Searching for Heavy Neutrino at Future Hadron Collider

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Based on arXiv:2103.03548

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Outline

- **Type I Seesaw in $U(1)_{B-L}$ extension model**
- **Heavy neutrino decay patterns**
- **LNV signature with tau lepton at the LHC upgrade**
- **Summary**

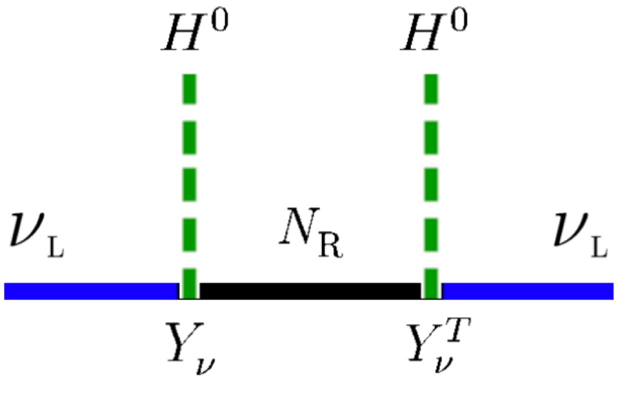
Seesaw model

Weinberg operator:

$$\mathscr{L} = -\frac{1}{2}\frac{g_{\alpha\beta}}{\Lambda}\left(\overline{\ell^{C}_{L\alpha}}\widetilde{H}^{*}\right)\left(\widetilde{H}^{\dagger}\ell_{L\beta}\right) + \text{H.c.}$$

Type-I seesaw: SM + right-handed neutrinos + L violation (Minkowski 1977; Yanagida 1979; Glashow 1979; Gell-Mann, Ramond, Slansky 1979; Mohapatra, Senjanovic 1980)

$$\begin{aligned} -\mathcal{L} &= \overline{\nu_{\rm L}} M_{\rm D} N_{\rm R} + \frac{1}{2}\overline{(N_{\rm R})^{c}} M_{\rm R} N_{\rm R} + \text{ h.c.} \\ &= \frac{1}{2}\left[\overline{\nu_{\rm L}} \;\; \overline{(N_{\rm R})^{c}}\right]\begin{pmatrix} 0 & M_{\rm D} \\ M_{\rm D}^{T} & M_{\rm R}\end{pmatrix}\begin{bmatrix}(\nu_{\rm L})^{c} \\ N_{\rm R}\end{bmatrix} + \text{h. c.}\end{aligned}$$



Seesaw formula:

$$M_\nu \approx -M_{\rm D} M_{\rm R}^{-1} M_{\rm D}^{T}$$

$U(1)_{B-L}$ extension

$U'(1)$ is a linear combination of $U(1)_Y$ and $U(1)_{B-L}$ after the spontaneous breaking of electroweak and B-L symmetry

$$D_\mu \ni ig_1 Y B_\mu + i(g_1' Y + g' Y_{BL}) B_\mu' = ig_1 Y B_\mu + ig_X (x_1' Y + x' Y_{BL}) B_\mu'$$

Most economical extension: $x' = 1, x_1' = 0$ $\quad$ $\mathrm{U}(1)' = \mathrm{U}(1)_{\mathrm{B-L}}$ and $g_X = g'$

A new scalar $S \sim (1, 1, 0, 2)$ is introduced to break the $U(1)_{B-L}$ symmetry and generate the masses of right-handed neutrinos $N_R \sim (1, 1, 0, -1)$

A new gauge boson Z' can get mass $M_{Z'} = 2g' v_S$ from the kinetic term

$$\mathcal{L}_k = (D_\mu S)^\dagger (D^\mu S) \quad \text{with} \quad D_\mu S = \partial_\mu S + i2g' B_\mu' S$$

The interaction for Z' and fermions ψ is obtained from the kinetic term

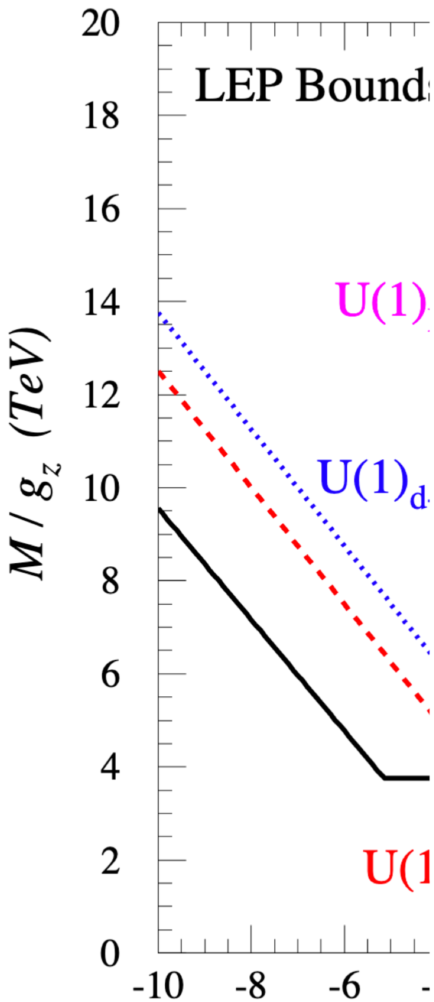
$$\mathcal{L}_k = i\overline{\psi}\gamma^\mu D_\mu \psi \quad \text{with} \quad D_\mu \psi = \partial_\mu \psi + ig' Y_\psi' B_\mu' \psi$$

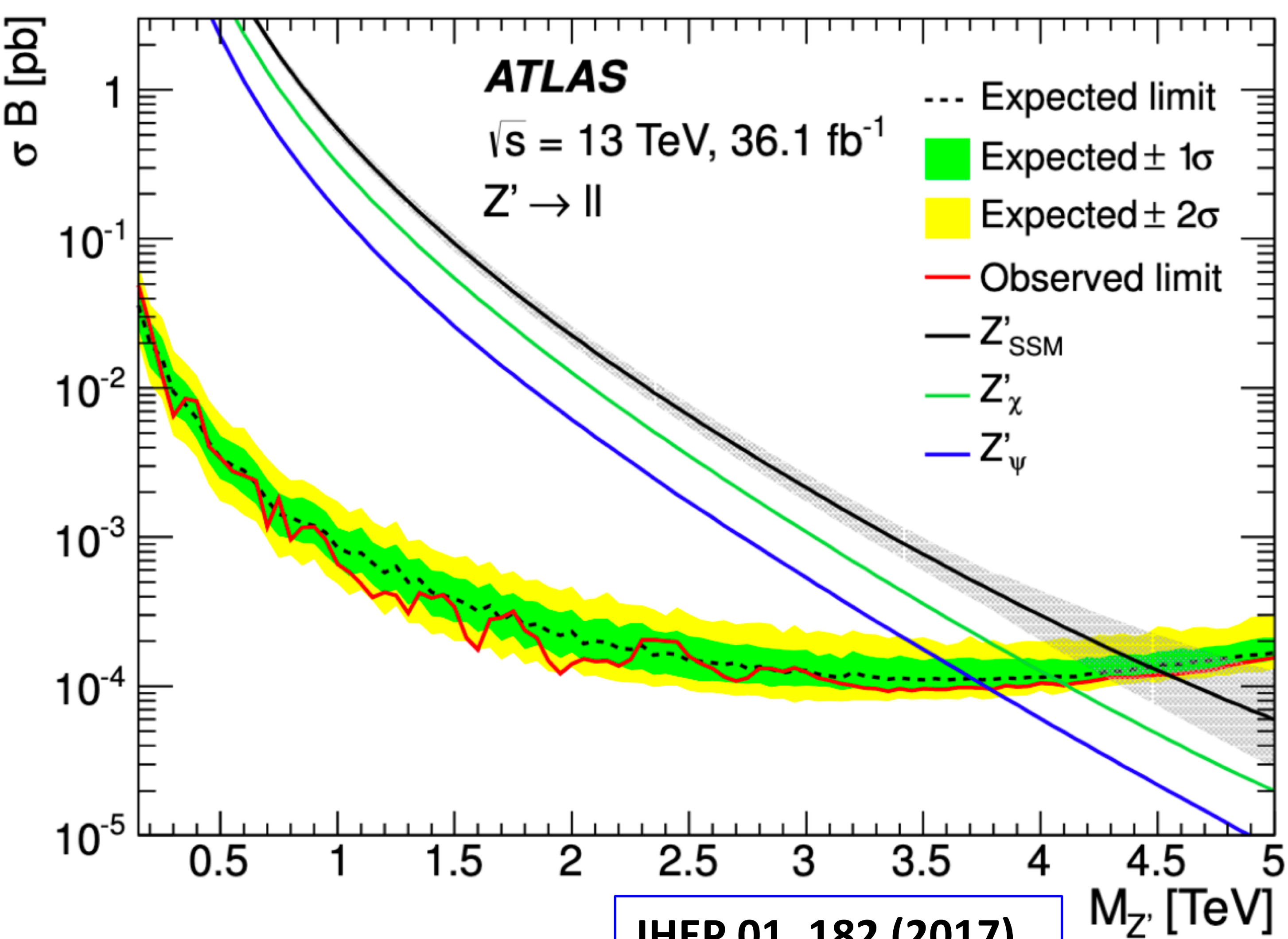
Production and decay of Z' $\quad$ $pp \to Z' \to NN,\ \ell^+\ell^-,\ \tau^+\tau^-$

Exp. constraints

LEP-II lower bounds $M_{Z'}/g' \gtrsim 6\text{TeV}$

LHC 13TeV 36 fb^{-1} lower limit $M_{Z'} \gtrsim 4.1\text{TeV}$





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Exp. constraints

Requirement of the $\mathbf{U'(1)}$ charge:

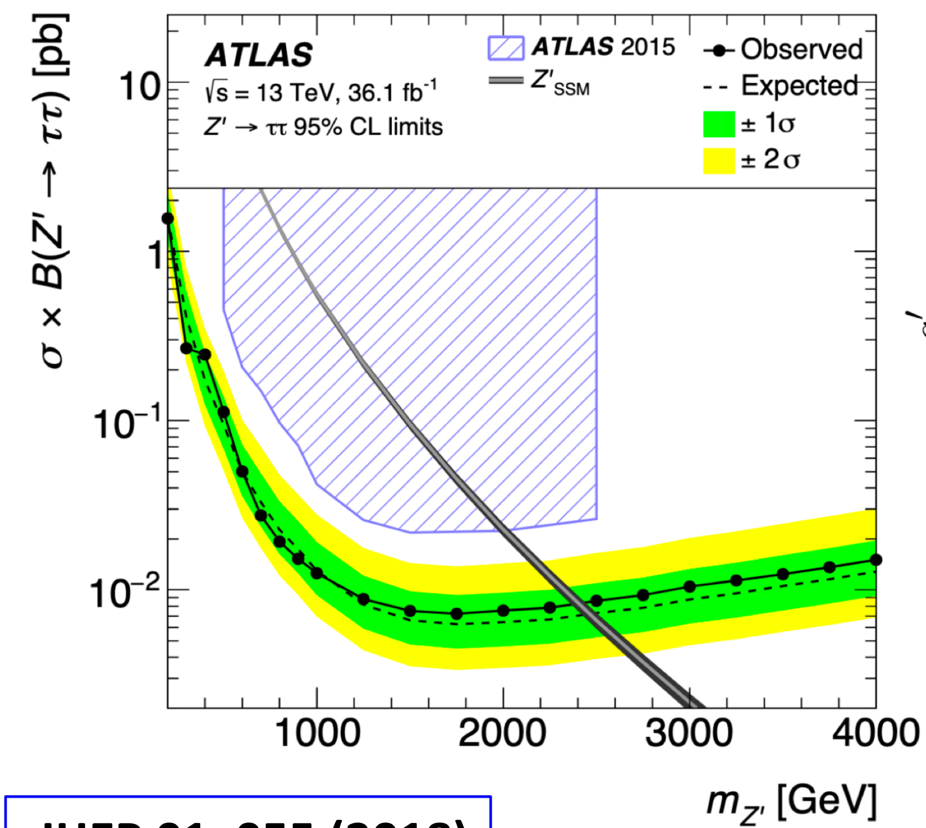
$$3(Q'_1 + Q'_2 + Q'_3) + Q'_e + Q'_\mu + Q'_\tau = 0$$

Quark charges **Lepton charges**

Flavored $\mathbf{U(1)_{(B-L)_3}}$

$$3Q'_3 = -Q'_\tau = 1 \qquad Q'_1 = Q'_2 = Q'_e = Q'_\mu = 0$$

The Z' can only be produced through $b\bar{b} \to Z'$ and decay into $\tau^+\tau^-$ and a pair of one single heavy neutrino



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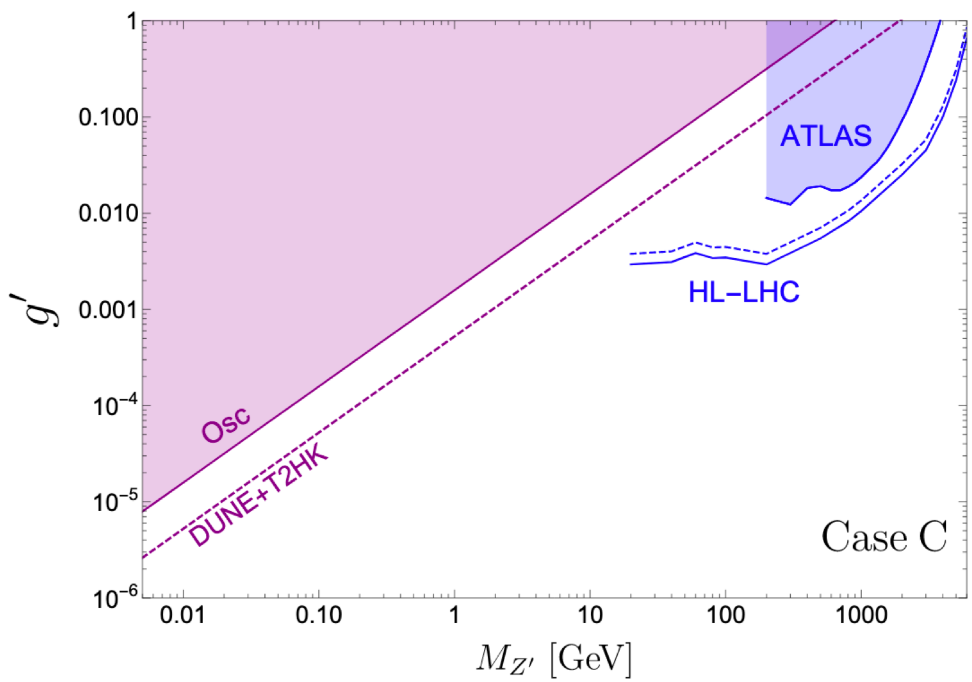


JHEP 11, 028 (2019)

$U(1)_{B-L}$ extension

B-L accidental symmetry + Majorana neutrino masses

$U'(1)$ is a linear combination of $U(1)_Y$ and $U(1)_{B-L}$ after the spontaneous breaking of electroweak and B-L symmetry

$$\mathrm{U}(1)_Y, \mathrm{U}(1)_{\mathrm{B-L}} \to \mathrm{U}'(1)$$

anomaly cancellation ⇐ N_R ⇒ **neutrino masses**

Yukawa interaction:

$$-\mathcal{L}_Y^I = Y_\nu^D \bar{l}_L \tilde{H} N_R + \frac{1}{2} Y_\nu^M \overline{(N^c)_L} N_R S + h.c.$$

$N_R \sim (1,1,0,-1)$ $S \sim (1,1,0,2)$

After H, S receives the vev $\langle H \rangle = v/\sqrt{2}$ and $\langle S \rangle = v_S/\sqrt{2}$, one has the diagonalization of the mass matrix

$$\mathbb{N}^\dagger \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix} \mathbb{N}^* = \begin{pmatrix} m_\nu & 0 \\ 0 & M_N \end{pmatrix}$$

with

$$M_R = Y_\nu^M v_S/\sqrt{2}$$

$$m_D = Y_\nu^D v/\sqrt{2}$$

$U(1)_{B-L}$ extension

Eigenstate transformation:

$$\begin{pmatrix} \nu_L \\ (N^c)_L \end{pmatrix} = \mathbb{N} \begin{pmatrix} \nu_L \\ (N^c)_L \end{pmatrix}_{mass} , \quad \mathbb{N} = \begin{pmatrix} U & V \\ X & Y \end{pmatrix}$$

The PMNS matrix and light-heavy mixing matrix:

$$E^\dagger U \equiv U_{PMNS} , \quad E^\dagger V \equiv V_{\ell N}$$

E **diagonalize the charged lepton mass matrix**

Relation between mixing matrices and mass eigenvalues:

$$U^*_{PMNS} m_\nu^{diag} U^\dagger_{PMNS} + V^*_{\ell N} M_N^{diag} V^\dagger_{\ell N} = 0$$

$$m_\nu^{diag} = (m_1, m_2, m_3)$$

$$M_N^{diag} = (M_{N_1}, M_{N_2}, M_{N_3})$$

Casas-Ibarra parametrization:

$$V_{\ell N} = U_{PMNS} (m_\nu^{diag})^{1/2} \Omega (M_N^{diag})^{-1/2}$$

For simplicity, we take the arbitrary orthogonal complex matrix as $\Omega = I$

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & e^{-i\delta}s_{13} \\ -c_{12}s_{13}s_{23}e^{i\delta} - c_{23}s_{12} & c_{12}c_{23} - e^{i\delta}s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{12}s_{23} - e^{i\delta}c_{12}c_{23}s_{13} & -c_{23}s_{12}s_{13}e^{i\delta} - c_{12}s_{23} & c_{13}c_{23} \end{pmatrix} \times \mathrm{diag}\left(e^{i\Phi_1/2}, 1, e^{i\Phi_2/2}\right)$$

Mixing parameters

Tree-flavor oscillation parameters **[NuFIT 5.0 (2020)]**

with SK atmospheric data		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
	$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
	$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
	$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
	$\delta_{CP}/^\circ$	197^{+27}_{-24}	$120 \to 369$	282^{+26}_{-30}	$193 \to 352$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

Decay patterns of *N*

Asymptotic behavior holds when $M_{N_i} \gg M_W, M_Z, M_h$

$$\Gamma(N_i \to \sum_\ell \ell^\pm W^\mp) \approx \Gamma(N_i \to \sum_\nu \nu Z + \bar{\nu} Z) \approx \Gamma(N_i \to \sum_\nu \nu h + \bar{\nu} h)$$

Partial decay width

$$\Gamma(N_i \to \ell^\pm W^\mp) = \frac{G_F}{8\sqrt{2}\pi} |V_{\ell N_i}|^2 M_{N_i} (M_{N_i}^2 + 2M_W^2) \left(1 - \frac{M_W^2}{M_{N_i}^2}\right)^2$$

Benchmark decay branching ratios of N_i for NH(IH) case

$\mathrm{BR}(N_i)$	$e^\pm W^\mp$	$\mu^\pm W^\mp$	$\tau^\pm W^\mp$
N_1	17% (17%)	1.85% (3.8%)	6.15% (4.2%)
N_2	7.43% (7.43%)	9.15% (7.14%)	8.42% (10.43%)
N_3	0.55% (0.56%)	14% (14.04%)	10.45% (10.4%)

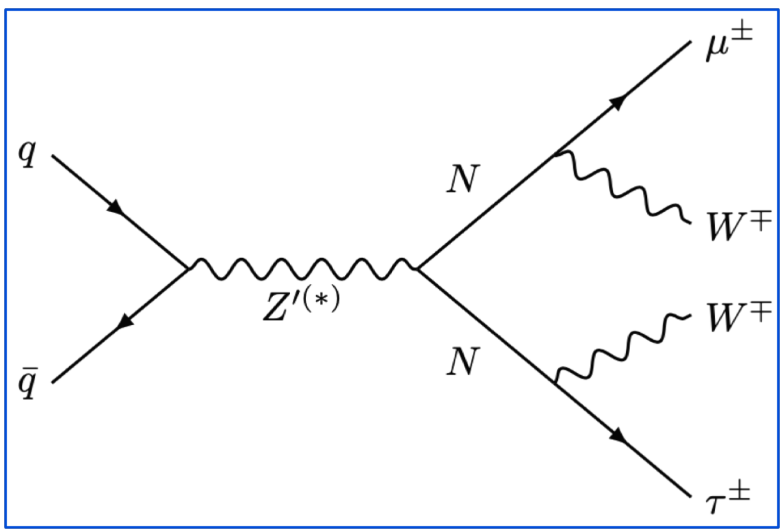
LNV signature

Signal

In the $\mathbf{U(1)_{(B-L)_3}}$ model, the most appealing signal channel is

$$b\bar{b} \to Z' \to NN \to \ell^{\pm}\tau^{\pm}W^{\mp}W^{\mp}$$

with hadronically decaying W boson



Background

The major irreducible SM backgrounds include

$$t\bar{t}W^{\pm} \to b\bar{b}W^{\pm}W^{\pm}W^{\mp}$$

$\mu^{\pm}\ \tau^{\pm}$ jj

$$t\bar{t}Z \to b\bar{b}W^{+}W^{-}Z$$

$\mu^{\pm}/\tau^{\pm}\,jj$ $\tau^{\pm}/\mu^{\pm}$

$$WZ + \text{jets}$$

$\tau^{\pm}/\mu^{\pm}$ $\mu^{\pm}/\tau^{\pm}$

Reconstruction & Cuts

Charged leptons

- select events with exactly one muon and one tau with same sign
- Muon with $|\eta(\mu)|<2.4$, $p_T>25$GeV and tau with $|\eta(\tau)|<2.5$, $p_T>25$GeV

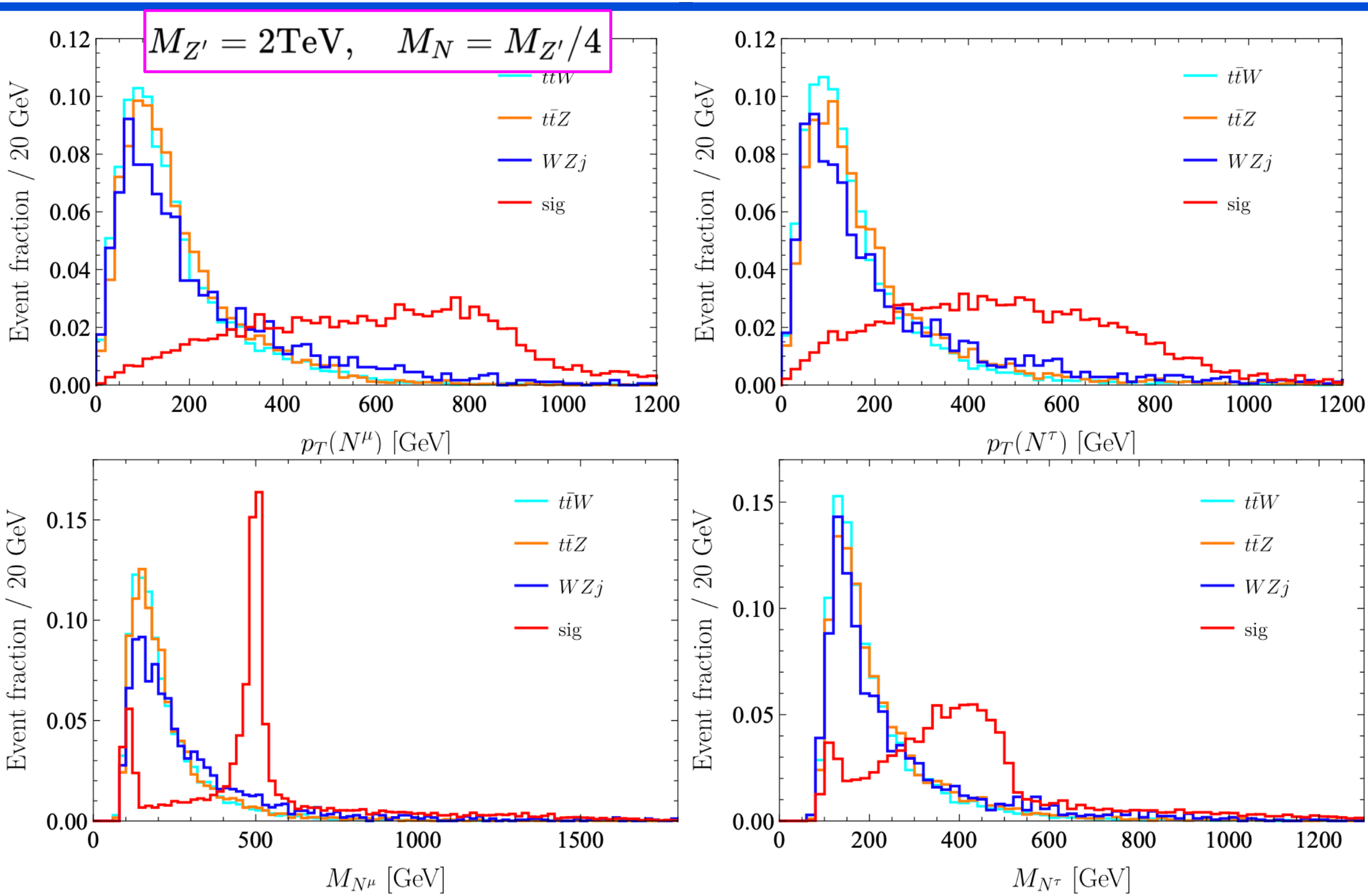
W boson

- Resolved W
  - reconstruct each W boson from two resolved jets with $|\eta|<2.4$, $p_T>25$GeV
- Boosted W
  - The fat jet is reconstructed via the anti-kT algorithm with $R=0.8$. The fat jet with $65<M_J<95$GeV, $p_T(J)>250$GeV and $|\eta(J)|<2.5$ is identified as boosted W candidate

Reconstruct N_R

- Given the same-sign μ and τ and the two reconstructed W bosons, we find the combination that minimizes $\Delta R(\mu, W_1) + \Delta R(\tau, W_2)$ and then construct N^μ and N^τ respectively denoting the heavy neutrino decay into μ and τ
- Apply p_T and mass window cut: $p_T(N^\mu)>250$GeV, $p_T(N^\tau)>200$GeV , $|M_{N\mu}-M_N|<0.1M_N$;

Distributions

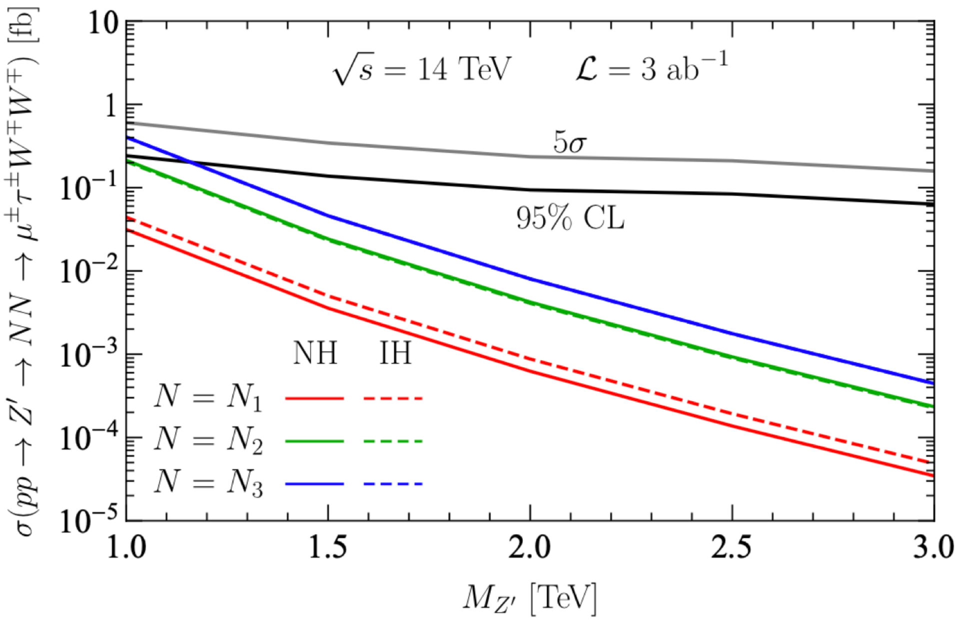


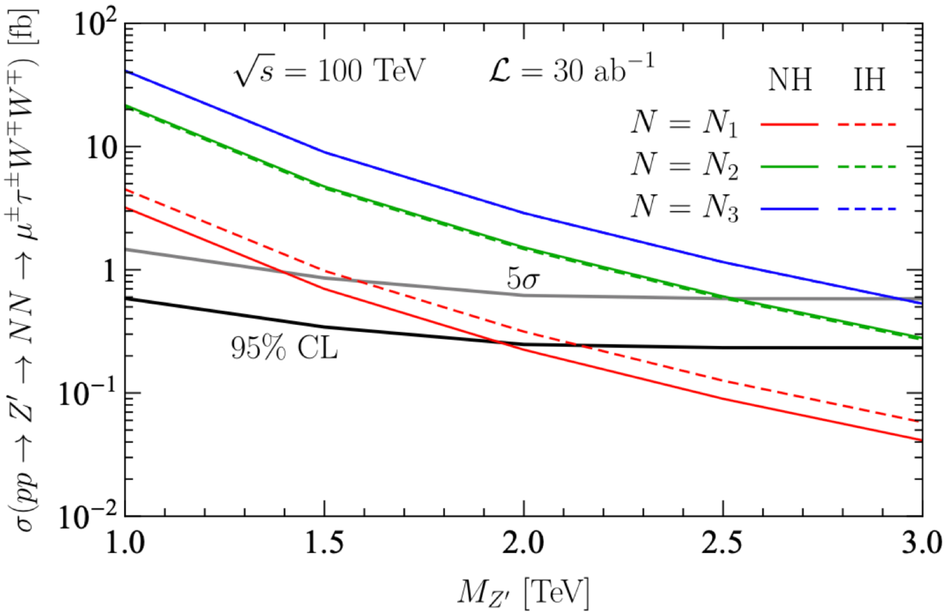
Projected sensitivity

The **significance** is calculated by the Gaussian method $S/\sqrt{B}$

$$S = L \times \sigma_0 \times 2 \times \mathrm{BR}^2(W^\pm \to q\bar{q}') \times \epsilon^\tau_{NN}$$

$$\sigma_0 \equiv \sigma(pp \to Z' \to NN) \times \mathrm{BR}(N \to \tau^\pm W^\mp) \times \mathrm{BR}(N \to \ell^\pm W^\mp)$$

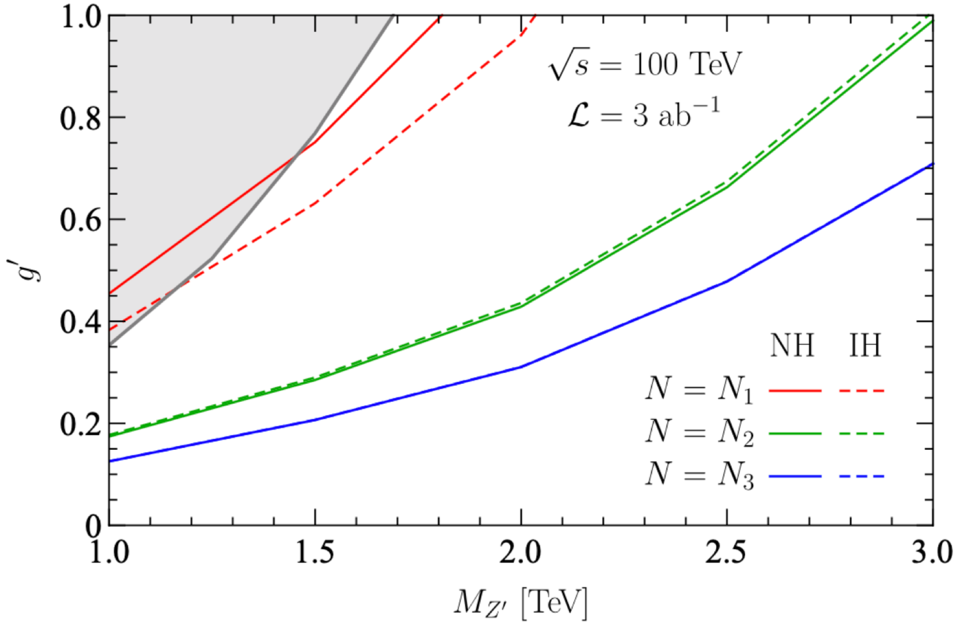


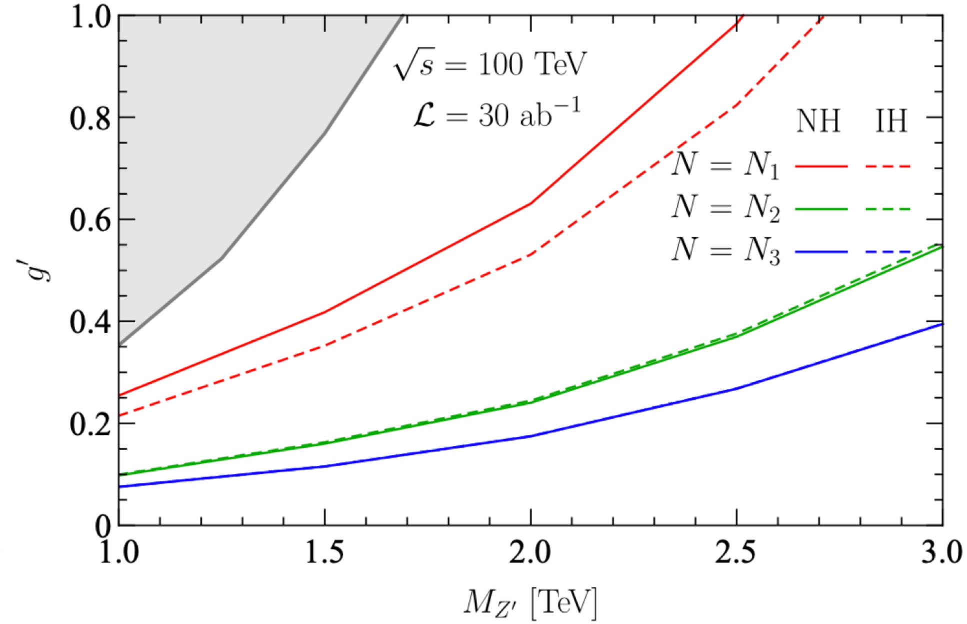


- **The HL-LHC can produce at most 20 LNV events for $M_{Z'}$ = 1 TeV and cannot reach 5σ discovery**
- **The FCC-hh can discover the LNV signal with tau lepton for $M_{Z'}$ up to 3 TeV and N = N_3 with the fixed g′ = 0.6 and the integrated luminosity of 30 ab^{-1}**

Projected sensitivity

Projected sensitivity of the gauge coupling g' versus $M_{Z'}$





- **The gray curve shows the 95% C.L. limit from the search for $Z' \to \tau\tau$ at LHC**
- **The searches for $Z' \to b\bar{b}$ or $Z' \to t\bar{t}$ do not place severe constraint**
- **The gauge coupling g' down to 0.12 (0.07) can be probed through the LNV signature with tau lepton by the FCC-hh with the integrated luminosity of 3 (30) ab^{-1} and $M_{Z'}$ = 1 TeV.**

Summary

- **The lepton number violation at colliders can be probed by the $U(1)_{B-L}$ extension of the canonical Type I Seesaw**
- **Flavored $U(1)_{(B-L)_3}$ model has weaker constraints from experiments**
- **The HL-LHC cannot reach 5σ discovery for heavy neutrinos**
- **The FCC-hh can discover the LNV signal with tau lepton for $M_{Z'}$ up to 2.2 (3) TeV with $g' = 0.6$ and the integrated luminosity of 3 (30) ab^{-1}**
- **The gauge coupling g' down to 0.12 (0.07) can be probed through the LNV signature with tau lepton by the FCC-hh with the integrated luminosity of 3 (30) ab^{-1} and $M_{Z'} = 1$ TeV.**

Backup

Lesson 1: two necessary conditions to test a seesaw model with heavy right-handed Majorana neutrinos at the LHC:

---Masses of heavy Majorana neutrinos must be of O (1) TeV or below

---Light-heavy neutrino mixing (i.e. *M_D/M_R*) must be large enough

Lesson 2: non-unitarity of the light ν flavor mixing matrix might lead to observable effects in ν oscillations and rare processes.

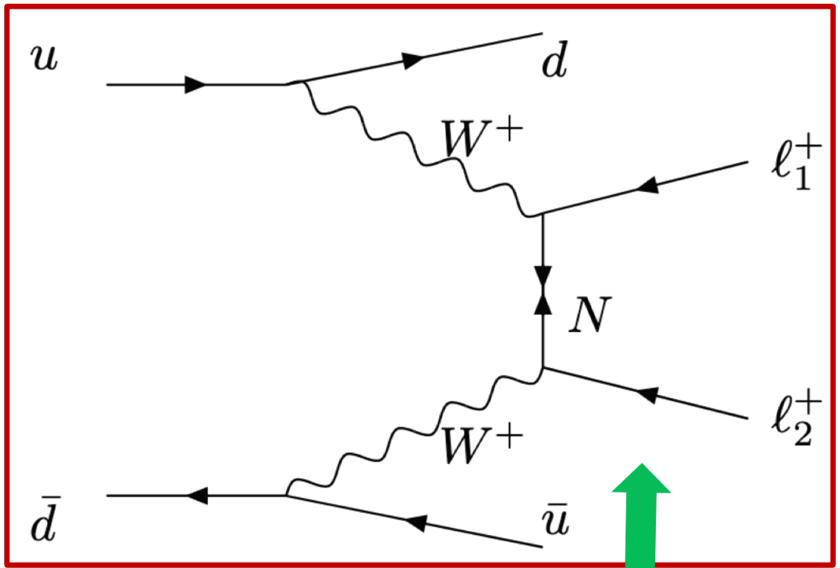
Lesson 3: nontrivial limits on heavy Majorana ν's could be derived at the LHC, if the SM backgrounds are small for a specific final state.

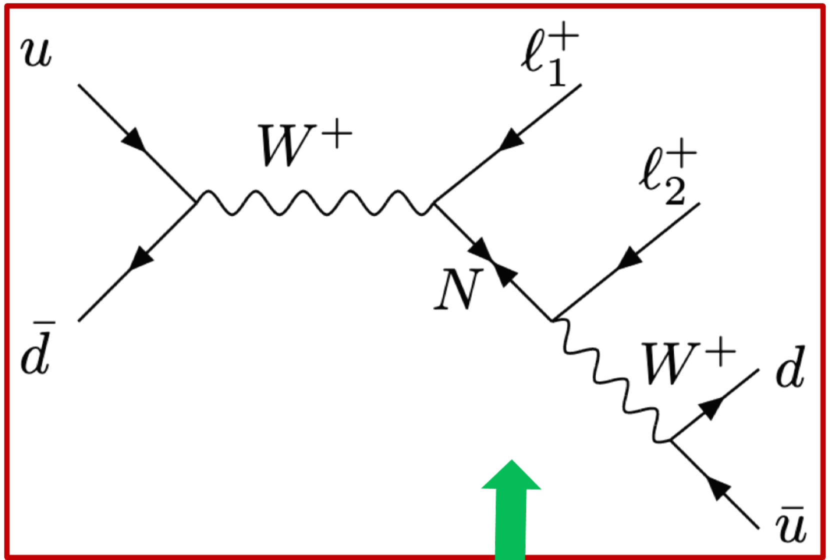
$\Delta L=2$ like-sign dilepton events

$$pp \to W^\pm W^\pm \to \mu^\pm \mu^\pm jj \quad \text{and} \quad pp \to W^\pm \to \mu^\pm N \to \mu^\pm \mu^\pm jj$$

Backup

Lepton number violation: **like-sign dilepton events at hadron colliders, such as Tevatron (~2 TeV) and LHC (~14 TeV).**





dominant channel

collider analogue to $0\nu\beta\beta$ decay

N **can be produced on resonance**

arXiv:0901.3589 [hep-ph] 23 Jan 2009