# Neutrino Physics in the Era of Future Accelerators

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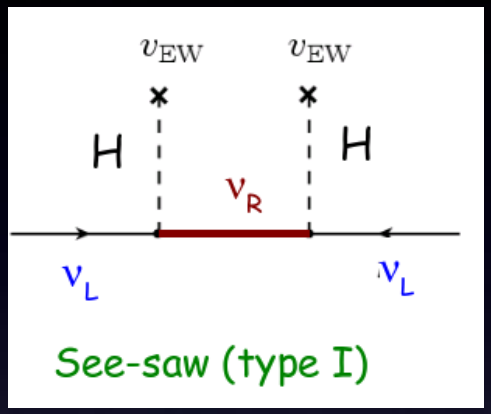
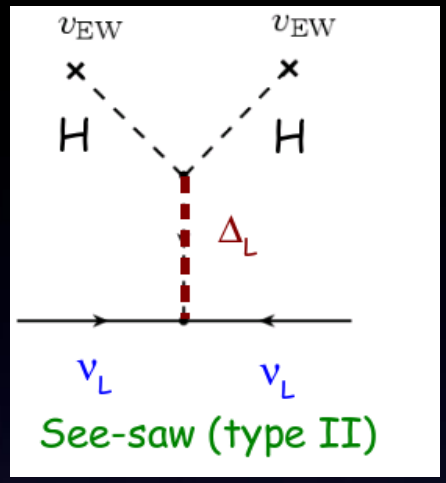
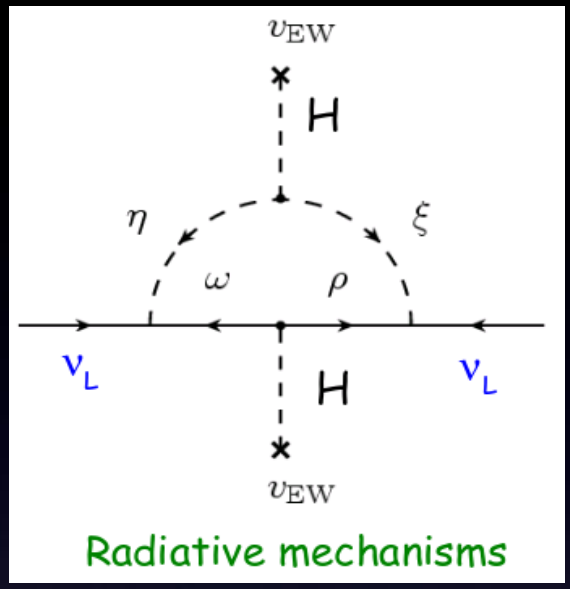
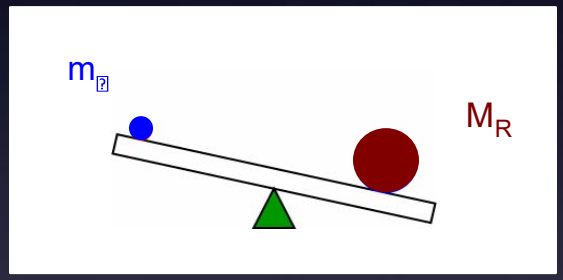
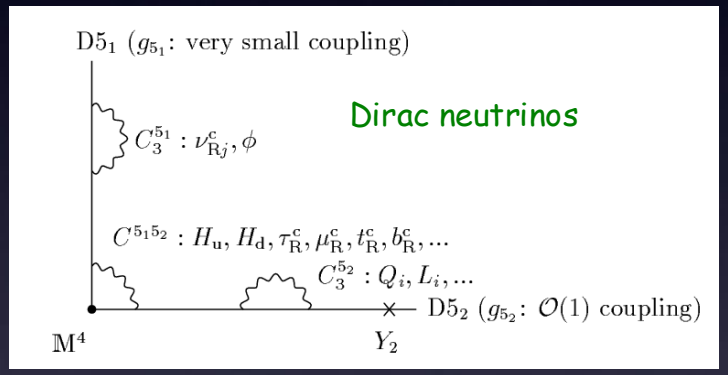
# Neutrino masses:
# How to extend the SM?

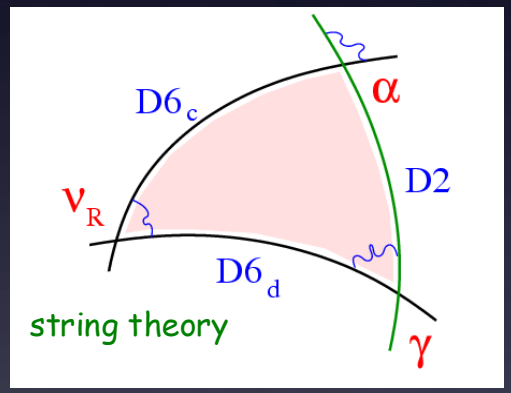


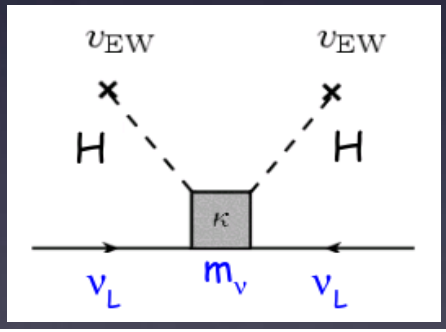


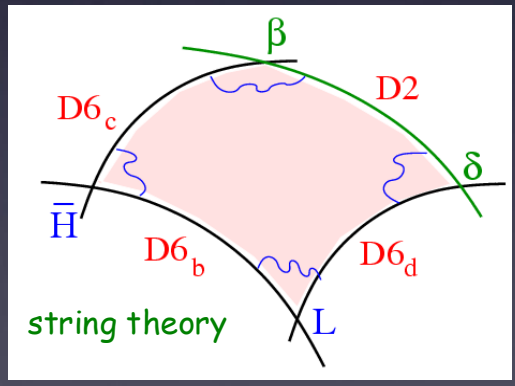




**Effective theory:**
**d=5 operator**




$$\delta\mathcal{L}^{d=5} = \frac{1}{2}\, c_{\alpha\beta}^{d=5} \left(\overline{L^c}_\alpha \tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger L_\beta\right) + h.c.$$




**Which mechanism?**
**At which scale?**
**Which type of $m_\nu$?**

# How can future accelerators contribute towards resolving these questions?

i) direct searches
ii) indirect searches

This talk: ... both aspects ... focus on HNLs (heavy neutral leptons) and on the FCC-ee/CEPC

# Outline

After a short motivation and introduction ...

## Direct searches for HNLs at the FCC-ee/CEPC

- Great sensitivity reach via displaced HNL decays
- Landscape of low scale HNL models: in the main testable parameter space HNLs are "pseudo-Dirac"
  → *more to discover then just a displaced vertex!*
- Test of LNV? Heavy neutrino-antineutrino oscillations!

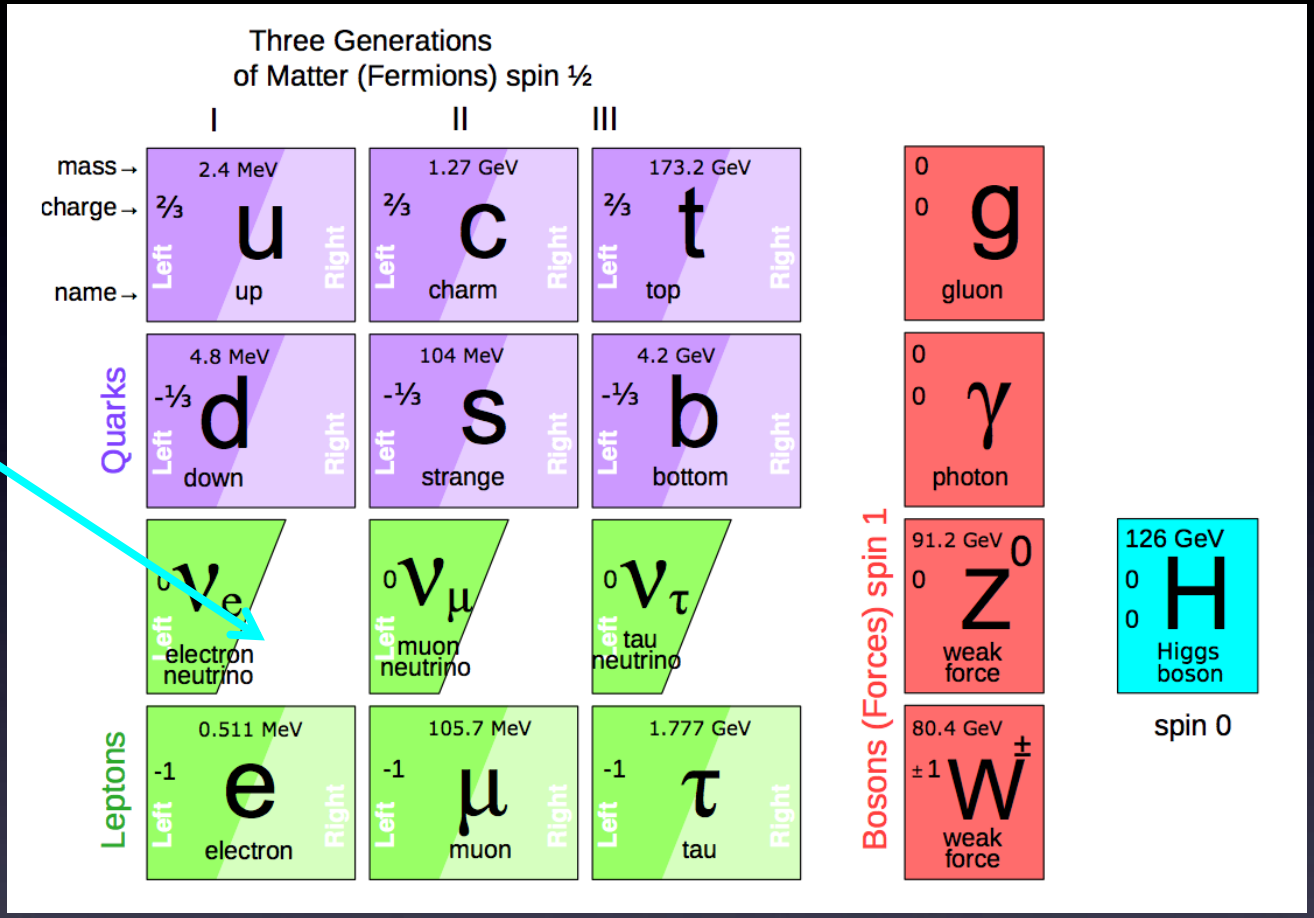
## Indirect searches: Non-unitarity of the PMNS matrix

- Generic effect when SM neutrinos mix with heavy neutral fermions
- Tests: EWPOs, lepton universality tests, cLFV, modified neutrino flavour oscillations

# *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:

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

M: HNL mass matrix

$Y_\nu$: neutrino Yukawa matrix (→ Dirac mass terms $m_D$)

# *Light Neutrino Masses via the "Seesaw Mechanism" (can be low-scale)*

Majorana mass matrix of the (three) light neutrinos

Mass matrix of the (2+n) sterile (= right-handed) neutrinos (masses of Majorana-type)

$$(m_\nu)_{\alpha\beta} = -\frac{v_{\rm EW}^2}{2}(Y_\nu^T M_N^{-1} Y_\nu)_{\alpha\beta}$$

Valid for $v_{EW}\, y_\nu << M_R$

**„Seesaw Formula"**

Neutrino Yukawa matrix

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

From neutrino oscillation experiments and mass searches:

$|m_3^2 - m_1^2| \approx 2.5 \cdot 10^{-3}\ \text{eV}^2$

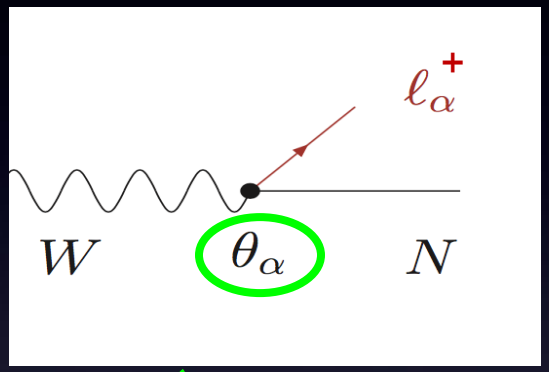
$m_2^2 - m_1^2 \approx 7.4 \cdot 10^{-5}\ \text{eV}^2$

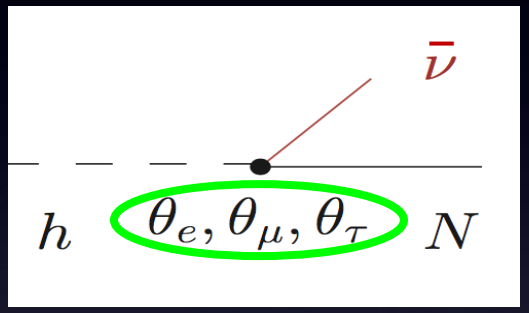
all three $m_\alpha$ below ~ O(0.1) eV

+ measurements of the leptonic mixing angles (from neutrino osc. experiments)

Note: At least two sterile neutrinos are required
➔ generate masses for two of the light neutrinos
(necessary for realizing the two observed mass splittings)

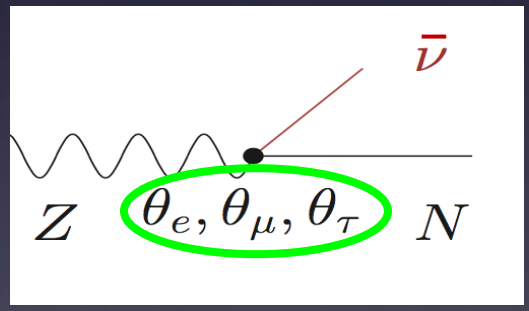
# In the SM + $N_{Ri}$: Heavy neutrino mass eigenstates (HNLs) interact due to mixing of $N_{Ri}$ with the active SM neutrinos*




**$\theta_\alpha$: "active-sterile" neutrino mixing angles"**

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



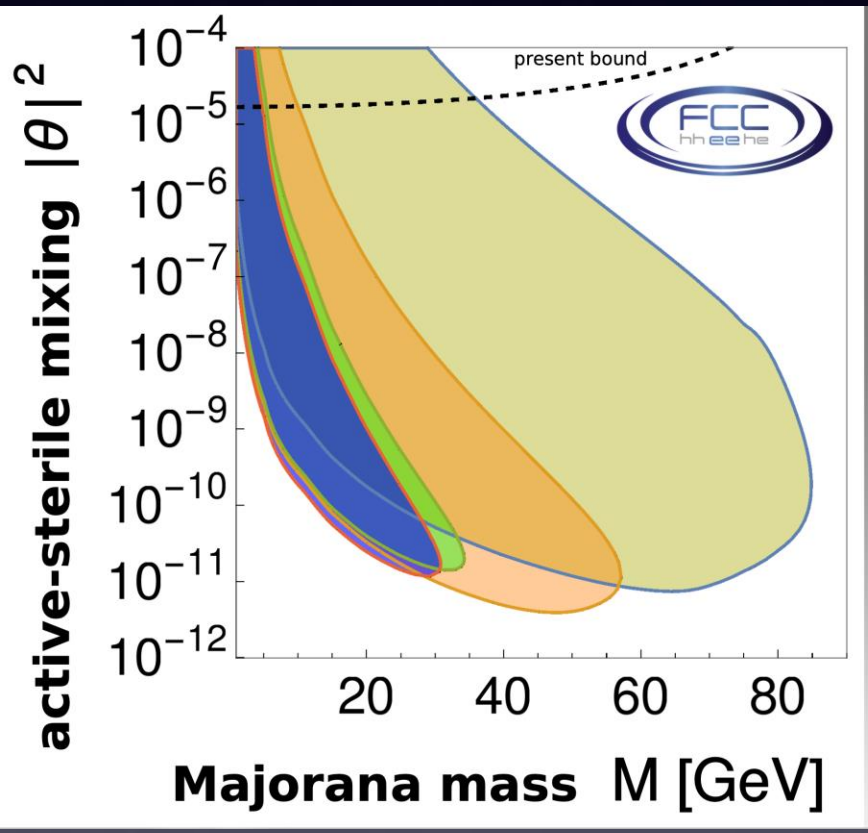

*) Scenario in this talk: SM + HNLs

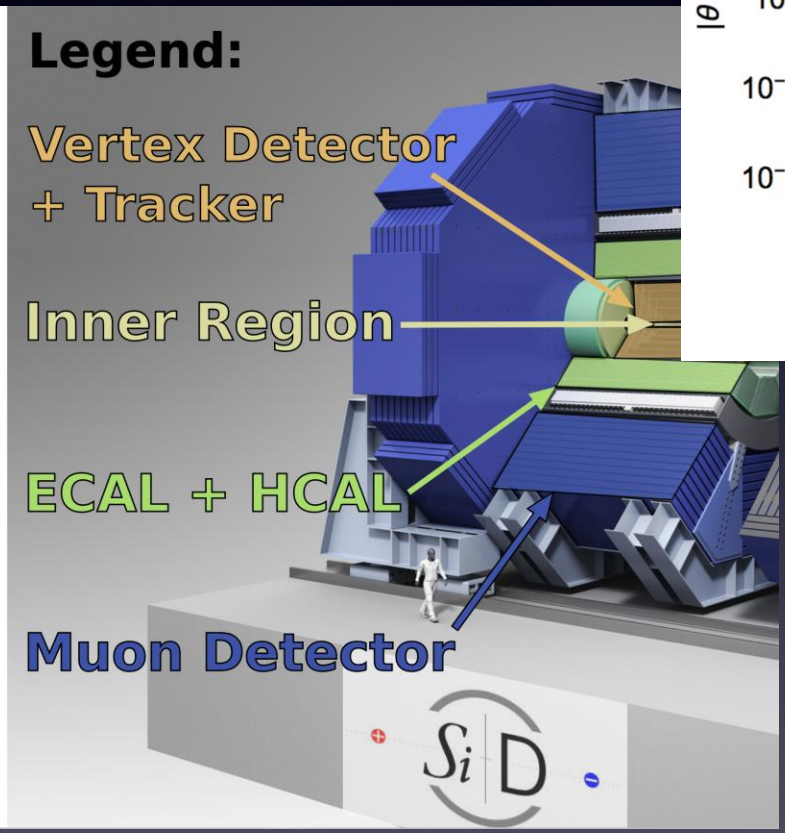
**Note: HNL production can be enhanced in extended scenarios (e.g. with Z', $W_R$)!**

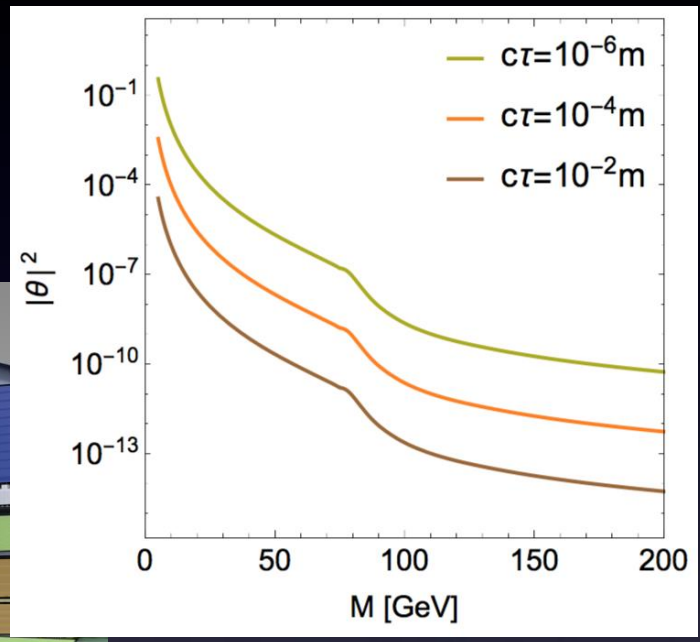
# Lifetime and decay length of heavy neutrinos:
# For M < $m_W$, the HNLs can be long-lived!

cf. e.g. S. A., E. Cazzato, O. Fischer
(arXiv:1604.02420, arXiv:1709.03797)

$$|\theta|^2 := \sum_\alpha |\theta_\alpha|^2$$




Decay length in the laboratory frame:

$$c\tau\sqrt{\gamma^2-1}$$

# Landscape of the Seesaw mechanism

# *Minimal example: 2 RH Neutrinos (2 HNLS)*

In the mass basis:

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

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

↓ **„Seesaw Formula“**

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

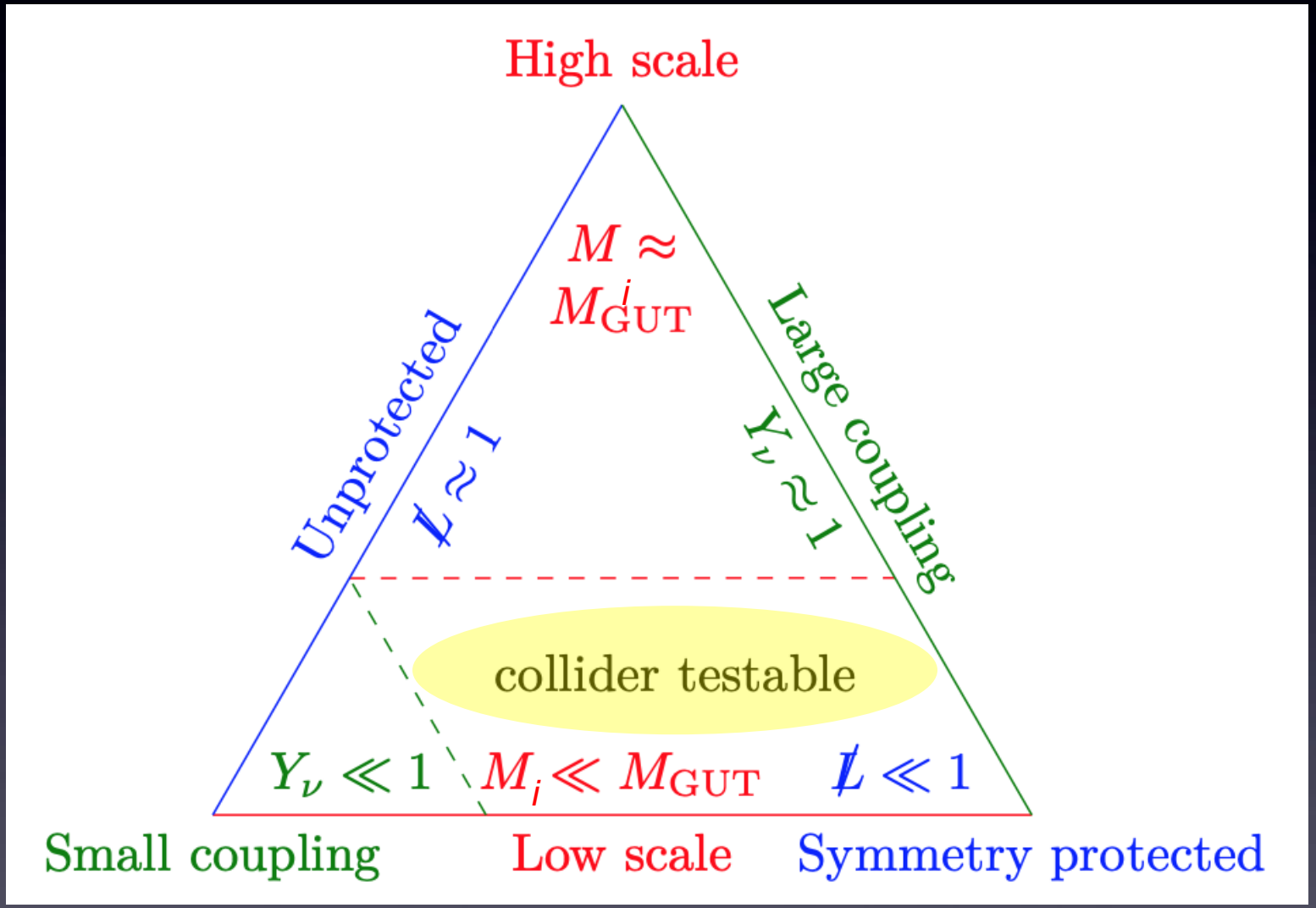
Type I Seesaw: P. Minkowski ('77), Mohapatra, Senjanovic, Yanagida, Gell-Mann, Ramond, Slansky, Schechter, Valle, …

# 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




*) In the SM + HNLs (this talk: masses > 5 GeV), barring fine-tuned scenarios

# Landscape of the Seesaw Mechanism

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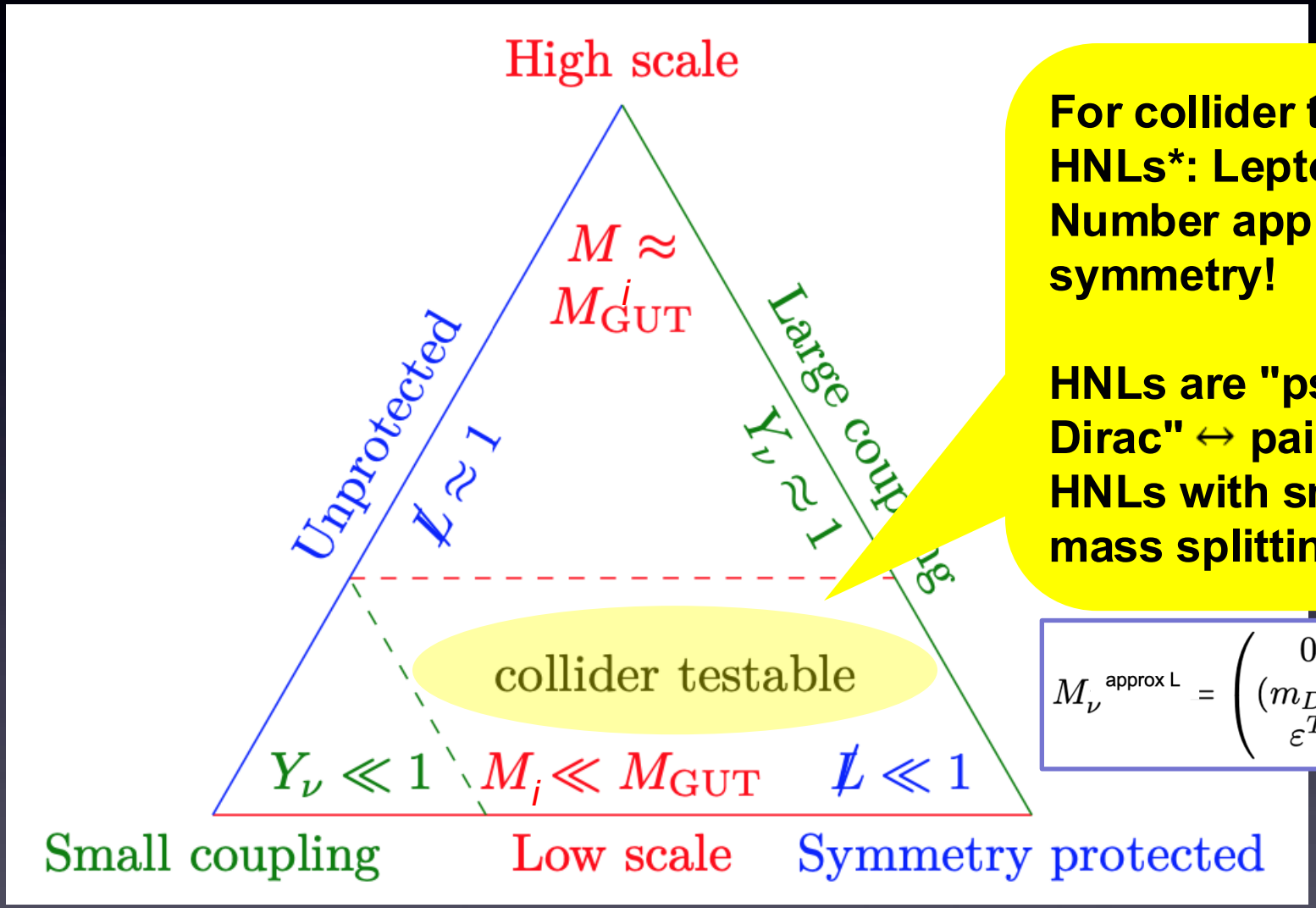


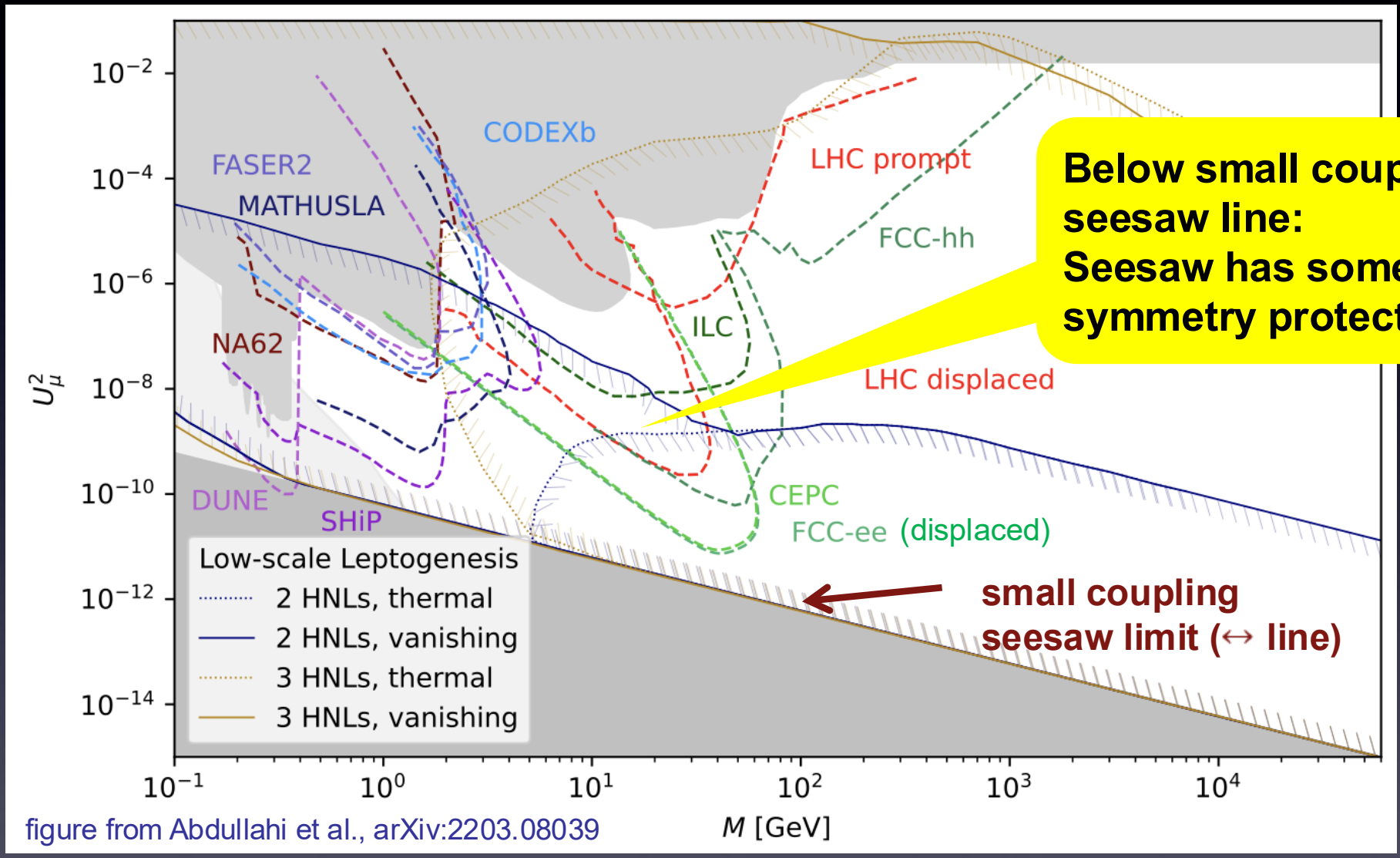

**For collider testable HNLs*: Lepton Number approximate symmetry!**

**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 (this talk: masses > 5 GeV), barring fine-tuned scenarios

# *Present constraints, future sensitivities and prospects for low scale leptogenesis*




towards high scale seesaw seesaw limit

*) In the SM + HNLs, barring fine-tuned scenarios

# Benchmark scenario for collider-testable low-scale seesaw models

# 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 $y_{\nu\alpha}$)

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

+ 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 by giving lepton number = 0 to them).

for phenomenology (pSPSS)

Main additional parameter: ΔM
plus: M, $\theta_\alpha$ where $\theta_\alpha = \frac{y_\alpha^*}{\sqrt{2}} \frac{v_{EW}}{M}$

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 $m_\nu$)?

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

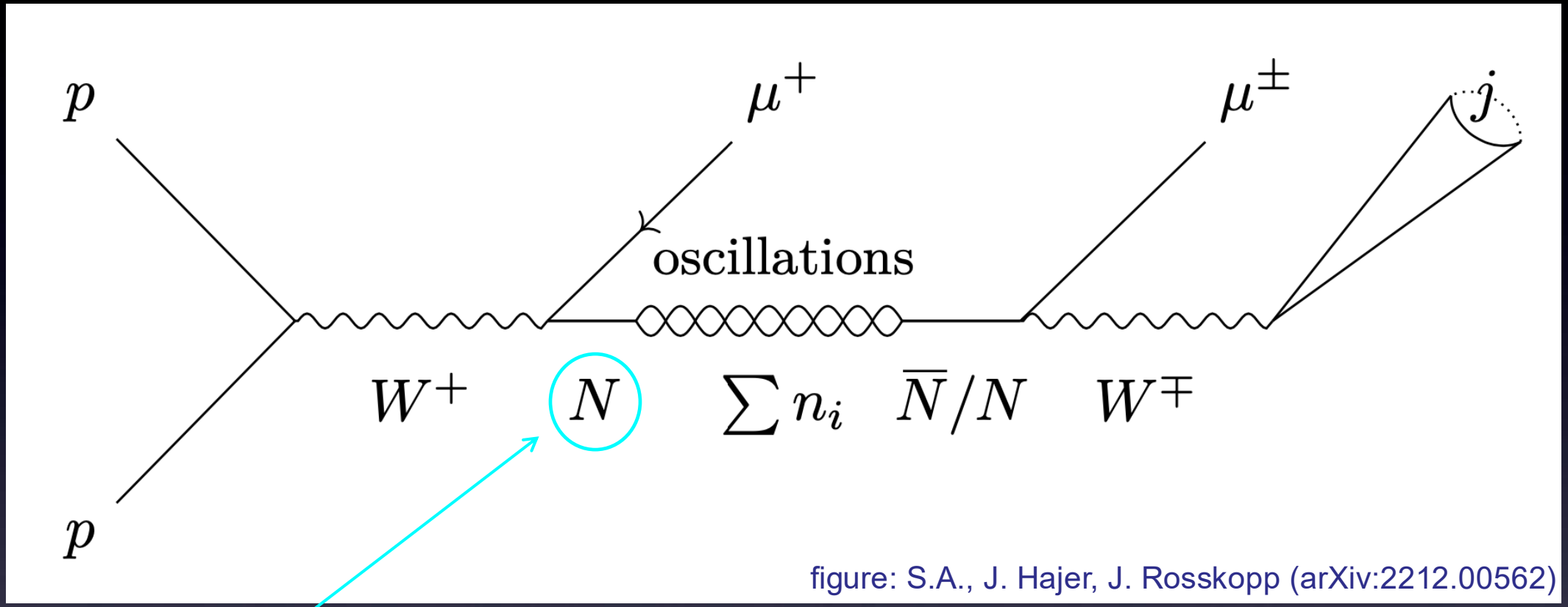



figure: S.A., J. Hajer, J. Rosskopp (arXiv:2212.00562)

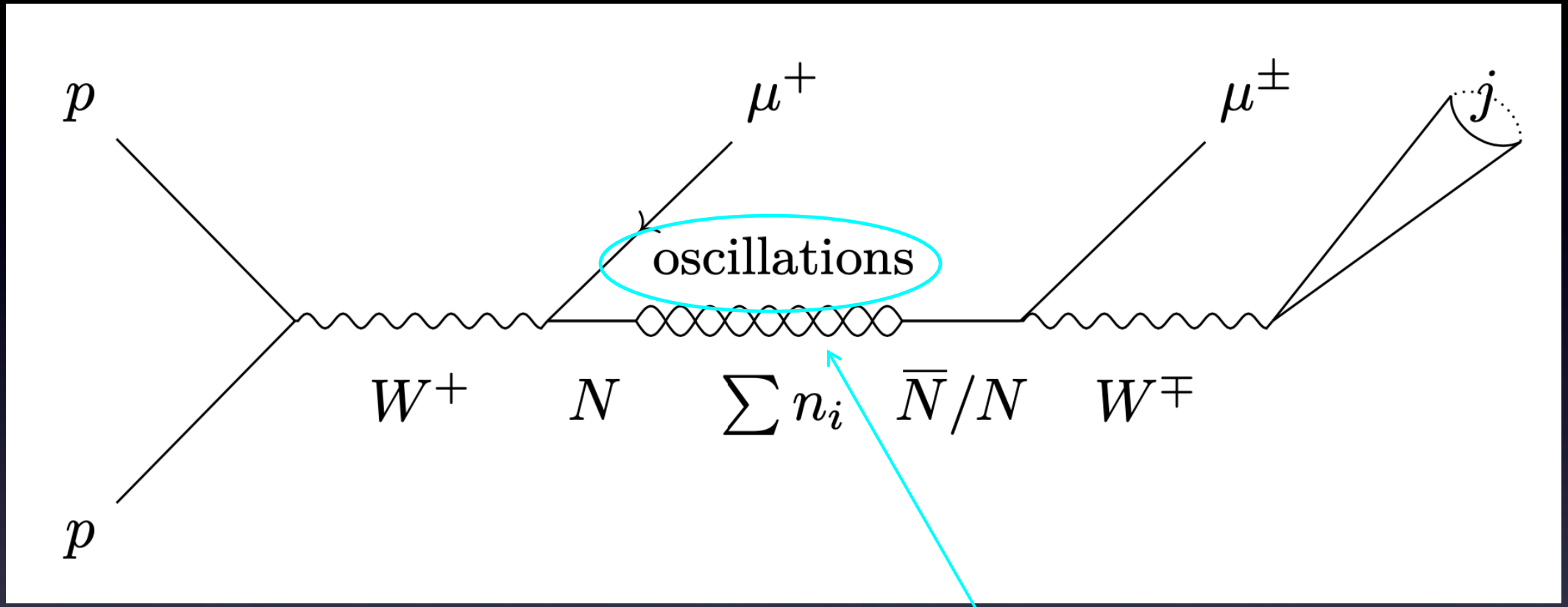
Interaction states: Produced from W decay
- "Heavy Neutrinos N" (together wilth $l_\alpha^+$)
- "Heavy Antineutrinos $\overline{N}$" (together wilth $l_\alpha^-$)

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

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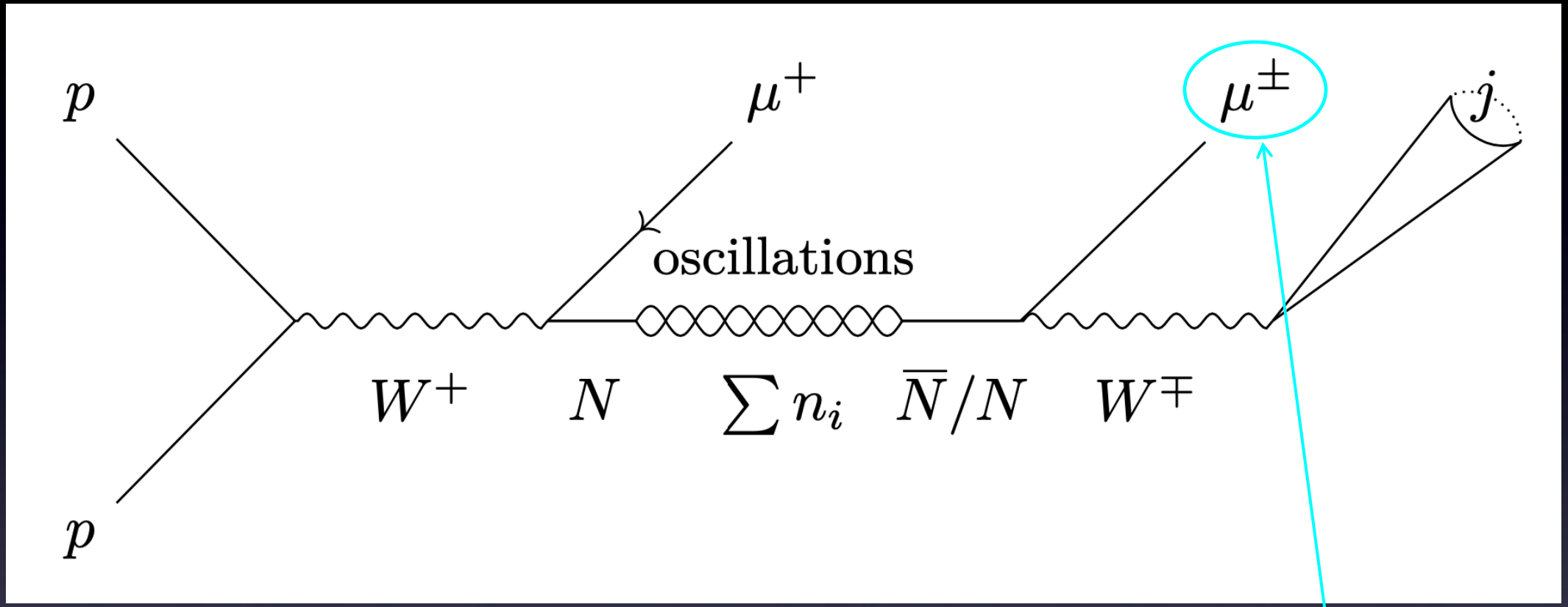
Due to the O($\varepsilon$) perturbations to generate the light neutrino masses: → **mass splitting ΔM** between the heavy mass eigenstates $N_4$ and $N_5$ → propagation of interfering mass eigenstates induces oscillations between $\overline{N}$ and N

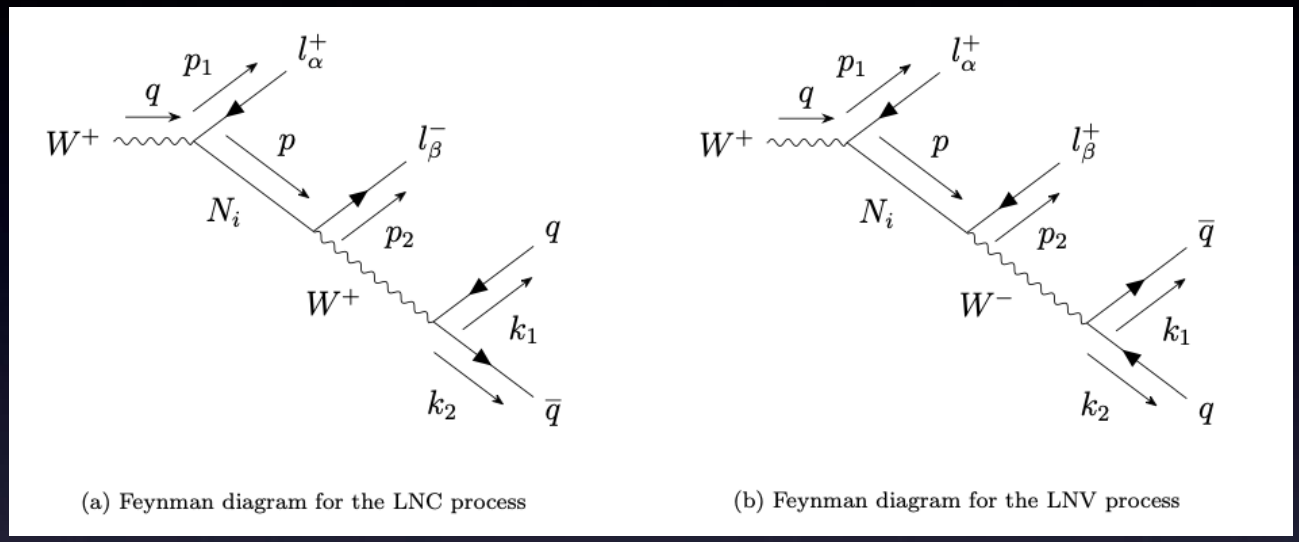
# Heavy Neutrino-Antineutrino Oscillations




Since an N decays into a $l_\alpha^-$ and a N into a $l_\alpha^+$, 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 $\varepsilon$-perturbations, in an expansion):

Oscillation probability

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

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

Survival probability

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

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

where

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

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

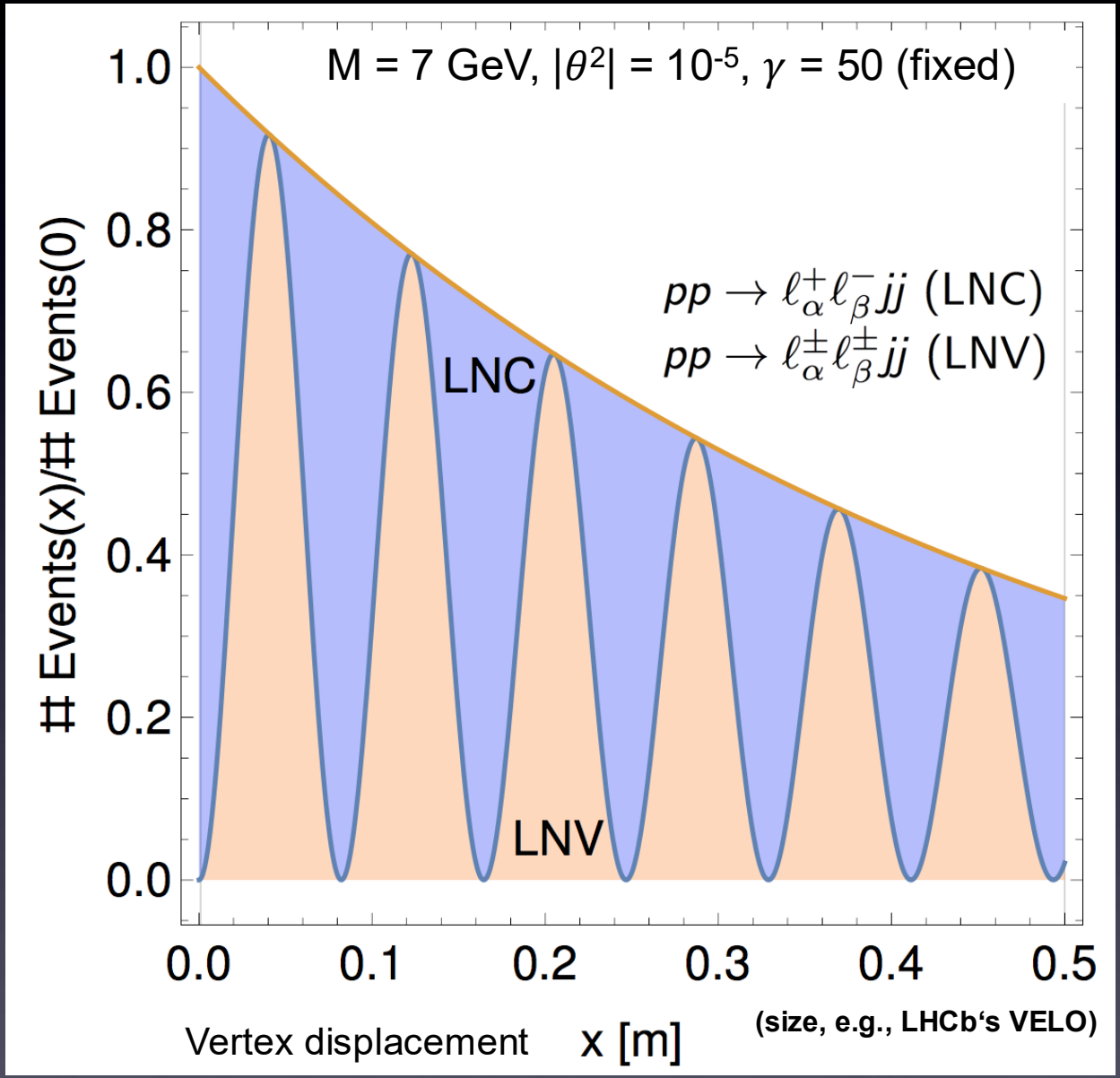
$$\Phi := \frac{1}{2}\mathrm{Arg}\left(\vec{\theta}' \cdot \vec{\theta}^*\right) \,.$$

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 $\gamma$ 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)*

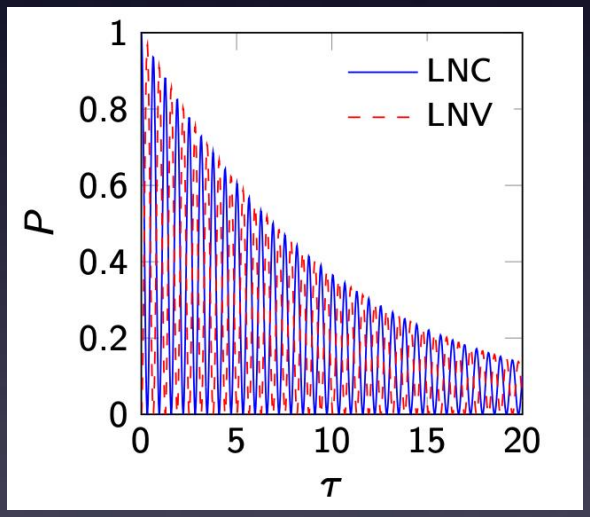
- LNV/LNC ratio ≈ 1
(oscillations averaged out)

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

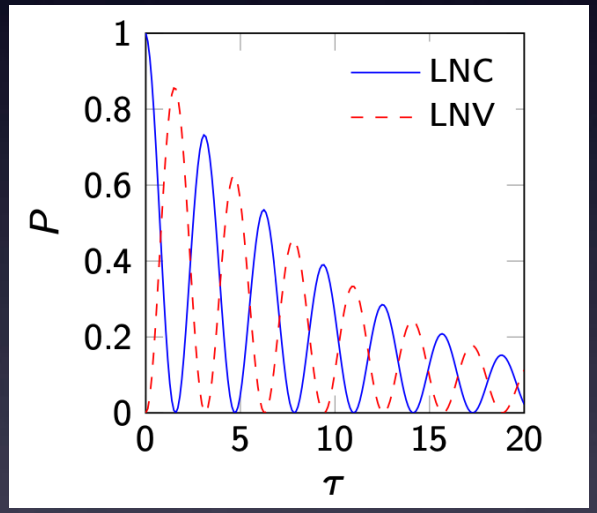
- Oscillations potentially observable, intermediate LNV/LNC ratio possible (mass splitting $\Delta M$ as additional pheno parameter)

→ "Pure Dirac HNL" limit

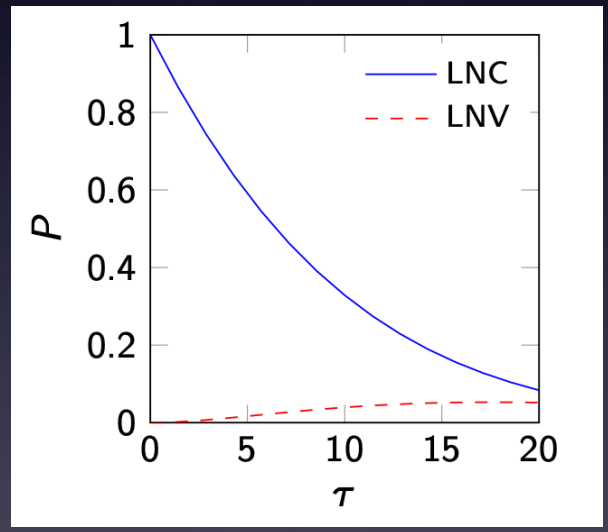
- no observable LNV
(oscillation length too large)




larger $\Delta M$



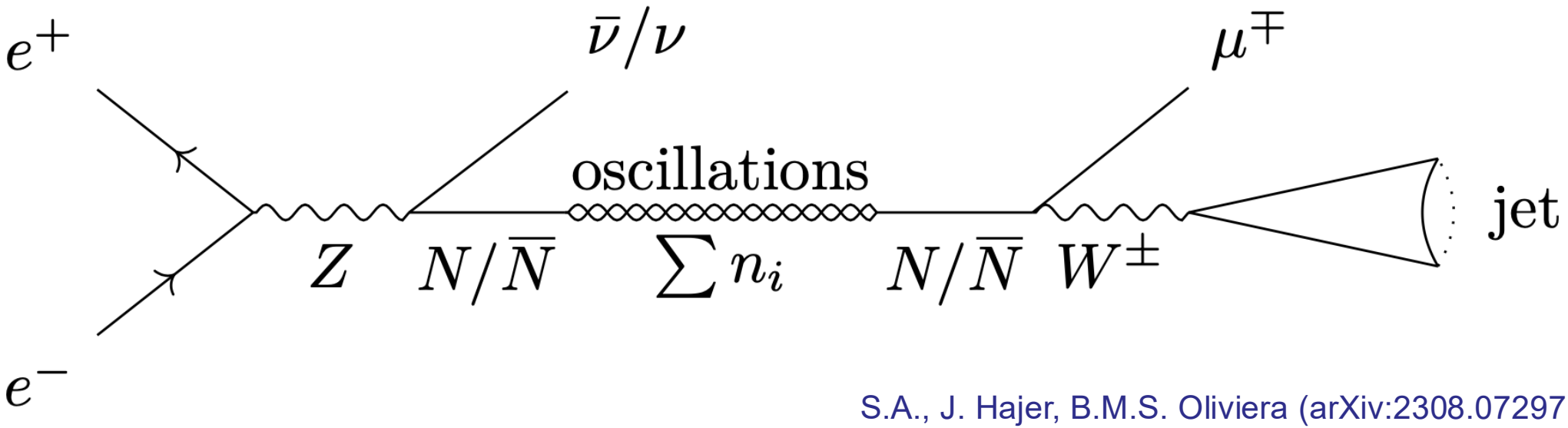

$\Delta M \to 0$




*) still approximate L symmetrty → small neutrino masses protected (too large $m_\nu$ 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 FCC-ee (for long-lived HNLs)?

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



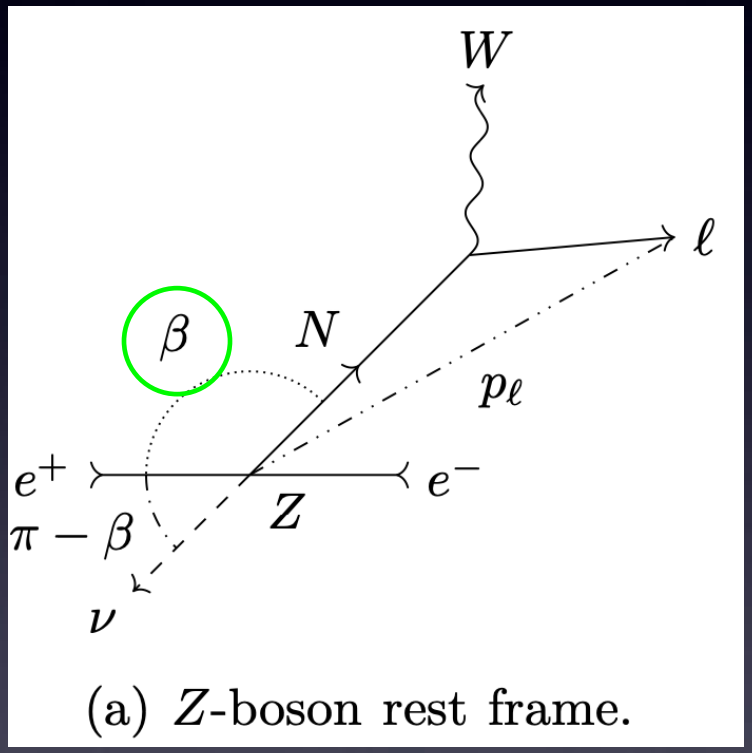

S.A., J. Hajer, B.M.S. Oliviera (arXiv:2308.07297)
S.A., J. Hajer, B.M.S. Oliviera (arXiv:2408.01389)

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

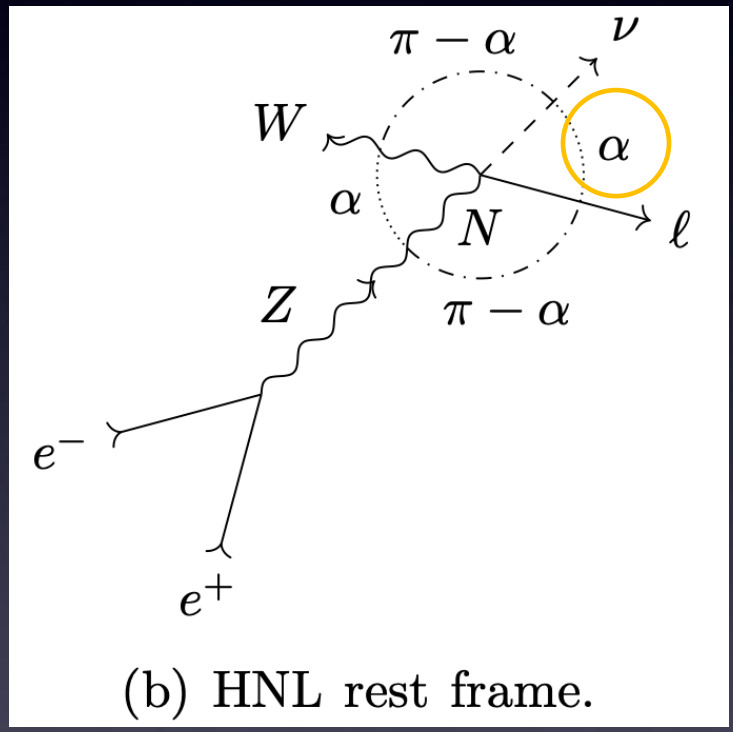
# Angular dependecies for HNLs at the FCC (Z-pole run)

**Polarisation of the Z → forward-backward asymmetry of the N vs. $\bar{N}$ 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)

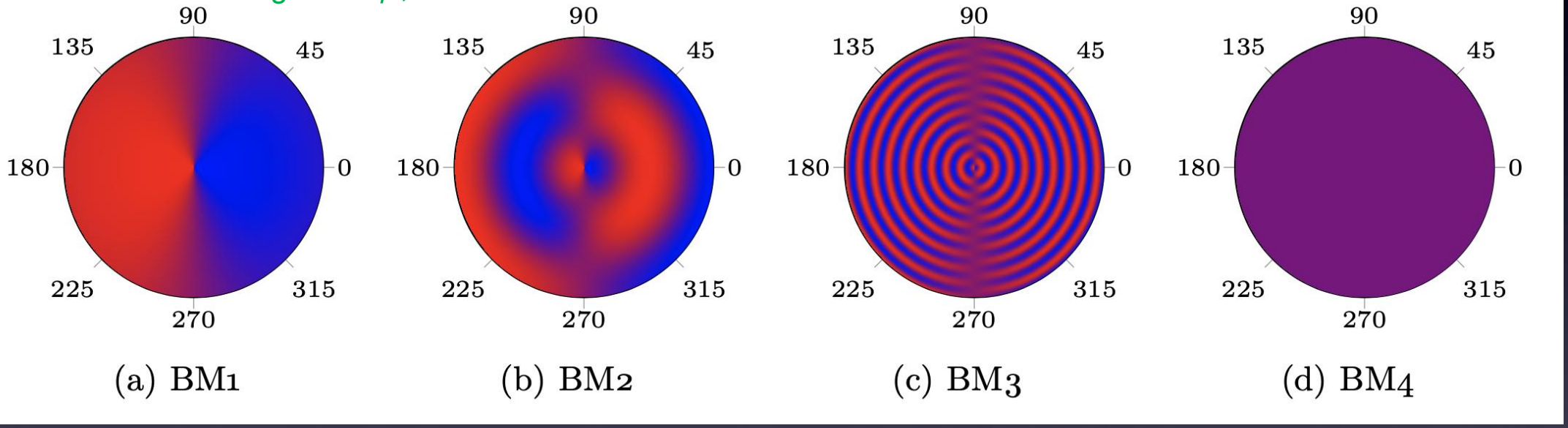
S.A., J. Hajer, B.M.S. Oliviera (arXiv:2408.01389)

# 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 = $\tau$




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)

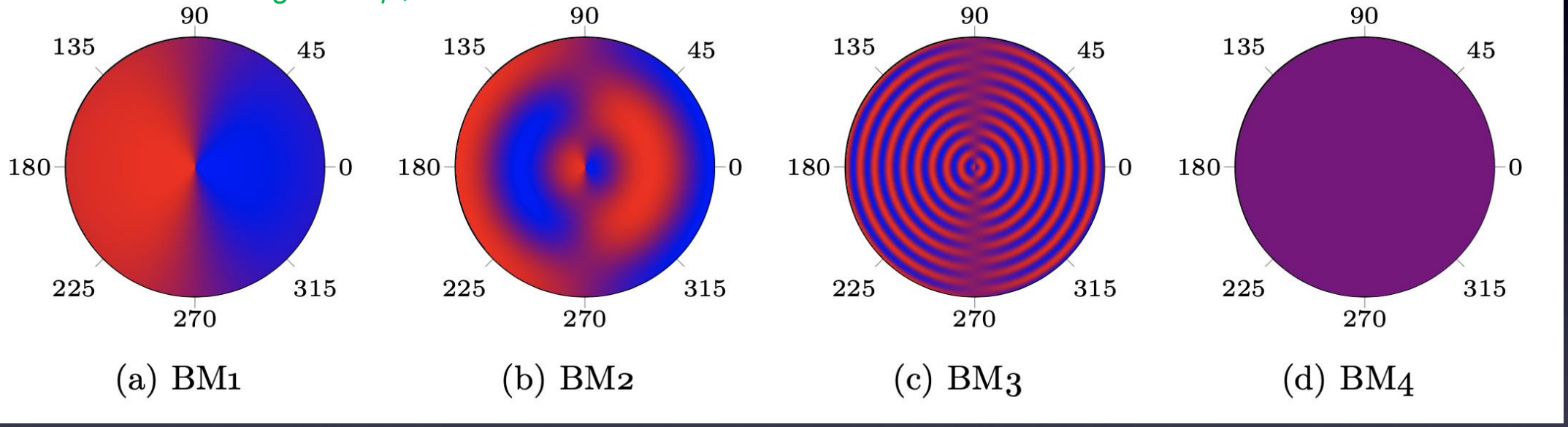
# Example Signal: Oscillating ratio of $l^+/l^-$ final states as function of HNL lifetime and polar angle of displaced vertex

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

blue: >1, red, <1

**For angular segment: Lepton # changes as function of $\tau$ → clear signal of LNV**

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

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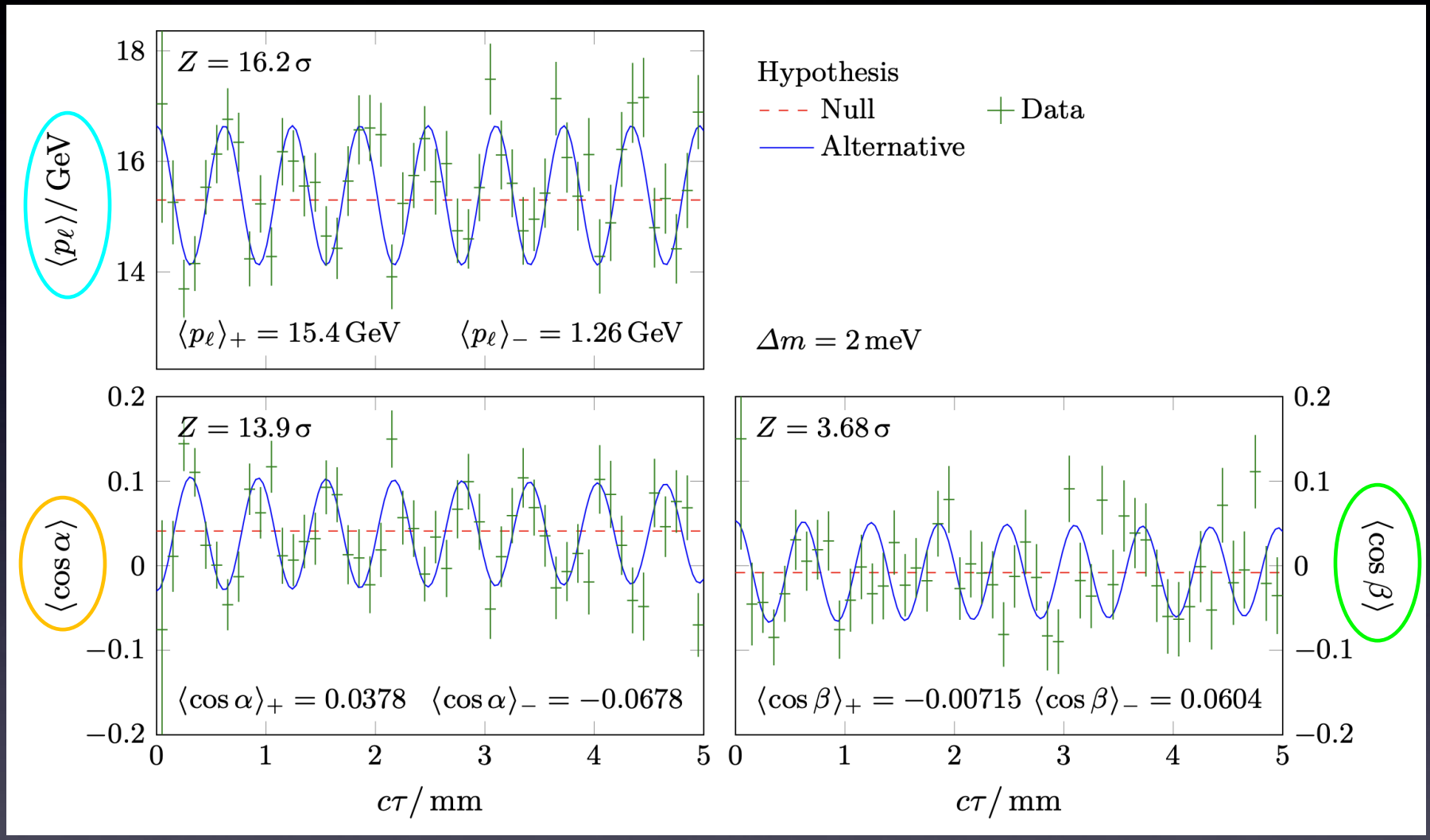
S.A., J. Hajer, B.M.S. Oliviera (arXiv:2308.07297)

# Comparison of sensitivities for various oscillating observables @ FCC-ee

Well accessible observsble, very good analysis power:

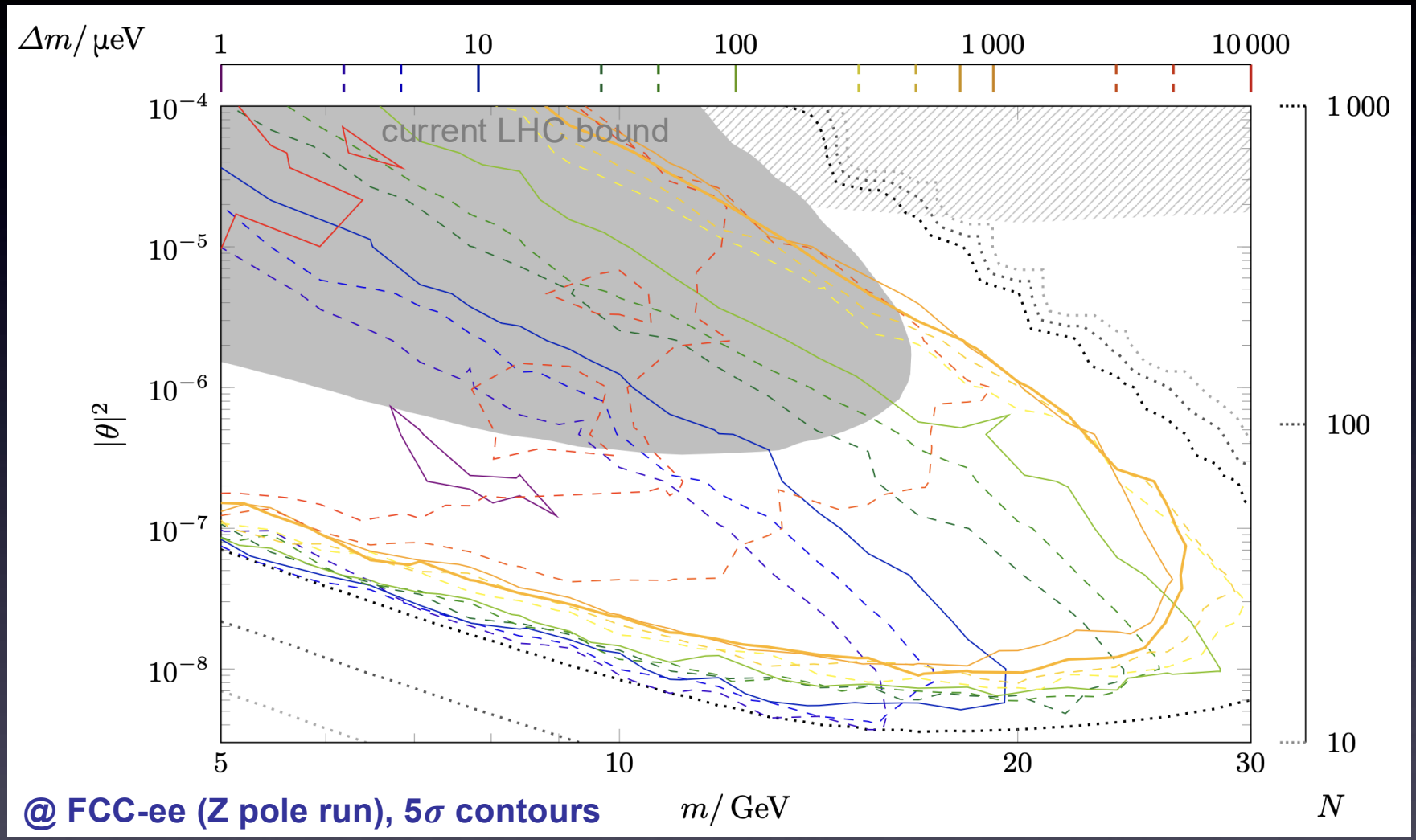
$p_\ell := |\vec{p}_\ell(m_Z)|$




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 $\Delta M$ for low scale linear seesaw (IH)

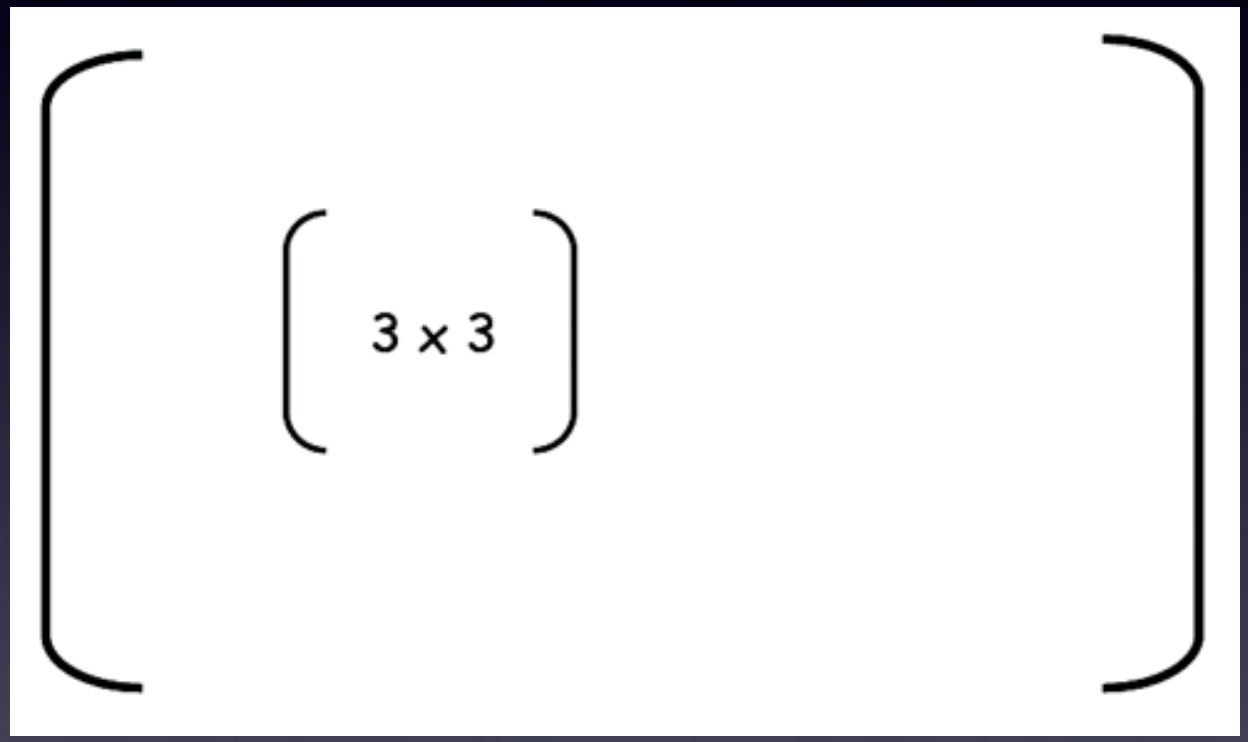
S.A., J. Hajer, B.M.S. Oliviera (arXiv:2408.01389)

# Indirect signature of new physics in the neutrino sector: Non-unitary $U_{PMNS}$

# *Non-unitary leptonic mixing (PMNS matrix)*

- Typical situation, intuitively:

(Effective) mixing matrix of light neutrinos is submatrix of a larger unitary mixing matrix (mixing with additional heavy neutral fermions)



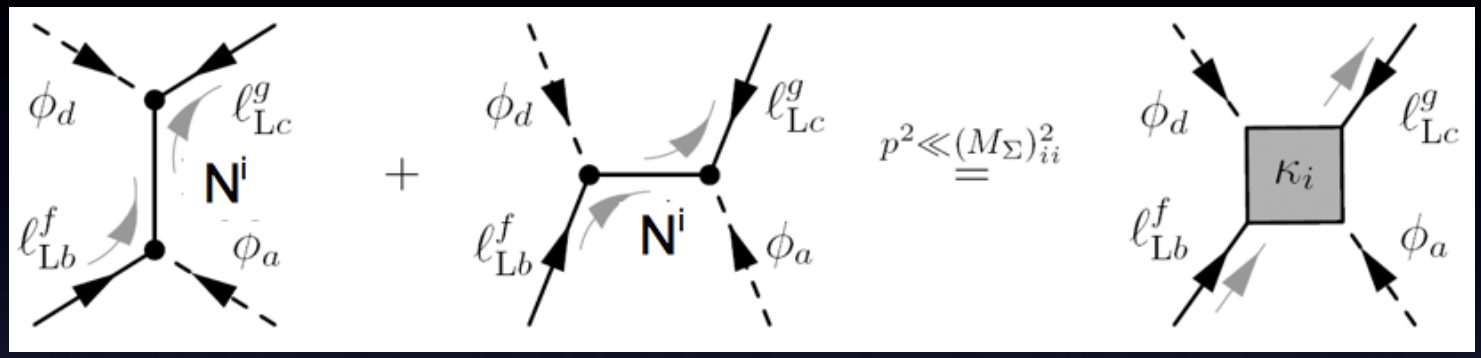

Langacker, London ('88)

$\Rightarrow U_{PMNS} \equiv N$ is non-unitary

Examples with possible large non-unitarity: 'inverse' and 'linear' seesaw, or 'multiple' seesaw, at TeV energies, SUSY with R-parity violation, large extra dimensions, ...

# Generic scenario: SM + heavy neutral leptons

Integrating out the heavy neutral leptons (= sterile neutrinos) generates dominantly the two effective operators:

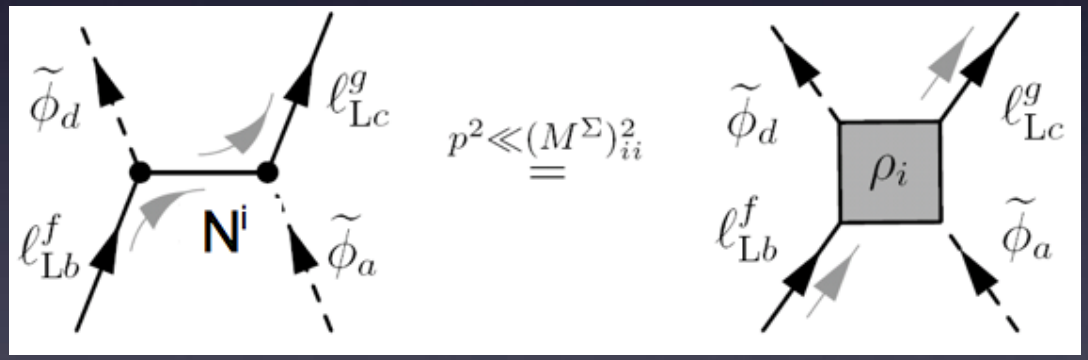



Neutrino mass operator (d=5)

$$\delta\mathcal{L}^{d=5} = \frac{1}{2}\, c^{d=5}_{\alpha\beta} \left(\overline{L^c}_\alpha \tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger\, L_\beta\right) + h.c.$$

$$c^{d=5}_{\alpha\beta} = (Y_N^T)_{\alpha I}(M_N)^{-1}_{IJ}(Y_N)_{J\beta}$$

$$(m_\nu)_{\alpha\beta} = -\frac{v^2_{\rm EW}}{2} c^{d=5}_{\alpha\beta}$$




Effective (d=6) operator which modifies the kin. terms of the neutrinos

$$\delta\mathcal{L}^{d=6} = c^{d=6}_{\alpha\beta} \left(\overline{L}_\alpha \tilde{\phi}\right) i\partial\!\!\!/ \left(\tilde{\phi}^\dagger L_\beta\right)$$

$$c^{d=6}_{\alpha\beta} = \sum_I (Y_N^\dagger)_{\alpha I}(M_N)^{-2}_{II}(Y_N)_{I\beta}$$

# *After EWSB: Non-canonical kinetic terms for the neutrinos*

- From the d=6 operator, after electroweak symmetry breaking:

non-canonical kinetic terms

$$\begin{aligned}\mathcal{L}^{eff} = & \frac{1}{2}\left(i\,\bar{\nu}_\alpha\,\partial\!\!\!/\,(NN^\dagger)^{-1}_{\alpha\beta}\,\nu_\beta - \overline{\nu^c}_\alpha\,[(N^{-1})^t m N^{-1}]_{\alpha\beta}\,\nu_\beta + h.c.\right) \\ & - \frac{g}{2\sqrt{2}}\left(W^+_\mu\,\bar{l}_\alpha\,\gamma^\mu\,(1-\gamma_5)\,\nu_\alpha + h.c.\right) \\ & - \frac{g}{2\cos\theta_W}\left(Z_\mu\,\bar{\nu}_\alpha\,\gamma^\mu\,(1-\gamma_5)\,\nu_\alpha + h.c.\right) + \ldots\,,\end{aligned}$$

# *In the mass basis: Non-unitary $U_{PMNS}$*

- Lagrangian in the mass basis ...

kinetic term

neutrino mass term

charged current interaction

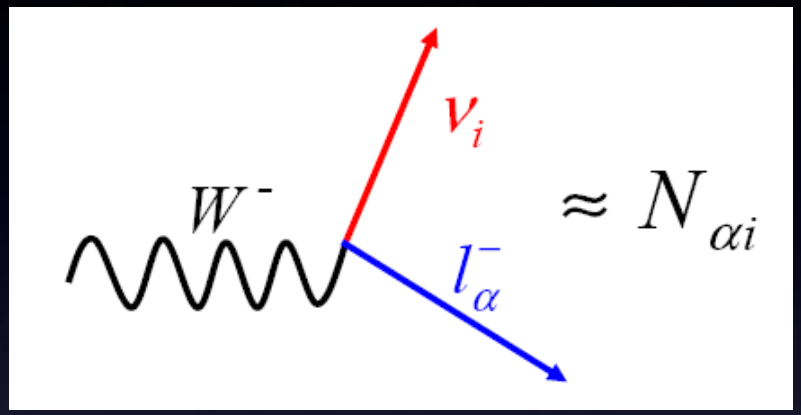
non-unitary mixing matrix N

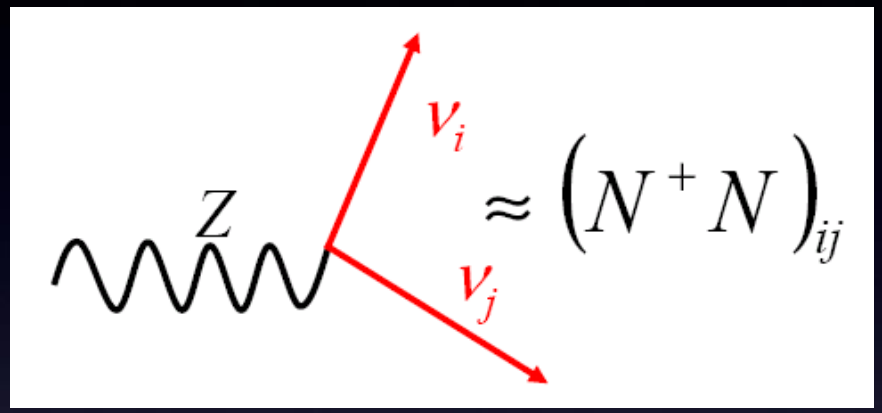
$$\mathcal{L}^{eff} = \frac{1}{2}\left(\bar{\nu}_i i \not{\partial} \nu_i - \overline{\nu^c}_i m_i \nu_i + h.c.\right) - \frac{g}{2\sqrt{2}}\left(W^+_\mu \bar{l}_\alpha \gamma_\mu (1-\gamma_5) N_{\alpha i} \nu_i + h.c.\right)$$
$$- \frac{g}{2\cos\theta_W}\left(Z_\mu \bar{\nu}_i \gamma^\mu (1-\gamma_5)(N^\dagger N)_{ij} \nu_j + h.c.\right) + \ldots$$

+ modification in neutral current interaction

Non-unitarity of the leptonic mixing matrix corresponds to non-canonical kinetic terms in the flavour basis (from d=6 operator)!

# EW interactions modified




Definition:
Non-unitarity parameters

$$(NN^\dagger)_{\alpha\beta} = (1_{\alpha\beta} + \varepsilon_{\alpha\beta})$$

(Hermitean matrix)

Theory predictions for various observables which involve weak interactions get modified!

S.A., Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon ('06)

# *Two comments ...*

- One can show that the off-diagonal non-unitarity parameters satisfy the following inequality:

$$|\varepsilon_{\alpha\beta}| \leq \sqrt{|\varepsilon_{\alpha\alpha}||\varepsilon_{\beta\beta}|}$$

S.A., E. Fernandez-Martinez, J. Baumann (arXiv:0807.1003)

This can provide an interesting consistency check!

- Furthermore, the diagonal non-unitarity parameters are always ≤ 0:

$$\varepsilon_{\alpha\alpha} \leq 0$$

# *Relation between parameters of full and effective theory*

**Active-sterile mixing angles $\theta_\alpha$ ($\alpha$=1,2,3)**

| | $y_{\nu_\alpha}$ | $\theta_\alpha$ | $\varepsilon_{\alpha\beta}$ |
|---|---|---|---|
| $y_{\nu_\alpha} =$ | – | $\frac{\sqrt{2}M}{v_{\rm EW}}\theta_\alpha^*$ | $-\frac{\sqrt{2}M}{v_{\rm EW}}\varepsilon_{\beta\alpha}/\sqrt{-\varepsilon_{\beta\beta}}$ |
| $\theta_\alpha =$ | $\frac{v_{\rm EW}}{\sqrt{2}M}y_{\nu_\alpha}^*$ | – | $-\varepsilon_{\beta\alpha}/\sqrt{-\varepsilon_{\beta\beta}}$ |
| $\varepsilon_{\alpha\beta} =$ | $-\frac{v_{\rm EW}^2 y_{\nu_\alpha}^* y_{\nu_\beta}}{2M^2}$ | $-\theta_\alpha^*\theta_\beta$ | – |

**PMNS non-unitarity**

# *Phenomenological consequences of non-unitary $U_{PMNS}$*

Examples:

- Electroweak precision observables (EWPOs)
- Universality tests (at low E and via W decays)
- Charged LFV decays
- Effects in neutrino oscillation experiments

For global fits and constraints on non-unitary PMNS, cf.:
S.A., O. Fischer (arXiv:1407.6607)
M. Blennow, E. Fernández-Martínez, J. Hernández-García, J. López-Pavón, X. Marcano, D. Naredo-Tuero (arXiv:2306.01040)

# *Electroweak precision observables*

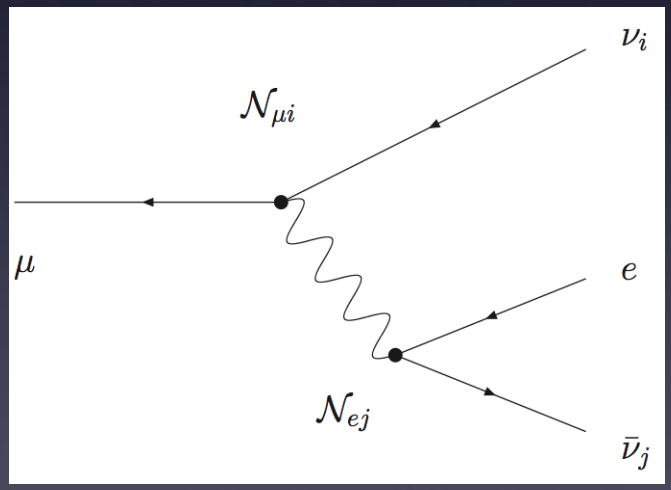
- Remark: As usual, one expresses the predictions for the EWPOs in terms of the very well measured quantities

$$\begin{aligned} \alpha(m_z)^{-1} &= 127.944(14)\,, \\ G_F &= 1.1663787(6)\times 10^{-5}\mathrm{GeV}^{-2}\,, \\ m_Z &= 91.1875(21)\,, \end{aligned}$$

- However: $G_F$ is measured in muon decays ... and thus gets modified due to the non-unitary mixing N (= $U_{PMNS}$):

$$G_\mu^2 = G_F^2 (NN^\dagger)_{\mu\mu}(NN^\dagger)_{ee}$$

→ affects many observables



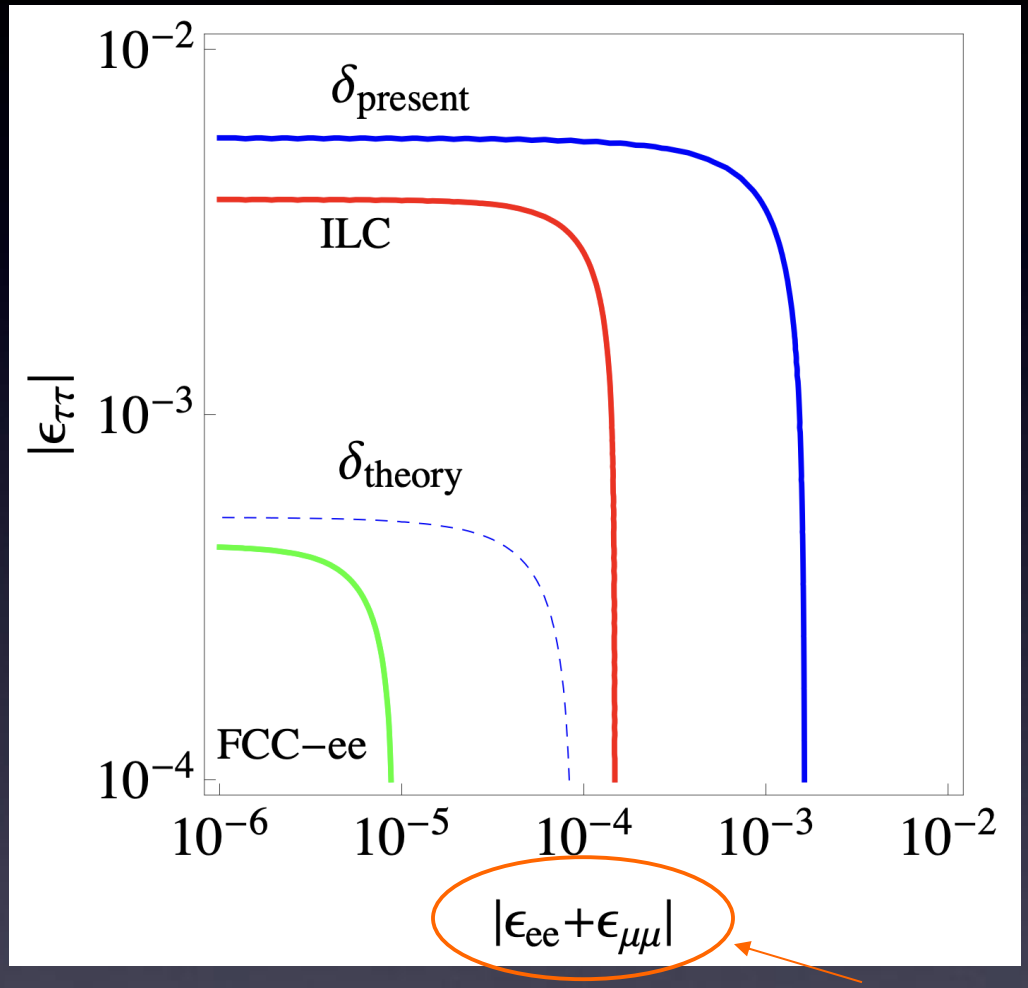
# Summary of modified EWPO predictions

| Prediction in MUV |
| --- |
| $[R_\ell]_{\rm SM}\,(1-0.15(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$ |
| $[R_b]_{\rm SM}\,(1+0.03(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$ |
| $[R_c]_{\rm SM}\,(1-0.06(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$ |
| $[\sigma^0_{had}]_{\rm SM}\,(1-0.25(\varepsilon_{ee}+\varepsilon_{\mu\mu})-0.27\,\varepsilon_{\tau\tau})$ |
| $[R_{inv}]_{\rm SM}\,(1+0.75(\varepsilon_{ee}+\varepsilon_{\mu\mu})+0.67\,\varepsilon_{\tau\tau})$ |
| $[M_W]_{\rm SM}(1-0.11(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$ |
| $[\Gamma_{\rm lept}]_{\rm SM}(1-0.59(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$ |
| $[(s^{\ell,\rm lep}_{W,\rm eff})^2]_{\rm SM}(1+0.71(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$ |
| $[(s^{\ell,\rm had}_{W,\rm eff})^2]_{\rm SM}(1+0.71(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$ |

Sensitivity via $G_F$!

S.A., O. Fischer (1407.6607)

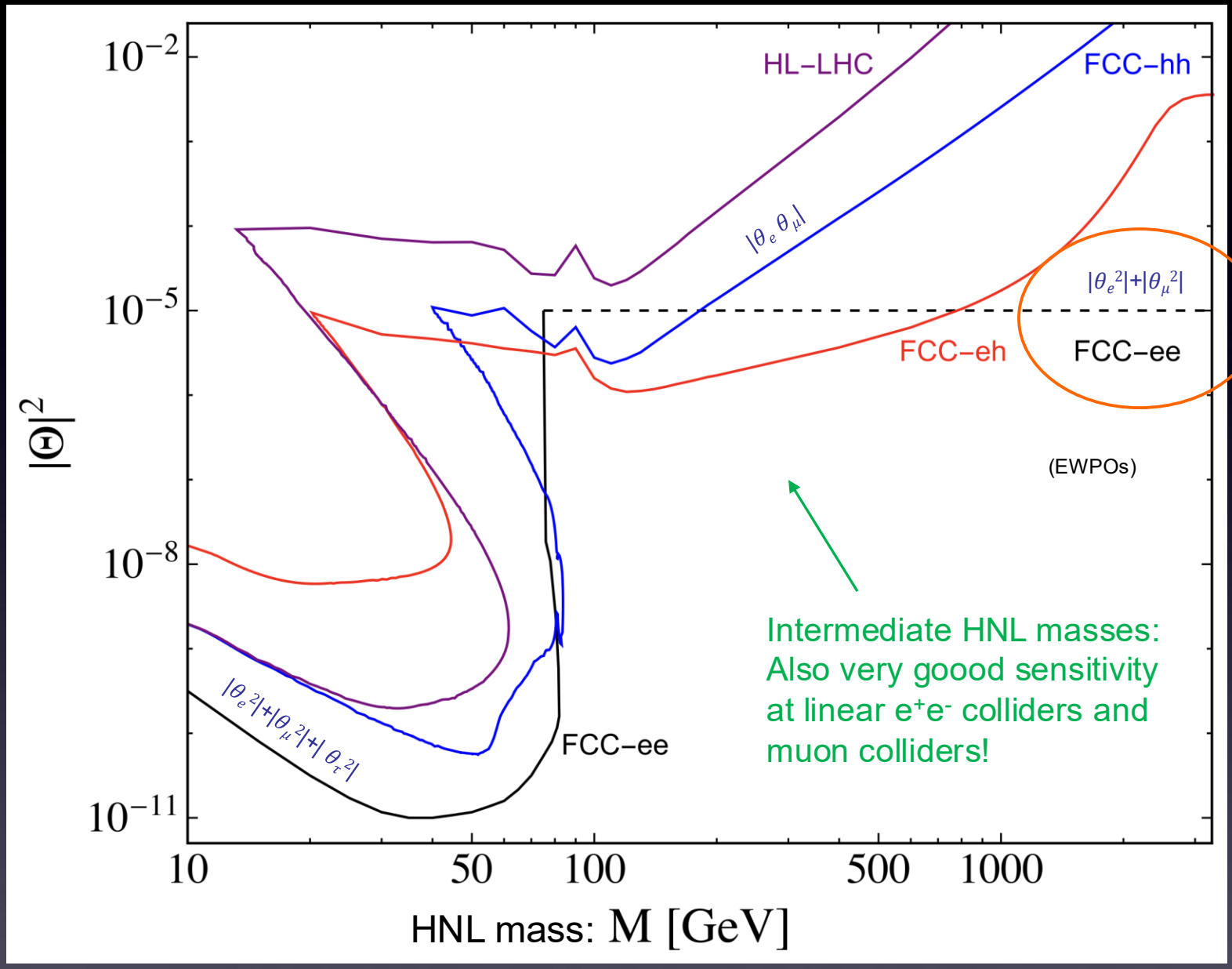
# FCC-ee (CEPC): estimated sensitivity via EWPOs




cf. S.A., O. Fischer (1407.6607)

The EWPOs are very sensitive to the sum $|\varepsilon_{ee} + \varepsilon_{\mu\mu}|$

# Summary: Sensitivity to HNLs and the FCC




FCC Physics Opportunities, Eur. Phys. J. C (2019) 79:474

# Other sensitive probes: Universality tests

Ratios of observables of the form:

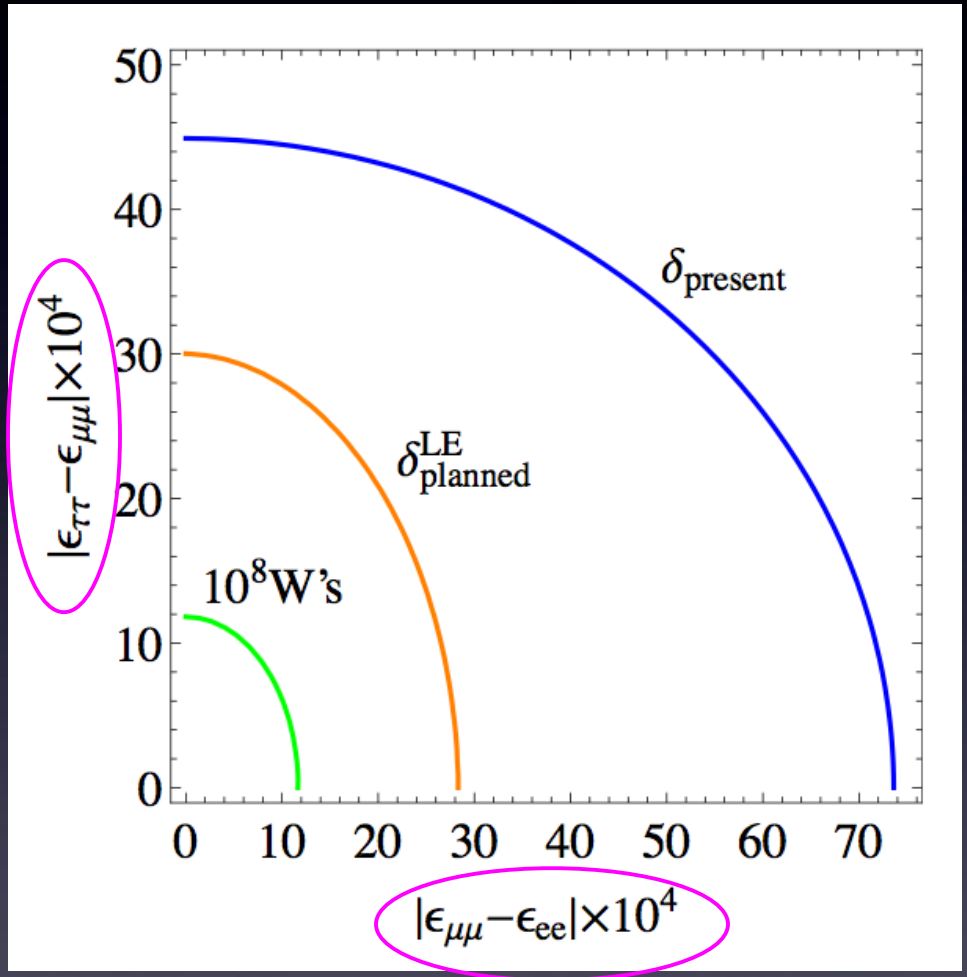
$$R_{\alpha\beta} = \sqrt{\frac{(NN^\dagger)_{\alpha\alpha}}{(NN^\dagger)_{\beta\beta}}} \simeq 1 + \frac{1}{2}(\varepsilon_{\alpha\alpha} - \varepsilon_{\beta\beta})$$

**Examples:**

| | Process* |
|---|---|
| $R^{\ell}_{\mu e}$ | $\frac{\Gamma(\tau \to \nu_\tau \mu \bar{\nu}_\mu)}{\Gamma(\tau \to \nu_\tau e \bar{\nu}_e)}$ |
| $R^{\ell}_{\tau\mu}$ | $\frac{\Gamma(\tau \to \nu_\tau e \bar{\nu}_e)}{\Gamma(\mu \to \nu_\mu e \bar{\nu}_e)}$ |
| $R^{W}_{e\mu}$ | $\frac{\Gamma(W \to e \bar{\nu}_e)}{\Gamma(W \to \mu \bar{\nu}_\mu)}$ |
| $R^{W}_{\tau\mu}$ | $\frac{\Gamma(W \to \tau \bar{\nu}_\tau)}{\Gamma(W \to \mu \bar{\nu}_e)}$ |

| | Process |
|---|---|
| $R^{\pi}_{\mu e}$ | $\frac{\Gamma(\pi \to \mu \bar{\nu}_\mu)}{\Gamma(\pi \to e \bar{\nu}_e)}$ |
| $R^{\pi}_{\tau\mu}$ | $\frac{\Gamma(\tau \to \nu_\tau \pi)}{\Gamma(\pi \to \mu \bar{\nu}_\mu)}$ |
| $R^{K}_{\tau\mu}$ | $\frac{\Gamma(\tau \to K \nu_\tau)}{\Gamma(K \to \mu \bar{\nu}_\mu)}$ |
| $R^{K}_{\tau e}$ | $\frac{\Gamma(\tau \to K \nu_\tau)}{\Gamma(K \to e \bar{\nu}_e)}$ |

# *Very sensitive tests of universality with W decays at FCC-ee/CEPC*



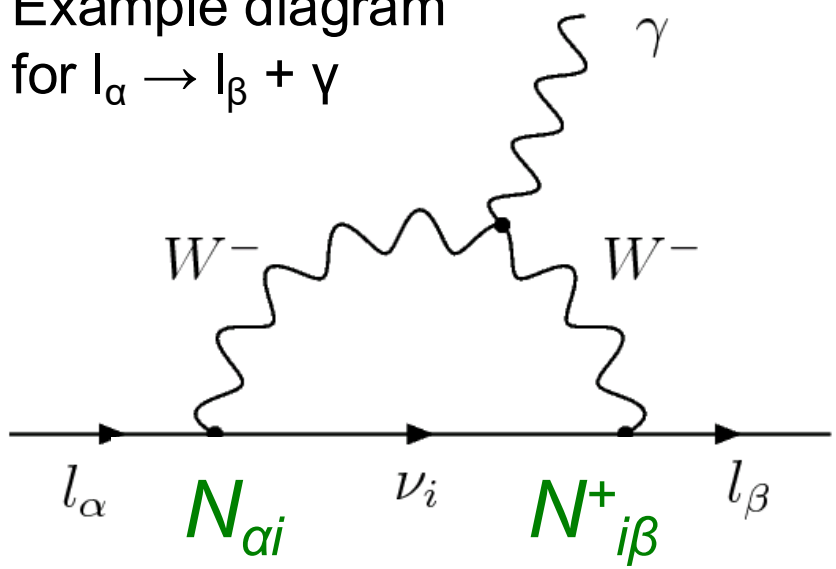

S.A., O. Fischer (1407.6607)

universality tests probe the differences between the $\varepsilon_{\alpha\alpha}$

# Constraints from LFV

- Bounds on LFV μ and τ decays $l_i \to l_j \gamma$ (and on $\mu \to 3e$ and $\mu \to e$ conversion in nuclei) lead to constraints on the $|\varepsilon_{\alpha\beta}|$:

Example diagram for $l_\alpha \to l_\beta + \gamma$




$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \nu_\alpha \ell_\beta \overline{\nu}_\beta)} = \frac{3\alpha}{32\pi} \frac{|\sum_k N_{\alpha k} N^\dagger_{k\beta} F(x_k)|^2}{(NN^\dagger)_{\alpha\alpha}(NN^\dagger)_{\beta\beta}}$$

irrelevant for unitary mixing matrix, but can lead to sizable Br's for non-unitary N!

$$F(x) \equiv \frac{10 - 43x + 78x^2 - 49x^3 + 4x^4 + 18x^3 \ln x}{3(x-1)^4}$$

where:

$$x_k \equiv m_k^2 / M_W^2$$

$m_k$: light neutrinos' masses

# Future sensitivities to the $\varepsilon_{\alpha\beta}$ from cLFV

from S.A., O. Fischer (1407.6607)

- Estimated sensitivities of planned experiments at 90% C.L.:

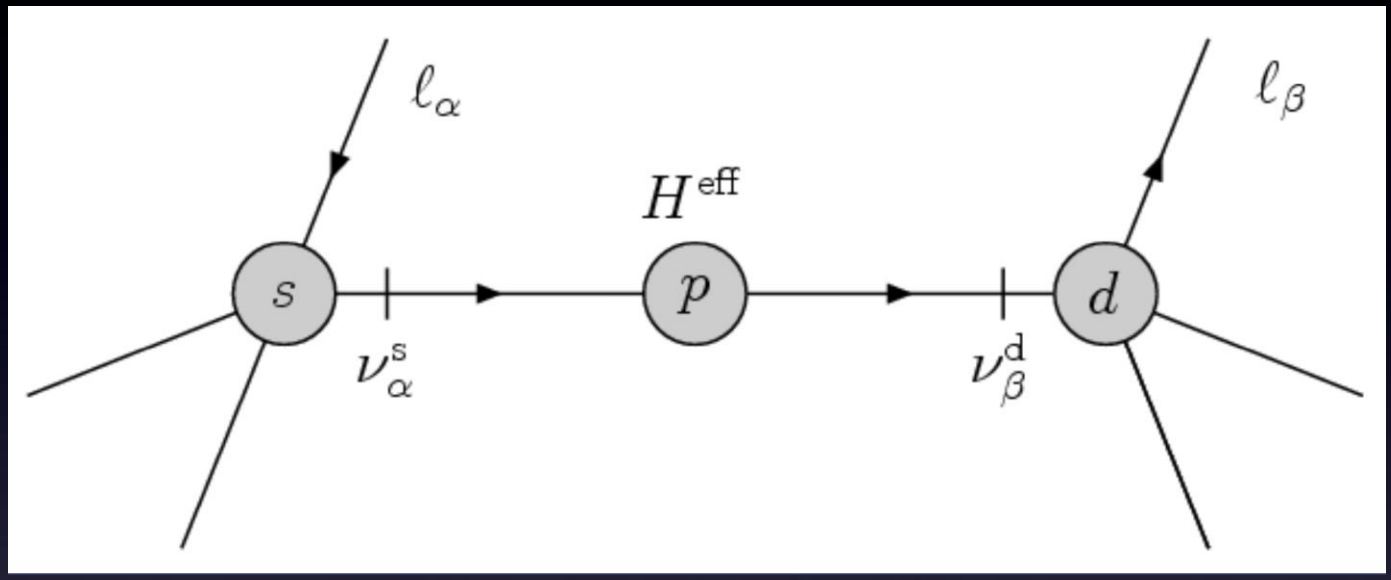
| Process | Prediction (within MUV) | Experiments | Sensitivity to non-unitarity |
|---|---|---|---|
| $Br_{\tau e}$ | $4.3 \times 10^{-4} \lvert\varepsilon_{\tau e}\rvert^2$ | $10^{-9}$ | $\varepsilon_{\tau e} \geq 1.5 \times 10^{-3}$ |
| $Br_{\tau \mu}$ | $4.1 \times 10^{-4} \lvert\varepsilon_{\tau \mu}\rvert^2$ | $10^{-9}$ | $\varepsilon_{\tau \mu} \geq 1.6 \times 10^{-3}$ |
| $Br_{\mu eee}$ | $1.8 \times 10^{-5} \lvert\varepsilon_{\mu e}\rvert^2$ | $10^{-16}$ | $\varepsilon_{\mu e} \geq 2.4 \times 10^{-6}$ |
| $R_{\mu e}^{Ti}$ | $1.5 \times 10^{-5} \lvert\varepsilon_{\mu e}\rvert^2$ | $2 \times 10^{-18}$ | $\varepsilon_{\mu e} \geq 3.6 \times 10^{-7}$ |

Various experiments forthcoming: MEG-II, Mu3e, Mu2e(-II), COMET, AMF – PRISM, BARBAR, Belle II ...

Note: from $|\varepsilon_{\alpha\beta}| \leq \sqrt{|\varepsilon_{\alpha\alpha}||\varepsilon_{\beta\beta}|}$

A future measurement of cLFV would also imply non-zero $\epsilon_{\alpha\alpha}$ and $\epsilon_{\beta\beta}$!

# *Effects at neutrino oscillation experiments: Non-unitarity effects at source, detector, with matter*




**Number of neutrino events:**

flux — oscillation probability — detection cross section

$$n_{events} \sim \int dE \, \frac{d\Phi_\alpha(E)}{dE} \, P_{\nu_\alpha \nu_\beta}(E, L) \, \sigma_\beta(E) \, \epsilon(E)$$

detector efficiency

## Effects on neutrino oscillations in vacuum (schematically, 2 family example):

$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right) + 2\,\mathrm{Im}(\varepsilon_{\alpha\beta})\sin(2\theta)\sin\left(\frac{\Delta m^2 L}{2E}\right) + 4\left|\varepsilon_{\alpha\beta}\right|^2$$

SM

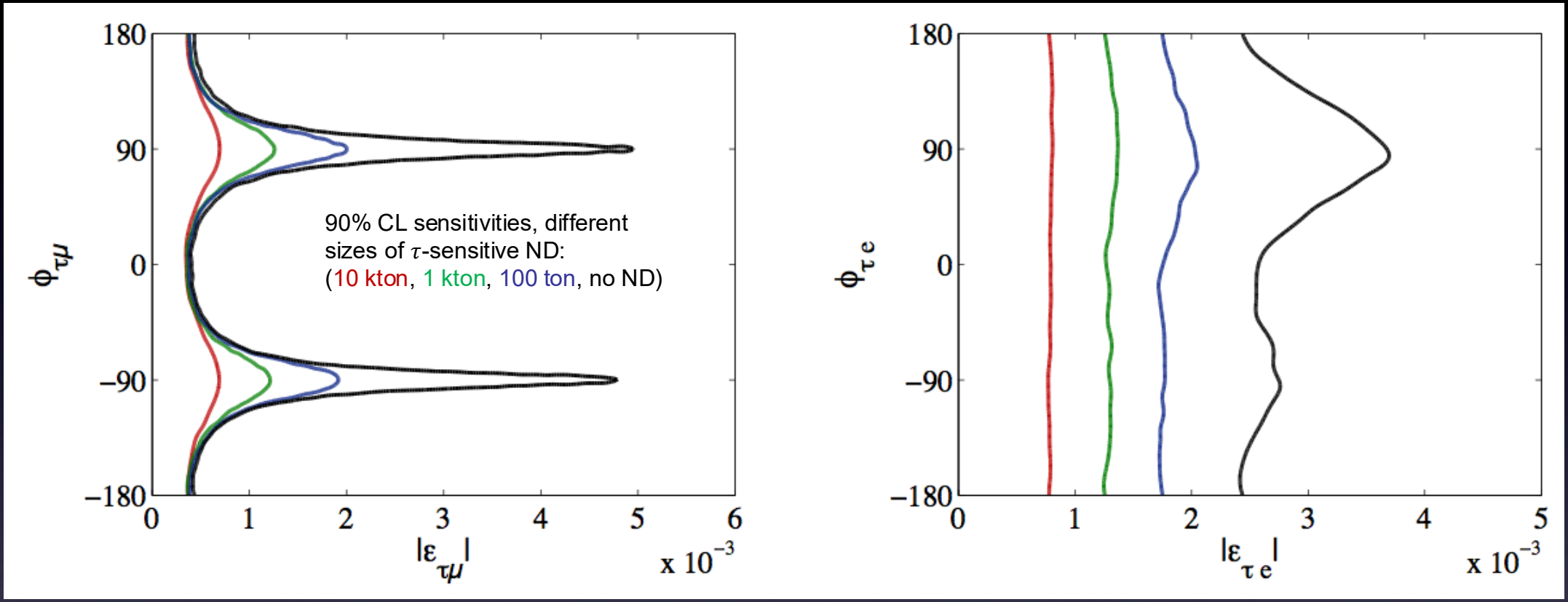
CP violating interference

Zero dist. effect

*+ additional effects of non-unitarity on the interaction with matter*

For full oscillation formulae with non-unitarity, cf.: S.A., Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon ('06)

# Possible sensitivity also to the phases of $\varepsilon_{\alpha\beta}$ at a neutrino factory?




- Interplay of (tau-sensitive) near and far detectors yields sensitivity also to the phases of the MUV parameters $\varepsilon_{\tau\mu}$ and $\varepsilon_{\tau e}$ (i.e. on the phases of $-\theta_\tau^*\theta_\mu$ and $-\theta_\tau^*\theta_e$)

  S.A., M. Blennow, E. Fernandez-Martinez, J. Lopez-Pavon (arXiv:0903.3986)

- On the other hand, with the given constraints: No sensitivity to non-unitarity e.g. at DUNE.

  J. Hernandez-Garcia, J. Lopez-Pavon (arXiv:1705.01840)

# *Summary and conclusions*

- Future colliders offer great opportunities for discovering signs of new physics in the lepton sector, and for getting deep insight into the mechanism of neutrino mass generation

- Example: Heavy Neutral Leptons (HNLs) @ FCC-ee/CEPC
- Direct searches:
  - Great sensitivity via displaced HNL decays
  - Exciting signature of low scale seesaw: heavy neutrino-antineutrino oscillations inducing oscillating ratio of LNV/LNC events

- Indirect signature: leptonic ($U_{PMNS}$) non-unitarity
  - Sensitive tests at FCC-ee/CEPC via EWPOs and universality tests

# Thanks for your attention!