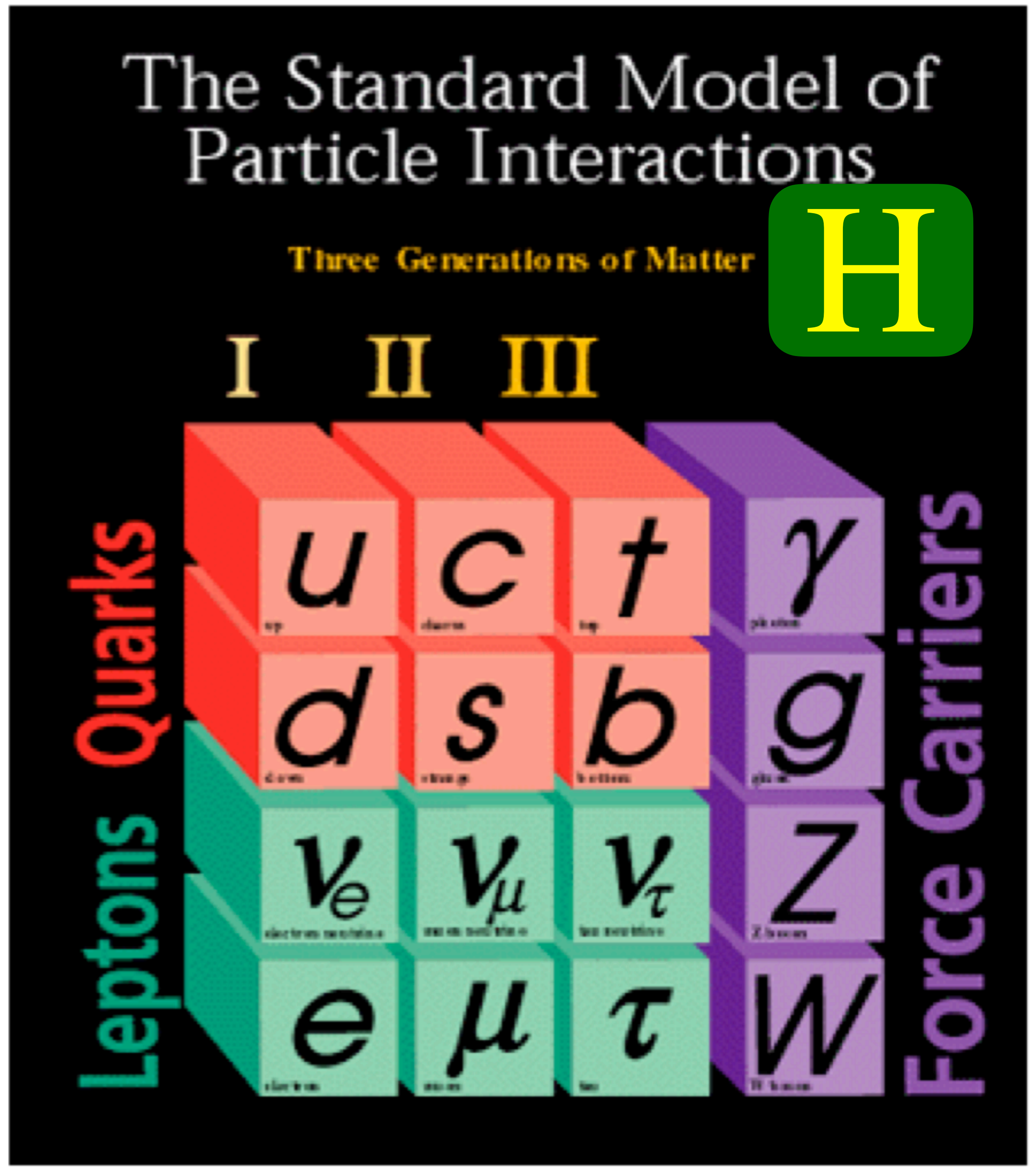
Searching for heavy neutral leptons in eleectron positron colliders

LCWS2024 July 9, 2024
The University of Tokyo

Arindam Das
Hokkaido University

Introduction



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

Birth of a new idea : generation of neutrino mass

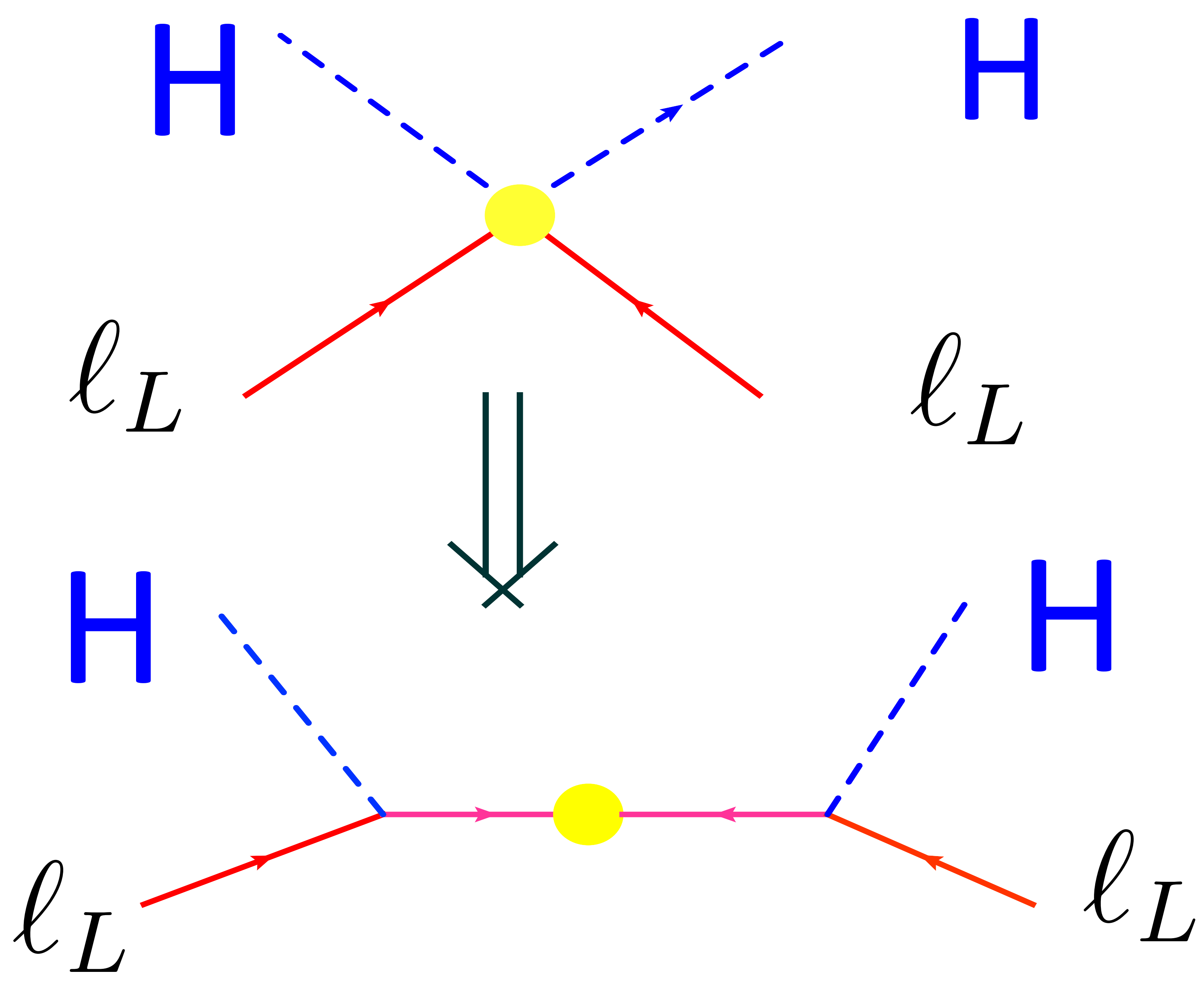
Weinberg Operator in SM (d=5), PRL 43, 1566(1979)

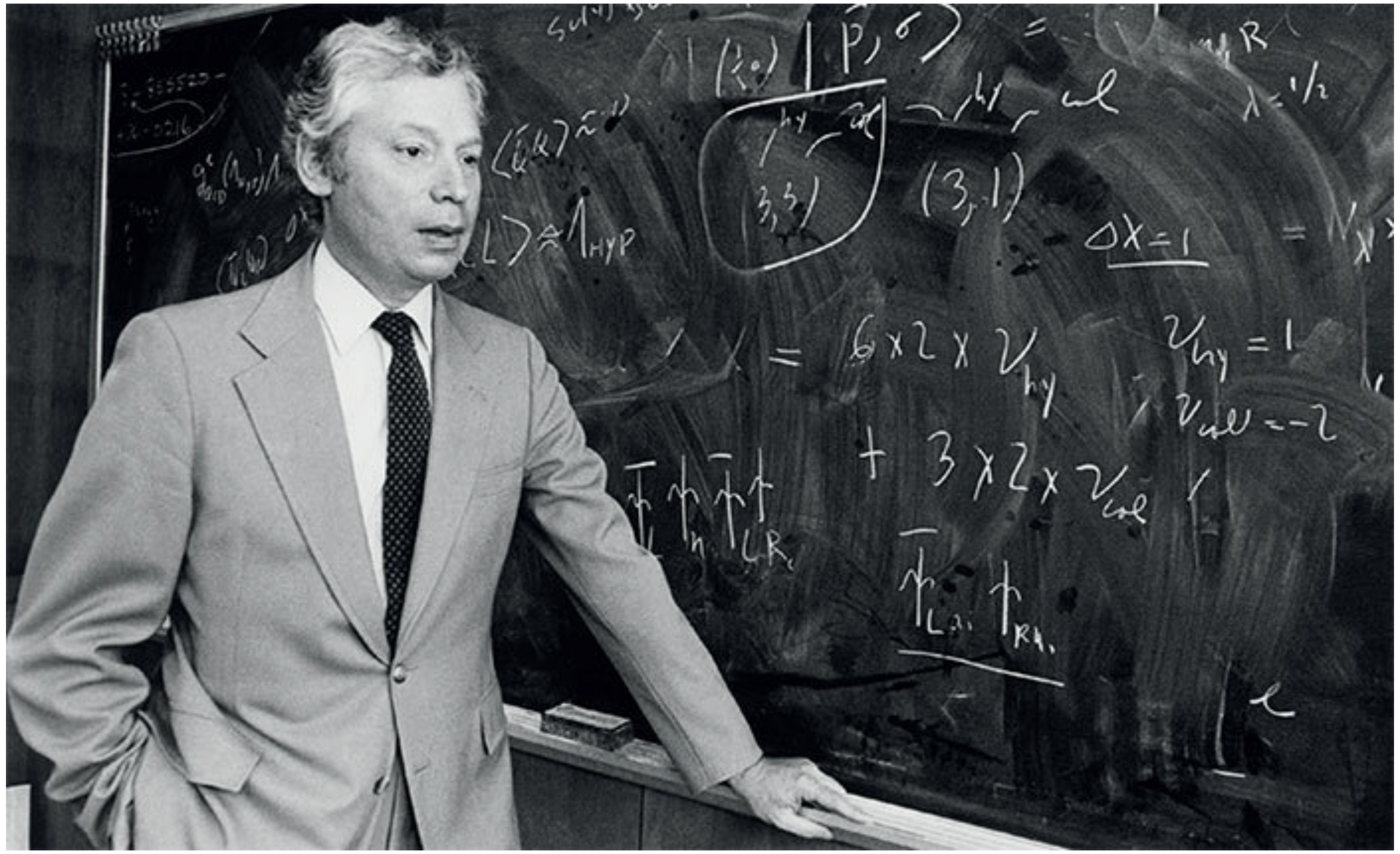
$$\frac{\overline{\ell_L} H \overline{\ell_L^c}^T H}{M}$$

within the Standard Model

Steven Weinberg : 1933 – 2021

The dimension 5 operator can be realized in the following ways





Majorana mass term is generated by the breaking of the lepton numbers by 2 units.


Scenarios
Neutrino mass
Tree level
SM + Particles
Gauge extension
Singlet, triplet fermions
Triplet scalars
Left – right
general U(1)
Seesaw, inverse seesaw
I, II, III
Quantum level
I, II, III . . .
Higher dimensional operators

Particle content

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

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

$$m_D^{ij} = \frac{Y_D^{ij}}{\sqrt{2}} v_h$$

$$m_{N^i} = \frac{Y_N^i}{\sqrt{2}} v_\Phi$$

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

Seesaw mechnism

Z' interactions

Interaction between the quarks and Z' $$\mathcal{L}^q = -g'(\overline{q}\gamma_\mu q^q_{x_L} P_L q + \overline{q}\gamma_\mu q^q_{x_R} P_R q) Z'_\mu$$

Interaction between the leptons and Z' $$\mathcal{L}^\ell = -g'(\overline{\ell}\gamma_\mu q^\ell_{x_L} P_L \ell + \overline{e}\gamma_\mu q^\ell_{x_R} P_R e) Z'_\mu$$

$q^f_{x_L} \neq q^f_{x_R}$ affects the phenomenology

Partial decay width

Charged fermions $$\Gamma(Z' \to 2f) = N_c \frac{M_{Z'}}{24\pi} \left(g^f_L\Big[g', x_H, x_\Phi\Big]^2 + g^f_R\Big[g', x_H, x_\Phi\Big]^2 \right)$$

light neutrinos $$\Gamma(Z' \to 2\nu) = \frac{M_{Z'}}{24\pi}\, g^\nu_L\Big[g', x_H, x_\Phi\Big]^2$$

heavy neutrinos $$\Gamma(Z' \to 2N) = \frac{M_{Z'}}{24\pi}\, g^N_R\Big[g', x_\Phi\Big]^2 \left(1 - 4\frac{m_N^2}{M_{Z'}^2}\right)^{\frac{3}{2}}$$

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

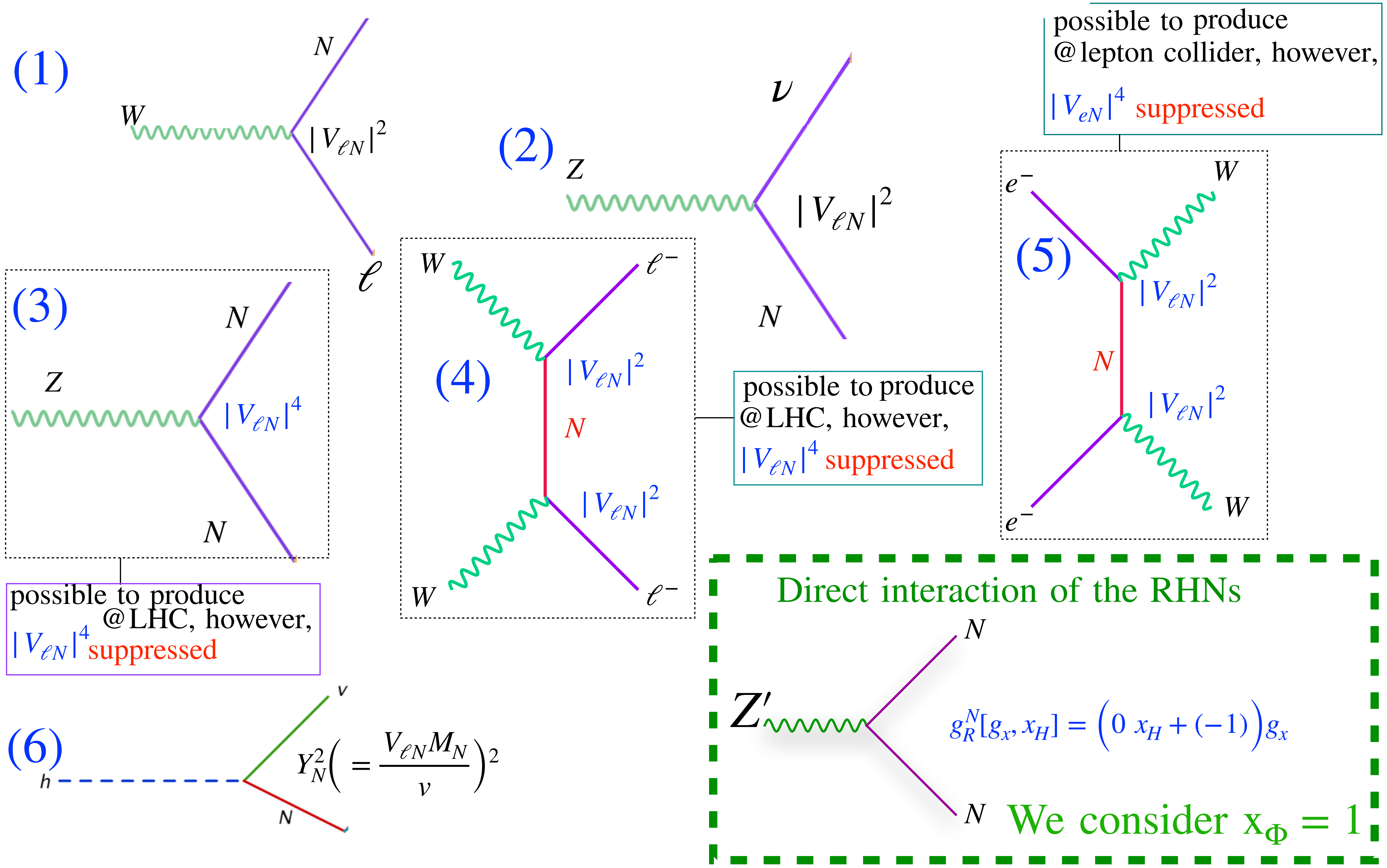
Flavor eigenstate can be expressed in terms of the mass eigenstate

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

PMNS matrix $\quad M_D M_N^{-1}$

We will consider the production of RHNs through mixing

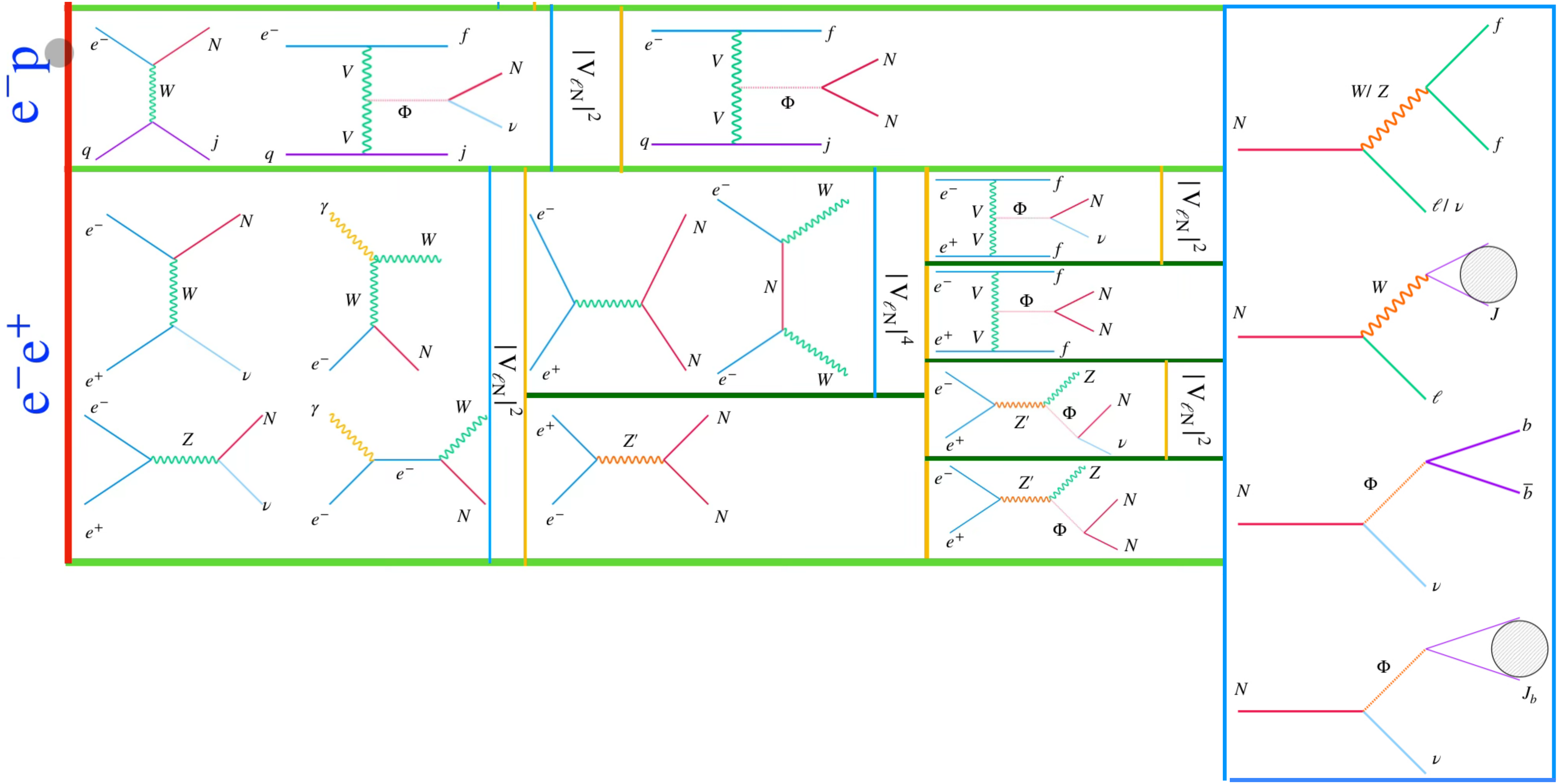
1207.3734



$e^-e^+ \to Z' \to N\,N$ at 250 GeV collider : Jurina Nakajima's poster, 1812.11931

Production of right handed neutrinos in electron colliders

Decay



Heavy neutrino searches at different coliders

Production : Mixing suppressed and direct

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

paired displaced RHN decay
is possible in this scenario

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

Such sceanrios will appear in pair

studying the tracks

rare to find from SM

Prompt, boosted in this talk

Production cross sections of RHNs in electron positron colliders

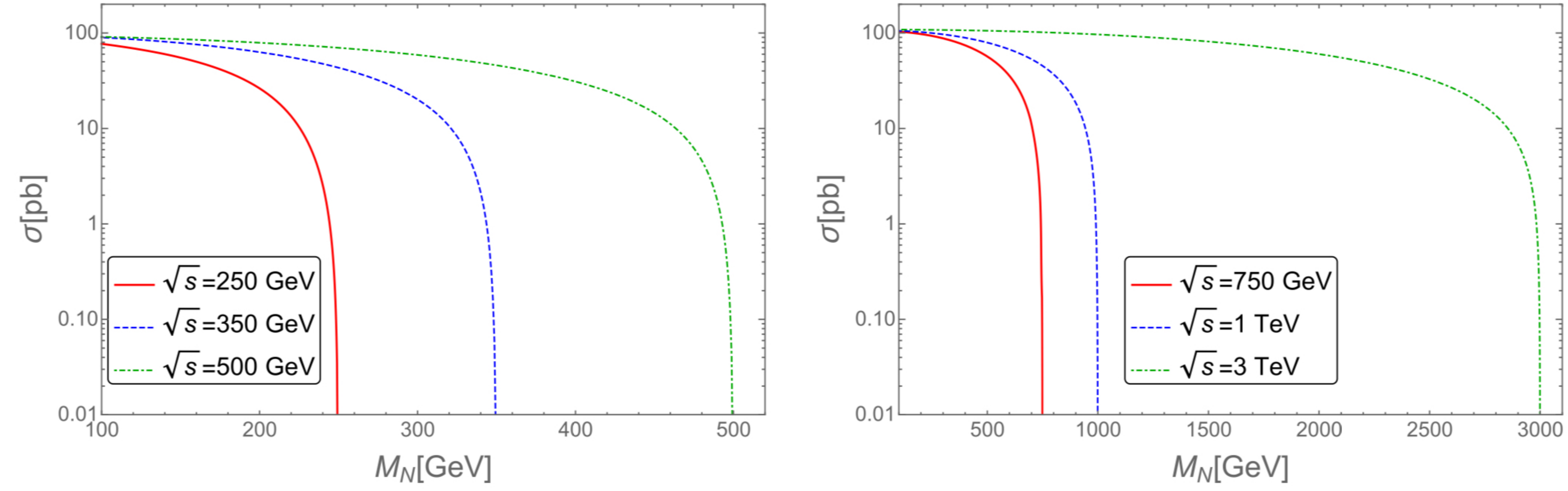


FIG. RHN production cross section at the linear collider considering $e^+e^- \to N_1\nu_1$ process at the different center of mass energies.

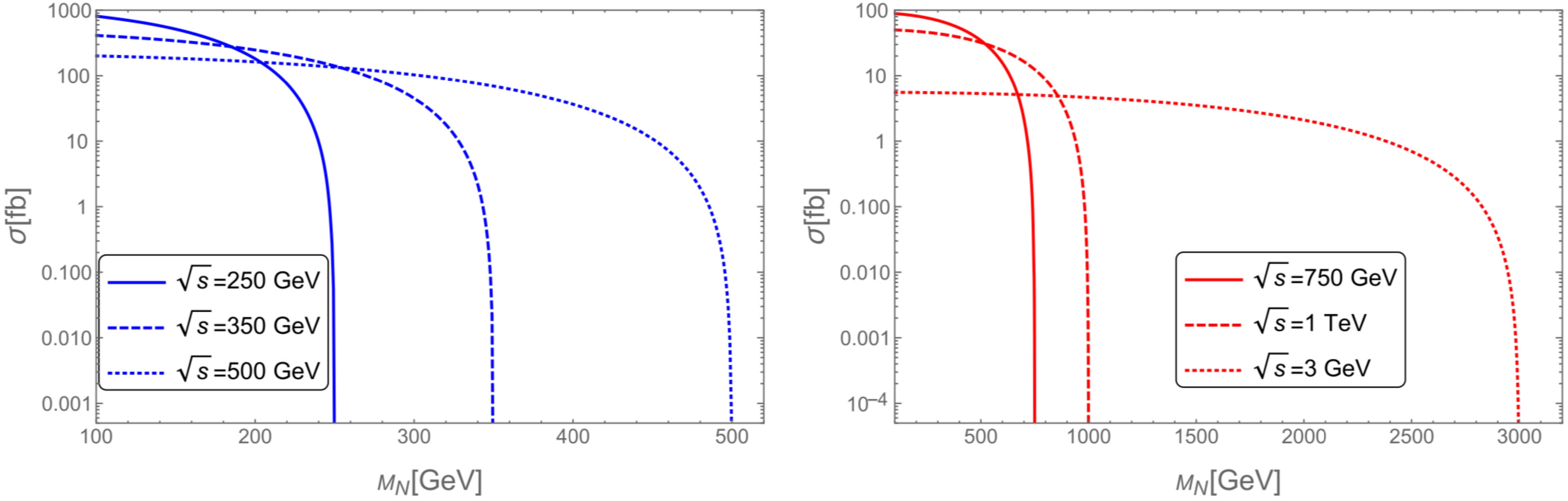


FIG. RHN production cross section at the linear collider considering $e^+e^- \to N_2\nu_2(N_3\nu_3)$ process at the different center of mass energies from the s channel Z boson exchange.

2304.06298

Signal : $\ell + \nu + J$

SM Backgrounds :

ν_eW, WW, ZZ $\to \nu\nu$jj, ZZ $\to$ eejj, $t\bar{t}$

Cuts : $\sqrt{s} = 1(3)$TeV

$P_T^J > 150(250)$ GeV

$P_T^\ell > 100(200)$ GeV

$M_J > 70$ GeV

$|\cos\theta_{\ell(e)}| \leq 0.85$

Limits on the mixing angle from electron positron collider

2304.06298

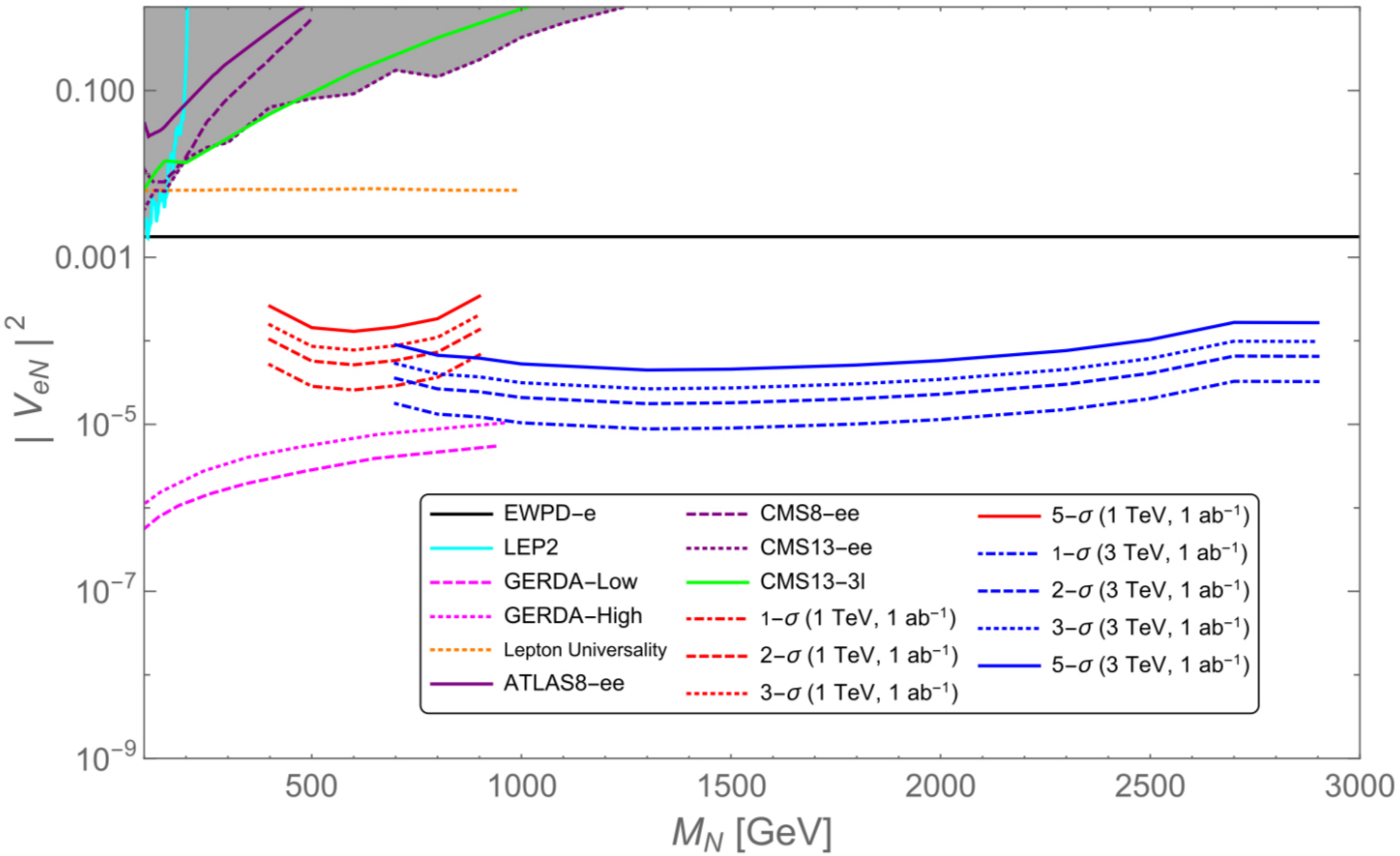


FIG. The prospective upper limits on $|V_{eN}|^2$ at the 1 TeV (red band) and 3 TeV (blue band) linear colliders at the 1 ab^{-1} luminosity for $e + J + p_T^{\rm miss}$ signal compared to EWPD [105–107], LEP2 [108], GERDA [109] $0\nu2\beta$ study from [13], ATLAS (ATLAS8-ee) [111], CMS (CMS8-ee) [112] at the 8 TeV LHC, 13 TeV CMS search for $e^\pm e^\pm + 2j$ (CMS13-ee) [113] and 13 TeV CMS search for 3ℓ (CMS13-ee) [113], respectively.

RHN production inelectron photon collider

2304.06298

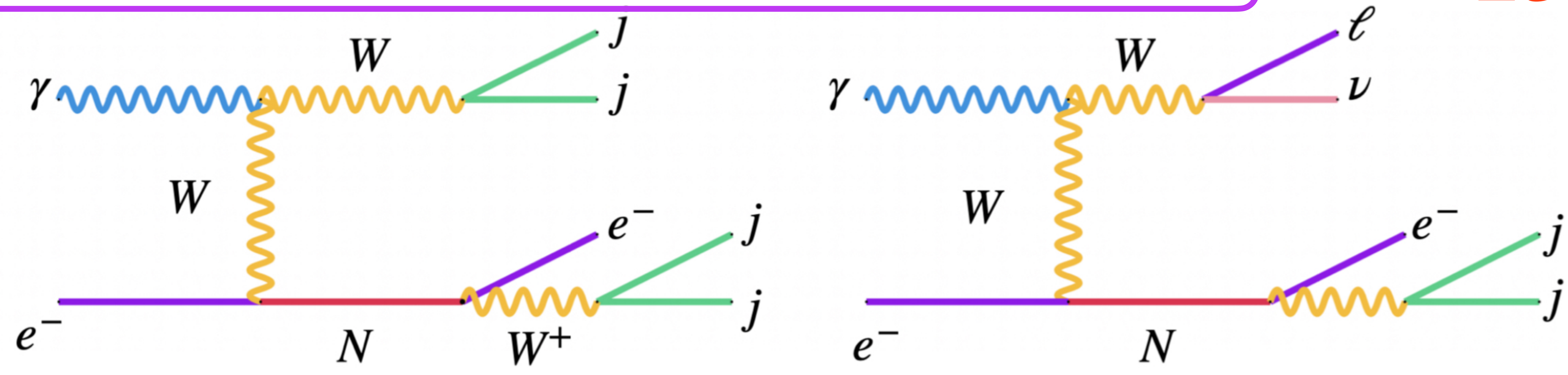


FIG. $e^{\pm}+4j$ (left) and SSDL (right, $\ell^- = e^-, \mu^-$) final states in the context of $e^-\gamma$ colliders. The SSDL signal is obtained combining SSSF and SSDF signals. The corresponding s-channel processes has been included in the analyses.

$e^{\pm}+4j, \sqrt{s} = 250$ GeV

$\sqrt{s}$ (GeV)	M_N (GeV)	Signal before cuts (fb)	Signal after cuts (fb)	Background before cuts (fb)	Background after cuts (fb)
250	20	4108	63.26	102.86	4.21
	40	3629	290.3	102.86	4.21
	60	2923	426.7	102.86	4.21
	80	3460	477.8	102.86	4.21

TABLE : Cross sections of the signal (normalized by $|V_{eN}|^2$) and generic background before and after cuts for $e^-\gamma$ collider at $\sqrt{s}$ =250 GeV for the final state $e^{\pm}+4j$. We have used the following cuts: 60 GeV $< m_{jj} <$ 100 GeV, $\cos\theta_{\ell_1} < 0.94$, $p_T^{j_1,\text{leading}} > 25$ GeV, $p_T^{j_2,\text{trailing}} > 15$ GeV, $p_T^{j_3,\text{trailing}} > 10$ GeV, $p_T^{j_4,\text{trailing}} > 7$ GeV and $p_T^{\ell} > 12$ GeV.

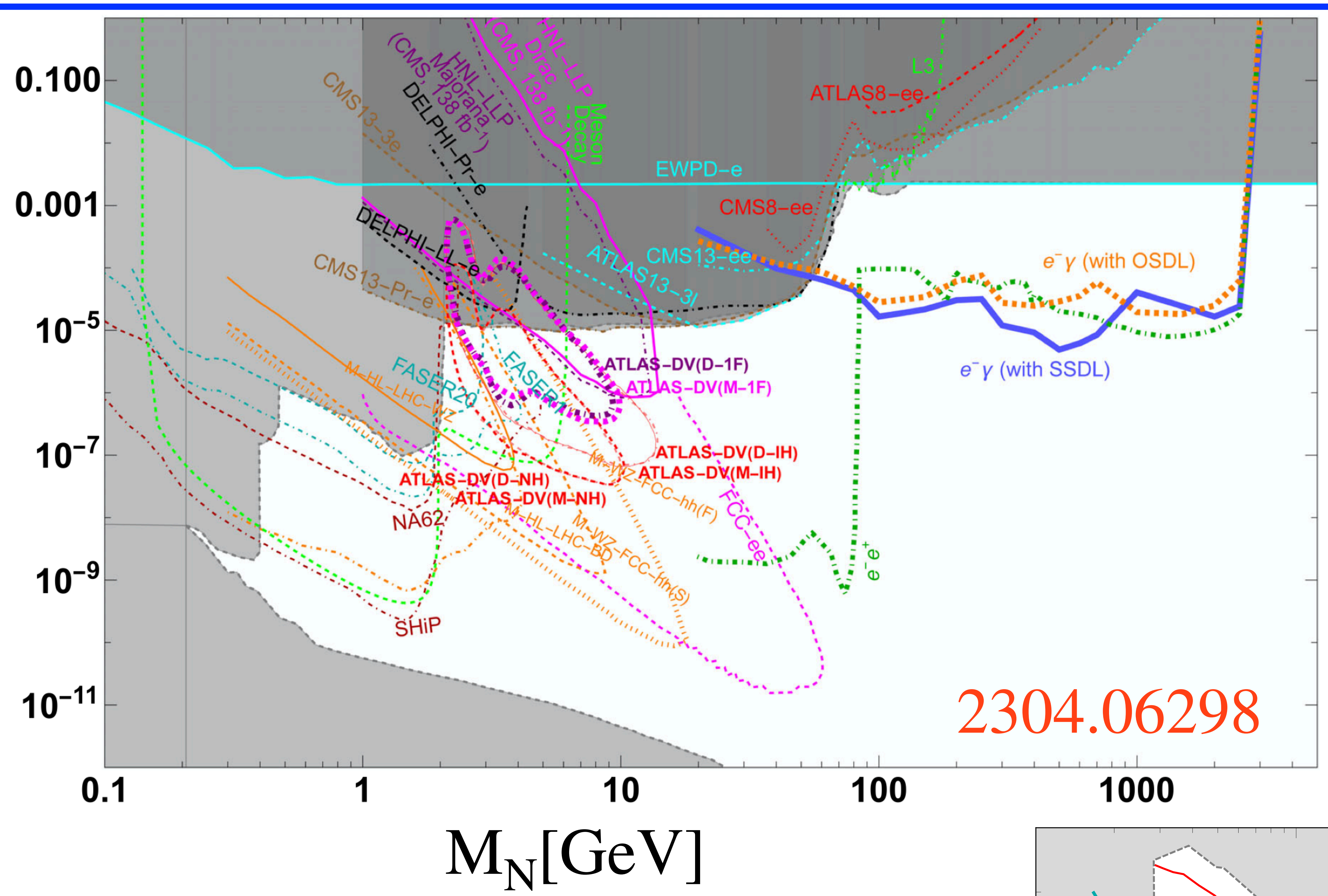
$e^{\pm}e^{\pm}+2j, \sqrt{s} = 250$ GeV

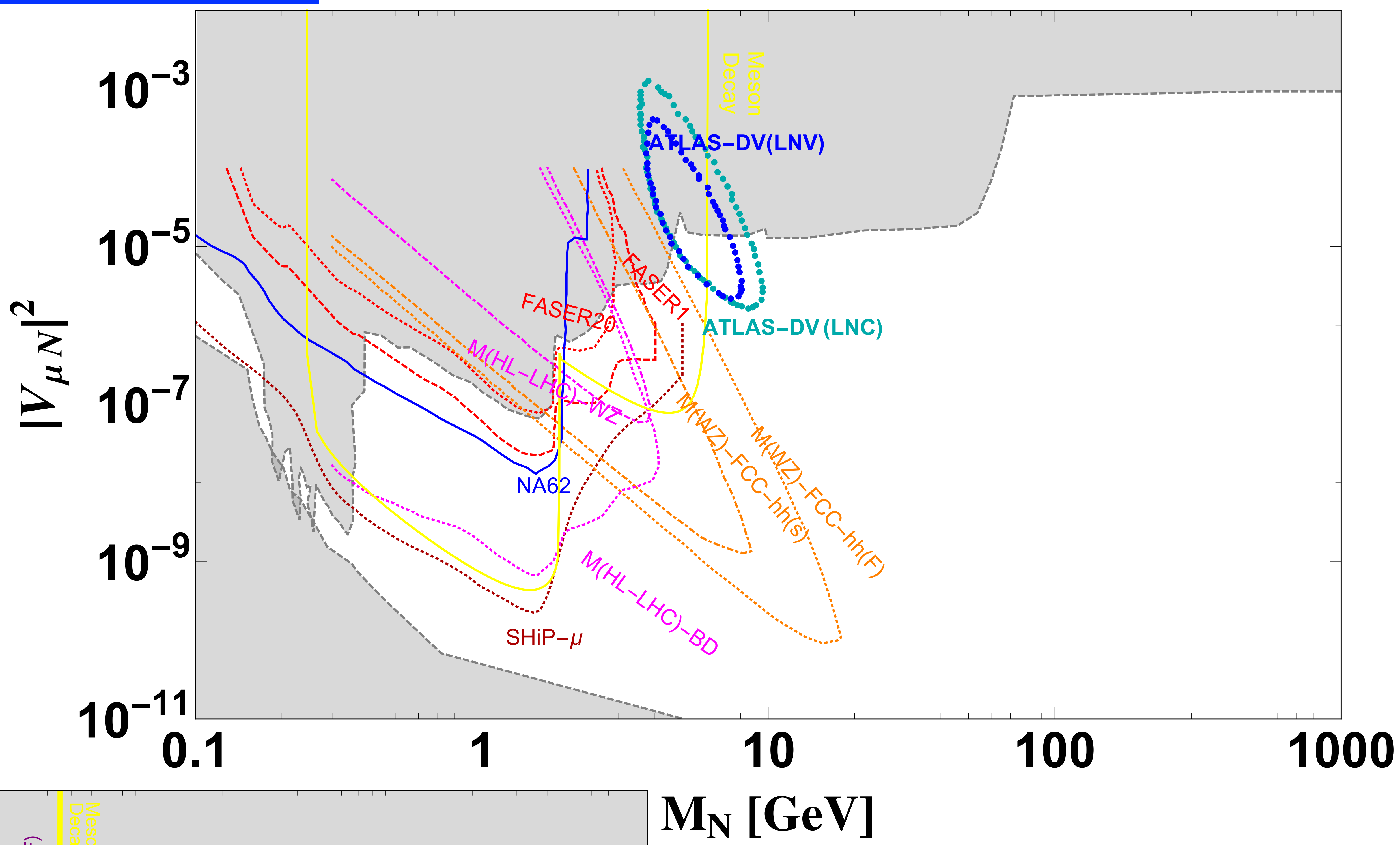
$\sqrt{s}$ (GeV)	M_N (GeV)	Signal before cuts (fb)	Signal after cuts (fb)	Background before cuts (fb)	Background after cuts (fb)
250	20	539.18	11.93	2.02	0.105
	40	467.44	24.71	2.02	0.105
	60	379.17	47.05	2.02	0.105
	80	1676.1	223.91	2.02	0.105

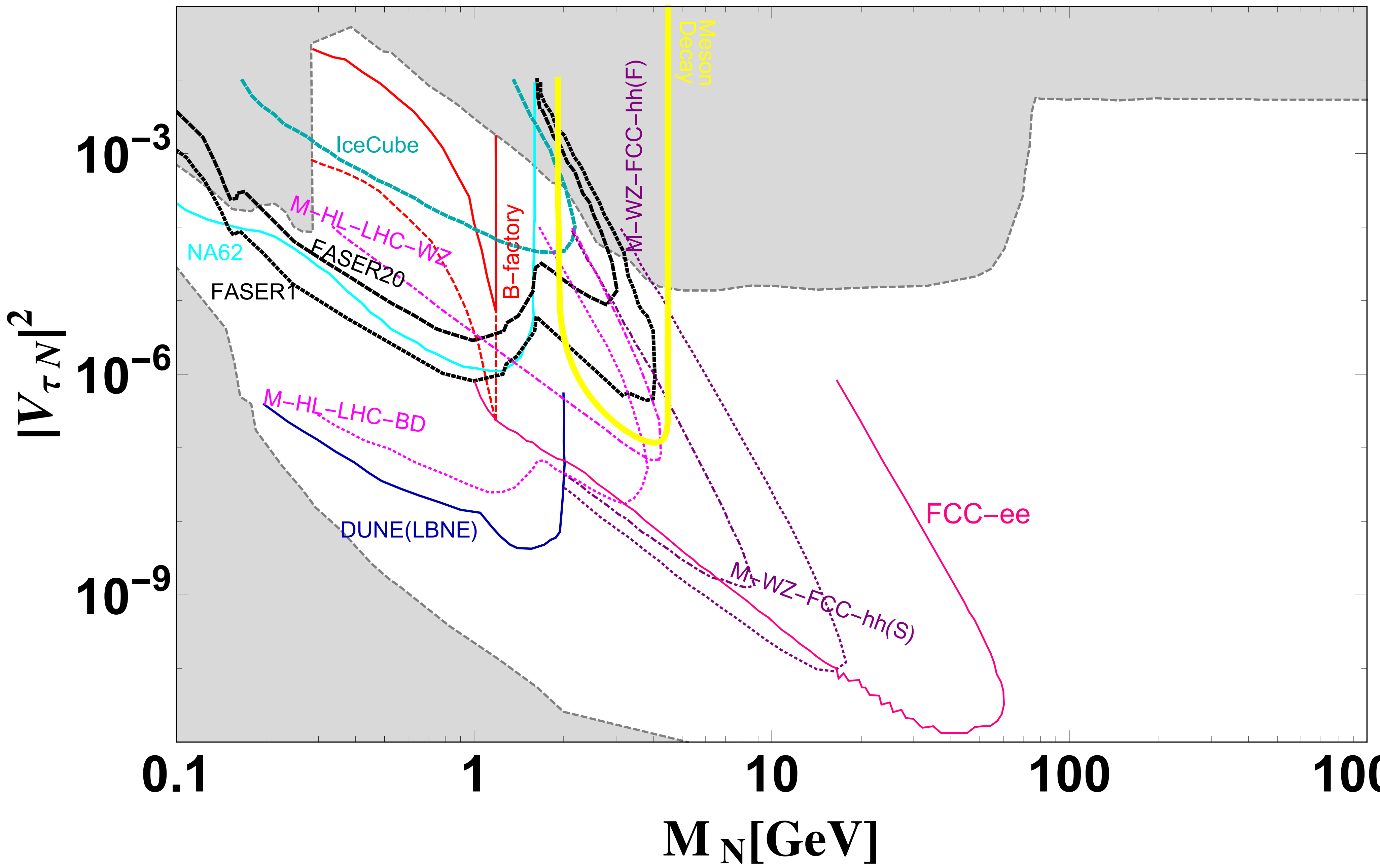
TABLE Cross sections of the signal (normalized by $|V_{eN}|^2$) and generic background before and after cuts for $e^-\gamma$ collider at $\sqrt{s}$ =250 GeV for the SSDL final state. We have used the following cuts: $p_T^{j_1,\text{leading}}$, $p_T^{j_2,\text{trailing}} > 10$ GeV, $p_T^{\ell_1,\text{leading}}$, $p_T^{\ell_2,\text{trailing}} > 10$ GeV, 60 GeV $< m_{j_1j_2} <$ 100 GeV and $\cos\theta_{l_{1,\text{leading}}} < 0.9$, $\cos\theta_{l_{2,\text{trailing}}} < 0.92$.

Existing and prospective bounds on the mixings

1502.06541 1805.00070 1908.09562







Conclusions

We are looking for a scenario where which can explain a variety of beyond the SM sceanrios .

The proposal for the generation of the tiny neutrino mass, from the seesaw mechanism, under investigation in electron – positron and electron photon colliders .

Mnay aspects can be addressed in these scenarios including the right handed neutrino searches at e^-e^+ colliders .

The motivations of these works is to find a new particle, a new force carrier as a part of the of the new physics search including various BSM aspects .