Neutrino and the Origin of Mass

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Pheno 2013, Pittsburgh, May 2013

Origin of mass?

Elementary particle masses:
Higgs (ABEGHK) mechanism

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

how to probe?

$$T \gtrsim 100\, GeV$$

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

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

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

Charged fermion masses

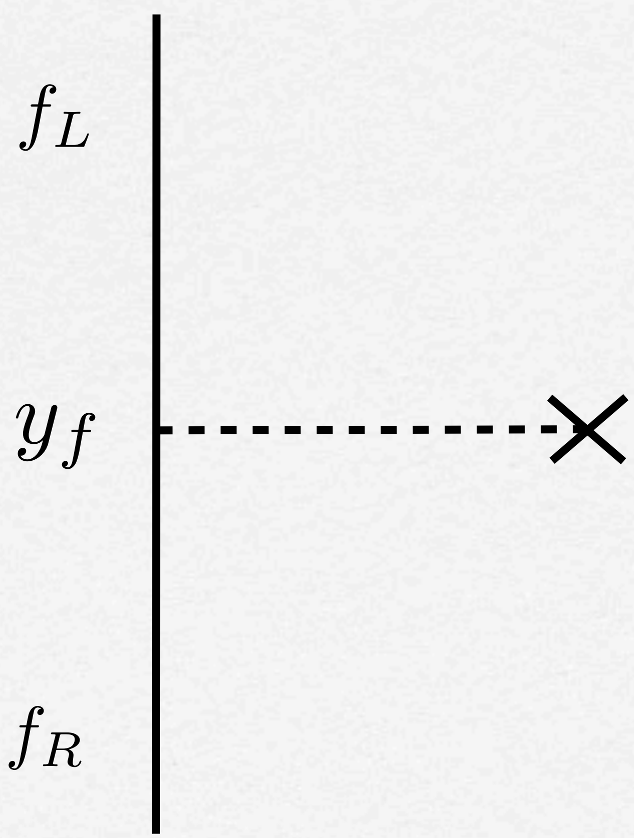
Goldstone '60

Higgs '64, '66

Weinberg '67

Goldstone - Higgs - Weinberg boson

mass from Yukawa couplings



$$y_f \, \phi \bar{f}_L f_R + h.c.$$

$$\Downarrow$$

$$y_f = \frac{g}{2} \, \frac{m_f}{m_W}$$

$$\Rightarrow \qquad \Gamma(h \to f\bar{f}) = \frac{G_F}{4\sqrt{2}\pi} m_h m_f^2$$

probing the origin of charged fermion masses

$$\Downarrow$$

measuring Higgs (Goldstone-Weinberg) branching ratios

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probing the origin of charged fermion masses

measuring Higgs (Goldstone-Weinberg)
branching ratios

same philosophy for neutrinos

$\Rightarrow$

$$\Gamma(h \to f\bar{f}) = \frac{G_F}{4\sqrt{2}\pi} m_h m_f^2$$

probing the origin of charged fermion masses

measuring Higgs (Goldstone-Weinberg)
branching ratios

LHC

same philosophy for neutrinos

Standard Model

often blamed for not being:

theory of dark matter

theory of genesis

theory of small numbers:
Higgs mass, cosmological constant

...

Standard Model

gauge theory of weak interactions

Standard Model

gauge theory of weak interactions

theory of neutrino mass: nu massless

Standard Model

gauge theory of weak interactions

theory of neutrino mass: nu massless

the only true failure of SM

window to new physics

What is so special of neutrinos?

text-book: can have both Dirac and Majorana masses

- Dirac:

add RH neutrino

$$y_D \, \phi \, \bar{\nu}_L \nu_R$$

$\Rrightarrow$

$$y_D = \frac{g}{2} \frac{m_\nu^D}{m_W} \simeq 10^{-12}$$ hopelessly small

- Majorana:

SM degrees of freedom

$$m_\nu^M = y_{eff}\,\frac{v_\phi^2}{M}$$

d=5 $\quad y_{eff}\,\frac{\phi\phi\,\ell\ell}{M} \quad \Rightarrow \quad y_M = y_{eff}\,\frac{v_\phi}{M}$

$$\ell = \begin{pmatrix} \nu \\ e \end{pmatrix}_L$$

Weinberg '79

$$y_M = \frac{g}{2}\,\frac{m_\nu^M}{m_W}$$

the same

often claimed:

large M more natural than
small coupling y_{eff}

makes no sense:

- small coupling protected - technically natural

- large M: hierarchy problem

Source of neutrino mass

What is behind it:

UV completion of SM?

Neutrino mass: seesaw

Seesaw (type I)

add RH neutrino to SM:

a mess

$$\begin{array}{c} \nu_L \\ \nu_R \end{array} \begin{pmatrix} 0 & M_D \\ M_D^T & M_{\nu_R} \end{pmatrix}$$

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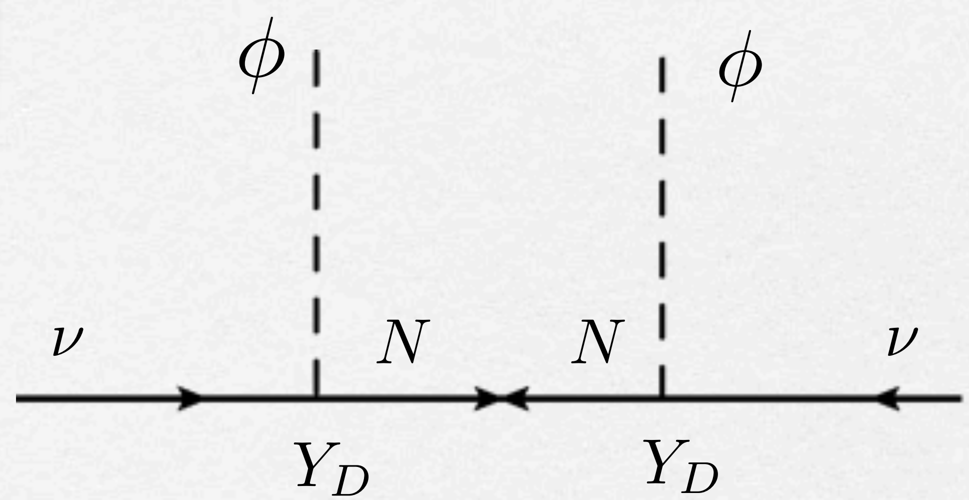
light $M_\nu = M_D^T \dfrac{1}{m_N} M_D$

heavy $m_N = m_{\nu_R}$



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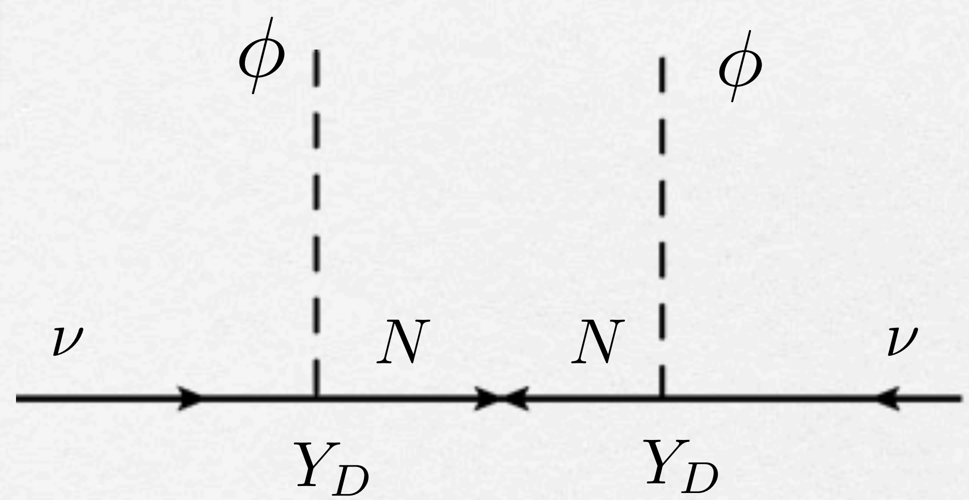

L-R

Minkowski '77

Mohapatra, GS '79

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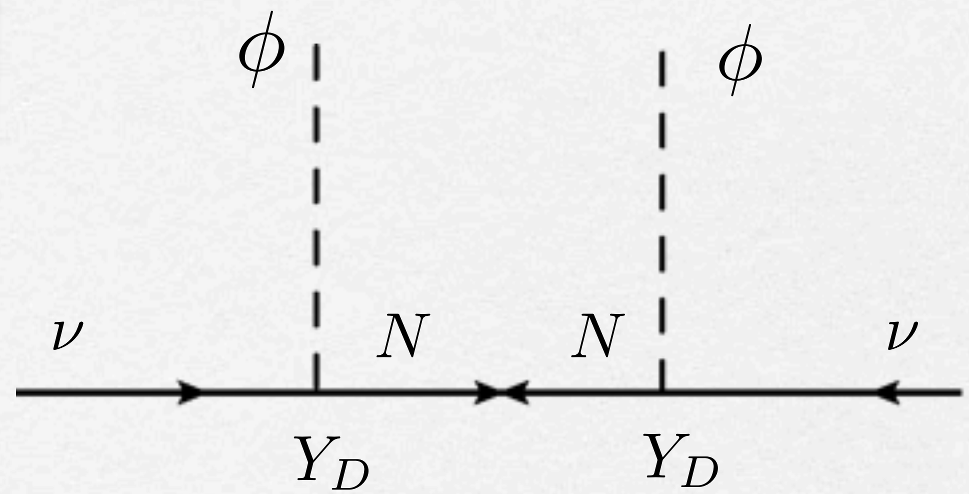

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SO(10)

Gell-Mann et al '79

Glashow '79

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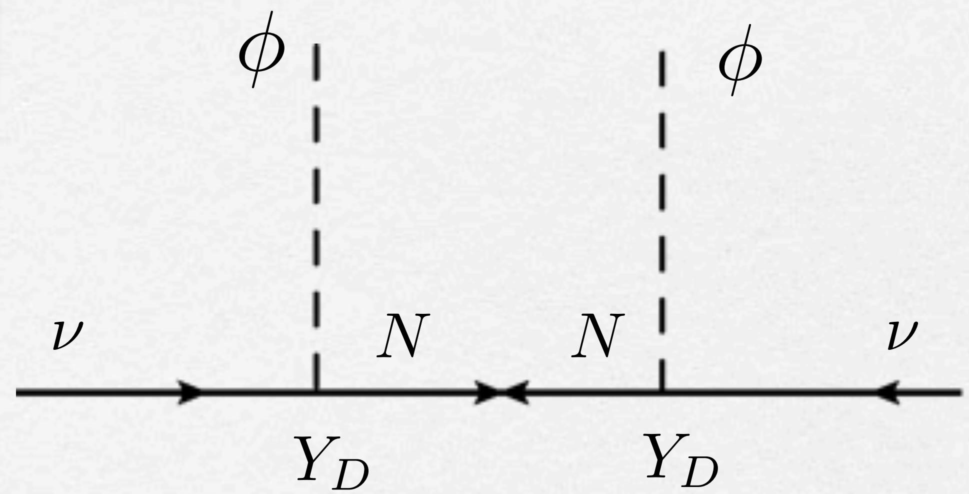

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family symmetry

Yanagida '79

Setbacks

- Cannot determine M_D

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

Casas, Ibarra '01

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

$\mathcal{O}^T\mathcal{O} = 1$ arbitrary complex orthogonal matrix

Not what we are after:

we wanted to predict Yukawa Dirac

- hard to produce N

needs large Dirac Yukawa (matrix O)

Han, Zhang '07

Atre, Han, Han, Pascoli '09

del Aguila, Aguilar-Saveedra, Pittau '09

neutrino lightness accidental -
no way of probing its origin

Kersten, Smirnov '07

Not what we are after

Occam's razor approach

Asaka, Blanchet, Shaposhnikov '05,

Shaposhnikov et al '2005 - 2013

- neutrino mass
- warm dark matter
- genesis

seesaw

fixes everything

light N: keV, GeV (2)

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fixes everything

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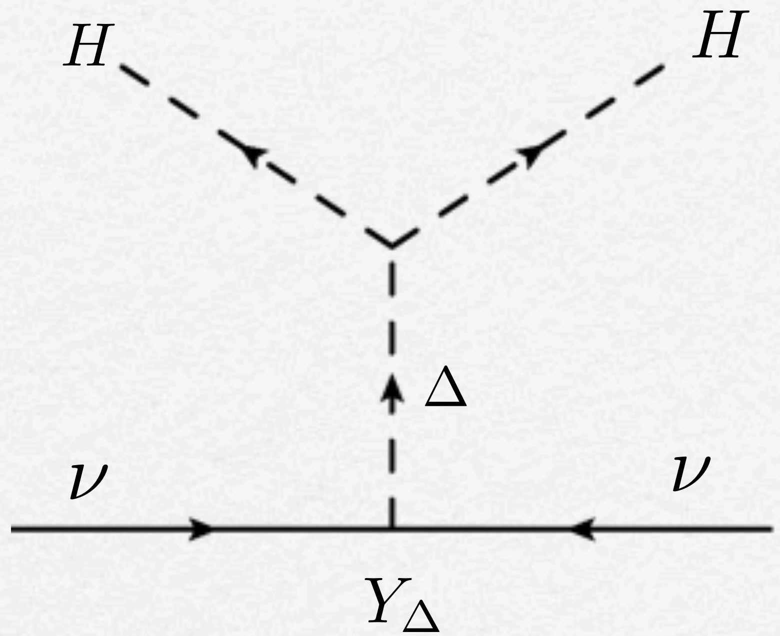
Not what I am after

Type II seesaw

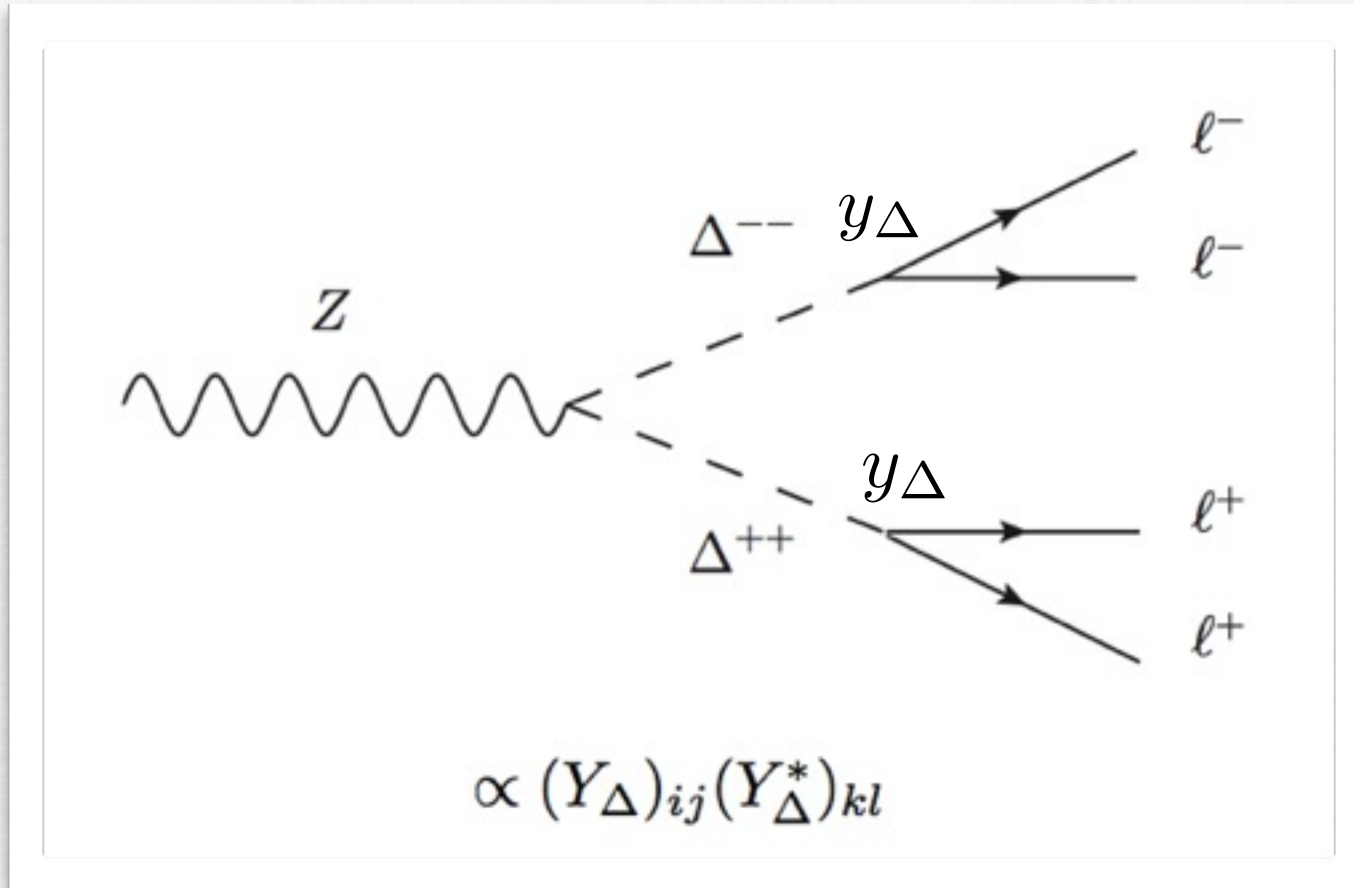
Magg, Wetterich '80
Cheng, Li '80
Mohapatra, GS '80
Lazarides, Shafi, Wetterich '80



$$\mathcal{L} = y_\Delta \ell \Delta \ell + \mu \phi \Delta^\dagger \phi + m_\Delta^2 \Delta^\dagger \Delta \quad + \dots$$

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

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



Majorana case

$$y_\nu = g\frac{m_\nu}{m_W}$$ hopeless

$$\Delta^{++} \to W^+W^+$$

probes v_Δ

Akeroyd, Aoki, Sugiyama '07

Fileviez-Perez, Han, et al '08

probe neutrino masses and mixings

Chun, Lee, Park '03

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

Schwetz, Garayoa '07

Kadastik, Raidal, Rebane '07

Why only the triplet?

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

vevs: color and charge singlets

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

ϕ (Y=1 doublet)

Δ (Y=2 triplet)

Type III Seesaw

RH neutrino (Type I): $\rightarrow$ SU(2) triplet fermion T

Foot, Lew, He, Joshi '89

T can be produced through gauge interactions

minimal realistic SU(5):

Bajc, GS '06

$m_T \lesssim TeV$

Bajc, Nemevsek, GS '07

Franceschini, Hambye, Strumia '08

LHC

del Aguila, Aguilar-Saveedra '08

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

Message

d=5

Seesaw

Neutrino Majorana

Neutrino = anti neutrino

Majorana '37

Lepton Number Violation

- neutrinoless double beta decay

Racah'37 Furry '38

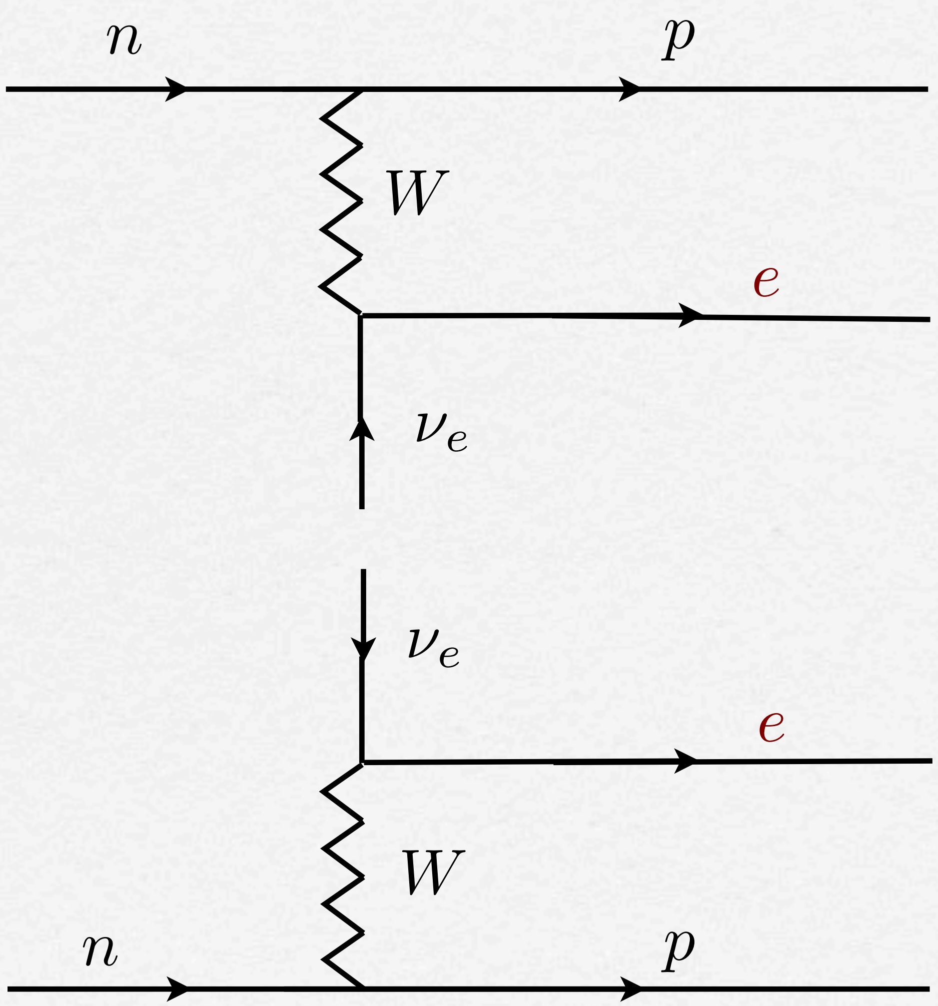
- same sign leptons at hadron colliders

Keung, GS '83

Double-beta decay

Goepert-Mayer '35

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



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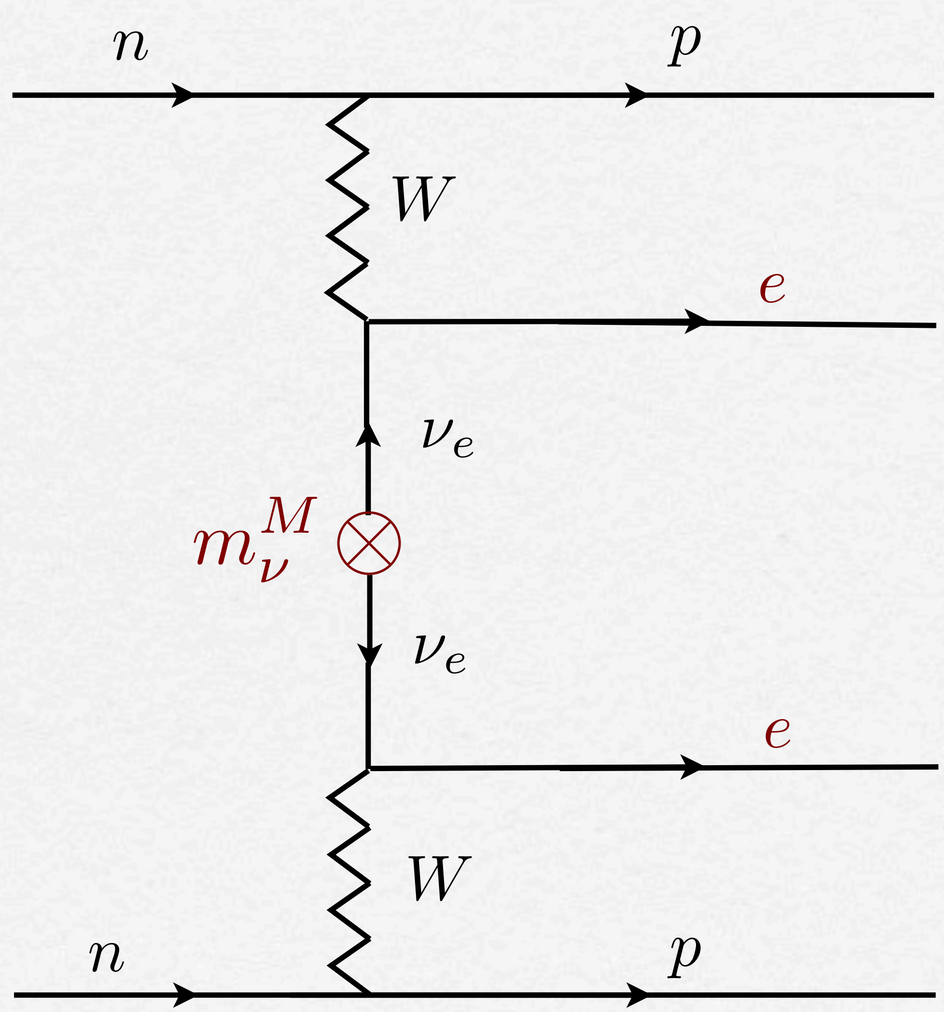

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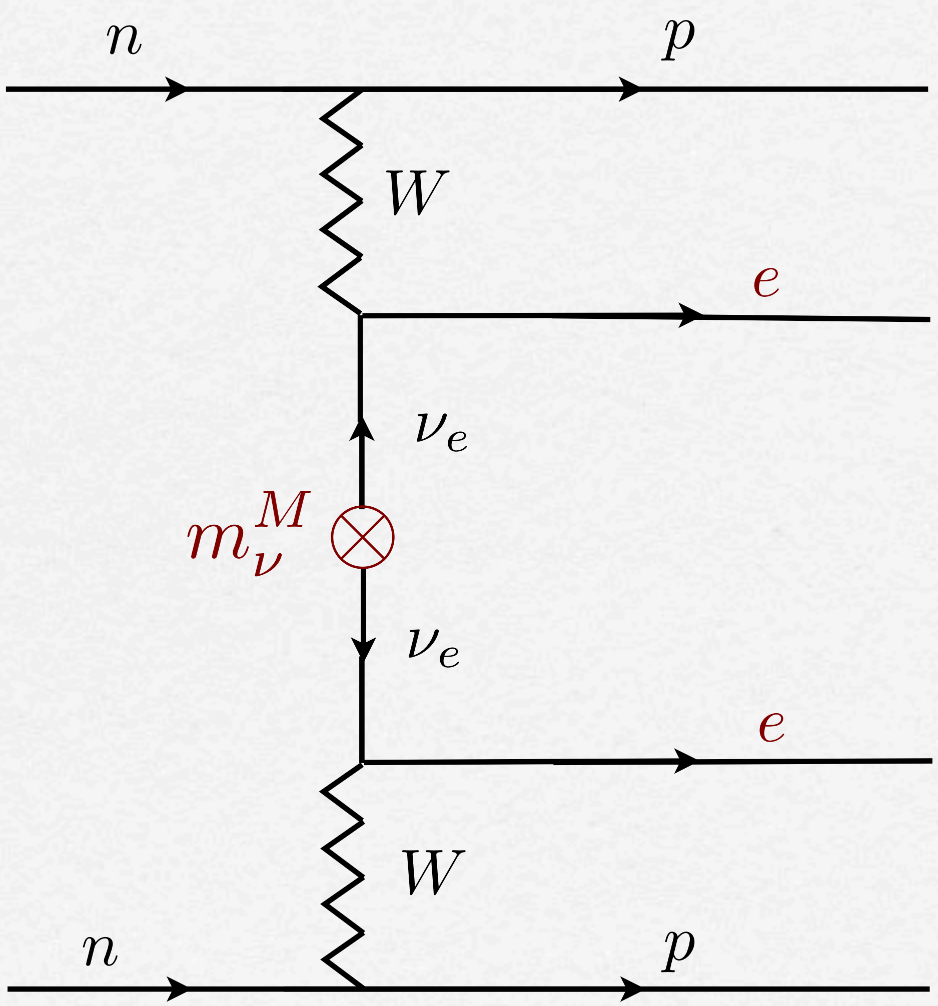
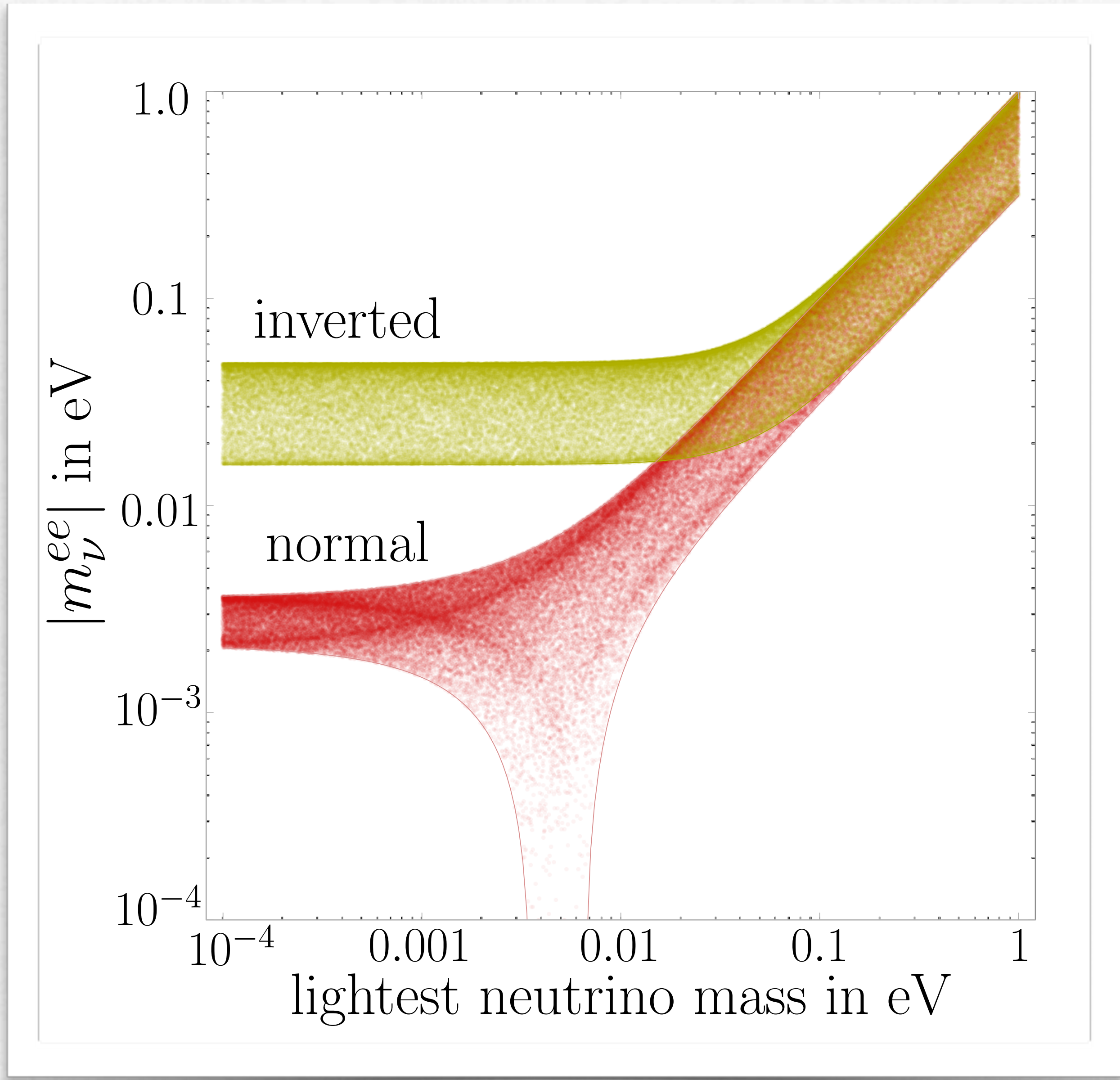


$$^{76}_{32}Ge \to ^{76}_{34} Se + e + e$$

Racah'37

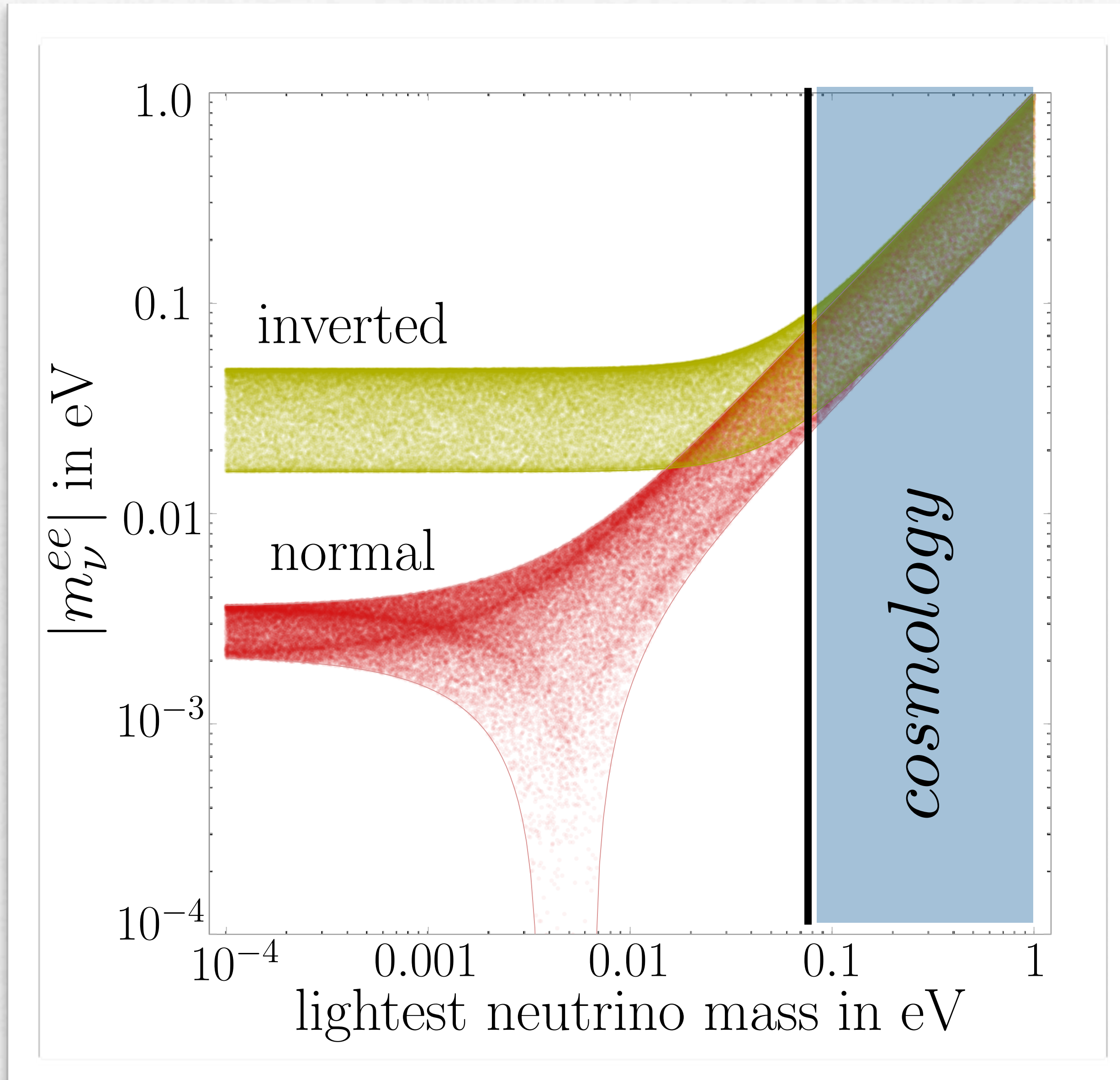
Furry '38

Neutrino mass contribution



Vissani '02

Neutrino mass contribution



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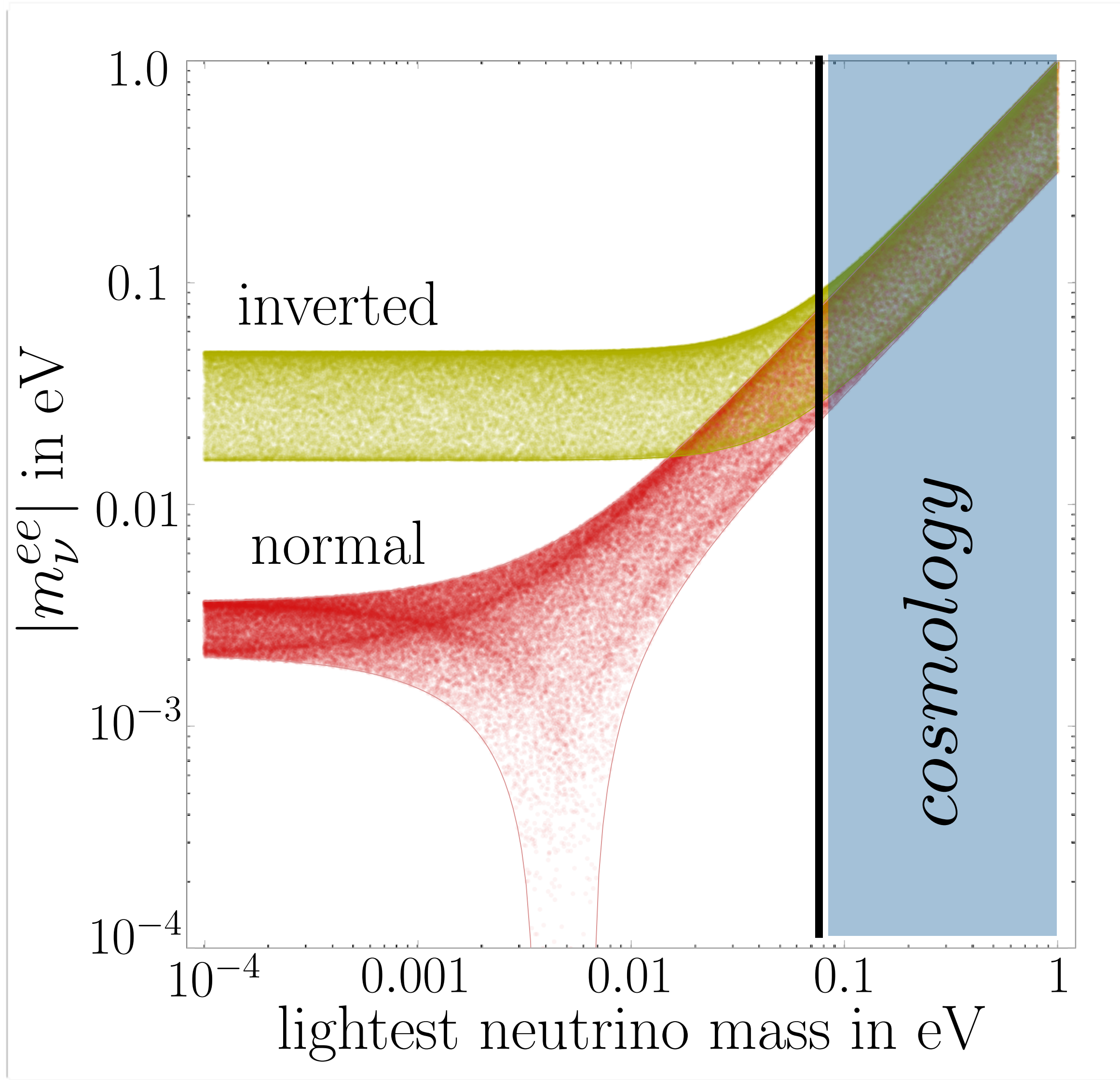


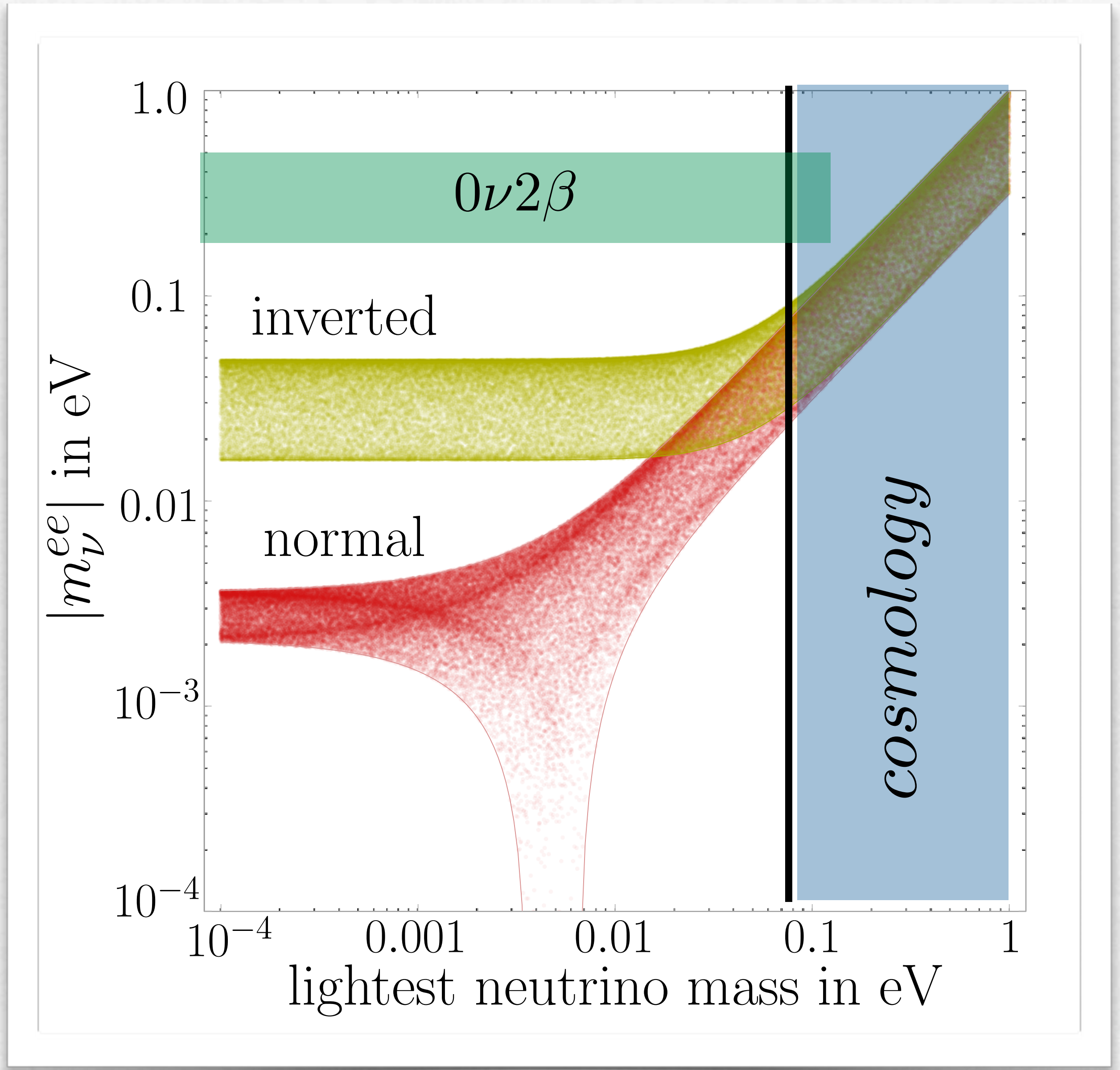
Hannestad et al '10

Vissani '02

Neutrino mass contribution

Klapdor '01-10

HM



Hannestad et al '10

Vissani '02

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				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

Schwingenheuer'12

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EXO-200 $|m_\nu^{ee}| \lesssim 0.3\, eV$ 1205.5608 Schwingenheuer'12

Kaml-Zen $|m_\nu^{ee}| \lesssim 0.6\, eV$ 1205.6130

Neutrino mass: theory

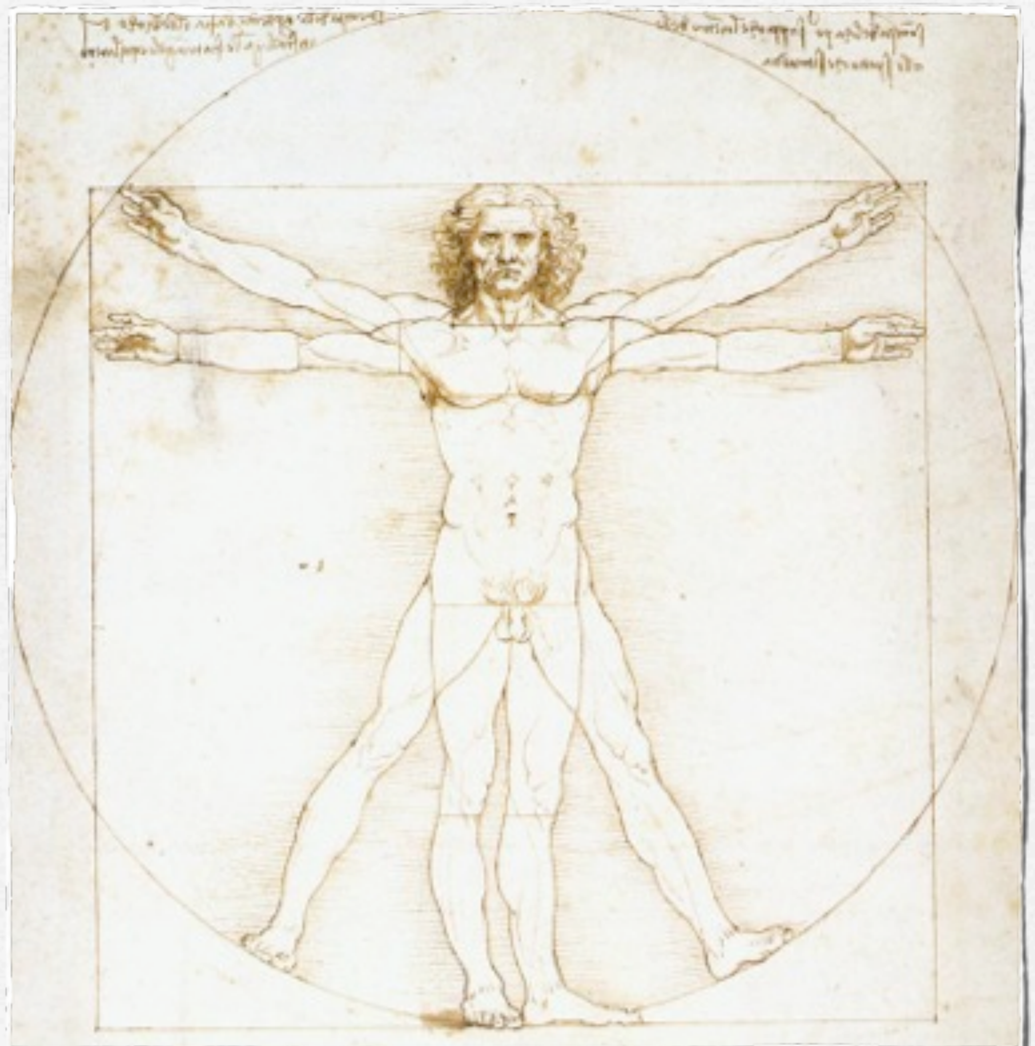
SM → L ↔ R

SM → L ↔ R

God may be left-handed, but not an invalid

SM

L R



God may be left-handed, but not an invalid

L-R symmetry

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

W_L $\qquad$ W_R

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

Pati, Salam '74

Mohapatra, GS '75

L-R symmetry

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$$W_L \qquad\qquad W_R$$

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

neutrino mass long before experiment

Pati, Salam '74
Mohapatra, GS '75

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

$\Downarrow$

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

crucial role: RH neutrinos

- cancel B-L anomaly

Curse:

neutrino massive -

just like the electron

Branco, GS '77

Neutrino mass: blessing

Minkowski '77

Mohapatra, GS '79

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

$m_\nu \propto M_{W_L}^2 / M_{W_R}$

connects neutrino mass to
the scale of P restoration

new physics:

N - gauge interactions:
WR and ZR

LHC?

$$\begin{array}{c} \nu_L \\ (\nu^C)_L \end{array} \begin{pmatrix} 0 & M_D \\ M_D^T & M_{\nu_R} \end{pmatrix}$$

LR symmetry

LR = C

$f_L \to (f^C)_L$

gaugeable: SO(10)

$M_D = M_D^T$

Falcone '03

Akhmedov, Frigerio '05

Hosteins et al '06

determines M_D

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

Nemevsek, GS, Tello '12

$$M_D = M_N \sqrt{\frac{1}{M_N} M_\nu} \qquad Y_D = g \frac{M_D}{M_W}$$

analogue to Goldstone-Higgs-Weinberg for charged fermions

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analogue to Goldstone-Higgs-Weinberg for charged fermions

determine M_ν and M_N

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Nemevsek, GS, Tello '12

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analogue to Goldstone-Higgs-Weinberg for charged fermions

determine M_ν and M_N

low E

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Nemevsek, GS, Tello '12

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Physics of Dirac mass

- Electric Dipole Moments
- Neutrinoless double beta
- Neutrino transition moments

Physics of Dirac mass

- Electric Dipole Moments
- Neutrinoless double beta
- Neutrino transition moments
- N decays: LHC

Model content & symmetry breaking

Mohapatra, GS '75, '81

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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

Model content & symmetry breaking

Mohapatra, GS '75, '81

bi-doublet

R - triplet

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

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

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

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

EW symmetry breaking

Model content & symmetry breaking

Mohapatra, GS '75, '81

bi-doublet

R - triplet

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

L - triplet

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

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

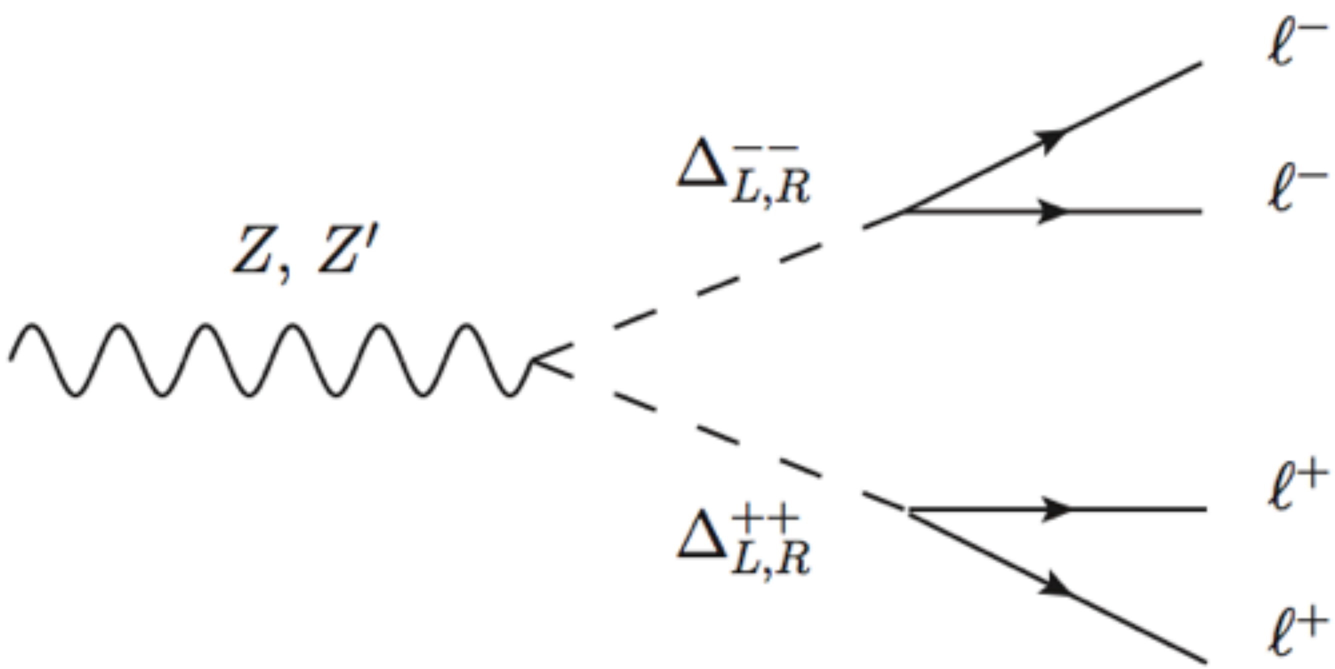
$$\langle \Delta_L \rangle = \begin{pmatrix} & \\ v_L & \end{pmatrix}$$

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

EW symmetry breaking

mass of ν (Majorana)

$$v_R \gg v \gg v_L$$



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

LHC

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

Higgs triplets:

doubly charged scalars

RH lepton mixing (PMNS)

L - R scale ?

Minimal model:

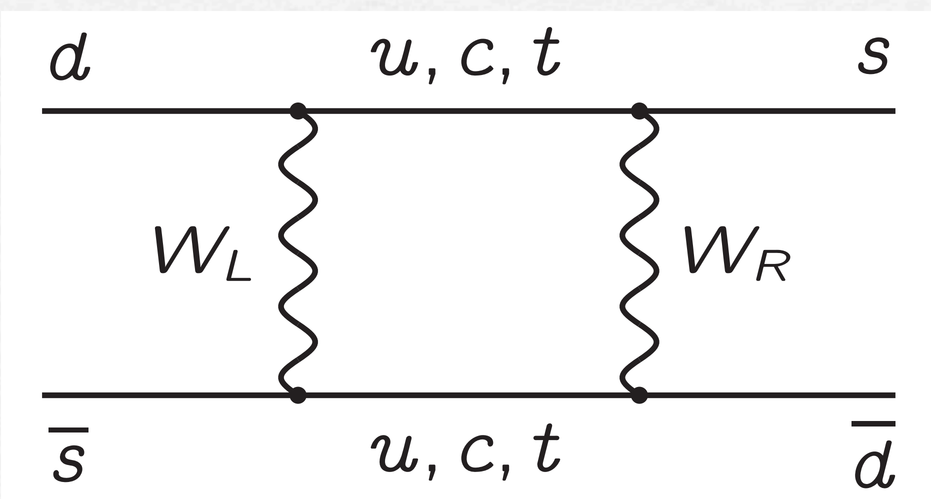
theoretical limit

$M_{W_R} \gtrsim 2.5\,\mathrm{TeV}$

Beall, Bander, Soni '81

.....

Maiezza, Nemevsek, Nesti, GS '10



$K_L - K_S$ mass difference

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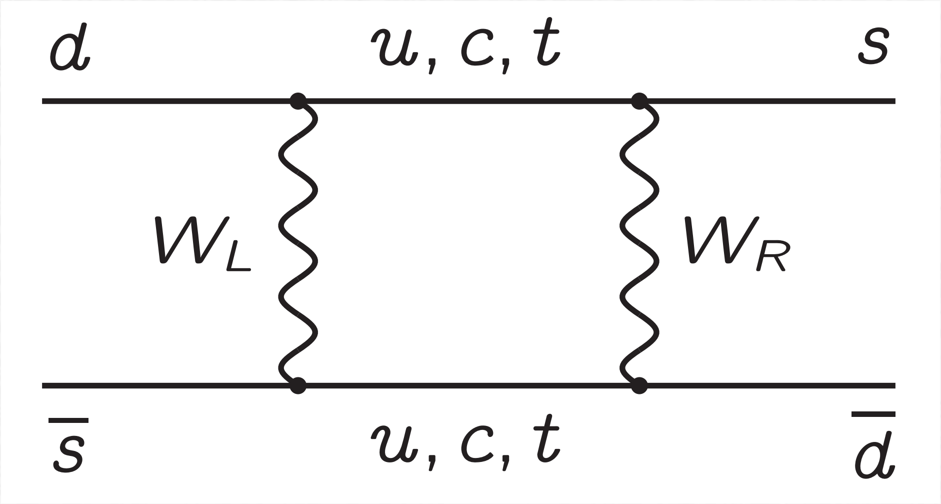


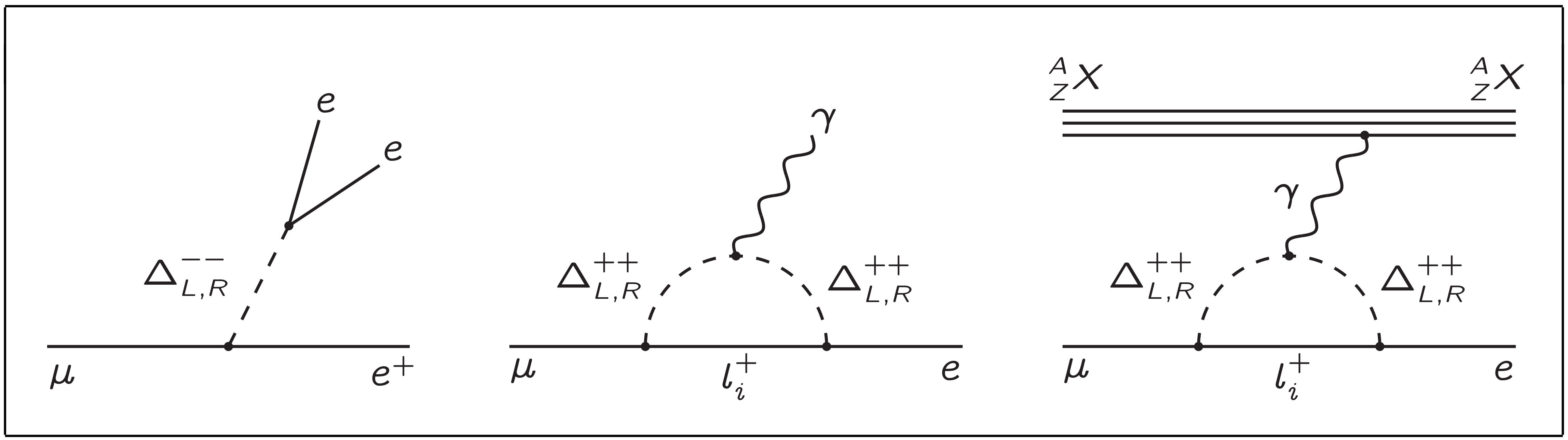
experiment is catching up

$K_L - K_S$ mass difference

LFV

important constraint

$\mu \to e\bar{e}e$ $\mu \to e\gamma$ $\mu \to e$ conversion



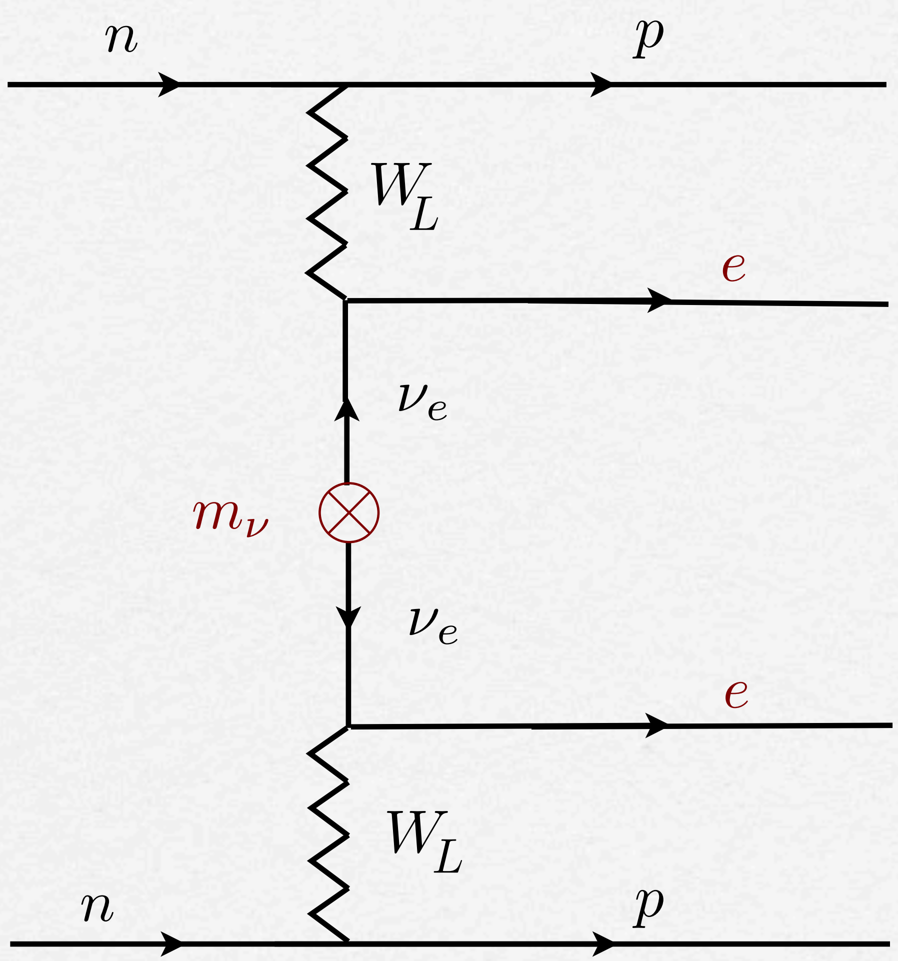
Cirigliano, Kurylov, Ramsey-Musolf, Vogel '04

example: type II seesaw $V_R = V_L^*$ $m_N \propto m_\nu$

Tello, Nemevsek, Nesti, GS, Vissani '10 ⇒ N lighter than Δ^{++}

New source for $0\nu 2\beta$

LL



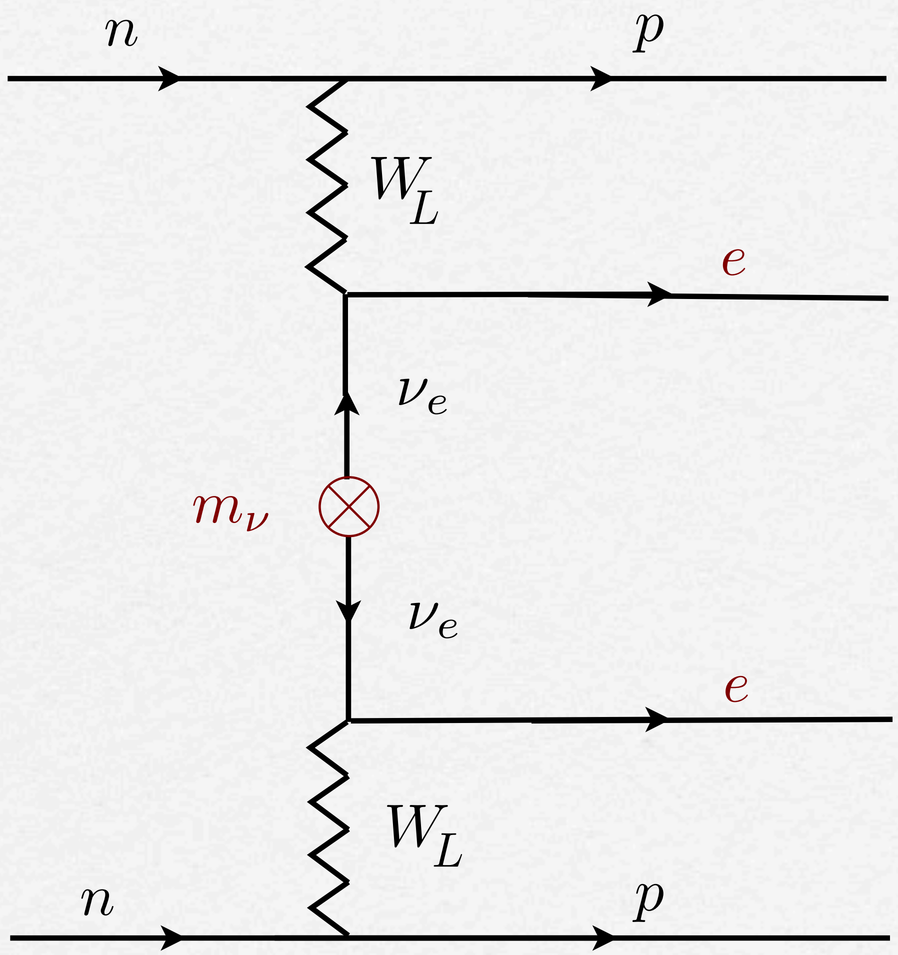
$$LL \propto \frac{1}{M^4_{W_L}} \frac{m_\nu}{p^2}$$

$$p \simeq 100 MeV$$

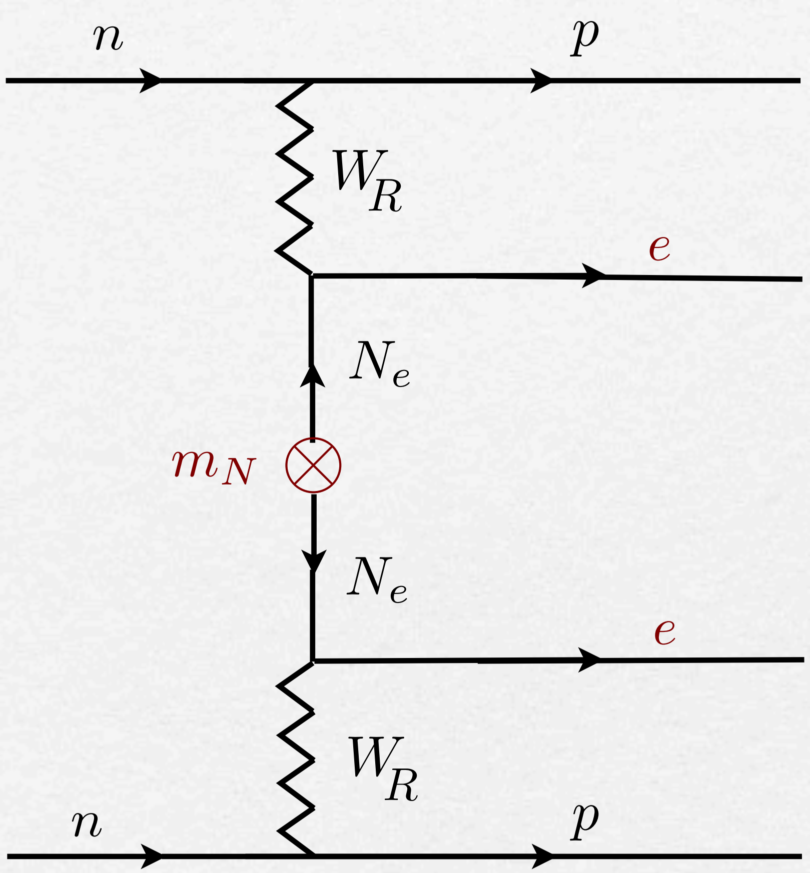
New source for $0\nu 2\beta$

Mohapatra, GS '81

LL



RR



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

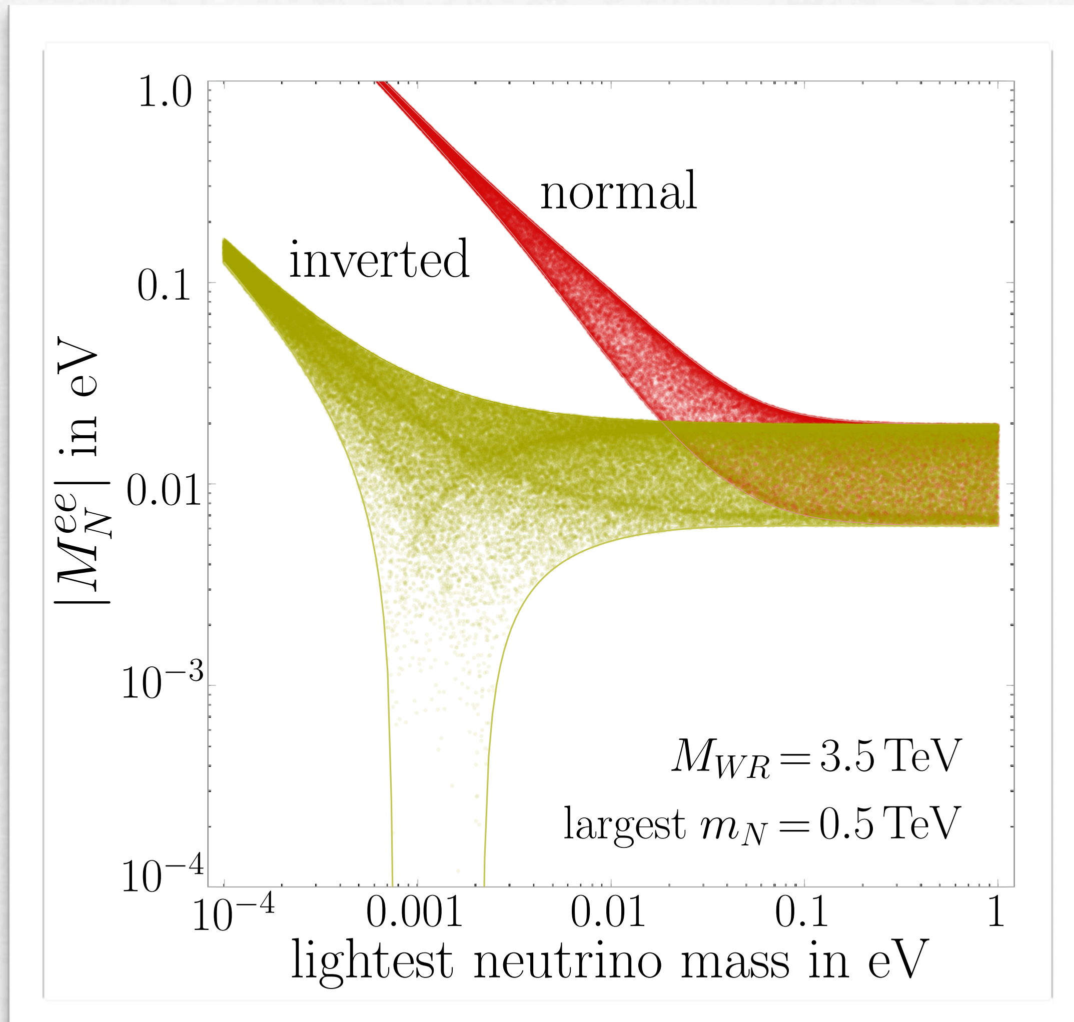
$$RR \propto \frac{1}{M_{W_R}^4} \frac{1}{m_N}$$

$$p \simeq 100 MeV$$

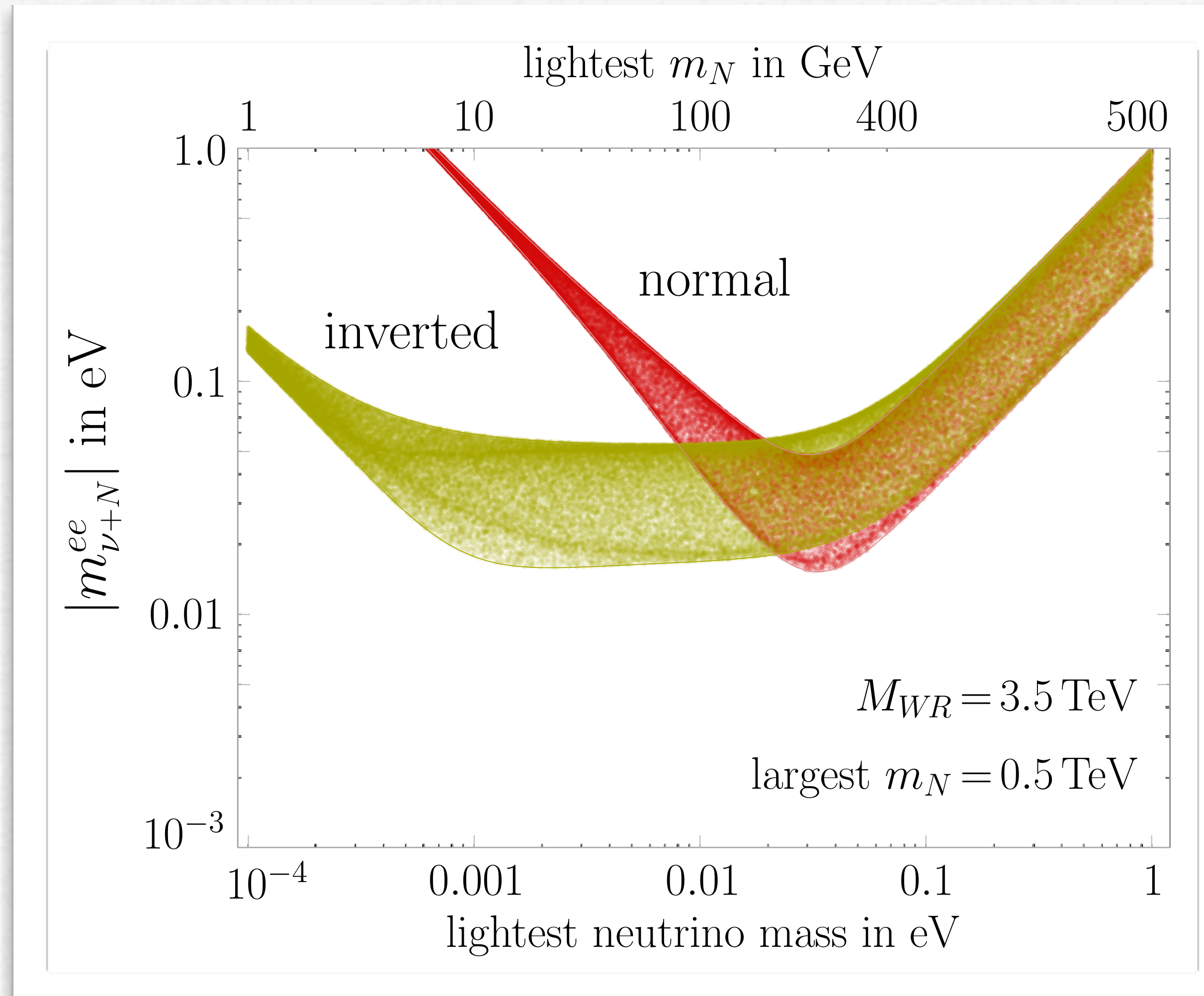
$$M_{W_R} \simeq m_N \simeq TeV$$

example: type II seesaw $V_R = V_L^*$ $m_N \propto m_\nu$

Right only



Left + Right



Tello, Nemevsek, Nesti, GS, Vissani '10

Chakraborrty, Devi, Goswami, Patra '12 Das, Deppisch, Kittel, Valle '12

Neutrinoless double beta decay

if neutrino mass small

new physics necessary

Feinberg, Goldhaber '59

Pontecorvo '64

Neutrinoless double beta decay

if neutrino mass small

new physics necessary

Feinberg, Goldhaber '59

Pontecorvo '64

$$\mathcal{A}_\nu \propto \frac{G_F^2 m_\nu^{ee}}{p^2} \qquad \mathcal{A}_{\mathcal{NP}} \propto \frac{G_F^2 M_W^4}{\Lambda^5}$$

$(p \simeq 100\, MeV)$

6 fermion, d=9 operator

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Feinberg, Goldhaber '59

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$(p \simeq 100\, MeV)$

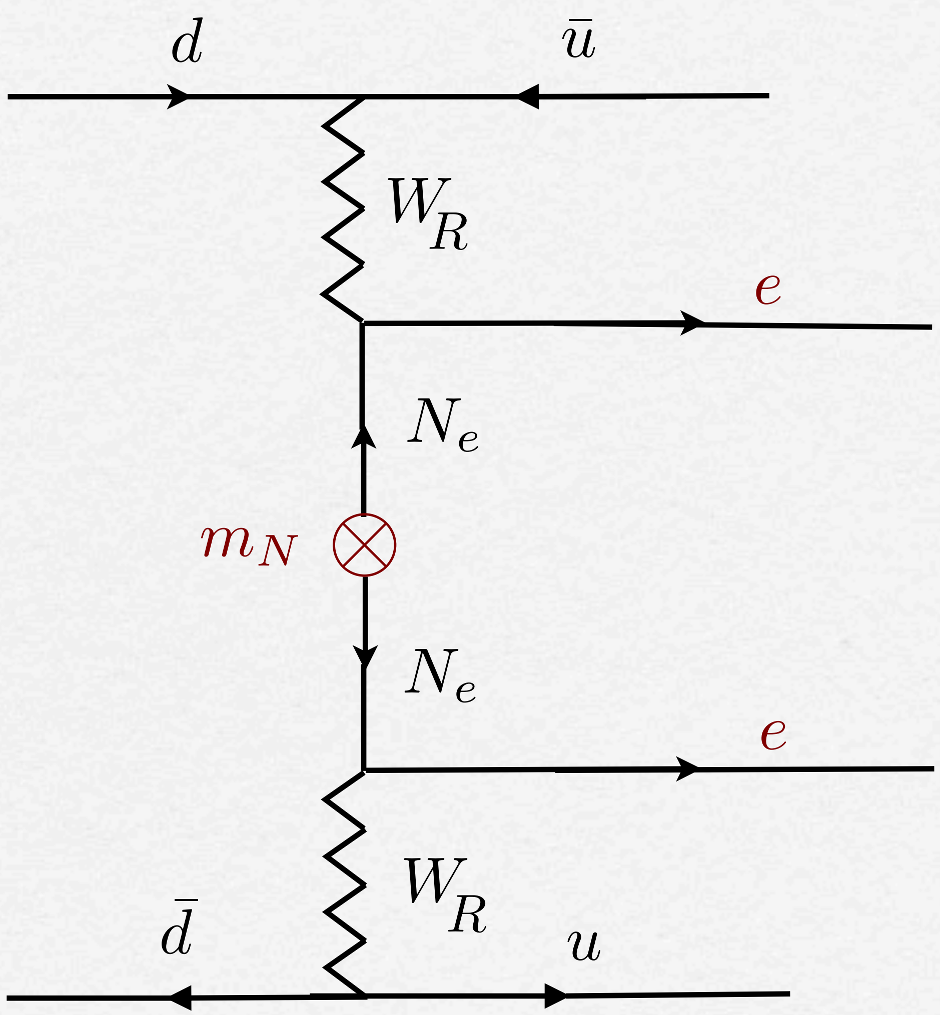
$$\Lambda \sim TeV$$

6 fermion, d=9 operator

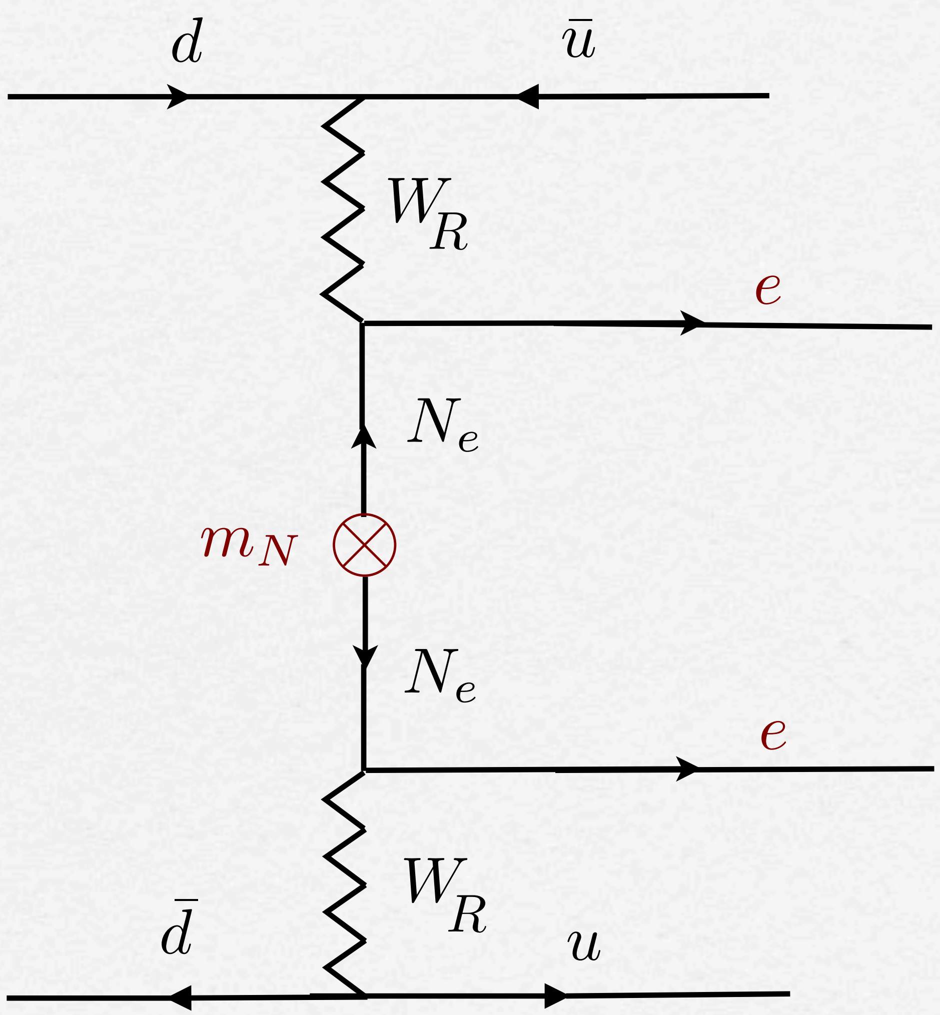
LHC

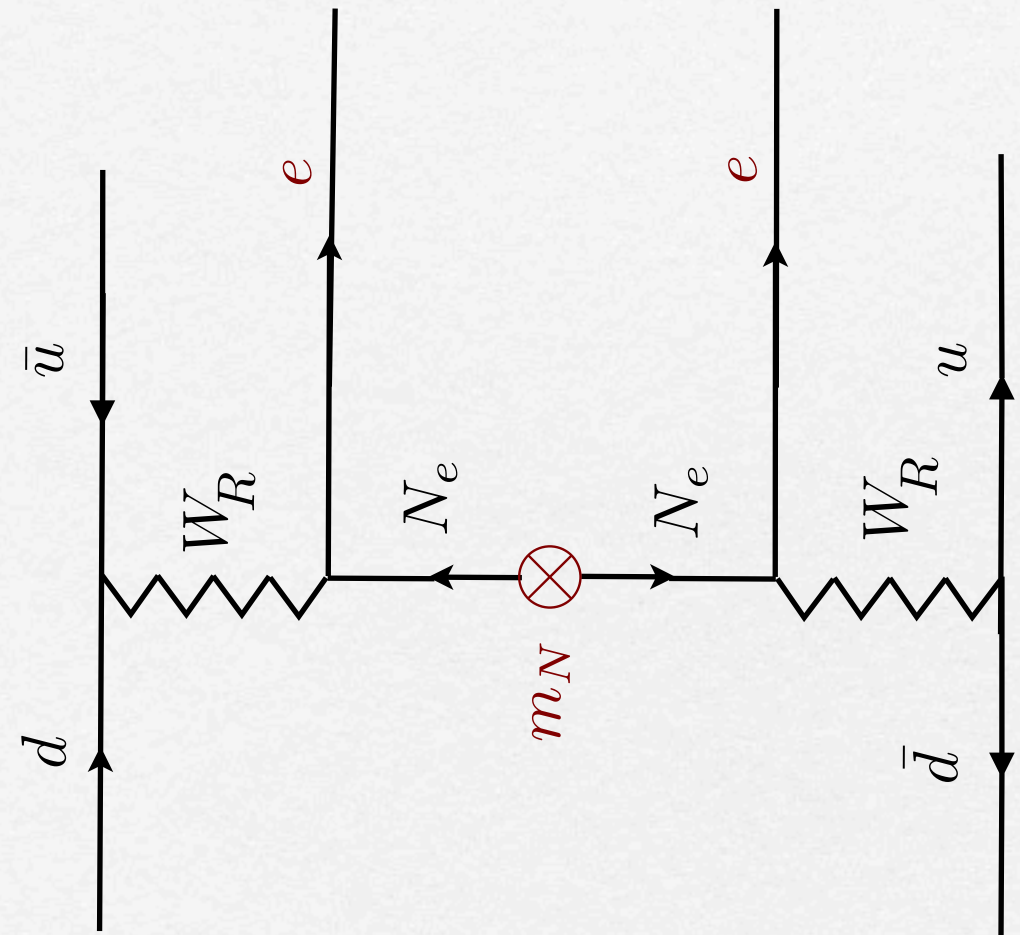
LHC connection

rotation in a plane



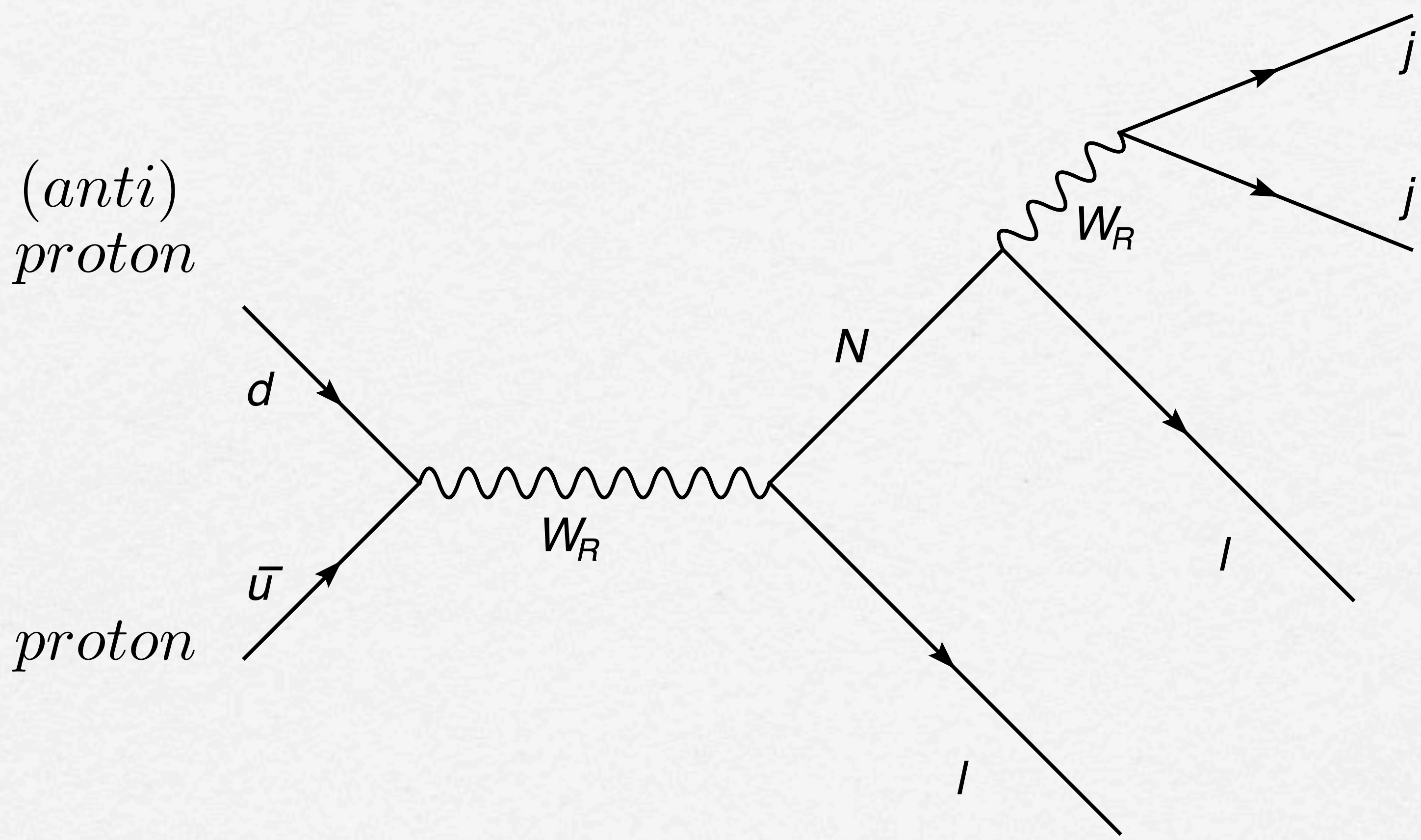
rotation in a plane





W_R production @ colliders

Keung, G.S. '83



- LNV: same sign leptons
- reconstruct WR, N masses; VR
- the chirality of WR: RH?

Ferrari et al '00 Han, Low, Ruiz, Si '12

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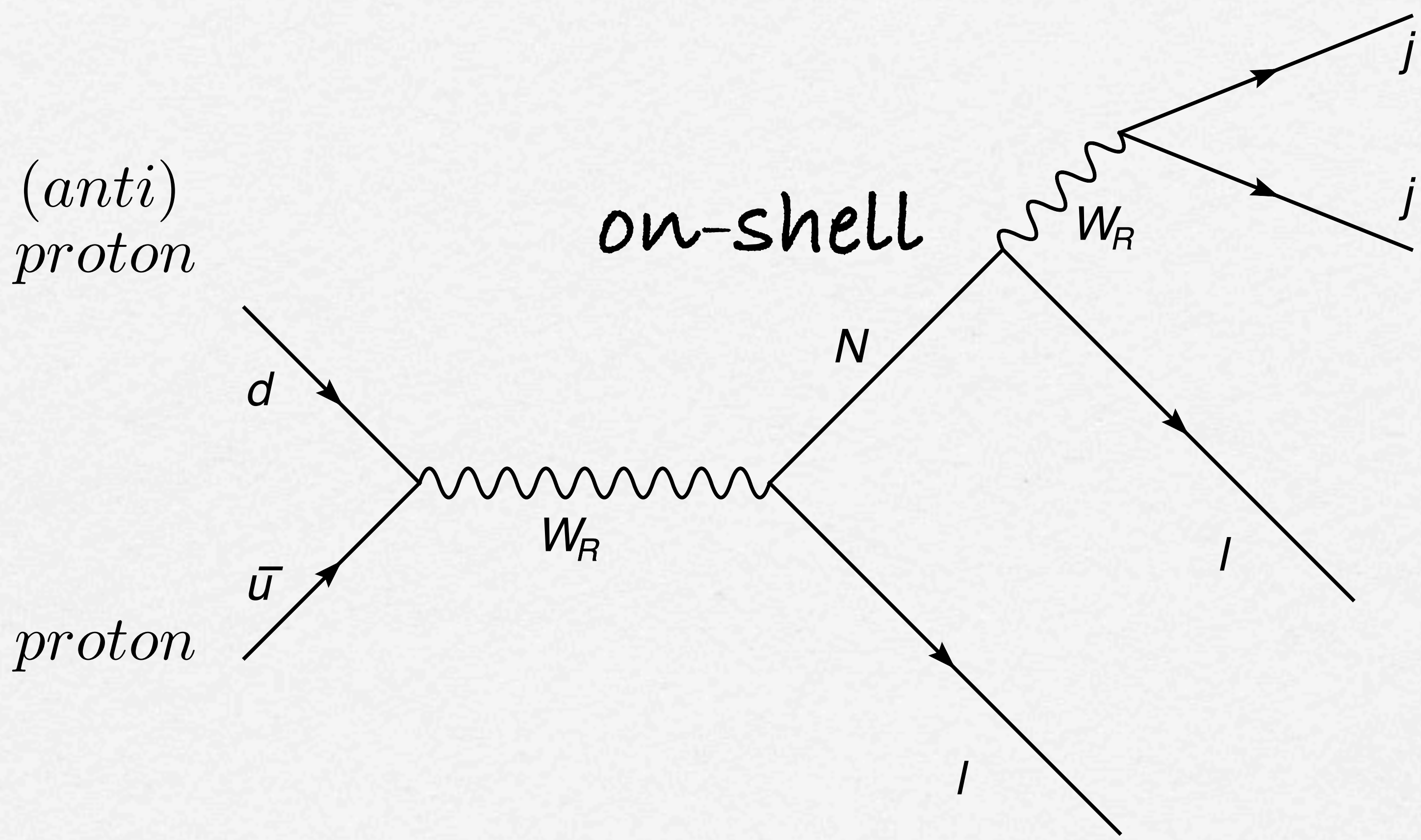

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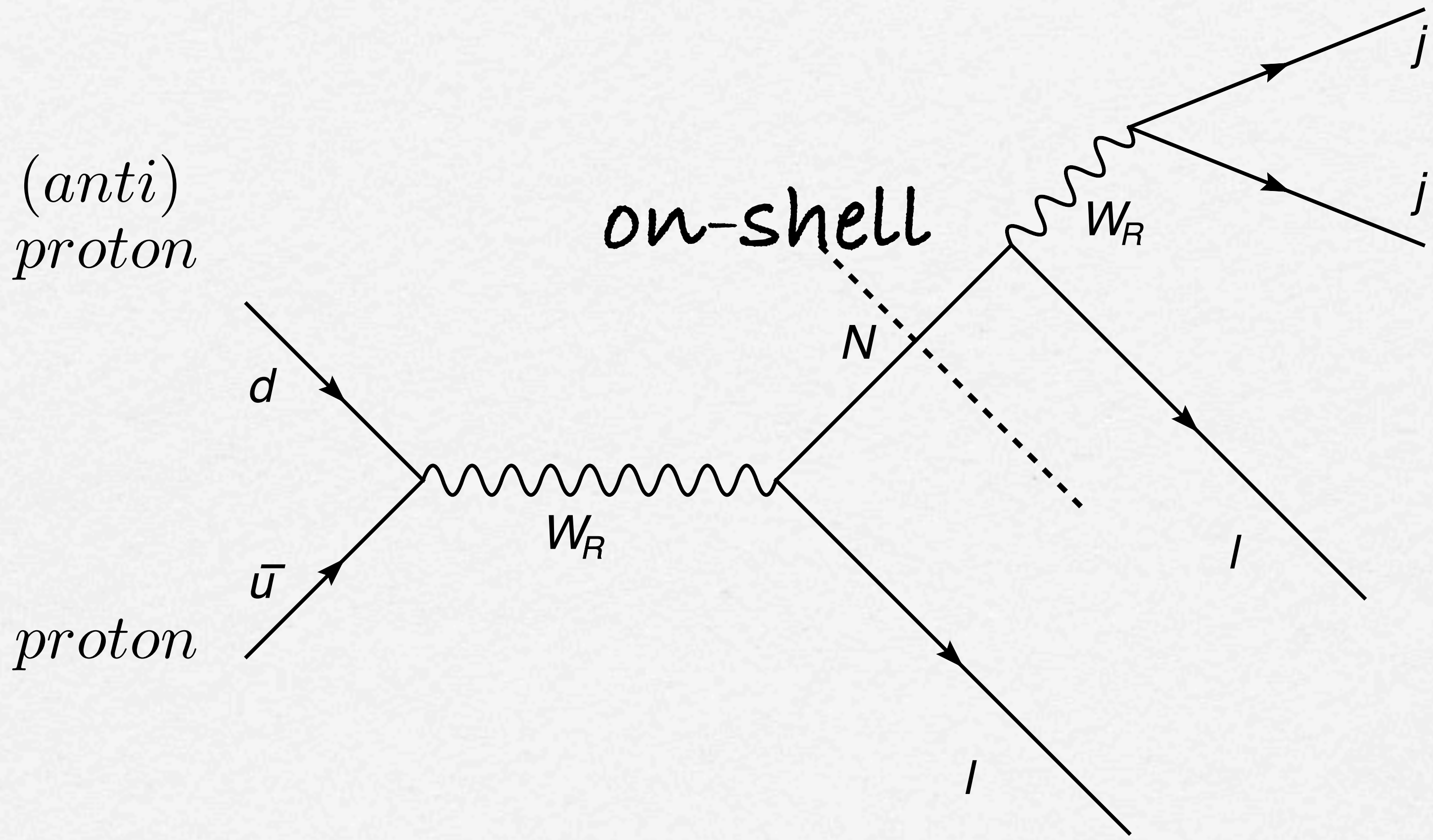

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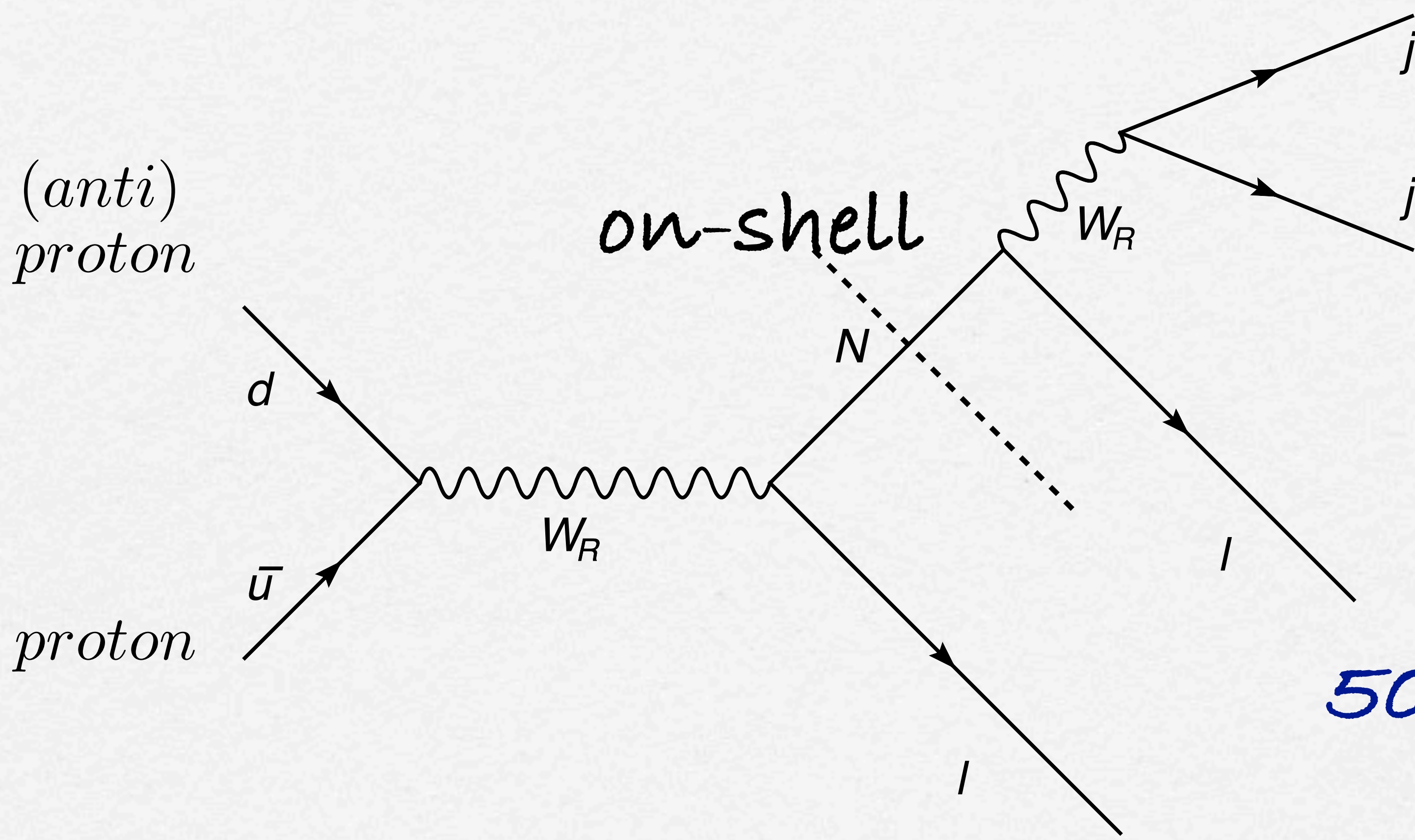

50% lepton - 50 % antileptons

- LNV: same sign leptons
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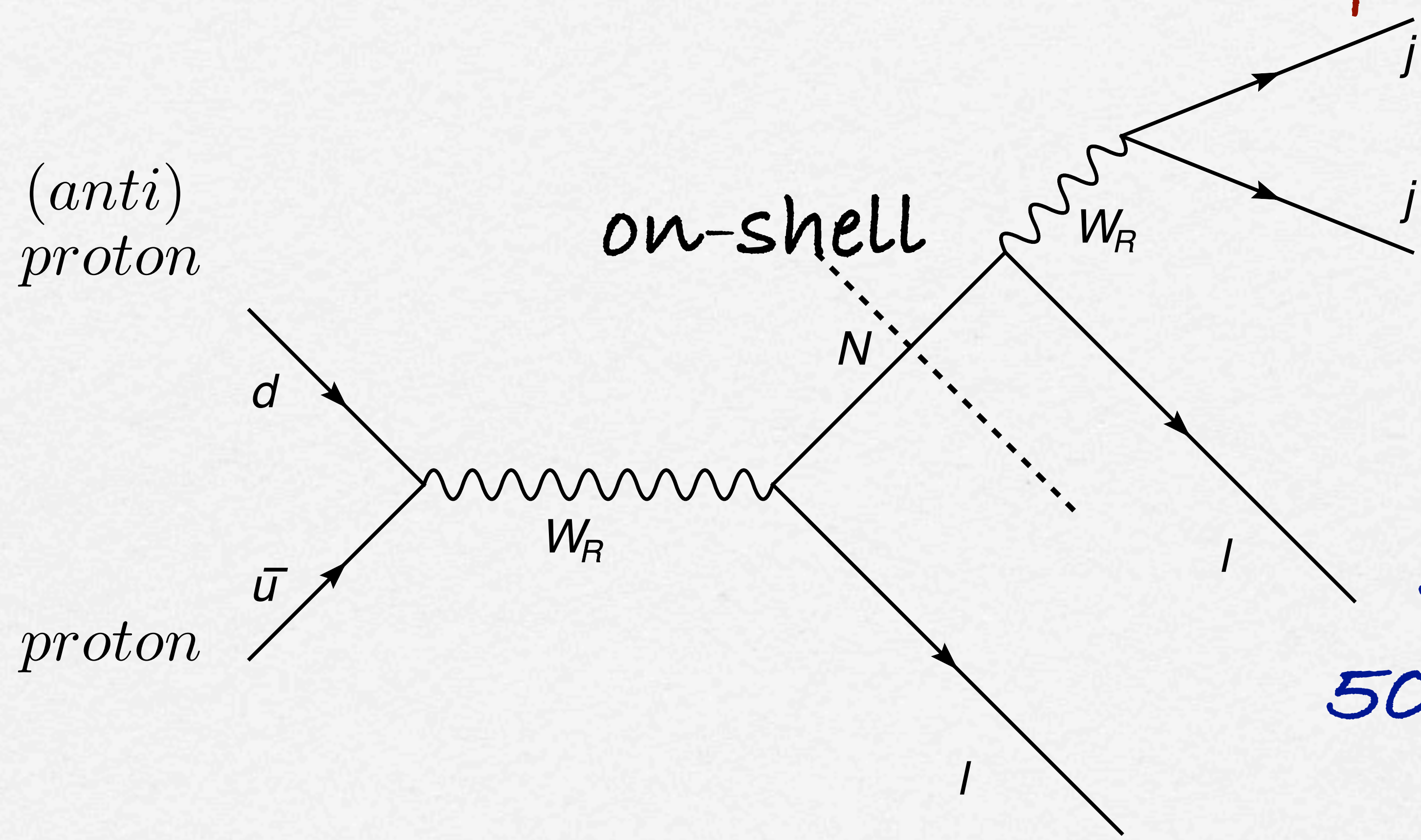
Ferrari et al '00   Han, Low, Ruiz, Si '12

W_R production @ colliders

Keung, G.S. '83

direct probe of Majorana nature



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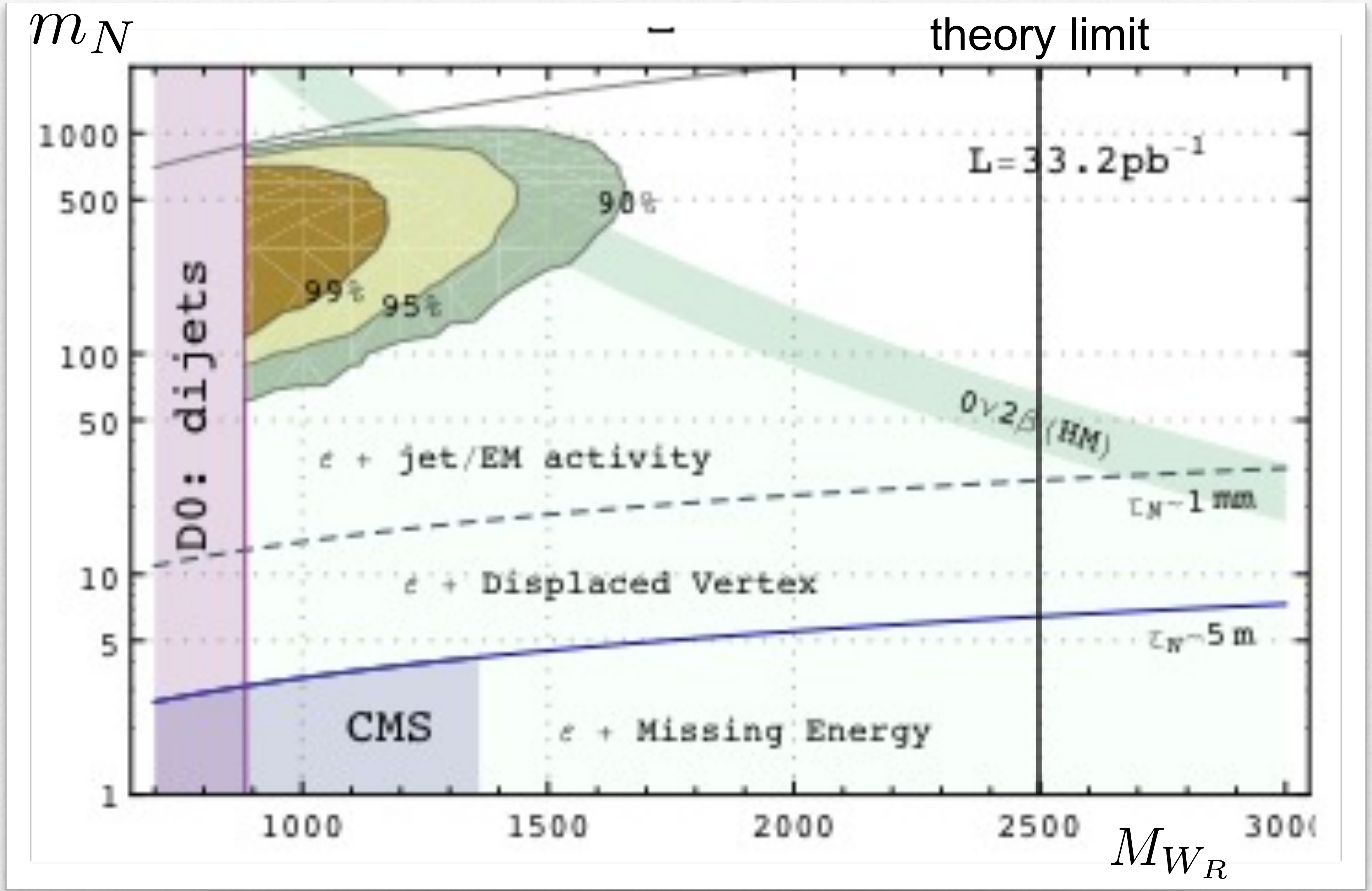
January '11

Nemevsek, Nesti, GS, Zhang, '11



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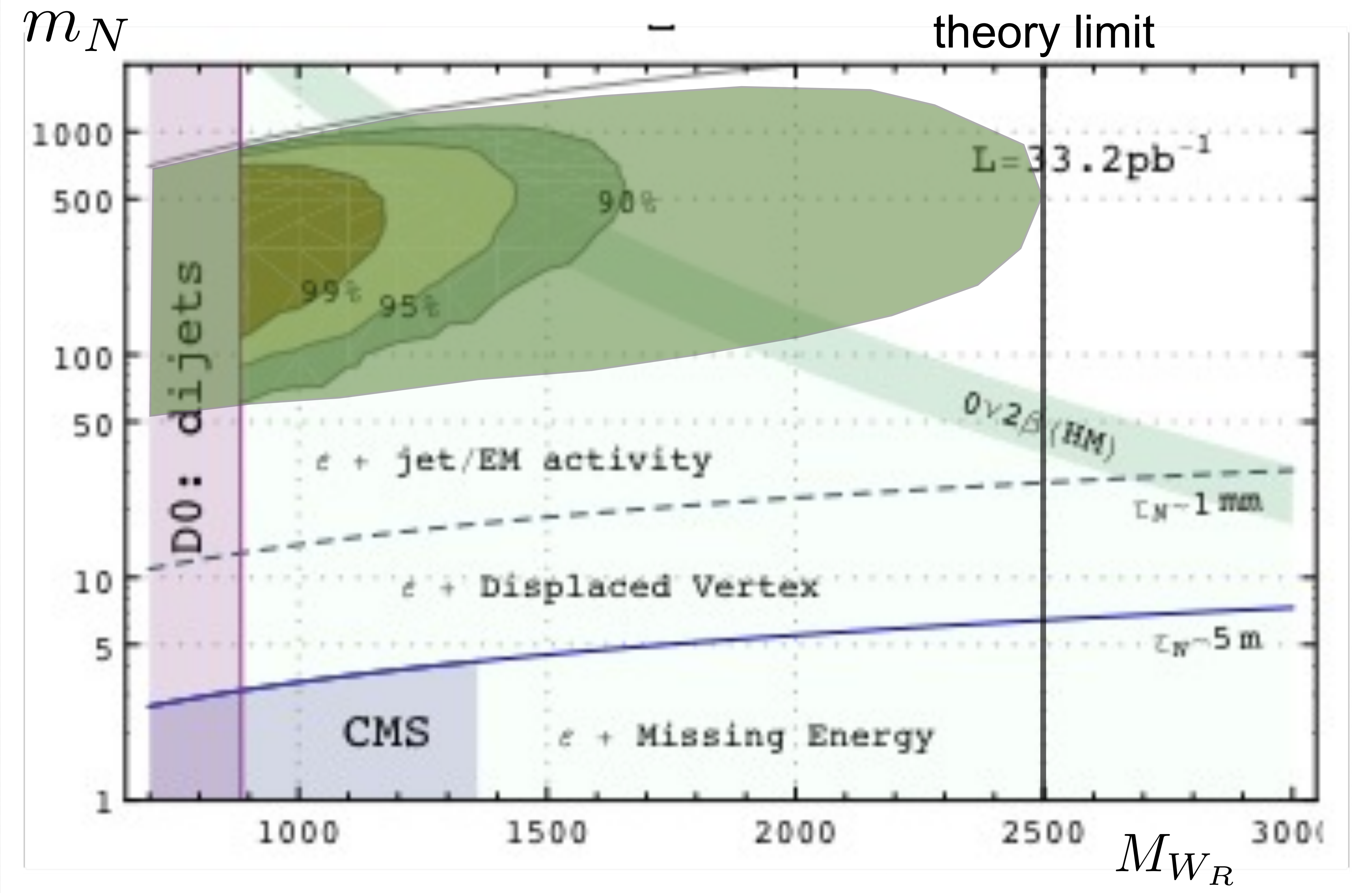
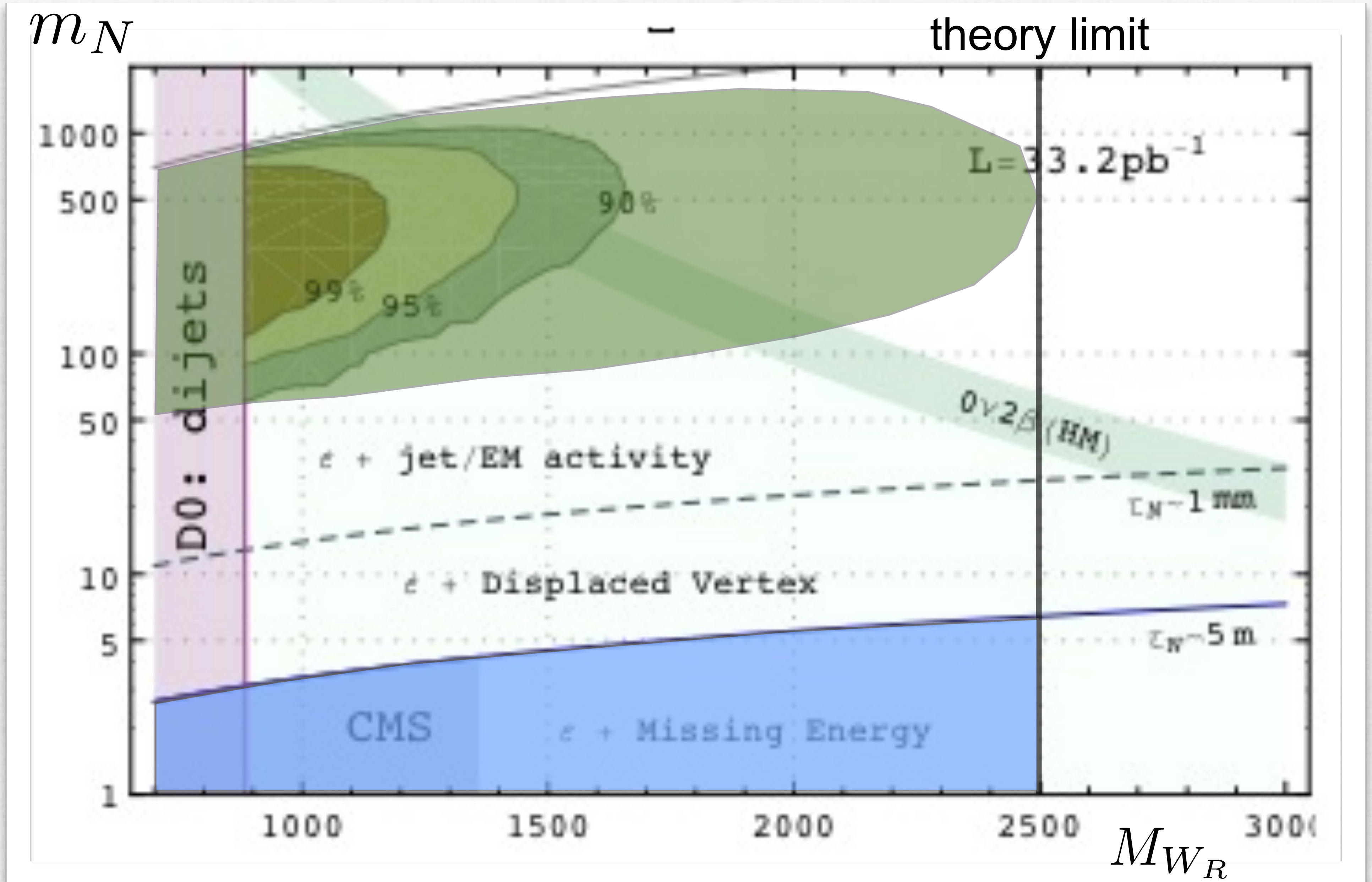


July '12

January '11

Nemevsek, Nesti, GS, Zhang, '11



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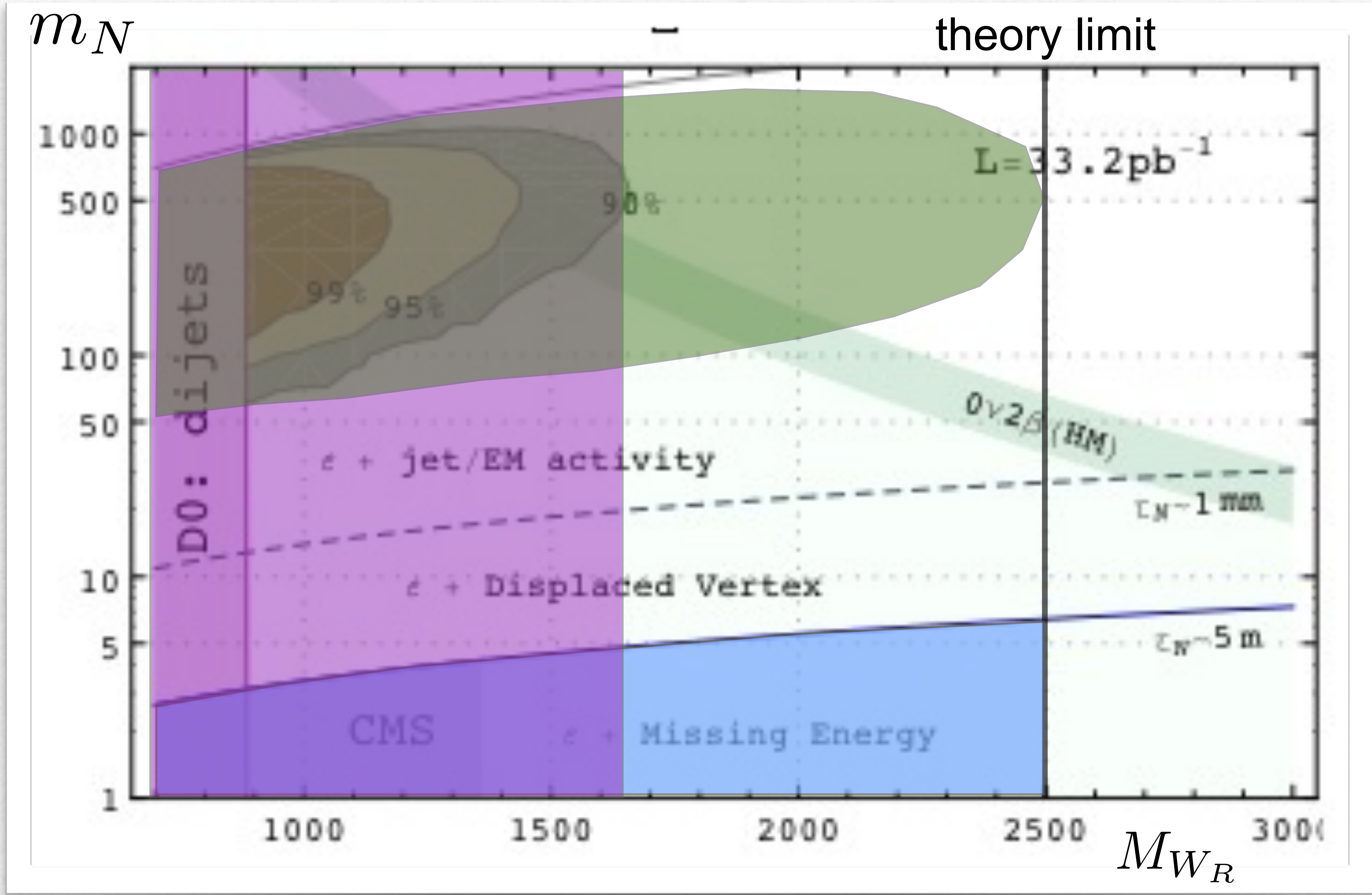

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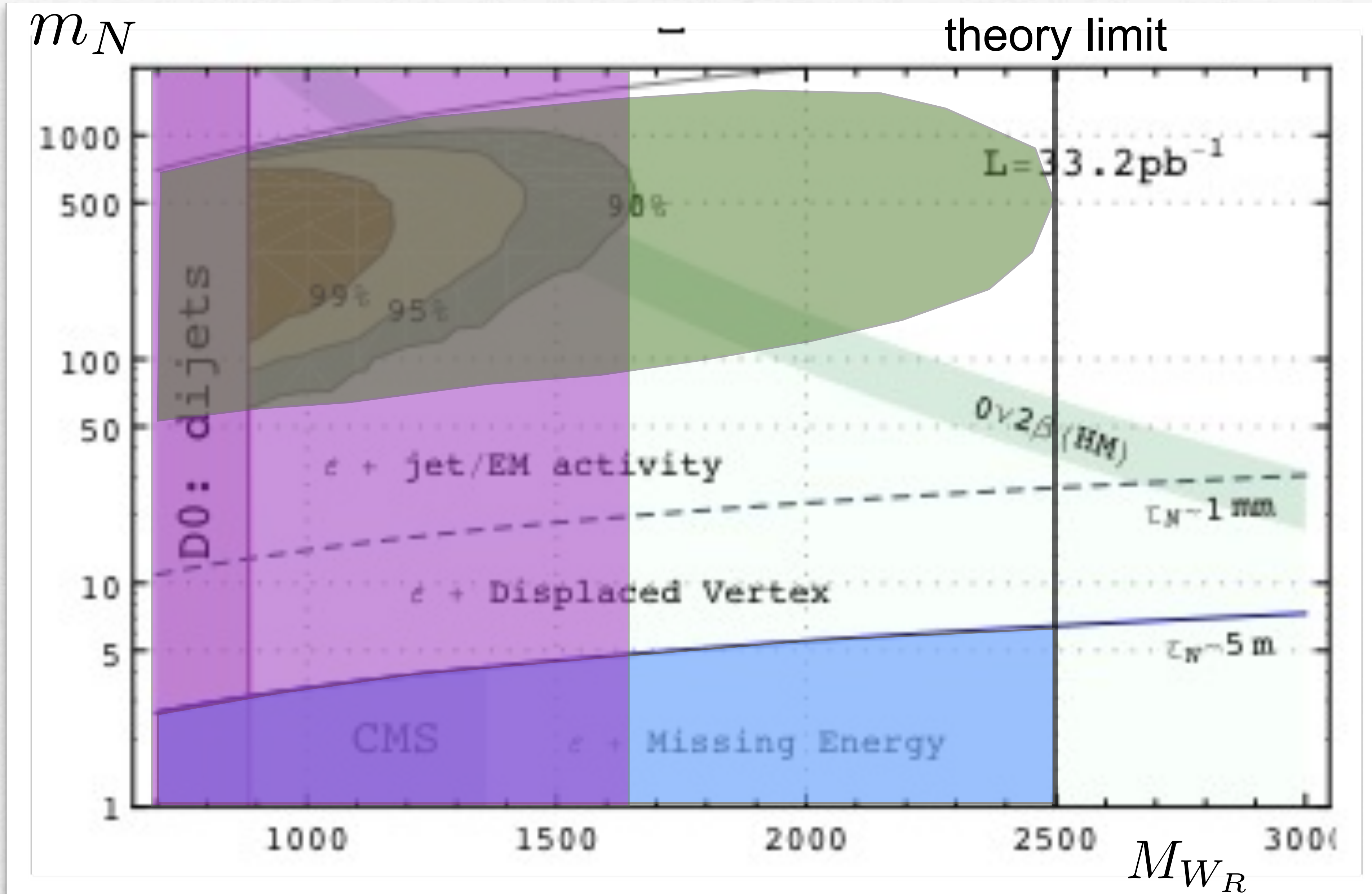


today:

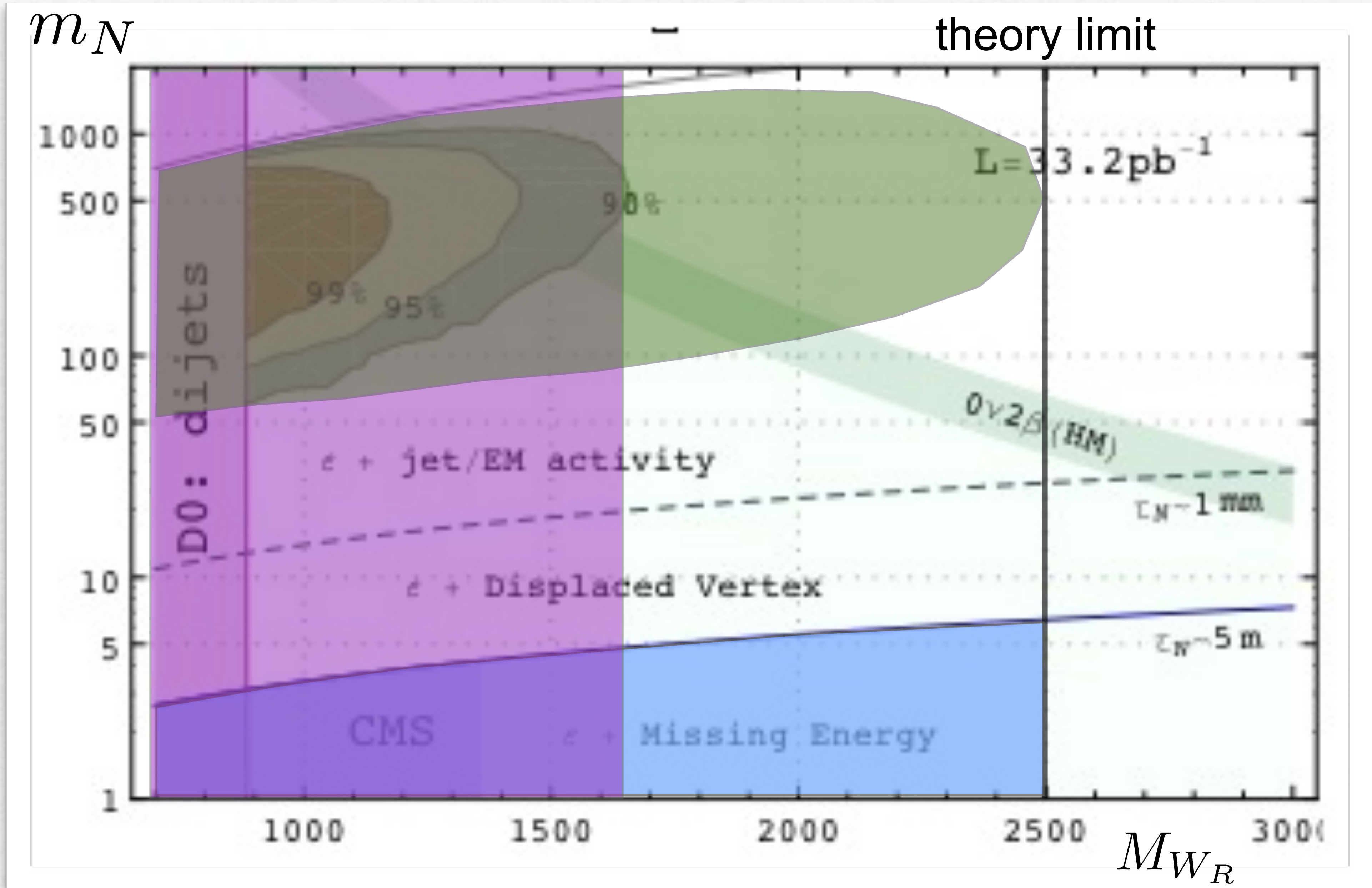
2.3 TeV, dijet

2.9 TeV, LNV

3.3. TeV missing E

July '12

January '11 Nemevsek, Nesti, GS, Zhang, '11



today:
2.3 TeV,
dijet
2.9 TeV,
LNV
3.3. TeV
missing E

July '12

- up to 4 TeV @ L= 30/fb
- up to ~ 6 TeV @ L= 300/fb

Gninenko et al '06 CMS

Ferrari et al, '00 ATLAS

Connection with neutrino mass?

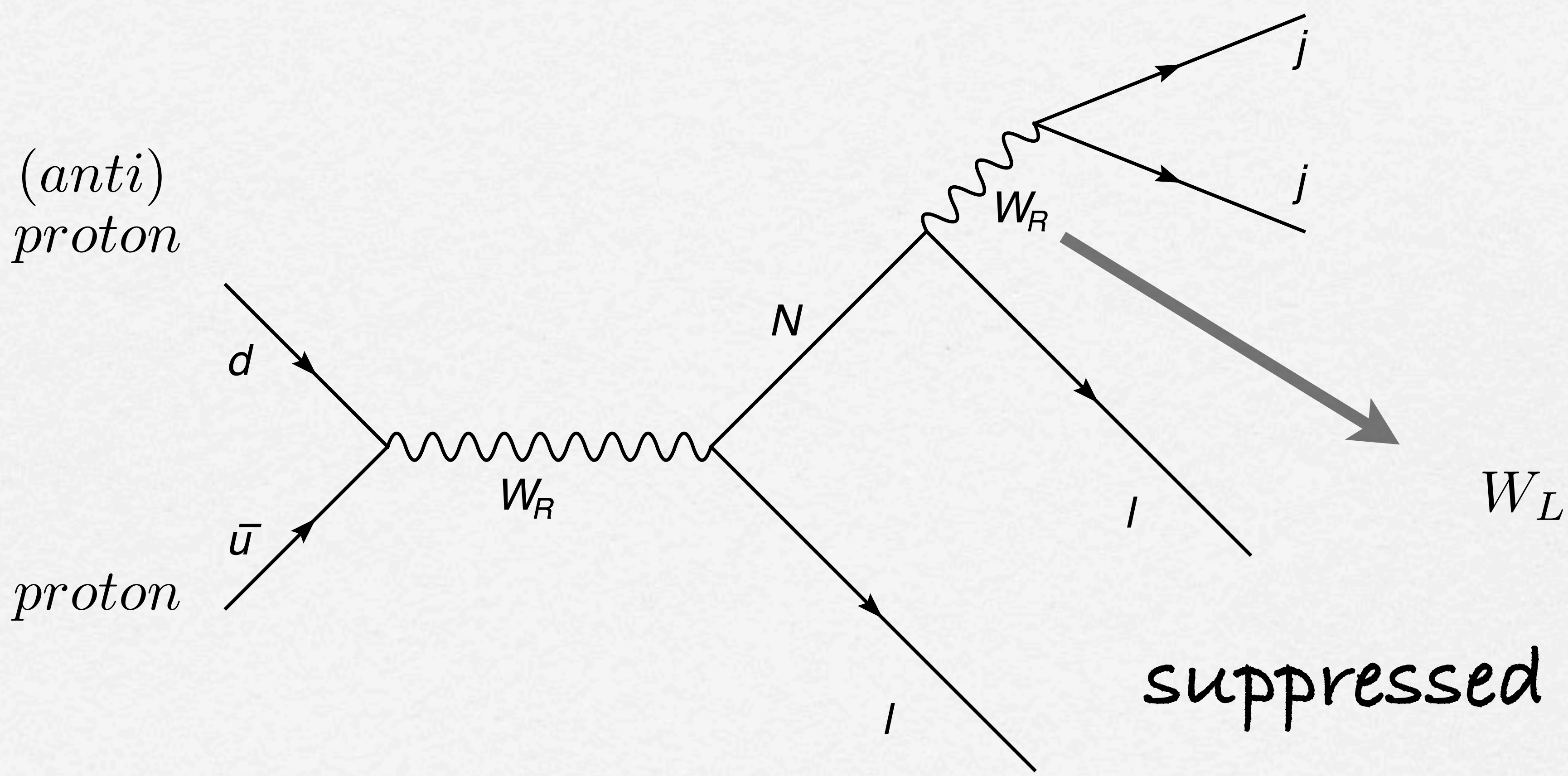
$$M_\nu = M_D \frac{1}{M_N} M_D \qquad M_N = V_R m_N V_R^T$$

verify Dirac mass

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

decays of N

W_R production @ colliders

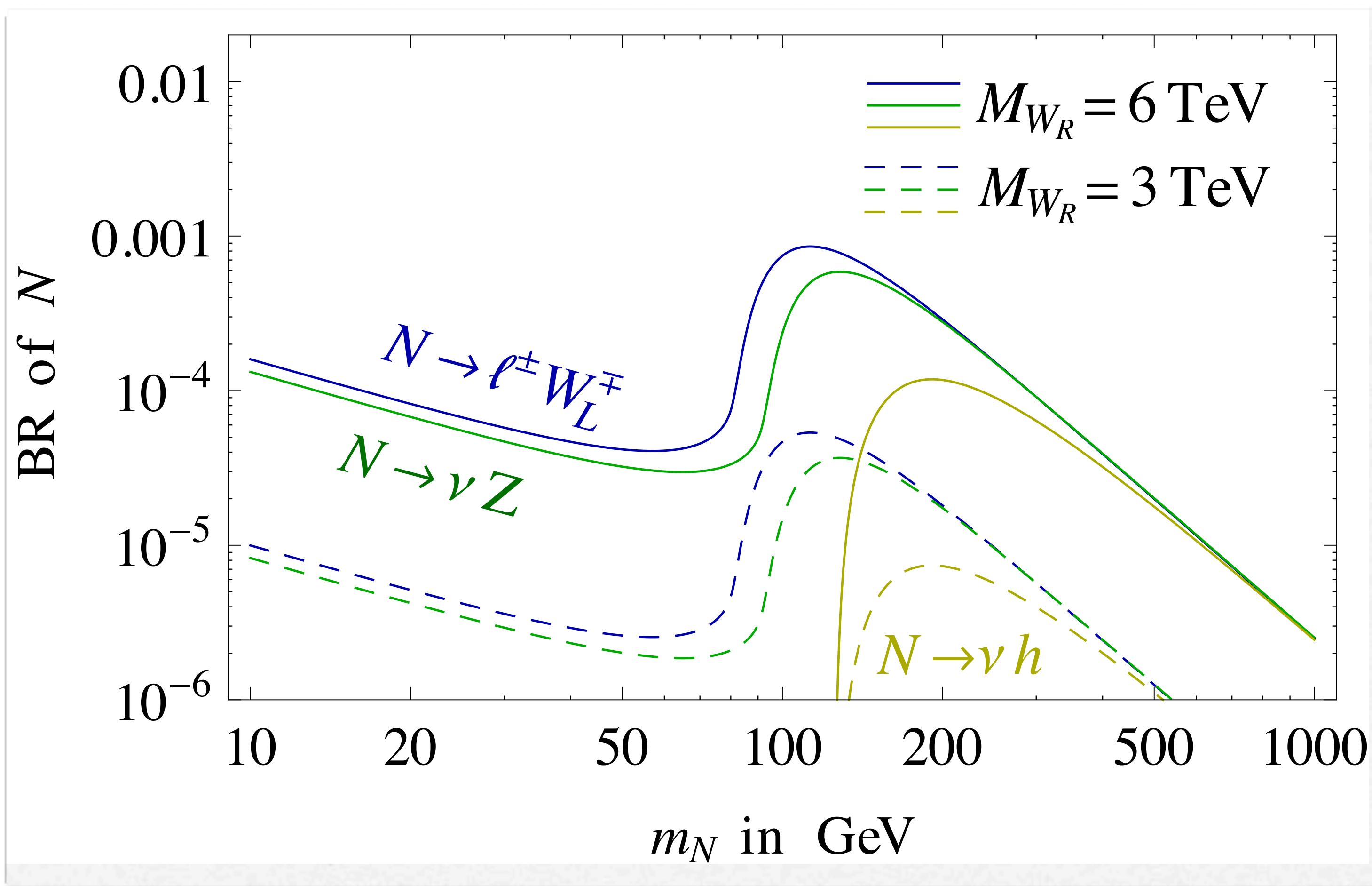


suppressed (small Yukawa)

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

leading N decays: $N \to \ell\, W_R^+$ $\quad (N \to \bar{\ell}\, W_R^-)$ through gauge

sub-leading : $N \to \ell\, W_L^+$ $\quad (N \to \bar{\ell}\, W_L^-)$ through Dirac



example: $V_R = V_L^*$

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

Nemevsek, GS, Tello '12

L-R theory

- understanding P violation
- gauge structure: new currents
- LNV@colliders
- see-saw: ν_R

L-R theory

- see-saw: ν_R

Neutrino Mass

– the only new established physics beyond SM

if Majorana

window to new physics

LHC could

LHC could

- observe lepton number violation

LHC could

- observe lepton number violation
- verify restoration of parity

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- observe lepton number violation
- verify restoration of parity
- directly see Majorana nature of N
- measure Yukawa Dirac: probe the origin of neutrino mass
- linked to low energy experiments: double beta, edm, LFV, cosmology
- same time scale roughly

Thank you

latest limits: 2012

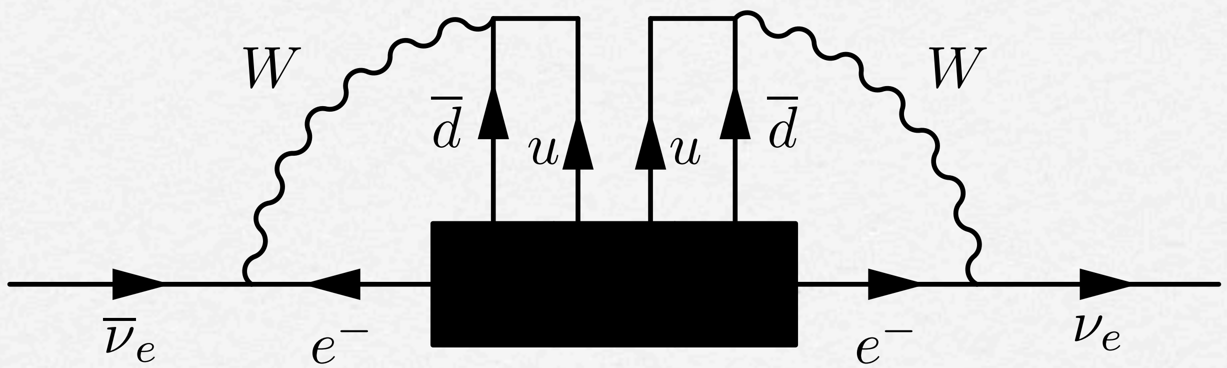
theory bound

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	$\ell\ell jj$	$\lesssim$ 2.5 TeV	ATLAS, CMS [43, 44]	heavy Majorana N [45]
Z_{LR}	$e^+e^-/\mu^+\mu^-$	$\sim$ 2 TeV	ATLAS [46]	see [47]
Z_{LR}	e^+e^-	$\sim$ 3 TeV	LEP [48]	indirect, see [49, 50]
Δ_L^{++}	$\ell_i^+\ell_j^+$	100-355 GeV	ATLAS [51]	spectrum dependent [52]
Δ_L^+	$\not{E}_T + j$	70-90 GeV	LEP [55]	chargino search [54]
Δ_L^0		45 GeV	LEP [48]	Z-boson width
Δ_R^{++}	$\ell_i^+\ell_j^+$	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":

$0\nu2\beta$ implies neutrino Majorana mass



Schecter , Valle '82

$0\nu2\beta$ - probe of neutrino (Majorana) mass

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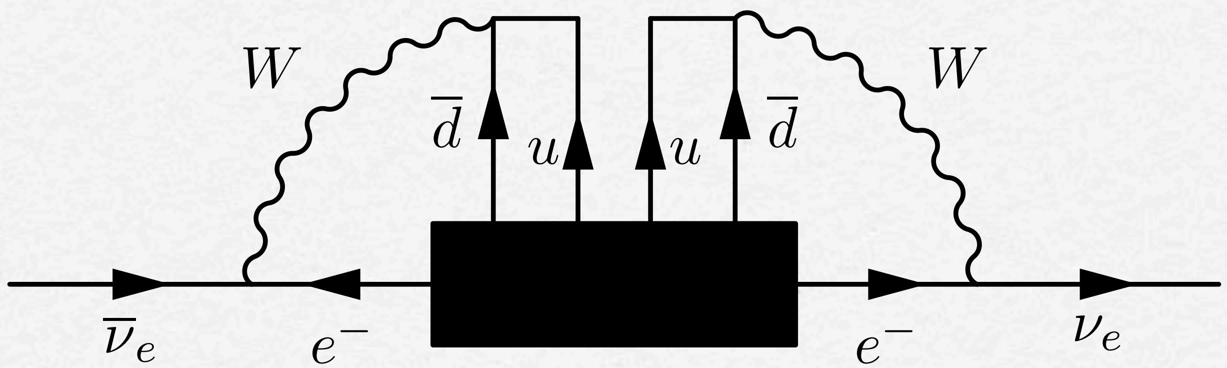

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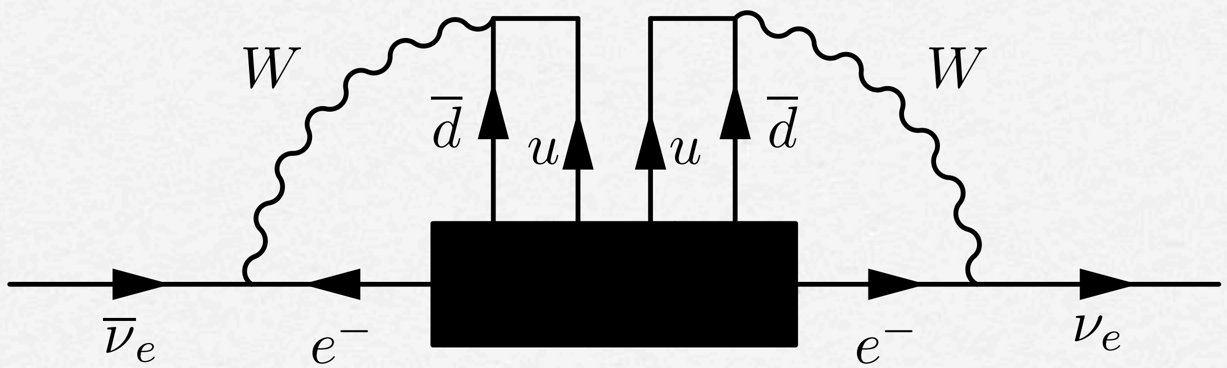

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effectively = 0

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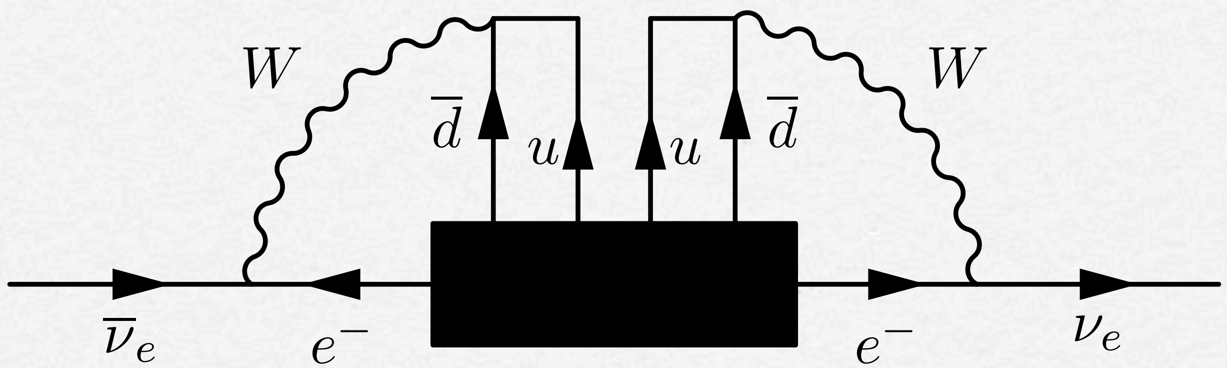


Schecter, Valle '82

$0\nu2\beta$ - probe of neutrino (Majorana) mass

suggests

Duerr, Lindner, Merle ' 11

effectively = 0

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

Planck scale seesaw

Akhmedov, Berezhiani, GS '91

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

Planck scale seesaw

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

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

complete theory

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

$$O = \sqrt{m_N} \sqrt{m_N^{-1} V_R^\dagger V_L^* m_\nu V_L^\dagger V_R^*}\, V_R^T V_L \sqrt{m_\nu^{-1}}$$ Casas-Ibarra

$$V_R = V_L \quad \Rightarrow \quad \mathcal{O} = 1$$

Neutral gauge boson

CMS-PAS EXO-11-019

Z_{LR}

July

" relative to $Z \to \ell^+\ell^-$ 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 "

allows to probe: $g_L \simeq g_R$

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

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.

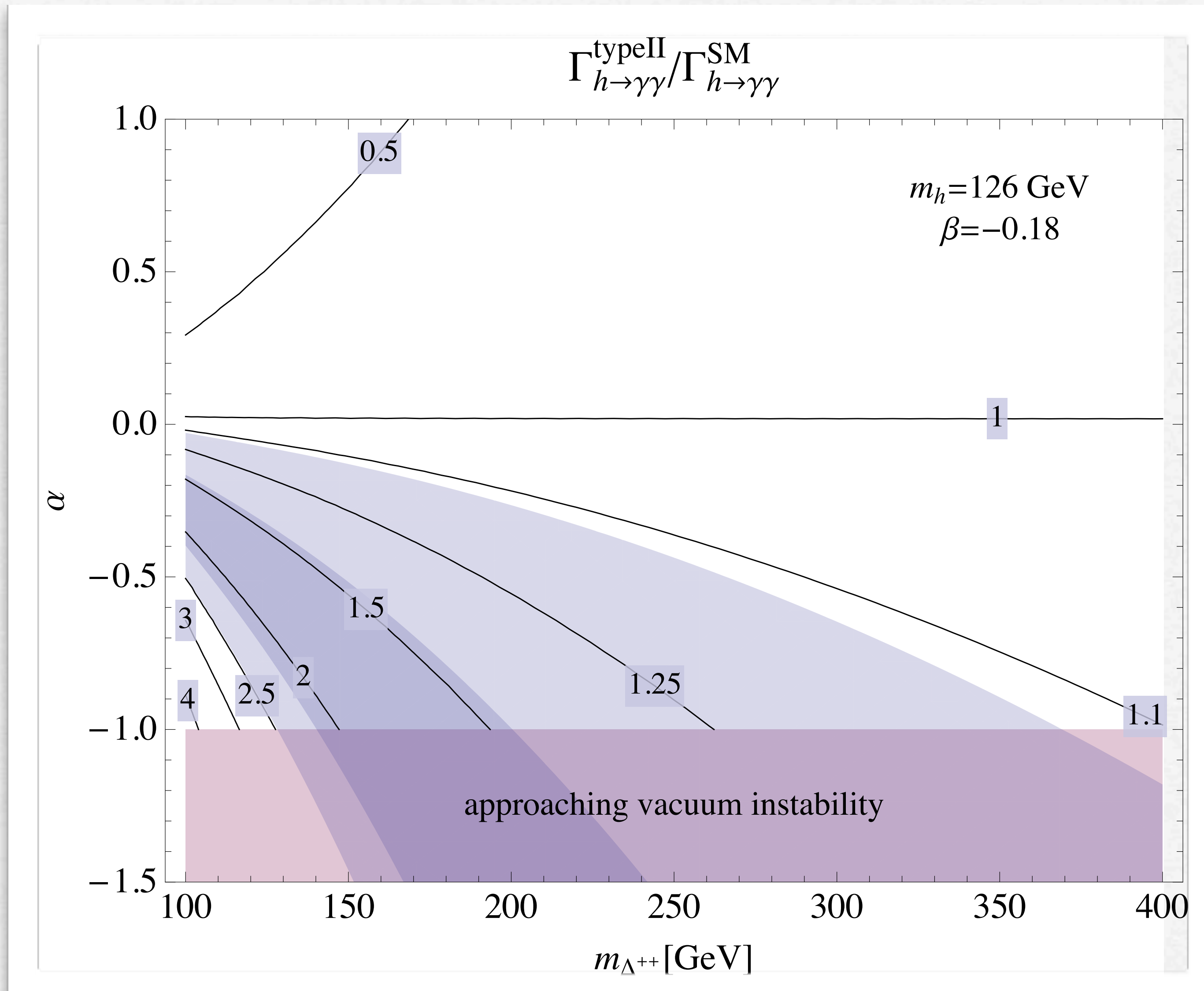
- One has to use the first decay $W_R \to eN$.
  - Determine the W_R direction (from the full event!)
  - Identify the first lepton. (the more energetic)
  - Its asymmetry wrt the W_R direction gives the 'Right' chirality.
- It is necessary to efficiently distinguish the two leptons. (More difficult 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}.

Higgs to two photons

Δ^{++}

Arhrib, Benbrik, Chabab, Moultaka, Rahilli '12



$$\alpha v \, h \Delta^{++} \Delta^{--}$$

negative - adds to dominant W contribution in SM

Melfo, Nemevsek, Nesti, GS, Zhang '12

Chun, Lee, Sharma '12

Grand Unification: Large M

SO(10) tailor made: q-l unification

minimal supersymmetric version:

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

Bajc, GS, Vissani '02

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

Goh, Mohapatra, Ng '03

....

GS: RNC '11

$\Downarrow$

T2K, Daya Bay

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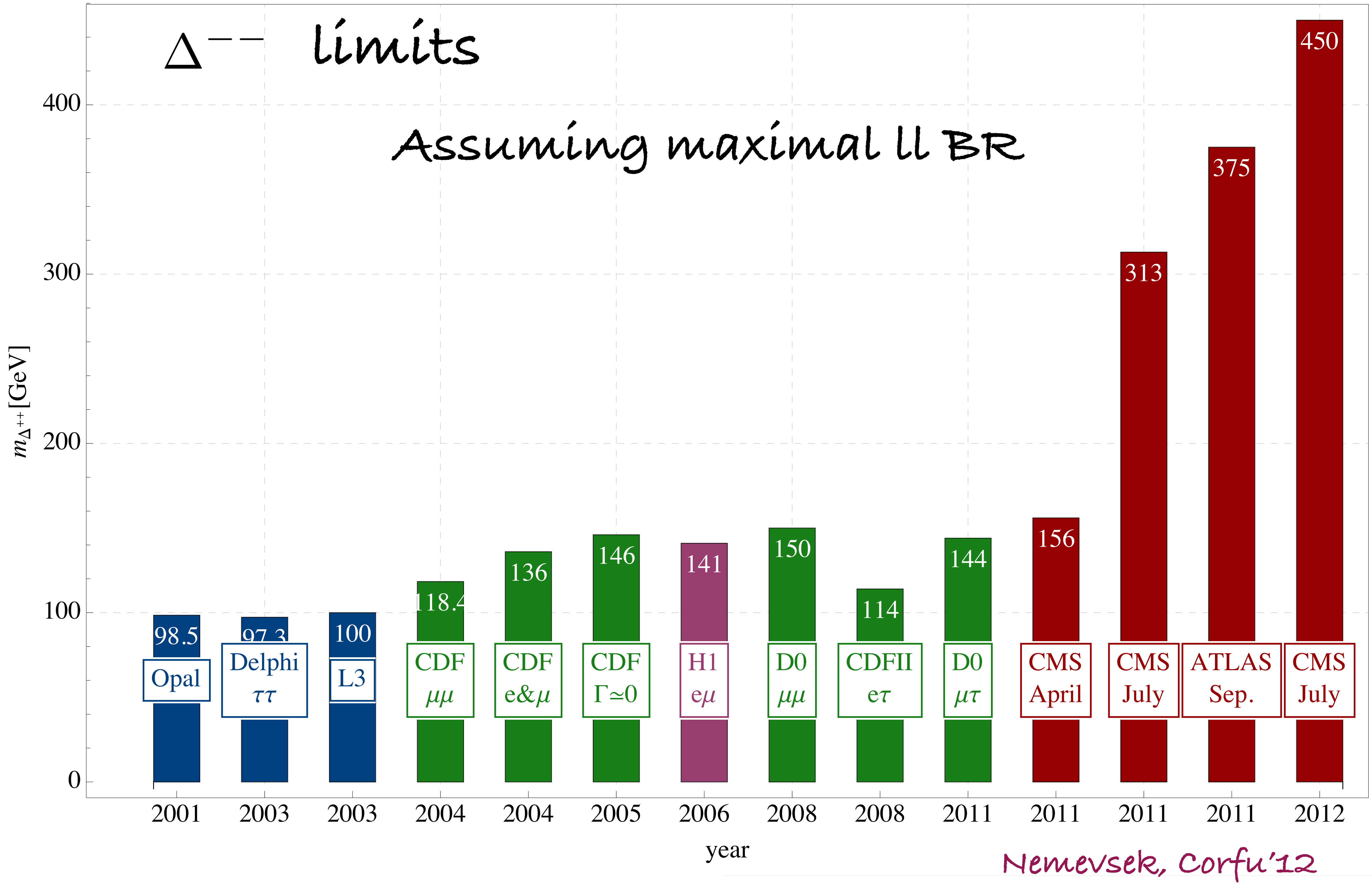
....

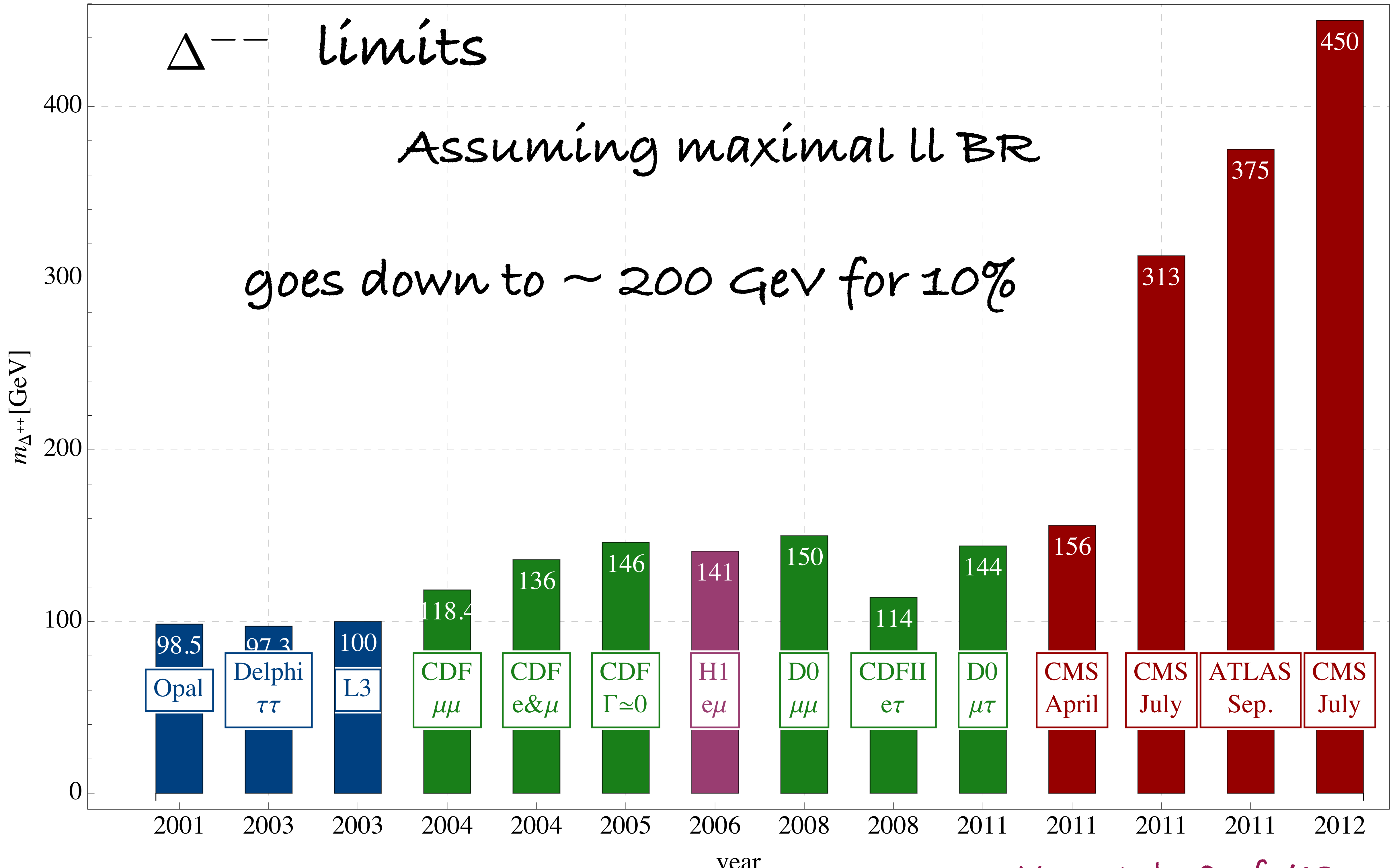
$\Downarrow$ GS: RNC '11

No LHC

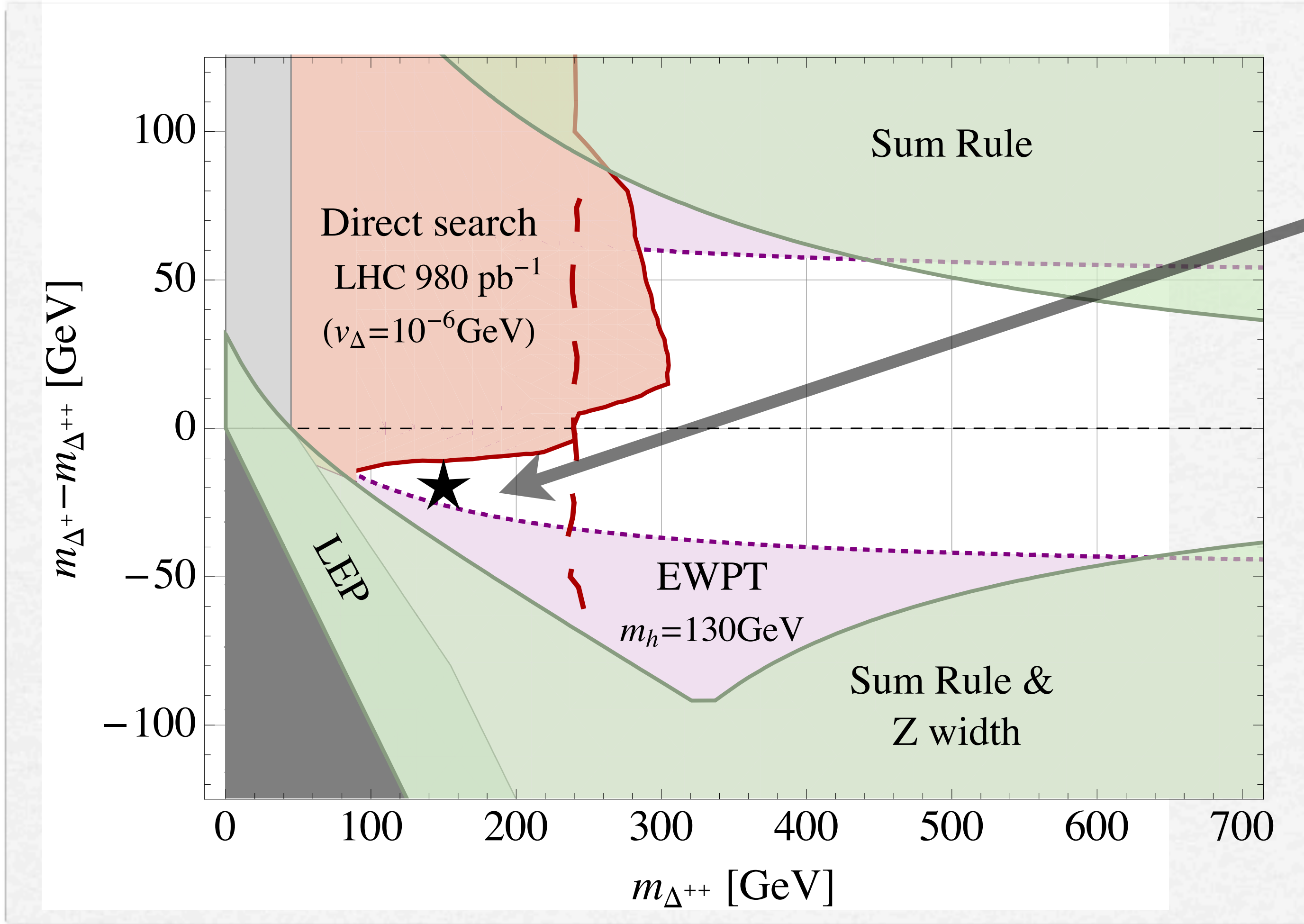
T2K, Daya Bay



Δ^{--} limits
Assuming maximal ll BR
$m_{\Delta^{++}}$[GeV]
400
300
200
100
0
98.5
Opal
97.3
Delphi
$\tau\tau$
100
L3
118.4
CDF
$\mu\mu$
136
CDF
e&μ
146
CDF
$\Gamma\simeq0$
141
H1
eμ
150
D0
$\mu\mu$
114
CDFII
eτ
144
D0
$\mu\tau$
156
CMS
April
313
CMS
July
375
ATLAS
Sep.
450
CMS
July
2001
2003
2003
2004
2004
2005
2006
2008
2008
2011
2011
2011
2011
2012
year
Nemevsek, Corfu'12



Nemevsek, Corfu'12



window

cascade decays

$$\Delta^{++} \to \Delta^{+} + W^{+}$$

$$\Delta^{+} \to \Delta^{0} + W^{+}$$

Akeroyd, Aoki '05

FIG. 2. Summary of all the experimental and theoretical constraints in the $m_{\Delta^{++}}$–$m_{\Delta^{+}}$ parameter space, for degenerate light neutrino masses. The LHC 2σ exclusion is shown by the region to the left of the red solid curve, relative to $v_\Delta = 10^{-6}$ GeV. The analogous curve for $v_\Delta = 10^{-9}$ GeV is red dashed. The purple (dotted) contour excluded by EWPT at 95% C.L. is shown for SM Higgs mass 130 GeV (left panel) and 300 GeV (right panel). The (green) region excluded by the Z-width bound and the mass sum rule in Eq. (4) is shown for the triplet-SM Higgs coupling $\beta = 3$.

Melfo, Nemevsek, Nesti, GS, Zhang '11