Theory overview of mass models

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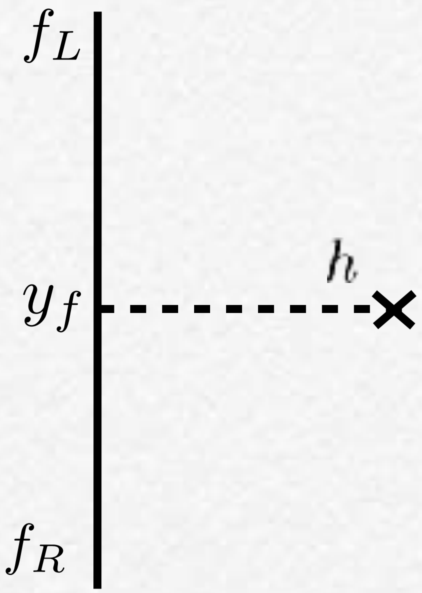
Better title:

Probe of origin and nature of neutrino mass

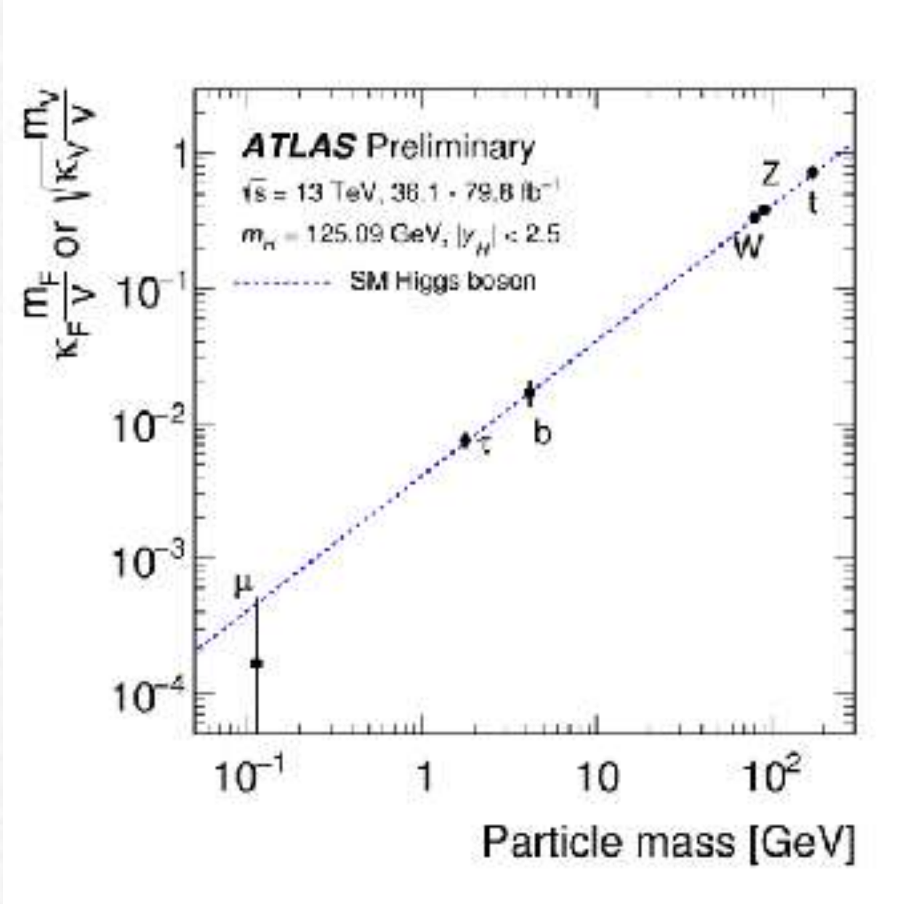
Search for a theory of neutrino mass

(Tello, GS '12 - present)

Origin of mass = SM Higgs mechanism



Charged fermions:
mass from Yukawa couplings



$$y_f = \frac{g}{2}\,\frac{m_f}{m_W} \quad \Rightarrow \quad \Gamma(h \to f\bar{f}) = \frac{G_F}{4\sqrt{2}\pi} m_h m_f^2$$

Crux = (maximal) parity violation

Lee, Yang '56

Wu et al '56

V-A Marshak, Sudarshan '57

Gauge ew theory ↓ Glashow '61

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \quad \Bigg| \quad \begin{matrix} u_R \\ d_R \end{matrix} \quad e_R$$

↓

fermions (and gauge bosons) massless

↓

need a Higgs doublet -and it suffices Weinberg '67

LR asymmetry a blessing - but a curse too

⬇

massless neutrino

⬇

Break LR symmetry spontaneously?

Motivation in itself, bring parity on the same footing as gauge symmetries

It makes all the difference

LR symmetric theory (of neutrino mass)

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

W_L $\qquad$ W_R

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

neutrino mass long before experiment

Pati, Salam '74

Mohapatra, Pati '74

Mohapatra, GS '75

GS '79

but why neutrino mass so small?

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

$$Q = T_{3L} + T_{3R} + \frac{B-L}{2}$$ B-L gauged

$$\Phi = \begin{bmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & -\phi_2^{0*} \end{bmatrix} \qquad (2,2,0)$$ bi-doublet - EW scale

$$\Delta_{L,R} = \begin{bmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{bmatrix}_{L,R} \qquad \begin{matrix} (3,1,2) \\ (1,3,2) \end{matrix}$$ L and R triplets - LR scale

$$\langle \Delta_L^0 \rangle = 0, \qquad \langle \Delta_R^0 \rangle = v_R$$

Masses: $\left\{ \begin{array}{l} W_R \text{ and } Z_R \\ \text{Higgs triplets} \\ \text{the second doublet} \\ \text{and RH neutrino} \end{array} \right.$

Neutrino mass

$$\mathcal{L}_Y = \bar{\ell}_L \, \Phi \, \ell_R + h.c.$$
$$+\ell_L^T \, \Delta_L \, C \, \ell_L + \ell_R^T \, \Delta_R \, C \, \ell_R$$

$$M_D \propto \langle \Phi \rangle$$

naive expectation $\quad m_D \simeq m_e$

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

$$\langle \Delta_R^0 \rangle = v_R$$

RH neutrino = heavy Majorana
neutral lepton N $\quad N_L = C \bar{\nu}_R^T$

$$N = N_L + C\overline{N_L}^T \qquad N = N^C$$

Majorana mass $\quad N^T C N$

$$M_N \propto \langle \Delta_R \rangle \propto M_{W_R}$$

seesaw

Seesaw

Minkowski '77

Mohapatra, GS '79

Yanagida '79

Glashow '79

Gell-Mann et al '79

nu - N mass matrix

$$\begin{array}{c c} \nu & \multirow{2}{*}{$\begin{pmatrix} 0 & M_D^T \\ M_D & M_N \end{pmatrix}$} \\ N & \end{array}$$

Majorana neutrino

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

neutrino mass related to amount of P violation

$$M_N \propto M_{W_R}$$

new physics:

N - gauge interactions with W_R and Z_R

LR scale?

Beall, Bander, Soni '81

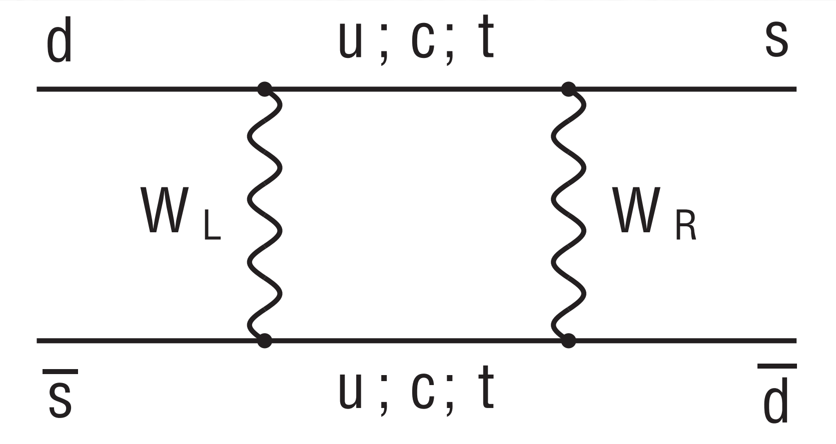
Mohapatra, GS, Tran '83

.....

Maiezza, Nemevsek, Nesti, GS '10

Bertolini, Maiezza, Nesti '15

K meson mixing



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

needed LHC

Neutrino Majorana mass

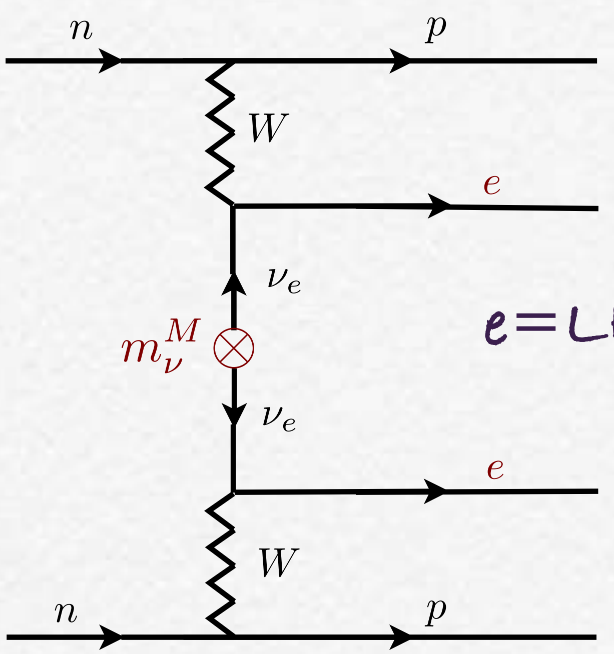
Majorana '37

Lepton Number Violation

- neutrinoless double beta — Furry '38
- hadronic colliders - LHC — Keung, GS '83

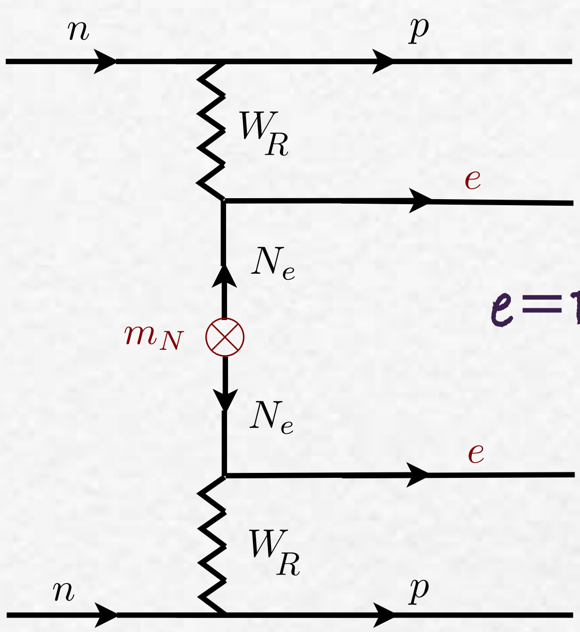
Neutrinoless double-beta decay

Mohapatra, GS '79, 81



e=LH

LR



e=RH

$$\mathcal{A}_\nu \propto \frac{G_F^2 m_\nu^{ee}}{p^2} \quad (p \simeq 100\, MeV)$$

$$\mathcal{A}_N \propto G_F^2 \frac{M_{W_L}^4}{M_{W_R}^4} \frac{1}{m_N}$$

$$\tau_{0\nu 2\beta} \gtrsim 10^{25} yr \rightarrow m_\nu \lesssim 1 eV$$

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

Tello et al '11

Effective interaction

d=9 operator

$$\frac{1}{\Lambda^5_{\not L}}(e\,e\,u\,u\,\bar{d}\,\bar{d}) \rightarrow \Lambda_{\not L} \gtrsim TeV$$

LHC energies

$$\mathcal{A}_\nu \propto \frac{G_F^2 m_\nu^{ee}}{p^2} \quad (p \simeq 100\, MeV) \qquad \mathcal{A}_{eff} = \frac{1}{\Lambda^5_{\not L}}$$

e = RH -> new physics
-potentially accessible @ LHC

What if e =LH? → It can still be new physics,
not neutrino mass

Dvali, GS, Maiezza, Tello to appear

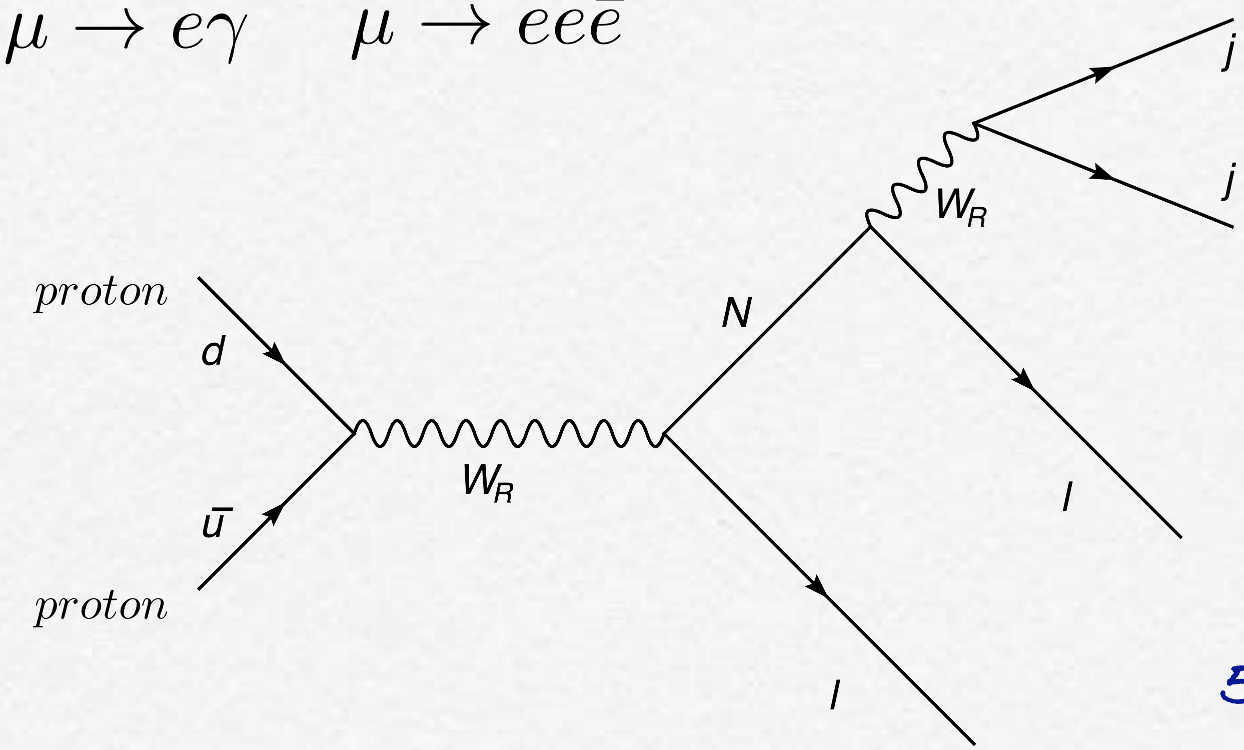
LNV @ hadron colliders

Keung, G.S. '83

moreover, LFV

Tello PhD thesis '12

$\mu \to e\gamma \qquad \mu \to ee\bar{e}$



probe of Majorana nature of N

50% lepton - 50 % antileptons

$$M_N = V_R m_N V_R^T$$

0nu2beta connection

Ferrari et al '00

Nemevsek, Nesti, GS, Zhang '11

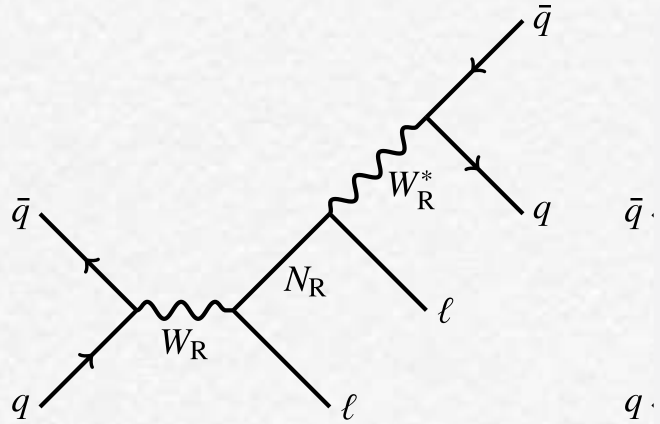
Vasquez '14

...

Nemevsek, Nesti, Popara '18

ATLAS hep-ex 1904.12679

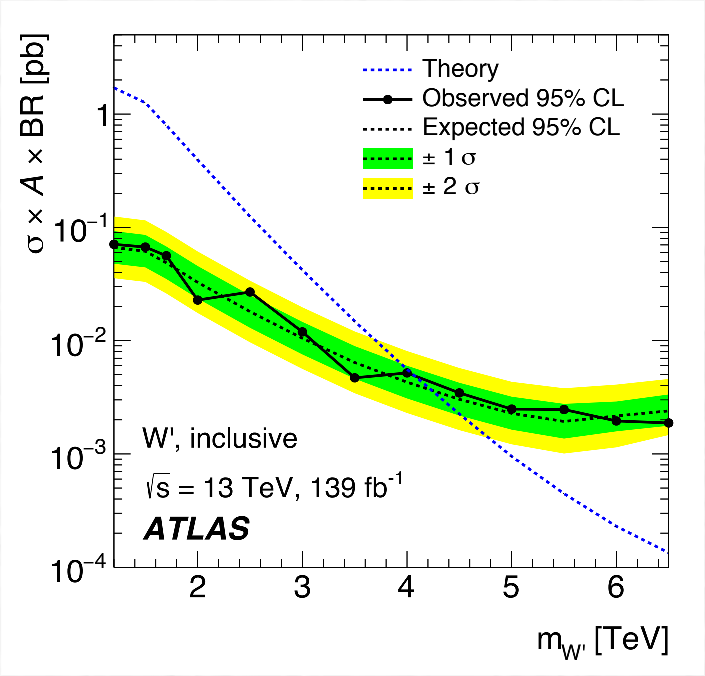
neutrinos (N_R). A search for W_R boson and N_R neutrino production in a final state containing two charged leptons and two jets ($\ell\ell jj$) with $\ell = e, \mu$ is presented here. The exact process of interest is the Keung–Senjanović (KS) process [10], shown in Figure 1. When the W_R boson is heavier than



(a)

Figure 1: The KS process, for (a) the $m_{W_R} > m_{N_R}$ case an

ATLAS 1910.08447



$M_R > 5$ TeV for $m_N \lesssim M_{W_R}$

di-jet $M_R > 4$ TeV

Origin of neutrino mass

M_ν - oscillations ...

M_N - colliders (LHC?)

Neutrino - N mixing $\Theta = M_D/M_N$

N decays $N \to \ell_L W^+$

Task: M_D from M_ν and M_N

LR = parity

GS, Tello 2016-2020

P: $f_L \to f_R$ ➔ $\bar\nu_L M_D \nu_R + \bar\nu_R M_D^\dagger \nu_L$ ➔ $M_D = M_D^\dagger$

$M_\nu = M_D^T \frac{1}{M_N} M_D$ ➔ $\frac{1}{\sqrt{M_N}} M_\nu^* \frac{1}{\sqrt{M_N}} = X X^*$ with $X = \frac{1}{\sqrt{M_N}} M_D \frac{1}{\sqrt{M_N^*}}$

$X = X^\dagger$

symmetric $XX^* = O S\, O^T$ O = orthogonal

⬇ (when S = real)

$X = O \sqrt{S}\, O^\dagger$ all fixed

LR = charge conjugation

Nemevsek, GS, Tello '12

C: $f_L \to f_R^*$ ➔ $M_D = M_D^T$

➔ $$M_\nu = M_D \frac{1}{M_N} M_D$$

(divide by MN on the left)

➔ $$\frac{1}{M_N} M_\nu = (\frac{1}{M_N} M_D)^2$$

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

Impossible in naive seesaw without LR

-back up slides

LR = theory of neutrino mass

illustrate $V_R = V_L$ → $M_D = V_L \sqrt{m_\nu m_N}\, V_L^\dagger$

manifestly order seesaw

→ $\Gamma(N_i \to W \ell_j) \propto V_{ij}^2 m_{\nu_i} \frac{m_{N_i}^2}{M_W^2}$

analog of SM for charged fermions $\Gamma(h \to f\bar{f}) \propto m_h m_f^2$

a plethora of other processes in the scalar sector -
all depend on MN and/or MD

cross checks GS, Tello 1812.03790 (hep-ph)

LHC reach

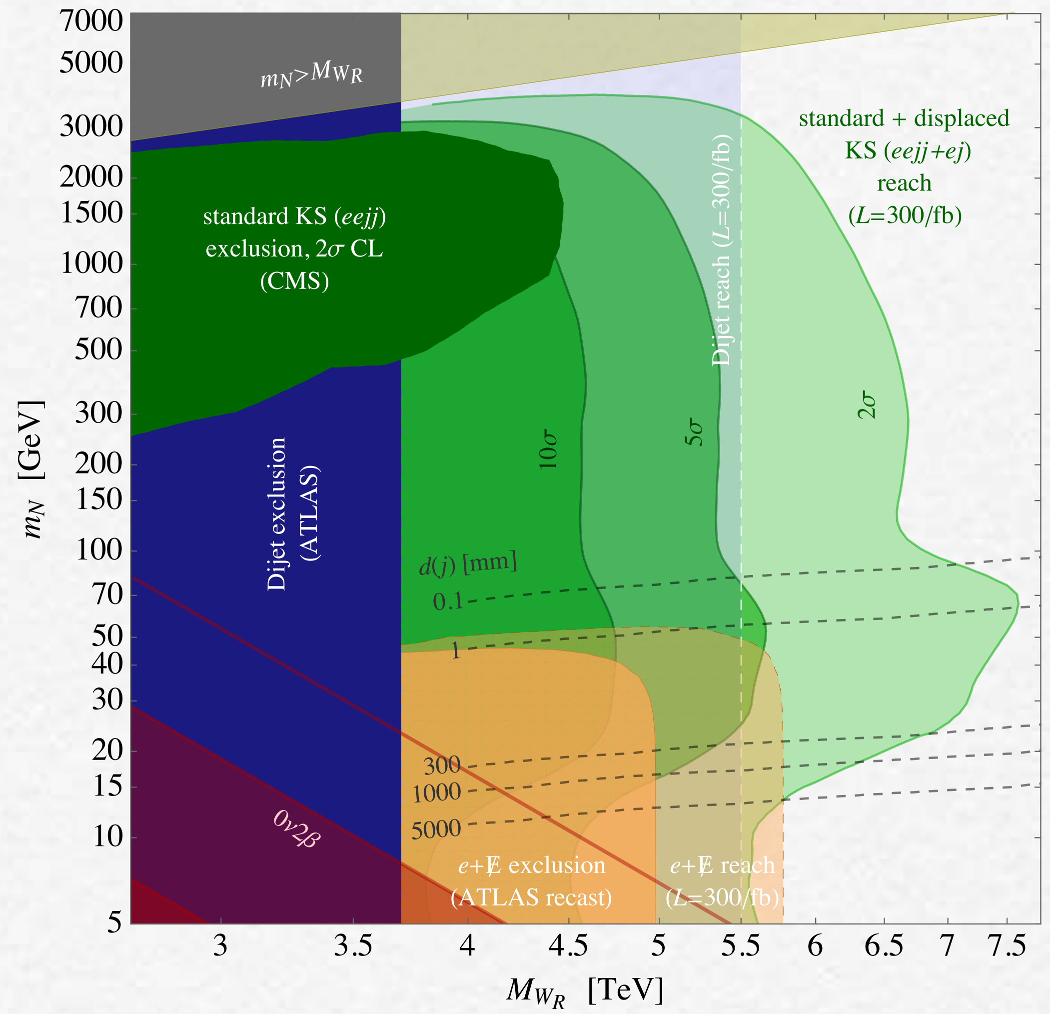


FIG. 9. Summary plot collecting all searches involving the KS process at LHC, in the electron channel. The green shaded areas represent the LH sensitivity to the KS process at 300/fb, according to the present work. The rightmost reaching contour represents the enhancement obtained by considering jet displacement.

Nemevsek, Nesti, Popara 1801.05813 (hep-ph)

Fritsch, Minkowski '74

SO(10) GUT

Georgi '74

$$\Psi_{16} = \begin{pmatrix} u \\ u \\ u \\ \nu \\ d \\ d \\ d \\ e \\ e^c \\ d^c \\ d^c \\ d^c \\ \nu^c \\ u^c \\ u^c \\ u^c \end{pmatrix}$$

Generation unified → (heavy) RH neutrino

↓

small neutrino mass

Beautiful, but not self-contained, hard to make predictions

- small Higgs representations: d=5 operators, too many couplings
- large representations: fewer couplings but (too?) many states

Vested interest, but must admit no accepted model emerged

SU(5) GUT

- Minimal model = SM -> neutrino massless — Georgi, Glashow '74

  (no unification)

- Minimal extension of the minimal model — Bajc, GS '06

  ⬇ neutrino mass + unification

  SU2 weak fermion triplet with m~TeV

but still, a lot of couplings, not worth dwelling in detail

Minimal Supersymmetric Standard Model

particle - sparticle

↓

zino (partner of Z) - role of RH neutrino

↓

neutrino mass through a small vev of sneutrino

too many parameters, not self-contained
- fix the parameter space!?

Model Building

Tailor made models

- add particles and/or symmetries to existing theories

- or take particles out of existing theories

  (e.g. a seesaw = keep only N out of LR theory)

a never ending saga

Does gravity matter?

Planck scale suppression?

Akhmedov, Berezhiani, GS '91

situation more subtle

Dvali, Folkerts, Franca 2013

gravitational anomaly

Dvali, Funcke 2016

additional ~ Higgs effect → $\langle \bar{\nu}_R \nu_L \rangle = \Lambda^3_{gravity}$ SU(2) doublet

(analog of QCD condensate)

can affect neutrino mass

Summary

LR self-contained and predictive theory

Completes the program of the origin of particle mass

- Neutrino mass origin $$\Gamma(N_i \to W\ell_j) \propto V_{ij}^2 m_{\nu_i} \frac{m_{N_i}^2}{M_W^2}$$

- link between LHC and low energy: double beta, LFV,...

- SO10 GUT, SSM: neutrino mass - but not predictive

Thank you

Trouble with naive seesaw

- Cannot determine M_D

$$M_\nu = M_D^T \frac{1}{M_N} M_D \quad \rightarrow \quad M_D = \sqrt{M_N} O \sqrt{M_\nu}$$

Casas, Ibarra '01

$$\mathcal{O}^T \mathcal{O} = 1$$

arbitrary complex orthogonal matrix

(no upper limit on the elements)

- produce N through $\Theta = M_D / M_N$

needs large O

neutrino lightness accidental -

not seesaw

Effective operator analysis

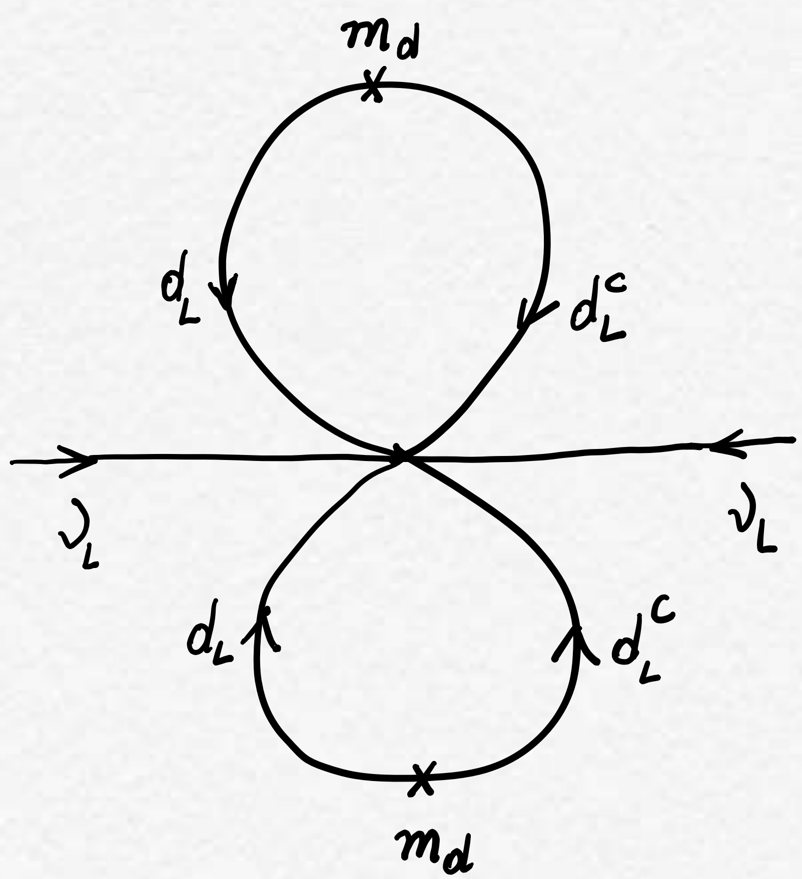
Dvali, GS, Maiezza, Tello   to appear

$$O = \frac{1}{\Lambda^5}(e_L e_L)(u_L u_L d^c_L d^c_L)$$ → $$O = \frac{1}{\Lambda^5}(\nu_L \nu_L)(d_L d_L d^c_L d^c_L)$$

typical operator

SU(2)

↓



neutrino mass

$$m_\nu \simeq \left(\frac{\alpha}{4\pi}\right)^2 \frac{m_d^2}{\Lambda}$$

↓

$$\Lambda \simeq TeV$$

$$m_\nu \simeq 10^{-1}\, eV$$

too close for comfort?

Generations - Lepton Flavour Violation?

$$O_\mu = \frac{1}{\Lambda^5}(\mu_L\mu_L)(c_Lc_Ld^c_Ld^c_L) \qquad O_e = \frac{1}{\Lambda^5}(e_Le_L)(u_Lu_Ld^c_Ld^c_L)$$

expect

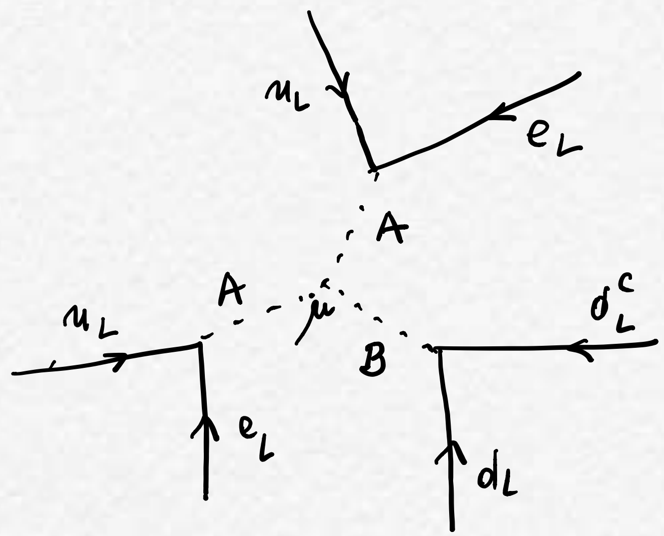
$$\frac{1}{\Lambda^2}(c\,\mu)(\bar{u}\bar{e}) \rightarrow \Gamma(D^0 \to \mu\bar{e}) \simeq \frac{m_D^5}{\Lambda^4} \rightarrow \Lambda \gtrsim 10^5 GeV$$

$0\nu2\beta$ hopelessly small

flavour could be conserved

(Poor person's) UV completion

$$\mathcal{L}_{new} = A(u_L e_L + d_L \nu_L) + B\, d_L^c d_L^c + \mu\, A\, A\, B$$



A = scalar leptoquark

B = scalar di-quark

$$\frac{1}{\Lambda^5} = \frac{\mu}{m_A^4\, m_B^2}$$

$m_B \gg m_A$ helps

$m_A \gtrsim 2\, TeV$

ATLAS 2006.05872

$$\frac{\mu}{m_B^2} \gtrsim 10^{-6}\, GeV^{-1}$$

$$m_\nu \simeq (\frac{\alpha}{4\pi})^2 \mu \frac{m_d^2}{m_B^2} \simeq 10^{-4}\, eV$$

negligible

flavour problem - but again, could be conserved

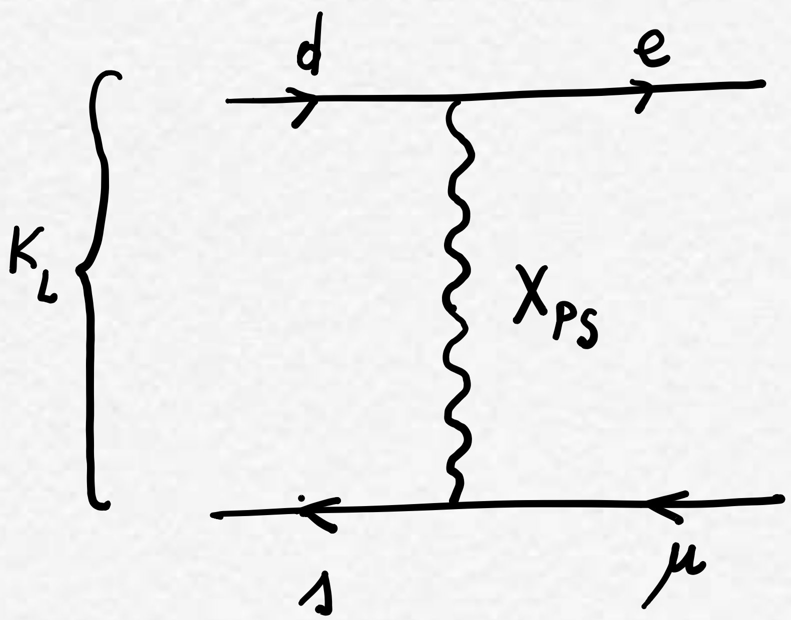
UV completion: theory

quark - lepton unification

Pati - Salam $SU(2) \times SU(2) \times SU(4)$

$$U = \begin{pmatrix} u \\ u \\ u \\ \nu \end{pmatrix} \quad D = \begin{pmatrix} d \\ d \\ d \\ e \end{pmatrix}$$

LFV in gauge boson interactions



$K_L \to \mu \bar{e}$

scale large

$\Lambda \gtrsim 10^5 GeV$

assume scalar leptoquarks light? → Could work, rather technical

Dvali, GS, Maiezza, Tello to appear

Origin of neutrino mass

nu - N mixing $\Theta = M_D/M_N$

N decays $N \to \ell_L W^+$

determine MD -
function of neutrino and N masses

$Y_D = M_D/v$

analog of SM - charged fermions $y_f = \frac{g}{2}\,\frac{m_f}{m_W}$

M_ν - oscillations ...

M_N - colliders (LHC?)

Trouble

- Cannot determine M_D $\quad$ $Y_D = M_D/v$ → decay rates

$$M_\nu = M_D^T \frac{1}{M_N} M_D \quad \rightarrow \quad M_D = \sqrt{M_N} O \sqrt{M_\nu}$$

Casas, Ibarra '01

$\mathcal{O}^T \mathcal{O} = 1$ $\quad$ arbitrary complex orthogonal matrix
(no upper limit on the elements)

- produce N through $\Theta = M_D/M_N$

needs large O

→

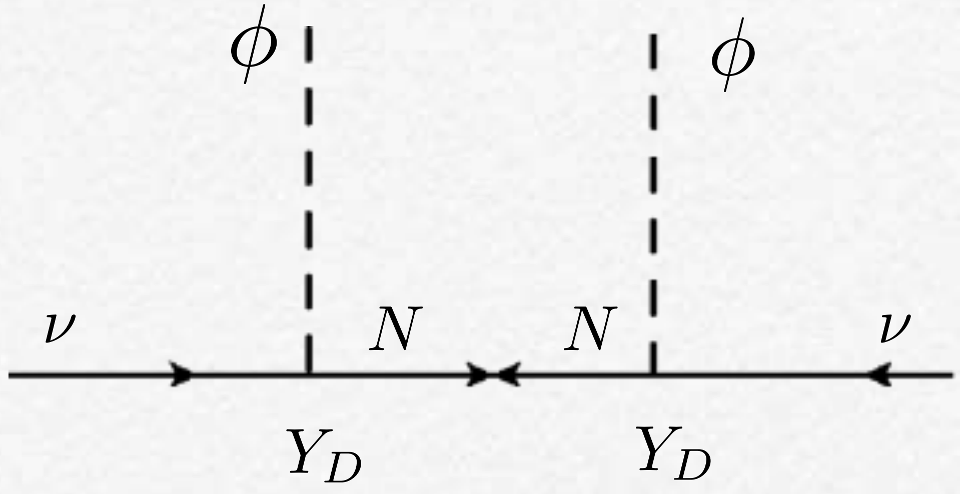
neutrino lightness accidental -
NOT seesaw

Seesaw (naive)

add heavy N to SM

$M_D = Y_D\, v$

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



$\Theta = M_D / M_N$ → $\theta_{ij} \ll 1$ = definition of seesaw

determines N production and decays:

$N \to \ell W$

$N \to \nu Z \qquad N \to \nu h$

Effective d=5 operator

only SM degrees of freedom

Weinberg '79

$$\mathcal{L}_{eff} = c_{ij}\frac{\phi\,\phi\,\ell_i\,\ell_j}{M}$$

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

$$M_\nu^{ij} \simeq c_{ij}\frac{M_W^2}{M}$$

Majorana mass

$$y_\nu^M = \frac{g}{2}\frac{m_\nu}{M_W}$$

negligible

no new observable physics,
all suppressed by c/M ~ nu mass

$$\mathcal{L}_{eff} \simeq M_\nu^{ij}\frac{\phi\,\phi\,\ell_i\,\ell_j}{M_W^2}$$

- Higgs sector: perturbativity limits

Maiezza, Nemevsek, Nesti '15

Chakraborrty, Gupta,, Jelinek, Srivastava '16

Dev, Mohapatra, Zhang '16

Maiezza, GS, Vasquez '16

potential problem: heavy doublet H violates flavor

$$\mathcal{L}_H = \frac{g}{2M_W c_{2\beta}} H^0 \bar{d}_L \, V_L^\dagger m_u V_R \, d_R + \ldots$$

$$m_{H^0} \gtrsim 15 \, TeV$$

$$m_H^2 = \frac{\lambda}{g^2} M_{W_R}^2$$

OK for M_R > 5 TeV (still @LHC)

- Strong CP phase computable

Beg, Tsao '78

Mohapatra, GS '78

$$\bar{\theta} \simeq \epsilon \, \frac{m_t}{2m_b} \quad \rightarrow \quad \epsilon \lesssim 10^{-11}$$

Maiezza, Nemevsek '14

- Quark sector: analytic determination of V_R

$$\langle\Phi\rangle = v\,\mathrm{diag}(\cos\beta, -\sin\beta e^{-ia})$$

$$(V_R)_{ij} \simeq (V_L)_{ij} - i\epsilon \frac{(V_L)_{ik}(V_L^\dagger m_u V_L)_{kj}}{m_{d_k} + m_{d_j}}$$

GS, Tello 1408.3835 (hep-ph)

$$\Downarrow \quad \epsilon = s_a t_{2\beta}$$

GS, Tello 1502.05704 (hep-ph)

$$\theta_R^{12} - \theta_L^{12} \simeq -s_a t_{2\beta} \frac{m_t}{m_s} s_{23} s_{13} s_\delta$$

$$\theta_R^{23} - \theta_L^{23} \simeq -s_a t_{2\beta} \frac{m_t}{m_b}\frac{m_s}{m_b} s_{12} s_{13} s_\delta$$

$$\theta_R^{13} - \theta_L^{13} \simeq -s_a t_{2\beta} \frac{m_t}{m_b}\frac{m_s}{m_b} s_{12} s_{23} s_\delta$$

long history

Zhang, An, Ji, Mohapatra '07

conspiracy of small mixings suppression

justifies quoted limits on

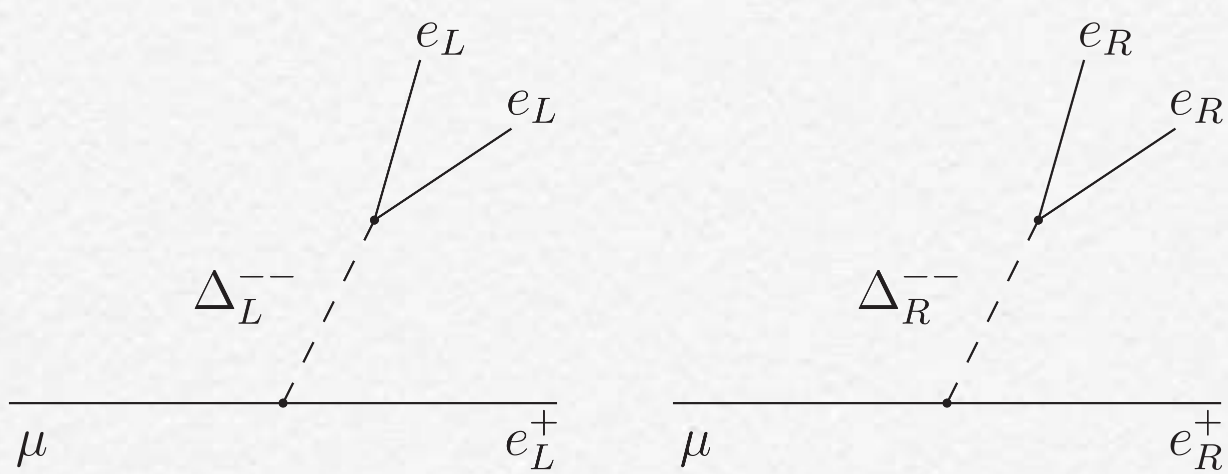
- assume same L & R mixings

Lepton flavour violation

Cirigliano, Kurylov, Ramsey-Musolf, Vogel '04

Tello PhD thesis '12

- mu -> 3 e $\qquad B_{\mu\to 3e} \lesssim 10^{-12}$ $\qquad$ SINDRUM



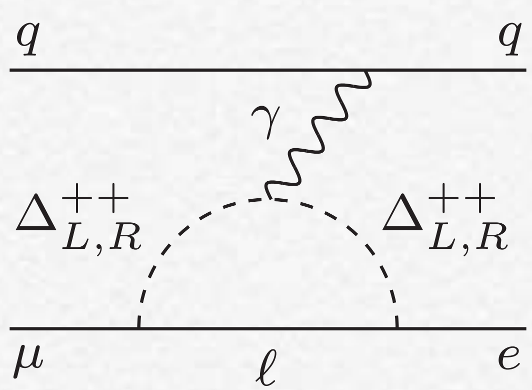
$$BR(\mu \to ee\bar{e}) = \frac{1}{2}\frac{M_W^4}{M_{W_R}^4}\left|\frac{M_N M_N}{m^2_{\Delta^{++}}}\right|^2_{e\mu}$$

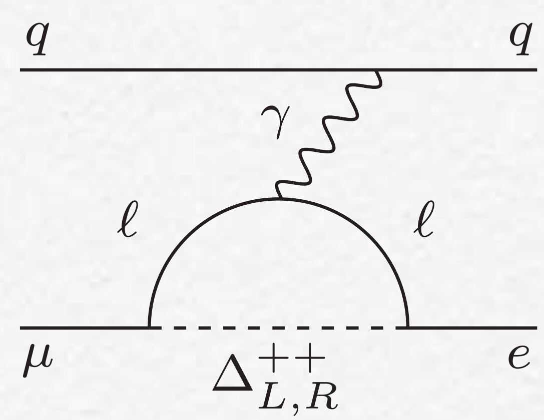
N light or degenerate

~ charm quark light

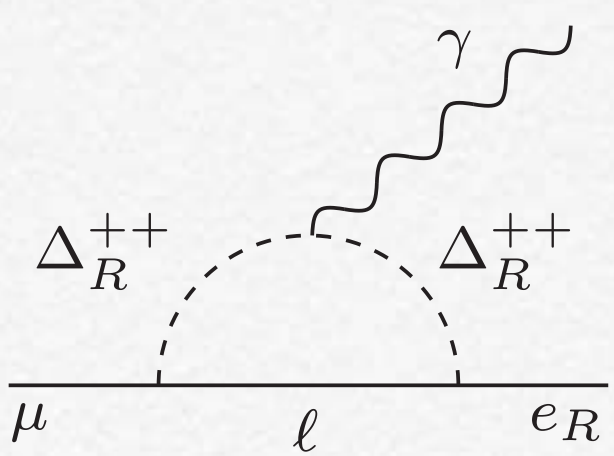
- mu - conversion: mu+x -> e + x $B_{\mu\to e} < 7\times 10^{-13}$ SINDRUM II

Comet @J-Parc; Mu2e@Fermilab - 4 orders of magnitude?





- mu ->e gamma $B_{\mu\to e\gamma} < 4\times 10^{-13}$ MEG '16



$$\Gamma(\mu X \to eX) \simeq \Gamma(\mu \to e\gamma)$$

discussed nicely in Tello PhD thesis '12

P: slightly more subtle

S = diagonal, but can be complex - with the form

$$S = diag(s, s_0, s^*)$$

$X = O\sqrt{S}EO^\dagger$ with $\sqrt{S}E^T = E\sqrt{S}^*$ $E = E^\dagger$ $EE^T = 1$

S = real $\Rightarrow$ $E = 1$

S = complex $\Rightarrow$ $E = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}$

general case - non zero vL

C:

C:

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

$$M_L = \frac{v_L}{v_R} M_N$$

$$M_D = M_D^T,$$

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

P:

P:

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

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

$$M_D = M_D^\dagger$$

$$X = \frac{1}{\sqrt{M_N}} M_D \frac{1}{\sqrt{M_N^*}} \qquad X = X^\dagger$$

Dark Matter

Bezrukov, Hettmansperger, Lindner '09

Nemevsek, GS, Zhang '12

spectrum and mixings completely determined

$m_{N_1} \simeq \text{keV}$ tau Dark Matter

$m_{N_2} \simeq m_\pi + m_\mu$ muon

diluters

$m_{N_3} \simeq m_\pi + m_e$ electron

no LNV at colliders

neutrinoless double beta decay imminent

Broken P

no analytic solution for M_D

Nemevsek, GS, Tello - struggling

instead, a perturbative approach = use small epsilon which measures spontaneous P breaking

$$\langle \Phi \rangle = v\,\mathrm{diag}(\cos\beta, -\sin\beta e^{-ia})$$

$$\epsilon = \tan 2\beta\, \sin\alpha \lesssim 10^{-2}$$

$$\tan\beta = v_2/v_1$$

GS, Tello PRL 2017

GS, Tello to appear in PRD

$$M_D^A \simeq \epsilon(m_\ell + M_D^H)$$

new physics (besides N decays) that depends on M_D (H)

- doubly charged scalars from Higgs triplets

$$\frac{\Gamma(\delta_L^{--} \to \ell_L^i \ell_L^j)}{\Gamma(\delta_R^{--} \to \ell_R^i \ell_R^j)} \simeq \frac{m_{\delta_L}}{m_{\delta_R}} \left[1 + \epsilon \frac{(M_D^H)^{ij}}{m_\ell^i + m_\ell^j} \right]$$

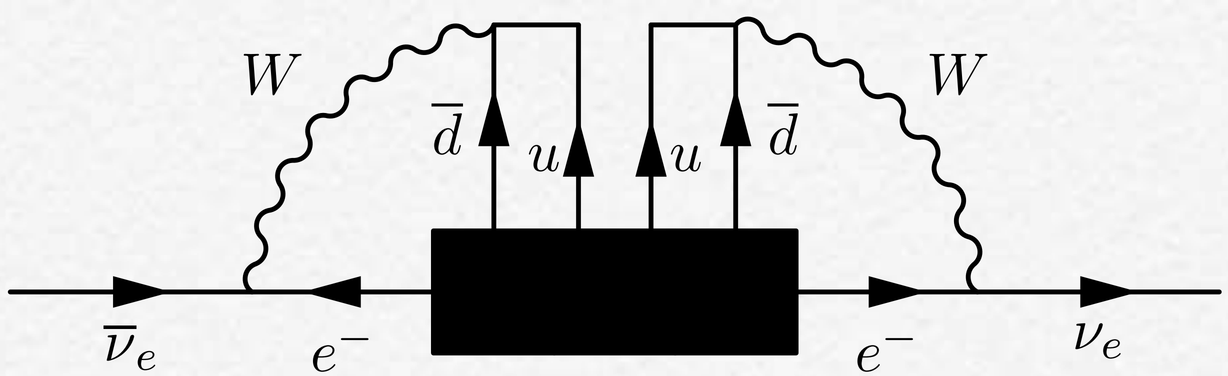
- heavy neutral scalar (from the heavy doublet)

$$\Gamma(H^0 \to \ell_i \bar{\ell}_j) \propto \frac{m_H}{M_{W_L}^2} |(M_D^H + \sin 2\beta \, m_\ell)_{ij}|^2$$

different decays correlated among themselves
and with the seesaw

Schechter-Valle "theorem":

$0\nu2\beta$ implies neutrino Majorana mass



Schecter, Valle '82

effectively = 0

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

Duerr, Lindner, Merle ' 11

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

Planck scale seesaw

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