Understanding Lepton Number Violation at Future Colliders

This talk: LNV induced by HNLs

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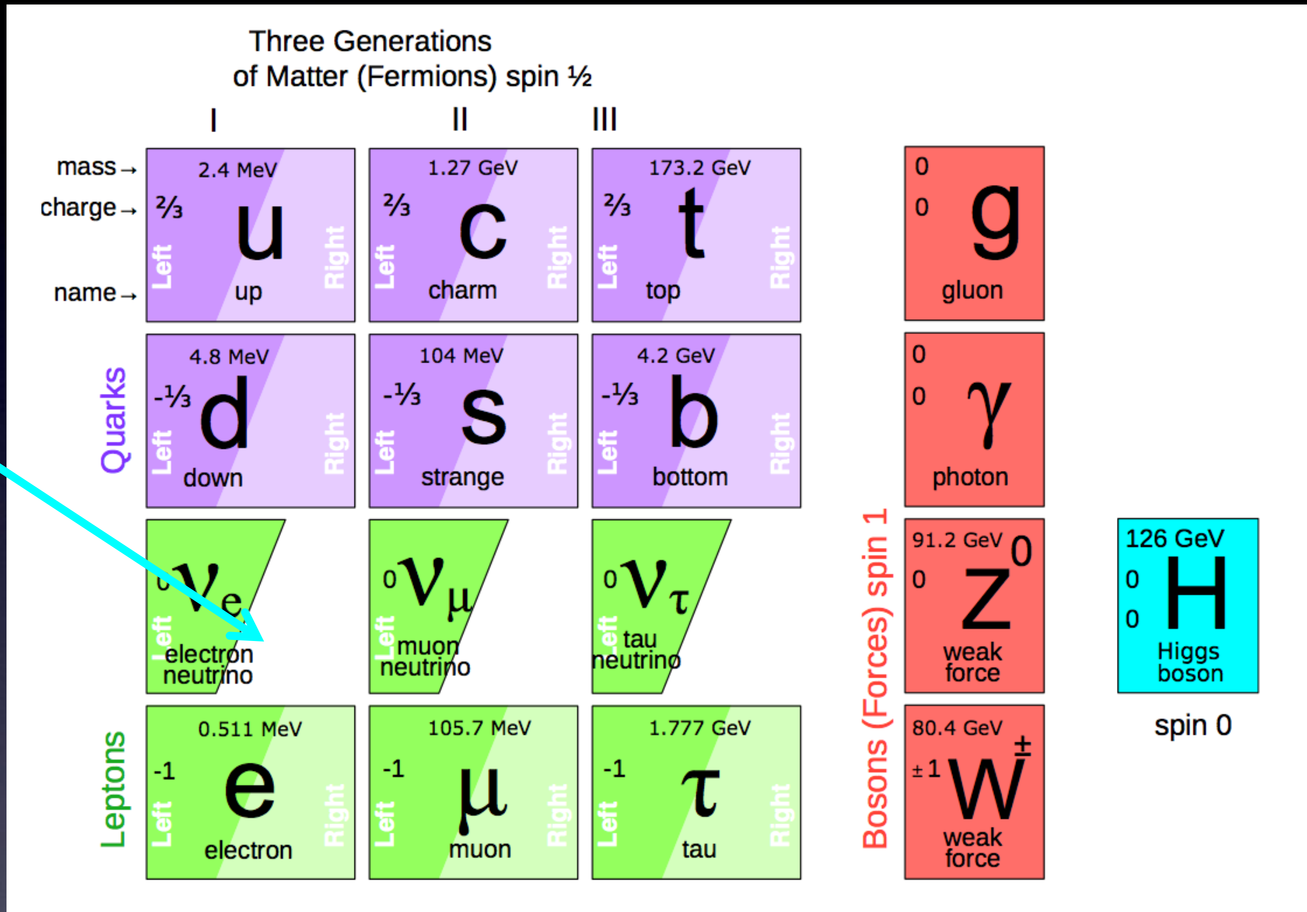
Heavy Neutral Leptons – the right SM extension to explain the light neutrino masses?

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:

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

M: HNL mass matrix

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

Outline

- Collider testable low-scale seesaw models feature pseudo-Dirac pairs of heavy neutrinos (L approx. symm., small mass splitting ΔM)
- LNV → 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 and Madgraph patch for including heavy neutrino-antineutrino oscillationsin collider simulations (HNLs from W)

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)

- Heavy neutrino-antineutrino oscillations at the FCC-ee (HNLs from Z)

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

Minimal example: 2 RH Neutrinos (2 HNLS)

In the mass N_R basis:

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

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

↓ **„Seesaw Formula“**

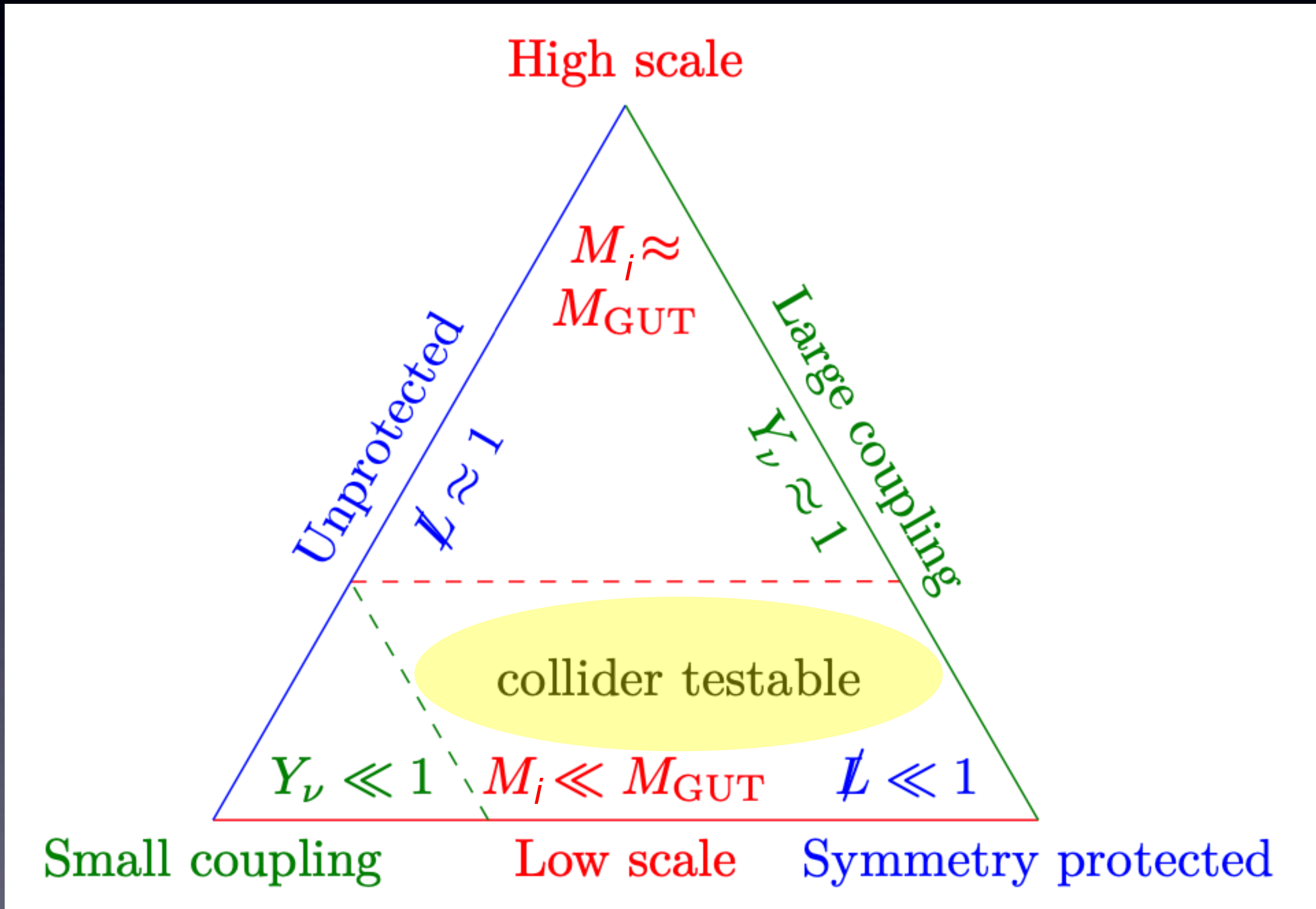
$$(m_\nu)_{\alpha\beta} = \frac{(m_D^{(1)})_\alpha (m_D^{(1)})_\beta}{M_1} + \frac{(m_D^{(2)})_\alpha (m_D^{(2)})_\beta}{M_2}$$

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 $m_{\nu\alpha}$?



Low Scale Seesaw with "Symmetry protection"

... from approximate L-like symmetry

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

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

→

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

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

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

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

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

mass basis: two mass-degenerate Majorana states forming an exact Dirac HNL

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From general 2 HNL seesaw to "symmetry limit"

For comparison: most general seesaw with 2 HNLs:

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

mass basis: two Majorana HNLs with large mass splitting

Low Scale Seesaw with "Symmetry protection"

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

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

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

Important: approximate "L-like symmetry → right-chiral neutrinos form "pseudo-Dirac pair"!

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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To generate the light neutrino masses → approximate symmetry

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

mass basis: two Majorana states with small mass splitting ΔM

when ε-terms "get larger"

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 $y_{\nu\alpha}$)

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

+ 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).

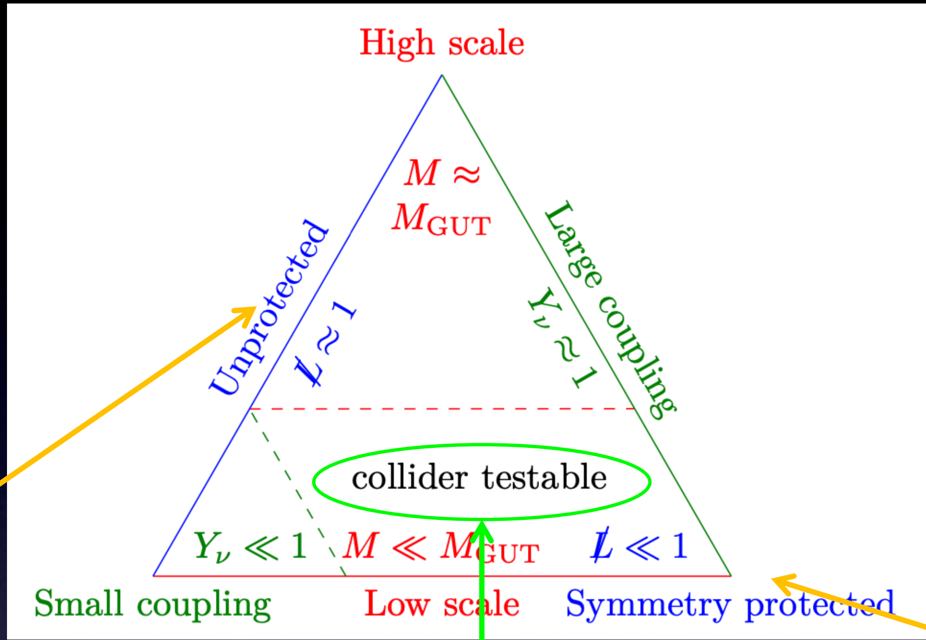
for phenomenology (pSPSS)

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)

Overview: Benchmark models for HNL studies



Two mass-separated Majorana HNLs (or a single Majorana HNL)

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

- LNV/LNC ratio 50%, no oscillations
- for observability at the (HL-)LHC one generates too large $m_{\nu\alpha}$ ☹
- single Majorana HNL not sufficient to describe m_ν

$\Delta M \sim M$ ←

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

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

- collider testable ☺
- can describe m_ν ☺
- interesting phenomenology ☺
- mass splitting ΔM as additional pheno parameter

$\Delta M \to 0$ →

Pure Dirac HNL

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

- no LNV, no oscillations
- limit of exact L-like symmetry
- no contribution to m_ν ☹

LNV from pseudo-Dirac HNLs:

Heavy neutrino-antineutrino oscillations

Heavy Neutrino-Antineutrino Oscillations

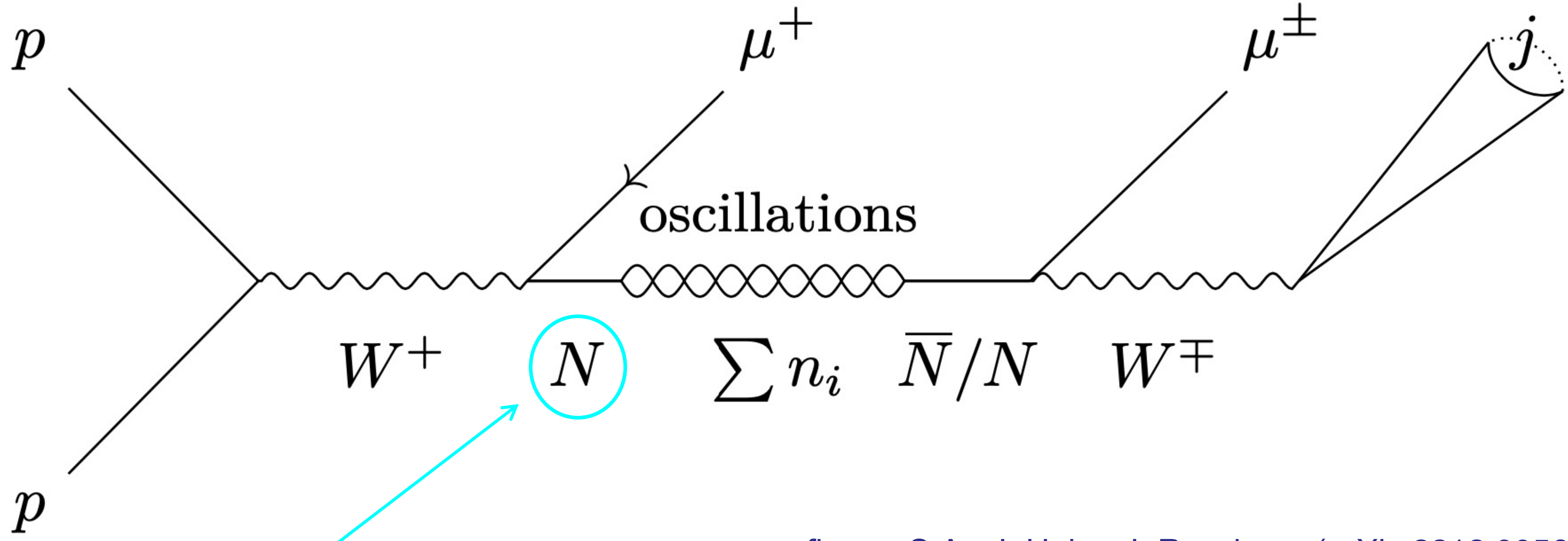


figure: S.A., J. Hajer, J. Rosskopp (arXiv:2212.00562)

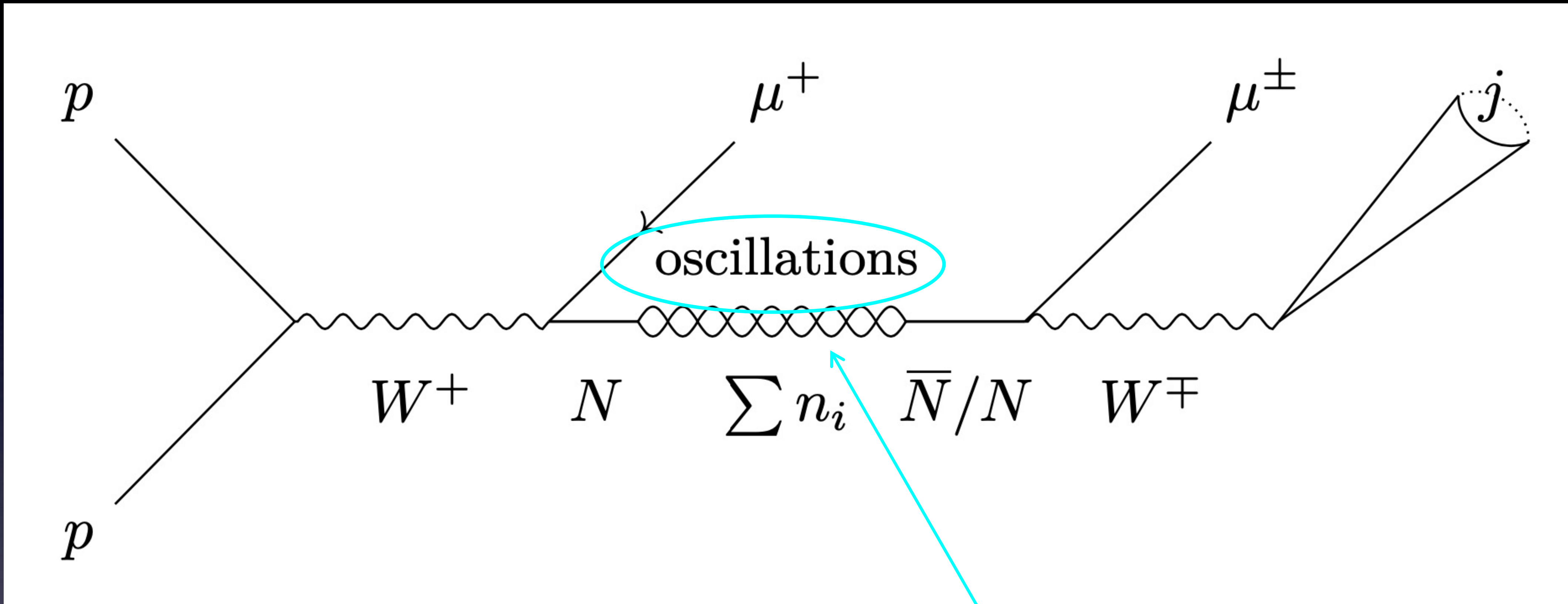
Interaction states: Produced from W decay
- "Heavy Neutrinos N" (together with l_α^+)
- "Heavy Antineutrinos $\overline{N}$" (together with l_α^-)

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



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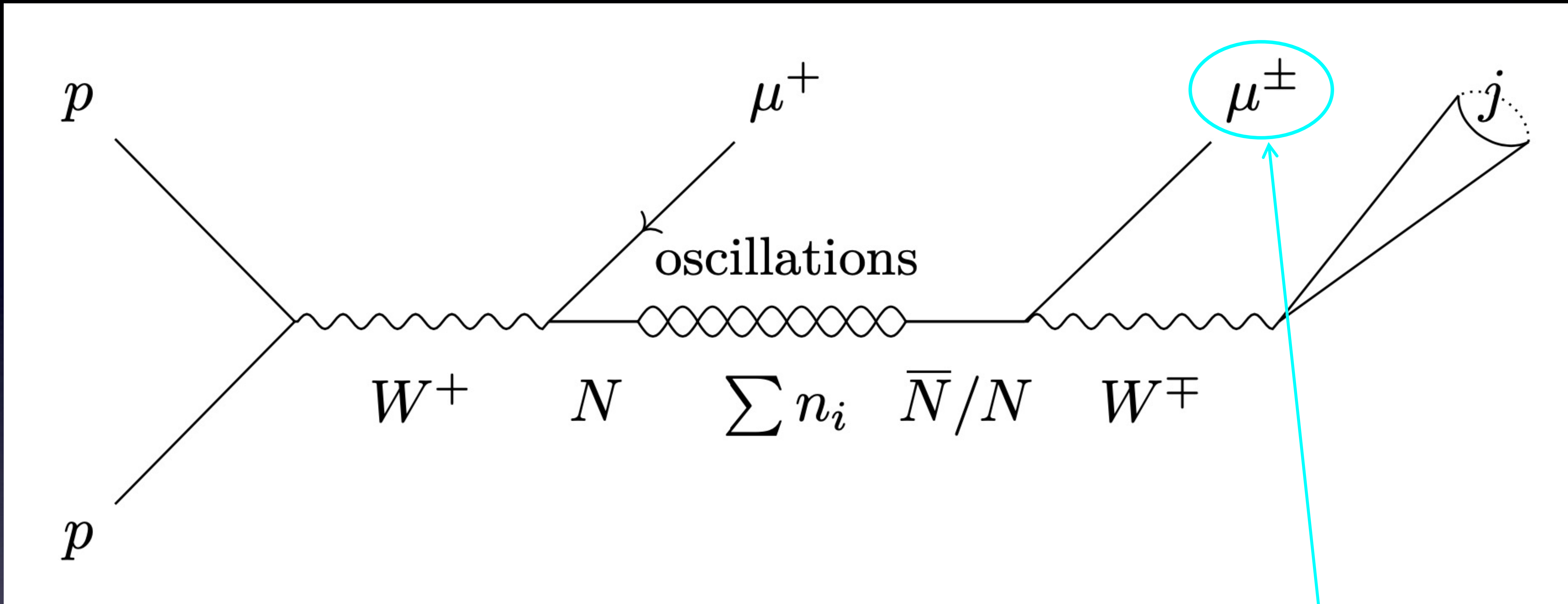
- "Heavy Antineutrinos N̄" (together wilth l_α^-)

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 N̄ and N

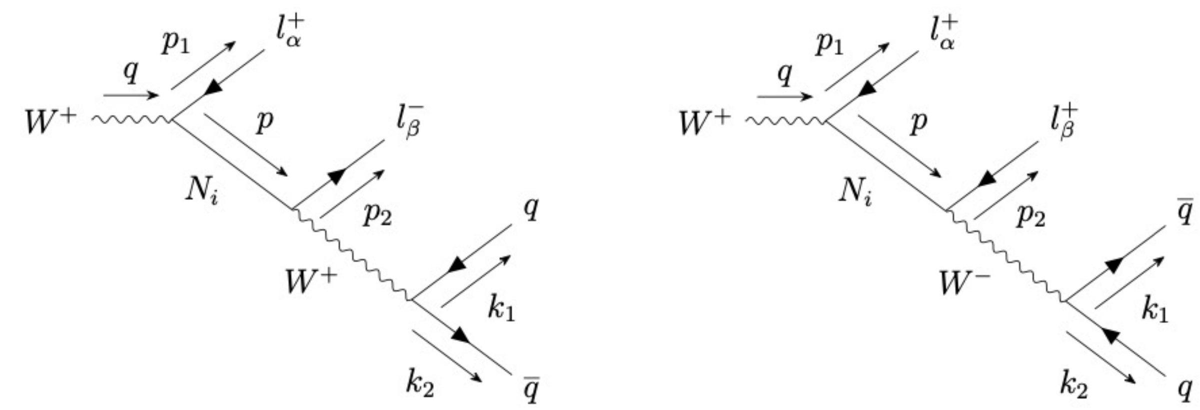
Heavy Neutrino-Antineutrino Oscillations



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

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

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

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

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

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

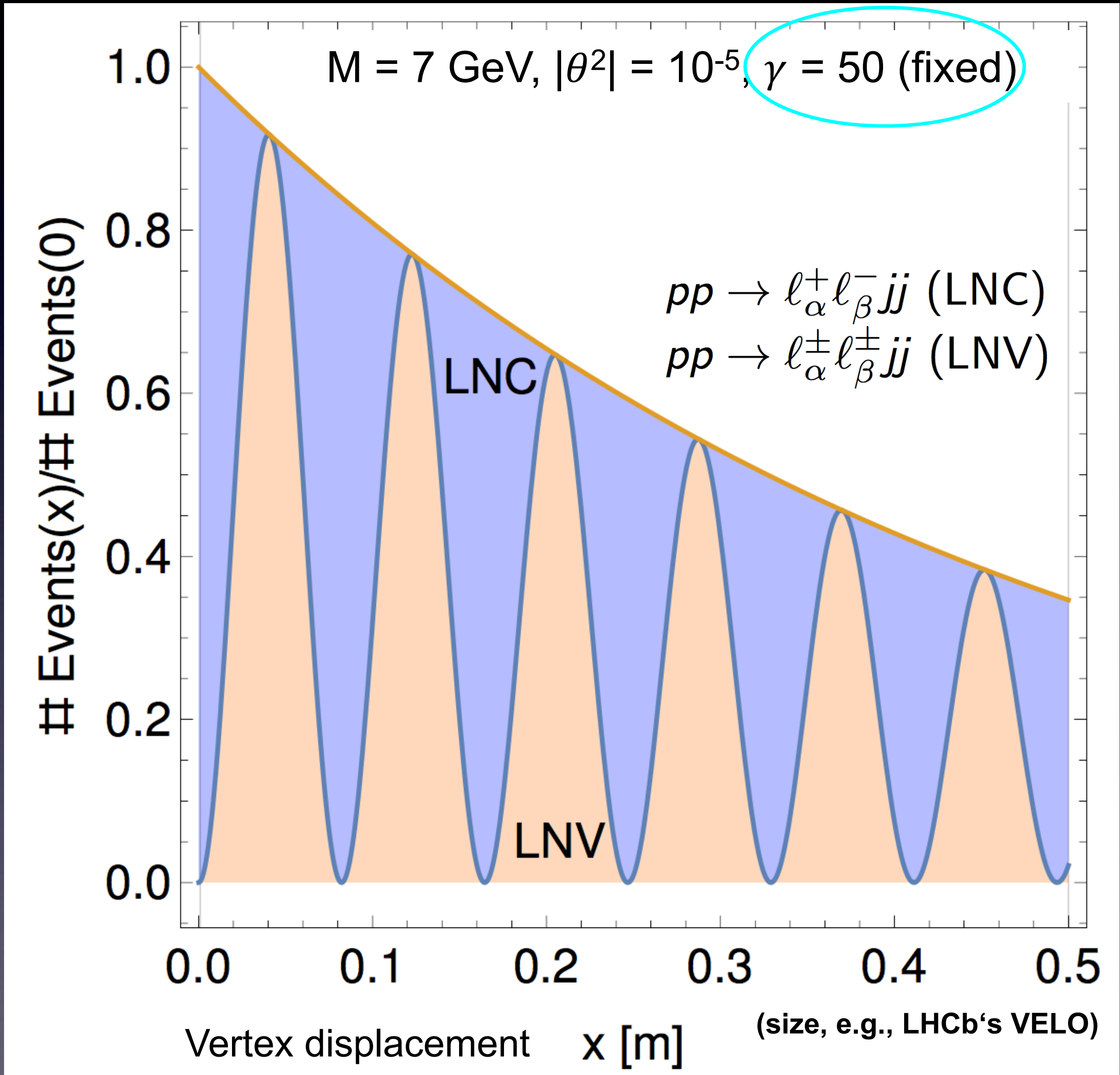
$$\Phi := \frac{1}{2}\mathrm{Arg}\left(\vec{\theta}'\cdot\vec{\theta}^*\right)\,.$$

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), cf. "extra slides" ...



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

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

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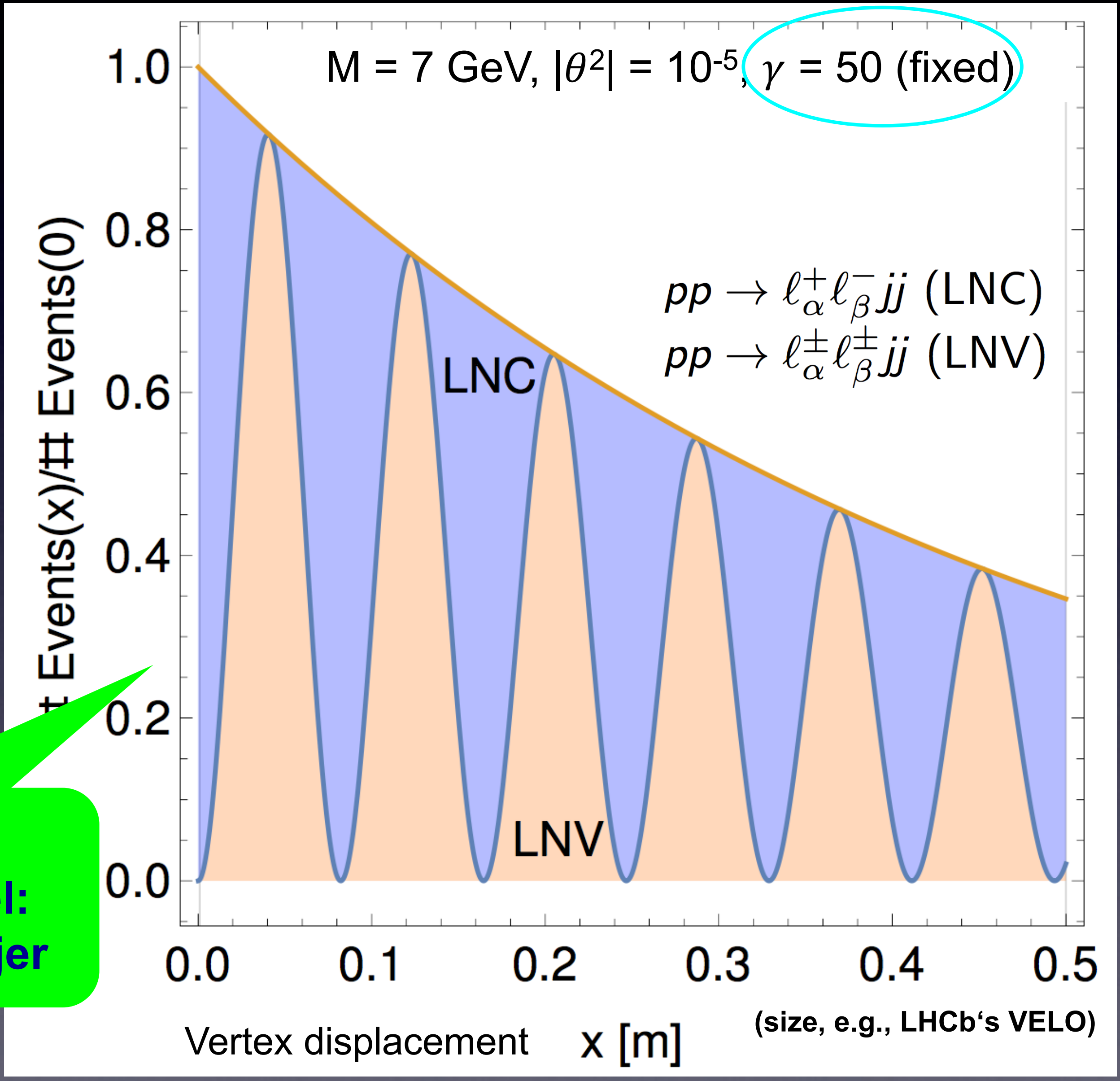

Analysis at the reconstructed level: see talk by Jan Hajer

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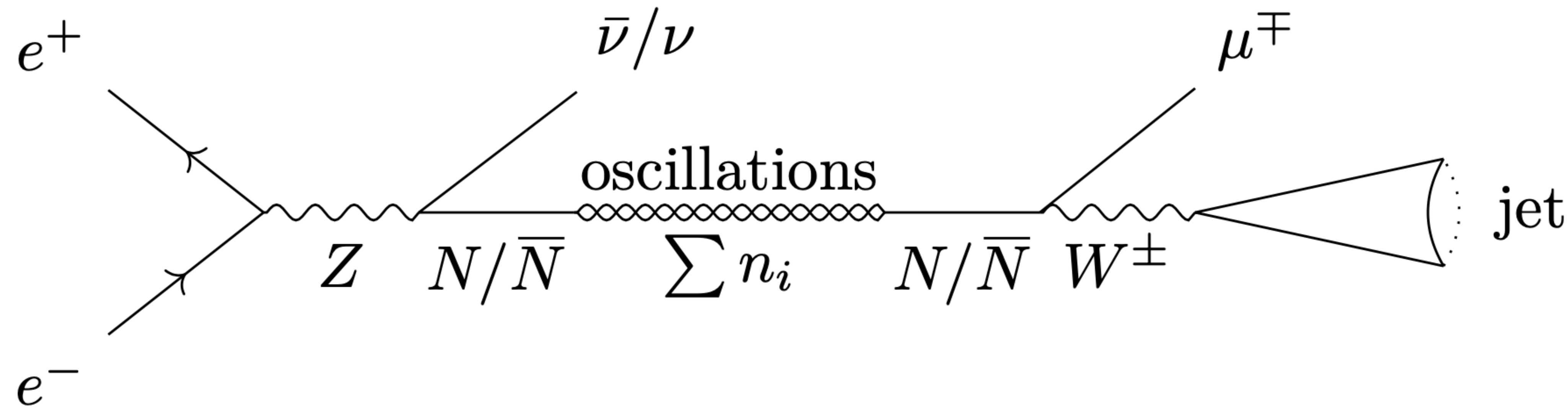
Heavy Neutrino-Antineutrino Oscillations at e⁺e⁻ Colliders (e.g. Z pole HNLs at FCC-ee)



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

Important difference: light neutrinos are not detected, so there is no direct information on whether a N or an $\overline{N}$ is produced!
-> Distinguishing LNV/LNC relies on final state angular distributions!

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

More details and observables in Jan Hajer's talk ...

Summary

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

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  - QFT calculation of oscillations (LO and NLO, decoherence effects)
  - Phenomenological (pSPSS) benchmark model and Madgraph patch for including heavy neutrino-antineutrino oscillationsin collider simulations (HNLs from W)

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  - Oscillations can be resolvable 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!

Extra Sildes

Low Scale Seesaw Scenarios with "Symmetry protection"

→ **Light neutrino masses induced from small breaking of the "L-like" symmetry ($m_\nu \sim \varepsilon$)**

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

+ symmetry breaking terms O(ε)

"Linear" seesaw:*

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

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

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:*

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

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

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

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

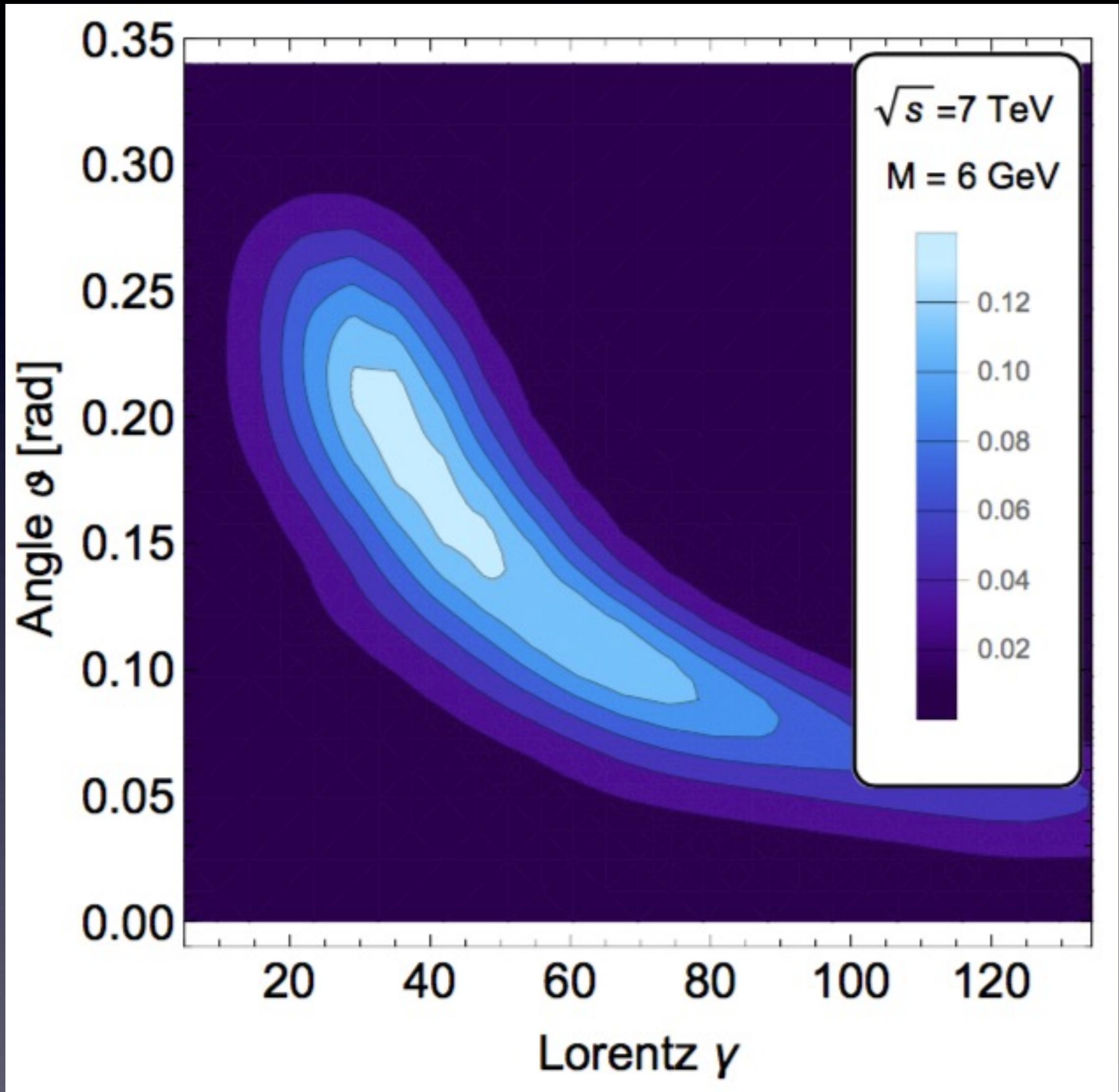
"loop seesaw"

*) 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) …

Typical distribution of the γ-factor of HNLs at LHCb

after cuts:

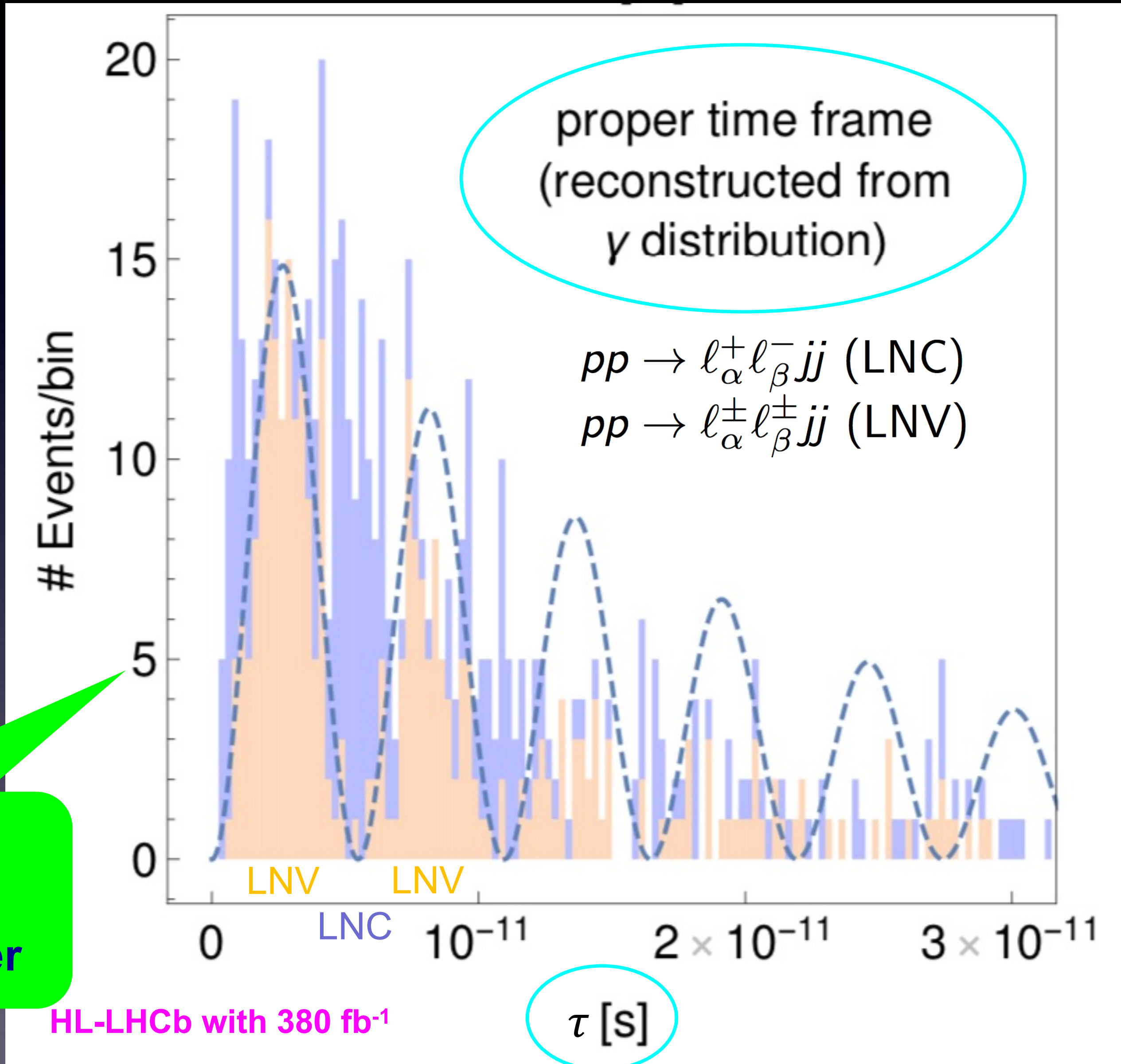


S. A., E. Cazzato, O. Fischer; arXiv:1706.05990

Estimate: Signal including uncertainties in proper time frame ...

Example:

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

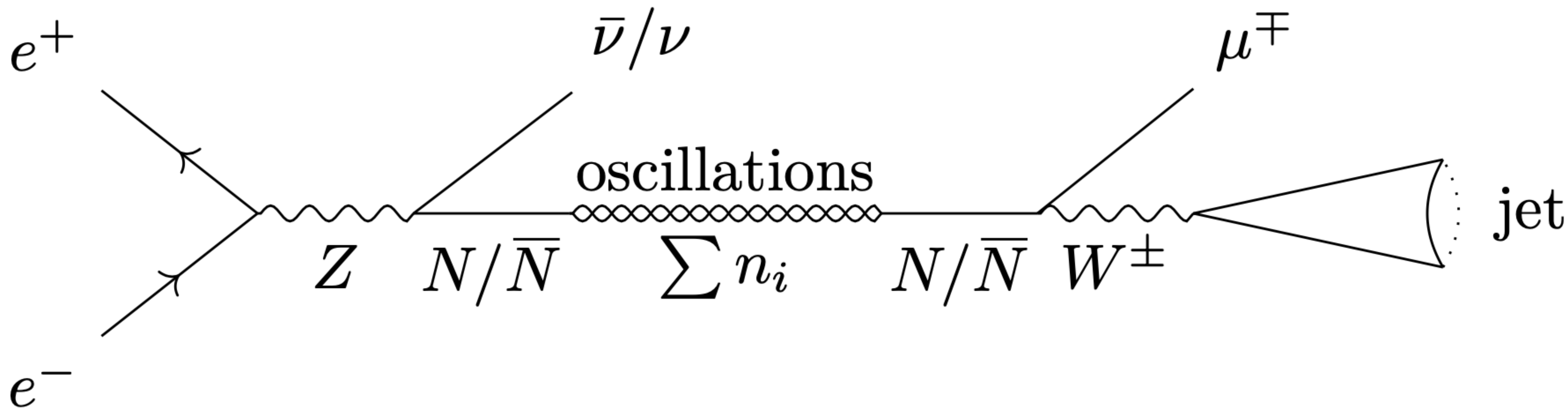


Analysis at the reconstructed level: see talk by Jan Hajer

Distribution of γ factors included → one has to reconstruct signal as function of lifetime (not displacement)

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

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)

Important difference: light neutrinos are not detected, so there is no direct information on whether a N or an $\overline{\text{N}}$ is produced!
-> Distinguishing LNV/LNC relies on final state angular distributions!

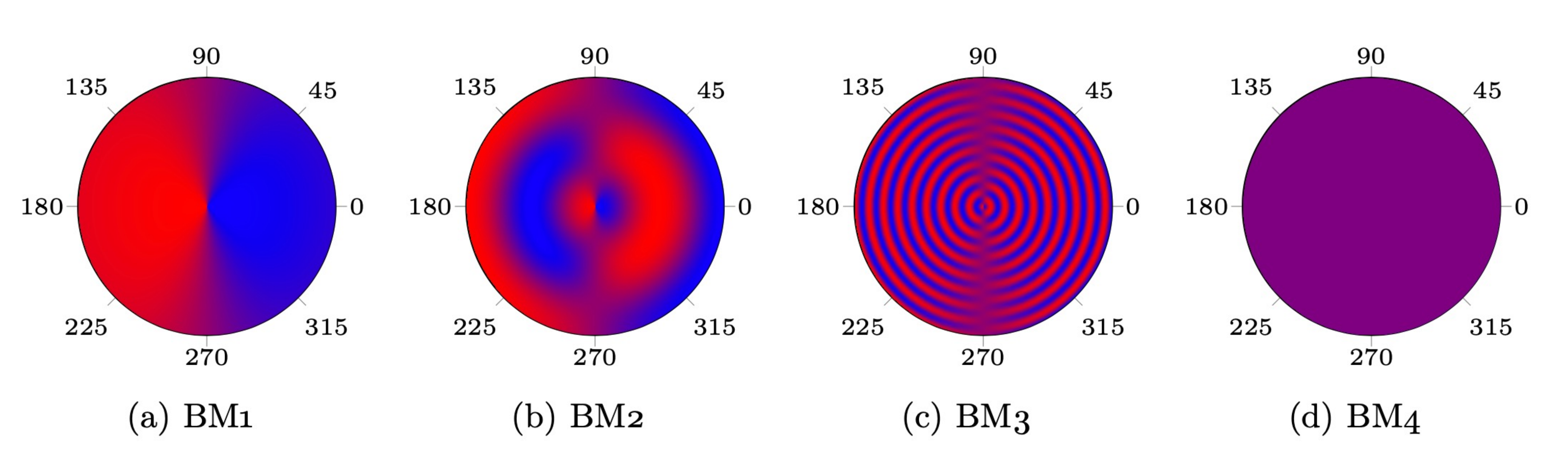
Remark: One source of angular dependence is the polarisation of Z from e+e- collisions of about 15% (due to parity violation) → Forward-backward asymmetry of produced N vs. $\overline{\text{N}}$

For pure Dirac or single Majorana HNL (no oscillations): A. Blondel, A. de Gouvêa and B. Kayser (arXiv: 2105.06576)

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



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 single Majorana HNL)

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

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

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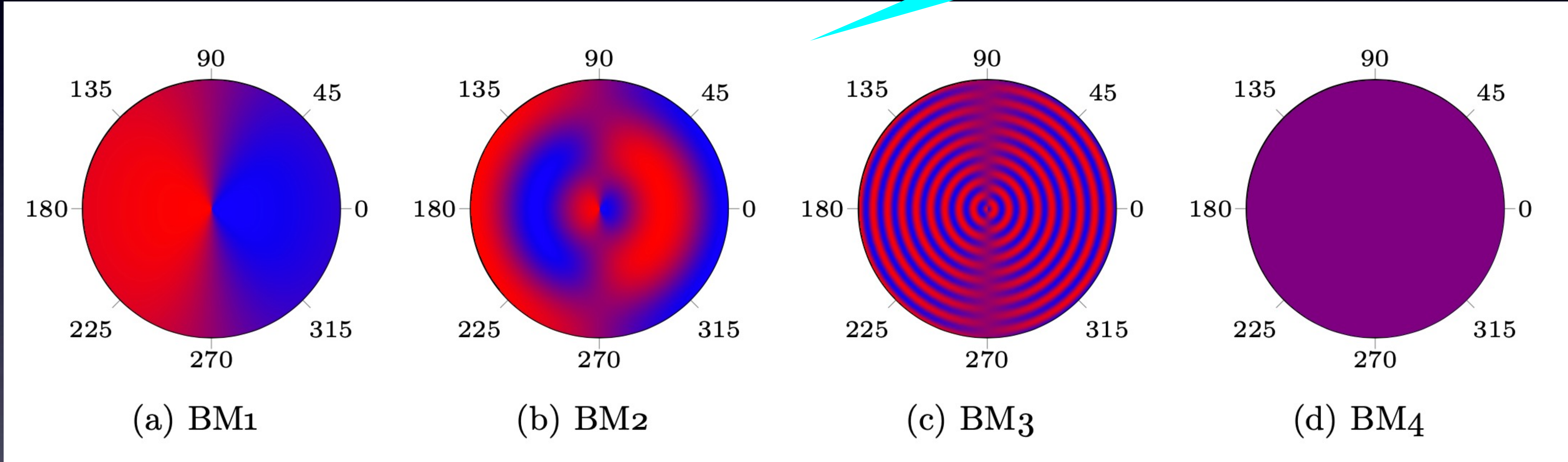
blue: >1, red, <1



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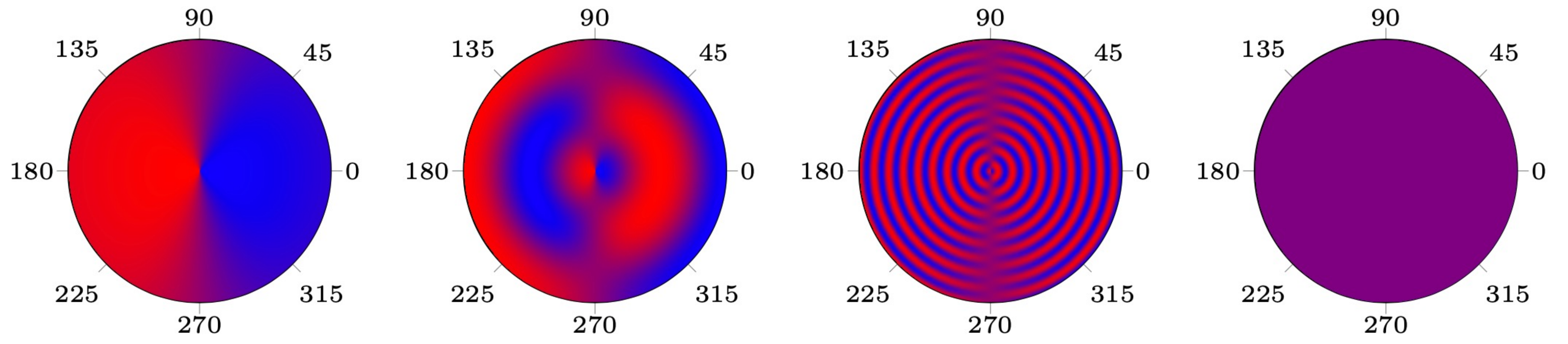

(a) BM1 (b) BM2 (c) BM3 (d) BM4

More details and observables in Jan Hajer's talk ...

pseudo Dirac with relatively small ΔM

pseudo Dirac with relatively large ΔM

pseudo-Dirac with very large ΔM (looks like single Majorana HNL)

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