Heavy Neutral Leptons at the FCC-hh: Where do we stand?

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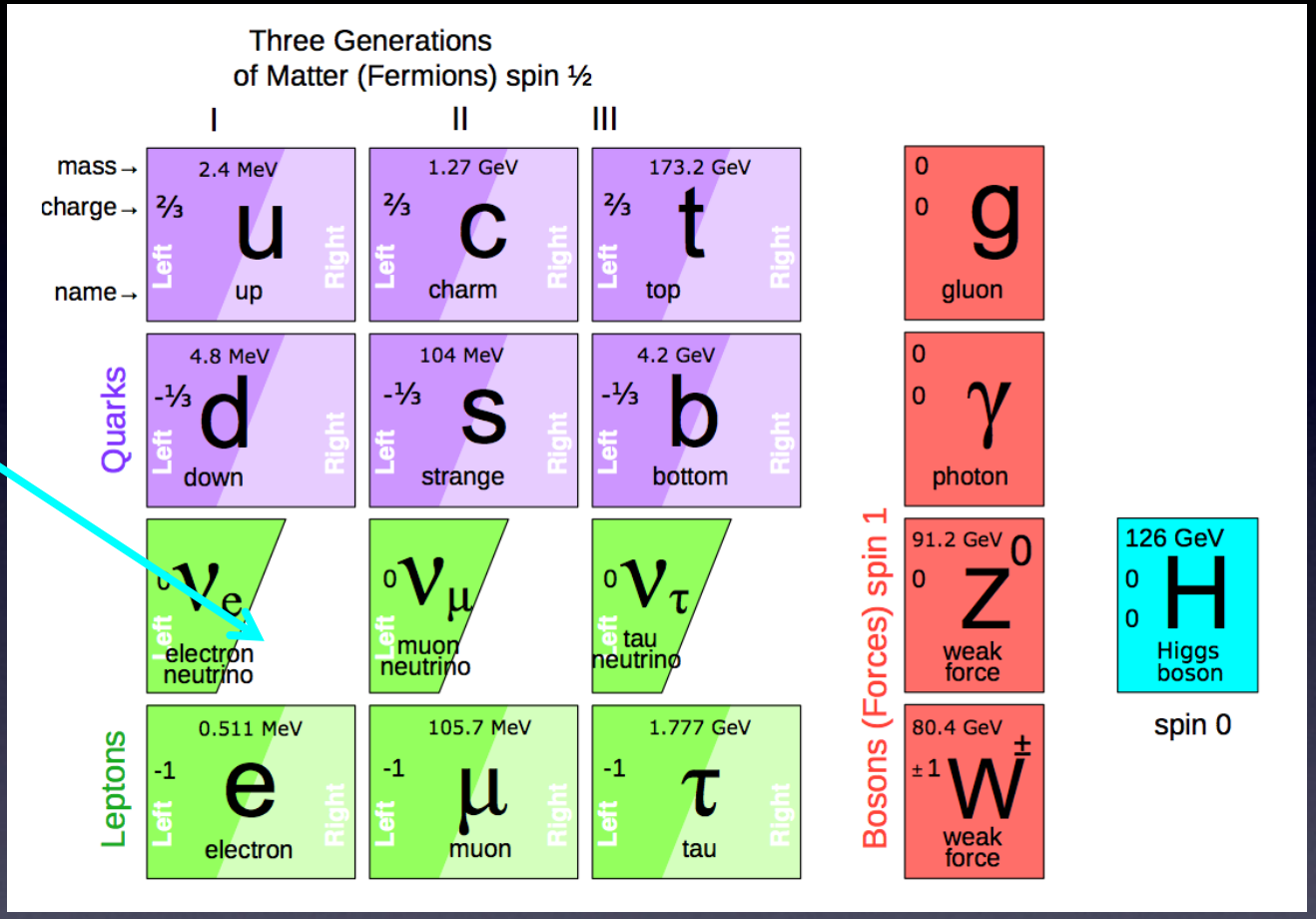
FCC-hh studies for the next European Strategy: kickoff meeting 3.9.2024

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



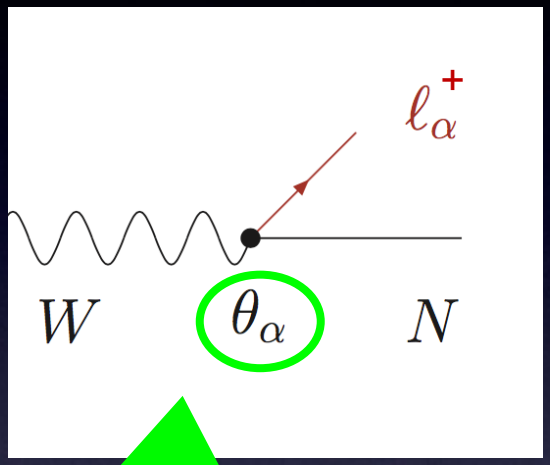
Adding N_{Ri} leads to the following extra terms in the Lagrangian density:

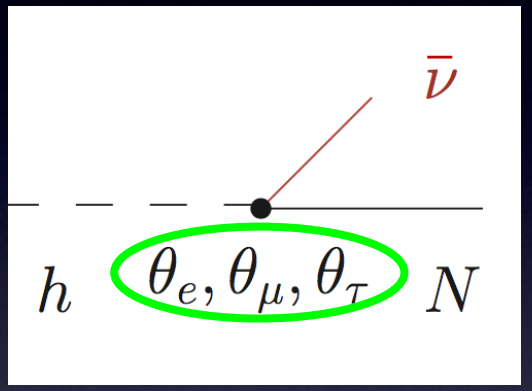
$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2}\overline{N_R^i} M_{ij} N_R^{cj} - (Y_\nu)_{i\alpha}\overline{N_R^i}\tilde{\phi}^\dagger L^\alpha + \text{H.c.}$$

M: HNL mass matrix

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

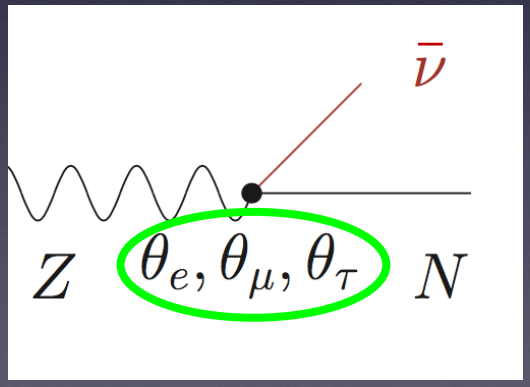
In the SM + N_{Ri}: Heavy neutrino mass eigenstates (HNLs) interact due to mixing of N_{Ri} with the active SM neutrinos



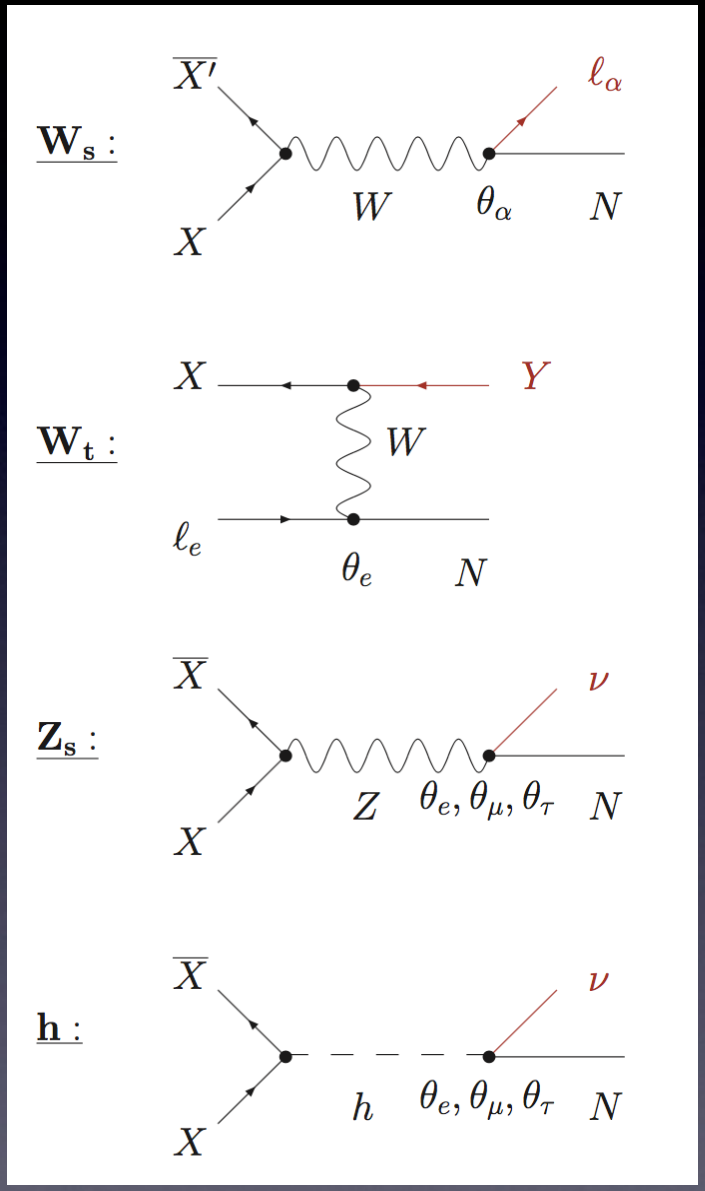


θ_α: "active-sterile" neutrino mixing angles"

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



Different opportunities at different collider types ...



cf. e.g. S.A., E. Cazzato, O. Fischer (arXiv:1612.02728)

Different LO production channels …

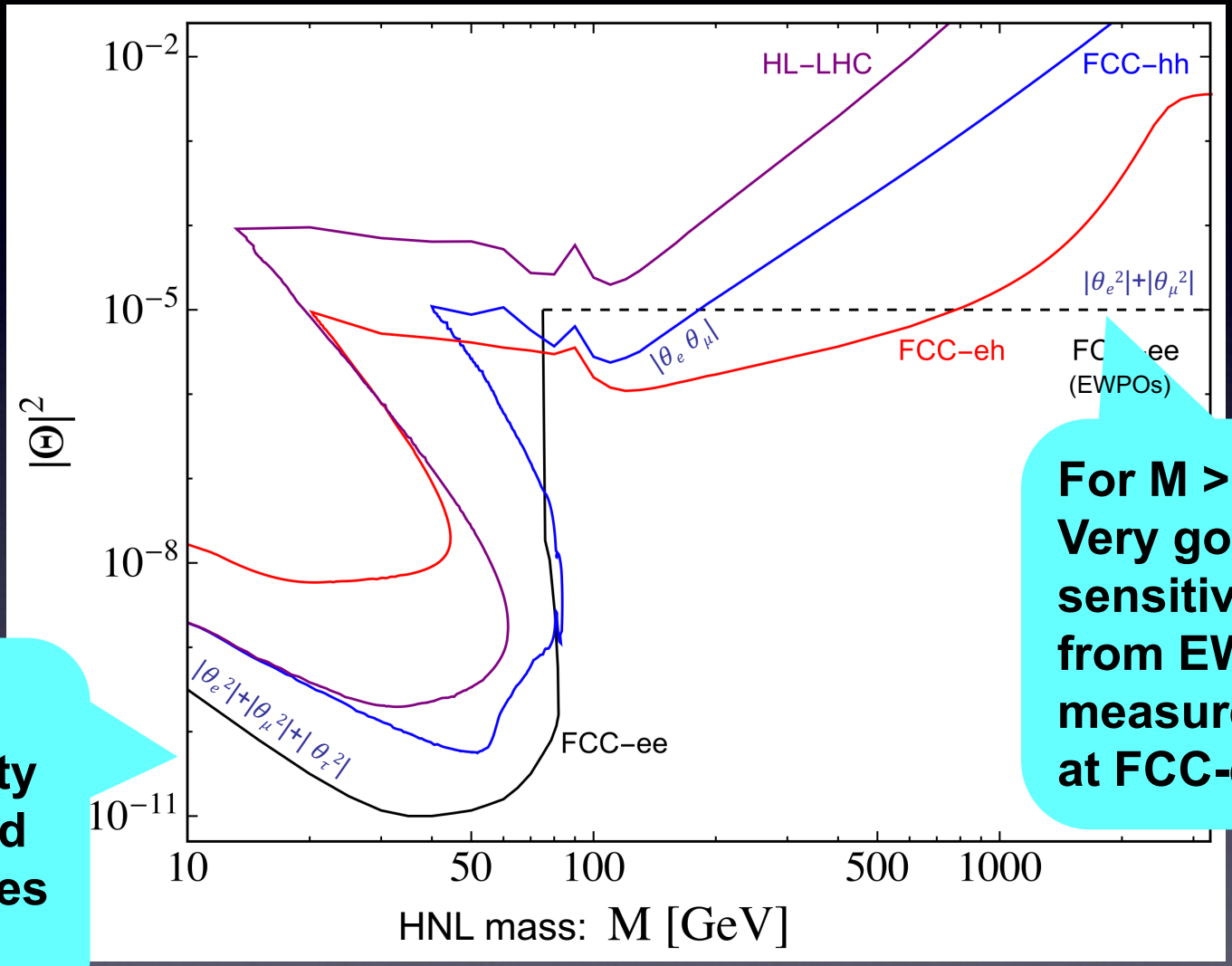
	e^-e^+**	pp	e^-p
$\mathbf{W_s}$	×	✓ + LNV/LFV	×
$\mathbf{W_t}$	✓	×	✓ + LNV/LFV *
$\mathbf{Z_s}$	✓	✓	×
$\mathbf{h}$	(✓)	(✓)	(✓)

... LNV and LFV channels great for suppressing SM background!

*) unambiguous (i.e. clear from final state), no SM background at parton level (but of course background with e.g. extra neutrinos)

**) at e+e- colliders: LNV signatures also possible, but only shows up in final state distributions; LFV signatures possible at loop level

FCC Design Study Report: Estimated sensitivities assuming only LNC channels



For M < m_W: Best sensitivity from displaced vertex searches at FCC-ee

For M >> O(TeV): Very good sensitivity from EWPO measurements at FCC-ee

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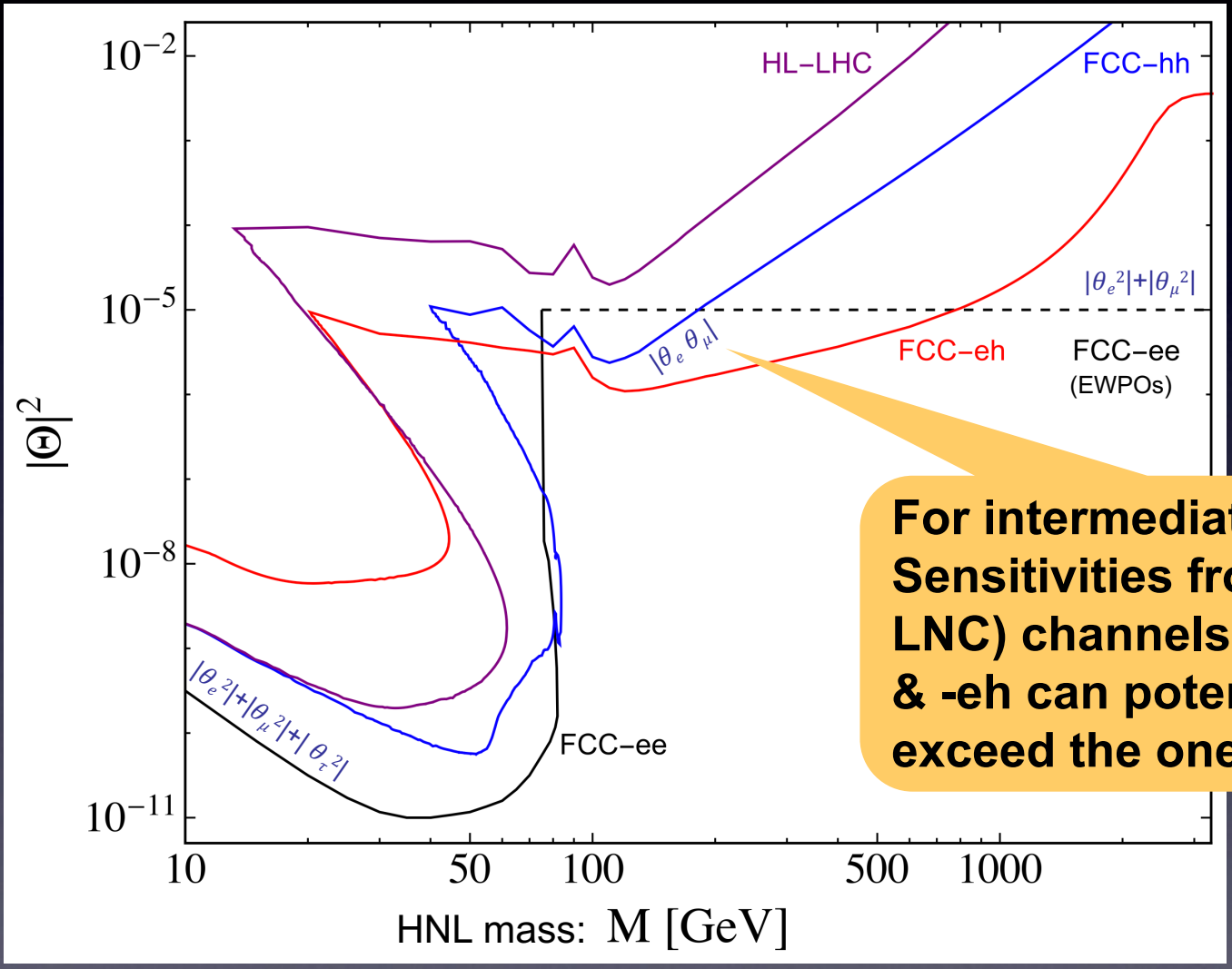
FCC Design Study Report: Estimated sensitivities assuming only LNC channels

Compared to FCC-ee: Sensitivity to different combinations of active-sterile mixing angles!



Note: future exp. on $\mu \to e\,\gamma, \mu \to 3e$, $\mu - e$ conversion in nuclei also very sensitive to $|\theta_e\,\theta_\mu|$!

For intermediate M: Sensitivities from LFV (but LNC) channels at FCC-hh & -eh can potentially exceed the ones at FCC-ee

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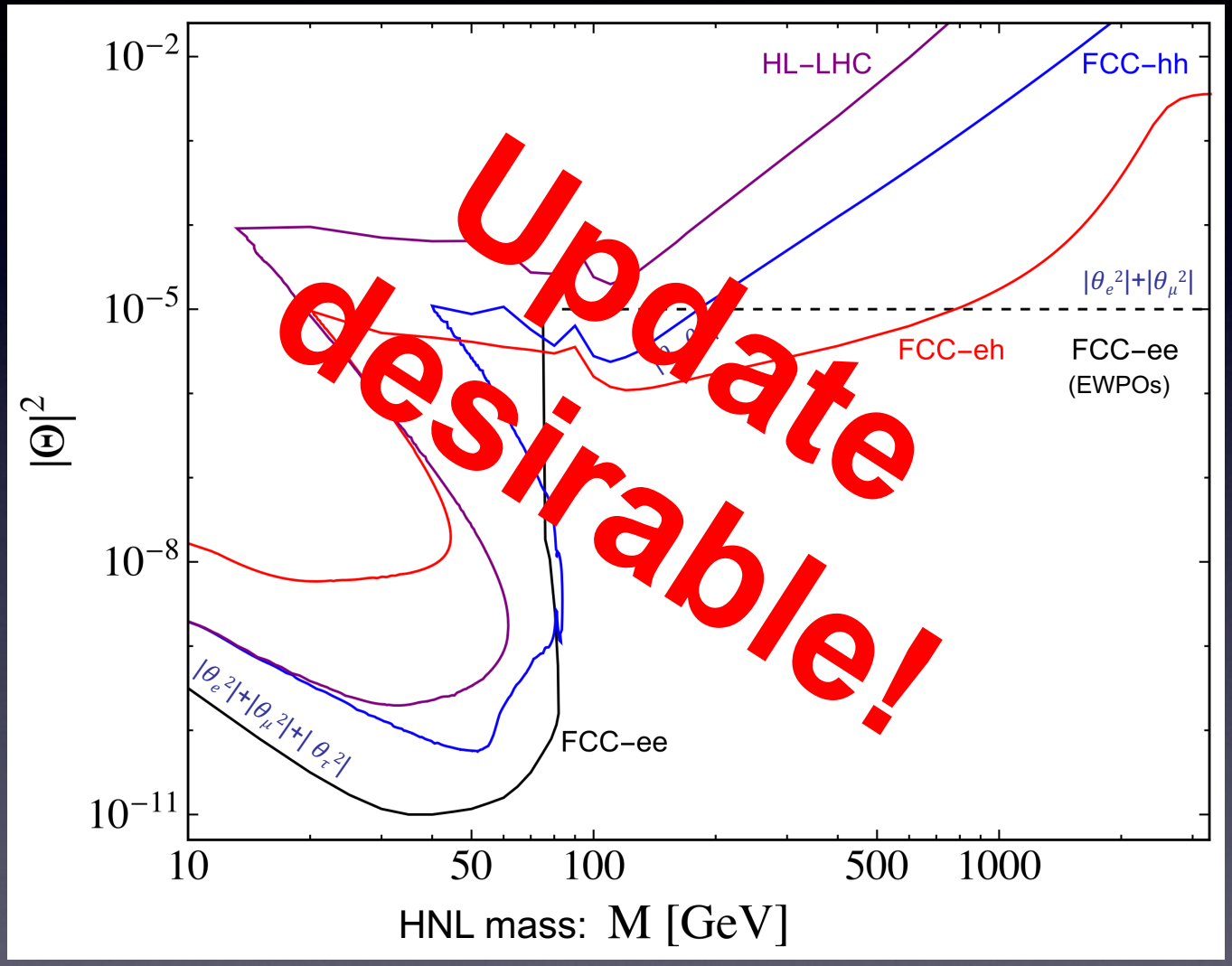
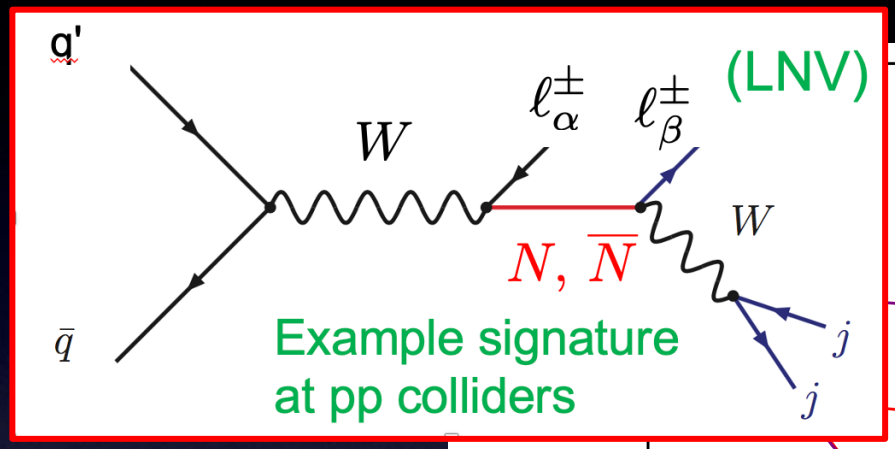
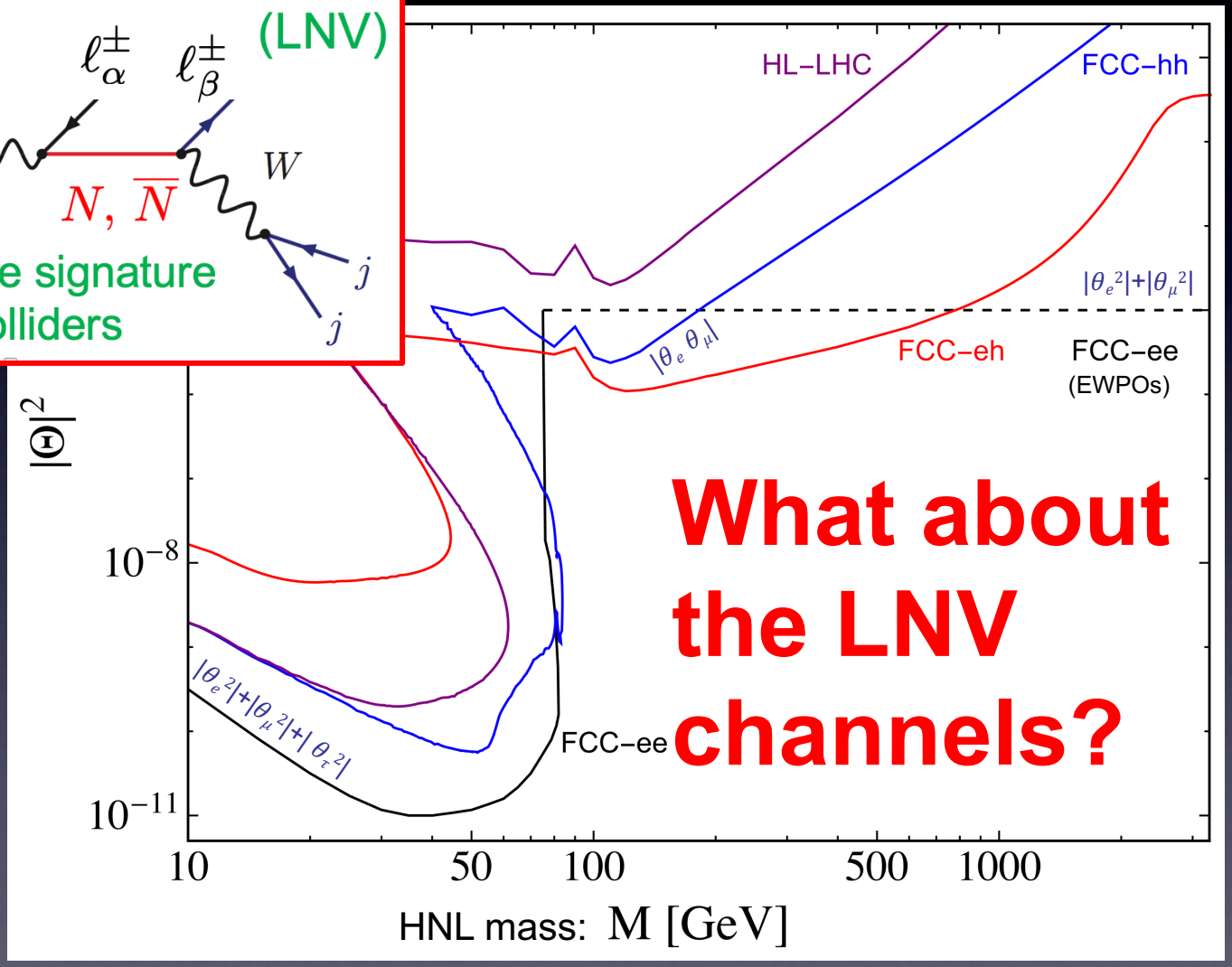
FCC Design Study Report: Estimated sensitivities assuming only LNC channels



FCC Design Study Report: Estimated sensitivities assuming only LNC channels



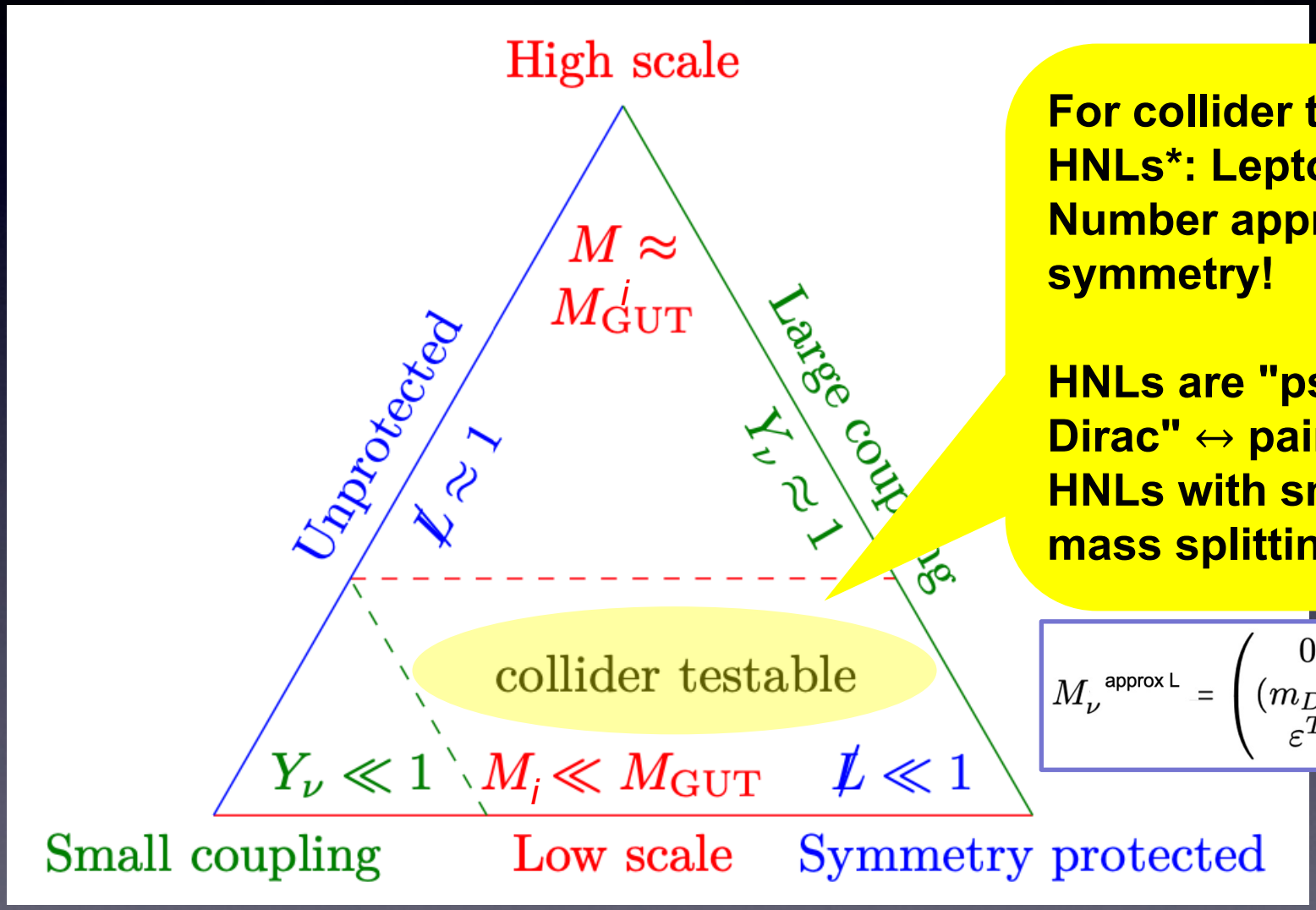


Landscape of the Seesaw Mechanism

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

↔ 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

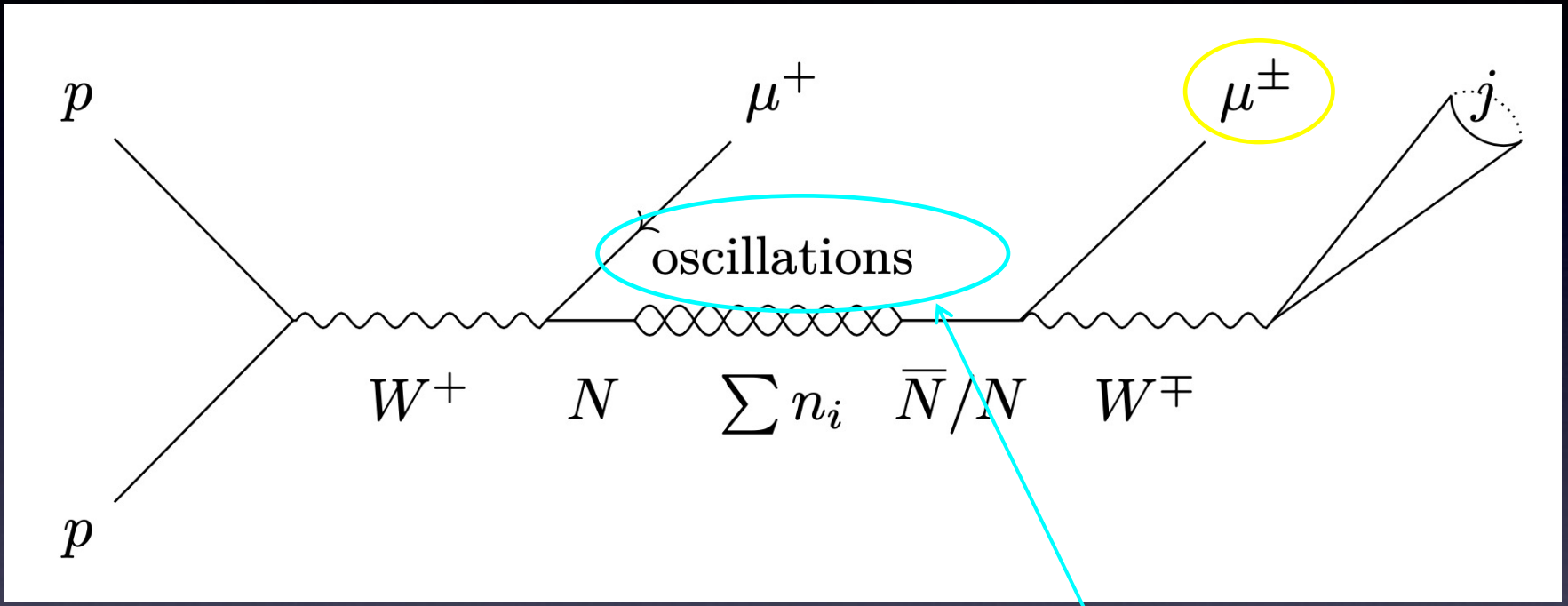
$$M_\nu^{\text{approx L}} = \begin{pmatrix} 0 & m_D & \varepsilon \\ (m_D)^T & \varepsilon' & M \\ \varepsilon^T & M & \varepsilon'' \end{pmatrix}$$

*) barring highly fine-tuned scenarios

New aspect: LNV induced by "Heavy Neutrino-Antineutrino Oscillations"

For intro, see e.g.: S.A., J. Hajer, J. Rosskopp (arXiv:2210.10738)

... so far not yet included in FCC-hh studies



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

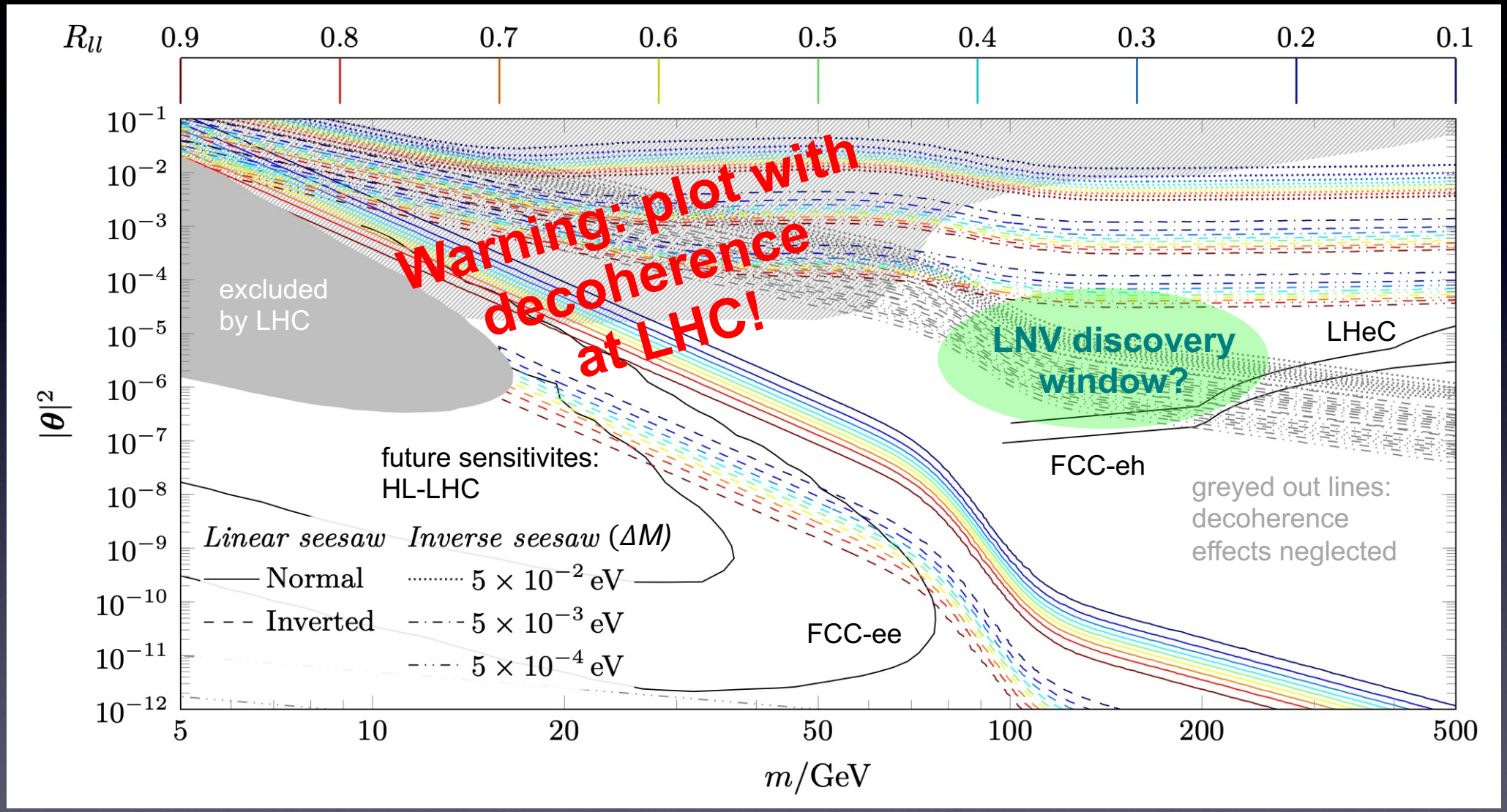
They are superpositions of the mass eigenstates:

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

Due to the mass splitting ΔM between the heavy mass eigenstates N_4 and N_5
→ propagation of interfering mass eigenstates induces oscillations between N and $\overline{N}$ ...
which then decay into leptons (LNC) or into antileptons (LNV)

Open question: For which HNL parameters can the FCC-hh discover HNLs with LNV?

Expectation: Oscillations and decoherence also govern discovery prospects for LNV at the FCC-hh



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

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

Thanks for your attention!

Recent developments on Heavy Neutrino-Antineutrino Oscillations

- Madgraph patch available for including the heavy neutrino-antineutrino oscillations in collider simulations
  S.A., J. Hajer, J. Rosskopp (arXiv:2210.10738)
- Oscillations resolvable for long-lived HNLs at the HL-LHC (confirmed for some benchmark points)
  S.A., J. Hajer, J. Rosskopp (arXiv:2212.00562)
- Calculation in QFT with external wave packets (including calculation of decoherence effects for HNLs at LHC)
  S.A., J. Rosskopp (arXiv:2012.05763)
  S.A., J. Hajer, J. Rosskopp (arXiv:2307.06208)
- Decoherence effects improve the prospects for observing LNV for HNLs with masses above M_W (studied so far only for the LHC)
  S.A., J. Hajer, J. Rosskopp (arXiv:2307.06208)

Recent developments on Heavy Neutrino-Antineutrino Oscillations

- At FCC-ee, the heavy neutrino-antineutrino oscillations lead to oscillating final state asymmetries ... S.A., J. Hajer, B.M.S. Oliviera (arXiv:2308.07297)

  ... allowing to resolve the oscillations (and thereby discover LNV) for long-lived HNLs

  For testable parameter region, see:
  S.A., J. Hajer, B.M.S. Oliviera (arXiv:2408.01389)