Testing right handed neutrinos at the linear collider

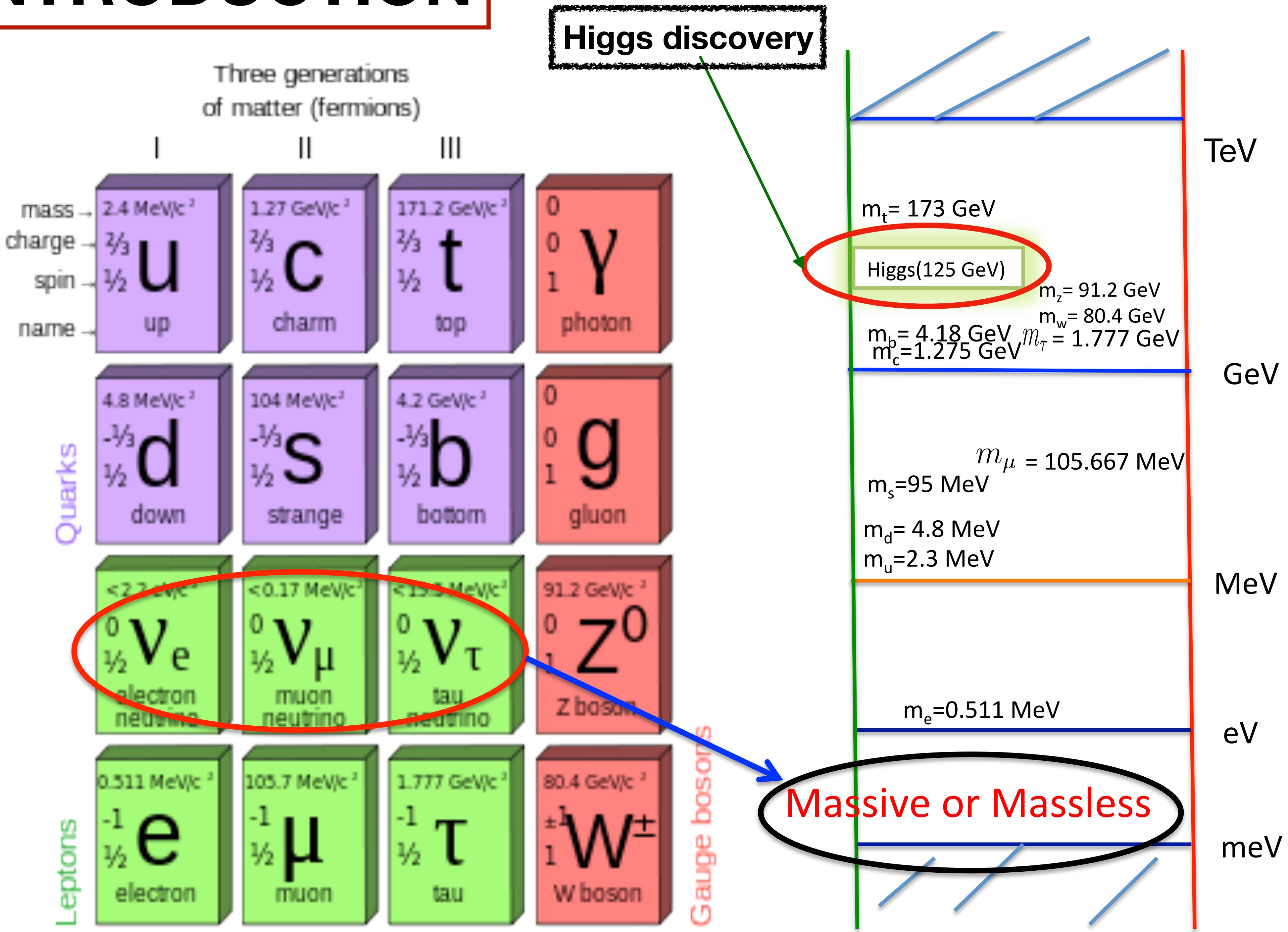
Arindam Das
Osaka University

Based on: 1207.3734,1811.04291 (also see 1812.11931)

大阪大学
OSAKA UNIVERSITY

9th April, 2019
Prospect of Neutrinos, Kavli- IMPU
(8th April- 12th April)

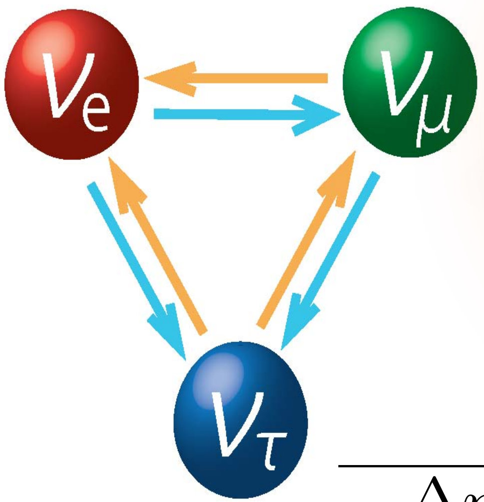
INTRODUCTION



Some interesting results in the neutrino sector

Super- Kamiokande, Sudbury Neutrino Observatory 1999 ,
Neutrino oscillation between mass and flavor eigenstates

Neutrinos are very special

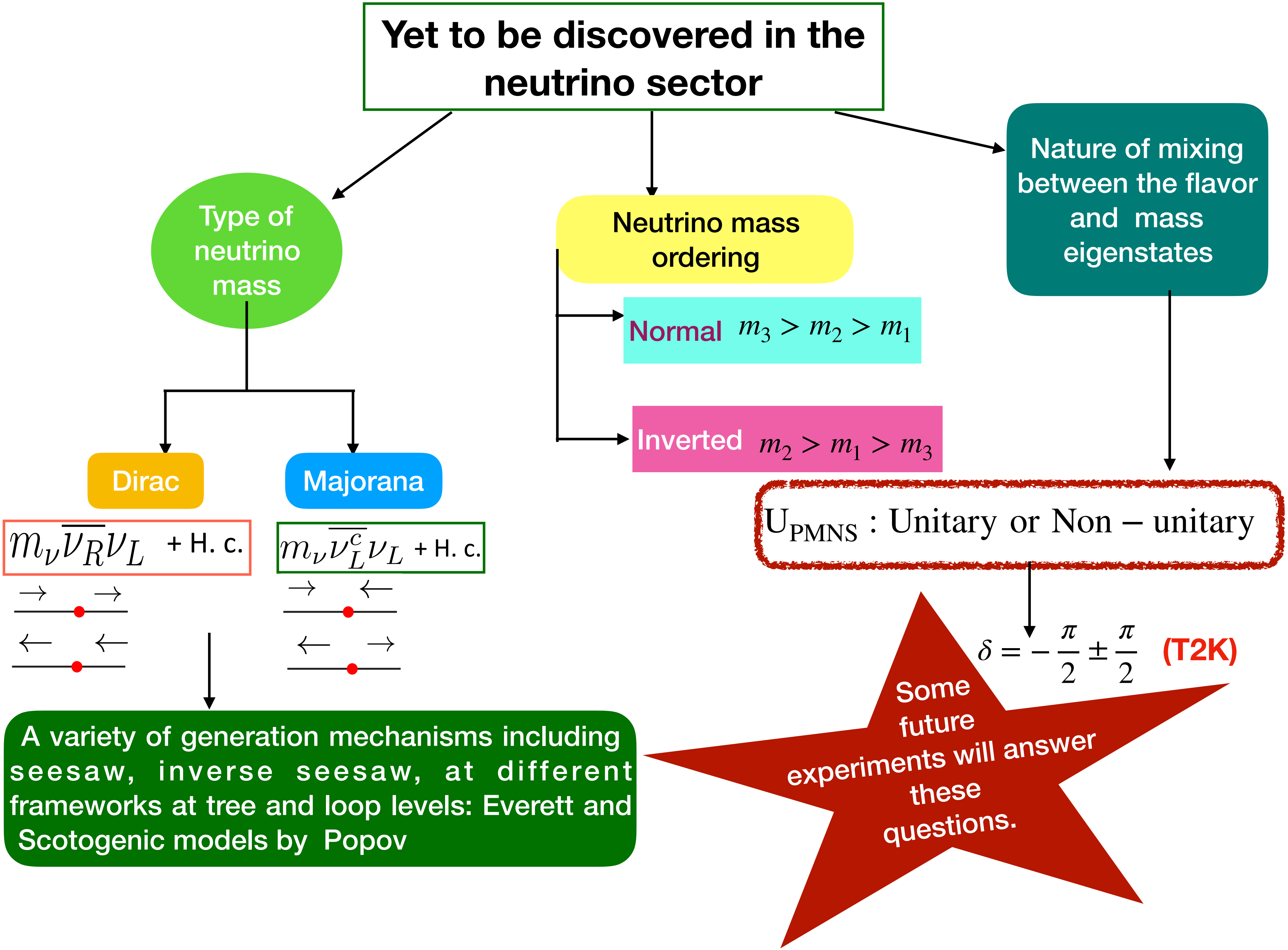


Physics Nobel Prize 2015

ν

Neutrino oscillation data

Δm^2_{21}	$7.6 \times 10^{-5}\mathrm{eV}^2$	SNO
$\lvert\Delta m_{31}\rvert^2$	$2.4 \times 10^{-3}\mathrm{eV}^2$	Super – K
$\sin^2 2\theta_{12}$	0.87	KamLAND, SNO
$\sin^2 2\theta_{23}$	0.999	T2K
	0.90	MINOS
$\sin^2 2\theta_{13}$	0.084	DayaBay2015
	0.1	RENO
	0.09	DoubleChooz


Yet to be discovered in the neutrino sector
Type of neutrino mass
Dirac
$m_\nu \overline{\nu_R} \nu_L$ + H. c.
Majorana
$m_\nu \overline{\nu_L^c} \nu_L$ + H. c.
A variety of generation mechanisms including seesaw, inverse seesaw, at different frameworks at tree and loop levels: Everett and Scotogenic models by Popov
Neutrino mass ordering
Normal $m_3 > m_2 > m_1$
Inverted $m_2 > m_1 > m_3$
Nature of mixing between the flavor and mass eigenstates
$\mathrm{U_{PMNS}}$: Unitary or Non – unitary
$\delta = -\frac{\pi}{2} \pm \frac{\pi}{2}$ (T2K)
Some future experiments will answer these questions.

Seesaw Mechanism

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

Extending the SM with SM-singlet right handed neutrino

$$\mathcal{L} \supset -\sum_{i=1}^{3}\sum_{j=1}^{2} Y_D^{ij}\overline{\ell_L^i} H N_R^j - \frac{1}{2}\sum_{k=1}^{2} m_N^k \overline{N_R^{kC}} N_R^k + \mathrm{H.c.}$$

Dirac Mass term — **Majorana Mass term**

Neutrino mass matrix

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & m_N \end{pmatrix}$$

$$m_D = \frac{Y_D}{\sqrt{2}} v$$

diagonalizing

$$m_\nu \simeq -m_D m_N^{-1} m_D^T.$$

Flavor eigenstate can be expressed in terms of the mass eigenstate

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

PMNS matrix — $M_D M_N^{-1}$

Inverse Seesaw Mechanism : Mohapatra(1986), Mohapatra & Valle (1986)

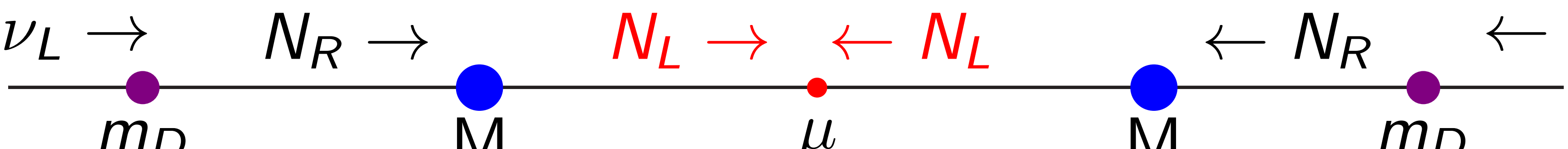
	SU(2)	$U(1)_Y$
ℓ_L	**2**	$-1/2$
H	**2**	$-1/2$
N_R^j	**1**	0
N_L^j	**1**	0

Relevant Part of the Lagrangian

$$\mathcal{L}_{mass} = \left(\overline{\nu_L^c} \quad \overline{N_R} \quad \overline{N_L^c}\right) \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R^c \\ N_L \end{pmatrix}$$

diagonalizing

$$m_\nu \simeq \mu \frac{m_D^2}{M^2}$$



$$\nu \simeq \mathcal{N}\nu_m + \mathcal{R}N_m$$

$$\mathcal{R} = m_D m^{-1}$$

$$\mathcal{N} = \left(1 - \frac{1}{2}\epsilon\right)U_{\rm MNS}$$

Alternative choices

$$\epsilon = \mathcal{R}^*\mathcal{R}^T$$

$$m_\nu = \mathcal{R}\mu\mathcal{R}^T = \frac{1}{M^2}m_D\mu m_D^T. = U^*_{\rm MNS}D_{\rm NH/IH}U^\dagger_{\rm MNS}.$$

$$\epsilon = \frac{1}{2}\mathscr{R}^*\mathscr{R}^{\rm T}$$

$$\epsilon = 2\mathscr{R}^*\mathscr{R}^{\rm T}$$

Non-unitarity

$$|\mathcal{N}\mathcal{N}^\dagger| = \begin{pmatrix} 0.994 \pm 0.00625 & 1.499\times10^{-5} & 8.764\times10^{-3} \\ 1.499\times10^{-5} & 0.995\pm0.00625 & 1.046\times10^{-2} \\ 8.764\times10^{-3} & 1.046\times10^{-2} & 0.995\pm0.00625 \end{pmatrix}$$

Abada, Antusch, Biggio, Bonnet Gavela, Fischer, Hambye, Ibarra, Lopez-Pavon, Petcov, Molinaro, Fernandez-Martinez

$$\mathcal{N}\mathcal{N}^\dagger \simeq \mathbf{1} - \epsilon$$

$$\mu \to e\gamma$$

$$|\epsilon| = \begin{pmatrix} 0.006\pm0.00625 & <1.5\times10^{-5} & <8.764\times10^{-3} \\ <1.5\times10^{-5} & 0.005\pm0.00625 & <1.046\times10^{-2} \\ <8.76356\times10^{-3} & <1.046\times10^{-2} & 0.005\pm0.00625 \end{pmatrix}$$

$$\tau \to e\gamma$$

$$\tau \to \mu\gamma$$

$$\epsilon = \frac{1}{M^2}m_D m_D^T = \frac{1}{\mu}U_{\rm MNS}D_{\rm NH/IH}U^T_{\rm MNS}$$

General Parametrization of the neutrino Dirac mass matrix

From the inverse seesaw formula

Flavor non-diagonal case

$$m_\nu = \mu \mathcal{R}\mathcal{R}^T = \frac{\mu}{M^2} m_D m_D^T = U^*_{\rm MNS} D_{\rm NH/IH} U^\dagger_{\rm MNS}$$

m_D carries the off-diagonal entries

$\mu,\ M$ diagonal

$$\mathcal{R}(\delta, \rho, x, y) = \frac{1}{\sqrt{\mu}} U^*_{\rm MNS} \sqrt{D_{\rm NH/IH}}\, O$$

general orthogonal matrix

$$O = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} = \begin{pmatrix} \cosh y & i\sinh y \\ -i\sinh y & \cosh y \end{pmatrix} \begin{pmatrix} \cos x & \sin x \\ -\sin x & \cosh x \end{pmatrix}$$

$$\epsilon(\delta, \rho, y) = \mathcal{R}^*\mathcal{R}^T = \frac{1}{\mu} U_{\rm MNS} \sqrt{D_{\rm NH/IH}}\, O^* O^T \sqrt{D_{\rm NH/IH}}^T U^\dagger_{\rm MNS}$$

$$\begin{pmatrix} \cosh^2 y + \sinh^2 y & -2i\cosh y \sinh y \\ 2i\cosh y \sinh y & \cosh^2 y + \sinh^2 y \end{pmatrix}$$

We can parametrize the mixing in terms of the phases and the general parameter considering bounds from non-unitarity

Impression/s at the ILC

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

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

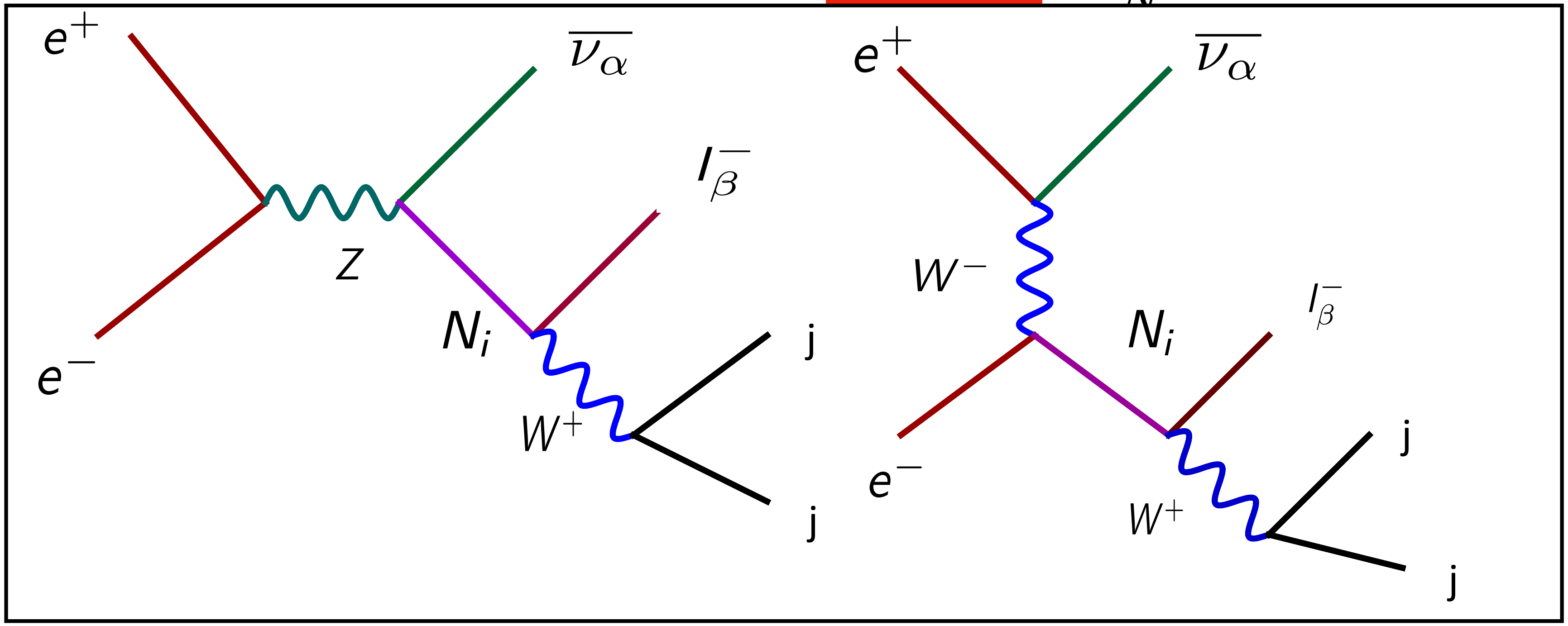
branching ratios

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

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

Leading mode

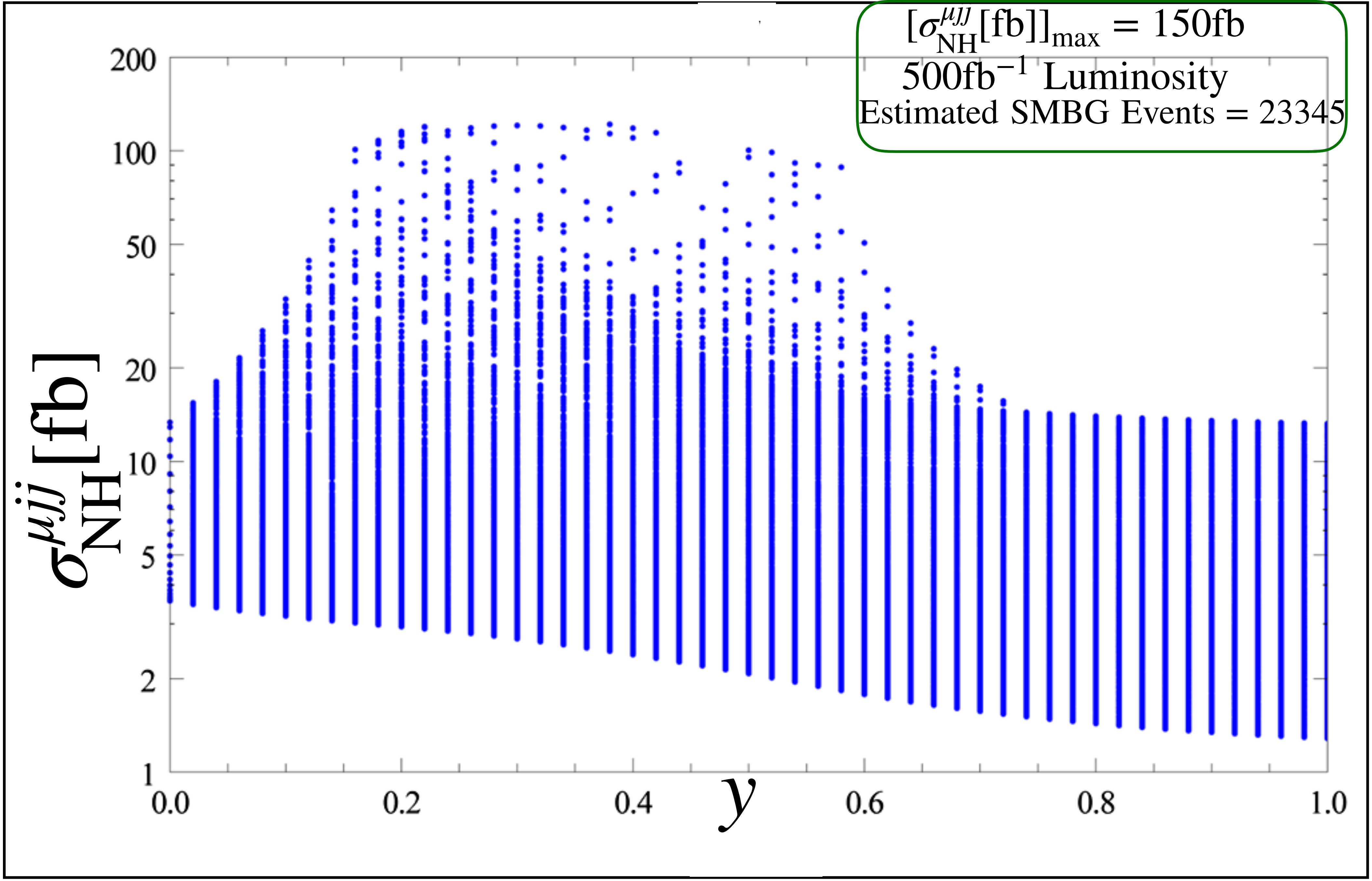
Signals $M_N = 150$ GeV.



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

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

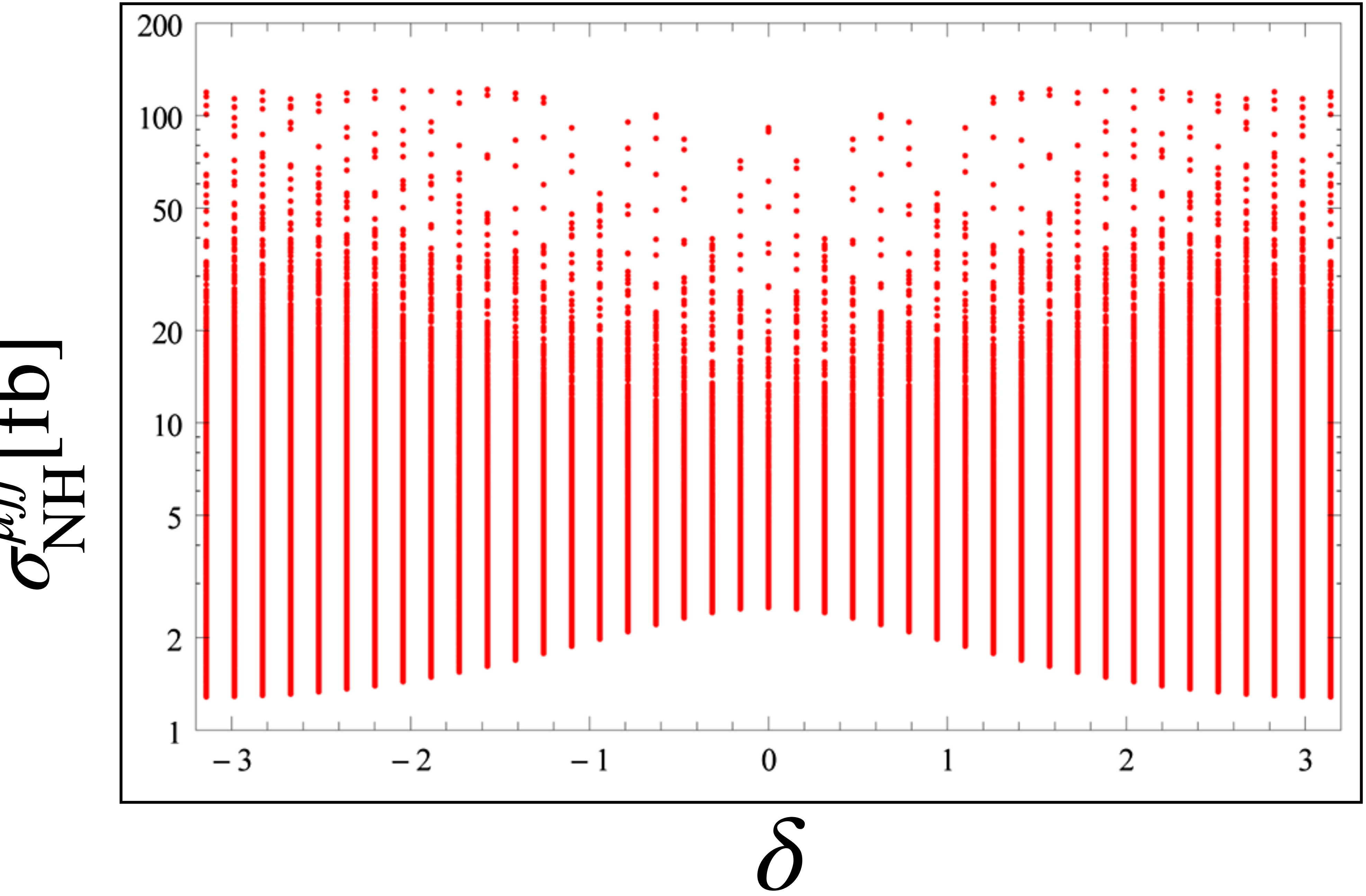
$M_N = 150$ GeV $\sqrt{s} = 500$ GeV **1207.3734**



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

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

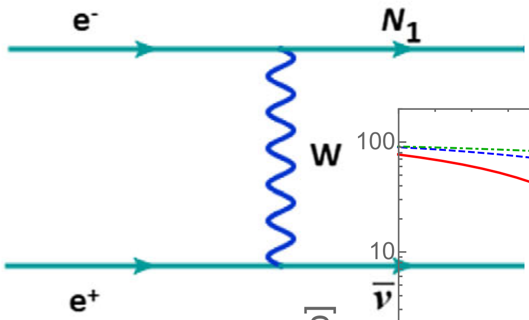
1207.3734



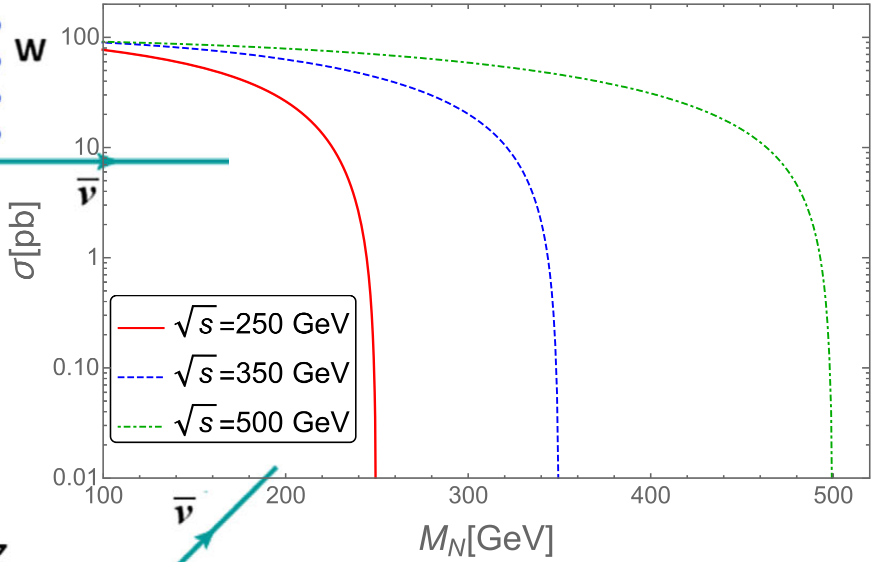
Production of the heavy neutrinos at the Linear Collider using fat jet

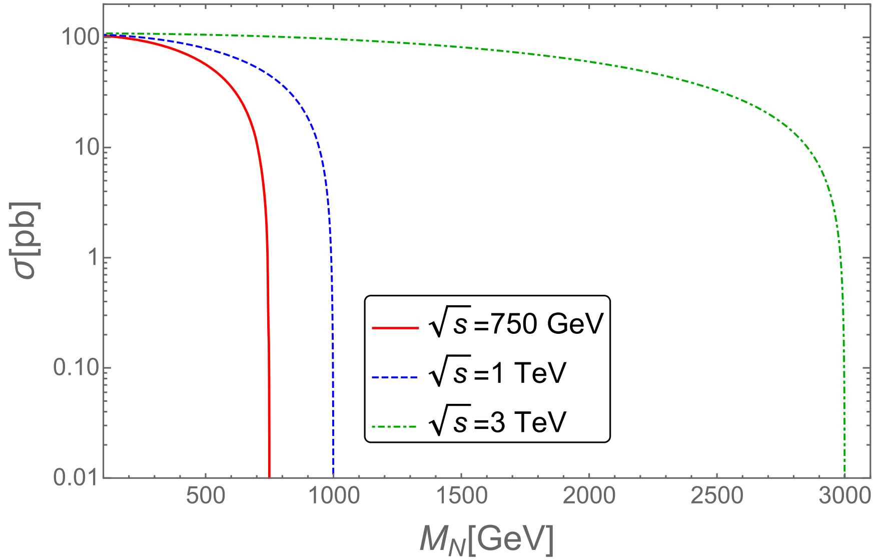
1811.04291

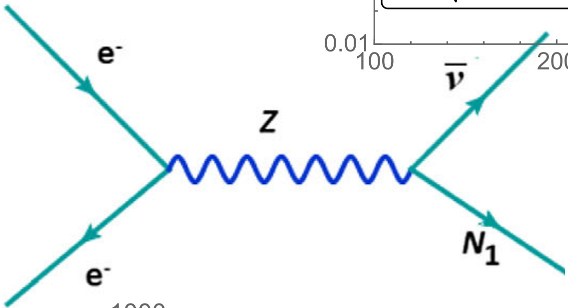
$\sqrt{s} = 1$ TeV, 3 TeV



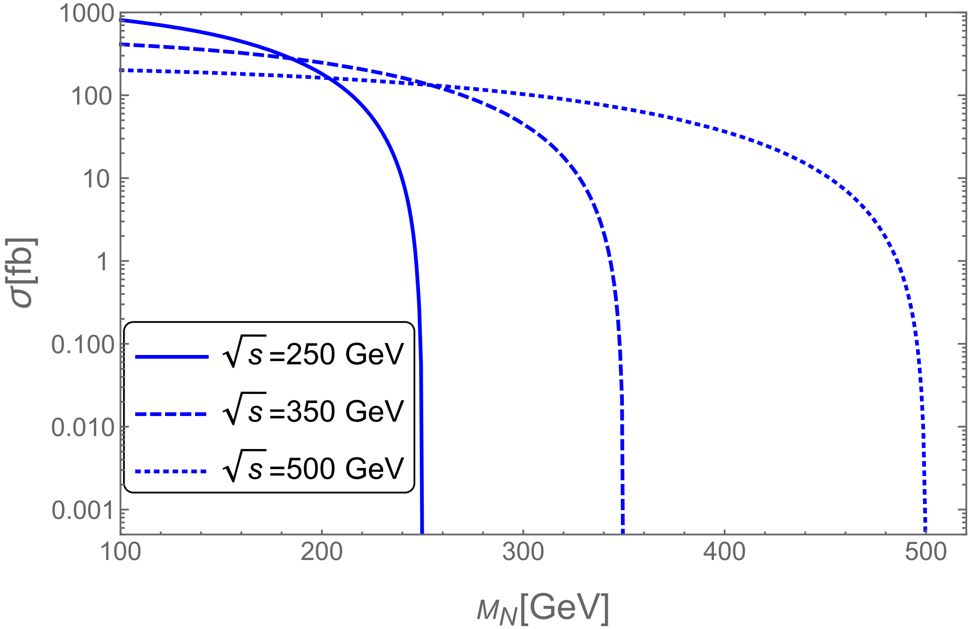
$$e^+e^- \to \nu_1 N_1$$

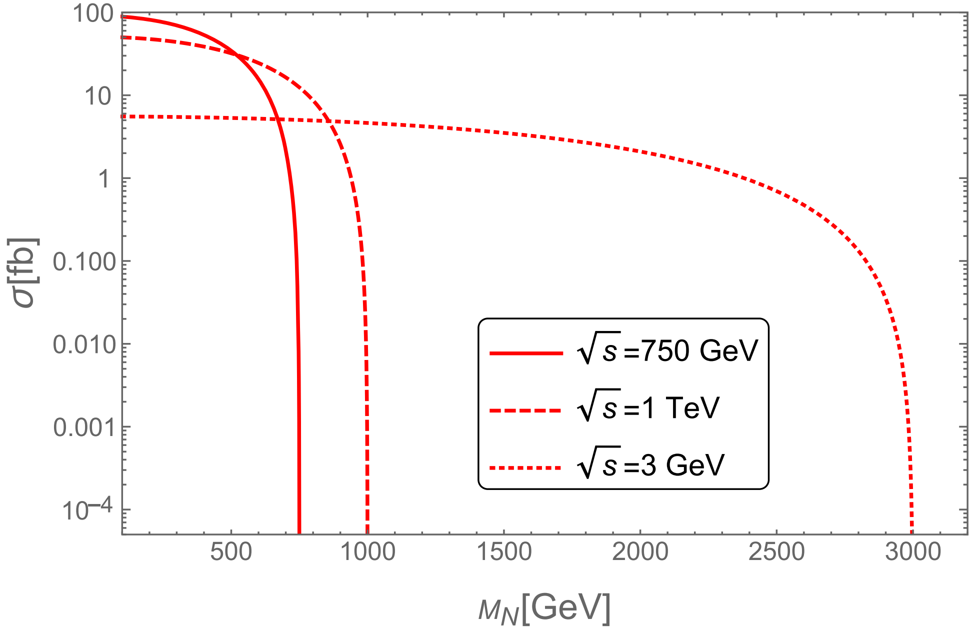




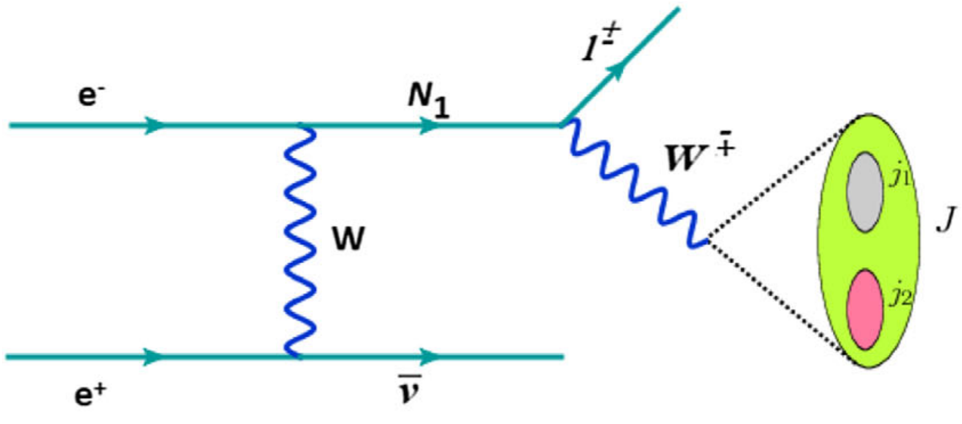


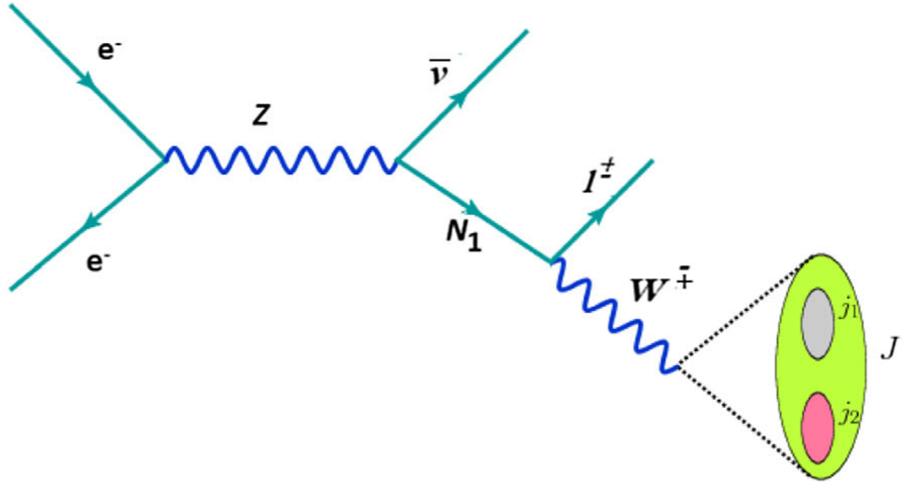
$$e^+e^- \to \nu_2 N_2 /\ \nu_3 N_3$$





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





1. Electrons in the final state should have the following transverse momentum (p_T^e) and pseudo-rapidity ($|\eta^e|$) as $p_T^e > 10$ GeV, $|\eta^e| < 2.5$.

Basic cuts

2. Jets are ordered in p_T, jets should have $p_T^j > 10$ GeV and $|\eta^j| < 2.5$.

3. Photons are counted if $p_T^\gamma > 10$ GeV and $|\eta^\gamma| < 2.5$.

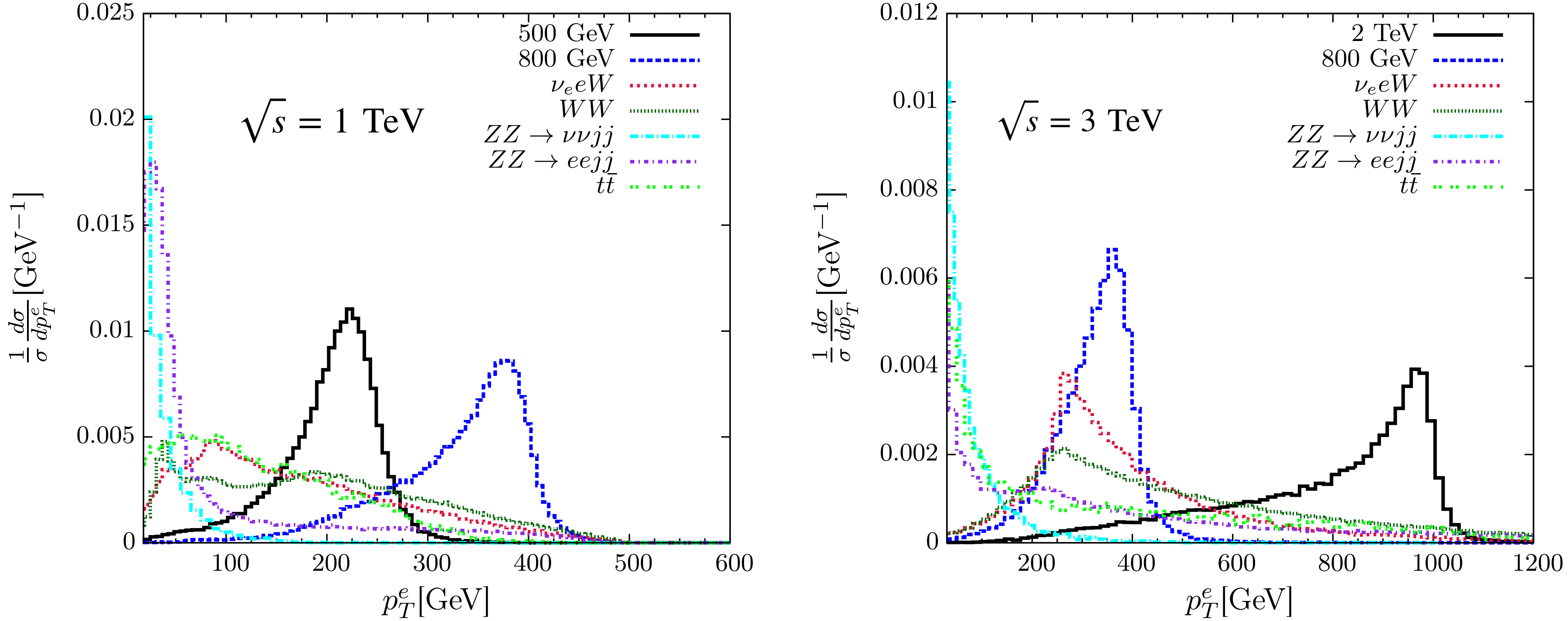
4. Leptons should be separated by $\Delta R_{\ell\ell} > 0.2$.

5. The leptons and photons are separated by $\Delta R_{\ell\gamma} > 0.3$.

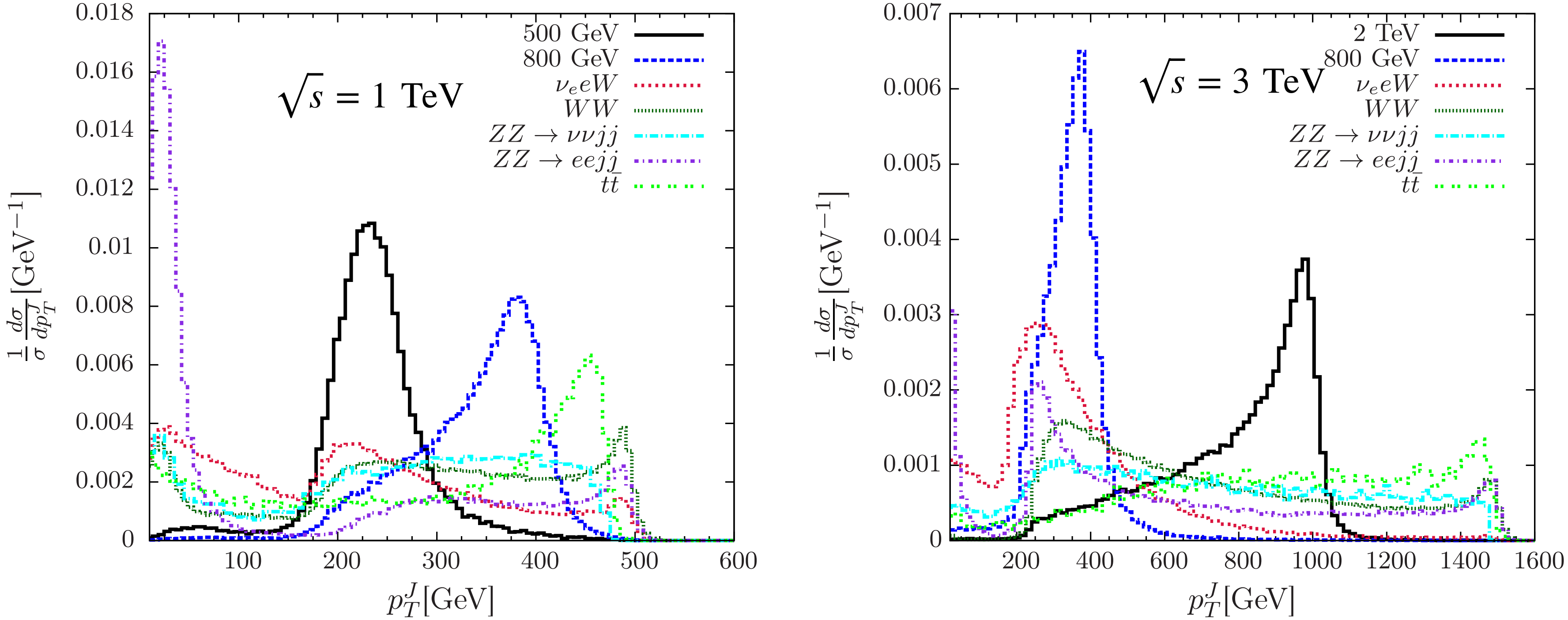
6. The jets and leptons should be separated by $\Delta R_{\ell j} > 0.3$.

7. Fat Jet is constructed with radius parameter $R = 0.8$.

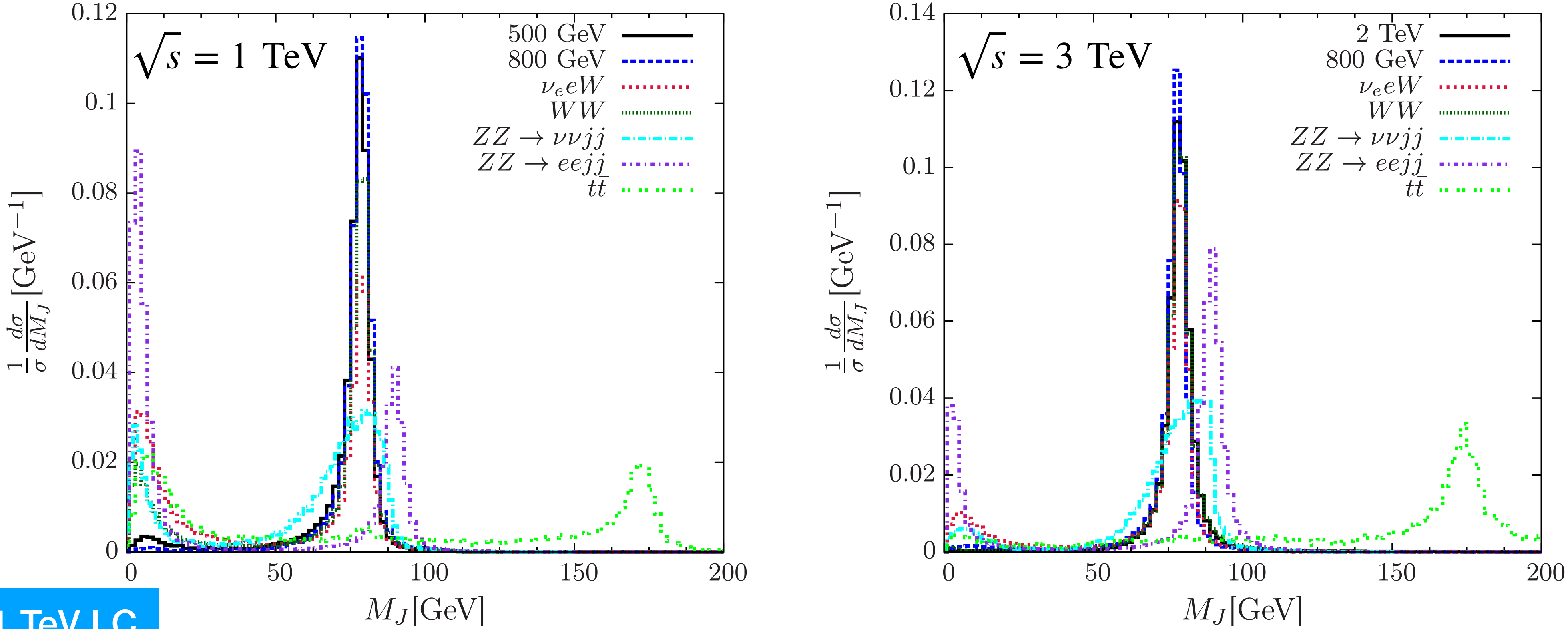
Transverse momentum distribution of the electron (p_T^e) from the signal and background events



Transverse momentum distribution of the fat jet (p_T^J) from the signal and background events



Jet mass (M_J) distribution of the fat jet from the signal and background events



1 TeV LC

Advanced cuts

- 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.

3 TeV LC

Advanced cuts

- 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.

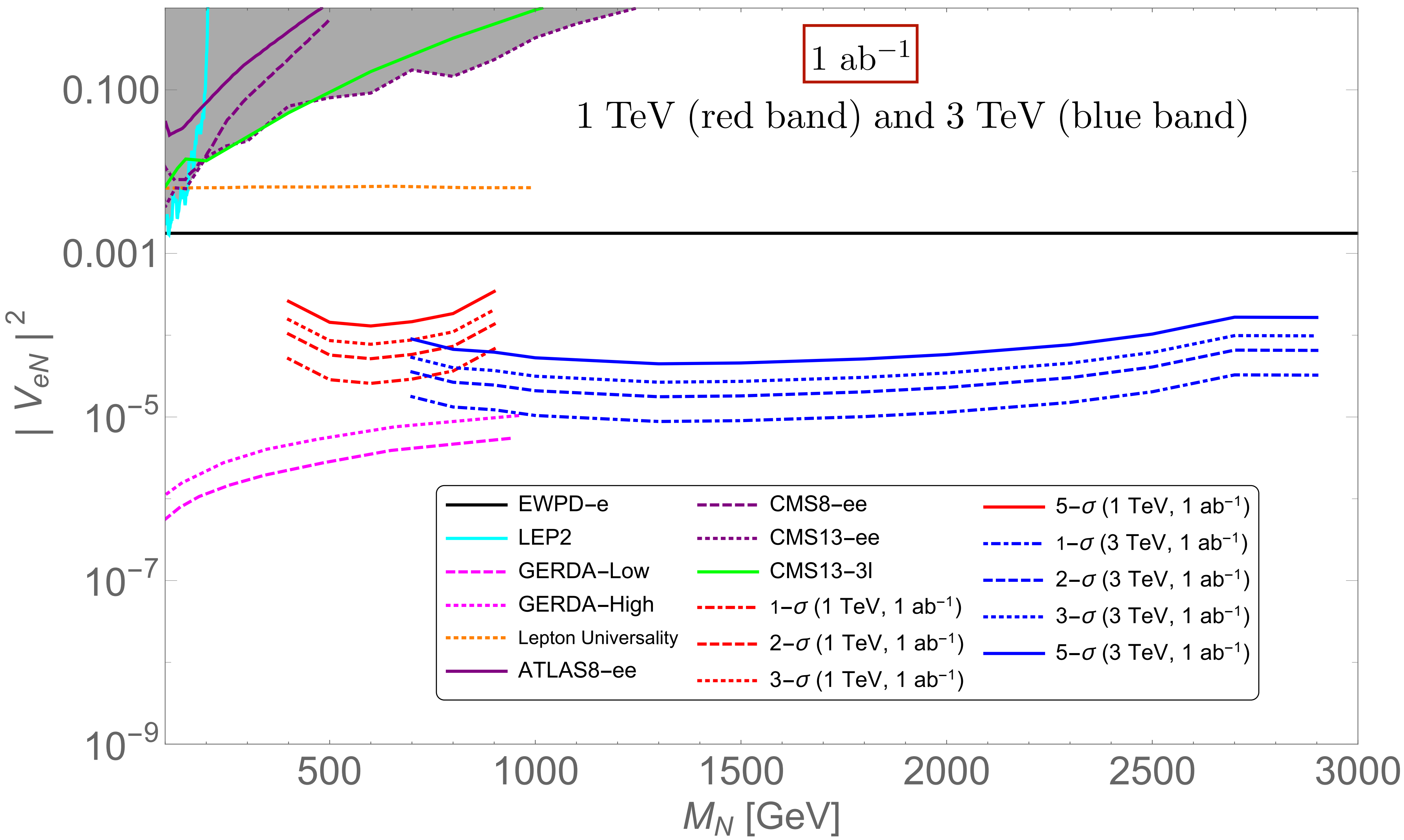
500 GeV @ 1 TeV LC

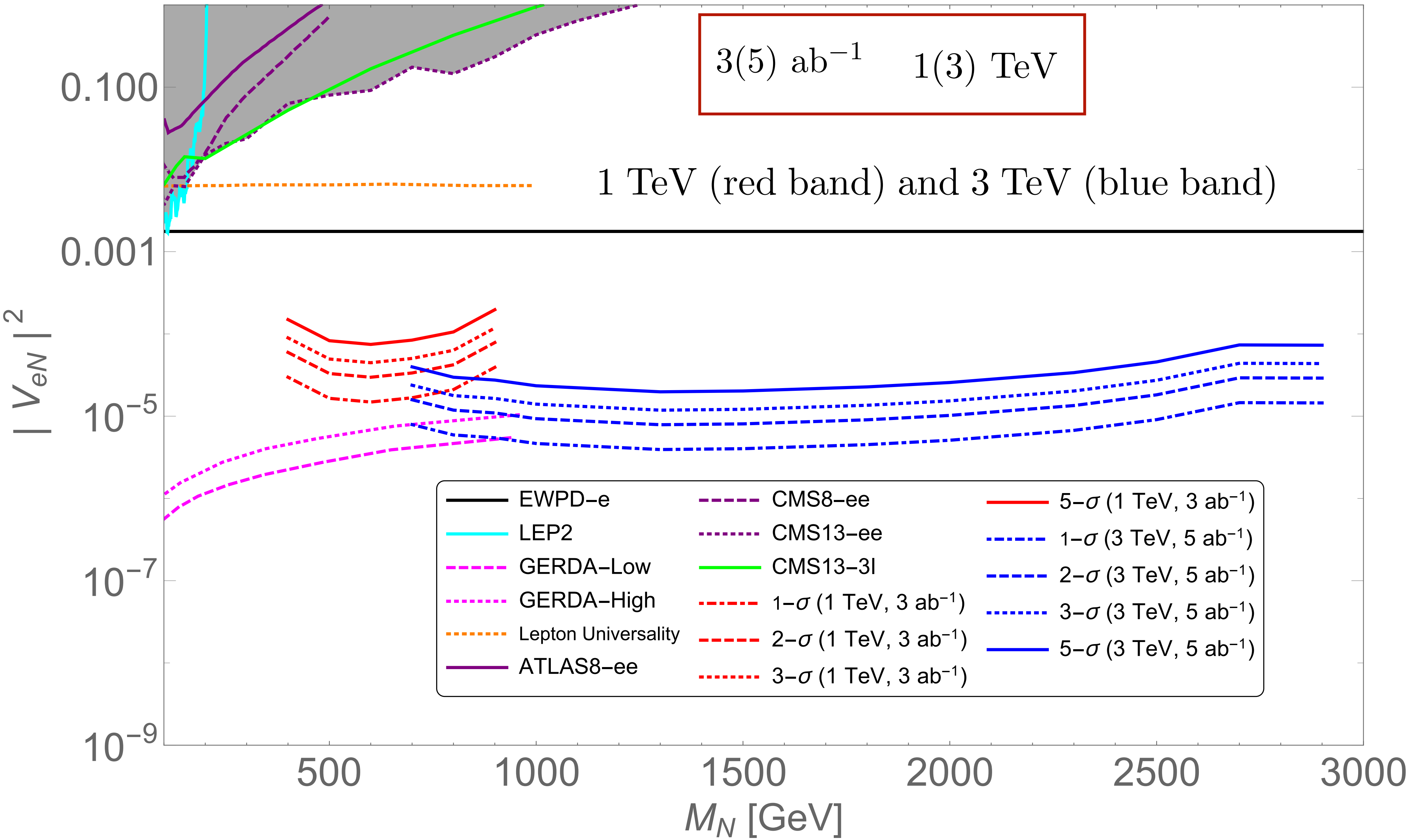
Cuts	Signal	Background				Total
		$\nu_e eW$	WW	ZZ	$t\bar{t}$	
Basic Cuts	12,996,200	201,586	72,244	7,200	4,300	285,330
$\lvert\cos\theta_J\rvert \leq 0.85$	12,789,800	148,802	44,910	3,800	4,100	201,600
$\lvert\cos\theta_e\rvert \leq 0.85$	12,671,800	79,008	40,574	2,800	3,900	126,280
$p_T^J > 150$ GeV	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

800 GeV @ 3 TeV LC

Cuts	Signal	Background				Total
		$\nu_e eW$	WW	ZZ	$t\bar{t}$	
Basic Cuts	21,789,900	193,533	12,135	1,361	271	207,301
$\lvert\cos\theta_J\rvert \leq 0.85$	13,599,300	126,980	4,766	406	215	132,367
$\lvert\cos\theta_e\rvert \leq 0.85$	12,163,300	21,110	4,609	390	195	26,304
$p_T^J > 250$ GeV	12,083,500	18,619	4,607	390	189	23,807
$M_J > 70$ GeV	11,287,000	17,442	4,411	385	176	22,416
$p_T^\ell > 200$ GeV	11,094,300	16,915	4,108	343	104	21,470

Mass-mixing limit plots





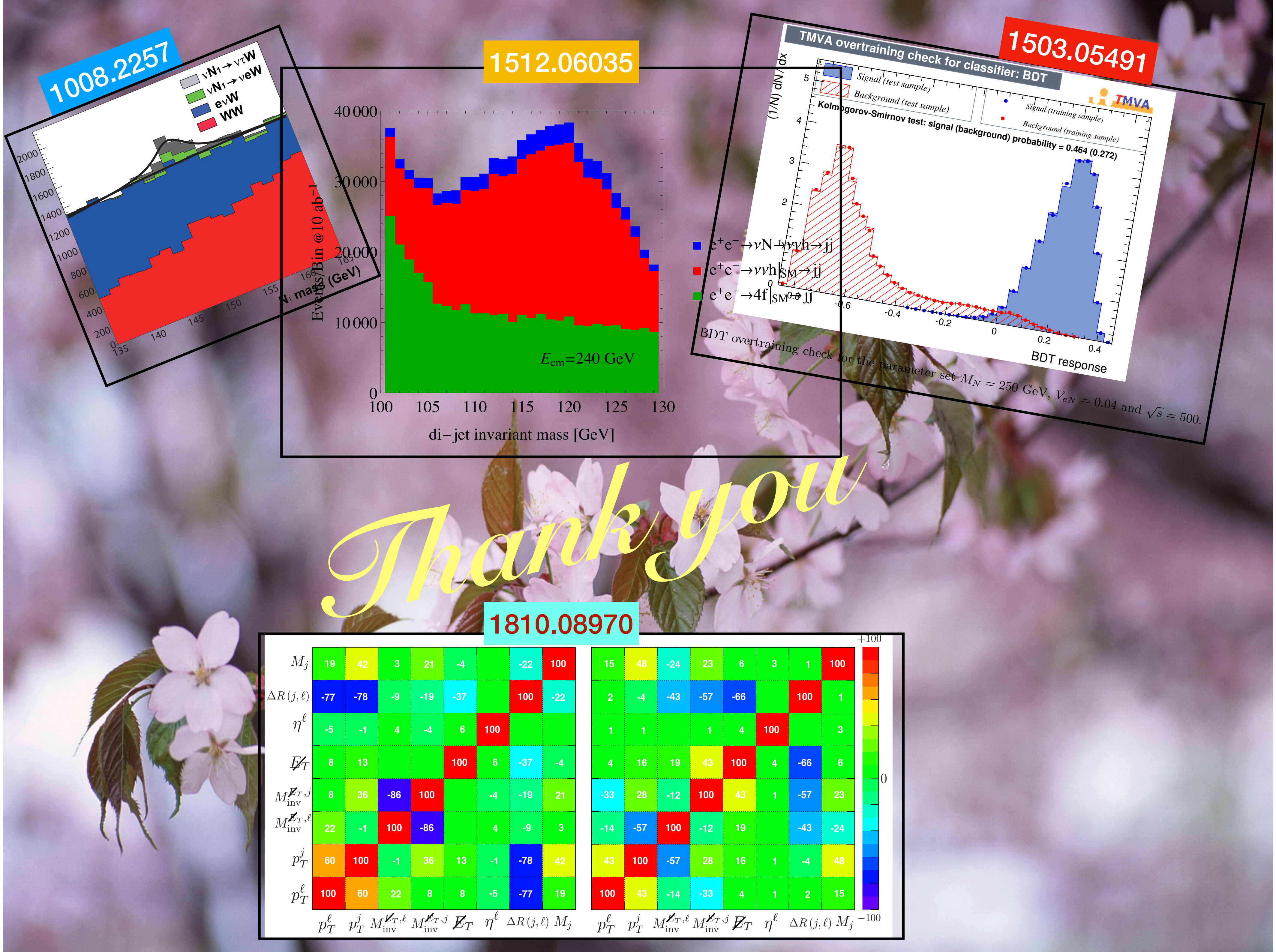
3(5) ab^{-1} 1(3) TeV
1 TeV (red band) and 3 TeV (blue band)
0.100
0.001
10^{-5}
10^{-7}
10^{-9}
$|V_{eN}|^2$
500
1000
1500
2000
2500
3000
M_N [GeV]
EWPD–e
LEP2
GERDA–Low
GERDA–High
Lepton Universality
ATLAS8–ee
CMS8–ee
CMS13–ee
CMS13–3l
1–σ (1 TeV, 3 ab^{-1})
2–σ (1 TeV, 3 ab^{-1})
3–σ (1 TeV, 3 ab^{-1})
5–σ (1 TeV, 3 ab^{-1})
1–σ (3 TeV, 5 ab^{-1})
2–σ (3 TeV, 5 ab^{-1})
3–σ (3 TeV, 5 ab^{-1})
5–σ (3 TeV, 5 ab^{-1})

Conclusions

The neutrino oscillation experiments confirm the existence of the tiny neutrino mass which lead to extend the Standard Model by right handed neutrino/s which mix with the SM neutrinos. There are several interesting simple (and next-to-simple) scenarios with different nice properties which efficiently explain the existence of the neutrino mass some of which which can be tested at the colliders such as at the proposed linear collider (also at the LHC) if the masses of the heavy neutrinos belong to the TeV scale or so.

In this presentation we have concentrated only on the signatures which can motivate the search of such heavy neutrinos at the linear collider. We have used the general parametrization based on the Casas-Ibarra conjecture. Using non-unitarity, neutrino oscillation data and indirect constraints from flavor violation and LEP experiments we have put bounds on the mixing angles to probe the signature of the heavy neutrinos. We have found that using the general parameters one can produce the heavy neutrinos followed by the leading decay modes up to a cross section of 150 fb including the mixing which can reach at a high discovery limit in future.

We have also studied the scenarios where the heavier neutrinos can be discovered at the linear collider from the boosted object search. In that case the heavy neutrinos will dominantly produce the boosted W boson which will further decay into a fat jet. Using jet substructure method we distinguish the signal and background. Finally we show a limit plot in the mass-mixing plane up to 5-sigma which is very strong compared to the EWPD.


1008.2257
νN₁→ ντW
νN₁→ νeW
eνW
WW
N₁ mass (GeV)
1512.06035
Events/Bin @10 ab⁻¹
E_cm=240 GeV
di−jet invariant mass [GeV]
e⁺e⁻→νN→ννh→jj
e⁺e⁻→ννh|SM→jj
e⁺e⁻→4f|SM→jj
1503.05491
TMVA overtraining check for classifier: BDT
Signal (test sample)
Background (test sample)
Signal (training sample)
Background (training sample)
Kolmogorov-Smirnov test: signal (background) probability = 0.464 (0.272)
(1/N) dN/dx
BDT response
TMVA
BDT overtraining check for the parameter set M_N = 250 GeV, V_eN = 0.04 and √s = 500.
Thank you
1810.08970