Long-lived particles at colliders

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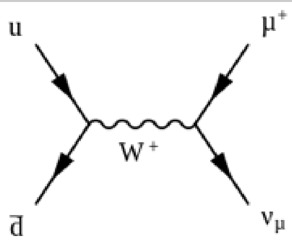
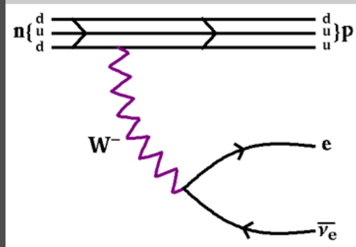
Long-lived particless (LLPs) in the Standard Model (SM)

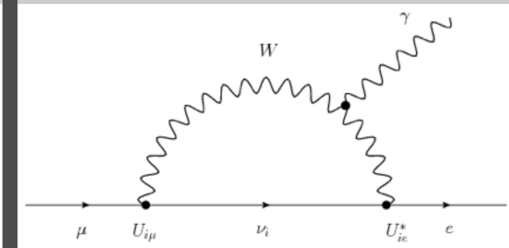
$\pi^+ \to \mu^+ \nu_\mu$



$n \to p e \overline{\nu}_e$



$\mu \to e\gamma$



Charged pion

- Decay via weak interactions
- Decay extremely off-shell

$$\Gamma_{\pi^+} \propto g_W^2 \left(\frac{m_\pi}{m_W}\right)^4 m_\pi$$

Muon

- Flavour changing neutral current
- Lepton flavour only violated by neutrino masses and Yukawa couplings

$$\mathrm{BR}\,(\mu \to e\gamma) \propto 10^{-13}$$

Neutron

- Proton and neutron are almost mass degenerate due to isospin
- Decay extremely off-shell

$$\Gamma_n \propto g_W^2 \left(\frac{\Delta_{np}}{m_W}\right)^4 \Delta_{np}, \quad \Delta_{np} = m_n - m_p$$

Generically

- Off-shell decay
- Small mass splitting
- Small coupling due to hierarchy or loop suppression

$$\Gamma \propto \lambda^2 \left(\frac{m}{M}\right)^n m$$

LLPs beyond the SM

New Physics

Any model with such features can contain LLPs

- Supersymmetry
- Dark Matter models
- Extended Higgs sectors

Portals to hidden sectors

- Many extension to the SM feature hidden sectors
- Often motivated by DM candidates

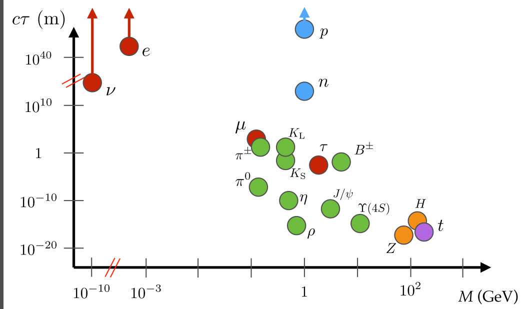
Prime examples

- Axion like particles
- Heavy neutral leptons (HNLs)
- Hidden U(1) / New gauge bosons

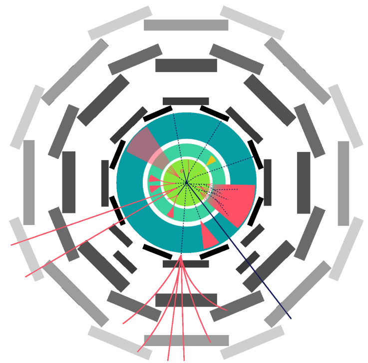
Search strategies

- Displaced tracks/vertices
- Emerging jets
- Disappearing tracks
- Kinked tracks
- Quasi-stable charged particles

LLPs in the SM [1903.04497]

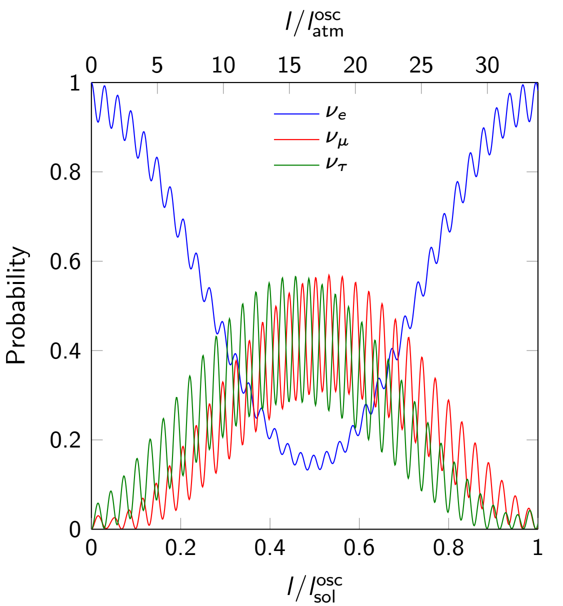


LLP signatures [1903.04497]



Neutrino flavour oscillations and seesaw mechanism

Observed neutrino flavour oscillations



Can be explained by

at least two massive neutrinos

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 governed by mixing parameter

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

Neutrino masses

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

Tiny neutrino masses are ensured for

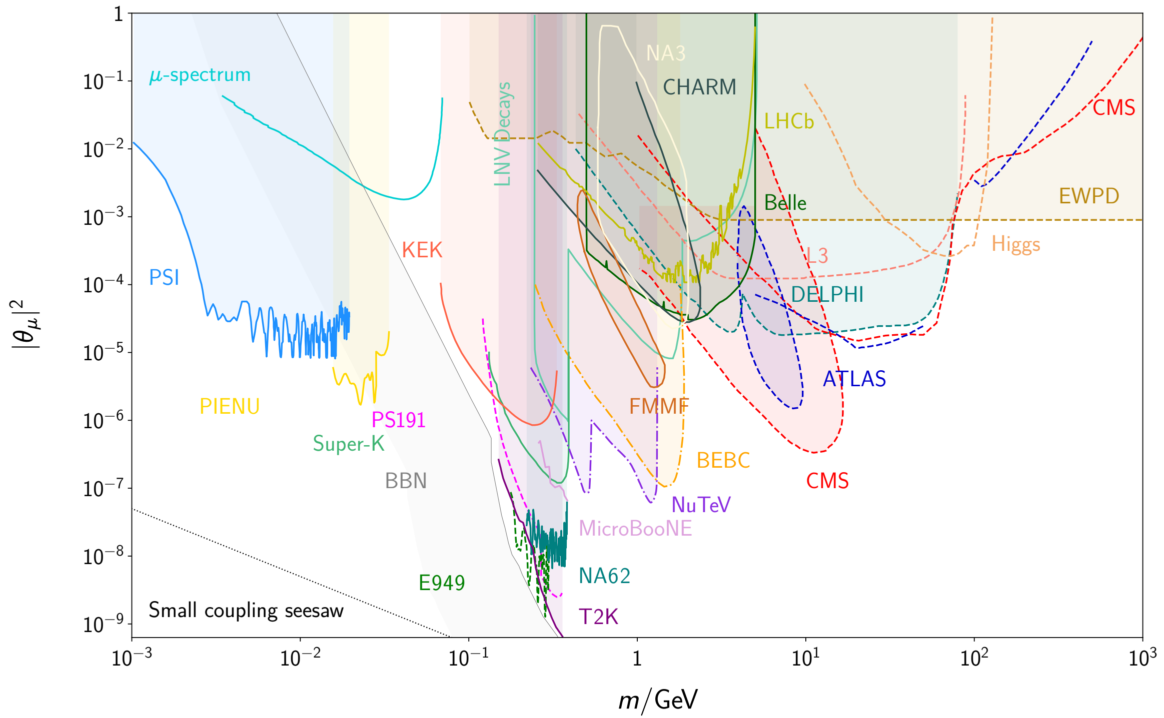
- large m_M — High scale seesaw
- small $\vec{m}_D$ — Small coupling seesaw

Sterile neutrinos/HNLs

- Inaccessibly heavy or
- Tiny interactions

Experimental searches

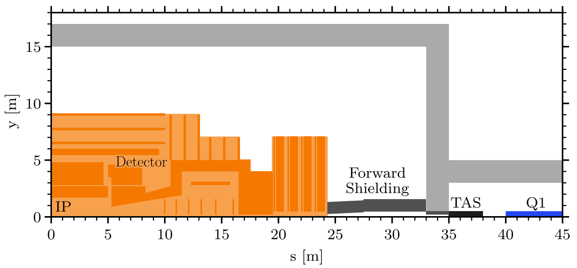
[sterile-neutrino.org]



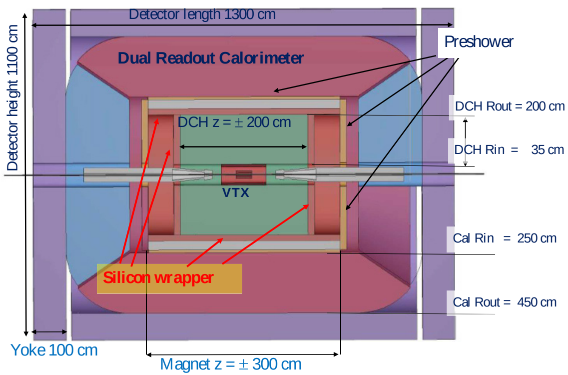
Inaccessible: ▪ Small coupling seesaw ▪ High scale seesaw (at the GUT scale)

FCC cavern and detector layout

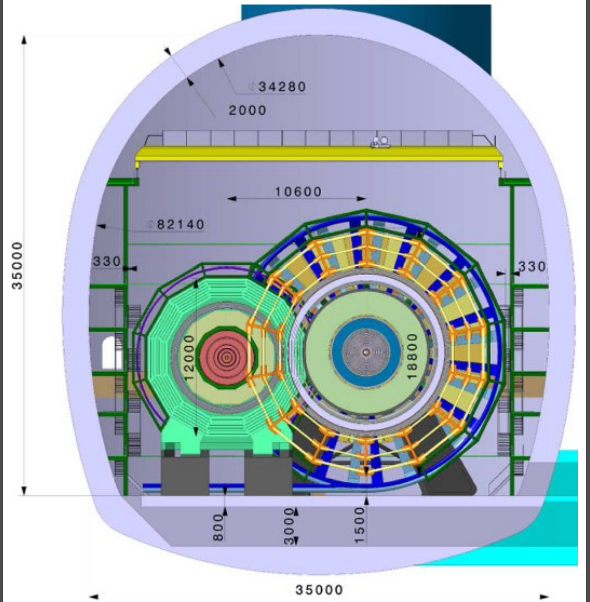
FCC caverns [FCC-*hh*]



FCC-*ee* IDEA detector [FCC-*ee*]



FCC-*ee* CLD vs. FCC-*hh* detector [FCC-*ee*]



Comparison

- Cavern size: $r \approx 15\,\mathrm{m}$, $z \approx 50\,\mathrm{m}$
- Detector size: $\mathcal{O}(10\,\mathrm{m})$

Proposal: HErmetic CAvern TrackEr (HECATE) [2011.01005]

Idea

- Exploit the additional space surrounding the FCC-*ee* detectors in the FCC-*hh* caverns
- Build a 4π LLP detector

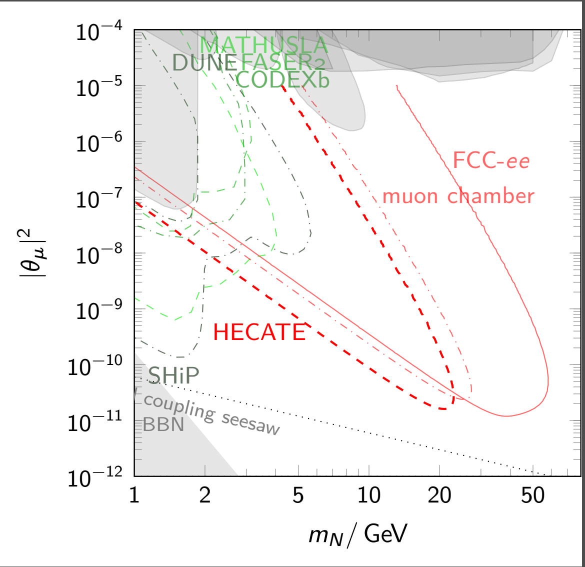
Layout

- Cover the cavern surface with detector material
- Minimum of two layers allows for timing
- Main detector serves as veto

For $\lambda \gg l_1 \gg l_0$

$$|\theta|^2 \propto \frac{1}{\sqrt{l_1}} \propto \frac{1}{\sqrt{L}}$$

Half a magnitude sensitivity gain in $|\theta|^2$



main detector		$l_0 = 5\,\text{mm}$, $l_1 = 1.22\,\text{m}$
muon chambers		$l_0 = 1.22\,\text{m}$, $l_1 = 4\,\text{m}$
HECATE		$l_0 = 4\,\text{m}$, $l_1 = 25\,\text{m}$

All efficiencies assumed to be 100 %

Symmetry-protected low-scale seesaw

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

Accidentally conserved in the SM

Generalisation: 'Lepton number'-like symmetry

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

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

Symmetry breaking in the mass matrix

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

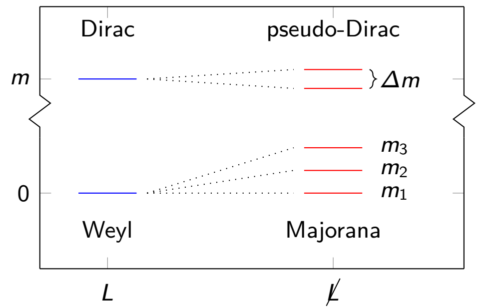
Symmetry L conserved

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

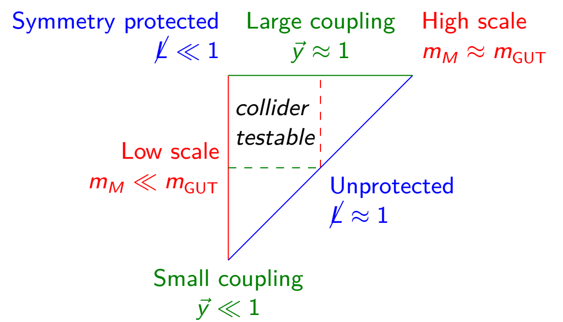
Small symmetry breaking $\not L$

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

Breaking induced neutrino mass splitting



Viable seesaw limits



Dirac vs. Majorana

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 lepton number violation (LNV)
- ϟ No neutrino masses

Majorana BM

- ✓ Correct production cross section
- ϟ Wrong decay width
- ✓ LNV
- ϟ Generically too much LNV

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

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

[2210.10738]

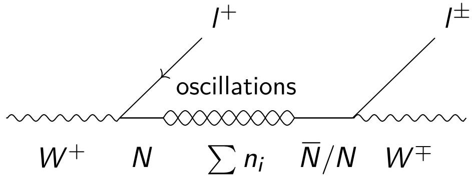
Oscillations between events that have

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

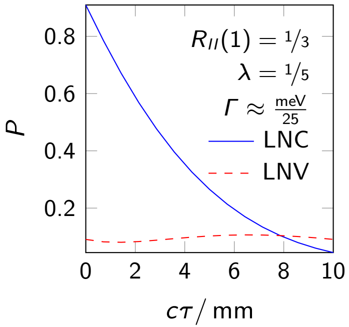
Oscillation frequency governed by Δm

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

Oscillating mass eigenstates n_i

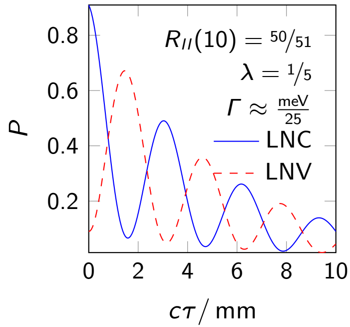


Almost Dirac limit



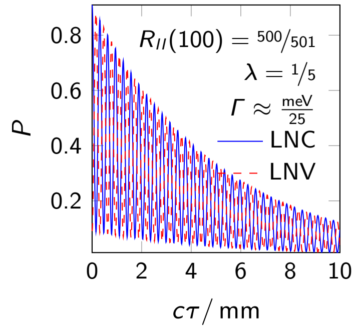
- Mostly LNC

Archetypical pseudo-Dirac



- Potentially resolvable

Double-Majorana limit



- Unresolvable
- LNV as frequent as LNC

Decaying oscillations

[2210.10738]

HNLs can be long-lived particless

$$P_{\text{decay}}(\tau) = -\frac{d}{d\tau}\exp(-\Gamma\tau) = \Gamma\exp(-\Gamma\tau)$$

Since they are pseudo-Dirac they oscillate

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

Collider signature: Decaying oscillations

$$P_{ll}^{\text{LNC/LNV}}(\tau) = P_{\text{decay}}(\tau) P_{\text{osc}}^{\text{LNC/LNV}}(\tau)$$

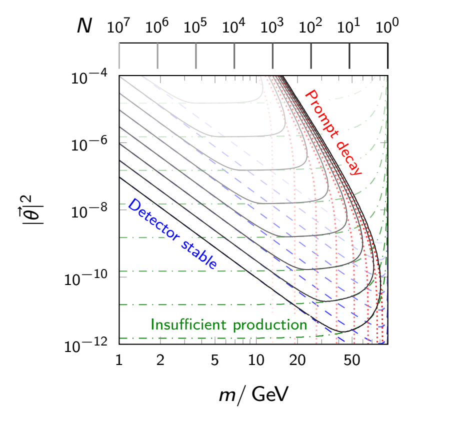
Time-integrated oscillations

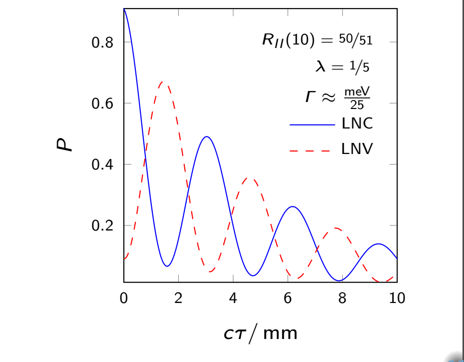
[2307.06208]

$$P_{ll}^{\text{LNC/LNV}} = \frac{1}{2} \pm \frac{1}{2}\frac{\Gamma^2}{\Gamma^2 + \Delta m^2}$$

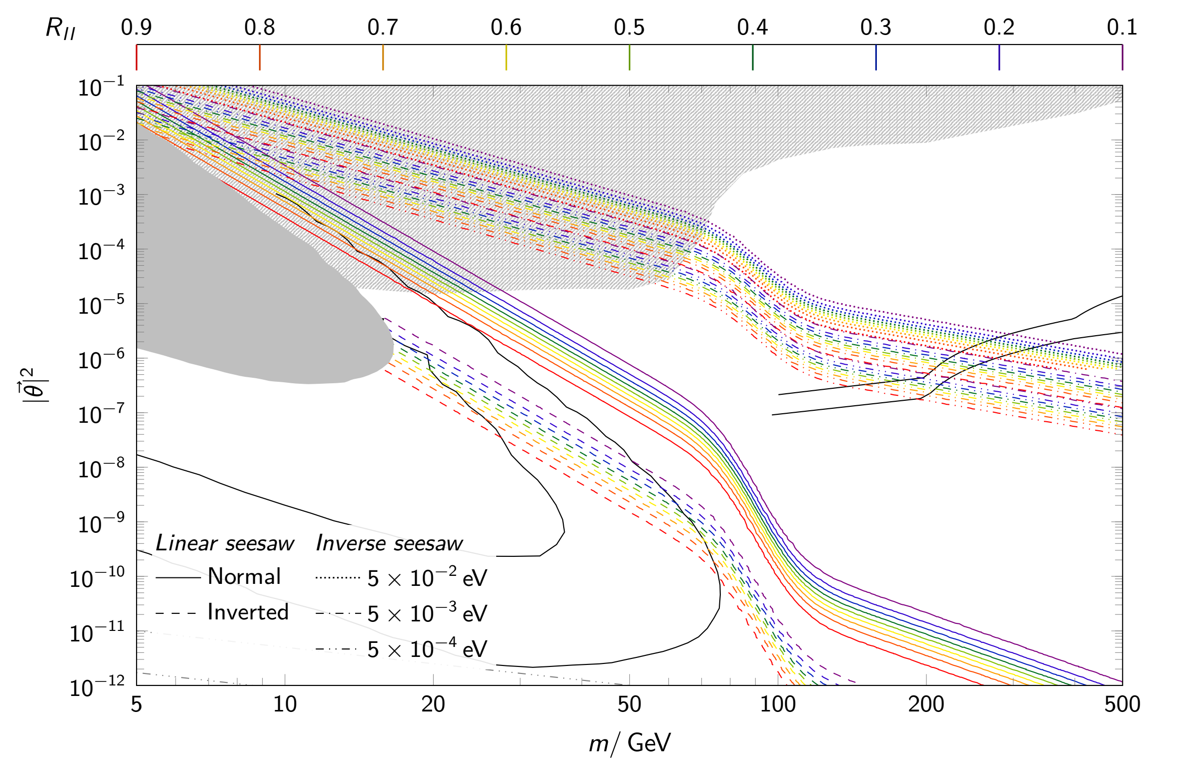
Charged lepton ratio

$$R_{ll} = \frac{P_{ll}^{\text{LNV}}}{P_{ll}^{\text{LNC}}} = \frac{\Delta m^2}{\Delta m^2 + 2\Gamma^2}$$



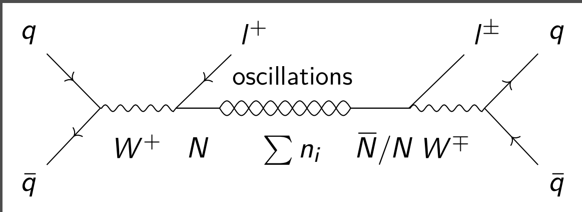


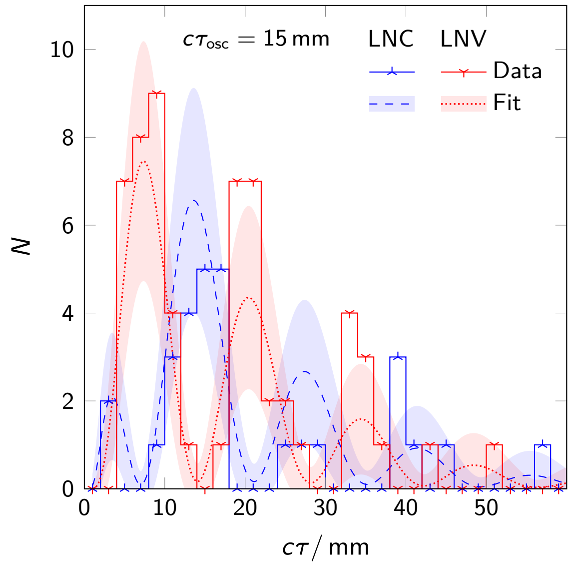
Naive lepton number violation for five BMs



Measuring LNV at the HL-LHC

[pSPSS, 2212.00562]

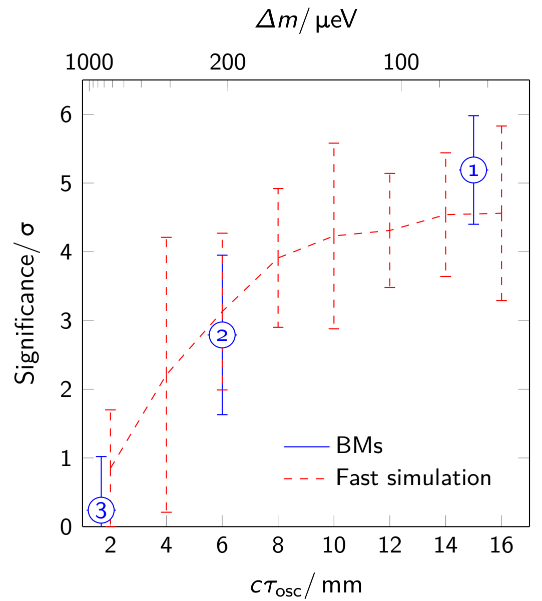




LNV can be measured

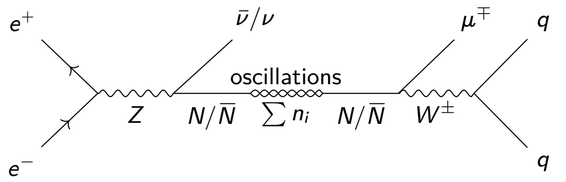
by counting the charges of the two leptons

Significance for a BM



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

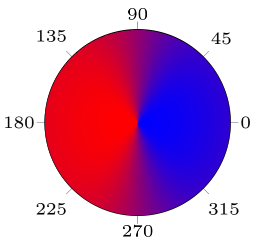
Angular dependent probability

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

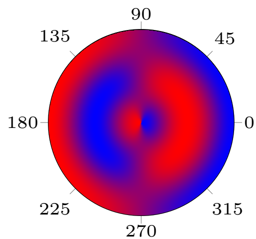
Probability of measuring charged leptons

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

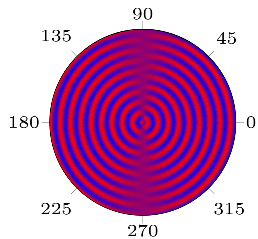
Almost Dirac limit



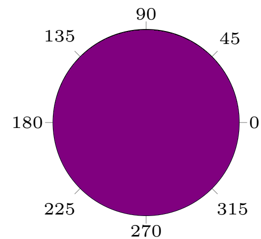
Slow oscillation



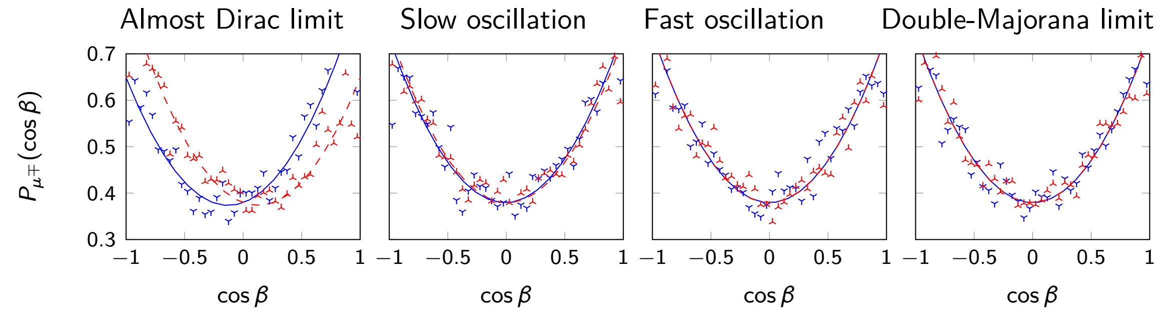
Fast oscillation



Double-Majorana limit



Time and angular integrated observable

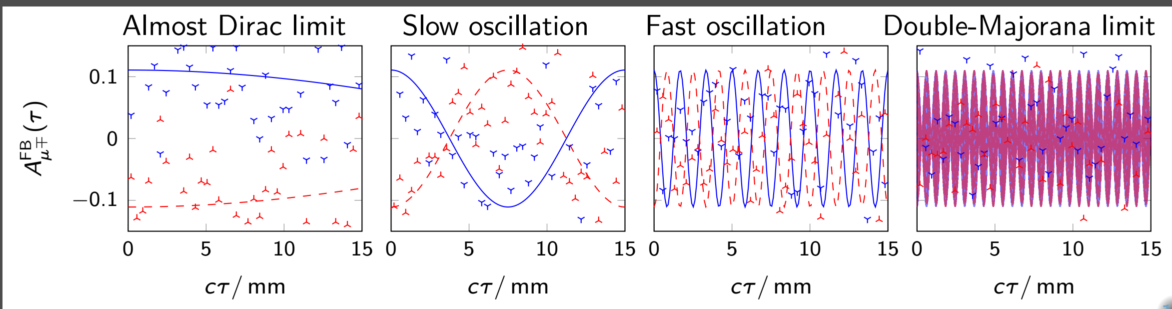


Time integrated probability

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

Angular integrated probability

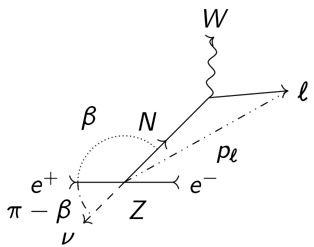
$$P_{l\mp}^{[\beta_{\min},\beta_{\max}]}(\tau) := \int_{\cos\beta_{\min}}^{\cos\beta_{\max}} P_{l\mp}(\tau, \cos\beta)\, d\cos\beta$$



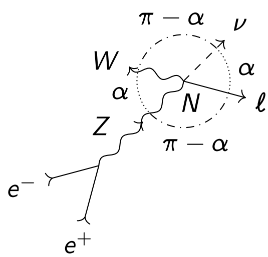
LNV in distributions at future lepton colliders

[2408.01389]

FBA



Opening angle asymmetry (OAA)



Sensitivity

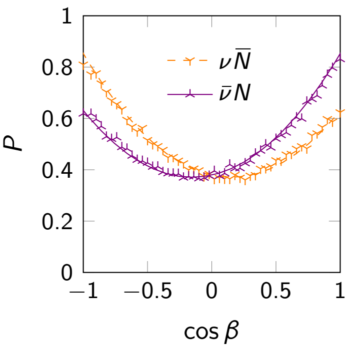
FBA $N/\overline{N}$

OAA LNC/LNV

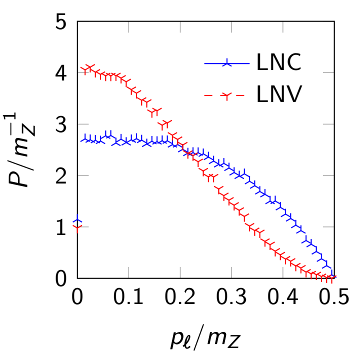
Lepton momentum modulus

same analysis power as OAA

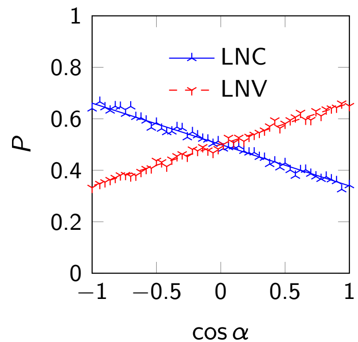
FBA



Lepton momentum modulus

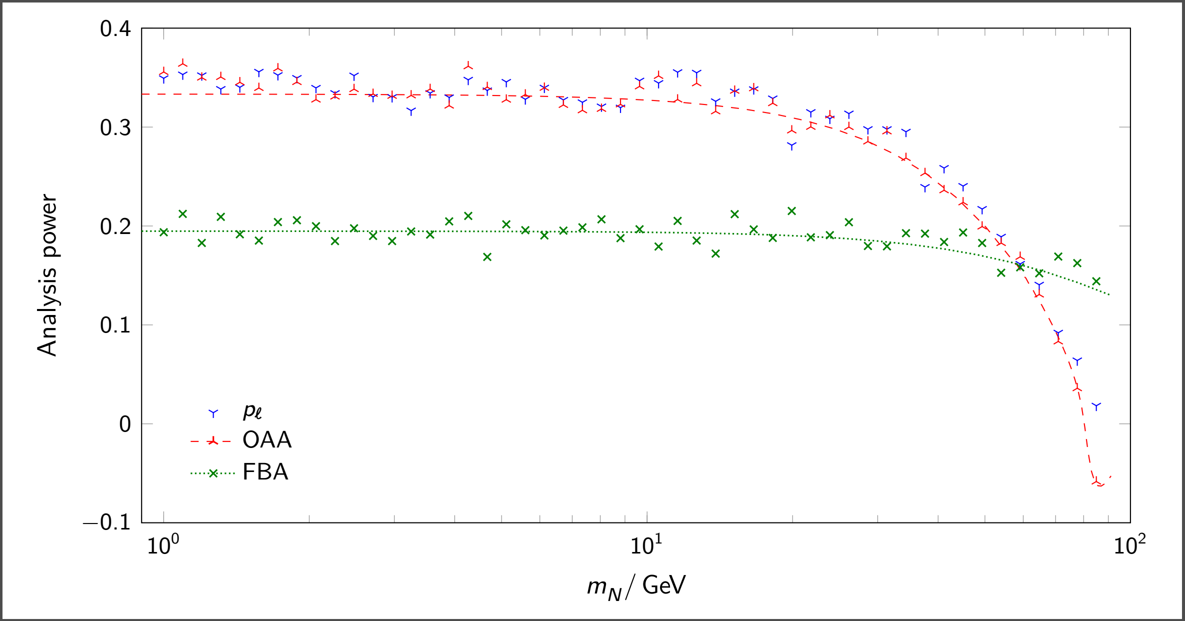


OAA



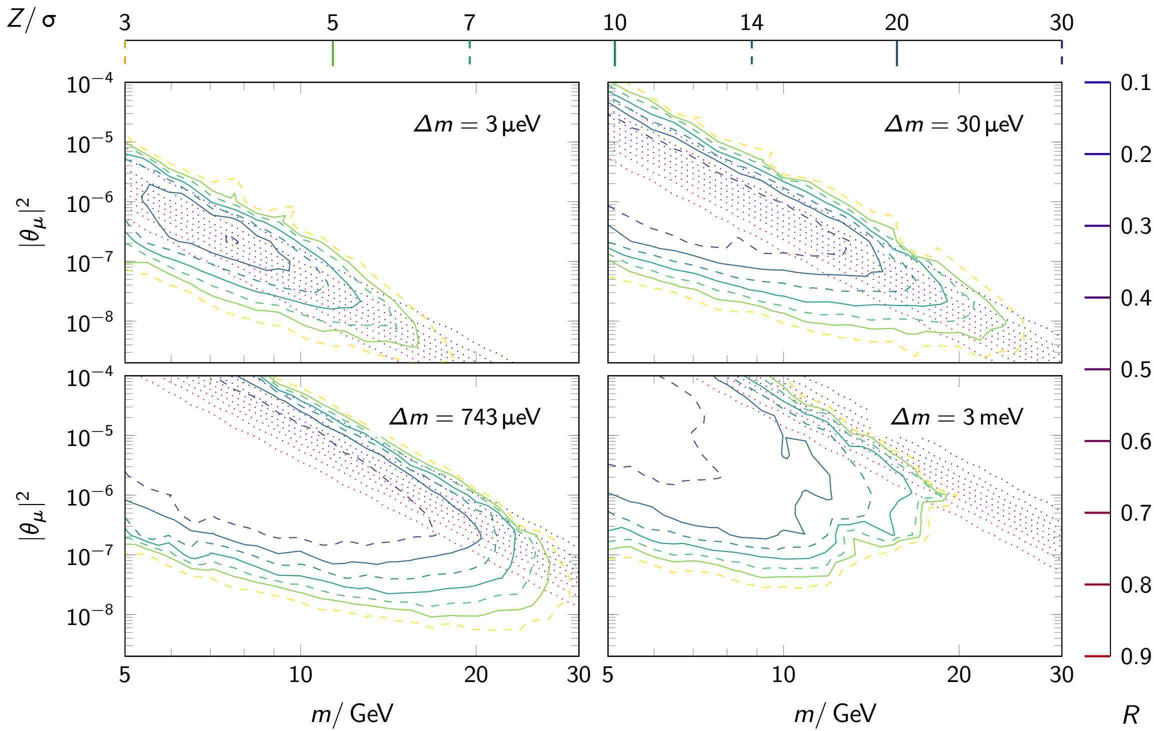
Analysis powers

[2408.01389]

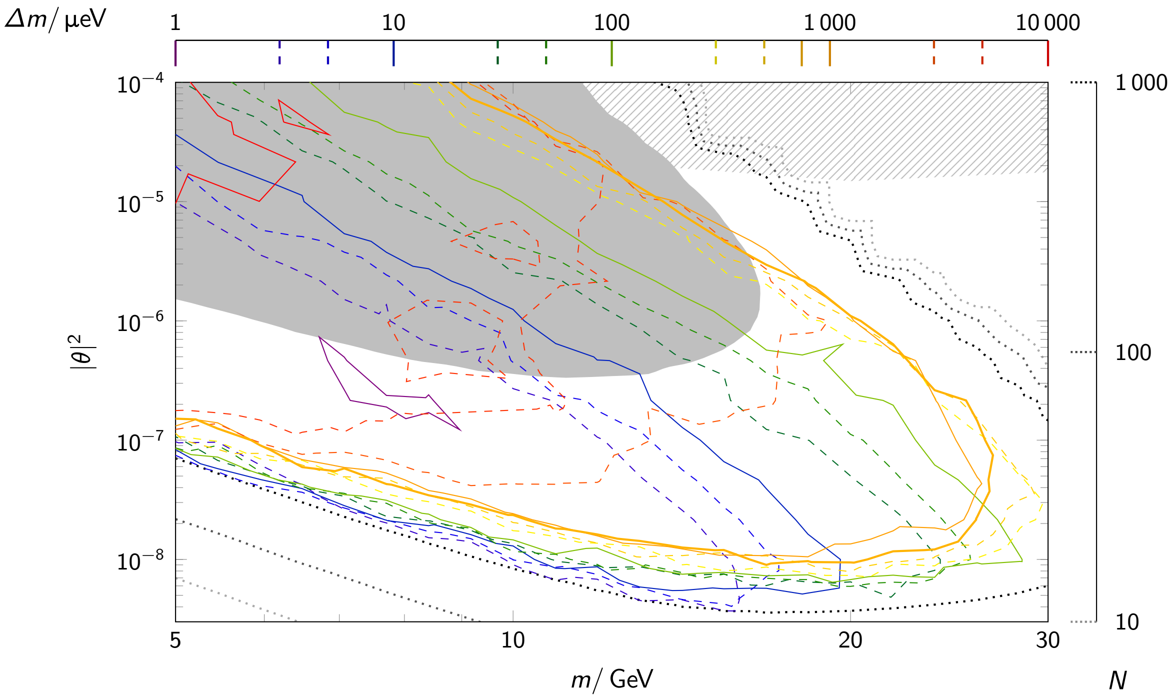


Significance at the FCC-ee for different mass splittings

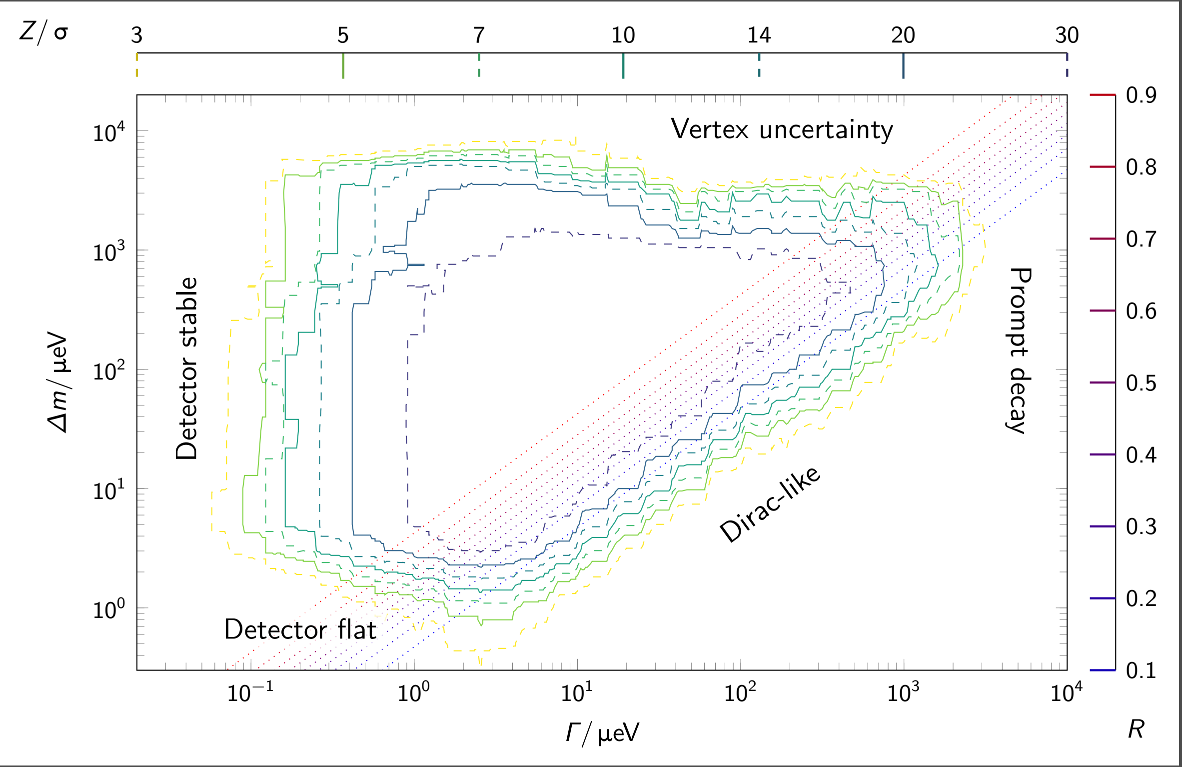
[2408.01389]



5 σ discovery reach of the FCC-ee

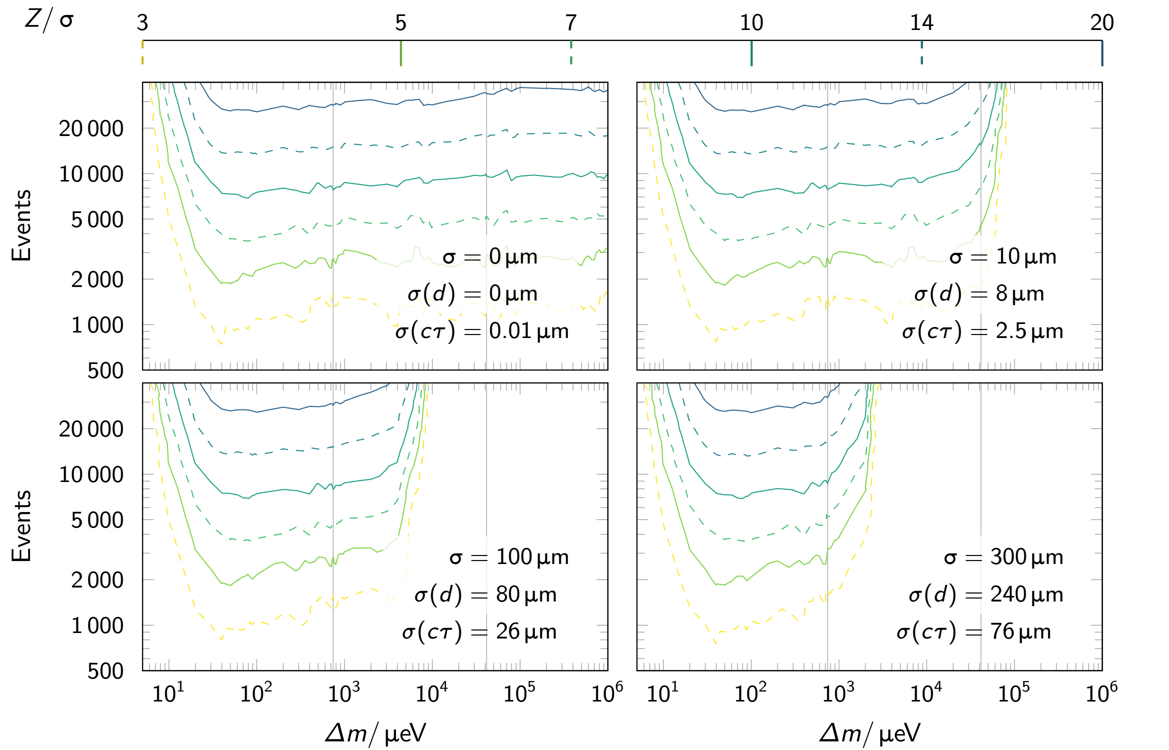


Maximal significance of the FCC-ee



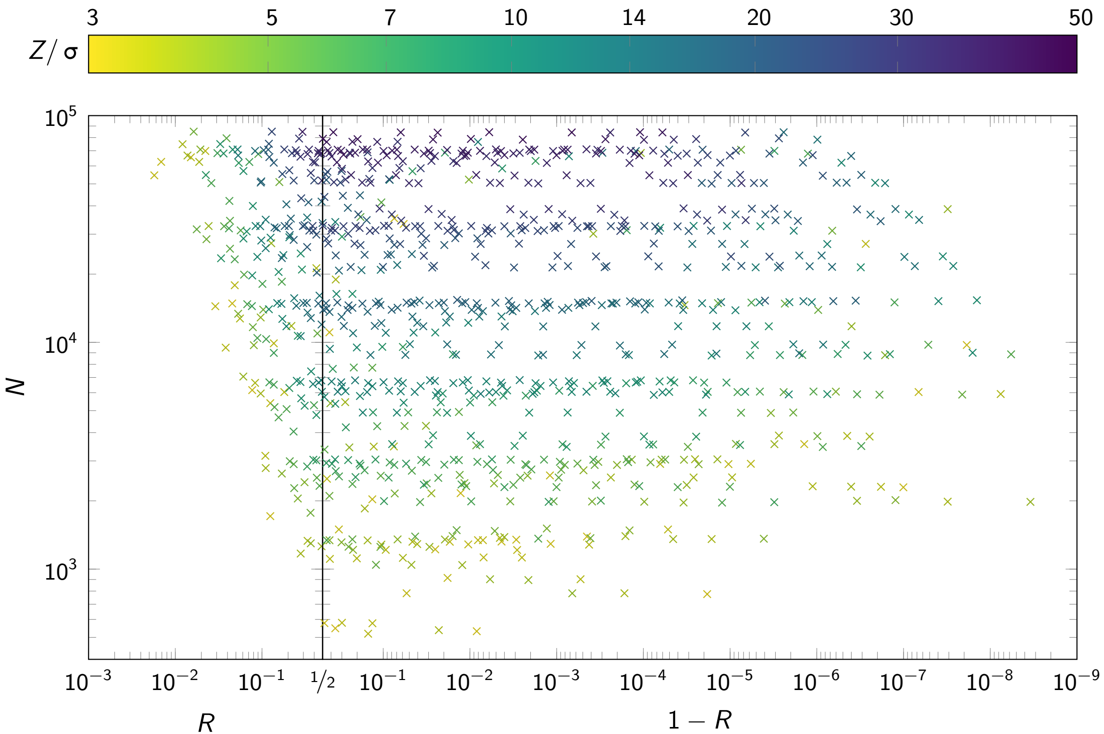
Significance dependents on the vertex reconstruction error

[2408.01389]



Testable values of the LNV ratio

[2408.01389]



Conclusions

- Long-lived particles (LLP) are prevalent in the SM and expected to also appear in new physics
- One typical benchmark model scenario consists of HNLs
- 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 the HL-LHC and future lepton colliders

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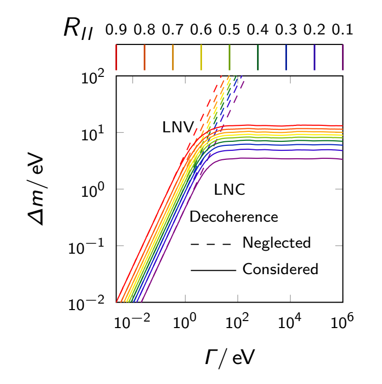
Problems measuring R_{ll}

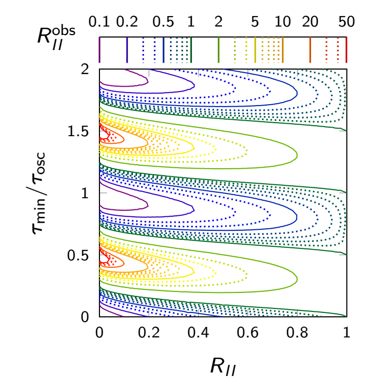
Integration limits correspond to [2210.10738]

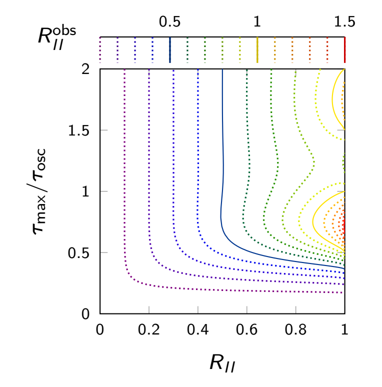
- Minimal distance cut
- Maximal measurable vertex distance

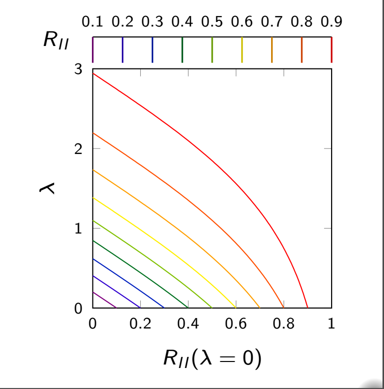
Decoherence [2307.06208]

- 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

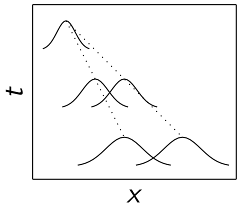
QFT with external wave packets

- 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

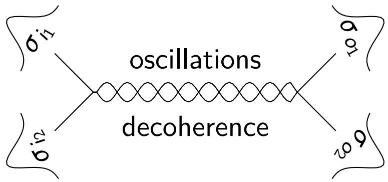
Damped oscillations

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

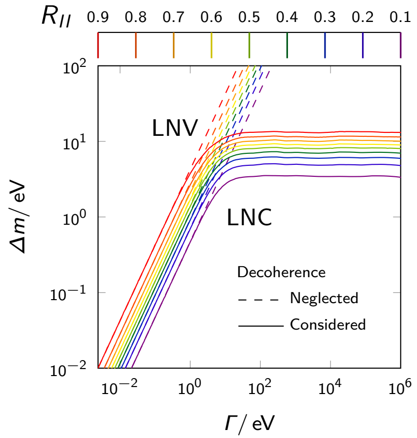
LNV can be

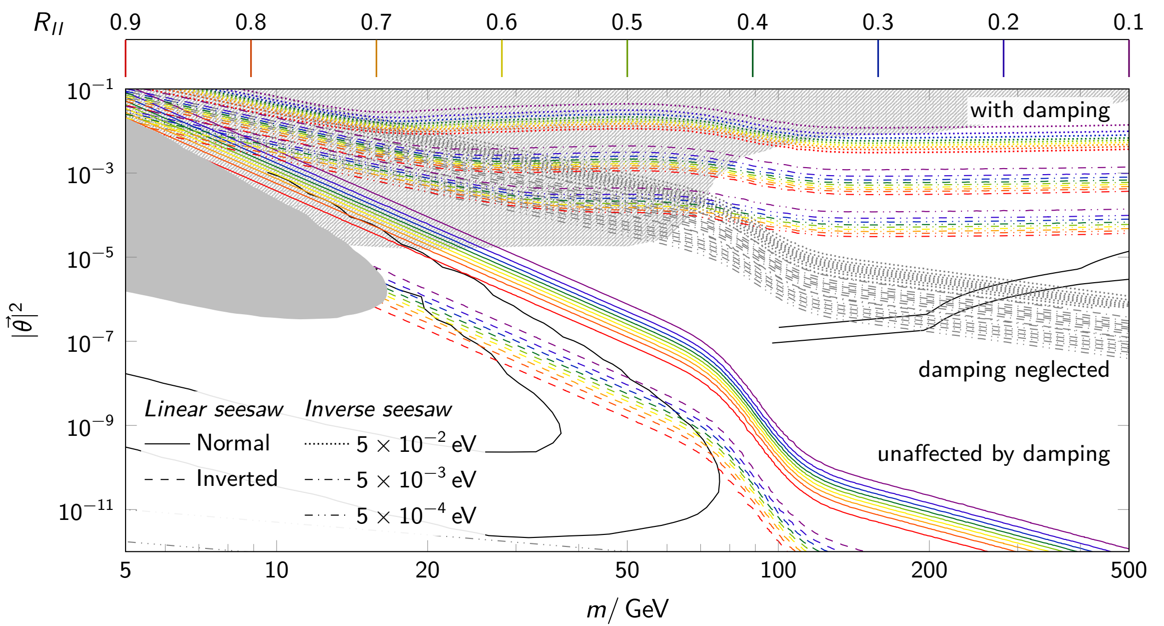
drastically enhanced

Width of external wave packets σ



Impact on $N\overline{N}$Os





Minimal linear seesaw	Inverse seesaw
Not affected by decoherence	LNV significantly increased