Parity and the origin of (neutrino) mass

Goran Senjanović
ICTP

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Keung ’83 Tello ’12 - present Maiezza, Nemevsek, Nesti, Vasquez, Zhang

Origin of neutrino mass = door to new physics

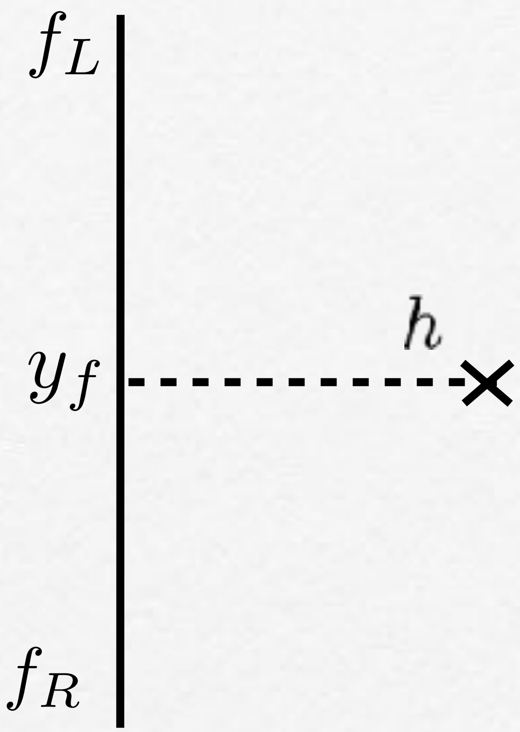
hadronic colliders (LHC?) - could open that door

probing origin of mass = probing Higgs mechanism

Charged fermions - origin of mass

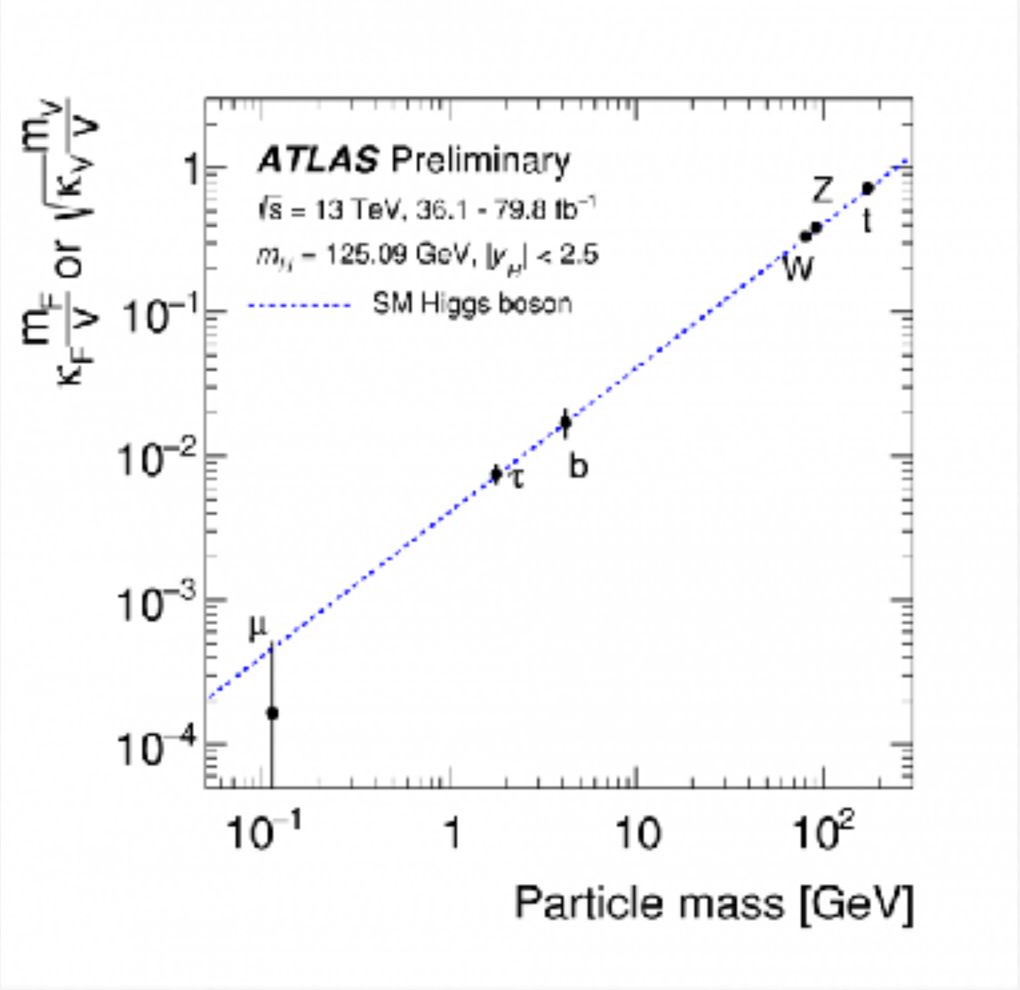
Weinberg '67

GIM '69



mass from Yukawa couplings

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



one important failure = neutrino massless

task: analog for neutrinos

SM: crux = maximal parity violation

Lee, Yang '56

Wu et al '56

↓

V-A Marshak, Sudarshan '57

↓ "V-A was the key"

Weinberg '09

Gauge ew theory

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad u_R \qquad d_R$$

↓

fermions (and gauge bosons) massless

need a Higgs doublet
-and it suffices

$$\Phi$$

→ gives mass to all :
W, Z, charged fermions

↓

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

diagonal in the physical
basis of mass eigenstates

↓

Natural Flavor Conservation
(NFC)
in neutral currents (GIM)

fermion mass ~W mass
(or smaller)

Imagine LR symmetric SM

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

directs mass terms

$$\overline{q_L} M q_R$$

miracle: how come M ~ MW?

gets worse

$$M_u = M_d$$

split: needs an adjoint (triplet) T

$$\mathcal{L}_Y = \overline{q_L}(M + Y_T T) q_R$$

$$\langle T \rangle = v\,\mathrm{diag}(1,-1)$$

$$M_u = M + vY_T, \quad M_d = M - vY_T$$

NFC $\rightarrow$ M and Y diagonal simultaneously

$\rightarrow$ M_u and M_d diagonal simultaneously

more T's = the same -
rotate in one vev direction

$\rightarrow$ $V_{CKM} = 1$

also $M_Z = 0$

needs more Higgs $\rightarrow$ all predictions gone

LR asymmetry a blessing - but a curse too

LR asymmetry $\rightarrow$ massless neutrino

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

vector-like world $\rightarrow$ massive neutrino

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

Catch 22

need Left-Right symmetry for neutrino

&

need maximal asymmetry for charged fermions

↓

break parity (LR) spontaneously

Theory of neutrino mass = L-R symmetry hidden

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

$$W_L \qquad\qquad W_R$$

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

neutrino mass long before experiment

Pati, Salam '74

Mohapatra, Pati '74

Mohapatra, GS '75

GS '79

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

Mohapatra, GS '79,'81

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

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

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

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

- W_R and N mass

mass of Higgs triplets;
mass of second doublet

Neutrino mass

$$\mathcal{L}_{\mathcal{Y}} = \bar{\ell}_L \, Y_\Phi \Phi \, \ell_R + \bar{\ell}_R \, Y_\Phi^\dagger \Phi^\dagger \, \ell_L$$
$$+ \ell_L^T \, Y_\Delta^L \, \ell_L + \ell_R^T \, Y_\Delta^R \, \ell_R + h.c.$$

Dirac mass $M_D = Y_\Phi \langle \Phi \rangle$

naive expectation $m_D \simeq m_e$

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

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

RH neutrino = heavy

Majorana neutral lepton N

$$M_N \propto M_{W_R}$$

$$N_L = C \bar{\nu}_R^T$$

Majorana mass $N^T C N$

$\Downarrow$

seesaw

LR symmetry?

gauge symmetry: $f_{L,R} \to U_{L,R}\, f_{L,R}$ $\quad \Phi \to U_L\, \Phi\, U_R^\dagger$

(i) Parity (P) $\quad f_L \to f_R \quad \Phi \to \Phi^\dagger \quad \Delta^L \to \Delta^R$

$$\Downarrow$$

$$Y_\Phi = Y_\Phi^\dagger \qquad Y_\Delta^L = Y_\Delta^R$$

(ii) Charge conjugation (C) $\quad f_L \to C\bar{f}_R^T \propto f_R^* \quad \Phi \to \Phi^T \quad \Delta^L \to \Delta^{R*}$

$$\Downarrow$$

$$Y_\Phi = Y_\Phi^T \qquad Y_\Delta^L = Y_\Delta^{R*}$$

Seesaw

Minkowski '77

Mohapatra, GS '79

Yanagida '79

Glashow '79

Gell-Mann et al '79

nu - N mass matrix

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

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 - WR

Seesaw - also type II

$$\langle \Delta_L \rangle = v_L$$

$$v_L = \lambda \frac{m_W^2}{v_R}$$

induced vev -
hierarchy of weak
isospin breaking

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

for simplicity and clarity
- ignore type II
- no loss of generality

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

$Y_D = M_D/v$

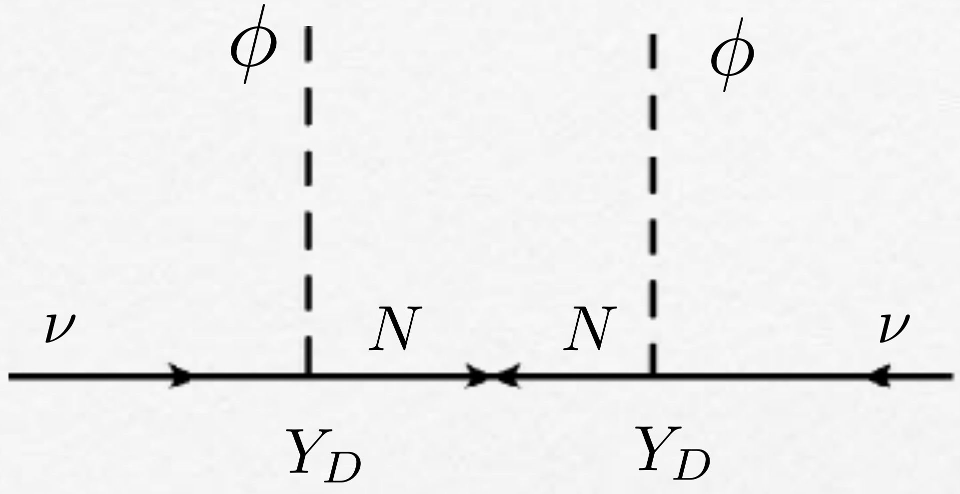
analog of SM - charged fermions $y_f = \frac{g}{2}\,\frac{m_f}{m_W}$

M_ν - oscillations ...

M_N - colliders (LHC?)

Forget LR - keep seesaw

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:

$$N \to \ell W$$

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

Trouble

- 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

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

needs large O (no upper limit on the elements)

neutrino lightness accidental -
not really seesaw → back to LR

Effective d=5 operator

only SM degrees of freedom

Weinberg '79

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

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

Majorana mass

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

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

negligible

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

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

Nature of neutrino mass

Majorana '37

seesaw -> Majorana

Lepton Number Violation

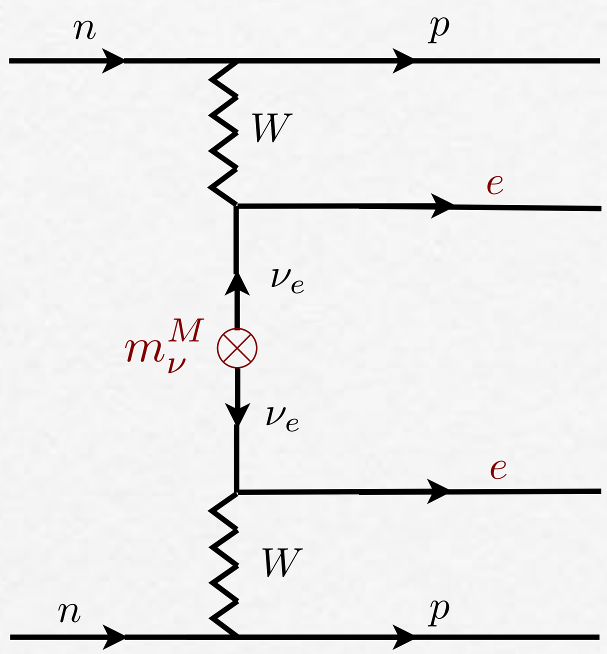
- neutrinoless double beta — Furry '38
- hadronic colliders - LHC — Keung, GS '83

talk -> connection between the two

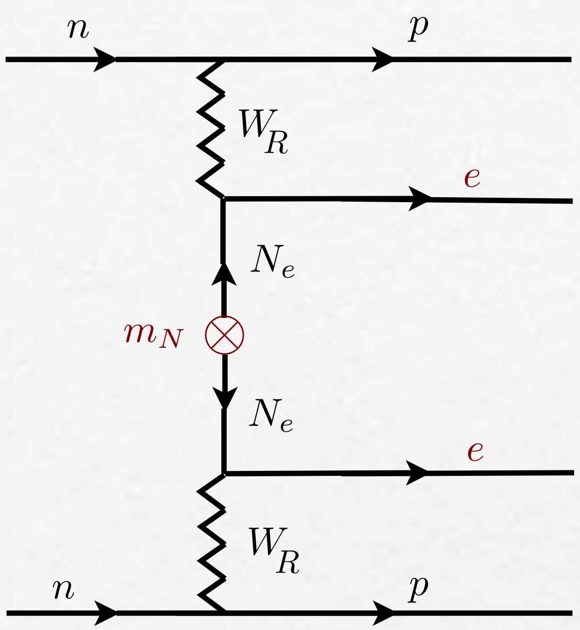
Neutrinoless double-beta decay

Mohapatra, GS '79, 81

Tello et al '11



L-R



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

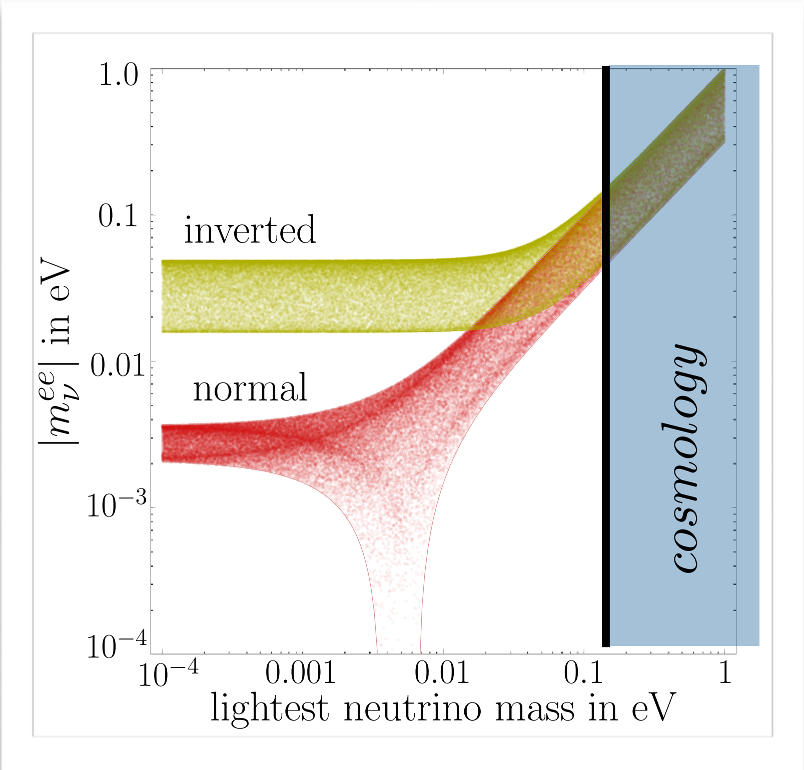
$$RR \propto \frac{1}{M_{W_R}^4} \frac{1}{m_N}$$

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

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

Probe of Majorana mass?

LHC connection?



- normal hierarchy not observable -would need new physics

- e comes out RH - would need new physics

Faessler et al '11

untangle with different isotopes

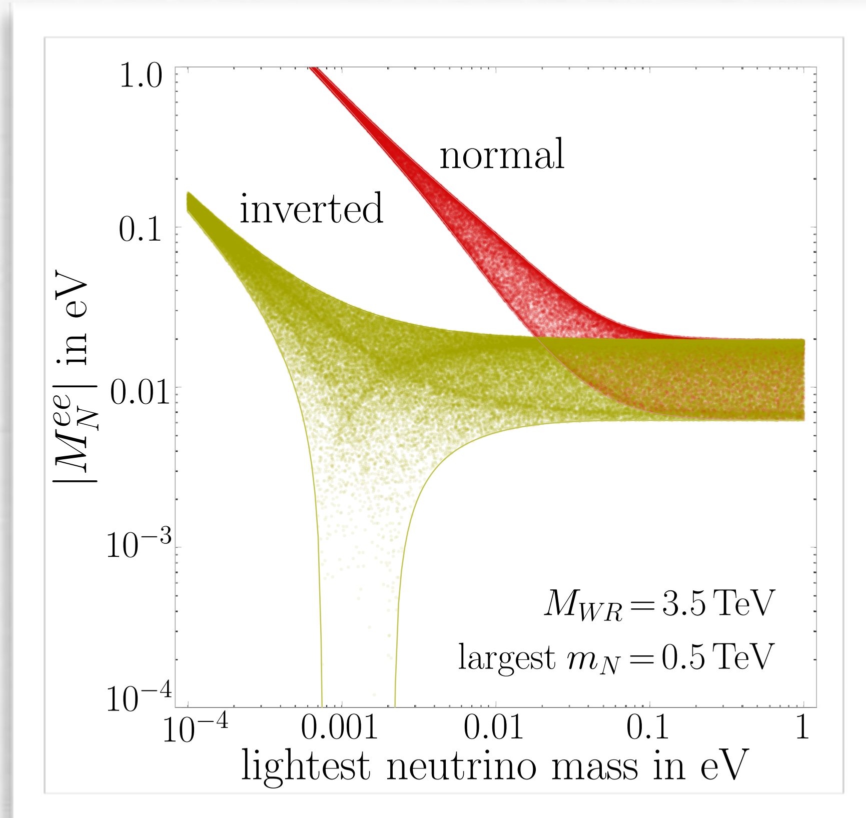
Ge, Lindner, Patra '15

Gerda, Exo, Majorana, Cuore =Heart...

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

Tello, Nemevsek, Nesti, GS, Vissani '10

Right

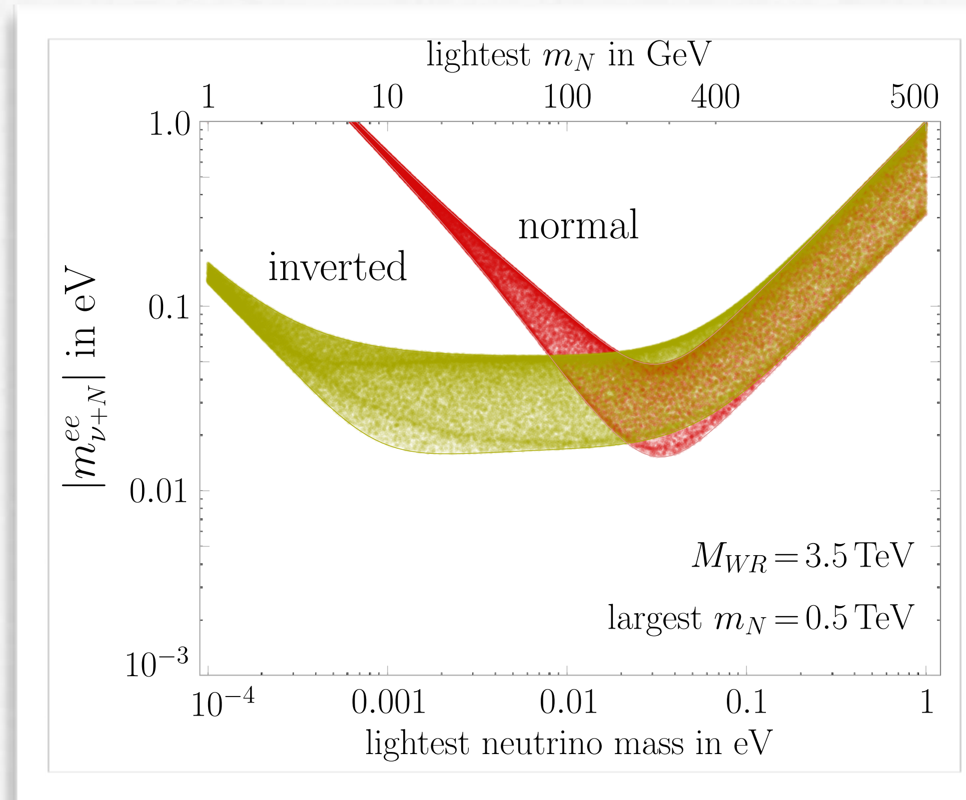


Huang, Lopez '14

Ge, Lindner, Patra '15

Awasthi, Dasgupta, Mitra '16

Left + Right



Das, Deppisch, Kittel, Valle '12

Chakraborrty, Devi, Goswami, Patra '12

Helo, Kovalenko, Hirsch '13

Effective interaction

low energy LNV

$$\frac{1}{\Lambda^5}\, n\, n\, p\, p\, e\, e \quad \rightarrow \quad \Lambda \gtrsim 10^3 - 10^4 GeV$$ LHC energies

$$\tau_{0\nu 2\beta} \gtrsim 10^{25} yr$$

compare with BNV

$$\frac{1}{\Lambda^2}\, q\, q\, q\, e \quad \rightarrow \quad \Lambda \gtrsim 10^{15} GeV$$

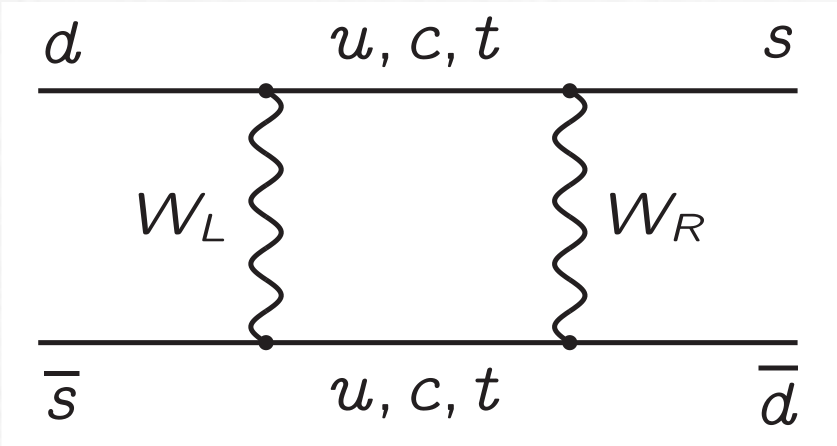
$$\tau_p \gtrsim 10^{34} yr$$

L-R scale?

Beall, Bander, Soni '81

Mohapatra, GS, Tran '83

K meson mixing



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

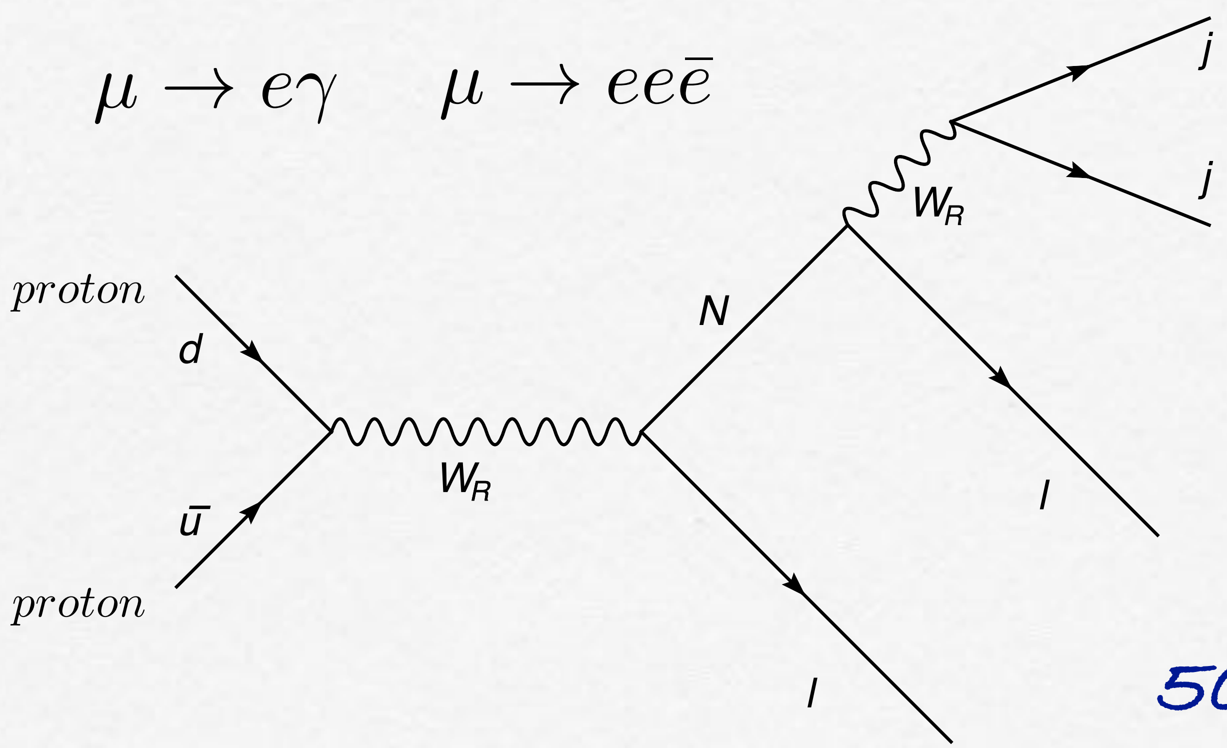
needed LHC

LNV @ colliders = same sign leptons

Keung, G.S. '83

moreover, LFV

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



probe of Majorana nature of N

50% lepton - 50 % antileptons

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

$$N = N^C$$

$$M_N = V_R m_N V_R^T$$

Ferrari et al '00

Nemevsek, Nesti, GS, Zhang '11

Vasquez '14

...

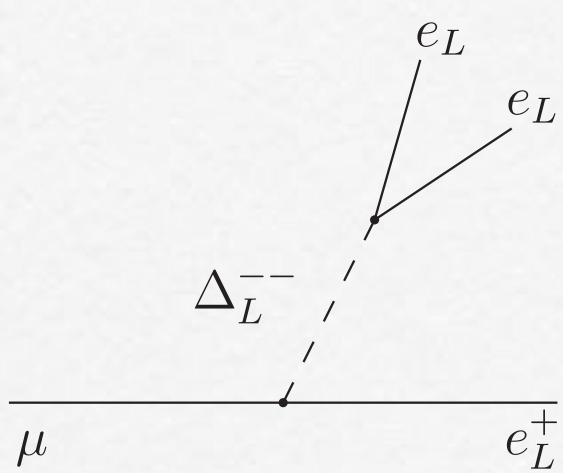
Nemevsek, Nesti, Popara '18

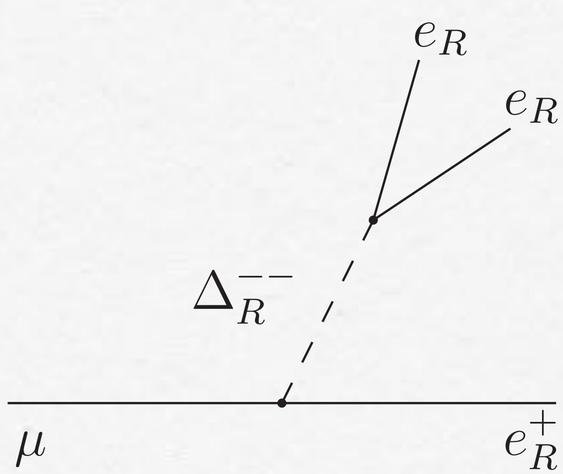
Lepton flavour violation

Cirigliano, Kurylov, Ramsey-Musolf, Vogel '04

Tello PhD thesis '12

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





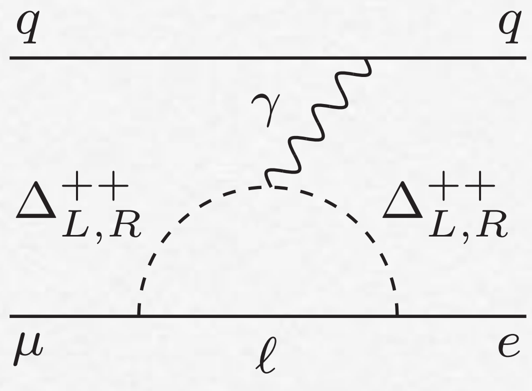
$$BR(\mu \to e e \bar{e}) = \frac{1}{2}\frac{M_W^4}{M_{W_R}^4}\left|\frac{M_N M_N}{m^2_{\Delta^{++}}}\right|^2_{e\mu}$$

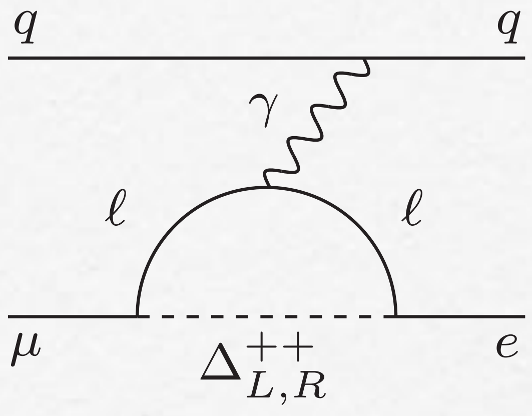
N light or degenerate

~ charm quark light

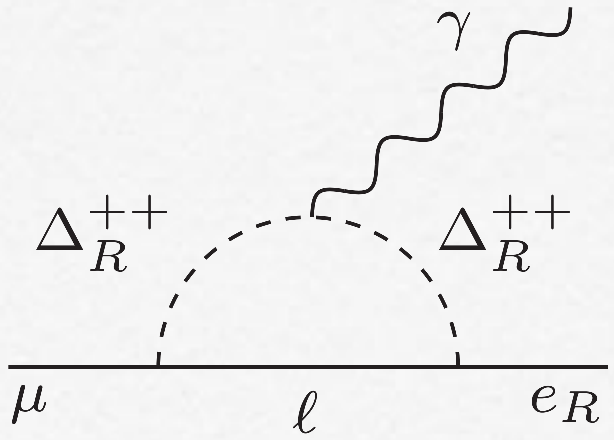
- mu - conversion: mu+x -> e + x $B_{\mu\to e} < 7\times 10^{-13}$ SINDRUM II

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

ATLAS hep-ex 1904.12679

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

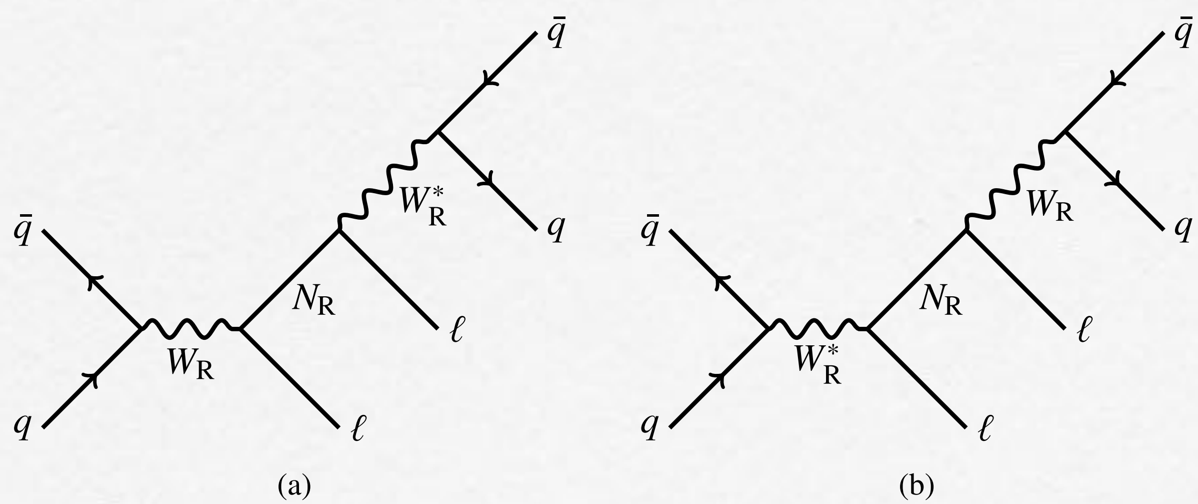
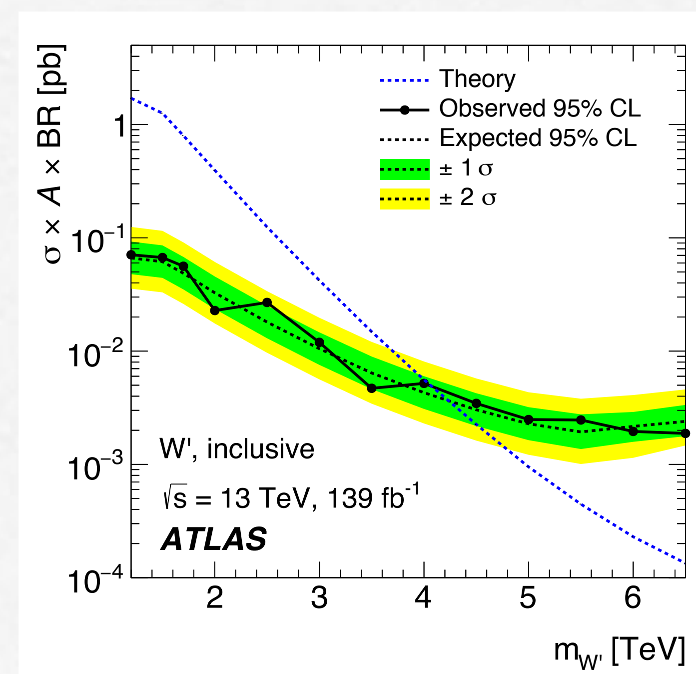


Figure 1: The KS process, for (a) the $m_{W_R} > m_{N_R}$ case and (b) the $m_{N_R} > m_{W_R}$ case.

ATLAS 1910.08447



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

di-jet $M_R > 4$ TeV

- 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)

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

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

LR = charge conjugation

Nemevsek, GS, Tello 1211.2387 (hep-ph)

$$Y_D = Y_D^T \quad \Rightarrow \quad M_D = M_D^T$$

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

central result

$$M_D = M_N \sqrt{\frac{1}{M_N} M_\nu} \qquad O = \sqrt{M_N}\sqrt{M_N^{-1} M_\nu}\sqrt{M_\nu}^{-1}$$

illustrate $V_R = V_L^*$

$$M_D = V_L^* \sqrt{m_\nu m_N} V_L^\dagger \quad \rightarrow \quad \Gamma(N_i \to W \ell_j) \propto V_{ij}^2 m_{\nu_i} \frac{m_{N_i}^2}{M_W^2}$$

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)

LR = parity

GS, Tello 1612.05503 (hep-ph)

GS, Tello 1812.03790 (hep-ph)

P: $M_D = M_D^\dagger$

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

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

$$X = X^\dagger$$

symmetric $\quad XX^* = OS\,O^T \quad$ O = orthogonal

$\downarrow$ (when S = real)

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

all fixed as in the case of C

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 $\sqrt{S}E^T = E\sqrt{S}^*$ $\quad E = E^\dagger \quad EE^T = 1$

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

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

illustrate

$$V_R = V_L$$

$$\Downarrow$$

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

manifestly order seesaw

talk by Vasquez, 21/5

case of small P breaking in the Dirac sector
- leave for questions

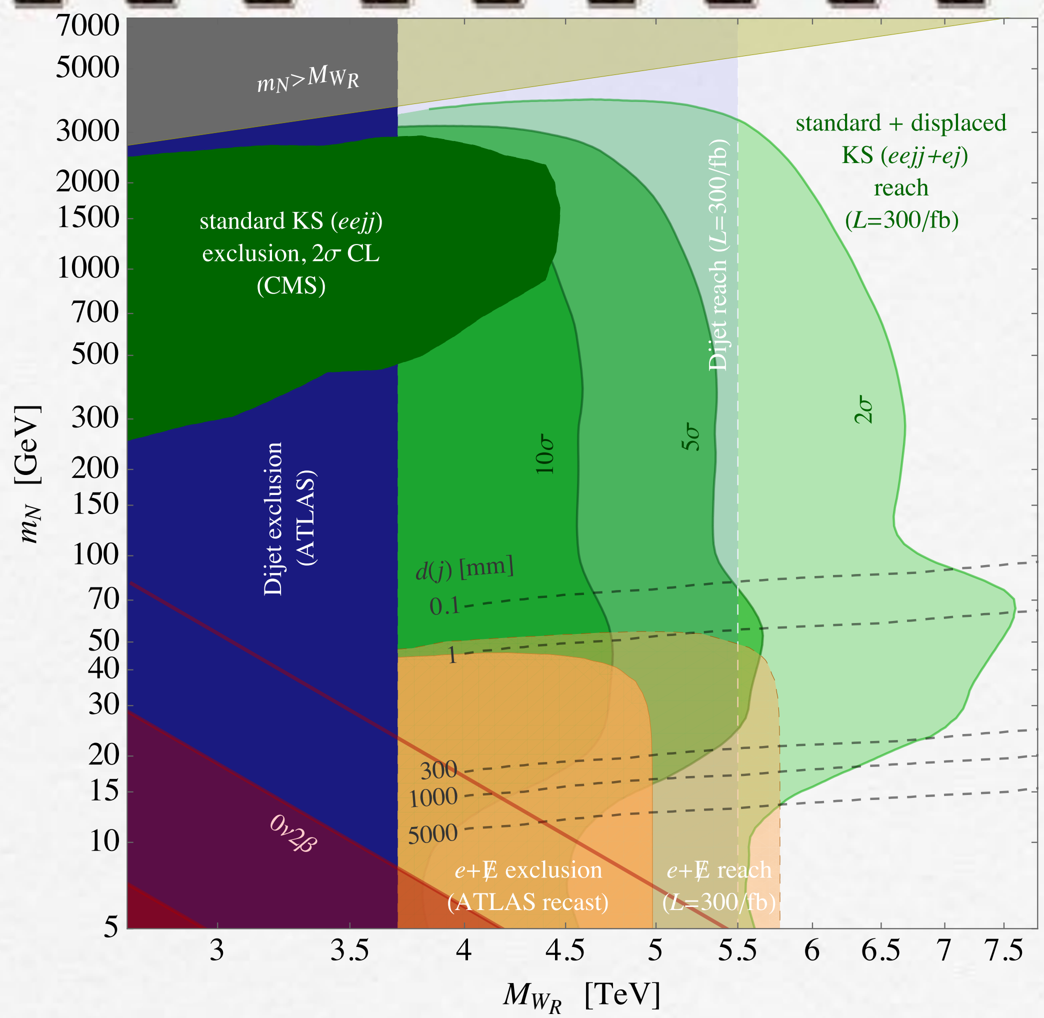
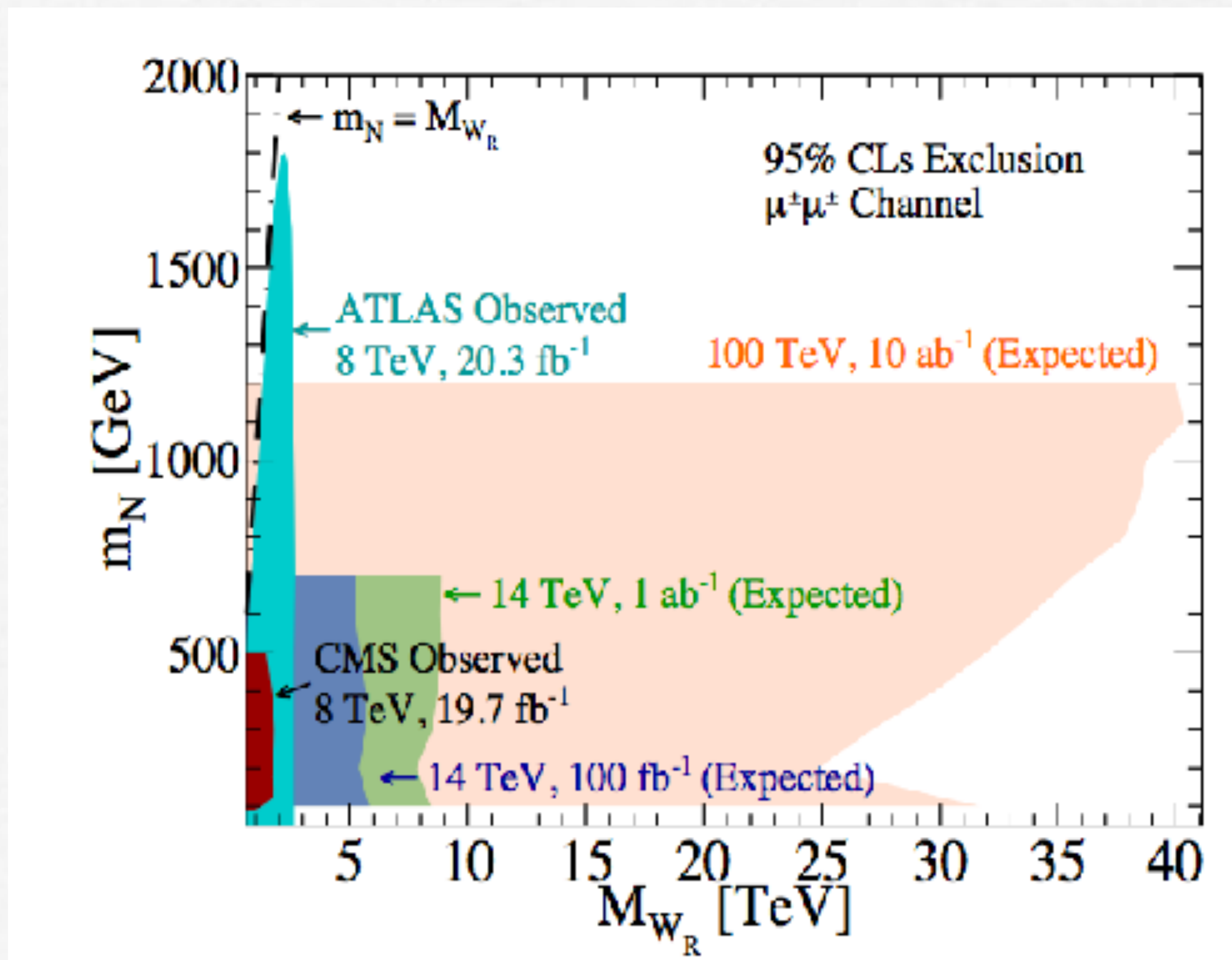


FIG. 9. Summary plot collecting all searches involving the KS process at LHC, in the electron channel. The green shaded areas represent the LH sensitivity to the KS process at 300/fb, according to the present work. The rightmost reaching contour represents the enhancement obtained by considering jet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

LHC reach

Nemevsek, Nesti, Popara 1801.05813 (hep-ph)



100 TeV collider reach

Ruiz 1703.04669 (hep-ph)

Summary

LRSM: self-contained & predictive theory of neutrino mass

SM - Higgs mechanism probe of charged fermions mass

$$\Gamma(h \to f\bar{f}) \propto m_h m_f^2$$

LRSM - Higgs mechanism probe of neutrino mass

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

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

Thank you

- 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

Broken P

no analytic solution for M_D

Nemevsek, GS, Tello - struggling

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

$$\epsilon = \tan 2\beta \, \sin\alpha \lesssim 10^{-2}$$
$$\tan\beta = v_2/v_1$$

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

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

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

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

diluters

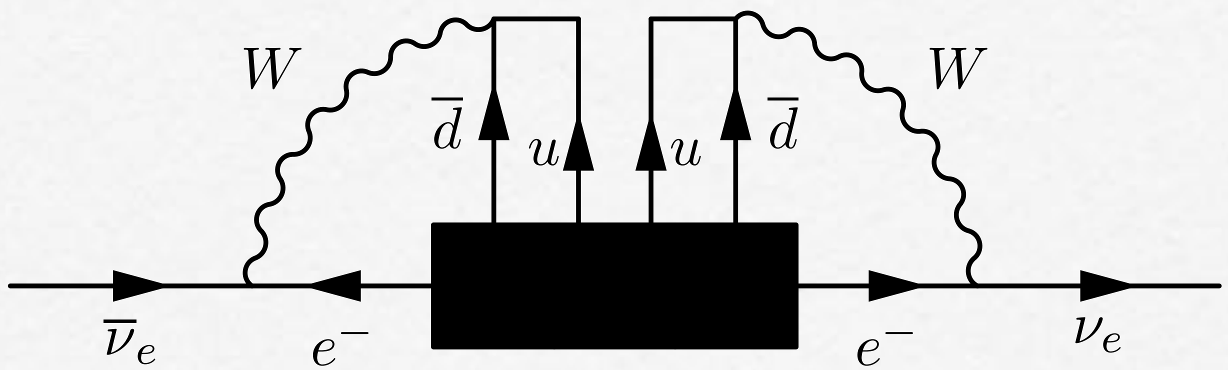
$m_{N_3} \simeq m_\pi + m_e$ electron

no LNV at colliders

neutrinoless double beta decay imminent

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

Planck scale seesaw

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

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