New physics search at electron positron collider

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Introduction

Standard Model

very stable

1. Neutrino mass and flavor mixing
2. Dark Matter candidate
3. May be more

New physics is strongly suggested

Theoretical

Experimental

We definitely need new physics to provide missing pieces

Particle content of the model

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$			$U(1)_X$
q_L^i	**3**	**2**	$+1/6$	x_q	$=$	$\frac{1}{6}x_H + \frac{1}{3}x_\Phi$
u_R^i	**3**	**1**	$+2/3$	x_u	$=$	$\frac{2}{3}x_H + \frac{1}{3}x_\Phi$
d_R^i	**3**	**1**	$-1/3$	x_d	$=$	$-\frac{1}{3}x_H + \frac{1}{3}x_\Phi$
ℓ_L^i	**1**	**2**	$-1/2$	x_ℓ	$=$	$-\frac{1}{2}x_H - x_\Phi$
e_R^i	**1**	**1**	-1	x_e	$=$	$-x_H - x_\Phi$
H	**1**	**2**	$+1/2$	x'_H	$=$	$\frac{1}{2}x_H$
N_R^i	**1**	**1**	0	x_ν	$=$	$-x_\Phi$
Φ	**1**	**1**	0	x'_Φ	$=$	$2x_\Phi$

$$m_{Z'} = 2\, g_X v_\Phi$$

x_H, x_Φ will appear the coupling with Z'

3 generations of SM singlet right handed neutrinos (anomaly free)

Charges before the anomaly cancellations

Charges after Imposing the anomaly cancellations

$U(1)_X$ **breaking**

$$\mathcal{L}_Y \supset -\sum_{i,j=1}^{3} Y_D^{ij}\overline{\ell_L^i}HN_R^j - \frac{1}{2}\sum_{i=k}^{3} Y_N^k \Phi \overline{N_R^{k\,c}} N_R^k + \text{h.c.},$$

$$\boxed{m_D^{ij} = \frac{Y_D^{ij}}{\sqrt{2}}v_h} \qquad \boxed{m_{N^i} = \frac{Y_N^i}{\sqrt{2}}v_\Phi}$$

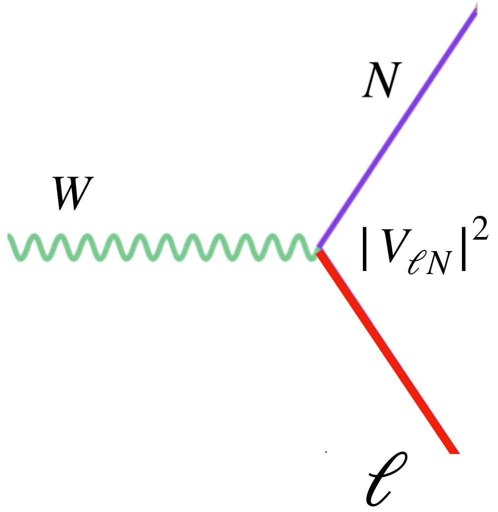
$$m_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix} \qquad m_\nu \simeq -M_D M_N^{-1} M_D^T$$

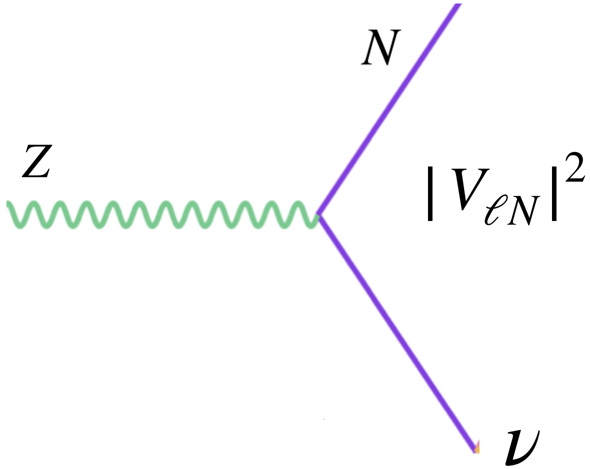
Seesaw mechnism

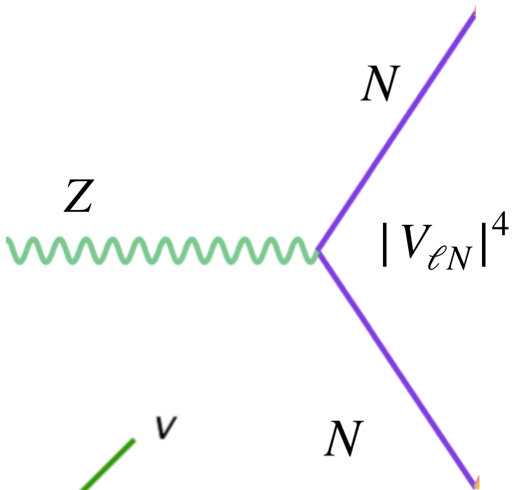
Direct interaction of the Right Handed Neutrinos through light – heavy mixing

Flavor eigenstate can be expressed in terms of the mass eigenstate

$$\nu_\ell \simeq \underbrace{U_{\ell m}}_{\text{PMNS matrix}} \nu_m + \underbrace{V_{\ell n}}_{M_D M^{-1}} N_n$$

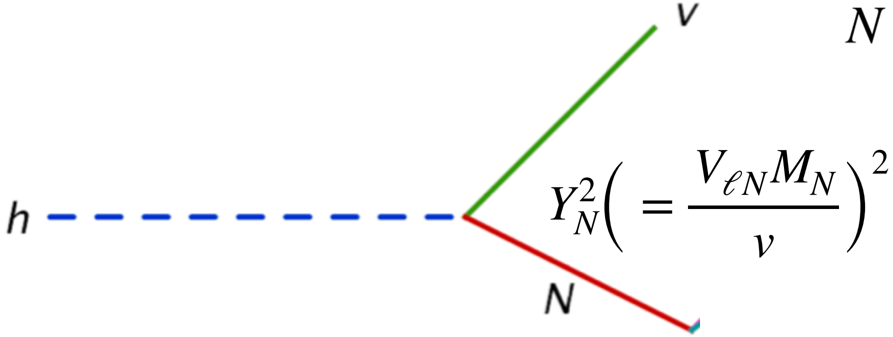


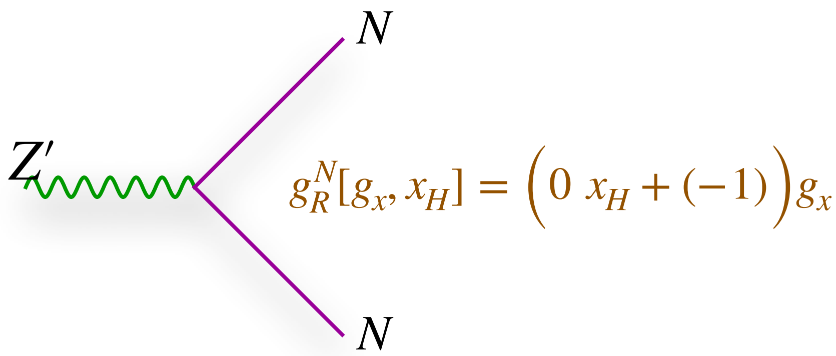


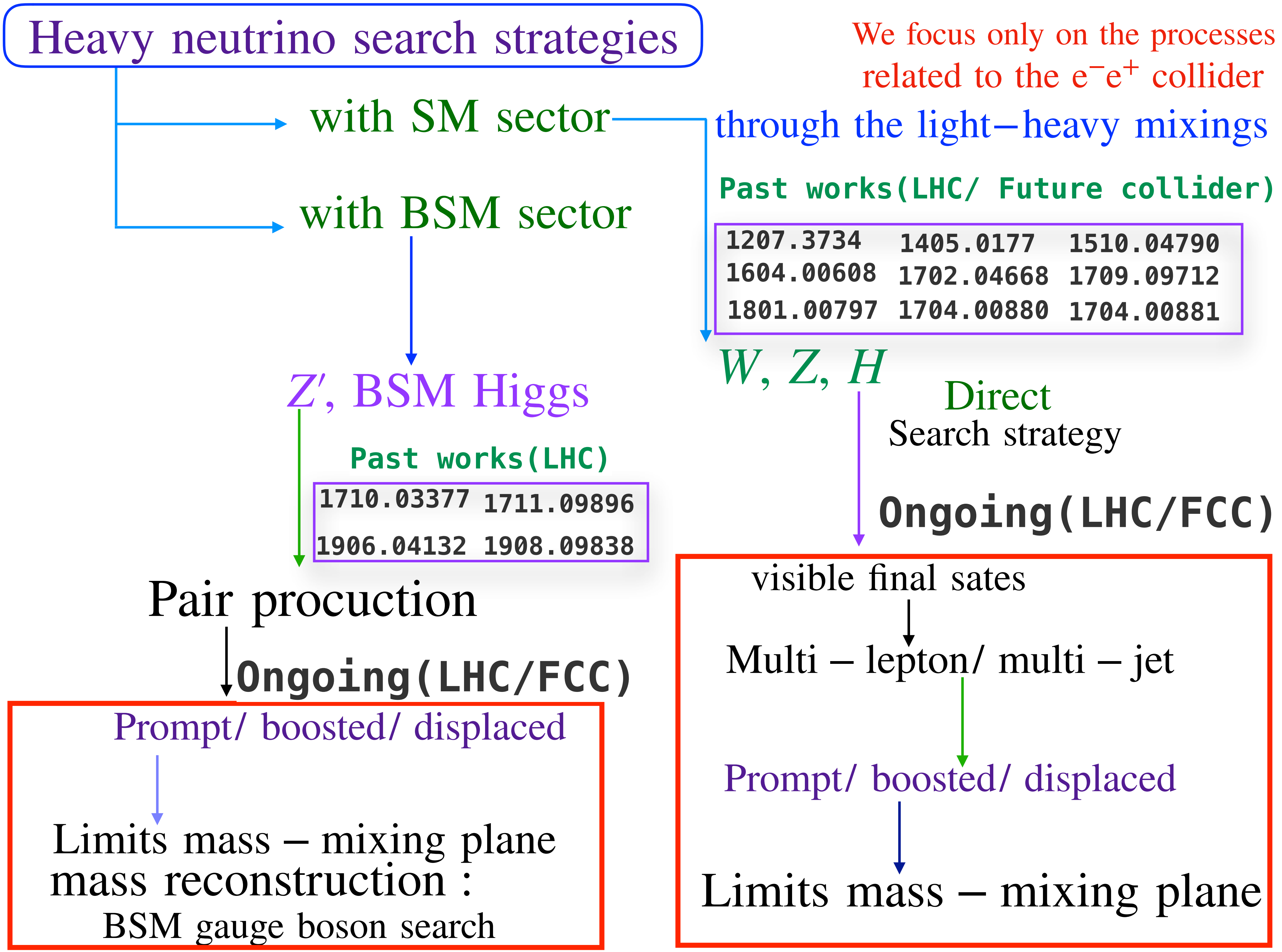


$\longrightarrow$ Suppressed

Direct interaction of the RHNs







Heavy neutrino search strategies
We focus only on the processes related to the e⁻e⁺ collider
with SM sector
through the light−heavy mixings
Past works(LHC/ Future collider)
1207.3734 1405.0177 1510.04790
1604.00608 1702.04668 1709.09712
1801.00797 1704.00880 1704.00881
with BSM sector
W, Z, H
Direct
Search strategy
Ongoing(LHC/FCC)
visible final sates
Multi – lepton/ multi – jet
Prompt/ boosted/ displaced
Limits mass – mixing plane
Z′, BSM Higgs
Past works(LHC)
1710.03377 1711.09896
1906.04132 1908.09838
Pair procuction
Ongoing(LHC/FCC)
Prompt/ boosted/ displaced
Limits mass – mixing plane
mass reconstruction :
BSM gauge boson search

Impression/s at the ILC

$$\sigma(e^+e^- \to \overline{\nu_\alpha} N_i) = \sigma_{\rm ILC} |\mathcal{R}_{\alpha i}(\delta, \rho, y)|^2$$

1207.3734

Using the general parameters and Casas – Ibarra conjecture

$|\mathcal{R}_{\alpha i}(\delta, \rho, y)|^2$

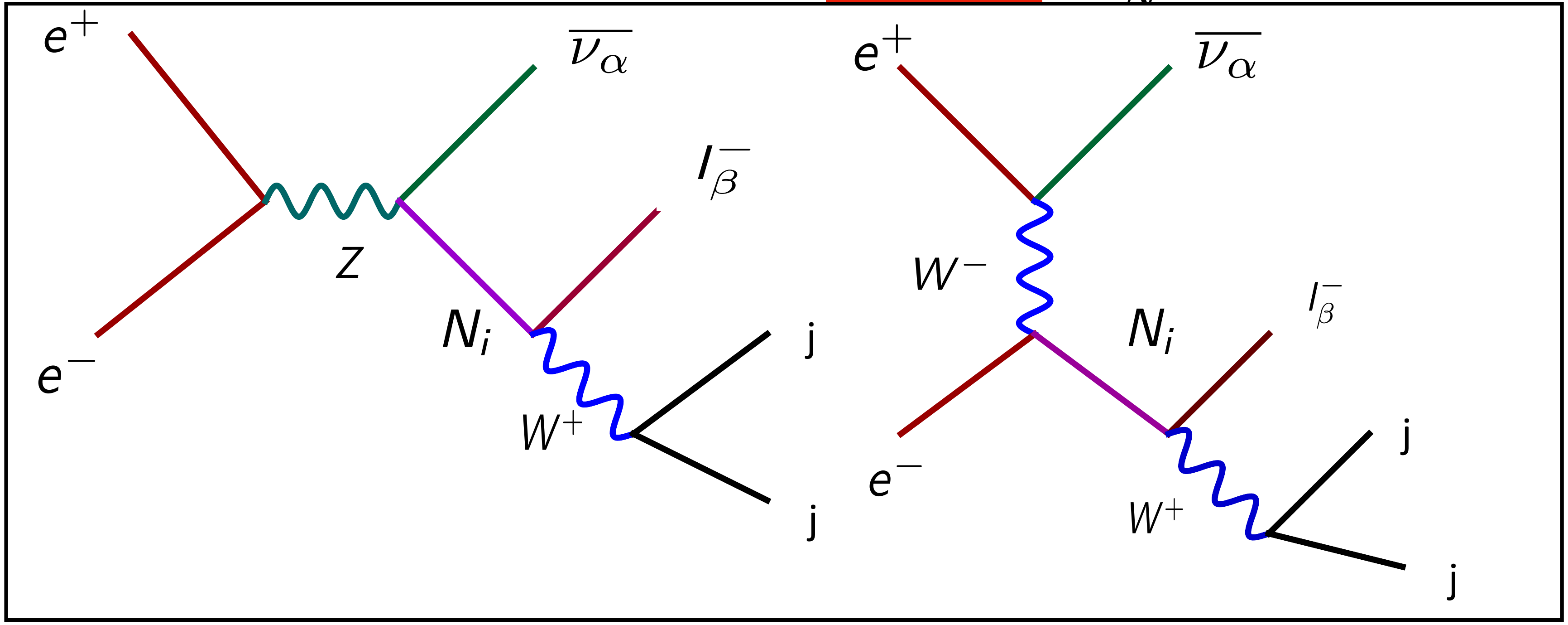
branching ratios

$$N_i \to \boxed{\ell^-_\alpha W^+} / \nu_\alpha Z / \nu_\alpha h$$

$\mathcal{N}^\dagger \mathcal{R} \simeq U^\dagger_{\rm MNS} \mathcal{R}$ because $|\epsilon_{\alpha\beta}| \ll 1$

Leading mode

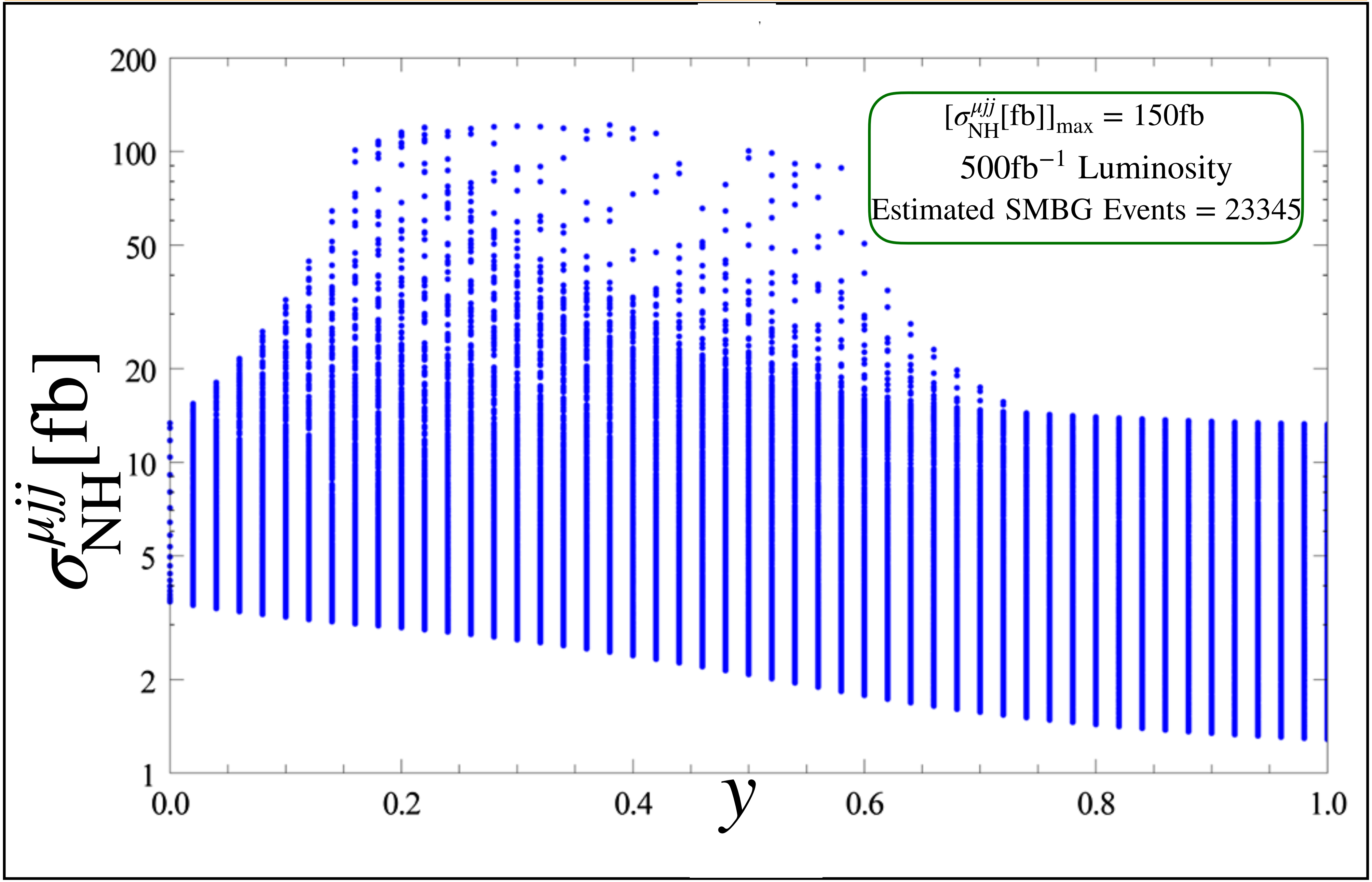
Signals $M_N = 150$ GeV



We scan over the phases and then general parameter to find the cross section as a function of the general parameter 'y', $-\pi < \delta, \rho < \pi, \quad 0 < y < 1$

$e^+e^- \to \nu N$, followed by the decay $N \to \ell W$ ($\ell = \mu$) $W \to q\bar{q}'$

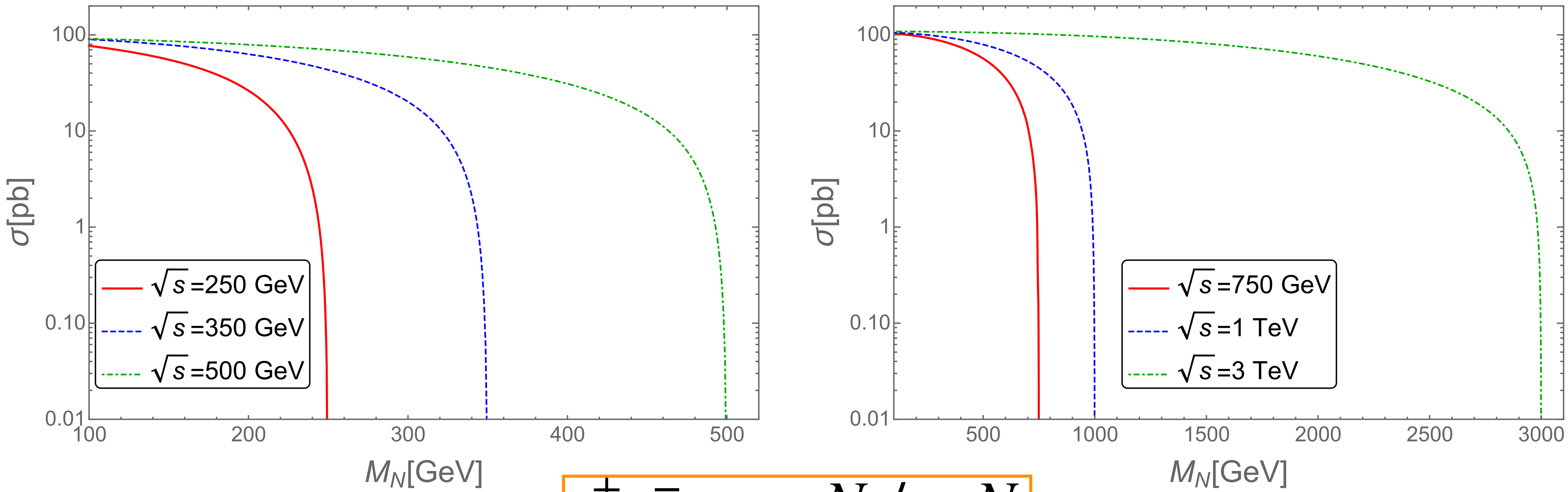
$M_N = 150$ GeV $\quad \sqrt{s} = 500$ GeV **1207.3734**



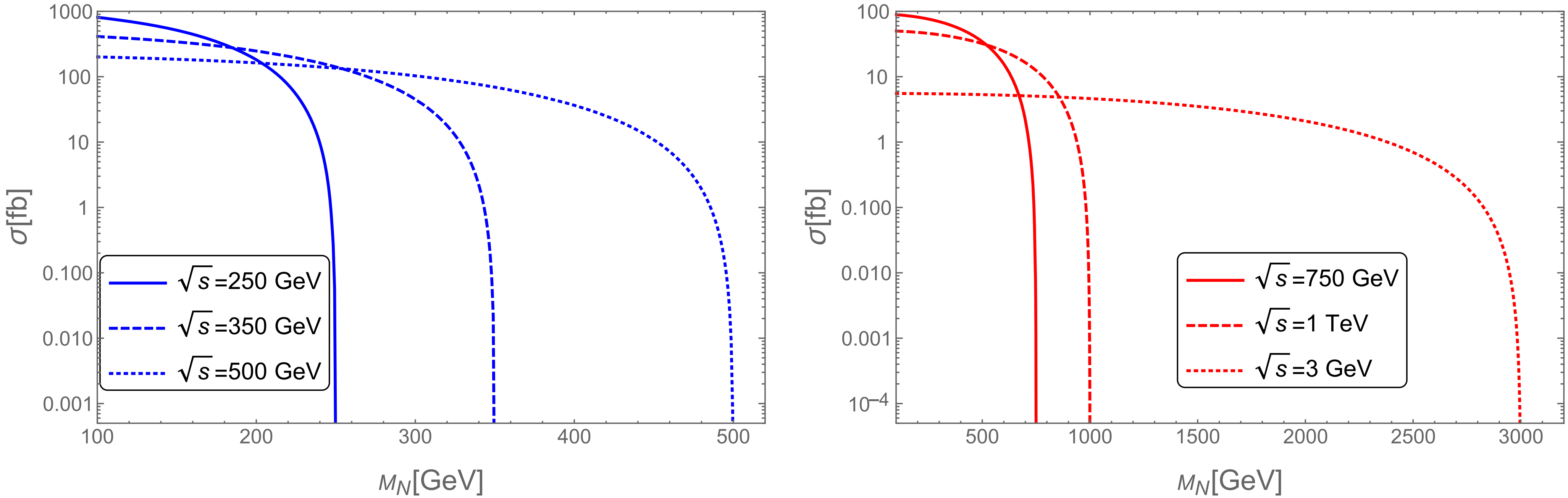
Production of the heavy neutrinos at the Linear Collider using fat jet

1811.04291

$$e^+e^- \rightarrow \nu_1 N_1$$

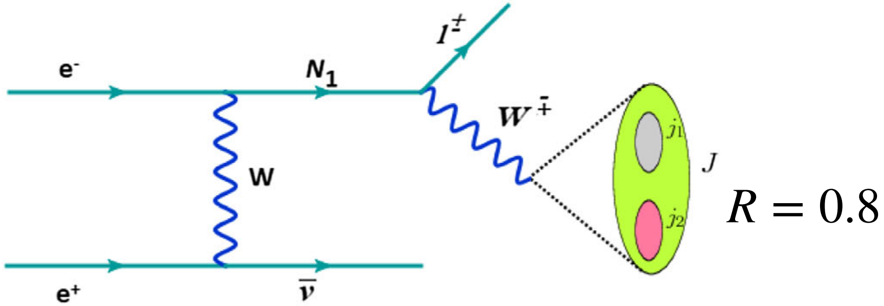


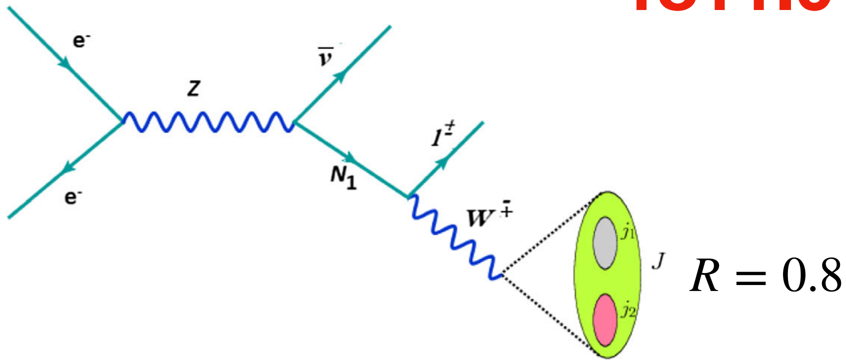
$$e^+e^- \rightarrow \nu_2 N_2 /\ \nu_3 N_3$$



$e + J + p_T^{\rm miss}$ final states at the linear colliders.

1811.04291





- Transverse momentum for fat-jet $p_T^J > 150$ GeV for M_N mass range 400 GeV-600 GeV and $p_T^J > 250$ GeV for M_N mass range 700 GeV-900 GeV.
- Transverse momentum for leading lepton $p_T^{e^\pm} > 100$ GeV for M_N mass range 400 GeV-600 GeV and $p_T^{e^\pm} > 200$ GeV for M_N mass range 700 GeV-900 GeV.
- Polar angle of lepton and fat-jet $|\cos\theta_e| < 0.85$, $|\cos\theta_J| < 0.85$.
- Fat-jet mass $M_J > 70$ GeV.

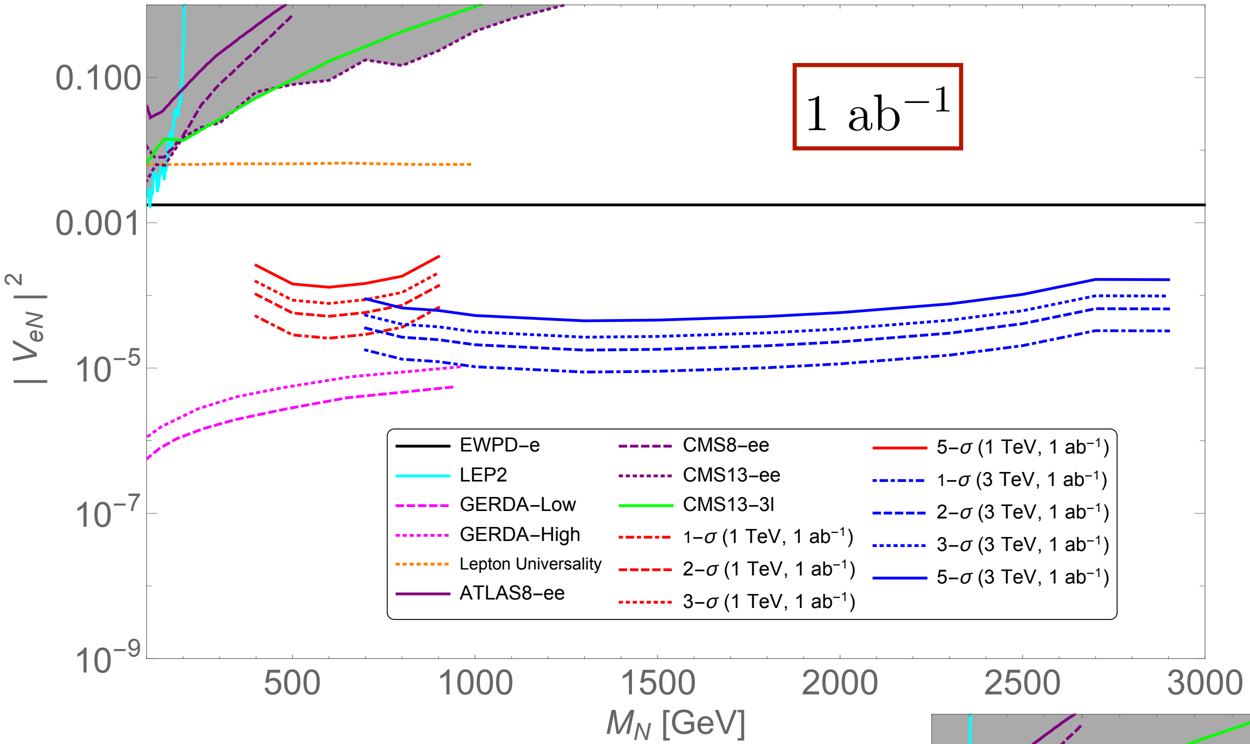
1 TeV e^-e^+ collider

- Transverse momentum for fat-jet $p_T^J > 250$ GeV for the M_N mass range 700 GeV-900 GeV and $p_T^J > 400$ GeV for M_N mass range $1 - 2.9$ TeV.
- Transverse momentum for leading lepton $p_T^{e^\pm} > 200$ GeV for M_N mass range $700 - 900$ GeV and $p_T^{e^\pm} > 250$ GeV for M_N mass range $1 - 2.9$ TeV.
- Polar angle of lepton and fat-jet $|\cos\theta_e| < 0.85$, $|\cos\theta_J| < 0.85$.
- Fat-jet mass $M_J > 70$ GeV.

3 TeV e^-e^+ collider

Mass-mixing limit plots

$\sqrt{s} =$ 1 TeV (red band) and 3 TeV (blue band)



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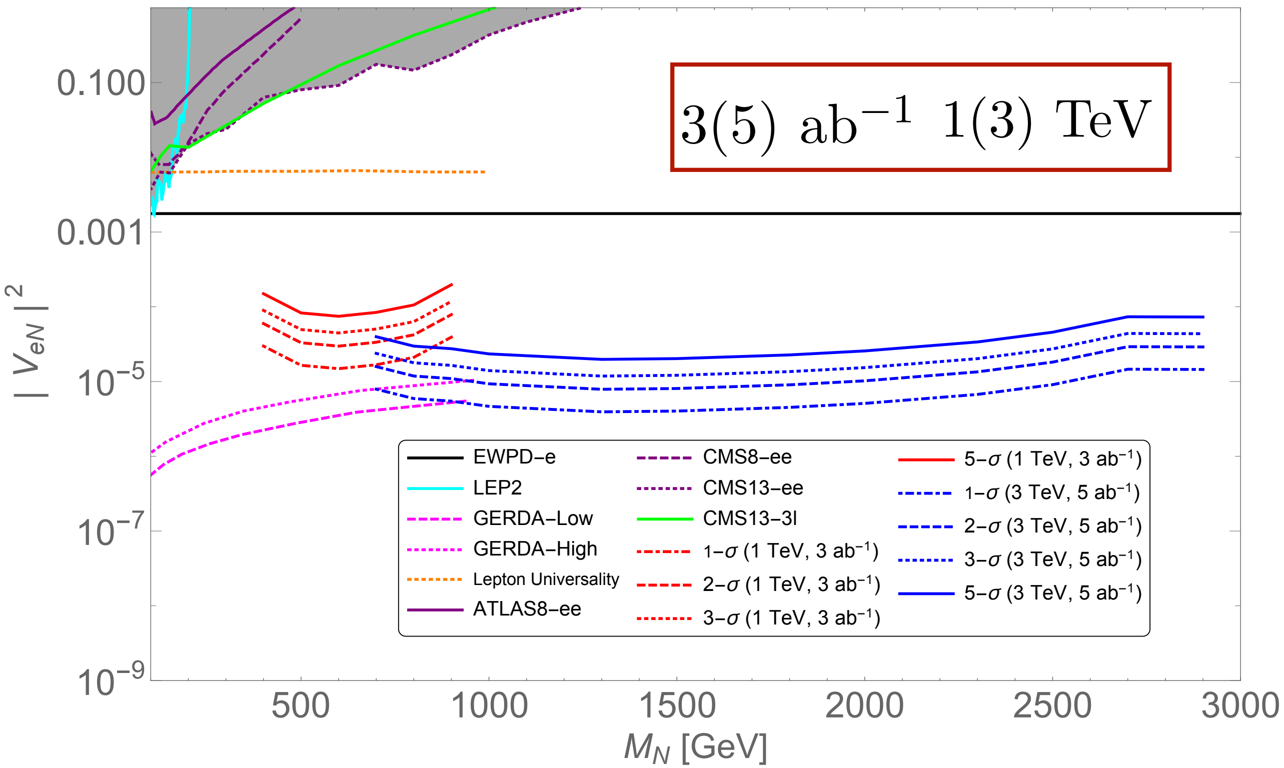
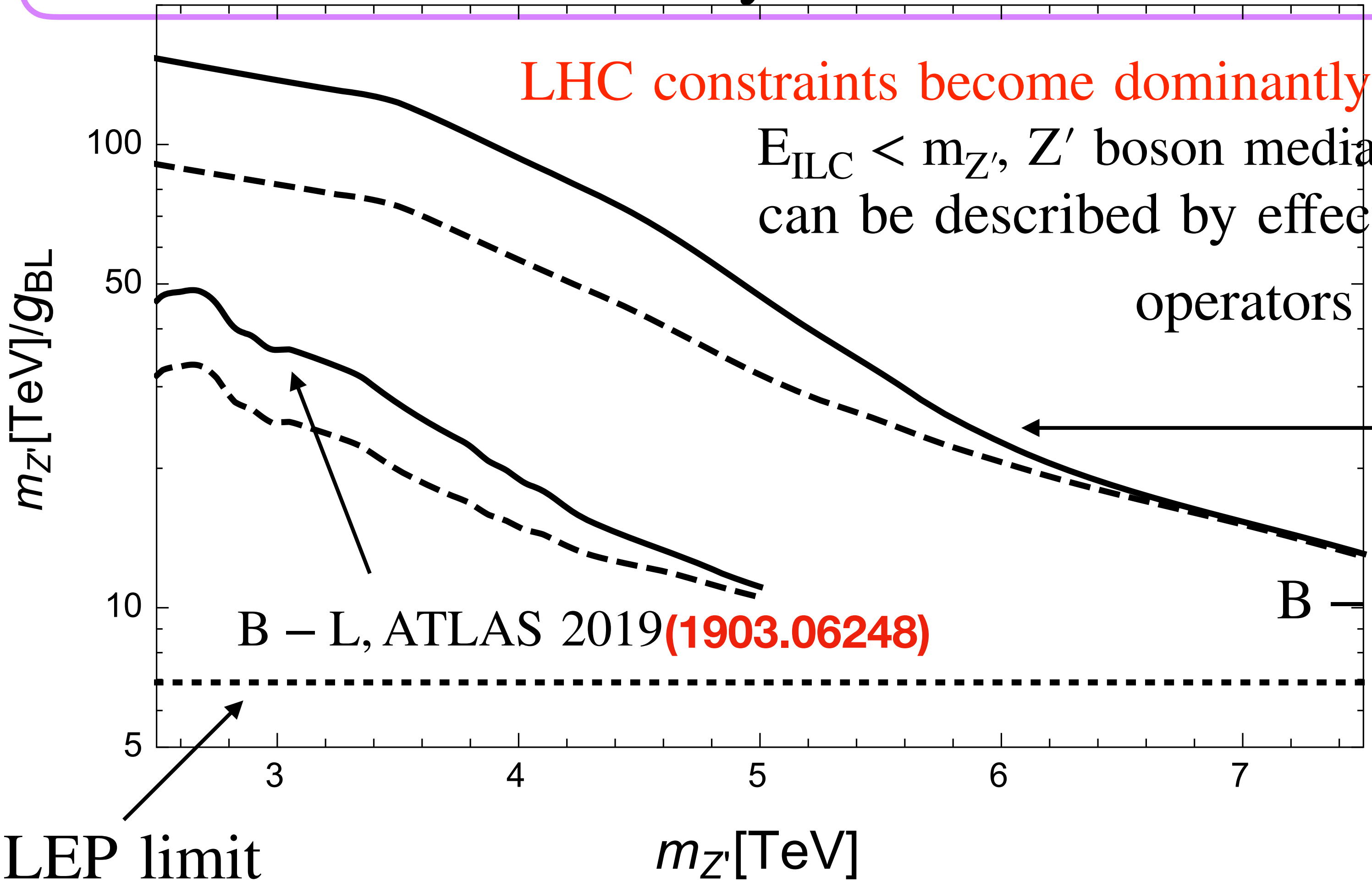


Production of the heavy neutrino at the ILC 1812.11931



LHC constraints become dominantly weaker with heavier Z'

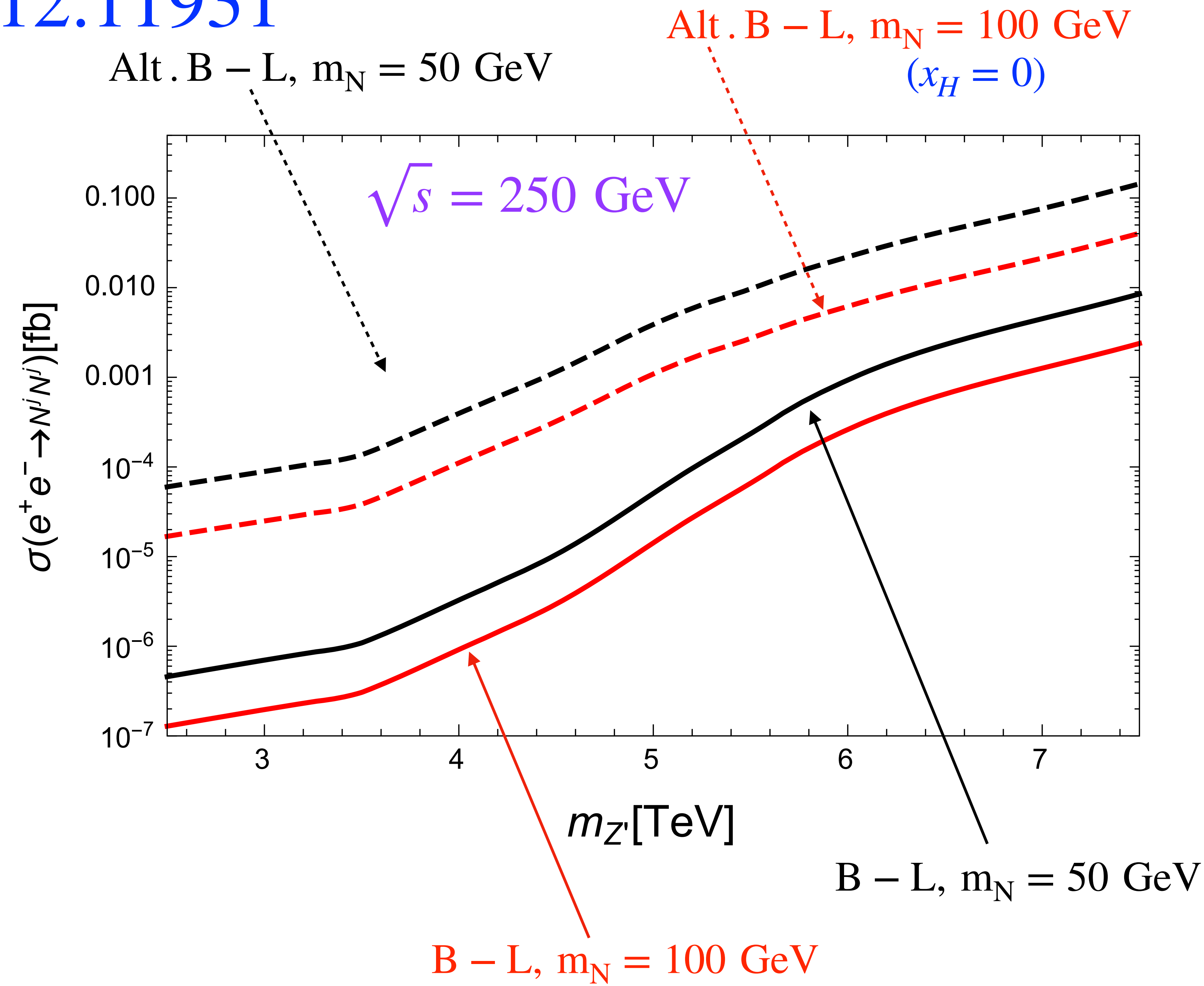
$E_{ILC} < m_{Z'}$, Z' boson mediated processes at the ILC can be described by effective higher dimensional operators $\propto \left(\frac{m_{Z'}}{g_{BL}}\right)^2$

Dashed lines represent the Atl. B – L case

$$\sigma(e^+e^- \to Z'^* \to N^i N^i) \simeq \frac{(Q_{N^i})^2}{24\pi} s \boxed{\left(\frac{g_{BL}}{m_{Z'}}\right)^4} \left(1 - \frac{4m_{N^i}^2}{m_{Z'}^2}\right)^{\frac{3}{2}}.$$

As a result ILC is a powerful machine to probe Z' beyond HL – LHC

1812.11931

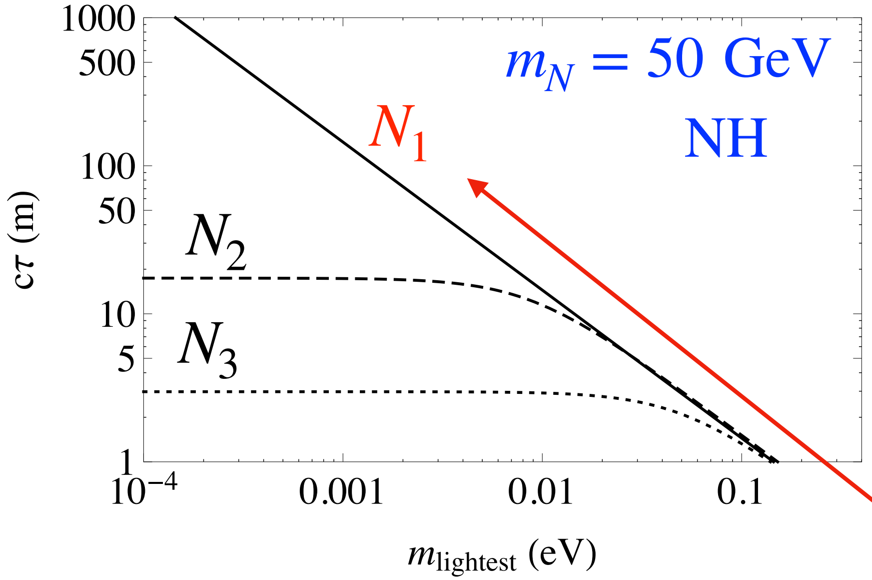


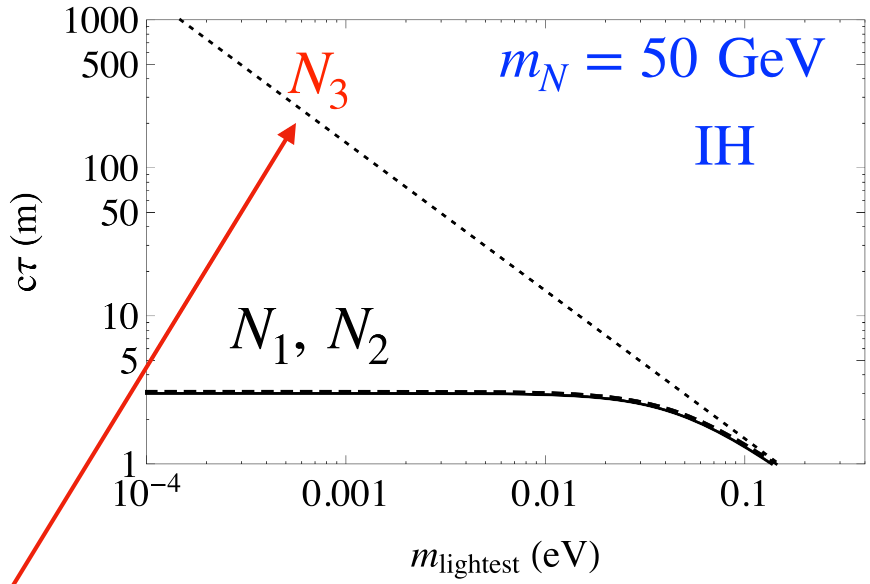
Alt . B − L, m_N = 100 GeV
(x_H = 0)
Alt . B − L, m_N = 50 GeV
√s = 250 GeV
0.100
0.010
0.001
10^−4
10^−5
10^−6
10^−7
σ(e+e−→N^i N^j)[fb]
3
4
5
6
7
m_Z'[TeV]
B − L, m_N = 50 GeV
B − L, m_N = 100 GeV

Long lived RHNs

B – L case

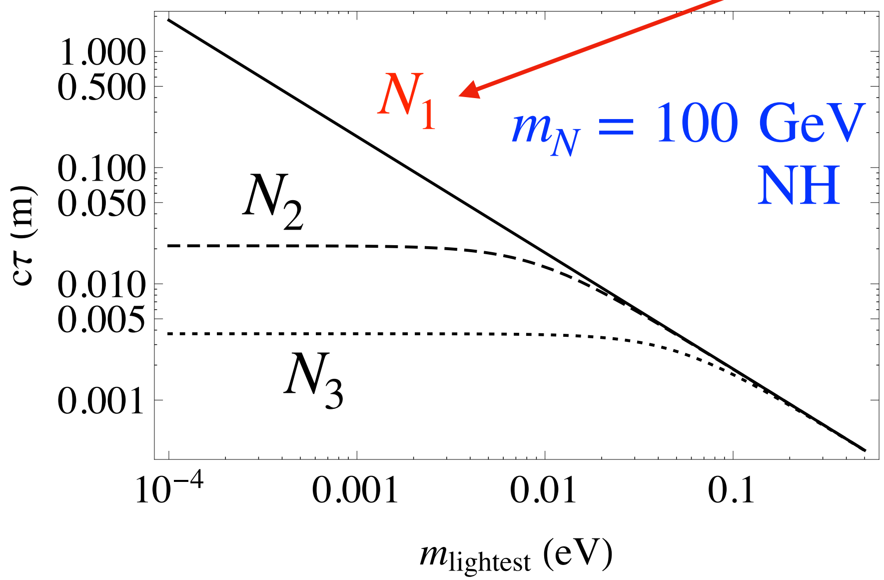
1812.11931

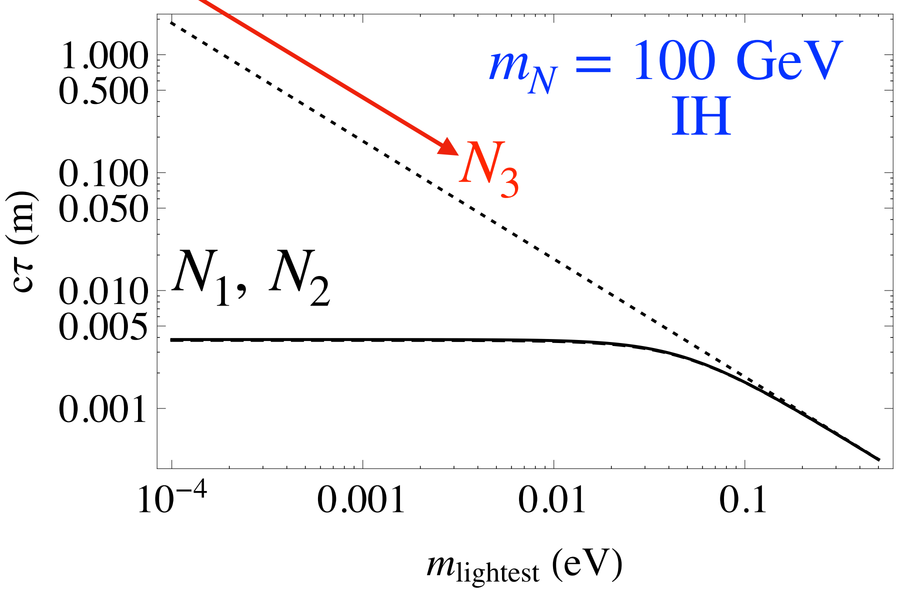




Longest lived RHN life time is inversely proportional to $\text{m}_{\text{lightest}}$

$\text{m}_{\text{lightest}} \rightarrow 0$ leads to the long lived species as a potential DM candiadte





Type – III seesaw

2005.02267, 2006.04123

$$\mathcal{L} = \mathcal{L}_{\rm SM} + {\rm Tr}(\overline{\Psi} i\gamma^\mu D_\mu \Psi) - \frac{1}{2} M {\rm Tr}(\overline{\Psi}\Psi^c + \overline{\Psi^c}\Psi) - \sqrt{2}(\overline{\ell_L} Y_D^\dagger \Psi H + H^\dagger \overline{\Psi} Y_D \ell_L)$$

$$\Psi = \begin{pmatrix} \Sigma^0/\sqrt{2} & \Sigma^+ \\ \Sigma^- & -\Sigma^0/\sqrt{2} \end{pmatrix} \text{ and } \Psi^c = \begin{pmatrix} \Sigma^{0c}/\sqrt{2} & \Sigma^{-c} \\ \Sigma^{+c} & -\Sigma^{0c}/\sqrt{2} \end{pmatrix}$$

$$-\mathcal{L}_{\rm mass} = \begin{pmatrix} \overline{e}_L & \overline{\Sigma}_L \end{pmatrix} \begin{pmatrix} m_\ell & Y_D^\dagger v \\ 0 & M \end{pmatrix} \begin{pmatrix} e_R \\ \Sigma_R \end{pmatrix} + \frac{1}{2} \begin{pmatrix} \overline{\nu_L^c} & \overline{\Sigma_R^0} \end{pmatrix} \begin{pmatrix} 0 & Y_D^T \frac{v}{\sqrt{2}} \\ Y_D \frac{v}{\sqrt{2}} & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \Sigma_R^{0c} \end{pmatrix} + h.c.$$

$$\boxed{m_\nu \simeq -\frac{v^2}{2} Y_D^T M^{-1} Y_D = M_D M^{-1} M_D^T}$$

$$\Gamma(\Sigma^\pm \to \nu W) = \frac{g^2 |V_{\ell\Sigma}|^2}{32\pi} \left(\frac{M^3}{M_W^2}\right) \left(1 - \frac{M_W^2}{M^2}\right)^2 \left(1 + 2\frac{M_W^2}{M^2}\right)$$

$$\Gamma(\Sigma^\pm \to \ell Z) = \frac{g^2 |V_{\ell\Sigma}|^2}{64\pi \cos^2\theta_W} \left(\frac{M^3}{M_Z^2}\right) \left(1 - \frac{M_Z^2}{M^2}\right)^2 \left(1 + 2\frac{M_Z^2}{M^2}\right)$$

$$\Gamma(\Sigma^\pm \to \ell h) = \frac{g^2 |V_{\ell\Sigma}|^2}{64\pi} \left(\frac{M^3}{M_W^2}\right) \left(1 - \frac{M_h^2}{M^2}\right)^2,$$

$$\Gamma(\Sigma^\pm \to \Sigma^0 \pi^\pm) = \frac{2G_F^2 V_{ud}^2 \Delta M^3 f_\pi^2}{\pi} \sqrt{1 - \frac{m_\pi^2}{\Delta M^2}}$$

$$\Gamma(\Sigma^\pm \to \Sigma^0 e \nu_e) = \frac{2G_F^2 \Delta M^5}{15\pi}$$

$$\Gamma(\Sigma^\pm \to \Sigma^0 \mu \nu_\mu) = 0.12\Gamma(\Sigma^\pm \to \Sigma^0 e \nu_e)$$

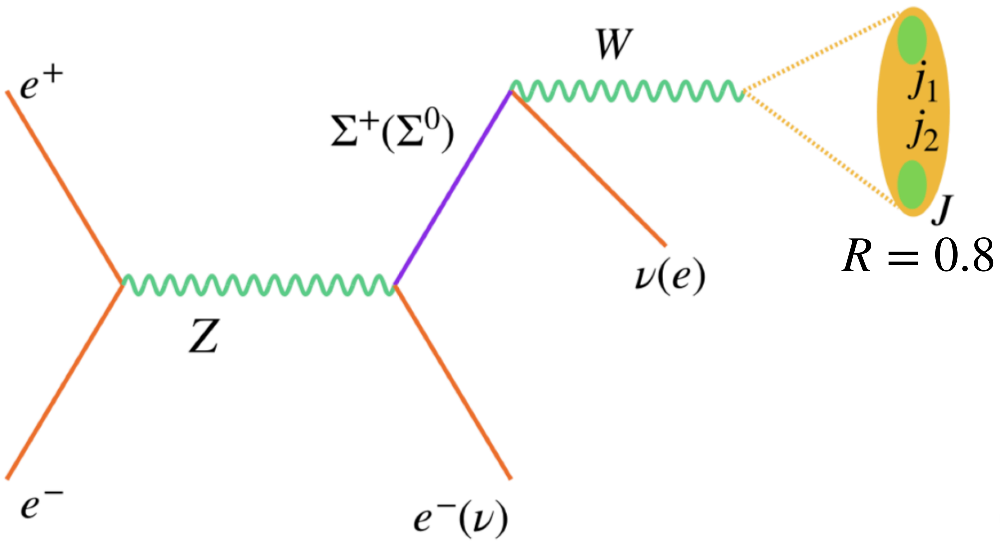
$$\Gamma(\Sigma^0 \to \ell^+ W) = \Gamma(\Sigma^0 \to \ell^- W) = \frac{g^2 |V_{\ell\Sigma}|^2}{64\pi} \left(\frac{M^3}{M_W^2}\right) \left(1 - \frac{M_W^2}{M^2}\right)^2 \left(1 + 2\frac{M_W^2}{M^2}\right)$$

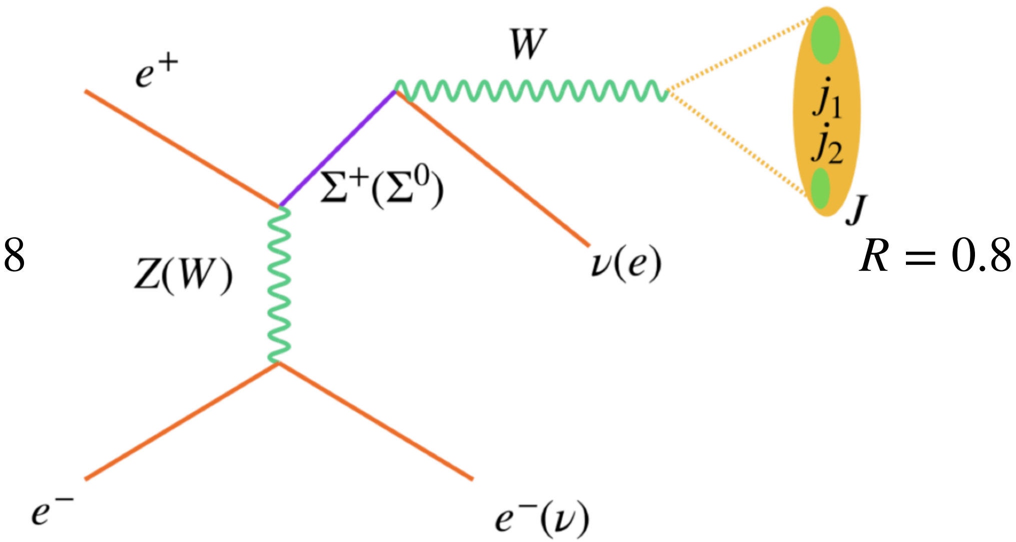
$$\Gamma(\Sigma^0 \to \nu Z) = \Gamma(\Sigma^0 \to \overline{\nu} Z) = \frac{g^2 |V_{\ell\Sigma}|^2}{128\pi \cos^2\theta_W} \left(\frac{M^3}{M_Z^2}\right) \left(1 - \frac{M_Z^2}{M^2}\right)^2 \left(1 + 2\frac{M_Z^2}{M^2}\right)$$

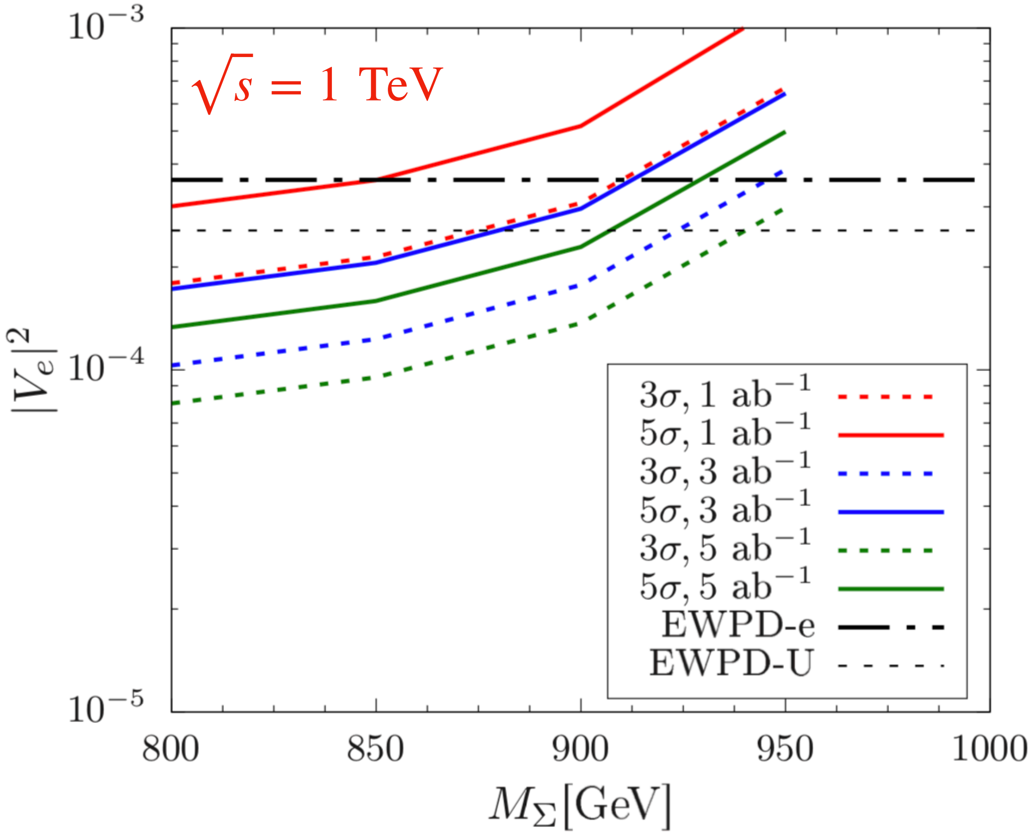
$$\Gamma(\Sigma^0 \to \nu h) = \Gamma(\Sigma^0 \to \overline{\nu} h) = \frac{g^2 |V_{\ell\Sigma}|^2}{128\pi} \left(\frac{M^3}{M_W^2}\right) \left(1 - \frac{M_h^2}{M^2}\right)^2,$$

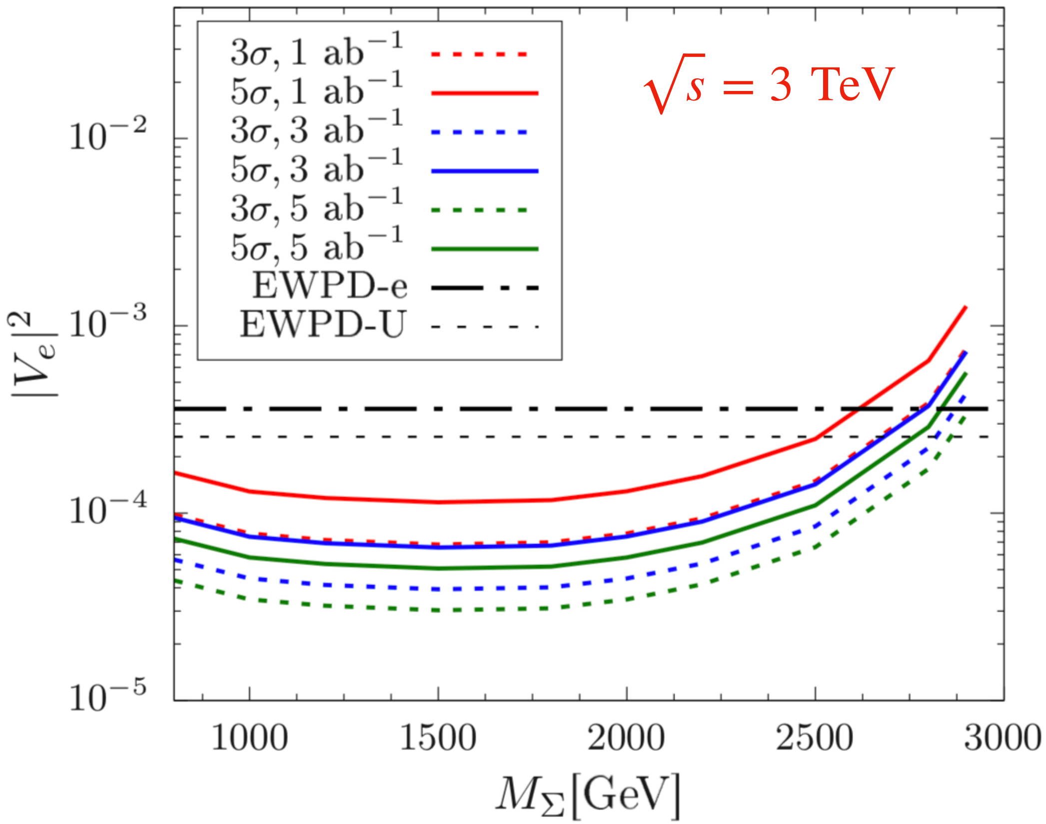
Mass-mixing limit plots

2005.02267





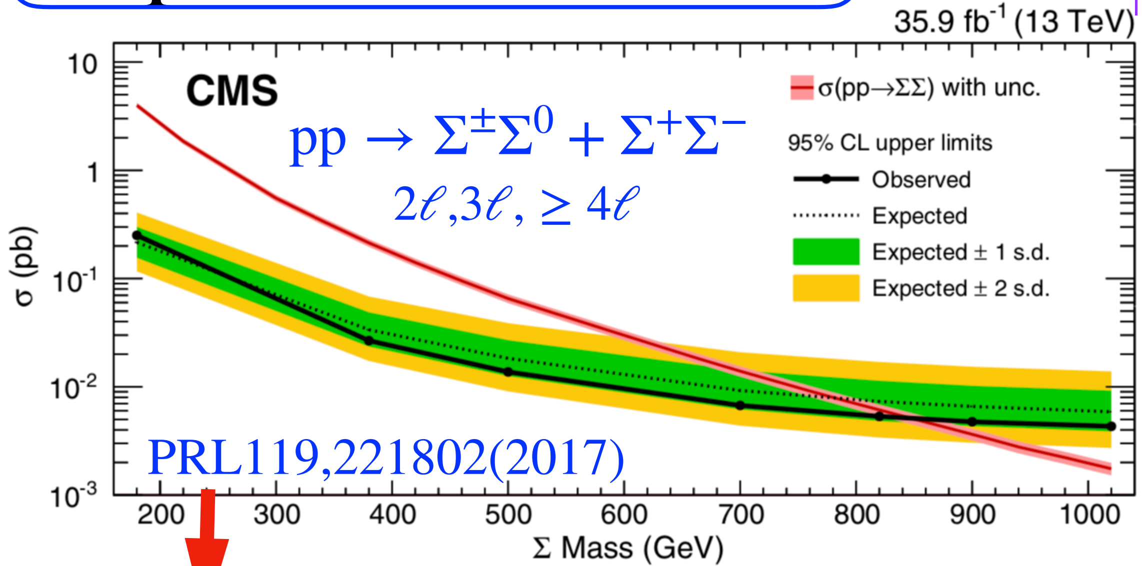


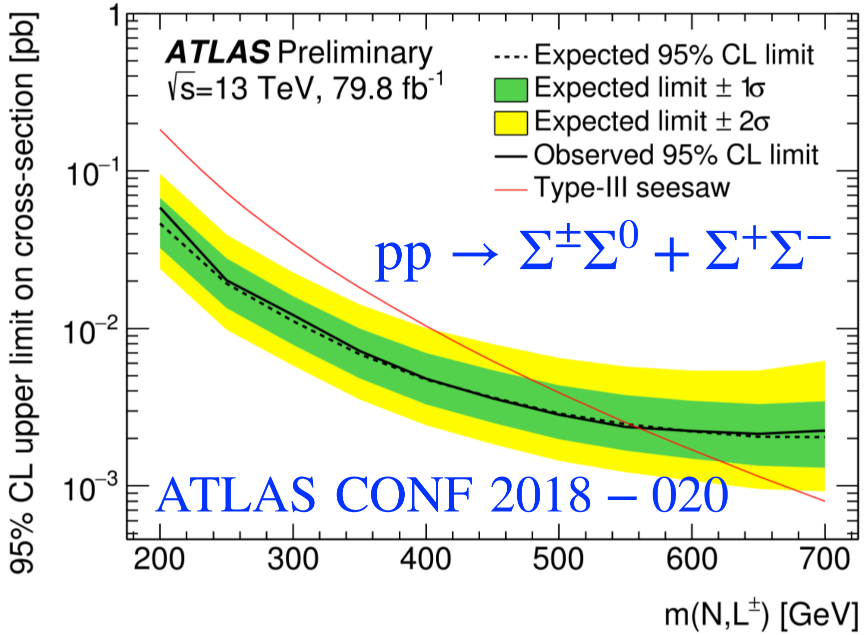


Experimental limits

$$\mathrm{BR} = B_\ell \propto \frac{|V_\ell|^2}{|V_e|^2 + |V_\mu|^2 + |V_\tau|^2} \quad B_e = B_\mu = B_\tau$$

Flavor – democratic scenario

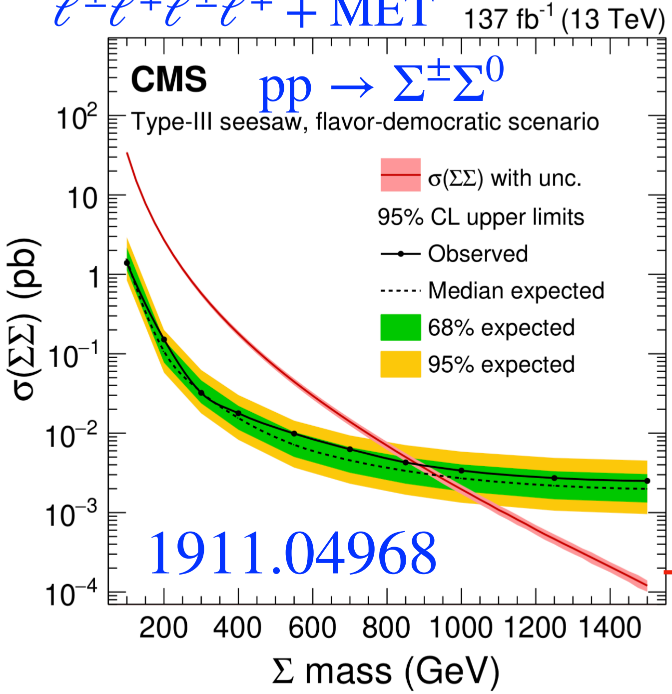




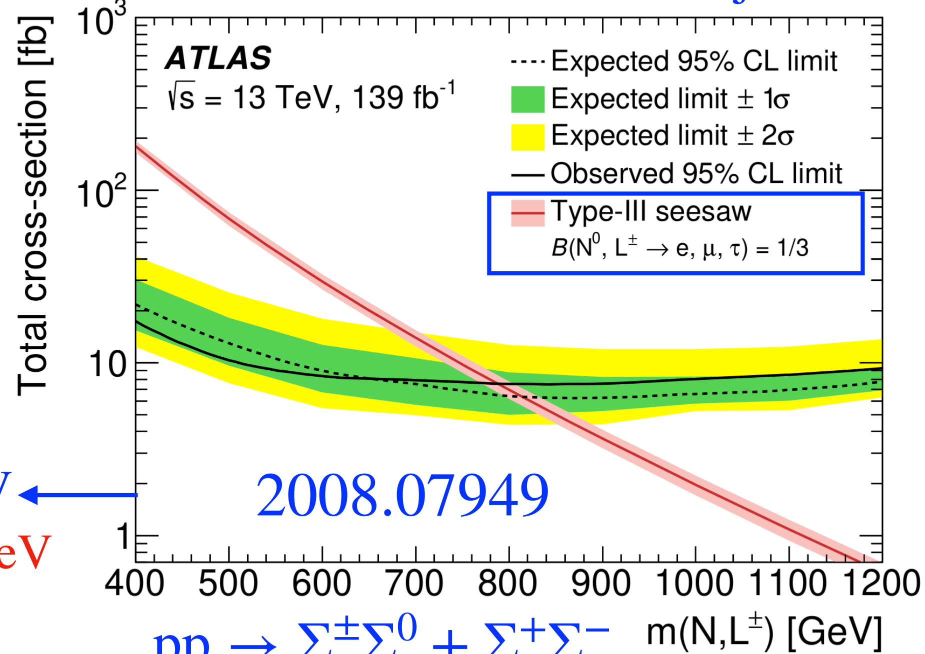
τ – phoic, $B_\tau = 0, M_\Sigma = 900$ GeV, 90 % CL

(e, μ) – phoic, $B_{e+mu} = 0, M_\Sigma = 390$ GeV, 90 % CL

$\ell^\pm\ell^\mp\ell^\pm\ell^\mp$ + MET



$\ell^\pm\ell^\pm + \ell^\mp\ell^\pm$ + MET + jets



$M_\Sigma \leq 800$ GeV

$M_\Sigma \leq 900$ GeV

$pp \to \Sigma^\pm\Sigma^0 + \Sigma^+\Sigma^-$

Conclusions

We study the models with the heavy leptons under the simple extensions of the SM where the neutrino mass is generated by the seesaw mechanism to reproduce the neutrino oscillation data.

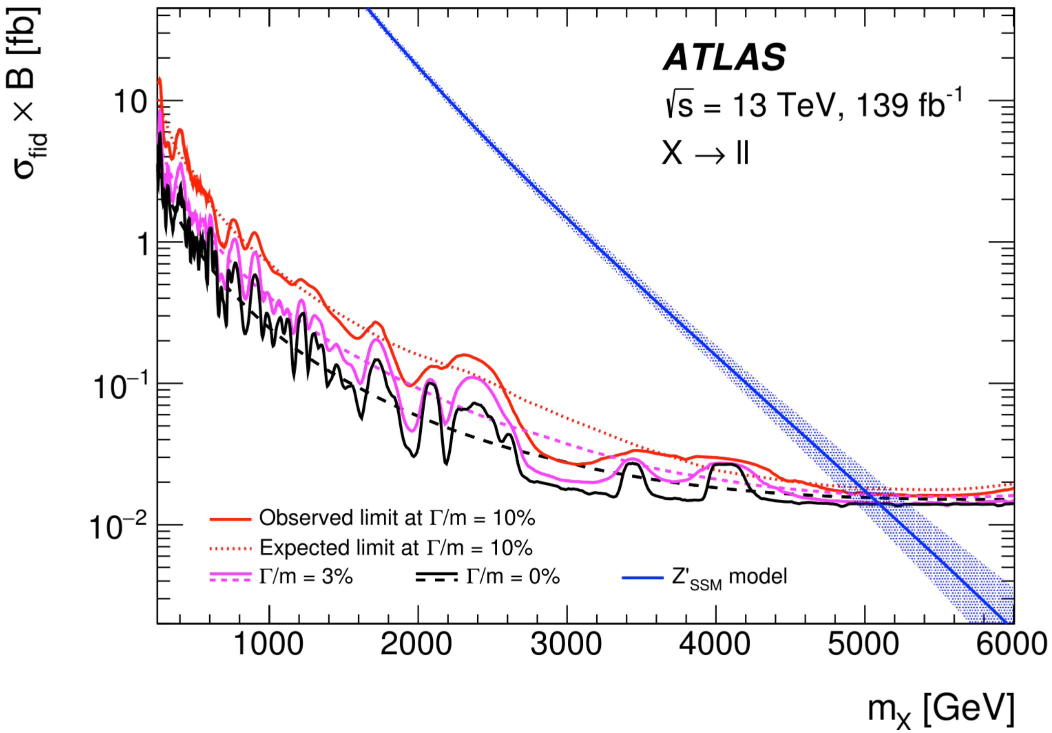
We find that such heavy fermions can be tested at the underground experiments at the electron positron collider. We have calculated the bounds on the light-heavy mixings for the electron-positron collider which could be probed in the near future.

Thank You

Backup slides

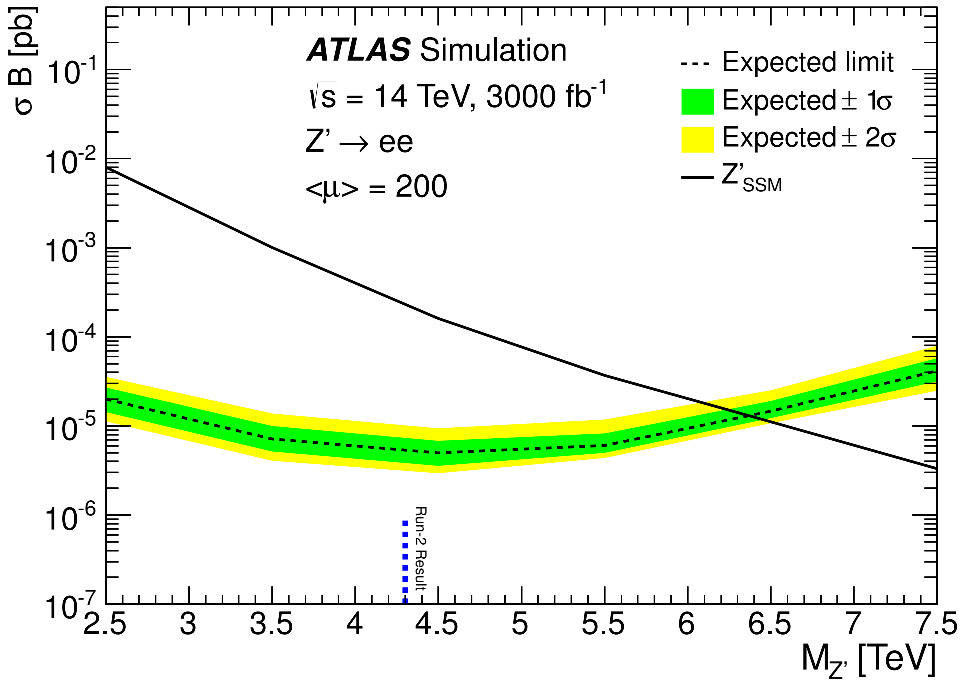
Bounds on the $U(1)_X$ gauge coupling

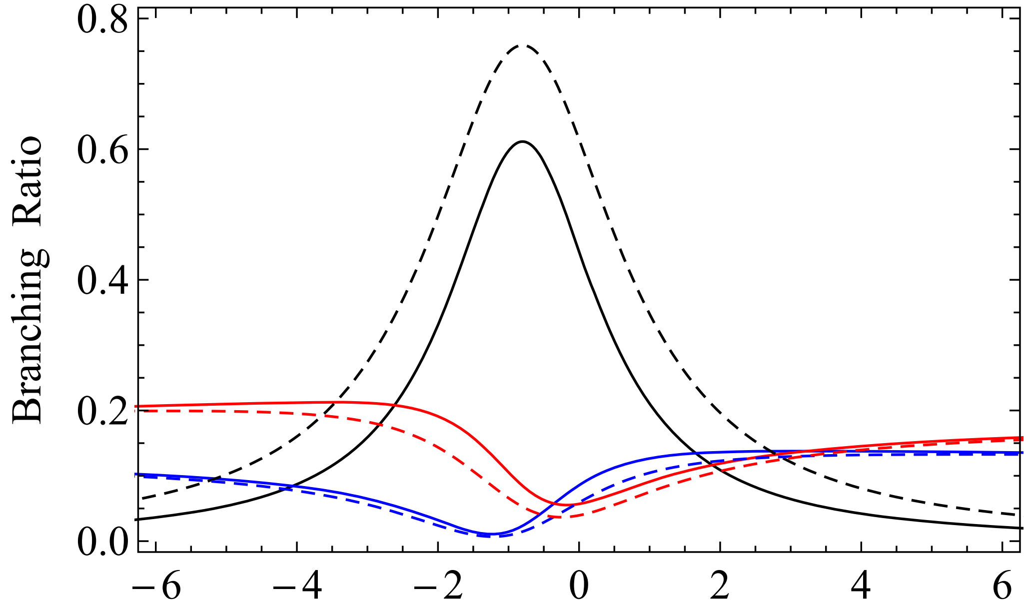
ATLAS: 1903.06248 (139/fb)



CMS (36/fb) and ATLAS (139/fb) searches at the LHC Run-1 and Run-2 respectively

ATLAS-TDR-027 (prospective)





$m_{Z'} = 3$ TeV.

Solid

$m_{N^1} = m_{Z'}/4$

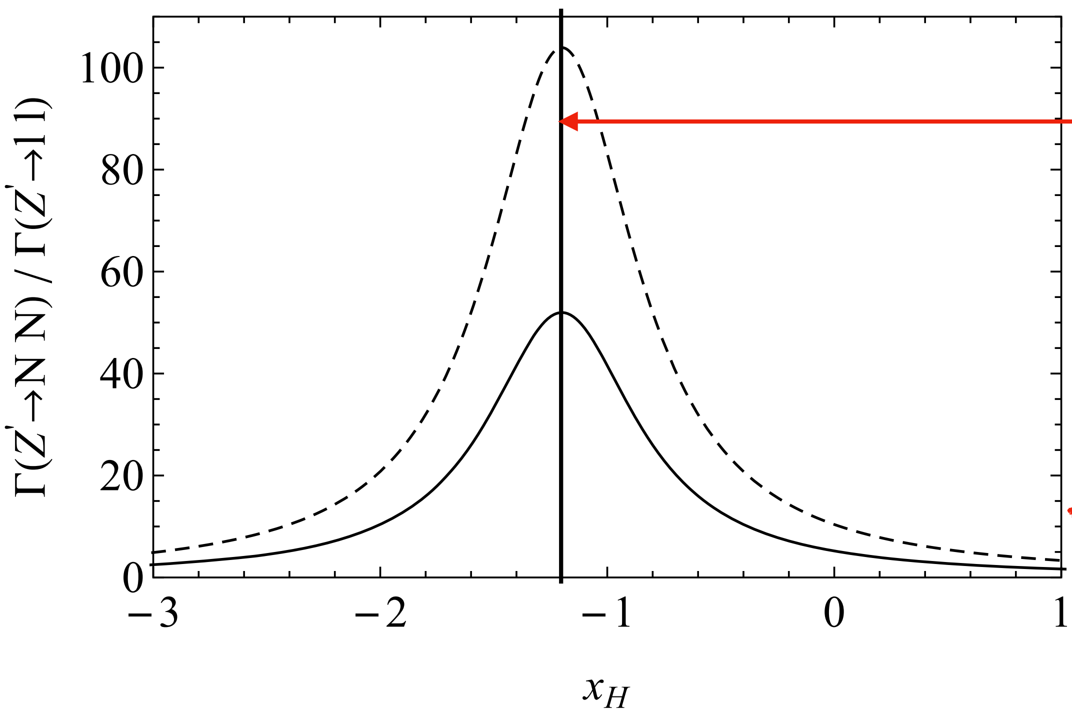
$m_{N^2} > m_{Z'}/2,$

Dashed

$m_{N^{1,2}} = m_{Z'}/4.$

Top → bottom : Solid (Red, Black, Blue) x_H

Up and down quarks Heavy neutrinos Charged leptons



$x_H = -1.2$

Solid $m_{N^1} = m_{Z'}/4$, $m_{N^2} > m_{Z'}/2,$

Dashed $m_{N^{1,2}} = m_{Z'}/4.$

$$\frac{\Gamma(Z' \to NN)}{\Gamma(Z' \to \bar{\ell}\ell)} = \frac{64}{8 + 12x_H + 5x_H^2}\left(1 - \frac{4m_N^2}{m_{Z'}^2}\right)^{3/2}$$

$m_{Z'} = 7.5$ TeV $\sqrt{s} = 250$ GeV 1812.11931

$$\sigma(e^+e^- \to Z'^* \to N^i N^i) = 0.0085 \text{ fb (B} - \text{L)}$$
$$= 0.14 \text{ fb (Alt. B} - \text{L)}$$

$$m_{N^{1,2,3}} = 50 \text{ GeV and } m_{N^{1,2}} = 50 \text{ GeV}$$

degenerate RHNs @ $\sum_{i=1}^{3} \sigma(e^+e^- \to Z'^* \to N^i N^i) = 0.026$ fb (B − L)

$\sum_{i=1}^{2} \sigma(e^+e^- \to Z'^* \to N^i N^i) = 0.29$ fb (Alt. B − L)

Luminosity = 2000 fb^{-1} 52 and 576 events respectively

satisfying constraints from the HL − LHC

Majorana RHNs will show $\ell^{\pm}\ell^{\pm}4j$ signal which can be a smoking gun signature data fitting. at the ILC to probe Majorana nature. Let's find the branching ratios after the neutrino

1812.11931

B – L

$m_N = 50$ GeV	$e + jj$	$\mu + jj$	$\tau + jj$
N^1	0.412	0.104	0.104
N^2	0.204	0.224	0.224
N^3	0.0154	0.310	0.310

$m_N = 100$ GeV	$e + jj$	$\mu + jj$	$\tau + jj$
N^1	0.587	0.148	0.148
N^2	0.276	0.304	0.304
N^3	0.0208	0.431	0.431

Alt . B – L

NH case

$m_N = 50$ GeV	$e + jj$	$\mu + jj$	$\tau + jj$
N^1	0.194	0.213	0.213
N^2	0.0154	0.318	0.318

$m_N = 100$ GeV	$e + jj$	$\mu + jj$	$\tau + jj$
N^1	0.276	0.304	0.304
N^2	0.0208	0.431	0.431

IH case

$m_N = 50$ GeV	$e + jj$	$\mu + jj$	$\tau + jj$
N^1	0.412	0.104	0.104
N^2	0.204	0.224	0.224

$m_N = 100$ GeV	$e + jj$	$\mu + jj$	$\tau + jj$
N^1	0.587	0.148	0.148
N^2	0.276	0.304	0.304

Finally $NN \to 2\ell^{\pm}4j$ will dominantly be between 16% – 34 % for the final results for the B – L → Alt . B – Lscenario .