Heavy Neutrino-Antineutrino Oscillations at Colliders

Stefan Antusch

University of Basel, Department of Physics

BLV 2024, Karlsruhe, Germany

9.10.2024

Main messages

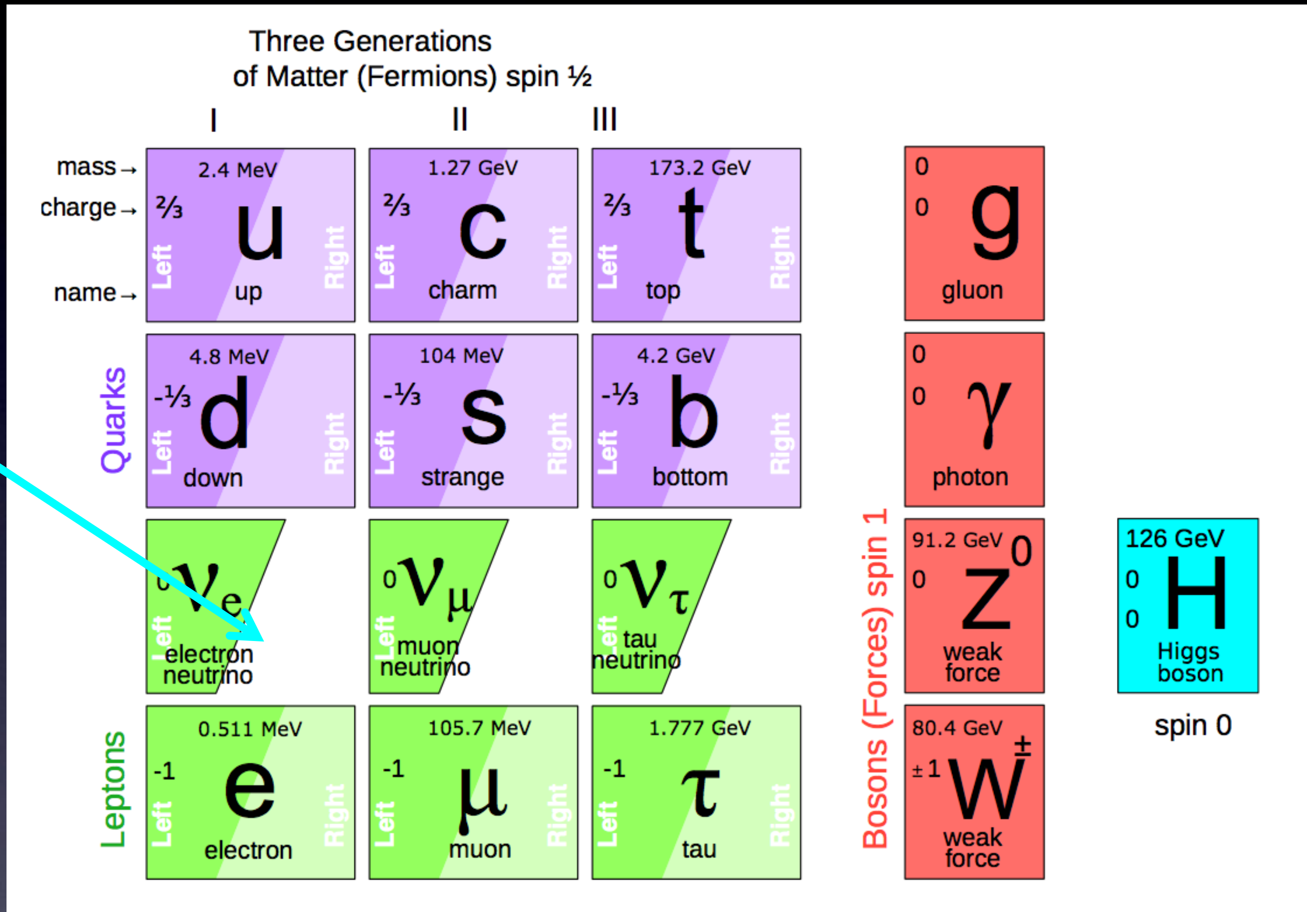
*) Scenario: SM + HNLs (with masses > 5 GeV), barring fine-tuning

- Collider testable low-scale seesaw models* feature pseudo-Dirac pairs of heavy neutrinos (L approx. symm., small mass splitting ΔM)
- Interesting phenomenon: heavy neutrino-antineutrino oscillations
- Relevant for collider phenomenology of HNLs → Can induce observable Lepton Number Violation (LNV)
- Outline of this talk:
  - Motivation for pseudo-Dirac HNLs
  - Introduction to LNV via heavy neutrino-antineutrino oscillations
  - Can the oscillations be resolved at HL-LHC? .. at FCC-ee?
  - Also when not resolvable: induced LNV important (impact of decoherence!)

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)



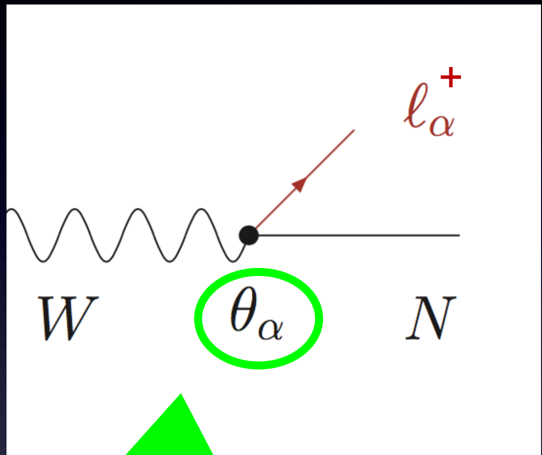
Adding N_{Ri} leads to the following extra terms in the Lagrangian density:

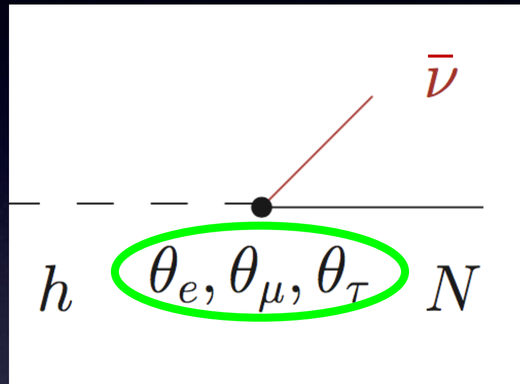
$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2}\overline{N_R^i} M_{ij} N_R^{cj} - (Y_\nu)_{i\alpha}\overline{N_R^i}\tilde{\phi}^\dagger L^\alpha + \mathrm{H.c.}$$

M: HNL mass matrix

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

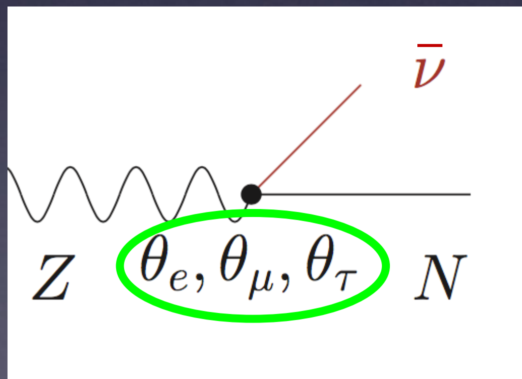
In the SM + N_{Ri}: Heavy neutrino mass eigenstates (HNLs) interact due to mixing of N_{Ri} with the active SM neutrinos*





θ_α: "active-sterile" neutrino mixing angles"

$$\theta_\alpha = \frac{y_\alpha^*}{\sqrt{2}} \frac{v_{\rm EW}}{M}, \qquad \alpha = e, \mu, \tau$$



*) Scenario in this talk: SM + HNLs

Minimal example: 2 RH Neutrinos (2 HNLS)

In the mass basis:

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

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

↓ „Seesaw Formula“

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

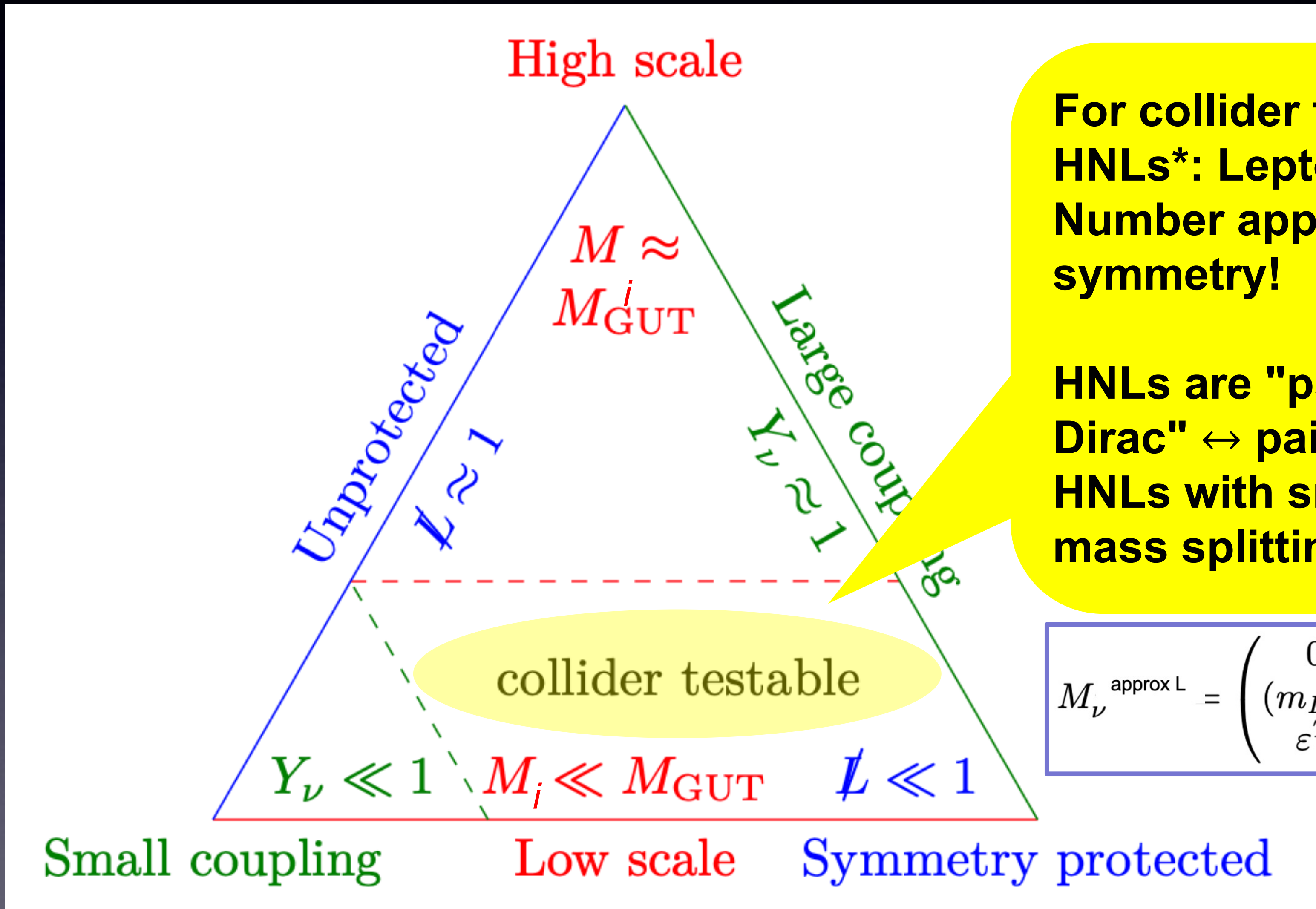
Type I Seesaw: P. Minkowski ('77), Mohapatra, Senjanovic, Yanagida, Gell-Mann, Ramond, Slansky, Schechter, Valle, …

Landscape of the Seesaw Mechanism

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

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

Example:
2 HNLs



For collider testable HNLs*: Lepton Number approximate symmetry!

HNLs are "pseudo-Dirac" ↔ pairs of HNLs with small mass splitting ΔM

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

*) In the SM + HNLs (with masses > 5 GeV), barring highly fine-tuned scenarios

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 $y_{\nu\alpha}$)

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

+ $O(\varepsilon)$ 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)

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

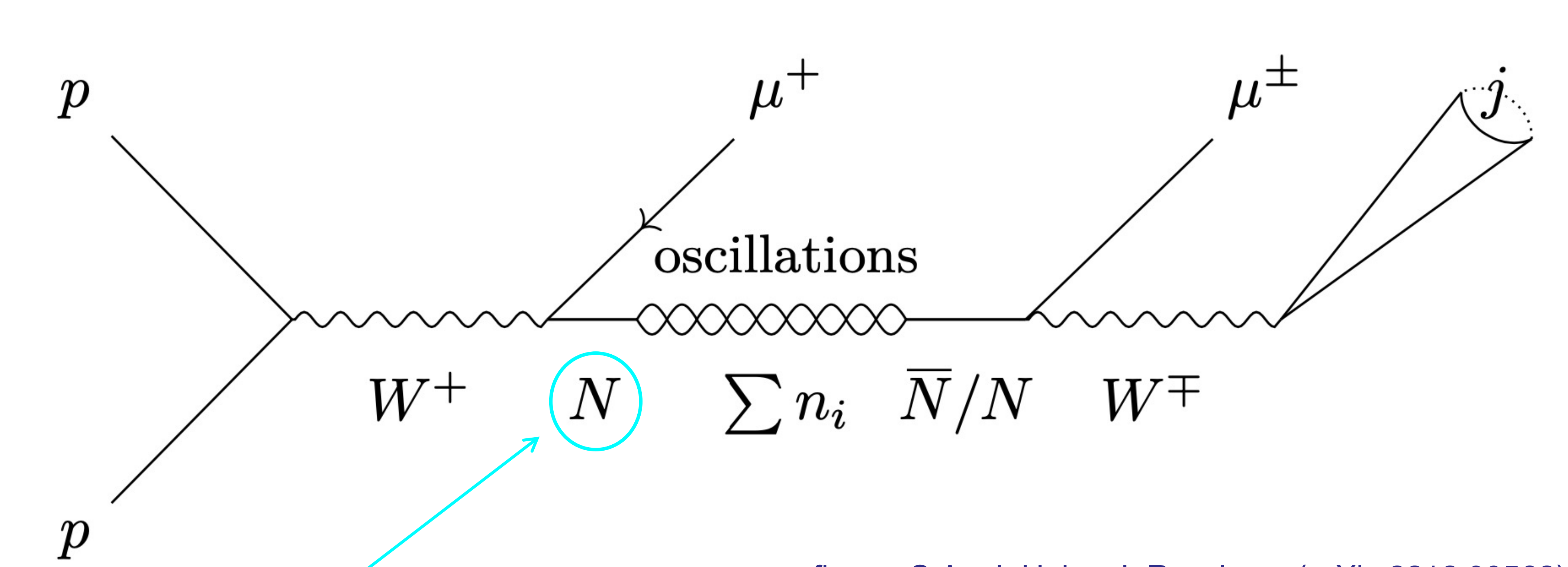


figure: S.A., J. Hajer, J. Rosskopp (arXiv:2212.00562)

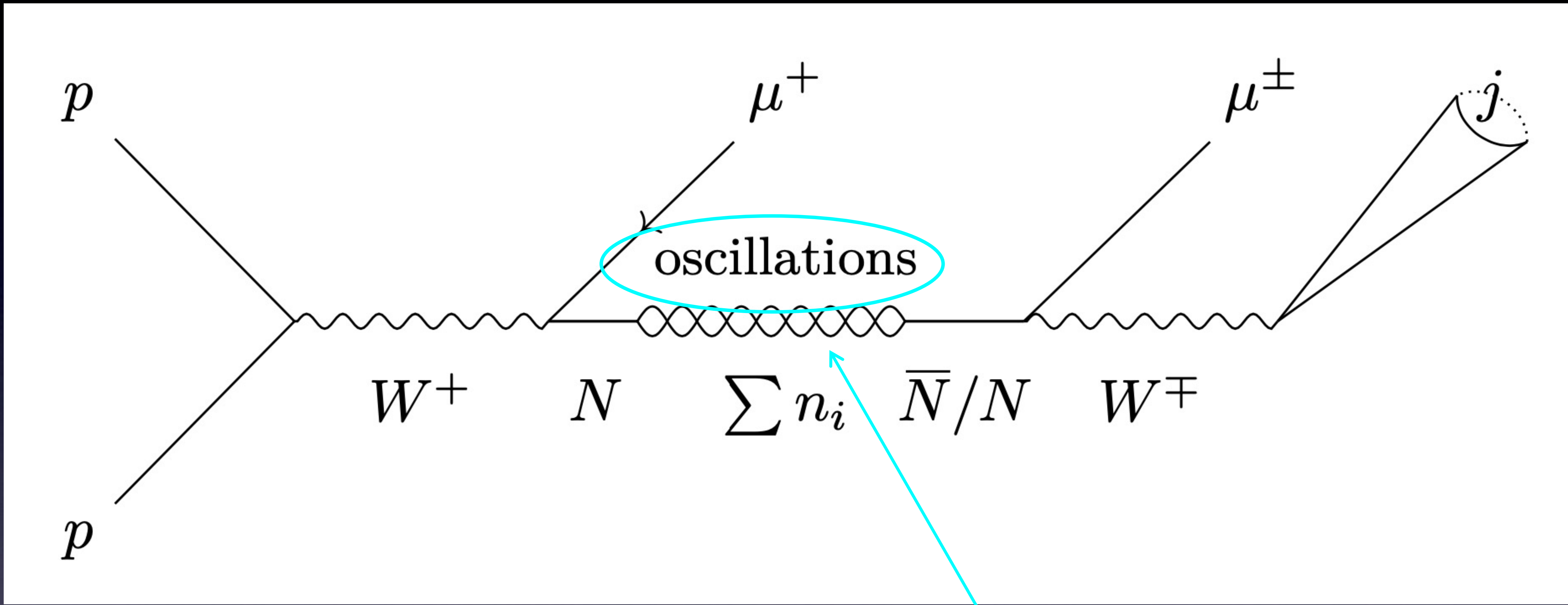
Interaction states: Produced from W decay
- "Heavy Neutrinos N" (together with l_α^+)
- "Heavy Antineutrinos $\overline{N}$" (together with l_α^-)

They are superpositions of the mass eigenstates:

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

Example process at the LHC – HNLs produced from W

Heavy Neutrino-Antineutrino Oscillations



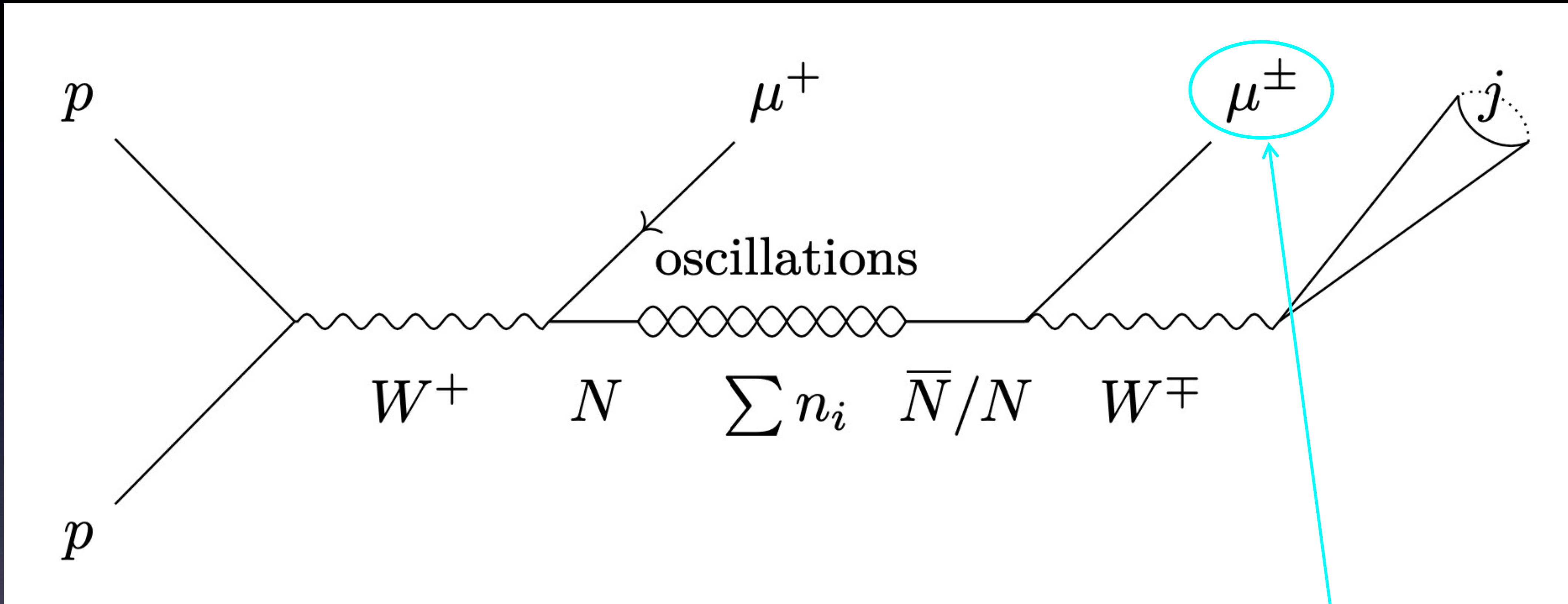
Interaction states: Produced from W decay
- "Heavy Neutrinos N" (together with l_α^+)
- "Heavy Antineutrinos $\overline{N}$" (together wilth l_α^-)

They are superpositions of the mass eigenstates:

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

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 $\overline{N}$ and N

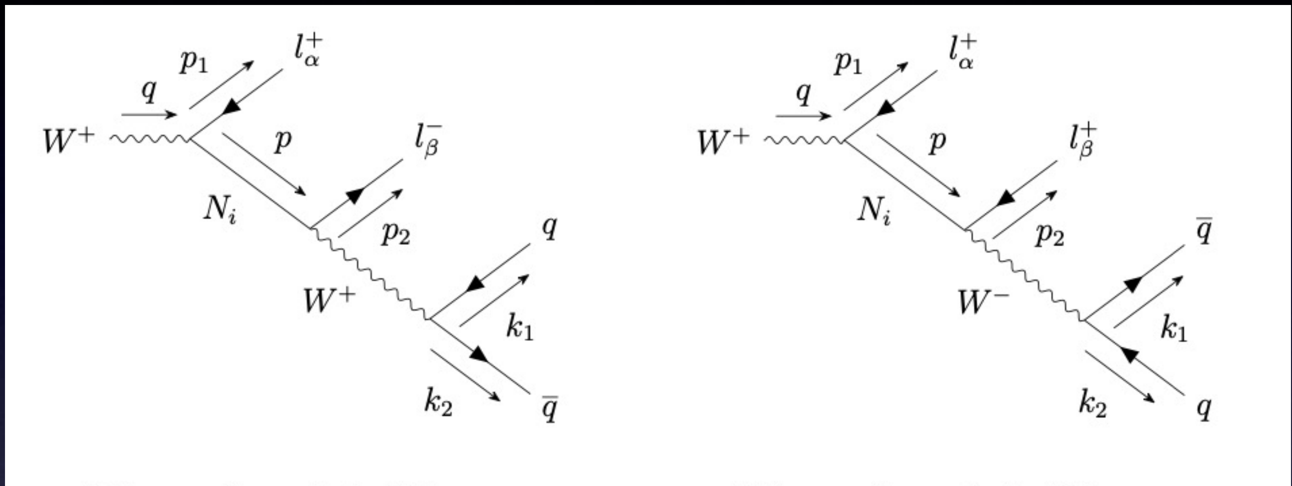
Heavy Neutrino-Antineutrino Oscillations



Since an N decays into a l_α^- and a N 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)

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

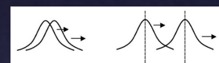
(b) Feynman diagram for the LNV process

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

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

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

→ Full oscillation formulae, decoherence effects, ...



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

Oscillation probability

$$P_{\alpha\beta}^{LNV}(L) = \frac{1}{2\sum_\beta |\theta_\alpha|^2|\theta_\beta|^2}\Big(|\theta_\alpha|^2|\theta_\beta|^2(1-\cos(\phi_{45}L)) \quad \leftarrow \text{LO}$$
$$- 2(I_\beta|\theta_\alpha|^2 + I_\alpha|\theta_\beta|^2)\sin(\phi_{45}L)\Big)\,, \quad \leftarrow \text{NLO}$$

Survival probability

$$P_{\alpha\beta}^{LNC}(L) = \frac{1}{2\sum_\beta |\theta_\alpha|^2|\theta_\beta|^2}\Big(|\theta_\alpha|^2|\theta_\beta|^2(1+\cos(\phi_{45}L)) \quad \leftarrow \text{LO}$$
$$- 2(I_\beta|\theta_\alpha|^2 - I_\alpha|\theta_\beta|^2)\sin(\phi_{45}L)\Big)\,. \quad \leftarrow \text{NLO}$$

where

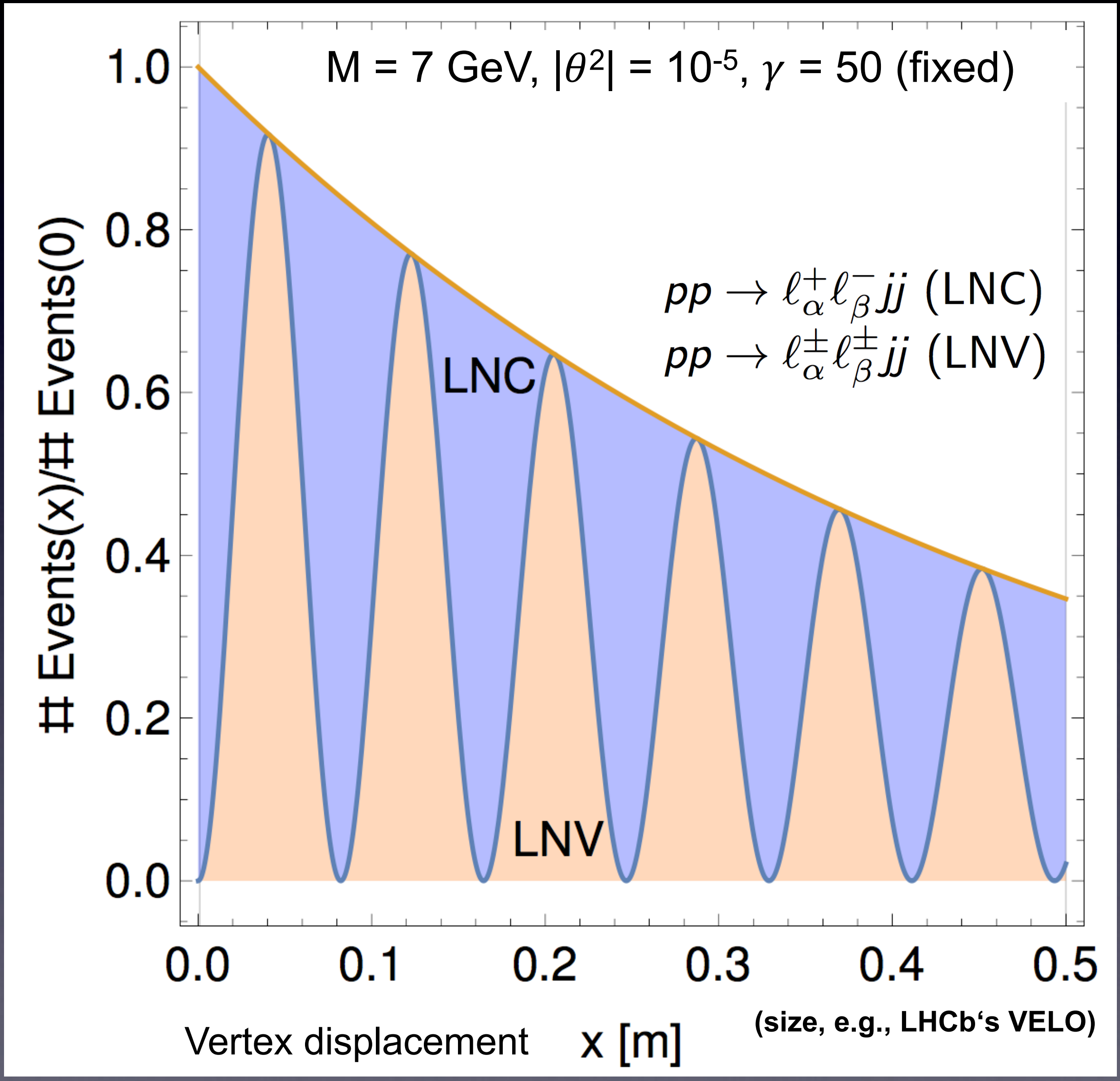
$$I_\beta := \mathrm{Im}(\theta_\beta^*\theta_\beta' \exp(-2i\Phi))\,,$$
$$\phi_{ij} := -\frac{2\pi}{L_{ij}^{osc}} = -\frac{M_i^2 - M_j^2}{2|\mathbf{p}_0|}\,,$$
$$\Phi := \frac{1}{2}\mathrm{Arg}\left(\vec{\theta}' \cdot \vec{\theta}^*\right)\,.$$

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)

Example:

→ using the prediction for ΔM in the "Minimal linear seesaw" model with inverse neutrino mass hierarchy (IH)



For this plot: fixed γ factor (instead of distribution), no uncertainties yet.

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

Remark: "Dirac" and "double Majorana" limits

→ "Double Majorana" HNLs limit
(similar, but not identical to single Majorana HNL)*

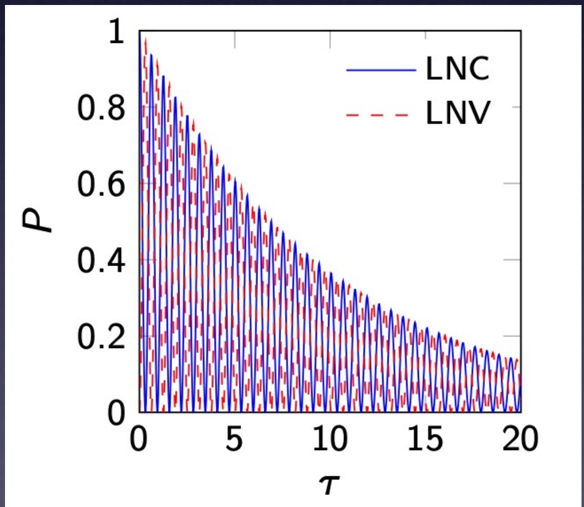
- LNV/LNC ratio ≈ 1
(oscillations averaged out)

Pseudo-Dirac pair of HNLs
(e.g. pSPSS benchmark model)

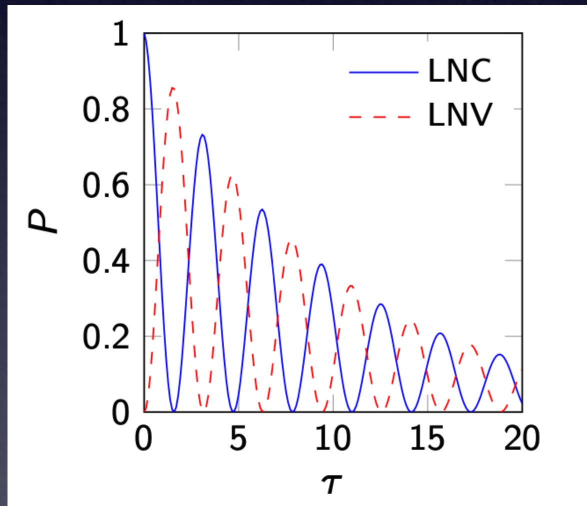
- Oscillations potentially observable, intermediate LNV/LNC ratio possible (mass splitting ΔM as additional pheno parameter)

→ "Pure Dirac HNL" limit

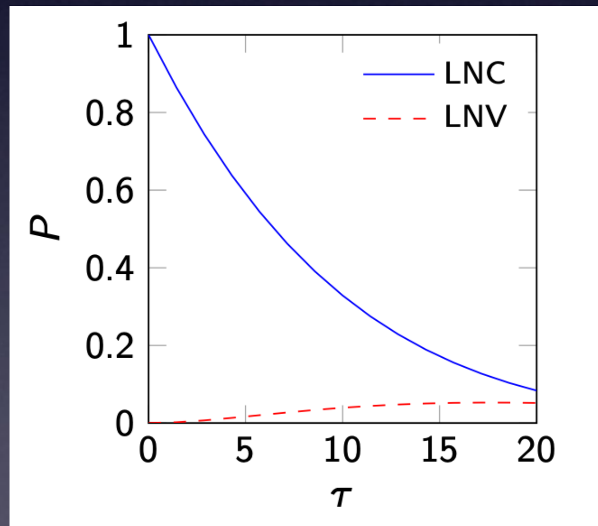
- no observable LNV
(oscillation length too large)



larger ΔM ←



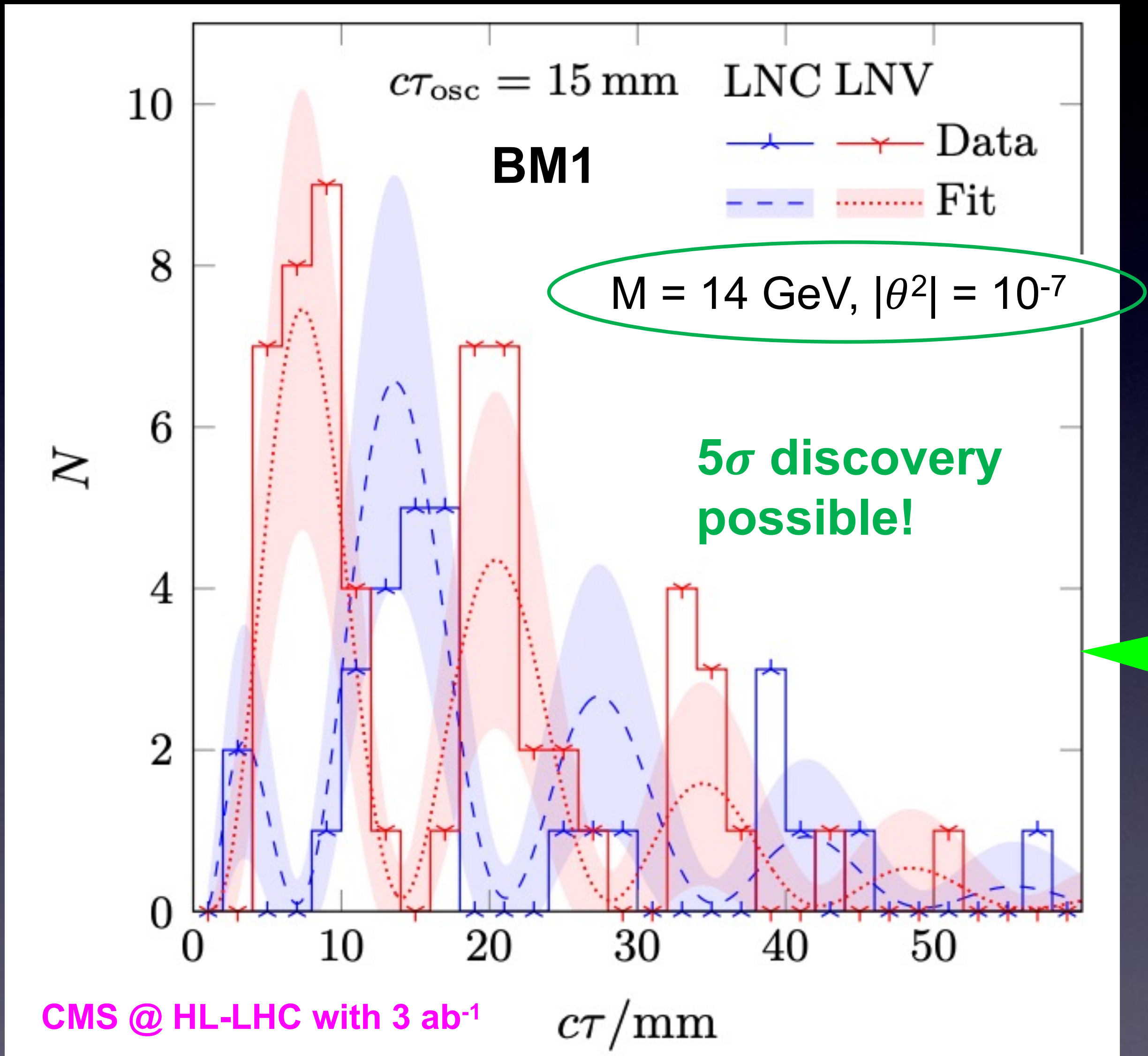
$\Delta M \to 0$ →



*) still approximate L symmetrty → small neutrino masses protected (too large m_ν for testable single Majorana HNL); observed two mass aplittings can be explained; no difference between production/decay rates for both limits (Remark: factor 2 difference for single Majorana HNL only probes # of degrees of freedom, not Majorana property)

Are heavy neutrino-antineutrino oscillations resolvable at the HL-LHC (for long-lived HNLs)?

Resolvable oscillations at HL-LHC



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

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

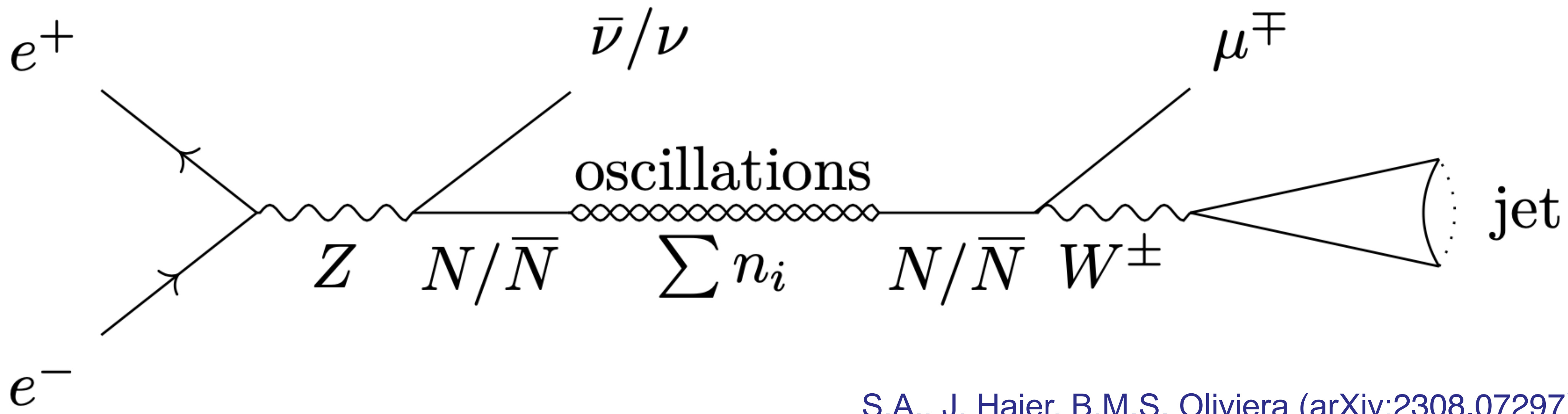
Analysis at the reconstructed level using Madgraph "patch" for simulating the oscillations with the pSPSS model file

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)

Are heavy neutrino-antineutrino oscillations resolvable at the FCC-ee (for long-lived HNLs)?

Heavy Neutrino-Antineutrino Oscillations at e^+e^- Colliders (e.g. Z pole HNLs at FCC-ee)



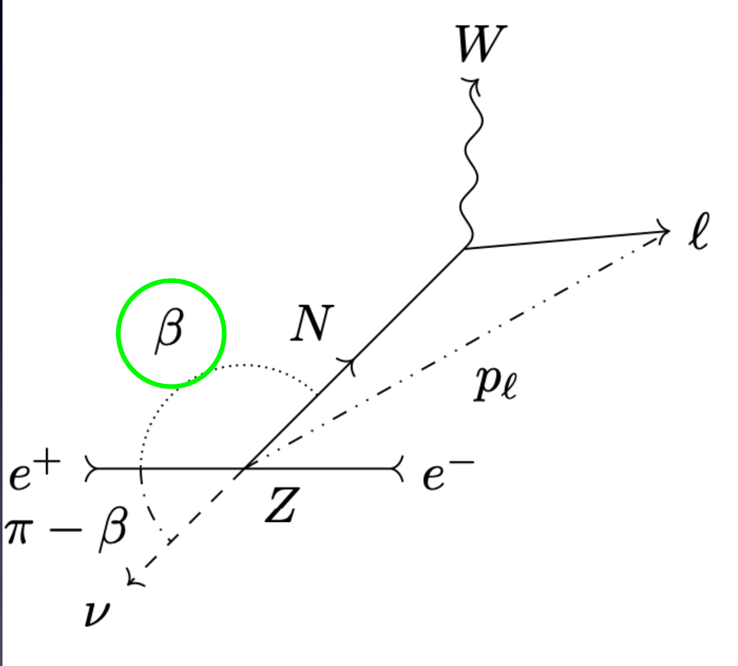
S.A., J. Hajer, B.M.S. Oliviera (arXiv:2308.07297)
S.A., J. Hajer, B.M.S. Oliviera (arXiv:2408.01389)

Important difference: since the light neutrinos are not detected, so there is no direct information on whether a LN is violated or not!
-> Distinguishing LNV/LNC relies on final state angular distributions!

→ N - $\overline{\text{N}}$ oscillations induce an oscillating pattern on top of the angular dependencies

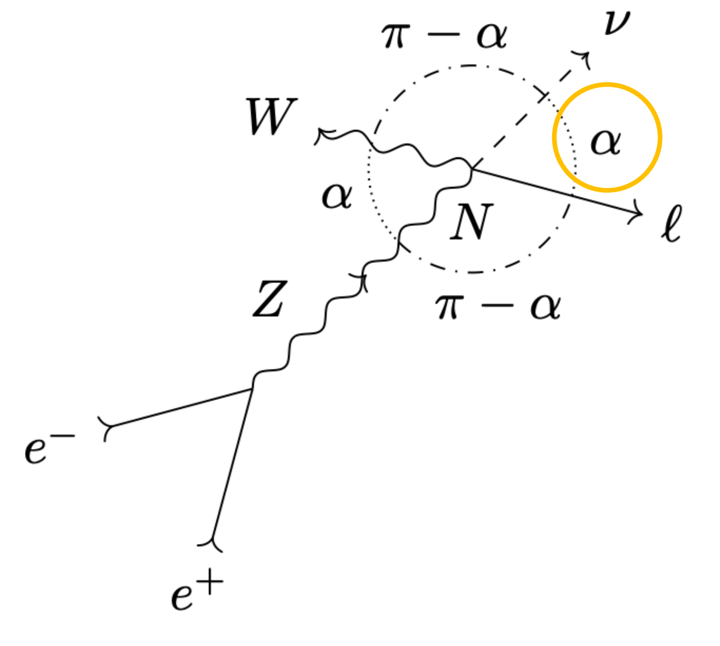
Angular dependecies for HNLs at the FCC (Z-pole run)

Polarisation of the Z → forward-backward asymmetry of the N vs. N̄ in the Z rest frame



(a) *Z*-boson rest frame.

Polarisation of the N → "opening angle" asymmetry of the charged lepton in HNL rest frame



(b) HNL rest frame.

+ various derived observables

Forward-backward asymmetry without oscillations, see e.g.:
A. Blondel, A. de Gouvêa and B. Kayser (arXiv: 2105.06576)

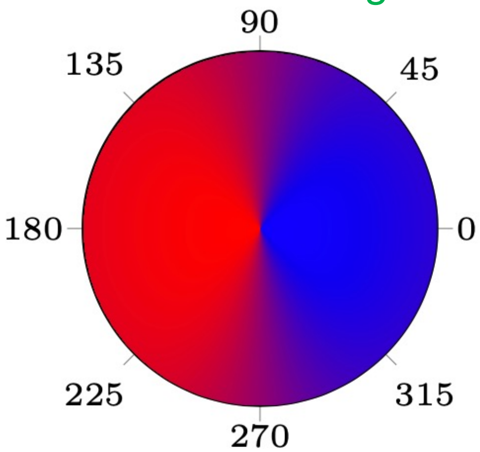
S.A., J. Hajer, B.M.S. Oliviera (arXiv:2408.01389)

Example Signal: Oscillating ratio of l^+/l^- final states as function of HNL lifetime and polar angle of displaced vertex

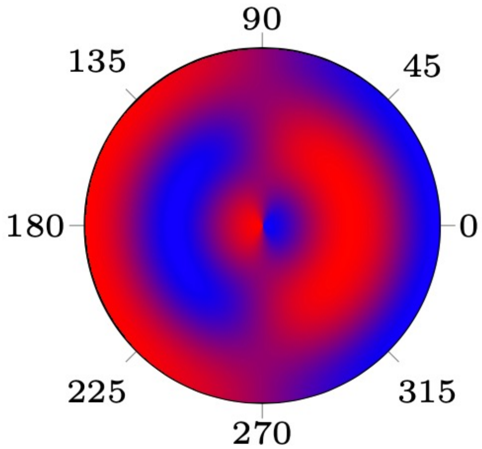
$$R_\ell(\tau, \cos\theta) = \frac{P_{\ell^-}(\tau, \cos\theta)}{P_{\ell^+}(\tau, \cos\theta)}$$

blue: >1, red, <1

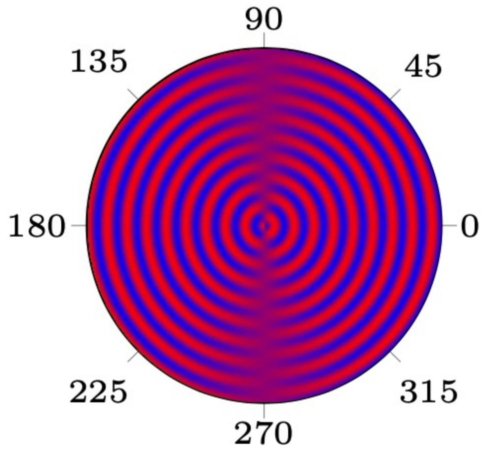
angle $\theta \equiv \beta$, radius = τ



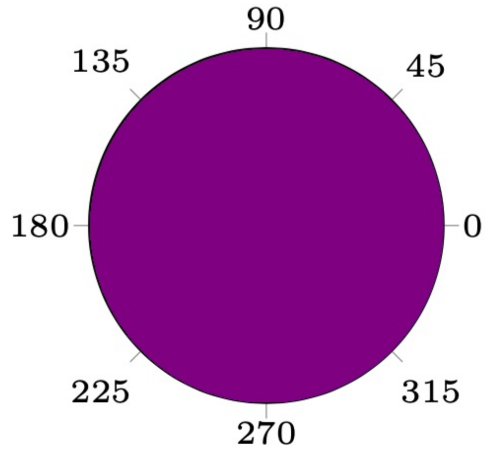
(a) BM1



(b) BM2



(c) BM3



(d) BM4

pseudo-Dirac with very small ΔM (looks like pure Dirac HNL)

pseudo Dirac with relatively small ΔM

pseudo Dirac with relatively large ΔM

pseudo-Dirac with very large ΔM (looks like "double Majorana HNLs")

S.A., J. Hajer, B.M.S. Oliviera (arXiv:2308.07297)

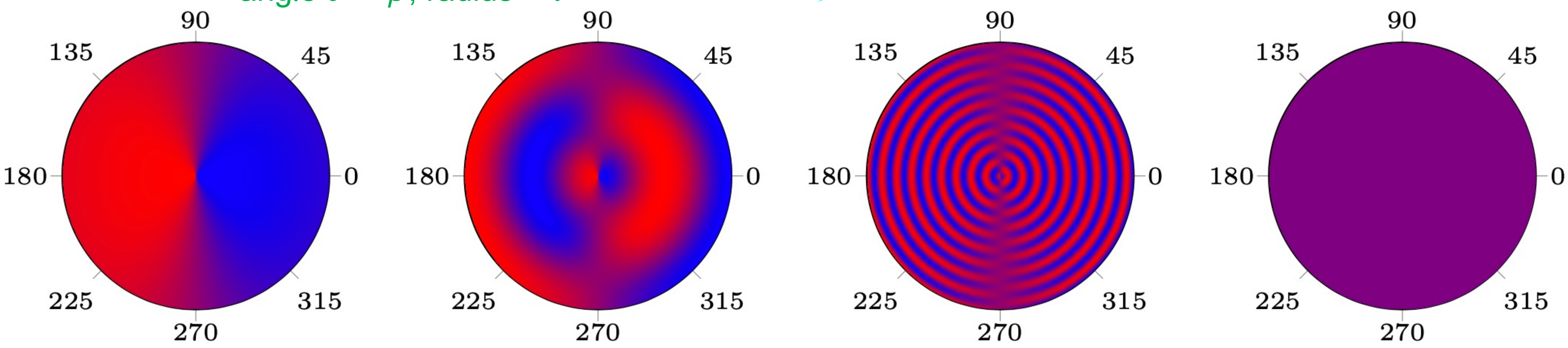
Example Signal: Oscillating ratio of l^+/l^- final states as function of HNL lifetime and polar angle of displaced vertex

For angular segment: Lepton # changes as function of τ → clear signal of LNV

$$R_\ell(\tau, \cos\theta) = \frac{P_{\ell^-}(\tau, \cos\theta)}{P_{\ell^+}(\tau, \cos\theta)}$$

blue: >1, red, <1

angle $\theta \equiv \beta$, radius = τ



(a) BM1 (b) BM2 (c) BM3 (d) BM4

pseudo-Dirac with very small ΔM (looks like pure Dirac HNL)

pseudo Dirac with relatively small ΔM

pseudo Dirac with relatively large ΔM

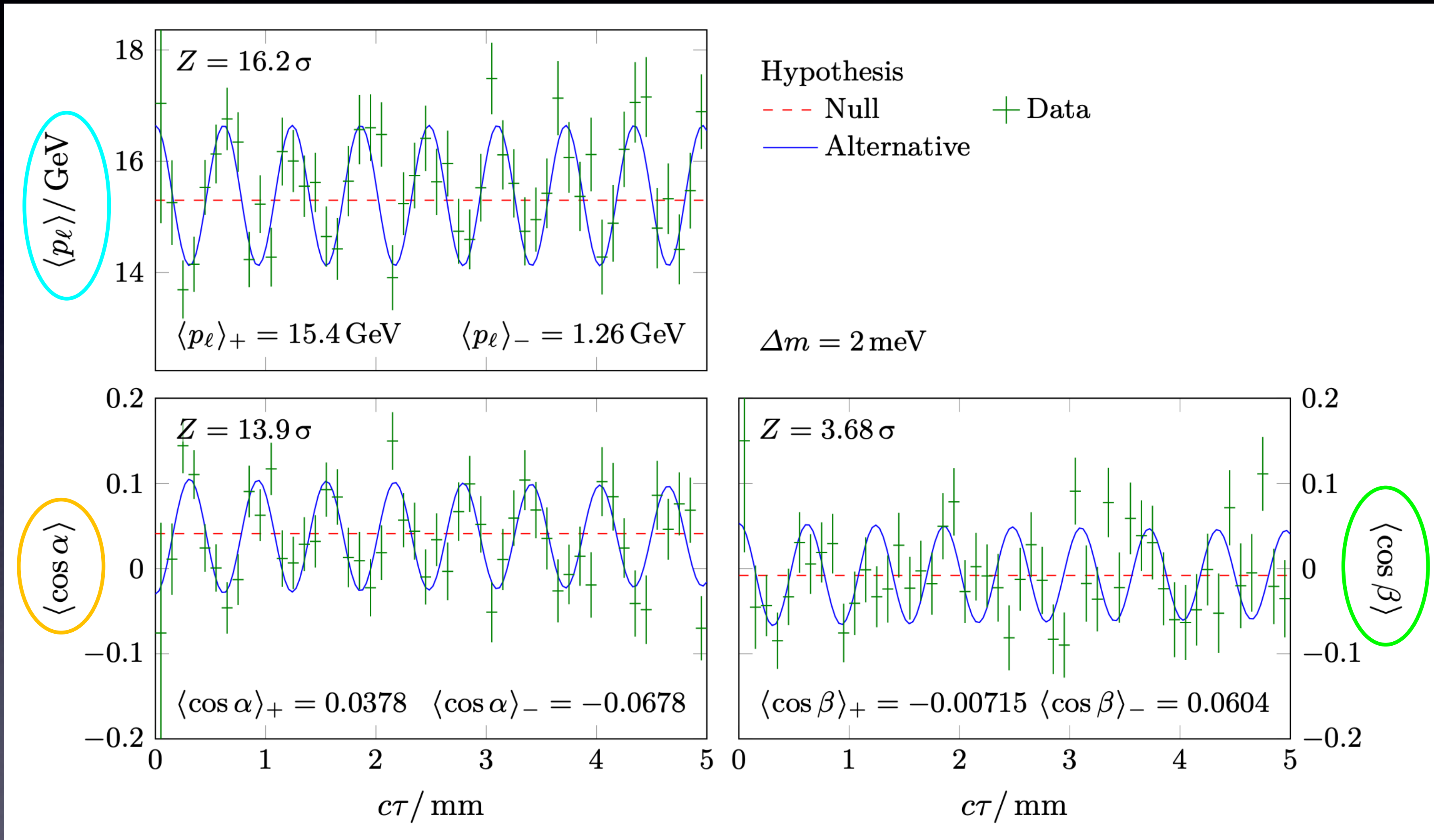
pseudo-Dirac with very large ΔM (looks like "double Majorana HNLs")

S.A., J. Hajer, B.M.S. Oliviera (arXiv:2308.07297)

Comparison of sensitivities for various oscillating observables @ FCC-ee

Well accessible observsble, very good analysis power:

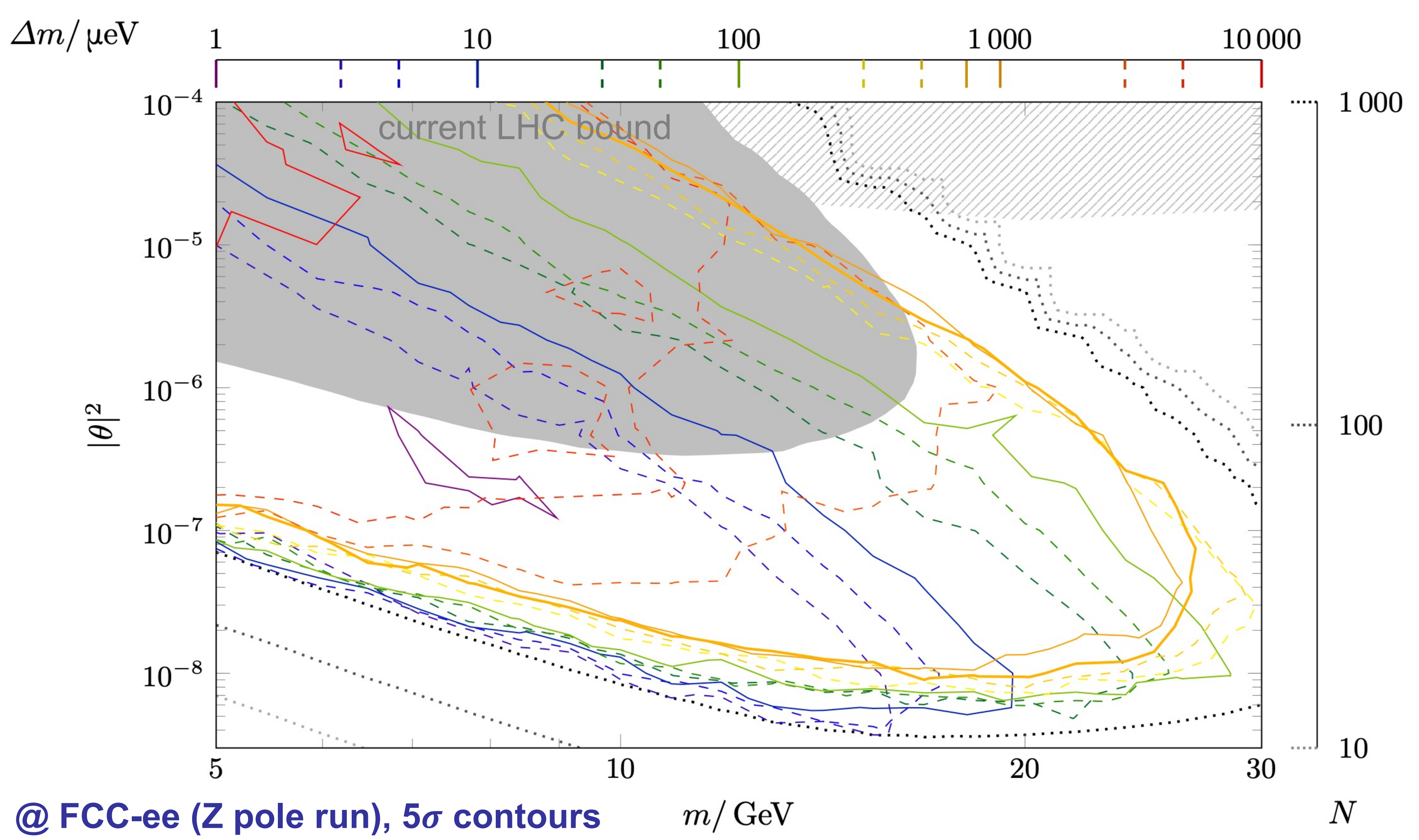
$p_\ell := |\vec{p}_\ell(m_Z)|$



S.A., J. Hajer, B.M.S. Oliviera (arXiv:2408.01389)

Parameter region where heavy neutrino-antineutrino oscillations are resolvable

Analysis using: $p_\ell := |\vec{p}_\ell(m_Z)|$

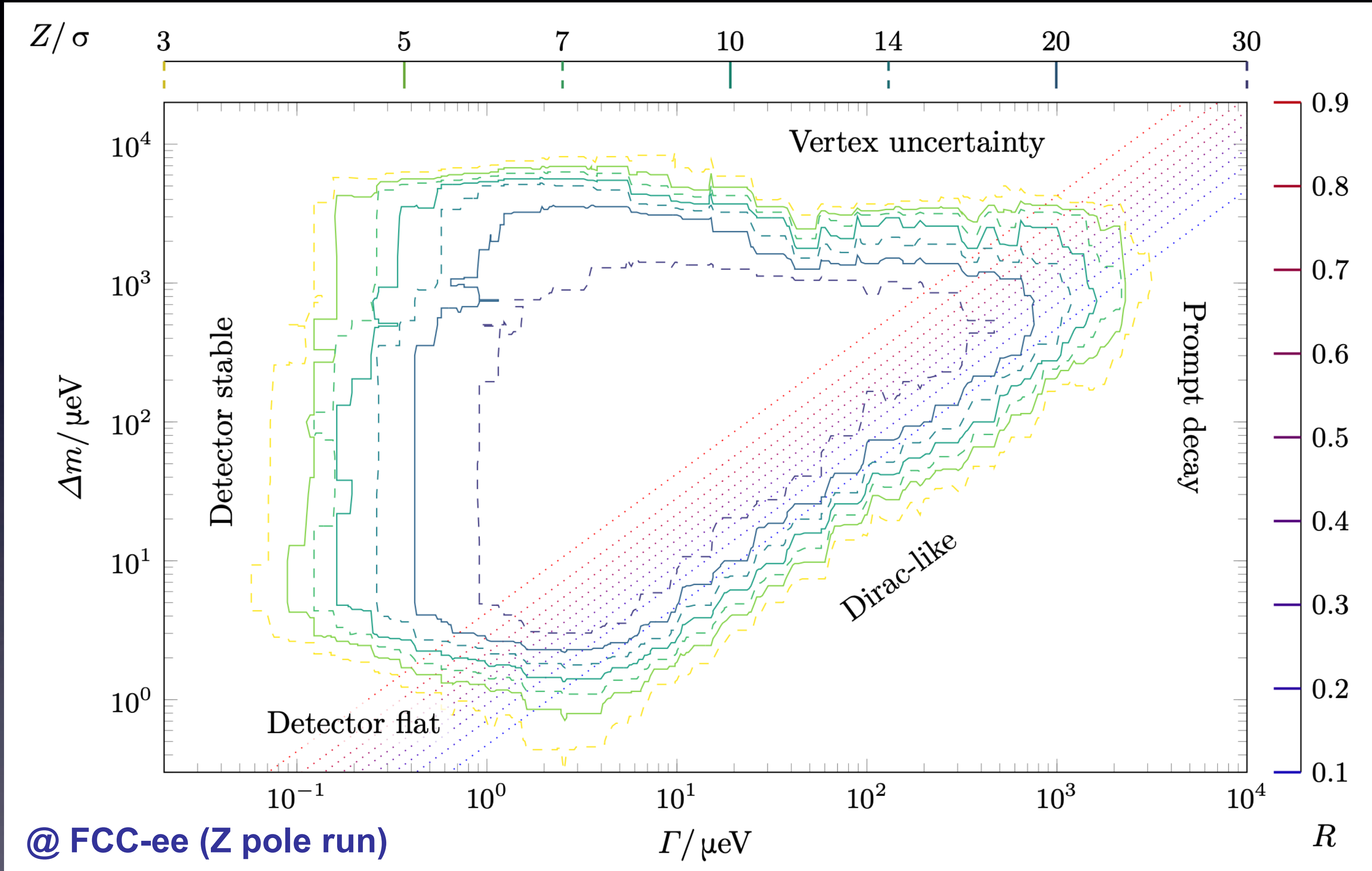


thick orange line: predicted ΔM for low scale linear seesaw (IH)

S.A., J. Hajer, B.M.S. Oliviera (arXiv:2408.01389)

Parameter region where heavy neutrino-antineutrino oscillations are resolvable

Analysis using: $p_\ell := |\vec{p}_\ell(m_Z)|$



S.A., J. Hajer, B.M.S. Oliviera (arXiv:2408.01389)

Even when not resolvable (e.g. short-lived HNLs, $m_N >$ m_W): heavy neutrino-antineutrino oscillations can observable induce LNV!

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

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

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:

$$R_{\ell\ell}(t_1, t_2) = \frac{\#(\ell^+\ell^+) + \#(\ell^-\ell^-)}{\#(\ell^+\ell^-)}$$

→ *

$$R_{ll}(0,\infty) = \frac{\Delta M^2}{2\Gamma^2 + \Delta M^2}$$

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

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

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

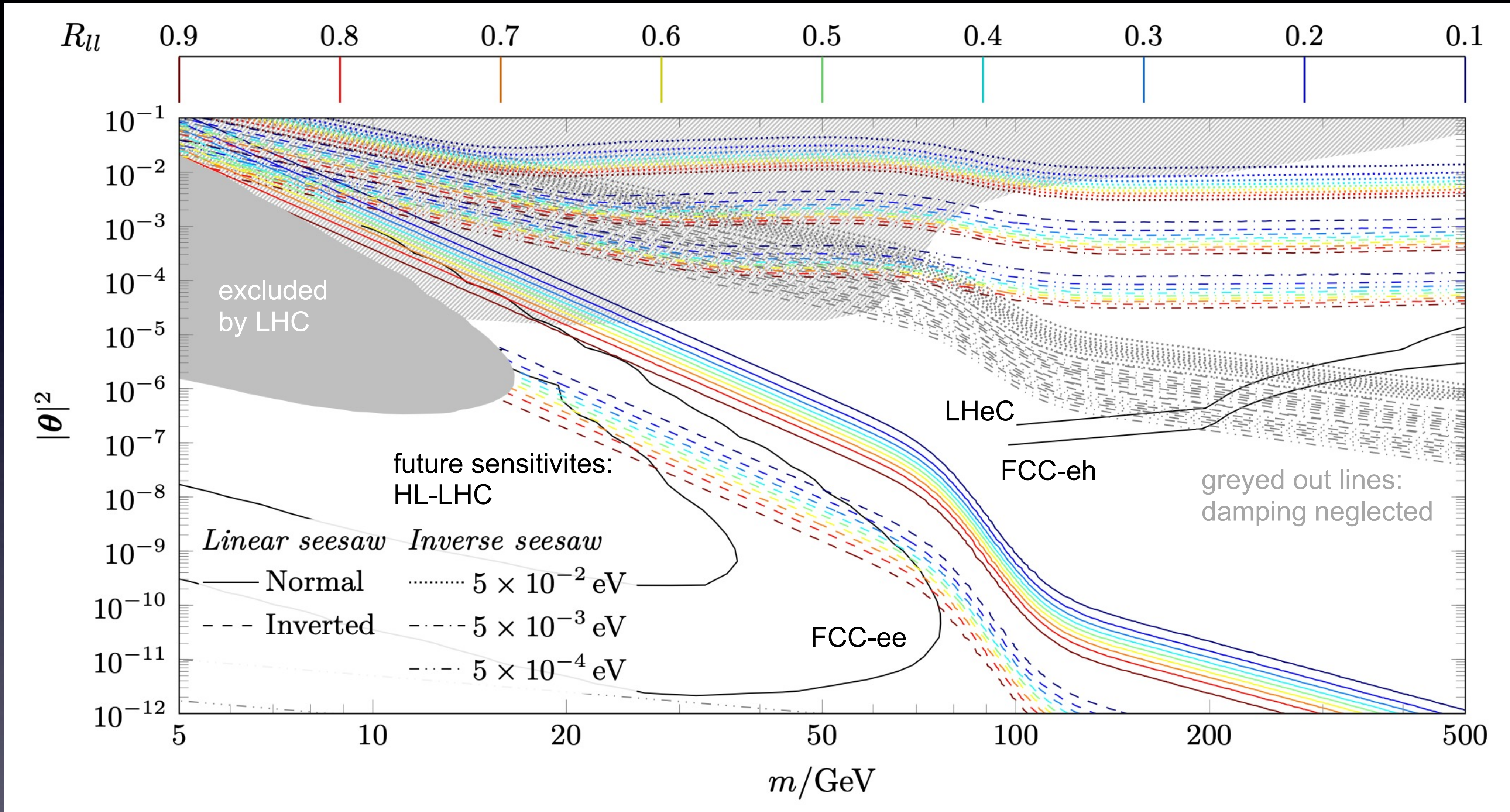
$$P_{\mathrm{osc}}^{\mathrm{LNC/LNV}}(\tau) = \frac{1 \pm \cos(\Delta M \tau)\exp(-\lambda)}{2}$$

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

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

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

Damping effects from decoherence (for HNLs at LHC) 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)

Main messages/Conclusions

*) Scenario: SM + HNLs (with masses > 5 GeV), barring fine-tuning

- 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
- Developments in the recent years: S.A., J. Rosskopp (arXiv:2012.05763)
  - QFT calculation of oscillations (LO and NLO, decoherence effects)
  - Phenomenological (pSPSS) benchmark model & Madgraph patch for including the 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)
  - Oscillations @ FCC-ee: S.A., J. Hajer, B.M.S. Oliviera (arXiv:2308.07297, arXiv:2408.01389)

Thanks for your attention!