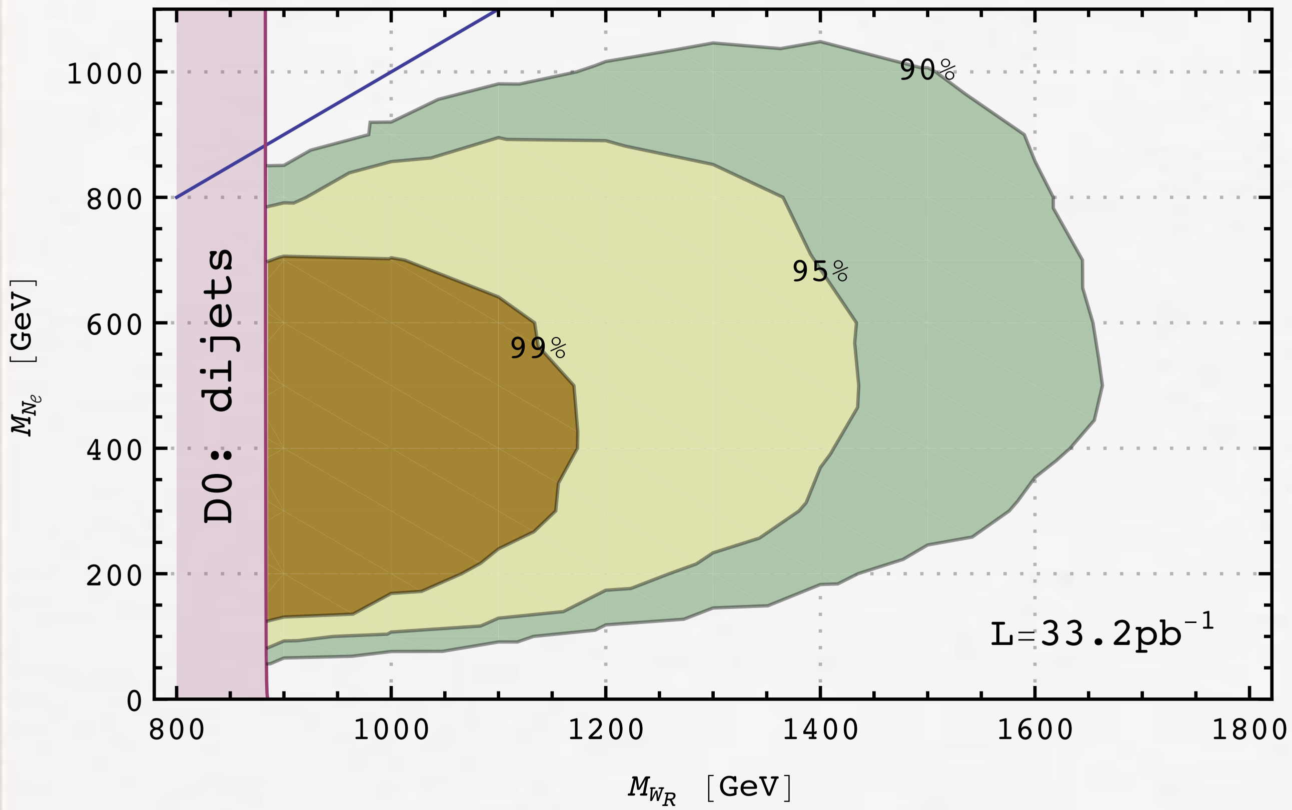
- up to 4 TeV @ L= 30/fb   Gninenko et al '06   CMS
- up to ~ 6 TeV @ L= 300/fb   Ferrari et al, '00   ATLAS

LHC @ E = 7 TeV

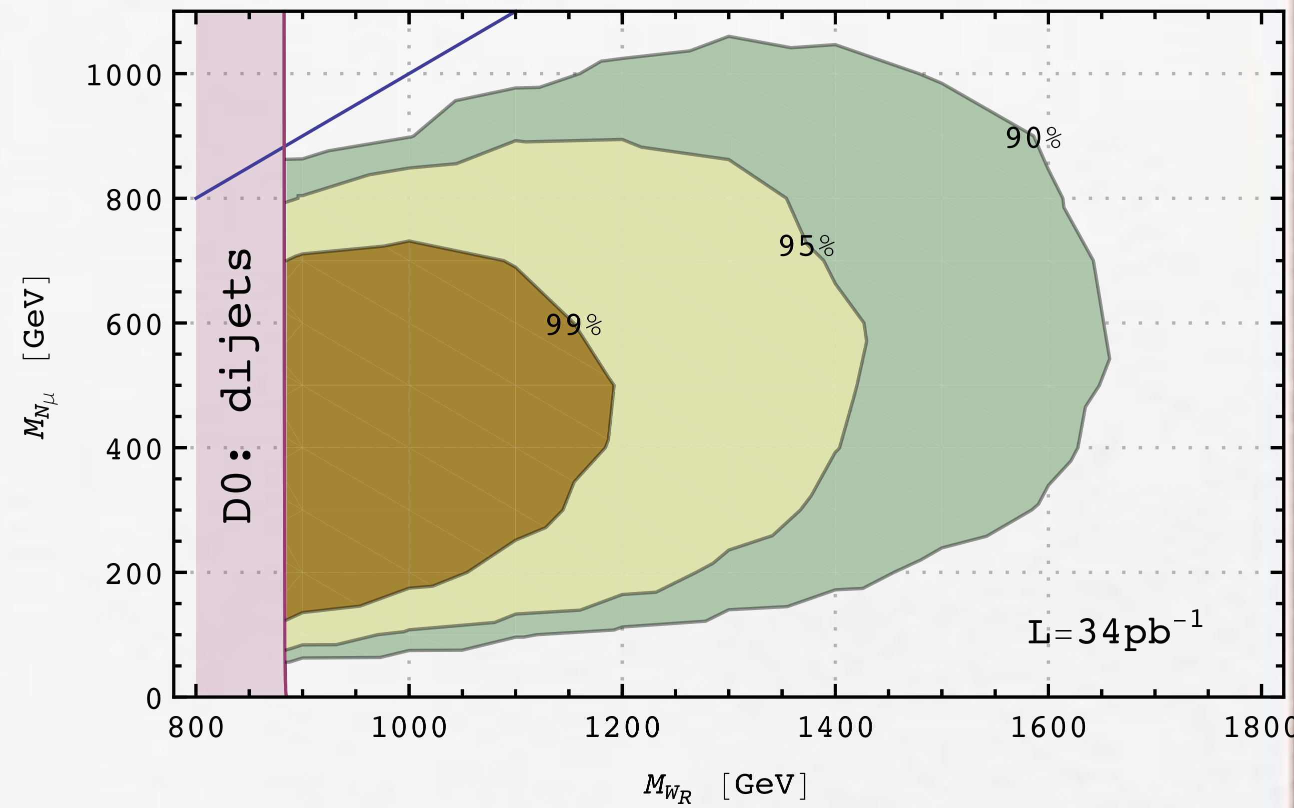
$l\,l\,j\,j$

Nemevsek, Nesti, GS, Zhang, '11

January



$e\,e$



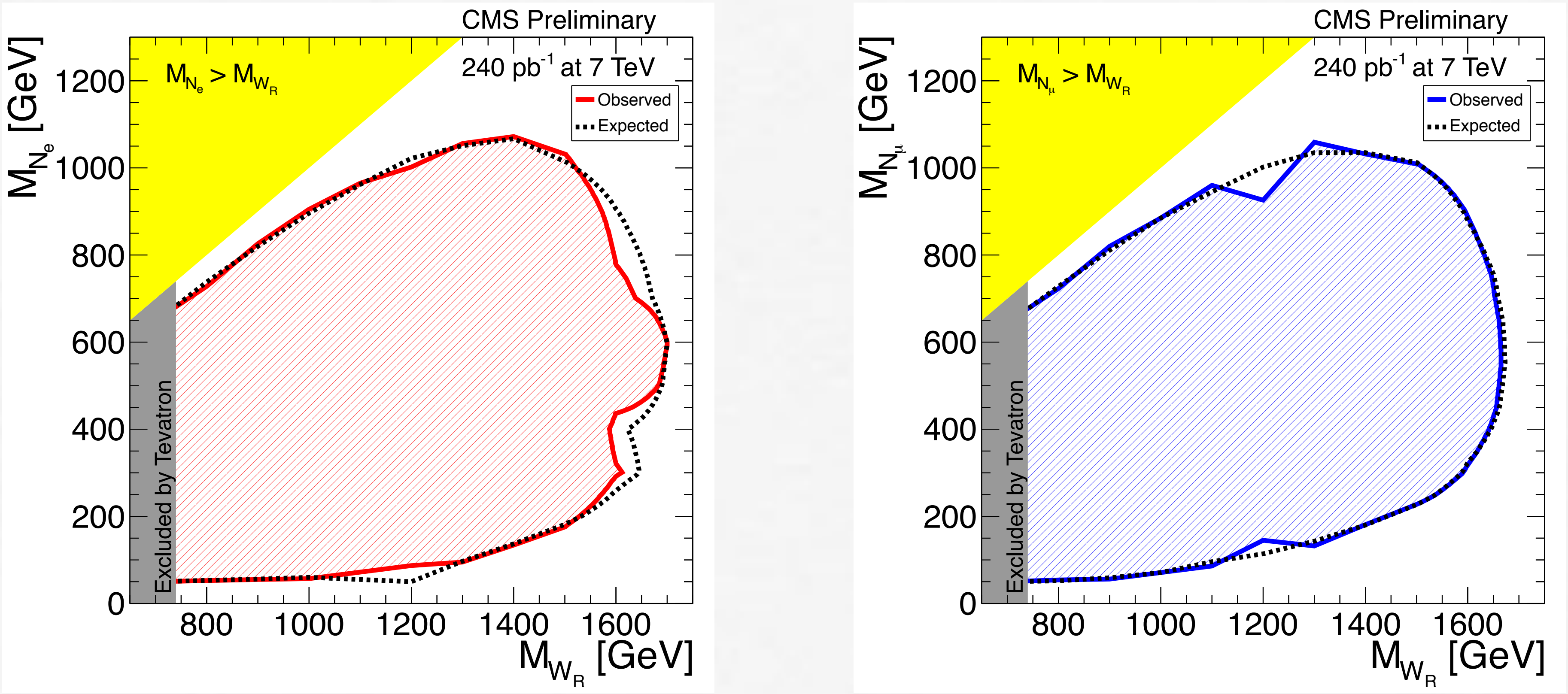
$\mu\,\mu$

early data: L=33-34/pb $M_{W_R} \gtrsim 1.4\,TeV$

estimate: L = 1/fb $M_{W_R} \gtrsim 2.2\,TeV$

LHC @ E = 7 TeV   latest: $M_{W_R} \gtrsim 1700\, GeV$ July

L = 240 /pb



(a) Electron channel   (b) Muon channel

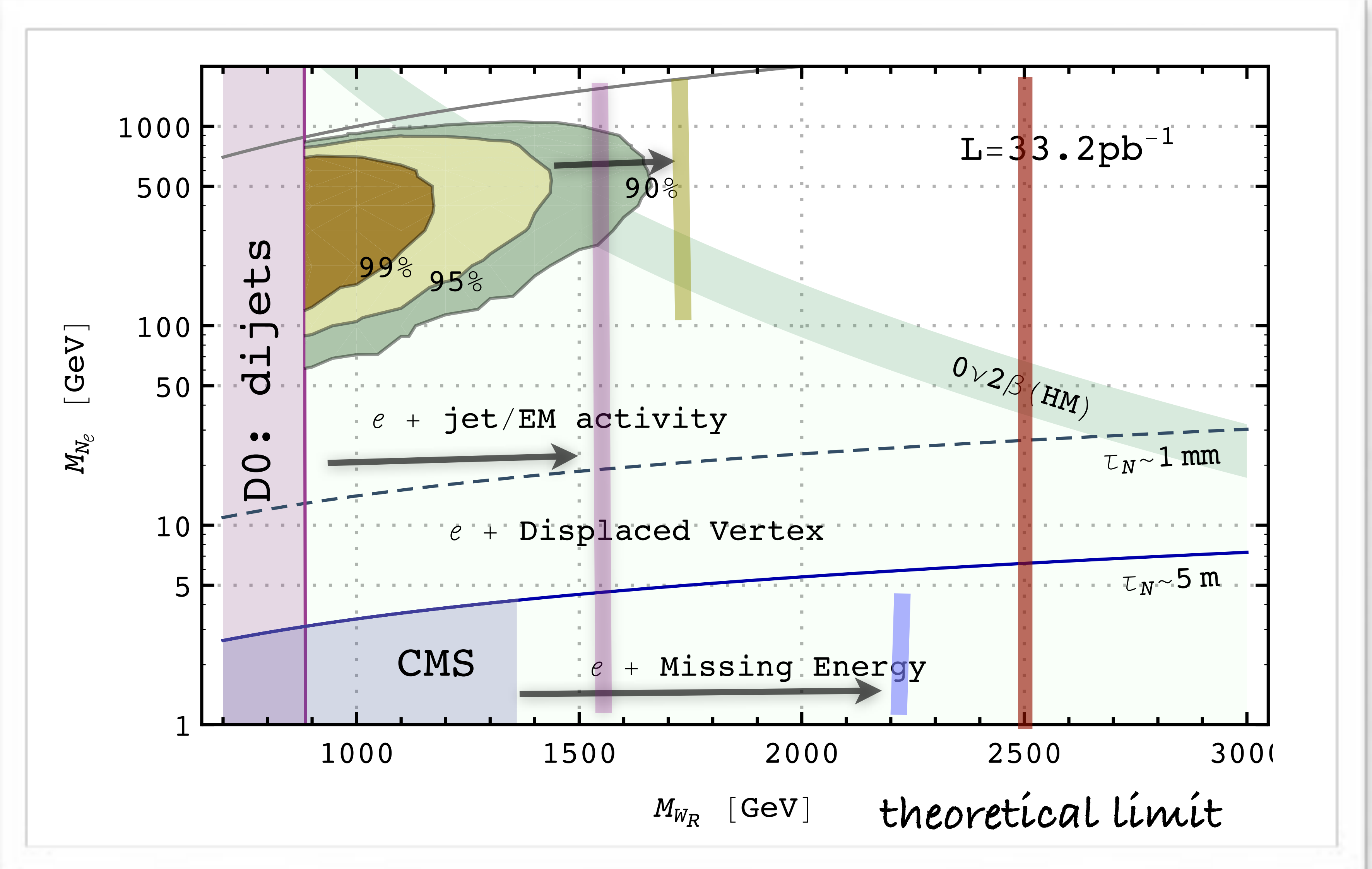
Figure 4: The 95% confidence level excluded (M_{W_R}, M_{N_ℓ}) region for the electron (left) and muon (right) channels.

CMS public note: CMS PAS EXO-11-002

Leonidopoulos, talk @ IECHEP, Grenoble, July

January '11

Nemevsek, Nesti, GS, Zhang, '11



July '11

Model content

Mohapatra, GS '75, '81

R - triplet

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

- mass of N (majorana)
- mass of W_R and Z_R

bi-doublet

$$\phi \sim (h_{\rm SM}, H_{\rm heavy})$$

$$\langle \phi \rangle = \begin{pmatrix} v & \\ & \sim v \end{pmatrix}$$

- EW symmetry breaking

L - triplet

$$\langle \Delta_L \rangle = \begin{pmatrix} & \\ v_L & \end{pmatrix}$$

- mass of ν (majorana)

$$v_R \gg v \gg v_L$$

Yukawa sector

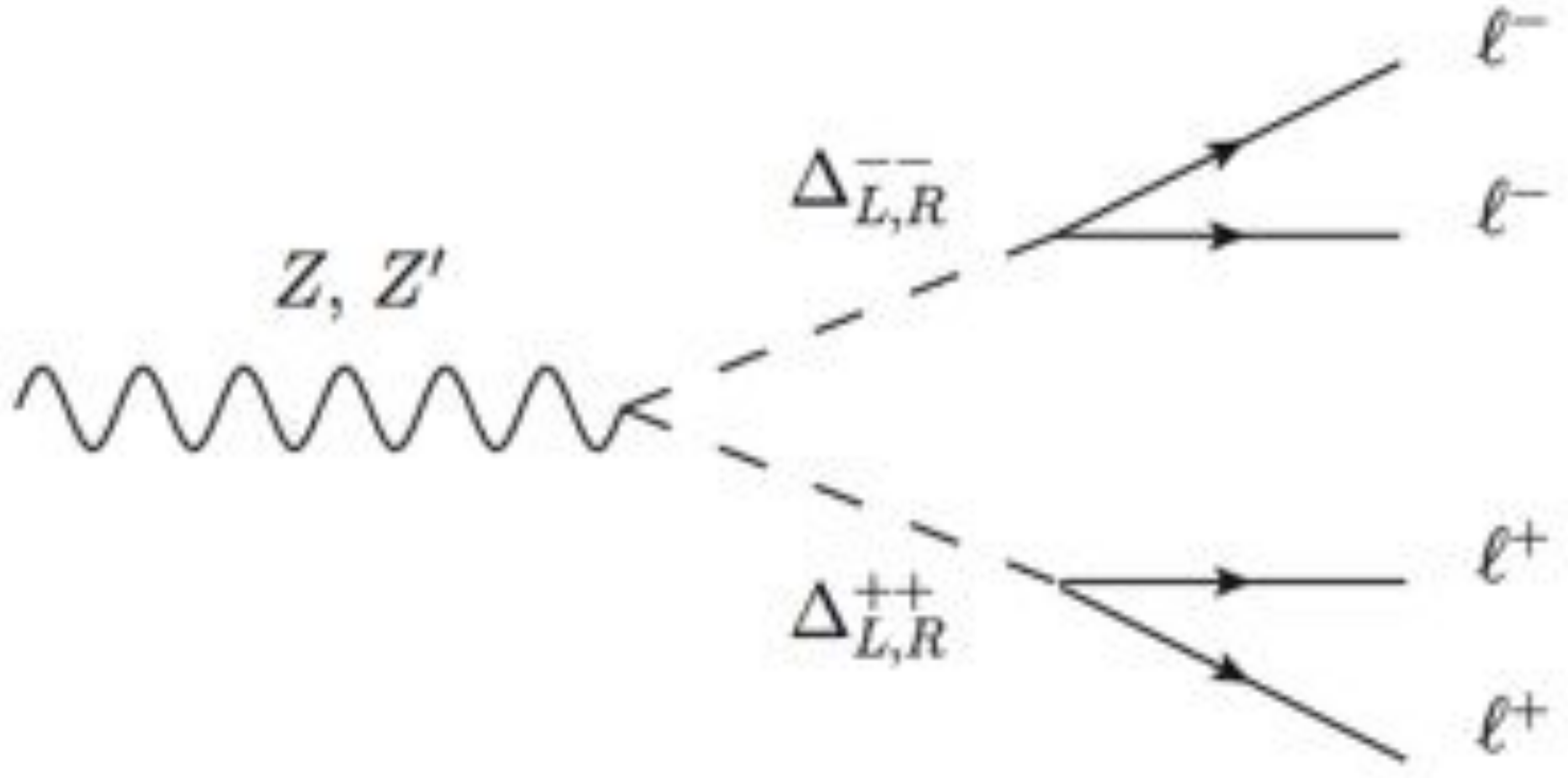
$$\mathcal{L}_Y = \frac{1}{2}\ell_L^T \varepsilon\, C\, Y_{\Delta_L} \Delta_L \ell_L + \frac{1}{2}\ell_R^T \varepsilon\, C\, Y_{\Delta_R} \Delta_R \ell_R$$
$$+ \bar{\ell}_L (Y_\Phi\, \Phi + \tilde{Y}_\Phi\, \tilde{\Phi}) \ell_R + \text{h.c.}$$

in components $\begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$

$v_{L(R)}$

small Yukawa Dirac

$\Rightarrow$ Type II



$$\propto (Y_\Delta)_{ij}(Y^*_\Delta)_{kl}$$

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

latest limits: 2012

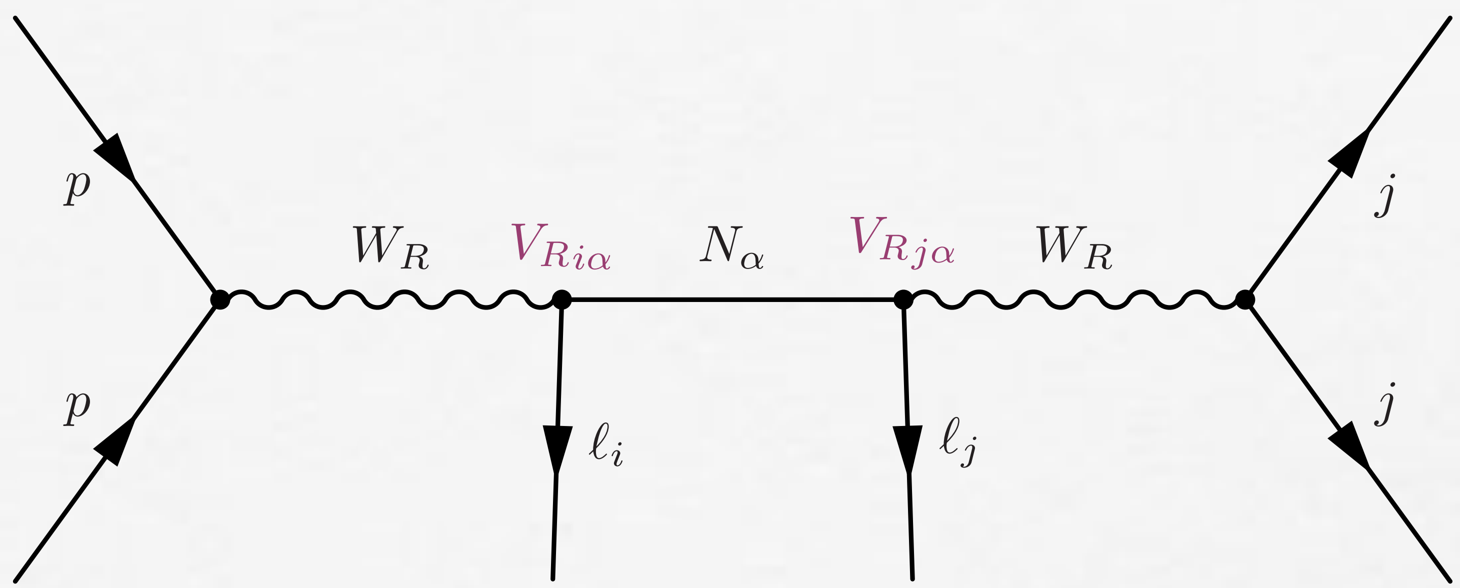
theory bound

Particle	Final states	Lower limit	Collaboration	Comments
W_R	$e/\mu + N$	2.5 TeV	CMS [35]	light N (missing energy)
W_R	$\ell\ell jj$	$\lesssim$ 1.7 TeV	CMS [36]	heavy Majorana N [37]
Z_{LR}	$e^+e^-/\mu^+\mu^-$	$\sim$ 2 TeV	ATLAS [38]	see [39]
Z_{LR}	e^+e^-	$\sim$ 3 TeV	LEP [40]	indirect, see [41, 42]
Δ_L^{++}	$\ell_i^+\ell_j^+$	100-355 GeV	ATLAS [43]	spectrum dependent [44]
Δ_R^{++}	$\ell_i^+\ell_j^+$	113-251 GeV	ATLAS [43], CDF [45]	flavor dependent

updated on Tuesday ATLAS

$\sim$ 2 - 2.5 TeV

LHC: measure m_N and V_R



in order to illustrate: type II seesaw

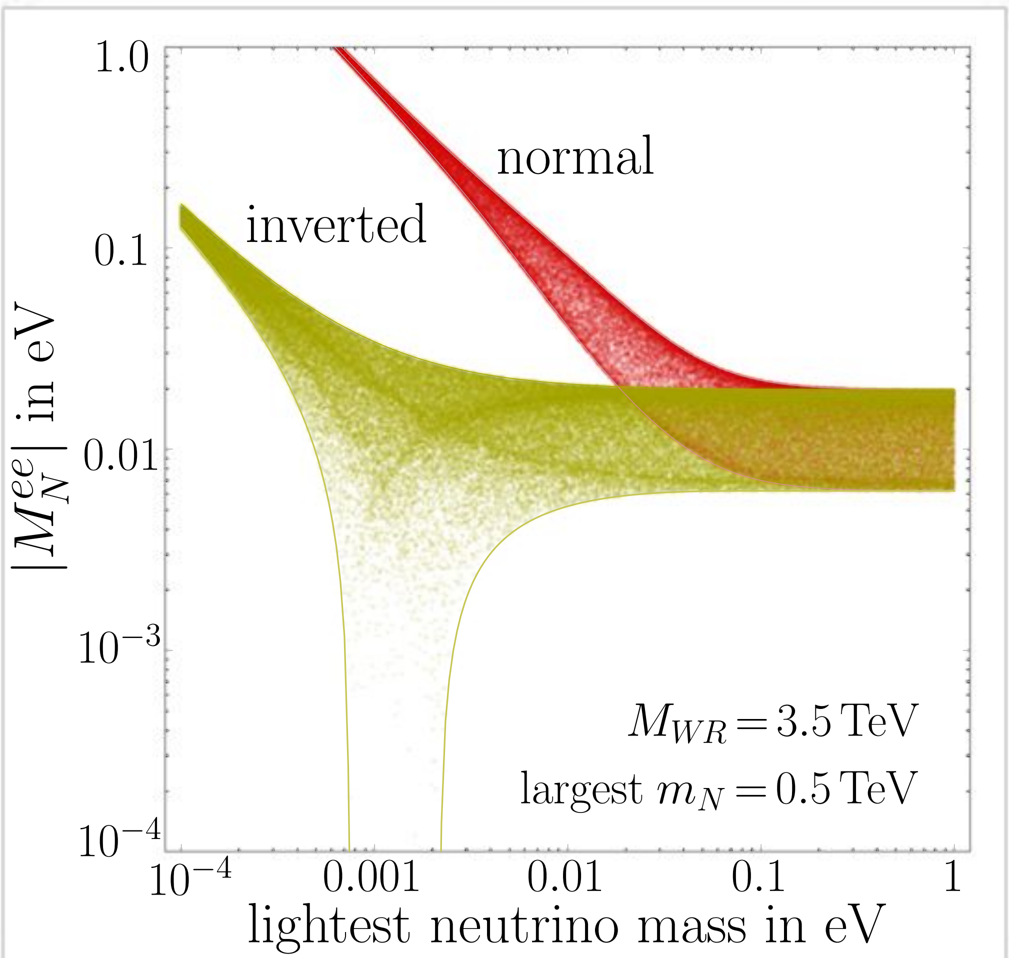
$$V_R = V_L^* \qquad m_N/m_\nu = const$$

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

Back to neutrinoless double beta decay

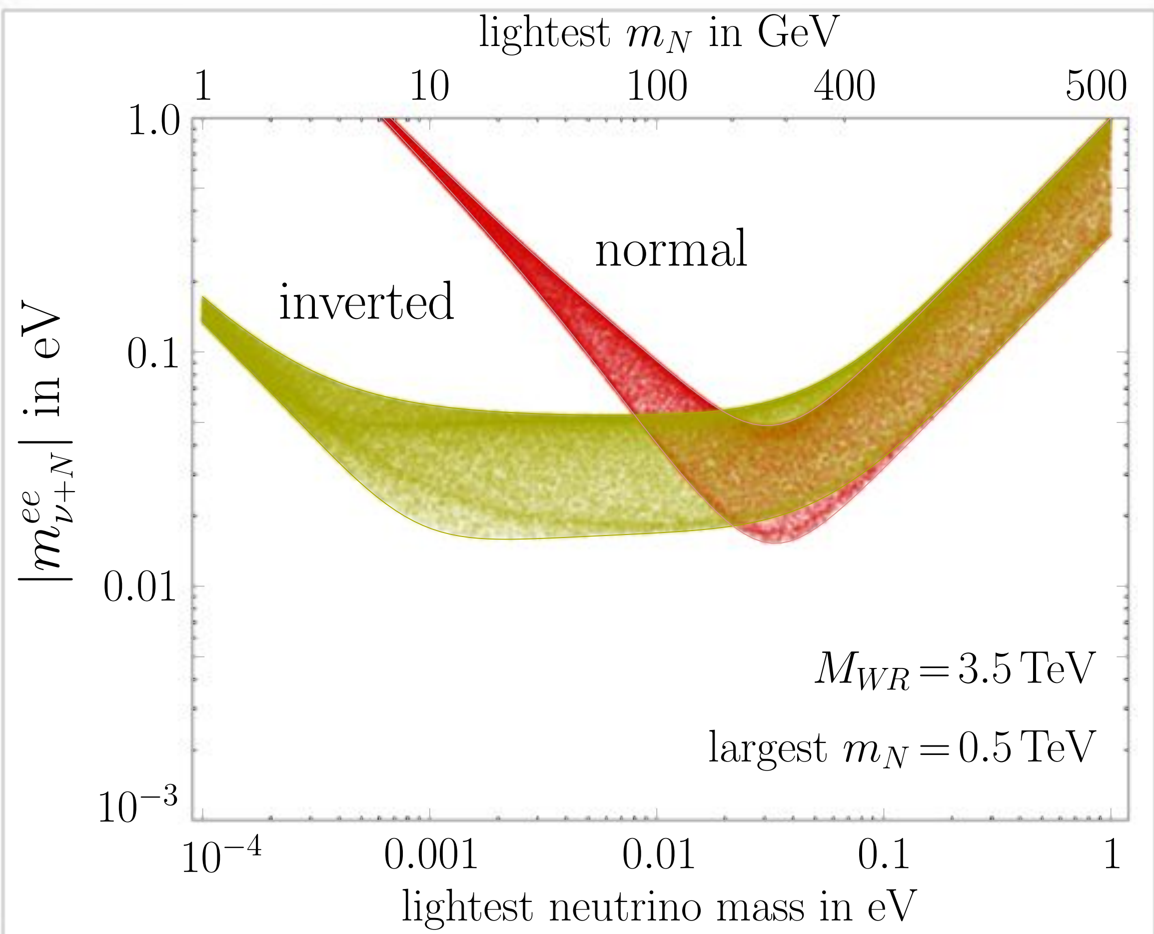
Tello et al '11

Right only



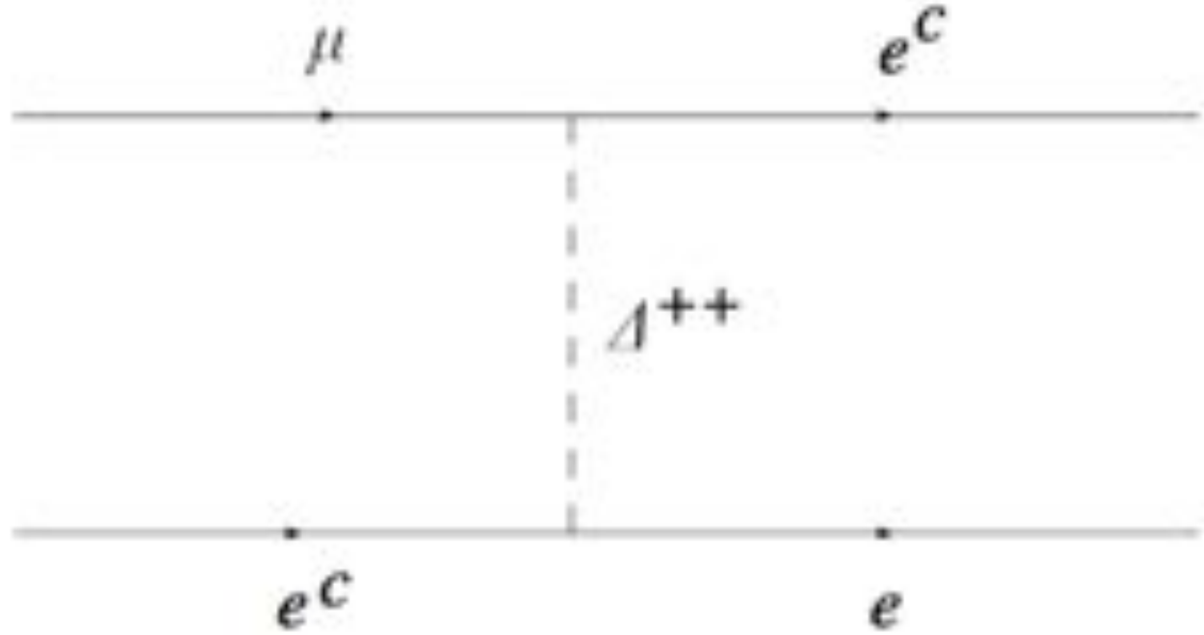
opposite from m_ν

Left + Right



non-vanishing

Lepton Flavor Violation



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

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

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

$\Rightarrow m_N \lesssim M_\Delta$

Cirigliano et al '04
Tello '08

(Loop: $\mu \to e\,\gamma$ $\quad\mu \to e$ conversion in nuclei)

Neutrino mass: back to basics

Effective operators and New Physics

SM degrees of freedom

two operators stand out

$$\mathcal{L}_\nu = Y^\nu_{eff} \frac{\ell\ell H H}{\Lambda_\nu}$$

$$\mathcal{L}_p = Y^p_{eff} \frac{qqq\ell}{\Lambda_p^2}$$

Weinberg '79

Wilczek, Zee '79

$$\Rightarrow Y^\nu_{eff} \frac{v^2}{\Lambda_\nu} \nu\nu$$

Majorana mass

$Y_{eff} \simeq 1$ ➡ $\Lambda_\nu \lesssim 10^{14}\, GeV$ $\quad \Lambda_p \gtrsim 10^{15}\, GeV$

Weinberg's d= 5 operator: UV completion = seesaw

$$(\ell^T \epsilon H) C (H^T \epsilon \ell) = (\ell^T \epsilon C \vec{\sigma} \ell)(H^T \epsilon \vec{\sigma} H) = (\ell^T \epsilon \vec{\sigma} H) C (H^T \epsilon \vec{\sigma} \ell)$$

singlet fermion (sterile)

Type I LR

triplet scalar Y=2

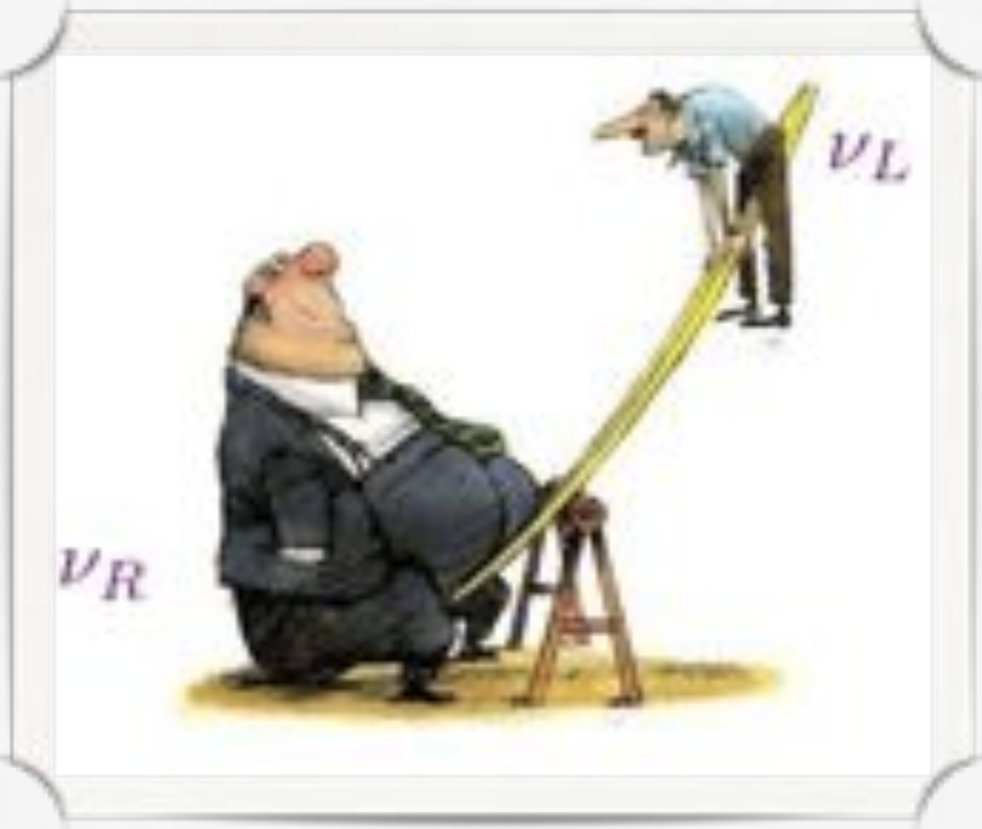
Type II LR

triplet fermion Y=0

Type III SU(5)

Seesaw mechanism: type I

SM + right-handed neutrino

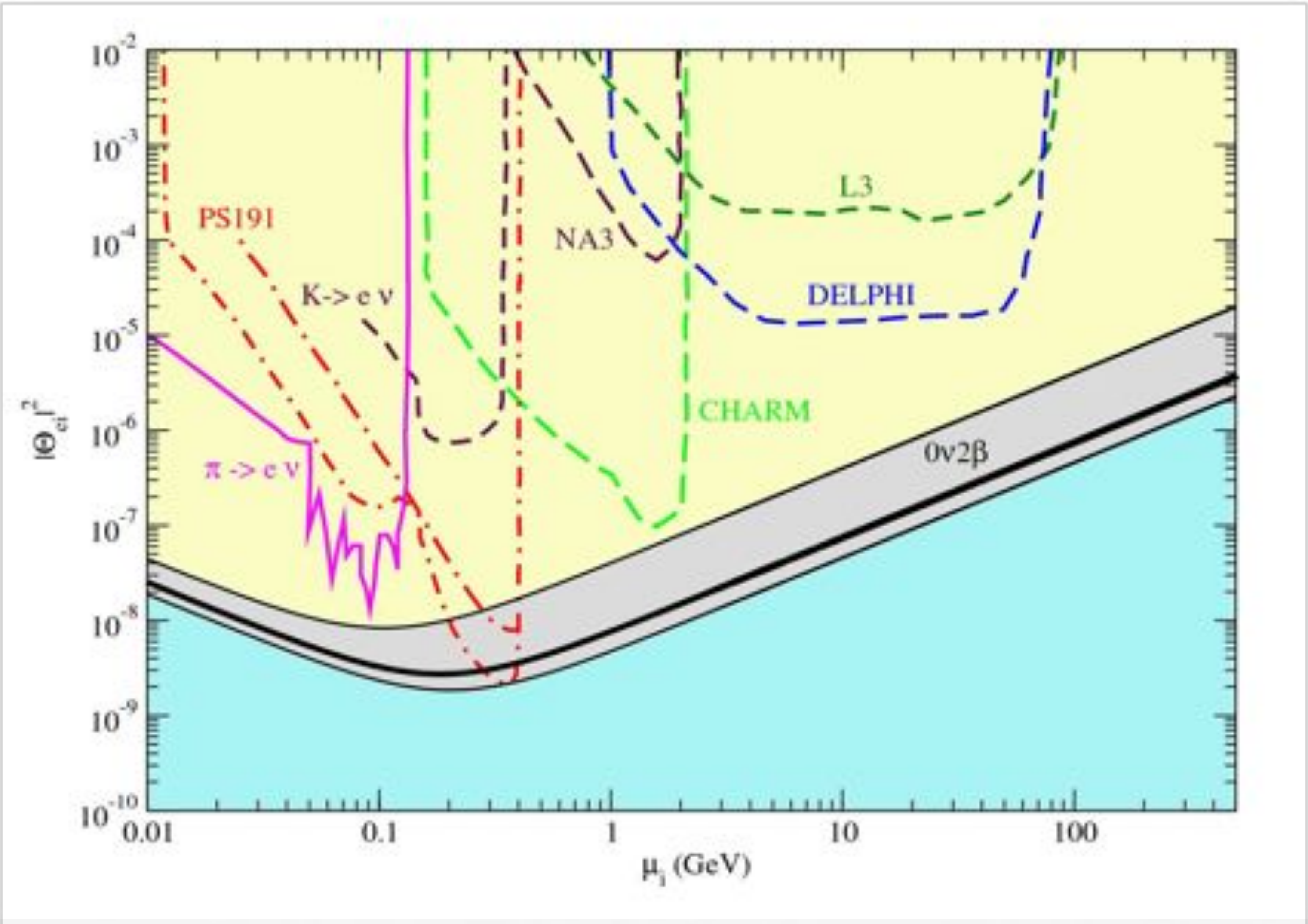


assumed heavy

decoupled
(except for tiny neutrino mass)

crying for W_R

Bounds on the e- N mixing



$\mu = m_N$

Atre, Han, Pascoli , Zhang '09

Mitra, GS, Vissani '11

N can be as light as you wish

light N:

neutrino mass,

baryogenesis,

DM

NuSM

Asaka, Blanchet, Shaposhnikov '05,

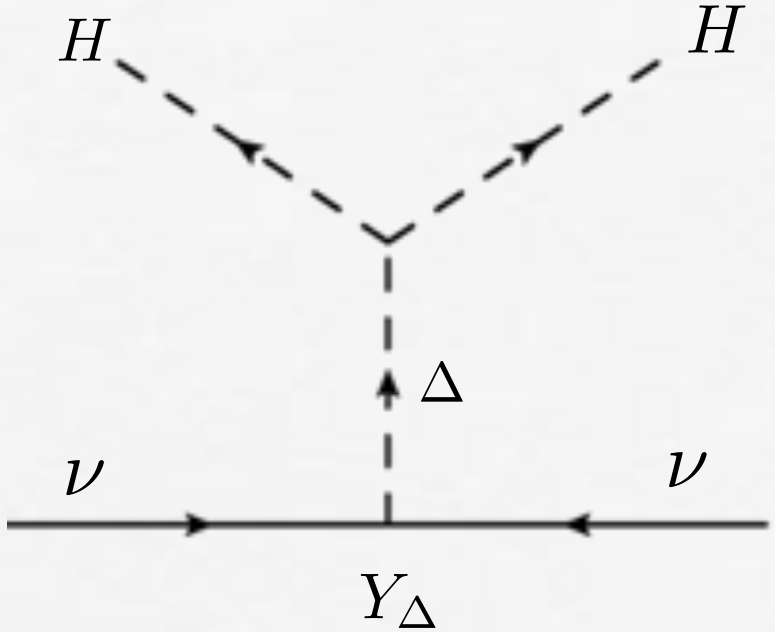
....

N can still do neutrinoless double beta

Probing seesaw @ LHC

Type II seesaw

Magg, Wetterich '80
Lazarides, Shafi, Wetterich '81
Mohapatra, GS '81

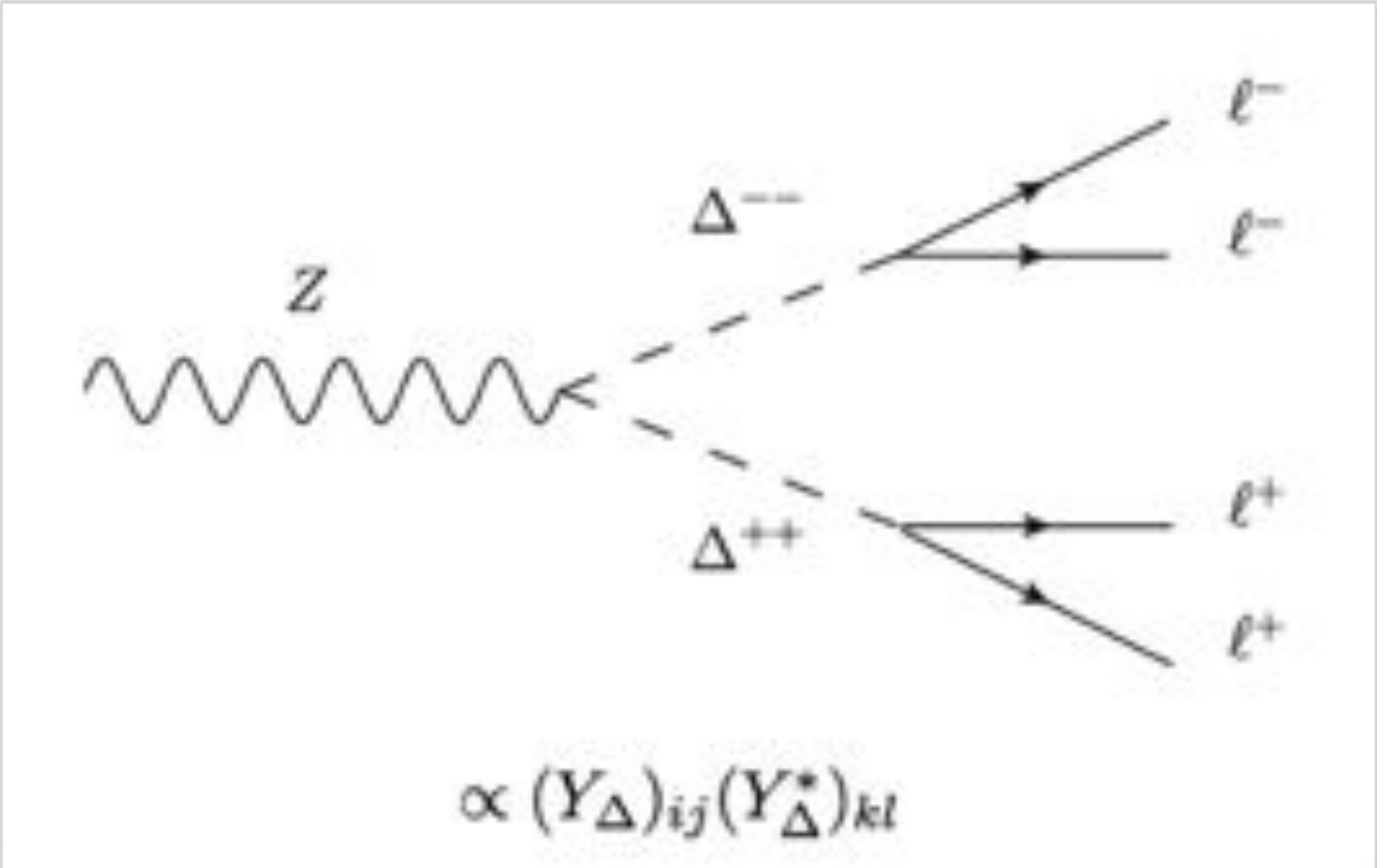


$$\mathcal{L} = Y_\Delta \ell^T \epsilon C \Delta \ell + \mu H^T \epsilon \Delta^\dagger H + m_\Delta^2 \Delta^\dagger \Delta$$

+ ...

$$v_\Delta \simeq \mu \frac{M_W^2}{m_\Delta^2} \lesssim GeV$$ (ρ parameter)

in components $\begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$



$$M_\nu = U_\ell^T m_\nu U_\ell = Y_\Delta v_\Delta$$

probe neutrino masses and mixings

Why only the triplet?

Principle: all "Yukawa" Higgs allowed by the SM symmetries

vevs: color and charge singlets

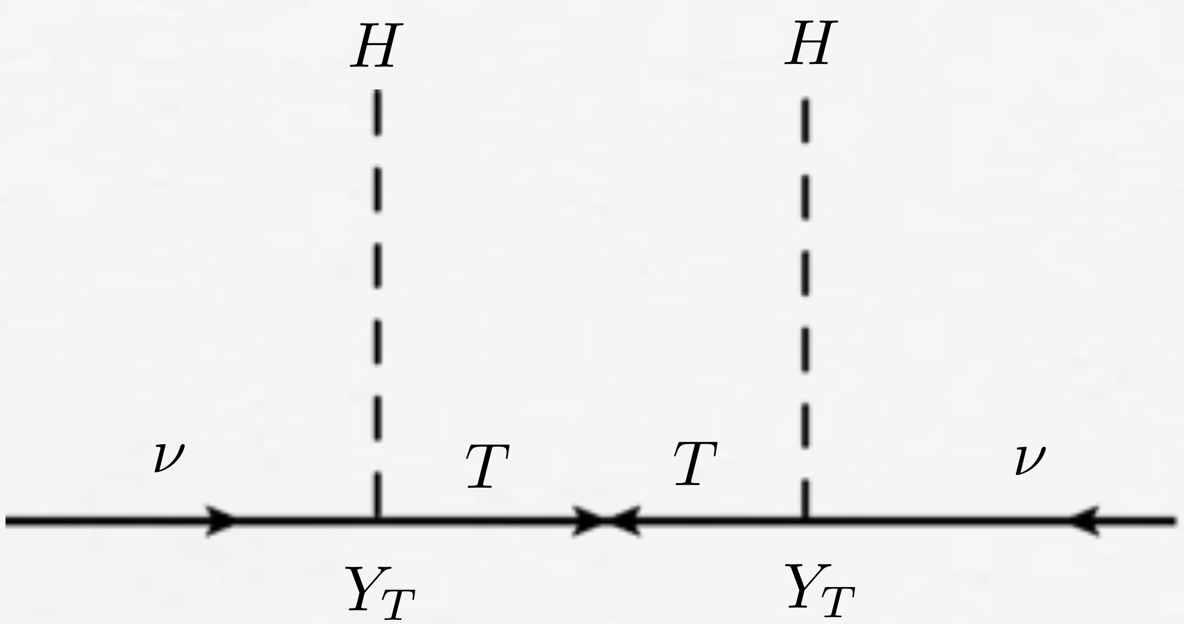
$$\ell = \begin{pmatrix} \nu \\ e \end{pmatrix}_L \qquad e_R \quad \Rightarrow$$

H : Y=1 doublet

Δ: Y=2 triplet

Type III seesaw: triplet fermions

Foot, Lew, He, Joshi '89



MINIMAL SU(5) Georgi-Glashow

- no unification
- neutrino massless

extra fermionic 24_F

Bajc, G.S. '06
Bajc, Nemevsek, G.S. '07

$$24_F = (1_C, 1)_0 + (1_C, 3)_0 + (8_C, 1) + (3_C, 2)_{5/6} + (\bar{3}_C, 2)_{-5/6}$$

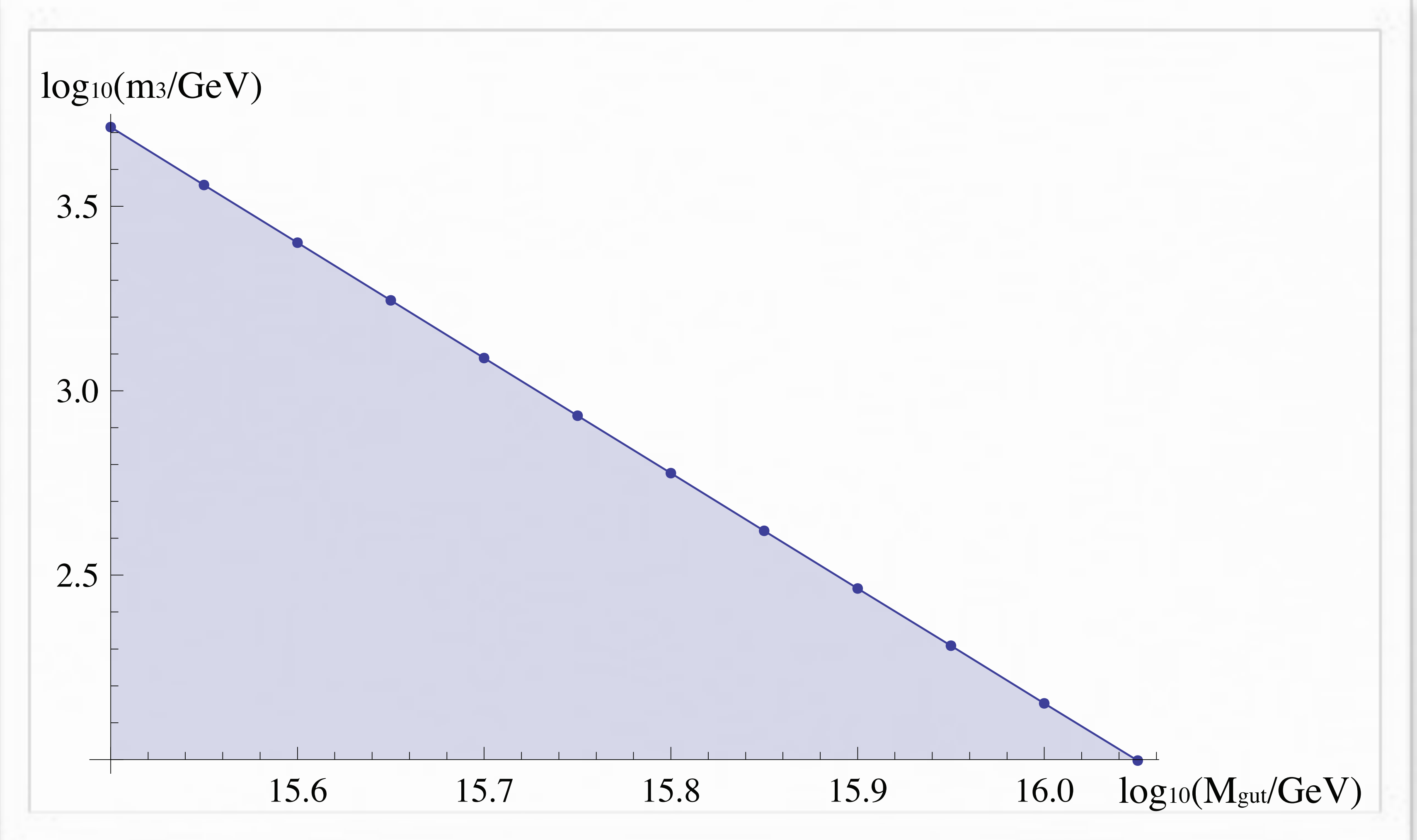
singlet S

triplet T

hybrid: type I + III

- one massless neutrino
- unification

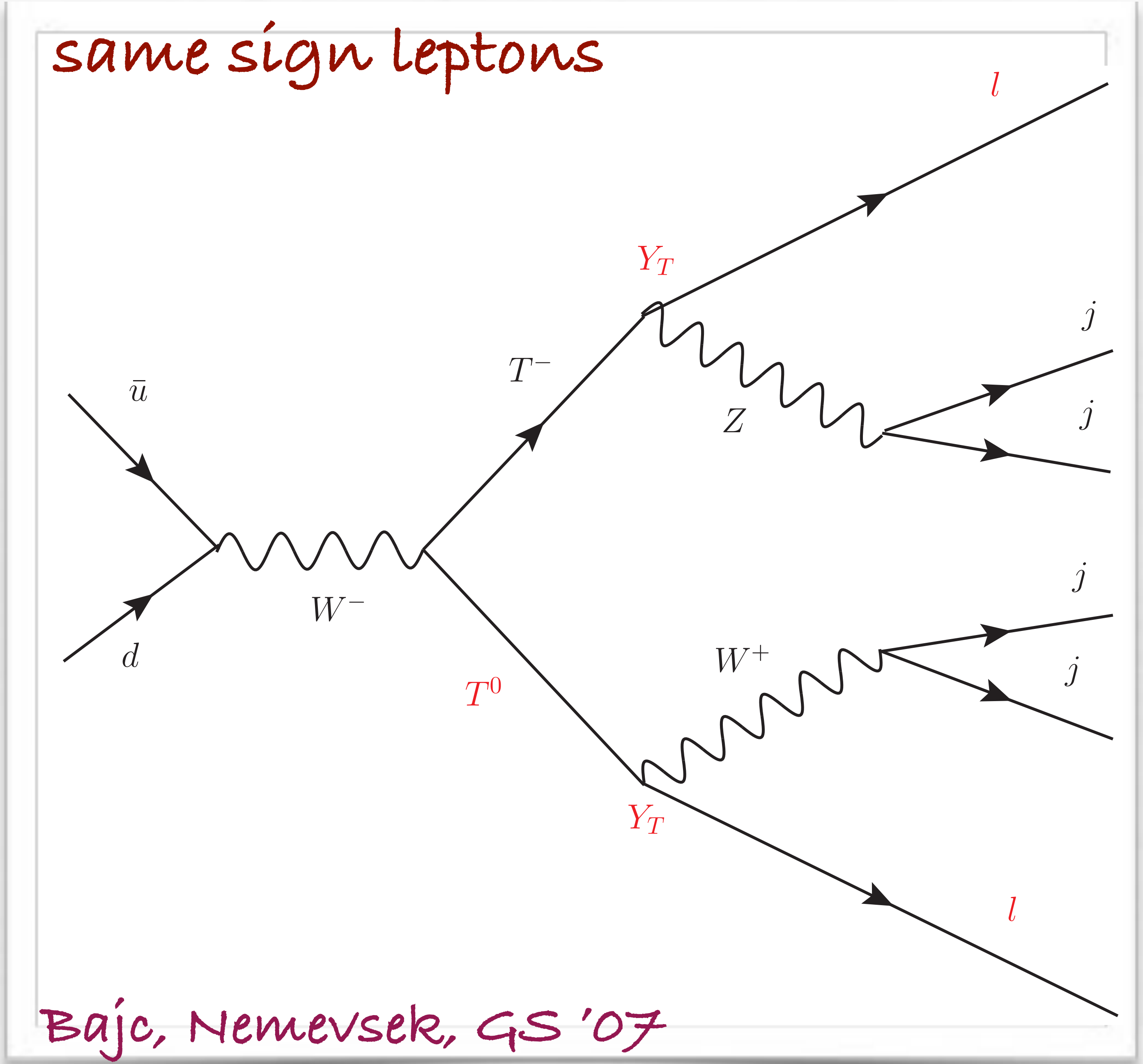
m_T vs M_{GUT}@ two loops



Bajc, Nemevsek, G.S. '07

LHC:

$\Delta L = 2$



LHC:

m_T ⇘

$450\,(700)\,GeV\,@\,L = 10\,(100)\,fb^{-1}$

del Aguila, Aguilar-Saavedra '08

Franceschini, Hambye, Strumia '08

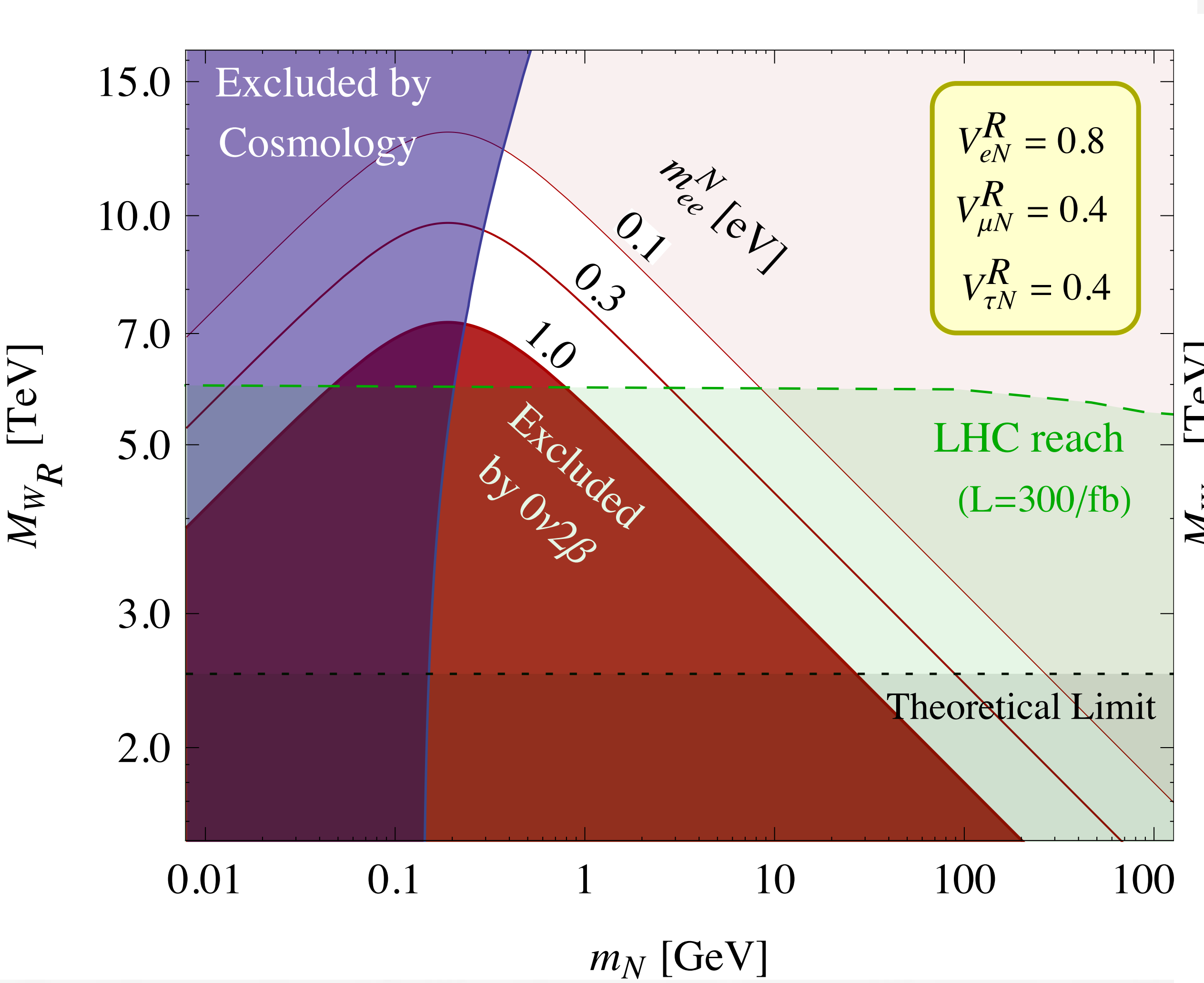
Arhrib, Bajc, Ghosh, Han, Huang, Puljak, GS '09

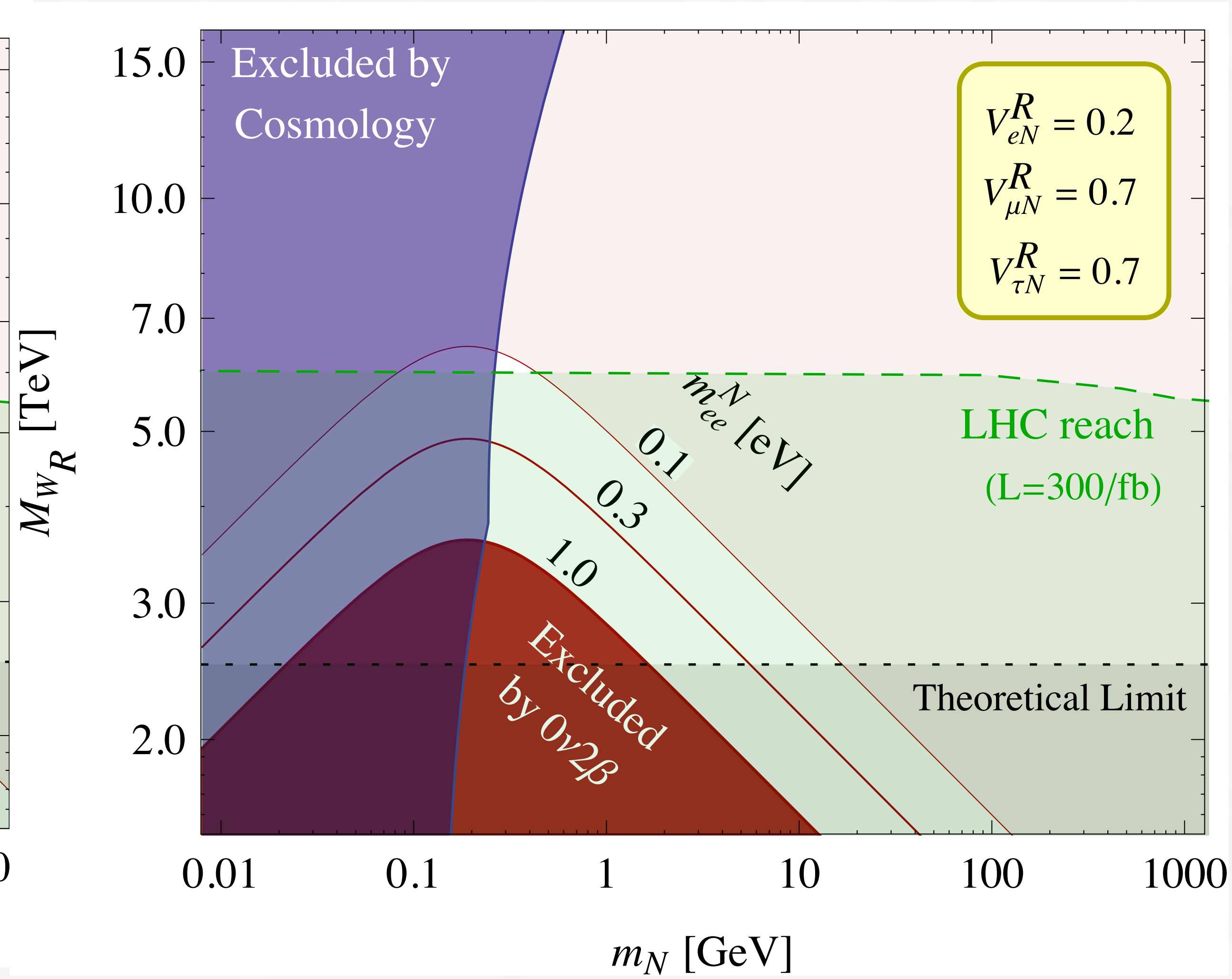
LHC:

- can probe the origin of neutrino mass
- can resolve the mystery of parity violation
- can directly observe lepton number violation
- can directly see Majorana nature

Thank you

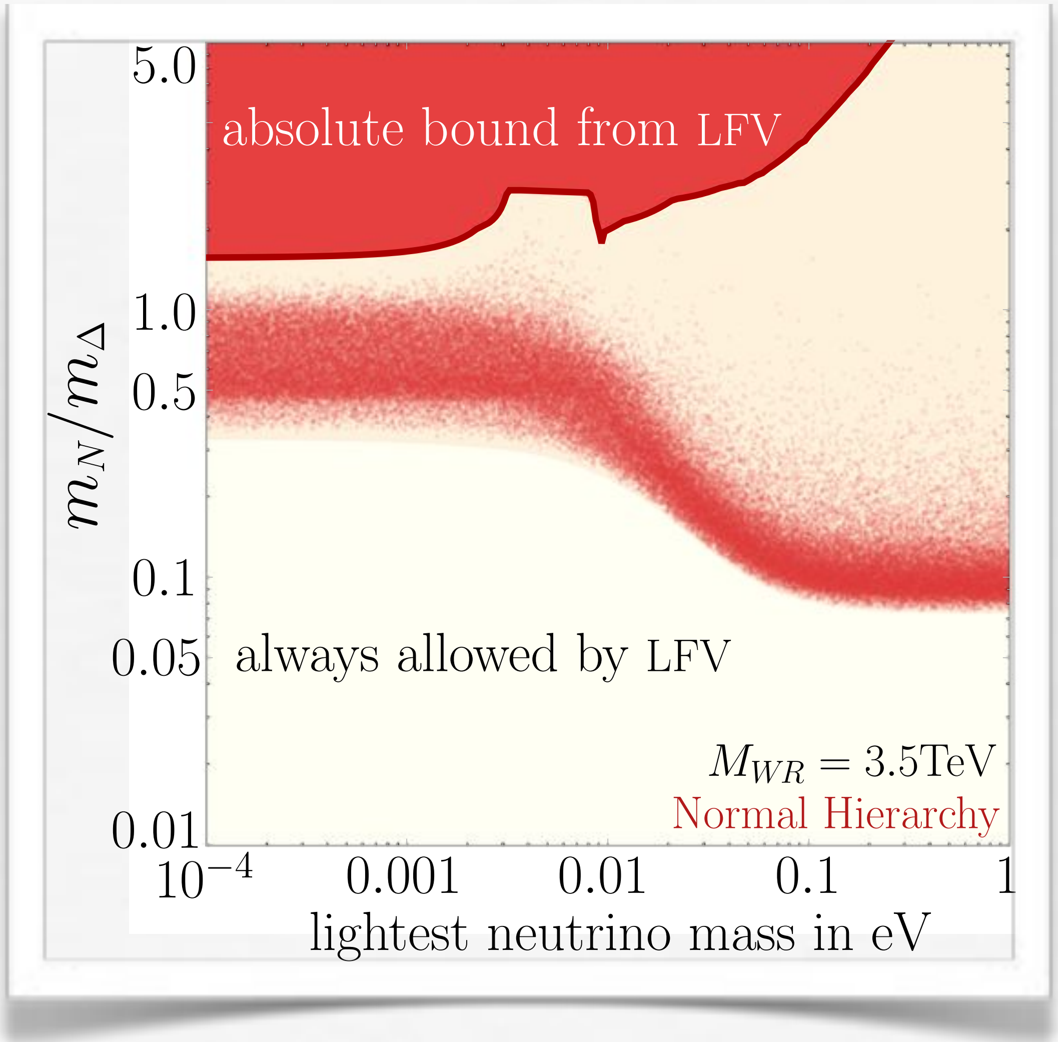
general results

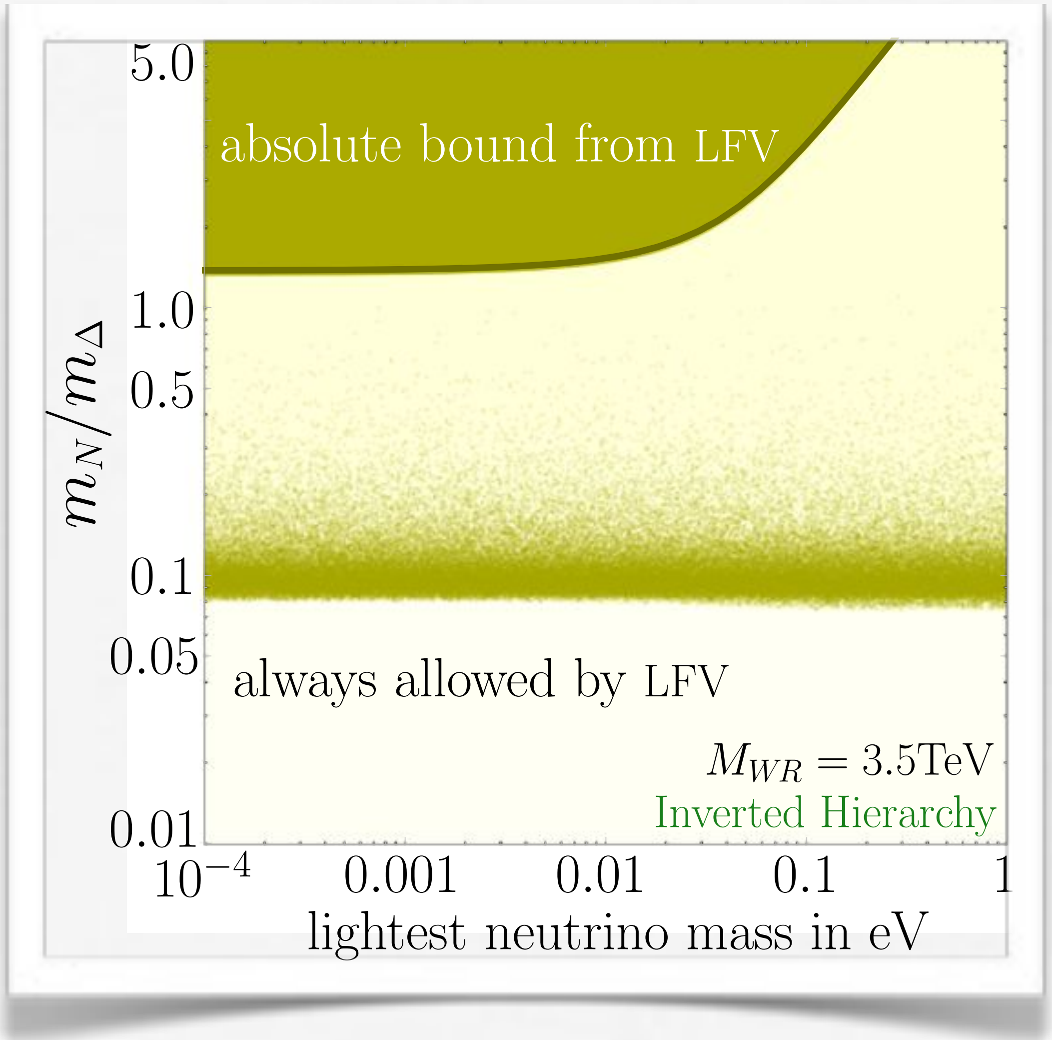




Lepton Flavor Violation

talk by Nemevsek, NuFact11 - saturday





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

Supersymmetry?

- can mimic many of the phenomena
- Type III - wino with R_P violation

$$\mathcal{W}_{\not R_p} = \lambda \ell \ell e^c + \lambda' q \ell d^c + \lambda'' u^c d^c d^c + \mu\, \ell H$$

- too many parameters

assumptions about sparticle masses

- supersymmetric seesaw?

subject in itself

Neutral gauge boson

CMS-PAS EXO-11-019

Z_{LR}

July

" relative to Z $\rightarrow \ell^+\ell^-$ are presented. These limits exclude at 95% confidence level a Z′ with standard-model-like couplings below 1940 GeV, the superstring-inspired Z'_ψ below 1620 GeV "

$$\frac{M_{Z_{LR}}}{M_{W_R}} = \frac{\sqrt{2} g_R/g_L}{\sqrt{(g_R/g_L)^2 - \tan^2\theta_W}} \,. \quad = 1.7 \text{ for } g_L = g_R$$

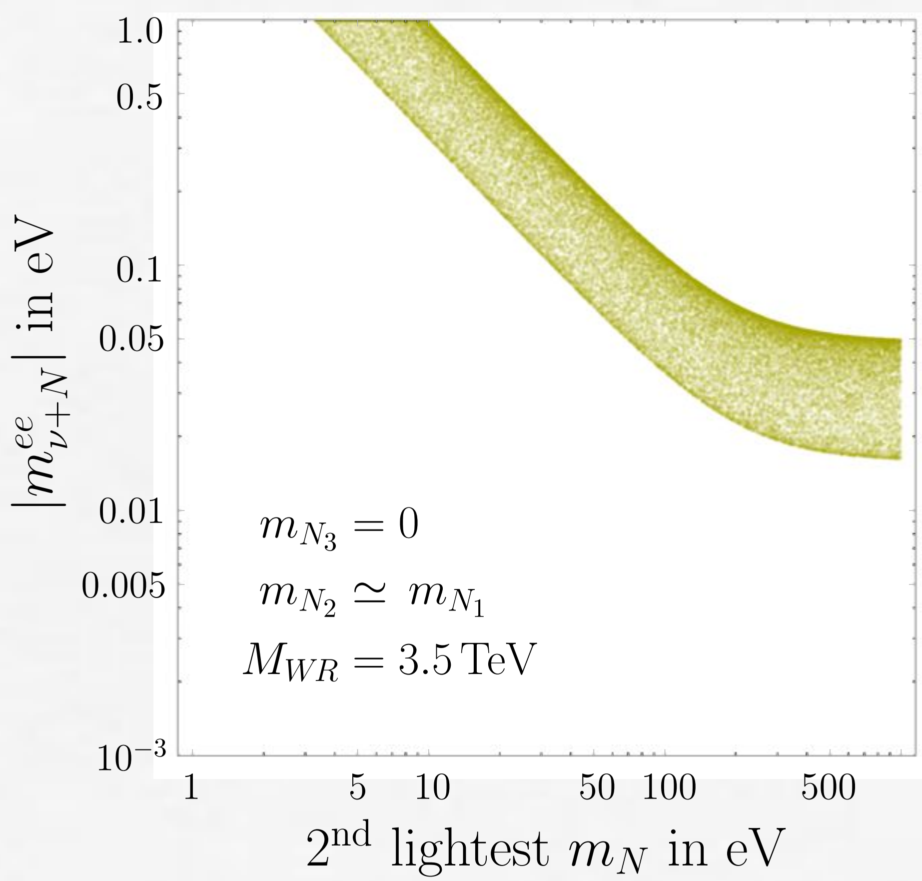
W_R How right is it?

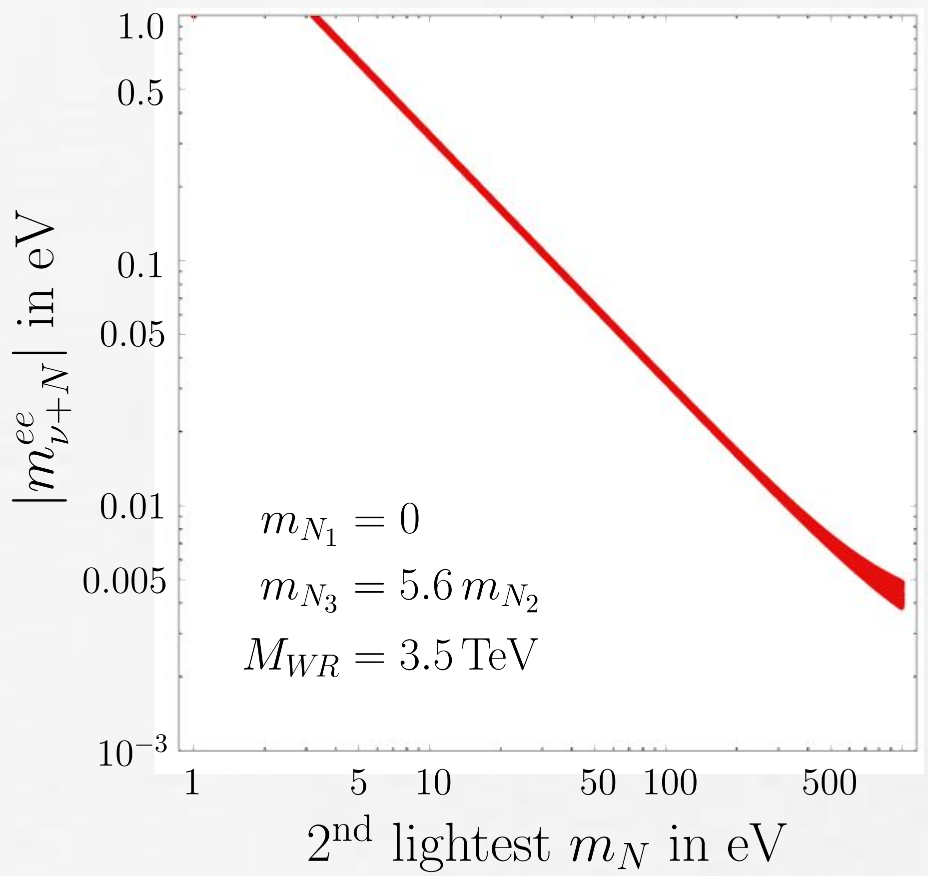
LHC is a *pp* symmetric machine, so it is not possible to use the simple A_{FB} asymmetry of W_R, to look for chirality of its interactions.

- One has to use the first decay $W_R \to eN$.
  - Determine the W_R direction (from the full event!)
  - Identify the first lepton. (the more energetic)
  - Its asymmetry wrt the W_R direction gives the 'Right' chirality.
- It is necessary to efficiently distinguish the two leptons. (More difficult for $M_N \neq 0.6 \div 0.8\, M_{W_R}$ [Ferrari '00])
- Also the subsequent decay $N \to \ell jj$ may be used.

Polarization seems to be visible in a wide range of masses M_{ν_R}, M_{W_R}.

BBN: $N_{eff} = 4$ → three $\nu + N_1$





IH

NH

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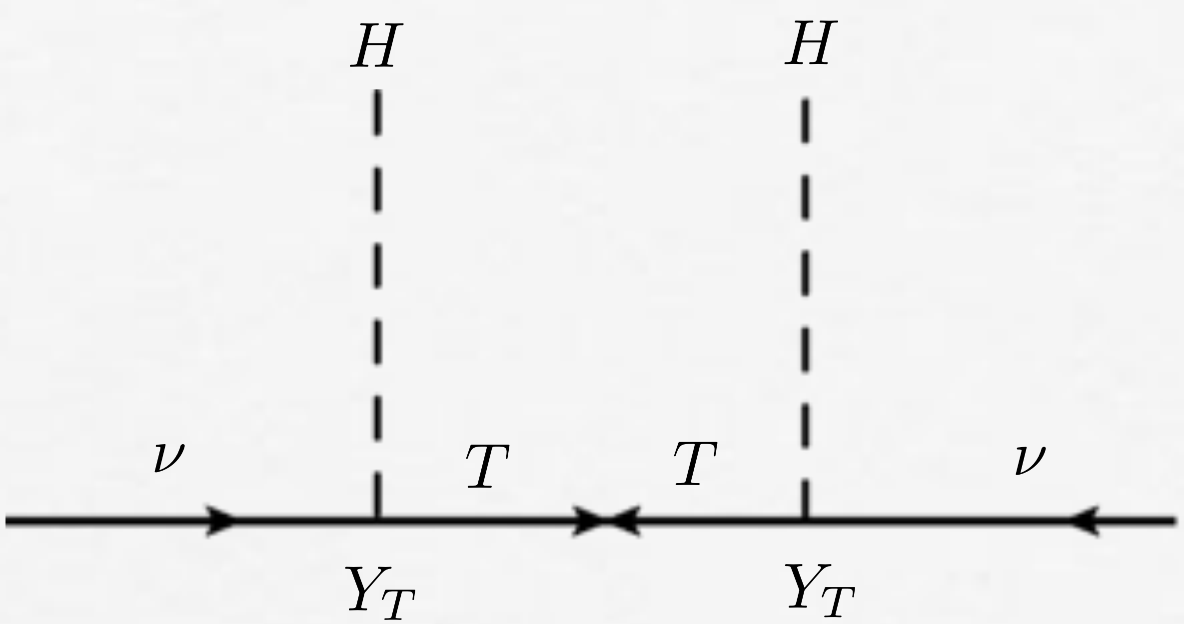

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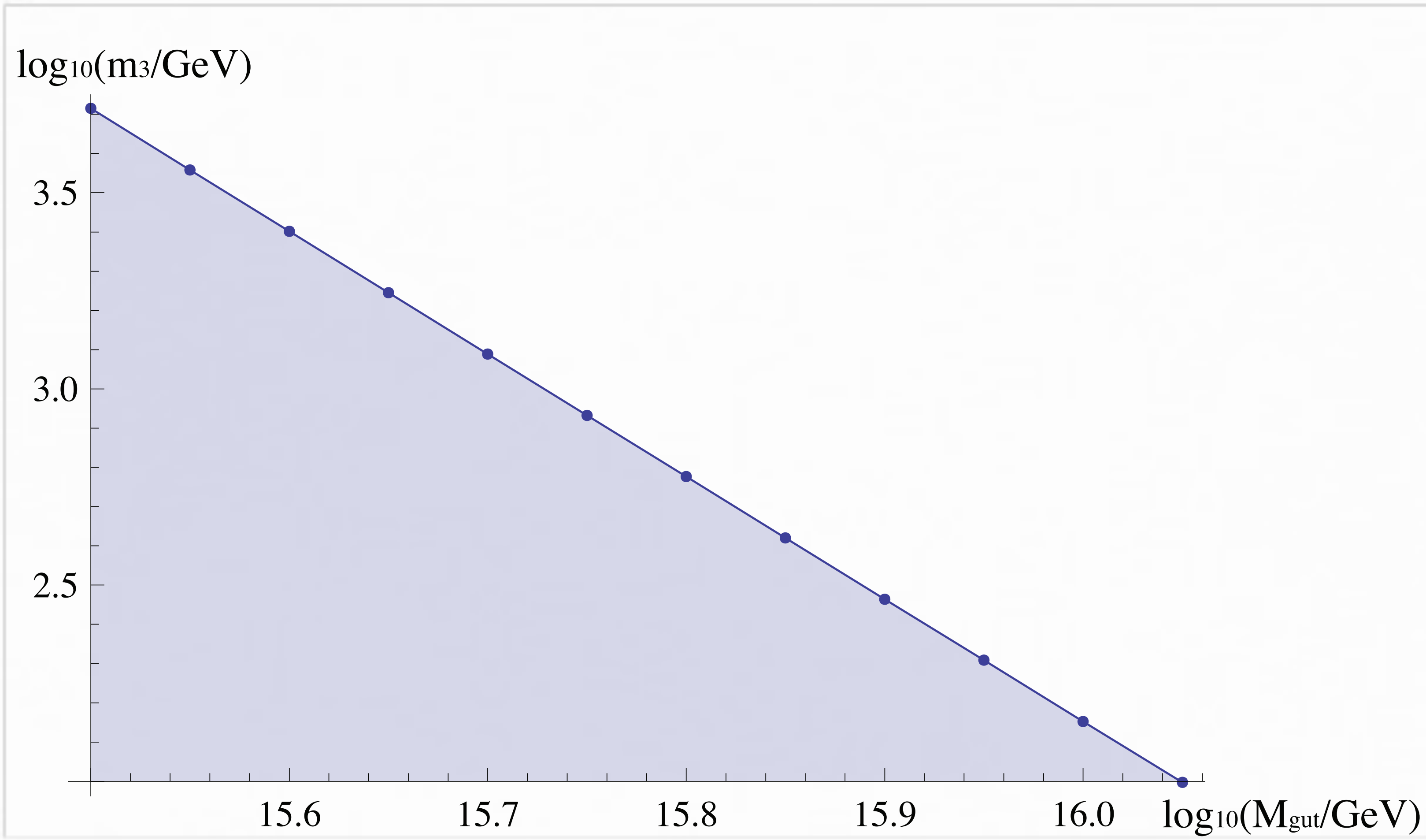

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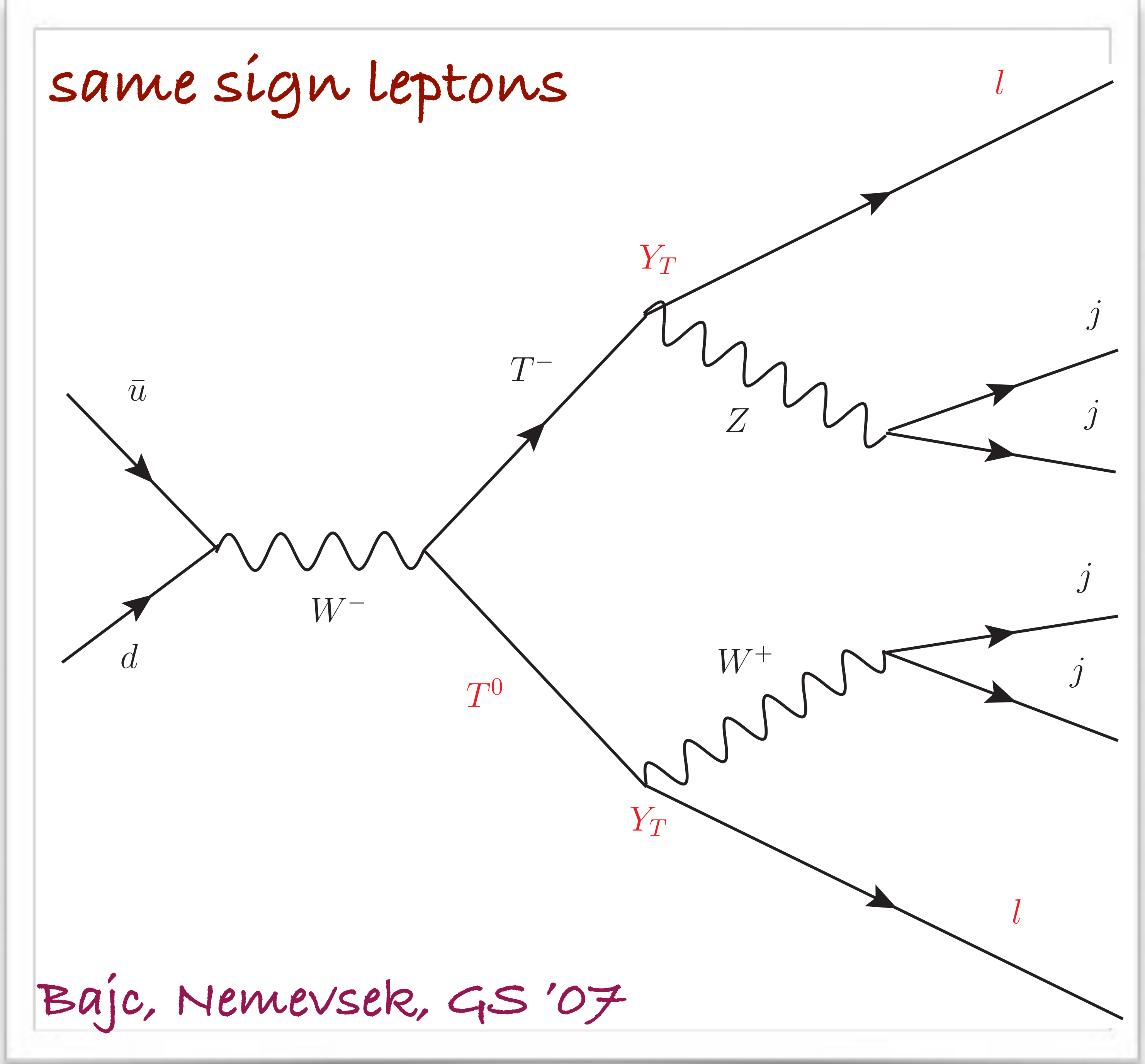
same sign leptons
l
Y_T
j
T^-
$\bar{u}$
Z
j
W^-
j
d
W^+
T^0
j
Y_T
l
Bajc, Nemevsek, GS '07