Measuring lepton number violation at colliders

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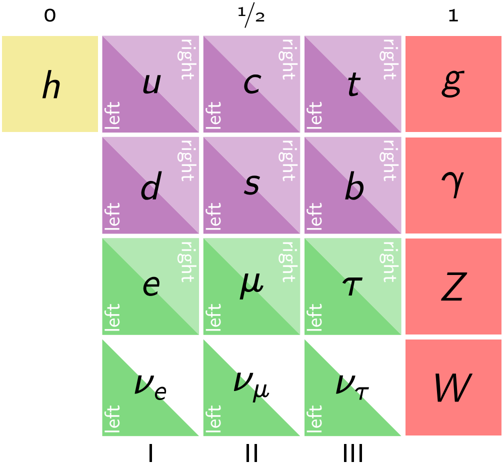
Searching for long-lived particles at the LHC and beyond:
Thirteenth workshop of the LLP Community

FCT Fundação para a Ciência e a Tecnologia

Standard Model neutrinos

Standard Model particle content



0	1/2			1
h	u	c	t	g
	d	s	b	γ
	e	μ	τ	Z
	ν_e	ν_μ	ν_τ	W
	I	II	III	

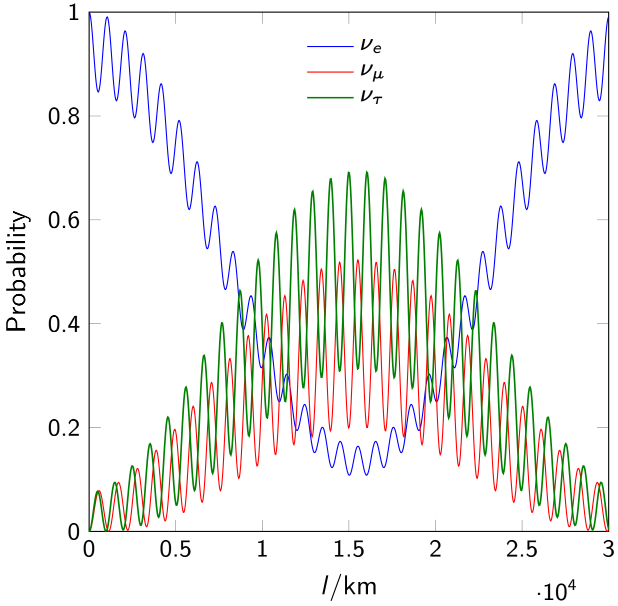
Neutrinos ν_α stand out

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

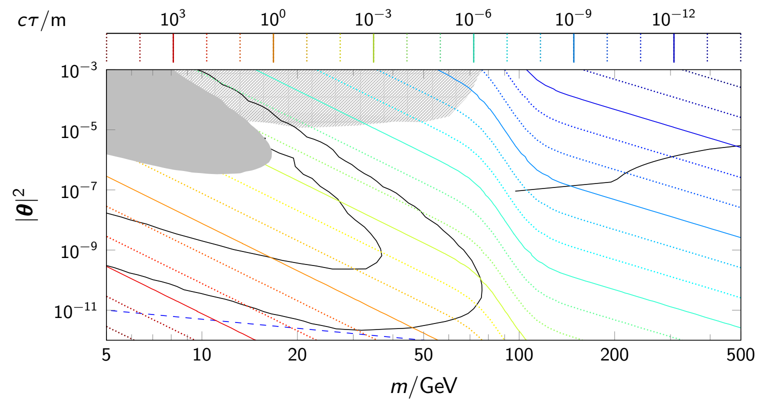
Simplest benchmark model candidates

Interactions of a Majorana or Dirac heavy neutral lepton (HNL)

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

Seesaw mass

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



Dirac

- No massive light neutrino
- No lepton number violation

Majorana

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

Inconsistency between both models

Predicted decay width proportional to number of Majorana DOFs.

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

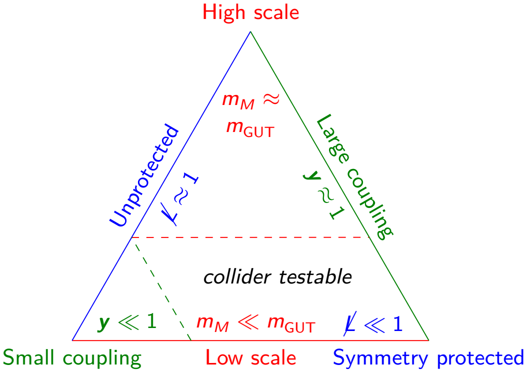
Neutrino oscillation pattern requires

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

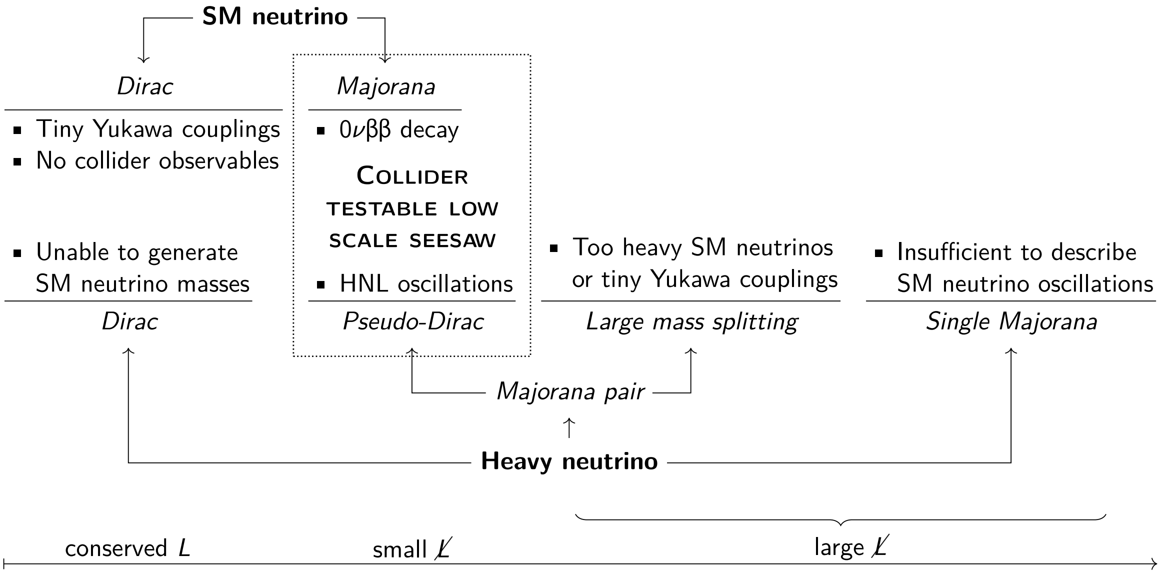


Neutrino masses are small for

- large m_M (GUT scale seesaw)
- small $\boldsymbol{y}$ (Naive seesaw line)
- symmetry protected cancellation

Are HNLs Majorana or Dirac Fermions?

[2210.10738]



SM neutrino

Dirac

- Tiny Yukawa couplings
- No collider observables

Majorana

- $0\nu\beta\beta$ decay

COLLIDER TESTABLE LOW SCALE SEESAW

- Unable to generate SM neutrino masses

Dirac

- HNL oscillations

Pseudo-Dirac

- Too heavy SM neutrinos or tiny Yukawa couplings

Large mass splitting

- Insufficient to describe SM neutrino oscillations

Single Majorana

Majorana pair

Heavy neutrino

conserved L small $\not{L}$ large $\not{L}$

Single Majorana and Dirac HNLs are

not predicted by low-scale seesaw models

Distinguishing Dirac from Majorana HNL

not a well posed research question/goal

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 / Γ wrong	↯
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 parameter set for single pseudo-Dirac

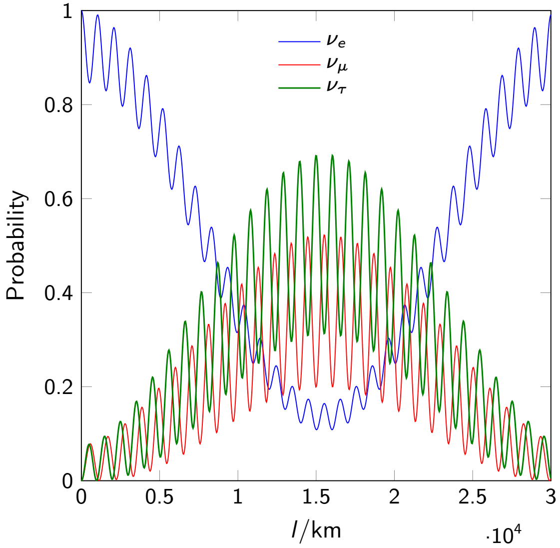
- Mass m
- Coupling vector $\boldsymbol{\theta}$
- Mass splitting Δm

The symmetry protected seesaw scenario (SPSS) is the minimal viable model

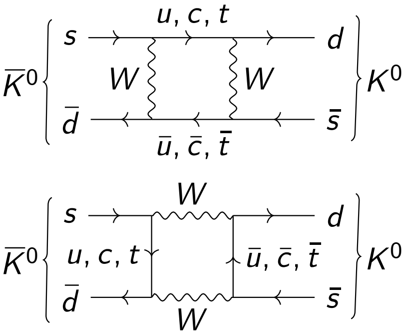
Heavy neutrino-antineutrino oscillations

Oscillations in the Standard Model

Light neutrinos



Mesons



Heavy neutrino-antineutrino oscillations

Oscillations between

LNC and LNV processes

Damping due to decoherence

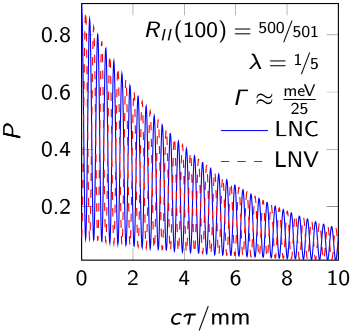
governed by λ

Oscillation length

governed by mass splitting Δm

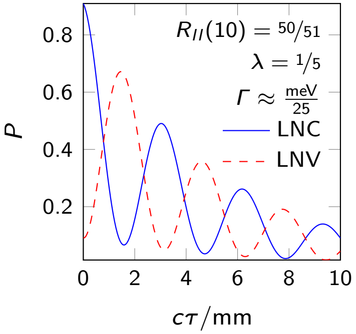
$$P_{\text{osc}}^{\text{LNC}/\text{LNV}}(\tau) = \frac{1 \pm \cos(\Delta m \tau)\exp(-\lambda)}{2}$$

Short oscillation length



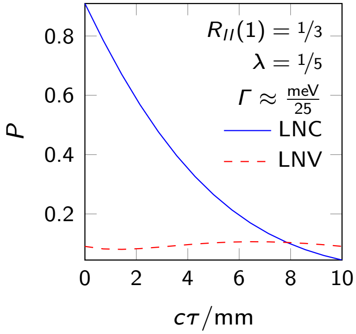
- Oscillations not resolvable
- Large R_{ll}
- ‘Majorana’ limit

Intermediate oscillation length



- Oscillations potentially measurable
- Pseudo-Dirac character crucial

Long oscillation length



- LNV strongly suppressed
- Small R_{ll}
- ‘Dirac’ limit

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

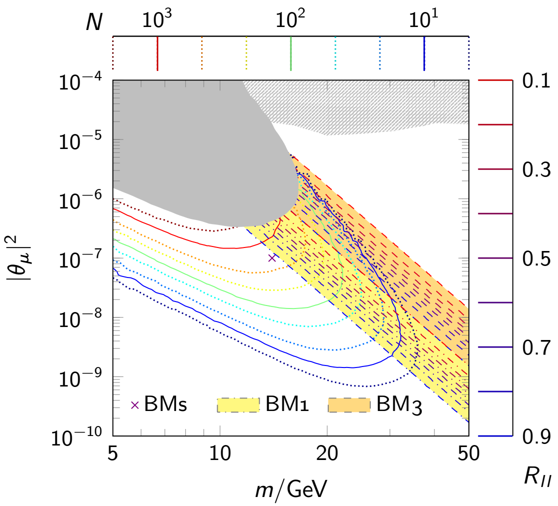
```
BLOCK PSPSS #
1   1.000000e+02   # mmaj
2   1.000000e-12   # deltam
3   0.000000e+00   # theta1
4   1.000000e-03   # theta2
5   0.000000e+00   # theta3
6   0.000000e+00   # damping
```

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()
```

Monte Carlo Simulation

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

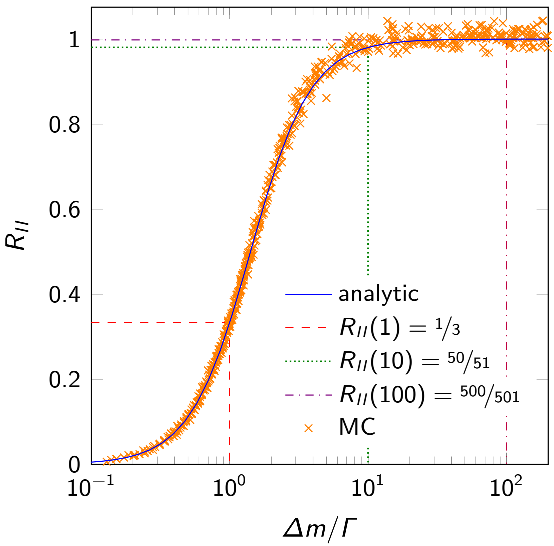


BM	$\Delta m/\mu\mathrm{eV}$	$c\tau_{\mathrm{osc}}/\mathrm{mm}$	R_{ll}
1	82.7	15	0.9729
2	207	6	0.9956
3	743	1.67	0.9997

Integrate oscillations from origin to infinity

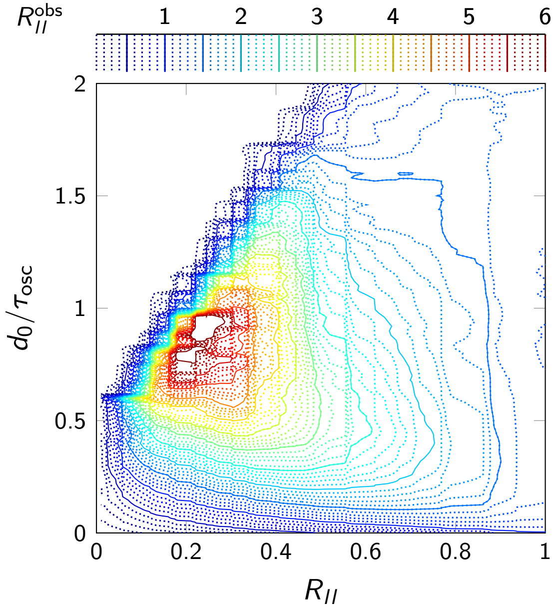
$$R_{ll} = \frac{N^{\mathrm{LNV}}}{N^{\mathrm{LNC}}} = \frac{\Delta m^2}{\Delta m^2 + 2\Gamma^2} .$$

R_{ll} simulation vs. calculation



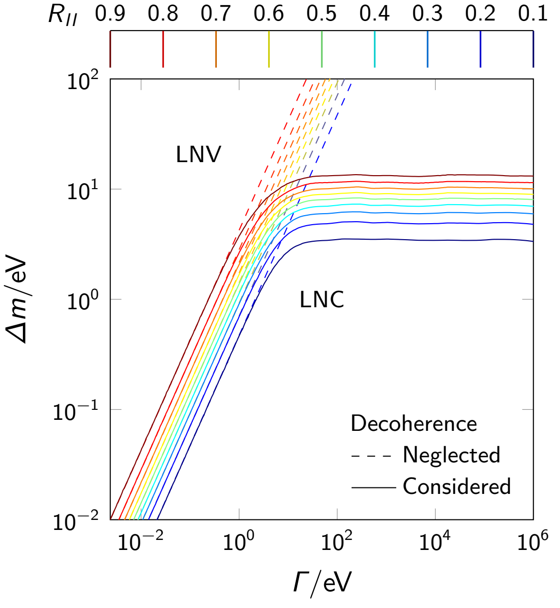
Impact of a d_0 cut and decoherence on R_{ll}

d_0 cut



Decoherence

[Antusch et al. 2023]

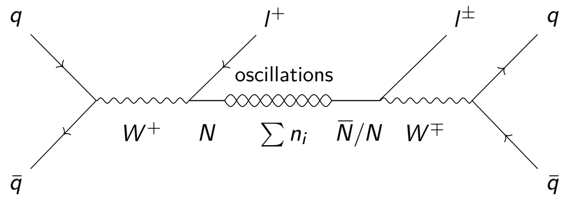


R_{ll} is a

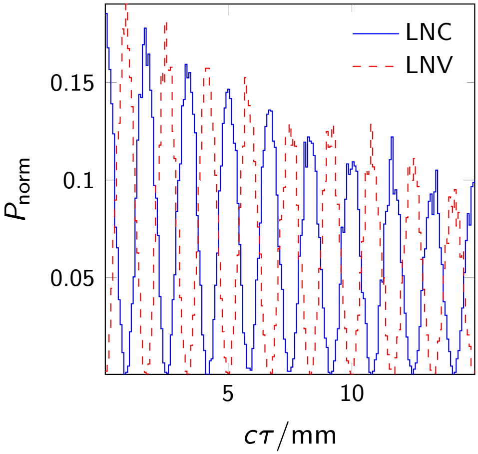
- great observable
- terrible benchmark model parameter

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

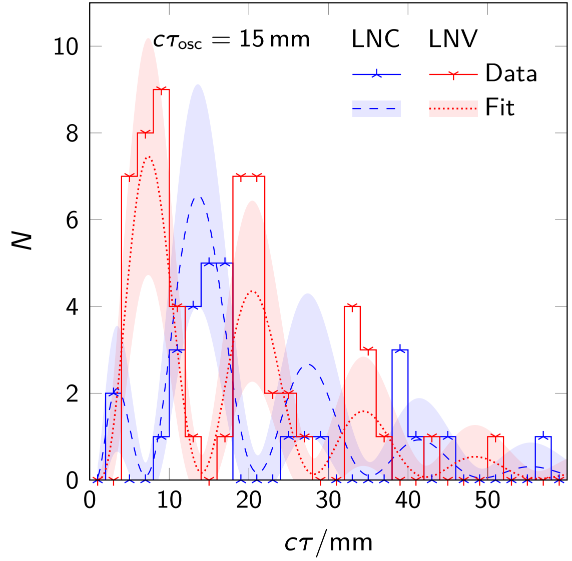
Observations after MADGRAPH

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

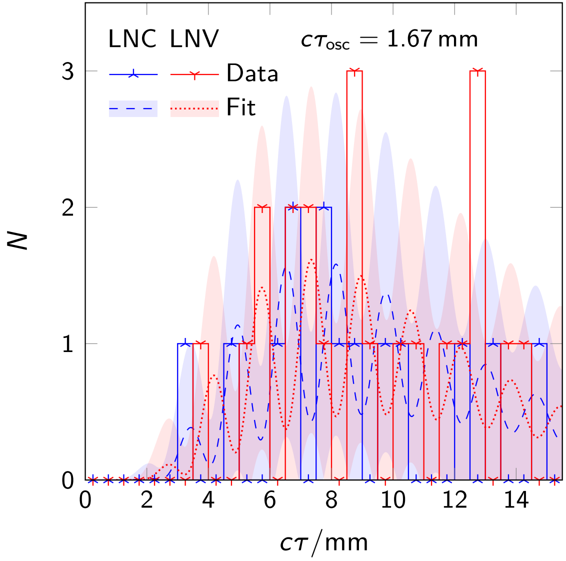
Detector simulation results at the LHC

[2212.00562]

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



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



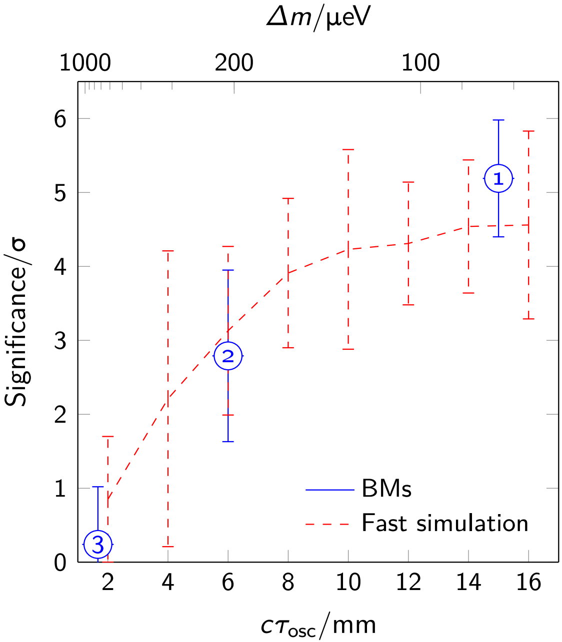
Results

- 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

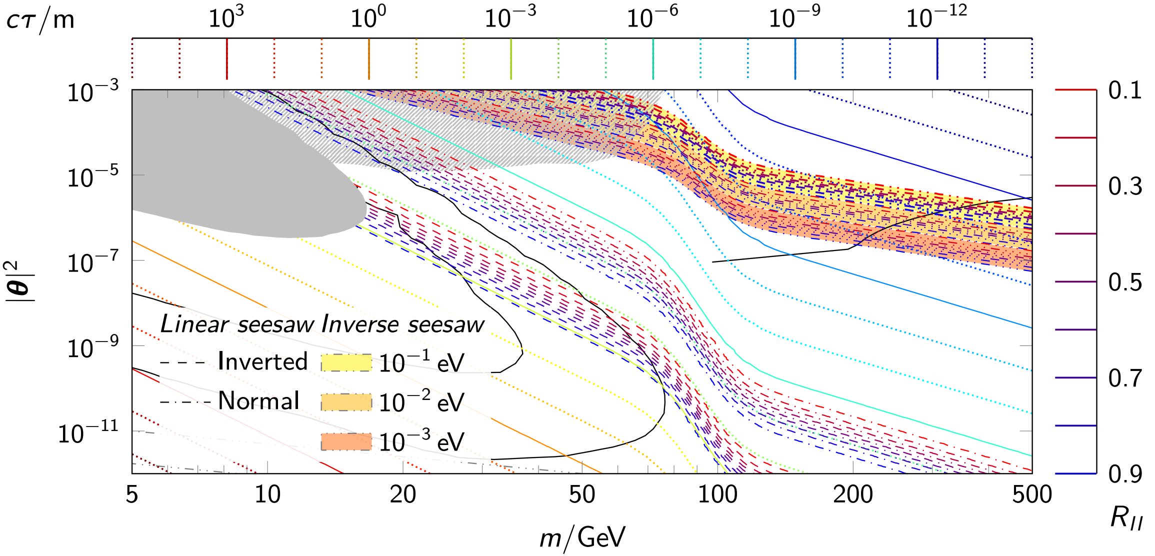
discovery possible

- Large mass splitting hard to resolve
- Lorentz factor reconstruction crucial

Future work

- Properly simulate secondary vertex smearing
- Improve Lorentz factor reconstruction
- Simulate signals at other detectors and colliders

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

Single Majorana decay widths are wrong by a factor of 2

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
- R_{ll} is an oscillation effect and depends on e.g. d_0 cuts and decoherence

References

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]

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]

Technical details

Single pseudo-Dirac symmetry protected seesaw scenario (SPSS) [2210.10738]

Exact limit

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

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

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

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 $\boldsymbol{\theta}$

Special cases captured by the symmetry protected seesaw

[2210.10738]

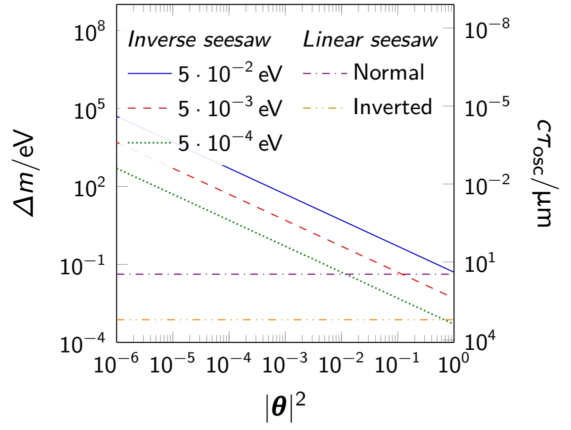
	Linear seesaw $\boldsymbol{\mu}_D$	Inverse seesaw μ_M	Seesaw independent μ'_M
$M_n =$	$\begin{pmatrix} 0 & \boldsymbol{m}_D & \boldsymbol{\mu}_D \\ \boldsymbol{m}_D^\mathsf{T} & 0 & m_M \\ \boldsymbol{\mu}_D^\mathsf{T} & m_M & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & \boldsymbol{m}_D & 0 \\ \boldsymbol{m}_D^\mathsf{T} & 0 & m_M \\ 0 & m_M & \mu_M \end{pmatrix}$	$\begin{pmatrix} 0 & \boldsymbol{m}_D & 0 \\ \boldsymbol{m}_D^\mathsf{T} & \mu'_M & m_M \\ 0 & m_M & 0 \end{pmatrix}$
$M_\nu =$	$\boldsymbol{\mu}_D \otimes \boldsymbol{\theta}$	$\mu_M \boldsymbol{\theta} \otimes \boldsymbol{\theta}$	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		$m_\nu = 0.5\,\text{meV}$
		$m_\nu = 5\,\text{meV}$
		$m_\nu = 50\,\text{meV}$

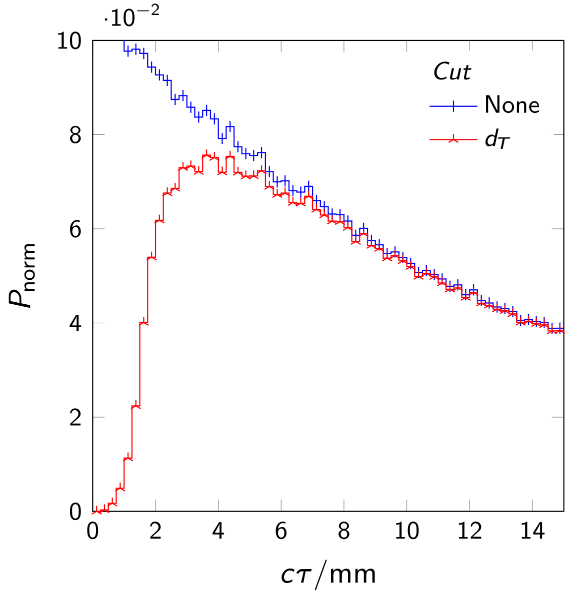
Generic seesaw

All small parameter μ are nonzero



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