Lepton number violation and heavy neutrino-antineutrino oscillations

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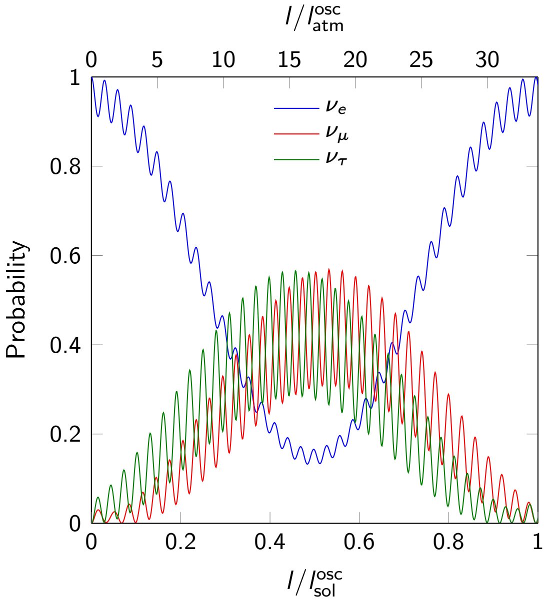
Neutrino flavour oscillations and seesaw mechanism

Observed neutrino flavour oscillations



Can be explained by

at least two massive neutrinos

Single right-handed Majorana neutrino N

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

Interaction strength fixed by mixing parameter

$$\vec{\theta} = \frac{\vec{m}_D}{m_M} \qquad \frac{\text{Dirac mass}}{\text{Majorana mass}}$$

Neutrino masses

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

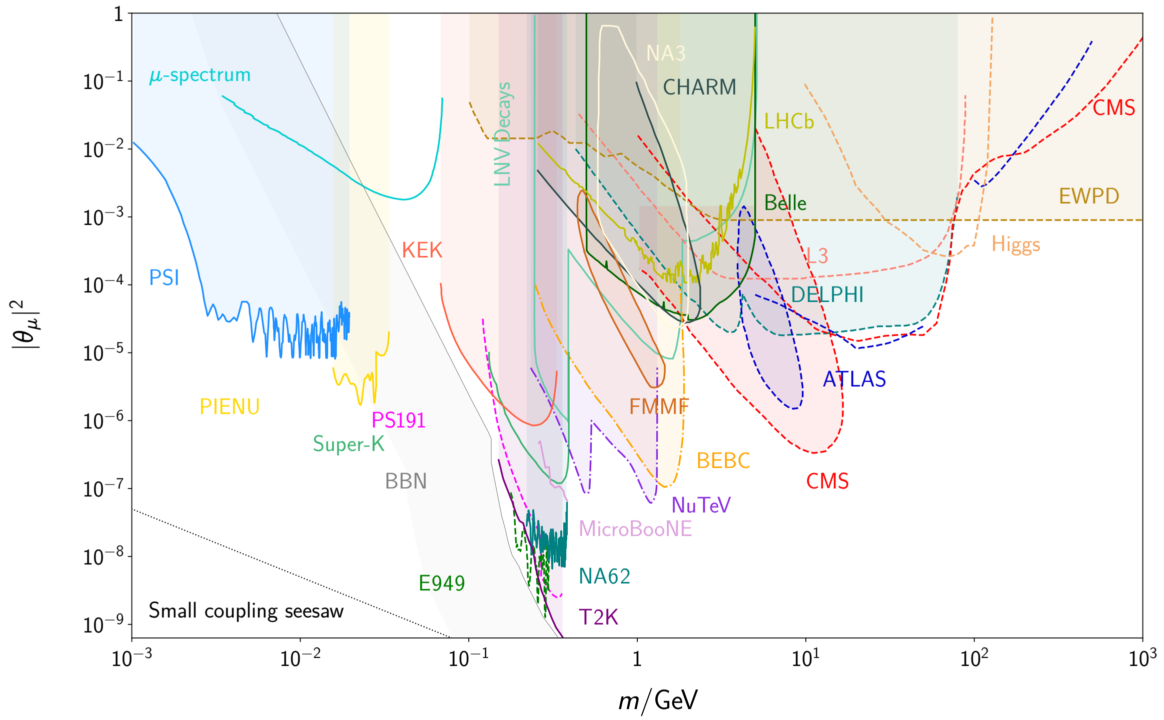
Tiny neutrino masses ensured for

- 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



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

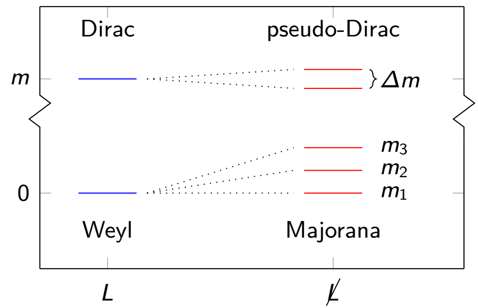
Symmetry breaking in the mass matrix

$$\mathcal{L}_m = \begin{pmatrix} \vec{\nu} \\ N_1 \\ N_2 \end{pmatrix}^t \begin{pmatrix} 0 & \vec{m}_D & \vec{\mu}_D \\ \vec{m}_D^\mathsf{T} & \mu'_M & m_M \\ \vec{\mu}_D^\mathsf{T} & m_M & \mu_M \end{pmatrix} \begin{pmatrix} \vec{\nu} \\ N_1 \\ N_2 \end{pmatrix}$$

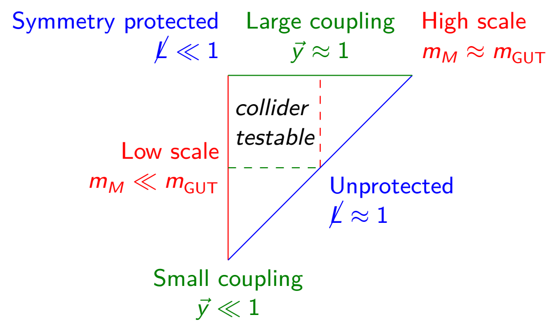
Small symmetry breaking $\not{L}$

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

Breaking induced neutrino mass splitting



Seesaw limits



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
- ϟ No LNV $R_{ll} = 0$
- ϟ Massless SM neutrinos

Majorana BM

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

$\rightarrow$ 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]

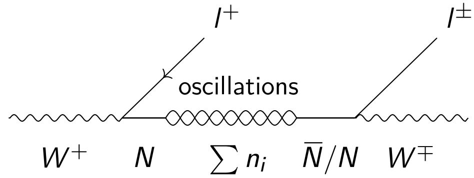
Oscillations between events that have

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

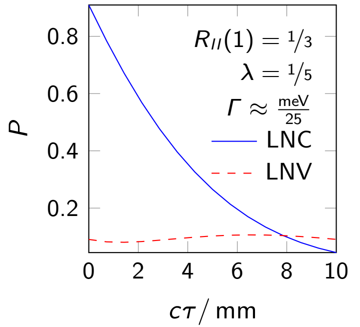
Oscillation frequency governed by Δm

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

Oscillating mass eigenstates n_i

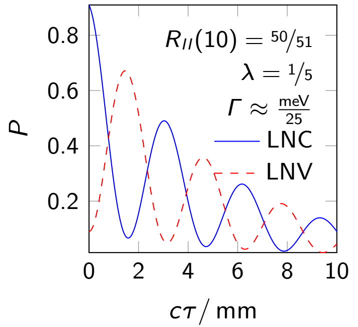


Almost Dirac limit



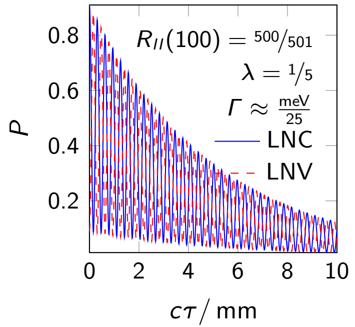
- Mostly LNC

Archetypical pseudo-Dirac



- Potentially resolvable

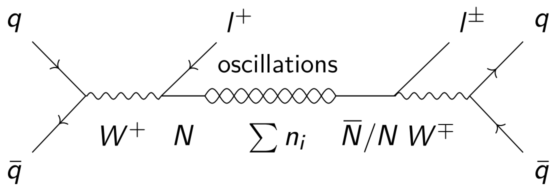
Double-Majorana limit



- Unresolvable
- LNV as frequent as LNC

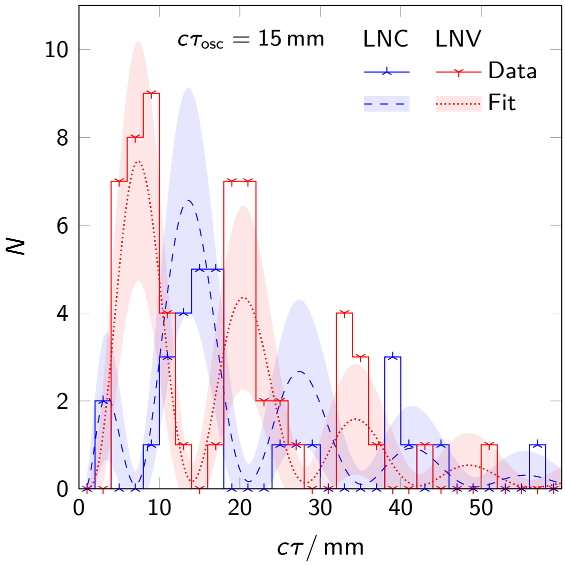
Measuring LNV at the HL-LHC

[pSPSS, 2212.00562]

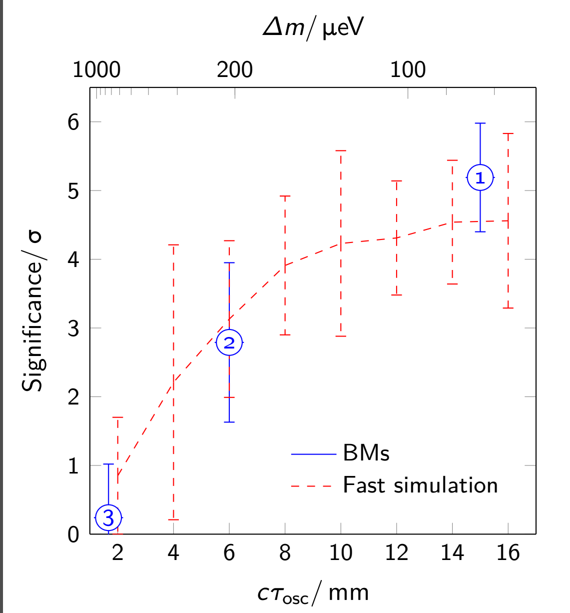


LNV can be measured

by counting the charges of the two leptons

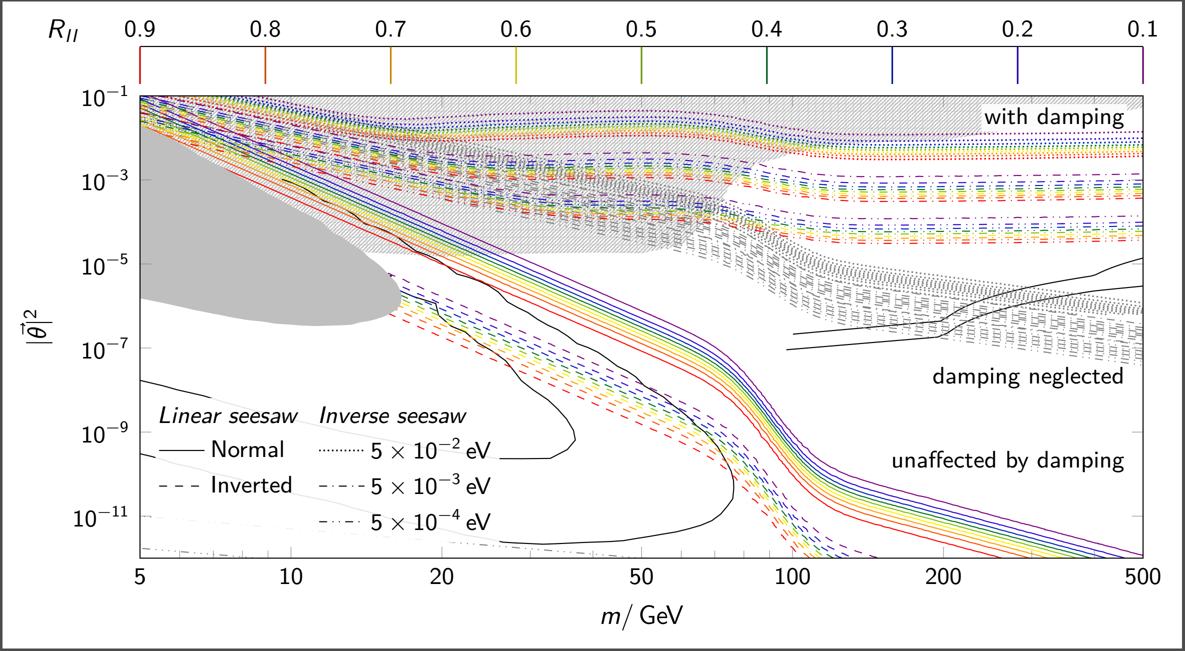


Significance for a BM



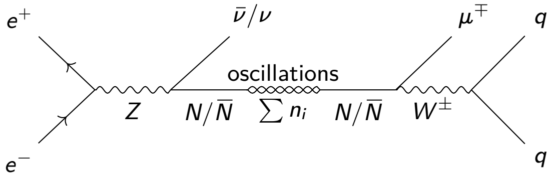
LNV and decoherence at the LHC for five BMs

[2307.06208]



Linear seesaw	Inverse seesaw
Not affected by decoherence	LNV significantly increased

Single charged lepton



Measurement

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

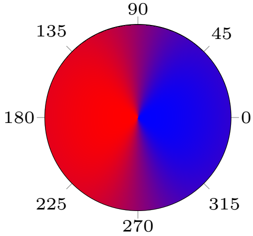
Angular dependent probability

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

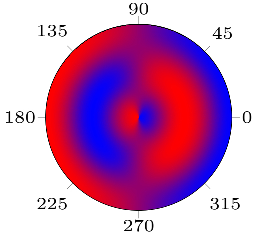
Probability of measuring charged leptons

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

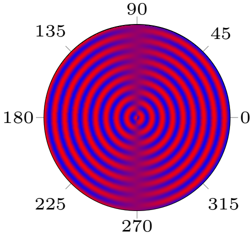
Almost Dirac limit



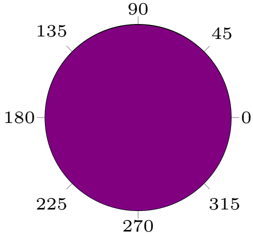
Slow oscillation



Fast oscillation



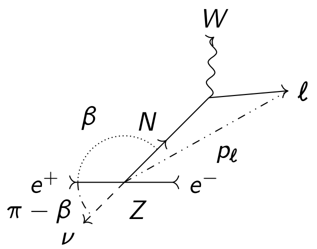
Double-Majorana limit



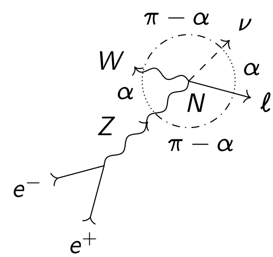
LNV in distributions at future lepton colliders

[2408.01389]

FBA



Opening angle asymmetry (OAA)



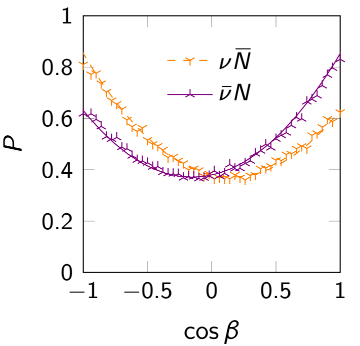
Sensitivity

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

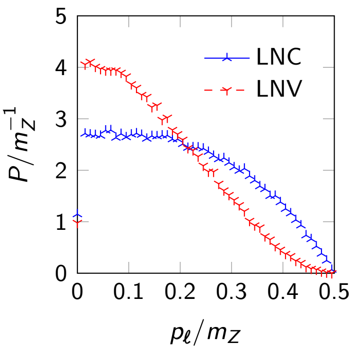
Lepton momentum modulus

same analysis power as OAA

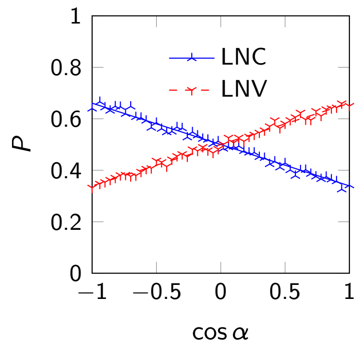
FBA



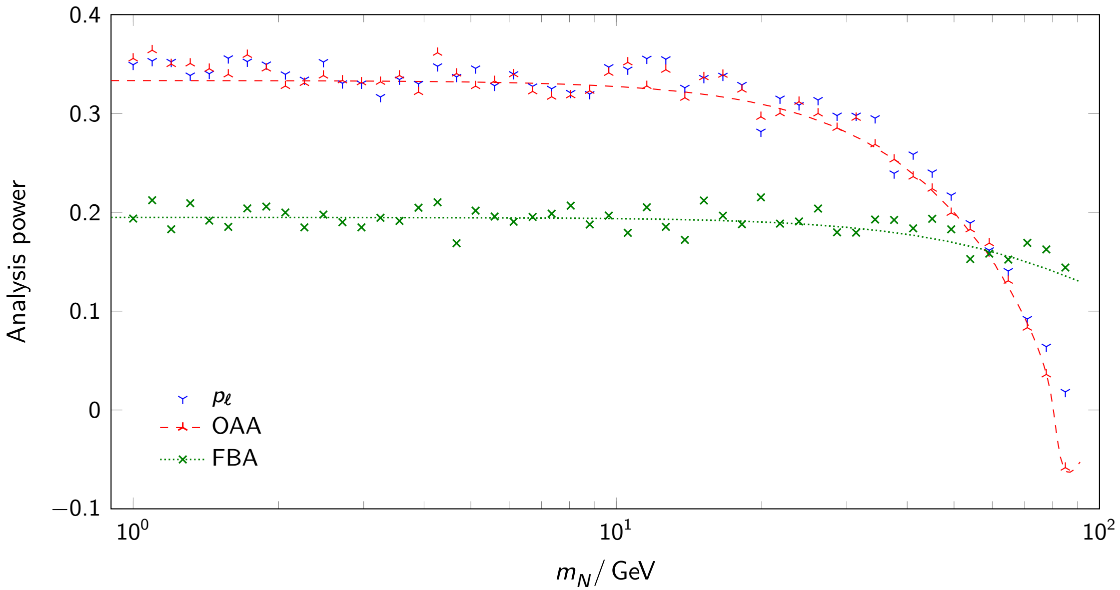
Lepton momentum modulus



OAA



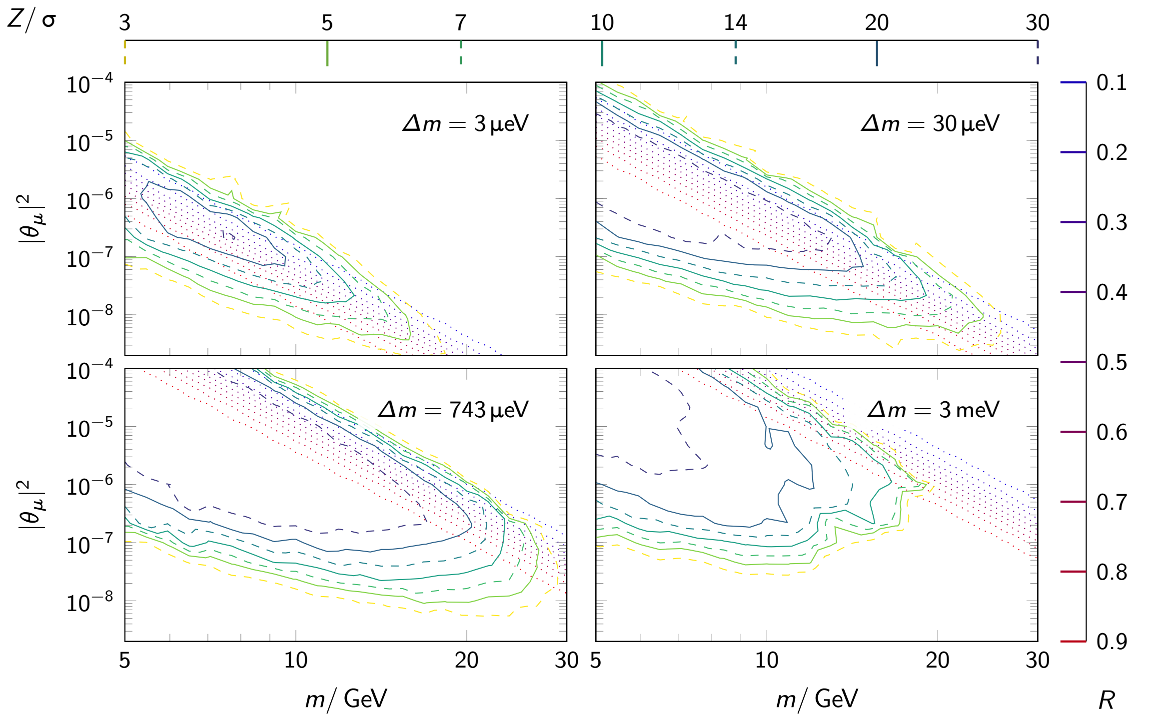
Analysis powers



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

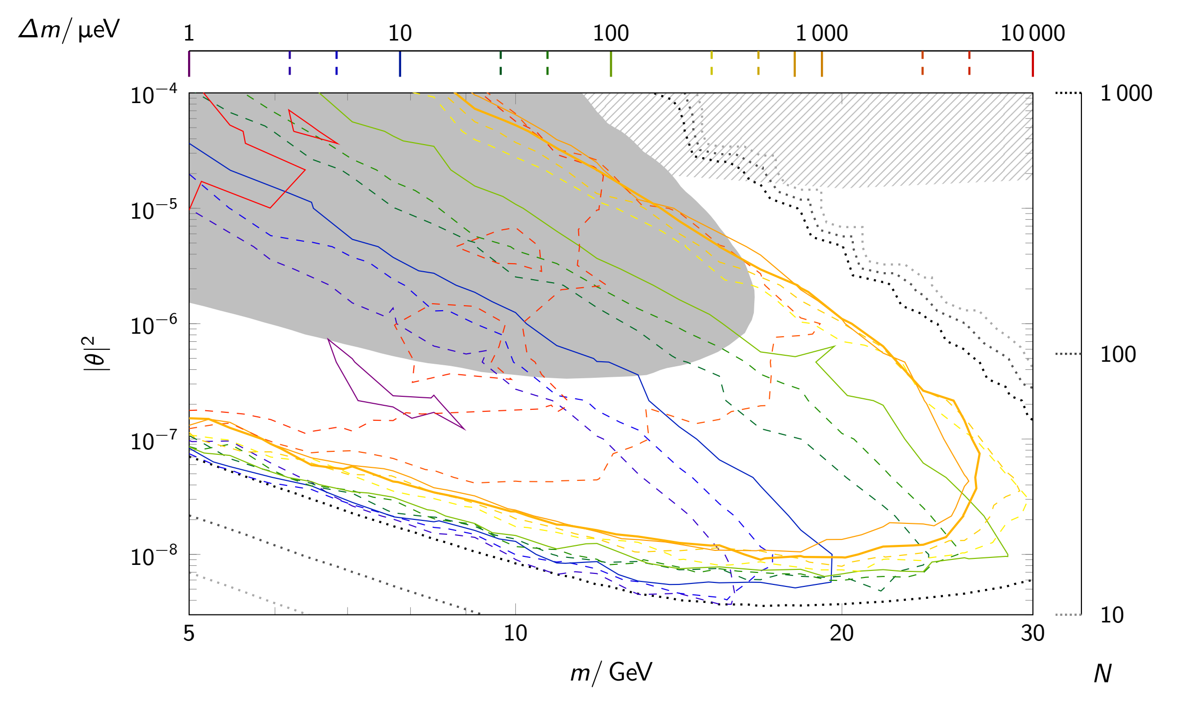
Study: Full scan using the lepton momentum modulus

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



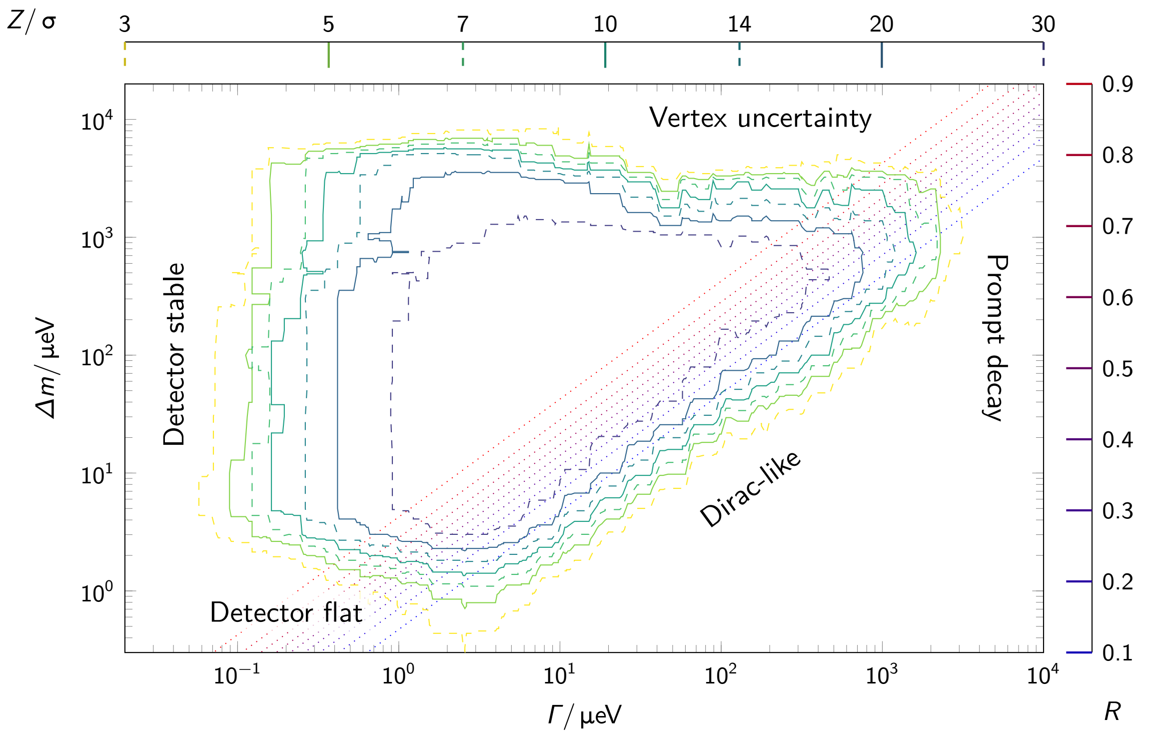
Sensitivity for $N\bar{N}$Os as function of mass, coupling and mass splitting

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



$5\,\sigma$ 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

References

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Inadequate frameworks for oscillating relativistic particles

- Quantum mechanics
- Plane-wave QFT

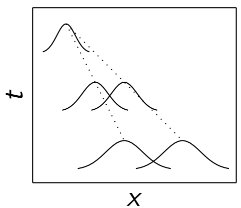
QFT with external wave packets

- 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

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

Decoherence



Result can be expressed with

effective damping parameter λ

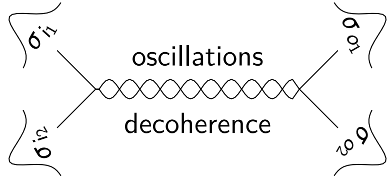
Damped oscillations

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

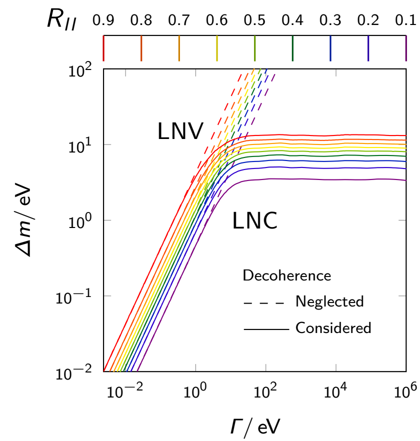
LNV can be

drastically enhanced

Width of external wave packets σ



Impact on $N\overline{N}$Os

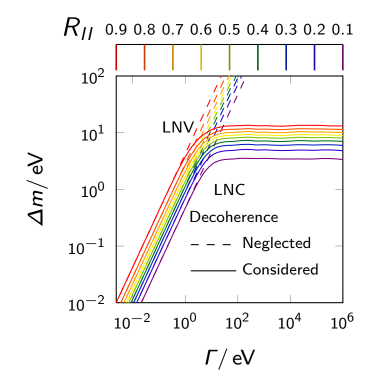


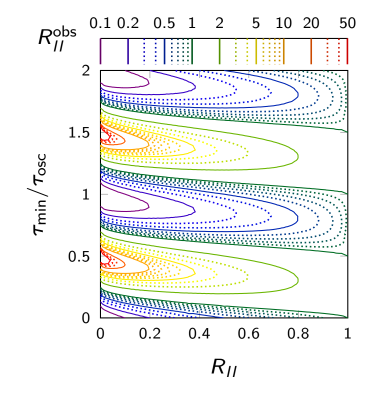
Integration limits correspond to [2210.10738]

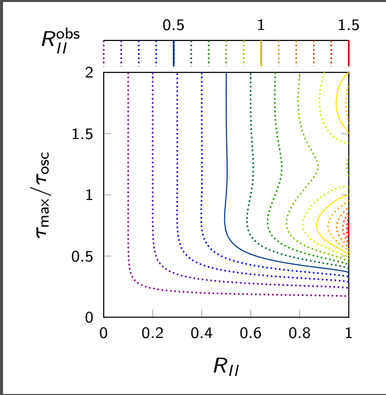
- Minimal distance cut
- Maximal measurable vertex distance

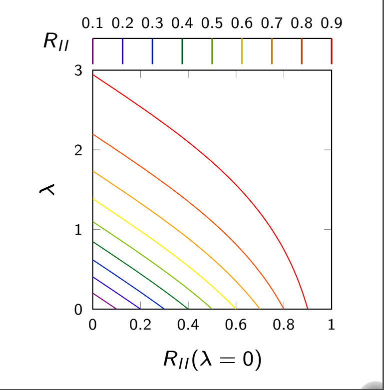
Decoherence [2307.06208]

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

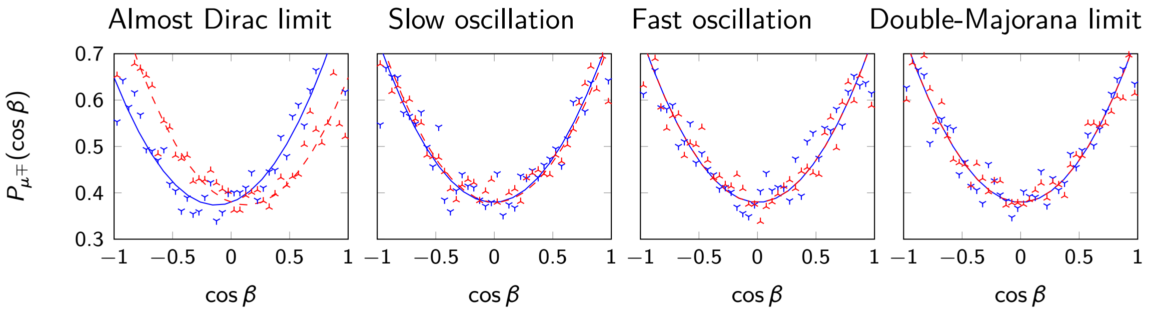








Time and angular integrated observable

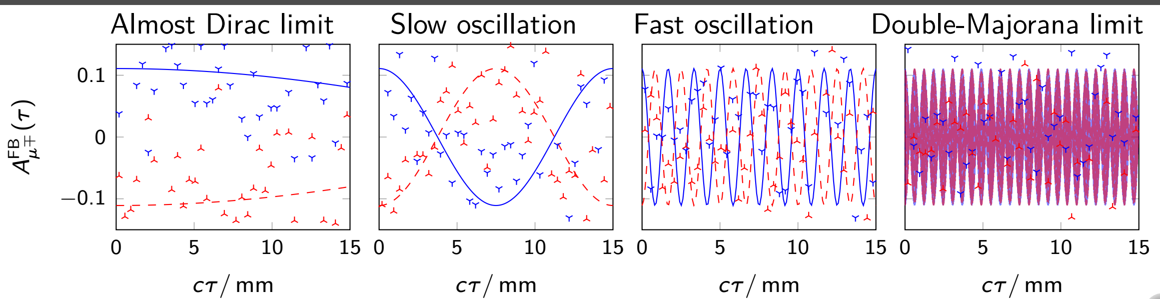


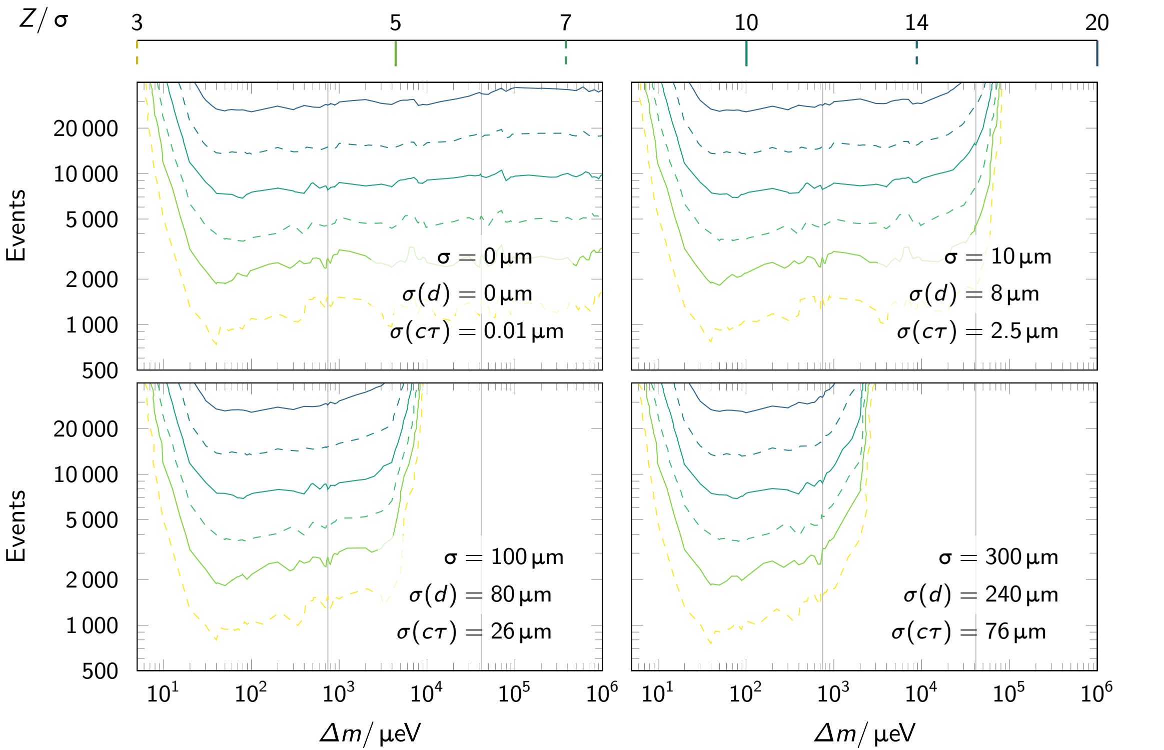
Time integrated probability

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

Angular integrated probability

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




Z/ σ
3
5
7
10
14
20
Events
20 000
10 000
5 000
2 000
1 000
500
σ = 0 µm
σ(d) = 0 µm
σ(cτ) = 0.01 µm
σ = 10 µm
σ(d) = 8 µm
σ(cτ) = 2.5 µm
σ = 100 µm
σ(d) = 80 µm
σ(cτ) = 26 µm
σ = 300 µm
σ(d) = 240 µm
σ(cτ) = 76 µm
10^1
10^2
10^3
10^4
10^5
10^6
Δm/ µeV