Probing heavy neutral leptons at the electron positron collider

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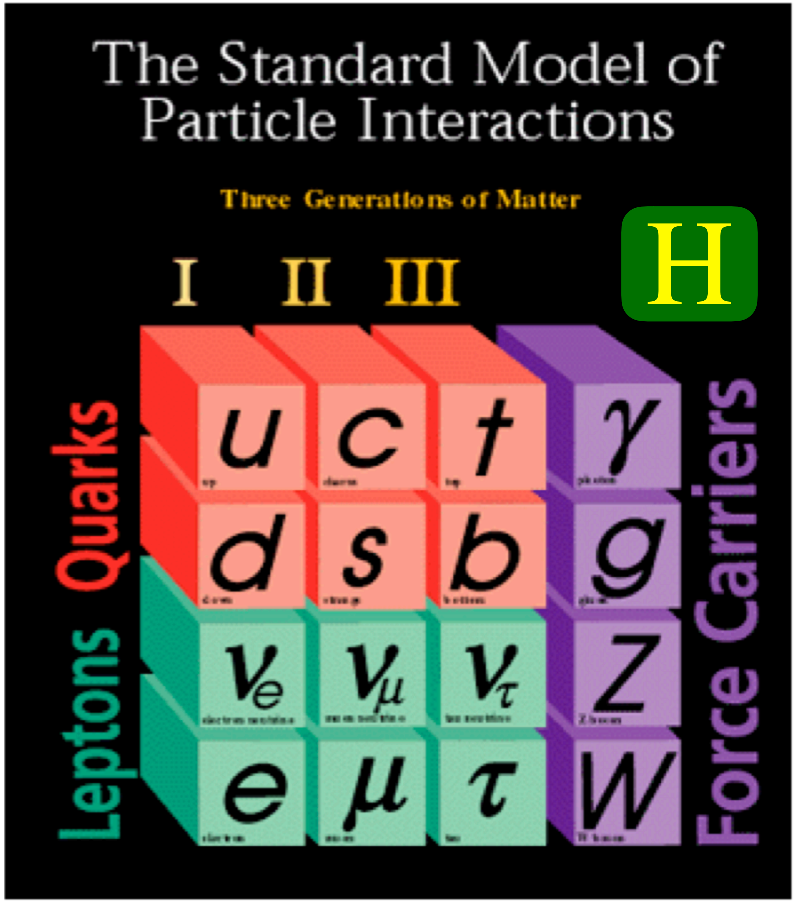
ILDAnalysis/ SoftwareMeeting November 4, 2020



Over the decades experiments have found each and every missing pieces

Verified the facts that they belong to this family

Finally at the Large Hadron collider Higgs has been observed
→ Its properties must be verified

Strongly established with interesting shortcomings

Few of the very interesting anomalies :

Tiny neutrino mass and flavor mixings → Neutrino oscillation experiment : SNO, Super – K, etc .

Relic abundance of dark matter . . .

- Nature : Majorana/ Dirac
- Ordering : Normal/Inverted
- Nature of the mixing between the mass and the flavor eigenstates

Unkown ←

SM can not explain them

Models of Neutrino to explain the origin of neutrino mass

There is a wide variety of neutrino mass models

The predicted models extend the SM minimally

At the tree level SM can be extended by Singlet fermions

→ Right handed neutrinos seesaw mechanism
inverse seesaw mechanism

Minkowski, Ramond, Slansky, Yanagida, Gell – Mann, Glashow, Mohapatra, Senjanovic

Linear, Hybrid

Alternative ideas extending the Standard Model

→ SU(2) triplet scalar : type – II seesaw

Schecter, Valle, Lazarides, Shafi, Wetterich, Mohapatra, Senjanovic

SU(2) triplet fermion : type – III seesaw

Foot, Lew, He, Joshi, Ma

One – loop and even at 2/3 – loop models also exist

→ For example : Ma – model, Zee – Model, Zee – Babu model, BNT, KNT, etc .

Babu, Leung, Hirsch, King, Nasri, Volkas Dev, Pilaftsis

→ Gauge extended : U(1), Left – Right

Pati, Salam; Mohapatra, Pati; Senjanovic, Mohapatra Buchmuller, Greub; Fileviez Perez, Han, Li; Deppisch, Desai, Valle; Kang, Ko, Li; Heeck, Teresi; Gluza, Chakrabortty Keung, Senjanovic; Ferrari et . al . ; Nemevsek, Nesti, Senjanovic, Zhang; Chen, Dev, Mohapatra; Dev, Mohapatra, Zhang; Dev, Goswami, Mitra AD, Dev, Mohapatra; AD, Okada, Raut

Particle content

Dobrescu, Fox; Cox, Han, Yanagida; AD, Okada, Raut; AD, Dev, Okada; Chiang, Cottin, AD, Mandal; AD, Takahashi, Oda, Okada

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$			$U(1)_X$
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

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

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

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

Seesaw mechnism

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

Antusch, Drewes, AD, Dev, Deppisch, Fischer

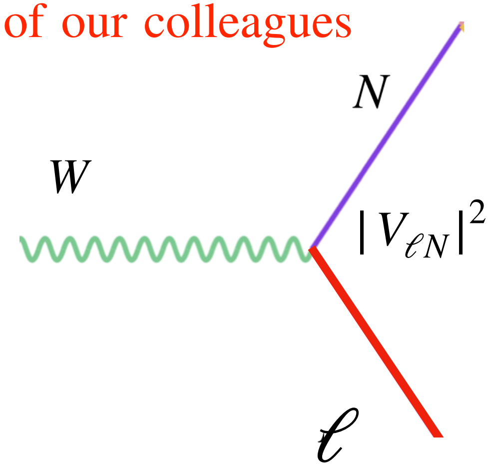
and many of our colleagues

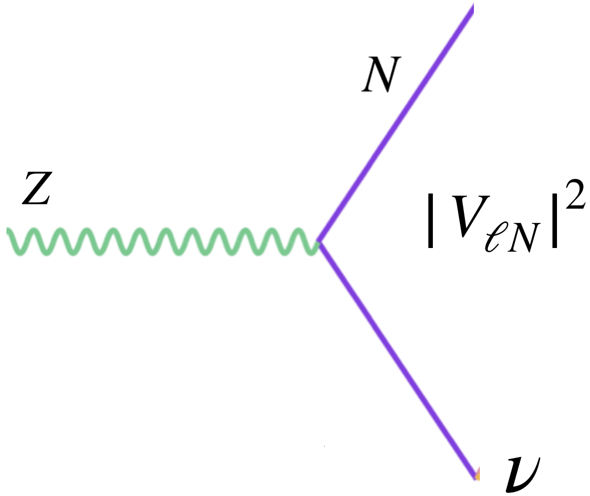
Flavor eigenstate can be expressed in terms of the mass eigenstate

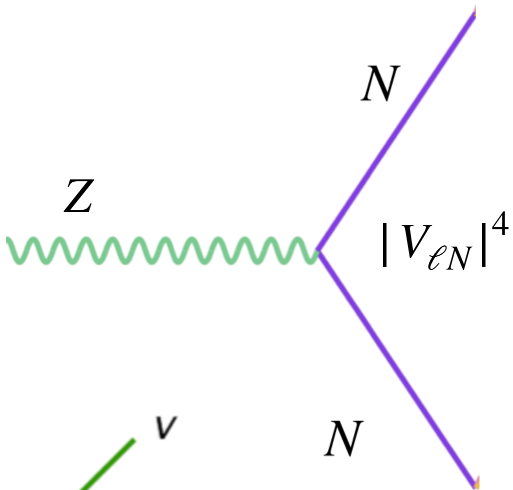
$$\nu_\ell \simeq U_{\ell m}\nu_m + V_{\ell n}N_n$$

$U_{\ell m}$ → **PMNS matrix**

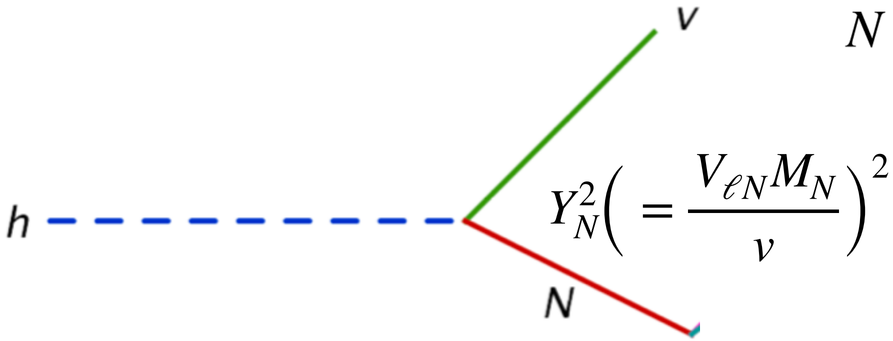
$V_{\ell n}$ → $M_D M_N^{-1}$



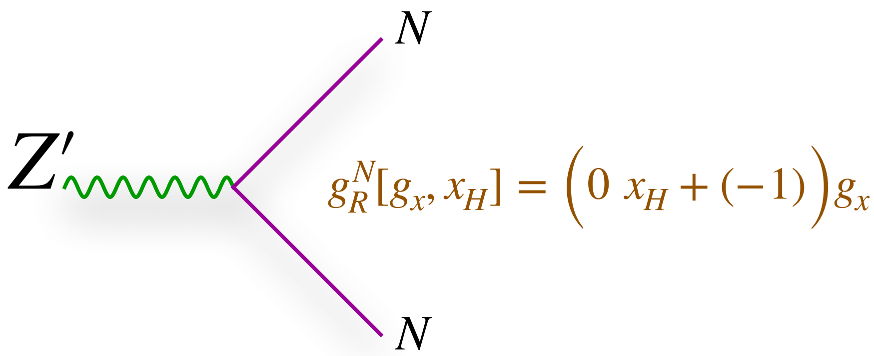




→ Suppressed



Direct interaction of the RHNs



Properties of the model and phenomenology

New particles

Z' boson

Heavy Majorana Neutrino

$U(1)_X$ Higgs boson

Phenomenology

Z' boson production and decay

Z' boson mediated processes

Heavy neutrino production

$U(1)_X$Higgs phenoemenology : Vacuum Stability

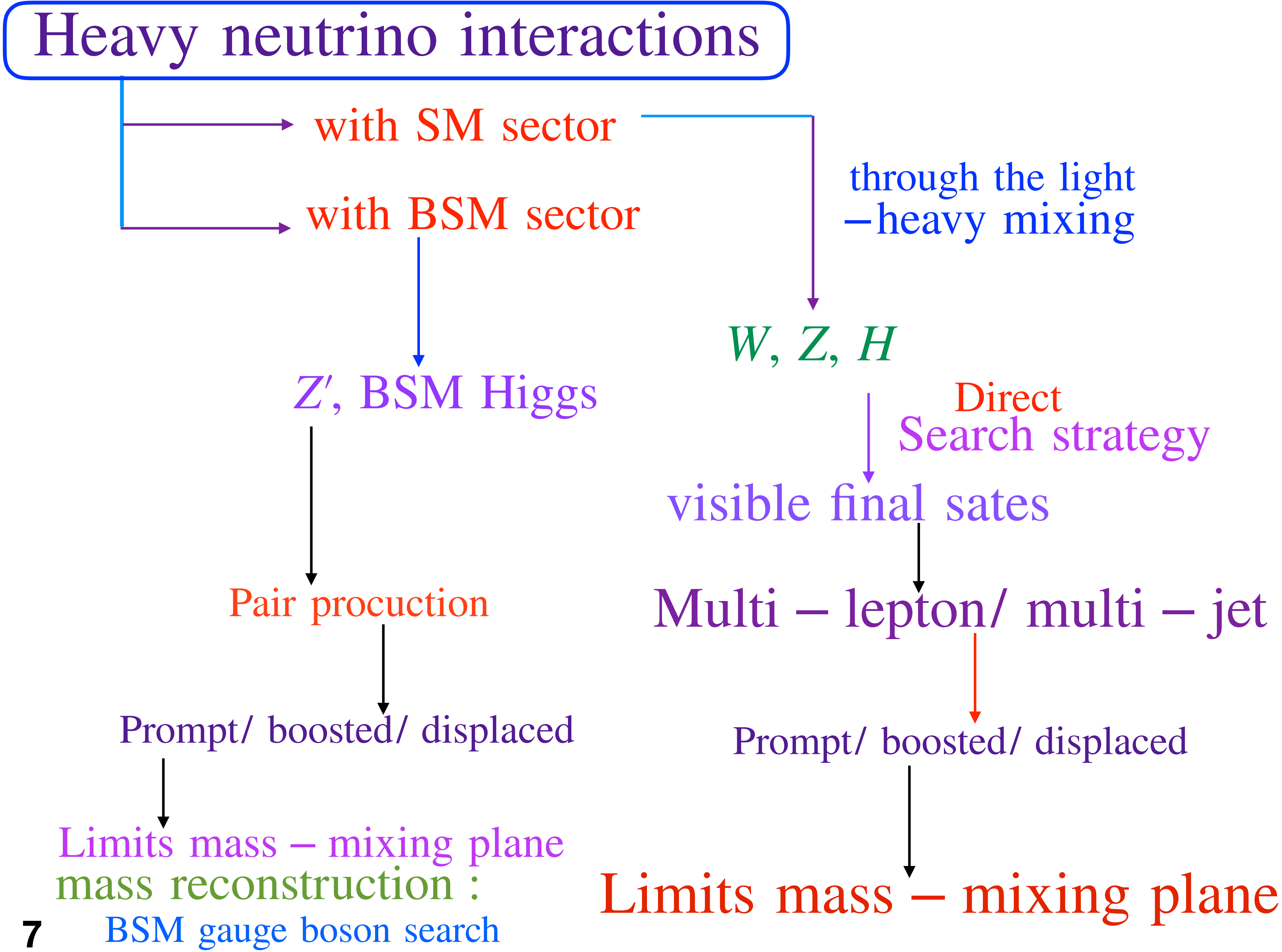
collider

Dark Matter

Leptogenesis and many more

Dev, Pilaftsis; Iso, Okada, Orikasa
Orikasa, Okada, Yamada; Dev, Mohapatra, Zhang

Z$'$ boson and heavy neutrino phenomenology


Heavy neutrino interactions
with SM sector
with BSM sector
through the light
–heavy mixing
W, Z, H
Z′, BSM Higgs
Direct
Search strategy
visible final sates
Pair procuction
Multi – lepton/ multi – jet
Prompt/ boosted/ displaced
Prompt/ boosted/ displaced
Limits mass – mixing plane
mass reconstruction :
BSM gauge boson search
Limits mass – mixing plane

Other interesting aspects in the $U(1)_X$ scenario

Ditect heavy neutrino searches

prompt/boosted/long – lived

from the heavy resonance induced pair production

Bossted objects like : W, Higgs

displaced decay of the heavy neutrino

discriminator : leptons insde the jet cone

Such sceanrios will appear in pair

rare in SM

In progress

paired displaced RHN decay is possible in this scenario

small to heavy mass range can be successfully probed from the heavy resonance

studying the tracks

Such models can successfully fit a potential Dark matter candidate (N_3)

Depending upon the model parameters

Relic

Z' portal, Higgs portal

Direct search

Mono – jet, mono – photon

LHC ILC

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

$$\begin{pmatrix} \cos(x+iy) & \sin(x+iy) \\ -\sin(x+iy) & \cos(x+iy) \end{pmatrix}$$

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

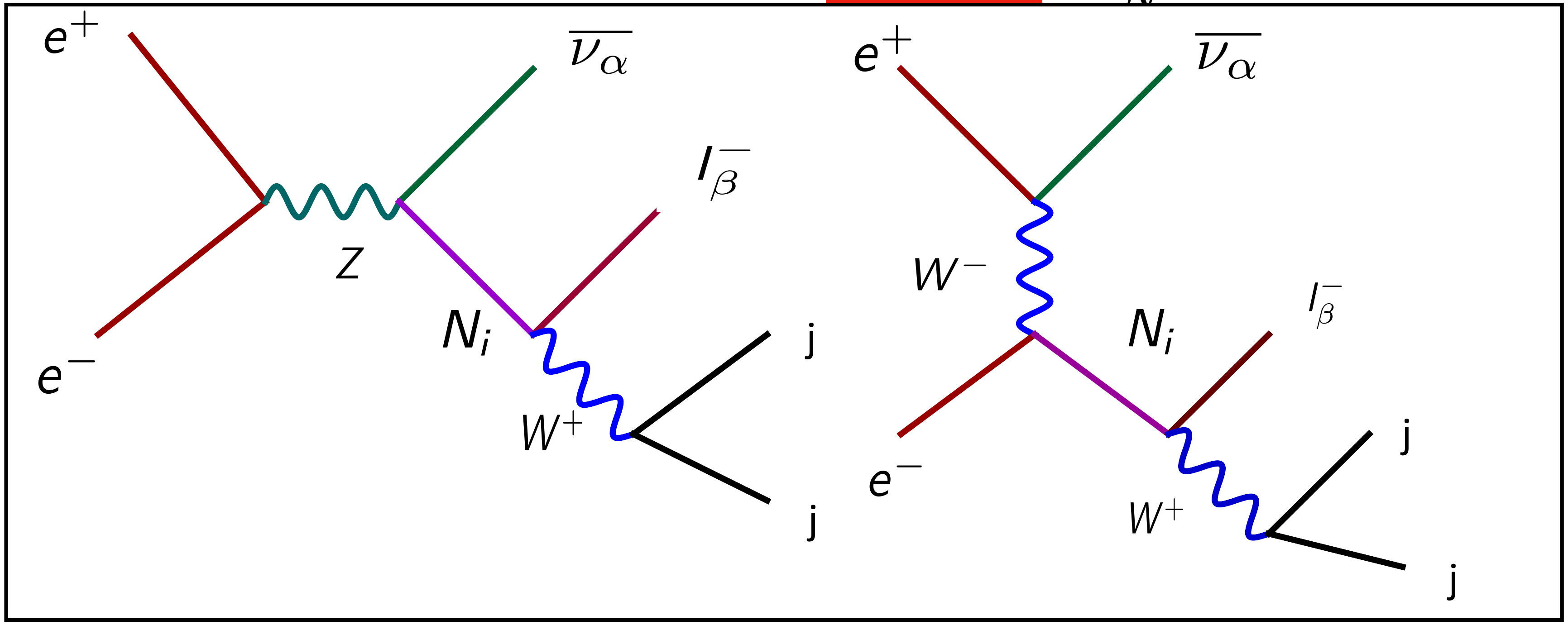
$\mathcal{N}^\dagger \mathcal{R} \simeq U^\dagger_{\rm MNS}\mathcal{R}$ because $|\epsilon_{\alpha\beta}| \ll 1$

branching ratios

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

Leading mode

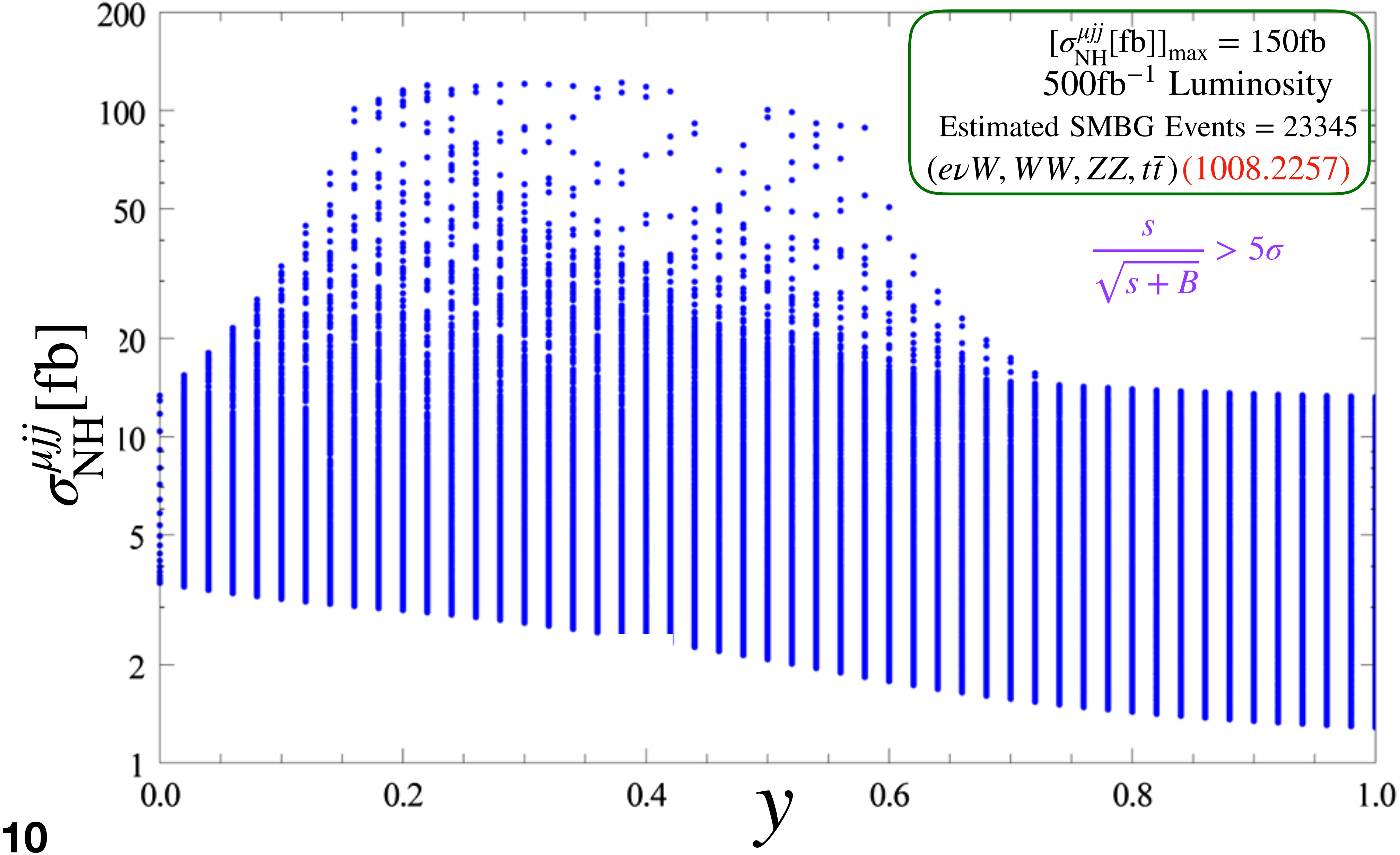
Signals $M_N = 150$ GeV



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 $\quad$ 1207.3734



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

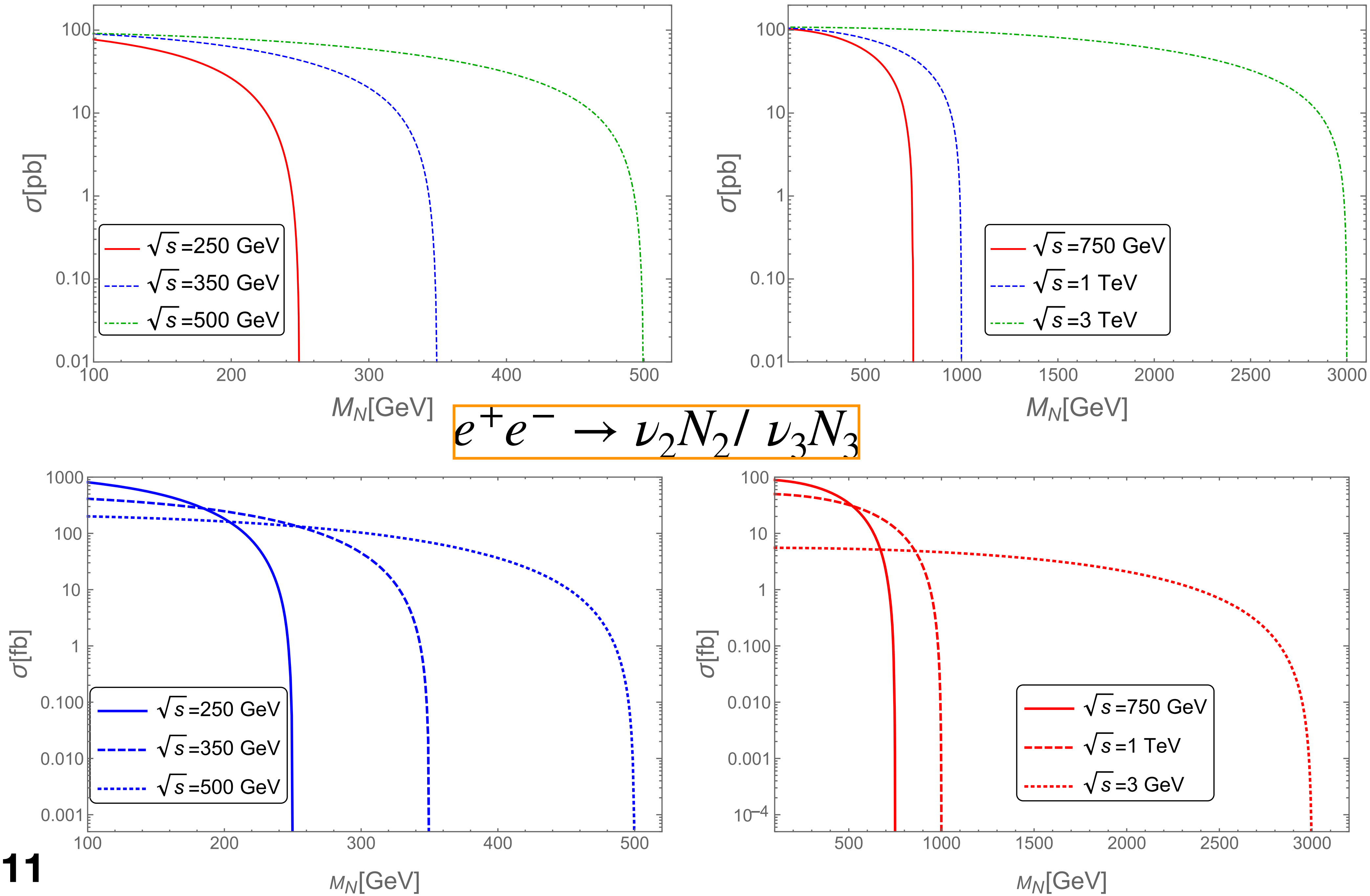
Normalized by mixing

1811.04291

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

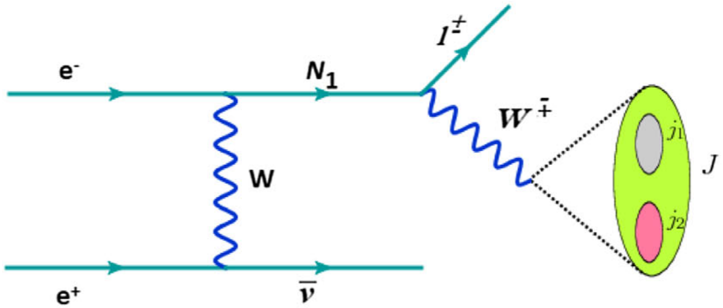
AD, Jana, Nandi, Mandal Chakraborty, Mitra, Shil
Banerjee, Dev, Ibarra, Mandal, Mitra Antusch, Fischer

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

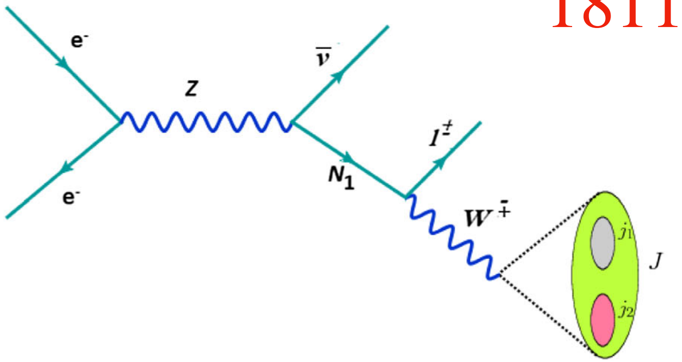


$e + J + p_T^{\rm miss}$ final states at the linear colliders.

1811.04291



$R = 0.8$



$R = 0.8$

- 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

Cut flow for the signal and background events for the final state $e^{\pm} + J + p_T^{\text{miss}}$ for $M_N = 500$ GeV at the $\sqrt{s} = 1$ TeV linear collider. The signal events are normalized by the square of the mixing.

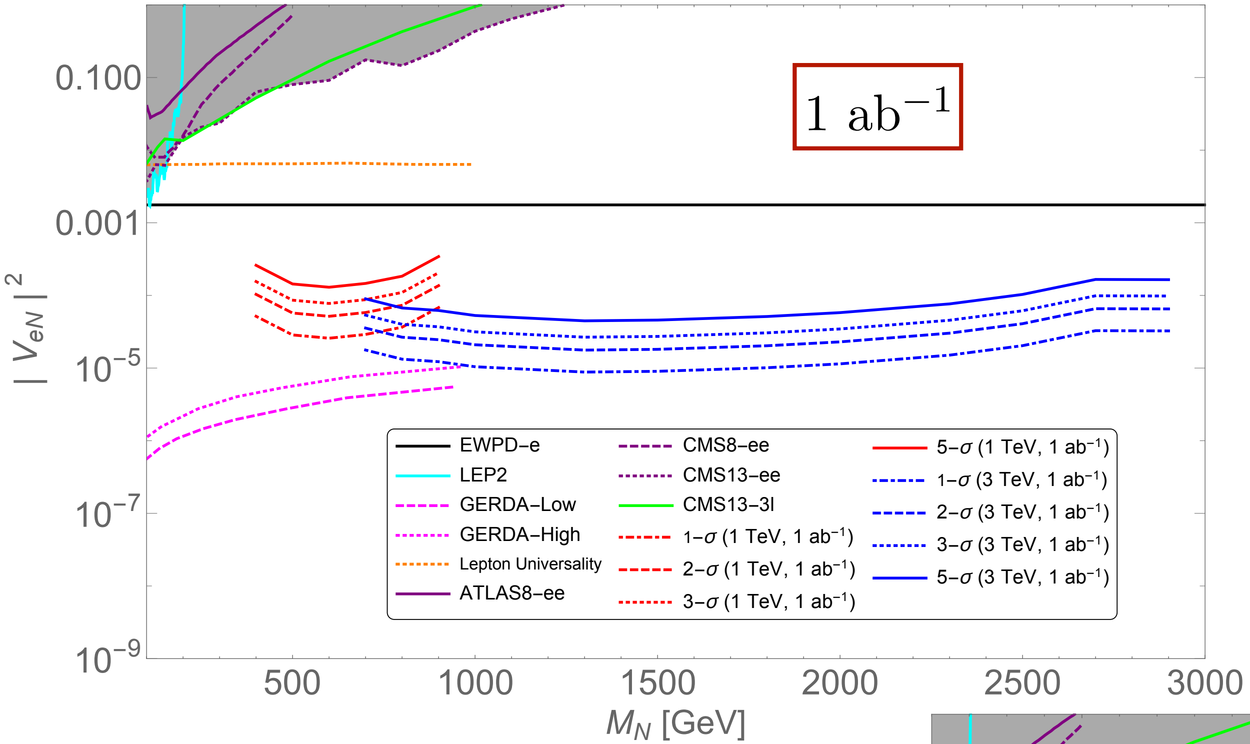
Cuts	Signal	Background				Total
		$\nu_e eW$	WW	ZZ	$t\bar{t}$	
Basic Cuts	12,996,200	201,586	72,244	7,200	4,300	285,330
$\lvert\cos\theta_J\rvert \leq 0.85$	12,789,800	148,802	44,910	3,800	4,100	201,600
$\lvert\cos\theta_e\rvert \leq 0.85$	12,671,800	79,008	40,574	2,800	3,900	126,280
$p_T^J > 150$ GeV	12,308,300	70,669	40,490	2,300	3,200	116,660
$M_J > 70$ GeV	10,923,100	62,303	37,043	2,100	2,300	103,700
$p_T^{\ell} > 100$ GeV	10,714,500	57,076	33,488	1,400	1,530	93,400

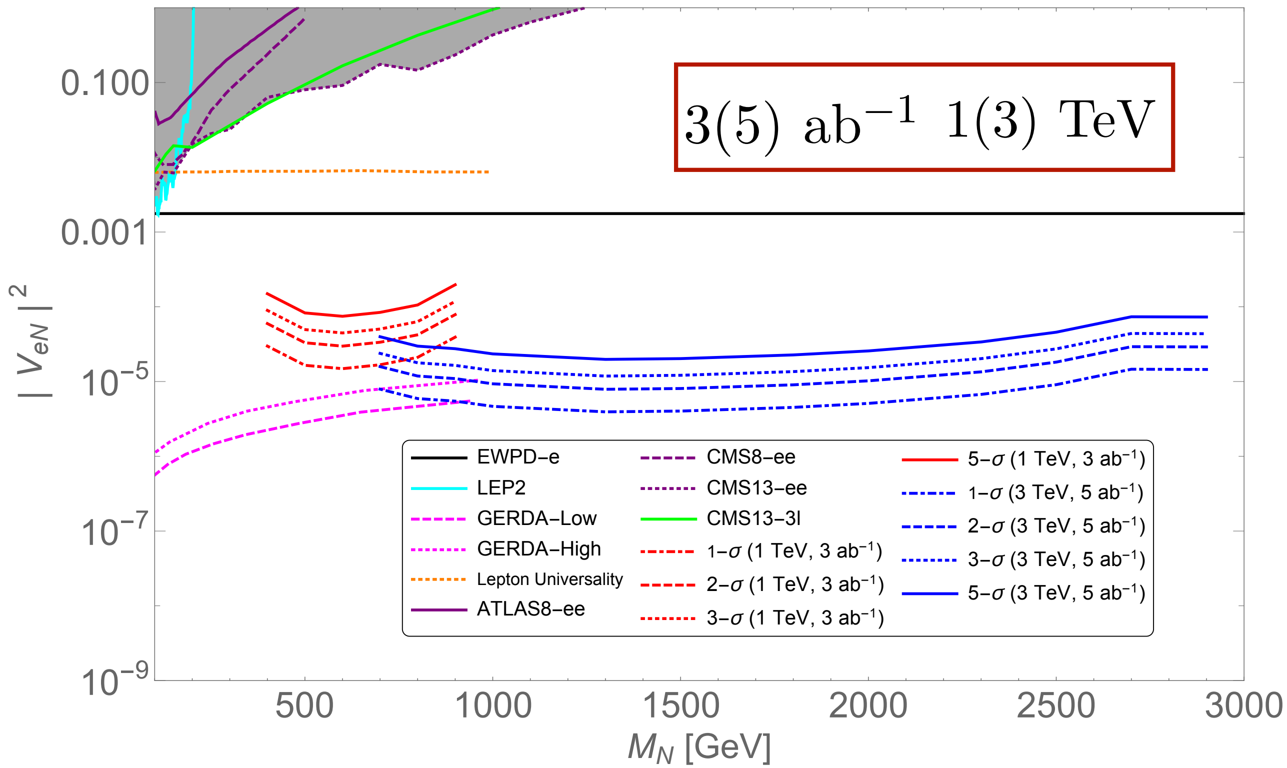
Cut flow for the signal and background events for the final state $e^{\pm} + J + p_T^{\text{miss}}$ for $M_N = 800$ GeV at the $\sqrt{s} = 1$ TeV linear collider. The signal events are normalized by the square of the mixing.

Cuts	Signal	Background				Total
		$\nu_e eW$	WW	ZZ	$t\bar{t}$	
Basic Cuts	8,684,990	201,586	72,244	7,200	4,300	285,330
$\lvert\cos\theta_J\rvert \leq 0.85$	8,649,570	148,802	44,910	3,800	4,100	201,600
$\lvert\cos\theta_e\rvert \leq 0.85$	8,618,420	79,008	40,574	2,800	3,900	126,280
$p_T^J > 250$ GeV	7,681,440	59,001	40,329	2,303	2,720	104,354
$M_J > 70$ GeV	7,176,280	53,990	36,997	2,187	2,282	95,437
$p_T^{\ell} > 200$ GeV	7,080,200	38,729	26,208	942	613	66,493

Mass-mixing limit plots

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





Alternative scenario under $U(1)_X$

AD, Okada, Raut

AD, Okada, Okada, Raut

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
q_{L_i}	**3**	**2**	$1/6$	$(1/6)x_H + (1/3)$
u_{R_i}	**3**	**1**	$2/3$	$(2/3)x_H + (1/3)$
d_{R_i}	**3**	**1**	$-1/3$	$-(1/3)x_H + (1/3)$
ℓ_{L_i}	**1**	**2**	$-1/2$	$(-1/2)x_H - 1$
e_{R_i}	**1**	**1**	-1	$-x_H - 1$
H	**1**	**2**	$-1/2$	$(-1/2)x_H$
$N_{R_{1,2}}$	**1**	**1**	0	-4
N_{R_3}	**1**	**1**	0	$+5$
H_E	**1**	**2**	$-1/2$	$(-1/2)x_H + 3$
Φ_A	**1**	**1**	0	$+8$
Φ_B	**1**	**1**	0	-10
Φ_C	**1**	**1**	0	-3

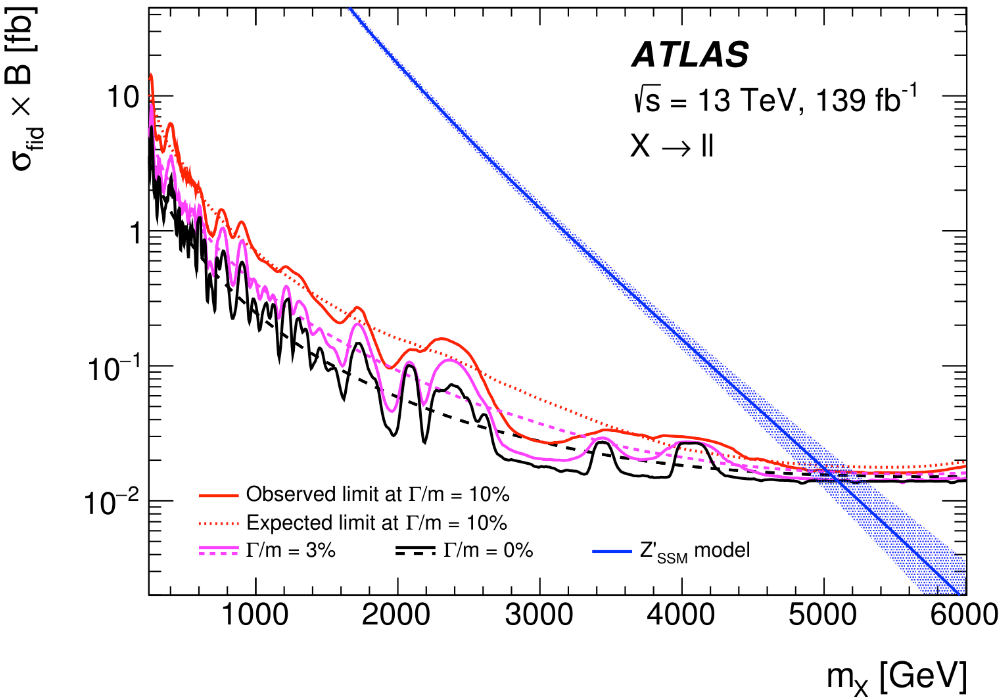
Possible alternative B – L, with $x_H = 0$

Detailed scalar sector study

In Progress

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

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

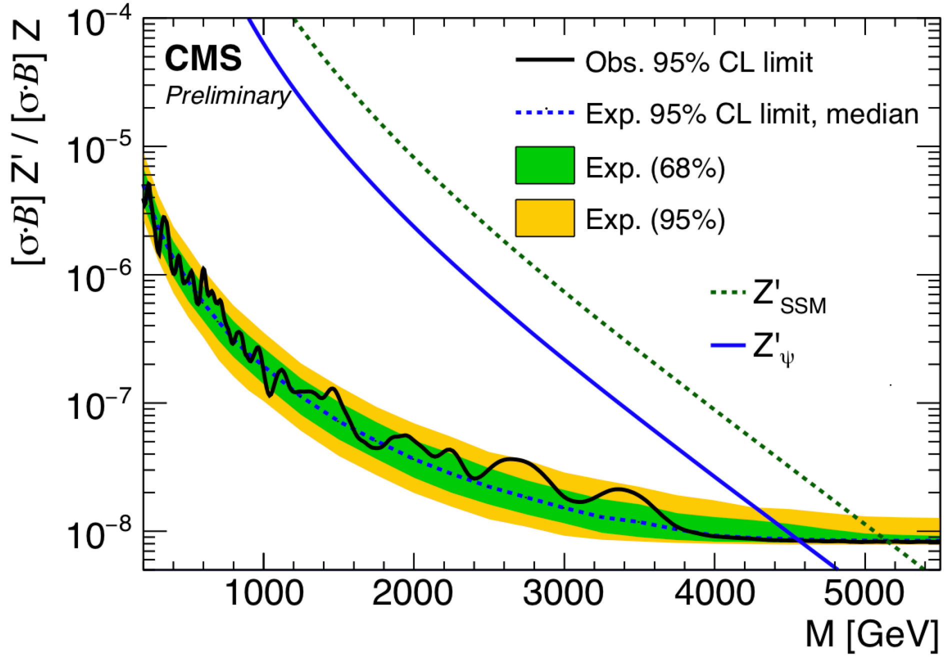


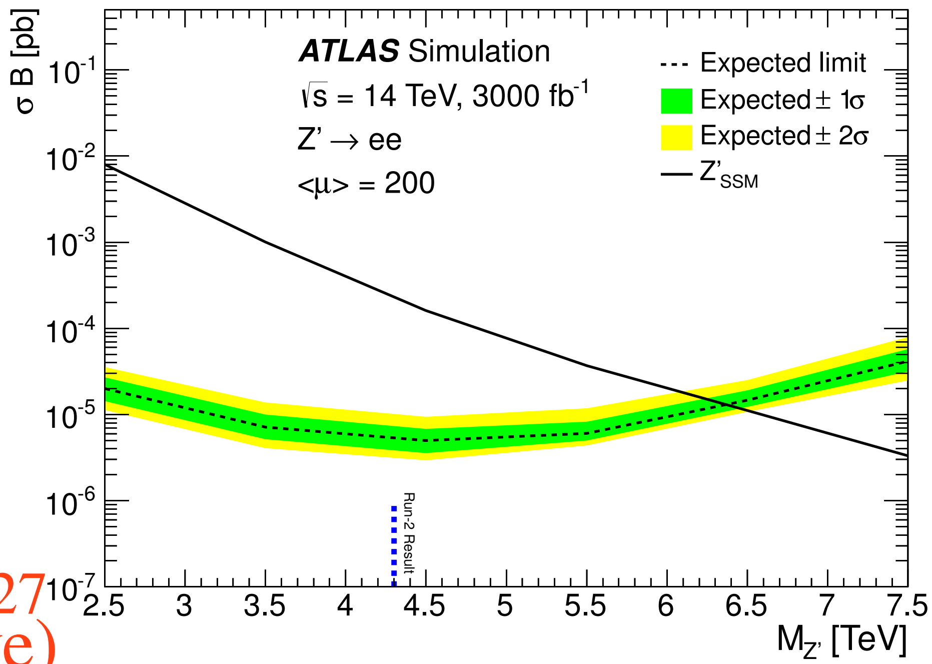
2ℓ, ATLAS : 1903.06248 (139 fb^{-1})

$$g' = \sqrt{\frac{\sigma^{\text{Observer}}_{\text{ATLAS/CMS}}}{\frac{\sigma_{\text{Model}}}{g^2_{\text{Model}}}}}$$

CMS PAS EXO – 19 – 019

$ee(139\ \text{fb}^{-1}) + \mu\mu(140\ \text{fb}^{-1})$





ATLAS – TDR – 027

ee (Prospective)

$m_{Z'} = 3$ TeV.

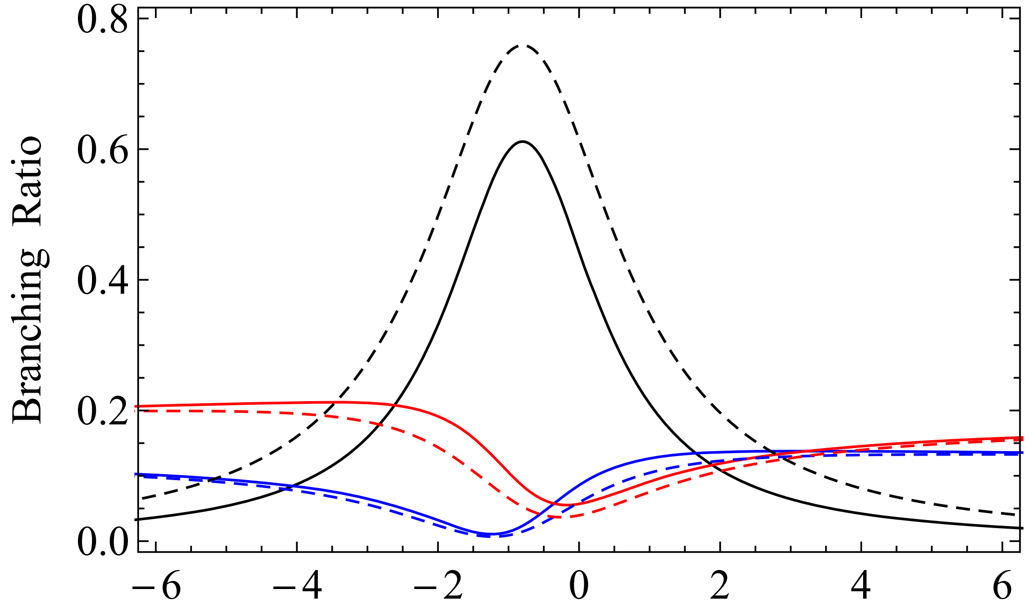
Solid

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

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

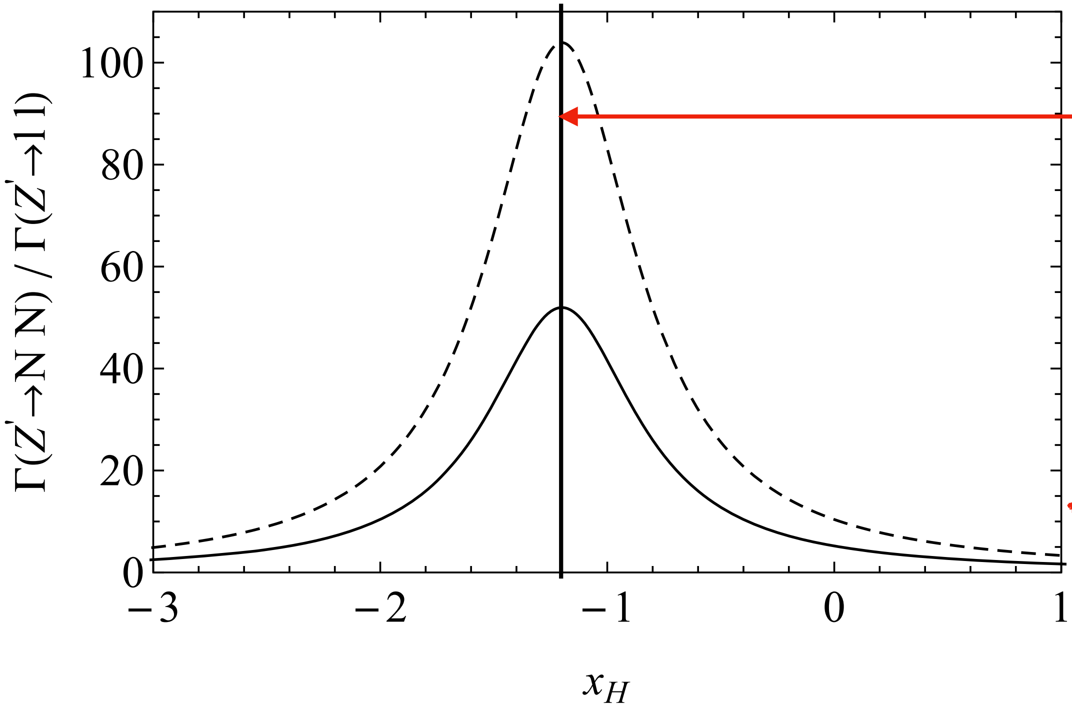
Dashed

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



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

Up and down quarks Heavy neutrinos Charged leptons



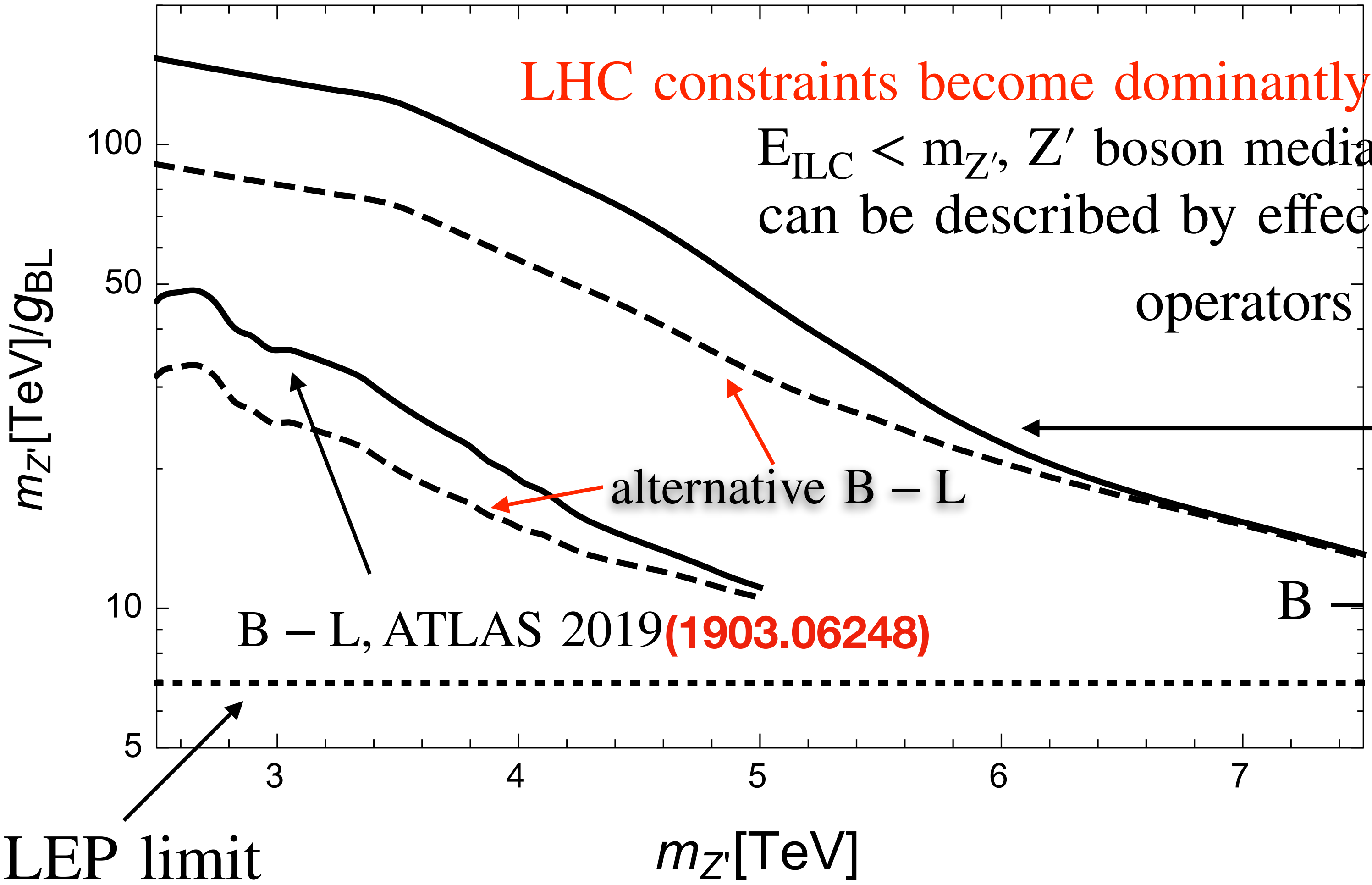
$x_H = -1.2$

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

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

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

Production of the heavy neutrino at the ILC



LHC constraints become dominantly weaker with heavier Z′

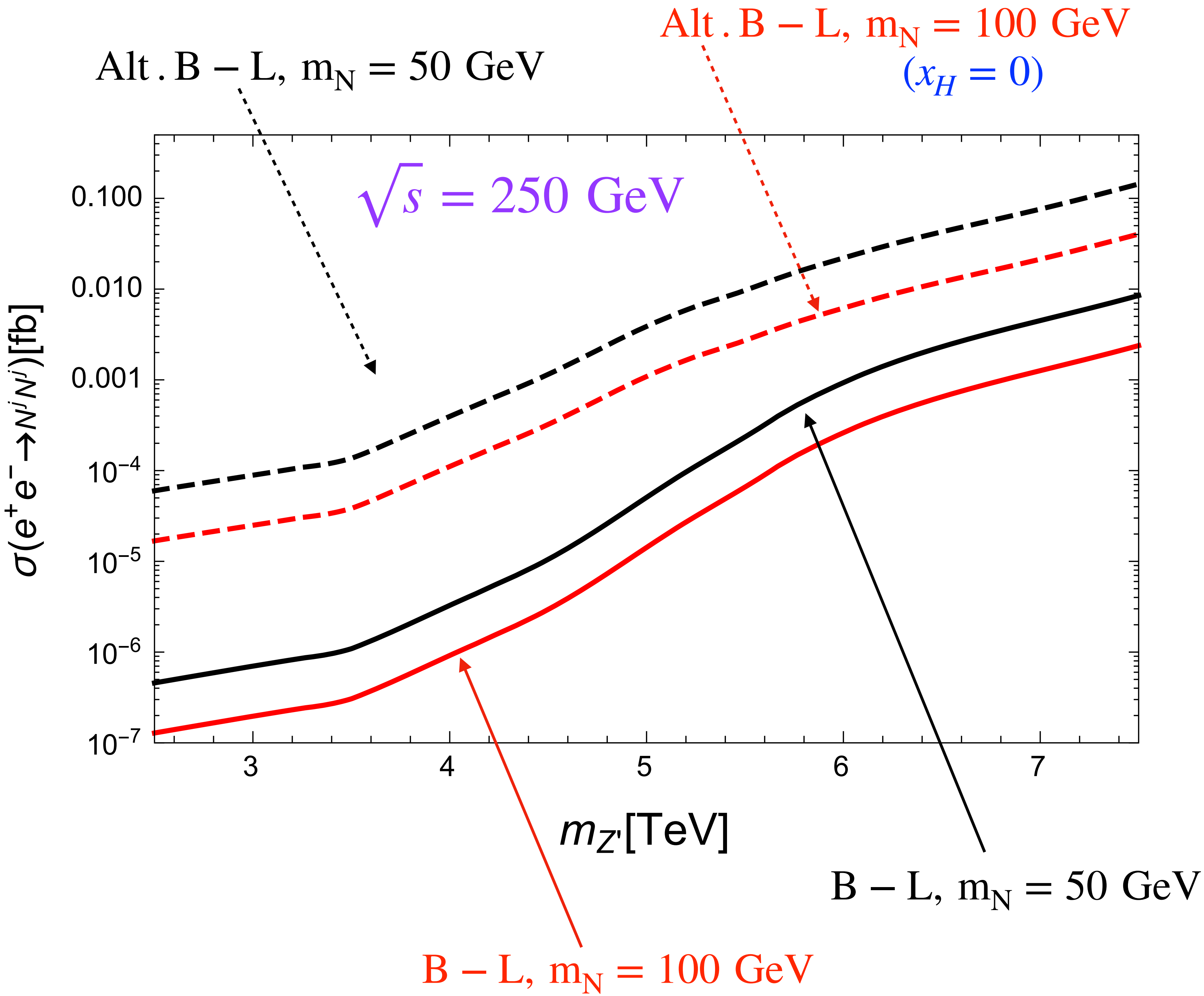
$E_{ILC} < m_{Z'}$, Z′ boson mediated processes at the ILC can be described by effective higher dimensional operators $\propto \left(\frac{m_{Z'}}{g_{BL}}\right)^2$

B – L, ATLAS – TDR

Dashed lines represent the Atl. B – L case

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

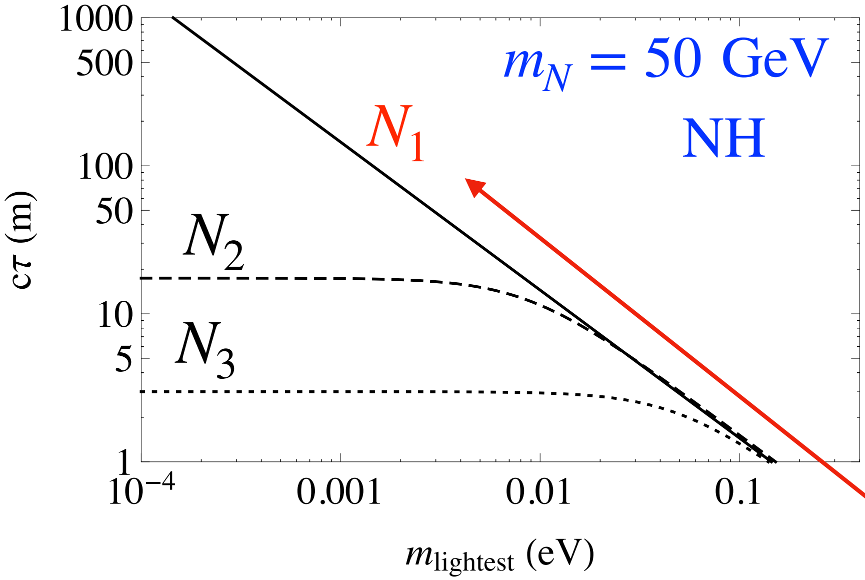
As a result ILC is a powerful machine to probe Z′ beyond HL – LHC

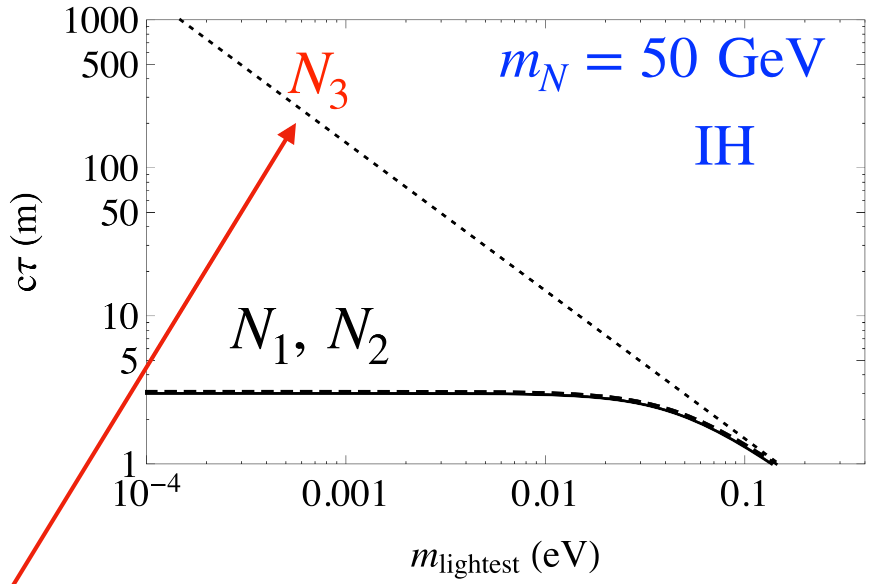


Alt . B − L, m_N = 100 GeV
(x_H = 0)
Alt . B − L, m_N = 50 GeV
√s = 250 GeV
0.100
0.010
0.001
10^−4
10^−5
10^−6
10^−7
σ(e+e−→N^jN^j)[fb]
3
4
5
6
7
m_Z'[TeV]
B − L, m_N = 50 GeV
B − L, m_N = 100 GeV

Long lived RHNs

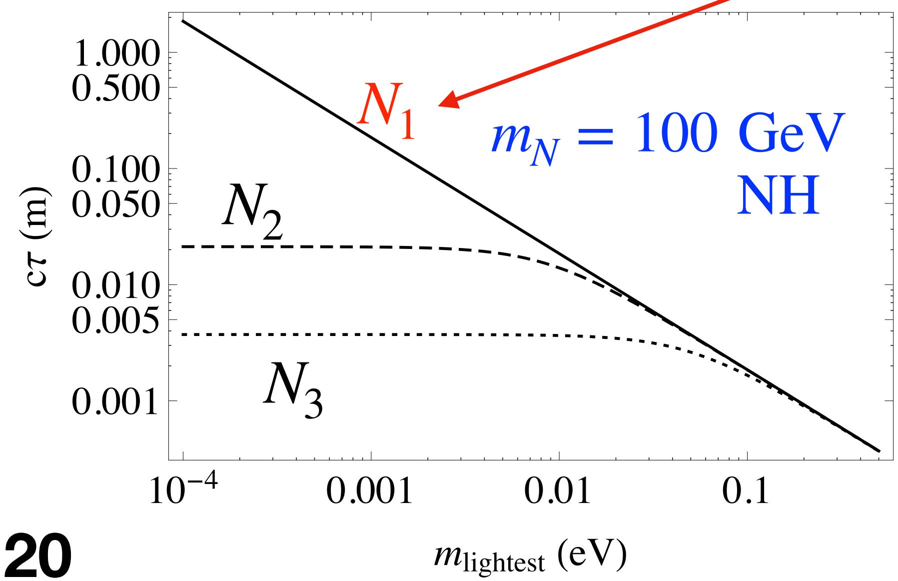
$B - L$ case, $x_H = 0$

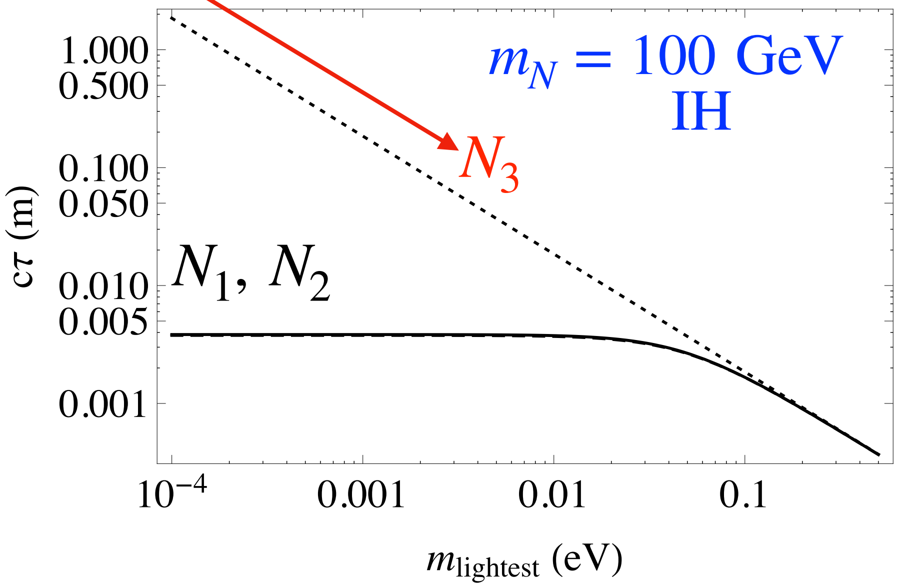




Longest lived RHN life time is inversely proportional to $m_{lightest}$

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





Conclusions

SM can not explain the orgin of the tiny neutrino mass.

We consider some benchmark models which can explain the origin of tiny neutrino mass.

These models are equiped with the heavy neutrinos under the simple extension of the SM.

These heavy neutrinos can mix with the light neutrinos.

Generalizing the mixings and reproducing the neutrino oscillation data we have studied the production of the RHNs : prompt and boosted.

We finally probed the light heavy mixings successfully beyond the EWPD at the e^-e^+ colliders.

In thsese models there is a neutral BSM gauge boson Z' which directly interacts with the heavy neutrinos.

This could be a good source to study the long – lived RHNs.

Thank You