Multimessenger Probes of Heavy Neutrinos

Sanjoy Mandal

Korea Institute For Advanced Study, Seoul, South Korea

KOREA INSTITUTE FOR ADVANCED STUDY

Email: smandal@kias.re.kr

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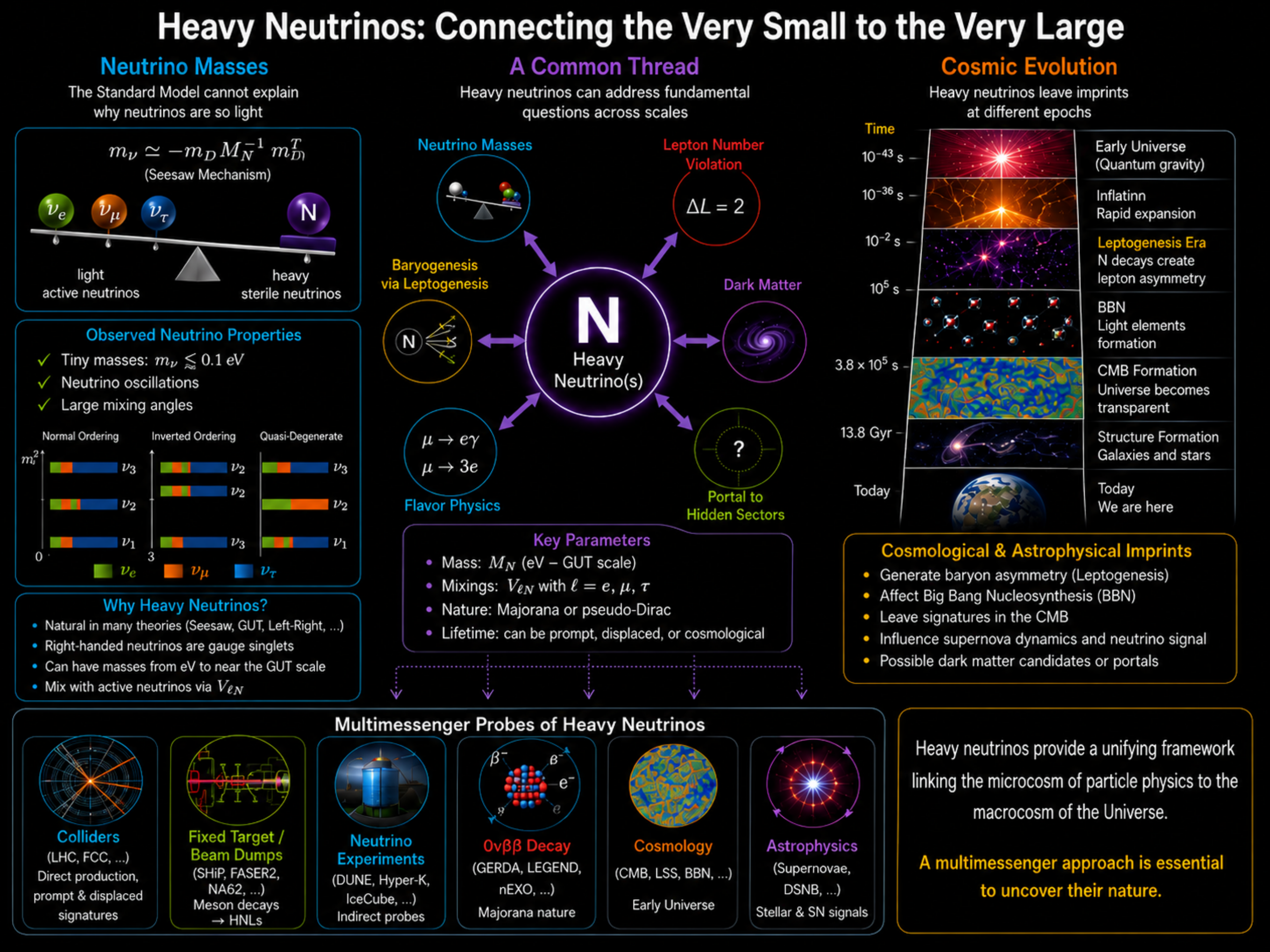

Heavy Neutrinos: Connecting the Very Small to the Very Large
Neutrino Masses
The Standard Model cannot explain why neutrinos are so light
$m_\nu \simeq -m_D M_N^{-1} m_D^T$
(Seesaw Mechanism)
ν_e ν_μ ν_τ N
light active neutrinos
heavy sterile neutrinos
Observed Neutrino Properties
✓ Tiny masses: $m_\nu \lesssim 0.1$ eV
✓ Neutrino oscillations
✓ Large mixing angles
Normal Ordering
Inverted Ordering
Quasi-Degenerate
m_i^2
ν_3 ν_2 ν_1
ν_2 ν_2 ν_3
ν_3 ν_2 ν_1
0
3
ν_e ν_μ ν_τ
Why Heavy Neutrinos?
• Natural in many theories (Seesaw, GUT, Left-Right, ...)
• Right-handed neutrinos are gauge singlets
• Can have masses from eV to near the GUT scale
• Mix with active neutrinos via $V_{\ell N}$
A Common Thread
Heavy neutrinos can address fundamental questions across scales
Neutrino Masses
Lepton Number Violation
$\Delta L = 2$
Baryogenesis via Leptogenesis
N
Heavy Neutrino(s)
Dark Matter
$\mu \to e\gamma$
$\mu \to 3e$
Flavor Physics
?
Portal to Hidden Sectors
Key Parameters
• Mass: M_N (eV – GUT scale)
• Mixings: $V_{\ell N}$ with $\ell = e, \mu, \tau$
• Nature: Majorana or pseudo-Dirac
• Lifetime: can be prompt, displaced, or cosmological
Cosmic Evolution
Heavy neutrinos leave imprints at different epochs
Time
10^{-43} s
Early Universe (Quantum gravity)
10^{-36} s
Inflatinn Rapid expansion
10^{-2} s
Leptogenesis Era
N decays create lepton asymmetry
10^{5} s
BBN
Light elements formation
3.8×10^{5} s
CMB Formation
Universe becomes transparent
13.8 Gyr
Structure Formation
Galaxies and stars
Today
Today
We are here
Cosmological & Astrophysical Imprints
• Generate baryon asymmetry (Leptogenesis)
• Affect Big Bang Nucleosynthesis (BBN)
• Leave signatures in the CMB
• Influence supernova dynamics and neutrino signal
• Possible dark matter candidates or portals
Multimessenger Probes of Heavy Neutrinos
Colliders
(LHC, FCC, ...)
Direct production, prompt & displaced signatures
Fixed Target / Beam Dumps
(SHiP, FASER2, NA62, ...)
Meson decays → HNLs
Neutrino Experiments
(DUNE, Hyper-K, IceCube, ...)
Indirect probes
$0\nu\beta\beta$ Decay
β^- β^- e^-
(GERDA, LEGEND, nEXO, ...)
Majorana nature
Cosmology
(CMB, LSS, BBN, ...)
Early Universe
Astrophysics
(Supernovae, DSNB, ...)
Stellar & SN signals
Heavy neutrinos provide a unifying framework linking the microcosm of particle physics to the macrocosm of the Universe.
A multimessenger approach is essential to uncover their nature.

$m_\nu \neq 0 \longrightarrow$ NP

(1). No right handed neutrino ν_R

No Dirac mass term $\quad \mathscr{L}_\nu = Y_\nu \overline{L}\tilde{\Phi}\nu_R + \text{h.c.}$

(2). Majorana mass with only ν_L:

$\mathscr{L}_\nu = \frac{1}{2}\overline{\nu_L} M \nu_L^c + \text{h.c}$ not gauge invariant

No RHNs + only doublet: neutrinos are massless, with distinguished by separate lepton numbers

$$\nu_e\,,\quad \nu_\mu\,,\quad \nu_\tau \longleftrightarrow L_e\,,\quad L_\mu\,,\quad L_\tau$$

Neutrino mass can only be generated by relaxing (1) or (2): need to extend the SM

Dirac neutrinos ? Add gauge singlet RHNs ν_R: $-\mathscr{L}^{\text{leptons}}_{\text{mass}} = \overline{L}Y_\ell \Phi e_R + \overline{L}Y_\nu \tilde{\Phi}\nu_R + \text{h.c.}$

After EWSB: $\boxed{-\mathscr{L}^{\text{leptons}}_{\text{mass}} = \underbrace{m_\ell \bar{\ell}_L \ell_R}_{\text{Charged lepton mass}} + \underbrace{m_\nu \bar{\nu}_L \nu_R}_{\text{Dirac neutrino mass}} + \text{h.c.}}$

$\boxed{m_\ell \sim Y_\ell v_\phi, \quad m_\nu \sim Y_\nu v_\Phi}$

Neutrinos are Dirac

The hierarchy problem:

$$\boxed{\frac{Y_\nu}{Y_e} = \frac{m_\nu}{m_e}} \Rightarrow \frac{0.1\ \text{eV}}{0.5 \times 10^6\ \text{eV}} \leq\ \sim 10^{-6} \Rightarrow Y_\nu \sim 10^{-12}$$

which is ridiculously small number without explanation

Type I seesaw

$$\mathscr{L} = Y_N \bar{L}\tilde{\Phi}N_R + \frac{1}{2}\overline{N_R^c}\, M_R\, N_R + \text{h.c.}$$

Schecther, Valle 80, Minkowski 77; Yanagida 79; Glashow 79; Gell-Mann, Ramond, Slanski 79; Mohapatra, Senjanovic 79;

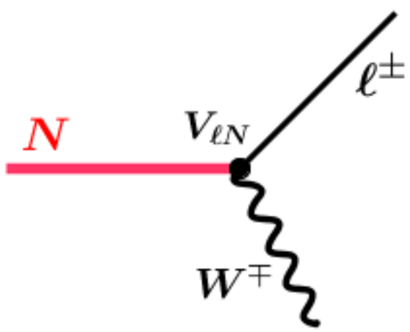
$$\mathscr{L}_{\text{mass}} = \frac{1}{2}\begin{pmatrix}\overline{\nu_L} & \overline{N_R^c}\end{pmatrix}\begin{pmatrix}0 & m_D \\ m_D^T & M_R\end{pmatrix}\begin{pmatrix}\nu_L^c \\ N_R\end{pmatrix} + \text{h.c.}$$

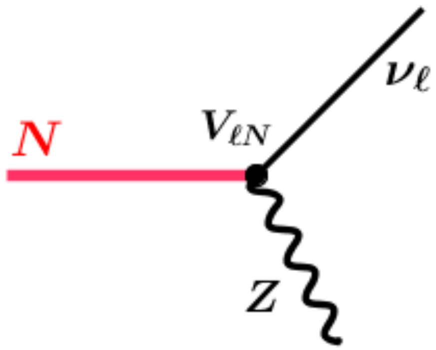
seesaw($M_R \gg m_D$): $m_\nu \approx m_D M_R^{-1} m_D^T$

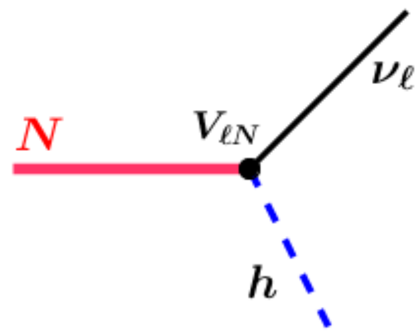
Flavor mixing: $\nu_\ell \approx U_{\ell m}\nu_m + V_{\ell N} N$

$m_D \sim Y_N v_\Phi$ $\quad V_{\ell N} \approx m_D M_R^{-1} \ll 1$

New interactions:





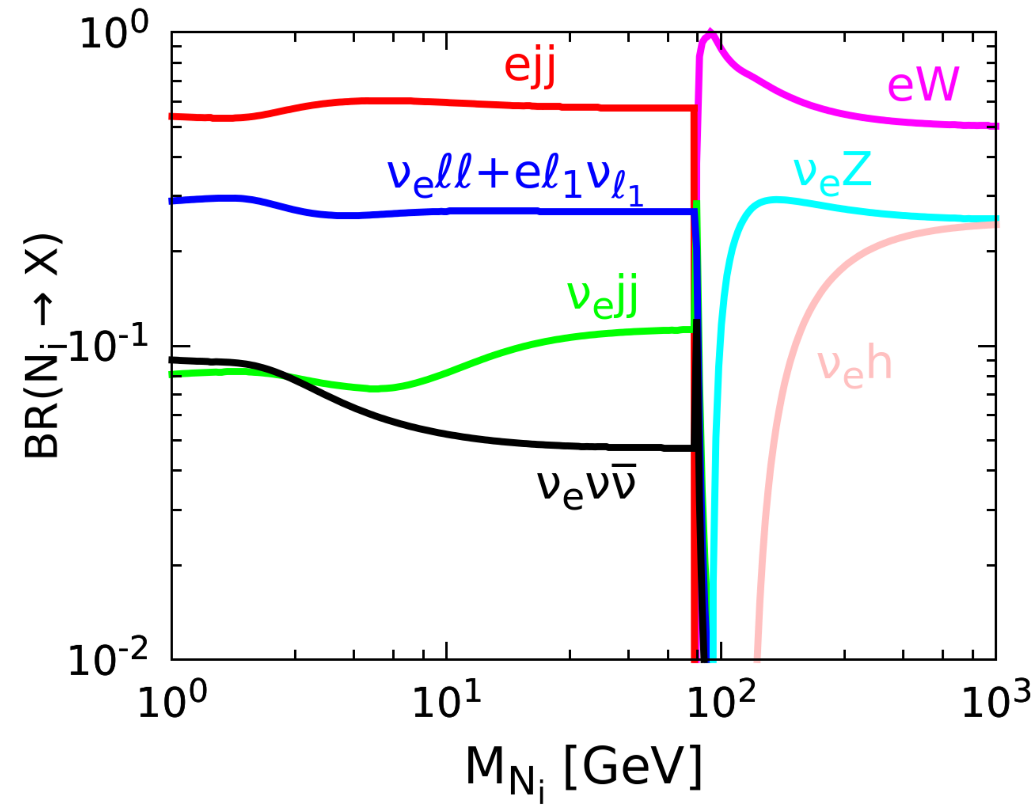


Production XS $\propto |V_{\ell N}|^2$

out of reach at colliders

To get $m_\nu = 0.1$ eV requires either $M_R \sim 10^{14}$ GeV or very small Yukawa $Y_N \sim 10^{-6}$ for $M_R \sim 1$ TeV

Classical seesaw is fine but boring!



Casas, Ibara: $Y_N \approx \frac{\sqrt{2}}{v_\Phi} U_{\text{lep}}^\dagger \sqrt{m_\nu^{diag}}\, R \sqrt{M_R}$ with $R^T R = 1$

If we want large mixings at accessible collider scales, e.g. $M_N \sim 1$ TeV, then some entries in R must be large or highly complex, leading to cancellations in mass matrix

Tuning can be reduced in inverse/linear/radiative seesaw

Avila, Karan, SM, Sadhukhan, Valle 25

Lowscale seesaw: Inverse / Linear

Valle et al 05 Akhmedov et al 95

Inverse seesaw:

Field content: add N_R and S_R $L[N_R]=1, L[S_R]=-1$

$$\mathscr{L} = Y_N \bar{L}\tilde{\Phi}N_R + \overline{N_R^c}\, M_R\, S_R + \frac{1}{2}\overline{S_R^c}\,\mu_S\, S_R + \text{h.c.}$$

$$\mathscr{L} = \begin{pmatrix} \overline{\nu_L} & \overline{N_R^c} & \overline{S_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_R \\ 0 & M_R^T & \mu_S \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \\ S_R \end{pmatrix} + \text{h.c}$$

$M_R \gg m_D \gg \mu_S$:

$$\boxed{\begin{gathered} m_\nu \simeq m_D (M_R^T)^{-1} \mu_S M_R^{-1} m_D^T \\ V_{\ell N} \sim m_D M_R^{-1} \end{gathered}}$$

Linear seesaw:

Field content: add N_R and S_R $L[N_R]=1, L[S_R]=-1$

$$\mathscr{L} = Y_N \bar{L}\tilde{\Phi}N_R + Y_S \bar{L}\tilde{\Phi}S_R + \overline{N_R^c}\, M_R\, S_R + \text{h.c.}$$

$$\mathscr{L} = \begin{pmatrix} \overline{\nu_L} & \overline{N_R^c} & \overline{S_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_D & M_L \\ m_D^T & 0 & M_R \\ M_L^T & M_R^T & 0 \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \\ S_R \end{pmatrix} + \text{h.c}$$

$M_L \sim Y_S v_\Phi$

$M_R \gg m_D \gg M_L$:

$$\boxed{\begin{gathered} m_\nu \simeq M_L M_R^{-1} m_D^T + m_D (M_R^T)^{-1} M_L^T \\ V_{\ell N} \sim m_D M_R^{-1} \end{gathered}}$$

Lowscale seesaw: soft LNV (μ_S or $M_L \to 0$) $\Rightarrow$ **small neutrino mass** + **sizable mixing**

Pair of quasi-Dirac heavy neutrinos: $\boxed{M_{N_1} = -M_R + \frac{\Delta M}{2}, \quad M_{N_2} = M_R + \frac{\Delta M}{2}, \quad \text{with } \Delta M \sim \mu_S \text{ or } M_L}$

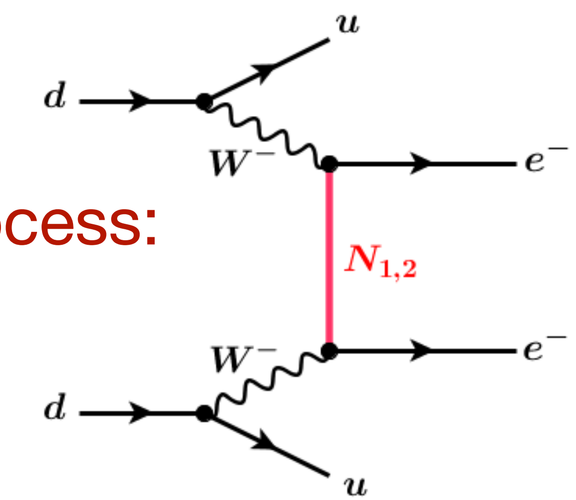
Rephasing of N_1: Pair of heavy neutrino with small-splitting ΔM and opposite CP phase

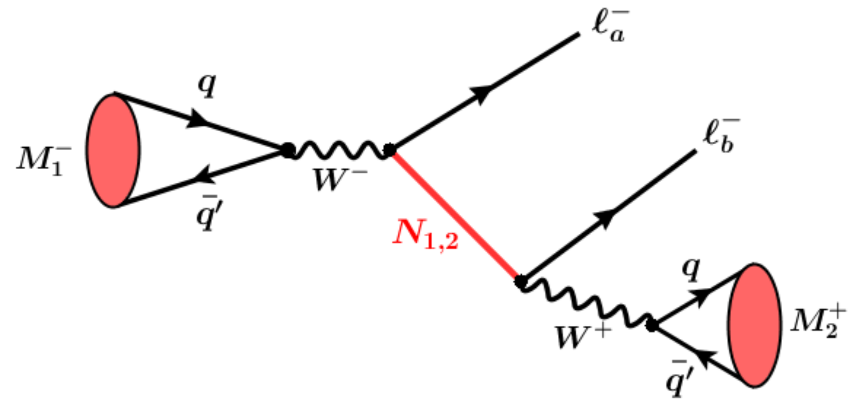
Flavor mixing: $\nu_L \sim P_L \begin{pmatrix} U & -iV_{\ell N} & V_{\ell N} \end{pmatrix} \begin{pmatrix} \nu_m \\ N_1 \\ N_2 \end{pmatrix}$

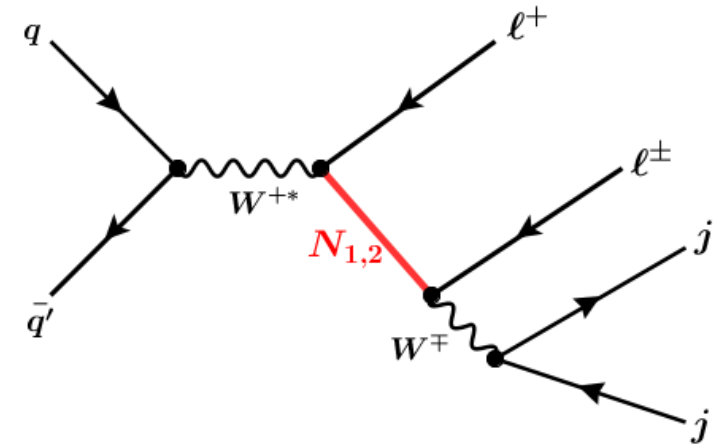
Collider testable but suppressed LNV!!

Are LNV always suppressed in lowscale seesaws?

LNV process:





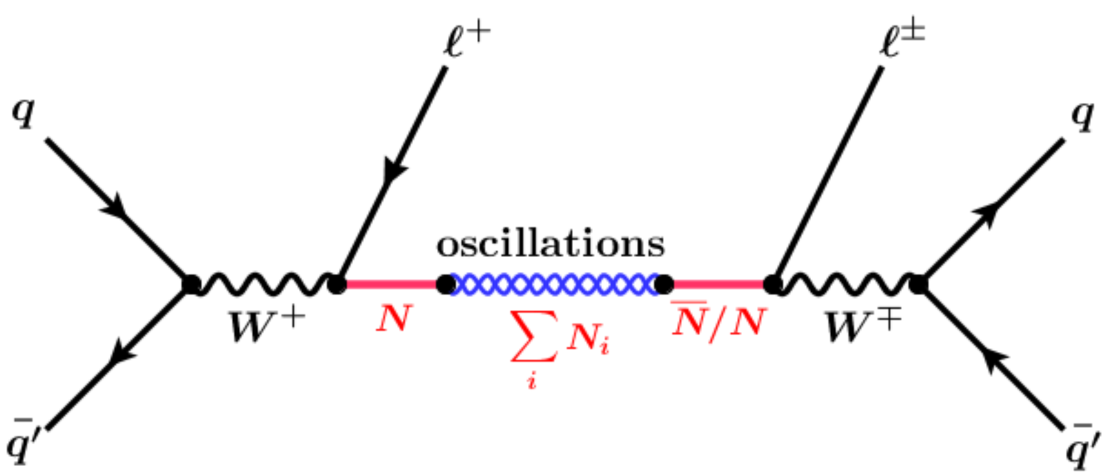


Relevant CC int: $-\mathscr{L}_{cc} \sim g/\sqrt{2}\, V_{\ell N}\, \bar{\ell}\gamma_\mu P_L(-iN_1 + N_2)/\sqrt{2}\, W^\mu + \text{h.c}$

$$\boxed{\text{Amp} \propto \frac{\Delta M}{M_N}}$$

LNV processes mediated by on-shell or virtual heavy neutrinos appear suppressed.

Not always true for LNV processes with on-shell N:



LNV via virtual propagation: $\Delta M/M_N$

LNV via on-shell propagation: $\Delta M/\Gamma_N$

Hirsch et al, 1607.05641

See Jose, Bruno talk

$$R = \frac{\#\,\text{LNV}}{\#\,\text{LNC}} = \frac{\Delta M^2}{2\Gamma_N^2 + \Delta M^2} = \frac{x^2}{2+x^2} \quad \text{with } x = \frac{\Delta M}{\Gamma_N}$$

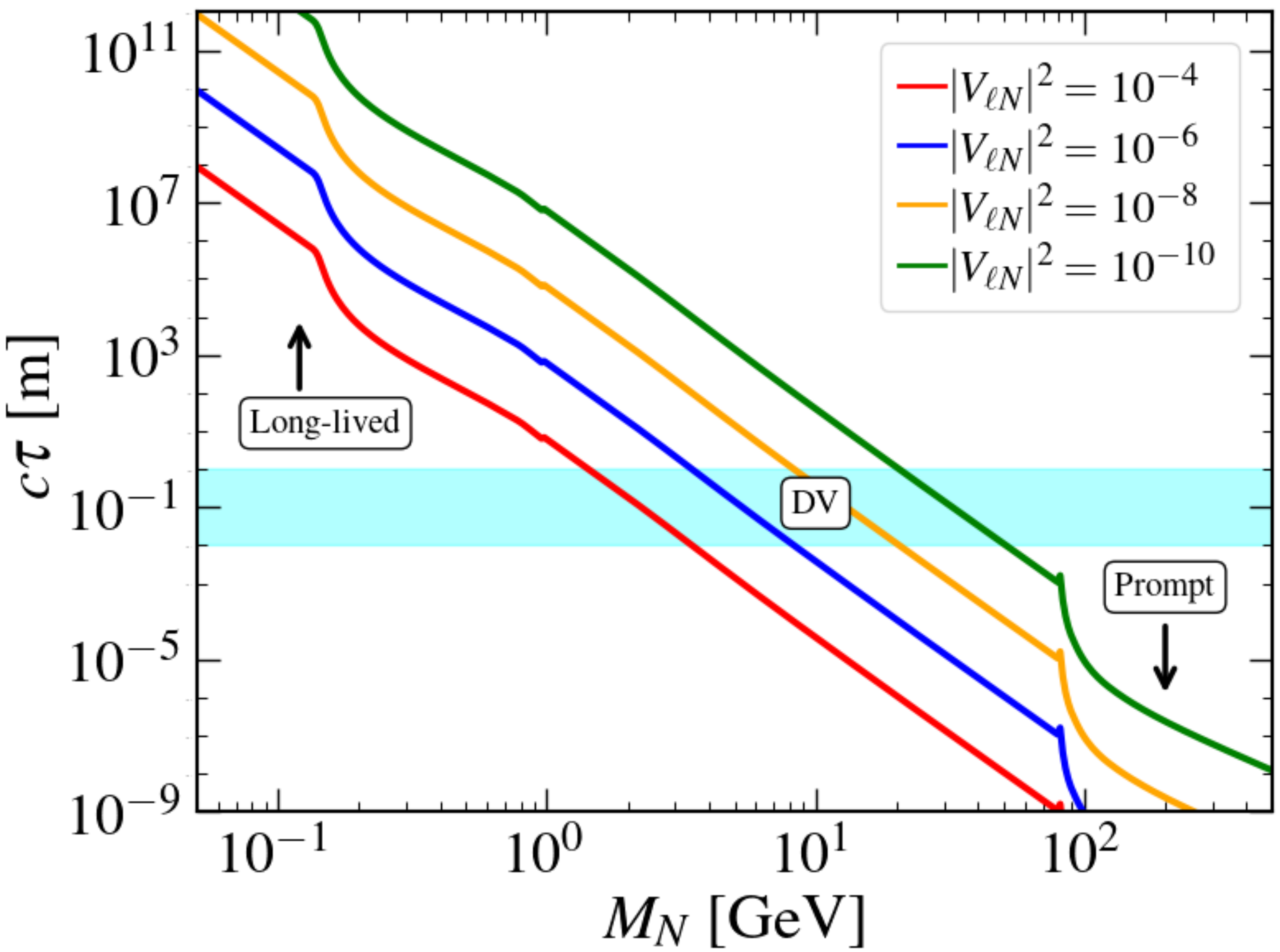
Pure Majorana: $R = 1$

Pure Dirac: $R = 0$

Quasi-Dirac: $0 \leq R \leq 1$ depending on the ratio $\Delta M/\Gamma_N$

For **discovery purposes**, take agnostic/pheno approach with generic $V_{\ell N}$ parametrization and one N mass eigenstate

Strategy for uncovering the signal



$M_N \sim$ eV: kinks in electron beta decay spectra

$M_N \sim$ KeV: peak searches in leptonic decays of pion and kaon

$M_N \sim$ MeV- few GeV: Long-lived: $L_N \gtrsim \mathcal{O}(100\text{ m})$, beam dump experiments

$M_N \sim 10$ GeV - M_W: displaced vertex: $L_N \sim (\text{cm} - \text{m})$, collider experiments

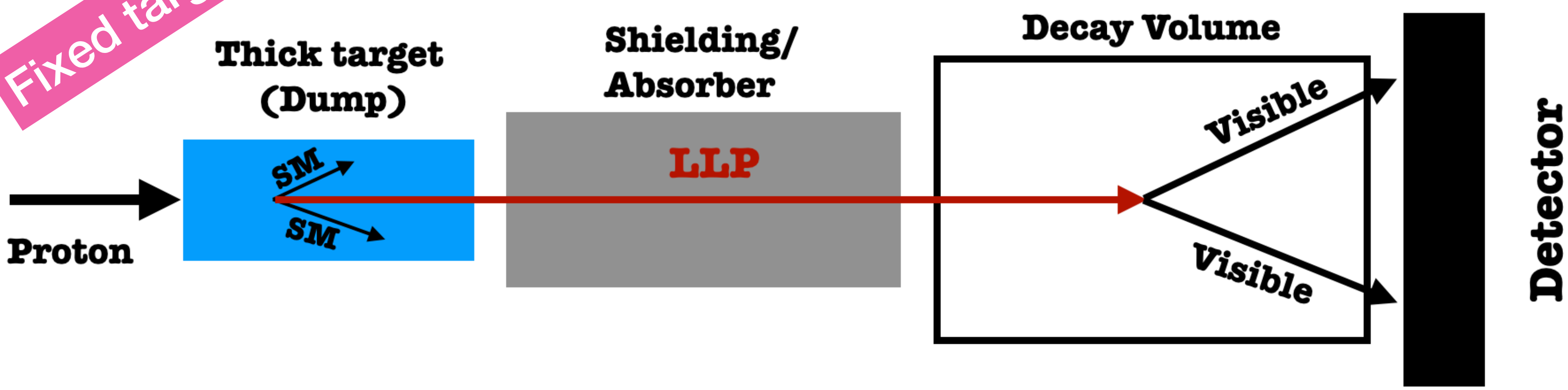
$M_N > M_W$: Prompt decay, collider experiments

$M_N \geq \mathcal{O}(1)$ TeV:

This mass range is out of reach of the present collider energy. N can be probed indirectly from loop processes such as $\mu \to e\gamma$, $\mu \to 3e$, etc

Beam dump experiments: $M_N \sim \mathcal{O}(\text{GeV})$

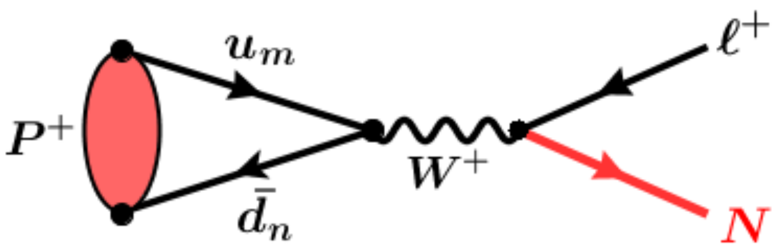
Fixed target:

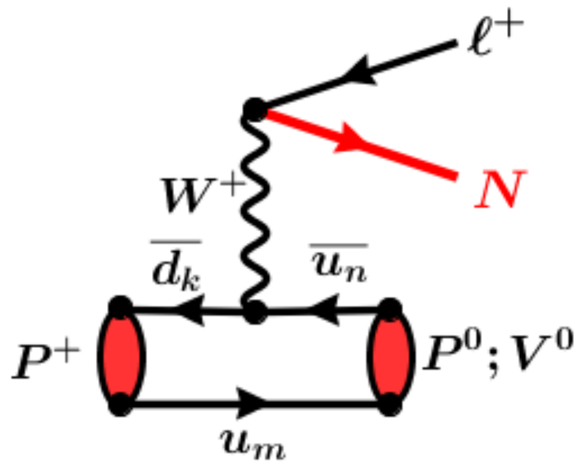


Past: LSND, CHARM, PS191, NOMAD....

Future: SHiP, NA62, HIKE, DUNE, DarkQuest......

High fluxes of protons on an appropriate target could produce the heavy neutrinos in meson decays:





SHiP: $N_{D,D_s} \sim 10^{17}$

NA62, HIKE: $N_K \sim 10^{13}$

Shiva, Das, SM 26

Chun, SM, Mitra, Sinha 19

Signal:

$$N_S = \sum_i N_{M_i} \cdot \text{BR}(M_i \to N + X) \cdot \langle P[N\,\text{decay}] \rangle \cdot \text{BR}(N \to \text{vis.})$$

$$\langle P[N\,\text{decay}] \rangle = e^{-\frac{L_{\min}}{L_N}} \left[1 - e^{-\frac{L_{\text{dec}}}{L_N}}\right] \Theta\Big(R - \tan\theta\,(L_{\min} + L_{\text{dec}})\Big)$$

$$L_N = \frac{p_N}{M_N \Gamma_N}$$

Depends on the detector geometry

Small $|V_{\ell N}|^2 \to$ too few HNL

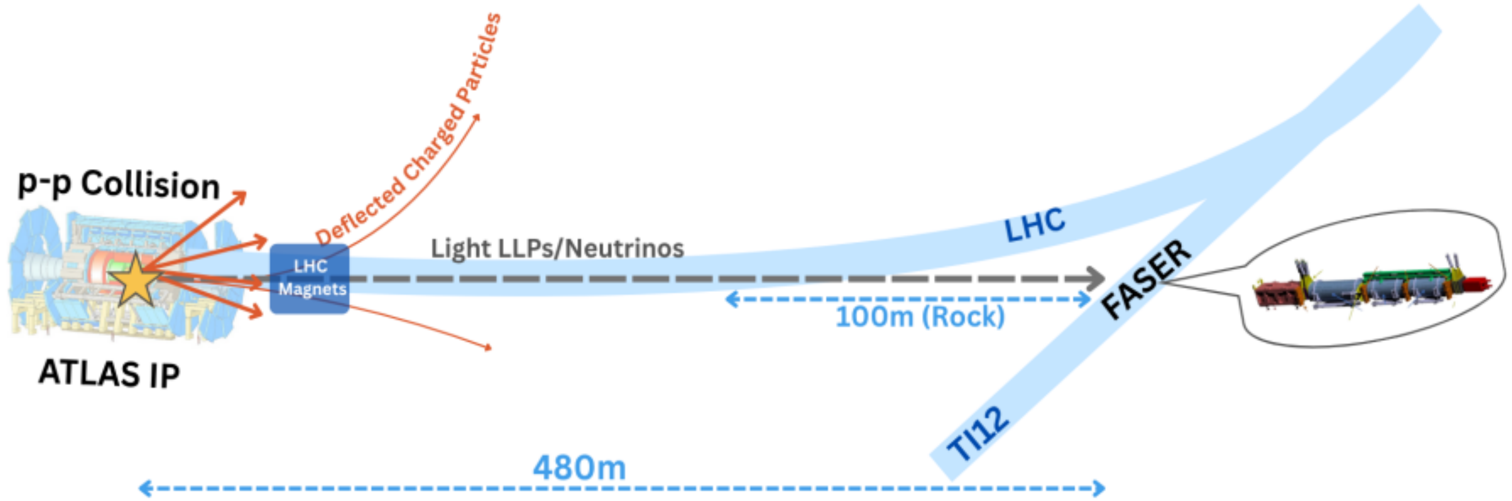
Optimal $|V_{\ell N}|^2 \to$ decay inside detector

Large $|V_{\ell N}|^2 \to$ decay before detector

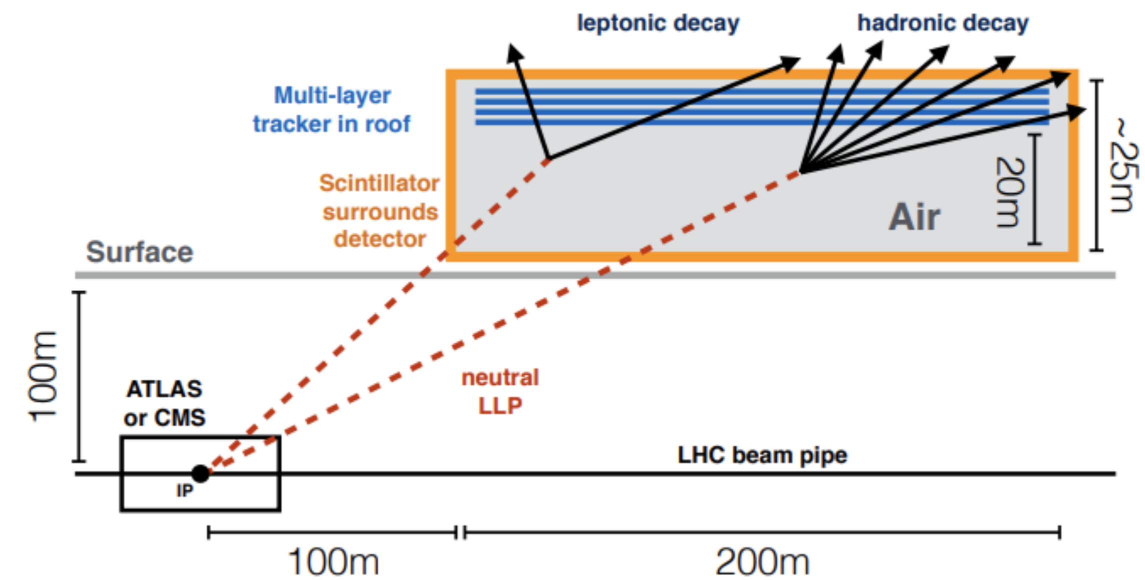
See also Doojin Kim talk

Collider beam dump

Forward detector
FASER, FACET



Transverse detector
MATHUSLA, ANUBIS, CODEX-b



At HL-LHC:

$\theta \lesssim \mathcal{O}(1)$ mrad

High flux of lighter mesons

Best sensitivity:
0.1 GeV $\leq M_N \leq 1$ GeV

$$N_\pi = 10^{18}, N_\eta = 10^{17}, N_D = 10^{16}, N_B = 10^{16}$$

$$N_M^{\text{actual}} = N_M^{\text{IP}}\left(\theta_{\min} \leq \theta \leq \theta_{\max}\right)$$

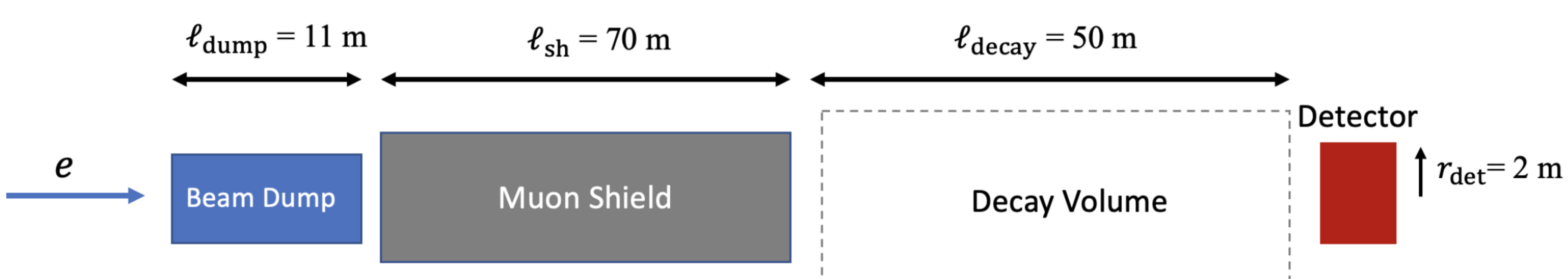
$\theta \sim \mathcal{O}(1)$ rad

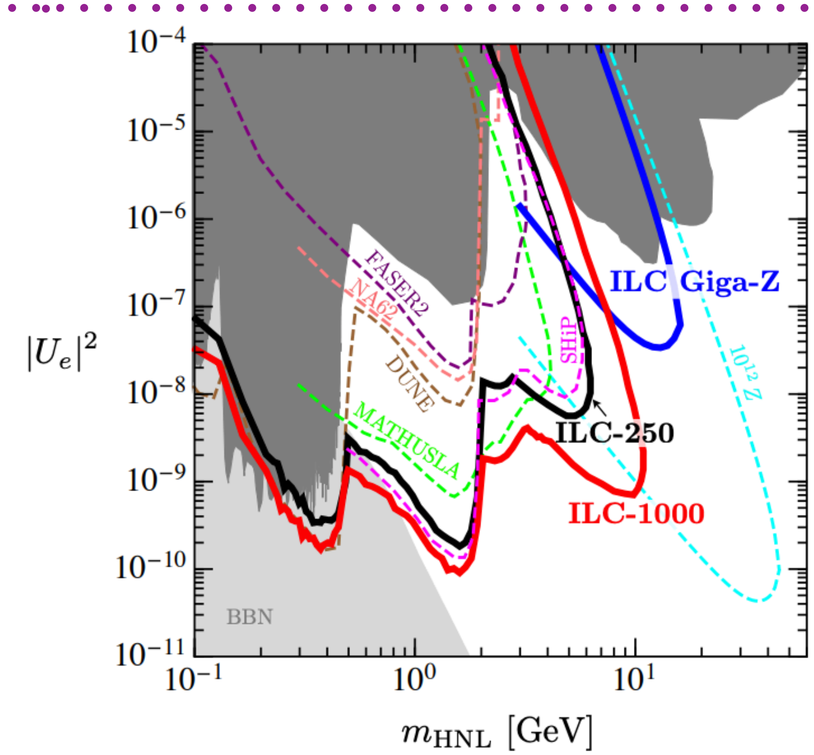
High flux of heavier mesons

Best sensitivity:
1 GeV $\leq M_N \leq 5$ GeV

Lepton collider beam dump

Asai et al 21, Giffin et al 22, Ueda et al 23

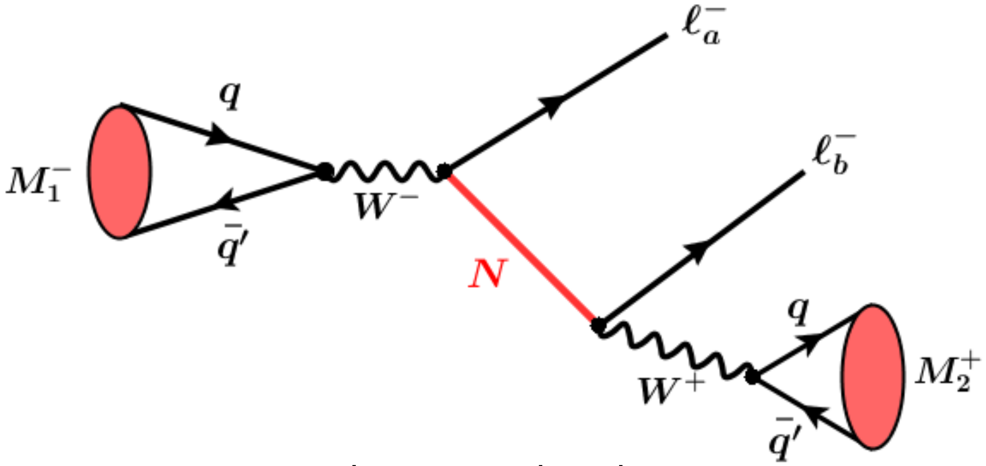




Muon collider beam dump ?

Sakaki, Ueda 26

Three body LNV Meson decays $M_N \sim \mathcal{O}(1)$ GeV

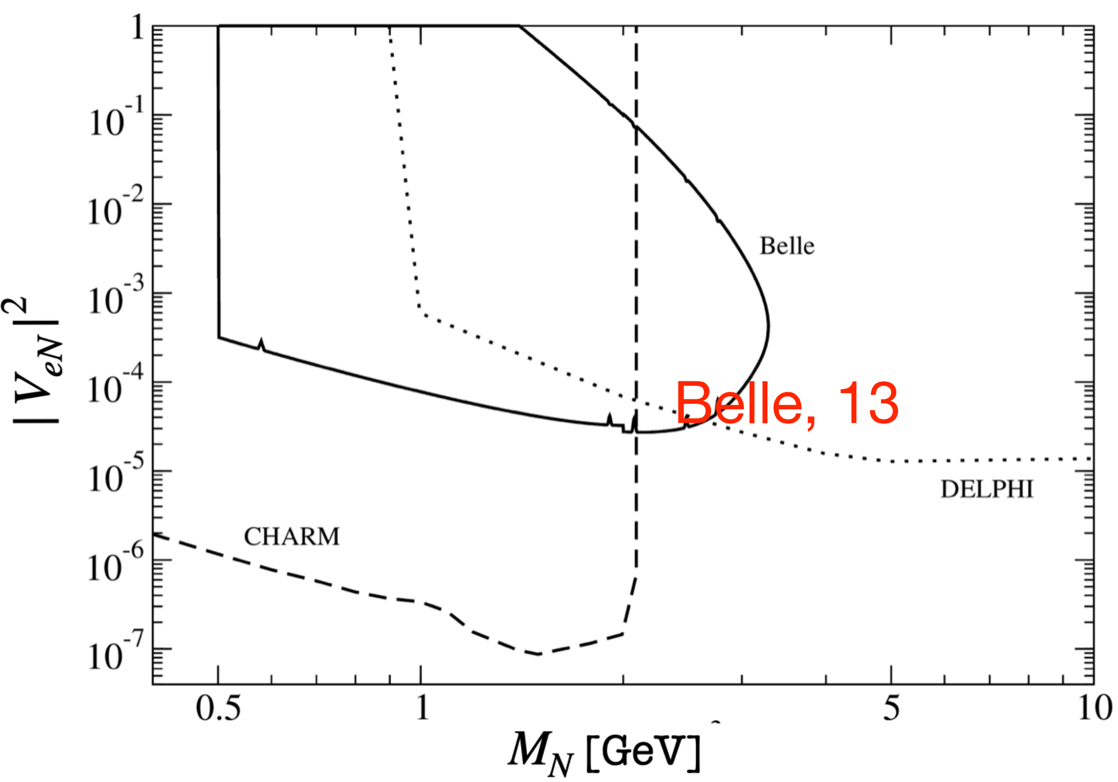


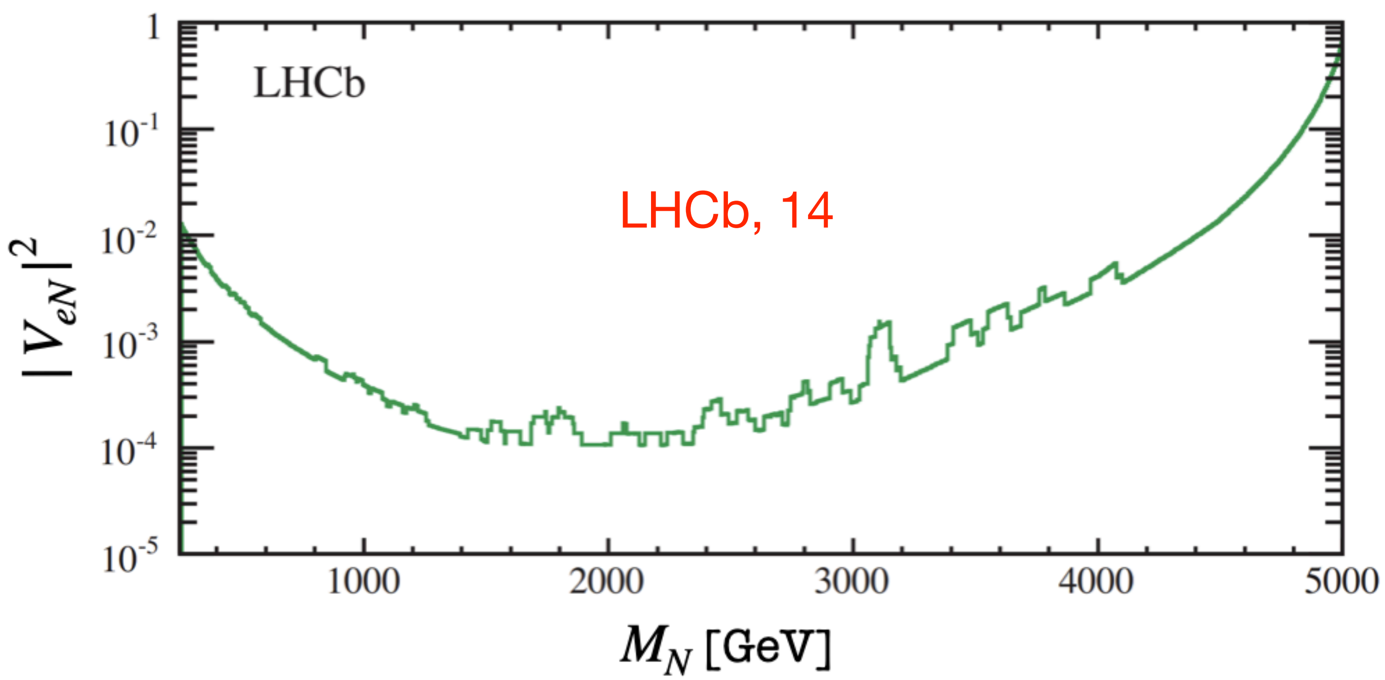
$$\Delta L = 2 : M_1^{\pm} \to \ell_a^{\pm} \ell_b^{\pm} M_2^{\mp}$$

Enhanced: If the mass of N lies in the range ~(100 MeV - 5 GeV), N on shell

$$\boxed{N_{\text{event}} = f(M_N, V_{\ell N}, p_{M_1}, L_D)}$$

Advantage compare to $0\nu\beta\beta$: lesser uncertainties in the meson decay constant compare to nuclear matrix elements.





Abada et al, 17

SM, Sinha, Mitra, 16

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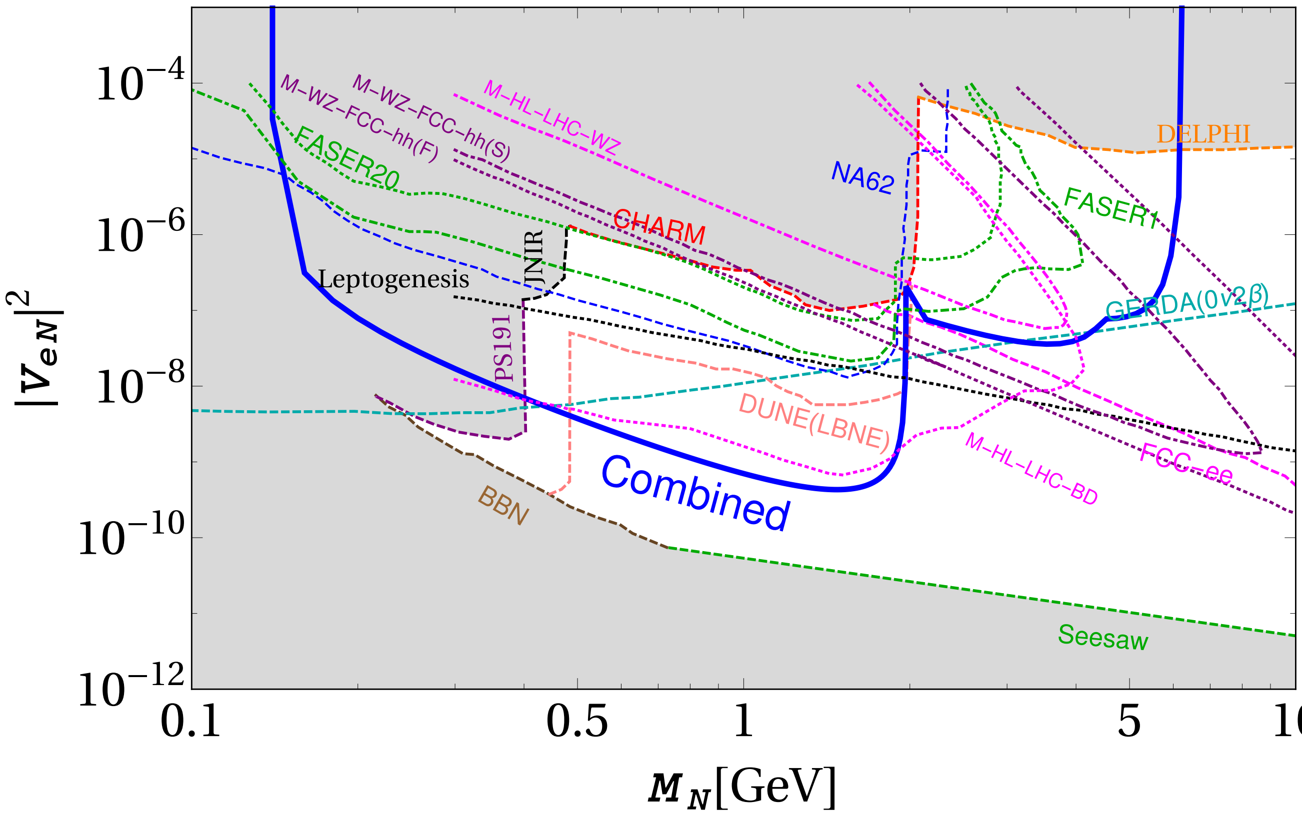
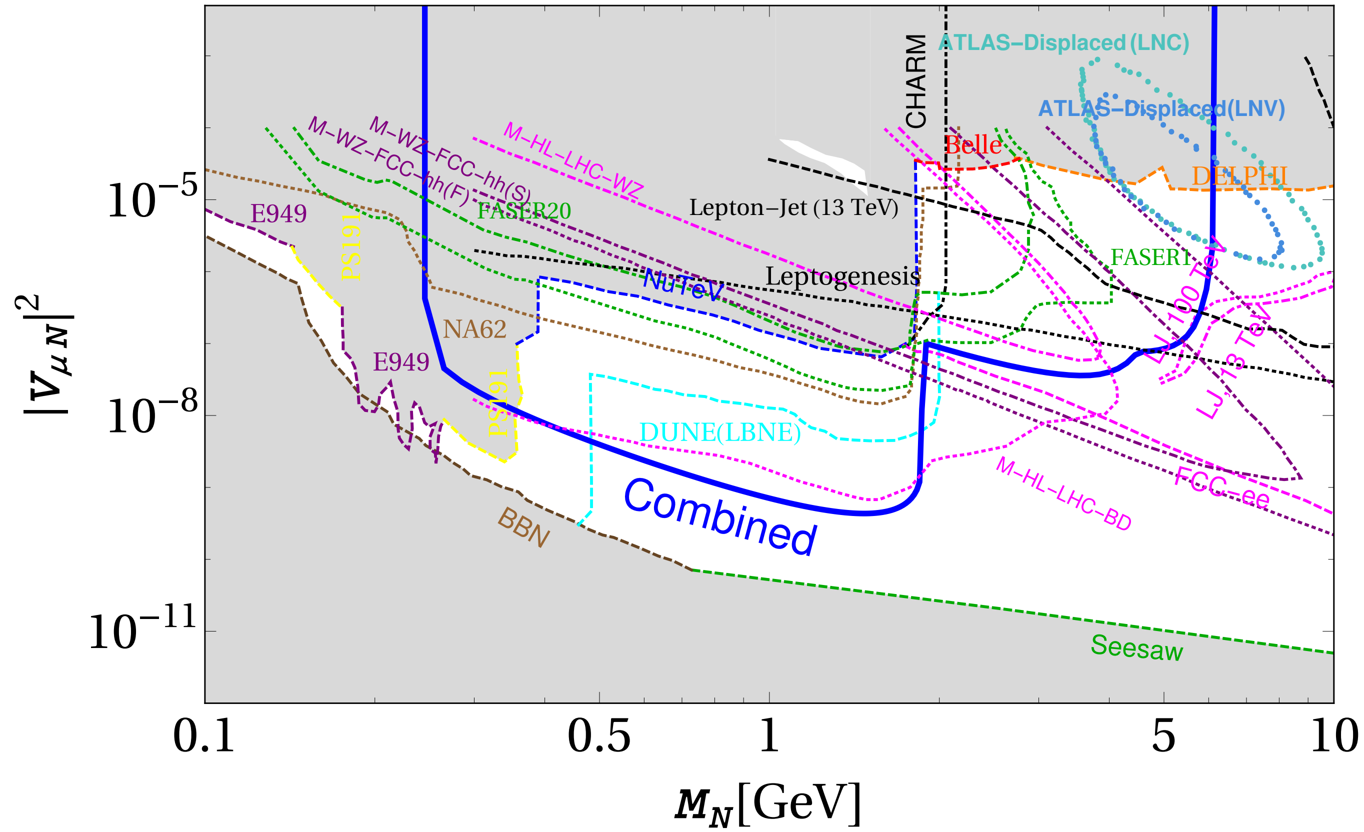
SM, Das, Shivasankar, 25

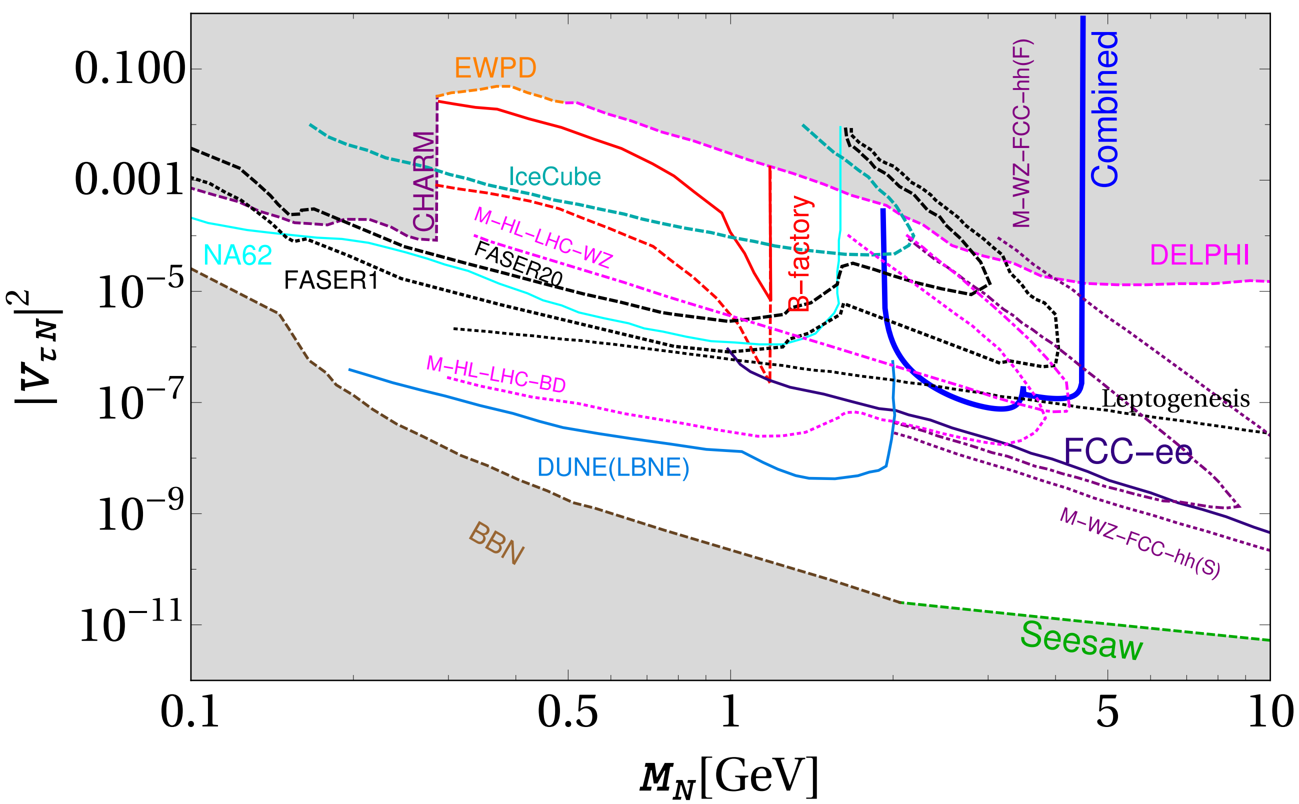
Godbole, Maharathy, SM, Mitra, Sinha, 20

Hello et al, 10

A. Atre et al, 09







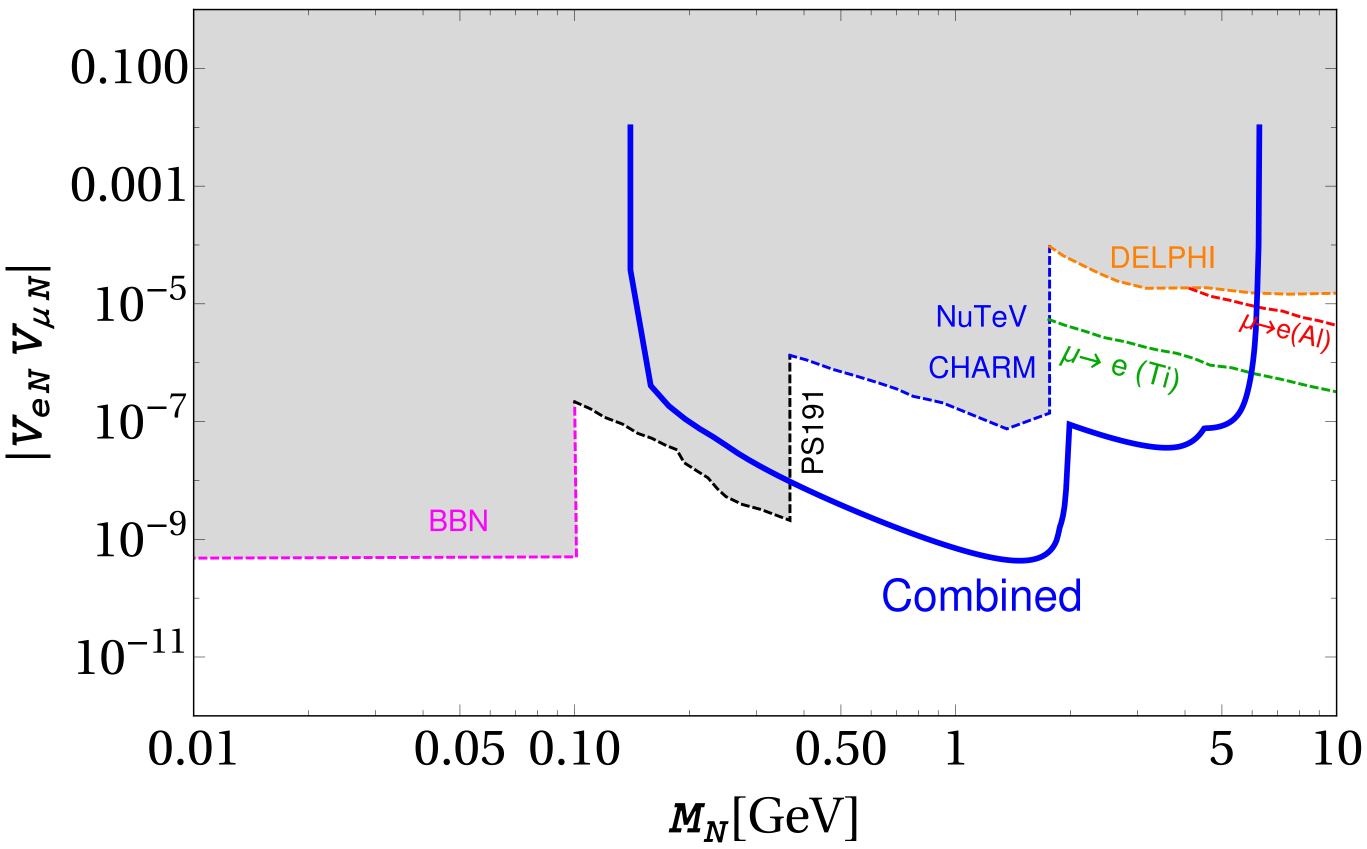
$N_K \sim 10^{13}$, $L_D \sim 100$ m, $p_K = 75$ GeV

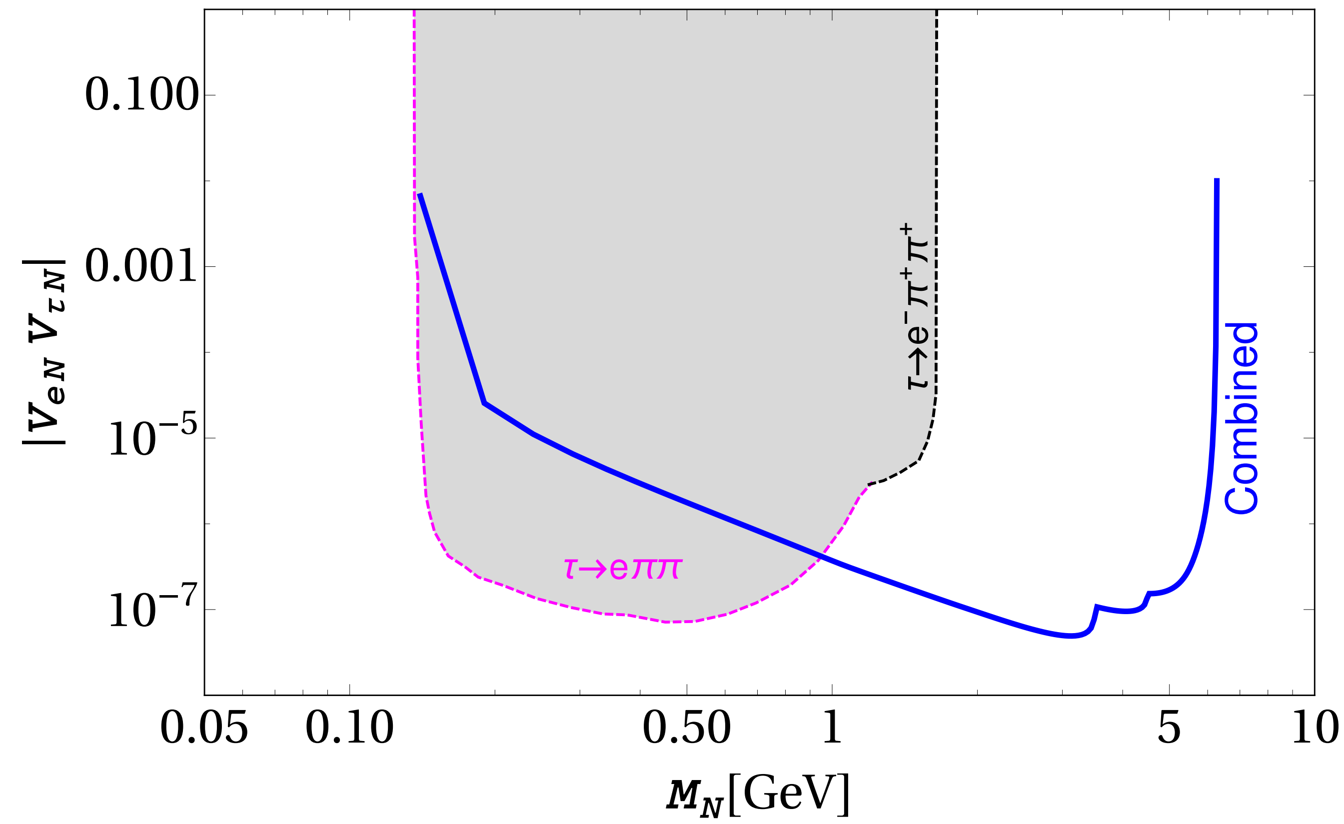
$N_{D,D_s,B} \sim 10^{10}$, $L_D \sim 1$ m, $p_{D,D_s,B} \sim 0$

$N_B \sim 10^{14}, N_D \sim 10^{13}$, $<\gamma_B> = 2.3$, $<\gamma_D> = 2.6$, $L_D \sim 50$ m

$N_B \sim 10^{12}$, $L_D \sim 1$ m, $p_B = M_Z/2$

$N_D \sim 10^{17}, N_{D_s} = 10^{16}, L_D \sim 60$ m
$p_{D,D_s} = 58$ GeV


0.100
0.001
10^{-5}
10^{-7}
10^{-9}
10^{-11}
$|V_{eN}\,V_{\mu N}|$
0.01 0.05 0.10 0.50 1 5 10
M_N[GeV]
BBN
PS191
NuTeV
CHARM
DELPHI
μ→e(Al)
μ→ e (Ti)
Combined


0.100
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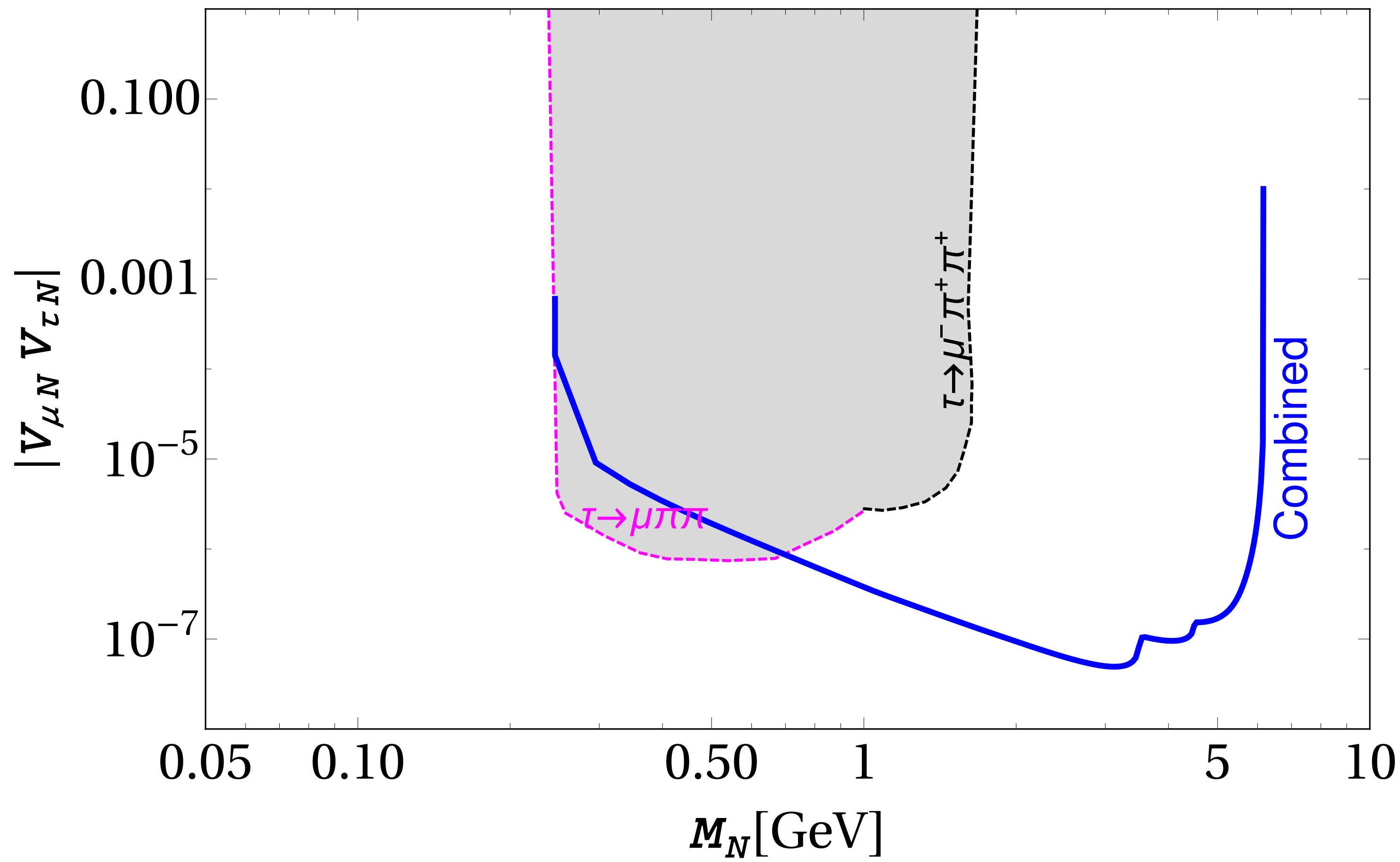
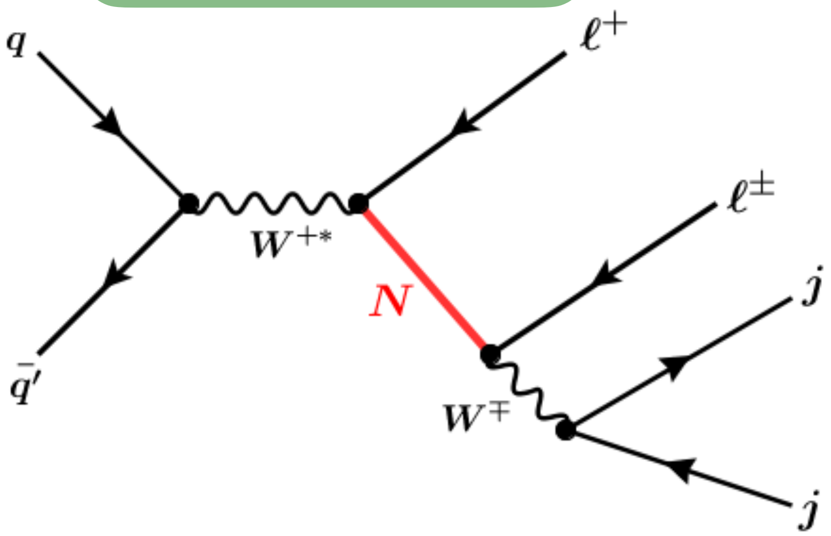
$|V_{eN}\,V_{\tau N}|$
0.05 0.10 0.50 1 5 10
M_N[GeV]
τ→e⁻π⁺π⁺
τ→eππ
Combined

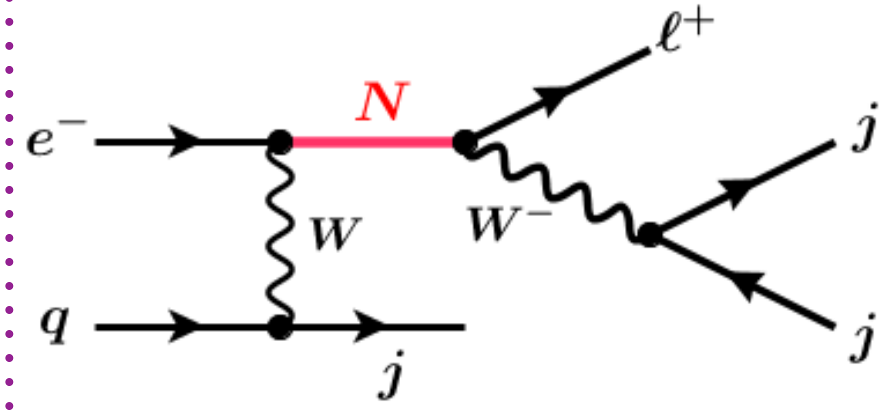

0.100
0.001
10^{-5}
10^{-7}
$|V_{\mu N}\,V_{\tau N}|$
0.05 0.10 0.50 1 5 10
M_N[GeV]
τ→μ⁻π⁺π⁺
τ→μππ
Combined

$M_N \gtrsim \mathcal{O}(10)$ GeV: High energy colliders

LHC, FCC-hh

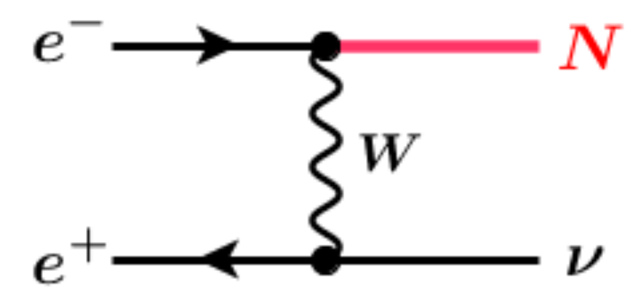


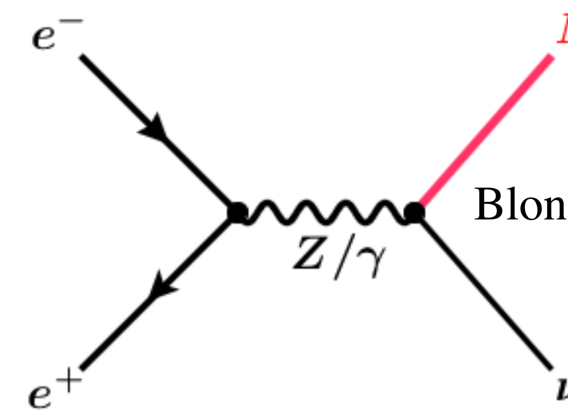
LHeC, FCC-eh



SM, Jana, Das, Nandi, 18

ILC, CLIC, FCC-ee





Blondel et al 14

Advantage: direct observation of LNV in fully reconstructed final state

If $R_{\ell\ell} = \frac{\#\,\text{LNV}}{\#\,\text{LNC}} \neq 0$ → Majorana neutrinos

$M_N \leq M_W$: displaced vertex — Cottin, Fischer, SM, Mitra, Padhan 21; Chiang, Cottin, SM 19

$M_N \geq M_W$: prompt searches — Das, LI, SM, Nomura, Zhang 24; Chun, SM, Padhan 24; Mitra, SM, Spannowsky 22

$M_N \gg M_W$: boosted jets -> fatjet — SM, Das, Shil, 23; Das, SM, Nomura, Shil 22; Das, Jana, SM, Nandi 18

At $\sqrt{s} = M_Z$:

$$N_{\text{event}} \approx 10^{12}\,|V_{eN}|^2$$

Can probe seesaw line:

$$|V_{eN}|^2 \sim m_\nu/M_N \sim 10^{-12}$$

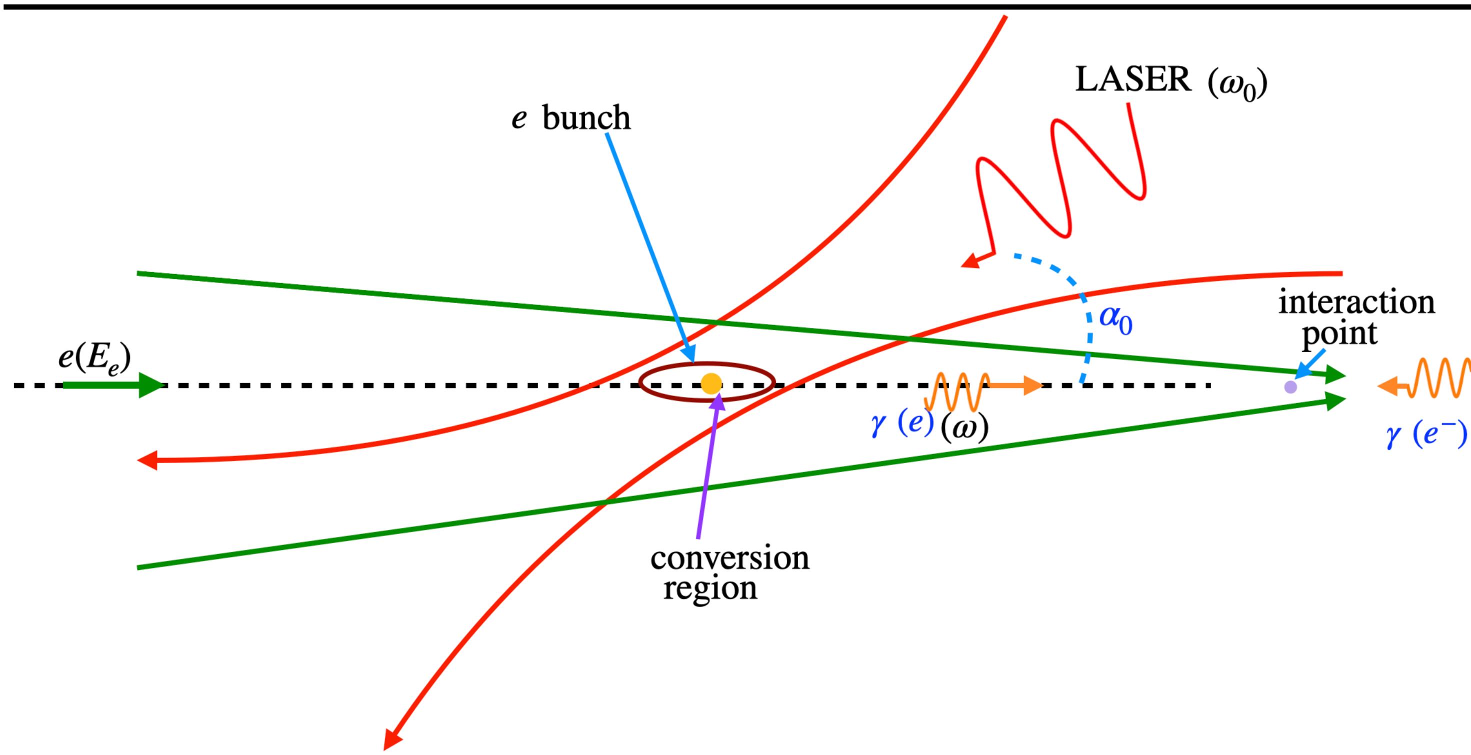
Neutrino in final state unobservable

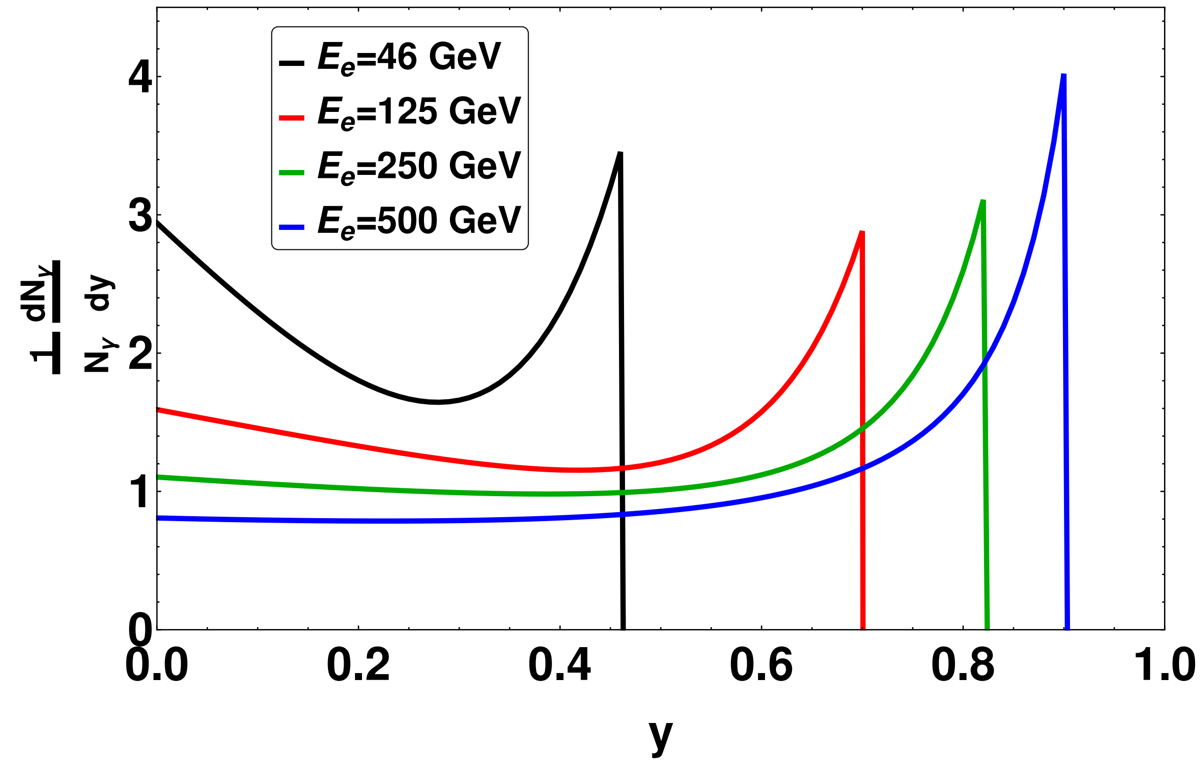
Angular distribution/polarisation of final state particles

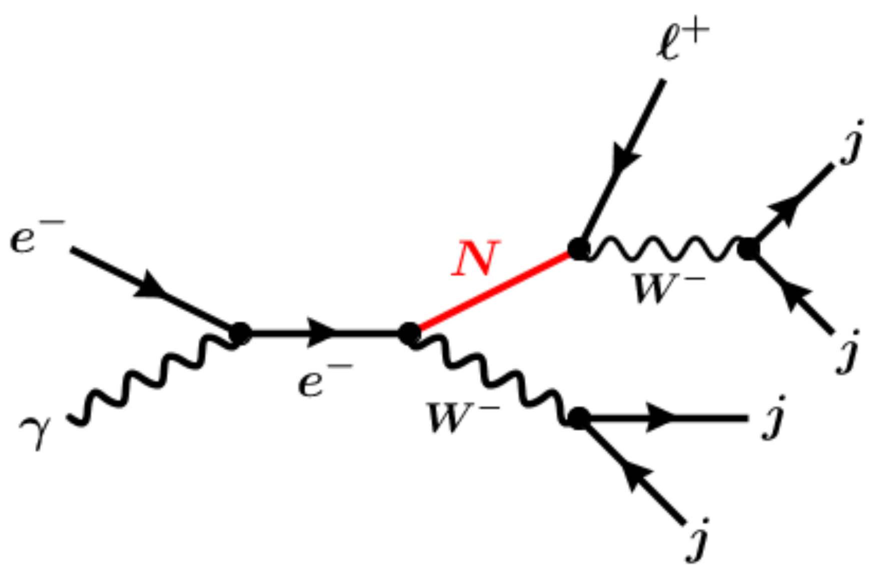
Blondel et al, 21

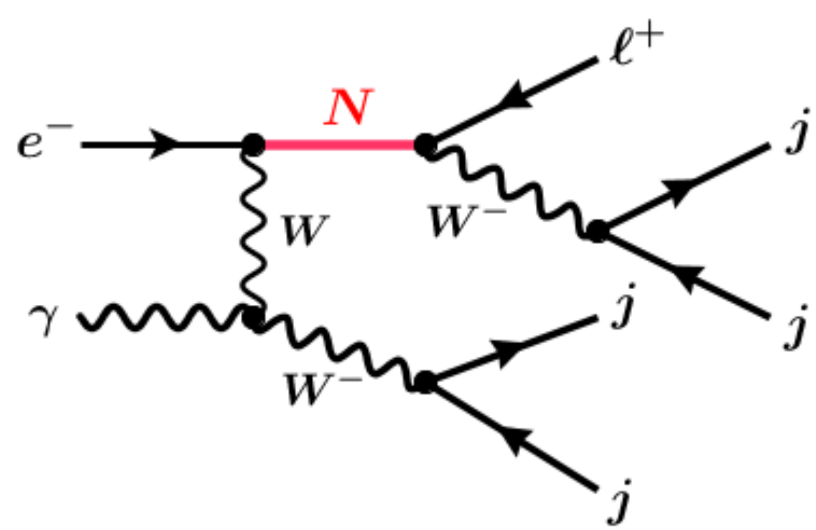
See talk by Andrea Gouvea

$e^-\gamma$ option at e^+e^- collider









Das, Li, SM, Nomura, Zhang, 24

Das, SM, Shil, 23

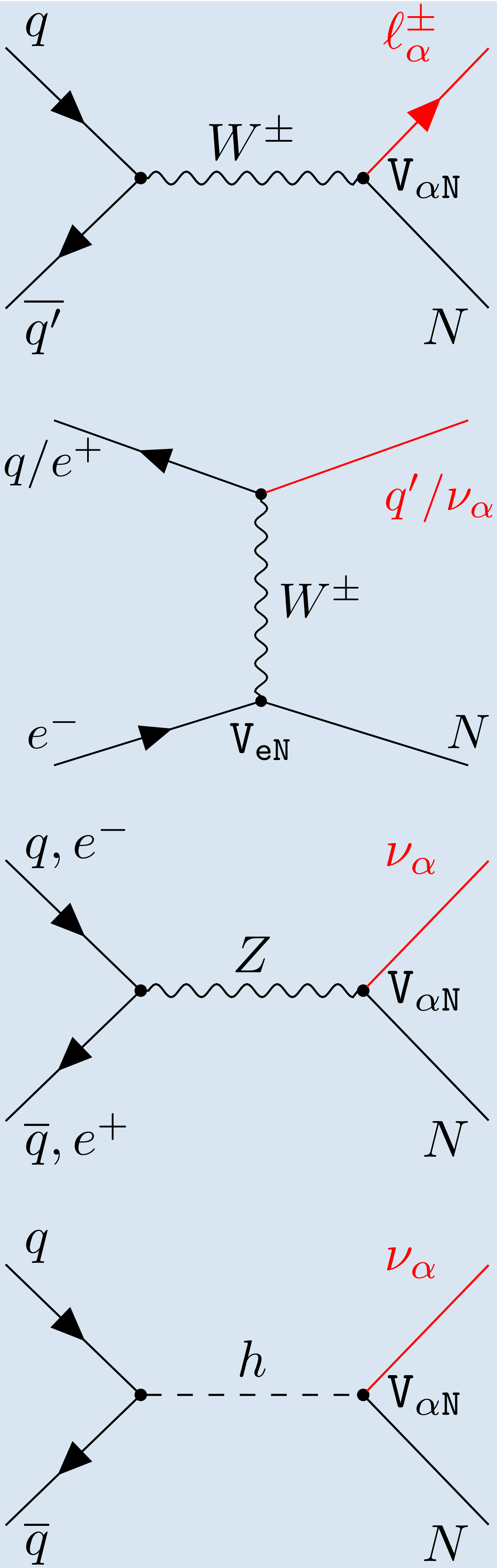
SM et al, 23

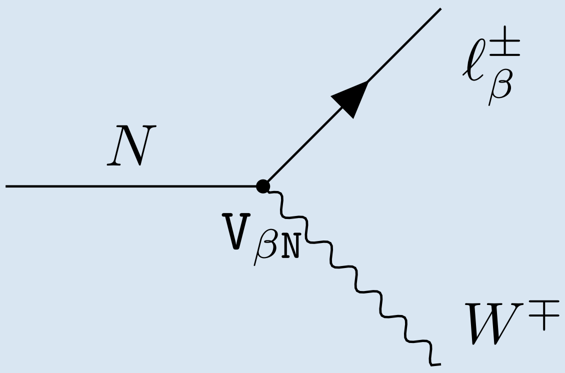
LNV: $e^-\gamma \to \ell^+ + 4j$

LNC: $e^-\gamma \to \ell^- + 4j$

$$R_{\ell\ell} = \frac{\#\,\text{LNV}}{\#\,\text{LNC}} \neq 0$$ if N is Majorana type

Systematic assessment of signatures of heavy neutrinos at colliders:

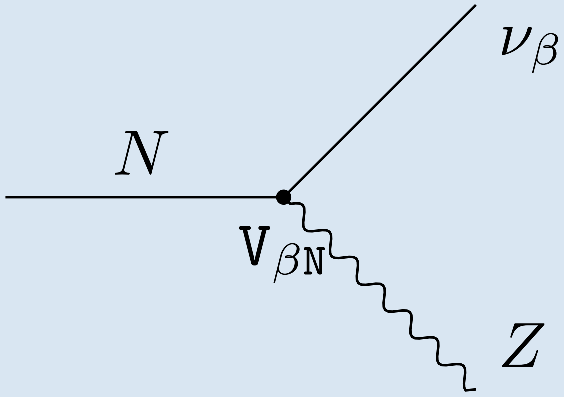




pp : $\ell_\alpha^\pm \ell_\beta^\pm jj$, $\ell_\alpha^\pm \ell_\beta^\pm \ell_\gamma^\mp \nu$

$\mathbf{e^-e^+, pp}$: $\ell_\beta^\pm jj\nu$, $\ell_\beta^\pm \ell_\gamma^\mp \nu\nu$

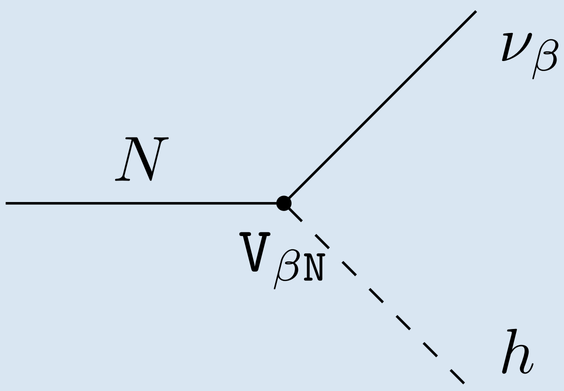
$\mathbf{e^-p}$: $\ell_\beta^\pm jjj$, $\ell_\beta^\pm \ell_\gamma^\mp j\nu$



pp : $\ell_\alpha^\pm jj\nu$, $\ell_\alpha^\pm \ell_\beta^\pm \ell_\beta^\mp \nu$, $\ell_\alpha^\pm \nu\nu\nu$

$\mathbf{e^-e^+, pp}$: $jj\nu\nu$, $\ell_\beta^\pm \ell_\beta^\mp \nu\nu$, $\nu\nu\nu\nu$

$\mathbf{e^-p}$: $jjj\nu$, $\ell_\beta^\pm \ell_\beta^\mp j\nu$, $j\nu\nu\nu$

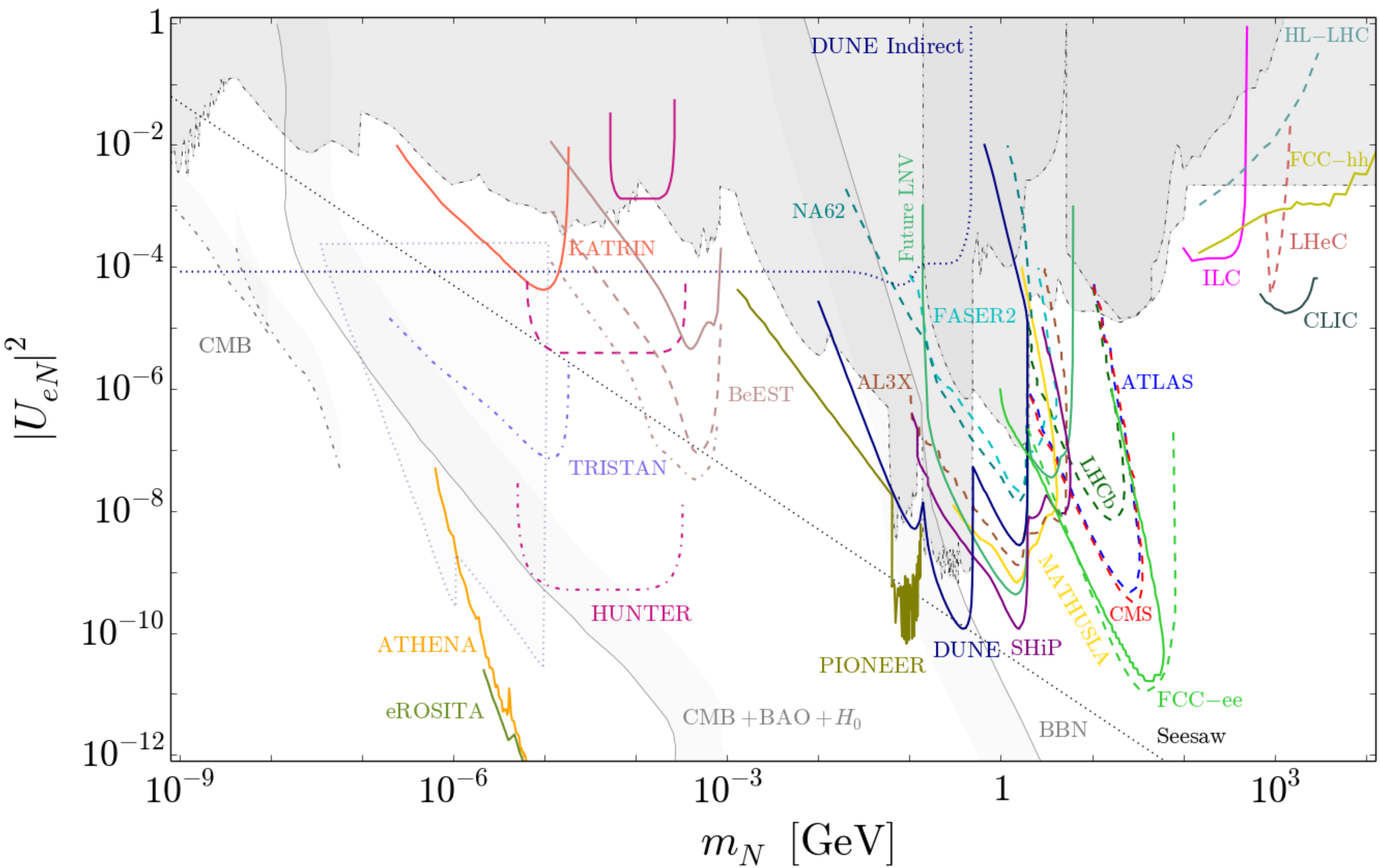


pp : $\ell_\alpha^\pm jj\nu$, $\ell_\alpha^\pm \ell_\beta^\pm \ell_\beta^\mp \nu$, $\ell_\alpha^\pm \nu VV$

$\mathbf{e^-e^+, pp}$: $jj\nu\nu$, $\ell_\beta^\pm \ell_\beta^\mp \nu\nu$, $\nu\nu VV$

$\mathbf{e^-p}$: $jjj\nu$, $\ell_\beta^\pm \ell_\beta^\mp j\nu$, $j\nu VV$

Summary of existing constraints



https://www.hep.ucl.ac.uk/~pbolton/plots.html

Heavy neutrino production beyond neutrino mixing

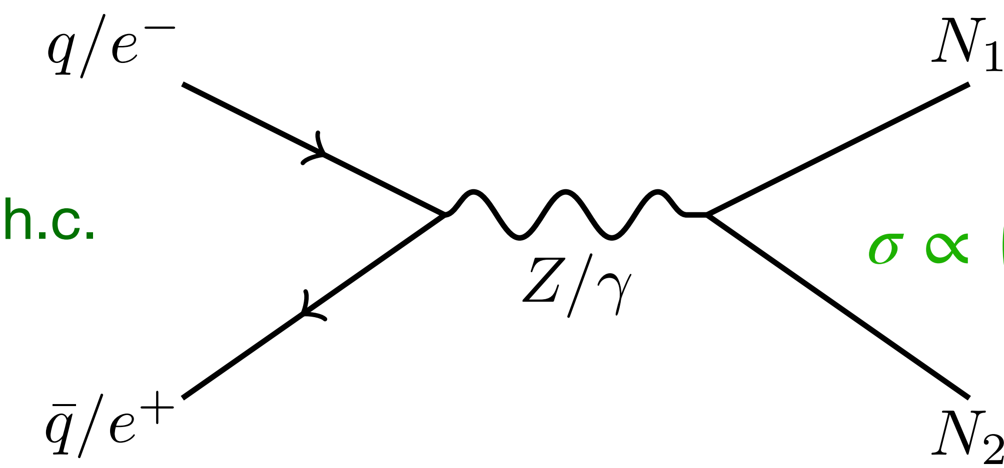
For any neutrino mass model: $\boxed{\sigma(\mathsf{LNV}) = \sigma(\mathsf{LNC})\, R}$ with $R = [0:1]$

In usual seesaw models: $\sigma(\mathrm{LNC}) \propto |V_{\ell N}|^2$, hence if $R < 1$, $\sigma(\mathrm{LNV})$ will be even smaller

With SM+RHNs, simple EFT argument suggests following dim-5 MMO:

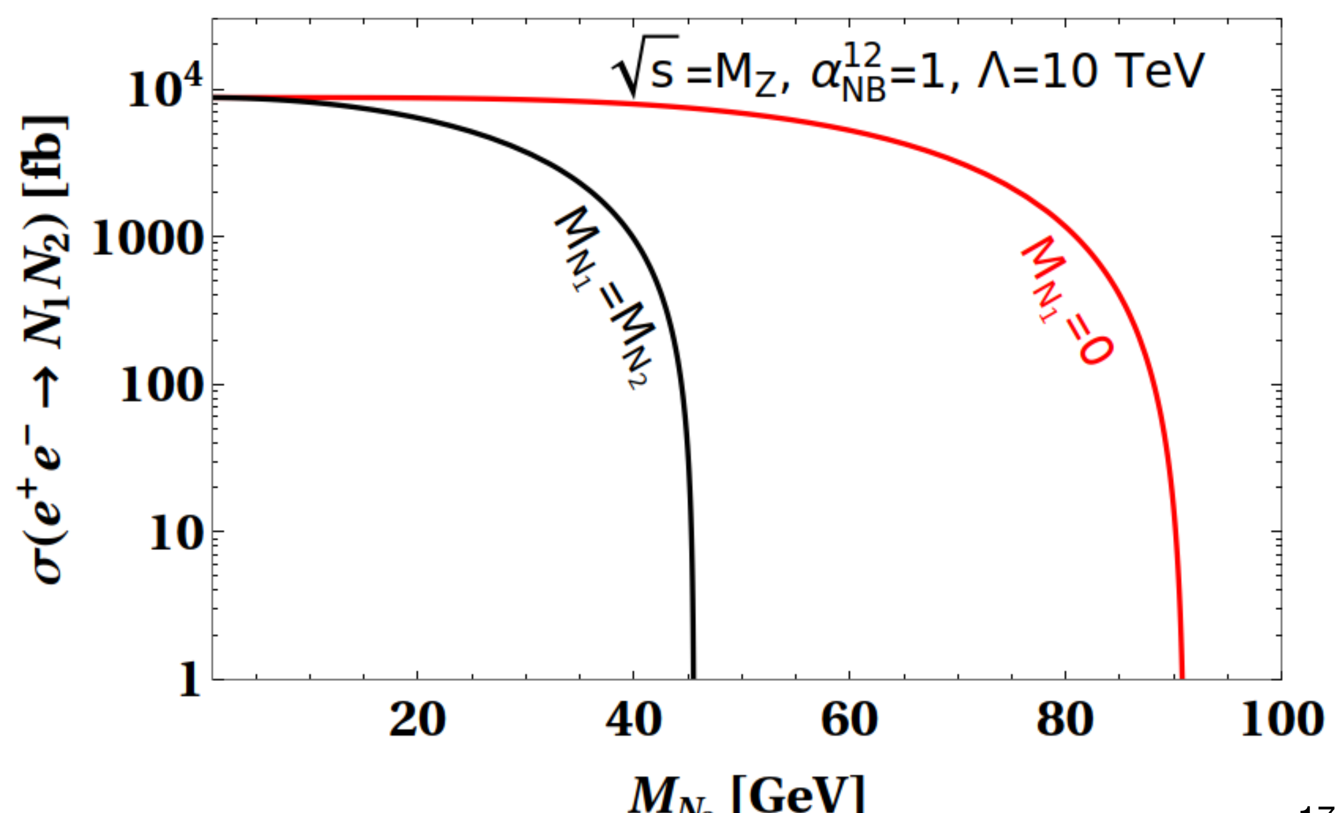
Chun, SM, Padhan 24

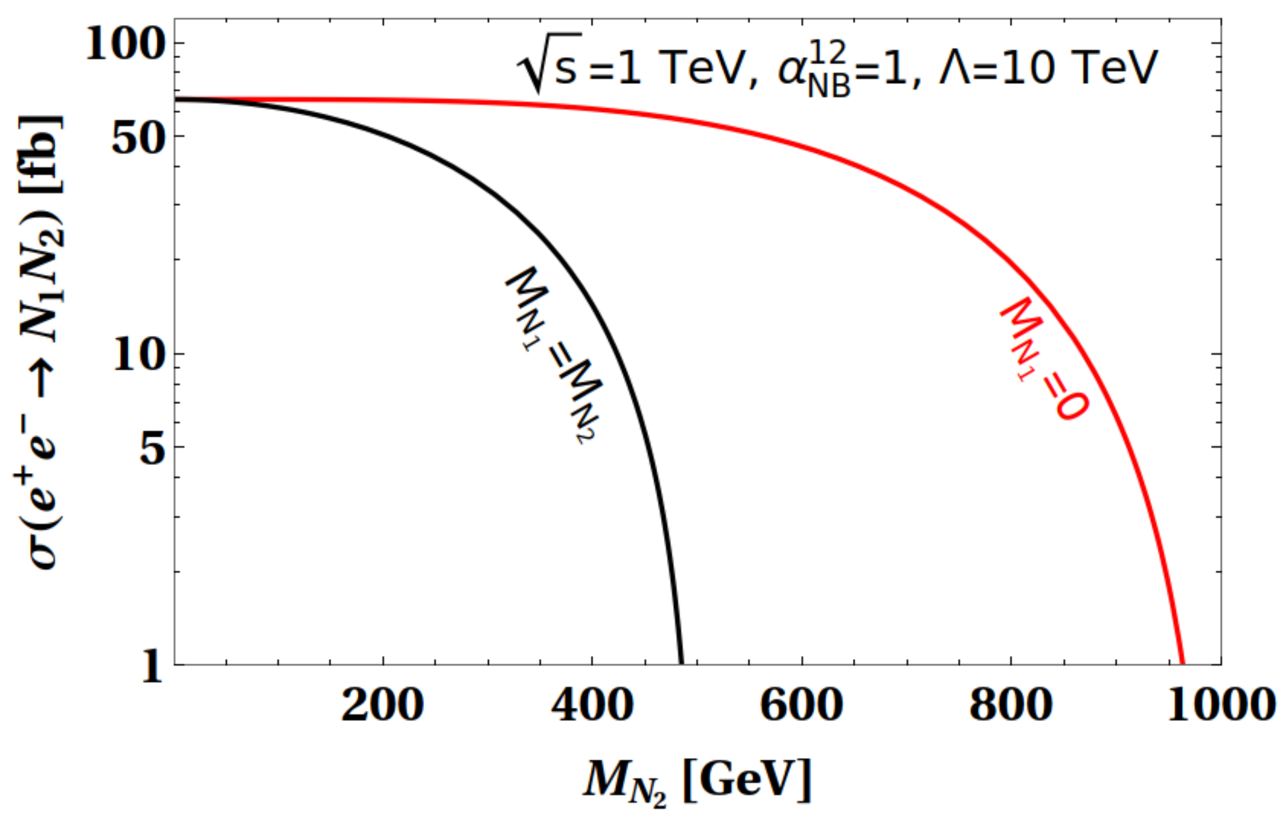
$$\mathscr{L}^5_{NB} = \frac{\alpha_{NB}}{\Lambda}\,\overline{N^c_R}\sigma_{\mu\nu}N_R\,B^{\mu\nu} + \text{h.c.}$$

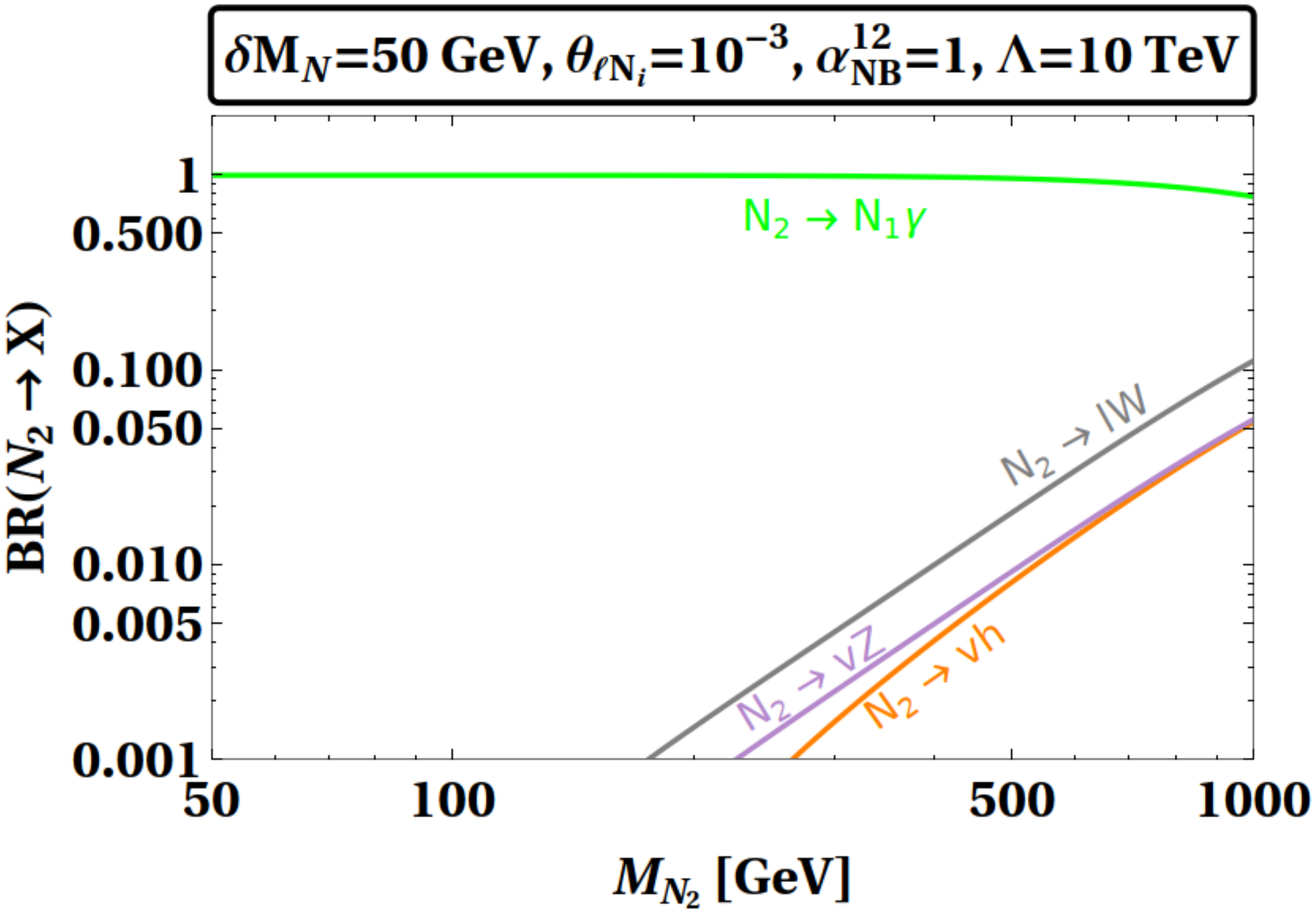


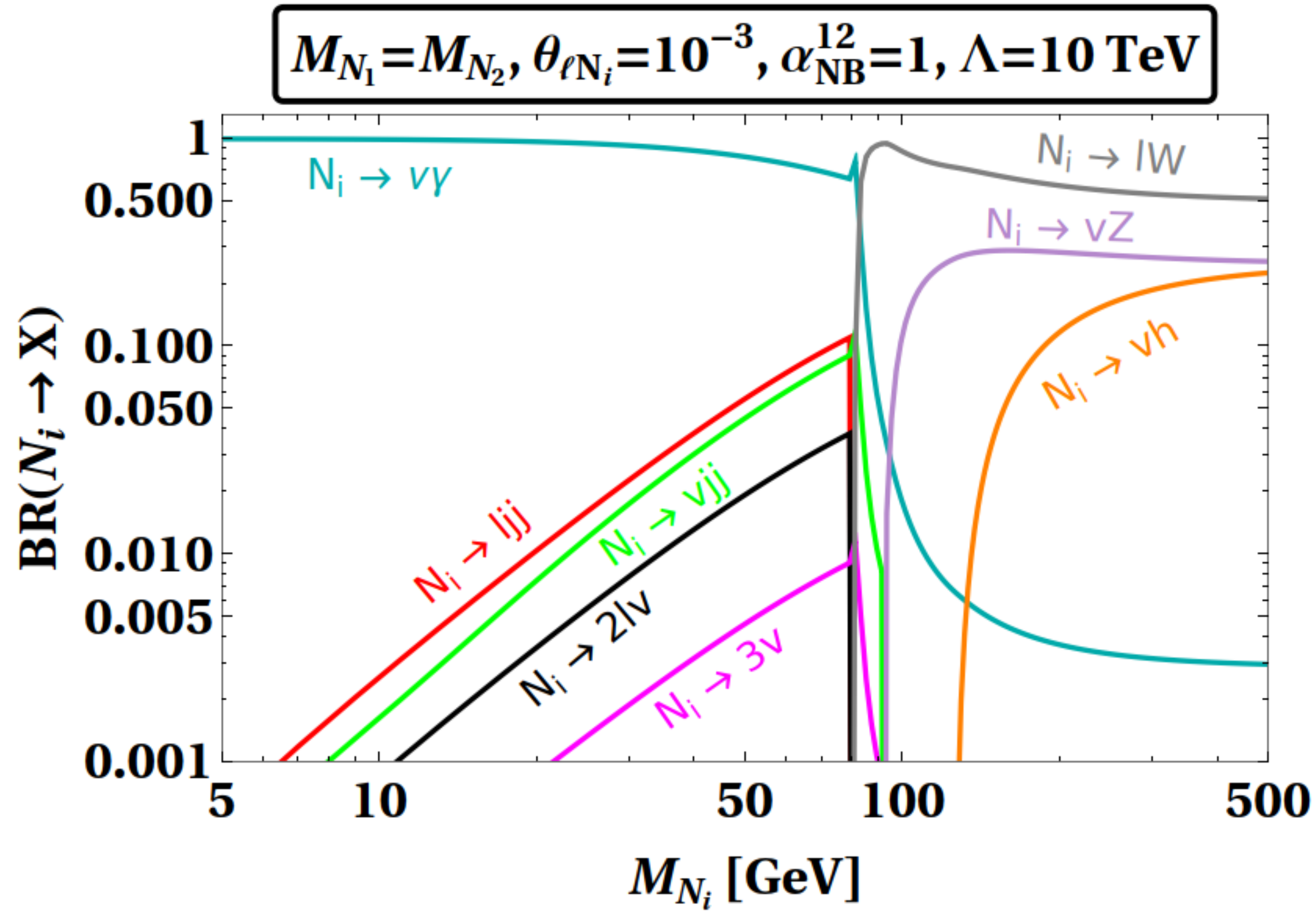
$$\sigma \propto \left(\frac{\alpha_{NB}}{\Lambda}\right)^2$$

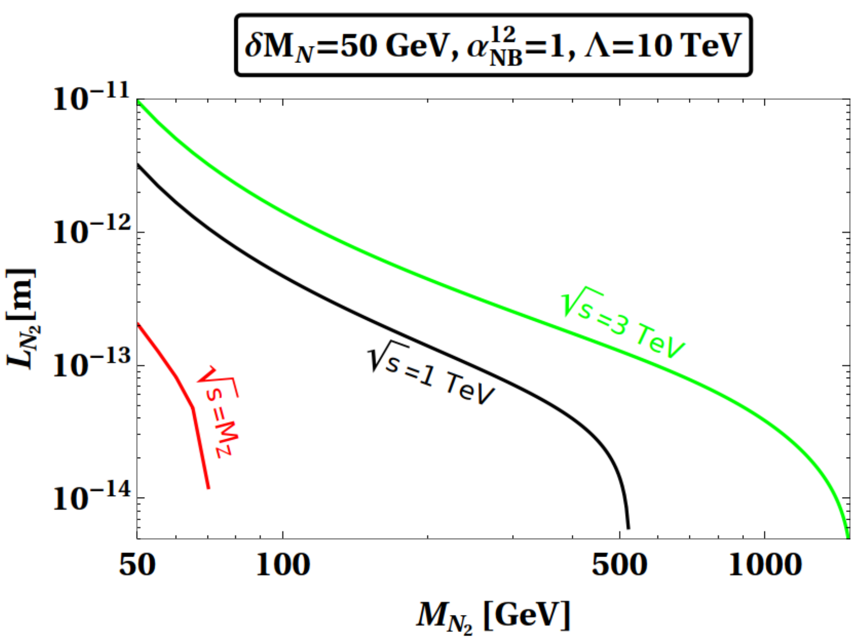
$$\sigma_{\text{seesaw}} \propto |V_{eN}|^4$$

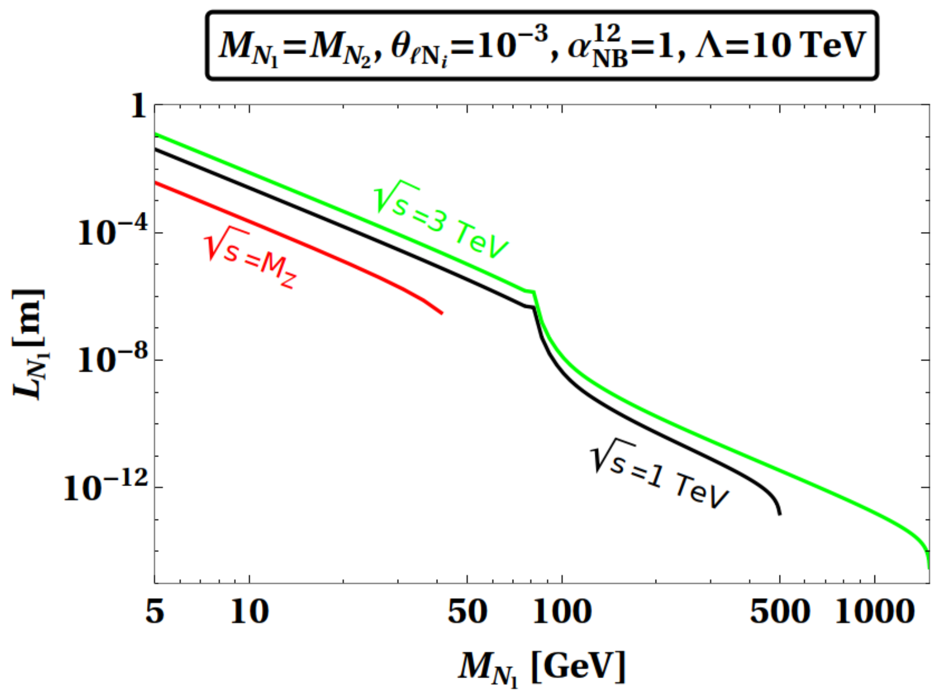


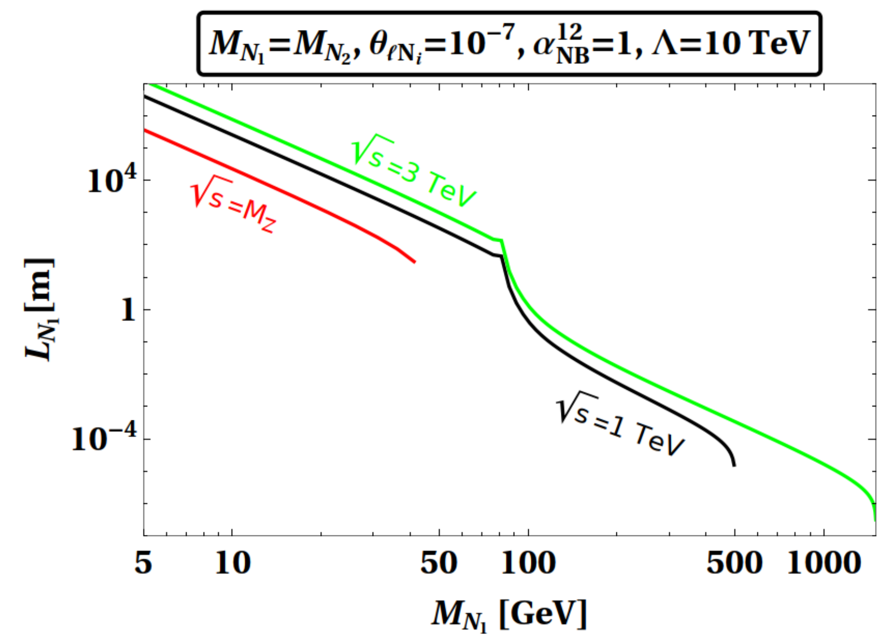












Degenerate case: $e^+e^- \to N_1 N_2,\ N_{1,2} \to \ell_a^\pm W^\mp,\ W^\mp \to jj$ ➡ $\ell_a^\pm \ell_b^\pm + 4j$

Non-degenerate case: $N_2 \to N_1\gamma,\ N_1 \to \ell_a^\pm W^\mp,\ W^\mp \to jj$ ➡ $\ell_a^\pm \ell_b^\pm + 4j + \gamma$

Minimal Linear seesaw with extra doublet

Here we realize linear seesaw within the Standard Model Gauge group itself:

$$-\mathscr{L} = Y_N \bar{L}\tilde{\Phi}N_R + Y_S \bar{L}\tilde{\chi}_L S_R + \overline{N_R^c}\, M_R\, S_R + \text{H.c.} \quad \text{with} \quad L[N_R]=1,\ L[S_R]=-1,\ L[\chi_L]=-2$$

SM, Valle et al, 23, 26

$$\mathscr{M}_\nu = \begin{pmatrix} 0 & m_D & M_L \\ m_D^T & 0 & M_R \\ M_L^T & M_R^T & 0 \end{pmatrix}$$

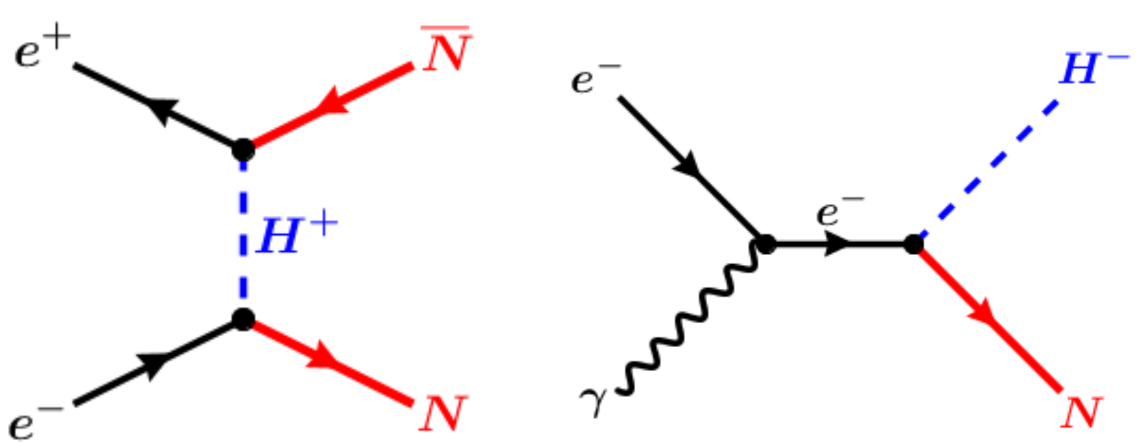
$M_L \sim Y_S v_\chi$ is small due to small v_χ. We take $Y_S \sim \mathscr{O}(1)$

How to obtain small v_χ? ➡ $V \subset -\left(\mu_{12}^2 \Phi^\dagger \chi_L + \text{h.c.}\right)$

break the global $U(1)_L$ lepton symmetry softly in the potential:

This gives the following induced VEV : $v_\chi \approx \dfrac{\mu_{12}^2 v_\Phi}{m_A^2}$ $\Rightarrow$ small for small μ_{12}

$Y_S \bar{L}\tilde{\chi}_L S_R \Rightarrow Y_S^\alpha \overline{\ell_\alpha} P_R \hat{N} H^- + \text{h.c}$



production is not mixing suppressed

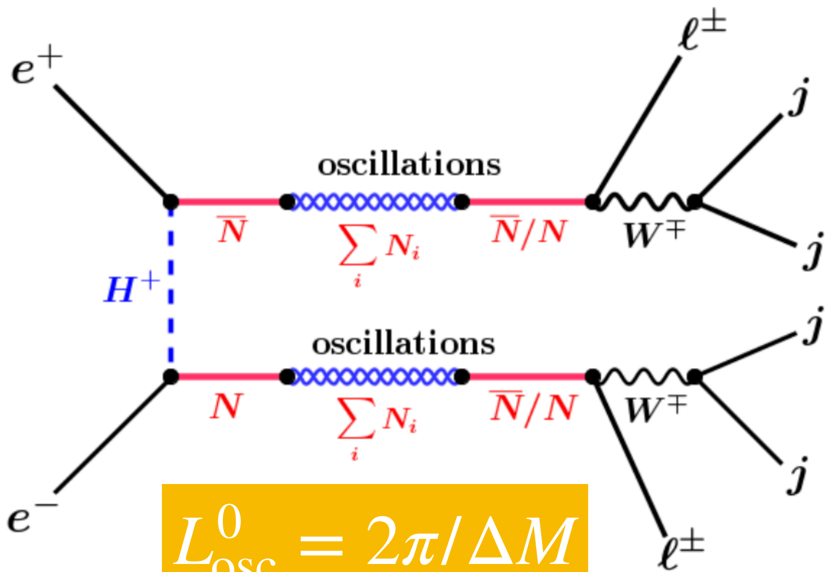
$m_{H^\pm} > M_N$: BR$(H^\pm \to \ell^\pm N) \approx 100\,\%$, BR$(N \to \ell^\pm jj) \approx 15\,\%$

$e^+e^- \to N\overline{N}$ → $\ell^\pm\ell^\pm + 4j$ (LNV); → $\ell^\pm\ell^\mp + 4j$ (LNC)

$e^-\gamma \to NH^-$ → $\ell^\pm\ell^-\ell^\pm + 4j$ (LNV); → $\ell^\pm\ell^-\ell^\mp + 4j$ (LNC)

Pair of quasi-Dirac HNL: $M_{N_1} = M_R - \dfrac{\Delta M}{2}, \qquad M_{N_2} = M_R + \dfrac{\Delta M}{2},$ with $\Delta M^{\text{NO}}(\Delta M^{\text{IO}}) = \Delta m_{32}(\Delta m_{21})$

LNC is large for large Y_S but if oscillation is not effective: LNV $\propto (\Delta M/M_N)^2$

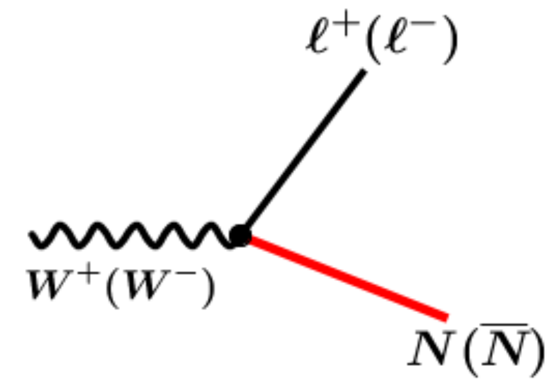


$L^0_{\rm osc} = 2\pi/\Delta M$

LNV/LNC states		Prob. factor
$N \rightsquigarrow N,\ \overline{N} \rightsquigarrow \overline{N} \Rightarrow \ell^+\ell^-4j$	[LNC]	$P^{N\to N}_{\rm osc}\, P^{\overline{N}\to\overline{N}}_{\rm osc}$
$N \rightsquigarrow \overline{N},\ \overline{N} \rightsquigarrow \overline{N} \Rightarrow \ell^+\ell^+4j$	[LNV]	$P^{N\to\overline{N}}_{\rm osc}\, P^{\overline{N}\to\overline{N}}_{\rm osc}$
$N \rightsquigarrow N,\ \overline{N} \rightsquigarrow N \Rightarrow \ell^-\ell^-4j$	[LNV]	$P^{N\to N}_{\rm osc}\, P^{\overline{N}\to N}_{\rm osc}$
$N \rightsquigarrow \overline{N},\ \overline{N} \rightsquigarrow N \Rightarrow \ell^+\ell^-4j$	[LNC]	$P^{N\to\overline{N}}_{\rm osc}\, P^{\overline{N}\to N}_{\rm osc}$

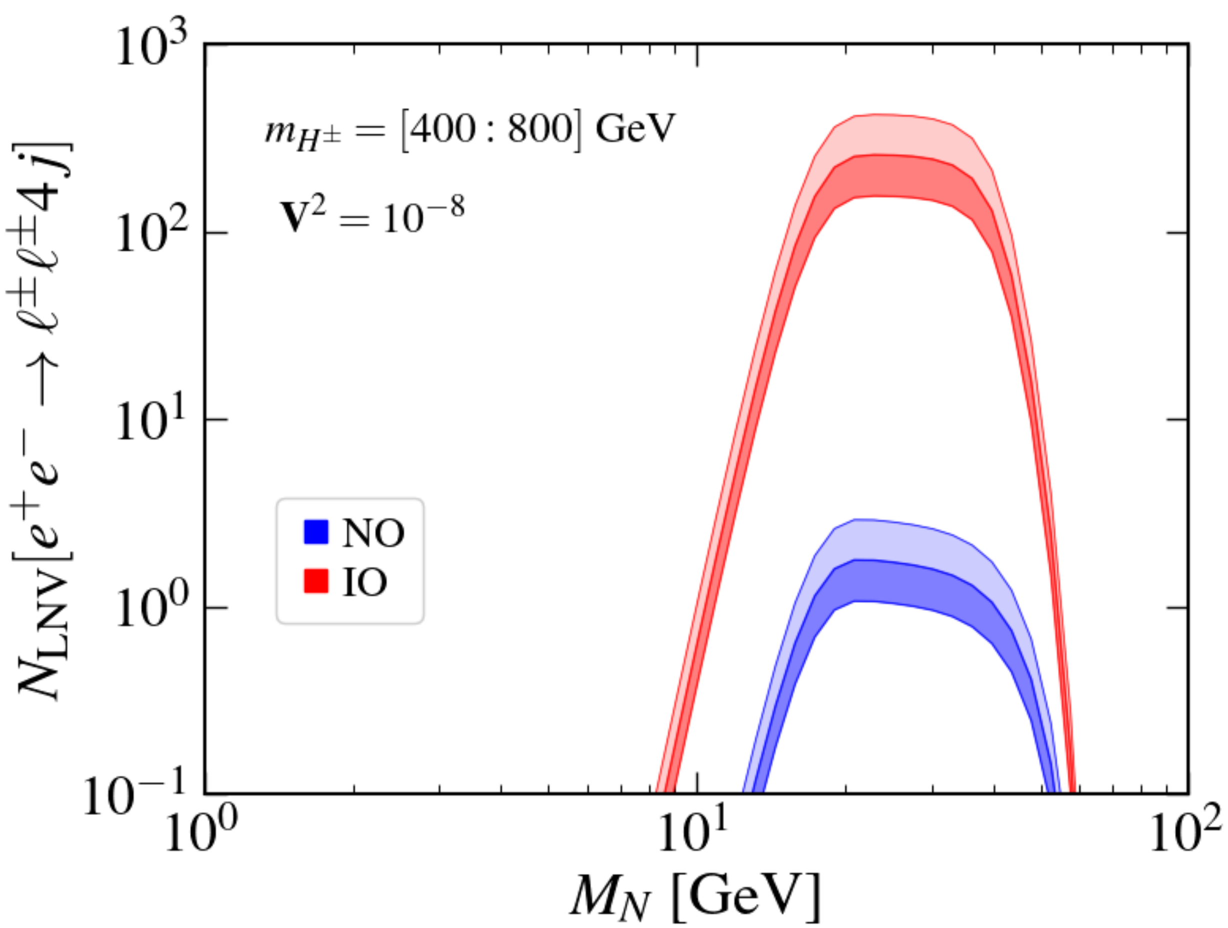
$N = (-iN_1 + N_2)/\sqrt{2}$

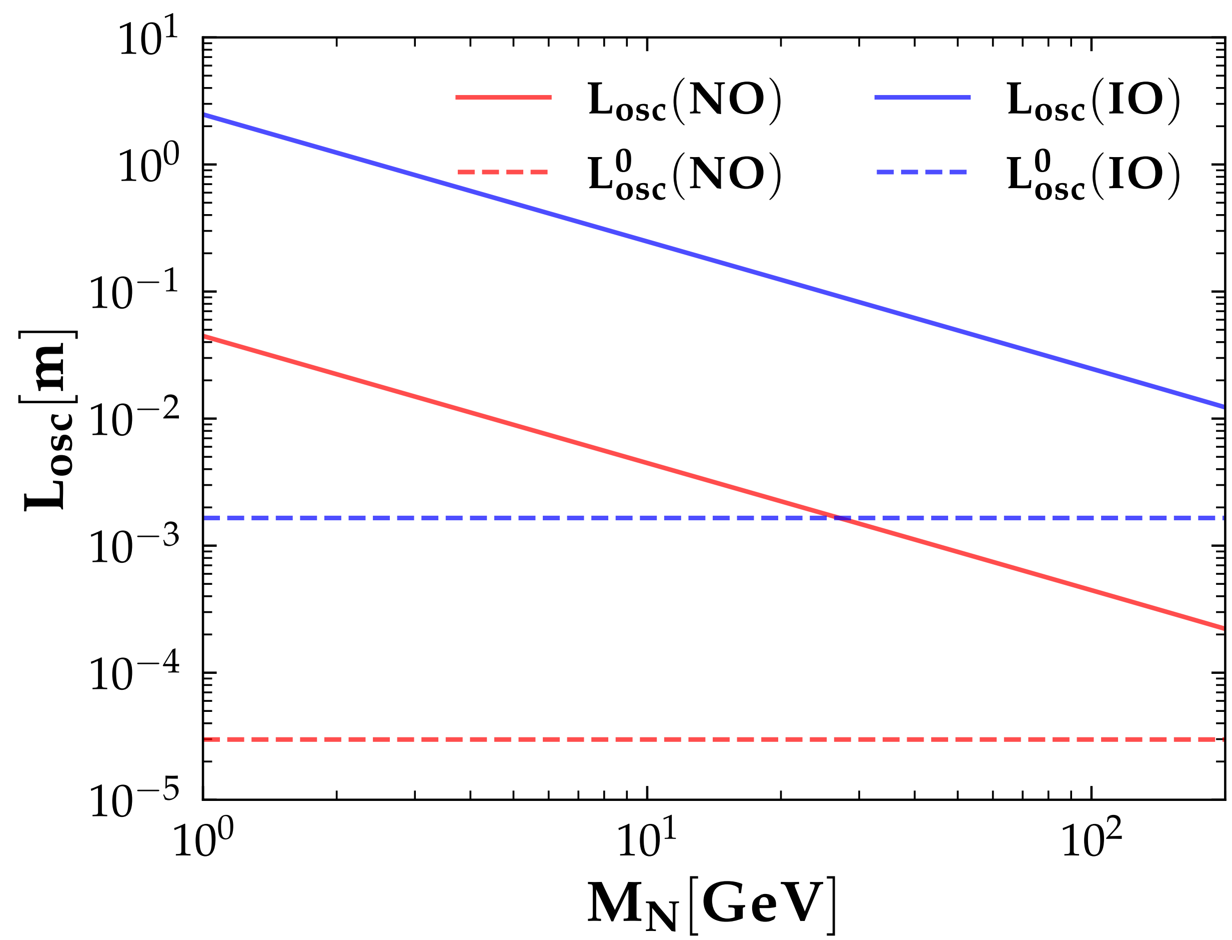
$\overline{N} = (iN_1 + N_2)/\sqrt{2}$



If $\Delta M \ll \Gamma_N$ ($L_N \ll L_{\rm osc}$) , decays before they have time to oscillate: destructive interference

If $\Delta M \gg \Gamma_N$ ($L_N \gg L_{\rm osc}$), they have time to oscillate many times before decay: oscillations are averaged out





Large LNV through Leptoquark ?

Matter stability + RHN coupling

RHN production can be large

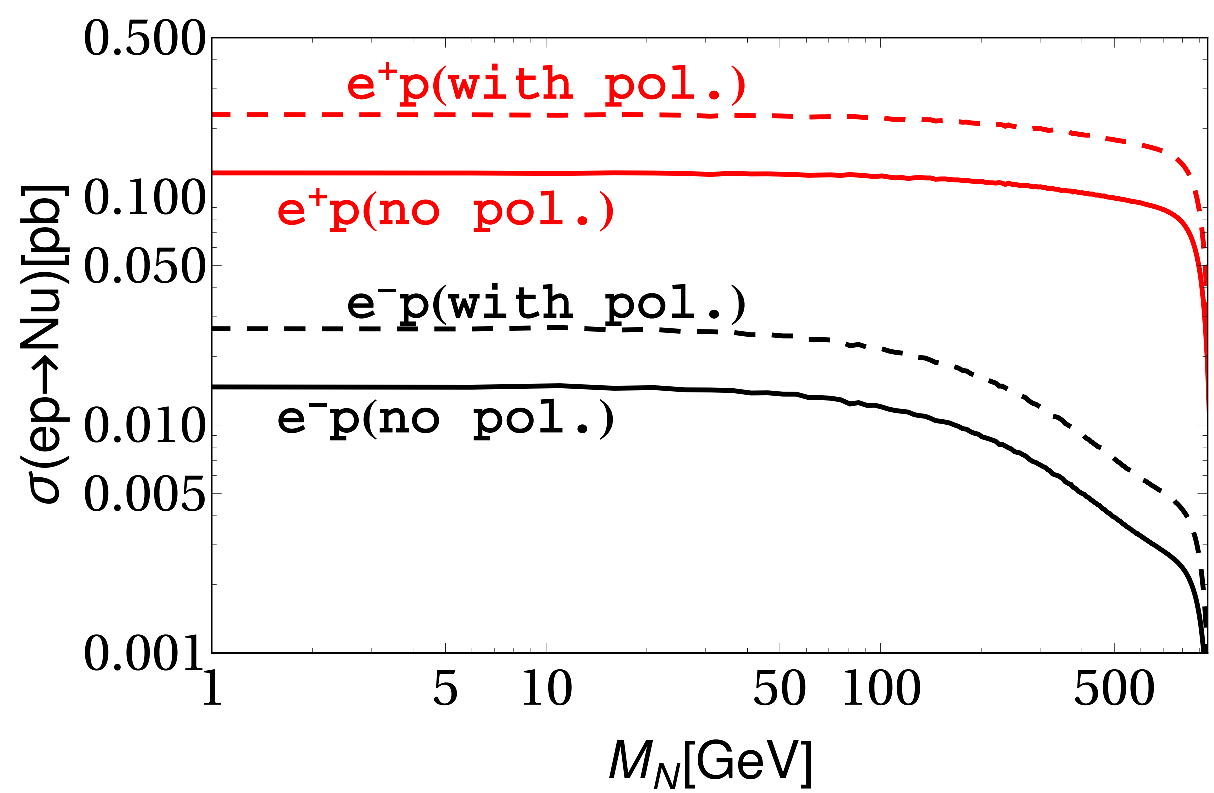
$$\mathcal{L} = -Y_{ij}\bar{d}^i_R \tilde{R}^a_2 \epsilon^{ab} L^{j,b}_L + Z_{ij}\bar{Q}^{i,a}_L \tilde{R}^a_2 N^j_R + h.c.,$$

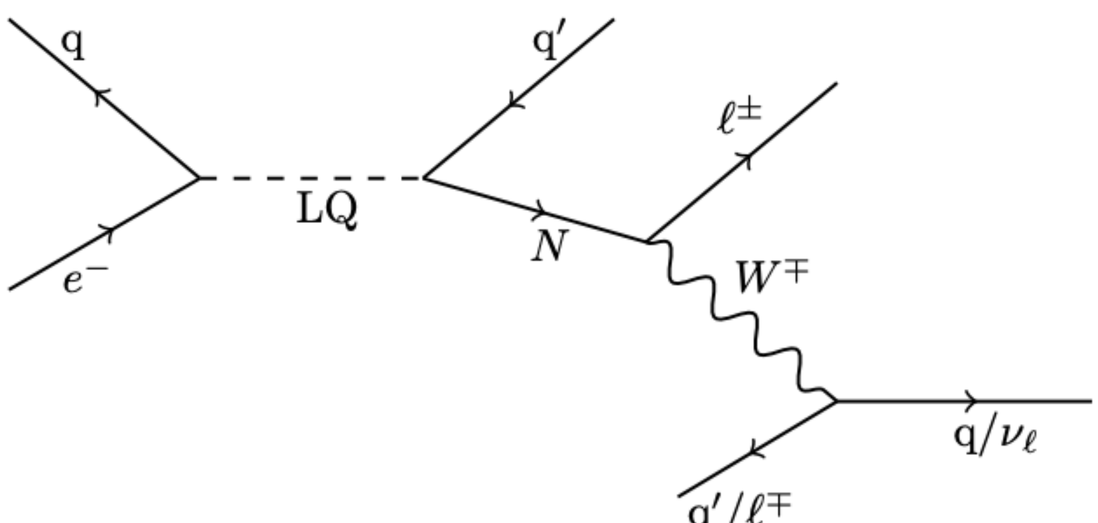
$$= -Y_{ij}\bar{d}^i_R e^j_L \tilde{R}^{2/3}_2 + (YU_{\rm PMNS})_{ij}\bar{d}^i_R \nu^j_L \tilde{R}^{-1/3}_2 + (V_{\rm CKM}Z)_{ij}\bar{u}^i_L N^j_R \tilde{R}^{2/3}_2 + Z_{ij}\bar{d}^i_L N^j_R \tilde{R}^{-1/3}_2 + h.c.,$$

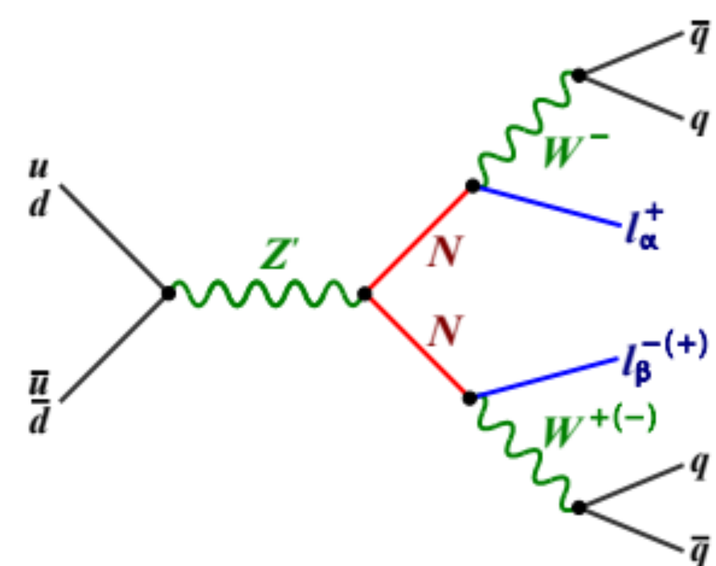
At e^-p and e^+p collider, the relevant couplings are: e^-_L – LQ – $\bar{d}$ and e^+_R – LQ – d

Quark parton distribution function is larger than that for anti-quark.

Due to e^-_L – LQ – $\bar{d}$ and e^+_R – LQ – d coupling:
Polarization enhancement







LNV: $e^-p \to \ell^+ + 3j$

N_R-EFT: SM+RHNs

In an effective field theory (EFT) framework, adding **gauge-singlet right-handed neutrinos** N allows a wide class of higher-dimensional operators, such as:

$$\mathscr{L} \equiv \mathscr{L}_{\rm SM} + \sum_{n>4} \frac{\mathscr{O}_n}{\Lambda^{n-4}} + \text{h.c.}$$

Dim-5 operators:

$$\mathscr{O}^5_W = \alpha_W (\overline{L^c_L}\tilde{H})(\tilde{H}^\dagger L_L), \quad \mathscr{O}^5_{NH} = \alpha_{NH}\overline{N^c_R}N_R(H^\dagger H)$$

$$\mathscr{O}^5_{NB} = \alpha_{NB}\overline{N^c_R}\sigma_{\mu\nu}N_R B^{\mu\nu}$$

Dim-6 operators:

	Operator	Notation	Operator	Notation
SF	$(\overline{l_L}N)\tilde{H}(H^\dagger H)$	$\mathcal{O}_{lNH}$ (+h.c.)		
	$(\overline{N}\gamma^\mu N)(H^\dagger i\overleftrightarrow{D}_\mu H)$	$\mathcal{O}_{HN}$	$(\overline{N}\gamma^\mu e_R)(\tilde{H}^\dagger iD_\mu H)$	$\mathcal{O}_{HNe}$ (+h.c.)
	$(\overline{l_L}\sigma_{\mu\nu}N)\tilde{H}B^{\mu\nu}$	$\mathcal{O}_{NB}$ (+h.c.)	$(\overline{l_L}\sigma_{\mu\nu}N)\sigma_I\tilde{H}W^{I\mu\nu}$	$\mathcal{O}_{NW}$ (+h.c.)
RRRR	$(\overline{N}\gamma_\mu N)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{NN}$		
	$(\overline{e_R}\gamma_\mu e_R)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{eN}$	$(\overline{u_R}\gamma_\mu u_R)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{uN}$
	$(\overline{d_R}\gamma_\mu d_R)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{dN}$	$(\overline{d_R}\gamma_\mu u_R)(\overline{N}\gamma^\mu e_R)$	$\mathcal{O}_{duNe}$ (+h.c.)
LLRR	$(\overline{l_L}\gamma_\mu l_L)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{lN}$	$(\overline{q_L}\gamma_\mu q_L)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{qN}$
LRRL	$(\overline{l_L}N)\epsilon(\overline{l_L}e_R)$	$\mathcal{O}_{lNle}$ (+h.c.)	$(\overline{l_L}N)\epsilon(\overline{q_L}d_R)$	$\mathcal{O}_{lNqd}$ (+h.c.)
	$(\overline{l_L}d_R)\epsilon(\overline{q_L}N)$	$\mathcal{O}_{ldqN}$ (+h.c.)	$(\overline{q_L}u_R)(\overline{N}l_L)$	$\mathcal{O}_{quNl}$ (+h.c.)

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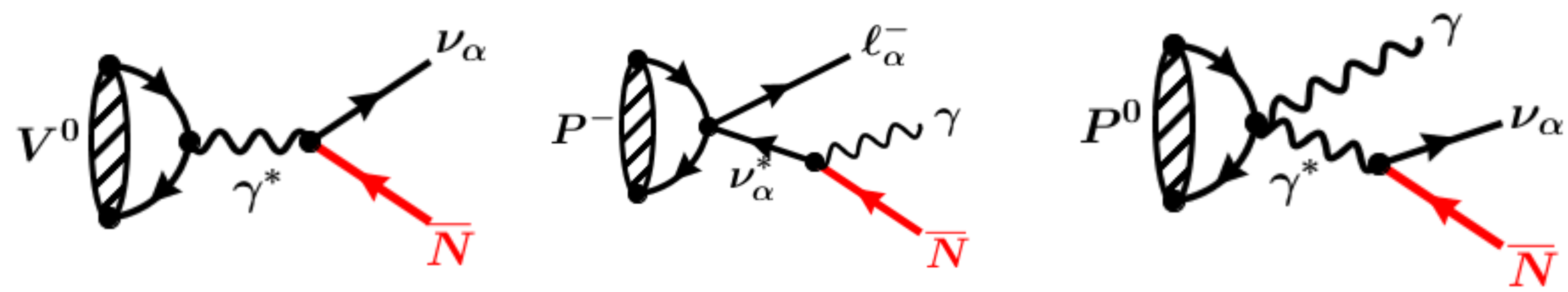
Mitra, SM, Padhan, Sarkar, Spannowsky 22

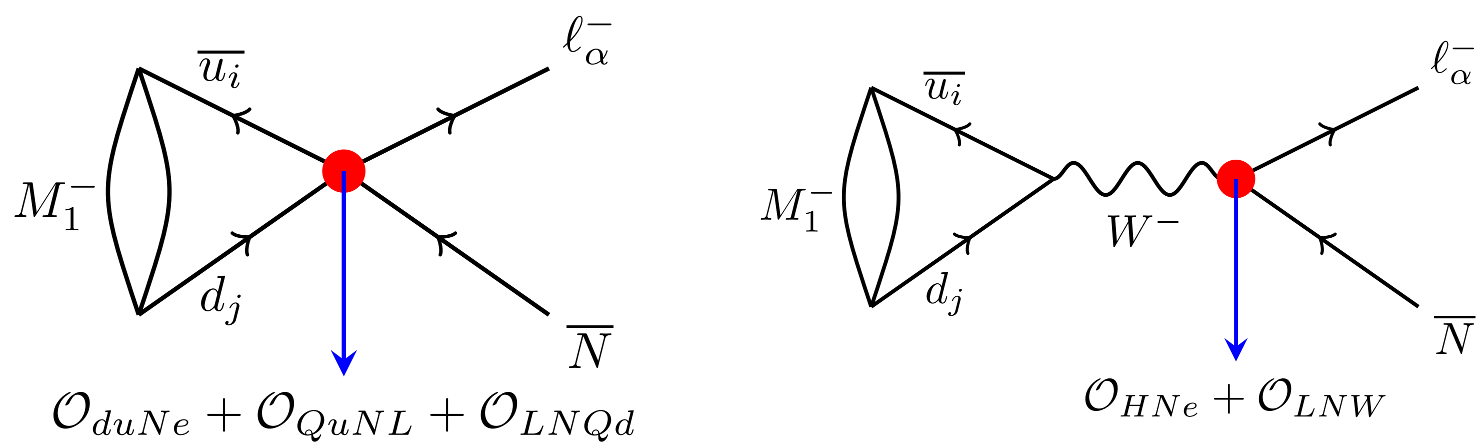
Production of heavy neutrinos and their decay modes at Beam Dump Experiments will vary depending on what kind of EFT operators we are considering

Dipole portal: $\bar{\nu}\sigma_{\mu\nu}NF^{\mu\nu}$

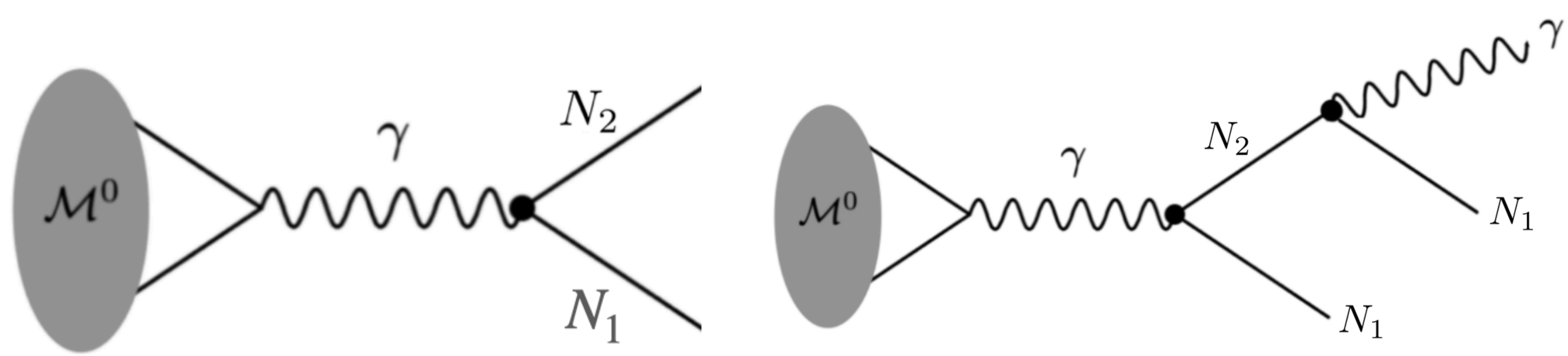


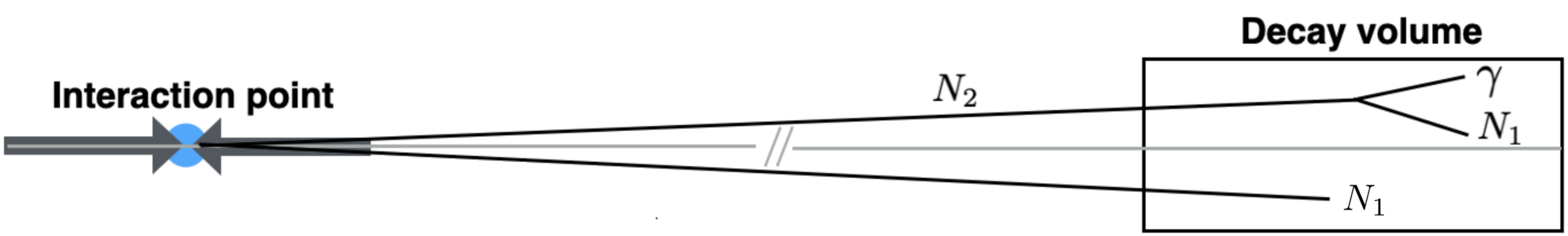
GRB221009A

Four-fermion:

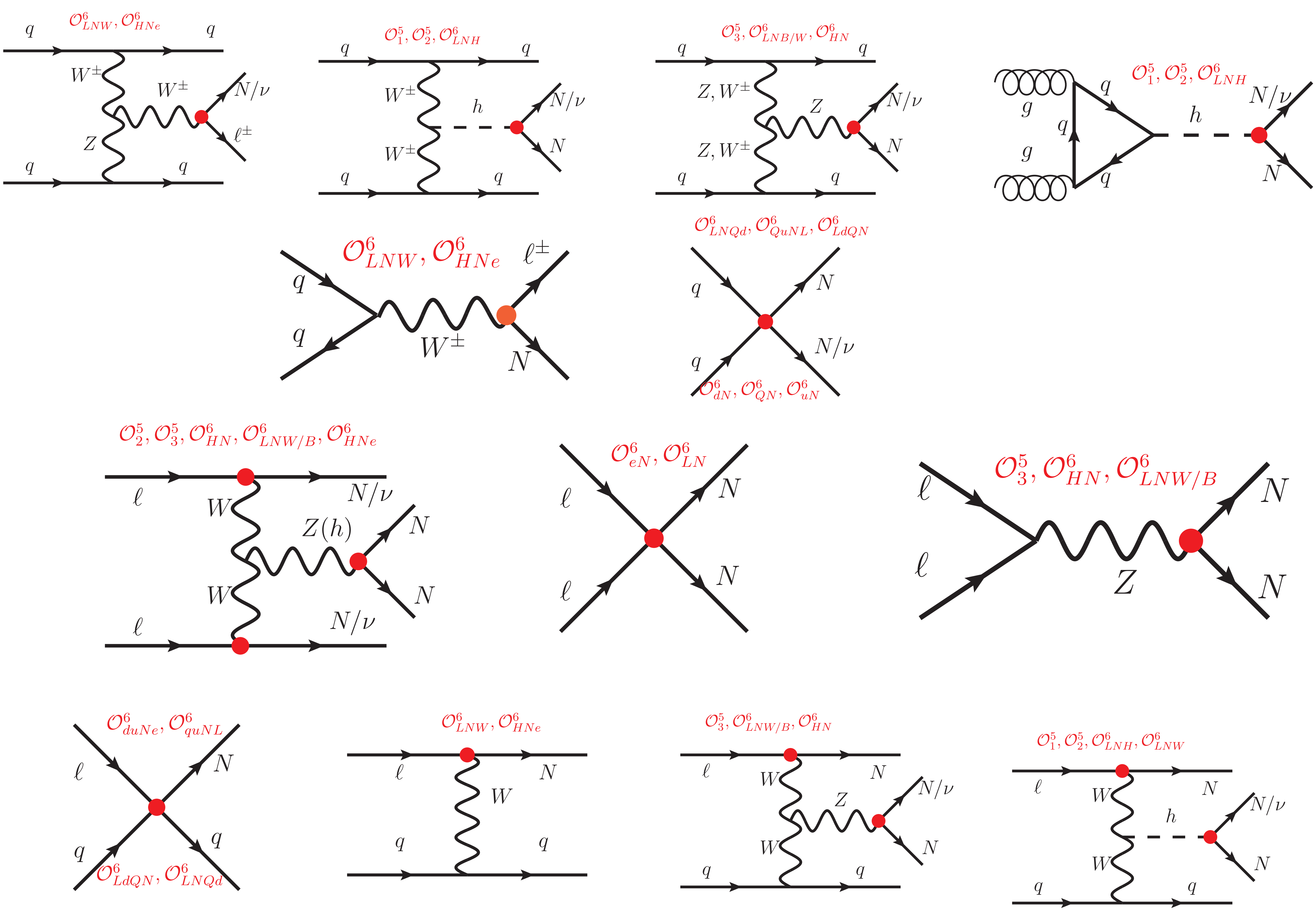


MMO: $\overline{N_R^c}\sigma_{\mu\nu}N_R B^{\mu\nu}$





Systematic study of all possible heavy neutrino production mechanism



Conclusions

- Understanding the neutrino mass mechanism will provide important insights into the BSM world

- Could shed light on other standing puzzles, such as the matter-antimatter asymmetry and dark matter

- If neutrinos are Majorana particles, the mechanism that generates their mass can generate LNV.

- Ratio of same-sign to opposite-sign di-lepton signal could test the Majorana vs. Dirac nature

- $\Delta L = 2$ processes at high energy collider: $pp \to \ell_\alpha^\pm \ell_\beta^\pm jj$, $e^- p \to \ell_\alpha^+ + 3j$, $e^- e^+ \to \ell_\alpha^\pm \ell_\beta^\pm + 4j$ and $e^- \gamma \to \ell_\alpha^+ + 4j$

- LNV can be comparable with LNC even for pseudo-Dirac case due to heavy neutrino oscillation

Back Up

Indirect effects can appear in low-energy observables. The EFT framework offers a powerful tool to systematically capture these effects

$$\mathscr{L} \equiv \mathscr{L}_{\text{SM}} + \sum_{n>4} \frac{\mathcal{O}_n}{\Lambda^{n-4}} + \text{h.c.}$$

Cooling of Supernova/red-giant,

Anisotropies in the CMB and BBN predictions

baryon asymmetry via leptogenesis

New heavy neutrino production mechanism

Heavy neutrinos as messengers of high energy Gamma-Ray Burst: GRB221009A

Source

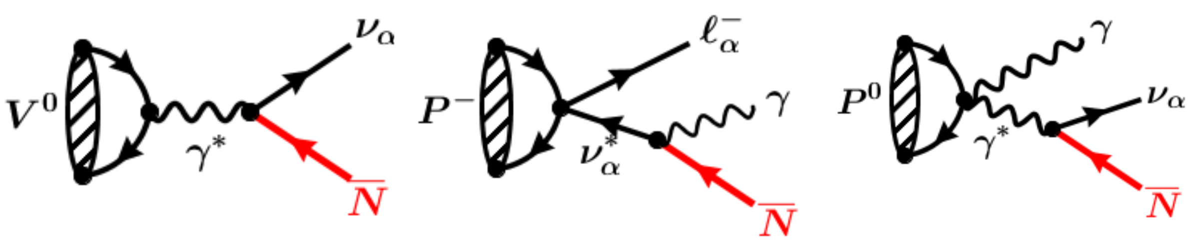
N rarely interact along the path of propagation $N \to \nu\gamma$

$$\pi^+/K^+ \to \mu^+\nu_\mu \to \mu^+N$$

$$\pi^+/K^+ \to \mu^+\nu_\mu^* \to \mu^+\gamma N$$

Dirac/Majorana/pseudo-Dirac nature of RHNs at beam dump experiments via the time dependence of: $N(\ell^+\ell^+)$

Production/decay modes at Beam Dump Experiments will vary depending on type of EFT operators



Dipole portal: $\bar{\nu}\sigma_{\mu\nu}NF^{\mu\nu}$

Our plan is to consider all possible effective operators involving heavy neutrinos N_R

Indirect effects can appear in low-energy observables. The EFT framework offers a powerful tool to systematically capture these effects

$$\mathscr{L} \equiv \mathscr{L}_{\mathrm{SM}} + \sum_{n>4} \frac{\mathscr{O}_n}{\Lambda^{n-4}} + \mathrm{h.c.}$$

$$\mathscr{O}^5_W = \alpha_W (\overline{L^c_L}\tilde{H})(\tilde{H}^\dagger L_L),\ \ \mathscr{O}^5_{NH} = \alpha_{NH}\overline{N^c_R}N_R(H^\dagger H$$

$$\mathscr{O}^5_{NB} = \alpha_{NB}\overline{N^c_R}\sigma_{\mu\nu}N_R B^{\mu\nu}$$

	Operator	Notation	Operator	Notation
SF	$(\overline{l_L}N)\tilde{H}(H^\dagger H)$	$\mathcal{O}_{lNH}$ (+h.c.)		
	$(\overline{N}\gamma^\mu N)(H^\dagger i\overleftrightarrow{D}_\mu H)$	$\mathcal{O}_{HN}$	$(\overline{N}\gamma^\mu e_R)(\tilde{H}^\dagger iD_\mu H)$	$\mathcal{O}_{HNe}$ (+h.c.)
	$(\overline{l_L}\sigma_{\mu\nu}N)\tilde{H}B^{\mu\nu}$	$\mathcal{O}_{NB}$ (+h.c.)	$(\overline{l_L}\sigma_{\mu\nu}N)\sigma_I\tilde{H}W^{I\mu\nu}$	$\mathcal{O}_{NW}$ (+h.c.)
RRRR	$(\overline{N}\gamma_\mu N)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{NN}$		
	$(\overline{e_R}\gamma_\mu e_R)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{eN}$	$(\overline{u_R}\gamma_\mu u_R)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{uN}$
	$(\overline{d_R}\gamma_\mu d_R)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{dN}$	$(\overline{d_R}\gamma_\mu u_R)(\overline{N}\gamma^\mu e_R)$	$\mathcal{O}_{duNe}$ (+h.c.)
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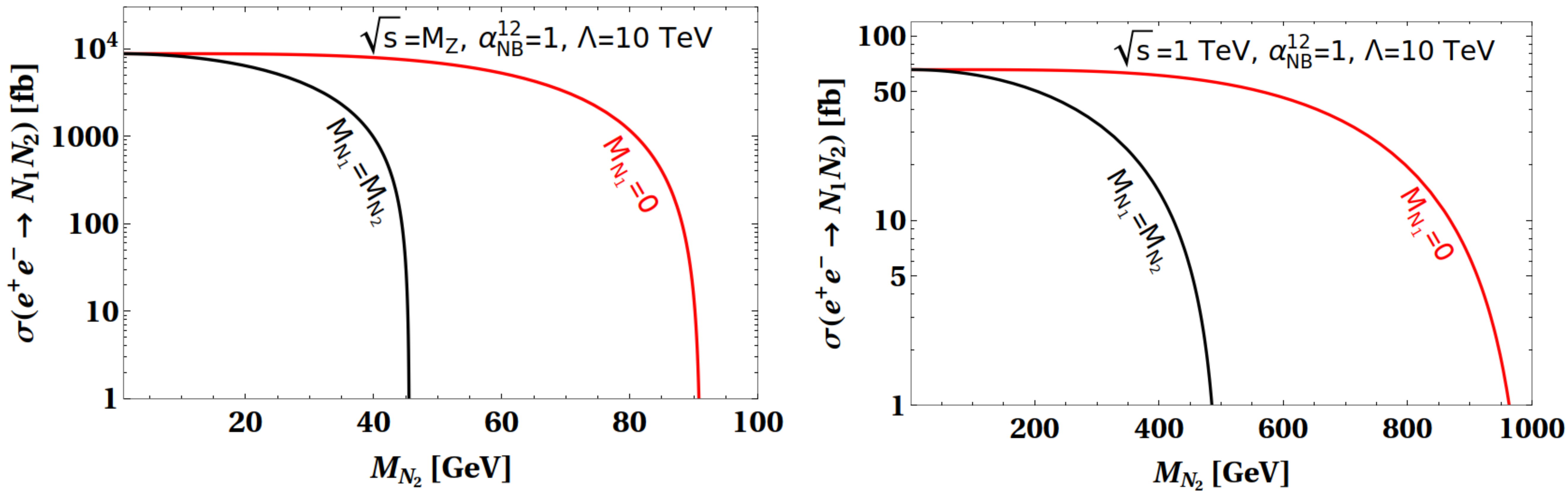
LRRL	$(\overline{l_L}N)\epsilon(\overline{l_L}e_R)$	$\mathcal{O}_{lNle}$ (+h.c.)	$(\overline{l_L}N)\epsilon(\overline{q_L}d_R)$	$\mathcal{O}_{lNqd}$ (+h.c.)
	$(\overline{l_L}d_R)\epsilon(\overline{q_L}N)$	$\mathcal{O}_{ldqN}$ (+h.c.)	$(\overline{q_L}u_R)(\overline{N}l_L)$	$\mathcal{O}_{quNl}$ (+h.c.)

Mitra, SM, Padhan, Sarkar, Spannowsky 22 Julien Alcaide et al, 19

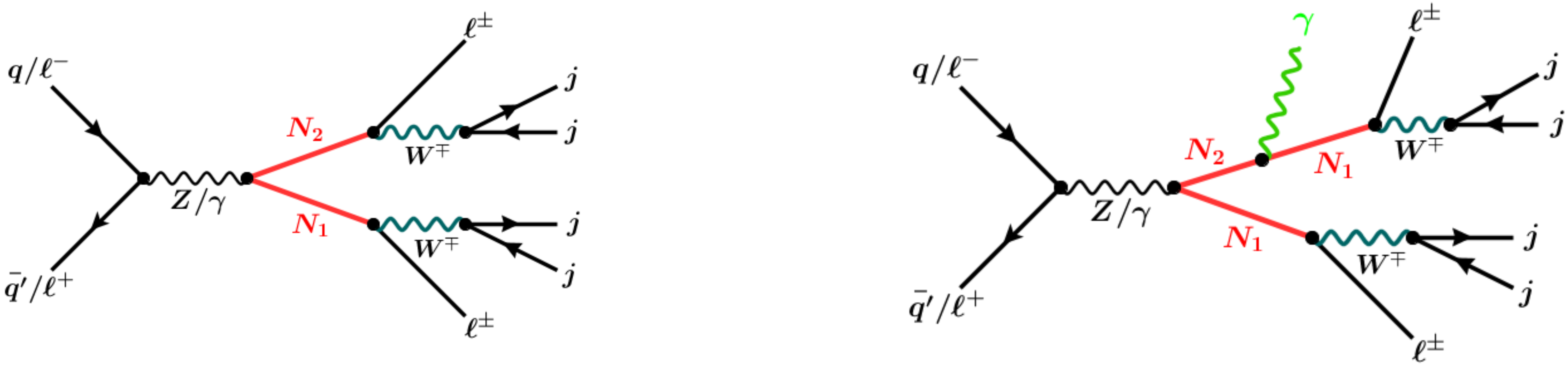
- Depending on the operators we will have different kind of cooling processes for supernova and red-giant stars
- Anisotropies in the CMB and BBN predictions are sensitive on the nature of heavy neutrinos and type of EFT operators
- Classify the EFT operators which can generate the required baryon asymmetry via leptogenesis
- Systematic study of all possible heavy neutrino production mechanism

Large LNV and Dark matter via MMO ?

$$\mathscr{L}^5_{NB} = \frac{\alpha_{NB}}{\Lambda}\,\overline{N^c_{iR}}\sigma_{\mu\nu}N_{jR}\,B^{\mu\nu} + \text{h.c.}$$



Recall: $\sigma(e^+e^- \to N\nu) \propto |V_{eN}|^2$ but due to MET not suitable to prove LNV or Majorana nature



DM Productions: $f\bar{f} \to Z/\gamma \to N_1 N_j$ and $N_j \to N_1\gamma$

Stability: $\Gamma(N_1 \to \nu\gamma) \sim \frac{1}{10^{28}\,\text{sec}}\left(\frac{10^{15}\,\text{GeV}}{\Lambda}\right)^2\left(\frac{|\theta|}{10^{-6}}\right)^2\left(\frac{M_{N_1}}{1\,\text{MeV}}\right)^3$

Heavy neutrinos as messengers of high energy Gamma-Ray Burst

GRB221009A: Swift-BAT+GBM+LHAASO observed very high energy ($E_\gamma \sim 18$ TeV) long-duration gamma rays from a gamma-ray burst named as GRB221009A at a red-shift of z=0.151 (645 Mpc)

Possible source: may have been caused by a massive star undergoing a supernova or by the birth of a black hole. Lots of pions, kaons productions and $\pi^0 \to \gamma\gamma$

Why unexpected: loose energy via pair creation, Compton scattering, and other mechanisms.

Possible explanation: transitional magnetic dipole moment:

$$\mathscr{L} = \frac{1}{2}\mu_\nu \overline{\nu_L}\sigma_{\mu\nu}N_R F^{\mu\nu} + \text{h.c.} \quad \Longrightarrow \quad N \to \nu\gamma$$

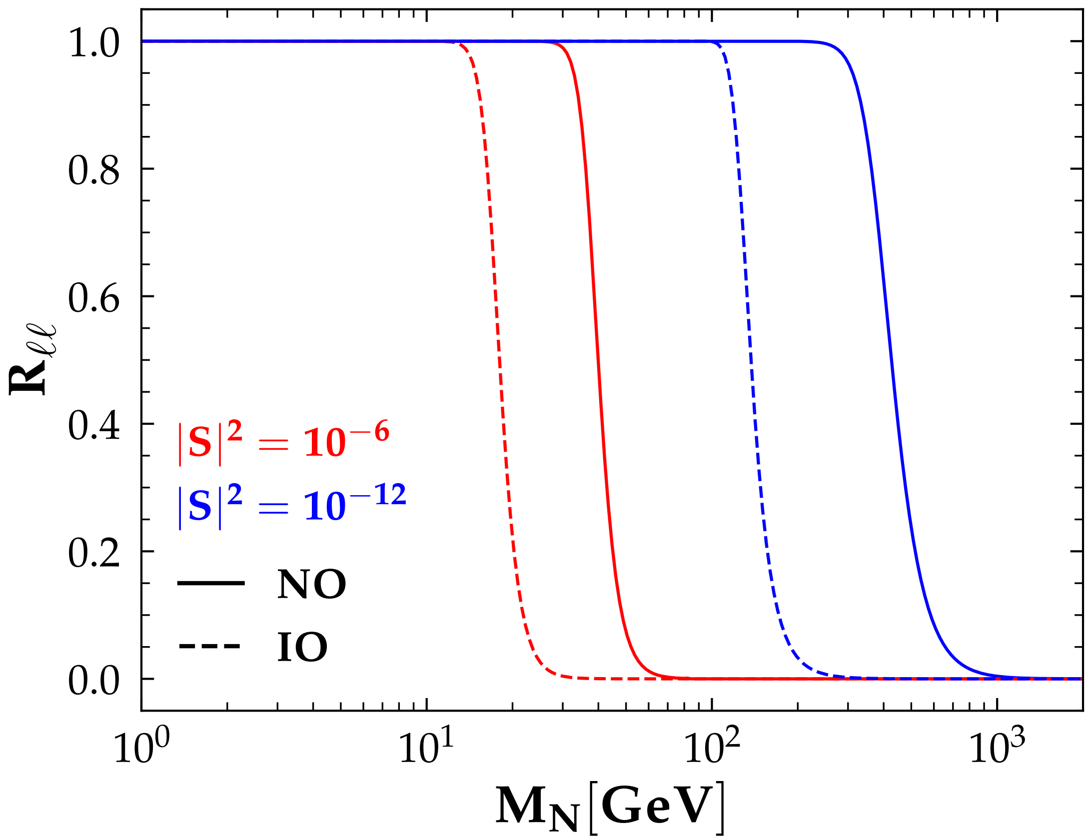
Source

N rarely interact along the path of propagation $\longrightarrow$ $N \to \nu\gamma$

$\pi^+/K^+ \to \mu^+\nu_\mu \to \mu^+ N$

$\pi^+/K^+ \to \mu^+\nu_\mu^* \to \mu^+\gamma N$

Dirac/Majorana/pseudo-Dirac nature of RHNs at beam dump experiments



Oscillation is effective:

$\Delta M/\Gamma_N \gg 1$ for small M_N

Majorana: $N(\ell^+\ell^+)$ (time independent)

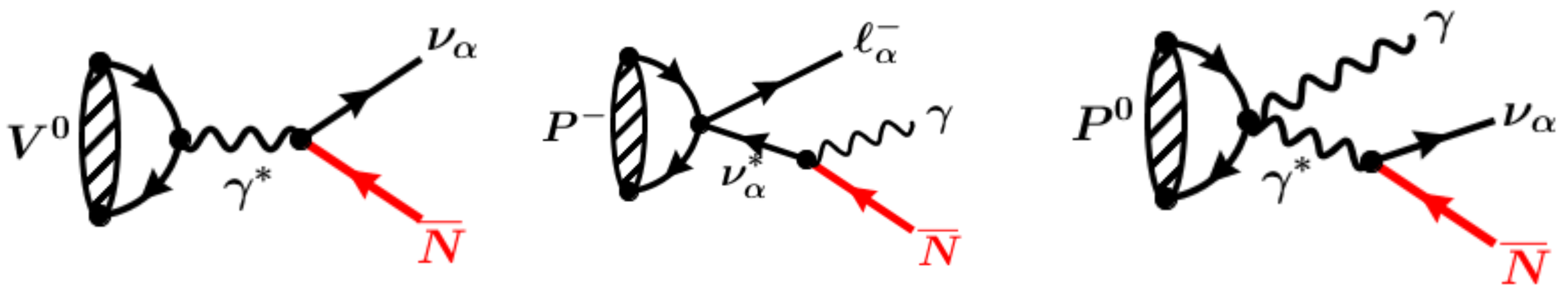
Pseudo-Dirac: $N(\ell^+\ell^+)$ (time/position independent)

Dirac: $N(\ell^+\ell^+)$=0 FASER, FASER2, SHiP

Other projects:

Production of heavy neutrinos and their decay modes at Beam Dump Experiments will vary depending on what kind of EFT operators we are considering

Dipole portal: $\bar{\nu}\sigma_{\mu\nu}NF^{\mu\nu}$



The Connection between Dirac Neutrinos and Dark Matter Stability

Is it testable??

Seesaw mass: $m_\nu \approx m_D M_R^{-1} m_D^T = \frac{v^2}{2} Y_\nu M_R^{-1} Y_\nu^T$

Casas-Ibara parameterisation: $Y_\nu \approx \frac{\sqrt{2}}{v_\Phi} U^\dagger_{\text{PMNS}} \sqrt{m_\nu^{diag}} R \sqrt{M_R}$ with $R^T R = 1$ arXiv:hep-ph/0103065

$R = \begin{pmatrix} 0 & 0 \\ \cos y & \sin y \\ -\sin y & \cos y \end{pmatrix}$ for **NO** $(m_1 = 0)$ and $R = \begin{pmatrix} \cos y & \sin y \\ -\sin y & \cos y \\ 0 & 0 \end{pmatrix}$ for **IO** $(m_3 = 0)$.

Complex: $y = a + ib$

With $R = I \Rightarrow$

High scale: If $m_\nu = 0.1$eV and $Y_\nu \sim \mathcal{O}(1)$ => $M_R \sim 10^{14}$ GeV and $V \sim 10^{-12}$

=> out of reach at colliders

Low scale: If $m_\nu = 0.1$eV and $M_R \sim 1$ TeV => $Y_\nu \sim 10^{-6}$ and $V \sim 10^{-7}$

=> still difficult to probe at colliders due to suppressed mixing

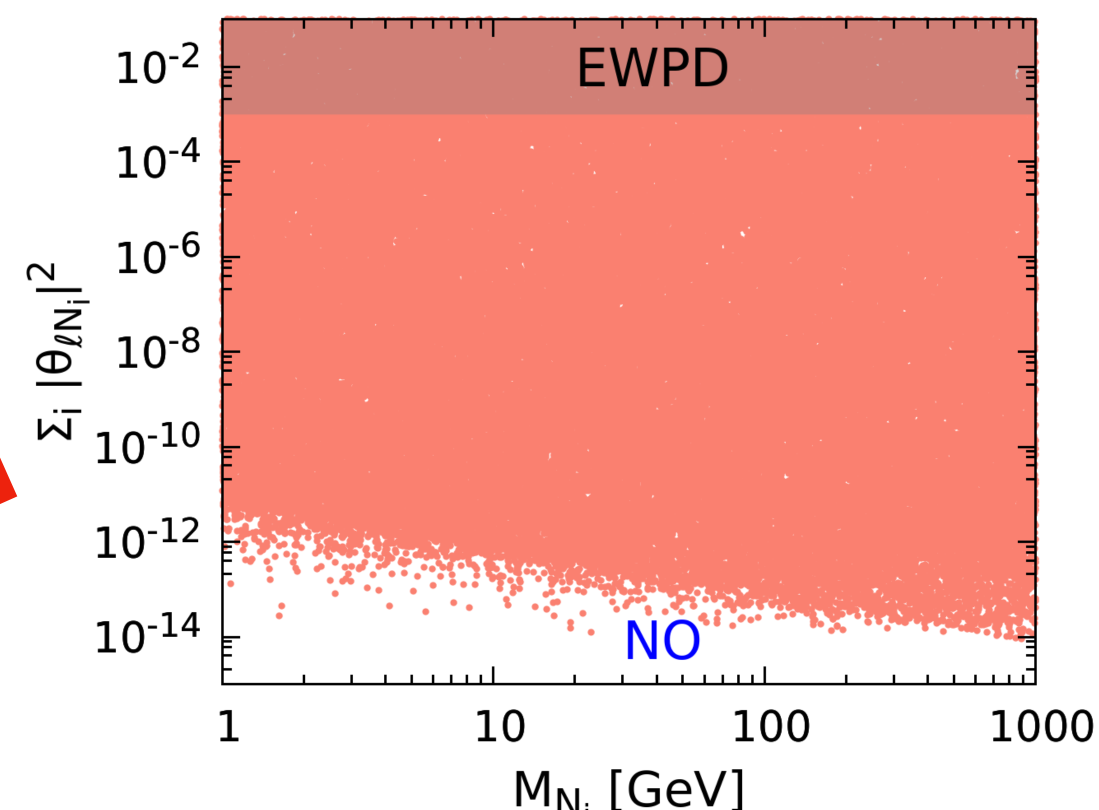
With $R =$ arbitary $\Rightarrow$

Order parameter: $\theta_p^2 = \text{Tr}(V^\dagger V)$ $y = a + ib$

$$\theta_p^2 = \mp \frac{(m_3 - m_2)\delta M_N \cos(2a)}{2M_{N_1}M_{N_2}} + \frac{(m_2 + m_3)(M_{N_1} + M_{N_2})\cosh(2b)}{2M_{N_1}M_{N_2}}$$

$$\xrightarrow{\text{large b}} \frac{(m_2 + m_3)(M_{N_1} + M_{N_2})\exp(2b)}{2M_{N_1}M_{N_2}}$$

Large mixing even for low M_N



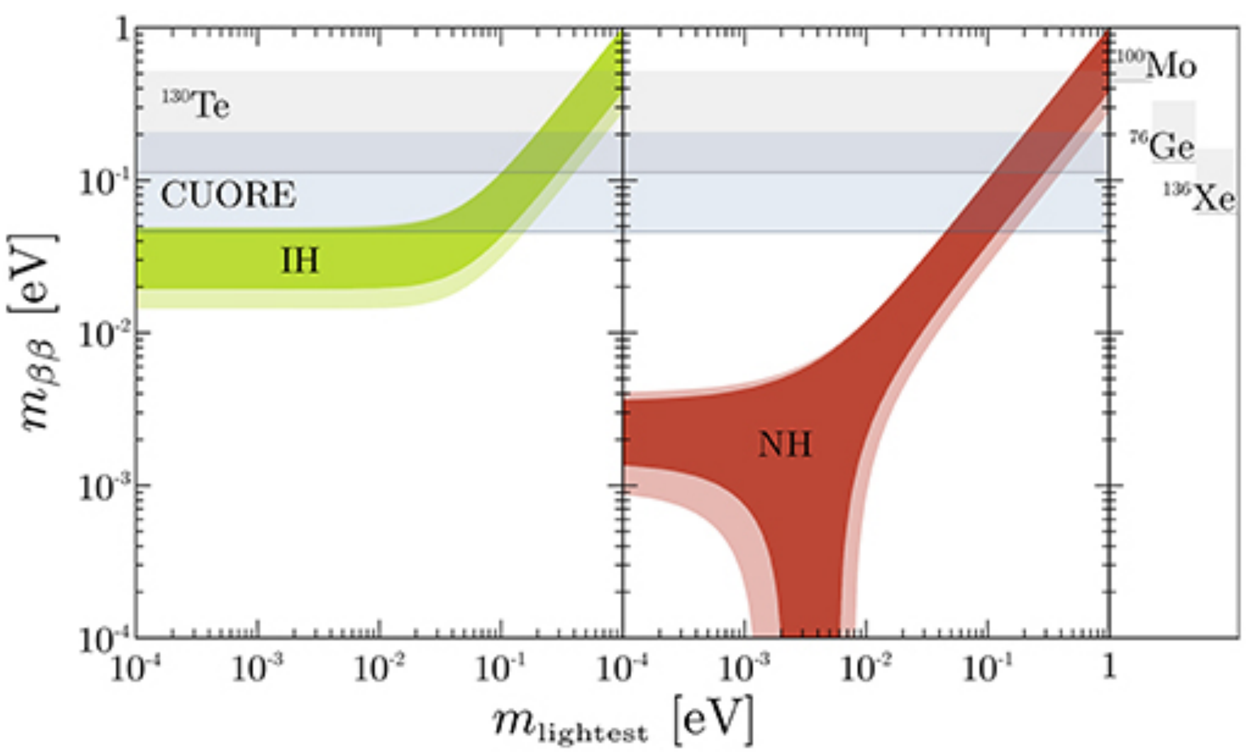
$0\nu\beta\beta$ with one neutrino massless

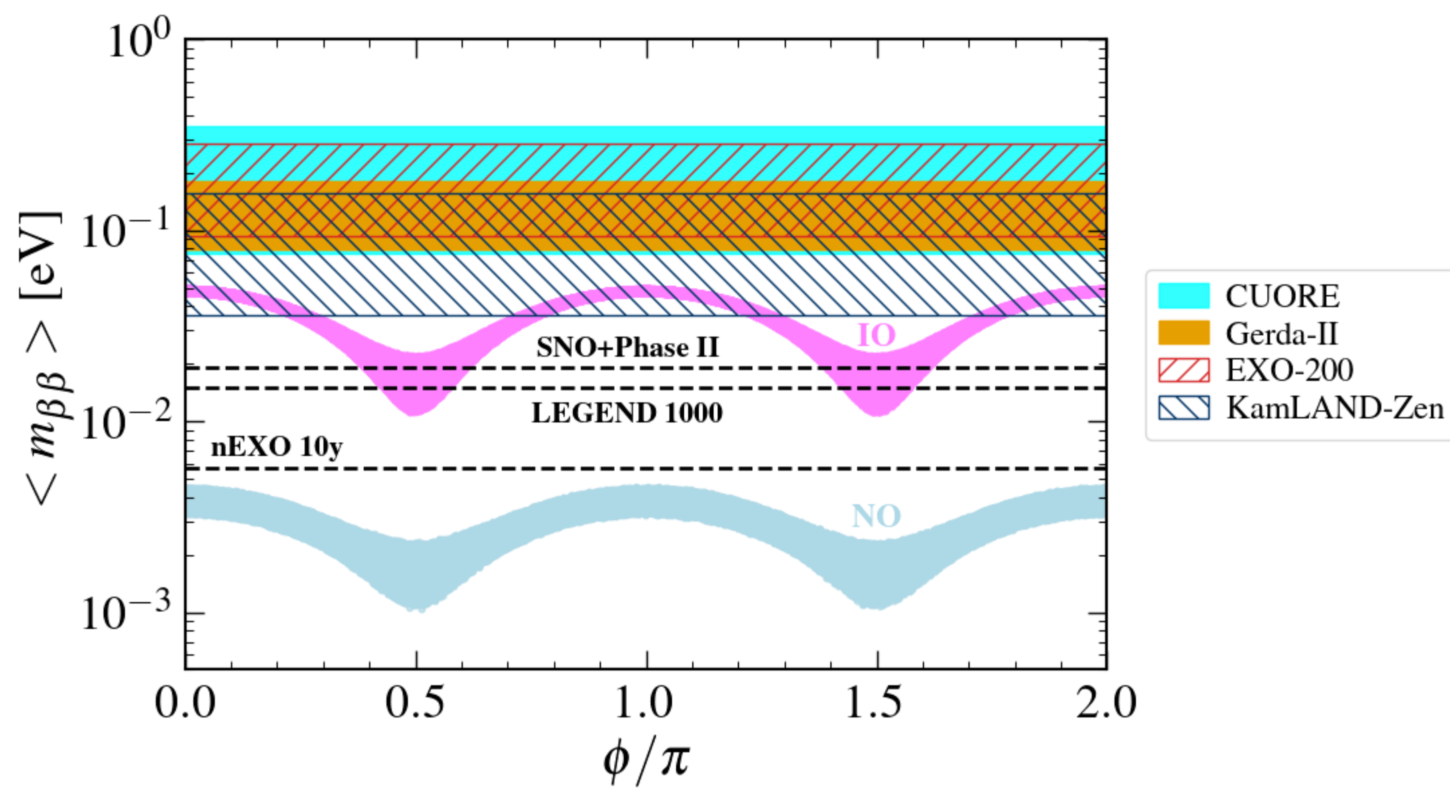
$$< m_{\beta\beta} > = \left| \sum_j U^2_{\nu,ej} m_j \right| = \left| \cos\theta^2_{12}\cos\theta^2_{13} m_1 + \sin\theta^2_{12}\cos\theta^2_{13} m_2 e^{2i\phi_{12}} + \sin\theta^2_{13} m_3 e^{2i\phi_{13}} \right|$$

As $m_1 = 0$, only one Majorana phase

$\phi \equiv \phi_{12} - \phi_{13} \Rightarrow 0\nu\beta\beta$ **has lower limit**

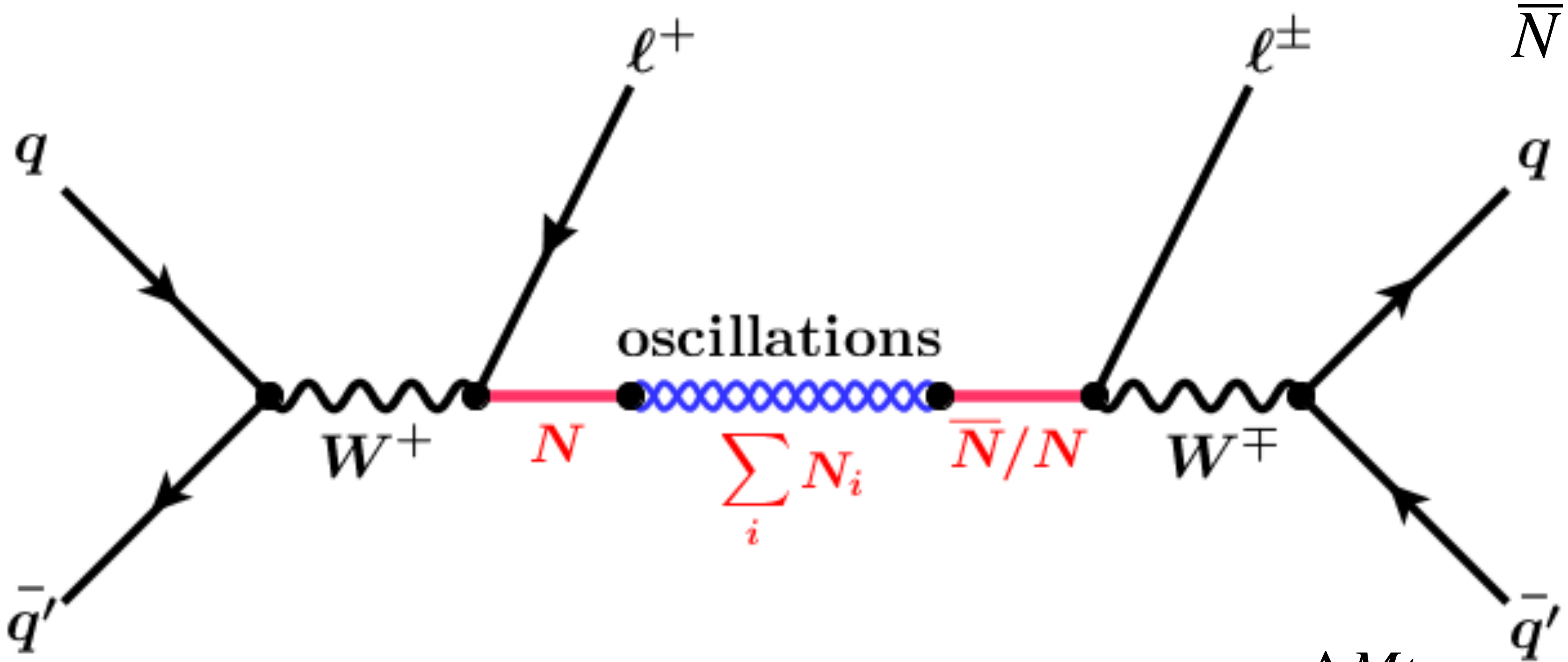
SM, Valle, Srivastava 2104.13401





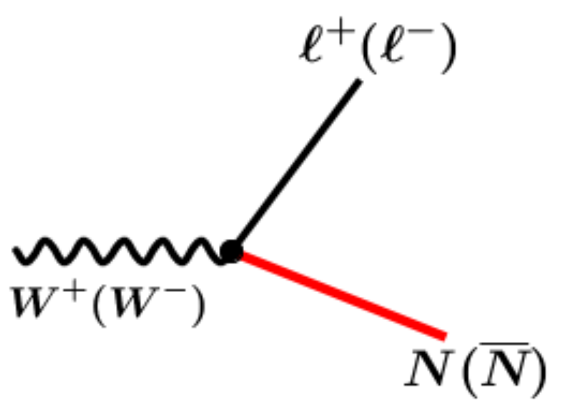
LNV from heavy neutrino oscillation

Oscillations for on-shell heavy neutrinos:



N is produced together with ℓ^+

$\overline{N}$ is produced together with ℓ^-



$$N = (-iN_1 + N_2)/\sqrt{2}$$

$$\overline{N} = (iN_1 + N_2)/\sqrt{2}$$

$$N(t) = g_+(t)\,N + g_-(t)\,\overline{N} \qquad g_+(t) = e^{-iM_N t} e^{-\frac{\Gamma_N t}{2}} \cos\left(\frac{\Delta M t}{2}\right)$$

$$\overline{N}(t) = g_-(t)\,N + g_+(t)\,\overline{N} \qquad g_+(t) = i e^{-iM_N t} e^{-\frac{\Gamma_N t}{2}} \sin\left(\frac{\Delta M t}{2}\right)$$

Hirsch et al, 1607.05641

SM et al, 2305.00994

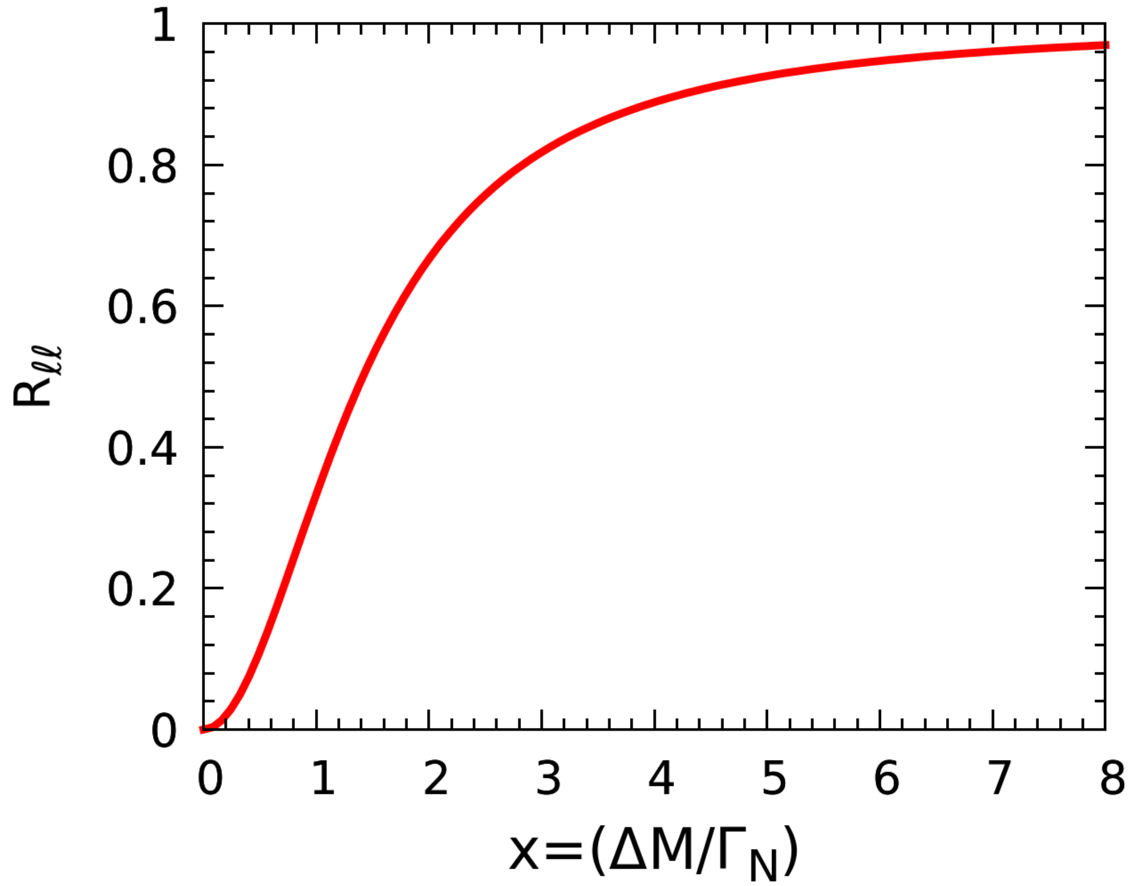
LNV $\sim \int_0^t |g_-|^2 dt$ and LNC $\sim \int_0^t |g_+|^2 dt$

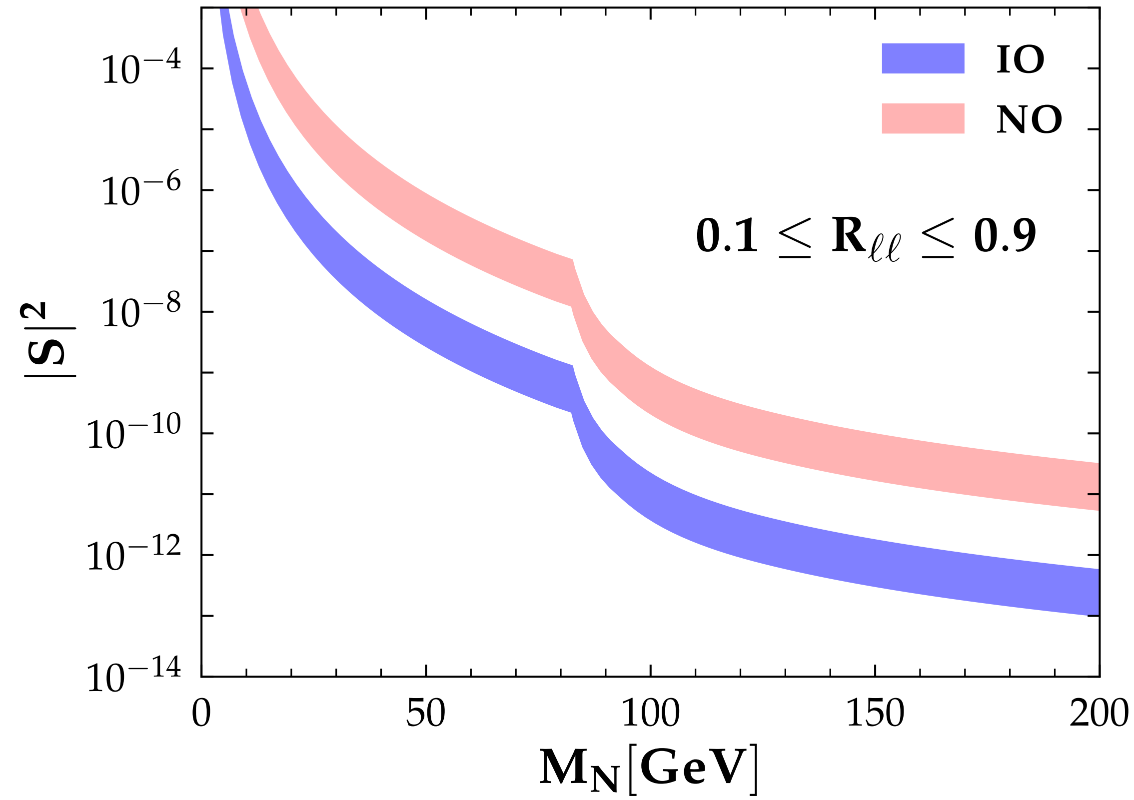
$$R = \frac{\#\text{LNV}}{\#\text{LNC}} = \frac{\Delta M^2}{2\Gamma_N^2 + \Delta M^2} = \frac{x^2}{2 + x^2} \text{ with } x = \frac{\Delta M}{\Gamma_N}$$

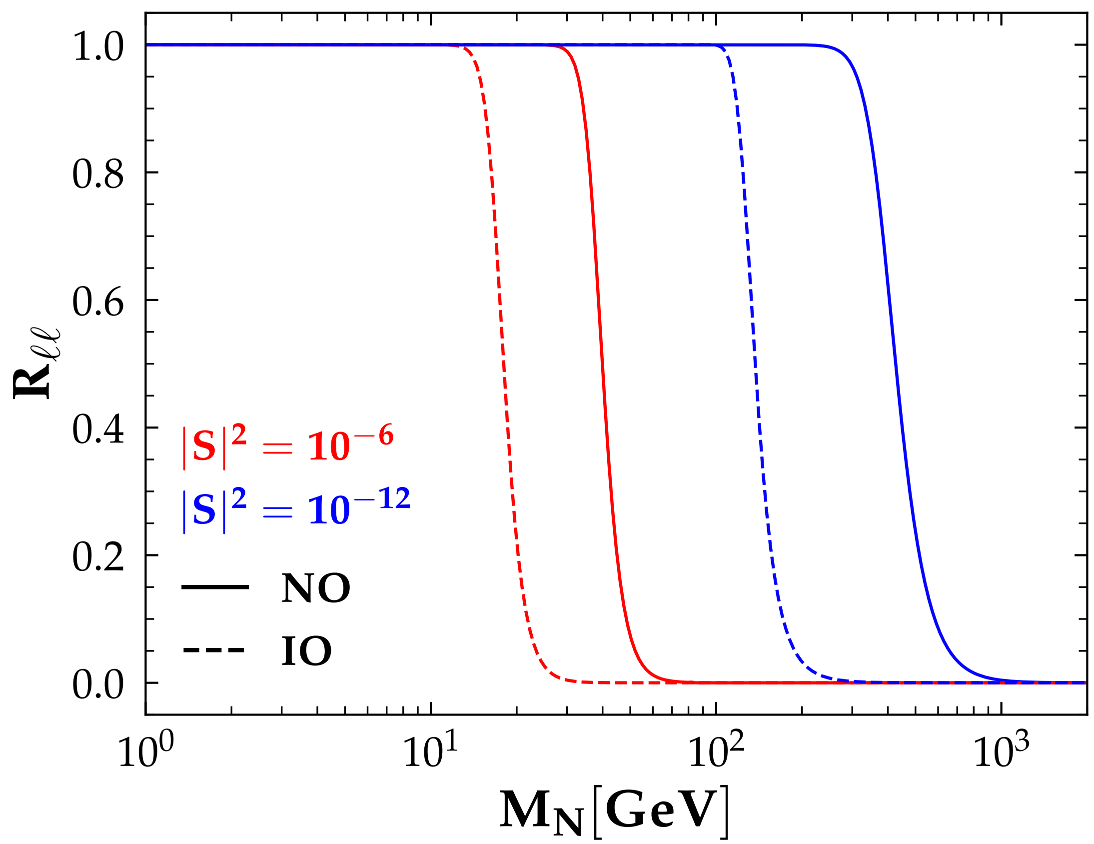
If $\Delta M \ll \Gamma_N$ ($L_N \ll L_{\rm osc}$) , decays before they have time to oscillate: destructive interference

If $\Delta M \gg \Gamma_N$ ($L_N \gg L_{\rm osc}$), they have time to oscillate many times before decay: oscillations are averaged out

$\boxed{R \to 1 \text{(pure Majorana)},\ R \to 0 \text{ (pure Dirac) and } R \to [0:1] \text{ (pseudo-Dirac)}}$







LNV via virtual propagation: $\Delta M / M_N$

LNV via on-shell propagation: $\Delta M / \Gamma_N$

For any neutrino mass model: $\boxed{\sigma(\text{LNV}) = \sigma(\text{LNC})\, R}$

$R = [0:1]$ depending on the nature of heavy neutrinos

In usual seesaw models: $\sigma(\text{LNC}) \propto |V_{\ell N}|^2$,

Hence if $R < 1$, $\sigma(\text{LNV})$ will be even smaller

Goal: enhance $\sigma(\text{LNC})$ such that even for $R \ll 1$, $\sigma(\text{LNV})$ is large enough

How to obtain small v_χ ? Break the global $U(1)_L$ lepton symmetry softly in the potential:

$$V = -\mu_\Phi^2 \Phi^\dagger \Phi - \mu_\chi^2 \chi_L^\dagger \chi_L + \lambda_1 (\Phi^\dagger \Phi)^2 + \lambda_2 (\chi_L^\dagger \chi_L)^2 + \lambda_3 \chi_L^\dagger \chi_L \Phi^\dagger \Phi + \lambda_4 \chi_L^\dagger \Phi \Phi^\dagger \chi_L - \underbrace{\left(\mu_{12}^2 \Phi^\dagger \chi_L + H.c.\right)}_{\text{Soft term}}$$

This gives the following induced VEV : $v_\chi \approx \dfrac{\mu_{12}^2 v_\Phi}{m_A^2}$ $\Rightarrow$ small for small μ_{12}

Physical scalars: $h, H, A, H^\pm$

Without the term $\mu_{12}^2 \Phi^\dagger \chi_L$, $m_A = 0$ (doublet majoron)

$\Rightarrow$ Excluded from invisible Z decay width at LEP

Model parameters (2HDM)

$m_H, m_A, m_{H^\pm}$ and α (h-H mixing),

$\tan\beta = v_\Phi / v_\chi$

Model parameters (our case)

In the limit $v_\chi \to 0$, $\alpha \approx 0, \beta \approx \pi/2$

Effectively one parameter: $\Rightarrow m_H \approx m_A \approx m_{H^\pm}$

Suppressed: $(H/A)WW$, $(H/A)ZZ$, $(H/A)\ell\ell$, $(H/A)qq$, AhZ, $H^\pm qq'$, $H^\pm W^\mp h \sim \mathcal{O}(v_\chi/v)$

Case 1: $m_{H^\pm}, m_{H/A} < M_{N_i}$

BR$(H^\pm \to \ell^\pm \nu) \approx 1$

BR$(H/A \to \nu\nu) \approx 1$

Case 2: $m_{H/A}, m_{H^\pm} > M_{N_i}$

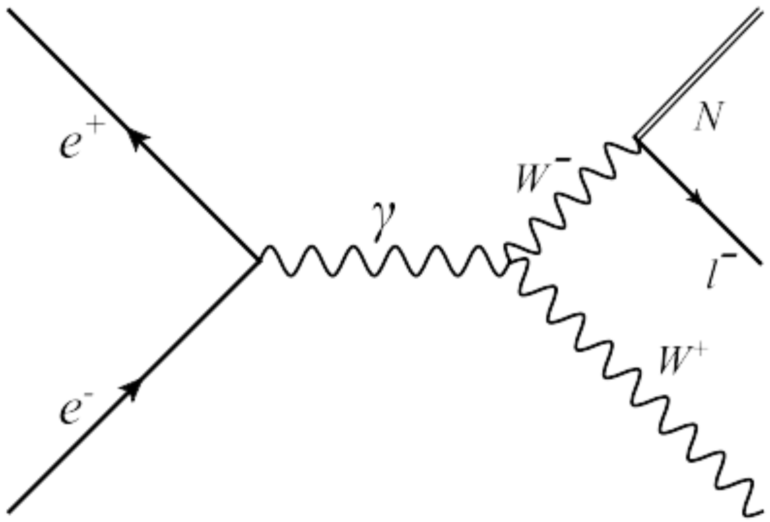
BR$(H^\pm \to \ell^\pm N) \approx 1$

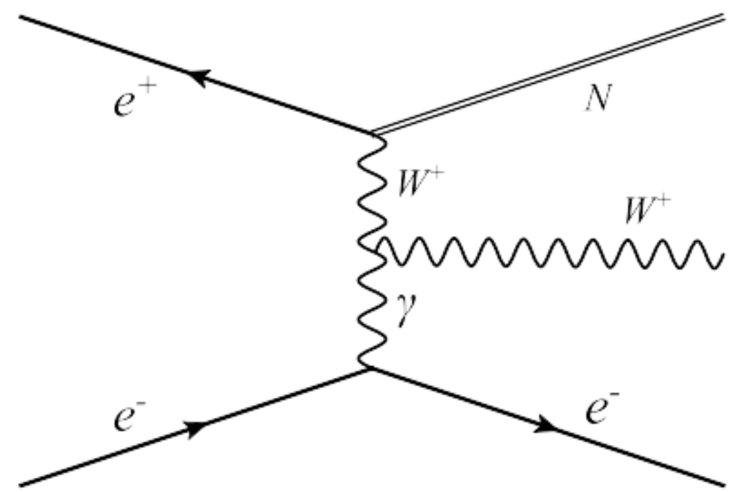
BR$(H/A \to \nu N) \approx 1$

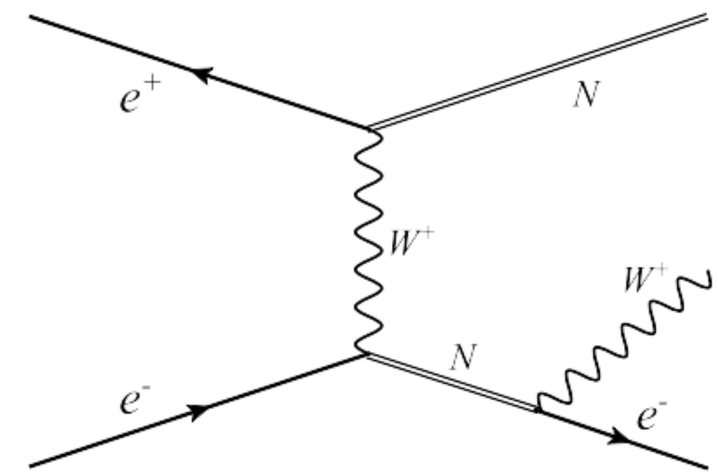
Collider phenomenology is different from 2HDM

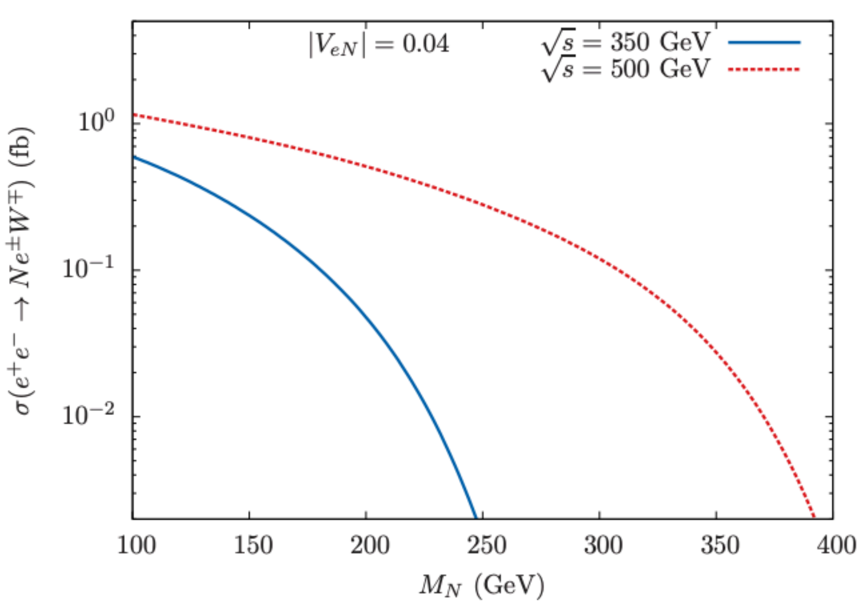
$H^\pm \to \ell^\pm N, N \to \ell^\pm W^*, W^* \to jj$

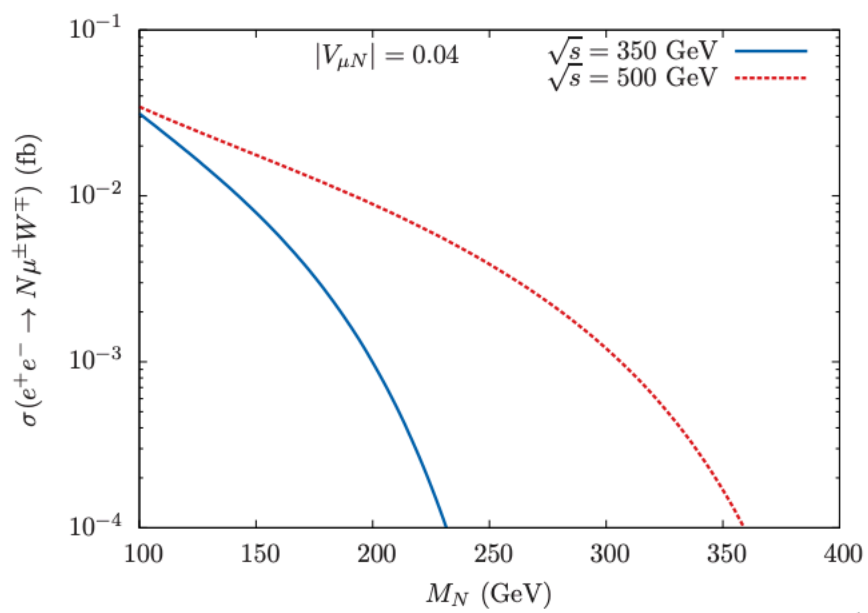
Probing Majorana nature at lepton collider….





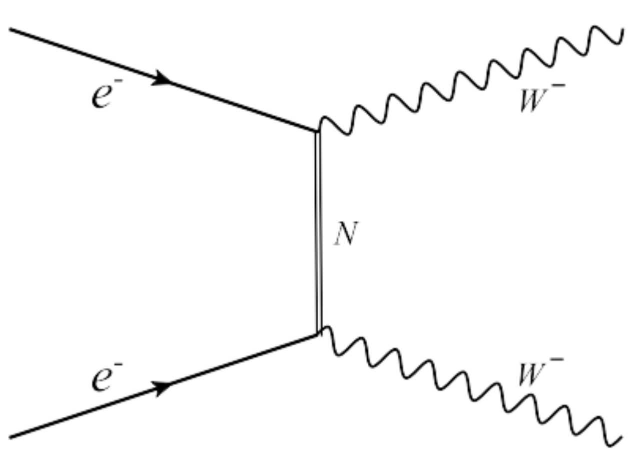






$$e^+e^- \to N\ell_\beta^\pm W^\mp$$

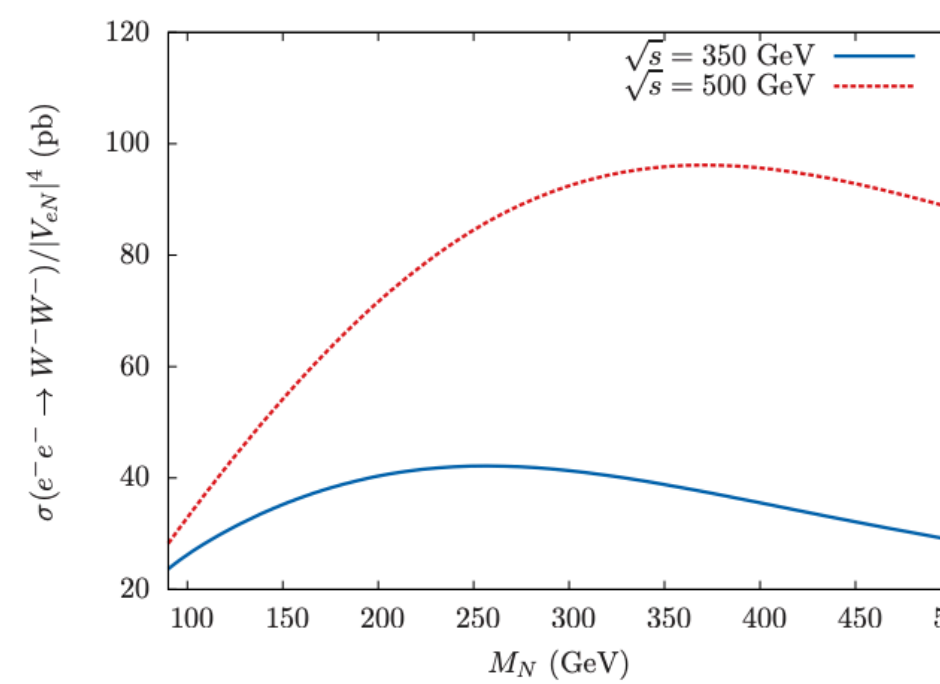
$\ell_\alpha^\pm \ell_\beta^\mp + 4j$ (LNC) $\ell_\alpha^\pm \ell_\beta^\pm + 4j$ (LNV)



LNV: $e^-e^- \to W^-W^- \to 4j$

Zhang et al, 1805.09520

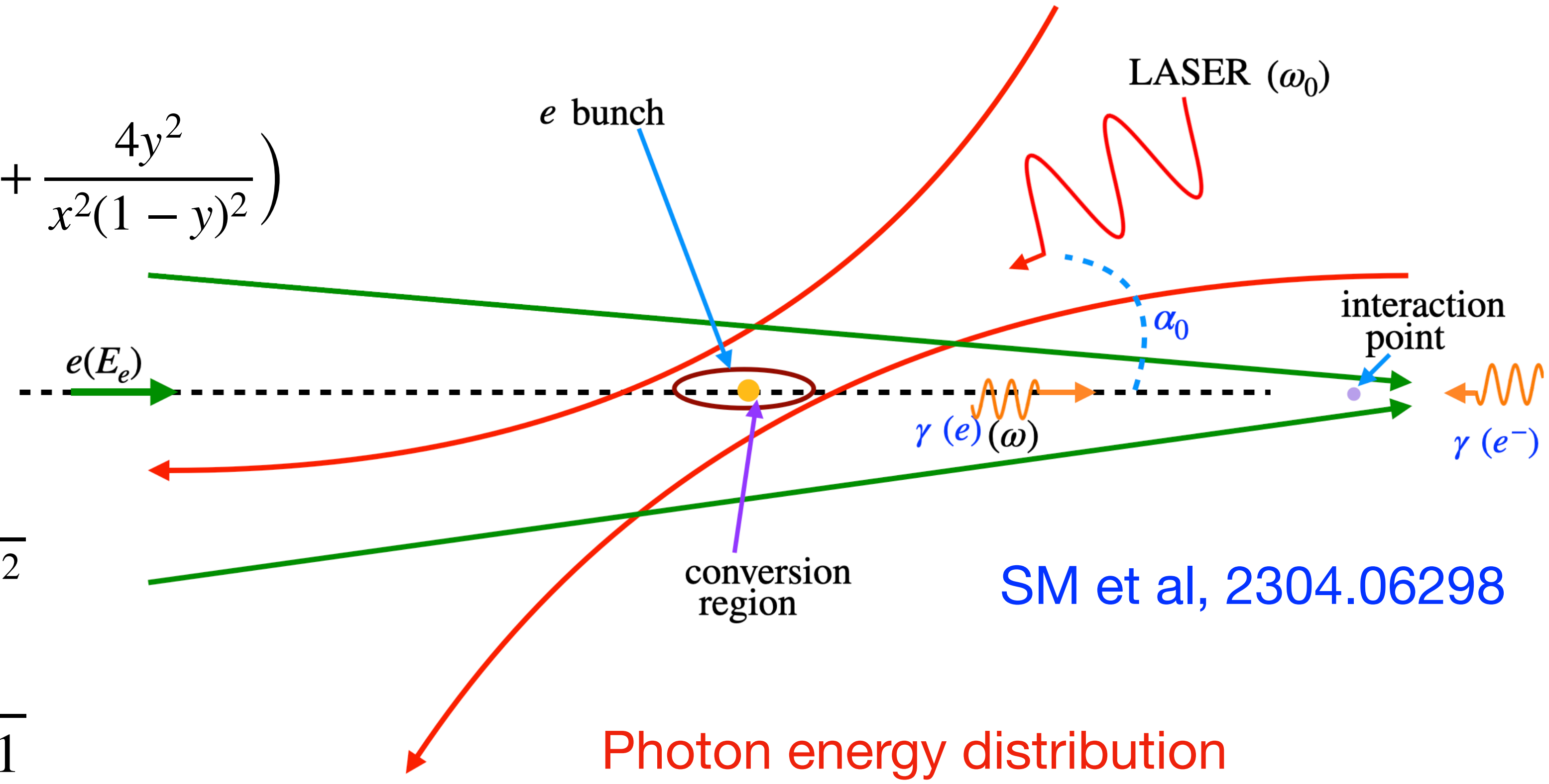
Shankha et al, 1503.05491



$e^-\gamma/\gamma\gamma$ option at e^+e^- collider

Energy spectrum of the photon:

$$\frac{1}{N_\gamma}\frac{dN_\gamma}{dy} \equiv F_{\gamma/e}(x,y) = \frac{1}{D(x)}\left(\frac{1}{1-y} + 1 - y - \frac{4y}{x(1-y)} + \frac{4y^2}{x^2(1-y)^2}\right)$$



SM et al, 2304.06298

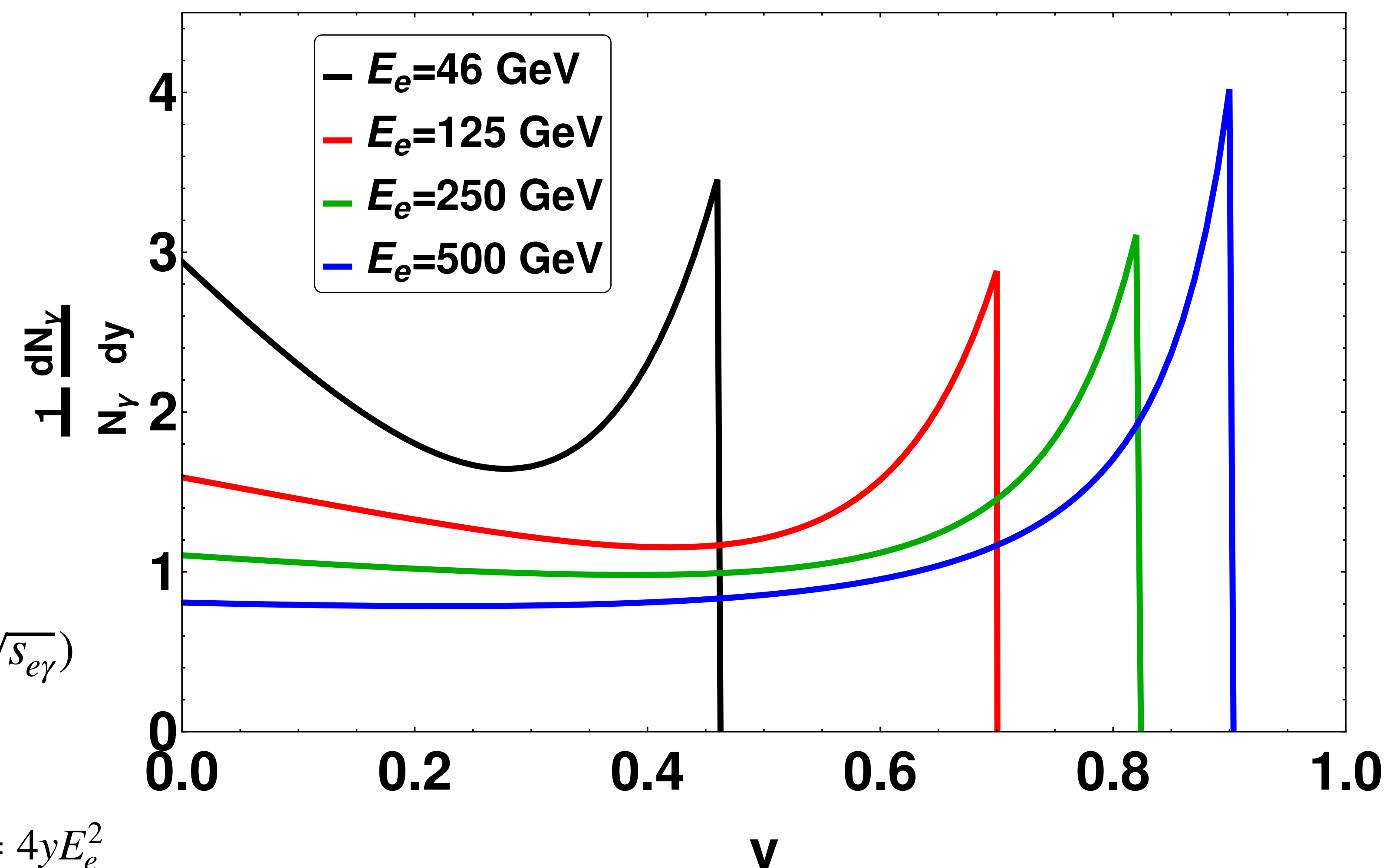
$$D(x) = \left(1 - \frac{4}{x} - \frac{8}{x^2}\right)\ln(1+x) + \frac{1}{2} + \frac{8}{x} - \frac{1}{2(1+x)^2}$$

$$x = \frac{4E_e\omega_0}{m_e^2}\cos^2\left(\frac{\alpha_0}{2}\right), \quad y = \frac{\omega}{E_e} \le y_m = \frac{\omega_m}{E_e} = \frac{x}{x+1}$$

ω_0 is the energy of the incident photon

α_0 is the collision angle and its small

Photon energy distribution

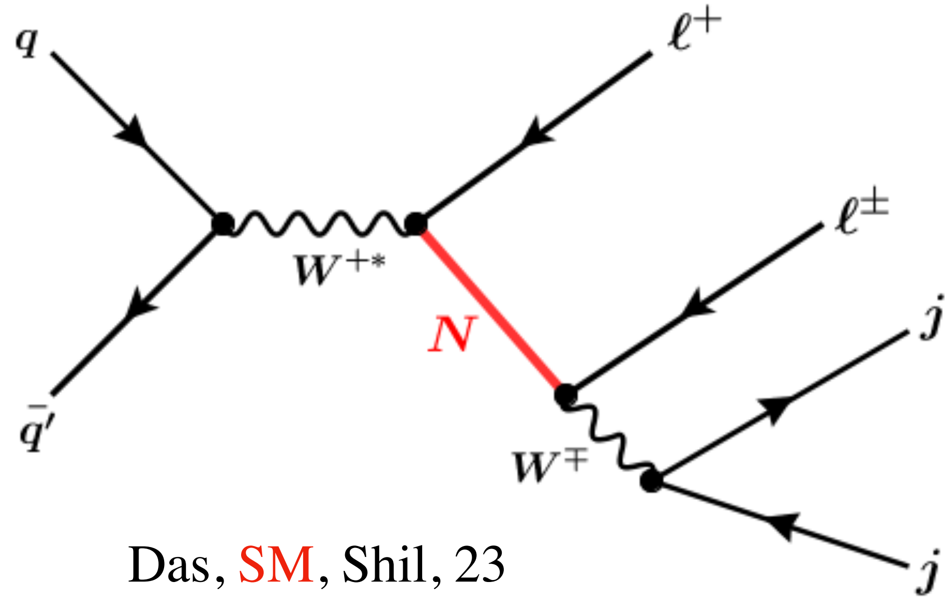


Cross section can be obtained being averaged over the photon spectrum:

$$<\sigma_{\gamma e\to AB}(\sqrt{s_{ee}})> = \int_{y_{\text{min}}}^{y_{\text{max}}} dy F_{\gamma/e}(x,y)\sigma_{\gamma e\to AB}(\sqrt{s_{e\gamma}})$$

$$s_{ee} = 4E_e^2, y_{\text{max}} = \frac{x}{1+x}, y_{\text{min}} = \frac{(M_A+M_B)^2}{s_{ee}}, \ s_{e\gamma} = 4yE_e^2$$

Lepton number violation at High energy colliders: $M_N \sim 100$ GeV



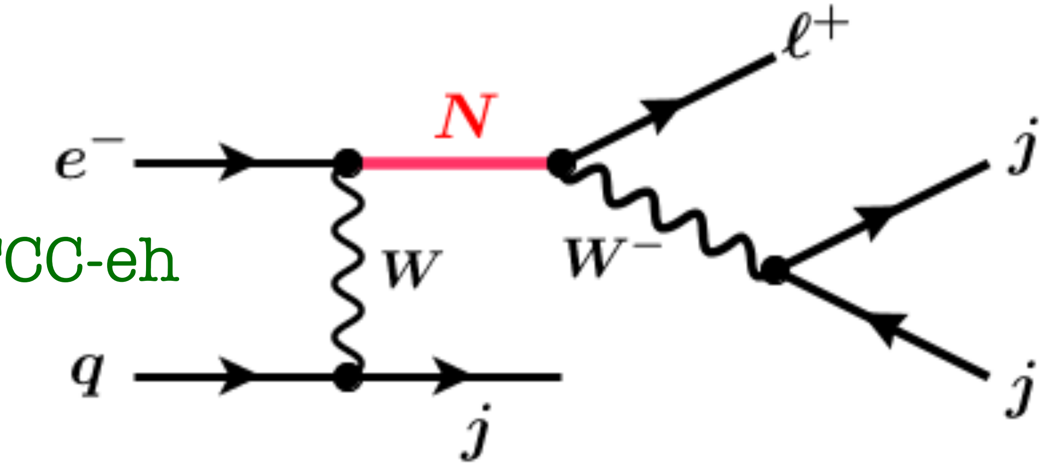
Das, SM, Shil, 23

LNV: $pp \to \ell^+\ell^+jj$ LNC: $pp \to \ell^+\ell^-jj$

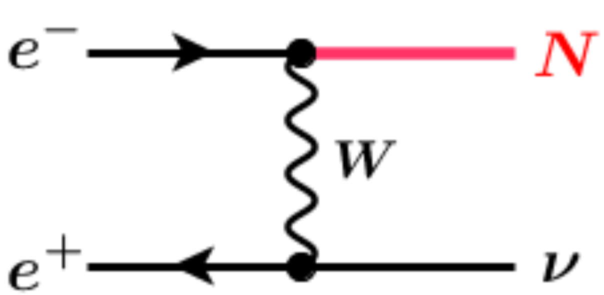
If N is pure Majorana type: $R_{\ell\ell} = \dfrac{\#\,\mathrm{LNV}}{\#\,\mathrm{LNC}} = 1$

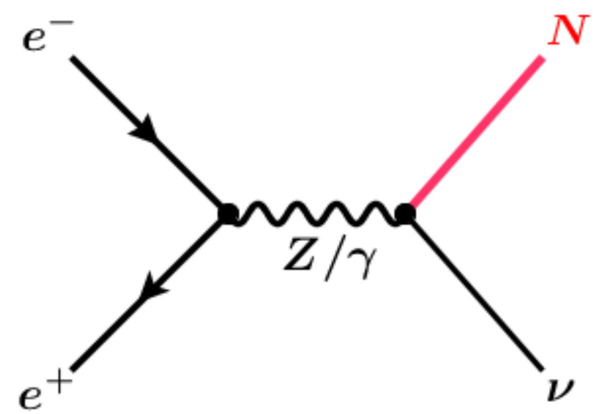
$R_{\ell\ell} \neq 0$ → Majorana neutrinos

LHeC, FCC-eh



What about the lepton colliders? ILC, CLIC, FCC-ee





At $\sqrt{s} = M_Z$: $N_{\mathrm{event}} \approx 10^{12}\,|V_{eN}|^2$

Can probe seesaw line:

$$|V_{eN}|^2 \sim m_\nu/M_N \sim 10^{-12}$$

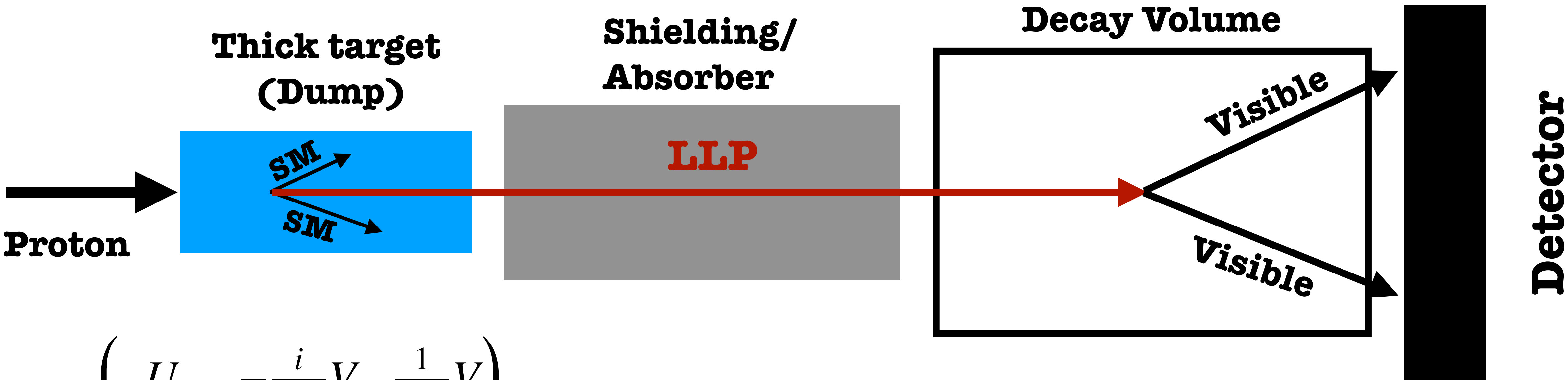
Neutrino in final state unobservable

SM, Jana, Das, Nandi, arXiv: 1811.04219

Forwards backward asymmetry relic of the Z parity violating couplings. Dirac keeps it, Majorana washes it out

$$A_D^{\mathrm{FB}}(N) \propto g_L^2 - g_R^2 \qquad A_D^{\mathrm{FB}}(\overline{N}) \propto g_R^2 - g_L^2 \qquad A_M^{\mathrm{FB}} = 0$$

Blondel et al, 21



$$\mathcal{U} \approx \begin{pmatrix} U & -\frac{i}{\sqrt{2}}V & \frac{1}{\sqrt{2}}V \\ 0 & \frac{i}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -V^\dagger & -\frac{i}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

	$E_{\rm beam}$	$N_{\rm beam}$	$L_{\rm min}$	$L_{\rm det/dec}$
LSND	0.8 GeV p	$\sim 1.8\times 10^{23}$	30 m	8.3 m
E137	20 GeV e^-	1.87×10^{20}	179 m	204 m
PS191	19.2 GeV p	8.6×10^{18}	128 m	12 m
CHARM	400 GeV p	2.4×10^{18}	480 m	35 m
NOMAD	450 GeV p	$\sim 4.1\times 10^{19}$	835 m	7.5 m

Experiment	E_p	$N_{\rm POT}$	$L_{\rm min}$
SHiP	400 GeV	2×10^{20}	$\sim 30-50$ m
NA62-dump	400 GeV	$10^{17} - 10^{18}$	~ 80 m
HIKE-dump	400 GeV	$\sim 10^{19}$	$\sim \mathcal{O}(80)$ m
DUNE	120 GeV	$\sim 10^{22}$	574 m
DarkQuest	120 GeV	$10^{18} - 10^{20}$	$\sim 5-20$ m