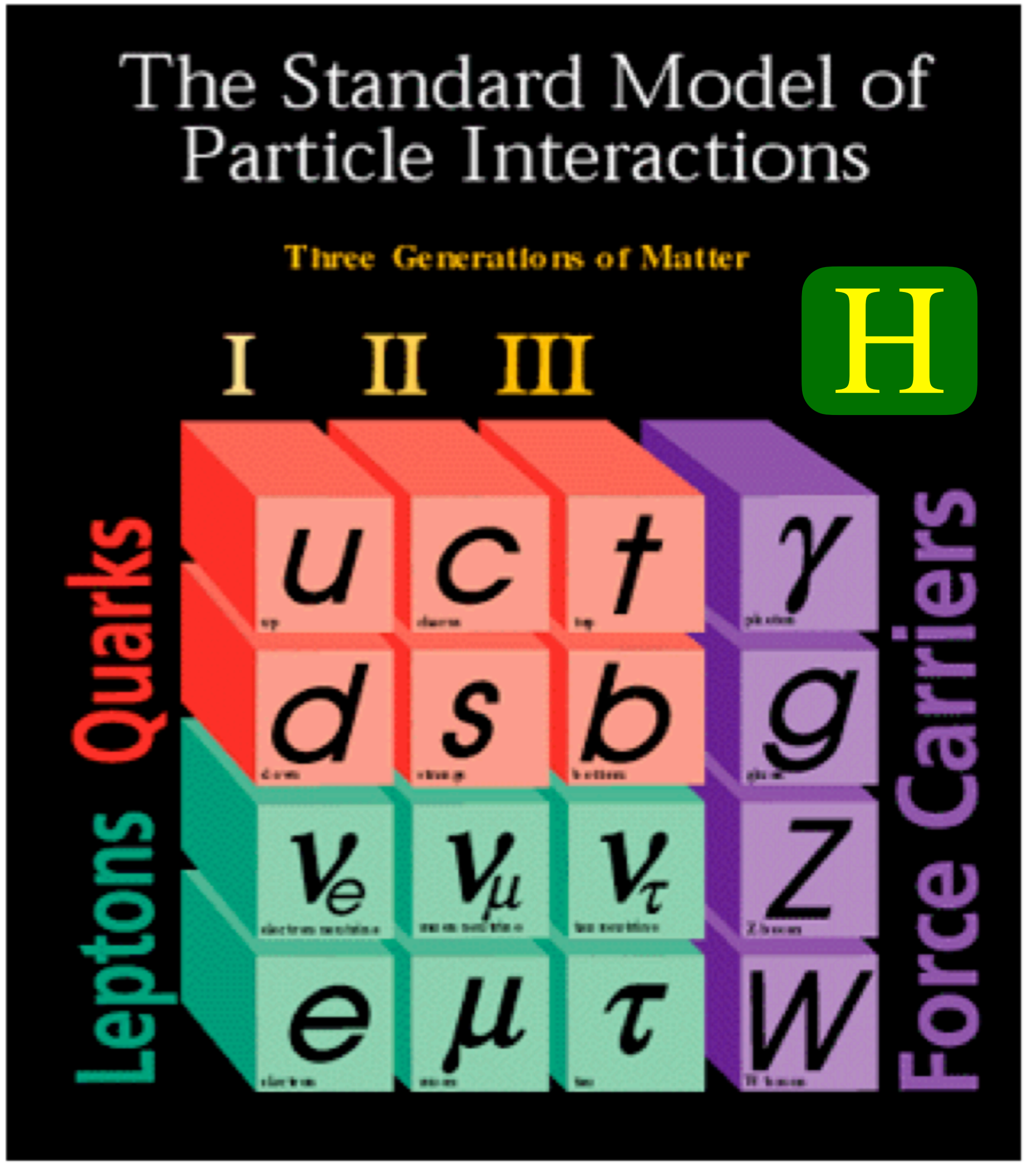
ILC and models of neutrino mass

ILC Snowmass 2022
February 11, 2021

Arindam Das
Hokkaido University



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

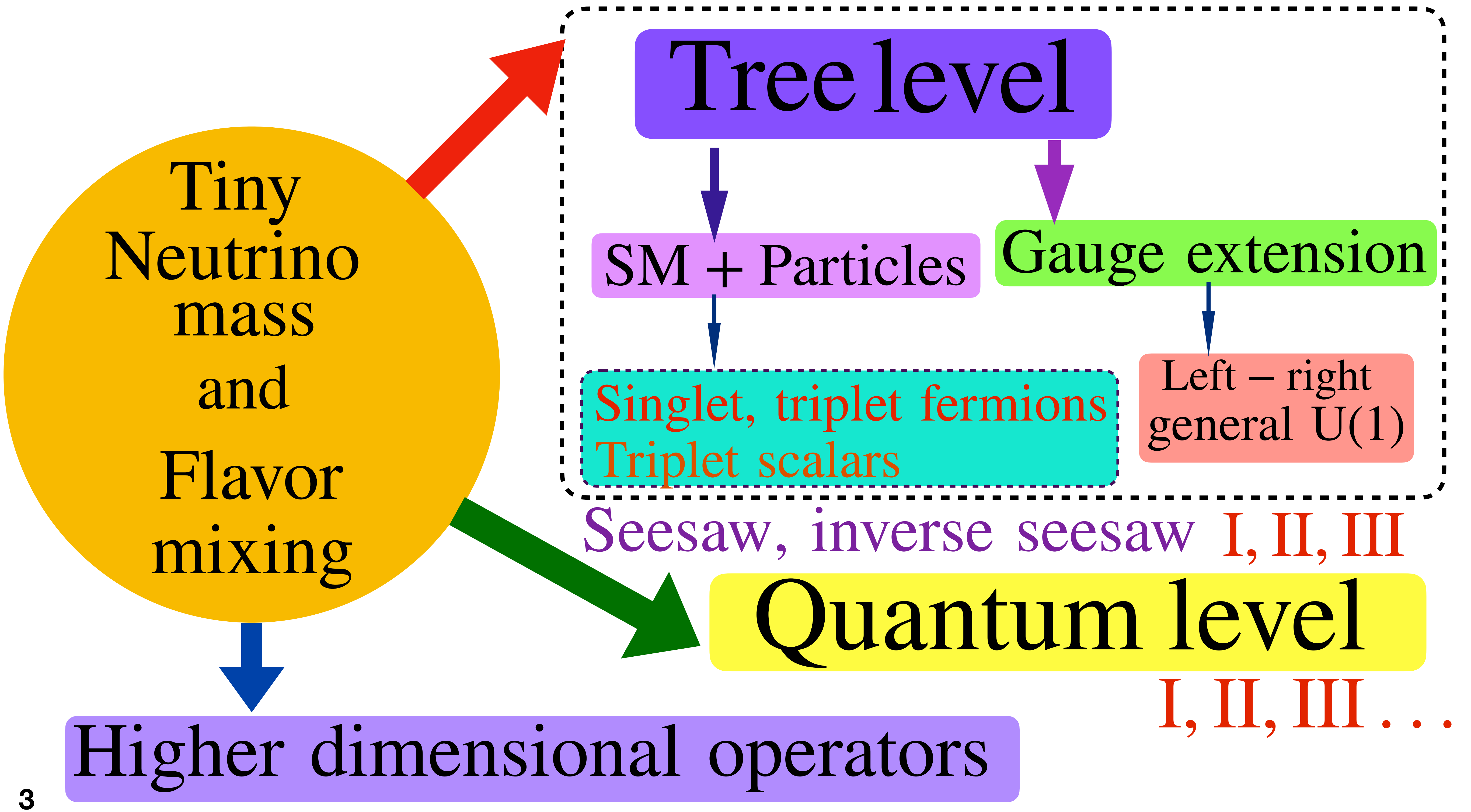
Few of the very interesting anomalies :

Tiny neutrino mass and flavor mixings

Relic abundance of dark matter . . .

SM can not explain them

Different aspects of neutrino mass generation mechanism



Particle content

Dobrescu, Fox; Cox, Han, Yanagida; AD, Okada, Raut; AD, Dev, 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'

B – L case

$x_H = 0,\ x_\Phi = 1$

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

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

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

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

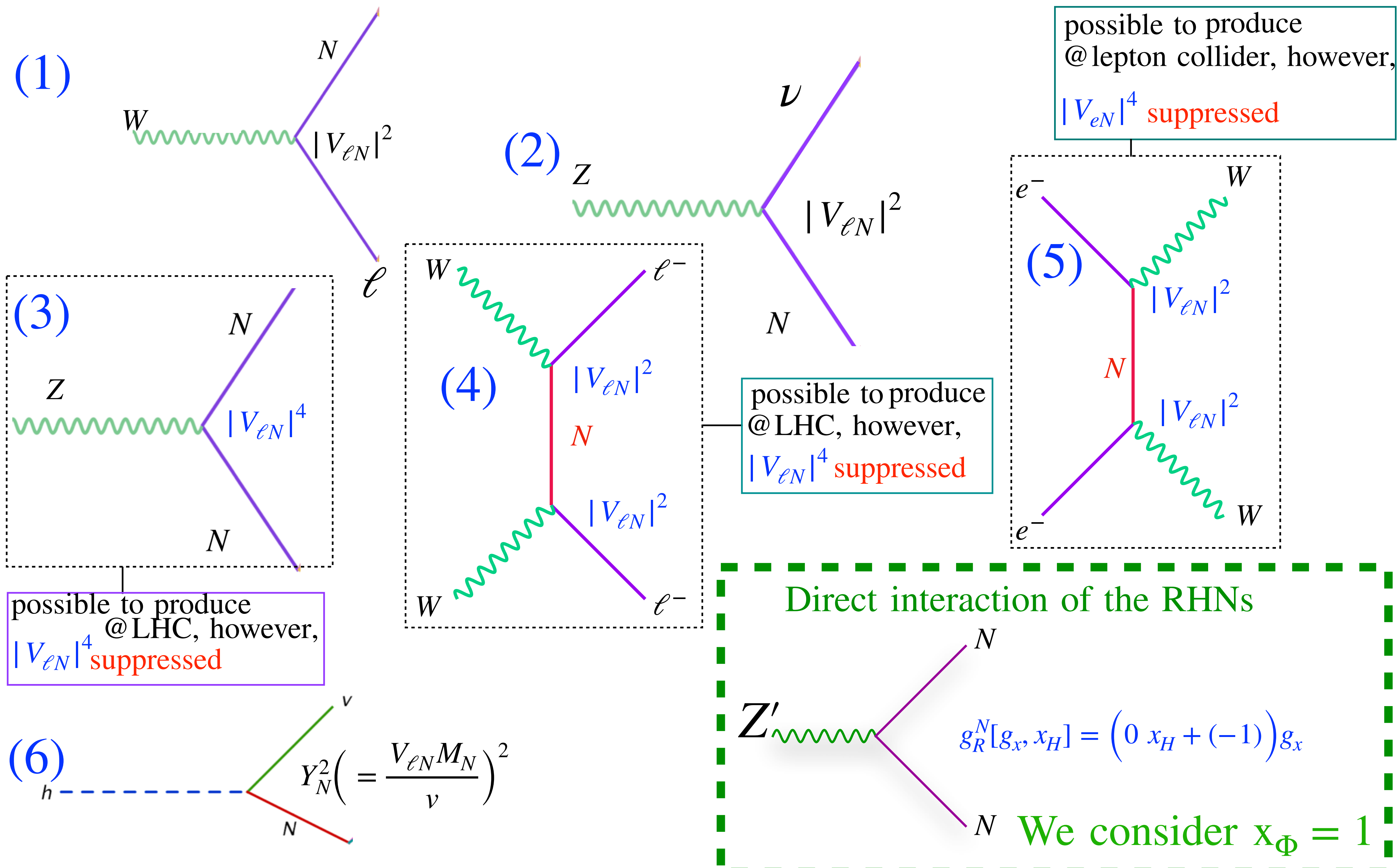
Seesaw mechnism

Production modes of the RHNs at the colliders : pp, e^-e^+, e^-p

Flavor eigenstate can be expressed in terms of the mass eigenstate

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

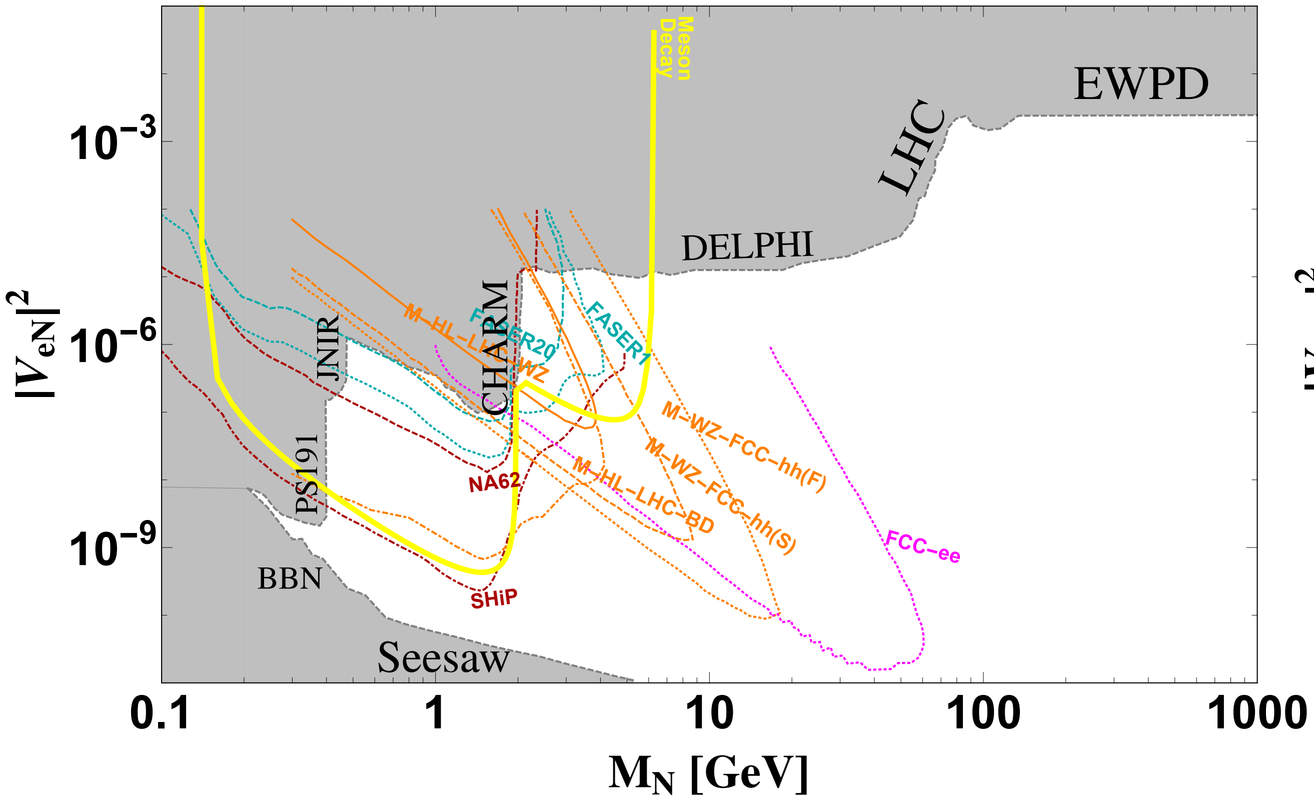
PMNS matrix ($U_{\ell m}$) $\quad$ $M_D M_N^{-1}$ ($V_{\ell n}$)

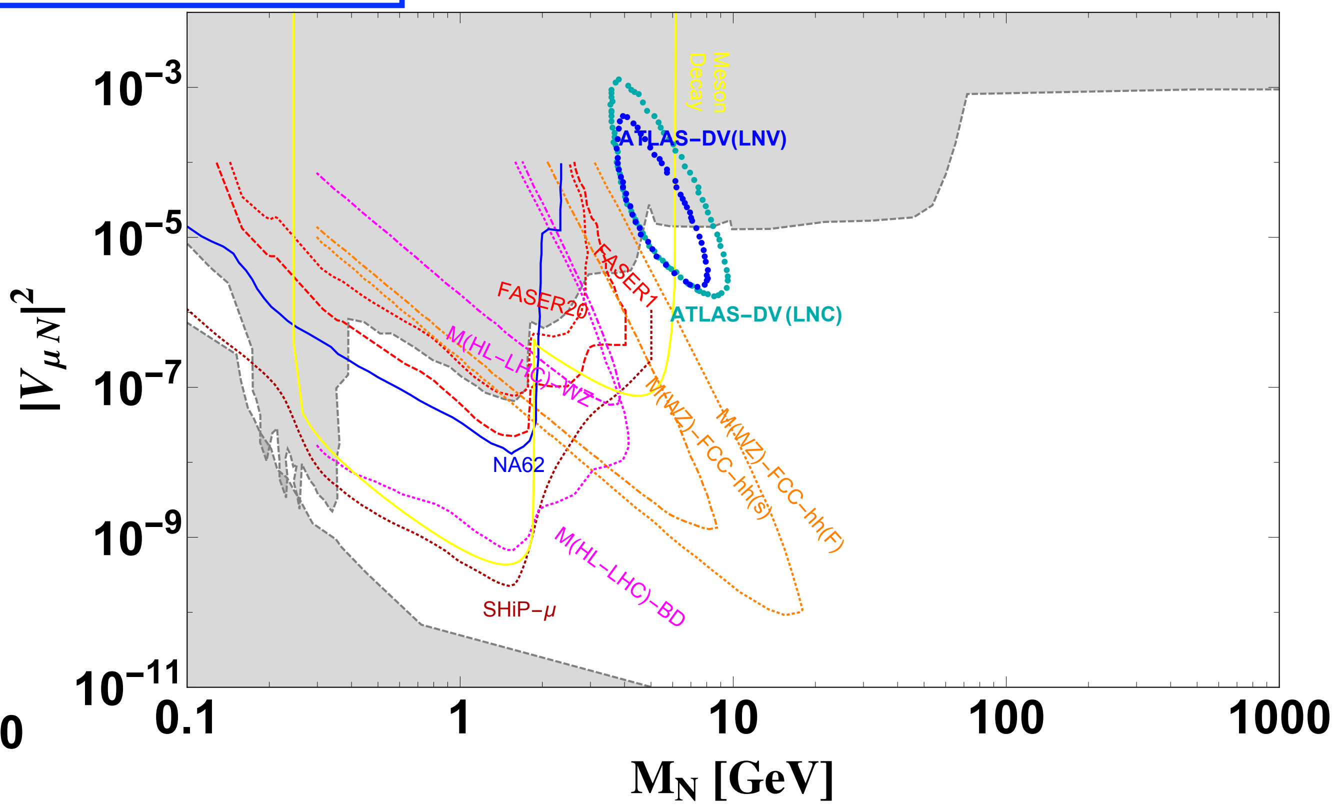


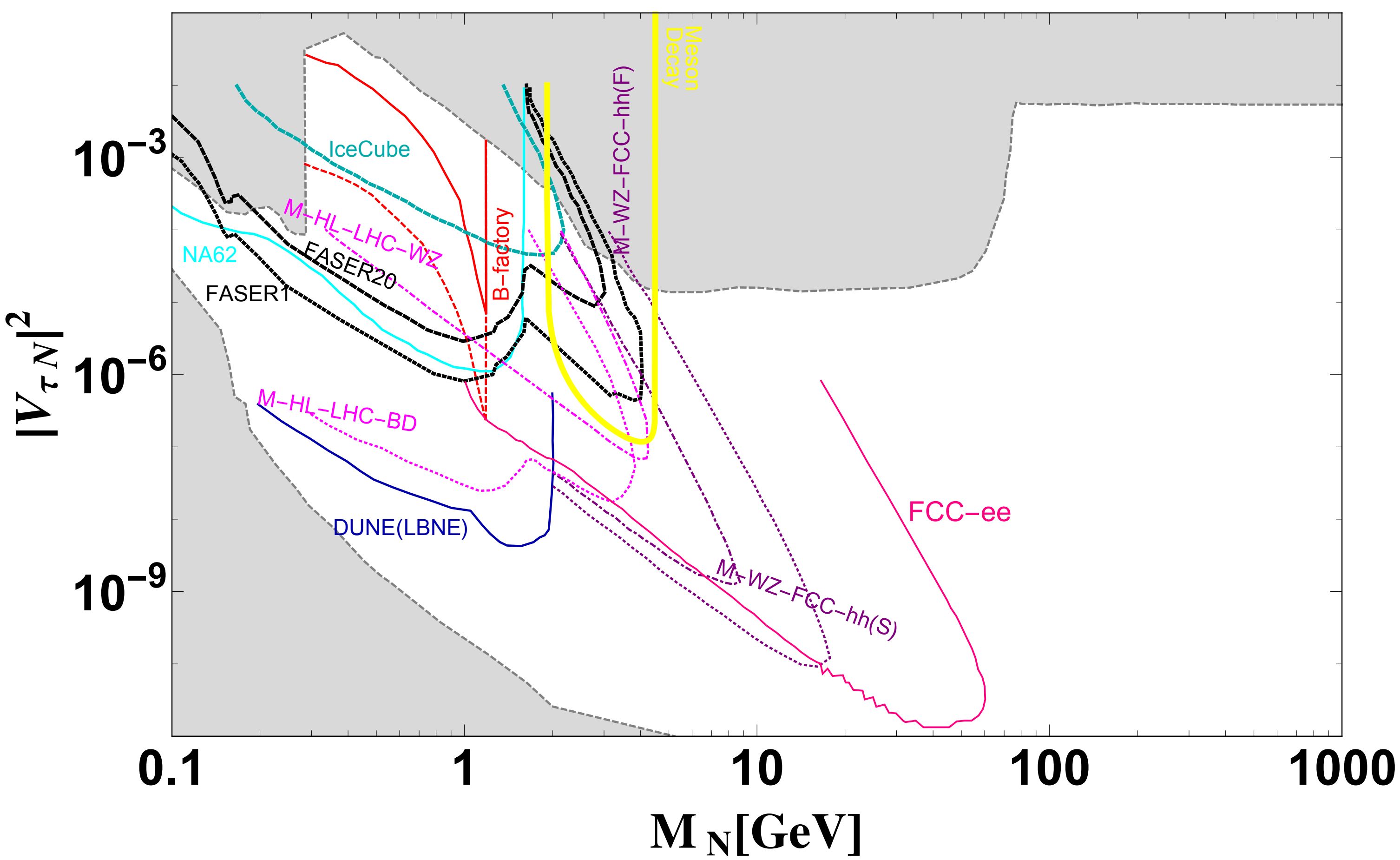
Jurina Nakajima's talk

Existing and prospective bounds on the mixings

1502.06541 1805.00070 1908.09562







CMS $\ell^{\pm}\ell^{\pm}$ + jets

1806.10905 13 TeV, 35.9 fb^{-1}

CMS 3ℓ + MET

1802.02965 13 TeV, 35.9 fb^{-1}

ATLAS 3ℓ + MET

1905.09787, 36.1 fb^{-1}

General Yukawa structure : 1702.04668

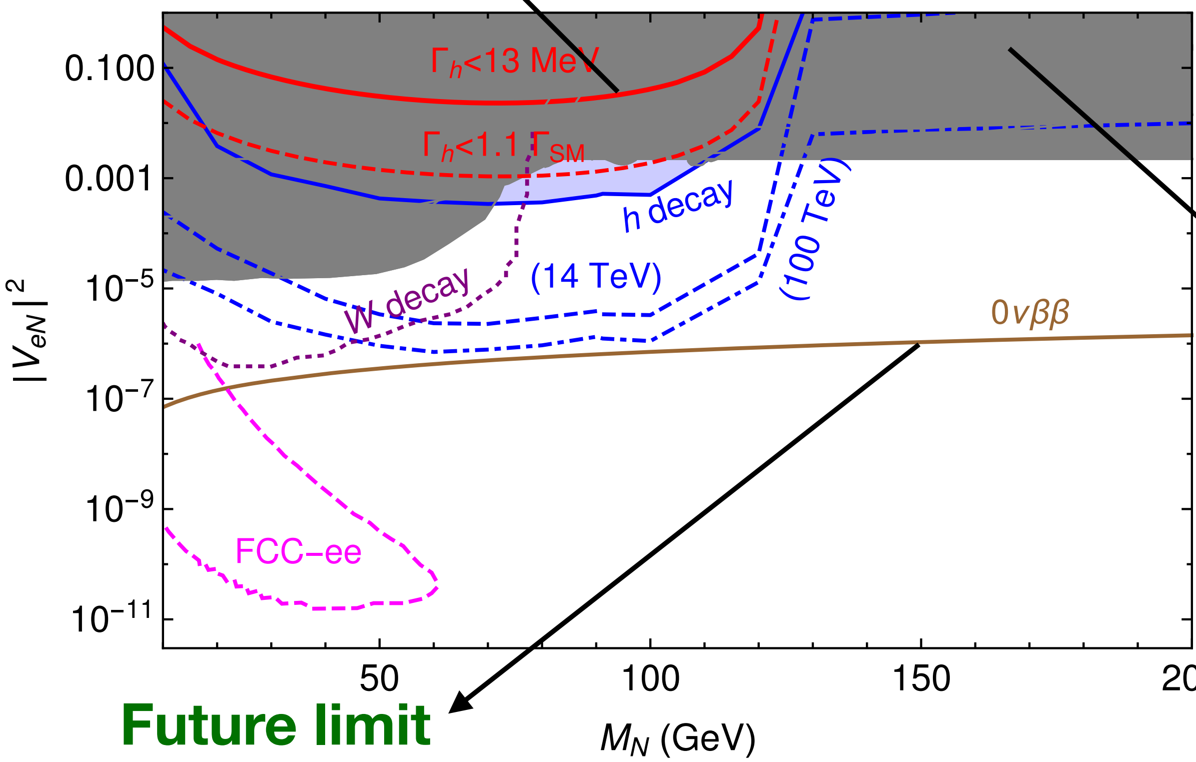
References : 1502.06541, 1908.09562

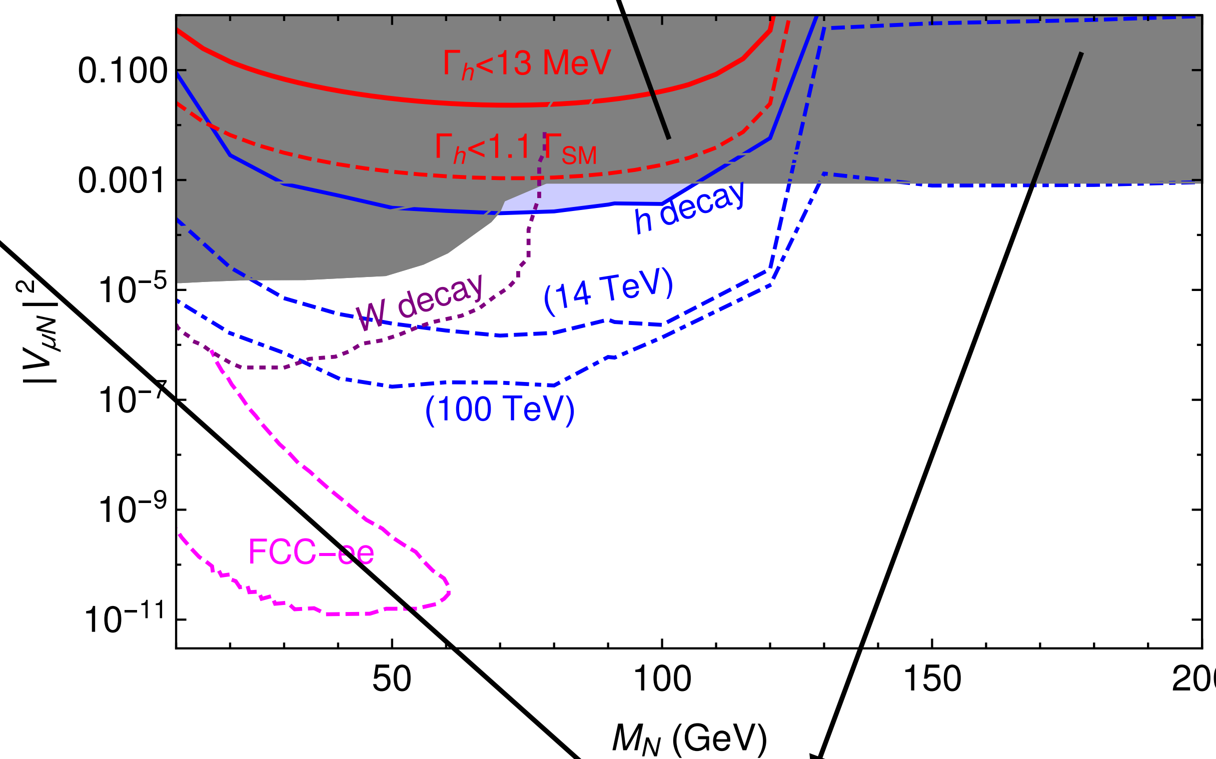
$2\ell + p_T^{\rm miss}$: bounds from the Higgs decay $(h \to N\nu, N \to 2\ell\nu)$

CMS, JHEP 09 (2016) 051: 7&8 TeV combined H $\longrightarrow$ W W*, upper limit on Yukawa as well as mixing

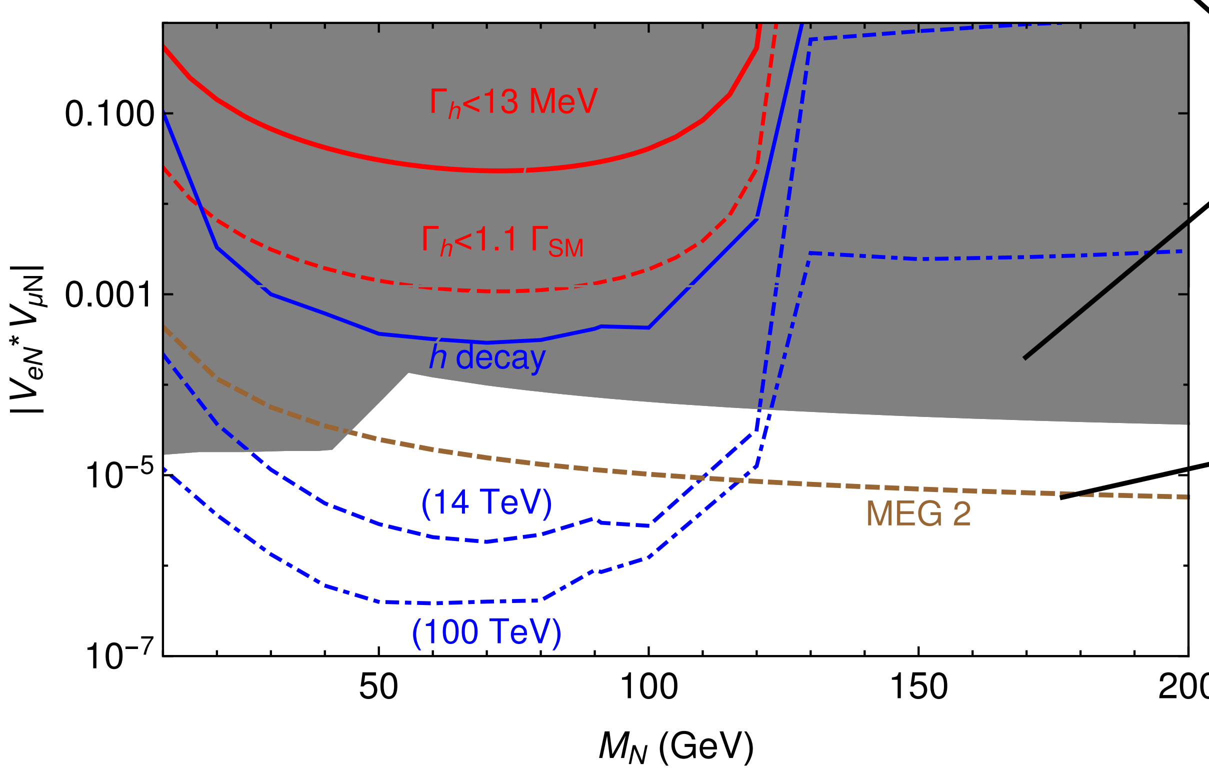
Future sensitivity can go down to 10%precise result at pp collider: arXiv:1606.09408

1704.00880
1704.00881





Future limit considering Majorana heavy neutrinos only



Excluded by LEP LHC,EWPD,

LFV limits from CMS is also included in the lower panel

FCC-ee : Limits from Z decay

W-decay @LHC

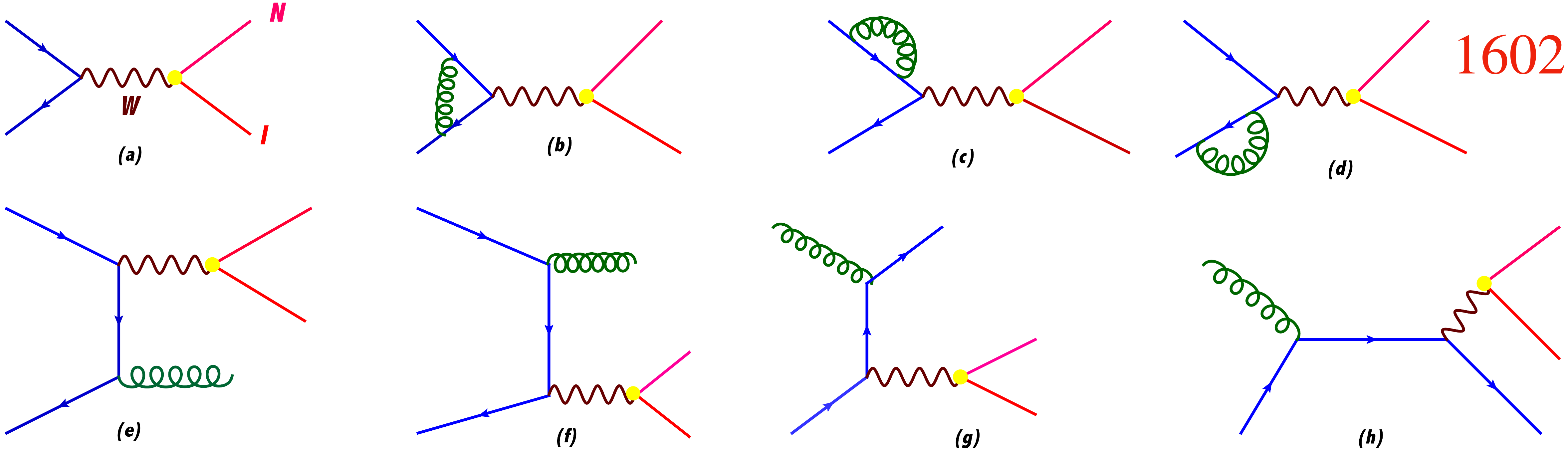
$\mu \to e\gamma$

~ future branching ratio $O(10^{-15})$

Future limits

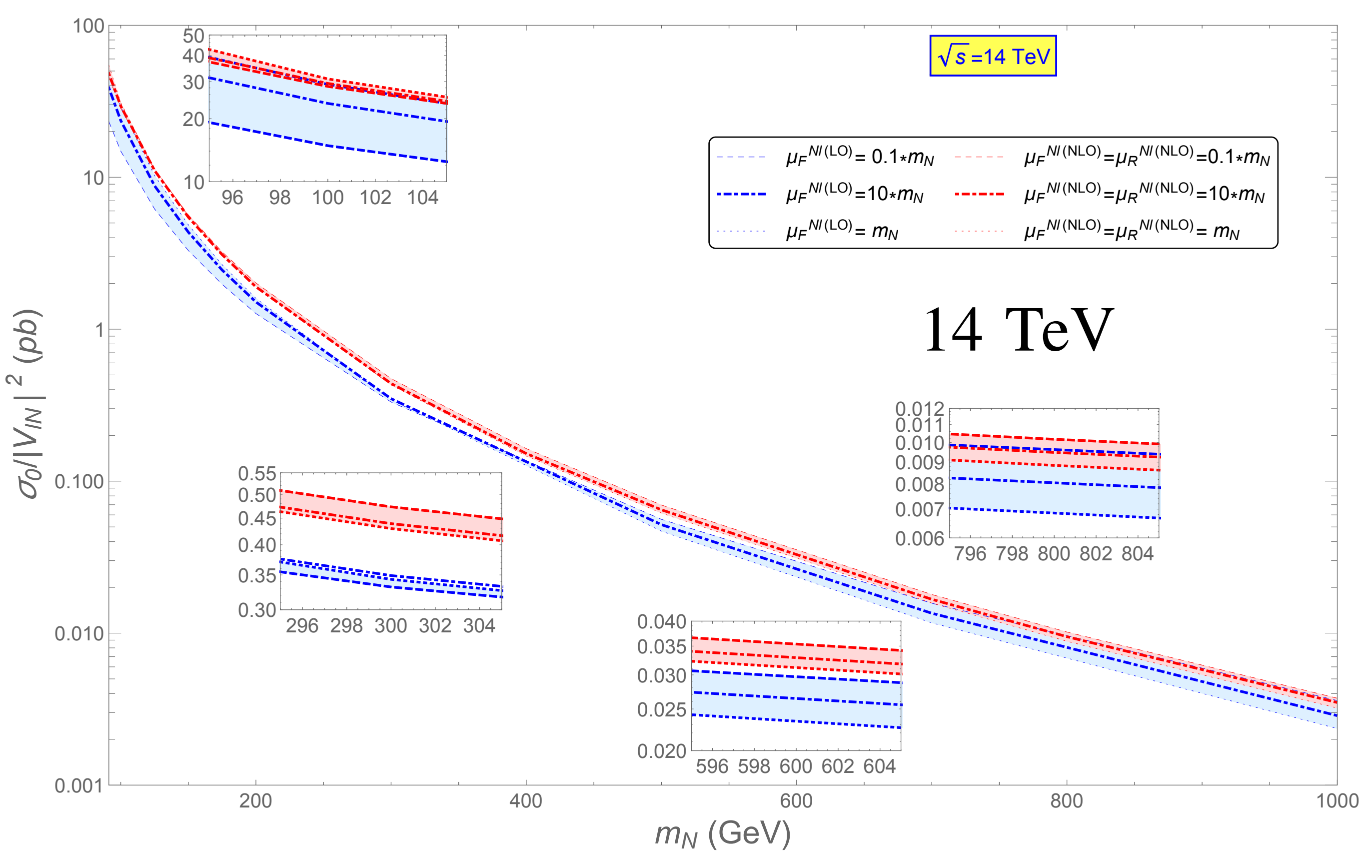
Dev, Franceschini, Mohapatra; Cely, Ibarra, Molinaro, Petcov; AD, Dev, Kim; AD, Gao, Kamon; Antusch, Fischer

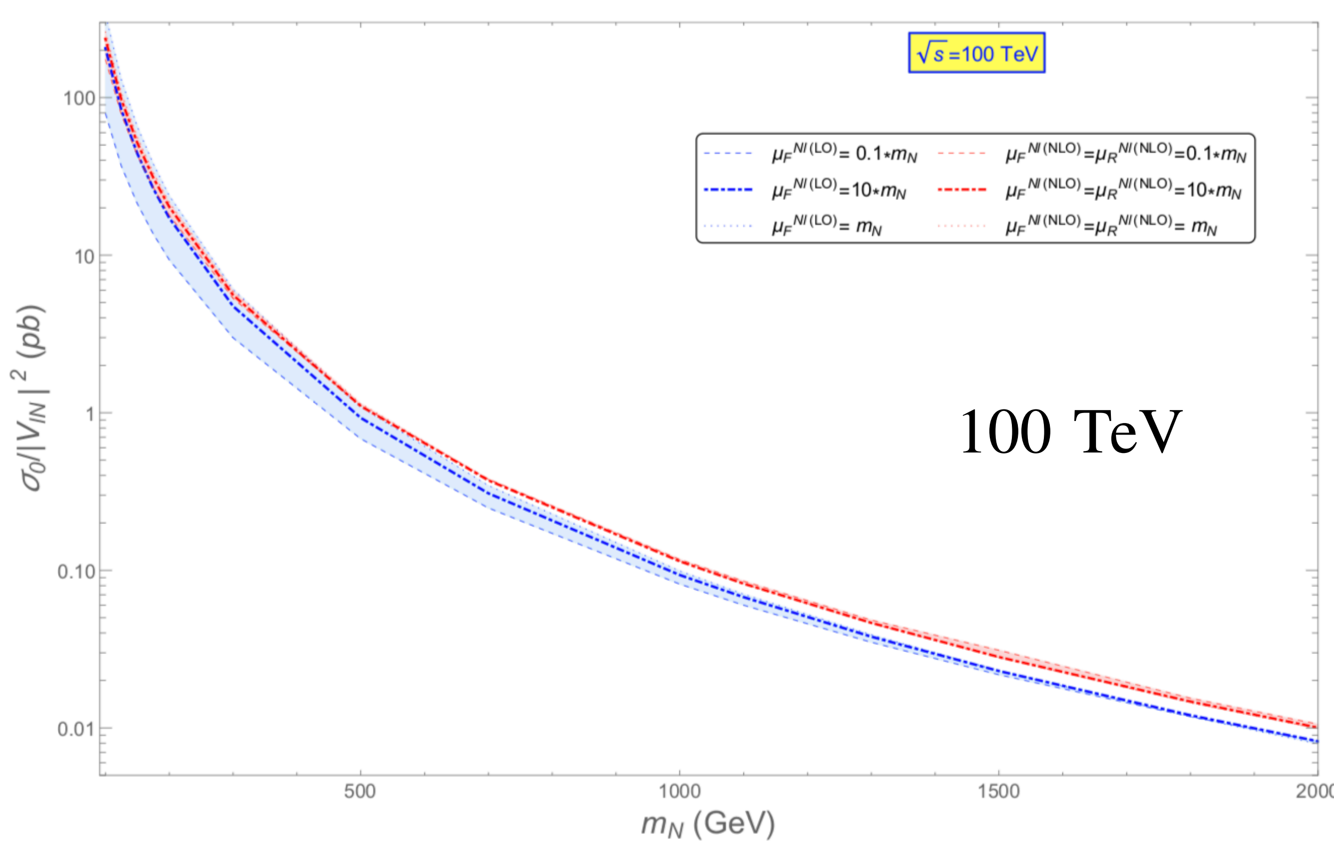
NLO – QCD production of the heavy neutrinos @ pp colloiders



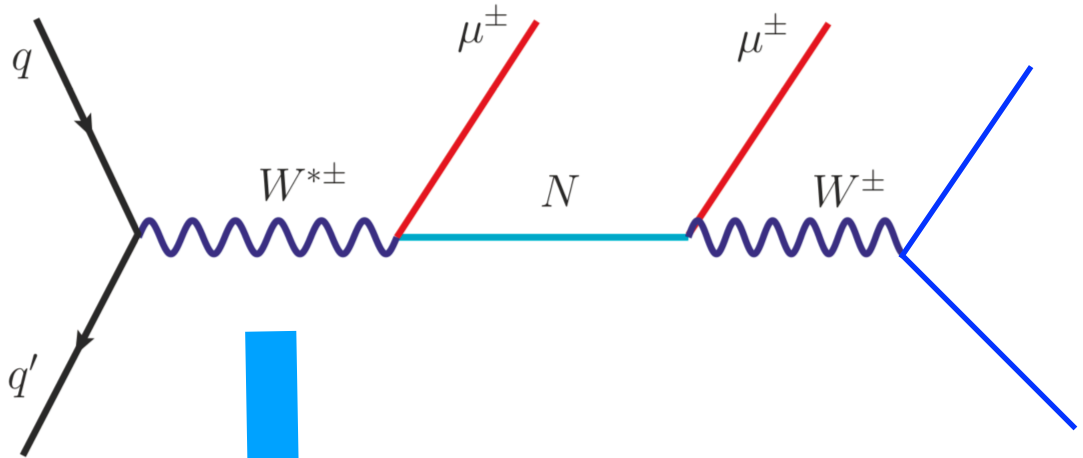
1602.06957

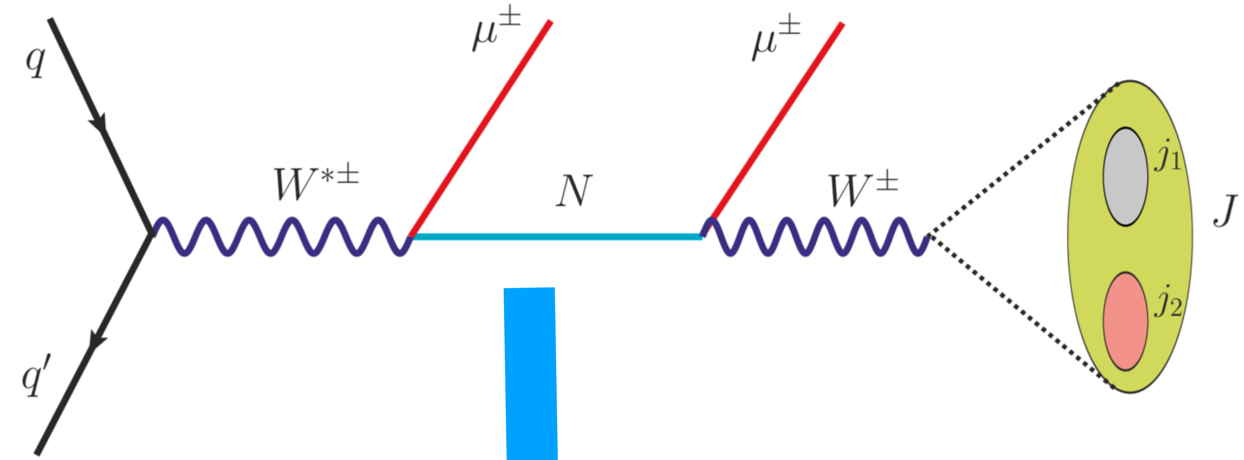
$\mu_F^{\mathrm{NLO}} = \mu_R^{\mathrm{NLO}} = \xi * m_N$ $\mu_F^{\mathrm{NLO}} = m_N,\ \mu_R^{\mathrm{NLO}} = \xi * m_N$ $\mu_F^{\mathrm{NLO}} = \xi * m_N,\ \mu_R^{\mathrm{NLO}} = \xi * m_N$ $0.1 \leq \xi \leq 10$





Normalized by $|V_{\ell N}|^2$

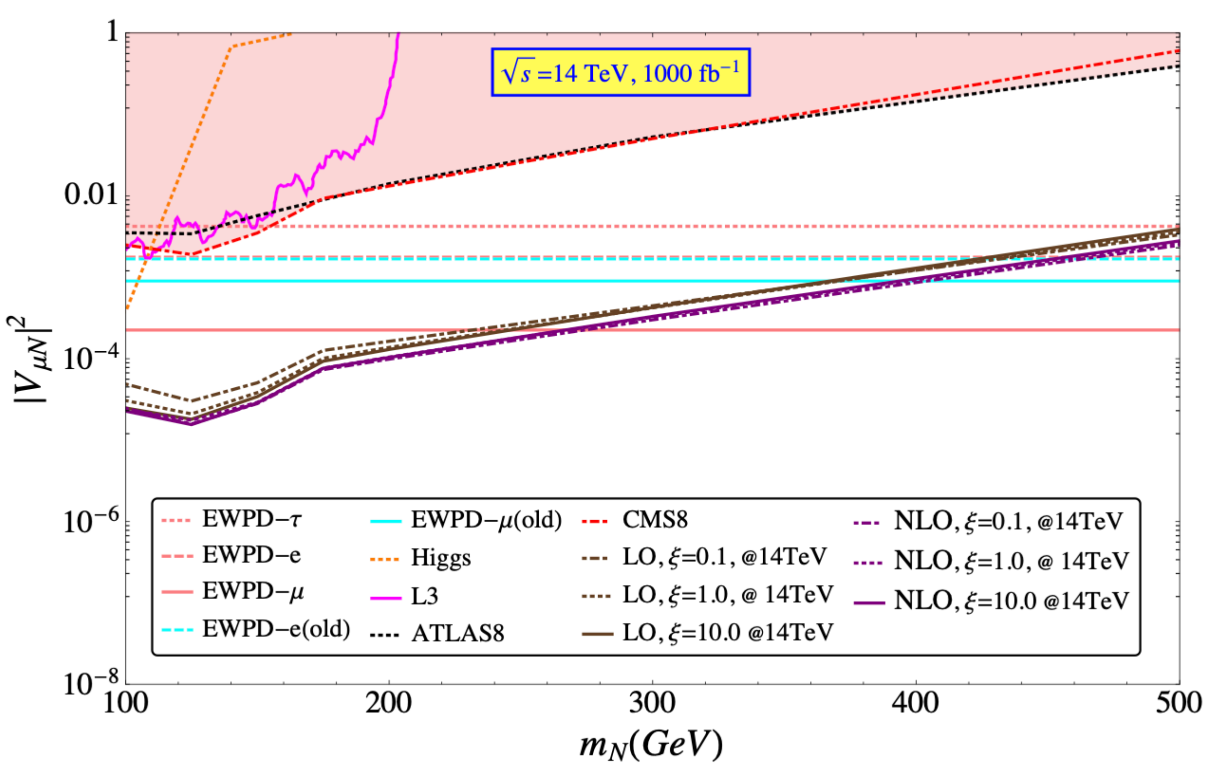




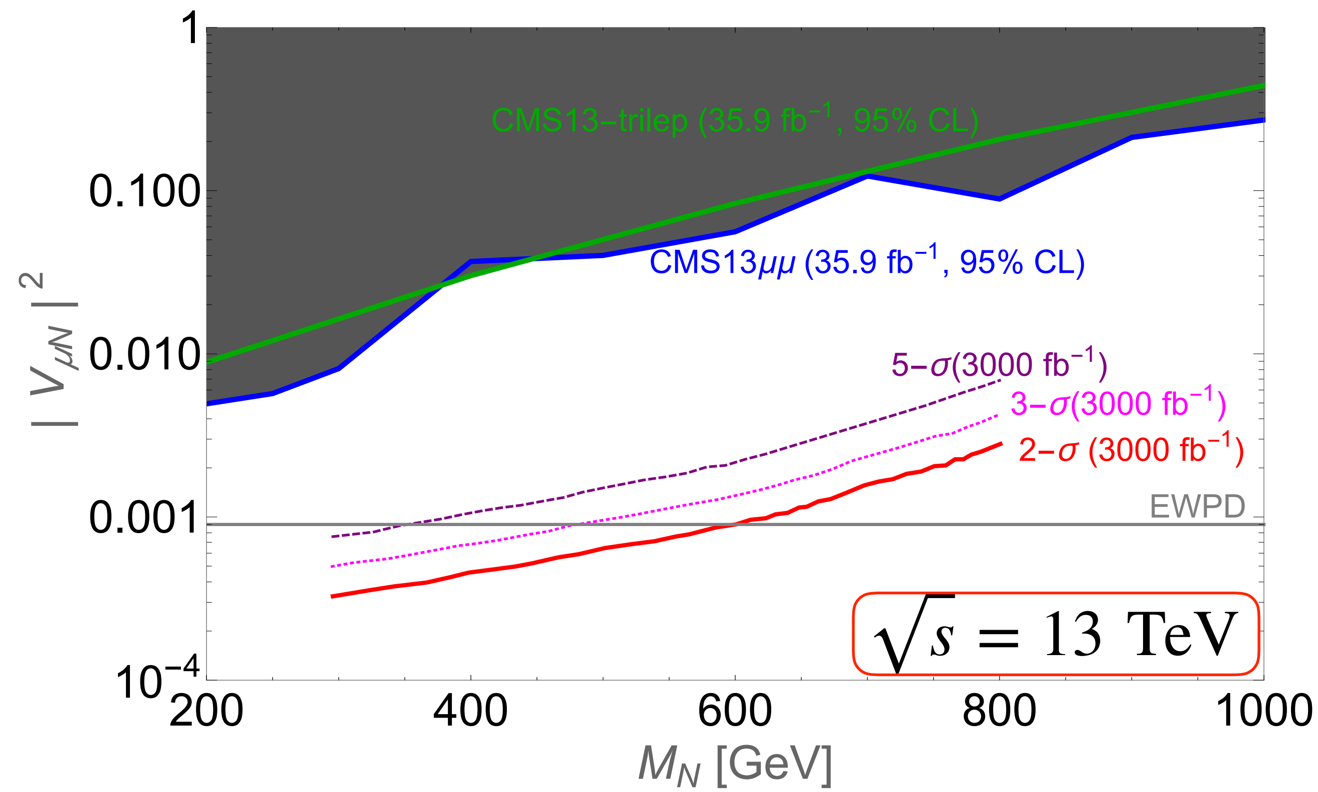
$R = 0.8,\ p_T^J > 150$ GeV, $\tau_{21}^J < 0.5$, $E_T^{miss} < 35$ GeV, $M^J > 50$ GeV

SSDL + 2 − jet

SSDL + 1 − Fat jet



14 TeV, 1000 fb^{-1}



$\sqrt{s}$ = 13 TeV

AD, Konar, Majhi 1602.06957

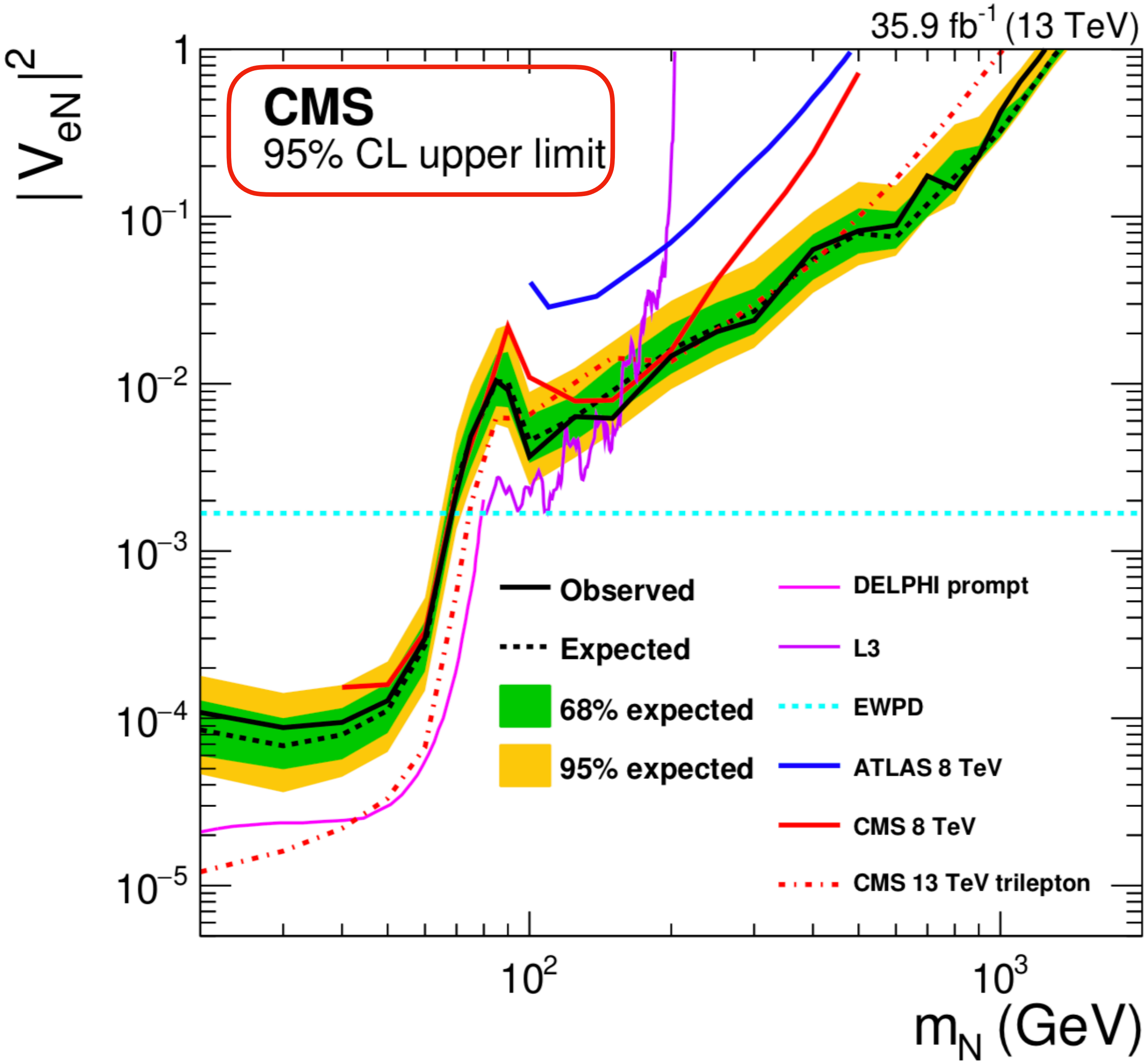
AD, Konar, Thalapillil 1709.09712

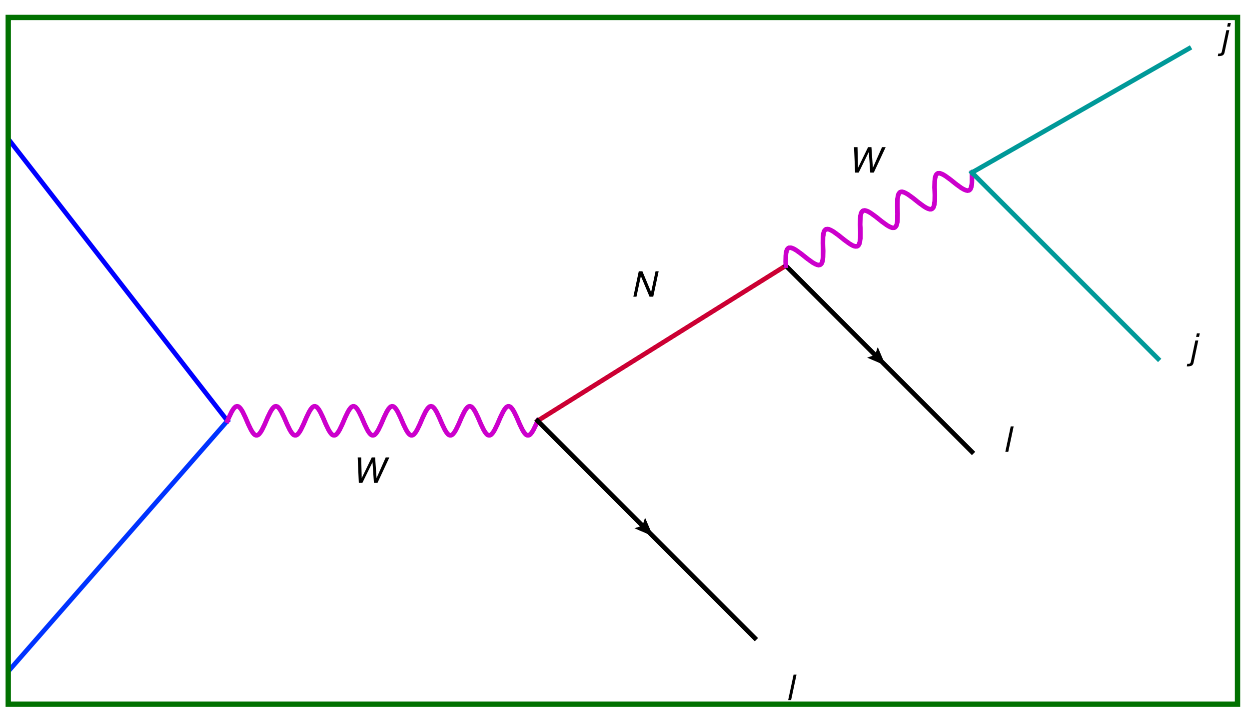
Experimental limits

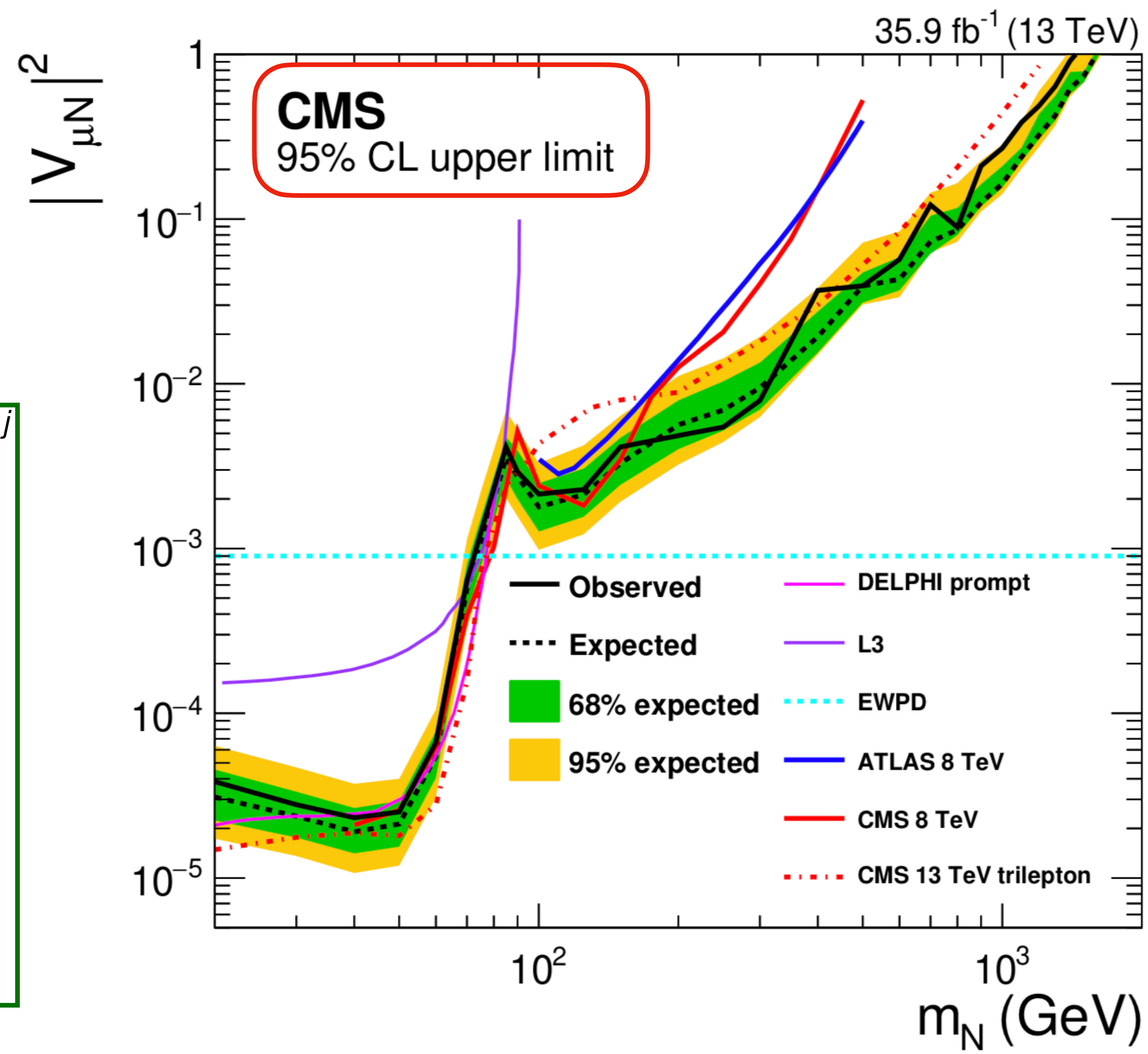
$\ell^{\pm}\ell^{\pm} + \text{jets}$

CMS

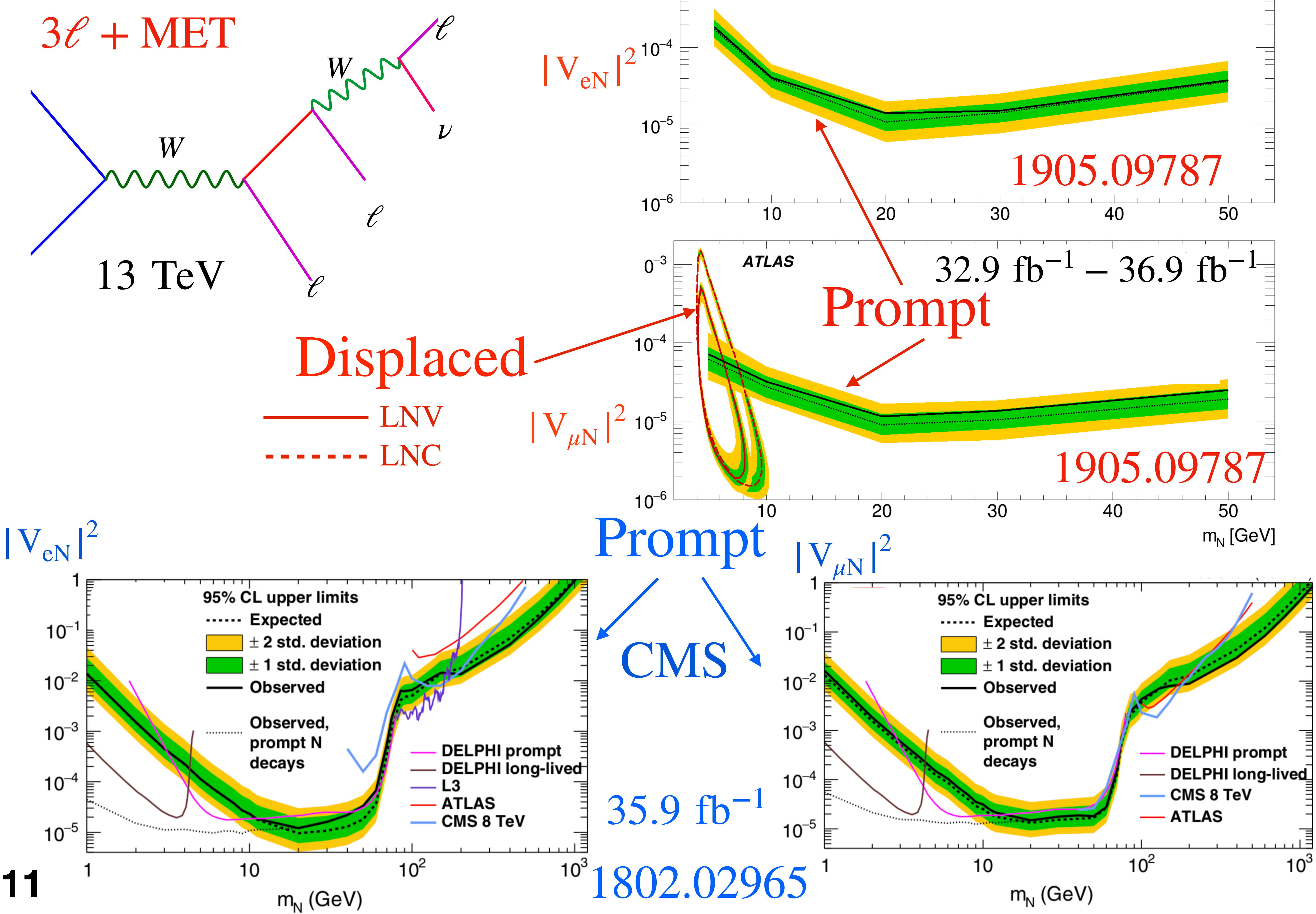
1806.10905 13 TeV, 35.9 fb^{-1}







Experimental limits

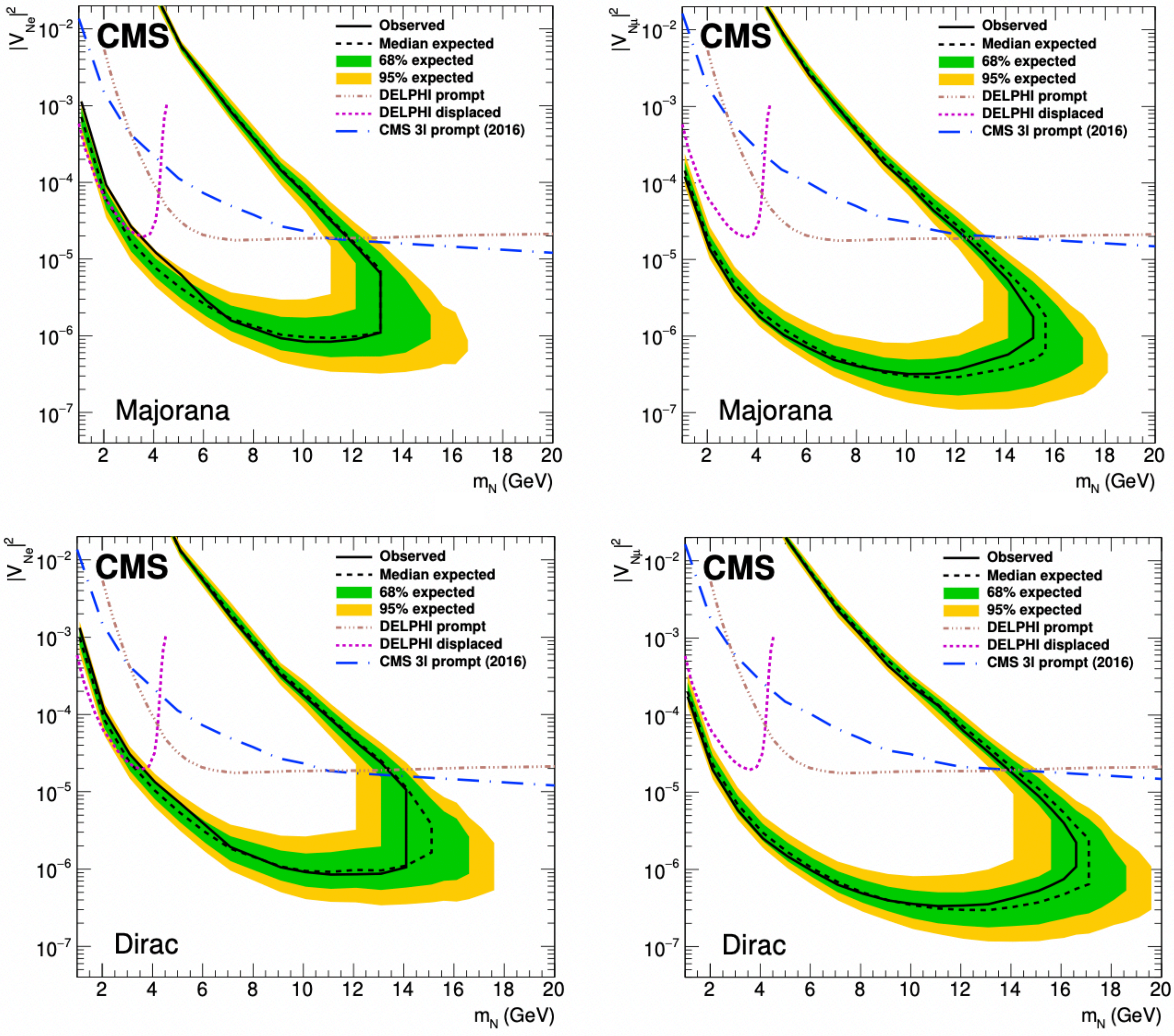


Long – lived HNL searches at CMS

Trilpeton mode : $pp \to N\ell, N \to \ell W, W \to \ell\nu$

$pp \to N\ell, N \to \nu Z, Z \to \ell\ell$

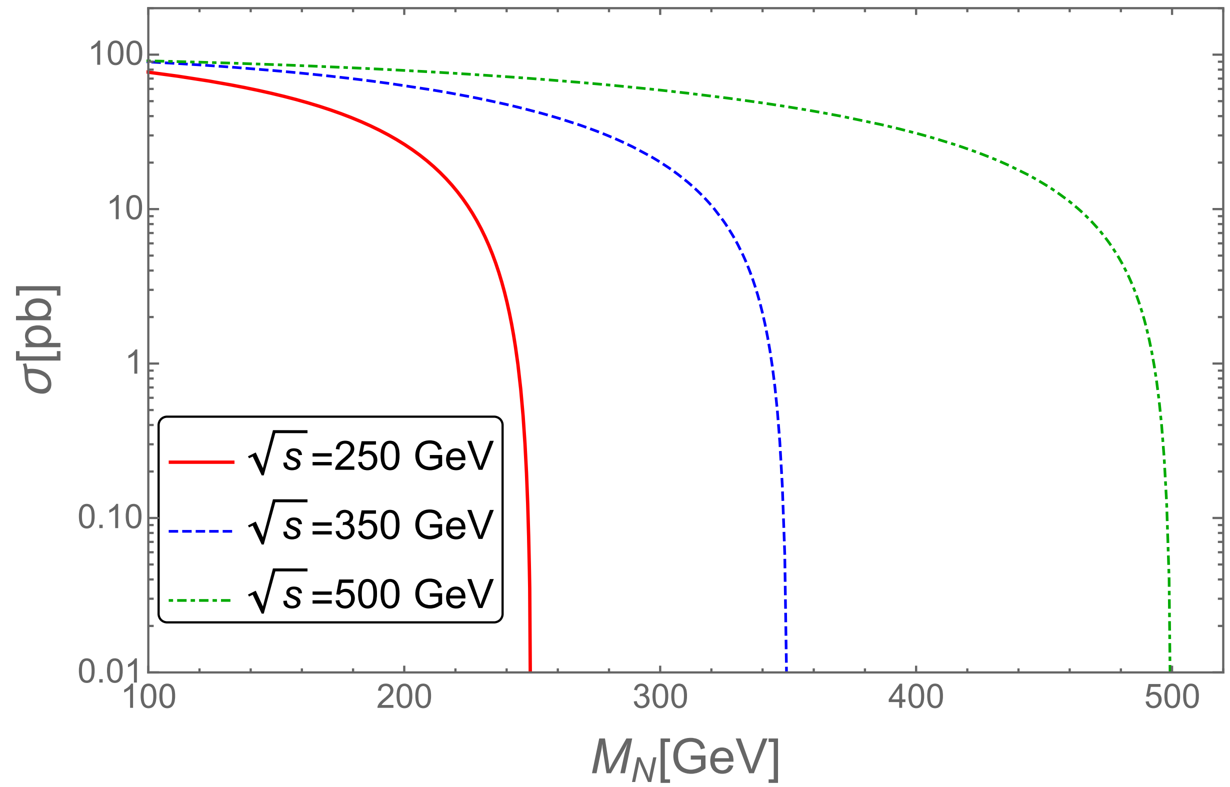
2201.05578

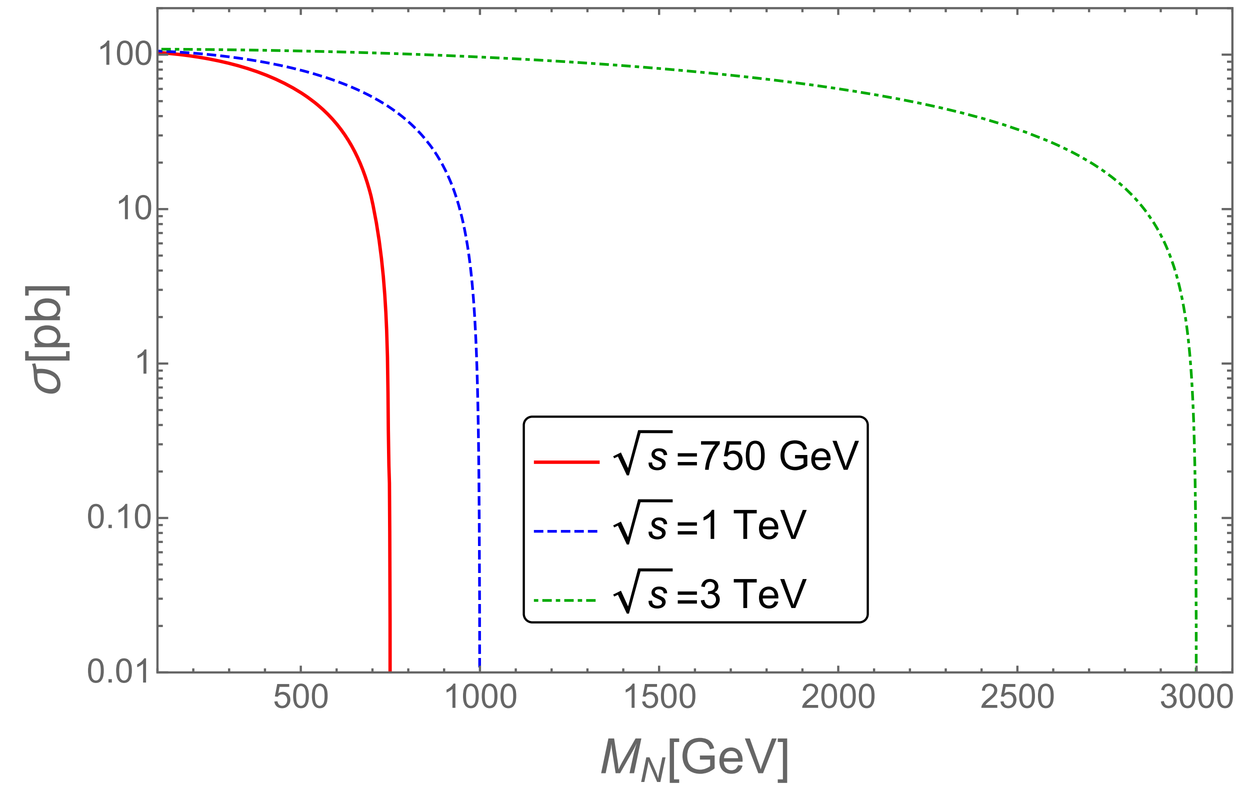


Production of the heavy neutrinos at the Linear Collider using fat-jet

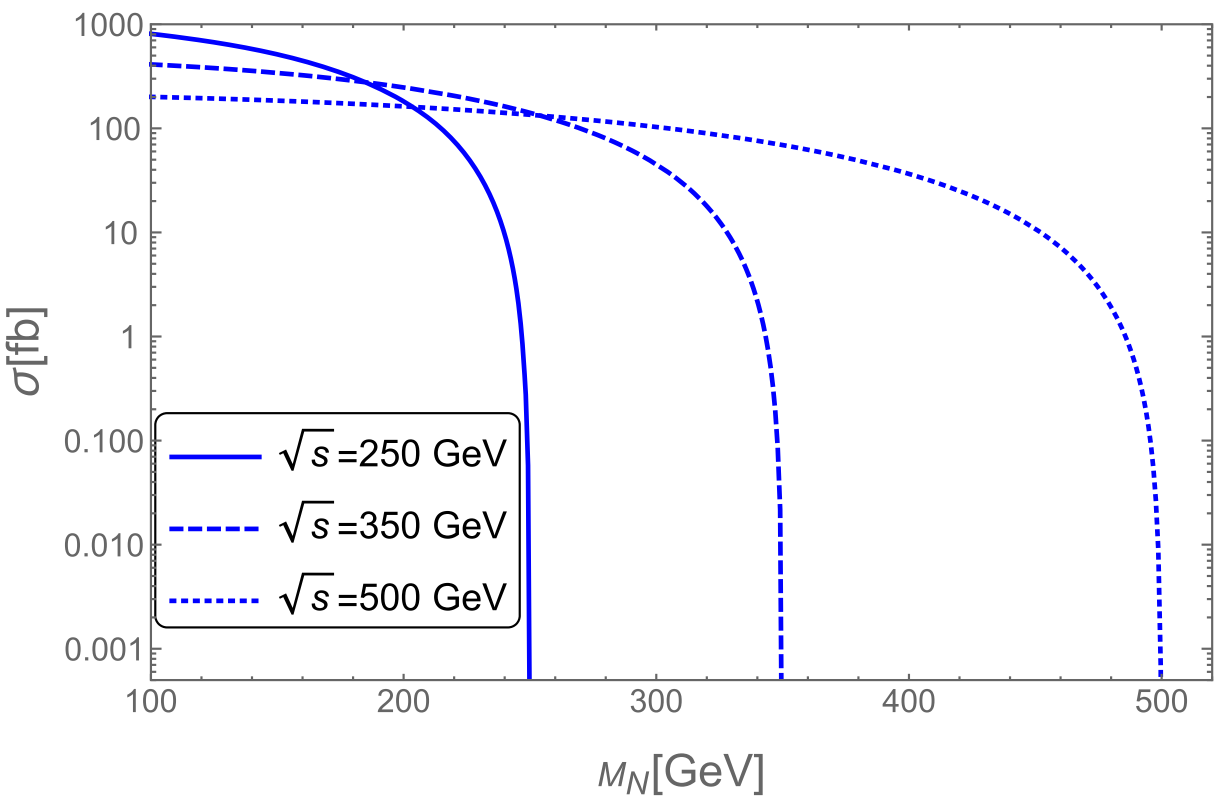
1207.3734, 1811.04291
1502.05915, 1503.05491

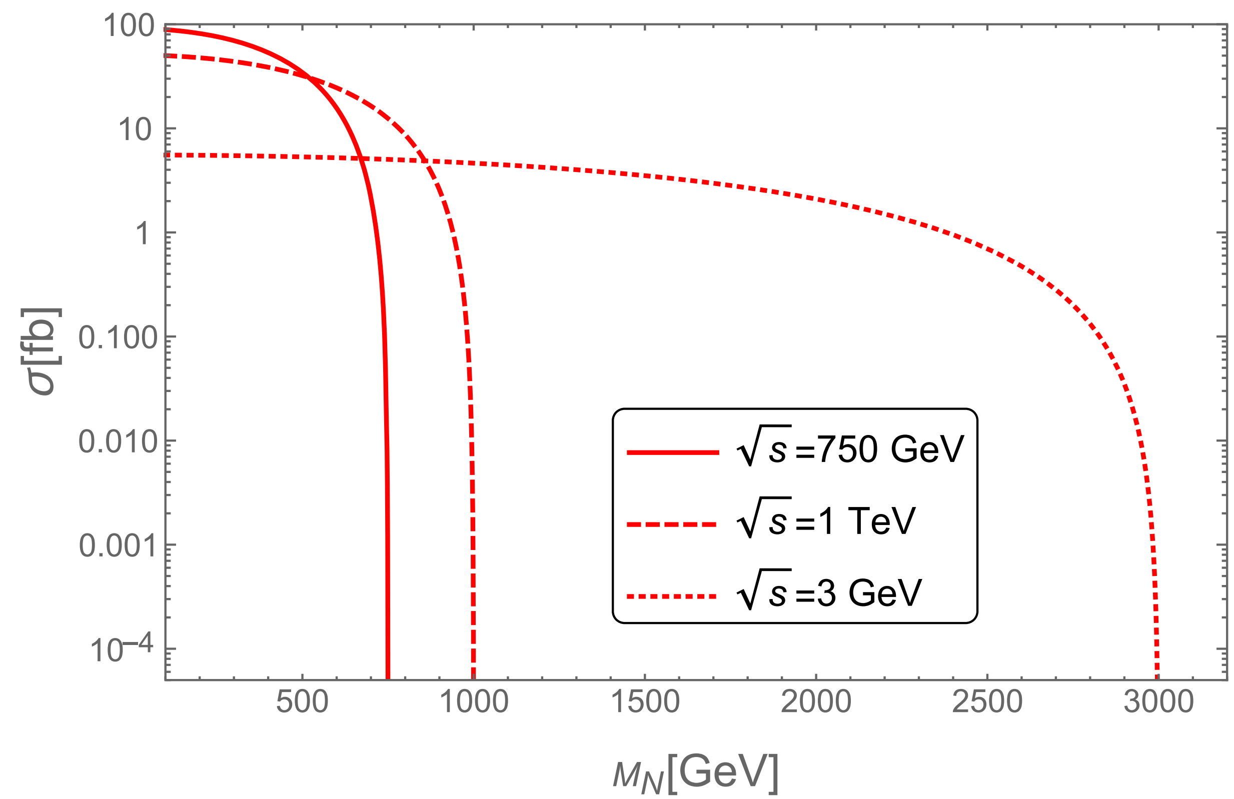
$e^+e^- \to \nu_1 N_1$ Includes s – channel and t – channel processes



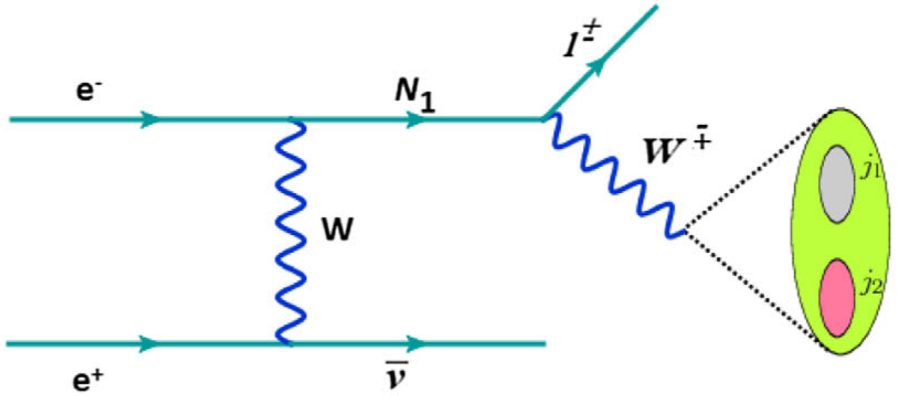


$e^+e^- \to \nu_2 N_2 / \nu_3 N_3$ Includes s – channel process, t – channel suppressed by off – diagonal Yukawa, away from the Z pole

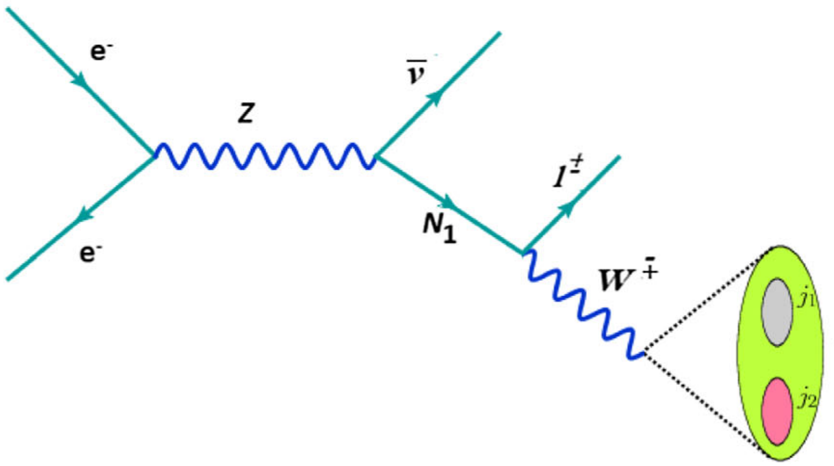




$e + J + p_T^{\rm miss}$ final states at the linear colliders.



$R = 0.8$



$R = 0.8$

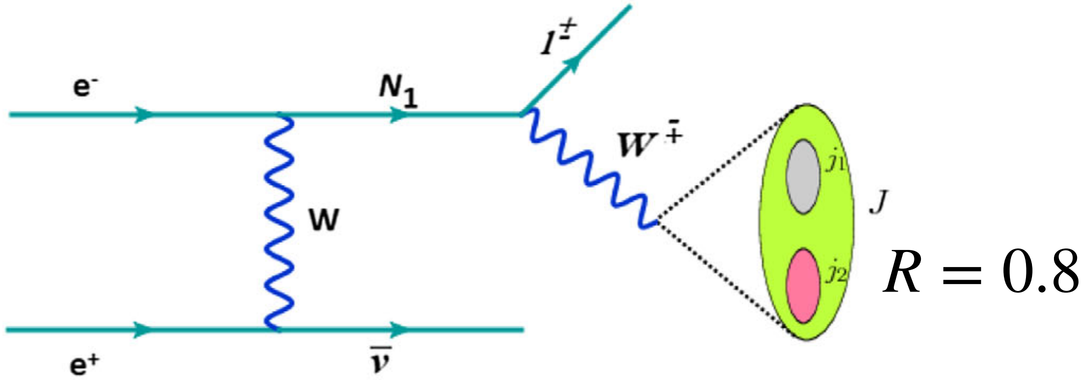
- Transverse momentum for fat-jet $p_T^J > 150$ GeV for M_N mass range 400 GeV-600 GeV and $p_T^J > 250$ GeV for M_N mass range 700 GeV-900 GeV.
- Transverse momentum for leading lepton $p_T^{e^\pm} > 100$ GeV for M_N mass range 400 GeV-600 GeV and $p_T^{e^\pm} > 200$ GeV for M_N mass range 700 GeV-900 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.

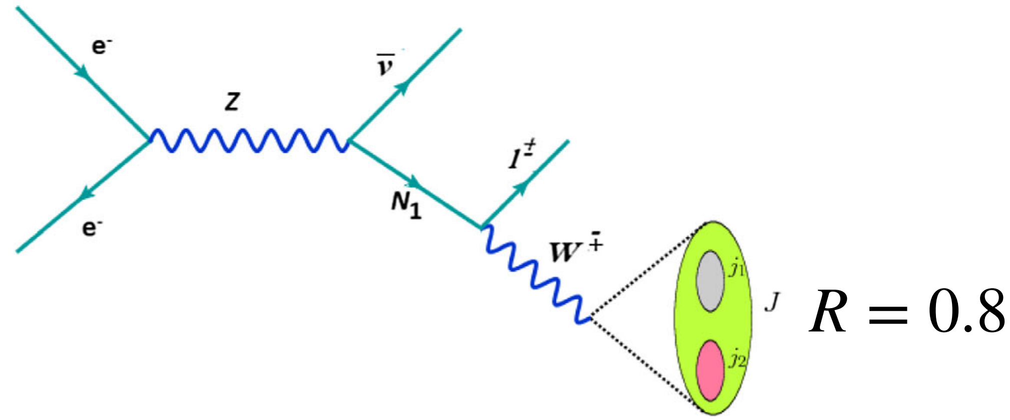
1 TeV e^-e^+ collider

- 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.

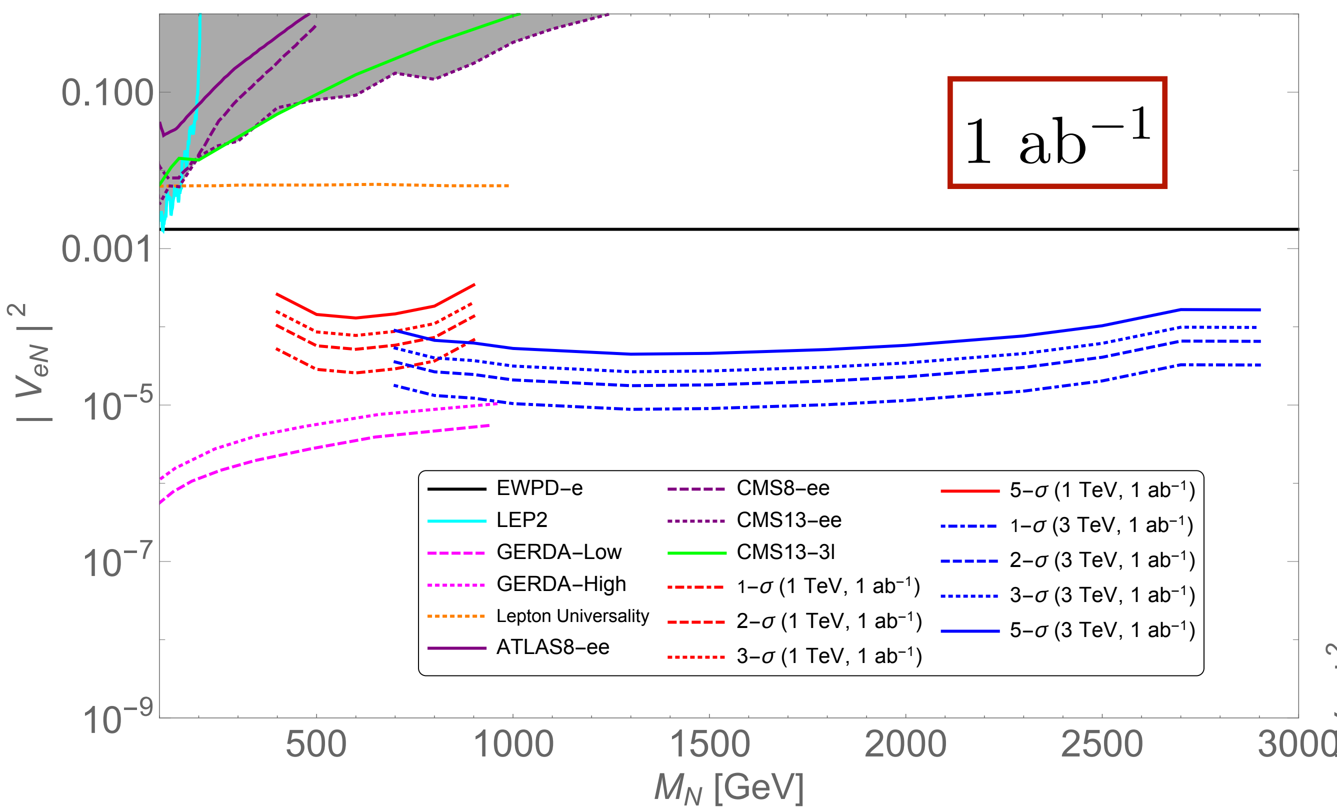
3 TeV e^-e^+ collider

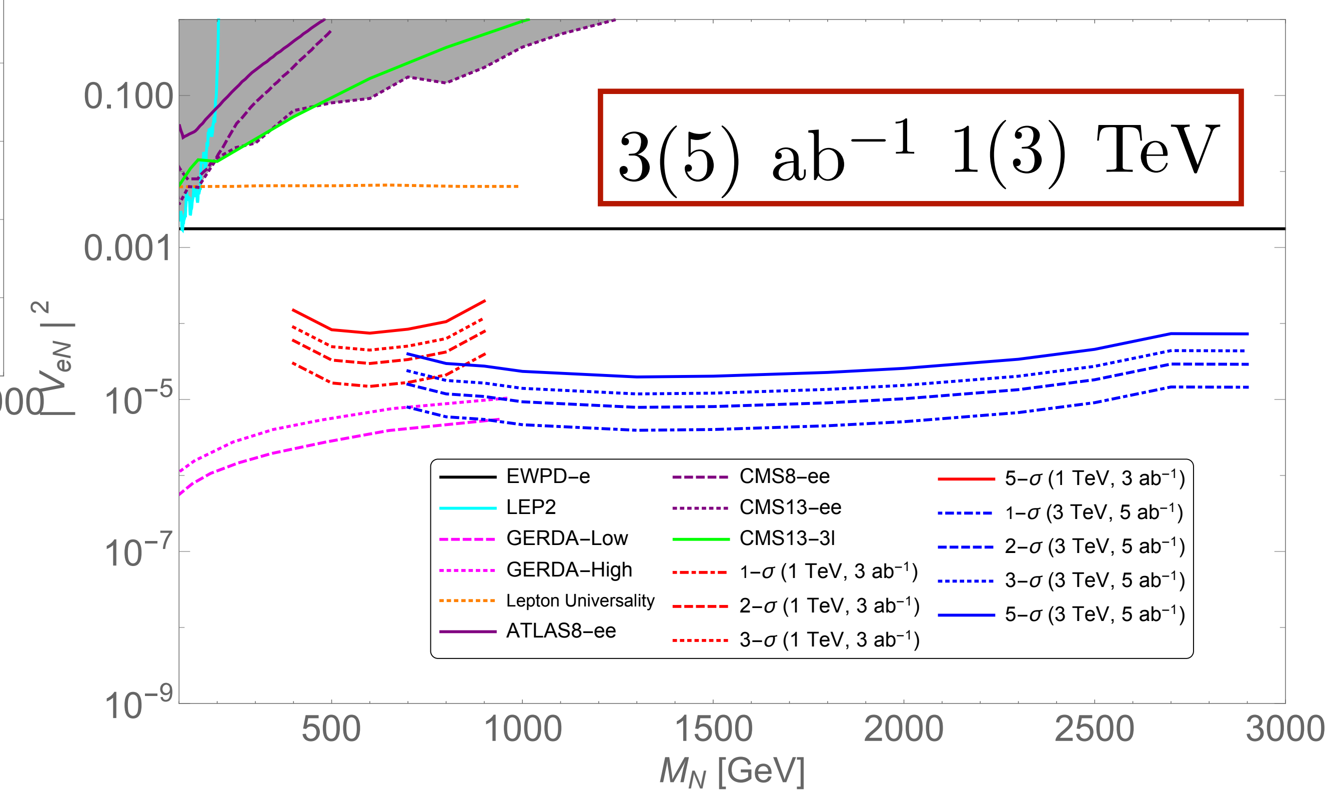
$e + J + p_T^{\rm miss}$ final states at the linear colliders





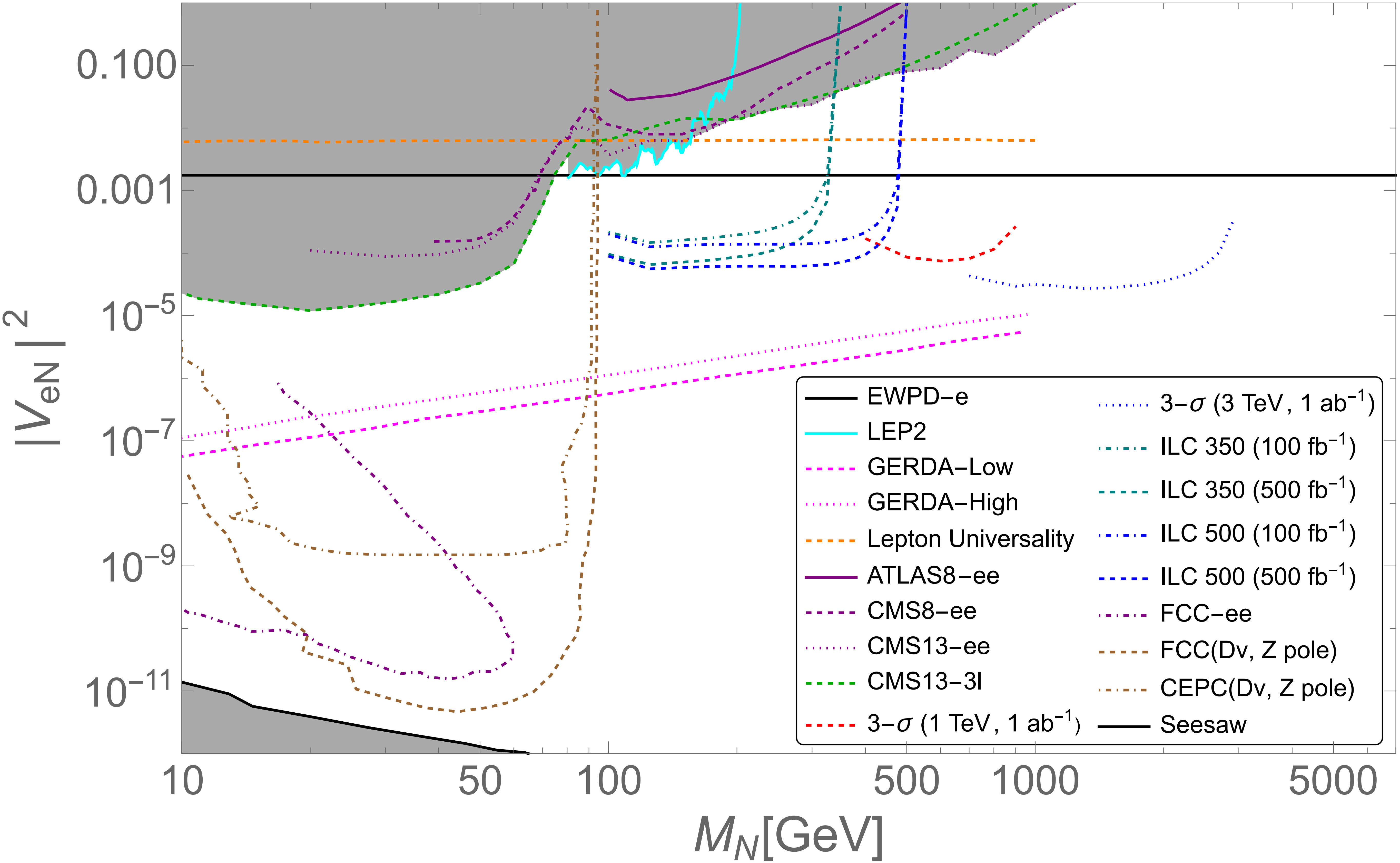
1 TeV (red band) and 3 TeV (blue band)





Existing and prospective bounds on $|V_{eN}|^2$

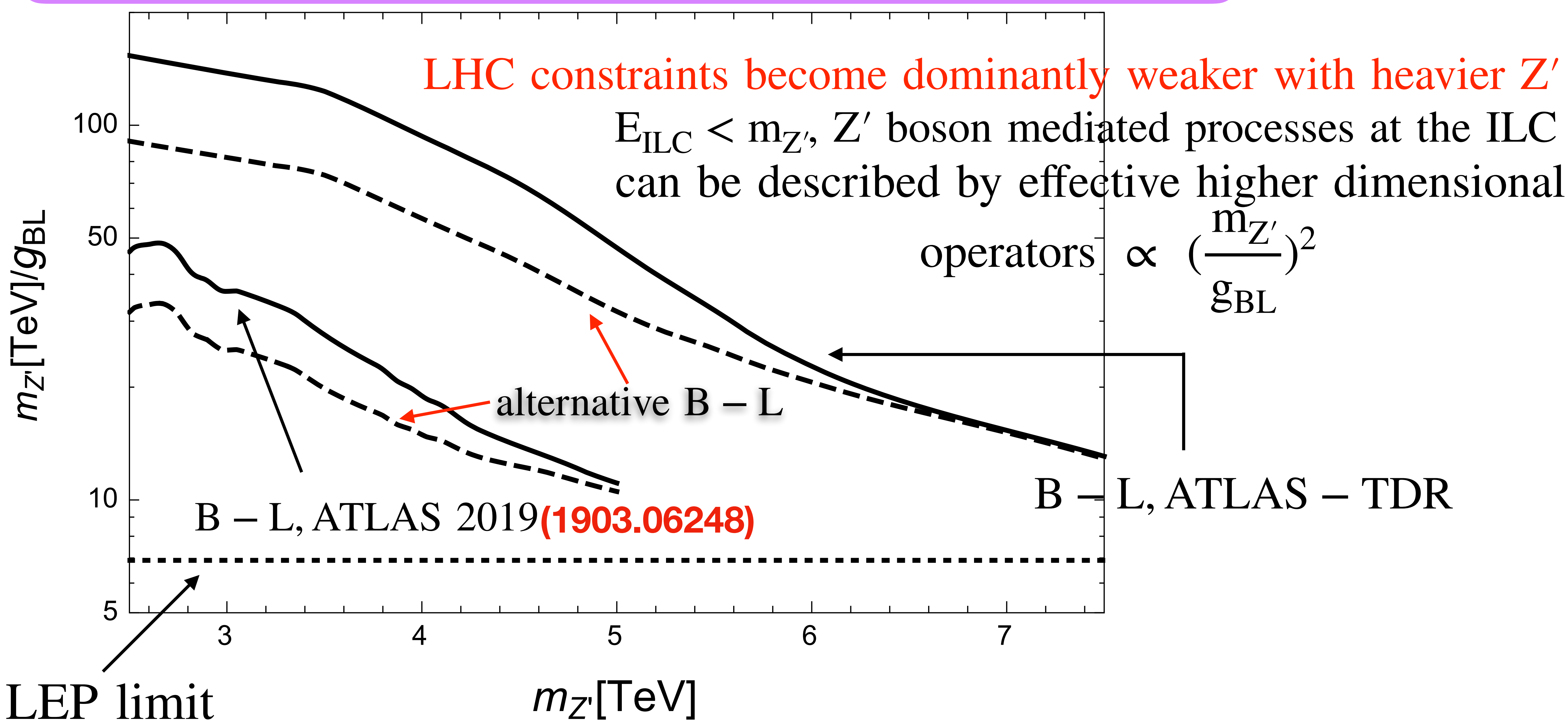
(Incomplete)



References : 1512.06035, 1604.02420, 1612.02728, 1702.04668, 1810.08970

Production of the heavy neutrino pair at the ILC from Z′

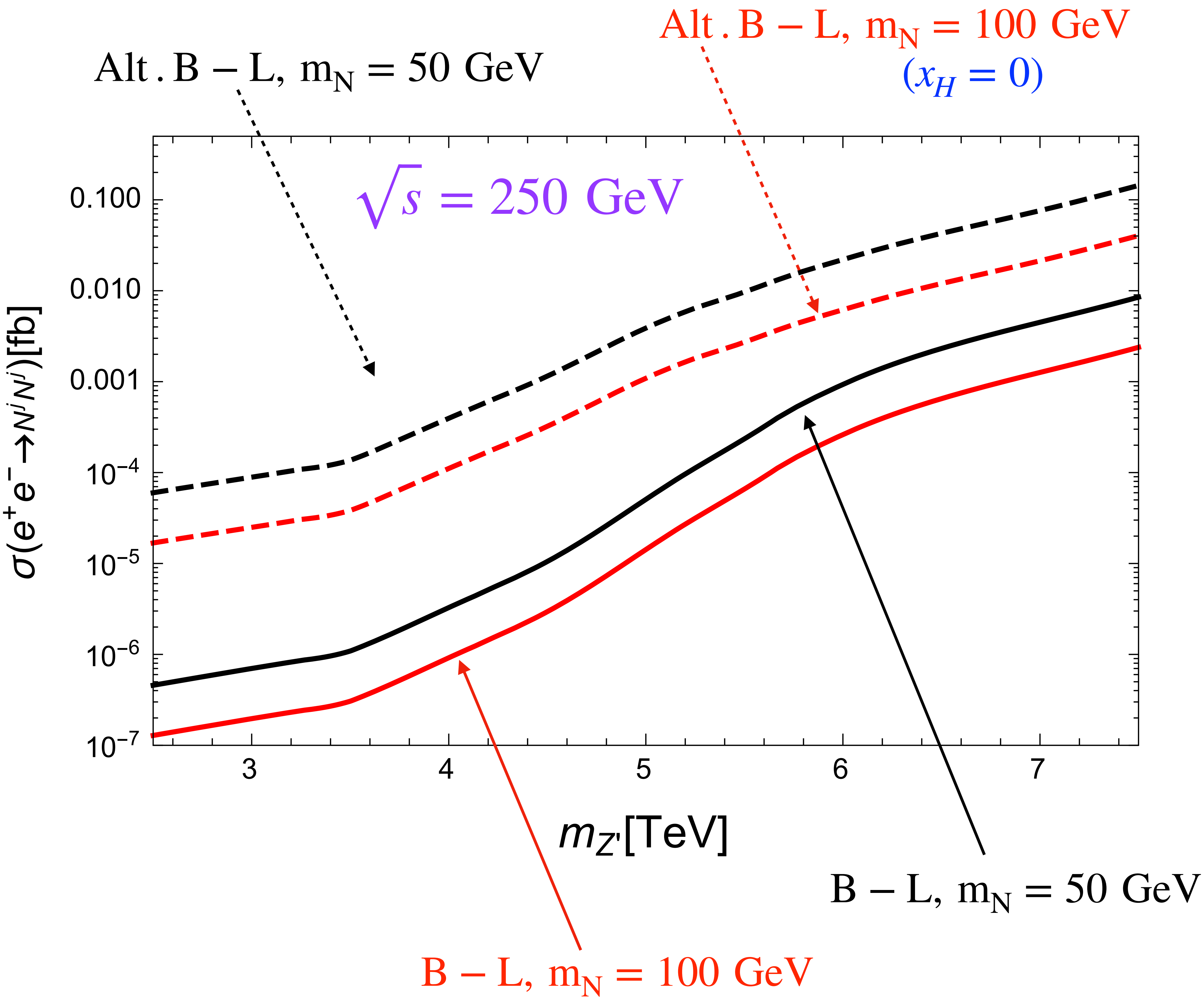
1812.11931



Dashed lines represent the Atl. B – L case

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

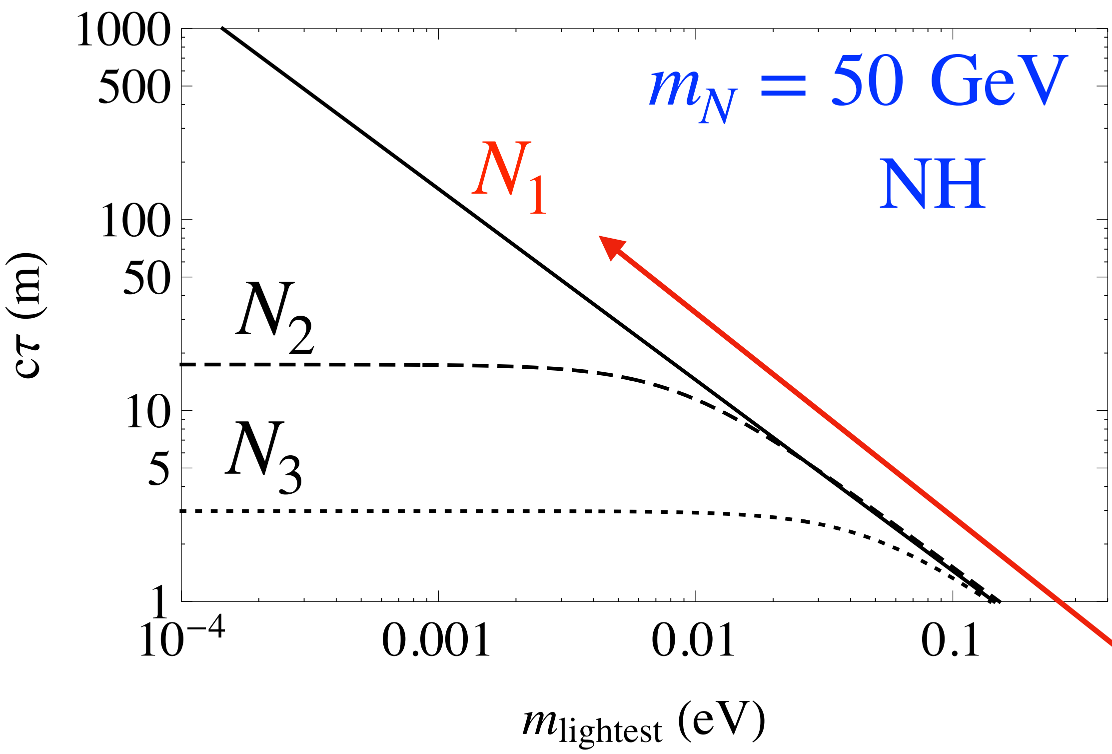
$$\sigma(e^+e^- \to Z'^* \to N^i N^i) \simeq \frac{(Q_{N^i})^2}{24\pi} s \left(\frac{g_{BL}}{m_{Z'}}\right)^4 \left(1 - \frac{4m_{N^i}^2}{m_{Z'}^2}\right)^{\frac{3}{2}}.$$

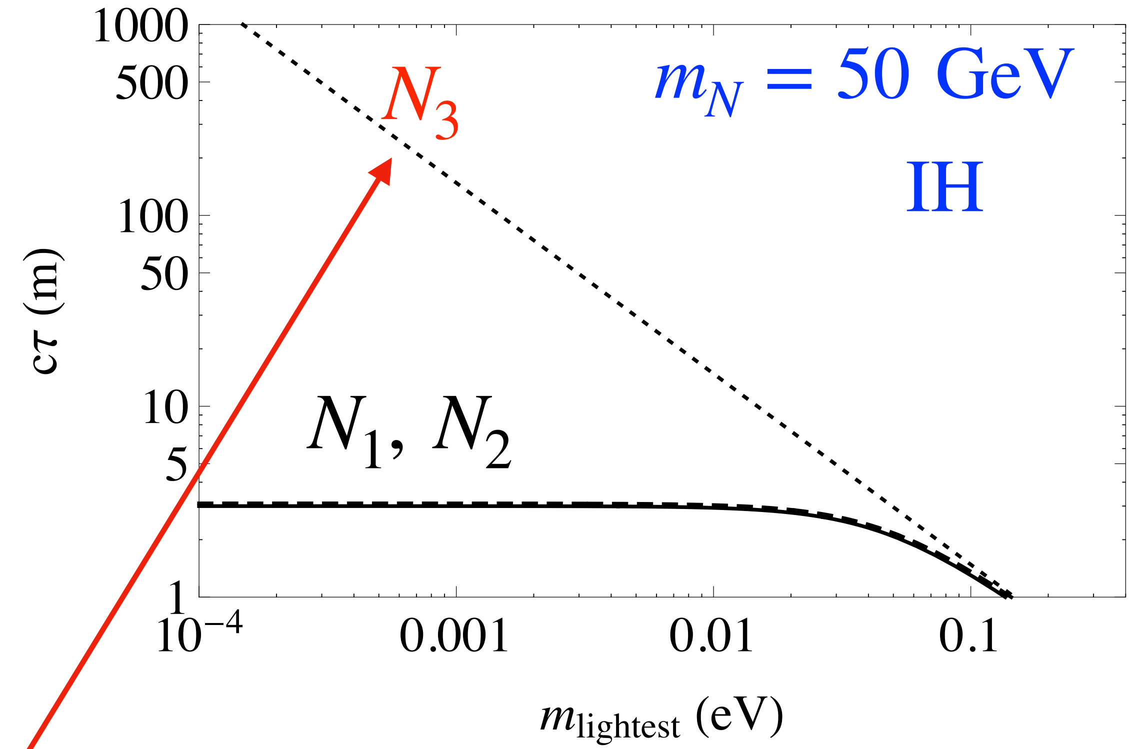


Alt . B − L, m_N = 50 GeV
Alt . B − L, m_N = 100 GeV
(x_H = 0)
√s = 250 GeV
0.100
0.010
0.001
10^−4
10^−5
10^−6
10^−7
σ(e^+e^−→N^iN^i)[fb]
3
4
5
6
7
m_Z'[TeV]
B − L, m_N = 50 GeV
B − L, m_N = 100 GeV

Long lived RHNs 1812.11931

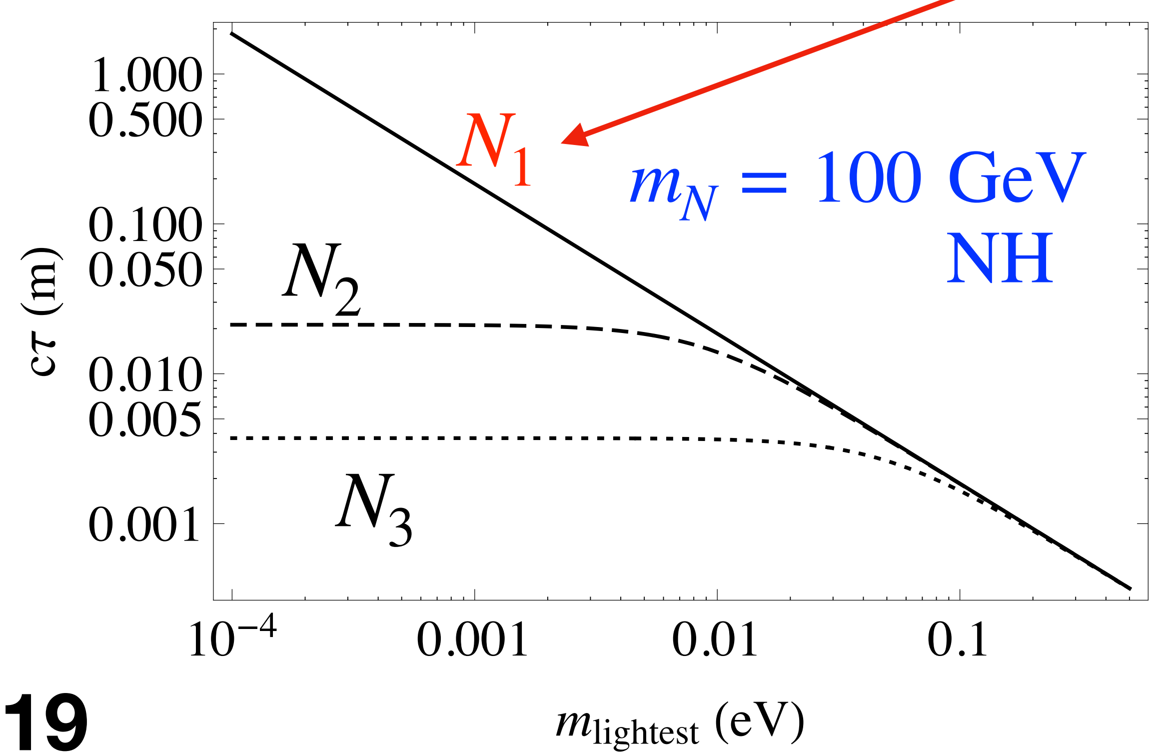
B − L case, $x_H = 0$

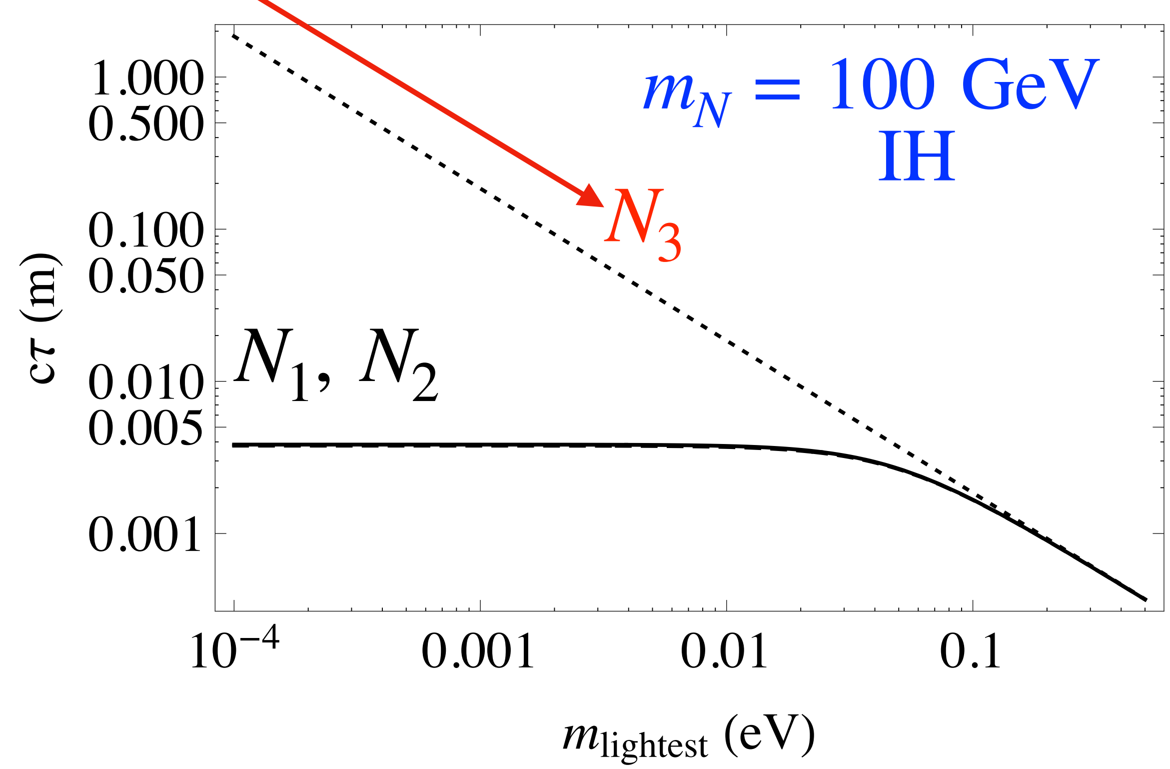




Longest lived RHN life time is inversely proportional to m_{lightest}

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





Type – III seesaw

SM + $SU(2)_L$ triplet fermion

Franceschini, Hambye, Strumia Biggio, Bonnet
Biggio, Fernandez Martinez, Hernandez Garcia, Lopez Pavon
AD, Mandal, Modak 2005.02267 AD, Mandal 2006.04123

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

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

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

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

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

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

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

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

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

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

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

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

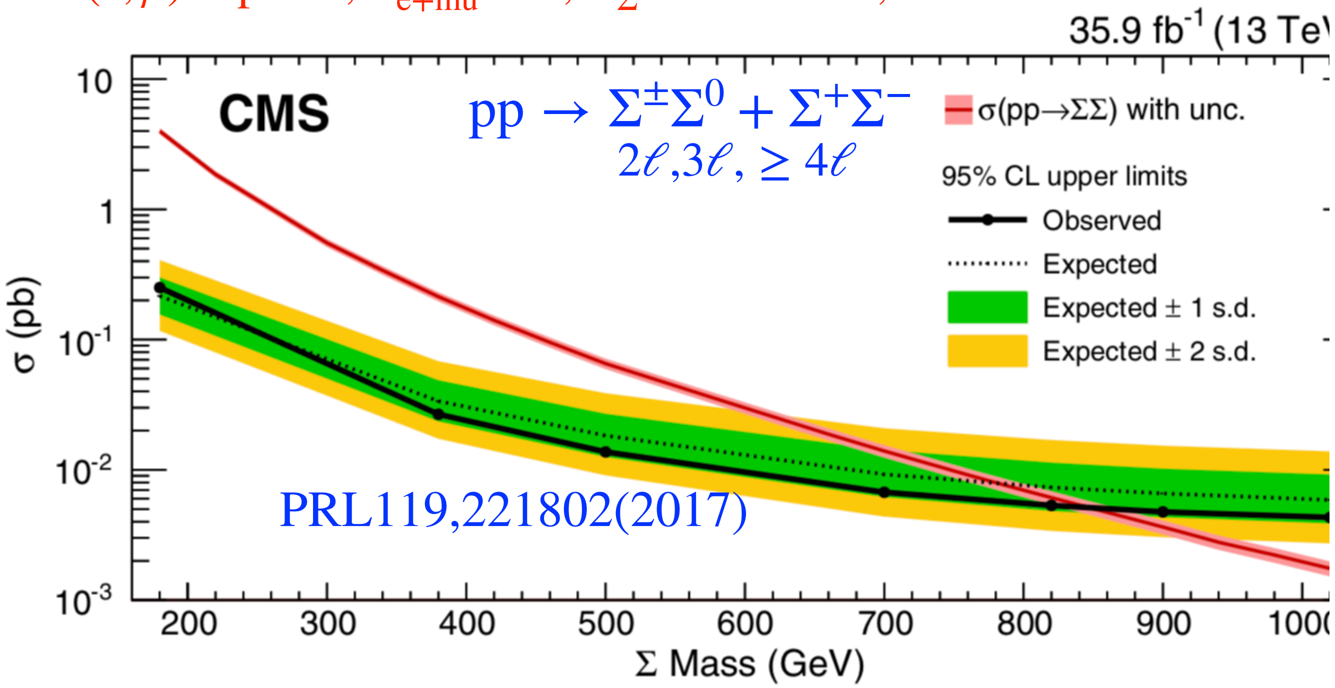
$$\Gamma(\Sigma^0 \to \nu h) = \Gamma(\Sigma^0 \to \overline{\nu} h) = \frac{g^2|V_{\ell\Sigma}|^2}{128\pi}\left(\frac{M^3}{M_W^2}\right)\left(1 - \frac{M_h^2}{M^2}\right)^2,$$

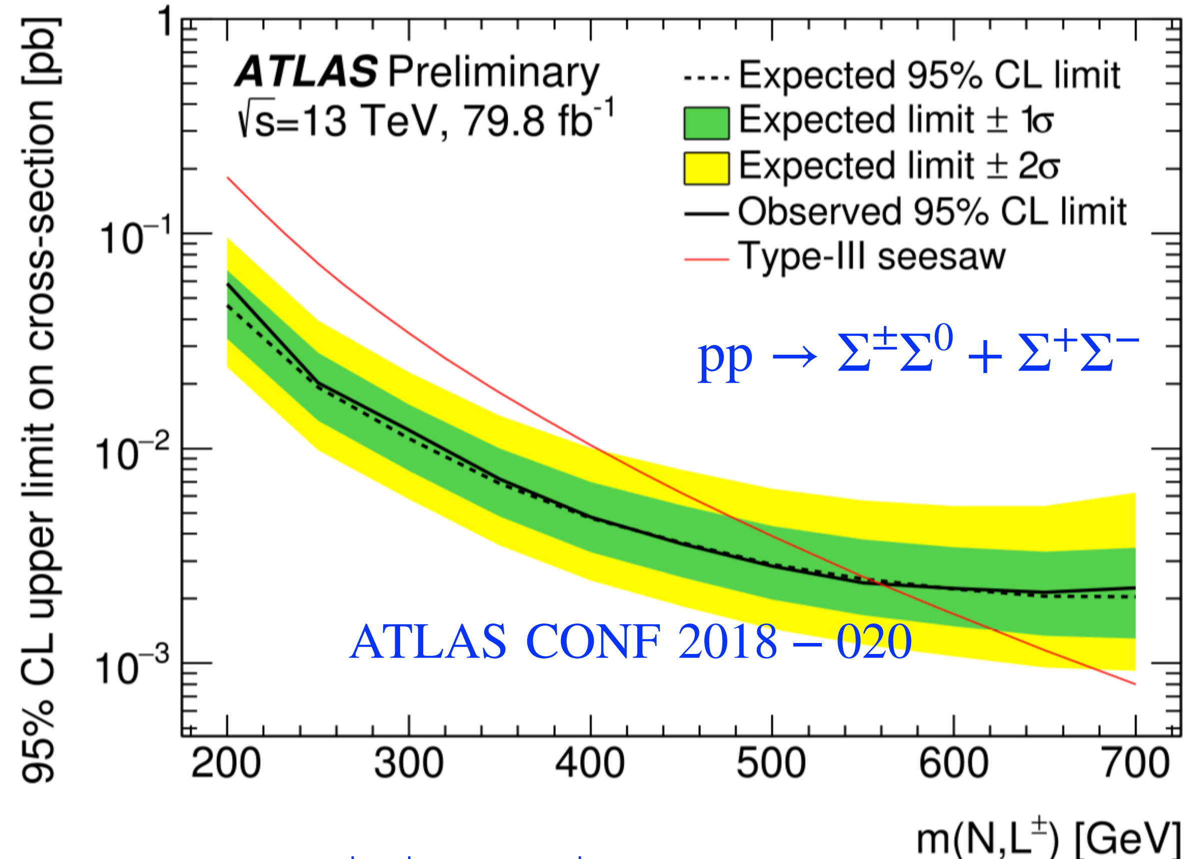
LHC limits

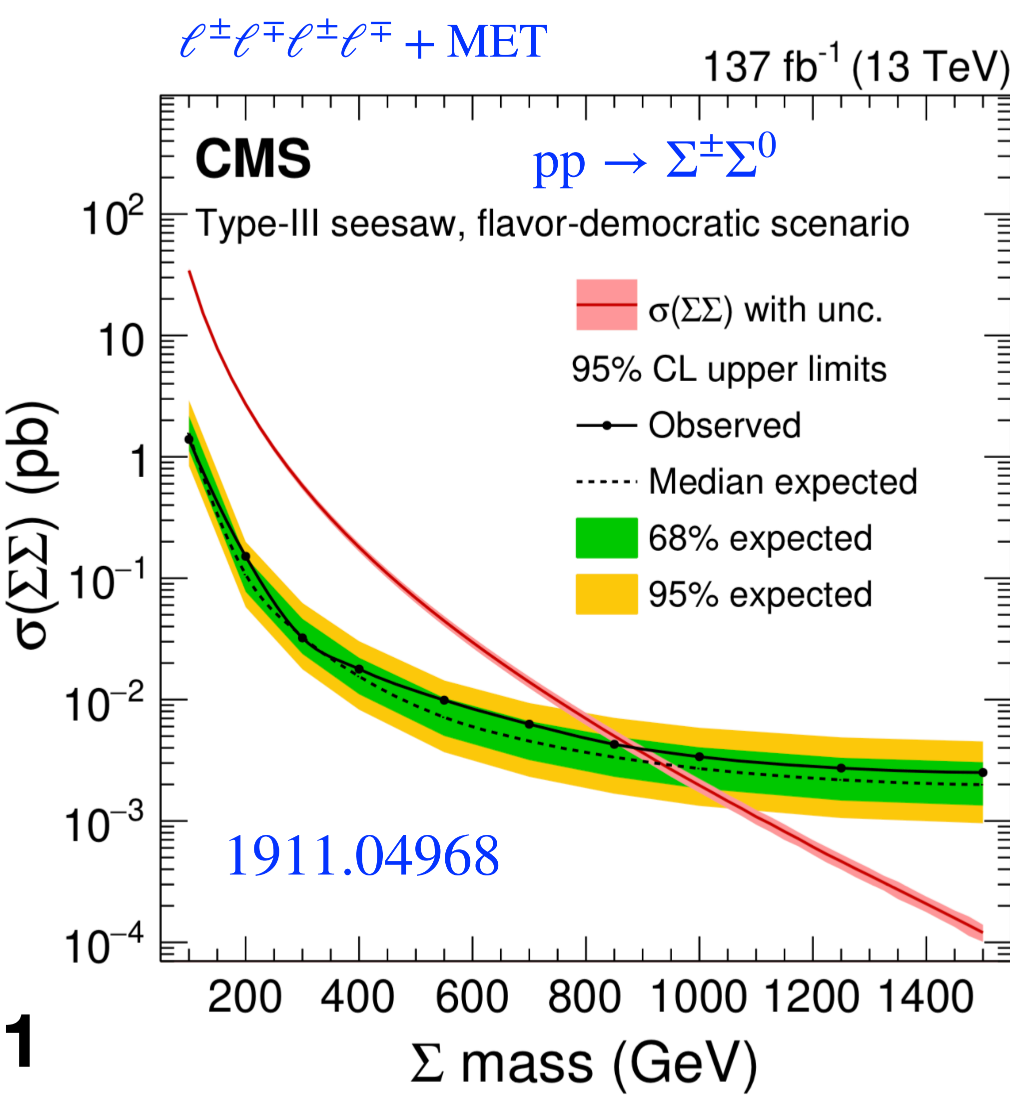
$$BR = B_\ell \propto \frac{|V_\ell|^2}{|V_e|^2 + |V_\mu|^2 + |V_\tau|^2} \quad B_e = B_\mu = B_\tau$$

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

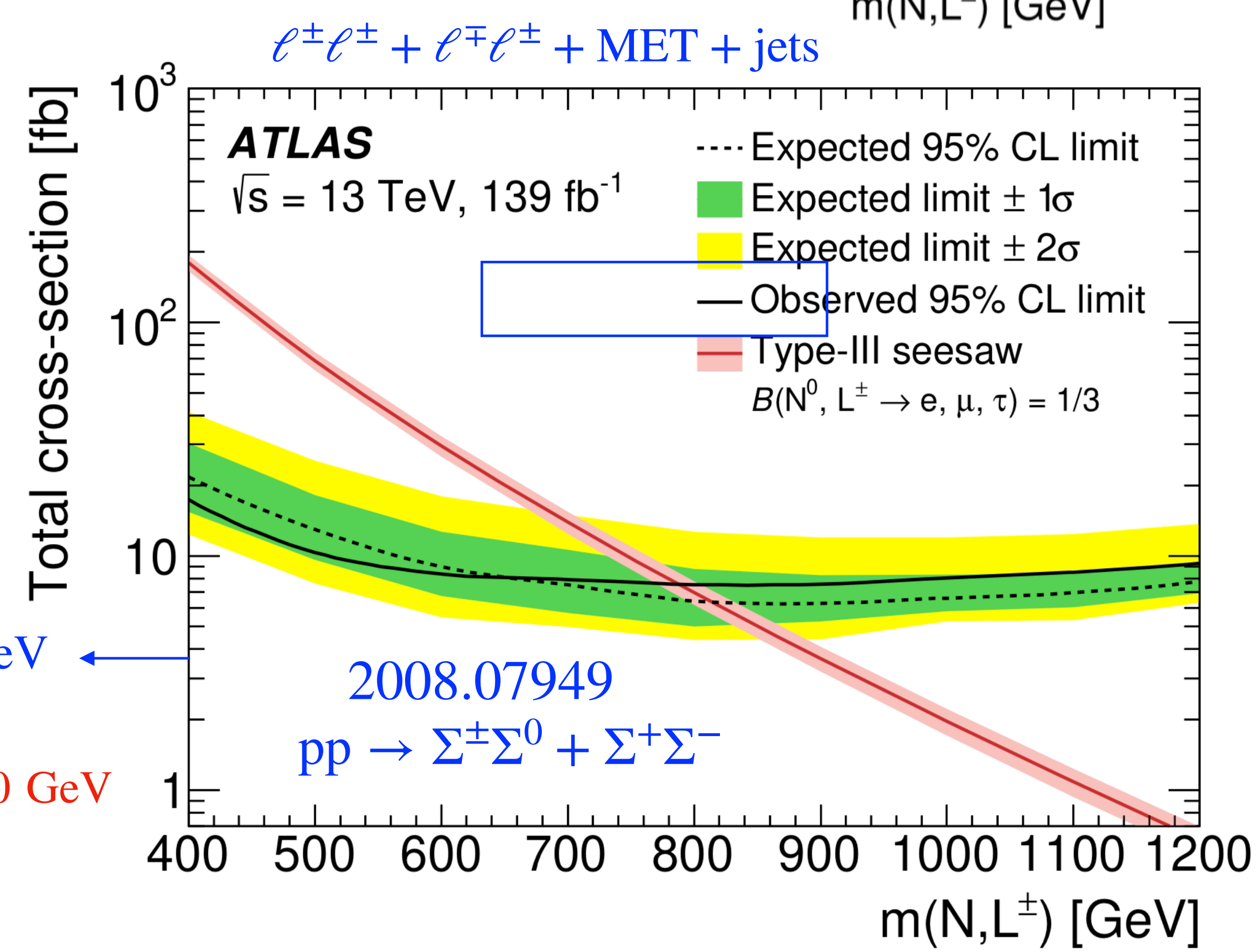




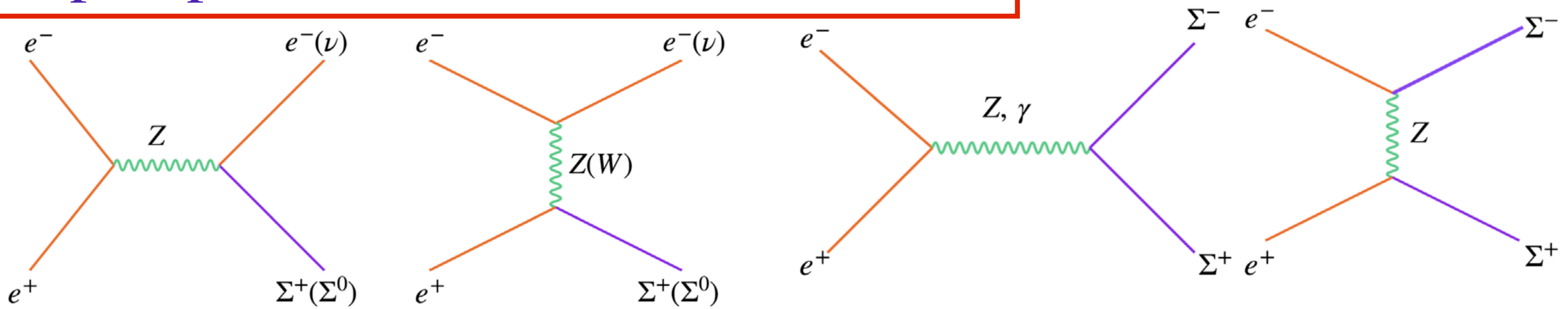


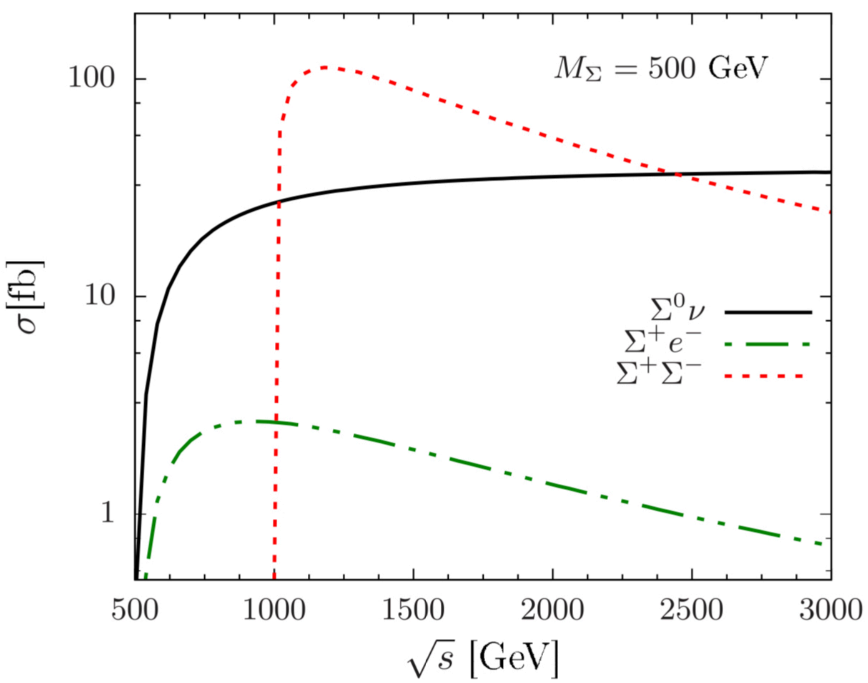
$M_\Sigma \leq 800$ GeV

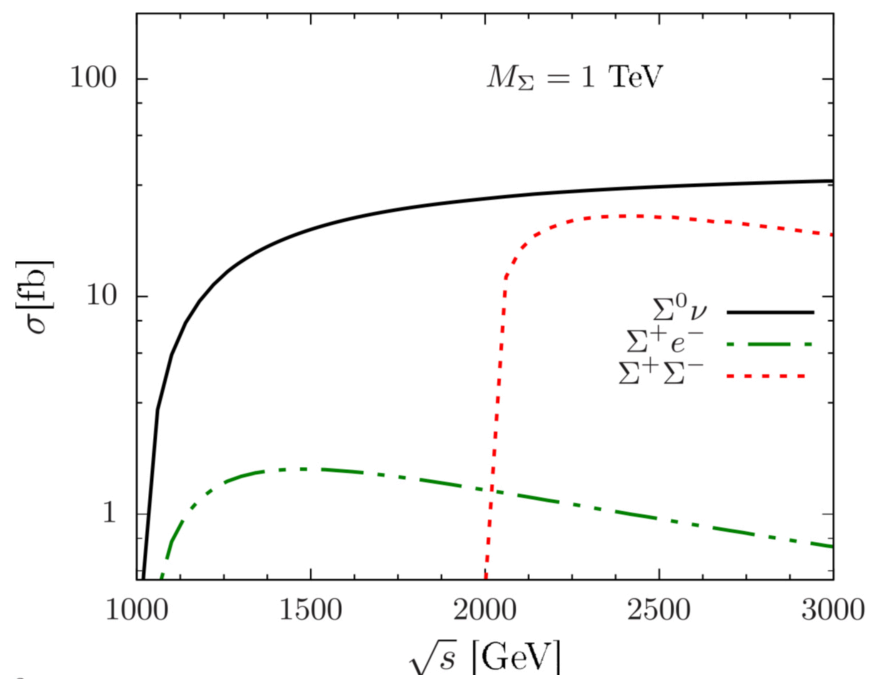
$M_\Sigma \leq 900$ GeV

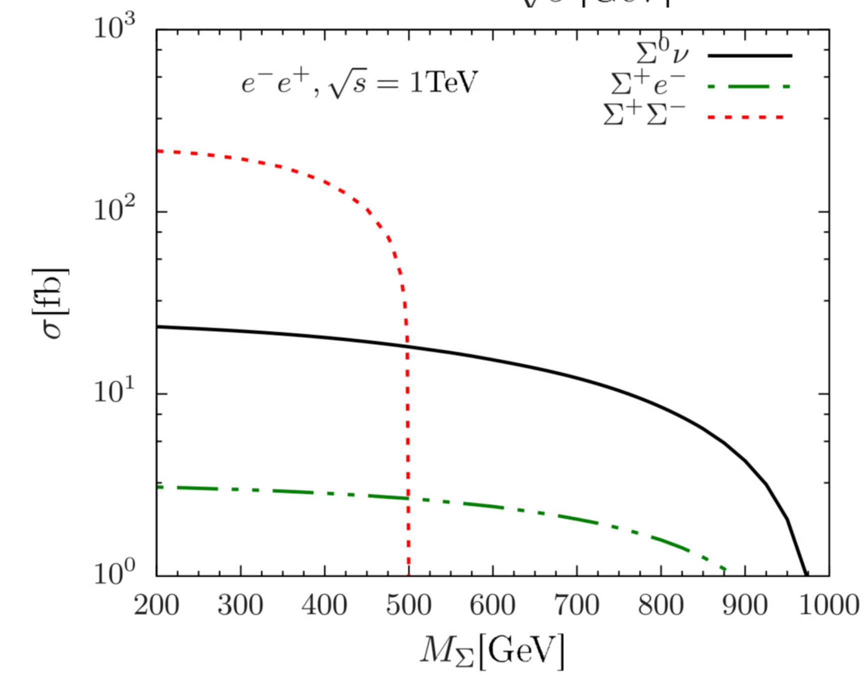


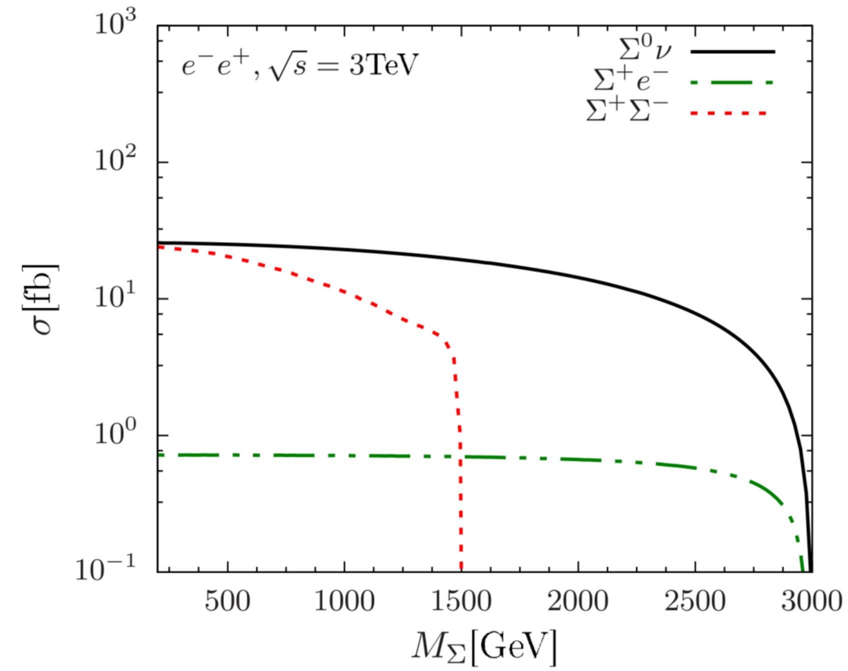
Triplet production at the e^-e^+ collider





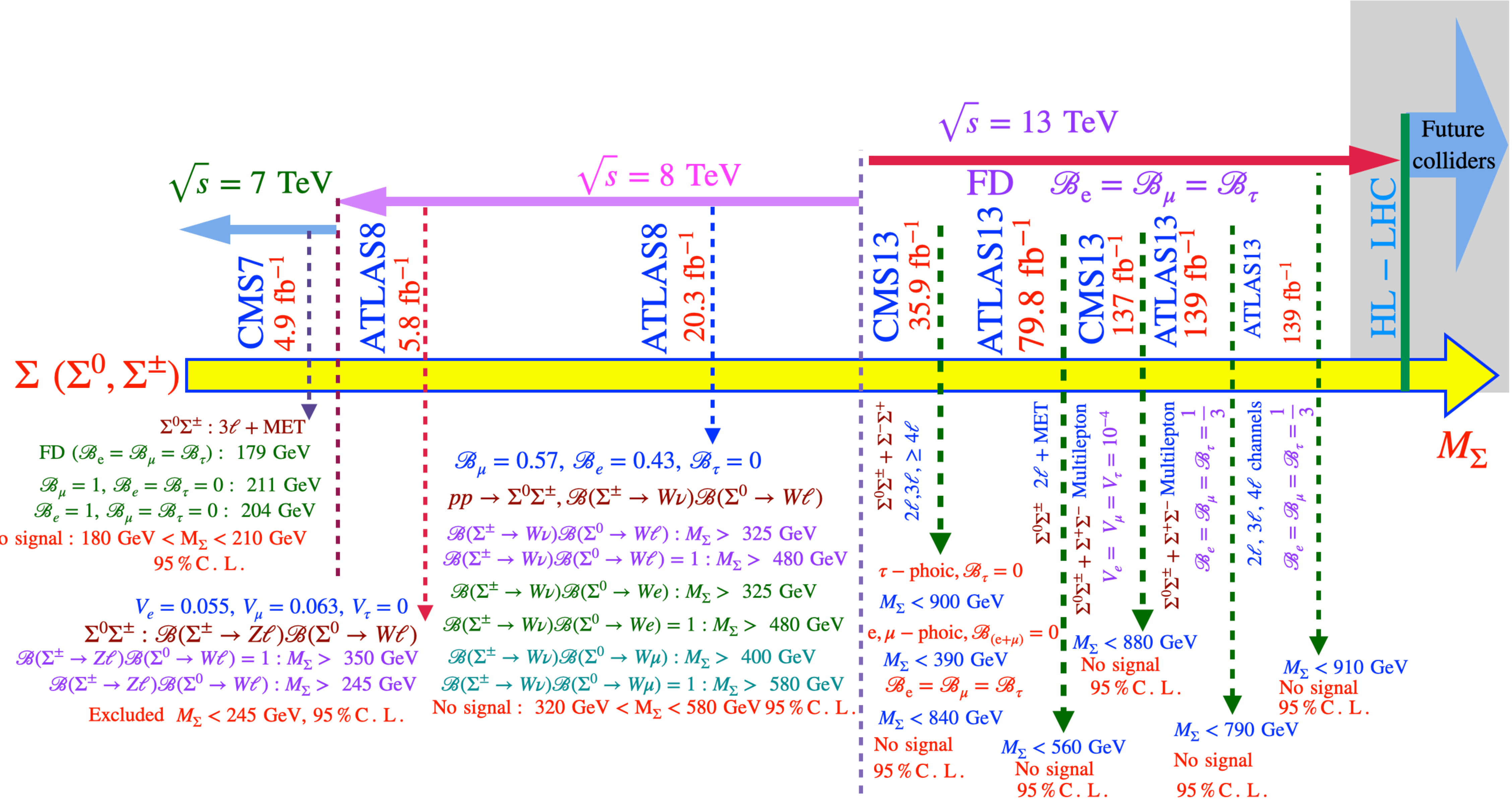


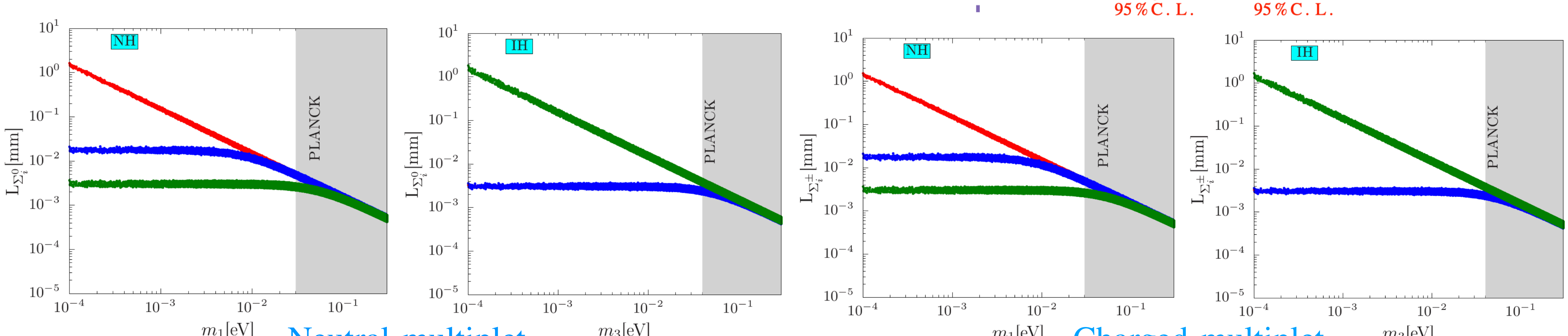




Experimental limits from ATLAS and CMS on type − III seesaw

2006.04123



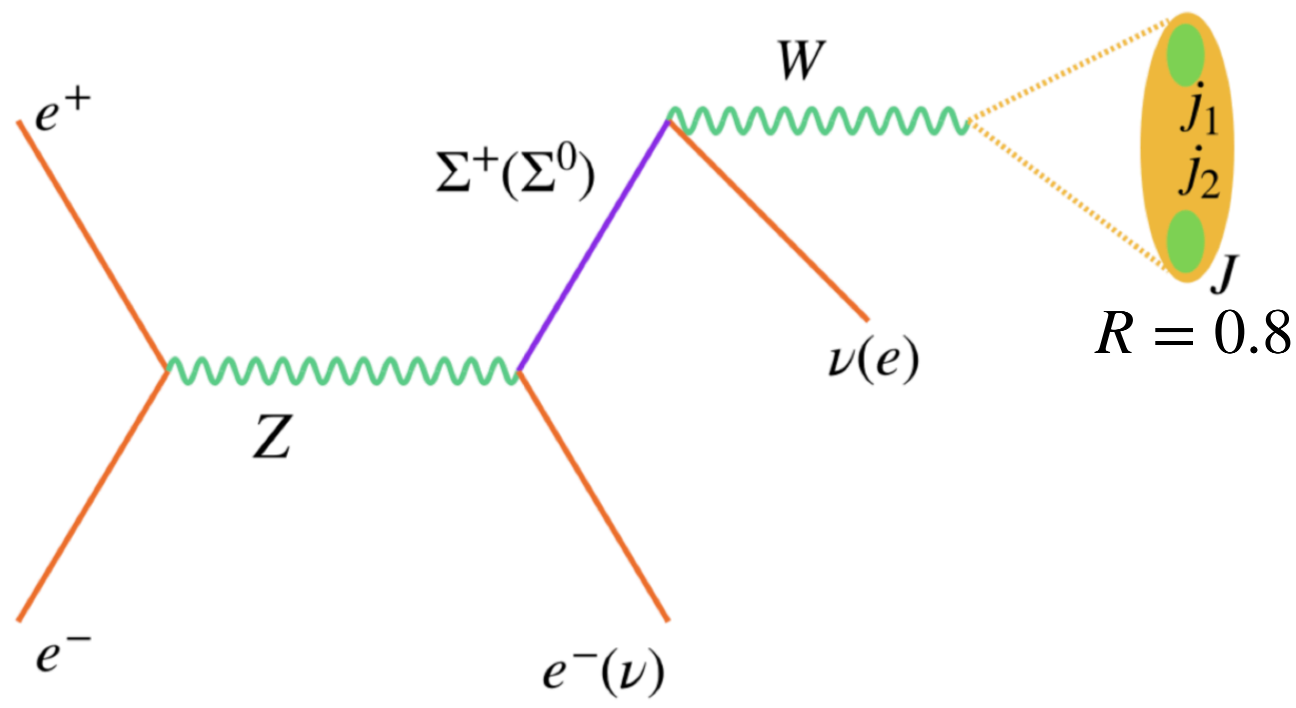


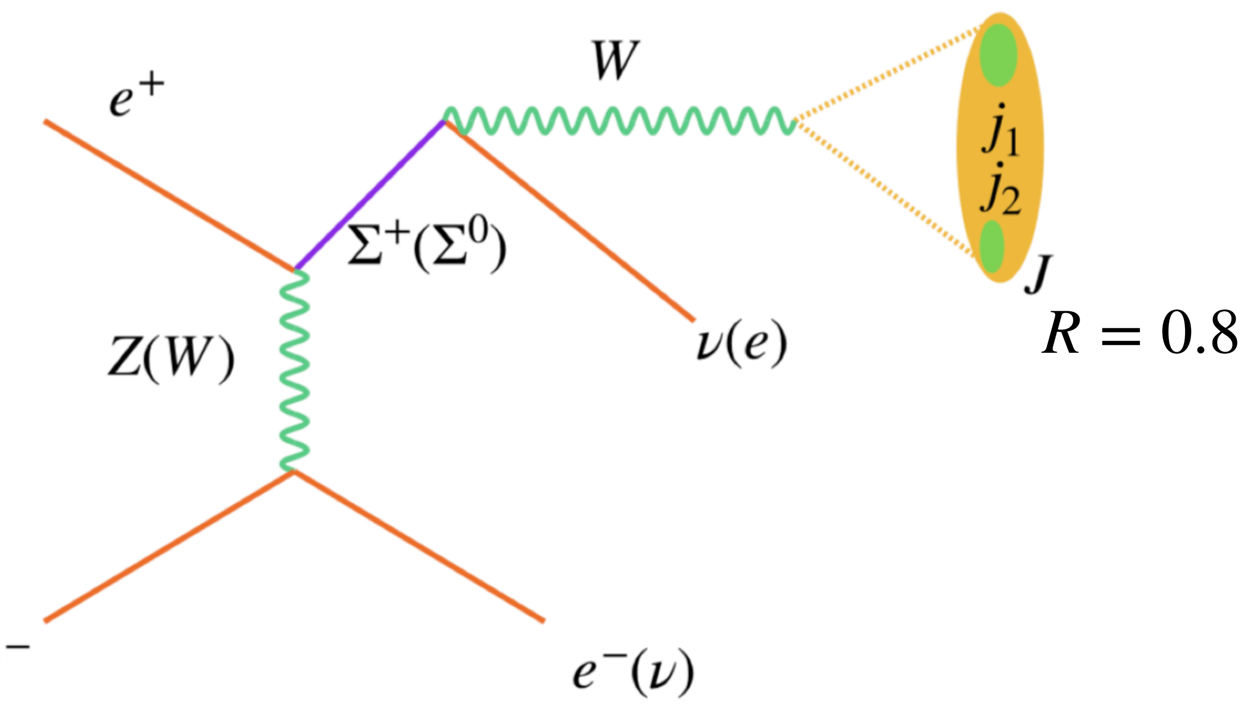
Neutral multiplet Charged multiplet

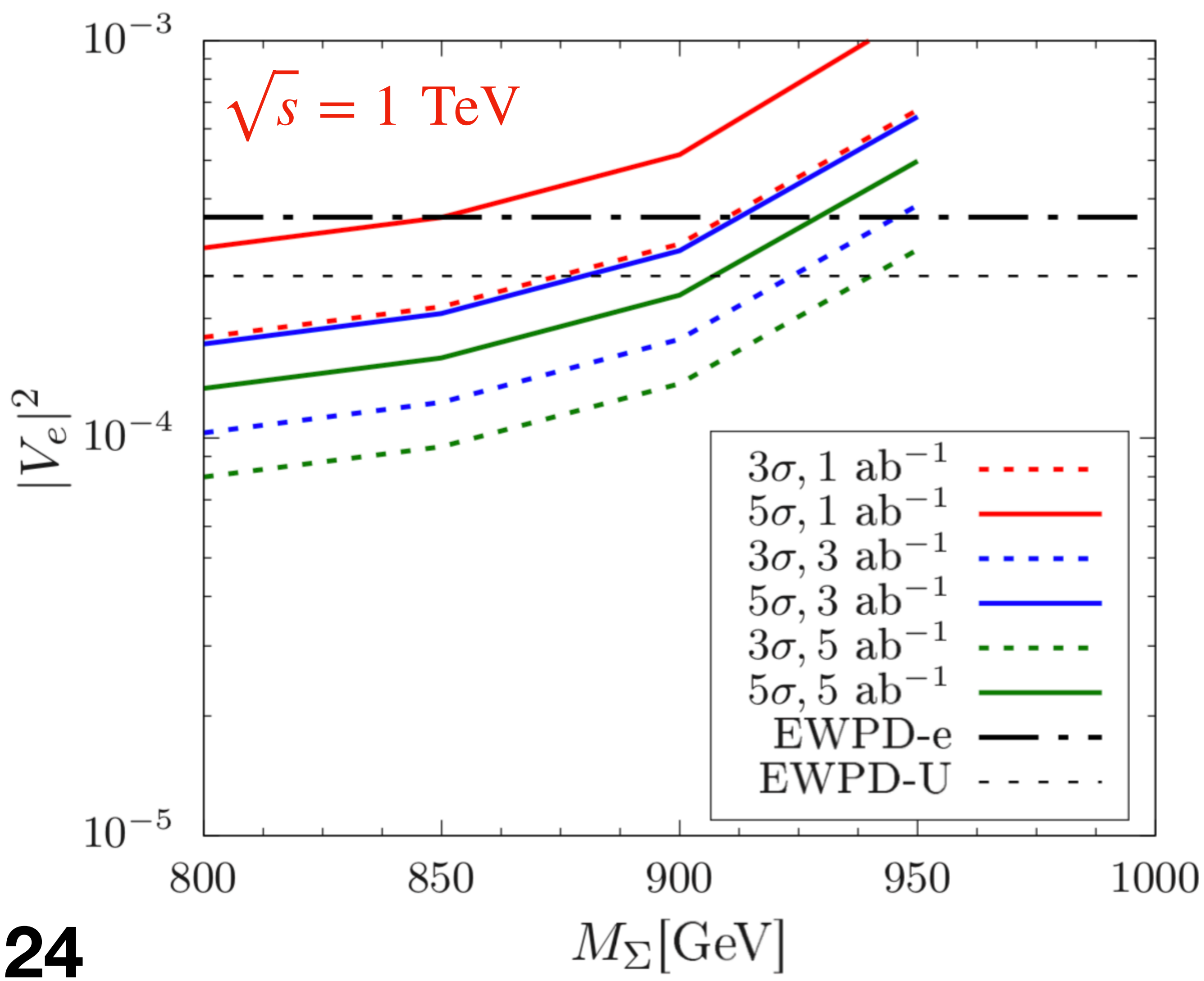
Lower in m_{lightest} increases L by (1 − 2) oreders of magnitude upto a steady value.

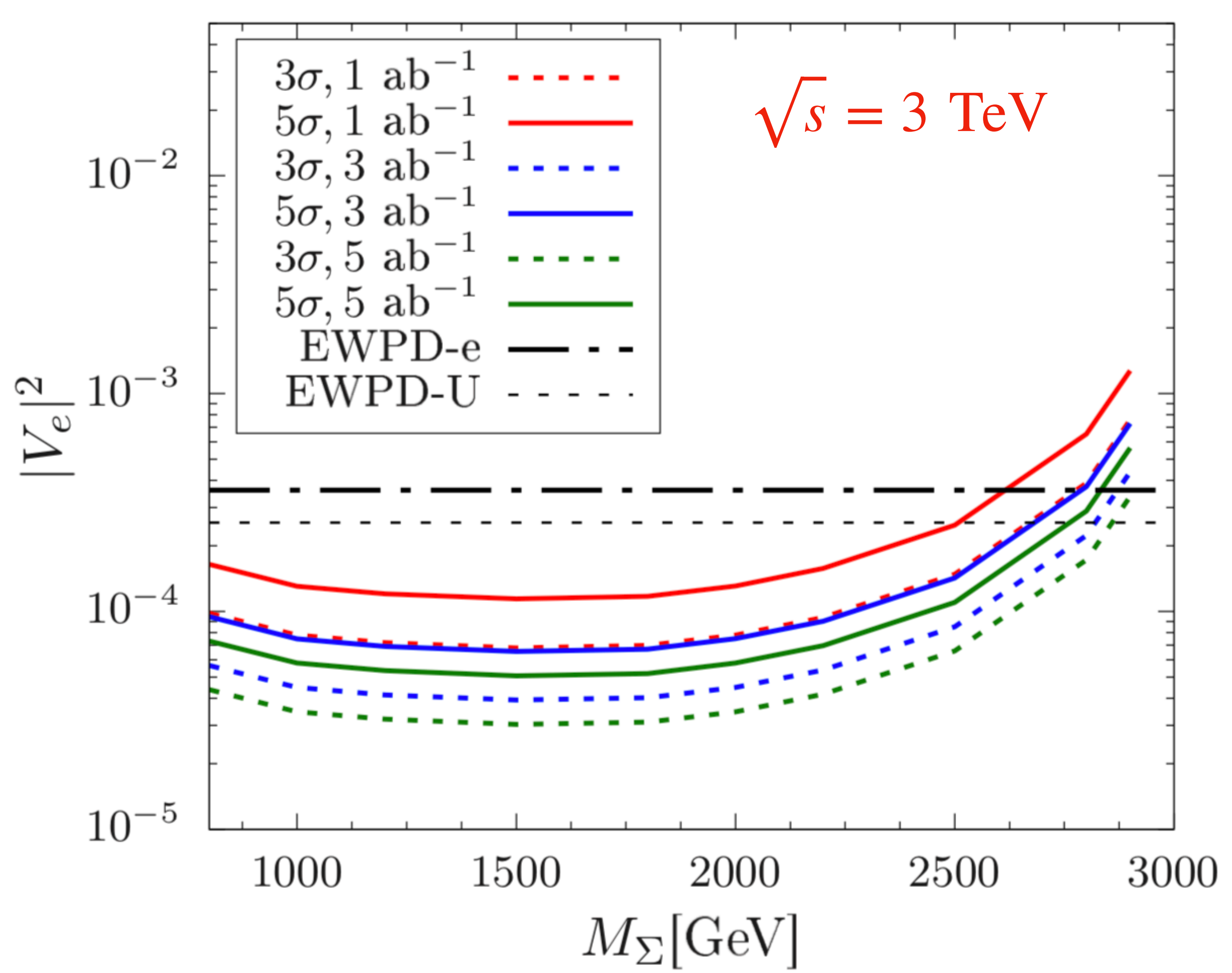
Mass-mixing limit plots

2005.02267









Other interesting aspects at the ILC

Type – II scenario : SM + SU(2) triplet scalat : Charged scalar

1206.6278, 1811.03476, 1803.00677

Left – Right Seesaw using Beam Polarization at an e^+e^- Collider : 1701.08751 W_R

Seesaw mechanism at the 250 GeV ILC : 1812.11931 Z'

1. Test of BSM gauge mediated processes

   Asymmetries

2. Pair – production of heavy neutrinos

   Prompt, Displaced/ LLP study

   Effect of polarization

3. Beam dump, Forward Physics Facility

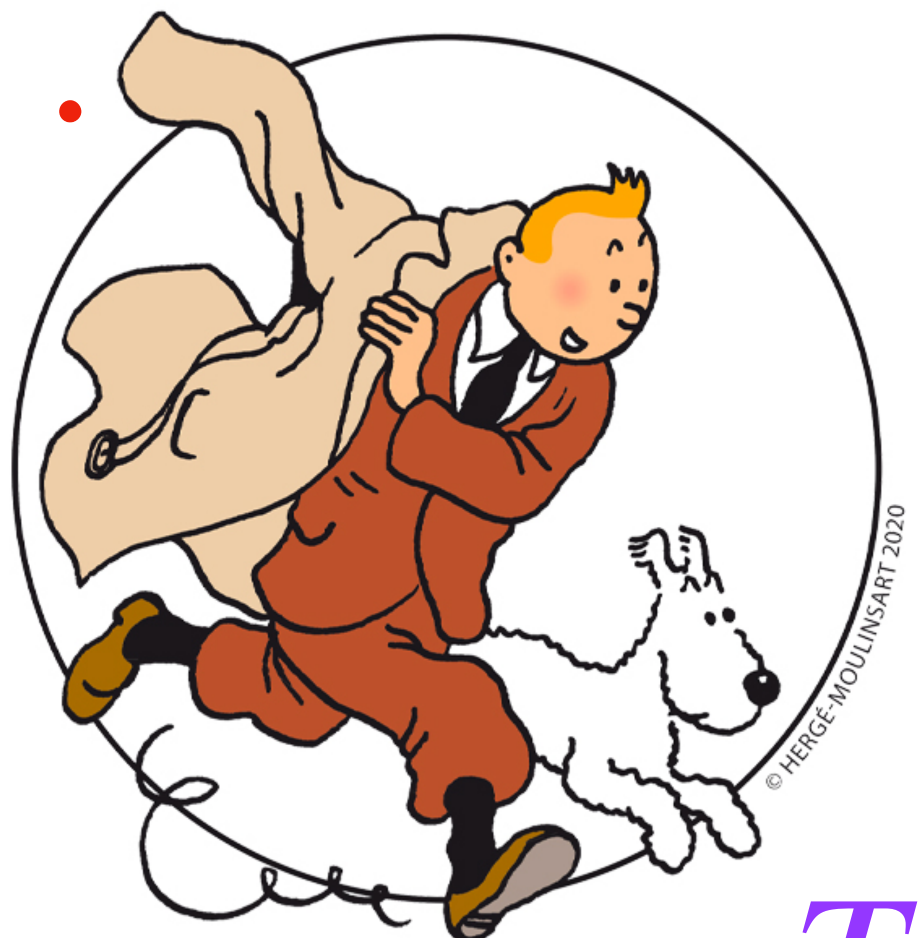
4. BSM scalar : Light/ Heavy, mixing with SM scalar

5. Prospect of e – γ scattering

Summary

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

Stay tuned . . .



Thank You

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