Exploring the nature of heavy neutral leptons in final state distributions

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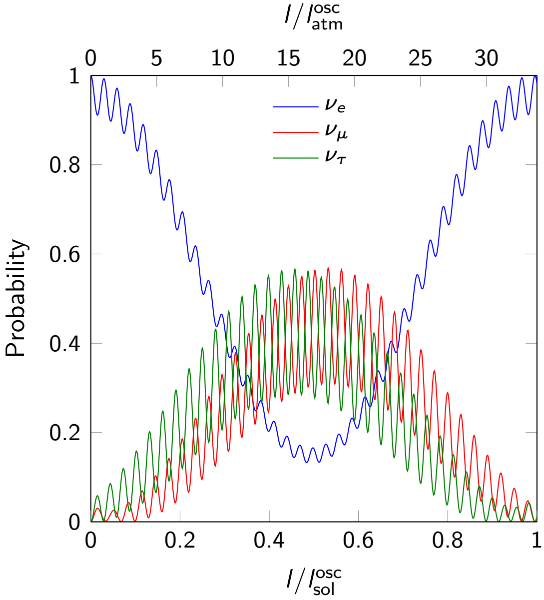
Neutrino flavour oscillations and seesaw mechanism

Observed neutrino flavour oscillations



Can be explained by

at least two massive neutrinos

Single right-handed Majorana neutrino N

$$\mathcal{L}_m = \begin{pmatrix}\vec{\nu}\\ N\end{pmatrix}^{\intercal} \begin{pmatrix}0 & \vec{m}_D\\ \vec{m}_D^{\intercal} & m_M\end{pmatrix} \begin{pmatrix}\vec{\nu}\\ N\end{pmatrix}$$

Interaction strength fixed by mixing parameter

$$\vec{\theta} = \frac{\vec{m}_D}{m_M}$$

Dirac mass

Majorana mass

Neutrino masses

$$M_\nu = \frac{\vec{m}_D \vec{m}_D^{\intercal}}{m_M} = m_M \vec{\theta}\vec{\theta}^{\intercal}$$

Tiny neutrino masses ensured for

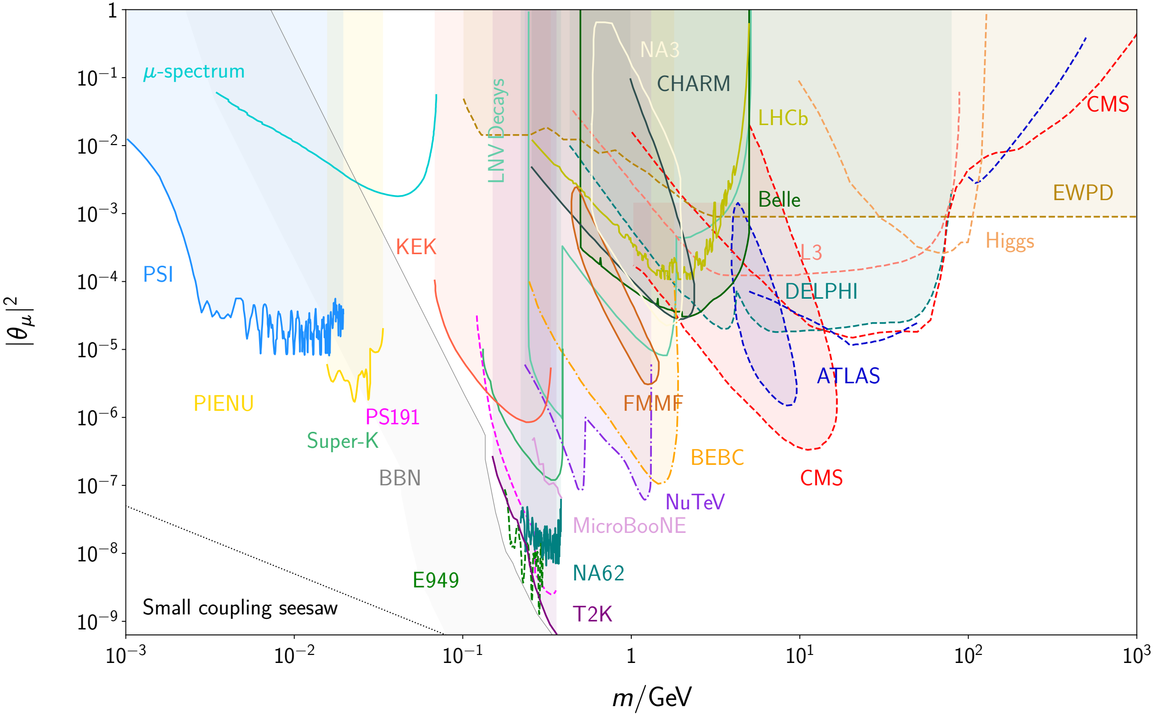
large m_M	High scale seesaw
small $\vec{m}_D$, $\vec{\theta}$	Small coupling seesaw

Sterile neutrinos/Heavy neutral leptons (HNLs)

- inaccessibly heavy or
- undetectable tiny interactions

Experimental searches for HNLs

[sterile-neutrino.org]



Inaccessible: ▪ Small coupling seesaw ▪ High scale seesaw (at the GUT scale)

Symmetry-protected low-scale seesaw

Lepton number $L = n_\ell - n_{\bar\ell}$

Standard Model (SM): Accidentally conserved

Generalisation: 'Lepton number'-like symmetry

e.g. $U(1)_L$
with charges

	$\vec\nu$	N_1	N_2
L	$+1$	-1	$+1$

Symmetry L conserved

- Three massless neutrinos
- Single Dirac heavy neutrino
  Corresponds to two degenerate Majoranas

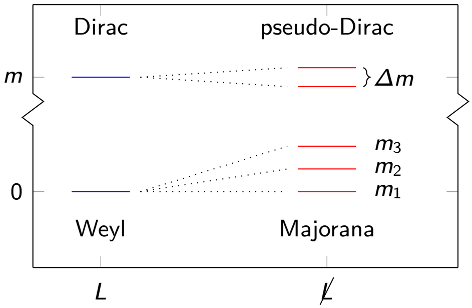
Symmetry breaking in the mass matrix

$$\mathcal{L}_m = \begin{pmatrix}\vec\nu\\ N_1\\ N_2\end{pmatrix}^t \begin{pmatrix}0 & \vec m_D & \vec\mu_D\\ \vec m_D^\intercal & \mu'_M & m_M\\ \vec\mu_D^\intercal & m_M & \mu_M\end{pmatrix} \begin{pmatrix}\vec\nu\\ N_1\\ N_2\end{pmatrix}$$

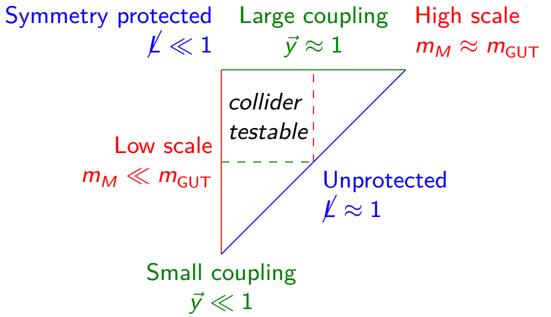
Small symmetry breaking $\not{L}$

- Light neutrino masses $m_\nu \propto \not{L}$
- Heavy neutrino mass splitting $\Delta m \propto \not{L}$

Breaking induced neutrino mass splitting



Seesaw limits



Symmetry protected
$\not{L} \ll 1$

Large coupling
$\vec y \approx 1$

High scale
$m_M \approx m_{\mathrm{GUT}}$

collider testable

Low scale
$m_M \ll m_{\mathrm{GUT}}$

Unprotected
$\not{L} \approx 1$

Small coupling
$\vec y \ll 1$

HNL: Dirac vs. Majorana and pseudo-Dirac properties

Symmetry-protected benchmark models (BMs) contain pseudo-Dirac HNLs

With care some properties can be correctly approximated by simpler BMs

Dirac BM

✓ Correct production cross section
✓ Correct decay width
⚡ No LNV $R_{ll} = 0$
⚡ Massless SM neutrinos

Majorana BM

✓ Correct production cross section
⚡ Wrong decay width
✓ Lepton number violation (LNV)
⚡ Generically too much LNV $R_{ll} = 1$
⚡ Generically too heavy SM neutrinos

Displaced vertex searches for Dirac HNLs

Generically correct

Prompt searches for LNV with Majorana HNLs

- Generically the bounds are too strong
- In many cases no bounds can be extracted
- Can be correct for some parameter points

→ Model depended reinterpretation necessary

Detectable pseudo-Dirac HNL

- Finite LNV $0 < R_{ll} < 1$
- Tiny mass splitting $\mathcal{O}(\text{meV})$
- Heavy neutrino-antineutrino oscillations ($N\overline{N}$Os)
- Damped oscillations due to decoherence

Viable alternatives

- Enhanced production e.g. W'-models
- Fine tuning

Heavy neutrino-antineutrino oscillations ($N\overline{N}$Os)

[2210.10738]

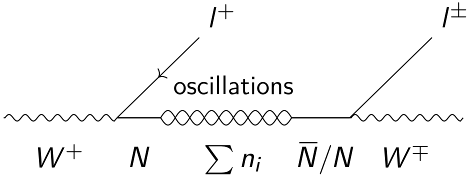
Oscillations between events that have

- Lepton number conservation (LNC) $l^\pm l^\mp$
- Lepton number violation (LNV) $l^\pm l^\pm$

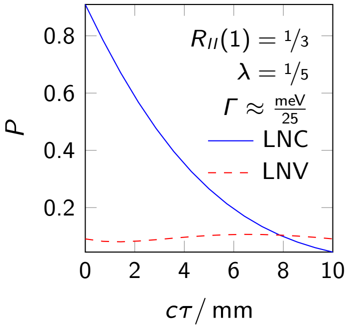
Oscillation frequency governed by Δm

$$P_{\text{osc}}^{\text{LNC}/\text{LNV}}(\tau) = \frac{1 \pm \cos(\Delta m \tau)}{2}$$

Oscillating mass eigenstates n_i

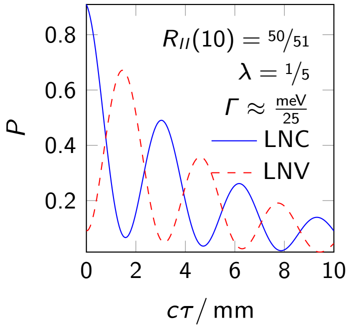


Almost Dirac limit



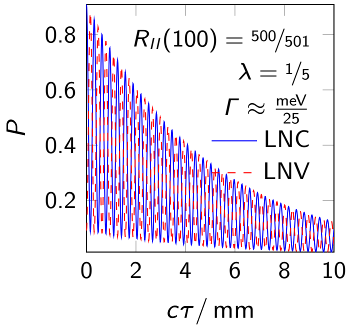
- Mostly LNC

Archetypical pseudo-Dirac



- Potentially resolvable

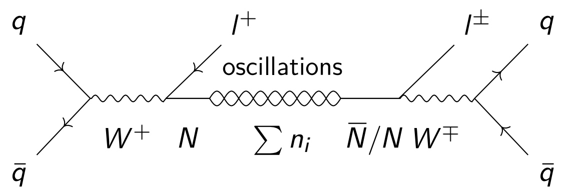
Double-Majorana limit

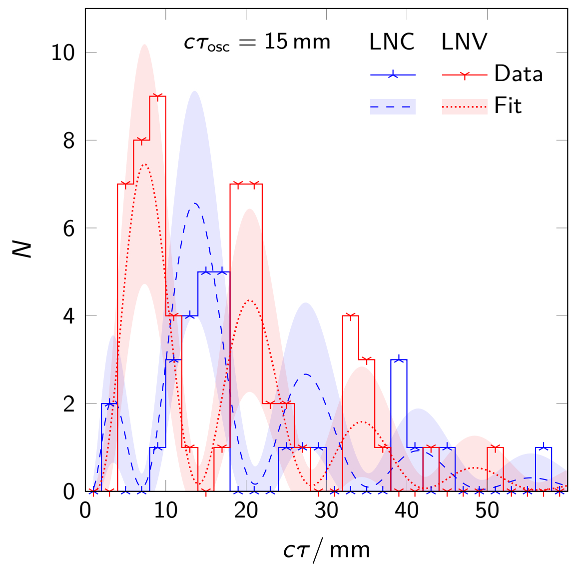


- Unresolvable
- LNV as frequent as LNC

Measuring LNV at the HL-LHC

[pSPSS, 2212.00562]

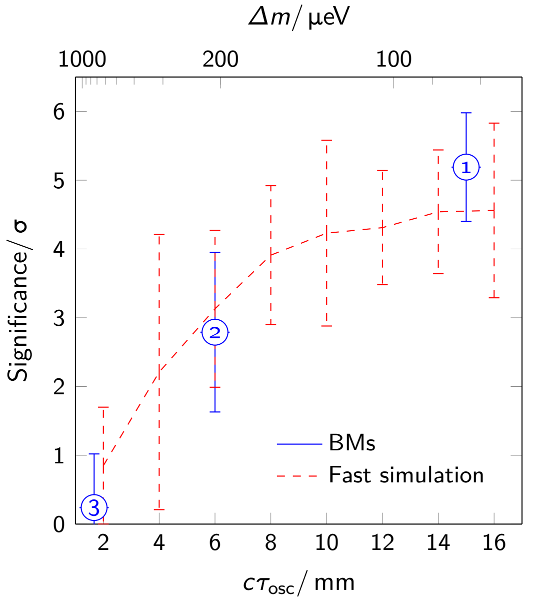




LNV can be measured

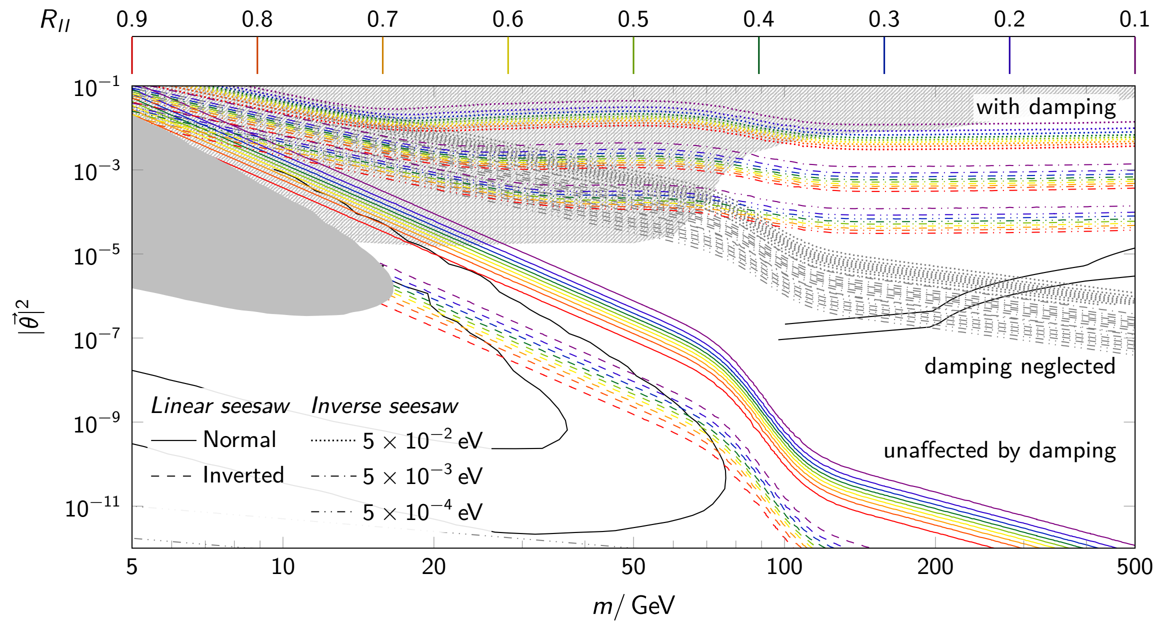
by counting the charges of the two leptons

Significance for a BM



LNV and decoherence at the LHC for five BMs

[2307.06208]



Linear seesaw

Not affected by decoherence

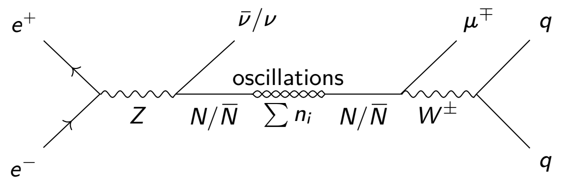
Inverse seesaw

LNV significantly increased

During the Z-pole run of the FCC-ee

[2308.07297]

Single charged lepton



Measurement

- LNV cannot be measured using two charges
- One can still measure angular distributions

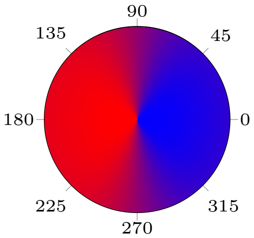
Angular dependent probability

$$P_{l^\mp}(\cos\theta,\tau) := \frac{1}{\sigma}\frac{d\sigma(\cos\theta)}{d\cos\theta}P_{\text{osc}}^{\text{LNC/LNV}}(\tau)$$

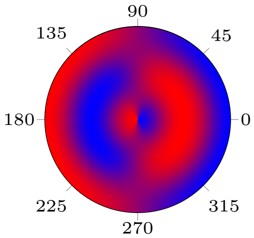
Probability of measuring charged leptons

- linked to forward backward asymmetry (FBA) of neutrino production (see ‘almost Dirac limit’)
- l^- from non-oscillating N or from oscillating $\bar{N}$ (similar for l^+)

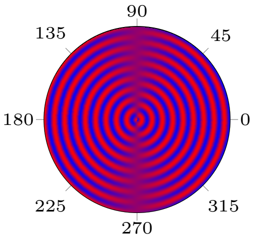
Almost Dirac limit



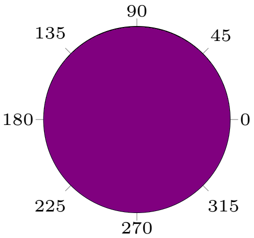
Slow oscillation



Fast oscillation

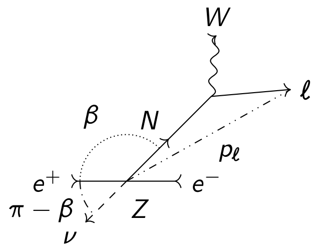


Double-Majorana limit

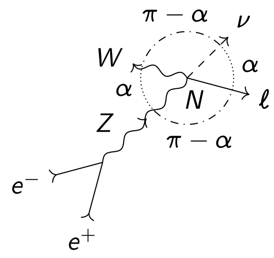


LNV in distributions at future lepton colliders [2408.01389]

FBA



Opening angle asymmetry (OAA)



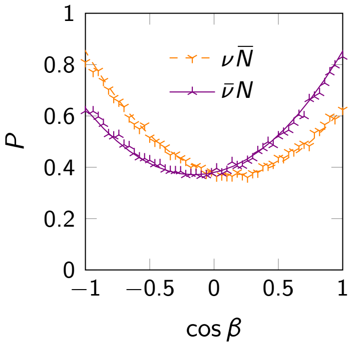
Sensitivity

FBA $N/\overline{N}$
OAA LNC/LNV

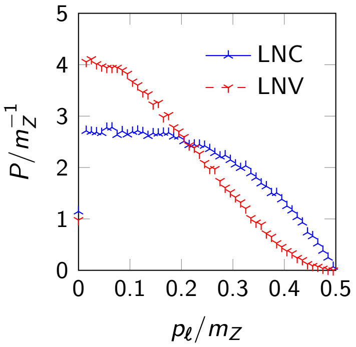
Lepton momentum modulus

same analysis power as OAA

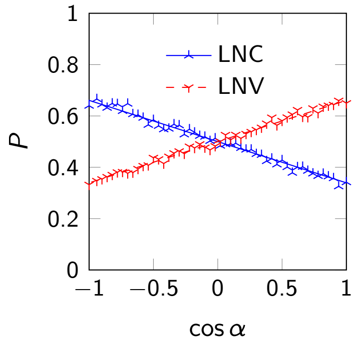
FBA



Lepton momentum modulus

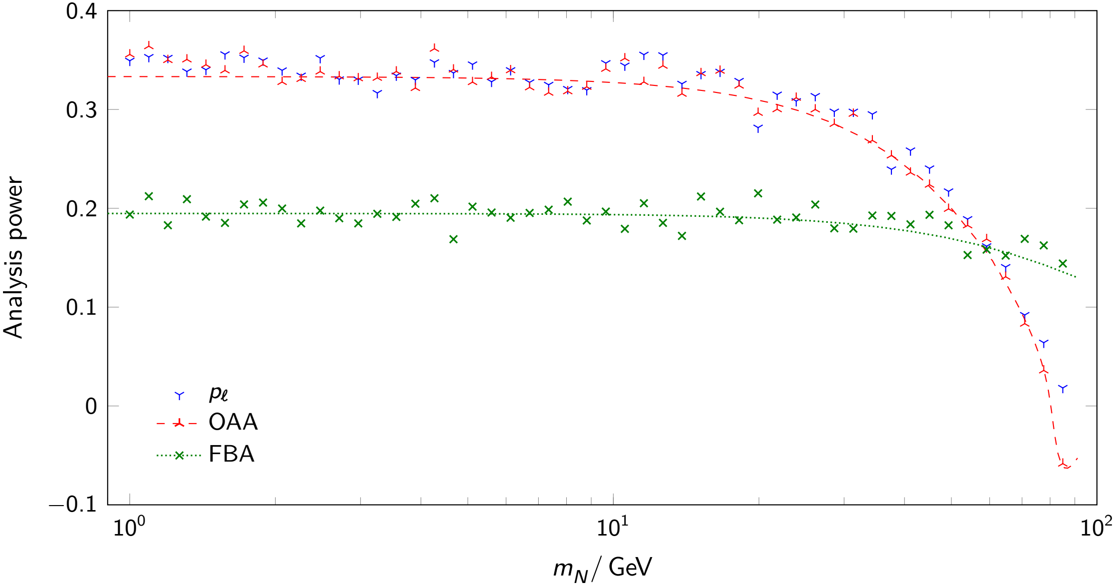


OAA



Analysis powers

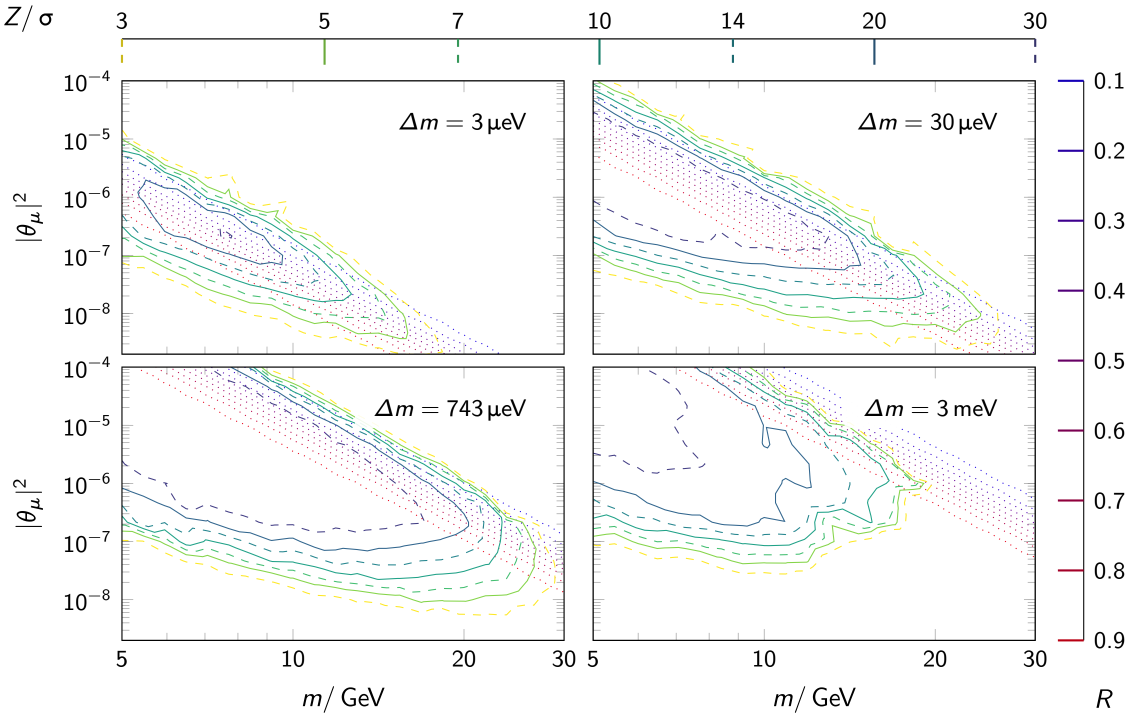
[2408.01389]



- Opening angle asymmetry (OAA) and lepton modulus have comparable analysis power
- Forward backward asymmetry (FBA) has smaller analysis power

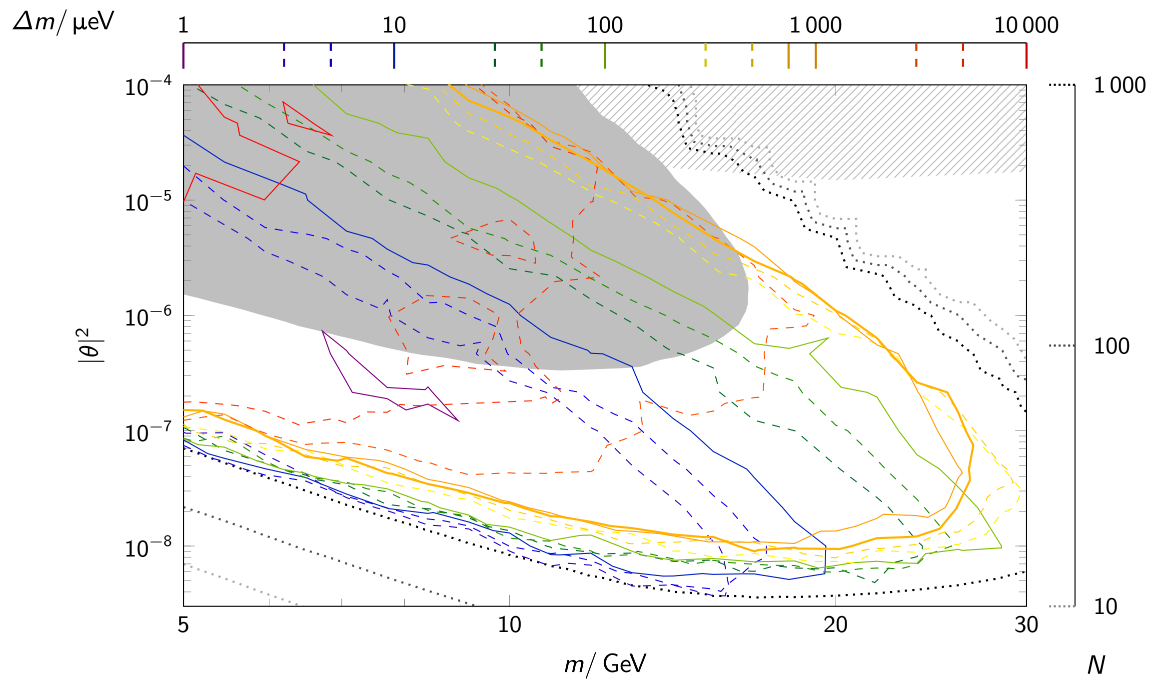
Study: Full scan using the lepton momentum modulus

Significance for $N\bar{N}$Os with different mass splittings at the FCC-ee [2408.01389]



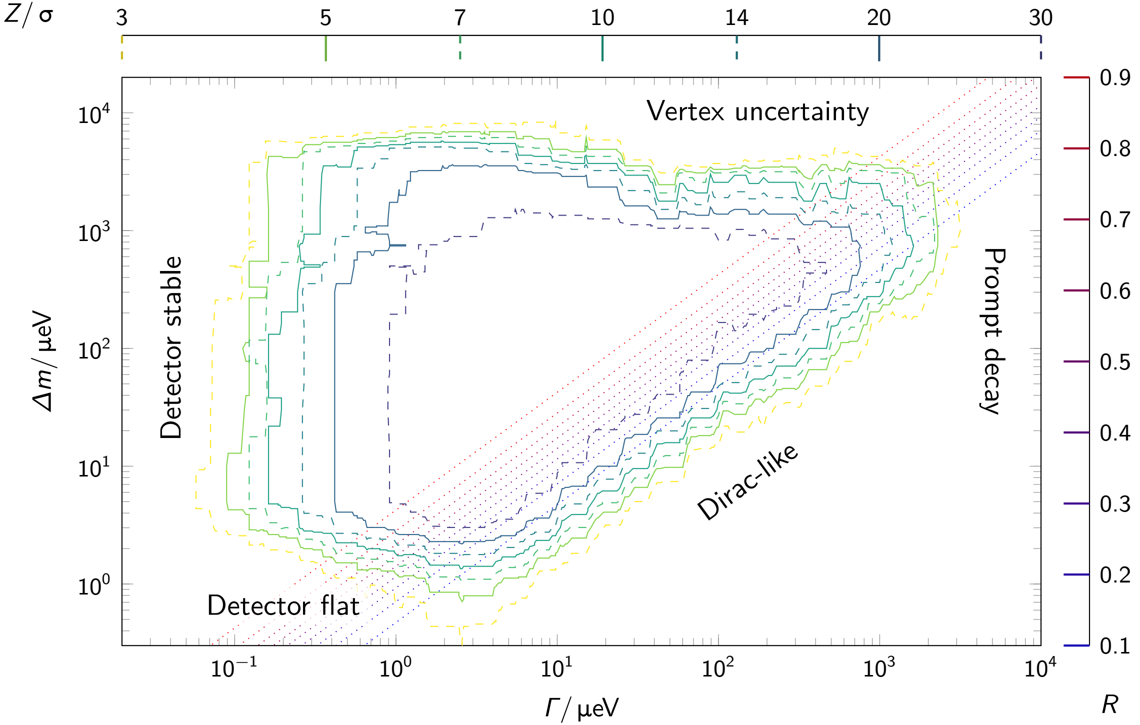
Sensitivity for $N\bar{N}$Os as function of mass, coupling and mass splitting

5 σ discovery reach of the FCC-*ee* for $N\bar{N}$Os



5 σ discovery requires at least 1 000 events

Maximal significance of the FCC-*ee*



Discover reach is limited by detector geometry and interplay between oscillations and decay

Conclusions

- Collider testable Type I seesaw models predict pseudo-Dirac HNLs
- Pseudo-Dirac HNLs can oscillate between LNC and LNV events
- Theses $N\overline{N}$Os are detectable at future lepton colliders

See also talks in the same session

Nicolò for the experimentalist view

Sofia for a focus on the flavour structure

Krzysztof for an application of the OAA at higher energies

References

[2210.10738] DOI: 10.1007/JHEP03(2023)110. In: *JHEP* 03 (2023), p. 110

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[2308.07297] DOI: 10.1007/JHEP10(2023)129. In: *JHEP* 10 (2023), p. 129

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[2408.01389] (Aug. 2024)

S. Antusch, J. Hajer, and B. M. S. Oliveira. 'Discovering heavy neutrino-antineutrino oscillations at the Z-pole'.

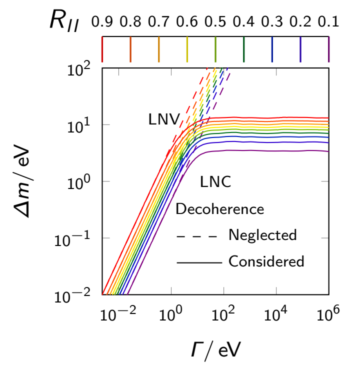
Problems measuring R_{ll}

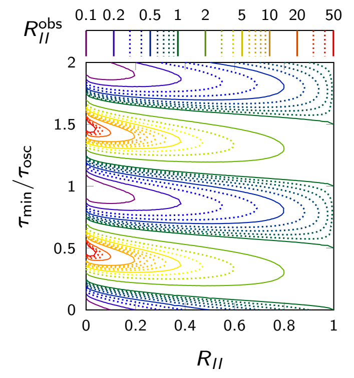
Integration limits correspond to [2210.10738]

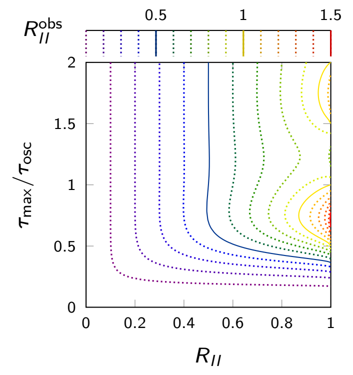
- Minimal distance cut
- Maximal measurable vertex distance

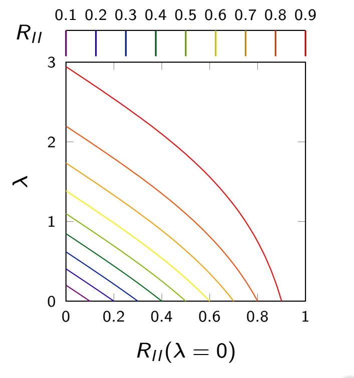
Decoherence [2307.06208]

- Quantum mechanical oscillations can suffer from decoherence
- Calculation in external wave packet formalism
- Can increase measurable LNV drastically
- Captured by single parameter λ









Oscillating particles in quantum field theory (QFT)

[2307.06208]

Inadequate frameworks for oscillating relativistic particles

- Quantum mechanics
- Plane-wave QFT

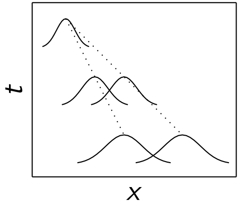
QFT with external wave packets

- Gaussian wave packets with width σ
- External widths are experiment depended parameters
- Internal widths are calculated

Transition amplitude in QFT with external wave packets Φ

$$z\mathcal{A}(x) = \left\langle \Phi(x'') \middle| \mathcal{T} \exp\left[-i \int \mathcal{H}(x)\, d^4x\right] - \mathbb{1} \middle| \Phi(x') \right\rangle$$

Decoherence



Result can be expressed with

effective damping parameter λ

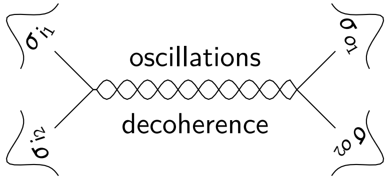
Damped oscillations

$$P_{\text{osc}}^{\text{LNC/LNV}}(\tau) = \frac{1 \pm \cos(\Delta m \tau) e^{-\lambda}}{2}$$

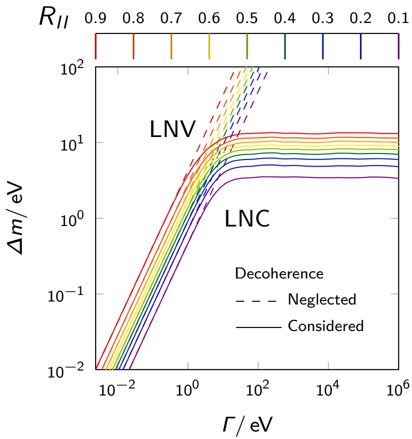
LNV can be

drastically enhanced

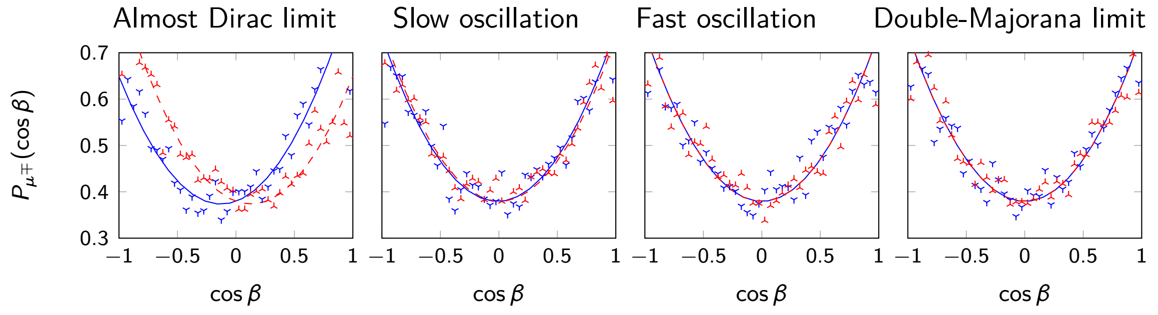
Width of external wave packets σ



Impact on $N\overline{N}$Os



Time and angular integrated observable

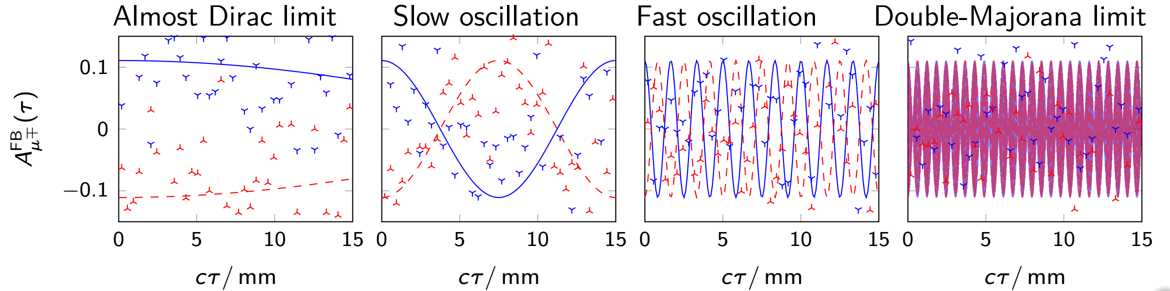


Time integrated probability

$$P_{l^\mp}(\cos\beta) := \int_0^\infty P_{l^\mp}(\tau,\cos\beta)\,d\tau$$

Angular integrated probability

$$P_{l^\mp}^{[\beta_{\min},\beta_{\max}]}(\tau) := \int_{\cos\beta_{\min}}^{\cos\beta_{\max}} P_{l^\mp}(\tau,\cos\beta)\,d\cos\beta$$



Significance dependents on the vertex reconstruction error

[2408.01389]