NEW AVENUES TO RHN PAIR @ HADRONIC COLLIDERS

THE JOINT KAVLI IPMU / DURHAM / KIAS WORKSHOP:
NEW PARTICLE SEARCHES CONFRONTING THE FIRST LHC RUN-2 DATA

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Low scale type-I seesaw and the search

- **Type-I seesaw: elegance in the dark**

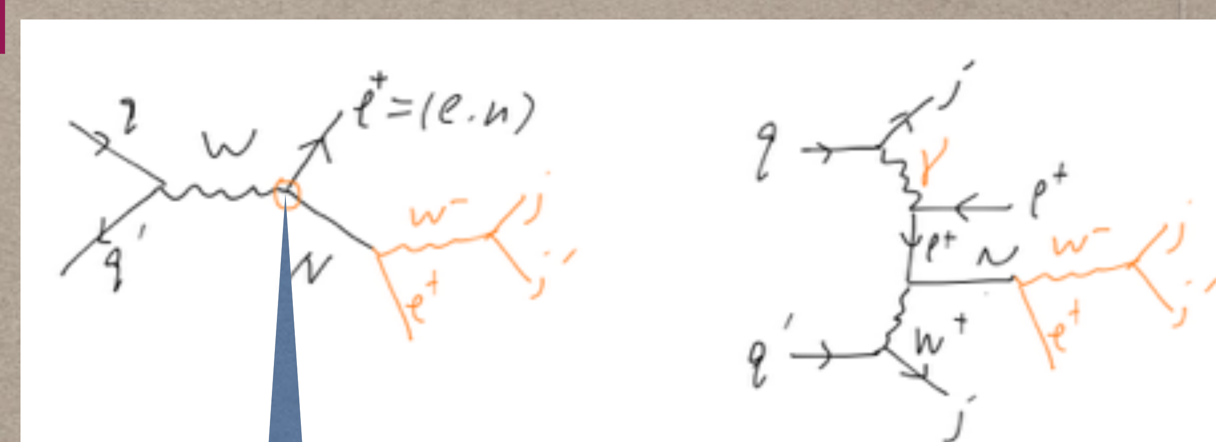
The most elegant way to understand non-zero mass of neutrinos, but they are subject to decoupling at low energy

$$y_{\nu_R}\bar{\ell}\Phi\nu_R + \frac{1}{2}M_{\nu_R}\nu_R^2 \Rightarrow m_\nu \sim -\, m_D^\dagger M_{\nu_R}^{-1} m_D^* \lesssim 0.1\,\mathrm{eV} \quad [m_D = y_{\nu_R} v \text{ with } v \simeq 246\,\mathrm{GeV}]$$

either light RHN (~TeV) & very small coupling ($<10^{-6}$) or heavy RHN (~GUT) & large coupling (~1), both hopeless at colliders

- **Large L-R mixing and same sign di-lepton (SSDL)**

For a single family, the sterile and active mixing angle $(m_\nu/M_{\nu_R})^{1/2} \ll 1$ but RHN flavor structure may allow a sizable mixing angle at the price of fine-tuning



suppressed by one mixing angle

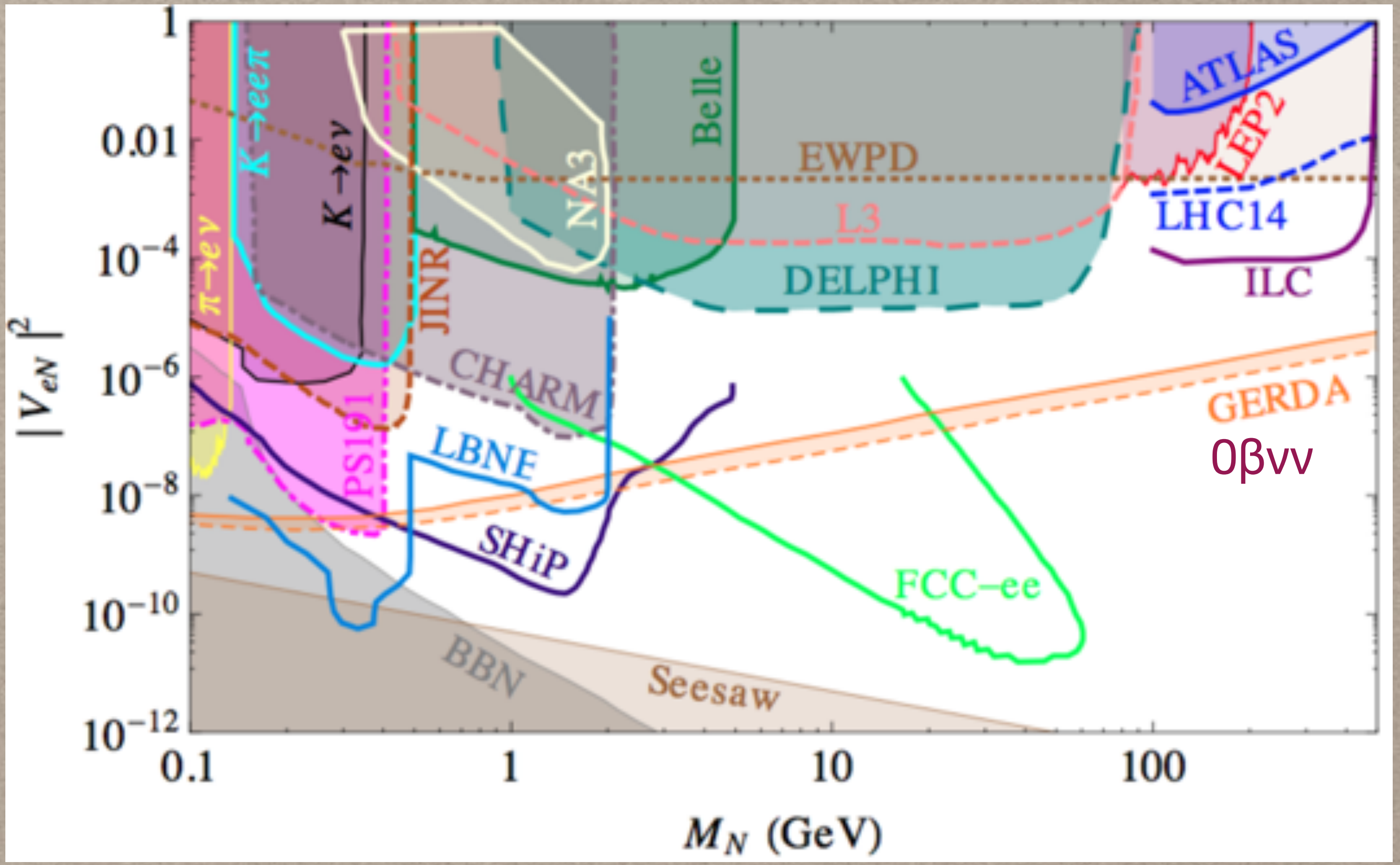
Low scale type-I seesaw and the search

- **RHN search: the current and future**

For heavy RHN above the weak scale, EWPT almost negates the potential at LHC

ILC may reach mixing with electron~10^{-4}

But neutrinoless double beta decay ($0\beta\nu\nu$) at GERDA shadows this potential, which already rules out mixing above 10^{-6} for heavy RHN



For other modes, mixing with μ has slightly better prospect at 14 TeV LHC; and it is hopeless for the mixing with τ

Dynamics of RHN leads to pair production

- **Why new dynamics?**

  Fermions may be arranged by gauge anomaly cancelation, thus RHNs having new gauge interactions

  RHNs mass may origin in a Higgs-like mechanism and thus they participate in new Yukawa interaction with heavy Higgs bosons.

  Simplified model description:

$$-\mathcal{L}_X = \frac{1}{2}M_X^2 X_\mu X^\mu + g_N \bar{N}\gamma_\mu P_R N X^\mu + g_q \bar{q}\gamma_\mu q X^\mu,$$

$$-\mathcal{L}_\phi = \frac{1}{2}m_\phi^2\phi^2 + \lambda_N \phi \bar{N} P_R N + \theta\frac{\alpha_s}{m_t}\phi GG$$

- **Benchmark: local B-L SM, giving both resonances**

	q_L	u_R	d_R	l_L	e_R	ν_R	H	Φ
$SU(3)_c$	3	3	3	1	1	1	1	1
$SU(2)_L$	2	1	1	2	1	1	2	1
$U(1)_Y$	1/6	2/3	-1/3	-1/2	-1	0	1/2	0
$U(1)_{B-L}$	1/3	1/3	1/3	-1	-1	-1	0	2

<Φ>~TeV breaks B-L, giving mass to Z' and RHNs

$$\mathcal{L}_Y = -y^\nu \bar{\ell}_L \nu_R \tilde{H} - \frac{1}{2} y^M \bar{\nu}_R^c \nu_R \Phi + h.c.$$

$$\Gamma(Z' \to \bar{f}f) = \frac{M_{Z'}}{12\pi} C_f (Q_f g_{B-L})^2 \left(1 + 2\frac{m_f^2}{M_{Z'}^2}\right)\sqrt{1 - \frac{4m_f^2}{M_{Z'}^2}},$$

Dynamics of RHN leads to pair production

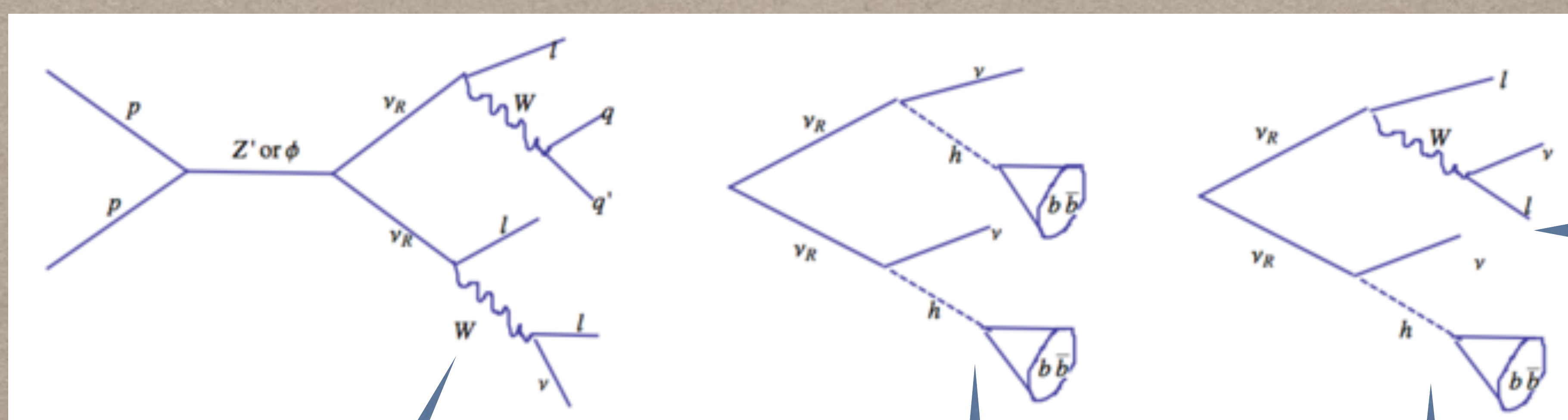
- **Pair production via *S*-channel resonance**
- **RHN Decay: specified by equivalence theorem**

$$\Gamma(N_\alpha \to W^- \ell_i^+) = \Gamma(N_\alpha \to W^+ \ell_i^-) \approx \frac{g^2}{64\pi M_W^2} M_N^3 |(U_{\nu N})_{i\alpha}|^2.$$

$$\Gamma(N_\alpha \to Z \nu_i) \approx \Gamma(N_\alpha \to h \nu_i) \approx \frac{g^2}{64\pi M_W^2} M_N^3 |(U_{PMNS}^\dagger U_{\nu N})_{i\alpha}|^2.$$

Hold in the massless limit.

- **3-channels: di-W & di-Higgs & the hybrid, hW**



The resonance mass is assumed to be above $2M\nu_R$

trilepton+jets

boosted di-Higgs+MET

boosted Higgs+dilepton

RHN pair @ 14 &100 TeV colliders

- **5-signal regions**

  Attempt to explore a wide region on the M_X-$2M_{\nu_R}$ plane.

  We consider five signal regions, corresponding to 5 patters of kinematic features of the final states

  Cuts are optimized with to 5 benchmarks points then applied to all other grids

S1: $M_{Z'} = 0.35$ **TeV and** $M_{\nu_R} = $ **150 GeV** Both particles are light, so neither ν_R nor its secondary decay product h/W is boosted. The resulting relatively soft jets and leptons are not easy to reconstructed.

S2: $M_{Z'} = 1.45$ **TeV and** $M_{\nu_R} =$**700 GeV** Both are heavy but Z' mass is near the threshold $2M_{\nu_R}$ such that ν_R is non-boosted; h/W is well boosted.

S3: $M_{Z'} = 1$ **TeV and** $M_{\nu_R} = 150$ **GeV** For this pattern ν_R is highly boosted while h/W is not. Its remarkable feature is that the final states from ν_R are substantially collimated, rendering the jets/leptons more or less overlapping:

$$\Delta R_{\ell W} \sim \frac{2M_{\nu_R}}{M_{Z'}/2} \sim 0.6. \tag{16}$$

S4: $M_{Z'} = 5$ **TeV and** $M_{\nu_R} = 700$ **GeV** Both ν_R and h/W are boosted. Like S3, there is a mild collimation effect, but the hardness of jets/leptons helps to overcome it.

S5: $M_{Z'} = 10.05$ **TeV and** $M_{\nu_R} = 5$ **TeV** It corresponds to a non-boosted ν_R nevertheless super boosted h/W. This pattern is only specific for the 100 TeV collider where that heavy ν_R is accessible.

- **Using multi variable analysis (MVA)**

RHN pair @ 14 &100 TeV colliders

- **Benchmark reaches @ 14&100 TeV (in bracket)**

Di-*W* channel with trilepton signature: the gold channel

	Cut	ϵ(SIG)	σ(BG)(fb)	signal reach(fb)@ 3000 fb^{-1}
S1	BDT>0.2[0.2]	0.0195[0.013]	0.27[9.9]	2.5[115]
S2	BDT> 0.5[0.4]	0.069[0.06]	7.9×10^{-3}[0.52]	0.073[1.5]
S3	BDT>0.4[0.3]	0.016[0.016]	5.0×10^{-3}[0.96]	0.25[9.6]
S4	BDT>0.6[0.5]	0.125[0.15]	8.8×10^{-4}[0.062]	0.013[0.11]
S5	BDT>NO[0.5]	NO[0.21]	NO[0.042]	NO[0.061]

S4=(5,0.7)TeV is the best~0.013 (0.11) /fb; S1=(0.35,0.15) TeV is the worst. In models the heavy S4 production is suppressed

The boosted di-*h* plus MET: lepton flavor independent

	Cut	ϵ(SIG)	σ(BG)(fb)	signal reach(fb)@ 3000 fb^{-1}
S2	BDT> 0.2[0.2]	0.015[0.0078]	0.012[0.067]	0.42[2.2]
S3	BDT>0.2[0.2]	0.01[0.0045]	0.39[2.01]	6.8[69.2]
S4	BDT>0.2[0.2]	0.048[0.029]	0.034[0.067]	0.24[0.6]
S5	BDT> NO[0.3]	NO[0.028]	NO[2.73]	NO[15.0]

For boosted Higgs like S2/S4/S5, sensitivity is a few times weaker than that of the di-W channel, but it improves @ 100 TeV, except for S5.

S5 gives super boosted Higgs, substructure technique fails

hW-channel: DL+boosted *h*+MET

	Cut	ϵ[SIG]	σ[BG][fb]	signal reach[fb]@ 3000 fb^{-1}
SR2	BDT> 0.2[0.2]	0.02[0.0075]	0.001 [0.015]	0.087[0.94]
SR3	BDT>0.2[0.15]	0.013[0.0063]	0.0076[0.49]	0.38[13.2]
SR4	BDT>0.2[0.2]	0.038[0.029]	2.5×10^{-4}[0.082]	0.023[0.18]
SR5	BDT>NO[0.3]	NO[0.055]	NO[0.47]	NO[1.4]

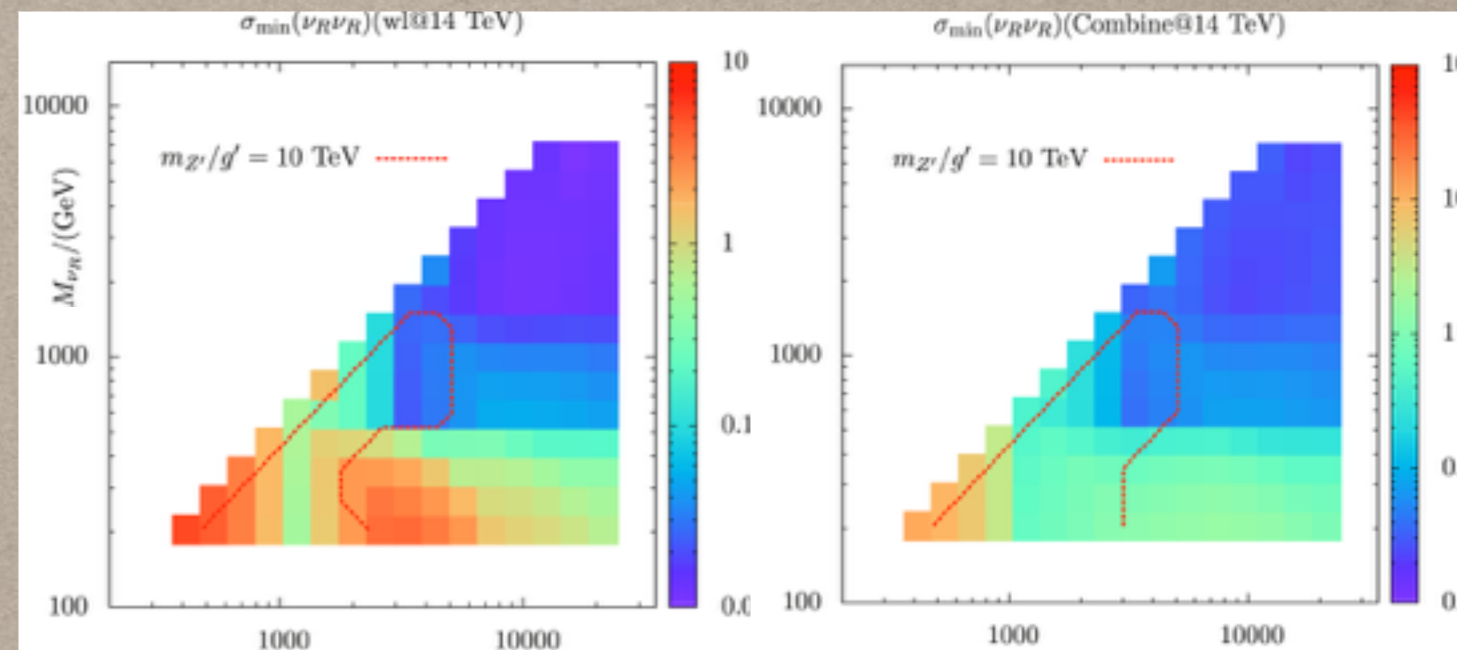
compared to the gold channel, even better like S2 @ 100 TeV

RHN pair @ 14 &100 TeV colliders

- **Preliminary results on the *M_X-2M_{ν_R}* plane**

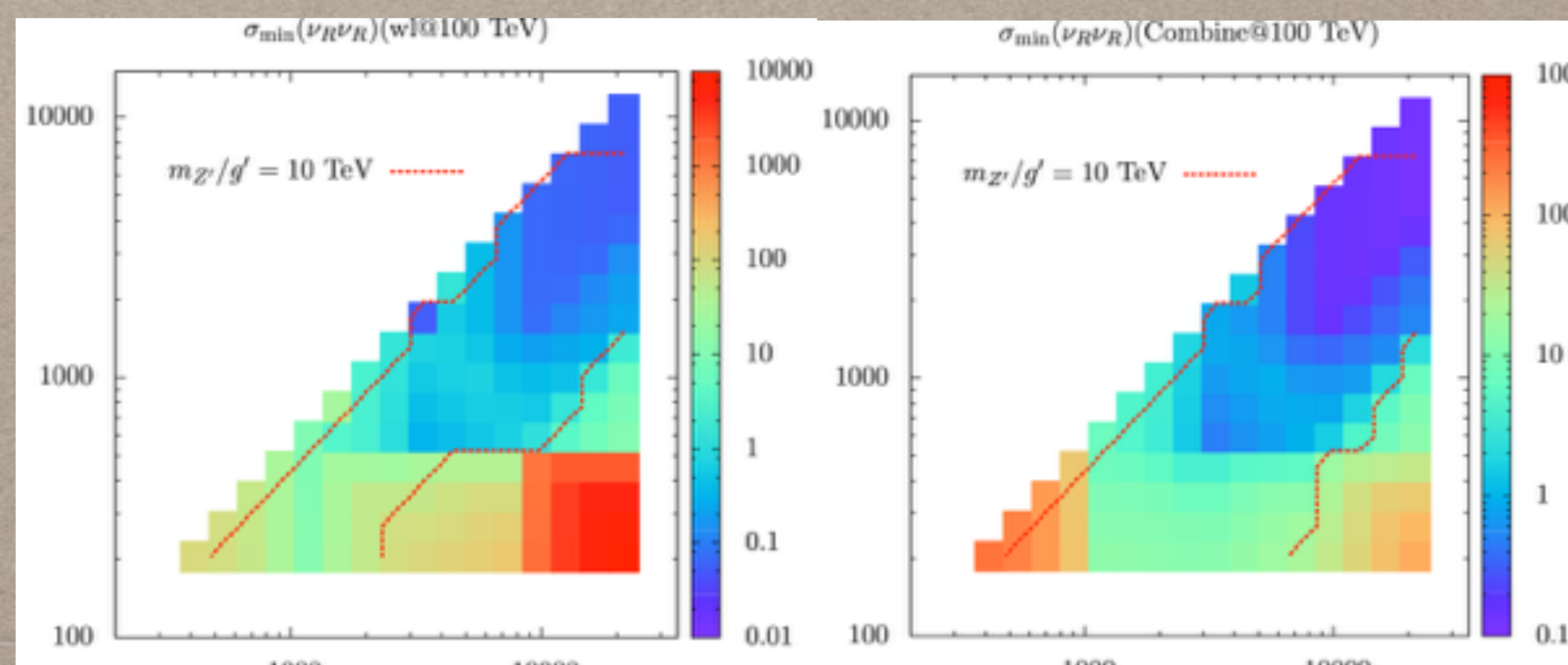
@ the end of 14 TeV, combine three channels (the di-*W* and *hW* channels dominate).

Fixing g’=0.6 (NWA limit) gets much better reach



@ the 100 TeV collider with 3000/fb

NWA breaks down for Z’ mass above ~6 TeV



Conclusions

- **The conventional search for RHN relies on large sterile-active neutrino mixing which requires fine-tuning in the flavor structure.**
- **Moreover, the search hardly reaches the TeV region**
- **It is well expected that RHNs are not sterile beyond SM, and new gauge/Yuakawa interactions lead to RHN pair production with resonant enhancement**
- **We explore di-W with trilepton, di-h with boosted di Higgs bosons plus MET and the hW channel at the 14 & 100 TeV colliders.**

Thank you!