TeV Scale Lepton number Violation and Origin of matter

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Quantization of the Yang-Mills Field*

R. L. ARNOWITT AND S. I. FICKLER†‡
Syracuse University, Syracuse, New York

(Received March 12, 1962)

Recent efforts in quantum field theory have given rise to increased interest in nonlinear, gauge-type field theories. In this paper, we examine the Yang-Mills field, which is a theory of this type, which lies between electrodynamics and general relativity in complexity. The quantum Yang-Mills field is introduced to satisfy the requirement of invariance under isotopic phase transformations of the second kind. The theory

V. QUANTIZATION IN THE GAUGE $b_3^a=0$

The radiation gauge possesses the drawback that a closed form solution of the constraint equations (for the desired variables) is not obtainable. It is thus not clear whether meaningful operator relationships exist. In this section, we examine an alternate gauge condition[18]:

$$b_3^a=0. \tag{5.1}$$

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Yang-Mills Field: A Canonical Quantization Approach. III*

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(Received 17 May 1971)

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s scalar particle makes its appearance in the covariant-

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One-Loop Diagrams in Yang-Mills Theory*

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- Origin of matter is a fundamental problem of cosmology and particle physics.

- Discovery of neutrino mass has led to widespread belief that lepton number is not good symmetry of nature and may provide a way to understand the origin of matter !

- The goal of the talk is to explore if these ideas are testable at the LHC and future colliders.

Lepton number violation and neutrino mass

- Neutrino masses are now known to be small ? How do we understand its smallness ?
- Discovery of 125.5 GeV Higgs h^0 has "solved" the mass problem for quarks and charged leptons !! $m_f = h_f v_{wk}$ $v_{wk} = < h^0 >$
- This does not, however, solve the neutrino mass problem, since $h_\nu v_{wk}$ is a trillion times larger than observed neutrino masses for $h_\nu \sim 1$

Weinberg Effective operator as a clue

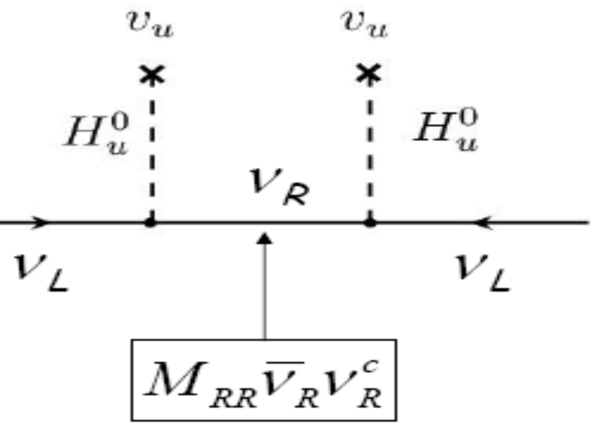
- Add effective operator to SM: $\lambda \frac{LHLH}{M}$
- After symmetry breaking $m_\nu = \lambda \frac{v_{wk}^2}{M}$
- M is BSM physics scale and arbitrary; can be large $M \gg v_{wk} \rightarrow \text{small } m_\nu$
- *Weinberg operator breaks lepton number*

So what is the Scale of L-violation M ?

- Important to know to test this idea
- Usual lore: $$m_\nu = \lambda \frac{v_{wk}^2}{M}$$
- Neutrino osc data→ m_ν << eV
- So if $\lambda \sim 1; M \sim 10^{14}$ GeV (Beyond reach!)
- Dimensional analysis arguments however can be quite misleading !!
- To explore true L violation scale, UV completion of Weinberg operator essential (build models) !!

Seesaw as step towards UV completion of Weinberg Op.

- Add right handed N_R and a Majorana mass for it: → Weinberg operator (*Seesaw mechanism)*:



$$m_\nu \cong -\frac{h_\nu^2 v_{wk}^2}{M_R}$$

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

- Majorana mass of N → L violation
- Could Majorana N be accessible (~TeV) ?

Bonus from Seesaw UV completion: Leptogenesis 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:

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

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

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

(Kuzmin, Rubakov,Schaposnikov'83)

- Related to neutrino mass and hence attractive; motivates search for CP violation in nu-oscillations !!

Can seesaw and hence leptogenesis scale be TeV's ?

- Search for explicit UV complete models
- Guiding principle in this search

(i) Existence of N should be predicted by theory

(ii) Seesaw scale should be related to symmetry

- Two simple theories that provide answers:

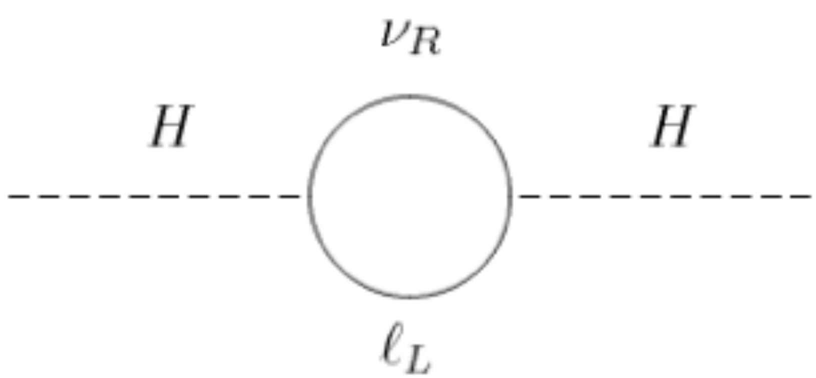
(i) Left-right model where N is the parity partner of ν_L and seesaw scale is $SU(2)_R$ scale could be TeV

(ii) SO(10) GUT where N+15 SM fermions =16 spinor and seesaw scale = GUT scale. *(Hard to test)*

General arguments for lower Seesaw scale

- Naturalness: Correction to Higgs mass from RHN Yukawa

$$\delta m_h^2 \simeq$$



$$\leq 1 \ \mathrm{TeV}^2$$

→ $M_R < 7 \times 10^7$ GeV (not a GUT scale)

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

SUSY+Leptogenesis also prefer low scale seesaw

- For leptogenesis to occur, $M_N < T_{reheat}$;

- Gravitino overclosing prefers that $T_{reheat} < 10^6$ GeV (Kohri et al.)

→ Hence preference of leptogenesis for lower seesaw scale !!

This talk: TeV Left-Right seesaw

- LR: A “natural” TeV scale theory for neutrinos
- SUSY LR requires few TeV scale L-violation in minimal models
- How to probe this TeV scale theory in colliders
- Leptogenesis with TeV scale $\not{L}$ and constraints

Left-Right Model Basics

- LR 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 understanding parity violation:
- A more physical electric charge formula
- Explains small neutrino masses via seesaw:
- Solves strong CP problem without axion:
- With supersymmetry, provides a naturally stable dark matter (automatic R-parity)
- Can explain the origin of matter (see later)

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) $M_N = f v_R$

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

$\downarrow$ κ

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

Seesaw

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

- If $v_R \sim$ TeV, L-violaion is TeV scale $m_\nu \simeq -\frac{(h\kappa)^2}{M_N}$

Minimal SUSY left-right requires low scale W_R

- Supersymmetrize this minimal LR seesaw model
- First consequence: Tree level global minimum violates electric charge: $< \Delta^{++} > \neq 0$

(i) unless R-parity is broken (Kuchimanchi, R. N. M.'94, '95)

(ii) W_R mass has an upper limit: $M_{W_R} \leq \frac{M_{SUSY}}{f}$

i.e. W_R is in TeV range !

However due to RPV, neutrino masses get complicated !

Minimal SUSYLR with exact R-parity

- Extend with a singlet and add one loop → RP exact !

(Babu, R. N. M.'08; Babu, Patra'14; Basso, Fuks, Krauss, Porod'15)

- *Upper bound on W_R required to conserve electric charge;*

- *Implies a light (< TeV) doubly charged Higgs*

- *Neutrino masses from usual seesaw*

Small Neutrino masses with TeV WR: Details

- . $\mathcal{L}_{\mathcal{Y}} = h\bar{L}\phi R + \tilde{h}\bar{L}\tilde{\phi}R + h.c.$
- Using $\phi = \begin{pmatrix} \kappa & 0 \\ 0 & \kappa' \end{pmatrix} \rightarrow$ $$M_\ell = h\kappa + \tilde{h}\kappa'$$ $$m_D = h\kappa' + \tilde{h}\kappa$$
- How to get small m_ν for TeV seesaw:

  (i) $\kappa' = 0; \tilde{h} \sim 10^{-5.5} \; (\sim h_e^{SM})$

  (ii) Cancellation with κ', κ similar

  (iii) *assume texture for Dirac mass*

  (ii)–(iii): $h, \tilde{h}$ much larger

Mass textures making TeV scale seesaw "natural"

- Neutrino Mass texture:

$$m_D = \begin{pmatrix} m_1 & \delta_1 & \epsilon_1 \\ m_2 & \delta_2 & \epsilon_2 \\ m_3 & \delta_3 & \epsilon_3 \end{pmatrix} \quad M_N = \begin{pmatrix} 0 & M_1 & 0 \\ M_1 & 0 & 0 \\ 0 & 0 & M_2 \end{pmatrix}$$

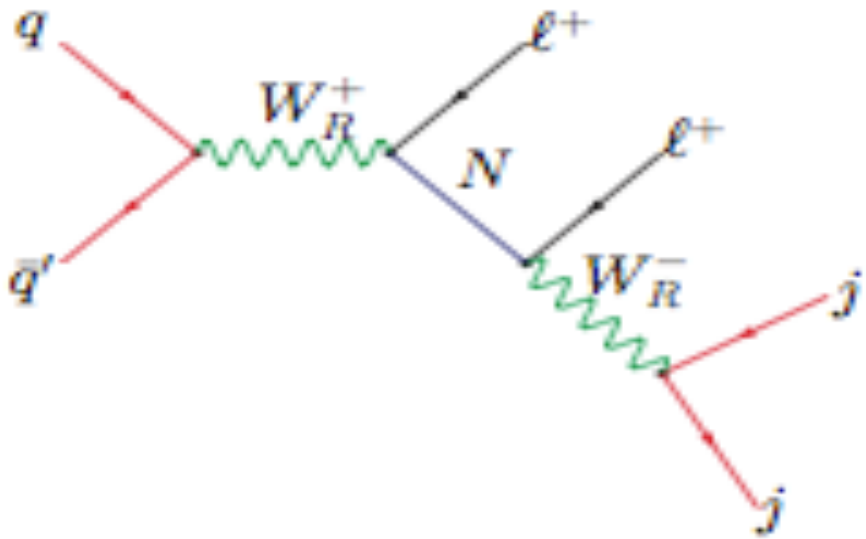
$$m_{D_{1,2,3}} \sim \; GeV \to Y_\nu \sim 10^{-2}\text{–}10^{-4}$$

- Sym limit $\epsilon_i, \delta_i \to 0$ → $m_\nu = m_D M_R^{-1} m_D^T = 0$
- sym. Br. $\delta_i, \epsilon_i \ll m_i$ → for TeV M_R, → small m_ν
- Small δ, ϵ arise from one loop SUSY breaking effects; *Good fit to neutrinos for LR seesaw* (Dev, Lee, RNM'13)

Tests of the model

- Look for W_{R}, Z', N_R at LHC and 100 TeV collider
- "Exotic" leptophilic Higgs e.g. Δ^{++}, Δ^{+}
- Search for $\beta\beta_{0\nu}$, $\mu \to e + \gamma,$ other leptonic rare decays
- Leptonic edm

WR Signals at LHC



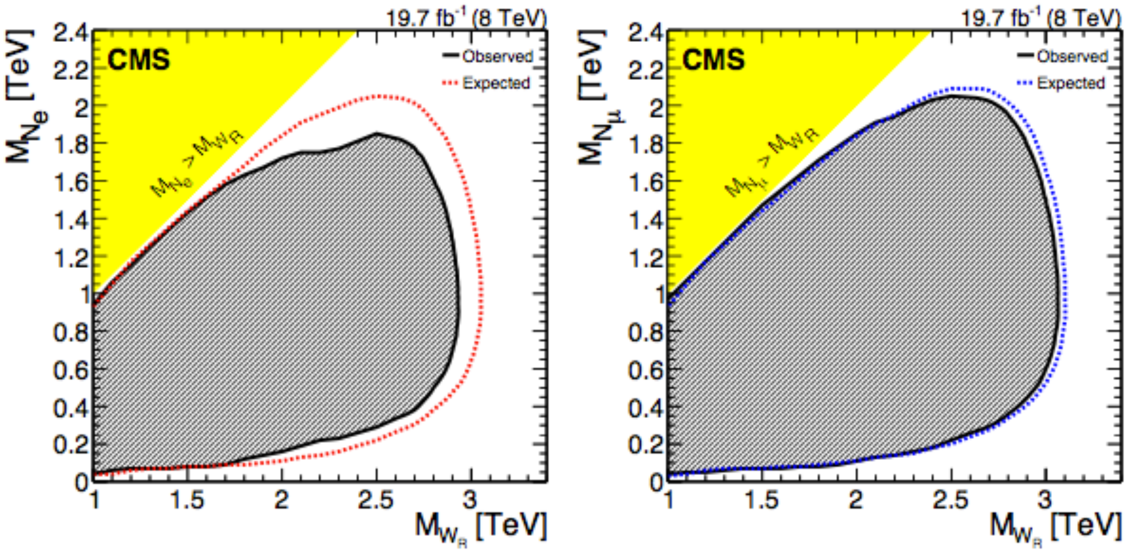
$$N \to l^{\pm} jj$$

(Keung, Senjanovic'83)

- Golden channel: $\ell_i \ell_k j j$;
- Probes RHN flavor pattern: $A_{\ell^+\ell^+jj} \propto M^{-1}_{N,ik}$

Current LHC analysis: only W_R graph

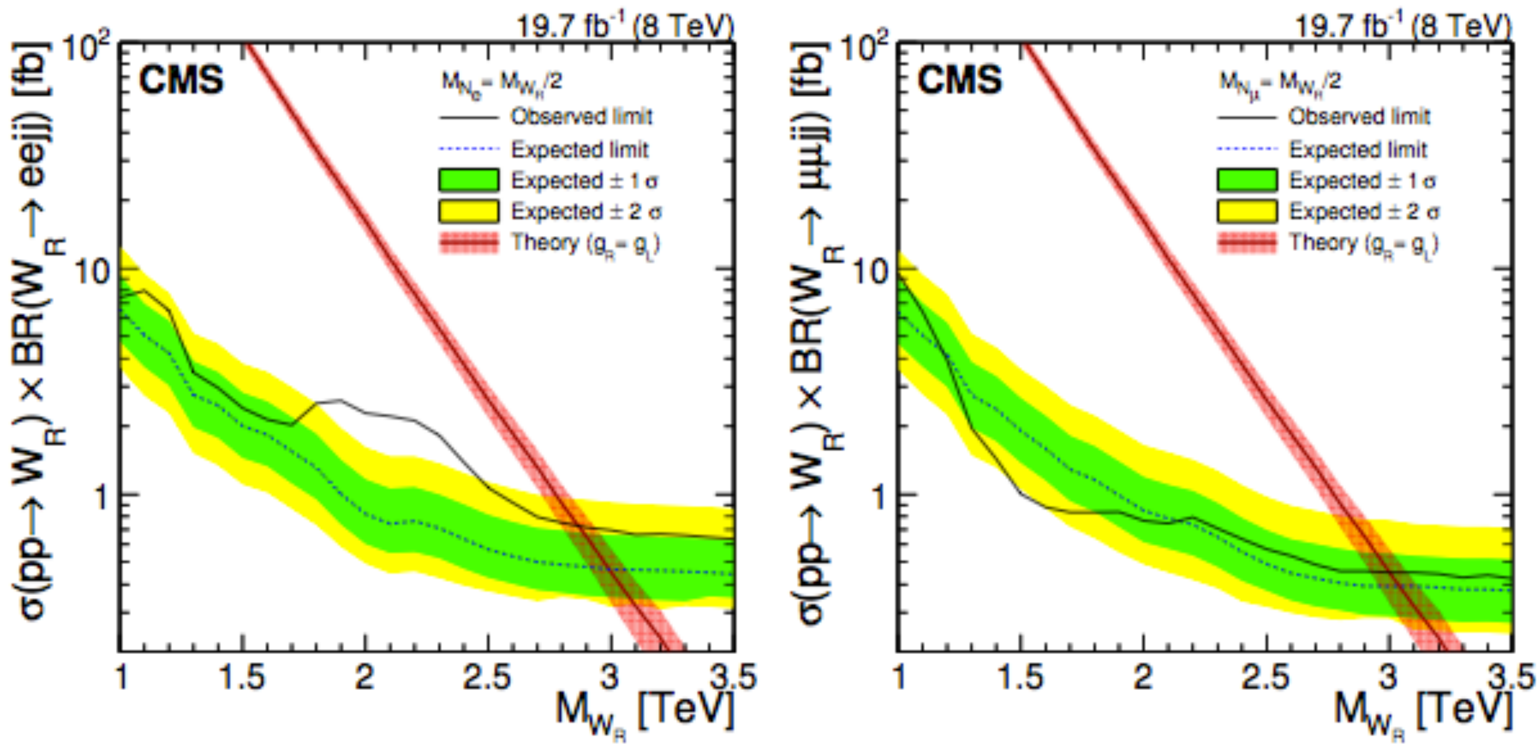
- Current W_R limits from CMS, ATLAS 2.9 TeV;



- 14-TeV LHC reach for M_{WR} < 6 TeV with 300 fb^{-1}
- 100 TeV collider can push limit to 30 TeV (Rizzo)

Intriguing excess in CMS

- . CMS: arXiv:1407.3683

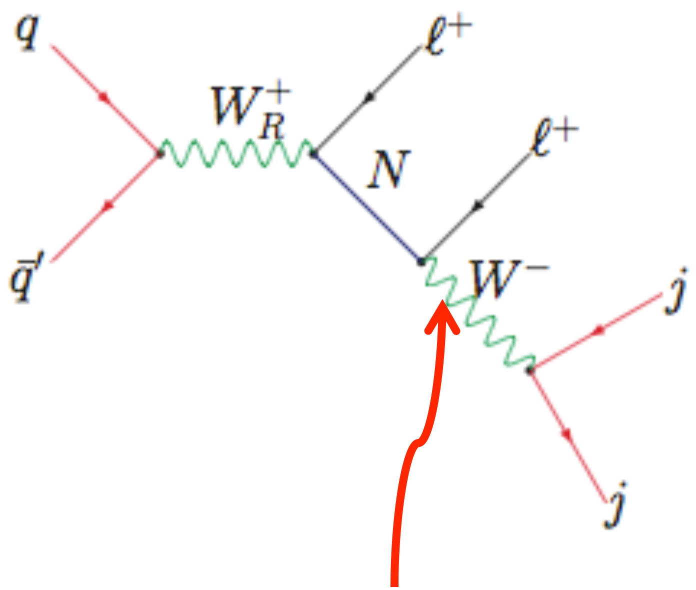


- Possible M_{WR} =2.1 TeV ? : (Deppisch Gonzalo,Patra,sahu,Sarkar; Heikinheimo, Raidal, Spethman; Aguilar-Saavedra, Joachim;Fowlie,Marzola'14; Gluza, Jelinsky'15)

New (RL) contribution to like sign dilepton signal

- When $V_{\ell N} \sim 0.01 - 0.001$, new contributions:

(Nemevsek, Tello, Senjanovic'12; Chen, Dev, RNM' arXiv: 1306.2342- PRD)



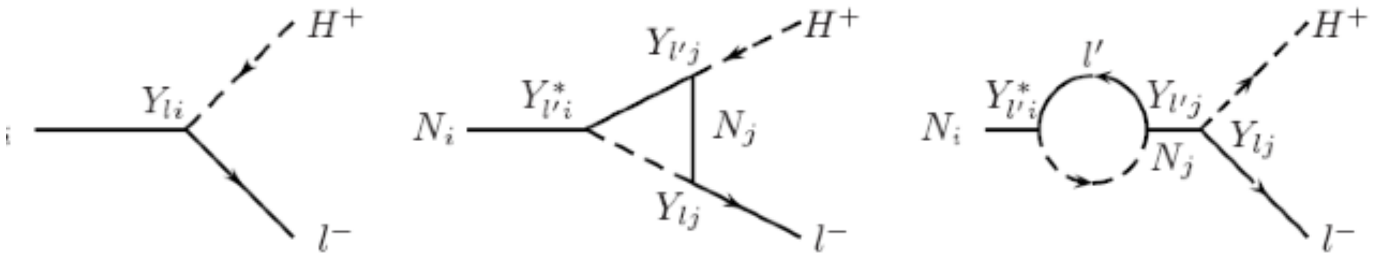
$$q\bar{q} \to W_R \to \ell + N;$$
$$N \to \ell W_L$$

Flavor dependence will probe Dirac mass M_D profile:

Understanding origin of matter with TeV scale L- violation !

TeV scale Resonant leptogenesis:

- RH neutrino mass ~ TeV scale(Flanz, Pascos, Sarkar; Pilaftsis, Underwood; Covi, Roulet, Vissan)i



$$\frac{n_B}{n_\gamma} \propto \frac{ImY^4}{|Y|^2} \frac{M_1 M_2 (M_2^2 - M_1^2)}{(M_2^2 - M_1^2)^2 + (M_1\Gamma_1 + M_2\Gamma_2)^2}$$

- Generic model requires extreme degeneracy among RHNs to get enough n_B/n_γ
- Built into our texture

Final baryon asymmetry from lepton asymmetry

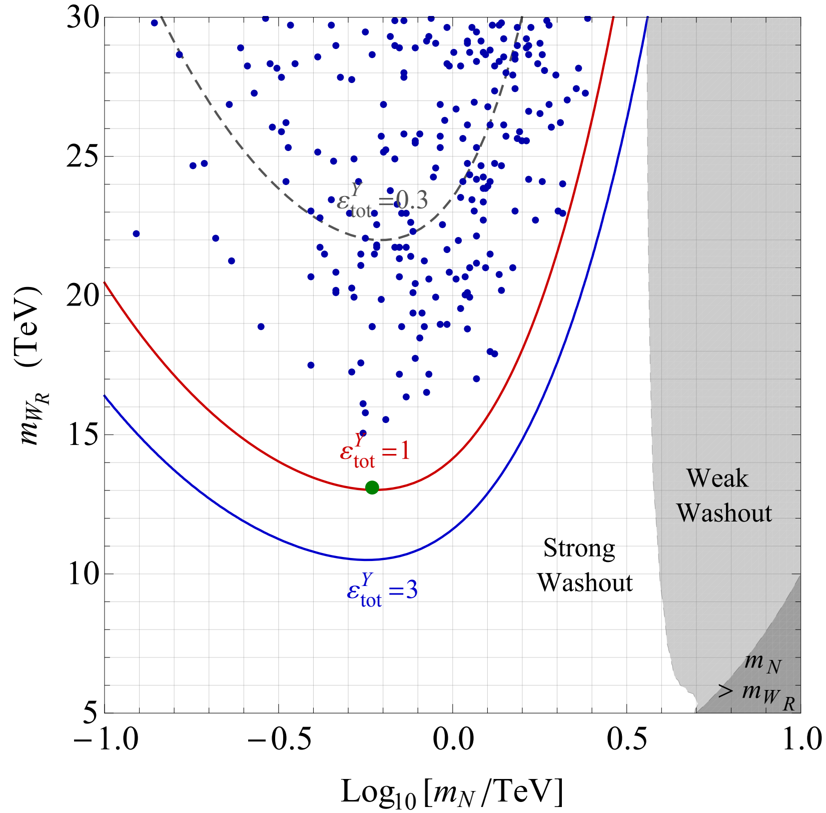
- Wash out effect important: (Buchmuller, Di Bari, Pliumacher)

$$\eta_B \simeq 10^{-2} \varepsilon\, \kappa^{\rm fin}$$

- In LR models, $\kappa(M_{W_R}, Y_\nu, ..)$
- Washout increases as neutrino Yukawas increase or M_{WR} decreases: lower bound on M_{WR}
- Two papers: small Y: M_{WR} >18 TeV (Frere,Hambye, Vertongen)

  Larger Y with nu fits: M_{WR} > 10-13 TeV (Dev, Lee, RNM.'14)

M_{WR} vs M_N Plot where leptogenesis works



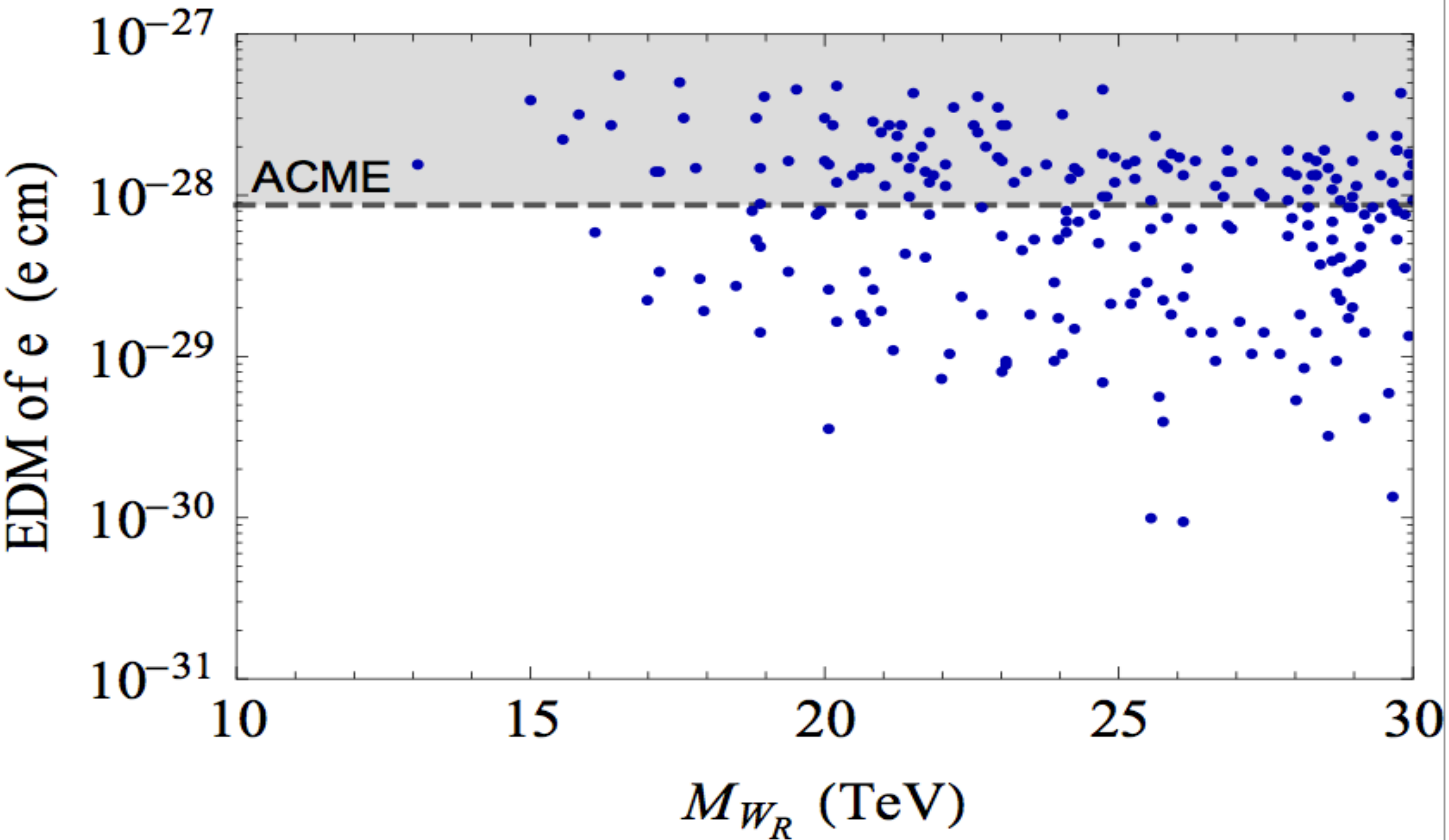
(Dev,Lee, RNM:arXiv:1503.04970)

$M_{WR} > 10$ TeV

$M_N > 585$ GeV

- Discovery of W_R below 10 TeV will rule out leptogenesis as a mechanism for origin of matter.

Electron edm as a test of such models



Summary

- Left-Right theories provide an attractive realization of TeV scale seesaw with testable collider implications (W_R , Z′, N..)!
- Minimal susy LR *requires* few TeV WR !!
- In particular, if colliders find W_R with mass < 10 TeV or $M_{WR} < M_N$ leptogenesis will be ruled out.

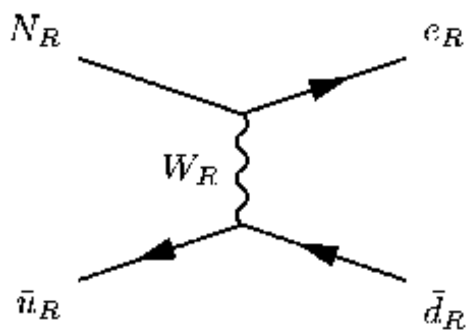
$$Thank\ you\ for\ your\ attention\ !$$

TeV W_R seesaw models

- Generic seesaw: small $m_\nu \to Y_\nu \sim 10^{-5.5}$ and fine tuned RHN masses !
- Special textured seesaw has two features:
  (i) Larger Yukawas $Y_\nu \sim 10^{-3.5}$
  (ii) Naturally deg $N_{1,2}$ since $M_N = \begin{pmatrix} 0 & M_1 & 0 \\ M_1 & 0 & 0 \\ 0 & 0 & M_2 \end{pmatrix}$
- Leptogenesis different:

Leptogenesis and TeV W_R :case of $Y=10^{-6}$

- Small Yukawa Leads to strong wash out : (Frere, Hambye, Vertongen'11) since



>> $\Gamma(\nu_R \to \ell H)$

- Strong wash-out κ too small Unless M_{WR} > 18 TeV;

→ Discover W_R below this mass at LHC→ rules out leptogenesis for *generic* TeV scale LR seesaw!!

How does the bound arise ?

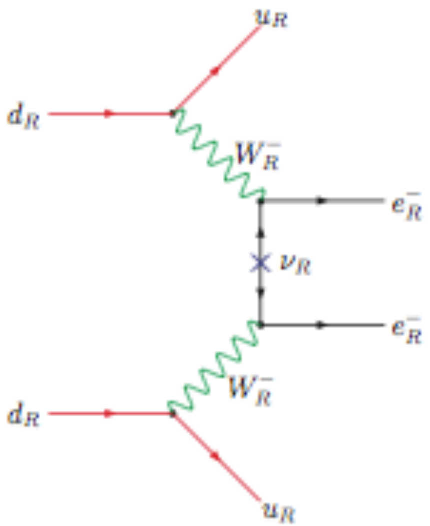
- Pre-washout CP asym. $\varepsilon \equiv \frac{\Gamma(\nu_R \to \ell h) - \Gamma(\nu_R \to \overline{\ell h})}{\Gamma(\nu_R \to \ell h) + \Gamma(\nu_R \to \overline{\ell h})}$
- Final asym: $\eta_\ell \simeq \frac{1}{K} \varepsilon \frac{\Gamma_D}{\Gamma_D + \Gamma_S}$
- In LR models, a crucial parameter is $\frac{\Gamma_D}{\Gamma_S}$

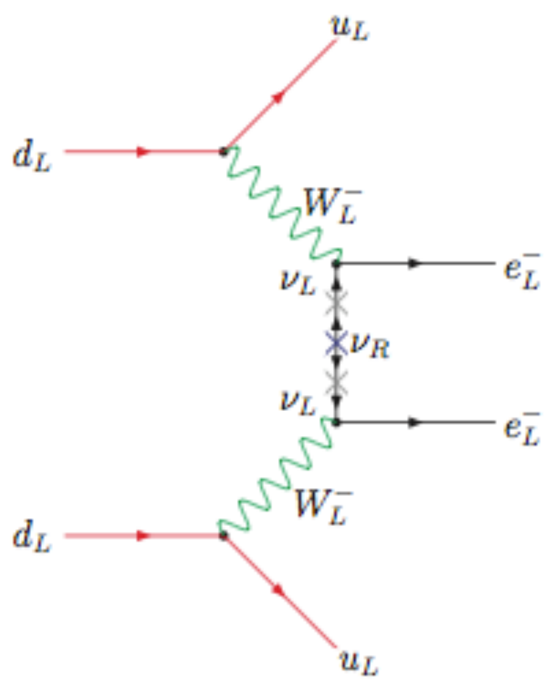
$\frac{\Gamma_D}{\Gamma_S} \propto \frac{Y^2}{g^4 (M_N / M_{WR})^4}$; generic TeV W_R → $Y \sim 10^{-6}$ → $\frac{\Gamma_D}{\Gamma_S} \sim 10^{-6}$ unless M_{WR} >18 TeV

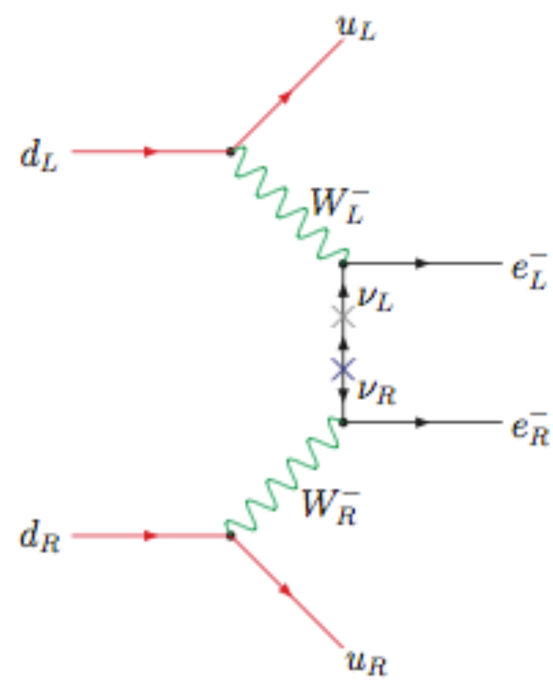
Case of $M_N > M_{WR}$

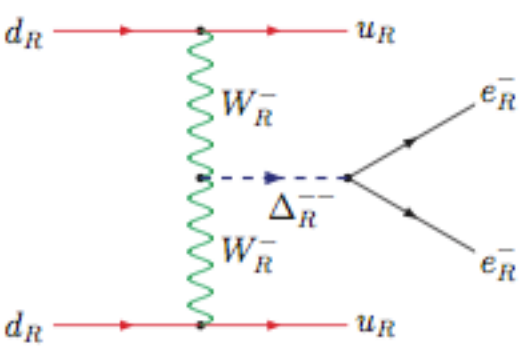
- CP conserving decay mode $N \to W_R + \ell$ dominates !
- Leptogenesis impossible (Deppisch, Harz, Hirsch'14)
- If experimentally it is found, $M_N > M_{WR}$, this by itself can rule out leptogenesis as a mechanism for origin of matter !!

New contributions to $\beta\beta_{0\nu}$







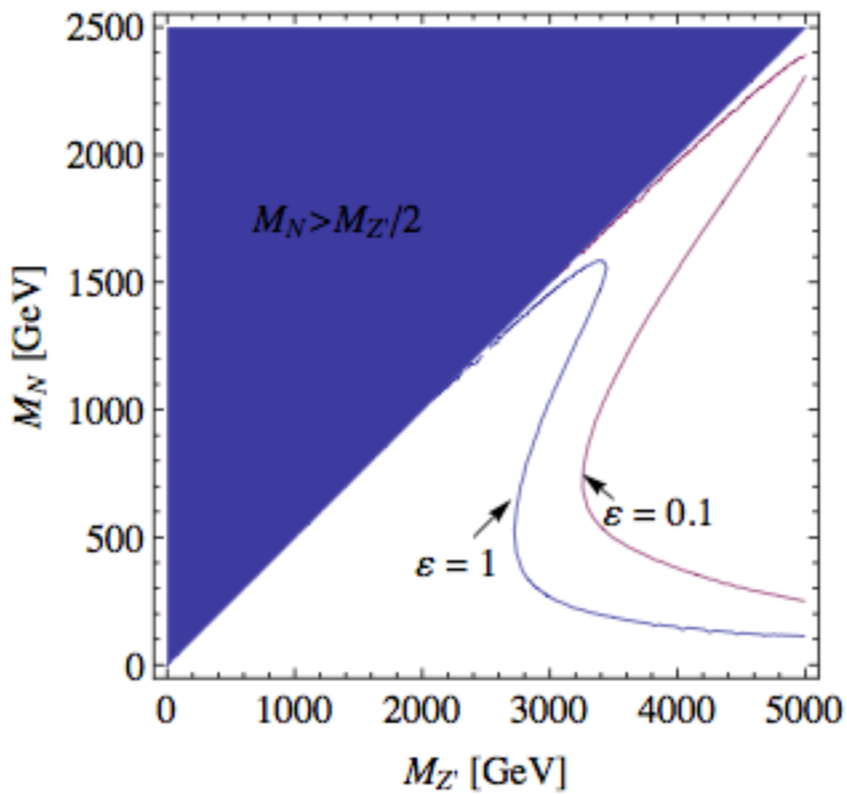


Leptogenesis with $M_{Z'} << M_{WR}$

- Effective theory: $SU(2)_L \times U(1)_{I_{3R}} \times U(1)_{B-L}$
- Z′ couples also to NN and effects leptogenesis
- Origin of CP asymmetry same as in WR case via resonant leptogenesis and requires deg $N_{1,2}$: $\mathcal{E}$ can be as large as 1.
- Washout has no W_R contribution but only NN→ Z′→ qq, ll type.
- Lower the Z′, more washout in generic case

Lower bound on $M_{Z'}$

- (Blanchet, Chacko, Granor, RNM'2009, PRD)

- 

$M_{Z'} > 3$ TeV

Directly probing leptogenesis in Z' case:

- Lepton asymmetry $\mathcal{E}$ is directly related to the following collider observable:

$$\frac{N(\ell^+\ell^+) - N(\ell^-\ell^-)}{N(\ell^+\ell^+) + N(\ell^-\ell^-)} = \frac{2\sum_i \varepsilon_i}{\sum_i 1}$$

- Makes it possible to see origin of matter directly.

New Higgs fields and Yukawa couplings

- LR bidoublet: $\phi = \begin{pmatrix} \phi_1{}^0 & \phi_2{}^+ \\ \phi_1{}^- & \phi_2{}^0 \end{pmatrix}$

- Triplet to break B-L and generate seesaw: $\Delta = \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta^+ & \Delta^{++} \\ \Delta^0 & -\frac{1}{\sqrt{2}}\Delta^+ \end{pmatrix}$

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

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

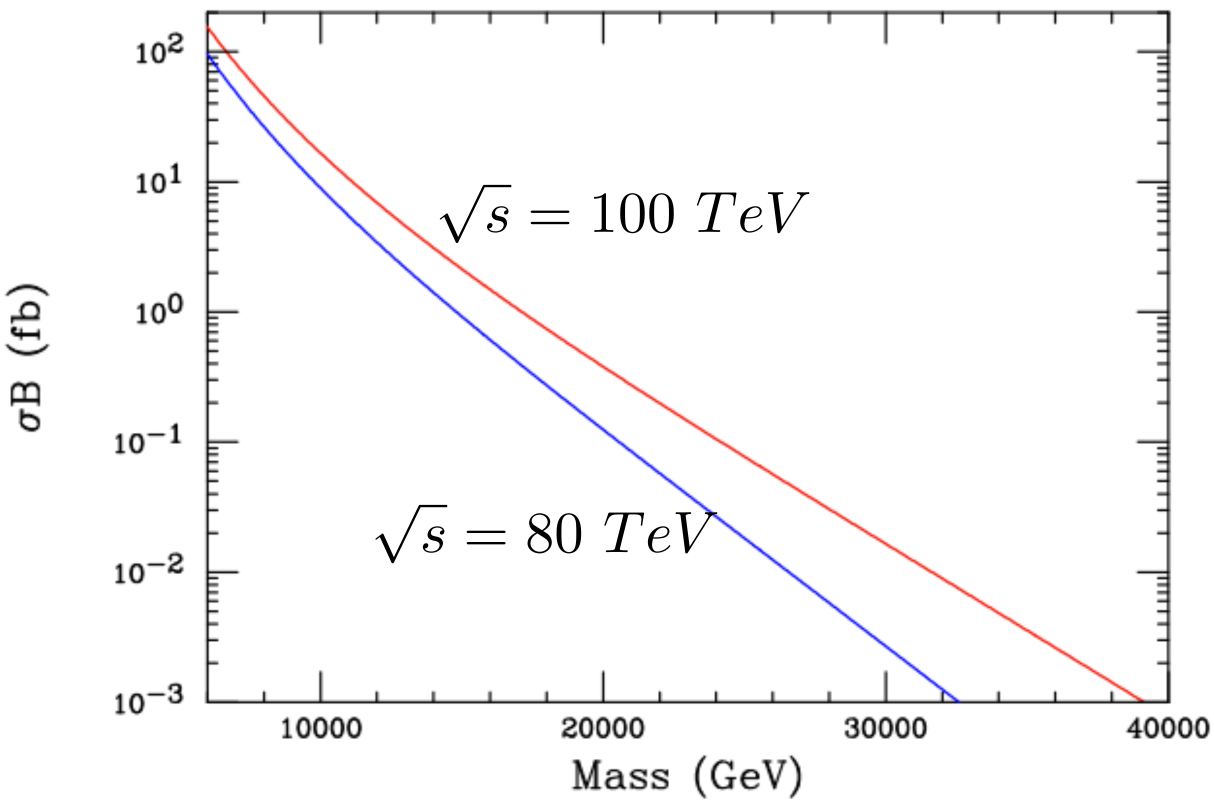
Texture alternative (iii):

- Low scale seesaw $v_R \sim 10$ TeV
- $\mu \to 3e,\ \mu \to e + \gamma,\ \tau \to 3e$ bounds restrict flavor structure of $M_N = f v_R$
- Favored texture:

$$M_N = \begin{pmatrix} 0 & M_1 & 0 \\ M_1 & 0 & 0 \\ 0 & 0 & M_2 \end{pmatrix}$$

Higher Mass WR probe at Future colliders

- So far one study by Rizzo: $W_R \to \ell + \nu'$ channel



$M_{WR} < 30$ TeV