Lepton Number Violation at Colliders via Heavy Neutrino-Antineutrino Oscillations

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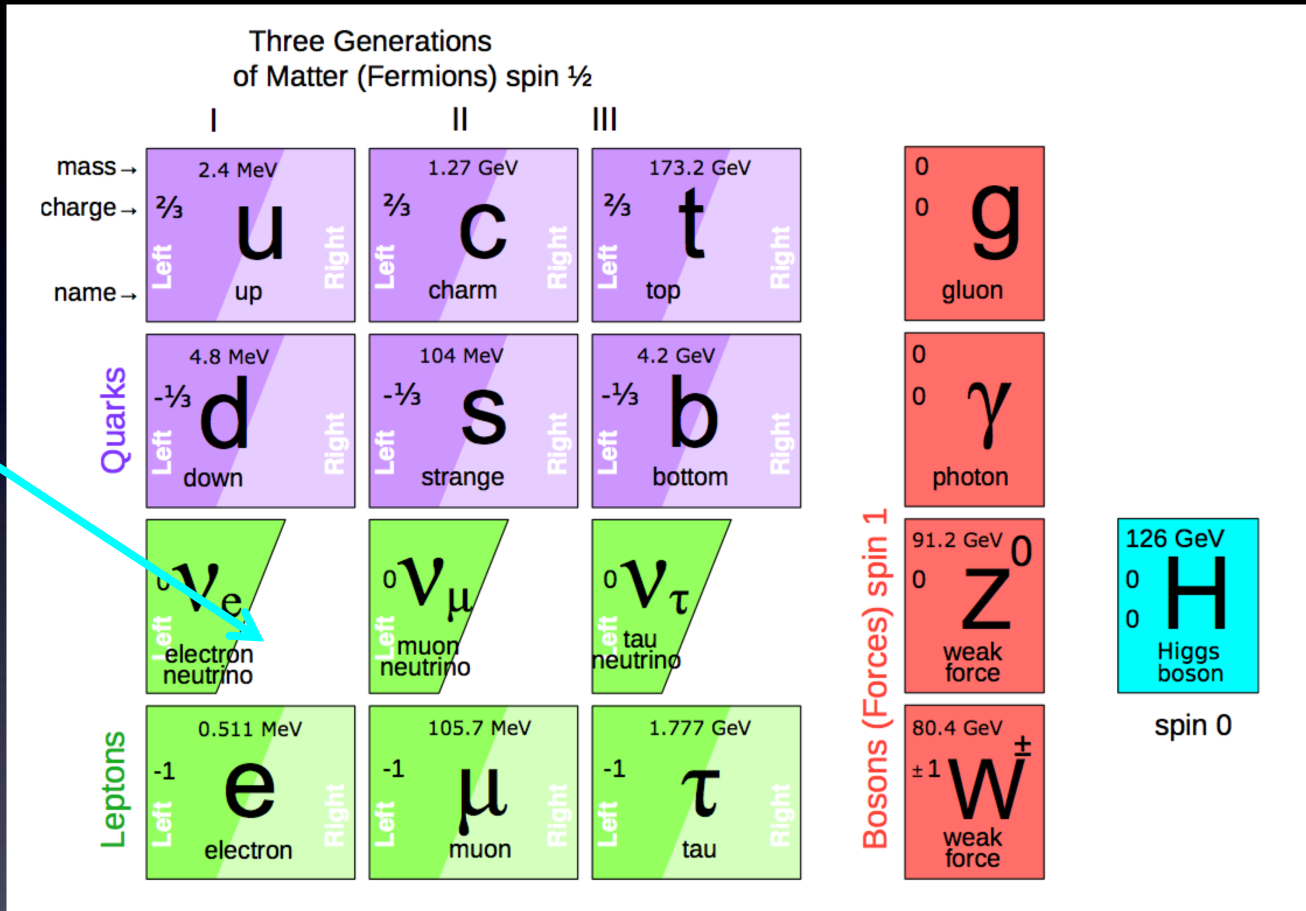
Heavy Neutral Leptons – the right SM extension to explain the light neutrino masses?

There are no right-chiral neutrino states N_{Ri} in the Standard Model

➔ N_{Ri} would be completely neutral under all SM symmetries (HNLs ↔ RH neutrinos ↔ sterile neutrinos)



Adding N_{Ri} leads to the following extra terms in the Lagrangian density:

$$\boxed{\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2}\overline{N_R^i} M_{ij} N_R^{cj} - (Y_\nu)_{i\alpha}\overline{N_R^i}\widetilde{\phi}^\dagger L^\alpha + \mathrm{H.c.}}$$

M: HNL mass matrix

Y_ν: neutrino Yukawa matrix (→ Dirac mass terms m_D)

Outline/Main messages/Conclusions

- Collider testable low-scale seesaw models feature pseudo-Dirac pairs of heavy neutrinos (L approx. symm., small mass splitting ΔM)
- LNV → Can be induced by heavy neutrino-antineutrino oscillations
- Recent developments: S.A., J. Rosskopp (arXiv:2012.05763)
  - QFT calculation of oscillations (LO and NLO, decoherence effects)
  - Phenomenological (pSPSS) benchmark model
  - Madgraph patch for including heavy neutrino-antineutrino oscillations in collider simulations S.A., J. Hajer, J. Rosskopp (arXiv:2210.10738)
  - Oscillations can be resolvable at HL-LHC (for benchmark parameters)
    S.A., J, Hajer, J. Rosskopp (arXiv:2212.00562)
  - From QFT calculation: Decoherence effects can have a large impact, e.g. enhance the total ratio of LNV/LNC events (known as R_{ll} ratio)
    S.A., J, Hajer, J. Rosskopp (arXiv:2307.06208)

Minimal example: 2 RH Neutrinos (2 HNLS)

In the mass basis:

$$\boxed{\mathcal{L}_N = -(m_D^{(1)})_\alpha \overline{\nu}_{\mathrm{L}}^\alpha N_{\mathrm{R}}^1 - (m_D^{(2)})_\alpha \overline{\nu}_{\mathrm{L}}^\alpha N_{\mathrm{R}}^2 - \frac{1}{2} M_1 \overline{N_{\mathrm{R}}^1} N_{\mathrm{R}}^{c1} - \frac{1}{2} M_2 \overline{N_{\mathrm{R}}^2} N_{\mathrm{R}}^{c2} + \mathrm{H.c.}}$$

where $(m_D^{(i)})_\alpha = \frac{v_{\mathrm{EW}}}{\sqrt{2}} (Y_\nu)_{i\alpha}$

$\downarrow$ **„Seesaw Formula“**

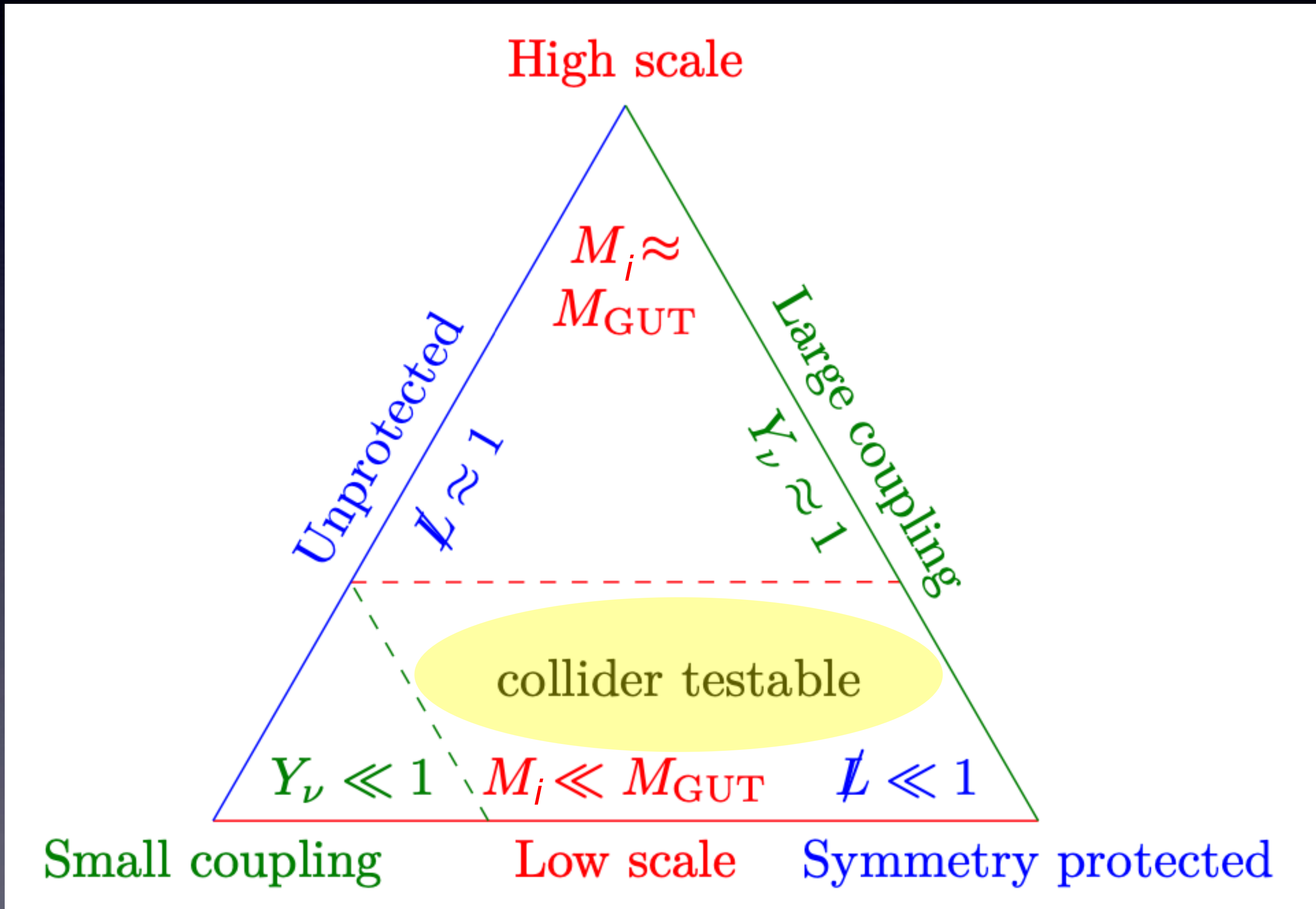
$$\boxed{(m_\nu)_{\alpha\beta} = \frac{(m_D^{(1)})_\alpha (m_D^{(1)})_\beta}{M_1} + \frac{(m_D^{(2)})_\alpha (m_D^{(2)})_\beta}{M_2}}$$

Type I Seesaw: P. Minkowski ('77), Mohapatra, Senjanovic, Yanagida, Gell-Mann, Ramond, Slansky, Schechter, Valle, …

Landscape of the Seesaw Mechanism

$$\boxed{(m_\nu)_{\alpha\beta} = \frac{(m_D^{(1)})_\alpha (m_D^{(1)})_\beta}{M_1} + \frac{(m_D^{(2)})_\alpha (m_D^{(2)})_\beta}{M_2}}$$

↔ Smallness of observed $m_{\nu\alpha}$?



Low Scale Seesaw with "Symmetry protection"

Example for protective "lepton number"-like symmetry (case of 2HNLs):

	L_α	N_{R1}	N_{R2}
"Lepton-#"	+1	+1	-1

→

With 2 HNLs (min # to explain m_ν) and exact symmetry

$$\mathscr{L}_N = - \overline{N_R}^1 M N_R^{c\,2} - y_\alpha \overline{N_R}^1 \tilde{\phi}^\dagger L^\alpha + \text{H.c.}$$

In the symmetry limit: $m_{\nu\alpha} = 0$

with basis $\Psi = (\nu_L, (N_R^1)^c, (N_R^2)^c)$

$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ (m_D)^T & 0 & M \\ 0 & M & 0 \end{pmatrix}$$

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From general 2 HNL seesaw to "symmetry limit"

For comparison: most general seesaw with 2 HNLs:

$$M_\nu^{\text{general}} = \begin{pmatrix} 0 & m_D & m'_D \\ (m_D)^T & M' & M \\ (m'_D)^T & M & M'' \end{pmatrix}$$

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Note: "Symmetry protection" → right-chiral neutrinos form "<u>pseudo-Dirac pair</u>"!

Two (Majorana) HNLs with small mass splitting ΔM << M

In the symmetry limit: $m_{\nu\alpha} = 0$

with basis $\Psi = (\nu_L, (N_R^1)^c, (N_R^2)^c)$

$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ (m_D)^T & 0 & M \\ 0 & M & 0 \end{pmatrix}$$

From general 2 HNL seesaw to "symmetry limit"

For comparison: most general seesaw with 2 HNLs:

$$M_\nu^{\mathrm{general}} = \begin{pmatrix} 0 & m_D & m_D' \\ (m_D)^T & M' & M \\ (m_D')^T & M & M'' \end{pmatrix}$$

To generate the light neutrino masses → approximate symmetry

$$M_\nu^{\text{L broken}} = \begin{pmatrix} 0 & m_D & \varepsilon \\ (m_D)^T & \varepsilon' & M \\ \varepsilon^T & M & \varepsilon'' \end{pmatrix}$$

when ε-terms "get larger"

Low Scale Seesaw with "Symmetry protection"

→ Light neutrino masses induced from small breaking of the "L-like" symmetry (m_ν ~ ε)

$$\mathscr{L}_N = - \overline{N_R}^1 M \; N_R^{c\,2} - y_\alpha \overline{N_R}^1 \tilde{\phi}^\dagger L^\alpha + \text{H.c.}$$

+ symmetry breaking terms O(ε)

"Linear" seesaw:*

$$M_\nu = \begin{pmatrix} 0 & m_D & \varepsilon \\ (m_D)^T & 0 & M \\ \varepsilon^T & M & 0 \end{pmatrix}$$

$$\rightarrow m_\nu \sim \frac{\epsilon^T m_D}{M}$$

In "Minimal linear seesaw" (2 HNLs):

$$\Delta M^{\text{lin}}_{\text{NH}} = m_{\nu_3} - m_{\nu_2} \overset{m_{\nu_1}=0}{=} 0.042 \text{ eV}$$

$$\Delta M^{\text{lin}}_{\text{IH}} = m_{\nu_2} - m_{\nu_1} \overset{m_{\nu_3}=0}{=} 0.00075 \text{ eV}$$

cf. S. A., E. Cazzato, O. Fischer (arXiv:1709.03797)

"Inverse" seesaw:*

$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ (m_D)^T & 0 & M \\ 0 & M & \varepsilon \end{pmatrix}$$

$$\rightarrow m_\nu \sim \epsilon \frac{m_D^T m_D}{M^2}$$

Estimate for induced HNL mass splitting ΔM in "inverse" seesaw:

$$\Delta M^{\text{inv}} = \frac{m_{\nu_\alpha}}{|\theta^2|}$$

(Note: Here only one ν_α gets mass)

also: ... no tree-level m_ν

$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ (m_D)^T & \varepsilon & M \\ 0 & M & 0 \end{pmatrix}$$

"loop seesaw"

*) Note: names "inverse" and "linear" seesaw used here to indicate the position of the ε-term in M_ν

For low scale seesaw models and discussions, see e.g.: D. Wyler, L. Wolfenstein ('83), R. N. Mohapatra, J. W. F. Valle ('86), M. Shaposhnikov (`07), J. Kersten, A. Y. Smirnov ('07), M. B. Gavela, T. Hambye, D. Hernandez, P. Hernandez ('09), M. Malinsky, J. C. Romao, J. W. F. Valle ('05), S.A., Hohl, King, Susic: arXiv:1712.05366) …

Benchmark scenario: The SPSS
(= Symmetry Protected Seesaw Scenario)

... captures the phenomenology of a dominant "pseudo-Dirac"-like HNL pair at colliders
... without the constraints of a restricted pure 2HNL model (↔ correlations between $y_{\nu\alpha}$)

$$\boxed{Y_\nu = \begin{pmatrix} y_{\nu_e} & 0 & \\ y_{\nu_\mu} & 0 & \cdots \\ y_{\nu_\tau} & 0 & \end{pmatrix}, \quad M_N = \begin{pmatrix} 0 & M & & 0 \\ M & 0 & & \\ & & \cdots & \\ 0 & & & \cdots \end{pmatrix}}$$

+ O(ε) perturbations to generate the light neutrino masss ...

Additional sterile neutrinos can exist, but assumed to have negligible effects at colliders (which can be realised easily, e.g. by giving lepton number = 0 to them).

for phenomenology (pSPSS)

Main additional parameter: ΔM

plus: M, θ_α where $\theta_\alpha = \frac{y_\alpha^*}{\sqrt{2}} \frac{v_{\mathrm{EW}}}{M}$

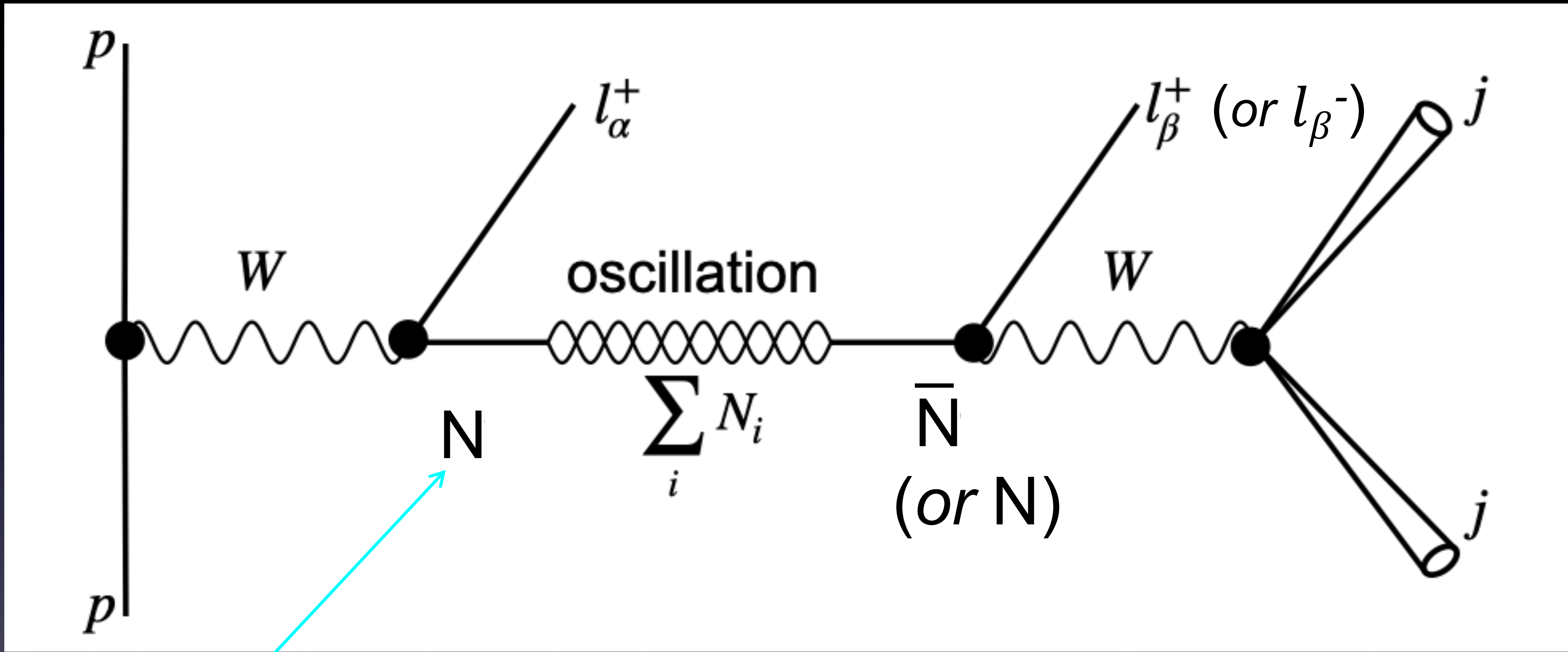
For details on the SPSS/pSPSS, see:
S.A., O. Fischer (arXiv:1502.05915)
S.A., E. Cazzato, O. Fischer (arXiv:1612:02728)
S.A., J. Hajer, J. Rosskopp (arXiv:2210.10738)

Beyond the "L-like"-symmetry (Dirac HNL) limit:

Can we observe LNV from the HNLs (required to generate light m_ν)?

Often assumed that LNV is strongly suppressed by the smallness of neutrino masses and thus practically unobservabvale ... no longer true when **heavy neutrino-antineutrino oscillations** are taken into account!

Heavy Neutrino-Antineutrino Oscillations



Interaction states: Produced from W decay
- "Heavy Neutrinos N" (together wilth l_α^+)
- "Heavy Antineutrinos $\bar{N}$" (together wilth l_α^-)

They are superpositions of the mass eigenstates:

$$\overline{N} = 1/\sqrt{2}(iN_4 + N_5) \quad N = 1/\sqrt{2}(-iN_4 + N_5)$$

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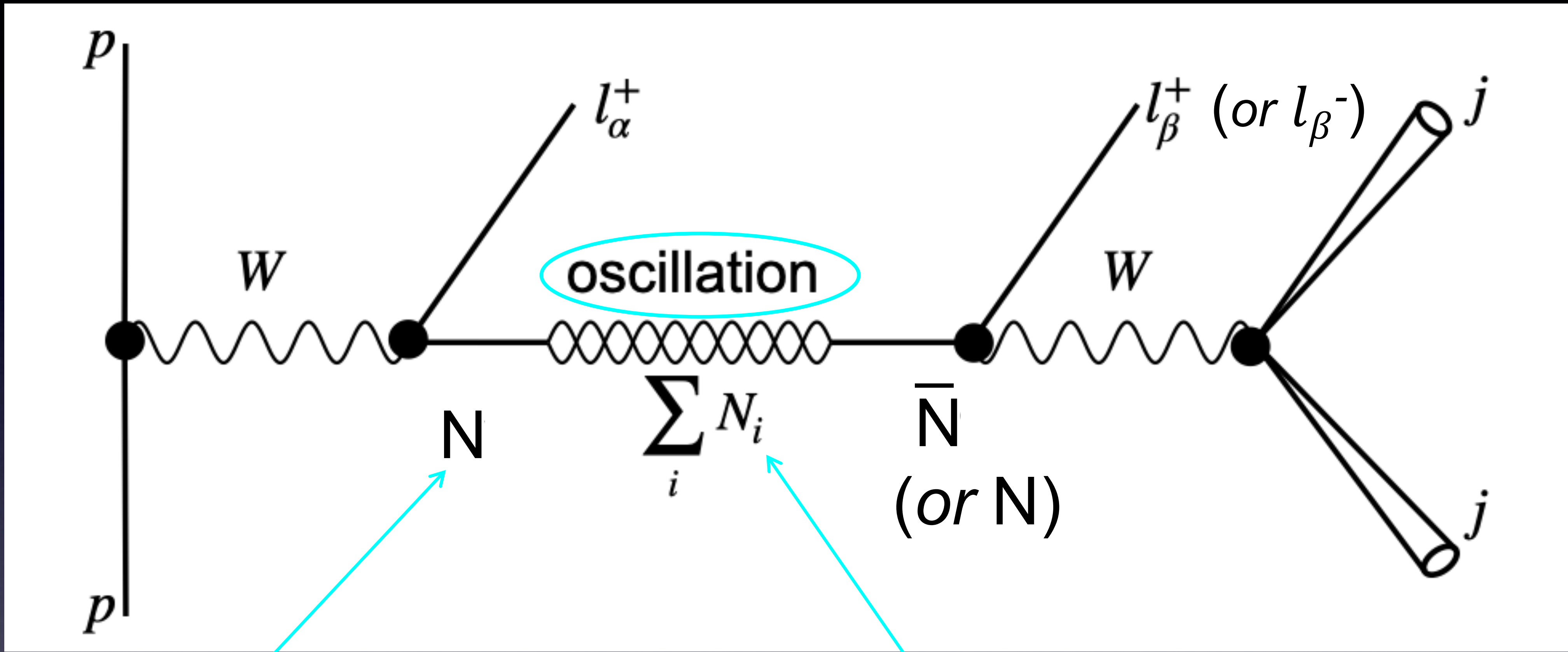

Interaction states: Produced from W decay
- "Heavy Neutrinos N" (together with l_α^+)
- "Heavy Antineutrinos N̄" (together with l_α^-)

Due to the O(ε) perturbations to generate the light neutrino masses: → **mass splitting ΔM** between the heavy mass eigenstates N_4 and N_5 → propagation of interfering mass eigenstates induces oscillations between N̄ and N

They are superpositions of the mass eigenstates:

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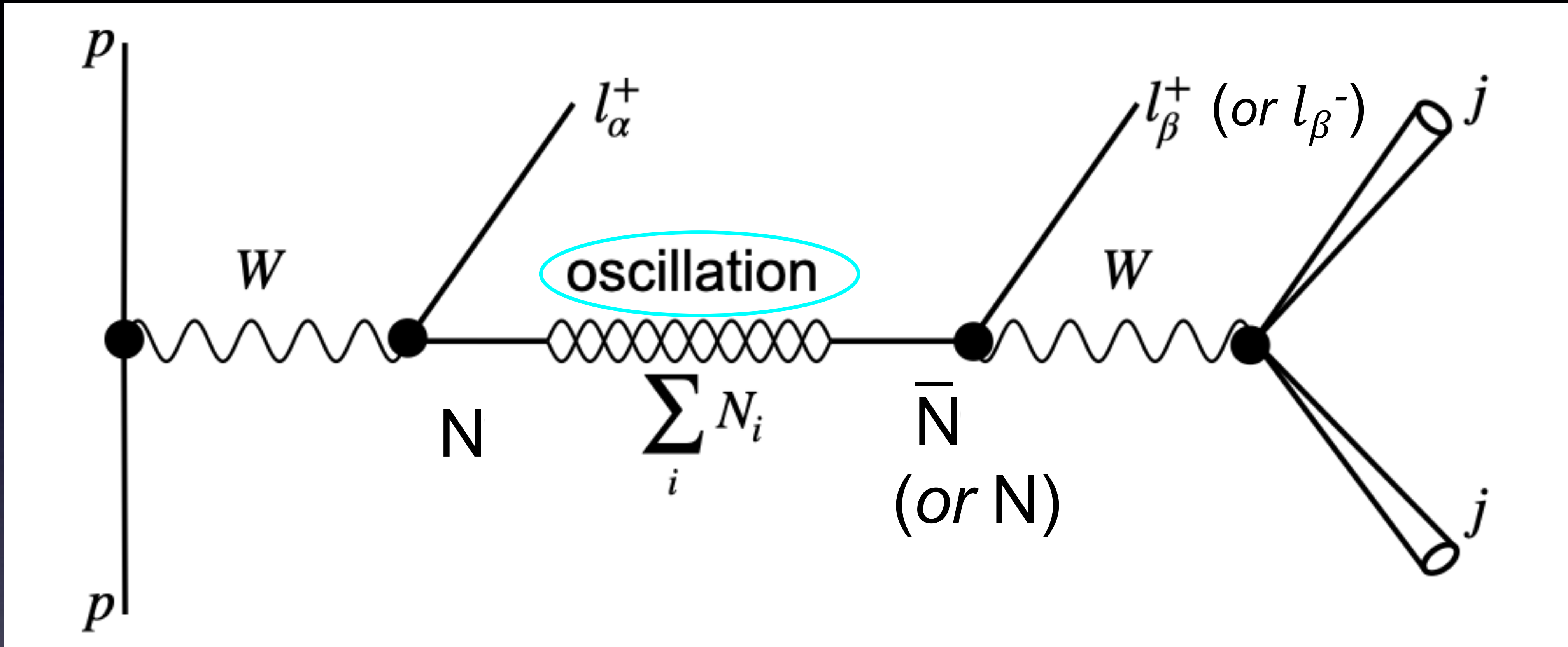
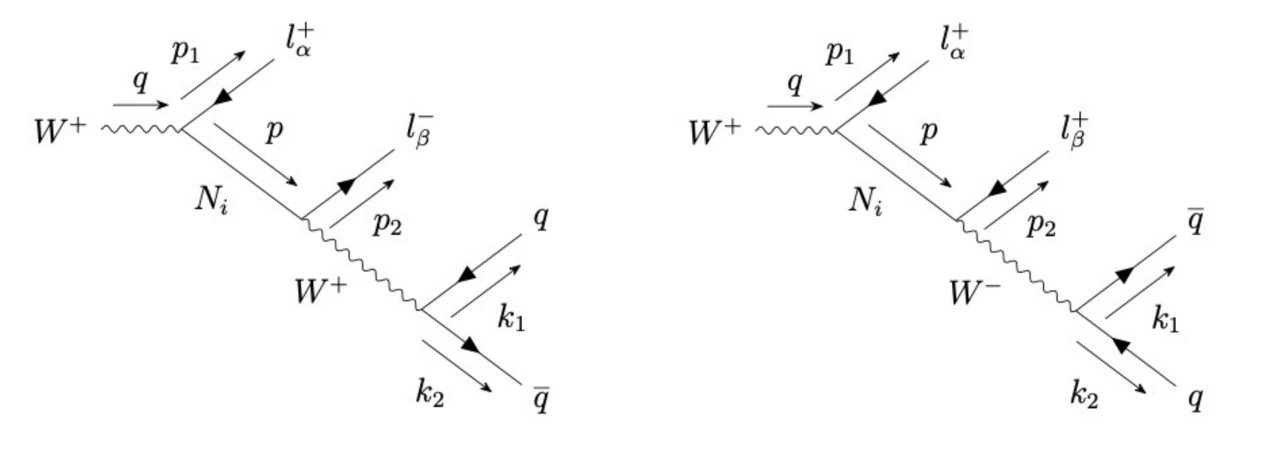
Heavy Neutrino-Antineutrino Oscillations



Since an N decays into a l_α^- and a N̄ into a l_α^+, the Heavy Neutrino-Antineutrino Oscillations lead to an **oscillation between LNC and LNV final states**, as a function of the oscillation time (or travelled distance)

We recently studied the Heavy Neutrino-Antineutrino Oscillations in QFT ...

Study in QFT (using the formlism of external wave packets [cf. Beuthe 2001])



(a) Feynman diagram for the LNC process

(b) Feynman diagram for the LNV process

S.A., J. Rosskopp (arXiv:2012.05763)

$$\mathcal{A} = \langle f | \hat{T}\left(\exp\left(-i\int \mathrm{d}^4x\,\mathcal{H}_I\right)\right) - \mathbf{1}\,|i\rangle$$

→ Full oscillation formulae

Oscillation formulae in the SPSS (with ε-perturbations, in an expansion):

$$P^{LNV}_{\alpha\beta}(L) = \frac{1}{2\sum_\beta |\theta_\alpha|^2|\theta_\beta|^2}\Big(|\theta_\alpha|^2|\theta_\beta|^2(1-\cos(\phi_{45}L))$$ ← LO

Oscillation probability

$$-2(I_\beta|\theta_\alpha|^2 + I_\alpha|\theta_\beta|^2)\sin(\phi_{45}L)\Big)\,,$$ ← NLO

$$P^{LNC}_{\alpha\beta}(L) = \frac{1}{2\sum_\beta |\theta_\alpha|^2|\theta_\beta|^2}\Big(|\theta_\alpha|^2|\theta_\beta|^2(1+\cos(\phi_{45}L))$$ ← LO

Survival probability

$$-2(I_\beta|\theta_\alpha|^2 - I_\alpha|\theta_\beta|^2)\sin(\phi_{45}L)\Big)\,.$$ ← NLO

where

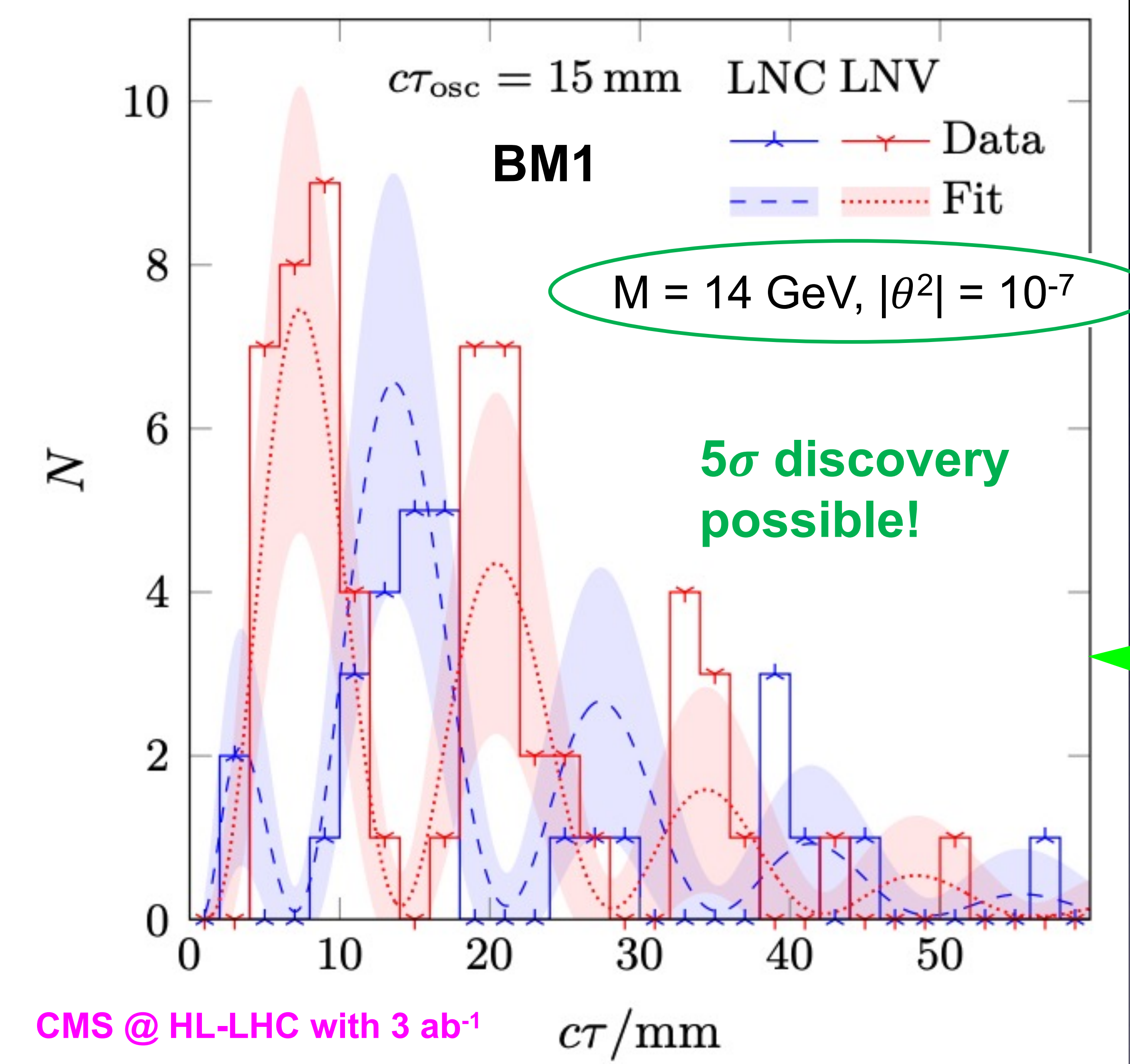
$$I_\beta := \mathrm{Im}(\theta^*_\beta\theta'_\beta\exp(-2i\Phi))\,,$$

$$\phi_{ij} := -\frac{2\pi}{L^{osc}_{ij}} = -\frac{M_i^2 - M_j^2}{2|\mathbf{p}_0|}\,,$$

$$\Phi := \frac{1}{2}\mathrm{Arg}\left(\vec{\theta}'\cdot\vec{\theta}^*\right)\,.$$

LO agrees with previous works, e.g.:
G. Anamiati, M. Hirsch and E. Nardi (2016),
G. Cvetic, C. S. Kim, R. Kogerler and J. Zamora-Saa (2015), ...

Signal: Oscillating fraction of LNV / LNC decays with lifetime (→ displacement)



S.A., J, Hajer, J. Rosskopp (arXiv:2212.00562)

BM	$\Delta m/\mu$eV	$c\tau_{osc}$/mm
1	82.7	15
2	207	6
3	743	1.67

Analysis at the reconstructed level using recently released Madgraph "patch" for simulating the oscillations with the pSPSS model file

Madgraph patch and pSPSS bechmark model: S.A., J. Hajer, J. Rosskopp (arXiv:2210.10738)

To see the oscillations, crucial to reconstruct γ and plot over tifetime τ: S.A., E. Cazzato, O. Fischer (arXiv:1709.03797)

Even if not resolvable → "integrated effect" (R_{ll} ratio)

(*) using LO formulae and when the "observability conditions" are satisfied (i.e. **assuming no decoherence**)

Ratio of LNV over LNC events between t_1 and t_2:

$$R_{\ell\ell}(t_1, t_2) = \frac{\#(\ell^+\ell^+) + \#(\ell^-\ell^-)}{\#(\ell^+\ell^-)} \xrightarrow{*} R_{ll}(0,\infty) = \frac{\Delta M^2}{2\Gamma^2 + \Delta M^2}$$

cf. G. Anamiati, M. Hirsch and E. Nardi, hep-ph/1607.05641

$$\Rightarrow \boxed{R_{ll}(0,\infty) = \frac{N_{\mathrm{LNV}}}{N_{\mathrm{LNC}}} = \frac{\Delta M^2}{\Delta M^2 + 2\Gamma^2} = \begin{cases} \approx 0 & \text{No LNV induced by oscillations} \\ > 0 & \text{LNV can be induced by oscillations} \end{cases}}$$

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Decoherence effects can be included by an effective "damping term" λ in the oscillation formula:

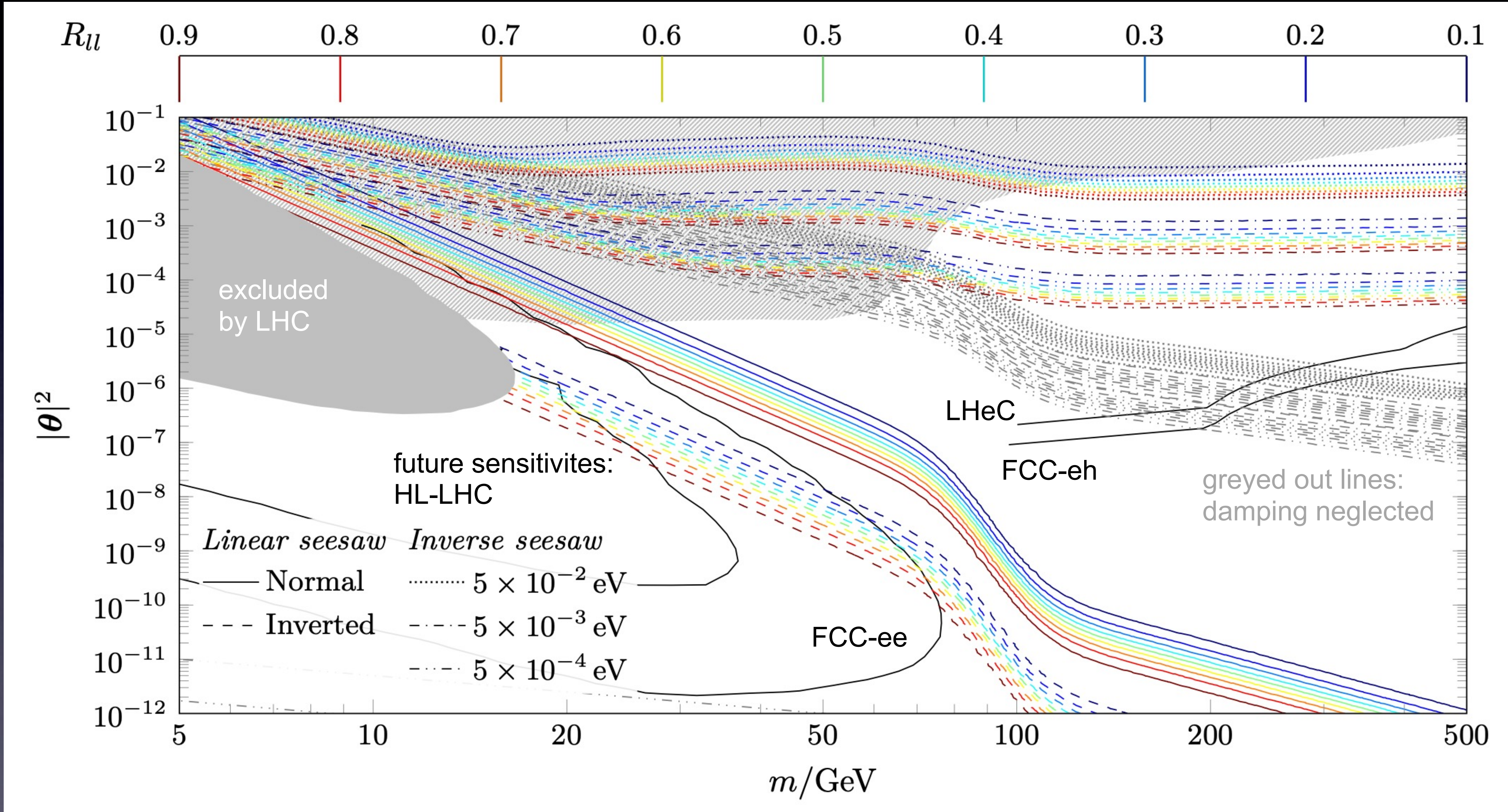
$$\boxed{P_{\rm osc}^{\rm LNC/LNV}(\tau) = \frac{1 \pm \cos(\Delta M \tau)\exp(-\lambda)}{2}}$$

... can have a strong impacton the R_{ll} ratio

S.A., J. Hajer, J. Rosskopp (arXiv:2210.10738)

Damping parameter λ calculated recently in:
S.A., J, Hajer, J. Rosskopp (arXiv:2307.06208)

Damping effects from decoherence can have a strong impact on R_{ll}



coloured: including decoherence effects which induce damping of the heavy neutrino-antineutrino oscillations

S.A., J, Hajer, J. Rosskopp (arXiv:2307.06208)

... a little remark on benchmark models

→ pSPSS (i.e. the SPSS with ΔM as additional parameter), appears to be a useful benchmark scenario (can capture all of the effects discussed in my talk ☺)*

→ ... effects cannot be described by
- 1 Majorana HNL (LNV/LNC ratio always 50%- no oscillations, for observable effects @ LHC too large $m_{\nu\alpha}$, need 2 HNLs to describe m_ν ☹)
- 1 Dirac HNL (no LNV – no oscillations, no contribution to m_ν ☹)

**) or alternatively of course a full 2+n HNL model*

Main messages/Conclusions

- Collider testable low-scale seesaw models feature pseudo-Dirac pairs of heavy neutrinos (L approx. symm., small mass splitting ΔM)
- LNV → Can be induced by heavy neutrino-antineutrino oscillations
- Recent developments:

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  - QFT calculation of oscillations (LO and NLO, decoherence effects)
  - Phenomeological (pSPSS) benchmark model available, plus ...
  - Madgraph patch for including heavy neutrino-antineutrino oscillations in collider simulations

    S.A., J. Hajer, J. Rosskopp (arXiv:2210.10738)
  - Oscillations can be resolable at HL-LHC (for benchmark parameters)

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  - From QFT calculation: Decoherence effects can have a large impact, e.g. enhance the total ratio of LNV/LNC events (known as R_{ll} ratio)

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Thanks for your attention!