

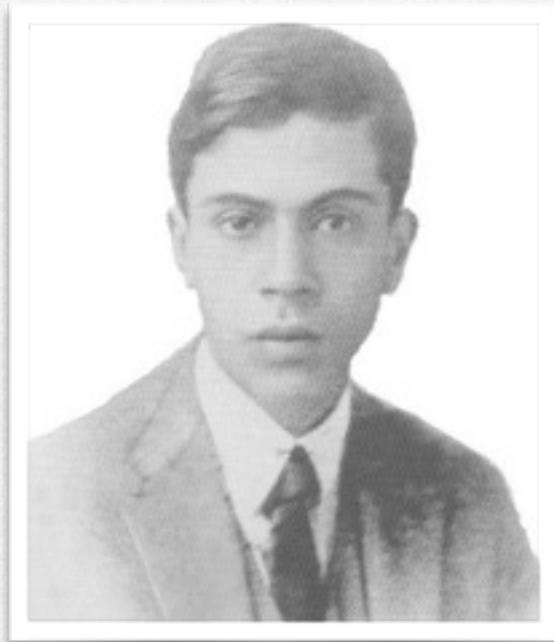
Looking for Majorana at the LHC

Goran Senjanović
GSSI & ICTP

Valencia, May 12, 2015

Ettore Majorana

a boy of via Panisperna (Fermi school)



March 25, 1938:

boat ride from Palermo to Napoli

only 32

disappears

"And then, there are geniuses, like Galileo and Newton. Ettore Majorana was one of them; unfortunately he lacked common sense."

Desperately searched for

Suicide?

*took all his savings
and his passport*

Monastery in Toscana?

*Lived happily in Venezuela:
city of Valencia?*

Left a legacy

Chi l'ha visto :



Ettore Majorana, ordinario di fisica teorica all'Università di Napoli, è misteriosamente scomparso dagli ultimi di marzo. Di anni 31, alto metri 1,70, snello, con capelli neri, occhi scuri, una lunga cicatrice sul dorso di una mano. Chi ne sapesse qualcosa è pregato di scrivere al R. P. E. Marianucci, Viale Regina Margherita 66 - Roma.

Ettore Majorana - Questo annuncio della famiglia Majorana apparve sulla «Domenica del Corriere» del 17 luglio 1938.

1937: given a job in Napoli by special merit,
on a condition to write a paper

Teoria simmetrica dell'elettrone e del positrone

Il Nuovo Cimento Vol. 14 (1937) p. 171

last paper before his disappearance



Dirac '31

Dirac equation '28

Skobeltsyn '29

Chao '29



positron Anderson '32

(anti-p Segre, Chamberlain '55)

particle \Rightarrow different antiparticle

for every fermion

not necessarily, says Majorana

neutrino = anti neutrino?

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

$\rightarrow \otimes \leftarrow \quad \leftarrow \otimes \rightarrow$



$\Delta L = 2$ lepton number violation

• neutrinoless double beta

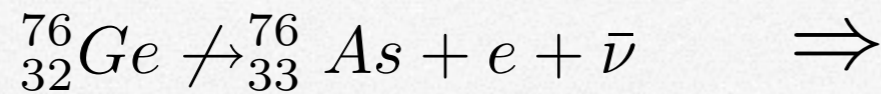
Racah '37, Furry '38

• hadronic colliders - LHC

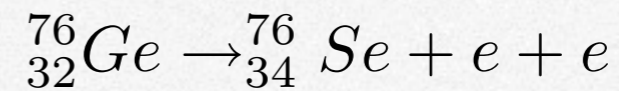
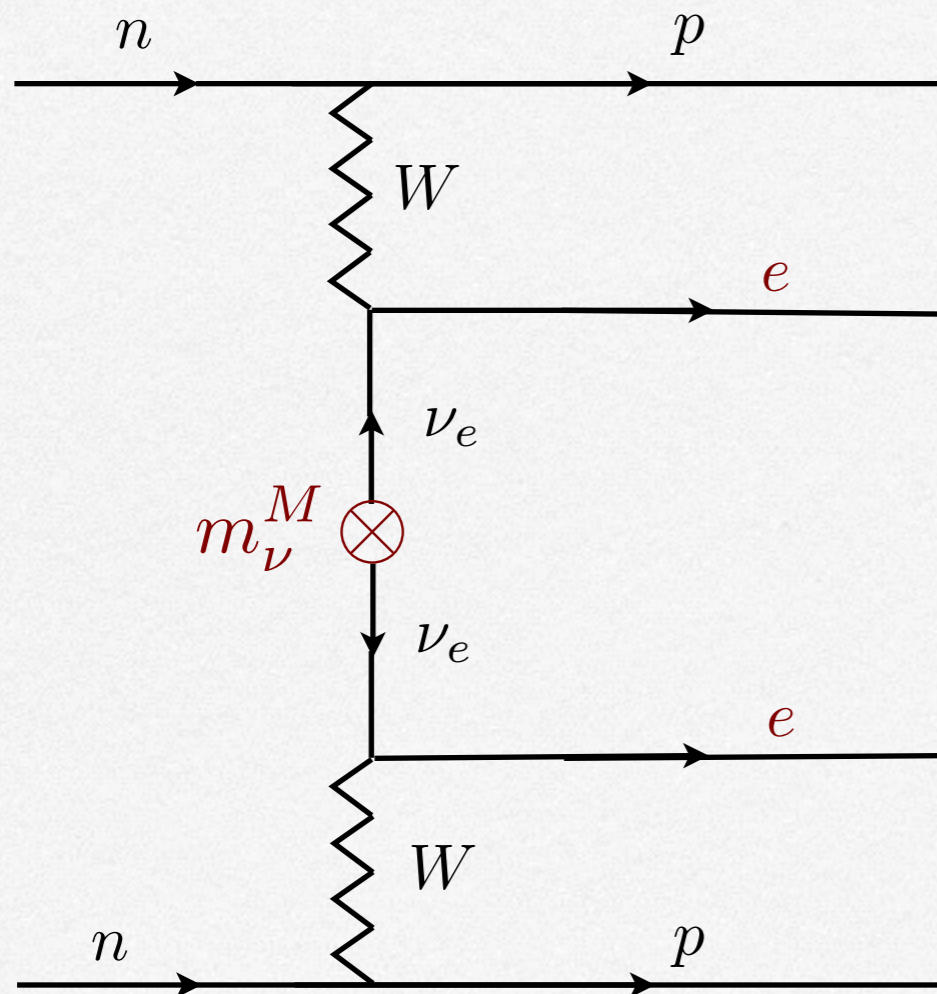
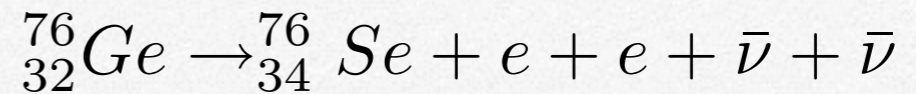
Keung, GS '83

Neutrinoless double-beta decay

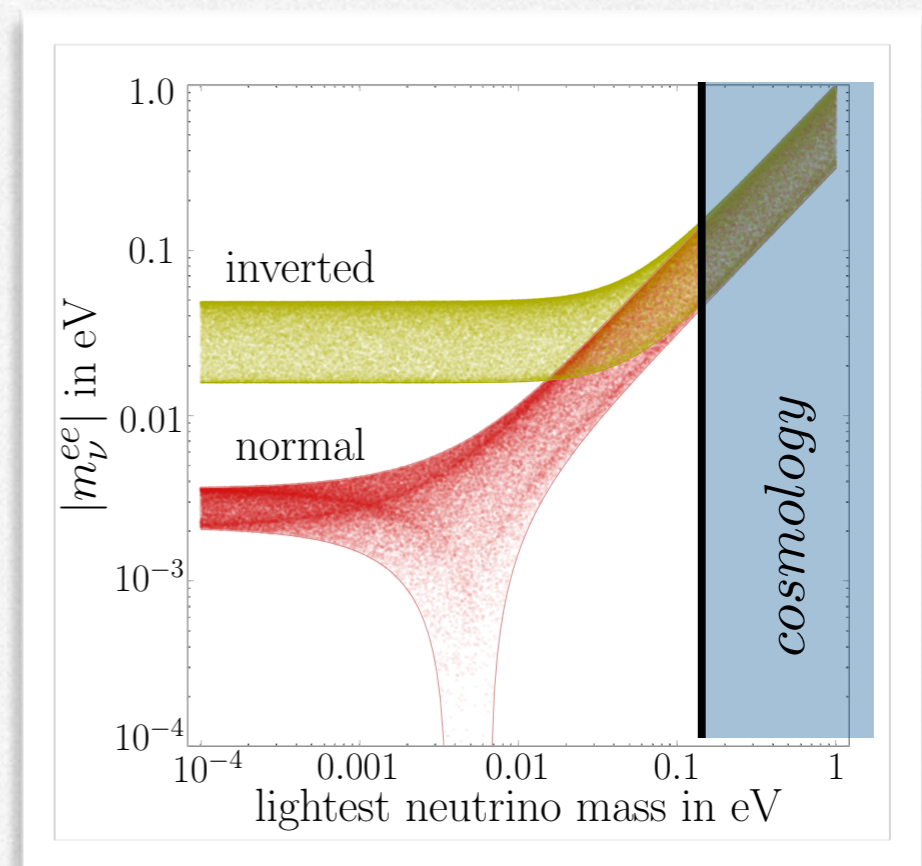
Goepert-Mayer '35



\Rightarrow



probe of neutrino Majorana mass!



Vissani '02

caveat:

new physics involved?

$$A_\nu \propto \frac{G_F^2 m_\nu^{ee}}{p^2} \simeq G_F^2 10^{-8} \text{ GeV}^{-1}$$

$$(p \simeq 100 \text{ MeV})$$

Feinberg, Goldhaber '59

Pontecorvo '64

$$A_{NP} \propto \frac{G_F^2 M_W^4}{\Lambda^5}$$



$$\Lambda \sim \text{few TeV}$$

$d=9$ operator

tailor made for LHC

Experiments

exp.	mass [kg]	f_A	bkg. [$\frac{10^{-3}\text{cnt}}{\text{keV}\cdot\text{kg}\cdot\text{yr}}$]	ΔE [keV]	eff.	enrich.	FOM	$T_{1/2}^{0\nu}$ 10^{25} yr	$m_{\beta\beta}$ meV
past experiments									
Hd-Moscow	11	0.35	120	7	1	0.86	1	1.9	170-530
Cuoricino	41	1	170	16	0.9	0.28	1	0.4	210-500
NEMO-3	6.9	2.1	1.2	400	0.06	0.9	0.3	0.1	310-900
running experiments									
EXO-200	100	0.55	1.5	100	0.55	0.81	6	4.2	75-170
Kaml.-Zen	12800	0.55	0.05	250	0.31	0.023	4	2.6	90-220
Kaml.-Zen2	12800	0.55	0.01	250	0.31	0.06	22	15	40-90
GERDA-I	15	0.35	20	8	0.8	0.86	2	3.9	120-370
GERDA-II	35	0.35	1	6	0.85	0.88	20	18	60-170
experiments under construction									
Major.-Dem.	30	0.35	1	6	0.9	0.9	20	17	60-170
CUORE	750	1	10	12	0.9	0.27	19	7.5	50-110
SNO+	780000	1.5	0.0002	230	0.33	5.6E-5	3	0.8	100-240
NEXT	100	0.55	0.8	25	0.25	0.9	9	5.2	70-160
proposed experiments									
S.NEMO	100	1.1	0.1	200	0.2	0.9	14	6.9	55-140
Lucifer	100	1.1	1	10	0.9	0.5	50	19	33-85

EXO-200 $|m_{\nu}^{ee}| \lesssim 0.3 \text{ eV}$

Kaml-Zen $|m_{\nu}^{ee}| \lesssim 0.6 \text{ eV}$

Schwingerheuer'12

What NEXT?

Origin of neutrino mass

Origin of mass?

Elementary particle masses:
Higgs (ABEGHK) mechanism

$$m = g \langle \phi \rangle$$

how to probe?

directly: see the phase transition at
high T (symmetry restoration)

$$T \gtrsim 100 \text{ GeV}$$



$$\langle \phi \rangle = 0$$

Kirzhnits, Linde '72
Weinberg; Dolan, Jackiw '74

Charged fermion masses

Goldstone '60

Higgs '64, '66

Weinberg '67

mass from Yukawa couplings

Goldstone - Higgs - Weinberg boson h

$y_f = \frac{g}{2} \frac{m_f}{m_W} \implies \Gamma(h \rightarrow f \bar{f}) = \frac{G_F}{4\sqrt{2}\pi} m_h m_f^2$

probe origin of charged fermion masses



measure Higgs (Goldstone-Weinberg) branching ratios



same philosophy for neutrinos

Neutrino mass

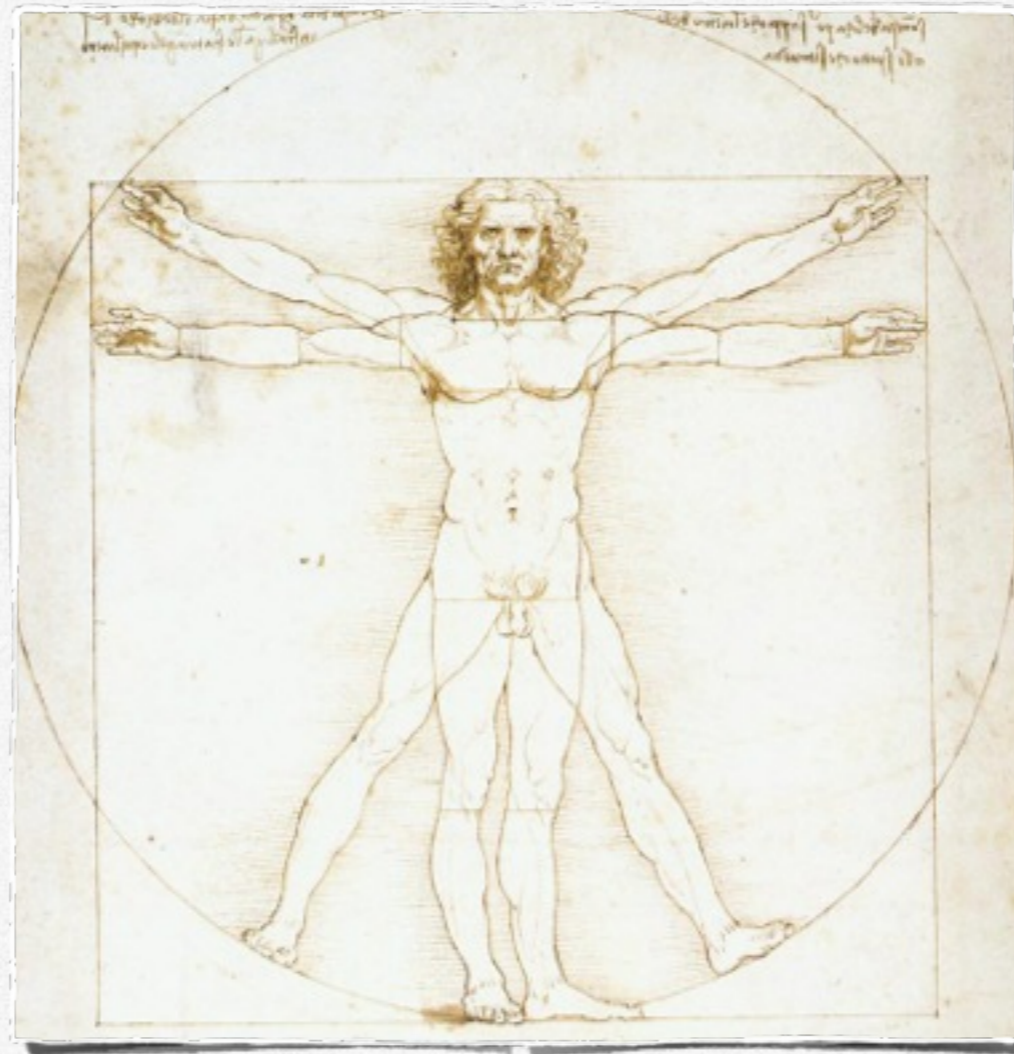
SM: L-R asymmetry $\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ e_R



neutrino massless

$\nu_L \nu_L$ forbidden by $SU(2)$ symmetry

~~Why~~ (how) parity: L \longleftrightarrow R broken?

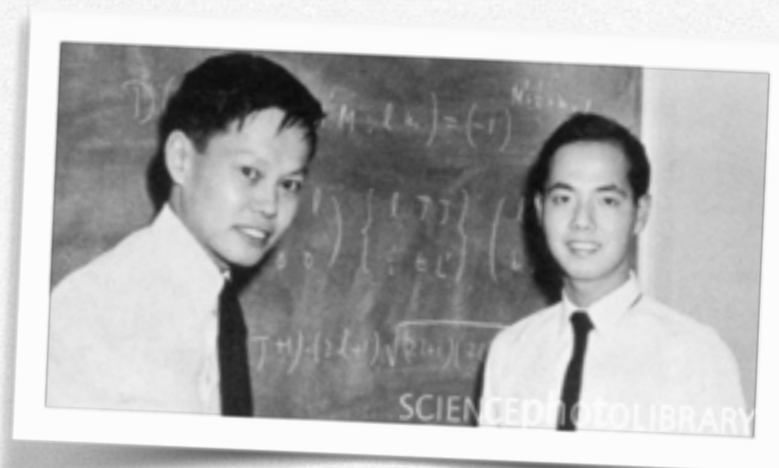


God may be left-handed, but not an invalid



Parity violation in weak interaction

Lee, Yang '56



not well known:
conjecture: LR is a
hidden symmetry *

* mirror fermions

L-R symmetry

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

e_R

u_R

d_R

W_L

L-R symmetry

Lee, Yang conjecture

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

W_L

$$\begin{pmatrix} \nu_R \\ e_R \end{pmatrix} \quad \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

W_R

neutrino massive

naïve expectation: $m_\nu \simeq m_e$ (if Dirac)

curse?

Pati, Salam '74

Mohapatra, GS '75

Theoretical motivation

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

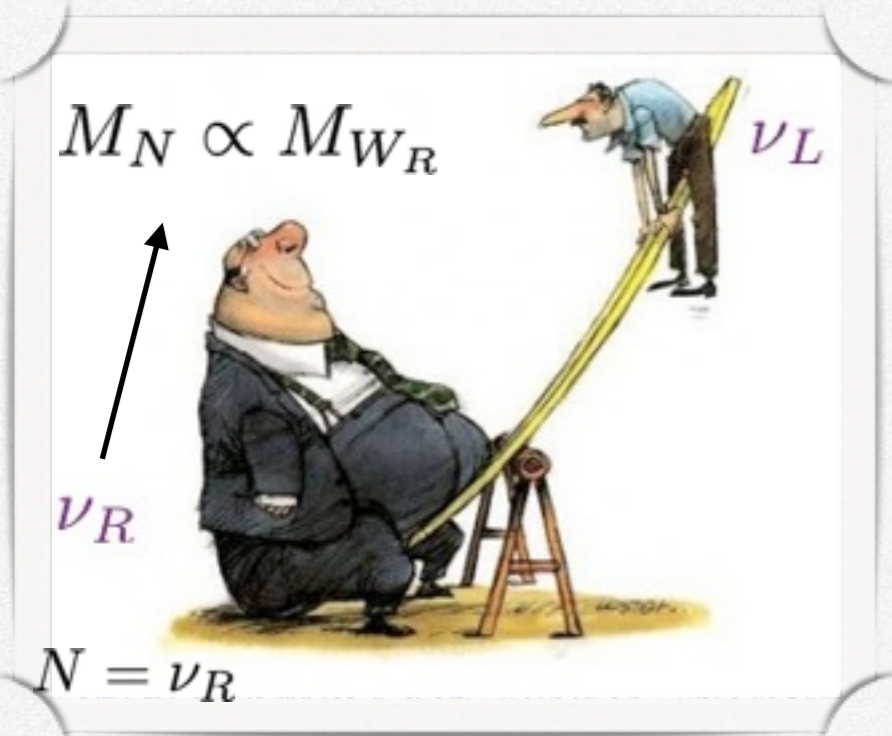


$$Q = T_L^3 + T_R^3 + \frac{B-L}{2}$$

Neutrino mass

seesaw

$M_D =$ Dirac mass



$$M_\nu = M_D^T \frac{1}{M_N} M_D$$

neutrino mass related to
amount of P violation



Minkowski '77

Mohapatra, GS '79

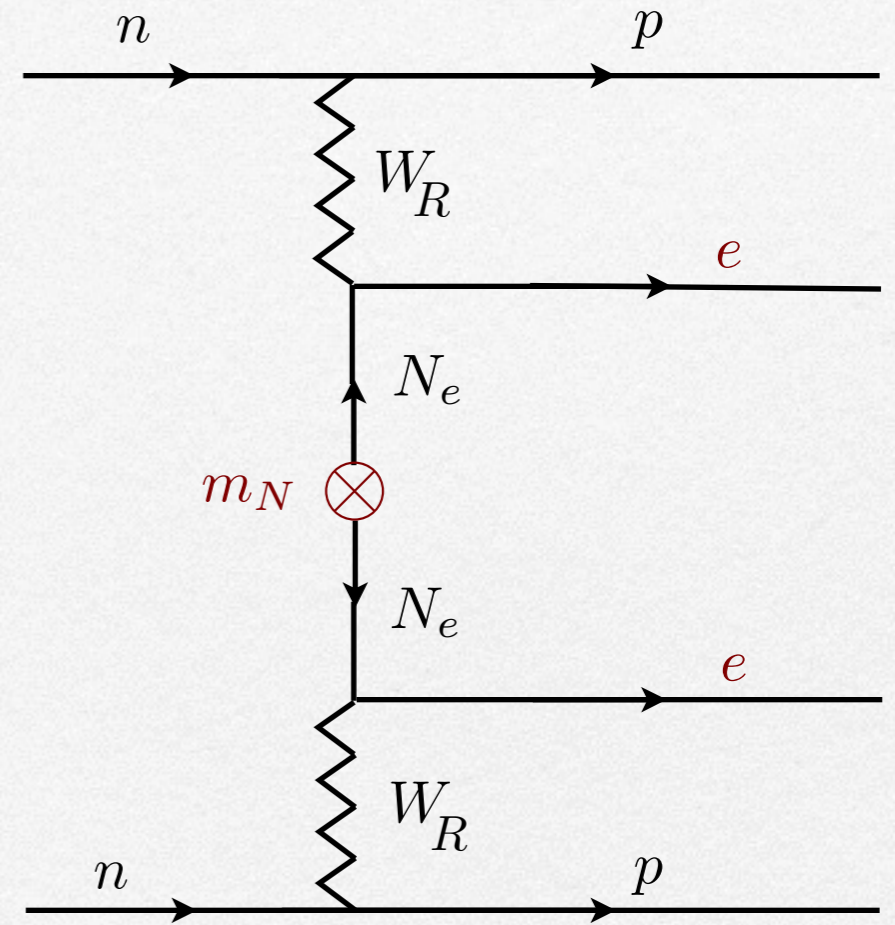
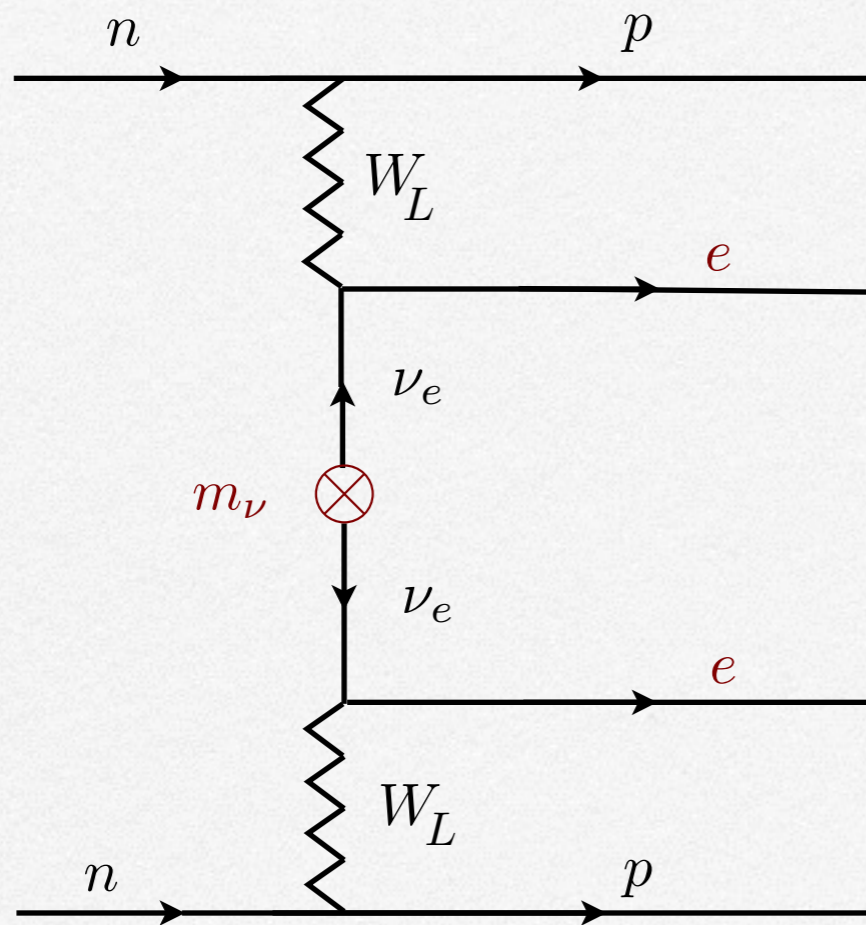
new physics:

N - gauge interactions:

W_R and Z_R

New source for $0\nu 2\beta$

Mohapatra, GS '79, 81



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

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

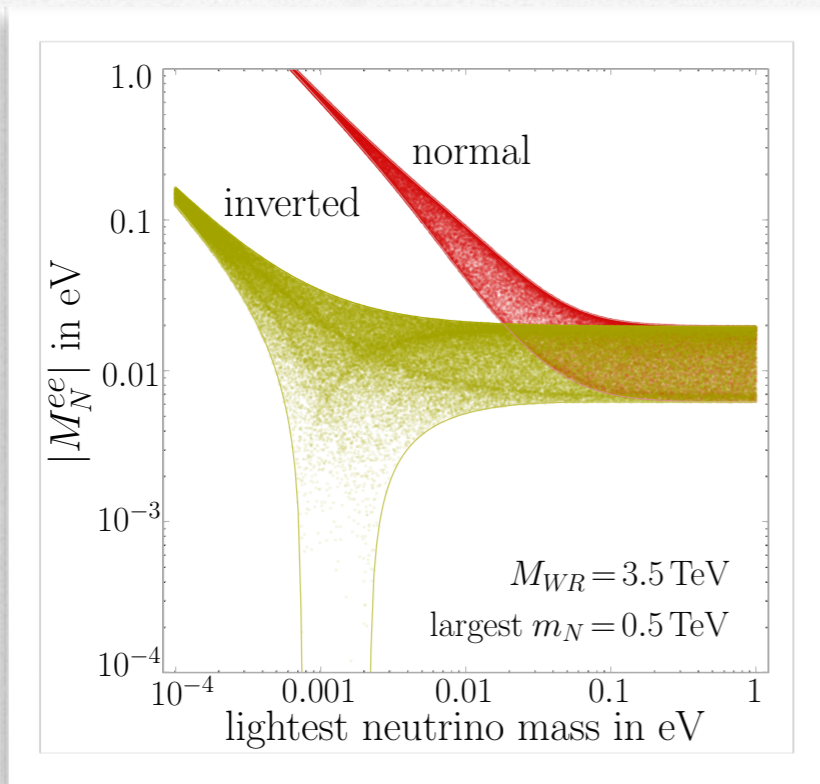
$$RR \propto \frac{1}{M_{W_R}^4} \frac{1}{m_N}$$

$$M_{W_R} \simeq m_N \simeq \text{TeV}$$

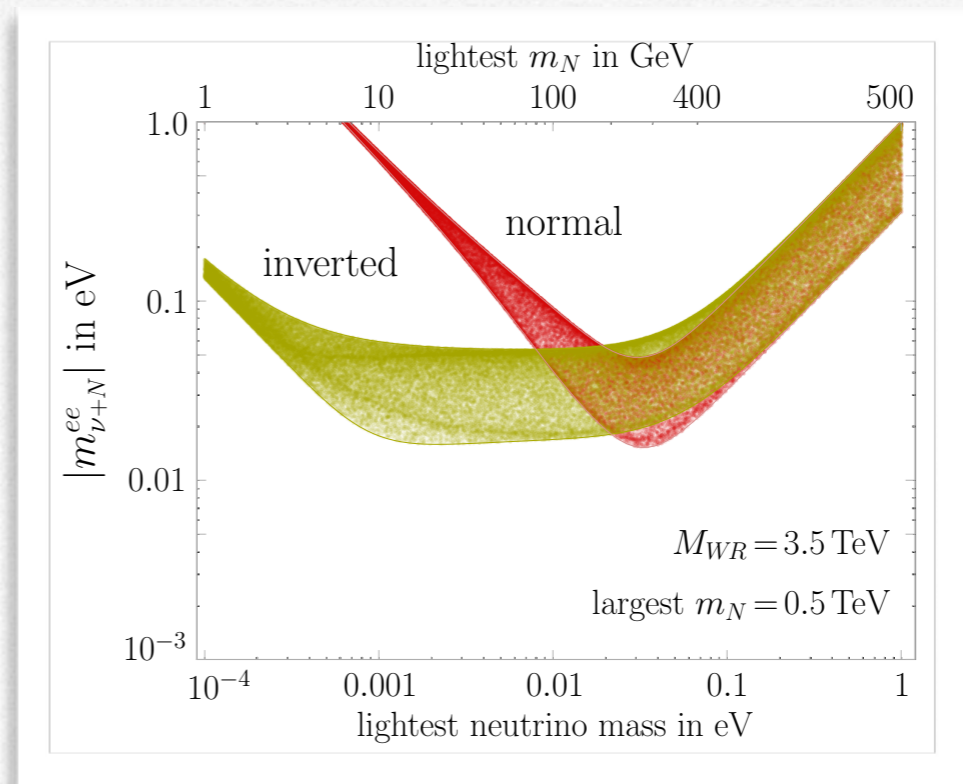
example: type II seesaw

$$V_R = V_L^* \quad m_N/m_\nu = \text{const}$$

Tello, Nemevsek, Nesti, GS, Vissani '11



Right



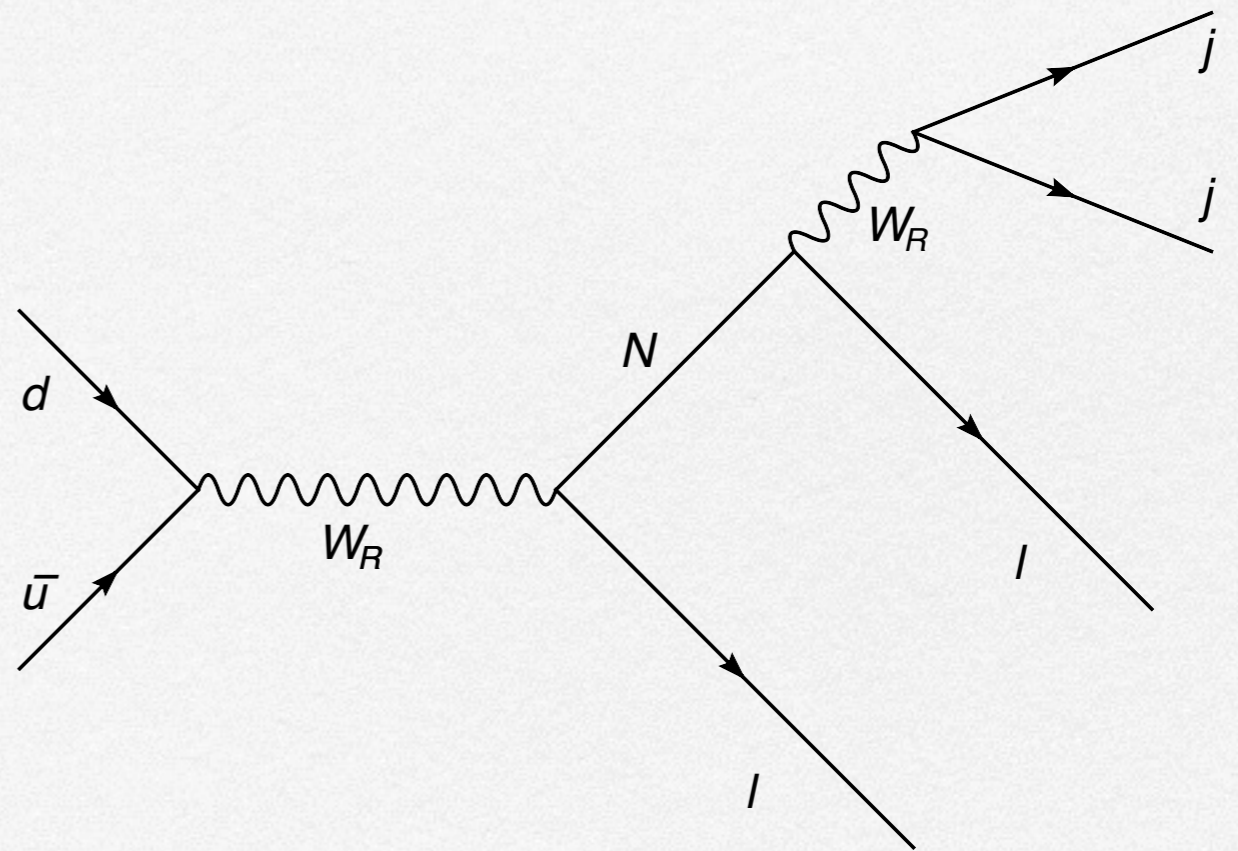
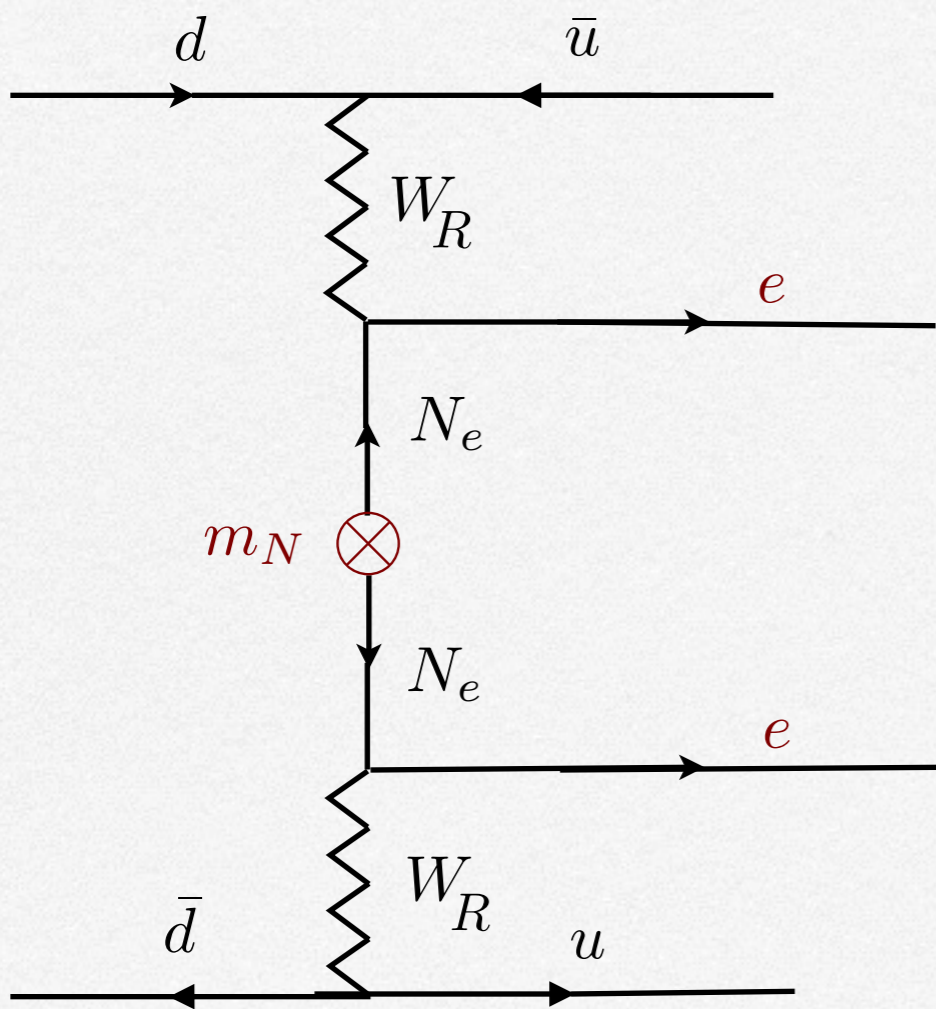
Left + Right

Das, Deppisch, Kittel, Valle '12

Helo, Kovalenko, Hirsch '13

LHC connection?

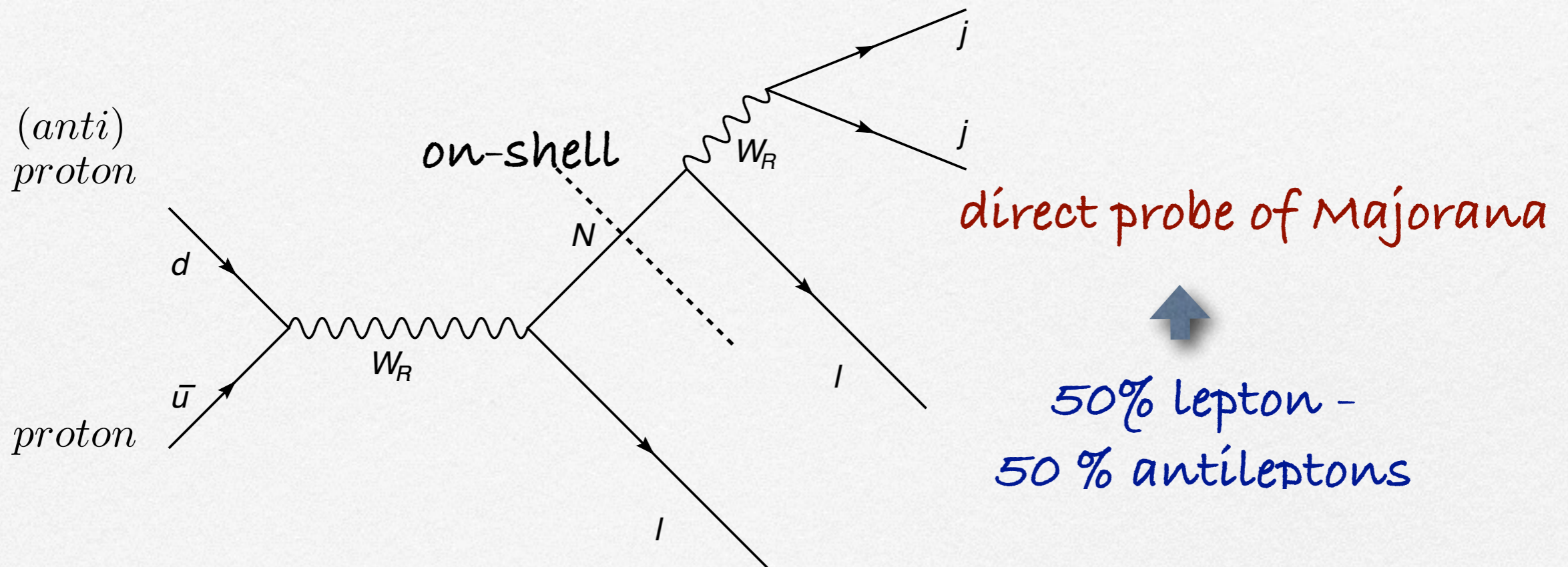
Rotation in a plane



same sign charged di-leptons

Production @ colliders

Keung, G.S. '83



- LNV: same sign leptons
- reconstruct W_R , N masses; V_R

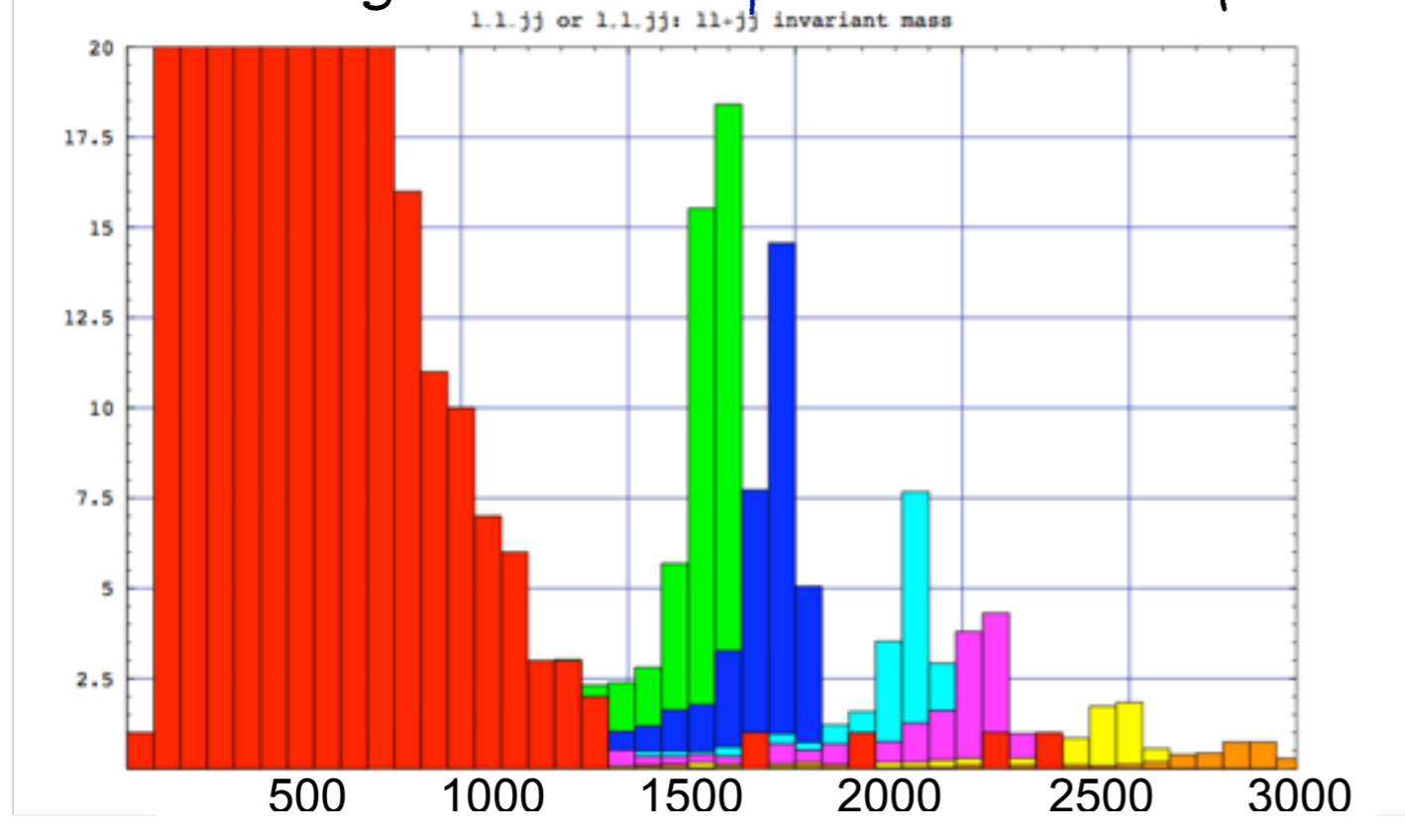
Vasquez '14

14 TeV LHC

Nesti '10

$$L = 10/f_0$$

red = background peaks = mass of WR



no background
above 1.5 TeV

up to ~ 6 TeV @ $L = 300/f_0$

Ferrari et al, '00

Connection with neutrino mass?

Nemevsek, GS, Tello '12

LR symmetry

$$\mathcal{C}: f_L \rightarrow (f^C)_L = C(\bar{f}_R)^T \propto f_R^*$$



$$M_D = M_D^T$$



$$M_D = M_N \sqrt{\frac{1}{M_N} M_\nu}$$

analogue of Goldstone-Higgs-Weinberg for charged fermions

$$\mathcal{P}: f_L \rightarrow f_R$$

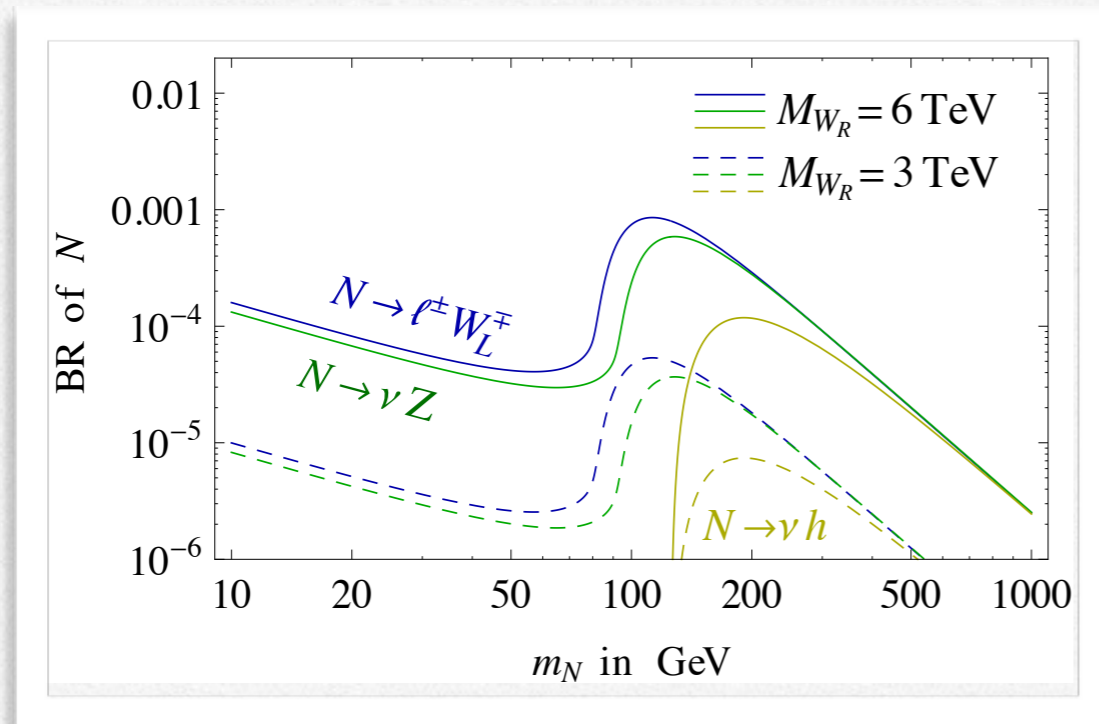


$$M_D = M_D^\dagger$$

Nemevsek, GS, Tello, to appear

leading: $N \rightarrow \ell^\pm W_R^\mp$

sub-leading: $N \rightarrow \ell^\pm W_L^\mp$ $\leftarrow \theta_{\nu-N} = \frac{M_D}{M_N}$



Nemevsek, GS, Tello '12

illustrate: type II seesaw

$$M_D = V_L^* \sqrt{m_\nu m_N} V_L^\dagger$$

chirality feasible

Ferrari et al '00

Han, Low, Ruiz, Si '12

L-R scale?

$K_L - K_S$ mass difference

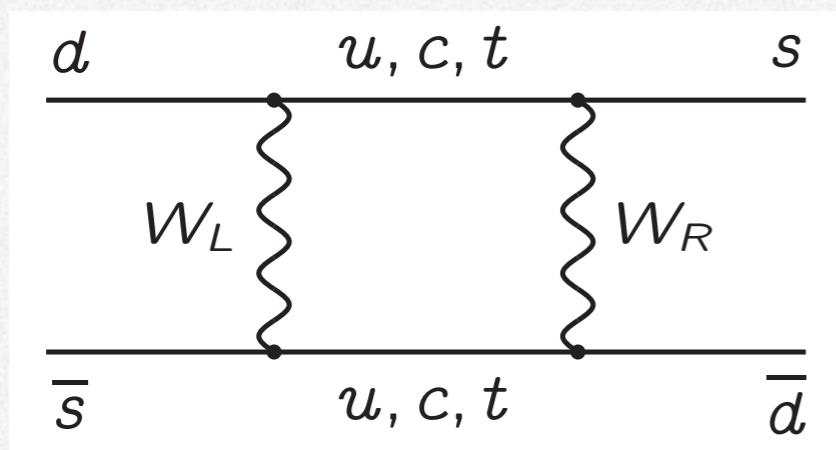


$$M_{W_R} \gtrsim 2.5 \text{ TeV}$$

Beall, Bander, Soni '81
Mohapatra, GS, Tran '83

.....
Zhang, An, Ji, Mohapatra '07

Maiezza, Nemevsek, Nesti, GS '10



experiment catching up

CMS 1407.3683

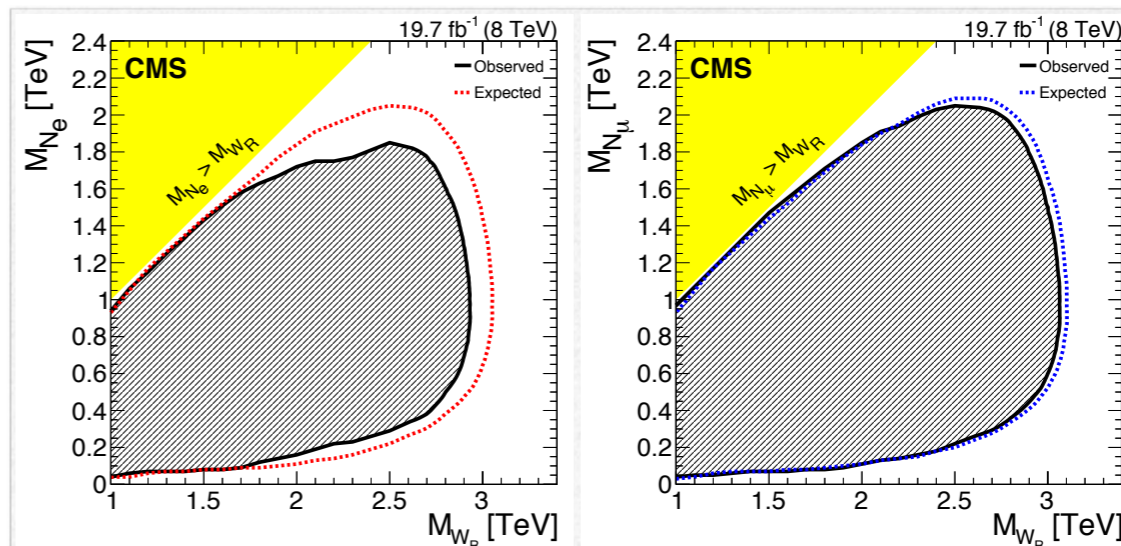
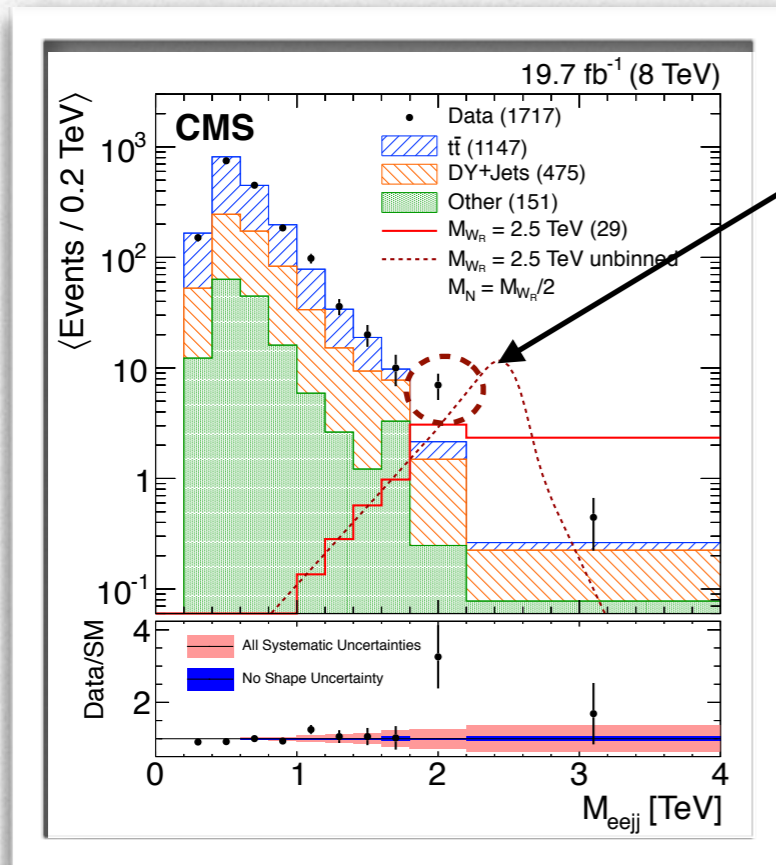


Figure 3: The 95% CL exclusion region (hatched) in the (M_{W_R}, M_{N_ℓ}) plane, assuming the model described in the text (see Section 1), for the electron (left) and muon (right) channels. Neutrino masses greater than M_{W_R} (yellow shaded region) are not considered in this search.

2.8 sigma excess in ee



Deppisch et al '14
 Heikinheimo et al '14
 Aguilar-Saavedra, Joaquim '14
 Gluza, Jelinski '15
 Deppisch et al '15
 ...

$$r = SS/OS = 1/14$$



pseudo-Dirac: degenerate N1 and N3,
 N2 decoupled (no muon excess)

Gluza, Jelinski '15



below the theoretical limit,
 but assumed $m_N = 1/2 M_{WR}$
 (*no Breit-Wigner)

MSSM?!

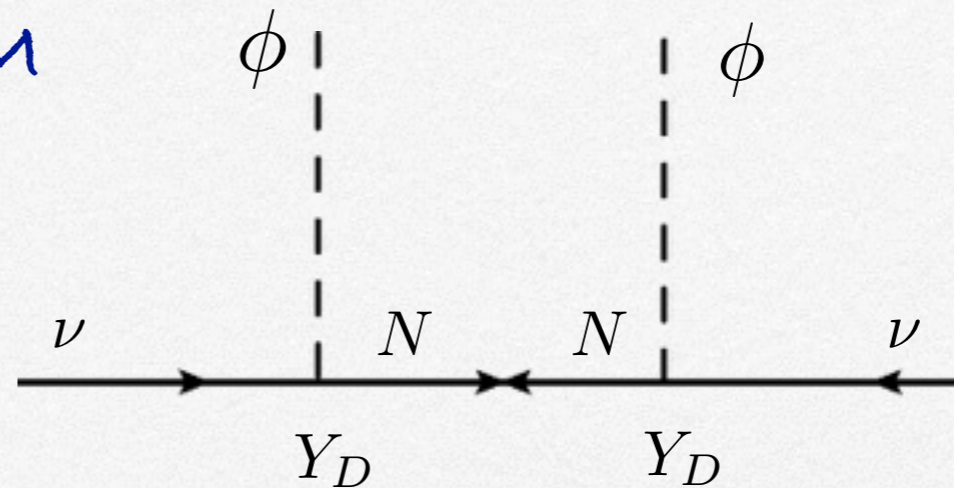
Custom-fit models: scenarios

Seesaw I

add heavy RH neutrino N to SM



$$M_\nu = M_D^T \frac{1}{m_N} M_D$$



not the way it happened

L-R

Minkowski '77

Mohapatra, GS '79

SO(10)

Gell-Mann et al '79

Glashow '79

family symmetry

Yanagida '79

Setback

$$M_\nu = M_D^T \frac{1}{m_N} M_D$$



Cannot determine M_D

$$M_D = \sqrt{m_N} O \sqrt{M_\nu}$$

O - arbitrary complex orthogonal matrix $O^T O = 1$

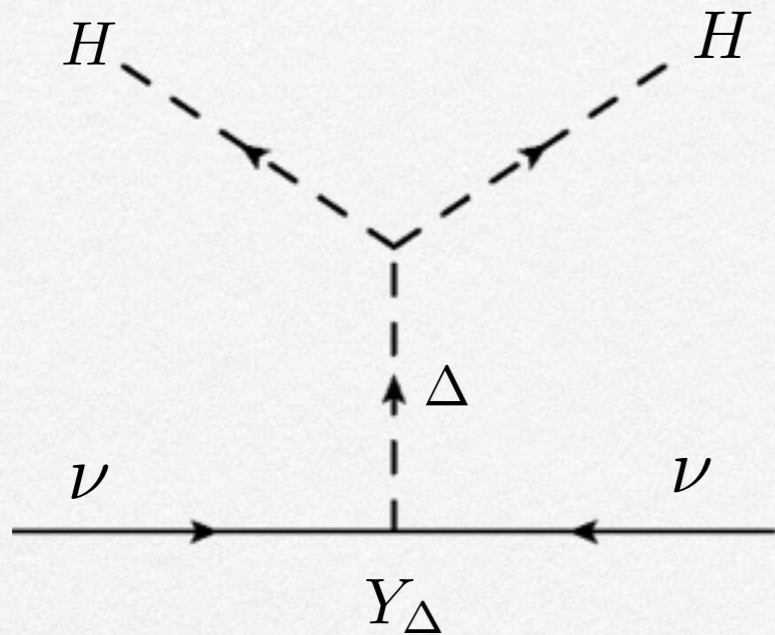
Casas, Ibarra '01

Leptogenesis?

hard to be wrong

Pauli :(

Seesaw II



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

no connection between
LHC and $\nu\mu\tau\beta$

Pauli :(

actually part of LR

Mohapatra, GS '81

Seesaw III

triplet fermion

and more:
quintet fermion

...

L-R theory

- understanding P violation
- gauge structure: new currents
- LNV@colliders: connected to $0\nu\beta\beta$
- *see-saw*: ν_R

Standard Model

- Electroweak unification
- gauge structure
- W - Z mass ratio
- neutral currents: Z boson

L-R theory

a complete, predictive theory of
neutrino mass



needs LHC

LHC:

- could probe the origin of neutrino mass
- could resolve the mystery of parity violation
- could directly observe lepton number violation
- could directly see Majorana nature of N
- connected with low energy: $0\nu 2\beta$, LFV

Gracies

Gracias

WR heavy?

if N light, SM Higgs h could help

if h mixes enough with the LR scale Higgs



Higgs Hunters Guida

$h \rightarrow NN$ decays

Graesser '07

Maiezza, Nemevsek, Nesti '15

Model content & symmetry breaking

Mohapatra, GS '75, '81

bi-doublet

R - triplet

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

L - triplet

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

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

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

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

EW symmetry
breaking

mass of ν
(Majorana)

$$v_R \gg v \gg v_L$$

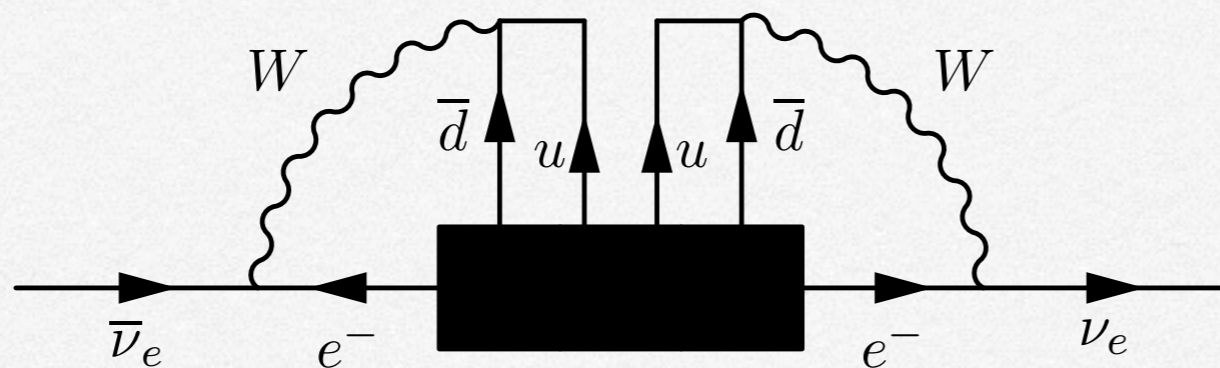
theory bound

Particle	Final state	Lower limit	Collaboration	Comments
W_R	jj	1.5 TeV	CMS [41]	independent on N mass
W_R	$e/\mu + N$	2.5 TeV	CMS [42]	light N (missing energy)
W_R	$lljj$	$\lesssim 2.5$ TeV	ATLAS, CMS [43, 44]	heavy Majorana N [45]
Z_{LR}	$e^+e^-/\mu^+\mu^-$	~ 2 TeV	ATLAS [46]	see [47]
Z_{LR}	e^+e^-	~ 3 TeV	LEP [48]	indirect, see [49, 50]
Δ_L^{++}	$l_i^+ l_j^+$	100-355 GeV	ATLAS [51]	spectrum dependent [52]
Δ_L^+	$\cancel{E}_T + j$	70-90 GeV	LEP [55]	chargino search [54]
Δ_L^0		45 GeV	LEP [48]	Z -boson width
Δ_R^{++}	$l_i^+ l_j^+$	113-251 GeV	ATLAS [51], CDF [53]	flavor dependent

Table 1. A summary of limits on the mass scales of the particles in LRSM from collider searches.

Schechter-Valle "theorem":

$0\nu 2\beta$ implies neutrino Majorana mass



Schechter, Valle '82

$0\nu 2\beta$ - probe of neutrino (Majorana) mass

suggests

effectively = 0

Duerr, Lindner, Merle '11

$$\delta m_\nu = 0 \quad \delta m_\nu \simeq 10^{-24} \text{ eV}$$

Planck scale seesaw

$$m_\nu \simeq 10^{-5} \text{ eV}$$

Akhmedov, Berezhiani, GS '91

to better appreciate

$$m_e^M / m_e^D \lesssim 10^{-28}$$

Mohapatra '79

$$m_\nu^M / m_\nu^D \simeq 10^{-25}$$

the black box

Grand Unification?

suggestive:

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

SO(10) tailor made

minimal supersymmetric version:

$$\theta_{\text{atm}} \simeq 45^\circ \Leftrightarrow \theta_{ub} \simeq 0$$

Bajc, GS, Vissani '02

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

Goh, Mohapatra, Ng '03



NO LHC

T2K, Daya Bay