MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Probing TeV scale origin of neutrino mass

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Neutrino mass- a signal of new physics beyond SM

- Understanding origin of nu mass will specify the direction of new BSM physics and thus a significant venue of research!
- Could this new physics be in the TeV scale, so it could be probed using current facilities ?

- This talk explores this question within the seesaw paradigm for neutrino masses and how we can look for its signals at LHC.

Left-right model for neutrino mass seesaw

- Two key ingredients of seesaw i.e.

  (i) Right handed neutrinos

  (ii) Broken B-L symmetry

  are both automatic in left-right models !
- A compelling model for type I seesaw is the left-right extension of standard model.
- Majorana mass of the RH neutrino is protected by a gauge symmetry- so seesaw scale is connected to the symmetry breaking scale.

Left-Right model:

- 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: $M_{W_R} \gg M_{W_L}$

(Pati, Salam'74; Mohapatra, Pati'74;'74; Senjanovic, Mohapatra'75)

Left-Right seesaw:

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

- Fermions

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

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(Pati, Salam'74; Mohapatra, Pati'74;'74; Senjanovic, Mohapatra'75)

Breaking of LR and type I seesaw

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

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

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

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

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

- Seesaw formula

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

Parity breaking as origin of Majorana Neutrino mass

- Electric charge formula in LR

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

- Above EW scale,

$$\Delta Q = \Delta I_{3L} = 0 \ \rightarrow \Delta I_{3R} = -\frac{1}{2}\Delta L$$

- Parity breaking → Majorana nu (RNM, Marshak'80)
- Small neutrino mass is why Weak Int. V-A

Other attractive features LR models

- Simple picture of naturally stable WIMP DM: Add B-L=0 triplet fermions: No susy required
  (Heeck, Patra'15; Nagata, Olive, Zheng'15)

- Solution of strong CP without axion:
  Parity makes mass matrices hermitean→ $\theta = 0$

  (Beg, Tsao'78; RNM, Senjanovic'78)

- Both prefer W_R mass in multi-TeV range: a motivation for exploring TeV LR seesaw !!

How do neutrino masses work in TeV LR seesaw?

- Typically, $m_D = h_\nu v_{wk}$;

- So for $h_\nu \simeq 10^{-5.5} \sim h_e$; seesaw scale v_R could easily be in the TeV range and fit oscillation data;
- Hence W_R, Z' accessible to colliders.

$$M_{W_R} = g_R v_R \sim \text{few}\,\text{TeV}$$

- Plus low energy effects e.g. $\beta\beta_{0\nu}$, $\mu \to e + \gamma$...

Doublet breaking of LR and Inverse seesaw alternative

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

$< \chi_R^0 >$ ↓ v_R (ΔL=0) $M_N = f v_R$

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

$< \phi_1^0 >$ ↓ κ

$U(1)_{em}$

$$\begin{pmatrix} \nu & N & S \end{pmatrix}$$

$$\begin{pmatrix} 0 & h\kappa & 0 \\ h\kappa & 0 & f v_R \\ 0 & f v_R & \mu \end{pmatrix}$$

(μ ~keV:weak ΔL=2)

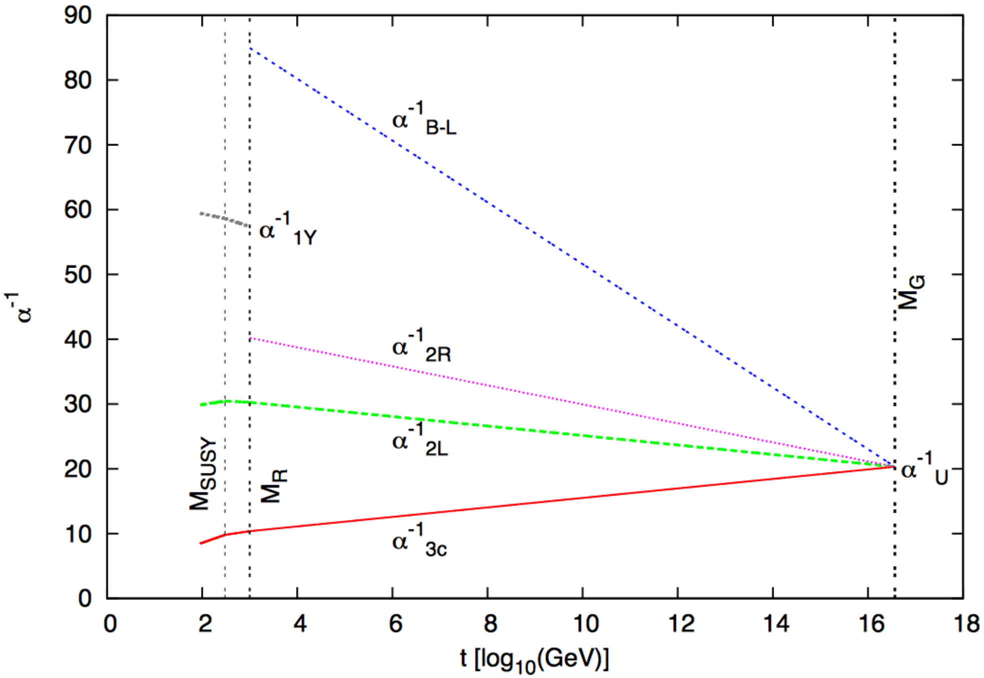
$$m_\nu \simeq m_D (f v_R)^{-1} \mu (f v_R)^{-1} m_D^T$$

(RNM’86; RNM, Valle’86)

- μ ~keV→ TeV LR

Left-right Inverse seesaw at TeV is GUT embeddable!

- Neutrino mass is determined by small mu-parameter → h_ν can be >> $10^{-5.5}$ (could even be ~h_t allowing for quark lepton unification)



(Dev, RNM'10)

SO(10) is the GUT theory for this.

Collider signals for TeV scale LR type I seesaw

- Vector boson signal: W_R , Z' *(M~TeVs)*

- New fermion signal: $N_{e,mu,tau}$ *(M~GeV-TeV)*

- Scalar boson signal: analog of SM Higgs

Vector boson signal: 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 (g_R /g_L)

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

- $g_R \neq g_L$ compatible with LR; $g_R/g_L > 0.6$

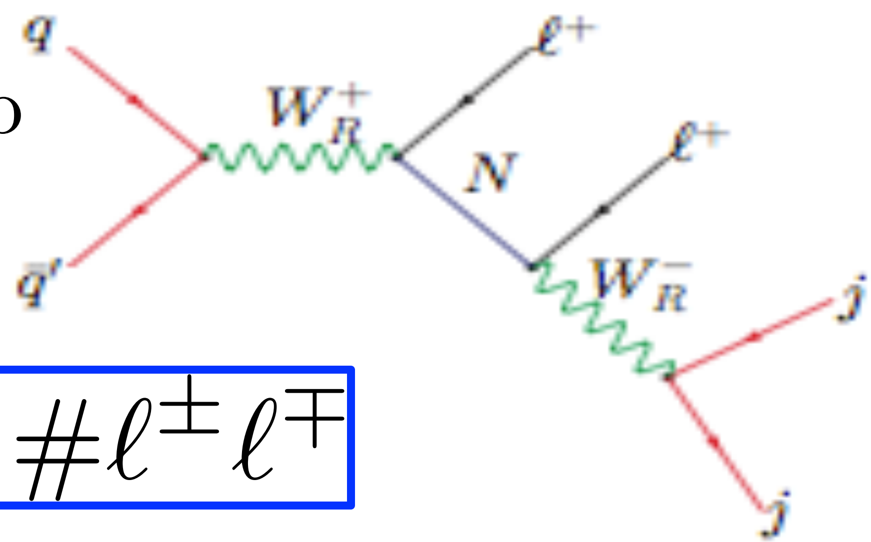
- Resolving ϵ'/ϵ puzzle→TeV W_R (Cirigliano, Dekens, de Vries,Mereghetti'16)

Collider signals of LR seesaw (Type I)

- Golden channel: $W_R \to \ell_i \ell_k j j$
- W_R mediated graph (Keung, Senjanovic'82; Mitra, et al.'16; T. Han'17)

$$\sigma(W_R) \times BR(Ne) \sim 14.8\text{fb}$$

M $_{WR}$ = 3 TeV



- Predicts $\#\ell^\pm\ell^\pm = \#\ell^\pm\ell^\mp$
- Unlikely to be SM signal $A_{\ell\ell jj} \propto m_D M_N^{-1} m_D$

What if $\#\ell^\pm\ell^\pm \neq \#\ell^\pm\ell^\mp$?

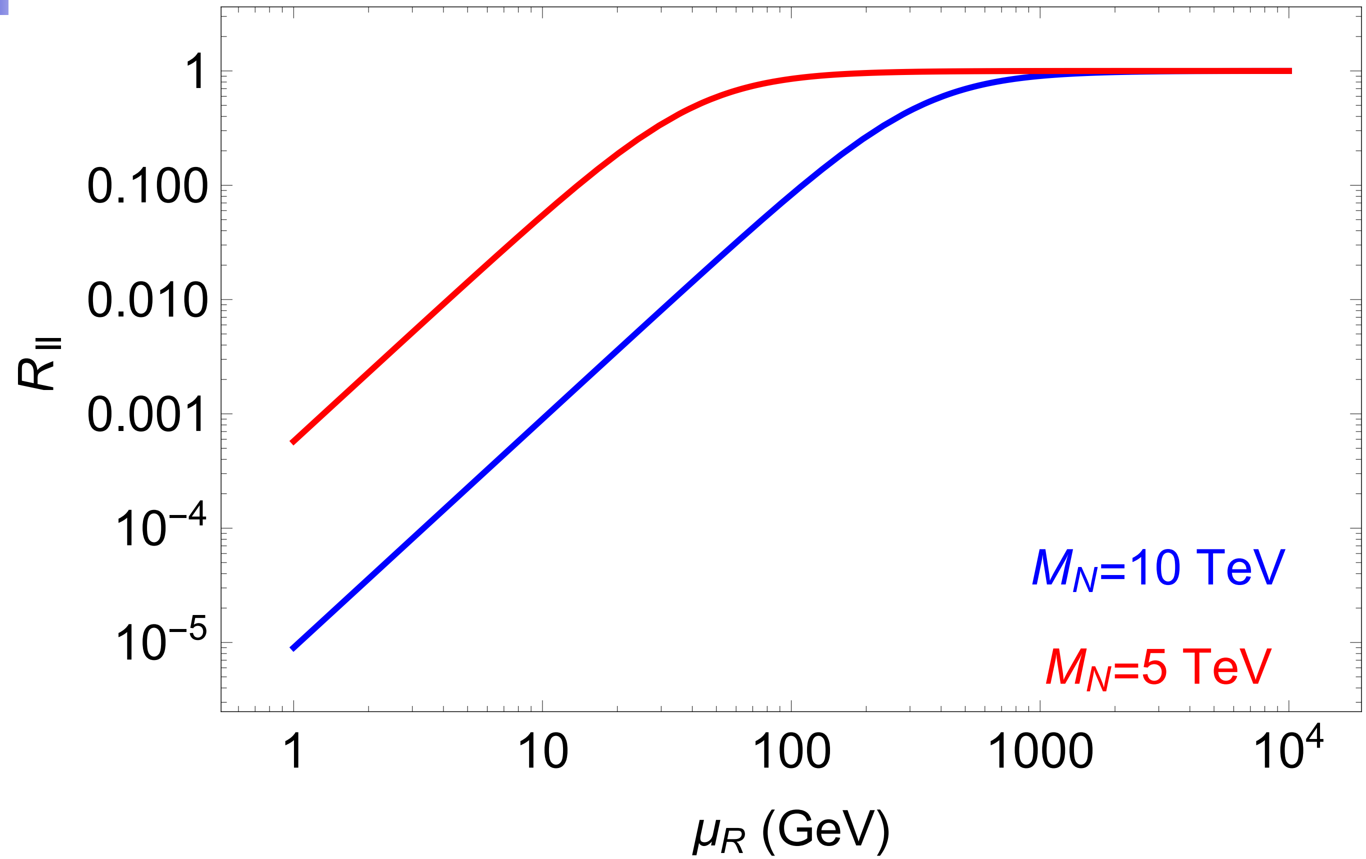
- General inverse seesaw $\begin{pmatrix} 0 & m_D & 0 \\ m_D^T & \mu_R & M_N \\ 0 & M_N^T & \mu_S \end{pmatrix}\begin{pmatrix} \nu \\ N \\ S \end{pmatrix}$
- N-S mix, α and split ΔM^2
- Coherence essential:($\Delta M^2 \leq 2E\Gamma_{W_R}$; Akhmedov; Kayser)

$$\frac{\ell^+\ell^+}{\ell^+\ell^-} \equiv R_{\ell\ell} = \frac{cos^2 2\alpha + \frac{4\Delta M^2}{\Gamma_0^2}}{1 + sin^2 2\alpha + \frac{4\Delta M^2}{\Gamma_0^2}} \neq 1$$

(Dev, RNM'15; Aniamati,Hirsch,Nardi'16; Das, Dev, RNM(to appear))

- Type I case: CPV in N-decay: (Gluza, Jelinski)

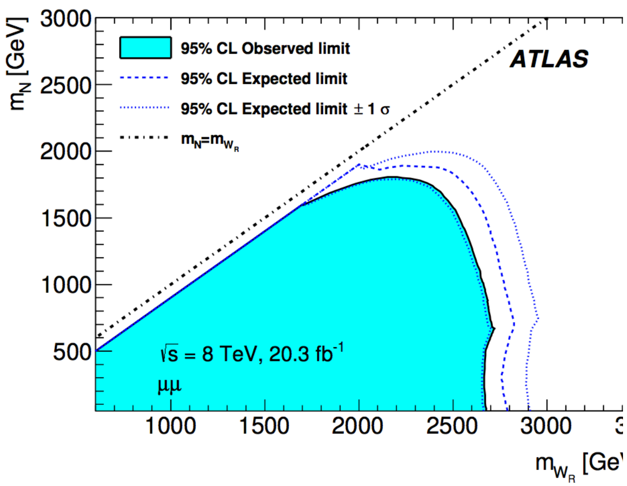
$\frac{\ell^+\ell^+}{\ell^+\ell^-} \equiv R_{\ell\ell}$ for inverse seesaw

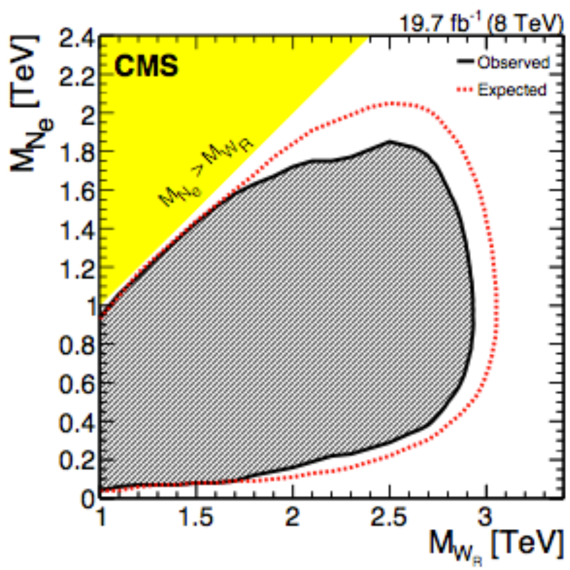


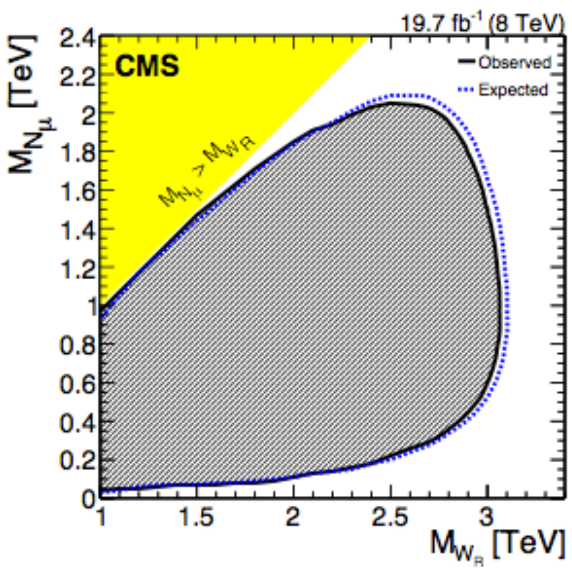
(Das, Dev, RNM'17)

Current limit from LHC

- $\ell\ell jj$ final state







- Current limit: 2.8 TeV ($g_L = g_R$)

Limits on Z'

- Minimal models:

Type I

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

$M_{Z'} > 5$ TeV;

Inverse seesaw

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

$M_{Z'} > 3.7$ TeV

- In general LR models, where above relations do not hold, $M_{Z'} > 3.2$ TeV from 13 TeV data on $Z' \to \ell\ell$

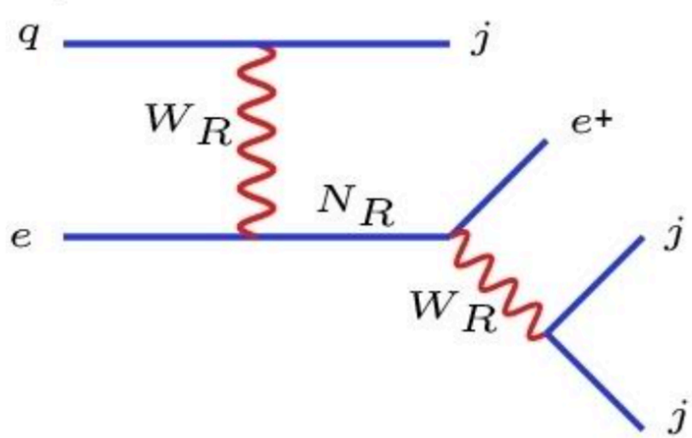
(Lindner, Queiroz, Rodejohann'16)

Prospects for LR in future colliders

- LHC14 reach 5-6 TeV; 100 TeV collider: 30 TeV

  signal: *pp→ lljj*

- LHeC: (~100 GeV e+7 TeV p) (M_{WR} < 6.5 TeV)



signal $pe^- \rightarrow e^+jjj$

(Lindner, Queiroz, Rodejohann, Yaguna'16)

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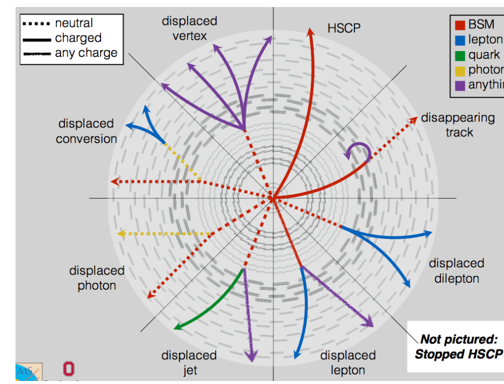
Displaced vertex signals: A new window to seesaw

- For low masses, new particles in seesaw are long lived → displaced vertices at LHC.

(SHiP; recent proposal:MATHUSLA detector)



(Curtin, Chou and Lubatti'16)

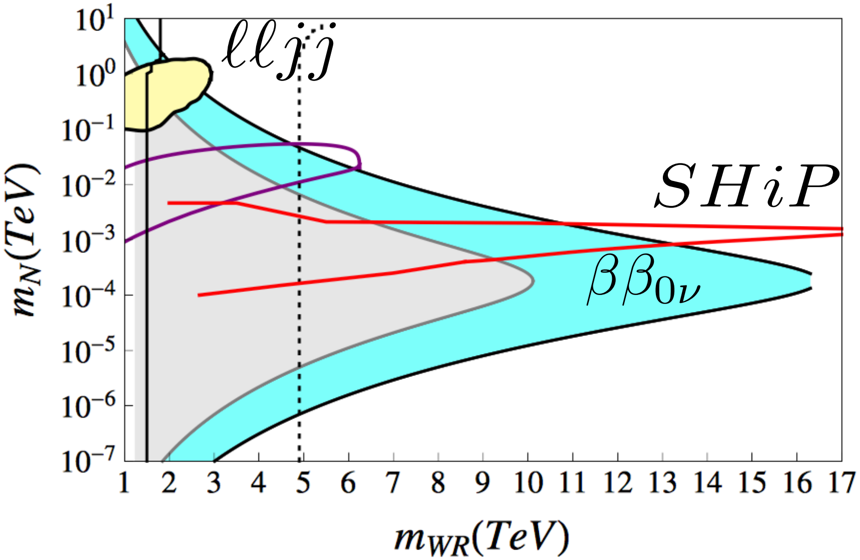
$$N_{obs} \sim N_X \cdot Br(X \to SM)\epsilon_{geom} \cdot \frac{L}{bc\tau}$$

- Fermion sector: X= light RHN
- Higgs sector: X=H_3 :seesaw Higgs

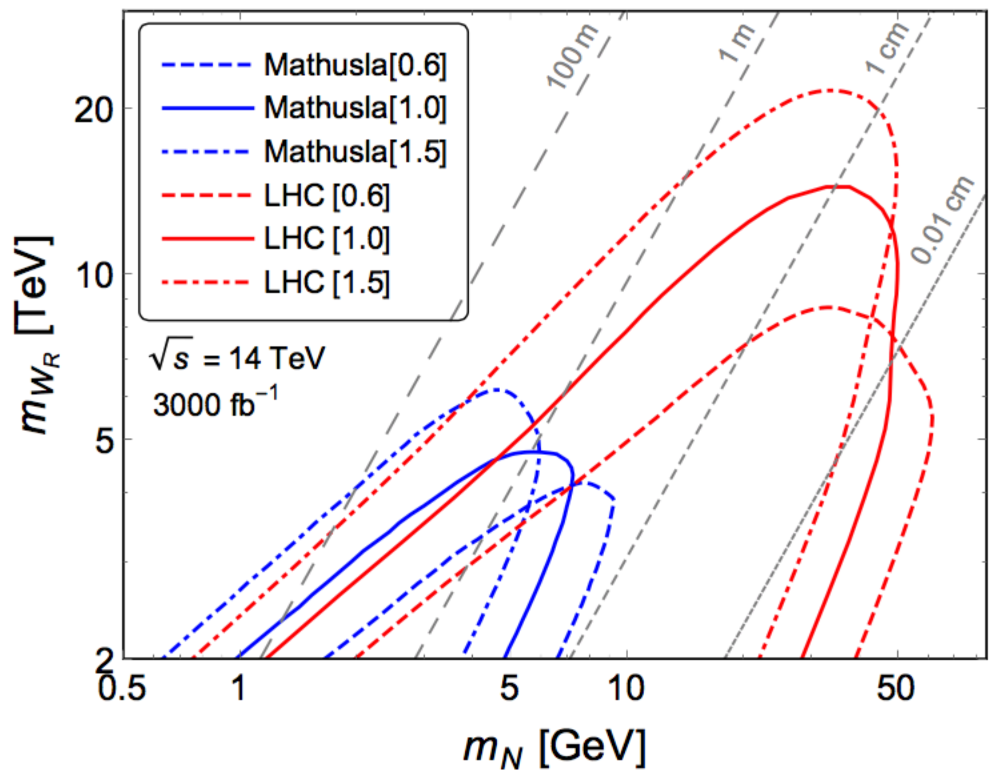
Light N and displaced vertices at LHC

$$\tau_N^0 \simeq 9.3 \times 10^{-3} \left(\frac{m_N}{10\,\text{GeV}}\right)^{-5} \left(\frac{M_{W_R}}{3\,\text{TeV}}\right)^{4} \left(\frac{g_R}{g_L}\right)^{-4} \text{m}$$

- SHiP reach:



(Helo, Hirsch'15)



(Helo, Hirsch, Dev, RNM, Zhang'17)

New Higgs bosons in LR and displaced vertices

- Parity partner of SM Higgs $H_1^0, A^0; \quad M_{H_1^0, A^0} \geq 10 \text{ TeV}$

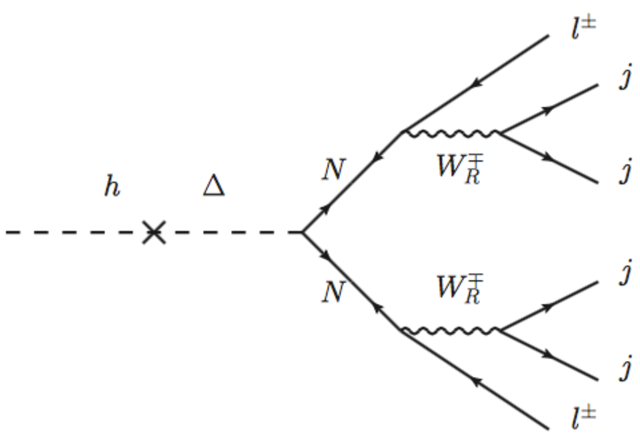
- New : Seesaw Higgs $H_3^0 \equiv Re\Delta_R^0$

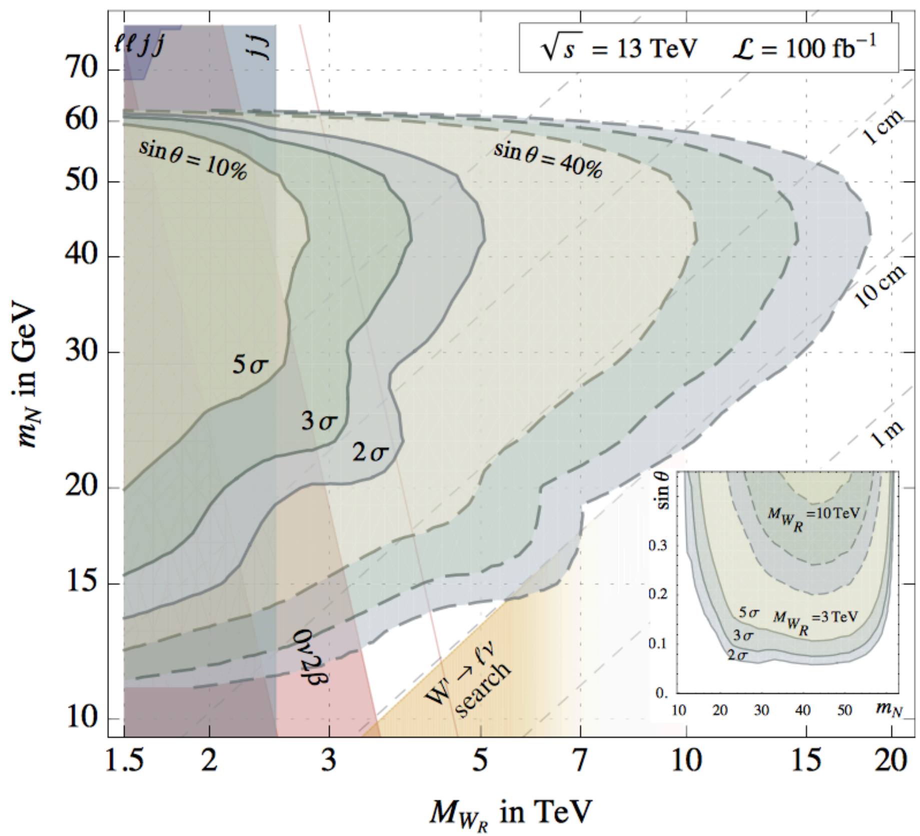
$$M_{H_3^0} \simeq 1 - 1000\text{GeV}$$

- Two domains of seesaw Higgs masses
- $M_{H3} \sim v_R >> M_h$
- $M_{H3} << M_h << v_R$ (~ few GeV to 100 MeV)

Rare SM Higgs decays: for heavy seesaw Higgs H_3

- . $h \to \ell\ell 4j$





(Maiezza, Nemevsek,Nesti'15)

Light Seesaw Higgs H_3 (few GeV)

- No phenomenological limit; could it be light?
- If $SU(2)_R \times U(1)_{B-L}$ is broken radiatively, there is a good chance that $H_3^0 \equiv Re\Delta_R^0$ is light:

$$\left(m_{H_3}^2\right)^{\rm loop} \simeq \frac{3}{2\pi^2}\left[\frac{1}{3}\alpha_3^2 + \frac{8}{3}\rho_2^2 - 8f^4 + \frac{1}{2}g_R^4 + (g_R^2 + g_{BL}^2)^2\right] v_R^2$$

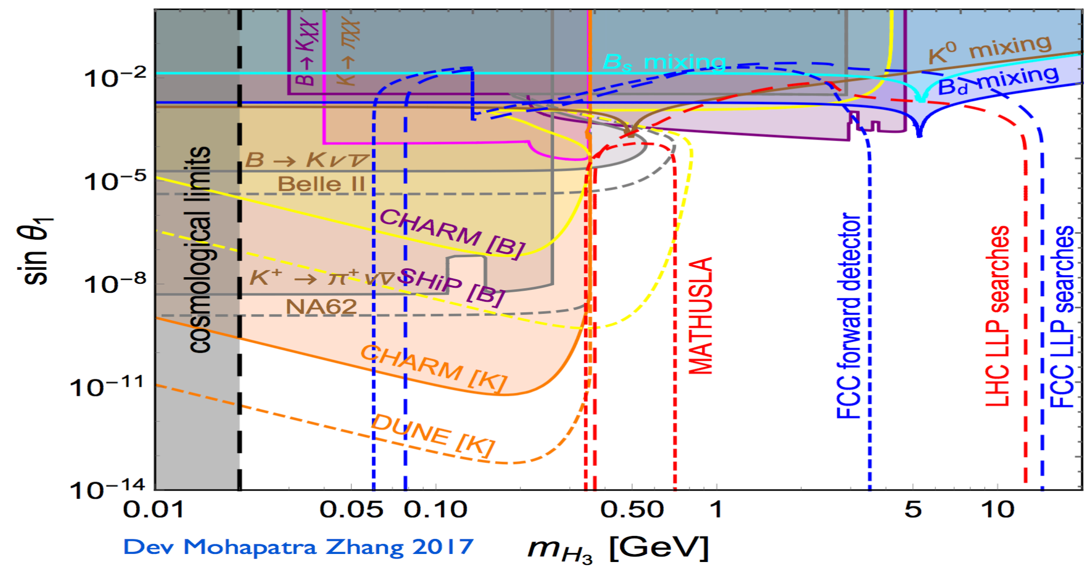
(Dev, RNM, Yongchao Zhang, PRD'17; 1703.02471)

- Radiative breaking inspired by a conformal approach to gauge hierarchy

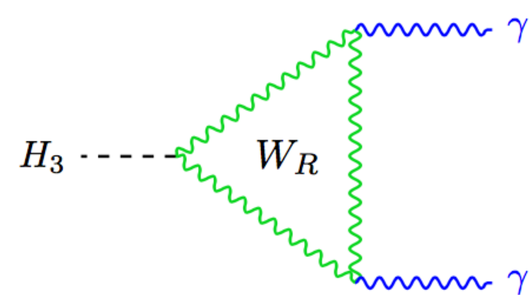
(Bardeen'95; Holthausen, Lindner, Schmidt'10)

How does light H_3 decay?

- H_3 decay to quarks and leptons suppressed by FCNC constraints.



- Dominant decay mode is $\gamma\gamma$
- *Very unique to LR models*



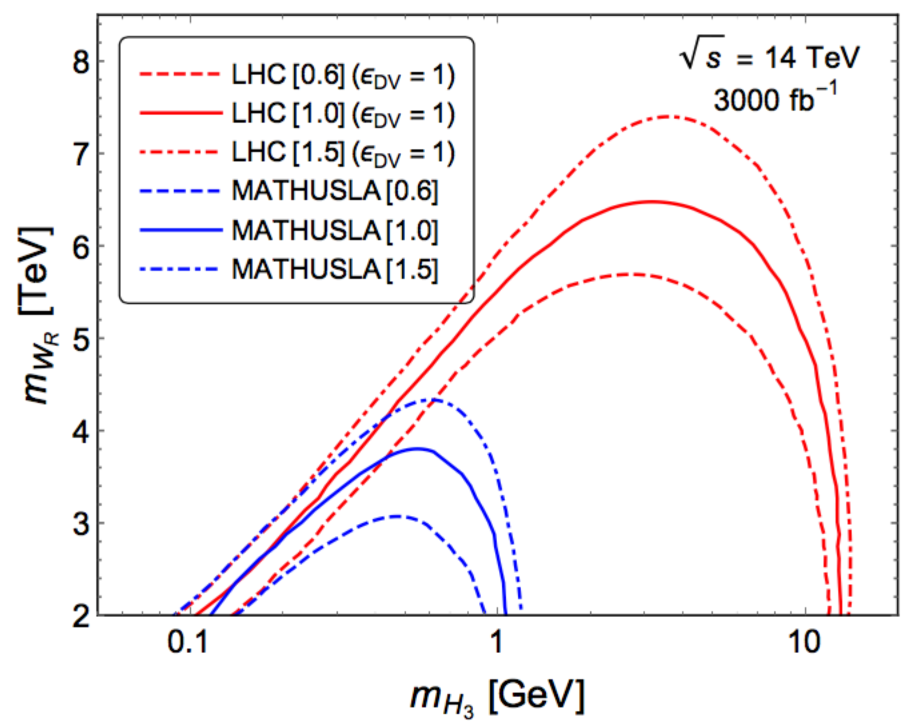
$\gamma\gamma$ Displaced vertices at LHC: signal of light H_3

- Near GeV mass H_3^0 accessible at the LHC via displaced vertices ($\gamma\gamma$ mode 100% BR)

(Dev, RNM, Yongchao Zhang'16)

- M_{H3}- M_{WR} reach at LHC via this mode.

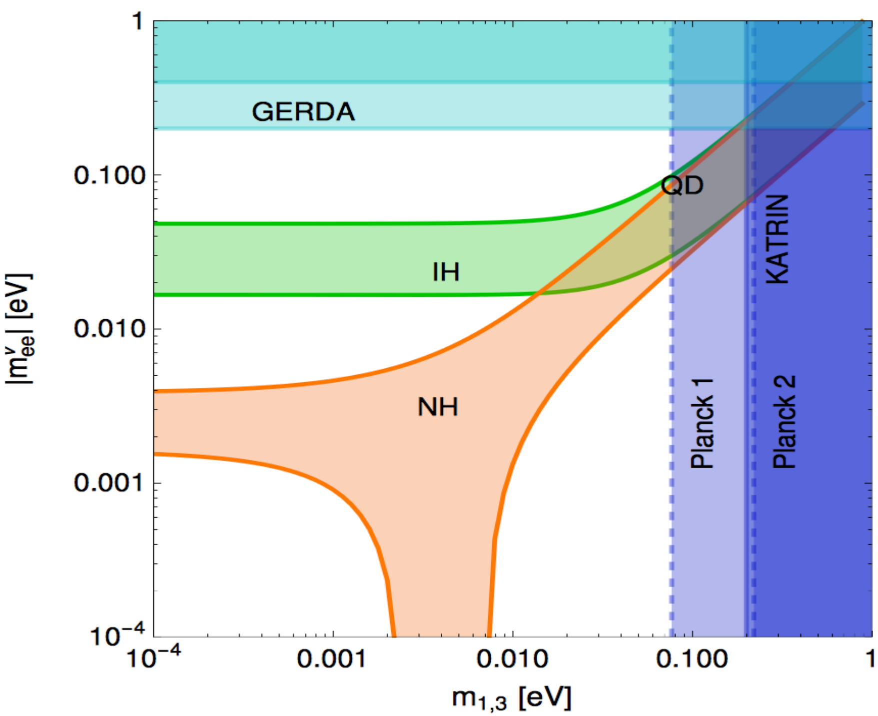
- MATHUSLA Blue line

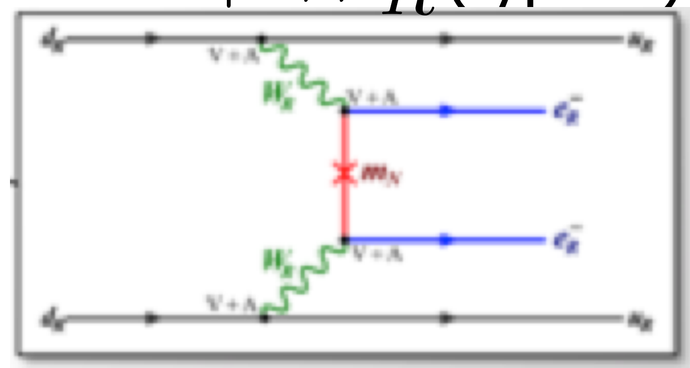


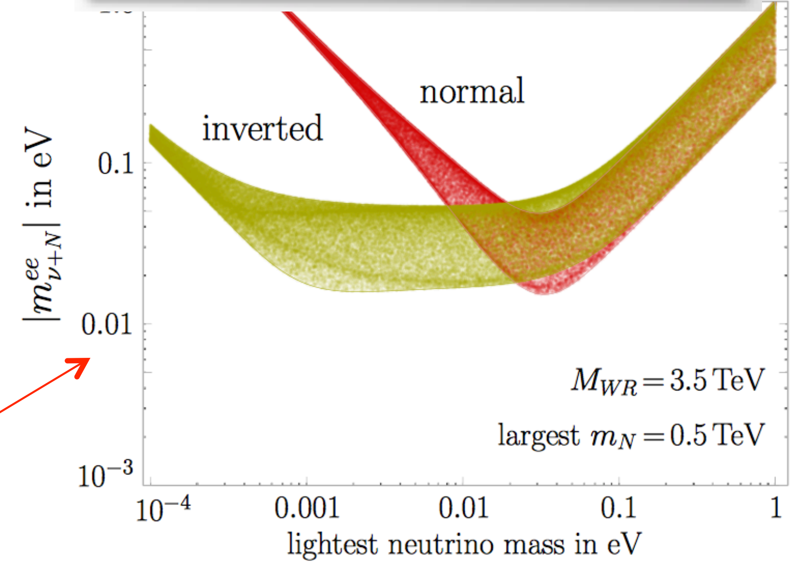
A spectacular effect of LR in $\beta\beta_{0\nu}$

Only ν exchange

$\nu + W_R$ (type II)







Tello, Nemevsek, Senjanovic, Nesti, Vissani'11

Take away 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*. Need supplemantary information from LHC to pinpoint this.
- Suppose long base line→ NH, any signal of $\beta\beta_{0\nu}$ at this level would strongly imply new particle effect e.g. W_R.
- Must find ways to disentangle heavy particle effects from light nu exchange

Implications of TeV WR for leptogenesis

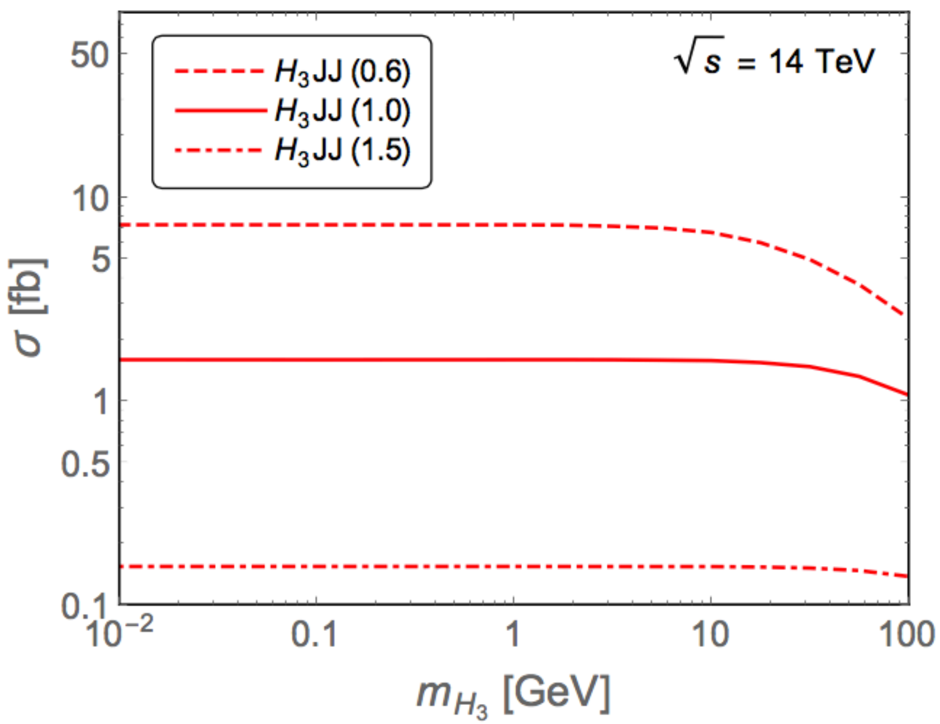
- A TeV W_R affects washout of lepton asymmetry
- Washout increases as M_{WR} decreases: →lower bound on $M_{WR} > 10$ TeV
- (Frere,Hambye, Vertongen'09; Dev, Lee, RNM.'14)
- Thus a discovery of W_R below 10 TeV will rule out leptogenesis as a way to understand the origin of matter

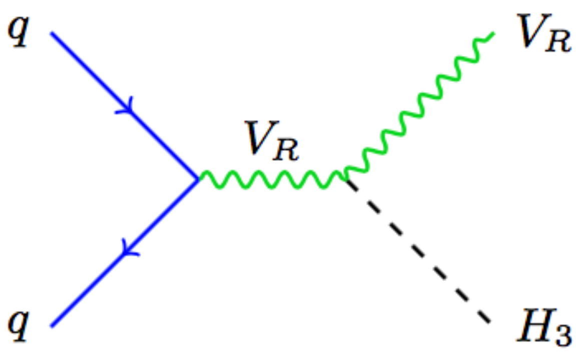
Summary

- Left-Right model with TeV scale seesaw: a compelling scenarios for neutrino masses:
- Rich set of predictions for colliders and low energies:(W_R ,Z', N, Δ_R^{++}, $\beta\beta_{0\nu}$ etc)
- Displaced vertex searches: a new window to seesaw physics.
- LHC can broaden our understanding of nu mass origin based on LR seesaw significantly!!

Happy birthday, Manfred!

Looking for this signal: Light H_3 production at LHC14





Light Higgs leads to displaced vertices at LHC

- H_3 is a linear combination of SM Higgs h and LR new Higgs H_1 (θ_1, θ_2) and has effective quark coupling of the form:

$$H_3 \bar{u} u \qquad \frac{1}{\sqrt{2}} \widehat{Y}_U \sin\tilde{\theta}_1 - \frac{1}{\sqrt{2}} \left(V_L \widehat{Y}_D V_R^\dagger \right) \sin\tilde{\theta}_2$$

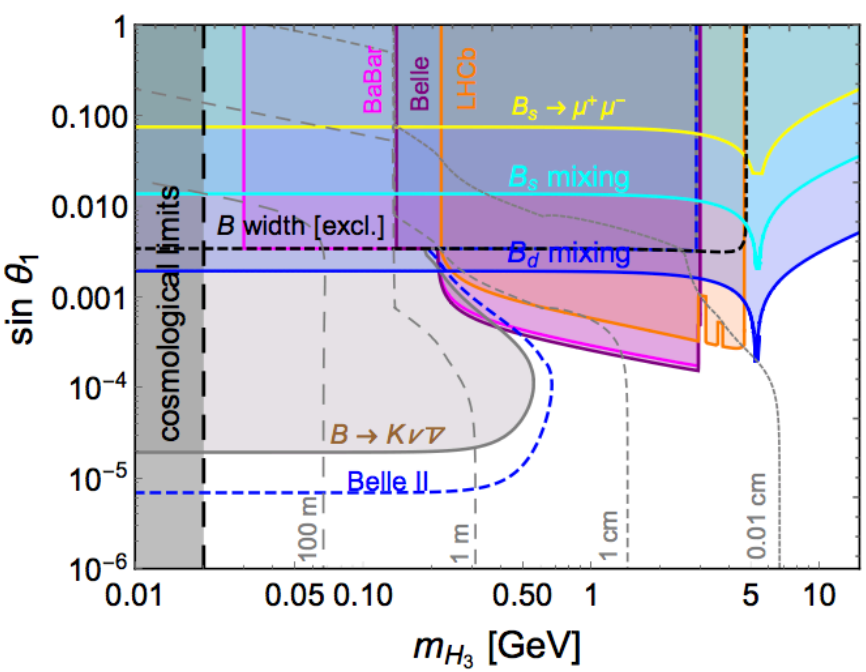
$$H_3 \bar{d} d \qquad \frac{1}{\sqrt{2}} \widehat{Y}_D \sin\tilde{\theta}_1 - \frac{1}{\sqrt{2}} \left(V_L^\dagger \widehat{Y}_U V_R \right) \sin\tilde{\theta}_2$$

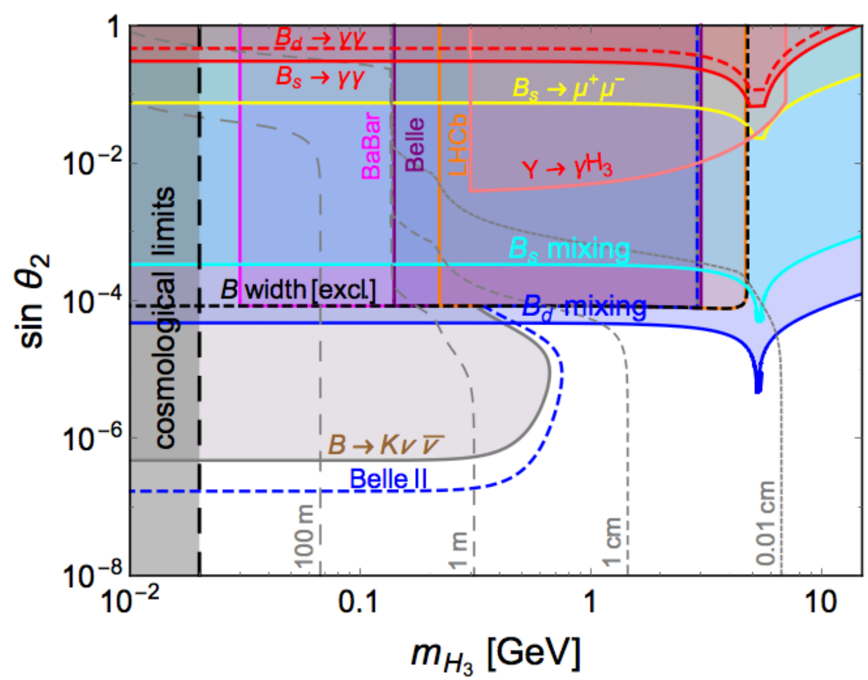
$$\sin\tilde{\theta}_2 = \sin\theta_2 + \xi \sin\theta_1$$

- For light H_3 , B and K-decays limit the value of mixing angles (barring cancellation)

constraints on H_3 mixings from B-decays (Babar,Belle,LHCb)

- Mixing with SM Higgs and heavy LR Higgs H^0 (θ_1, θ_2) are strongly constrained for m~GeV;



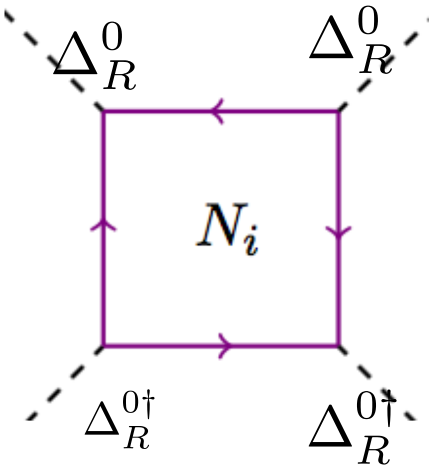


(Dev, RNM, Zhang'16-17)

Theoretical upper limit on M_N

- Like the top quark in the SM, very large RHN mass will destabilize the vacuum. This gives an upper limit on:

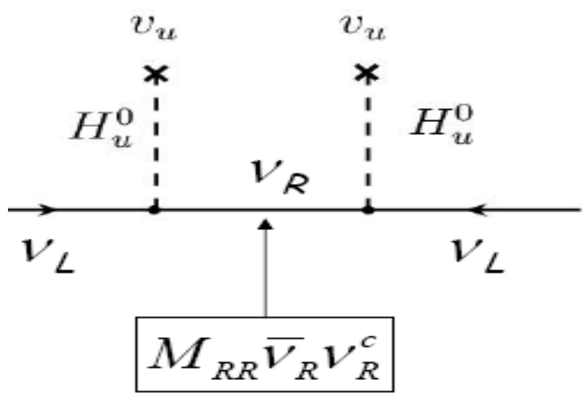
$$\left\{ \sum_i M^4_{N_{R,i}} \right\}^{1/4} \leq 1.18\, M_{W_R}$$



(RNM'86)

Seesaw paradigm for small m_ν

- SM+ RH neutrinos ν_R but with heavy Majorana mass



$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_{\nu_R} \end{pmatrix}$$

→

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

(type I)

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

- ν_R Majorana mass breaks B-L maximally !