Theory: open questions

Jan Hajer

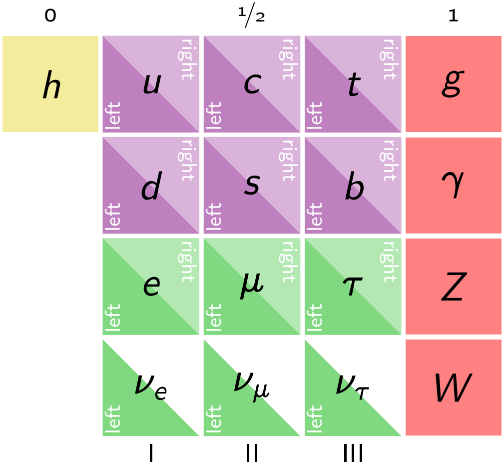
Centro de Física Teórica de Partículas, Instituto Superior Técnico, Universidade de Lisboa

Heavy Neutral Lepton search potential of future HET factories

Fundação para a Ciência e a Tecnologia

Standard Model neutrinos

Standard Model particle content



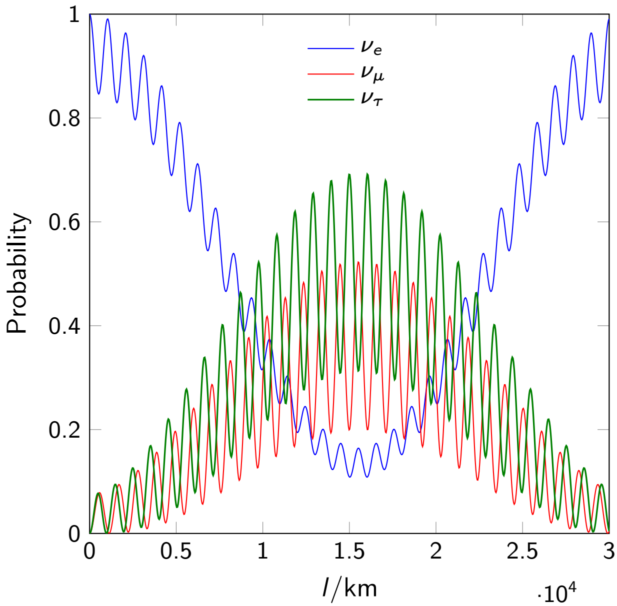
Neutrinos ν_α stand out

purely left-chiral and massless

Right-chiral or sterile Neutrinos

neutral under SM symmetries

Observed neutrino flavour oscillations



Flavour oscillations are explained by

right-chiral neutrinos allowing mass terms

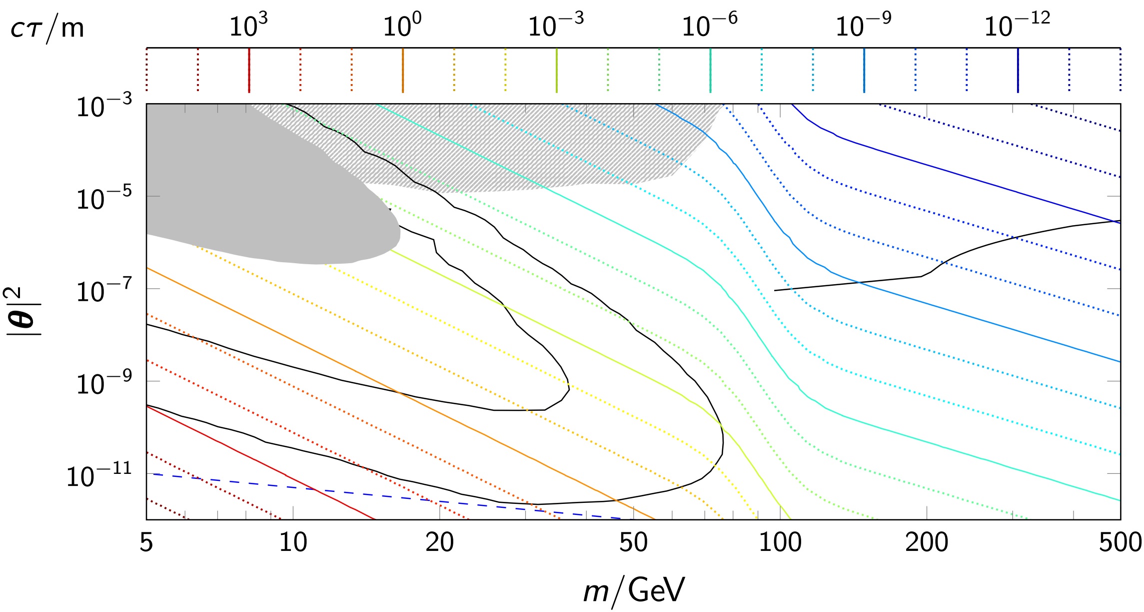
Simplest model

Interactions of a Majorana or Dirac HNL

$$\mathcal{L}_N = -\frac{m_W}{v}\overline{N}\boldsymbol{\theta}^*\gamma^\mu e W_\mu^+ - \frac{m_Z}{\sqrt{2}v}\overline{N}\boldsymbol{\theta}^*\gamma^\mu \nu Z_\mu - \frac{m}{\sqrt{2}v}\boldsymbol{\theta} h\bar{\nu}N + \text{H.c.}$$

Seesaw mass

$$M_\nu = m_M \boldsymbol{\theta} \otimes \boldsymbol{\theta}$$



Majorana vs. Dirac

Interactions of a Majorana or Dirac HNL

$$\mathcal{L}_N = -\frac{m_W}{v}\overline{N}\boldsymbol{\theta}^*\gamma^\mu e W_\mu^+ - \frac{m_Z}{\sqrt{2}v}\overline{N}\boldsymbol{\theta}^*\gamma^\mu \nu Z_\mu - \frac{m}{\sqrt{2}v}\boldsymbol{\theta} h\bar{\nu}N + \text{H.c.}$$

Dirac

- No massive light neutrino
- No lepton number violation

Majorana

- Single massive light neutrino
- Generated mass is correct for small coupling or GUT scale

Inconsistency between both models

Predicted decay width differs by a factor of 2.

Proposals to distinguish these models at the FCC [2105.06576; 2210.17110]

- Forward-backward asymmetry
- Difference in lepton spectrum

Seesaw model regimes

Dirac mass

$$\mathcal{L}_D = -m_{D\alpha}\bar{\nu}_\alpha N + \text{h.c.}\,, \qquad \boldsymbol{m}_D = v\boldsymbol{y}$$

Majorana mass

$$\mathcal{L}_M = -\frac{1}{2} m_M \overline{N} N^c + \text{h.c.}$$

Coupling strength is determined by

$$\boldsymbol{\theta} = \boldsymbol{m}_D / m_M$$

Majorana mass introduces

lepton number violation (LNV)

Majorana mass vanishes if

lepton-number L is conserved

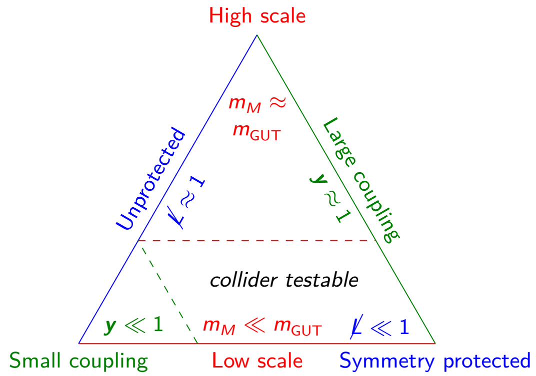
Neutrino oscillation pattern requires

at least two massive neutrinos

Neutrino mass matrix from two sterile neutrinos

$$M_\nu = \frac{\boldsymbol{m}_D^{(1)} \otimes \boldsymbol{m}_D^{(1)}}{m_M^{(1)}} + \frac{\boldsymbol{m}_D^{(2)} \otimes \boldsymbol{m}_D^{(2)}}{m_M^{(2)}}$$

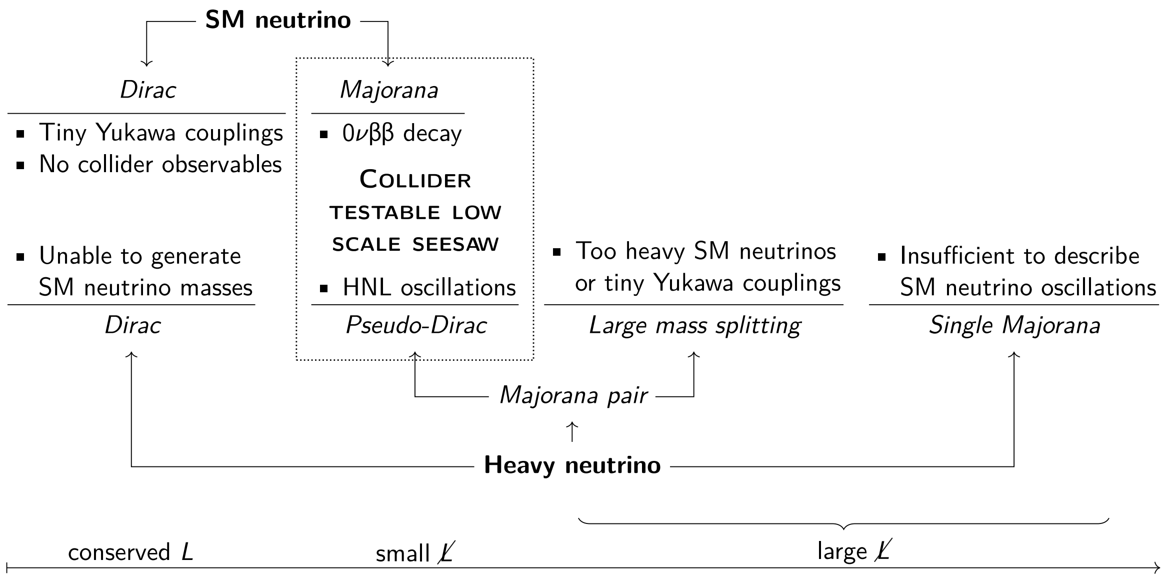
Viable seesaw models



Neutrino masses are small for

- small $\boldsymbol{y}$
- large m_M
- symmetry protected cancellation

Are HNLs Majoran or Dirac Fermions? [2210.10738]



Single Majorana and Dirac HNLs are

- not predicted by low-scale seesaw models

Unique phenomenology of pseudo-Dirac HNLs

- Heavy neutrino-antineutrino oscillations
- $0 < R_{ll} = \frac{N_{\text{LNV}}}{N_{\text{LNC}}} < 1$
- Governed by mass splitting Δm

Particle content of benchmark model candidates

Number of Majorana degrees of freedom (DOFs)

DOF	Particles	Properties	
1	Majorana	One massive light neutrino	↯
2	Dirac	No massive light neutrino	↯
	pseudo-Dirac	Minimal linear seesaw / pSPSS	✓
	2 Majorana	Light neutrinos too heavy	↯
3	pseudo-Dirac + Majorana	νMSM (Dark Matter)	✓
		Majorana active (no Dark Matter)	✓
4	2 pseudo-Dirac	Minimal inverse seesaw	✓
5	2 pseudo-Dirac + Majorana	...	
6	3 pseudo-Dirac	...	

Good benchmark model

- Reproduces neutrino mass scale
- Captures dominant collider effects
- Minimal possible number of parameters

Minimal set of parameters for single pseudo-Dirac

- Mass m
- Coupling vector $\boldsymbol{\theta}$
- Mass splitting Δm

Benchmark models in flavour space

[2207.02742]

Commonly used benchmark models

Single flavour interactions

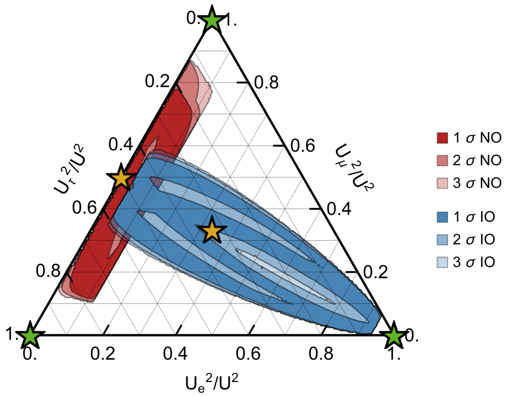
Criteria for new benchmark points

- Consistent with neutrino oscillation data for minimal models
- Sufficiently different from other points
- Consistent with flavour symmetry models
- Simple ratios
- Compatible with leptogenesis

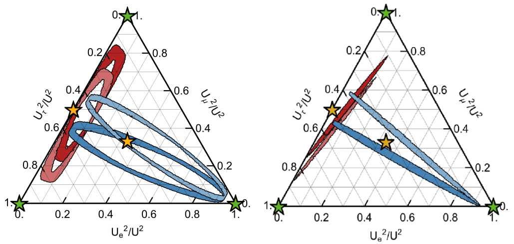
Benchmark points

BM	e	μ	τ
1	1	0	0
2	0	1	0
3	0	0	1
4	0	1	1
5	1	1	1

Benchmark models



Projections for 15 years of DUNE



Symmetry protected seesaw scenario

Exact limit

$$\mathcal{L}^{L}_{\mathrm{SPSS}} = -m_M \overline{N}_1 N_2^c - y_1 \widetilde{H}^\dagger \overline{\ell} N_1^c + \text{h.c.}$$

Small breaking terms $v y_2 \approx \mu_M \approx \mu'_M \ll m_M$

$$\mathcal{L}^{\not L}_{\mathrm{SPSS}} = -y_2 \widetilde{H}^\dagger \overline{\ell} N_2^c - \mu'_M \overline{N}_1 N_1^c - \mu_M \overline{N}_2 N_2^c + \text{h.c.}$$

Lepton number-like symmetry

generalises accidental SM lepton number L

One simple choice of charges

	ℓ	N_1	N_2
L	$+1$	-1	$+1$

Other new fields

further terms in Lagrangian

Neutrino mass matrix M_n

contains seesaw information

Basis

$n = (\nu, n_4, n_5)$

Dirac masses

$\boldsymbol{m}_D = \boldsymbol{y}_1 v, \quad \boldsymbol{\mu}_D = \boldsymbol{y}_2 v$

Symmetric limit

$$M_n^L = \begin{pmatrix} 0 & \boldsymbol{m}_D & 0 \\ \boldsymbol{m}_D^\mathsf{T} & 0 & m_M \\ 0 & m_M & 0 \end{pmatrix}$$

- Massless neutrinos $M_\nu = 0$
- Dirac HNL

Mild symmetry breaking

$$M_n^{\not L \ll 1} = \begin{pmatrix} 0 & \boldsymbol{m}_D & \boldsymbol{\mu}_D \\ \boldsymbol{m}_D^\mathsf{T} & \mu'_M & m_M \\ \boldsymbol{\mu}_D^\mathsf{T} & m_M & \mu_M \end{pmatrix}$$

- Pseudo-Dirac HNL (small Δm Majorana pair)
- Phenomenology governed by small parameters μ

Large symmetry breaking

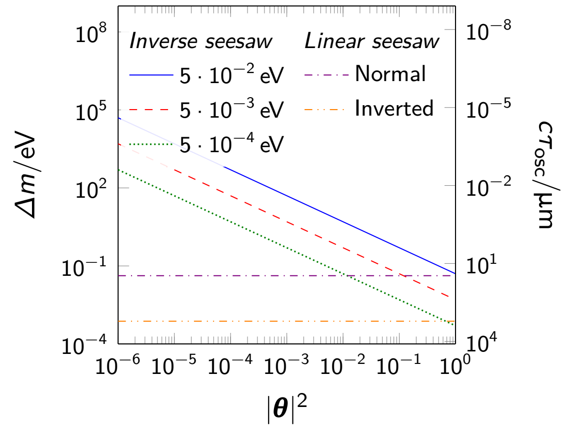
$$M_n^{\not L \gg 0} = \begin{pmatrix} 0 & \boldsymbol{m}_D & \widehat{\boldsymbol{m}}_D \\ \boldsymbol{m}_D^\mathsf{T} & \widehat{m}'_M & m_M \\ \widehat{\boldsymbol{m}}_D^\mathsf{T} & m_M & \widehat{m}_M \end{pmatrix}$$

- Large Δm Majorana pair
- Requires large m_M or tiny $\boldsymbol{\theta}$

	Linear seesaw $\boldsymbol{\mu}_D$	Inverse seesaw μ_M	Seesaw independent μ'_M
$M_n =$	$\begin{pmatrix} 0 & \boldsymbol{m}_D & \boldsymbol{\mu}_D \\ \boldsymbol{m}_D^T & 0 & m_M \\ \boldsymbol{\mu}_D^T & m_M & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & \boldsymbol{m}_D & 0 \\ \boldsymbol{m}_D^T & 0 & m_M \\ 0 & m_M & \mu_M \end{pmatrix}$	$\begin{pmatrix} 0 & \boldsymbol{m}_D & 0 \\ \boldsymbol{m}_D^T & \mu'_M & m_M \\ 0 & m_M & 0 \end{pmatrix}$
$M_\nu =$	$\boldsymbol{\mu}_D \otimes \boldsymbol{\theta}$	$\mu_M \boldsymbol{\theta} \otimes \boldsymbol{\theta}$	0 (at tree level)
$\Delta m =$	Δm_ν	$m_\nu \lvert\boldsymbol{\theta}\rvert^{-2}$	$\lvert\mu'_M\rvert$

Benchmark models

Seesaw	Hierarchy	BM
Linear	Normal	$\Delta m_\nu = 42.3\,\text{meV}$
	Inverted	$\Delta m_\nu = 748\,\mu\text{eV}$
Inverse		$m_\nu = 0.5\,\text{meV}$
		$m_\nu = 5\,\text{meV}$
		$m_\nu = 50\,\text{meV}$



Generic seesaw

All small parameter μ are nonzero

Software implementation of the phenomenological SPSS

[pSPSS; 2210.10738]

Mass splitting

$$m_{4/5} = m_M\left(1 + |\boldsymbol{\theta}|^2/2\right) \mp \Delta m/2$$

Phenomenological SPSS (pSPSS) adds

Δm Heavy neutrino-antineutrino oscillations

λ Decoherence damping

FeynRules model file

Pseudo-Dirac HNLs in the pSPSS

Available online

feynrules.irmp.ucl.ac.be/wiki/pSPSS

Parameter

BLOCK PSPSS #		
1	1.000000e+02	# mmaj
2	1.000000e-12	# deltam
3	0.000000e+00	# theta1
4	1.000000e-03	# theta2
5	0.000000e+00	# theta3
6	0.000000e+00	# damping

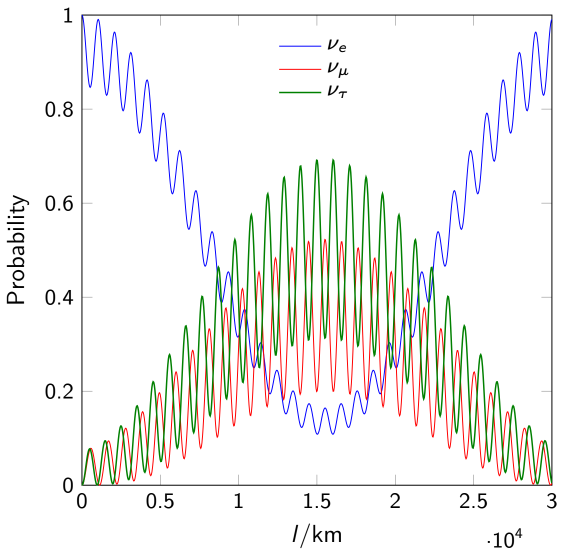
Oscillations implemented in MadGraph

```
mass_splitting = param_card.get_value('PSPSS', 2)
damping = param_card.get_value('PSPSS', 6)
for event in lhe:
    leptonnumber = 0
    write_event = True
    for particle in event:
        if particle.status == 1:
            if particle.pid in [11, 13, 15]:
                leptonnumber += 1
            elif particle.pid in [-11, -13, -15]:
                leptonnumber -= 1
    for particle in event:
        id = particle.pid
        width = param_card['decay'].get((abs(id),)).value
        if width:
            if id in [8000011, 8000012]:
                tauo = random.expovariate(width / cst)
                if 0.5 * (1 + math.exp(-damping)*math.cos(
                      mass_splitting * tauo / cst)) >= random.
                      random():
                    write_event = (leptonnumber == 0)
                else:
                    write_event = (leptonnumber != 0)
                vtim = tauo * c
            else:
                vtim = c * random.expovariate(width / cst)
            if vtim > threshold:
                particle.vtim = vtim
    # write this modify event
    if write_event:
        output.write(str(event))
output.write('</LesHouchesEvents>\n')
output.close()
```

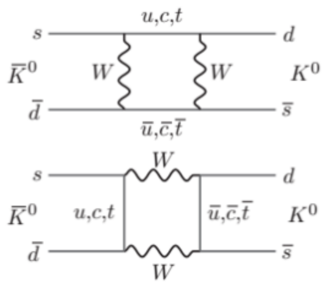
Heavy neutrino-antineutrino oscillations

Oscillations in the Standard Model

Light neutrinos



Mesons



Heavy neutrino-antineutrino oscillations

Oscillations

between LNC and LNV processes

Damping due to decoherence

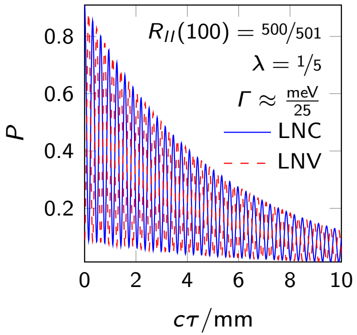
governed by λ

Oscillation length

governed by mass splitting Δm

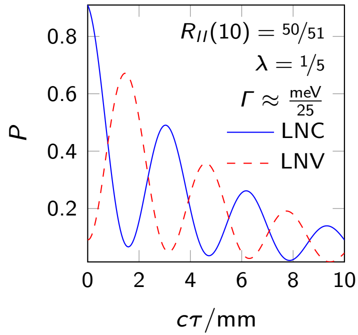
$$P_{\text{osc}}^{\text{LNC}/\text{LNV}}(\tau) = \frac{1 \pm \cos(\Delta m \tau)\exp(-\lambda)}{2}$$

Short oscillation length



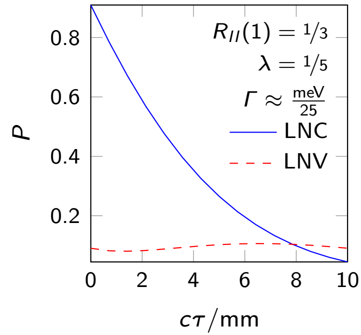
- Oscillations not resolvable
- Large R_{ll}
- 'Majorana' limit

Intermediate oscillation length



- Oscillations potentially measurable
- Pseudo-Dirac character crucial

Long oscillation length



- LNV strongly suppressed
- Small R_{ll}
- 'Dirac' limit

Integrated effect: R_{ll}

Oscillation probability

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

Decay probability density

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

Probability to decay with oscillation between τ_{min} and τ_{max}

$$P_{ll}^{\text{LNC/LNV}}(\tau_{\text{min}}, \tau_{\text{max}}) = \int_{\tau_{\text{min}}}^{\tau_{\text{max}}} P_{\text{osc}}^{\text{LNC/LNV}}(\tau) P_{\text{decay}}(\tau)\, d\tau$$

Integrated

$$P_{ll}^{\text{LNC/LNV}}(\tau_{\text{min}}, \tau_{\text{max}}) = \Gamma \frac{P^{\text{LNC/LNV}}(\tau_{\text{max}}) - P^{\text{LNC/LNV}}(\tau_{\text{min}})}{2}$$

where

$$P^{\text{LNC/LNV}}(\tau) = P(\tau, \Gamma, 0) \pm \frac{P(\tau, \Gamma_-, \lambda) + P(\tau, \Gamma_+, \lambda)}{2}$$

In the limit

$$\tau_{\text{min}} \to 0\,, \quad \tau_{\text{max}} \to \infty\,, \quad \lambda \to 0$$

Probability simplifies

$$P_{ll}^{\text{LNC/LNV}} = \frac{1}{2}\begin{cases} \frac{\Gamma^2}{\Delta m^2 + \Gamma^2} + 1 & \text{LNC} \\ \frac{\Delta m^2}{\Delta m^2 + \Gamma^2} & \text{LNV} \end{cases}$$

Ratio is easily measurable

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

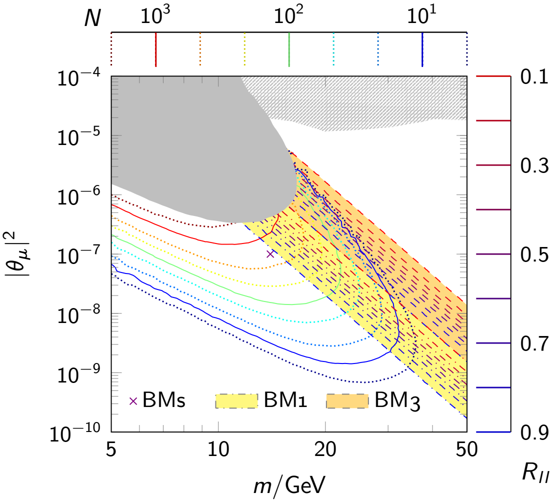
with

$$P(\tau, \Gamma, \lambda) = -\frac{e^{-\lambda - \Gamma\tau}}{\Gamma}$$

$$\Gamma_\pm = \Gamma \pm i\Delta m$$

Monte Carlo Simulation

HL-LHC event number with $\mathscr{L} = 3\,\mathrm{ab}^{-1}$

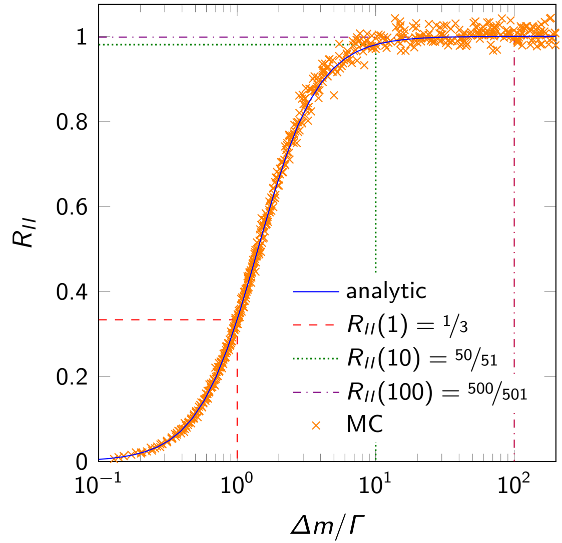


BM	$\Delta m/\mu\mathrm{eV}$	$c\tau_{\mathrm{osc}}/\mathrm{mm}$	R_{ll}
1	82.7	15	0.9729
2	207	6	0.9956
3	743	1.67	0.9997

Integrate oscillations from origin to infinity

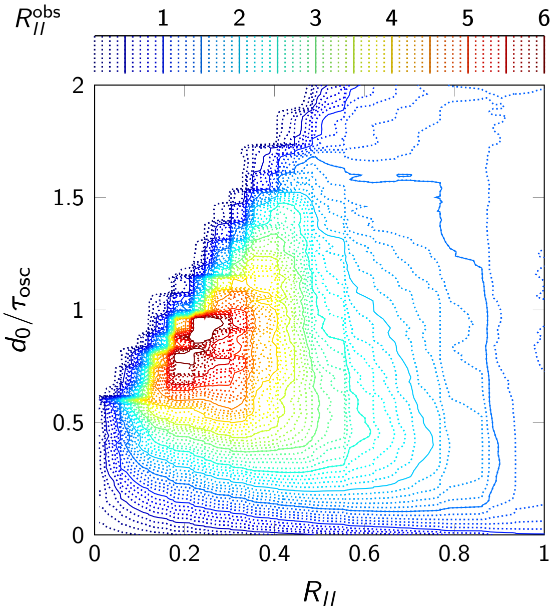
$$R_{ll} = \frac{N^{\mathrm{LNV}}}{N^{\mathrm{LNC}}} = \frac{\Delta m^2}{\Delta m^2 + 2\Gamma^2} .$$

R_{ll} simulation vs. calculation



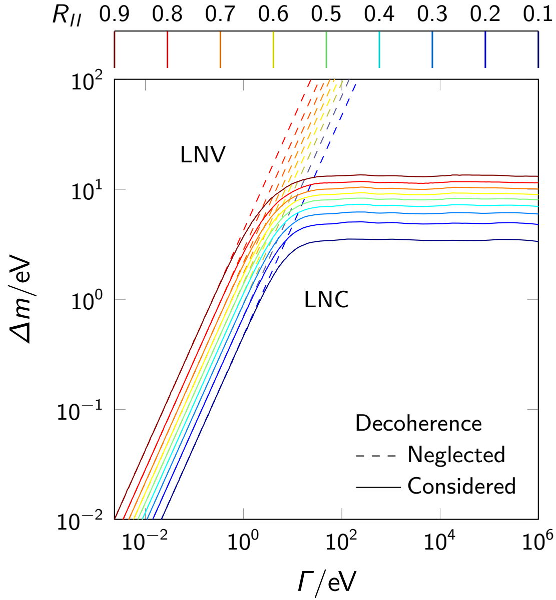
Impact of a d_0 cut and decoherence on R_{ll}

d_0 cut



Decoherence

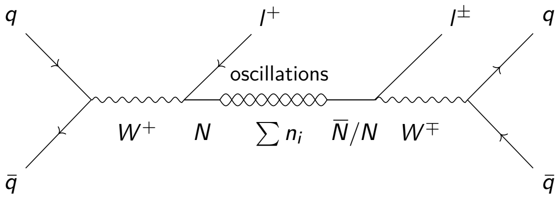
[Antusch et al. 2023]



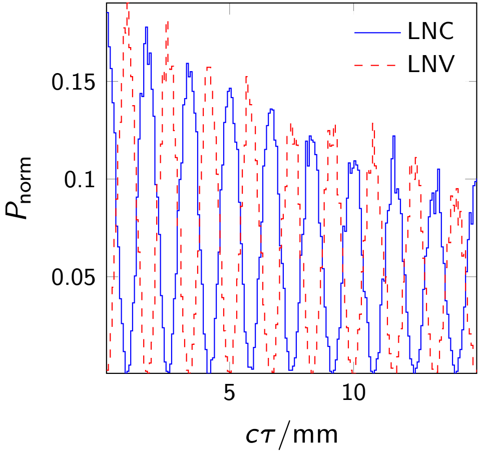
$$R_{ll} = \frac{P_{ll}^{\text{LNV}}}{P_{ll}^{\text{LNC}}} = \frac{\Delta m^2}{\Delta m^2 + 2\Gamma^2}$$

Heavy neutrino-antineutrino oscillations at the LHC

Production, oscillation, and decay



Proper time frame



Idea

Observe heavy neutrino-antineutrino oscillations in long-lived decays

Process

- Production of interaction eigenstates N or $\overline{N}$
- Oscillations between n_4 and n_5 due to Δm
- LNC decay into l^- or LNV decay into l^+

Simulation

- Model implementation in FeynRules
- Event generation in MadGraph
- CMS Detector simulation in Delphes

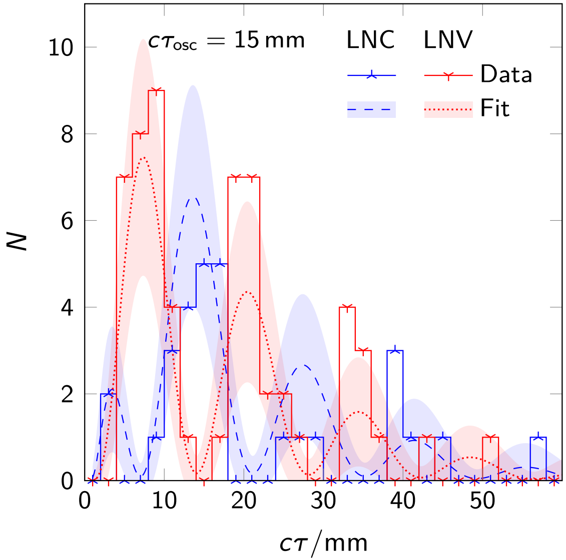
Observations after MadGraph

- No oscillations in lab frame
- Oscillations appear in proper time frame
- Crucial to reconstruct Lorentz factor γ
- Depends on final states without neutrinos

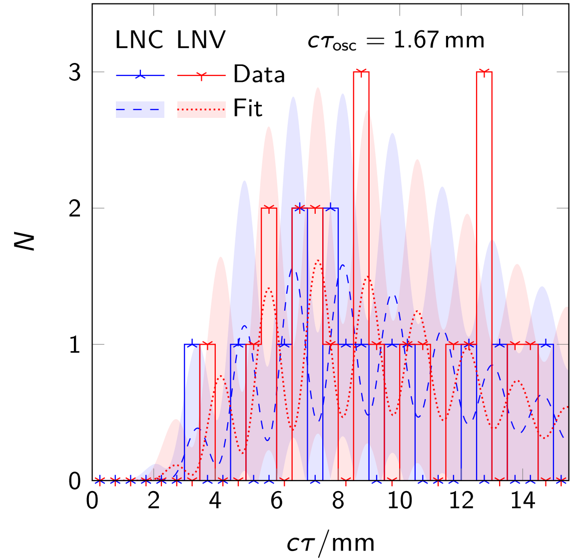
Detector simulation results at the LHC

[2212.00562]

BM1 with $c\tau_{\text{osc}} = 15\,\text{mm}$ and $Z = 6.66\,\sigma$



BM3 with $c\tau_{\text{osc}} = 1.67\,\text{mm}$ and $Z = 0.67\,\sigma$



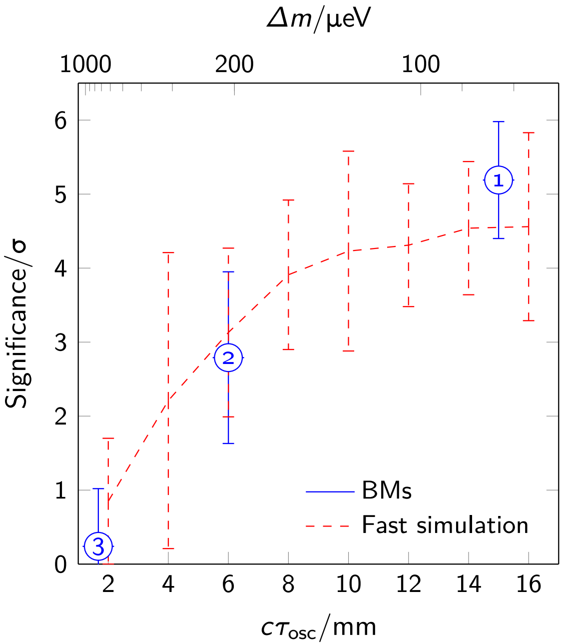
Results

- Large parts of accessible parameter space excluded by LHC
- HL-LHC can measure oscillations in some BMs with $5\,\sigma$

Detector simulation results

[2212.00562]

Discovery potential



HL-LHC

discovery possible

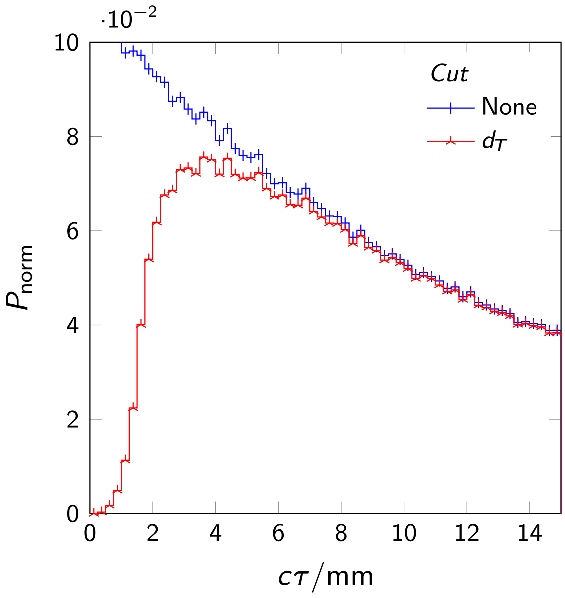
Large mass splitting hard to resolve
Neutrino Lorentz factor reconstruction crucial

Future work

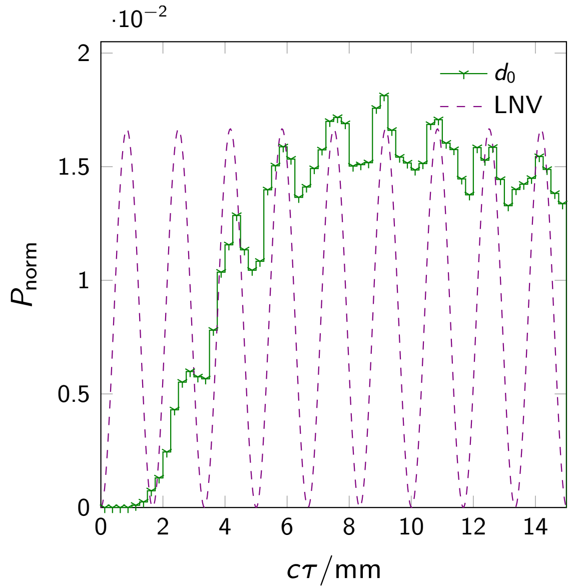
Properly simulate secondary vertex smearing
Improve Lorentz factor reconstruction

Impact of d_0 cut on $N = N_{\mathrm{LNC}} + N_{\mathrm{LNV}}$

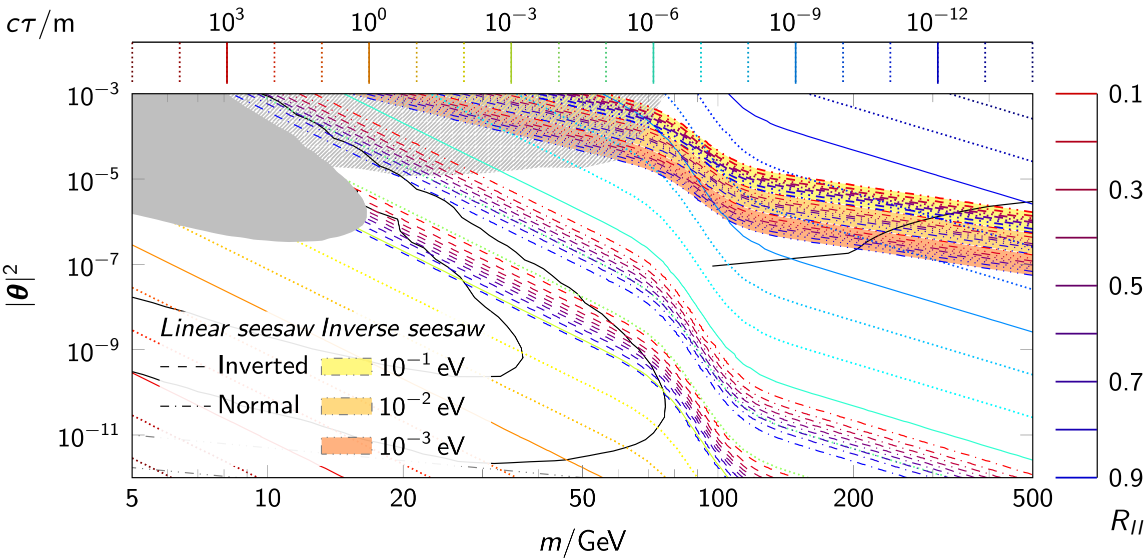
Impact of a d_T cut



LNV oscillation pattern after a d_0 cut



Reinterpretation of HNL searches as exclusion on low-scale seesaw models



Displaced searches

- Dirac HNLs good approximation when integrating over oscillations

Prompt LNV searches

- Model dependency governed by Δm
- Inconsequential above R_{ll} band

Depending on the Lagrangian one of the two benchmark models gets factor of 2 wrong

Conclusion

- Low-scale seesaw models predict pseudo-Dirac HNLs
- Pseudo-Dirac HNLs oscillate between LNC and LNV decays
- The symmetry protected seesaw scenario captures the relevant physics in a simple model
- We have implemented and published the necessary tools to simulate these oscillations
- Displaced HNL oscillations are resolvable at the HL-LHC
- Oscillations at the FCC are not studied at all
- R_{ll} is an oscillation effect and depends on e.g. d_0 cuts and decoherence

References

A. Blondel, A. de Gouvêa, and B. Kayser (2021). 'Z-boson decays into Majorana or Dirac heavy neutrinos'. In: *Phys. Rev. D* 104.5, p. 55027. DOI: 10.1103/PhysRevD.104.055027. arXiv: 2105.06576 [hep-ph]. №: FERMILAB-PUB-21-227-T

M. Drewes (2022). 'Distinguishing Dirac and Majorana Heavy Neutrinos at Lepton Colliders'. In: *PoS ICHEP* 2022, p. 608. DOI: 10.22323/1.414.0608. arXiv: 2210.17110 [hep-ph]. №: IRMP-CP3-22-52

S. Antusch, J. Hajer, and J. Rosskopp (Oct. 2022a). 'Simulating lepton number violation induced by heavy neutrino-antineutrino oscillations at colliders'. arXiv: 2210.10738 [hep-ph]

M. Drewes, J. Klarić, and J. López-Pavón (2022). 'New benchmark models for heavy neutral lepton searches'. In: *Eur. Phys. J. C* 82.12, p. 1176. DOI: 10.1140/epjc/s10052-022-11100-7. arXiv: 2207.02742 [hep-ph]

J. Hajer and J. Rosskopp (Oct. 2022). 'pSPSS: Phenomenological symmetry protected seesaw scenario'. FeynRules model file. DOI: 10.5281/zenodo.7268362. GitHub: heavy-neutral-leptons/pSPSS. URL: feynrules.irmp.ucl.ac.be/wiki/pSPSS

S. Antusch, J. Hajer, and J. Rosskopp (2023). 'Decoherence effects on lepton number violation from heavy neutrino-antineutrino oscillations'. in preparation

S. Antusch, J. Hajer, and J. Rosskopp (Dec. 2022b). 'Beyond lepton number violation at the HL-LHC: Resolving heavy neutrino-antineutrino oscillations'. arXiv: 2212.00562 [hep-ph]