TeV Scale Origin of Neutrino Mass and B-L Violation

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Symmetry Tests in Nuclei and Atoms

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Two issues in neutrino mass physics

- **New Scale for neutrino mass physics**

- **Why are the neutrino mixing patterns so different from quark mixings?** (M. C. Chen talk)

Where does neutrino mass come from ?

- Charged fermion masses come from the Higgs vev:

$$m_f = h_f v_{wk} \qquad v_{wk} = < h^0 >$$

★ Discovery of the 125 GeV Higgs h^0 confirms this.

- For neutrinos, if we add ν_R to SM (new physics) and then use Higgs to get nu mass like other fermions, we get too large a mass unless $h_\nu \leq 10^{-12}$!!
- This implies new physics as source of neutrino mass beyond just adding ν_R!

Weinberg Effective operator as a clue to the new physics

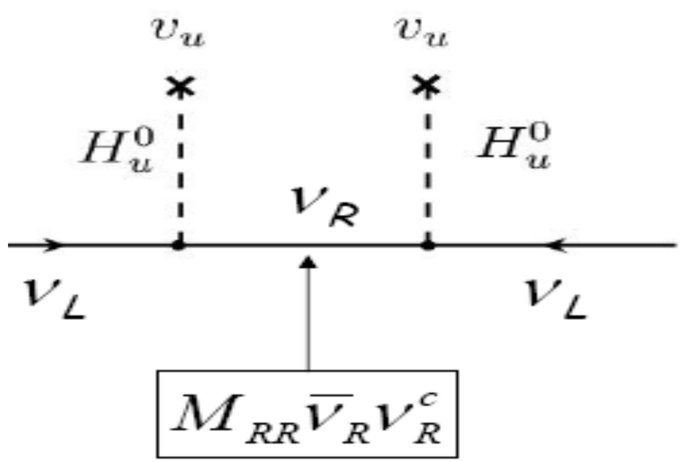
- Add effective operator to SM: $\lambda \frac{LHLH}{M}$

$$\rightarrow \quad m_\nu = \lambda \frac{v_{wk}^2}{M}$$

- $\lambda \sim 1; M$ big → $m_\nu \ll m_f$ naturally !
- **What is the Physics of M?**
- To explore this, seek UV completion of Weinberg operator

Seesaw as first step to UV completion of Weinberg Op.

- SM+ RH neutrinos ν_R but with heavy Majorana mass (Breaks B-L)



→ $$m_\nu \simeq -\frac{m_D^2}{M_{\nu_R}}$$

Minkowski'77; Mohapatra,Senjanovic;Gell-Mann,Ramond, Slansky; Yanagida; Glashow'79

- $m_D \sim m_e$ → $M_{\nu_R} \sim \mathrm{TeV}$ Testable physics!

BONUS OF SEESAW UV COMPLETION: ORIGIN OF MATTER

- Fukugita and Yanagida (1986) RH neutrino is its own anti-particle: so it can decay to both leptons and anti-leptons:
- Proposal: Heavy ν_R decays:

$$\nu_R \to L + H \quad R = (1 + \varepsilon)$$

$$\nu_R \to \bar{L} + \bar{H} \quad \bar{R} = (1 - \varepsilon)$$

- Generates lepton asymmetry: ΔL (Leptogenesis)
- Sphalerons convert leptons to baryons

(Kuzmin, Rubakov,Schaposnikov'83)

Weinberg operator, simplest but not the only way ?

- It could be other higher dim operators e.g.

$$\mathcal{O}_2 = L^i L^j L^k e^c H^l \epsilon_{ij}\epsilon_{kl}$$

$$\mathcal{O}_3 = \{L^i L^j Q^k d^c H^l \epsilon_{ij}\epsilon_{kl}, \;\; L^i L^j Q^k d^c H^l \epsilon_{ik}\epsilon_{jl}\}$$

$$\mathcal{O}_4 = \{L^i L^j \bar{Q}_i \bar{u^c} H^k \epsilon_{jk}, \;\; L^i L^j \bar{Q}_k \bar{u^c} H^k \epsilon_{ij}\}$$

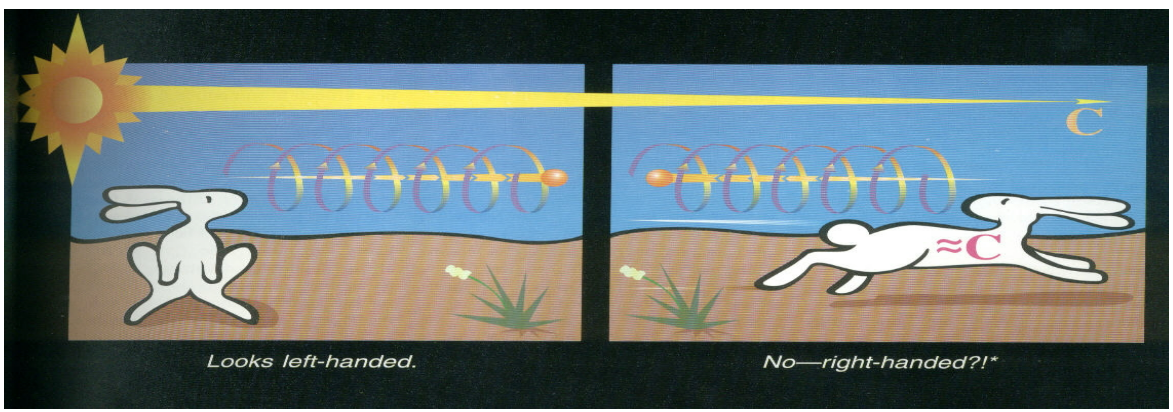
- .... (Babu, Leung'01; de Gouvea, Jenkins'07)
- Examples of models: Zee'80, Cheng, Li'80; Babu'88; Babu, Nandi,Tavartkhiladze..
- Also leads to low scale neutrino mass but not clear, if they lead to simple understanding of origin of matter

This talk:

- TeV scale left-right symmetric model of neutrino mass and origin of matter

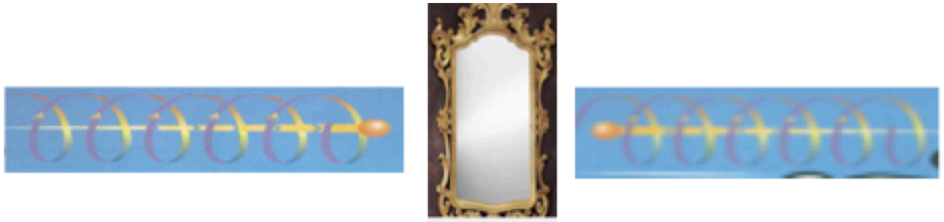
Why is Left-right symmetry compelling for nu mass?

- Theory of relativity→ massive fermions must have two helicities:



Belief was that

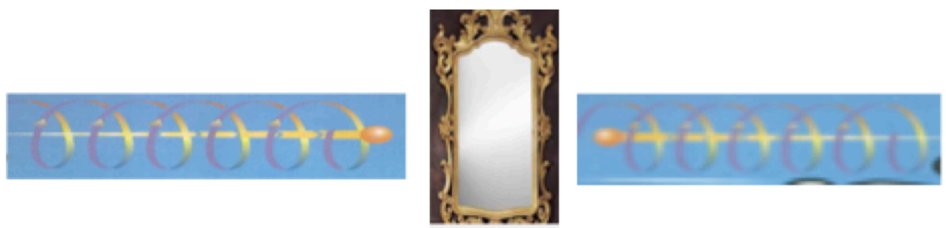
- All fermions participating in Strong, E&M, forces have mass (2 helicity states)→ explaining possibly why these forces are parity invariant.



- On the other hand, neutrino was believed to be massless and participated exclusively in weak interactions; that was considered as explaining why weak interactions violate parity.

Neutrino mass and parity

- Now that neutrinos are known to have mass, could it imply that weak interactions are really parity invariant like other forces?



- This is the basis for a simple extension of SM to make it parity symmetric and understand neutrino mass !!

Left-Right Model Basics

- Gauge group: $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$

- Fermions

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

$$L = \frac{g}{2}[\vec{J}_L{}^{\mu} \cdot \vec{W}_{\mu L} + \vec{J}_R{}^{\mu} \cdot \vec{W}_{\mu R}]$$

- Parity a spontaneously broken symmetry: $M_{W_R} \gg M_{W_L}$ (Mohapatra, Pati, Senjanovic'74-75)

Why these models are attractive ?

- New way to understand parity violation:
- A more physical electric charge formula

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

(RNM, Marshak'79,80)

- Explains small neutrino masses via seesaw:
- L-violation→ $\Delta B = 2$ (neutron-anti-neutron osc.)
- Can explain the origin of matter (see later)

New Higgs fields and Yukawa couplings

- LR bidoublet: $\phi = \begin{pmatrix} \phi_1{}^0 & \phi_2{}^+ \\ \phi_1{}^- & \phi_2{}^0 \end{pmatrix}$
- Break B-L to generate seesaw: $\Delta = \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta^+ & \Delta^{++} \\ \Delta^0 & -\frac{1}{\sqrt{2}}\Delta^+ \end{pmatrix}$

$$\mathcal{L}_Y = h\bar{L}\phi R + \tilde{h}\bar{L}\tilde{\phi}R + fRR\Delta_R + h.c.$$

$$<\Delta_R> = \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix} \qquad \phi = \begin{pmatrix} \kappa & 0 \\ 0 & \kappa' \end{pmatrix}$$

Seesaw scale is $SU(2)_R$ breaking Scale

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

$\downarrow$ v_R (ΔL=2) $\quad M_N = f v_R$

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

$\downarrow$ κ $\quad \Rightarrow \quad M_{\nu,N} = \begin{pmatrix} 0 & h\kappa \\ h\kappa & f v_R \end{pmatrix}$

$$U(1)_{em}$$

$$m_\nu \simeq -\frac{(h\kappa)^2}{M_N}$$

- If $h\kappa \sim m_e$, v_R ~ TeV, $m_\nu \sim \mathrm{eV}$

$\Rightarrow$ L-violation is TeV scale and hence testable

Type I and type II seesaw formula for neutrino masses

- . In general, the neutrino mass matrix in LR is:

$$M_{\nu.N} = \begin{pmatrix} f v_L & h\kappa \\ h\kappa & f v_R \end{pmatrix}$$

- Type II Type I

$$M_\nu = \gamma (M_{W_L}/v_R)^2 M_{RR} - m_{LR} M_{RR}^{-1} m_{LR}^T$$

- Models where either one dominates

Other arguments for TeV seesaw

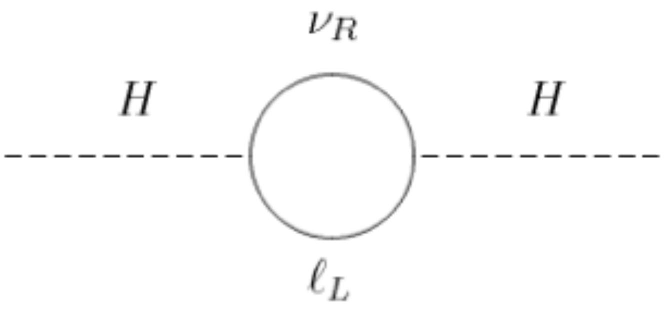
- GUT seesaw attractive but very hard to test !
- With SUSY, possible LFV signal $\mu \to e + \gamma$ for lower slepton masses – *where is susy ?*
- SUSY hinders leptogenesis→ Gravitino problem

BBN → $M_N < T_{reheat} < 10^6$ GeV (Kawasaki, Kohri, Moroi, Yatsuyanagi)

- Naturalness of Higgs:

$M_R < 7 \times 10^7$ GeV

(Vissani'97; Clarke,Foot, Volkas'15)



LR seesaw: How light can W_R Be?

- New interactions of quarks with W_R affects low energy observables e.g. K_L-K_S, ϵ, ϵ', B_s-$B_{s\text{-bar}}$,

  → M_{WR} > 2.5 TeV

(Zhang, An, Ji, RNM; Maiezza, Nemevsek,Nesti, Senjanovic; Blanke, Buras,Gemmler,Hiedsieck)

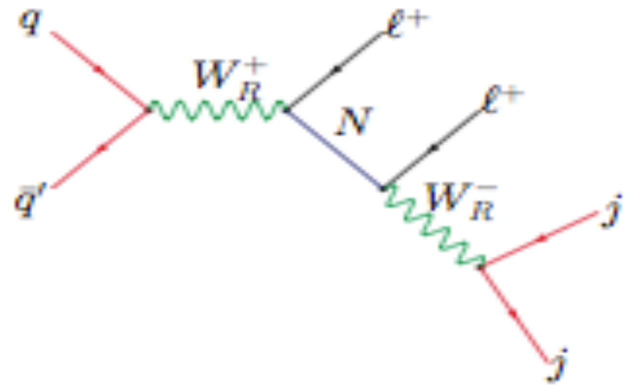
- LHC searches: W_R , N_R, Δ_R^{++} ,Z_2

$$M_{Z_2} = \sqrt{\frac{2\cos^2\theta_W}{\cos 2\theta_W}} M_{W_R}$$

(model test)

- M_{WR} > 2.8 TeV depending on N-mass

$W_{R,}$ N_R search at LHC



- Golden channel:

$$W_R \to \ell_i \ell_k j j$$

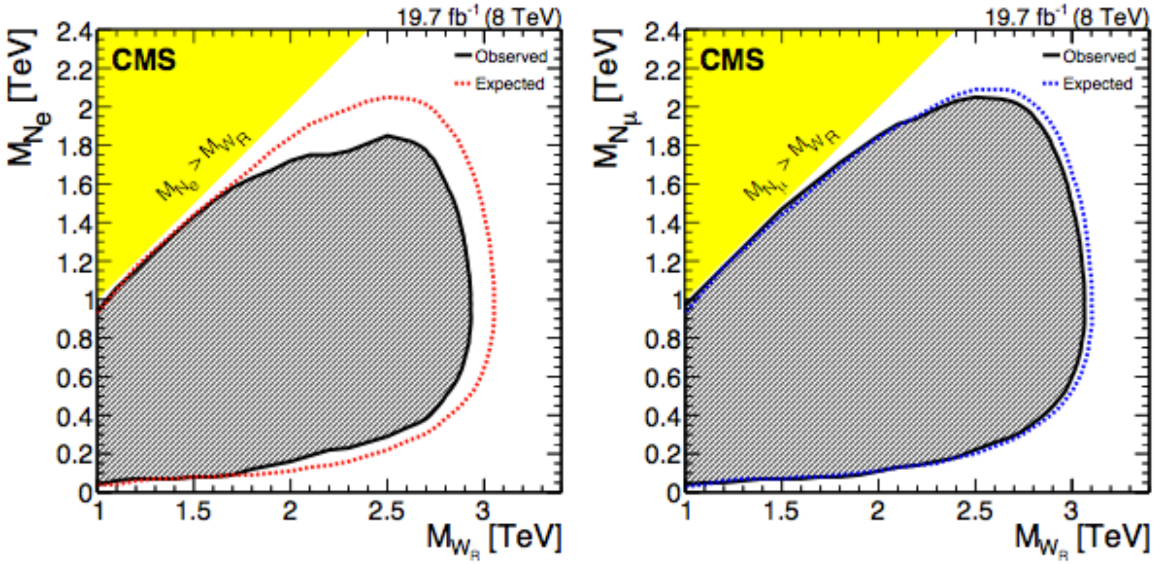
(Both like and unlike sign di-leptons) (Keung, Senjanovic'82)

- Other channels: $W_R \to jj$

$$W_R \to WZ, Wh$$

Current LHC data

- Current W_R limits from CMS, ATLAS using $\ell_i \ell_k j j$

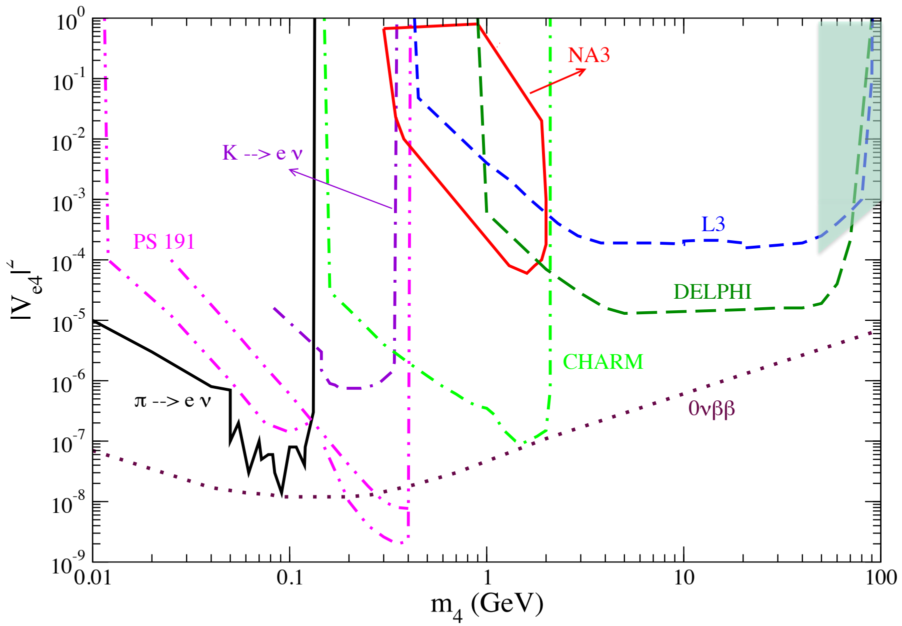


$g_L = g_R \rightarrow M_{WR} > 2.8$ TeV;

$g_L \neq g_R$ some hints at 2 TeV in the 8 TeV data.

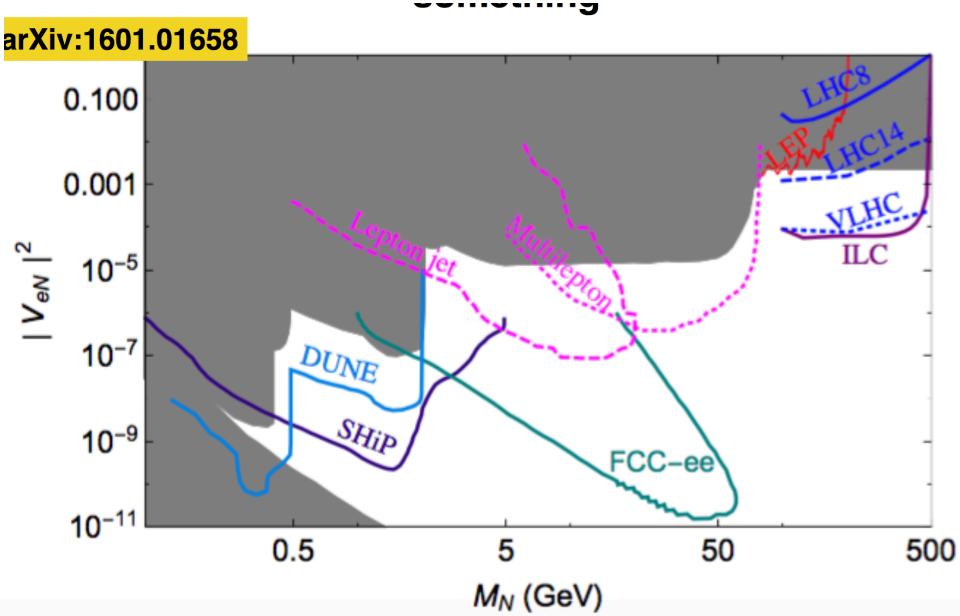
Another aspect of seesaw: N- ν mixing:

- Present limits



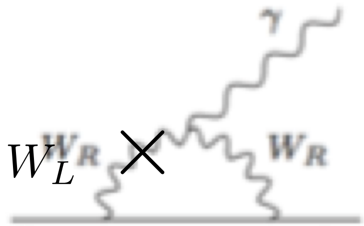
- (Atre, Han, Pascoli,Zhang)

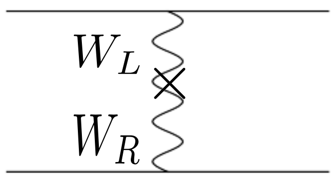
Future possibilities



(Deppisch, Dev and Pilaftsis)

Neutron edm and constraints on M_{W_R}

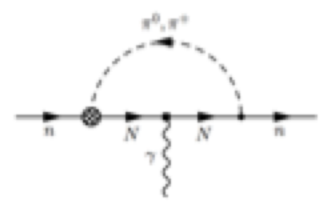
- W_L-W_R mixing phase leads to two kinds of operators: expect larger edm compared to SM
- 



$$\mathcal{H}_{LR} = \frac{\sqrt{2} G_F m_d e}{3} c_{LR} \bar{u} \sigma_{\mu\nu} \gamma_5 u F^{\mu\nu}$$

$$\mathcal{H}_{LR} \simeq 3\, G_F\, c_{LR} \left[\left(\overline{u} \gamma_5 u \right) \left(\overline{d} d \right) - \left(\overline{u} u \right) \left(\overline{d} \gamma_5 d \right) \right]$$

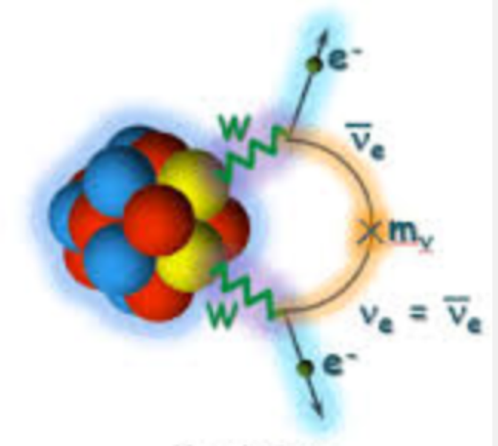
$$c_{LR} = \mathrm{Im} \left(V_{Lud} V^*_{Rud}\, \xi \right) .$$

- Long distance contribution from 4-quark op. dominates  +… (chpt)

  → M_{WR} > 3 TeV; (Maiezza,Nemevsek'14; Xu,An, Ji'10)

A crucial seesaw prediction: Majorana neutrinos

- Predicts neutrinoless double beta decay:



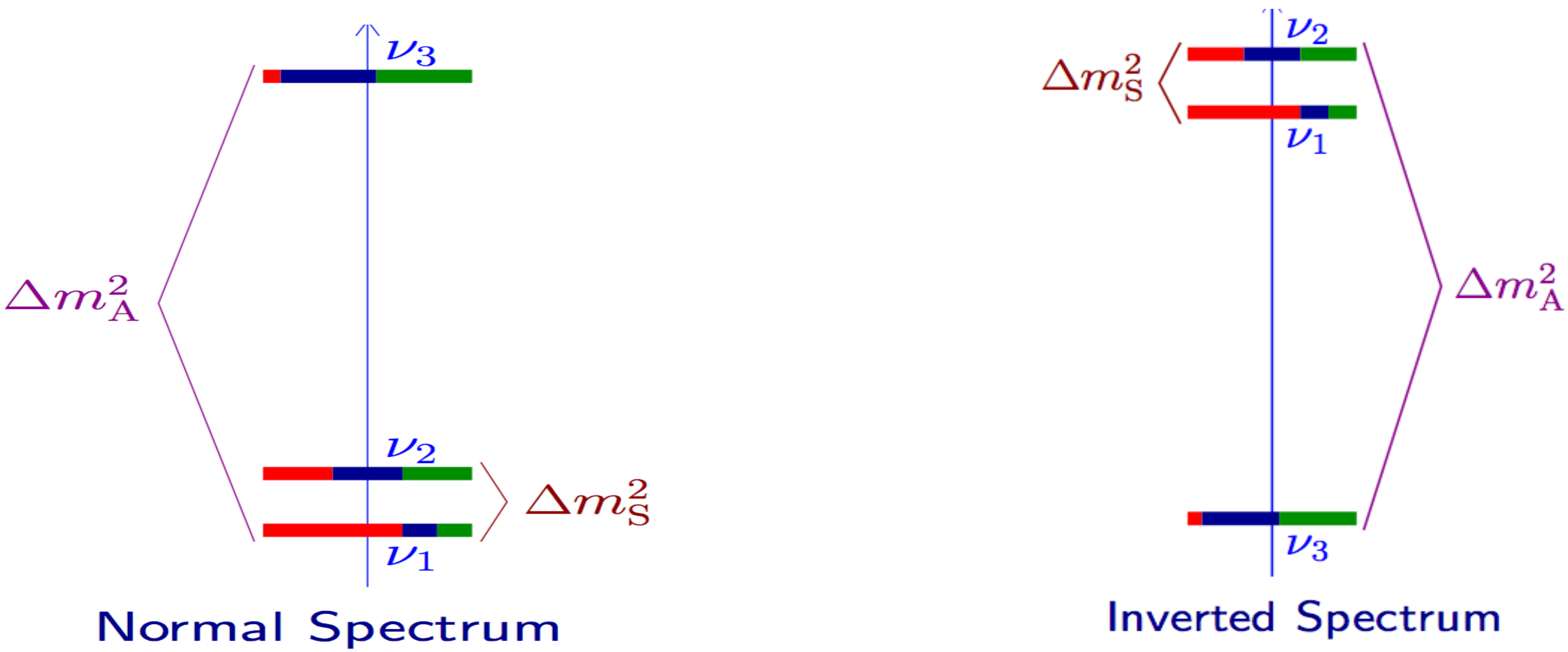
- Generic neutrino mass contribution (SM seesaw)

+New contributions from new physics

- $\beta\beta_{0\nu}$ as a key barometer of new physics

Neutrino mass contributions to $\beta\beta_{0\nu}$ decay without LR

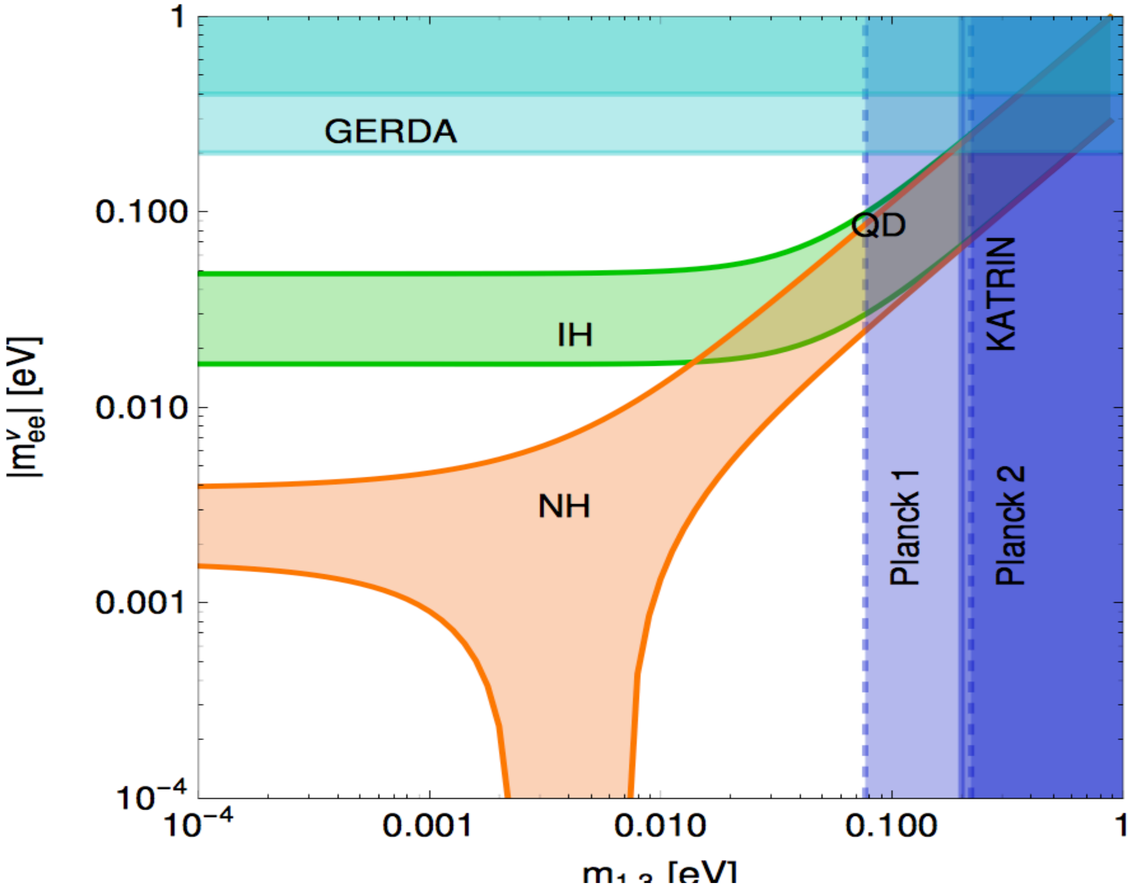
- Depends on mass ordering: inverted vs normal



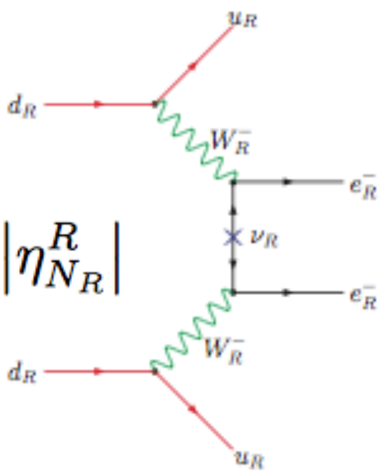
- $T^{0\nu}_{1/2}(\mathrm{Ge76}) > 3.0 \times 10^{25}$ yr GERDA $T^{0\nu}_{1/2}(\mathrm{Xe136}) > 1.1 \times 10^{26}$ yr Kamland-Zen
- $T^{0\nu}_{1/2}(Xe136) \geq 1.1 \times 10^{25} yrs$ Exo Future $>10^{28}$ yrs

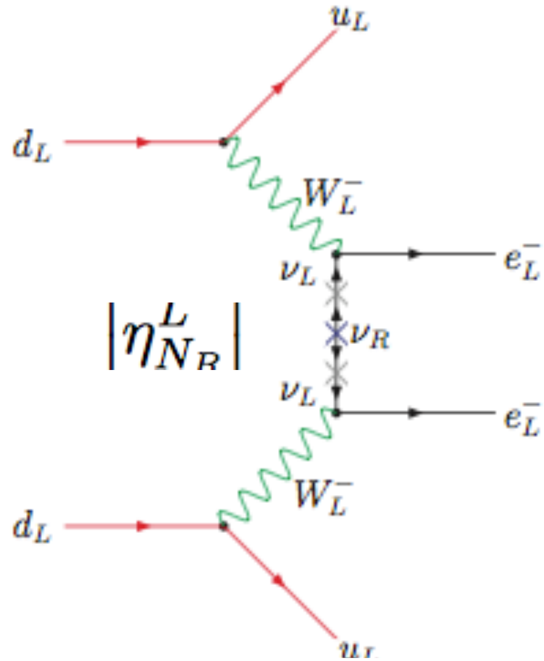
Predictions (pure nu mass)

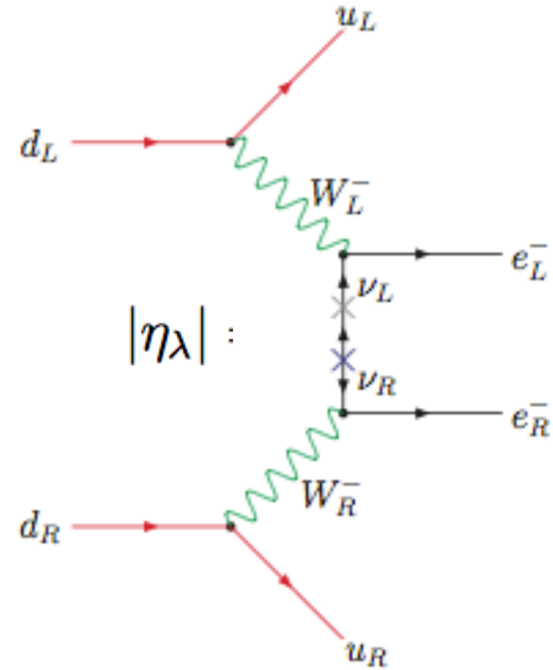
- .

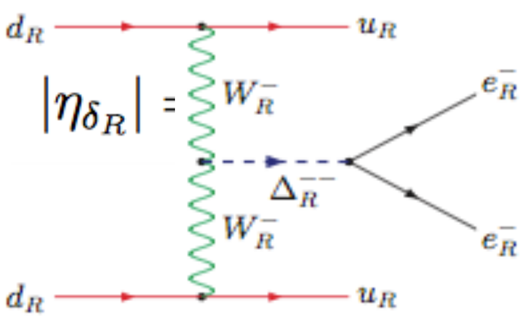


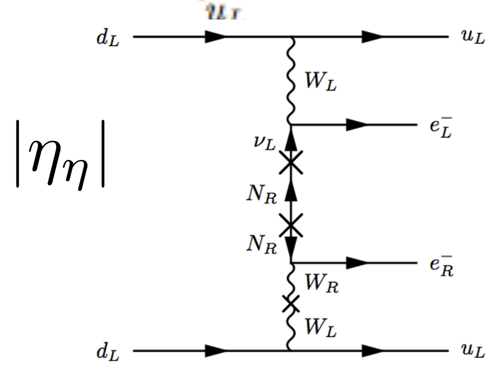
New contributions to $\beta\beta_{0\nu}$ in LR seesaw











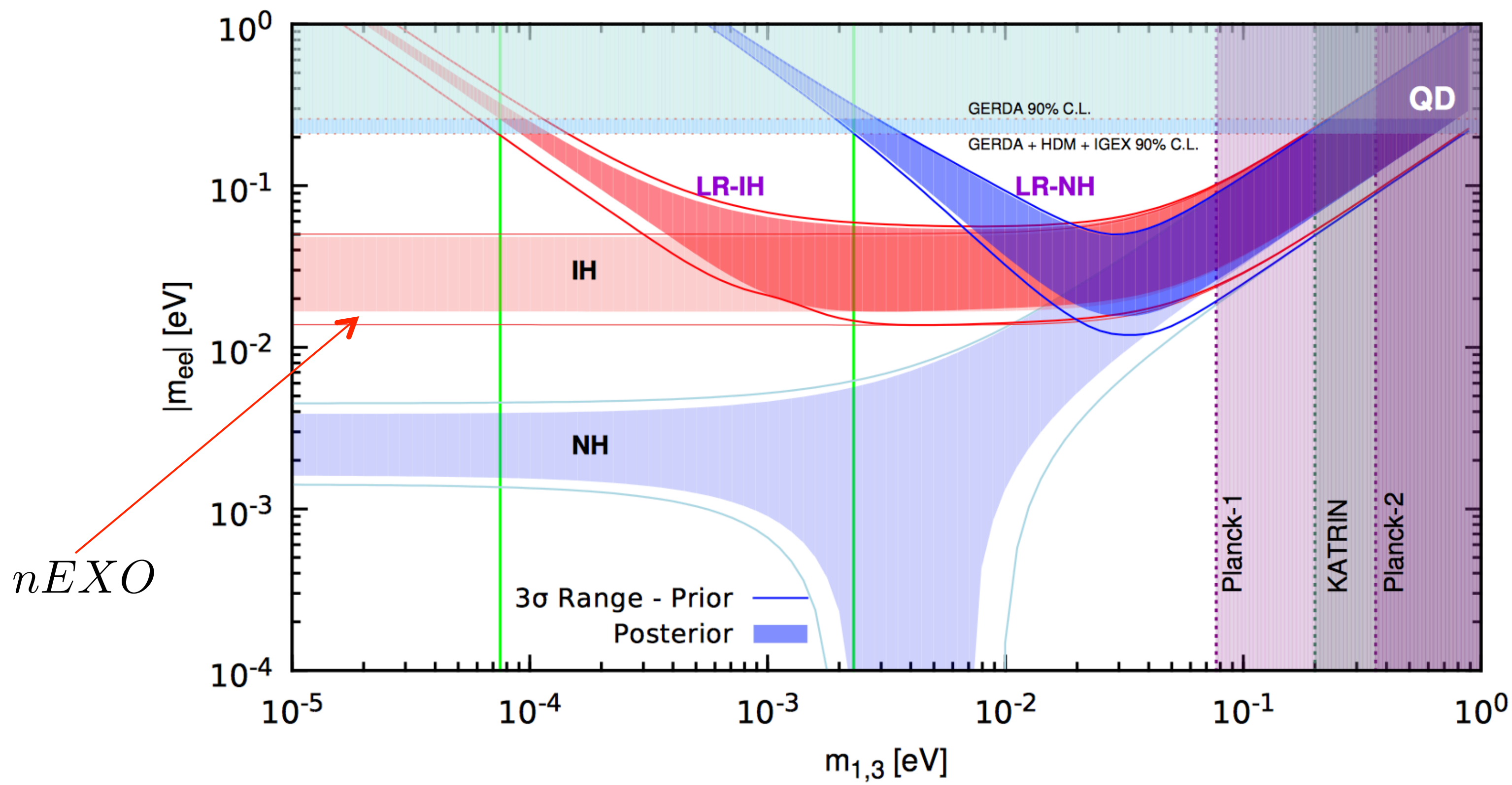
(b) $\mathcal{A}_\eta$

Current expectations for $M_{W_R} = M_N = 1$ TeV

mechanism	amplitude	current limit
light neutrino exchange ($\mathcal{A}_\nu$)	$\frac{G_F^2}{q^2} \left\| \boldsymbol{U_{ei}^2 m_i} \right\|$	0.36 eV
heavy neutrino exchange ($\mathcal{A}_{N_R}^L$)	$G_F^2 \left\| \frac{\boldsymbol{S_{ei}^2}}{\boldsymbol{M_i}} \right\|$	7.4×10^{-9} GeV^{-1}
heavy neutrino exchange ($\mathcal{A}_{N_R}^R$)	$G_F^2 m_{W_L}^4 \left\| \frac{\boldsymbol{V_{ei}^{*2}}}{\boldsymbol{M_i m_{W_R}^4}} \right\|$	1.7×10^{-16} GeV^{-5}
Higgs triplet exchange ($\mathcal{A}_{\delta_R}$)	$G_F^2 m_{W_L}^4 \left\| \frac{\boldsymbol{V_{ei}^2 M_i}}{\boldsymbol{m_{\delta_R^{--}}^2 m_{W_R}^4}} \right\|$	1.7×10^{-16} GeV^{-5}
λ-mechanism ($\mathcal{A}_\lambda$)	$G_F^2 \frac{m_{W_L}^2}{q} \left\| \frac{\boldsymbol{U_{ei} T_{ei}^*}}{\boldsymbol{m_{W_R}^2}} \right\|$	8.8×10^{-11} GeV^{-2}
η-mechanism ($\mathcal{A}_\eta$)	$G_F^2 \frac{1}{q} \left\| \tan\xi \sum_i \boldsymbol{U_{ei} T_{ei}^*} \right\|$	3.0×10^{-9}

- Barry, Rodejohann'13

Predictions for a specific model with type II seesaw



M_{WR} =2 TeV

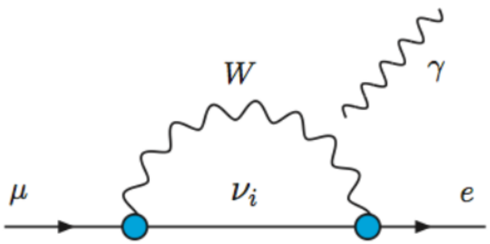
(Ge, Lindner, Patra'2015; Dev, Goswami, Mitra, Rodejohann'2013; Awasthi,Dasgupta,Mitra'16)

Some Important lessons

- Observation of $\beta\beta_{0\nu}$ at the level of 20 to 30 meV does not mean inverse hierarchy- could be W_R effect.
- Suppose long base line→ NH, any signal of $\beta\beta_{0\nu}$at this level would imply new particle effect e.g. WR.
- Must find ways to disentangle heavy particle effects from nu exchange

Lepton Flavor violation signals of WR

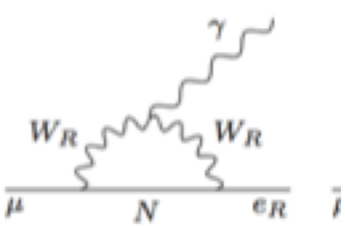
- Small neutrino mass in SM (without LR)→

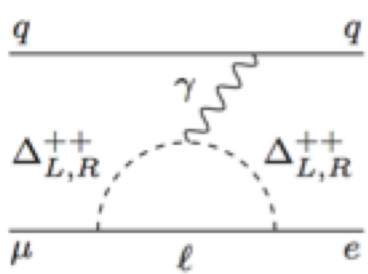


$BR(\mu \to e\gamma)$ negligible as are

$\mu \to 3e,\ \mu \to e$ BR

- LR model→ new graphs:

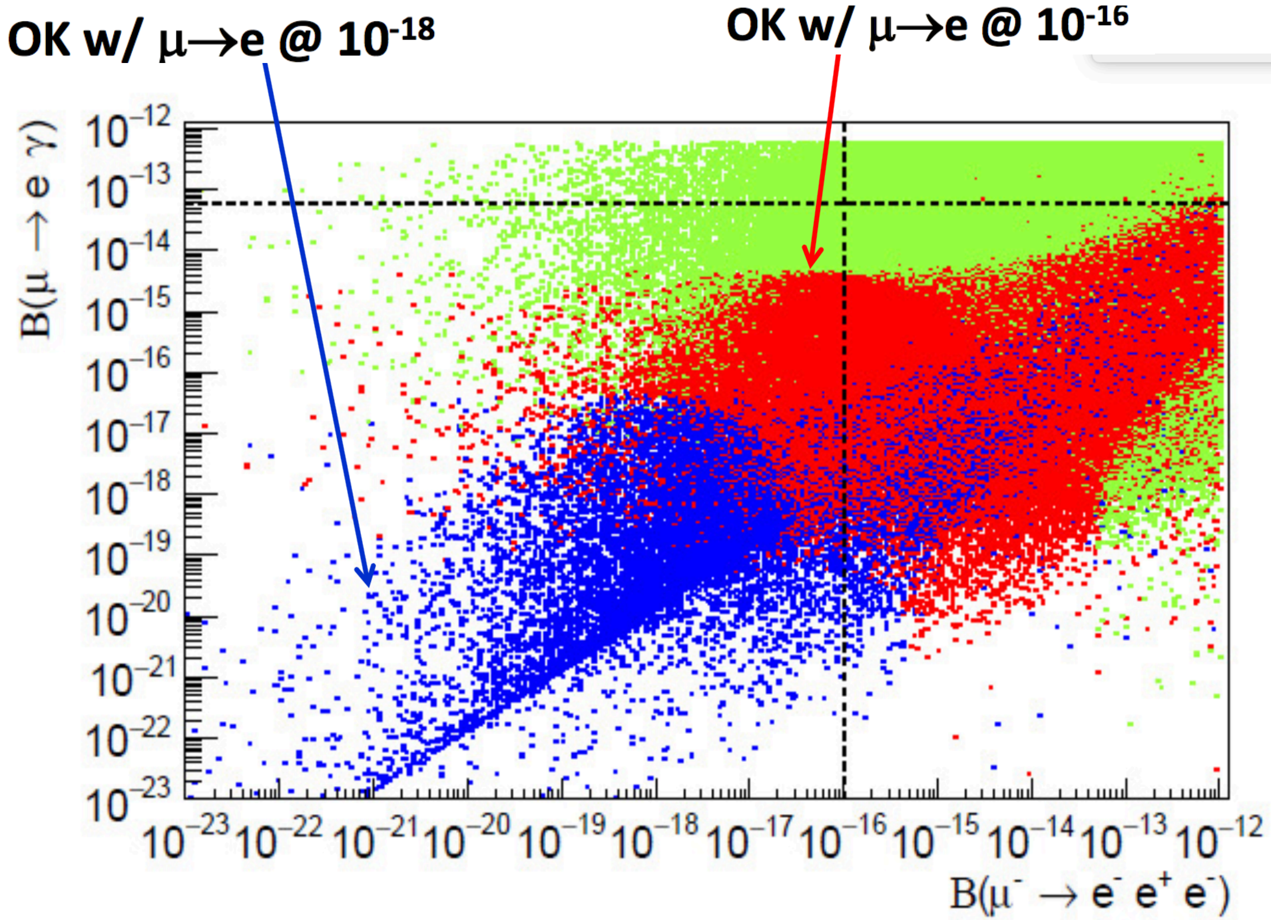




Correlated predictions

$M_N < 10\mathrm{TeV}$

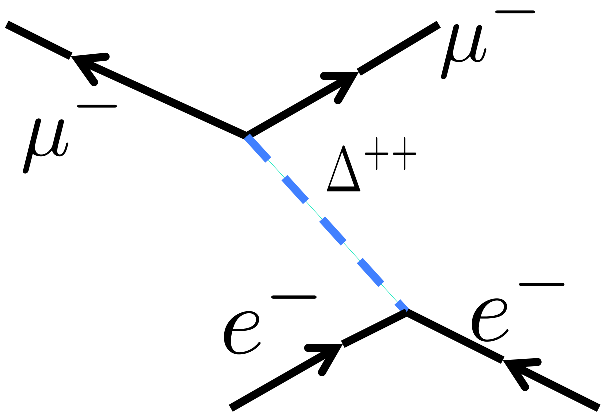
$M_{WR} = 5\ \mathrm{TeV}$



Hewett, Rizzo, deBlas, Reuter'16; Bora, Dasgupta'16

Muonium-anti-muonium oscillation

- A signature of doubly charged Higgs boson Δ^{++}



$$\mu^+ e^- \to \mu^- e^+$$

- Limits from PSI: $G_{M-\bar{M}} \leq 3 \cdot G_F \cdot 10^{-3}$ (Willmann et al'98)
- TeV Δ^{++}, expectations are at that level.

Leptogenesis constraints on WR scale via N-decay

- Final baryon asymmetry $\frac{n_B}{n_\gamma} \sim 10^{-2} \epsilon_{CP} \kappa_{eff}$
- In LR, $\kappa_{eff} \propto \frac{\Gamma_D/\Gamma_S}{1+\Gamma_D/\Gamma_S} \ll 1$

$\Gamma_D \propto Y^2$

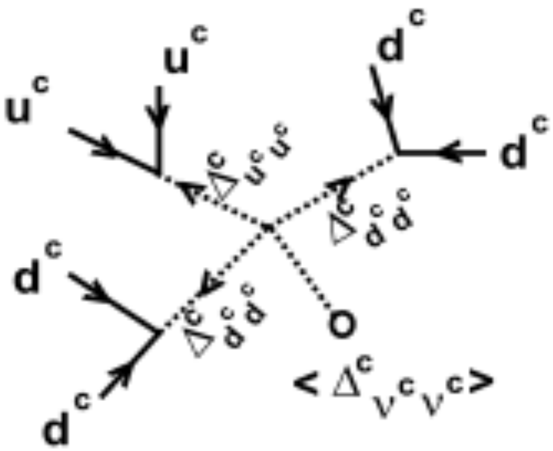
$\Gamma_S \propto M_{W_R}^{-4}$

- Given Y, Washout increases as M_{WR} decreases:
- Generic small Y-models: M_{WR} >18 TeV (Frere,Hambye, Vertongen'09)

Larger Y with nu fits: M_{WR} > 10 TeV (Dev, Lee, RNM.'14)

From L-violation to B-violation via B-L

- Embed $SU(3)_c xU(1)_{B-L}$ → $SU(4)_C$; unifies quarks leptons: lead to observable neutron oscillation



$$\frac{1}{M^5} u_R d_R d_R u_R d_R d_R$$

(RNM, Marshak'80)

- Observable for TeV scale seesaw

Why searching for nnbar important?

- If NNbar is observed, then leptogenesis cannot work since NNbar interactions will be in equilibrium and erase all baryons !!

Free neutron oscillation probe

- Define free oscillation time $\tau_{n\bar{n}} = \dfrac{\hbar}{\delta m_{n\bar{n}}}$
- Probability of transition in vacuum: $P_{n\to\bar{n}} \approx \left(\dfrac{t}{\tau_{n\bar{n}}}\right)^2$

  $\Delta M \approx 0$
- Figure of merit: # of $\bar{n}$ = flux of n $P_{n\bar{n}}$ (running time)
- Current direct search limit **ILL** $\tau > 8.6 \times 10^7$ sec

  (Baldo-ceolin et al'94)

→ $\delta m_{n\bar{n}} < 7 \times 10^{-33}$ GeV ; ESS plan for a new search

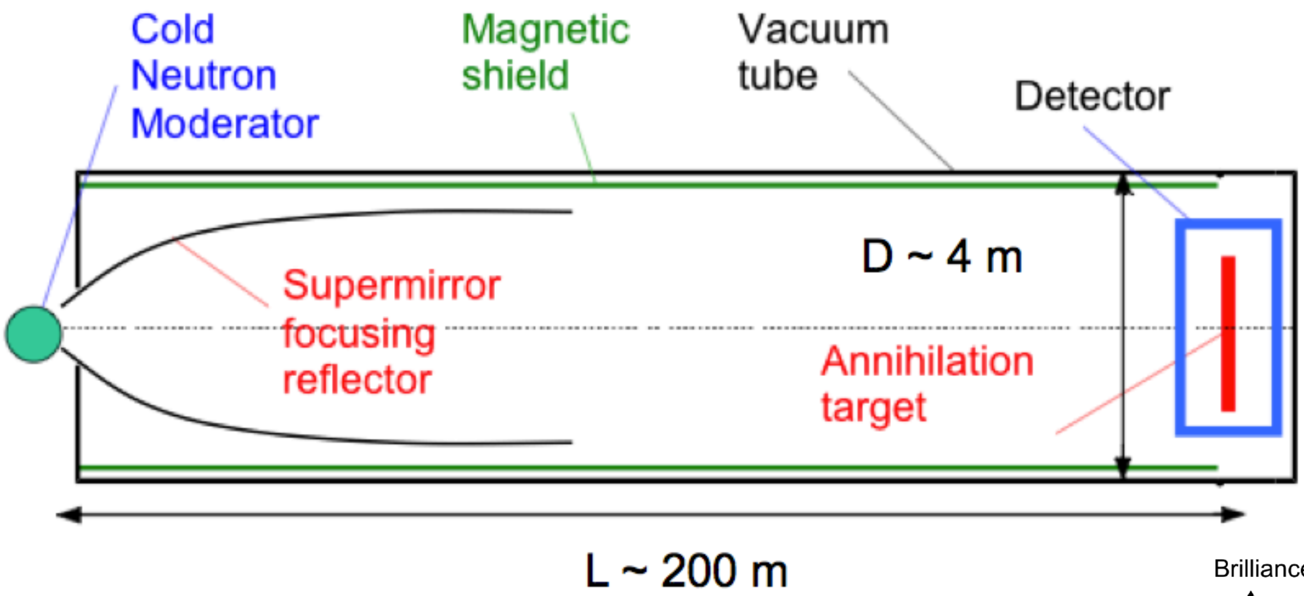
Summary

- TeV scale Left-Right theory-a compelling model for neutrino mass with testable collider signals (W_R, Z', N, Δ_R^{++}).
- observable LFV, $\beta\beta_{0\nu}$ and NEDM
- Leptogenesis bound on W_R→ *M_{WR}> 10 TeV*
- Evidence for W_R < 10 TeV or neutron oscillation will rule out leptogenesis scenario.
- Should provides new impetus to search for $n-\bar{n}$

Thank you for your attention !

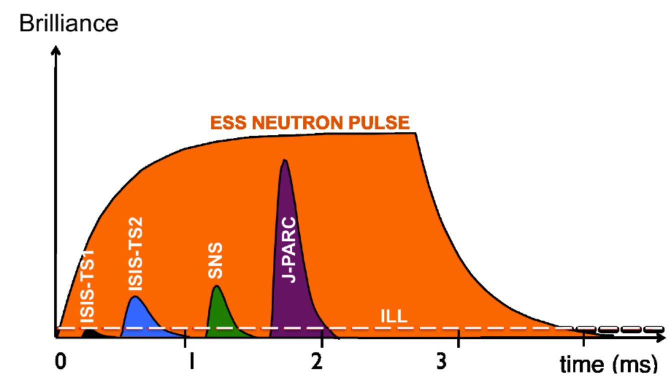
Plan for a new expt at ESS

- Layout: horizontal cold neutron beam



~factor of 500 in rate over ILL

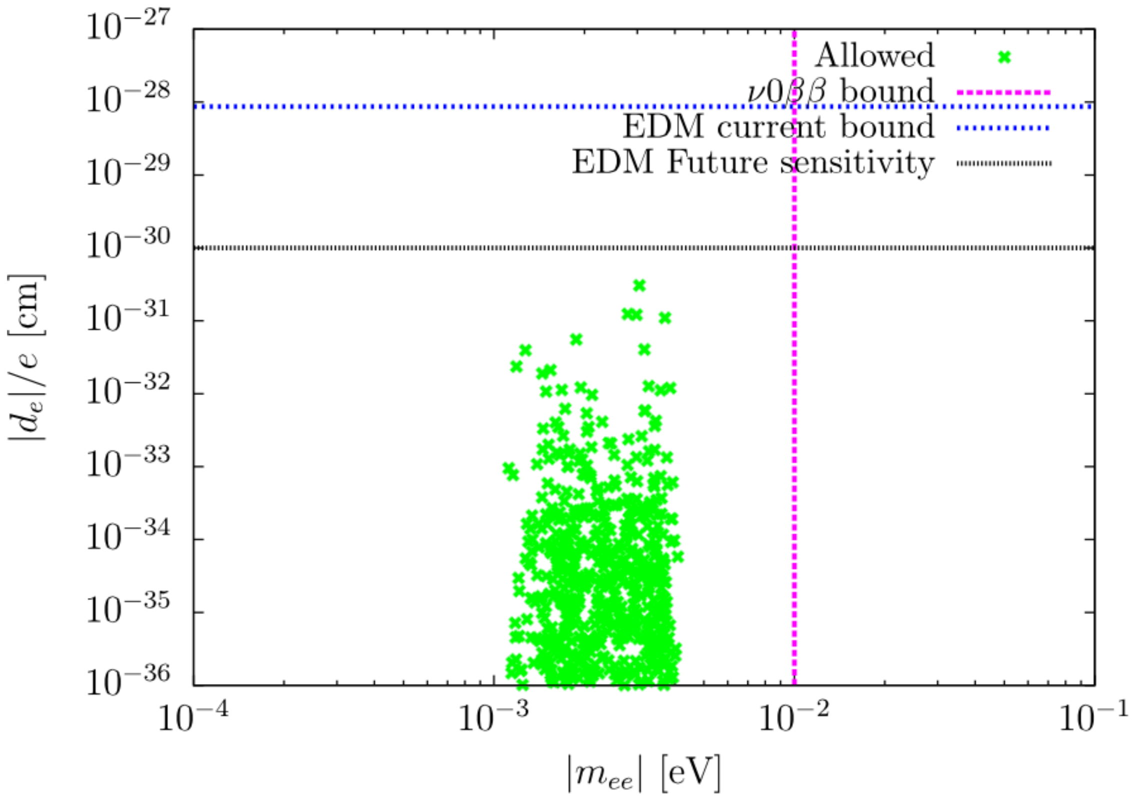
- < Flux>~ 10^{15} n/cm^2 sec.
- V_n ~700m/s
- arXiv:1410.1100 (Phys. Reports'2016)



Leptogenesis and lepton edm

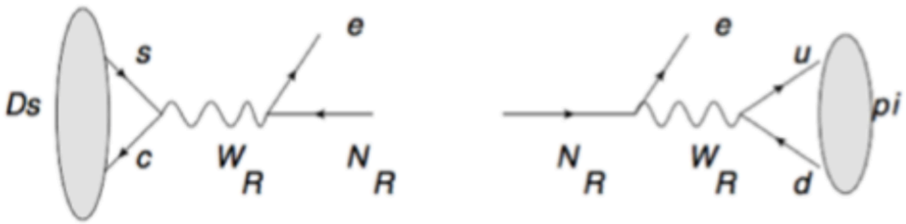
- Leptogenesis needs leptonic CP violation:
- Testable in long base line nu-oscillation searches (DUNE)
- Electron edm for inverse seesaw case

(Abada, Toma'16)

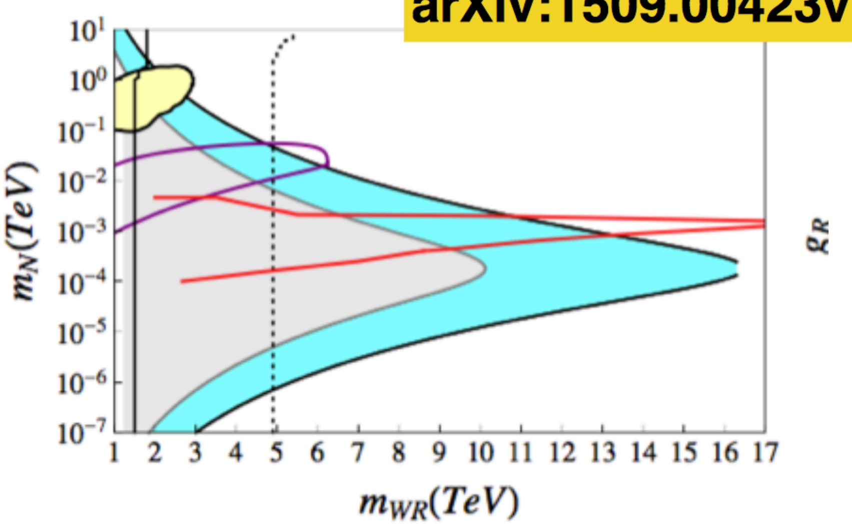


SHIP Experiment- light N

- Helo, Hirsch,Kovalenko



arXiv:1509.00423v1



WR and N mass reach

- (Deppisch, Dev, Pilaftsis)