Probing left-right seesaw in colliders

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Why left-right seesaw?

- Two basic ingredients of seesaw:

  (i) Right handed neutrinos

  (ii) Broken B-L symmetry

- Both automatic in left-right models

- If scale is in the TeV range,

a plethora of experimental implications

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

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

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

- Parity a spontaneously broken symmetry: $M_{W_R} \gg M_{W_L}$

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

Breaking of LR and type I seesaw

$$\begin{tikzcd} SU(2)_L \times SU(2)_R \times U(1)_{B-L} \arrow[d, "v_R \ (\Delta L=2)"] & \\ SU(2)_L \times U(1)_Y \arrow[d, "\kappa"] \arrow[r] & M_{\nu,N} = \begin{pmatrix} 0 & h\kappa \\ h\kappa & fv_R \end{pmatrix} \\ U(1)_{em} & \end{tikzcd}$$

$$M_N = fv_R$$

(Mohapatra, Senjanovic'79)

- Seesaw formula

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

Symmetry origin of Majorana Neutrinos

- Electric charge formula:

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

- Above EW scale,

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

Parity breaking as origin of Majorana Neutrino mass

- Electric charge formula in LR *(contrast this with SM)*

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

- 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)

Can type I seesaw scale be in the TeV range?

- 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.

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

Doublet breaking of LR and Inverse seesaw alternative

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

$$\begin{tikzcd}
SU(2)_L \times SU(2)_R \times U(1)_{B-L} \arrow[d, "<\chi_R^0>"', "v_R"] \\
SU(2)_L \times U(1)_Y \arrow[d, "<\phi_1^0>"', "\kappa"] \arrow[r, Rightarrow] & \begin{pmatrix} 0 & h\kappa & 0 \\ h\kappa & 0 & fv_R \\ 0 & fv_R & \mu \end{pmatrix} \\
U(1)_{em}
\end{tikzcd}$$

(ΔL=0) $M_N = fv_R$

$$\begin{array}{ccc} (\nu & N & S) \\ \end{array}$$

$$\begin{pmatrix} 0 & h\kappa & 0 \\ h\kappa & 0 & fv_R \\ 0 & fv_R & \overset{\uparrow}{\mu} \end{pmatrix}$$

(μ ~keV:weak ΔL=2)

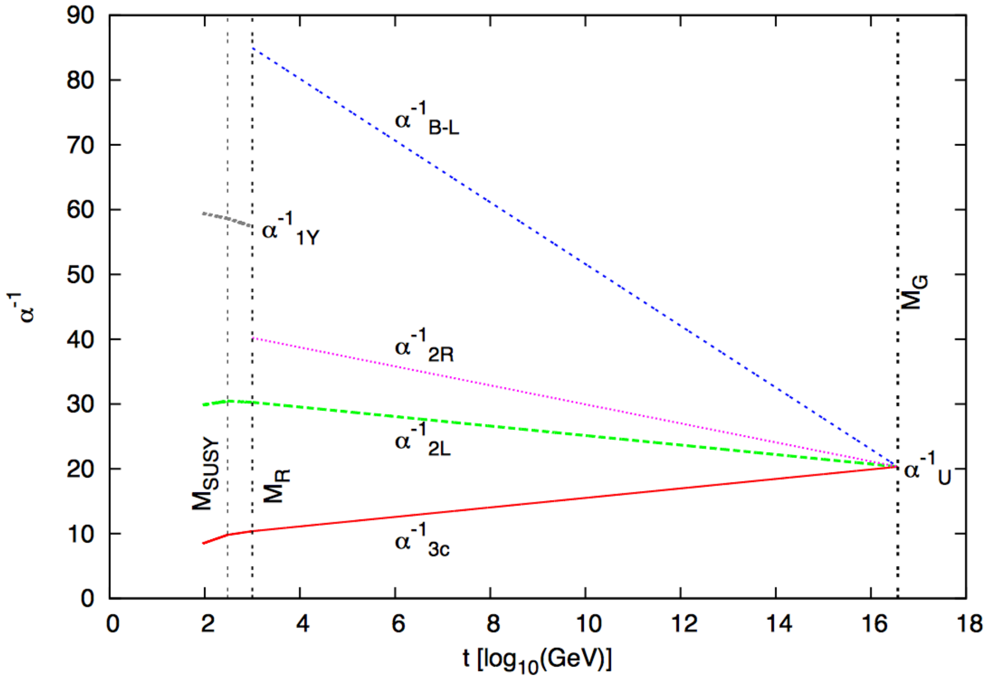
$$\boxed{m_\nu \simeq m_D (fv_R)^{-1} \mu (fv_R)^{-1} m_D^T}$$

(RNM'86; RNM, Valle'86)

- Inverse seesaw more natural in LR; TeV scale.

Inverse seesaw and GUTs

- 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)

TeV Inverse seesaw embeddable in GUTs

unlike TeV scale type I.

Rich phenomenology with TeV scale LR seesaw (type I)

- Allows collider probes of seesaw ✓
- Large lepton flavor violation $\mu \to e + \gamma, \mu \to e$
- Large lepton number violating processes $\beta\beta_{0\nu}$

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 Bosons:

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-$B_{s\text{-bar}}$,

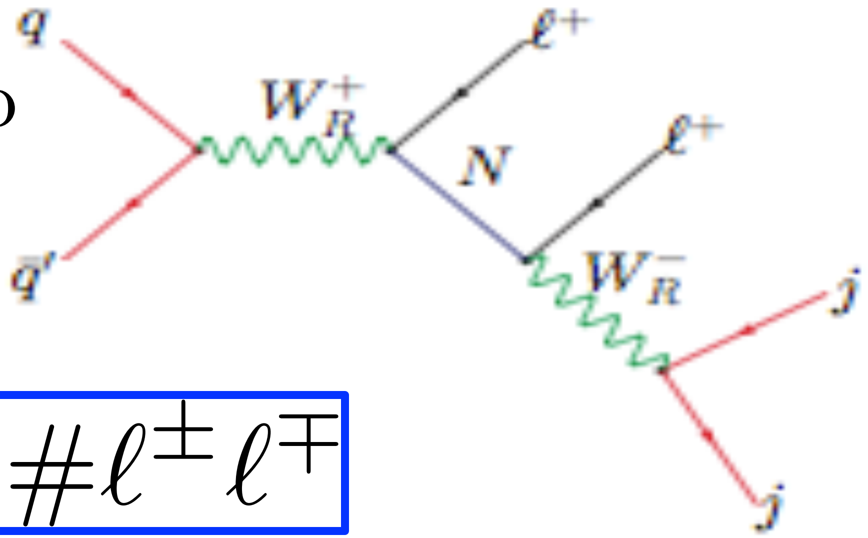
  → $M_{W_R} > 2.5$ TeV (g_R/g_L)

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

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

Collider signals of LR seesaw (Type I)

- Golden channel: $W_R \to \ell_i \ell_k j j$ (Two sources)
- W_R mediates graph (Keung, Senjanovic'82)



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

M $_{WR}$ = 3 TeV

- Predicts $\boxed{\#\ell^\pm\ell^\pm = \#\ell^\pm\ell^\mp}$

and $A_{\ell_i \ell_j jj} \propto M_{N,ij}$

What if $\boxed{\#\ell^\pm\ell^\pm \neq \#\ell^\pm\ell^\mp}$?

- One resolution: General inverse seesaw

$$\begin{pmatrix} 0 & h\kappa & 0 \\ h\kappa & M_N & fv_R \\ 0 & fv_R & \mu \end{pmatrix} \qquad M_N \sim fv_R$$

- Neutrino mass is still tiny but collider signal diff.

(Dev, RNM; Aniamati,Hirsch,Nardi):

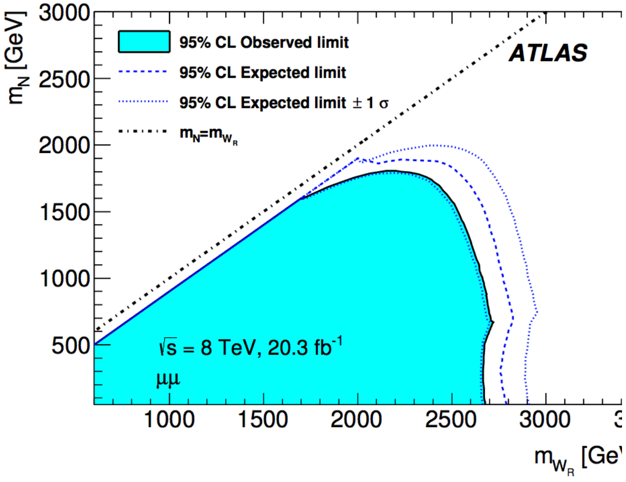
- Second resolution: CPV in N-decay: (Gluza, Jelinski)

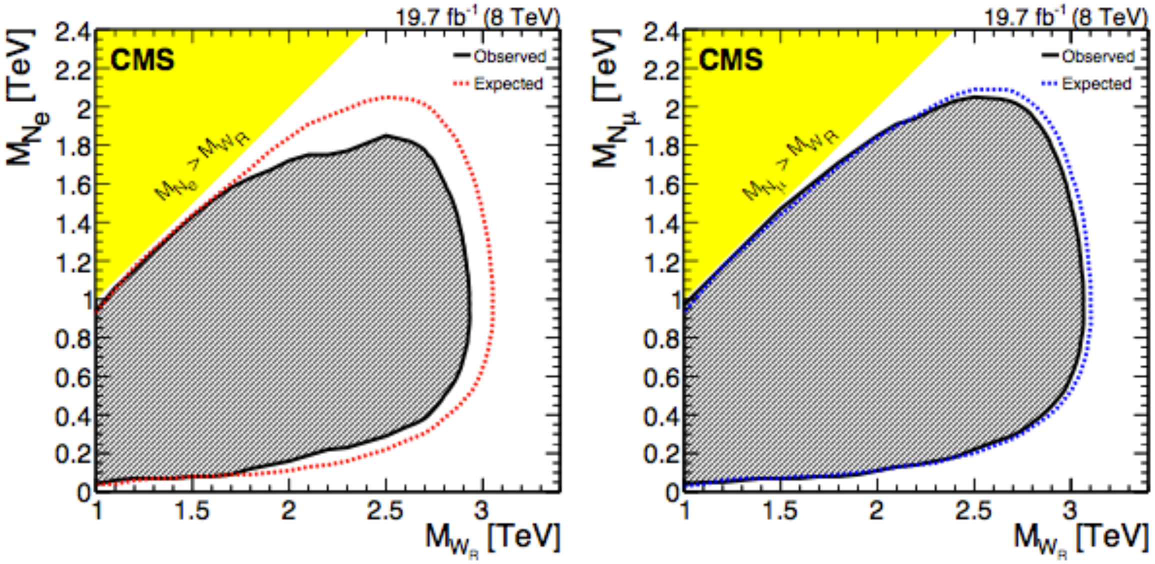
Current LHC searches

- 0.1 $M_{WR} < M_N < M_{WR}$;
- Leptons, jets clearly separated
- Look for bumps in $\ell\ell jj$ inv. Mass
- $p_T > 60 \text{ GeV}$ for one lepton
- $p_T > 40 \text{ GeV}$ for the other

  and also for jets (CMS)

Current limit from LHC





- Current limit from dijet data: 2.8 TeV($g_L = g_R$)
- LHC14 reach 5-6 TeV

$g_L = g_R$ depends on scale of P breaking

- In general if P-breaking takes place at a higher scale than $SU(2)_R$ breaking, $g_R < g_L$ (Chang, RNM, Parida'84)
- Important because this allows W_R to be lighter than apparent collider and FCNC limits;

- How low can g_R be? Theoretical lower bound: $g_R > 0.66\, g_L$

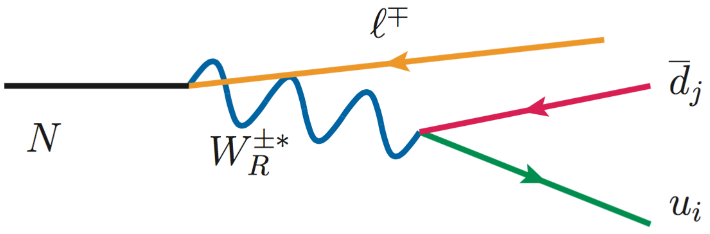
(Brehmer, Hewett, Rizzo, Kopp,Tattersel'14; Dev, RNM, Zhang'16)

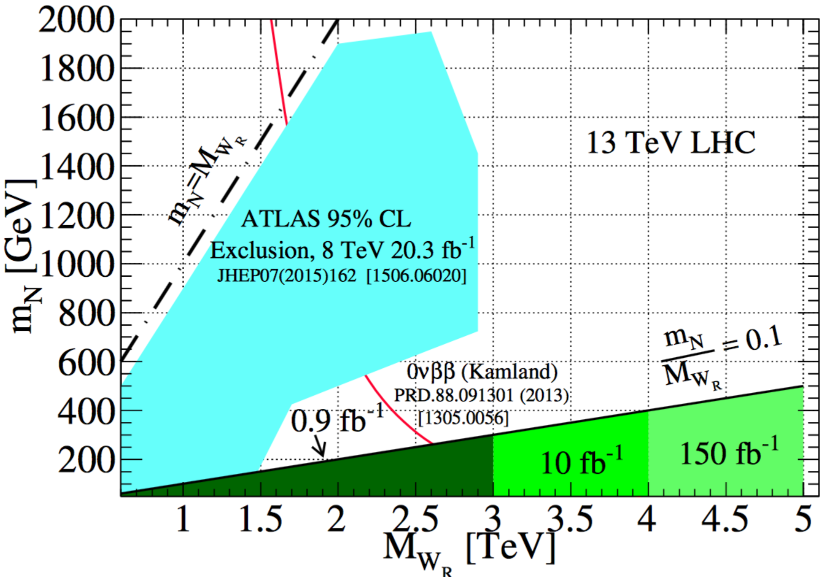
$M_N < 0.1\ M_{WR}$

- ATLAS/CMS sensitivities break down

(Mitra, Ruiz, Scott, Spanowsky'16)

- Use neutrino jets instead to recover lost sensitivity



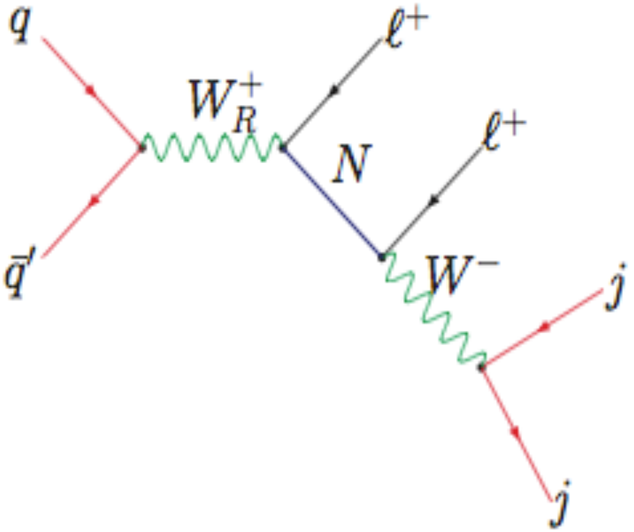


Signature: $pp \rightarrow \ell^{\pm} + j_{\mathrm{Fat}} + X$

Other contributions in LR

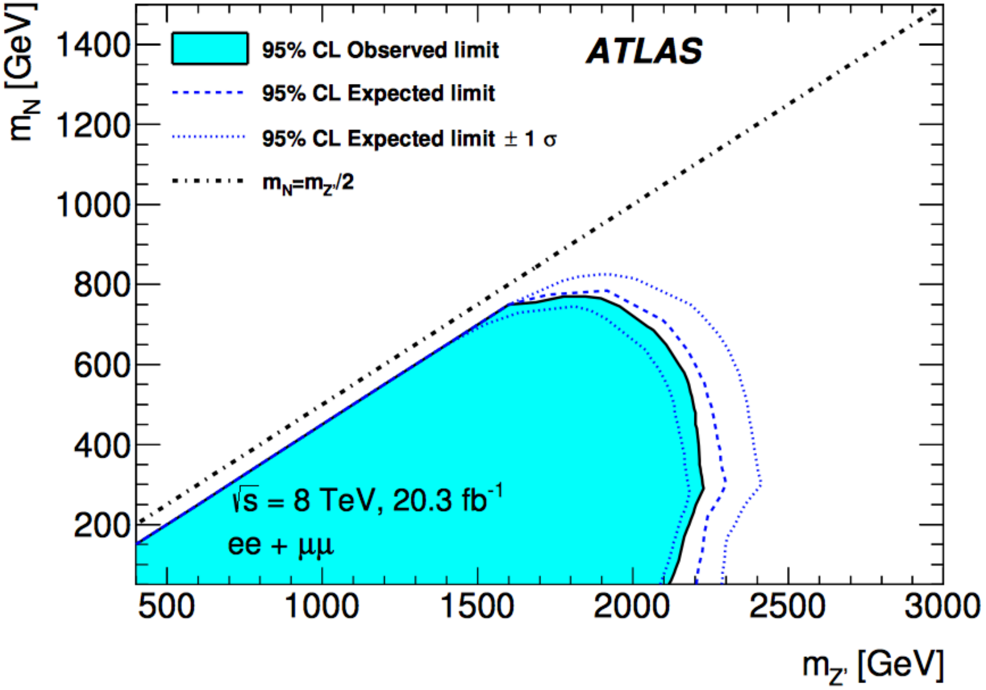
- Golden channel: $W_R \rightarrow \ell_i \ell_k j j$ (second source)
- Heavy light mixing W_L (RL)
- mediated (Chen, Dev, RNM'13)

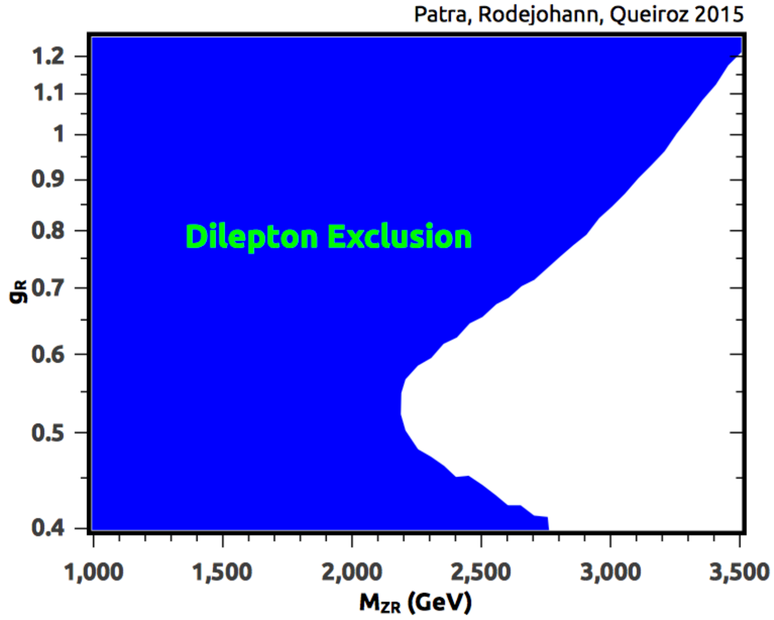
$$q\bar{q} \rightarrow W_R \rightarrow \ell + N;$$
$$N \rightarrow \ell W_L$$



- Measures M_D

Limits on Z_R Boson from LHC





- W_R –Z′ mass relation a test of LR ($g_L = g_R$)

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

Type I

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

Inverse

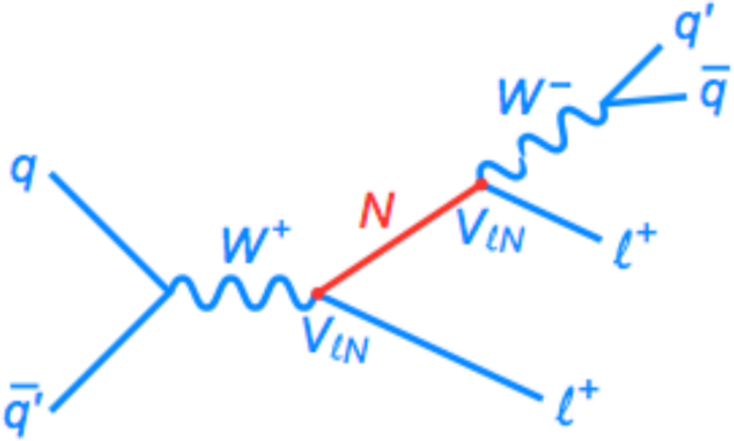
SM or LR

$$W \to \ell + N$$

$$\hookrightarrow \ell^{\pm} + W$$

(A. Das talk)

$$\sigma = \sigma_0 |V_{\ell N}|^2$$



- ❖Like sign dileptons signal same as in LR case:
- ❖But SM signal unobservable since $\boxed{V_{\ell N} \simeq \sqrt{\frac{m_\nu}{M_N}}}$ $\leq 10^{-5}$
- ❖Current reach at LHC ~ 10^{-3}

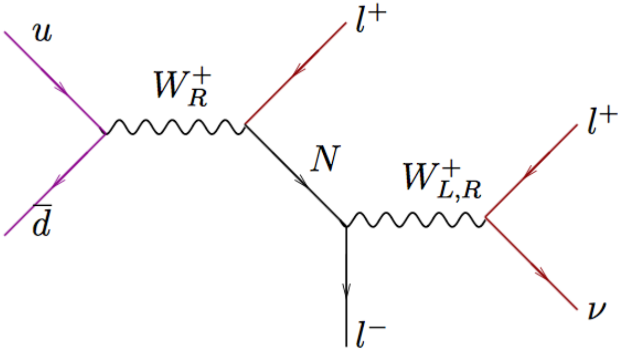
$\ell^\pm \ell^\pm jj$ signal with enhanced $V_{\ell N}$ in SM seesaw?

- There have been attempts to build type I extensions of SM models where $V_{\ell N}$ is much larger!
- Conjecture: they will likely not increase the production rate in the mass range $M_W << M_N$, where $A_{\ell\ell jj} \propto m_D M_N^{-1} m_D$ and hence small due to type I seesaw formula !!
- If true, observation of $\ell^\pm \ell^\pm jj$ could point to existence of W_R (?).

Signal of minimal inverse seesaw (ISS)

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

- Neutrino mass is still tiny but collider signal diff. trilepton and L-conserving.



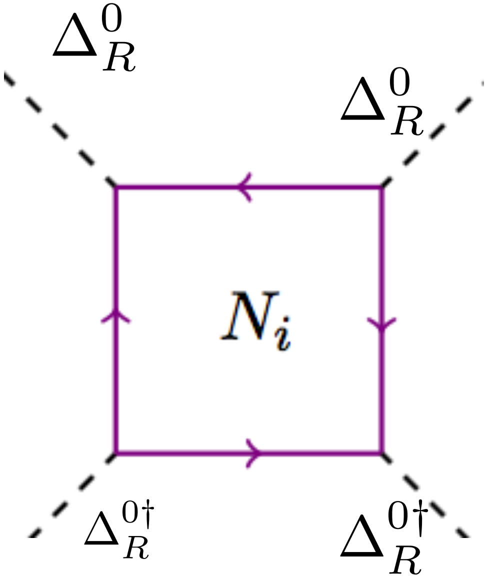
(Chen, Dev'11; Das and Okada'12)

- New fermions: $N_{1,2,3}$

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:

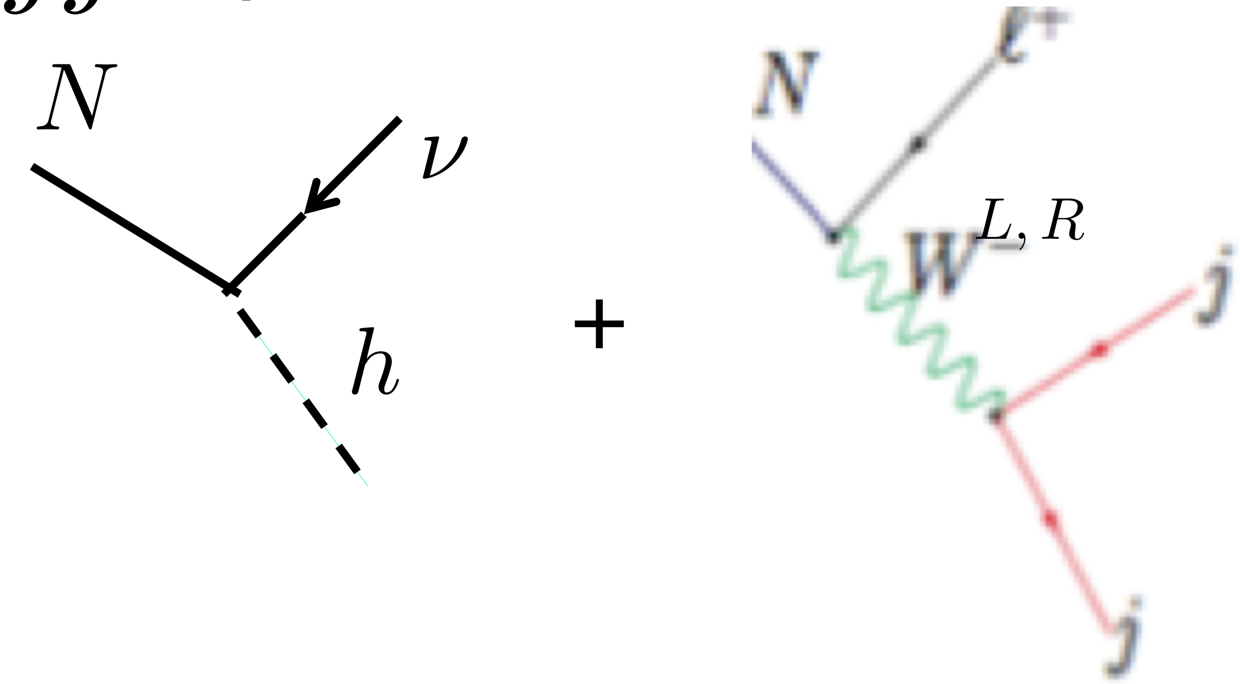
$$\left\{ \sum_{i} M^{4}_{N_{R,i}} \right\}^{1/4} \leq 1.18\ M_{W_R}$$



(RNM, PRD’86)

High mass range~0.1-1 TeV
$M_N < M_{WR}$

- Life time very short- Look for invariant mass of $\ell j j$ system

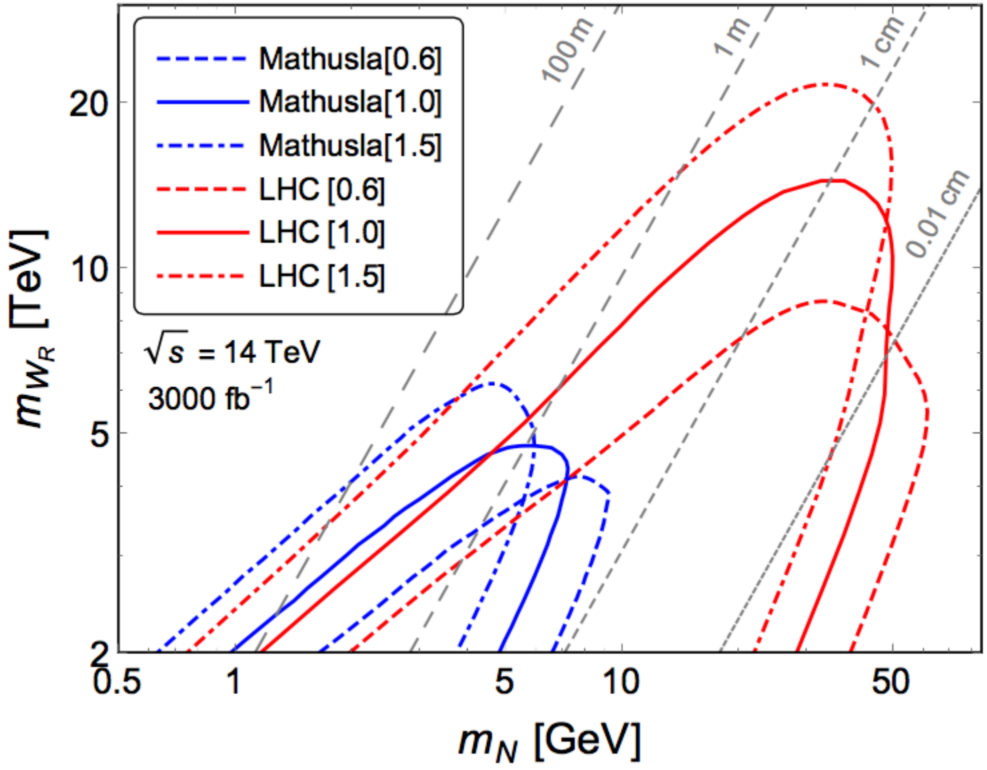


light N: possible displaced vertex searches at LHC

- .

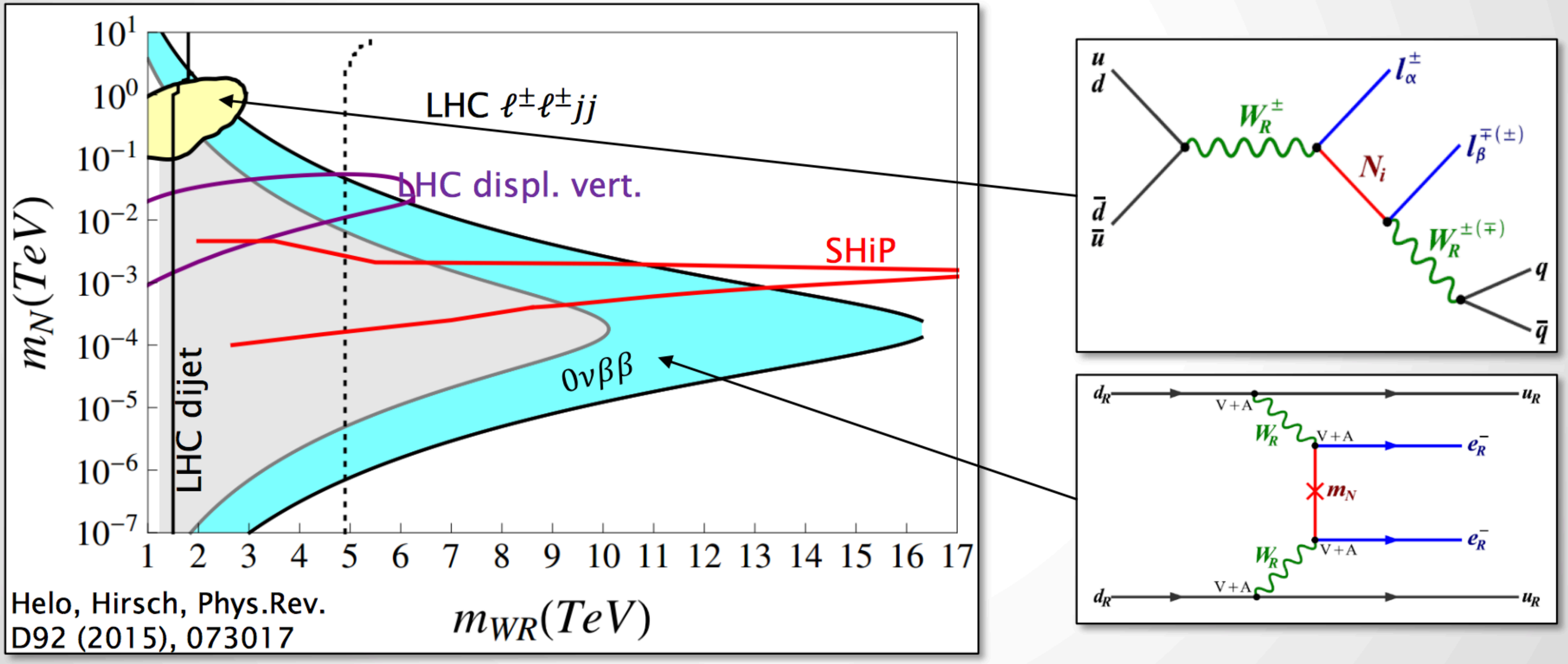
$$\tau_N^0 \simeq 9.3\times 10^{-3}\left(\frac{m_N}{10\,\mathrm{GeV}}\right)^{-5}\left(\frac{M_{W_R}}{3\,\mathrm{TeV}}\right)^{4}\left(\frac{g_R}{g_L}\right)^{-4}\ \mathrm{m}$$

25



- (Helo, Hirsch, Dev, RNM, Zhang (@LHC))

SHIP Experiment- light N



Helo, Hirsch, Phys.Rev. D92 (2015), 073017

Scalars

New heavy neutral Higgs

- LR is a two Higgs doublet model with the second Higgs coupling related to the SM Higgs by parity:
- They have FCNH couplings which imply

$$H_1^0, A^0; \quad M_{H_1^0, A^0} \geq 10 \text{ TeV}$$

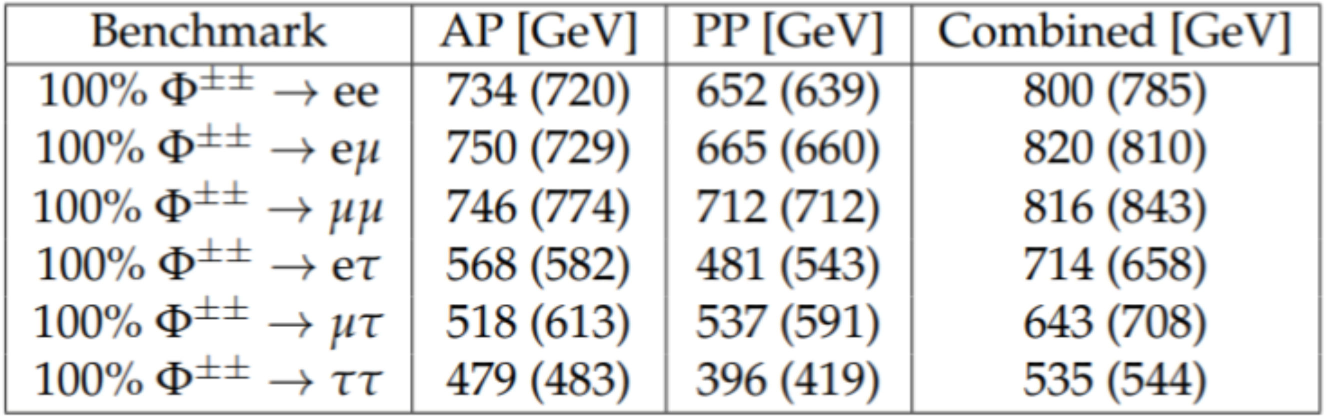
- Need higher energy colliders (HE-LHC, 100 TeV…)

signature decay $H_1^0 \to b\bar{b}$

Seesaw related Higgs:Doubly charged scalars

$$\Delta^{++}$$

- CMS



Benchmark	AP [GeV]	PP [GeV]	Combined [GeV]
100% $\Phi^{\pm\pm} \to ee$	734 (720)	652 (639)	800 (785)
100% $\Phi^{\pm\pm} \to e\mu$	750 (729)	665 (660)	820 (810)
100% $\Phi^{\pm\pm} \to \mu\mu$	746 (774)	712 (712)	816 (843)
100% $\Phi^{\pm\pm} \to e\tau$	568 (582)	481 (543)	714 (658)
100% $\Phi^{\pm\pm} \to \mu\tau$	518 (613)	537 (591)	643 (708)
100% $\Phi^{\pm\pm} \to \tau\tau$	479 (483)	396 (419)	535 (544)

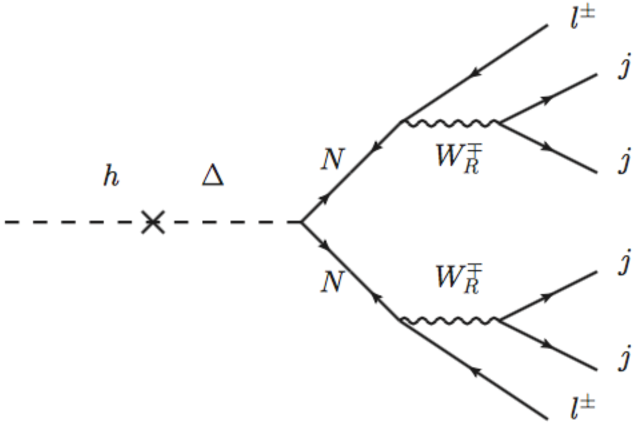
- Neutral scalars : several

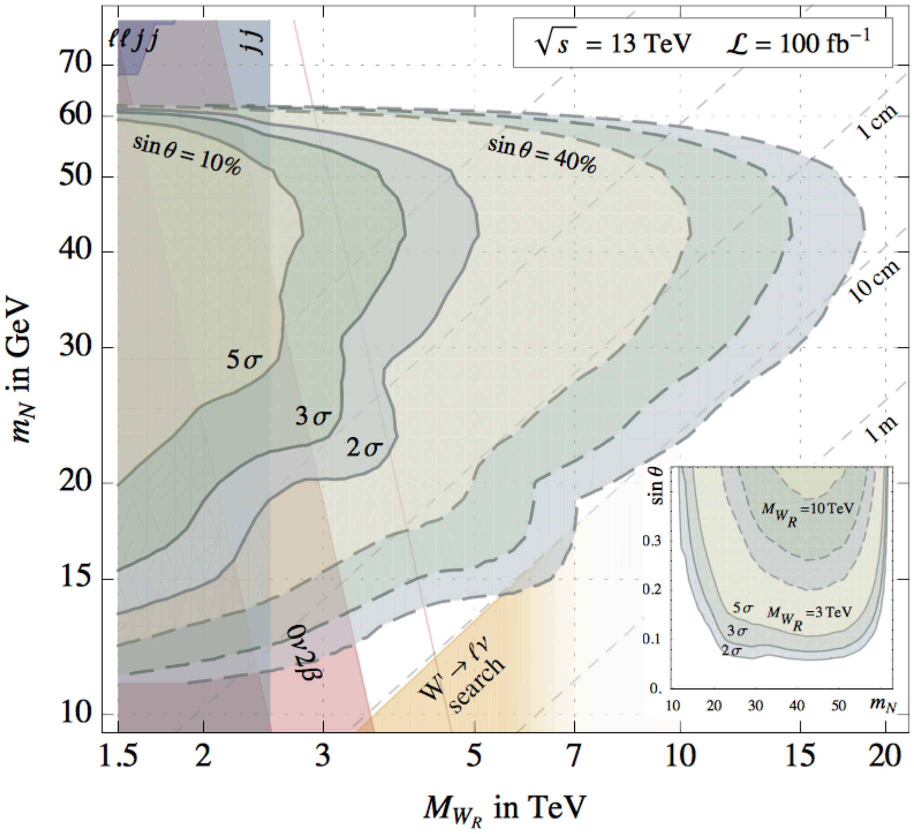
Neutral Seesaw Higgs

- $H_3^0 \equiv Re\Delta_R^0 \quad M_{H_3^0} \simeq 1 - 1000\mathrm{GeV}$
- Three domains of B-L breaking Higgs $\mathbf{\Delta^0_R}$ masses (M_{H3})
- $M_{H3} \sim v_R >> M_h$ → (Maiezza, Nemevsek, Nesti'15;Dev, RNM, Zhang'16)
- $M_{H3} << v_R \sim M_h$
- $M_{H3} << M_h << v_R$ (~ few GeV to 100 MeV) (Dev, RNM, Zhang'17)

Rare decays of SM Higgs from seesaw

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





- Displaced vertices at LHC

(Maiezza, Nemevsek,Nesti'15; Miha's talk;
However, similar decay for SM seesaw: Lopez-Pavon et al'17)

Light H_3 (0.1-10 GeV) and displaced vertices

- Motivation for light Higgs H_3
- H_3 analog of SM Higgs- connected to B-L breaking.

- If $SU(2)_R$ x $U(1)_{B-L}$ is broken radiatively, there is a good chance that $H_3^0 \equiv Re\Delta_R^0$ is light:

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

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

Reason for displaced vertices:FCNC constraints:

- 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:

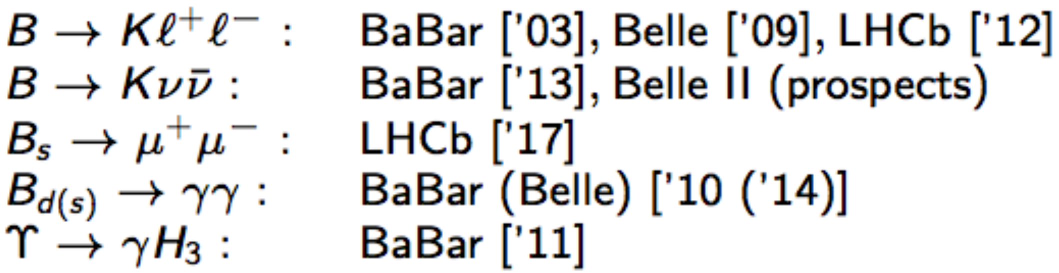
$$
\begin{array}{ll}
H_3\bar{u}u & \frac{1}{\sqrt{2}}\widehat{Y}_U \sin\tilde{\theta}_1 - \frac{1}{\sqrt{2}}\left(V_L \widehat{Y}_D V_R^\dagger\right)\sin\tilde{\theta}_2 \\
H_3\bar{d}d & \frac{1}{\sqrt{2}}\widehat{Y}_D \sin\tilde{\theta}_1 - \frac{1}{\sqrt{2}}\left(V_L^\dagger \widehat{Y}_U V_R\right)\sin\tilde{\theta}_2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

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

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

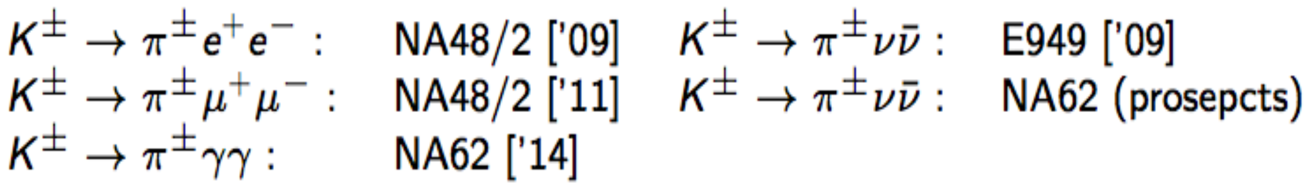
FCNC Processes:

- Expts: For B decays:



$B \to K\ell^+\ell^-$:	BaBar ['03], Belle ['09], LHCb ['12]
$B \to K\nu\bar{\nu}$:	BaBar ['13], Belle II (prospects)
$B_s \to \mu^+\mu^-$:	LHCb ['17]
$B_{d(s)} \to \gamma\gamma$:	BaBar (Belle) ['10 ('14)]
$\Upsilon \to \gamma H_3$:	BaBar ['11]

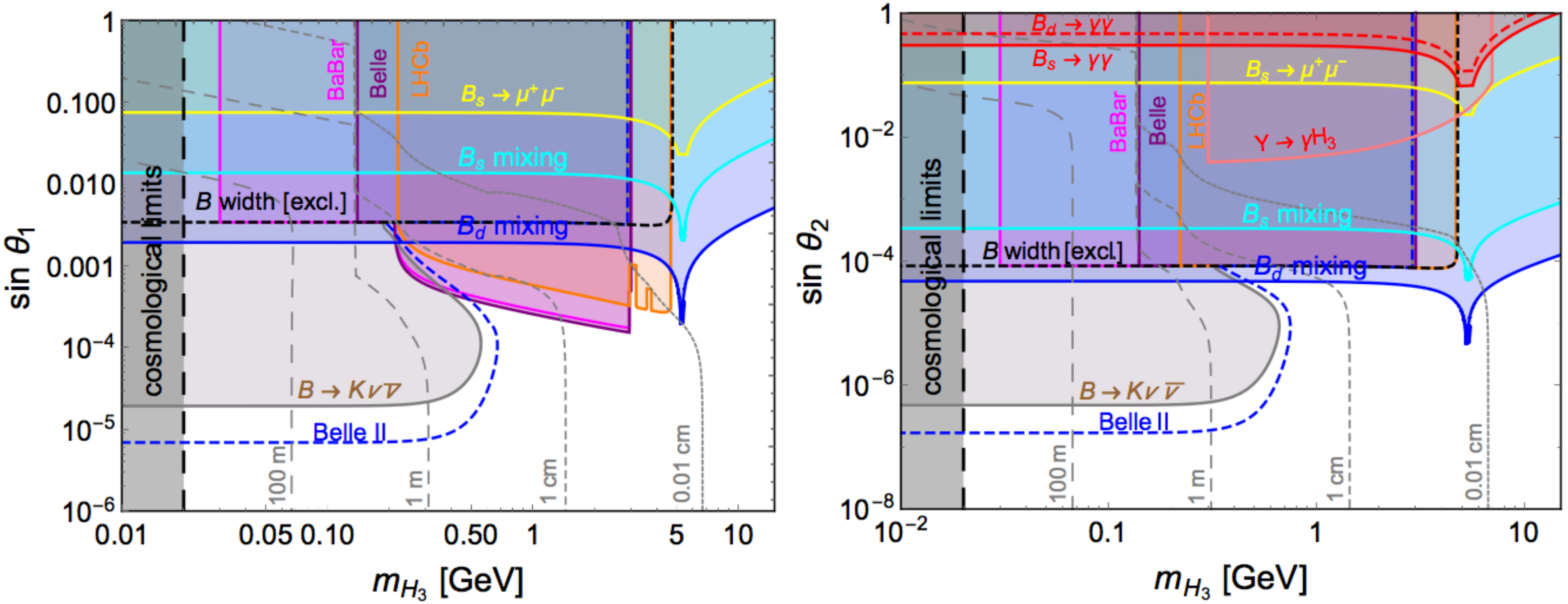
- K-decays:



$K^\pm \to \pi^\pm e^+ e^-$:	NA48/2 ['09]	$K^\pm \to \pi^\pm \nu\bar{\nu}$:	E949 ['09]
$K^\pm \to \pi^\pm \mu^+ \mu^-$:	NA48/2 ['11]	$K^\pm \to \pi^\pm \nu\bar{\nu}$:	NA62 (prosepcts)
$K^\pm \to \pi^\pm \gamma\gamma$:	NA62 ['14]		

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

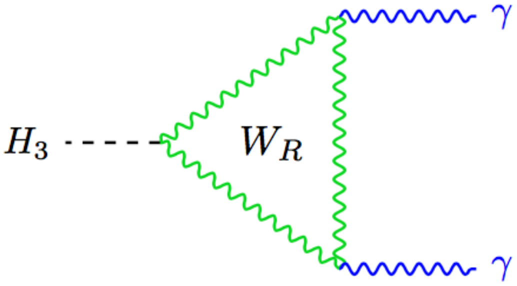
- Mixing with SM Higgs and heavy LR Higgs H^0 (θ_1, θ_2) are strongly constrained for m~GeV;



(Dev, RNM, Zhang'16-17)

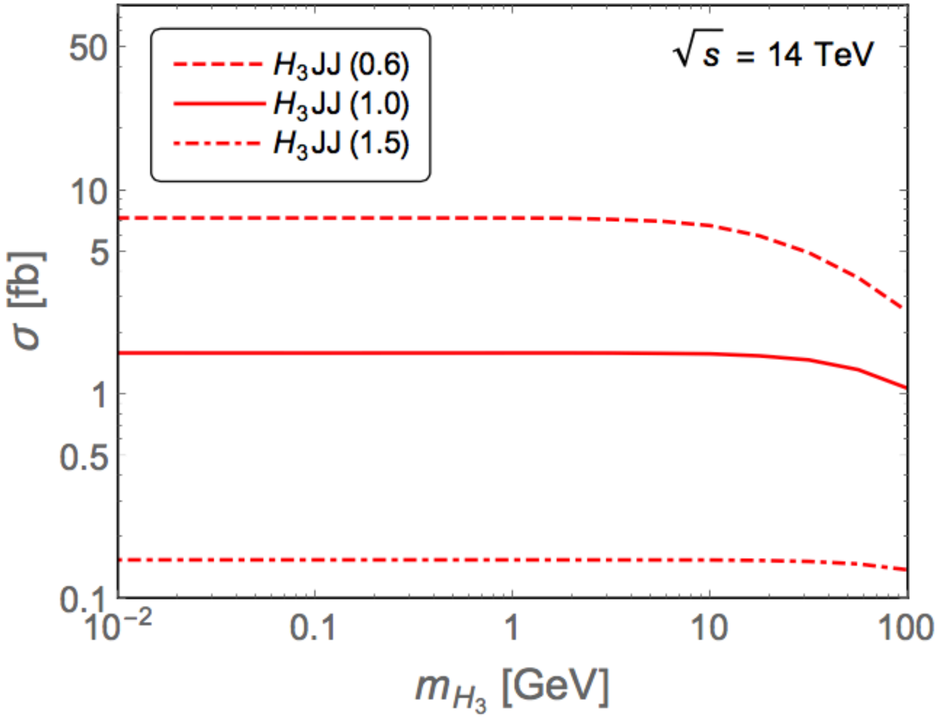
How does light H_3 decay?

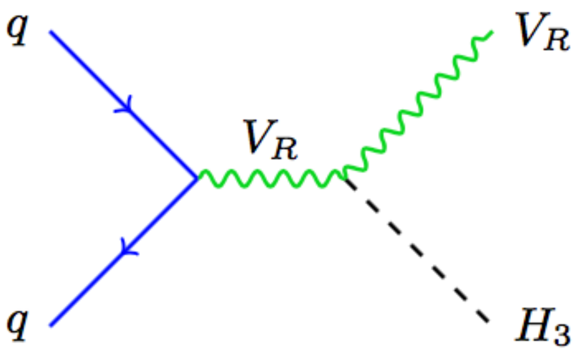
- H_3 decay to quarks and leptons suppressed by FCNC constraints.
- Dominant decay mode is $\gamma\gamma$
- *Very unique to LR models*



- Different from any other BSM light scalar (e.g. multi Higgs or NMSSM) which will decay predominantly to leptons and jets since its mixing with *h* is not suppressed as in LR.

Light H_3 production at LHC14



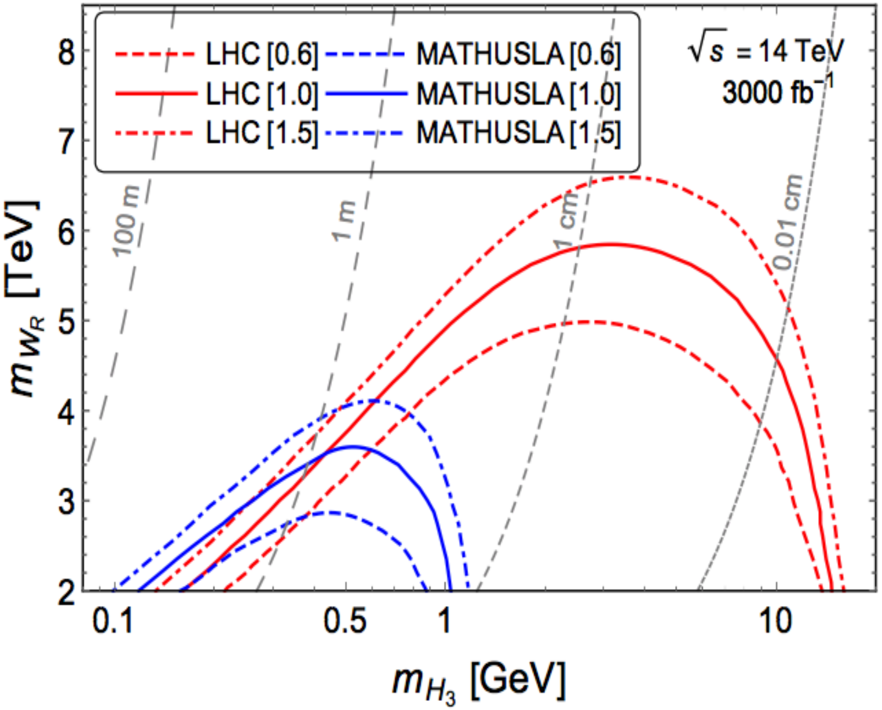


$\gamma\gamma$ Displaced vertices at LHC: W_R –H_3 reach

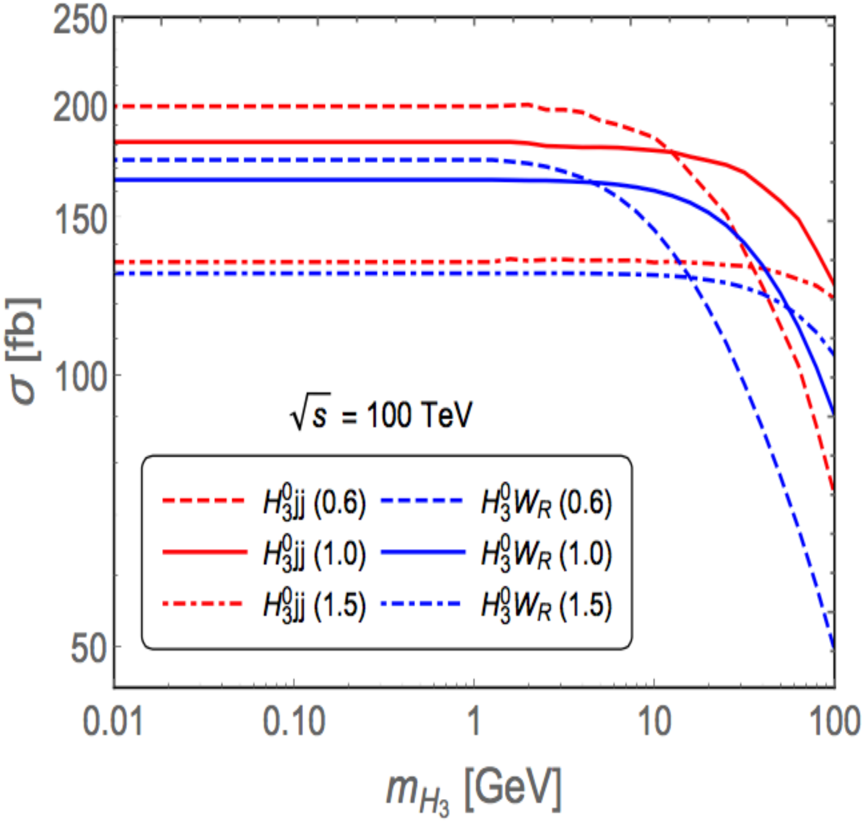
- Near GeV mass H_3^0 accessible at the LHC via displaced vertices ($\gamma\gamma$ mode 100% BR)

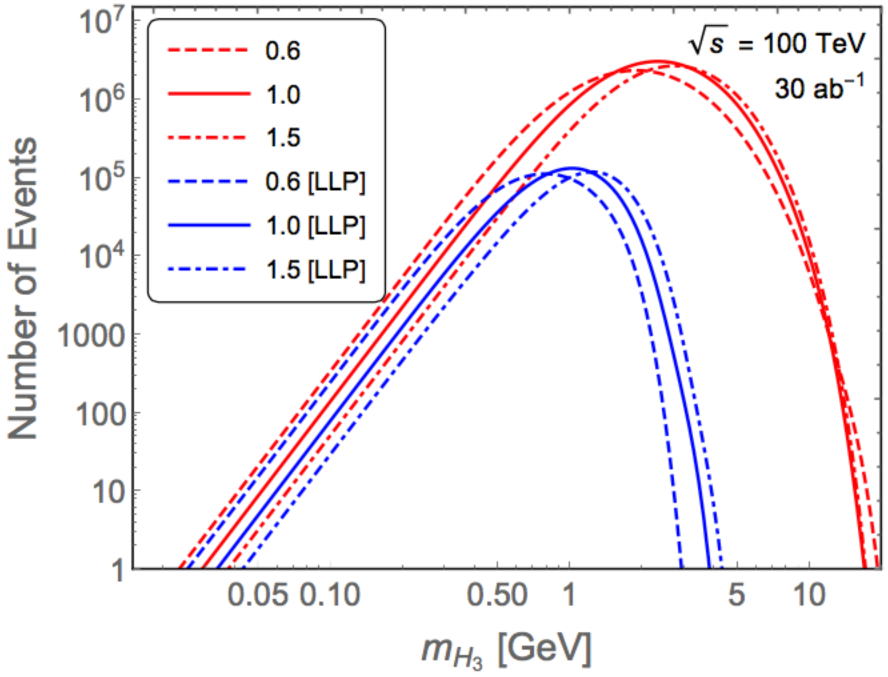
(Dev, RNM, Yongchao Zhang'16)

- $\gamma\gamma$ mode typical of left-right seesaw
- Gammas highly collimated: *challenging*

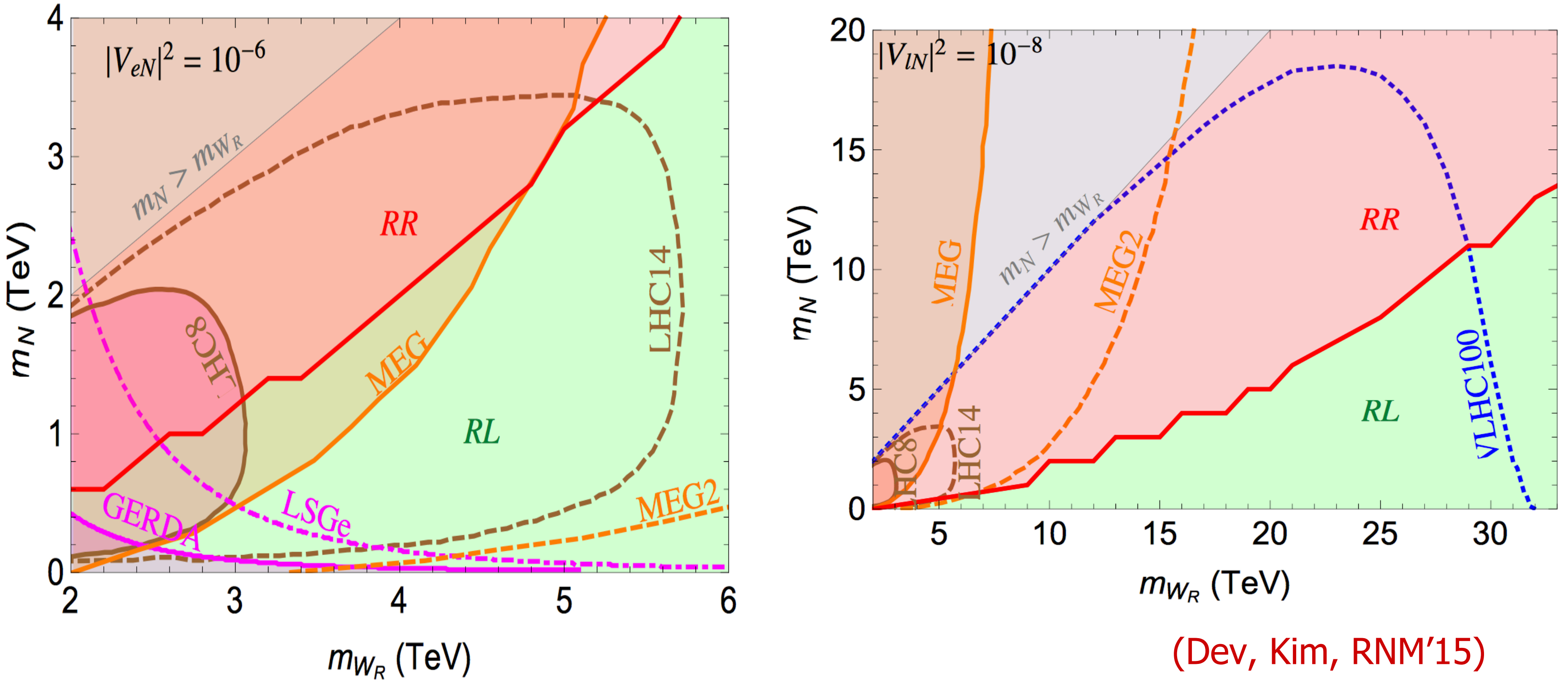


Light H_3 at 100 TeV collider





Future reach for type I LR seesaw



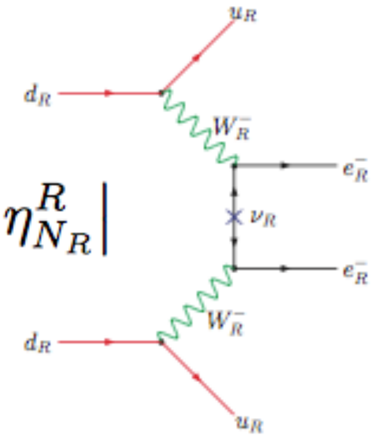
(Dev, Kim, RNM’15)

Summary

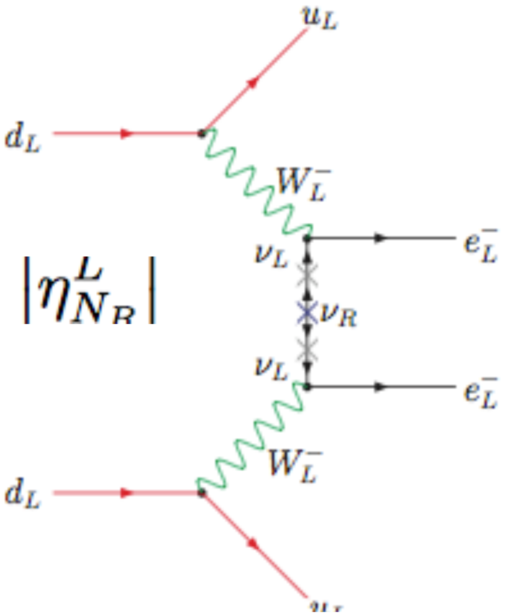
- Left-Right theory with TeV scale seesaw: a compelling scenarios for neutrino masses:
- Rich set of predictions for colliders and low energies:(W_R ,Z', N, Δ_R^{++}, $\beta\beta_{0\nu}$ etc)
- Probe of light seesaw Higgs (analog of SM h) using displaced vertices- a new way to understand seesaw mechanism!
- LHC can broaden our understanding of nu mass origin based on LR seesaw significantly!!

Low energy effects:(i) $\beta\beta_{0\nu}$ in LR seesaw (Type I)

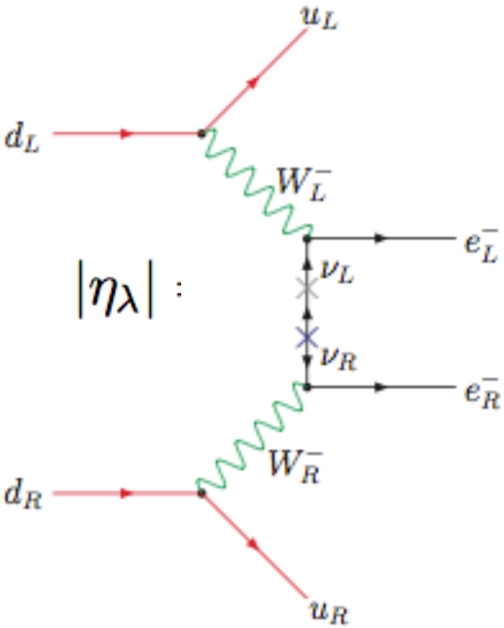
$|\eta^R_{N_R}|$



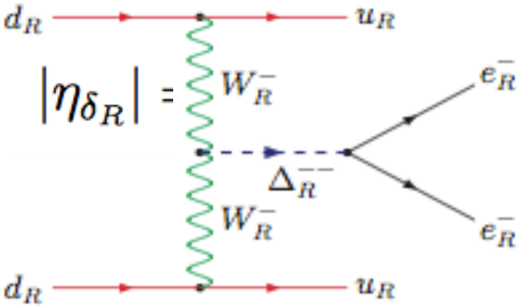
$|\eta^L_{N_R}|$



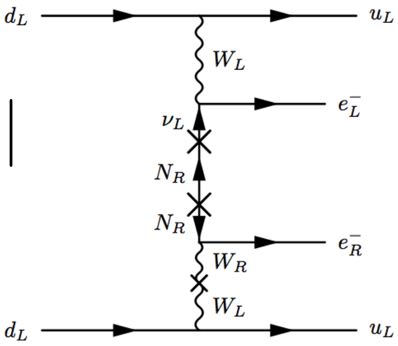
$|\eta_\lambda|$:



$|\eta_{\delta_R}|$ =

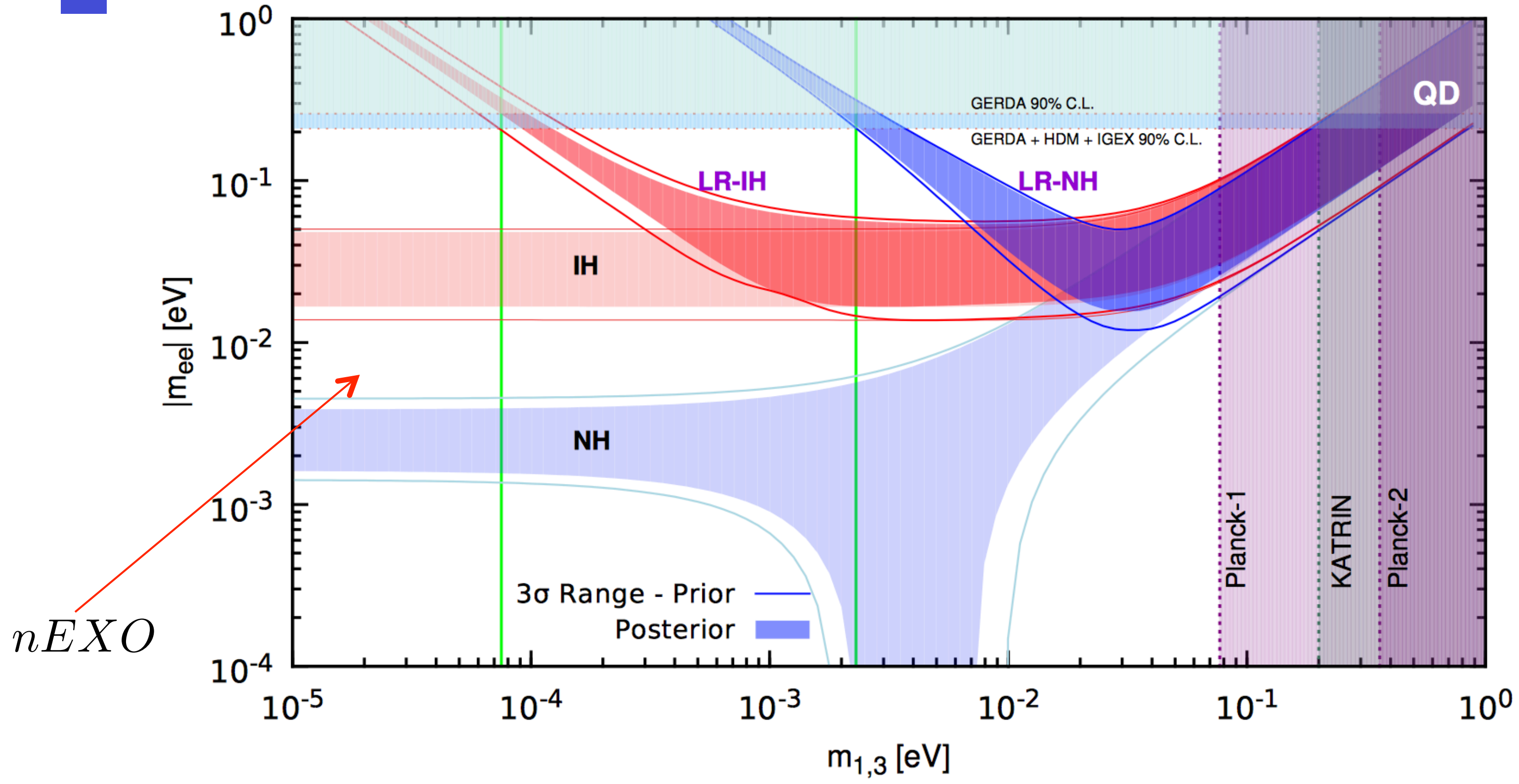


$|\eta_\eta|$



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

Predictions for a LR with type II seesaw



M_{WR} =2 TeV

(Tello, Nemevsek, Senjanovic, Nesti, Vissani'10; Ge, Lindner, Patra'2015; Dev, Goswami, Mitra, Rodejohann'2013)

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

Bigger $V_{\ell N}$ Low energy test of Inverse seesaw

- Low energies: Observable departure from PMNS unitarity for ISS. (η can be close to limit)

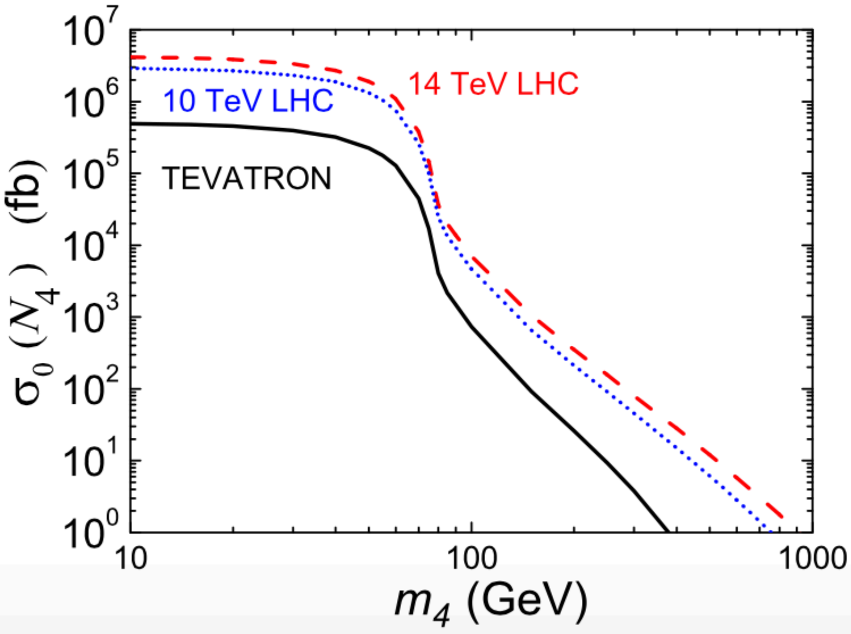
(Fernandez, Garcia, Lopez-Pavon,Vicente'15; Antusch, Fischer'14, Abada et al'07)

- Current bounds: (LFV etc)
- $$\eta < \begin{pmatrix} 0.9979 - 0.9998 & < 10^{-5} & < 0.0021 \\ < 10^{-5} & 0.9996 - 1.0 & < 0.0008 \\ < 0.0021 & < 0.0008 & 0.9947 - 1.0 \end{pmatrix}$$

(Antusch, Fischer)

SM seesaw:

- .



Heavy neutrino poduction in SM:

$$\sigma(pp \to W^* \to l_\alpha^\pm + N_k) \propto |U_{\alpha k}|^2 \sigma_0$$

this plot from:

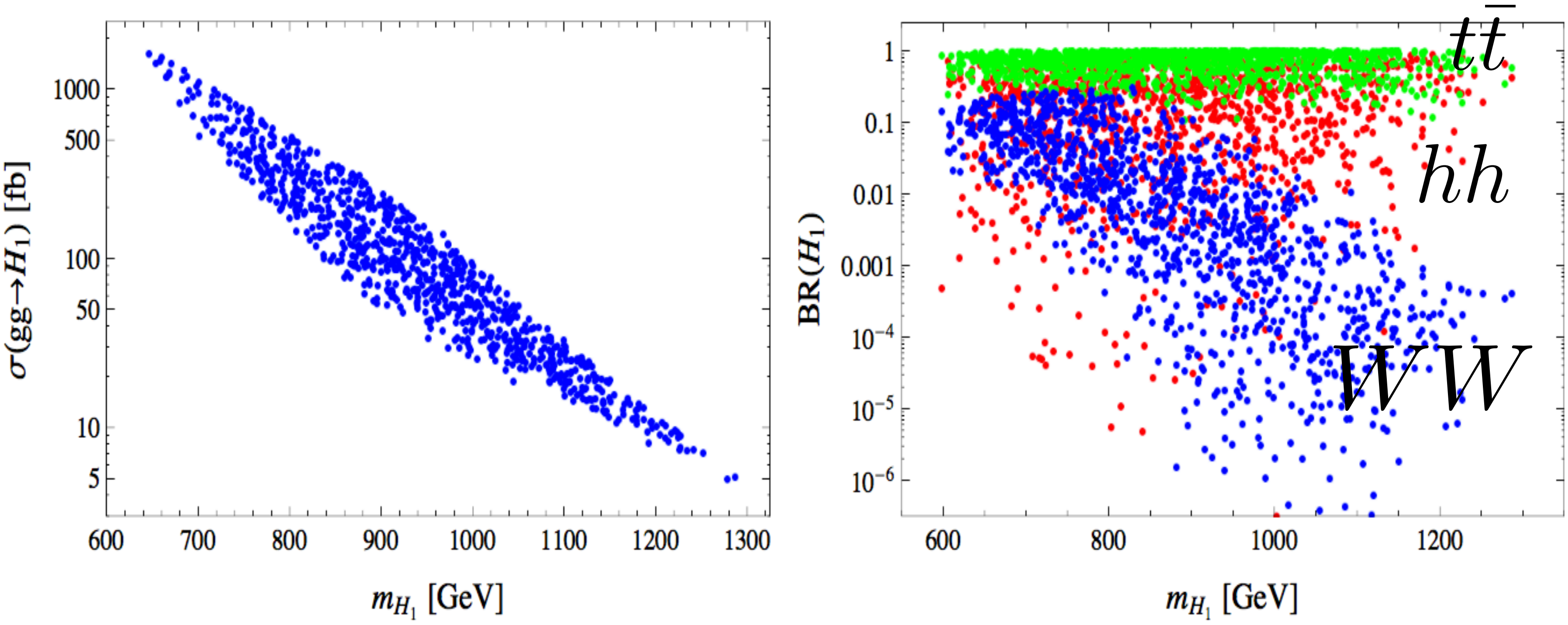
Atre et al, JHEP 0905 (2009) 030

Beyond minimal left-right seesaw and a second neutral Higgs@LHC

An LHC accessible second Higgs in LR?

- LR is a natural 2 Higgs doublet model.
- Parity fixes the coupling of 2nd Higgs to quarks.
- In minimal LR, this leads to large FCNC effects and implies → $M_{H1} > 10$ TeV
- It is possible to extend the model so that it gives effective LR near few TeV and FCNC constraints become weaker→
- $M_{H1} <$ few TeV. (RNM, Yongchao Zhang'15)

Decays and production at LHC 14



Dominant decay mode different from minimal LR!