Heavy Neutrino-Antineutrino Oscillations at Colliders

Bruno M. S. Oliveira

Centro de Física Teórica de Partículas (CFTP), Instituto Superior Técnico (IST), Universidade de Lisboa (UL)

CERN/FIS-PAR/0002/2021 and CERN/FIS-PAR/0019/2021

PLANCK2024

The 26th International Conference From the Planck Scale to the Electroweak Scale

Standard Model

$$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$$

u	c	t	g	γ
d	s	b	Z	W
e	μ	τ	H	
ν_e	ν_μ	ν_τ		

Standard Model

$$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$$

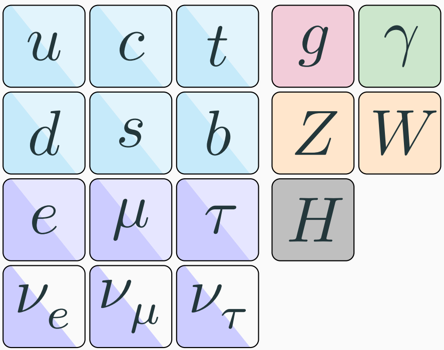
u	c	t	g	γ
d	s	b	Z	W
e	μ	τ	H	
ν_e	ν_μ	ν_τ		

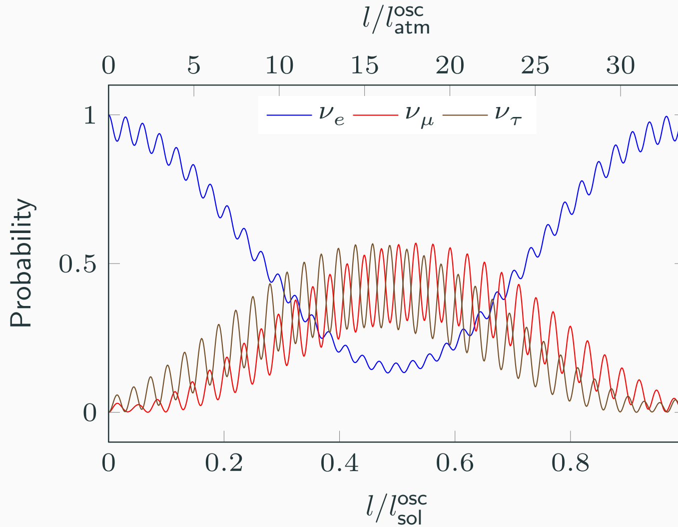
Neutrinos are special:

Colourless Neutral **Only left-chiral** **Massless**

Standard Model

$$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$$



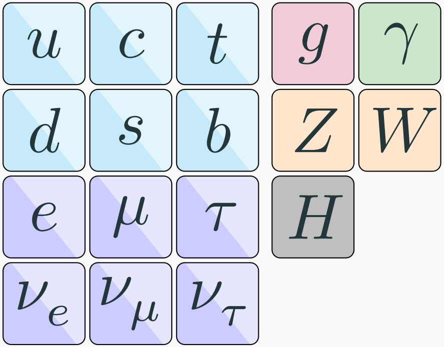


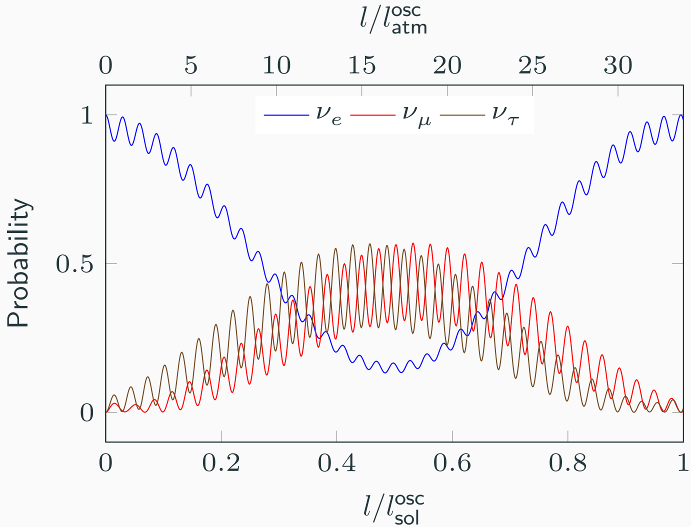
Neutrinos are special:

Colourless | Neutral | **Only left-chiral** | **Massless**

Unable to explain neutrino flavour oscillations

$$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$$





Neutrinos aren't so special:

Colourless | Neutral | ~~Only left-chiral~~ | ~~Massless~~

Explains neutrino flavour oscillations

Seesaw Mechanism [2210.10738, 2212.00562]

Dirac Mass Lagrangian:

$$\mathcal{L}_D = -[M_D]_{\alpha i} \overline{\nu_{L\alpha}} \nu_{Ri} + \text{h.c.}$$

Conserves lepton number (LNC)

Majorana Mass Lagrangian:

$$\mathcal{L}_M = -\frac{1}{2}[M_M^R]_{ij} \overline{\nu_{Ri}} \nu_{Rj} + \text{h.c.}$$

Violates lepton number (LNV)

Seesaw Mechanism [2210.10738, 2212.00562]

Dirac Mass Lagrangian:

$$\mathcal{L}_D = -[M_D]_{\alpha i}\overline{\nu_{L\alpha}}\nu_{Ri} + \text{h.c.}$$

Conserves lepton number (LNC)

Majorana Mass Lagrangian:

$$\mathcal{L}_M = -\frac{1}{2}[M_M^R]_{ij}\overline{\nu_{Ri}}\nu_{Rj} + \text{h.c.}$$

Violates lepton number (LNV)

Light Neutrinos ν:

$$M_\nu \simeq -\theta M_M^R \theta^T$$

Left-Right Mixing:

$$\theta = [M_D][M_M^R]^{-1}$$

Heavy Neutrinos n:

$$M_n \simeq M_M^R$$

Dirac Mass Lagrangian:

$$\mathcal{L}_D = -[M_D]_{\alpha i}\overline{\nu_{L\alpha}}\nu_{Ri} + \text{h.c.}$$

Conserves lepton number (LNC)

Majorana Mass Lagrangian:

$$\mathcal{L}_M = -\frac{1}{2}[M_M^R]_{ij}\overline{\nu_{Ri}}\nu_{Rj} + \text{h.c.}$$

Violates lepton number (LNV)

Light Neutrinos ν:

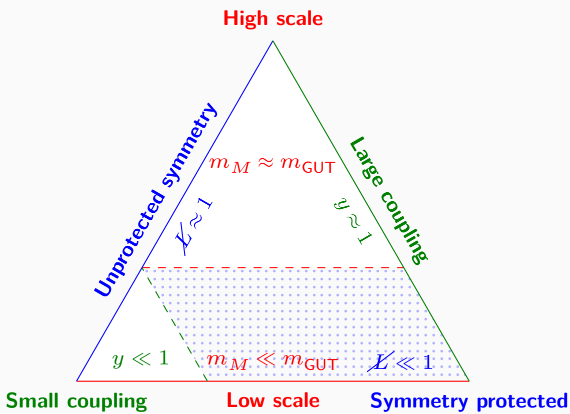
$$M_\nu \simeq -\theta M_M^R \theta^T$$

Left-Right Mixing:

$$\theta = [M_D][M_M^R]^{-1}$$

Heavy Neutrinos n:

$$M_n \simeq M_M^R$$



Dirac Mass Lagrangian:

$$\mathcal{L}_D = -[M_D]_{\alpha i}\overline{\nu_{L\alpha}}\nu_{Ri} + \text{h.c.}$$

Conserves lepton number (LNC)

Majorana Mass Lagrangian:

$$\mathcal{L}_M = -\frac{1}{2}[M_M^R]_{ij}\overline{\nu_{Ri}}\nu_{Rj} + \text{h.c.}$$

Violates lepton number (LNV)

Light Neutrinos ν:

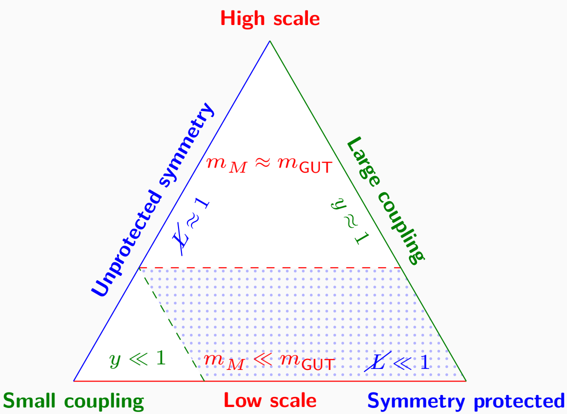
$$M_\nu \simeq -\theta M_M^R \theta^T$$

Left-Right Mixing:

$$\theta = [M_D][M_M^R]^{-1}$$

Heavy Neutrinos n:

$$M_n \simeq M_M^R$$



Two neutrinos:

$$M = \begin{pmatrix} 0_{3\times3} & m_D^{(1)T} & m_D^{(2)T} \\ m_D^{(1)} & m_M^{(1)} & 0 \\ m_D^{(2)} & 0 & m_M^{(2)} \end{pmatrix}$$

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

Symmetry Protected Seesaw Scenarios [2210.10738]

Symmetric limit

$$M = \begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & m_M \\ 0 & m_M & 0 \end{pmatrix}$$

Mild symmetry breaking

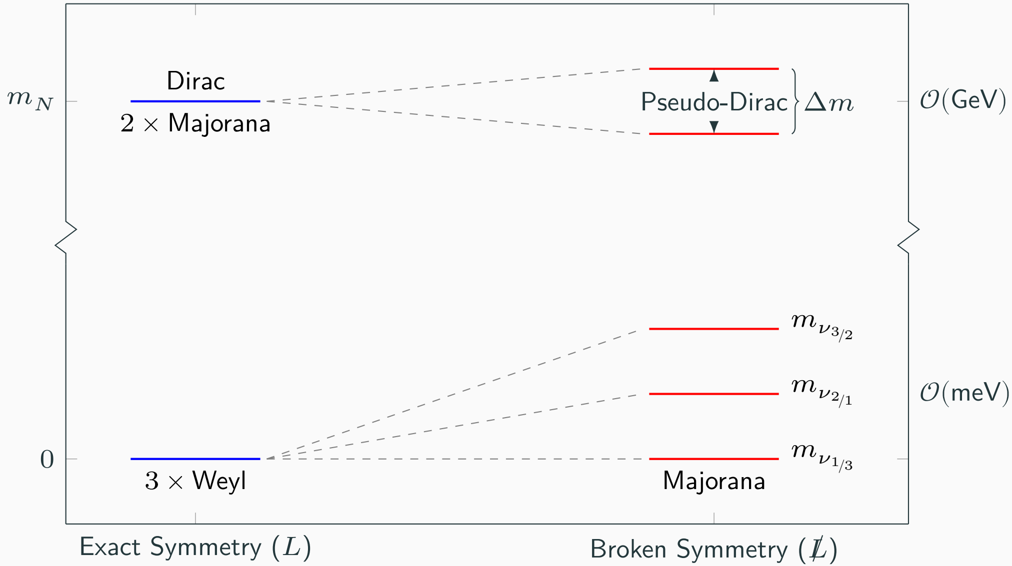
$$M = \begin{pmatrix} 0 & m_D^T & \mu_D^T \\ m_D & \mu'_M & m_M \\ \mu_D & m_M & \mu_M \end{pmatrix}$$

$$\mu_D, \mu_M, \mu'_M \ll m_M$$

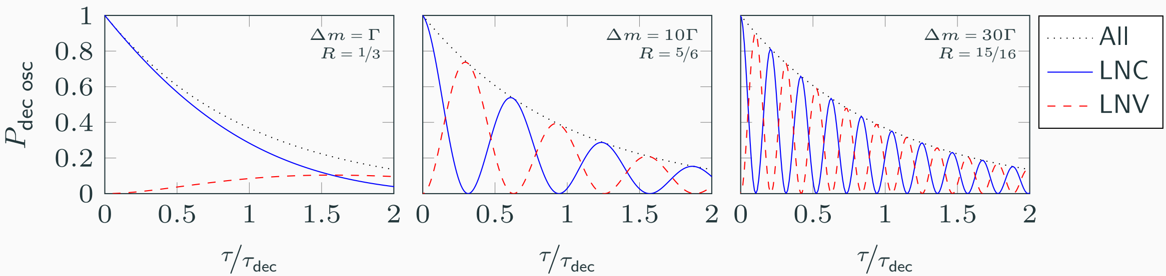
Large symmetry breaking

$$M = \begin{pmatrix} 0 & m_D^T & \hat{m}_D^T \\ m_D & \hat{m}'_M & m_M \\ \hat{m}_D & m_M & \hat{m}_M \end{pmatrix}$$

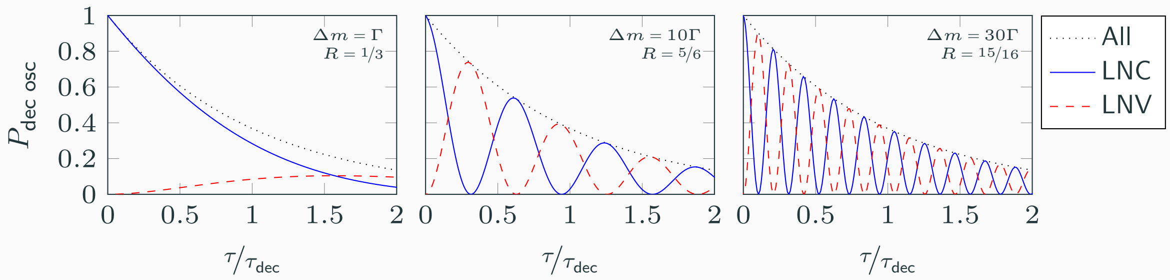
$$\hat{m}_D, \hat{m}_M, \hat{m}'_M \sim m_M$$



Decaying Oscillations [2012.05763, 2210.10738, 2212.00562, 2307.06208]



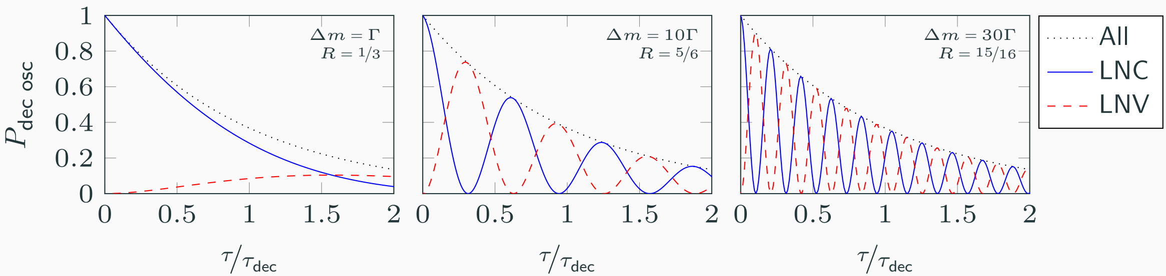
$$P^{\text{LNC}/\text{LNV}}_{\text{dec osc}}(\tau) = \left[P_{\text{decay}}(\tau) = \Gamma e^{-\Gamma\tau}\right] \times \left[P^{\text{LNC}/\text{LNV}}_{\text{osc}}(\tau) = \frac{1}{2}[1 \pm e^{-\lambda}\cos(\Delta m \tau)]\right]$$



$$P^{\text{LNC}/\text{LNV}}_{\text{dec osc}}(\tau) = \left[P_{\text{decay}}(\tau) = \Gamma e^{-\Gamma\tau}\right] \times \left[P^{\text{LNC}/\text{LNV}}_{\text{osc}}(\tau) = \frac{1}{2}[1 \pm e^{-\lambda}\cos(\Delta m\tau)]\right]$$

Time-integrated behaviour:

$$\underbrace{R = 0}_{\text{Pure Dirac HNL}} < \underbrace{R = \frac{P^{\text{LNV}}}{P^{\text{LNC}}} = \frac{\Delta m^2}{\Delta m^2 + 2\Gamma^2}}_{\text{Pseudo-Dirac HNL}} < \underbrace{R = 1}_{\text{Single Majorana HNL}}$$



$$P^{\text{LNC}/\text{LNV}}_{\text{dec osc}}(\tau) = \left[P_{\text{decay}}(\tau) = \Gamma e^{-\Gamma\tau}\right] \times \left[P^{\text{LNC}/\text{LNV}}_{\text{osc}}(\tau) = \frac{1}{2}[1 \pm e^{-\lambda}\cos(\Delta m\tau)]\right]$$

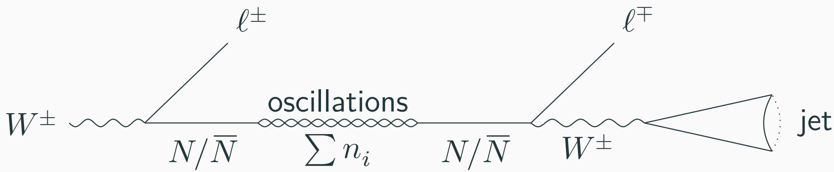
Time-integrated behaviour:

$$\underbrace{R = 0}_{\text{Pure Dirac HNL}} < \underbrace{R = \frac{P^{\text{LNV}}}{P^{\text{LNC}}} = \frac{\Delta m^2}{\Delta m^2 + 2\Gamma^2}}_{\text{Pseudo-Dirac HNL}} < \underbrace{R = 1}_{\text{Single Majorana HNL}}$$

More details in [Jan Hajer's Talk]

Detecting Lepton Number Violation

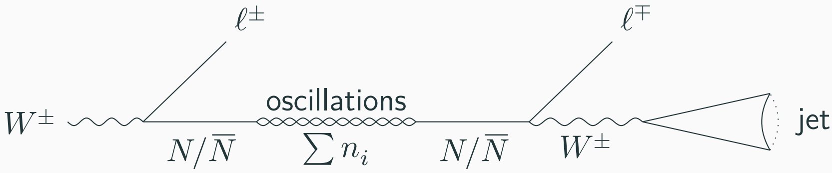
W **decay** (LHC, FCC-ee's WW Threshold):



LNV **can** be directly measured

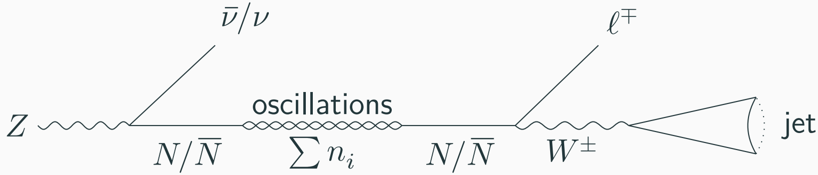
Detecting Lepton Number Violation

W **decay** (LHC, FCC-ee's WW Threshold):



LNV **can** be directly measured

Z **decay** (FCC-ee's Z Pole):

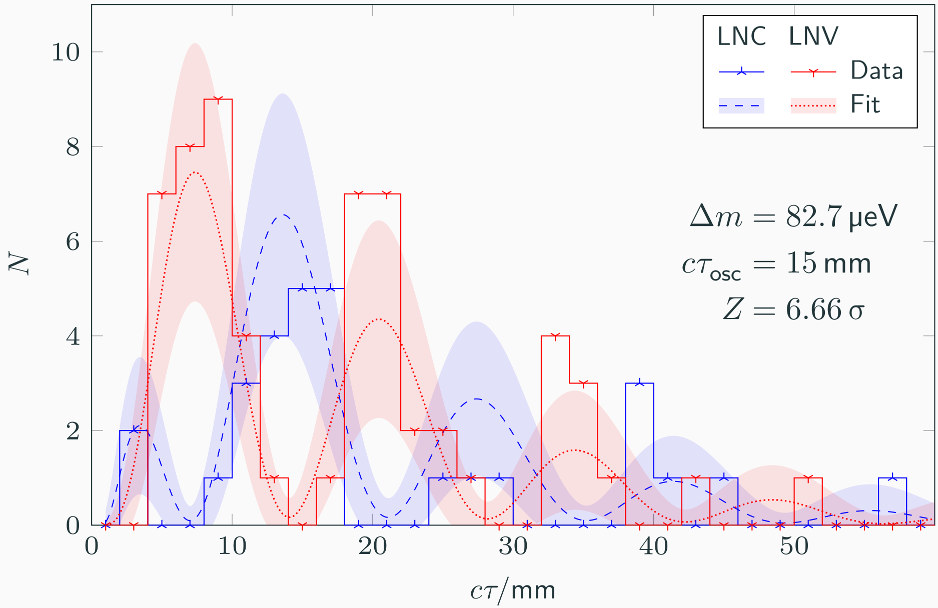


LNV **cannot** be directly measured

$\Downarrow$

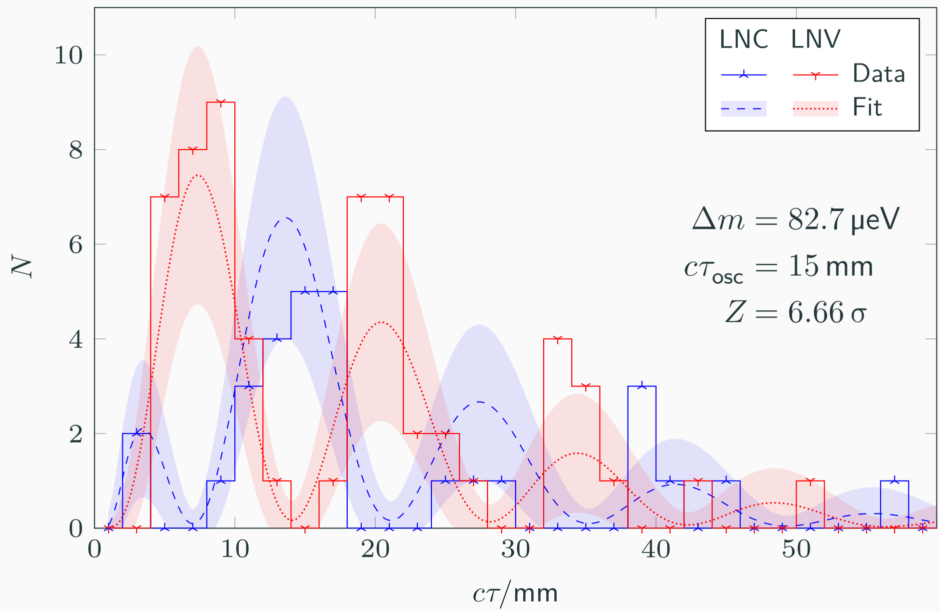
Must be **induced** from final state observables

Resolving Heavy Neutrino-Antineutrino Oscillations [2212.00562]



Group LNC/LNV events ⇒ **Fit** oscillations ⇒ **Analyse** significance

Resolving Heavy Neutrino-Antineutrino Oscillations [2212.00562]



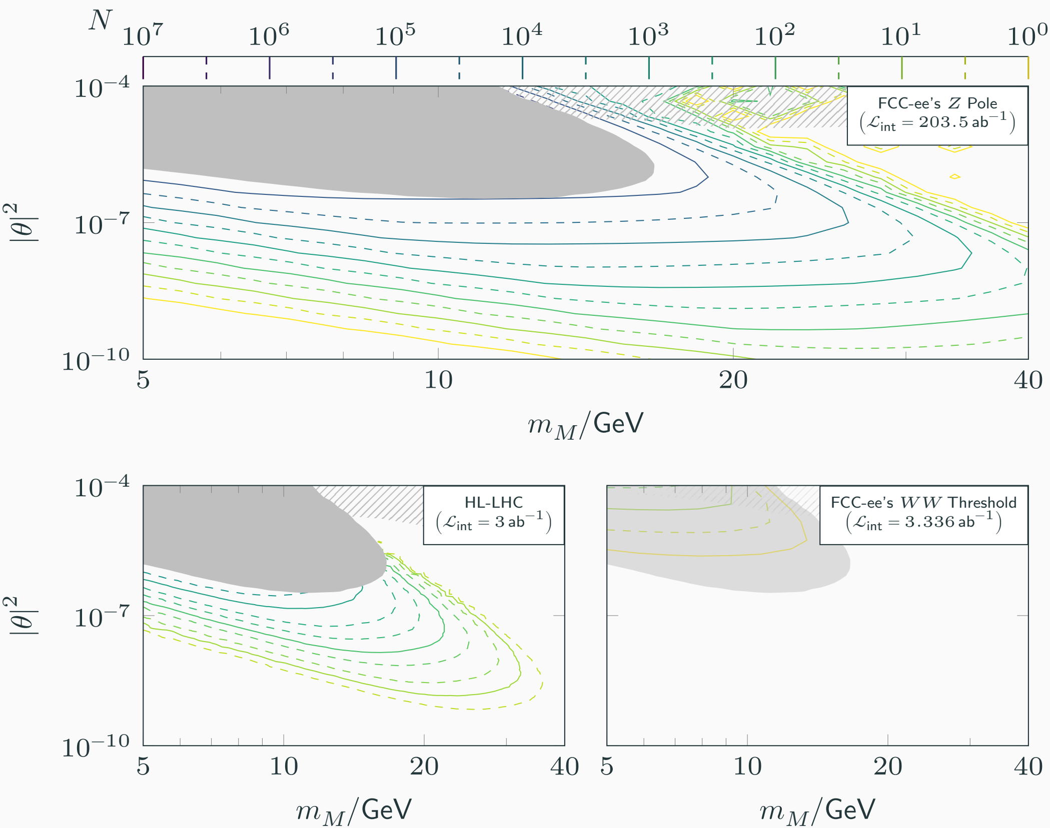
Group LNC/LNV events ⇒ **Fit** oscillations ⇒ **Analyse** significance

HL-LHC:

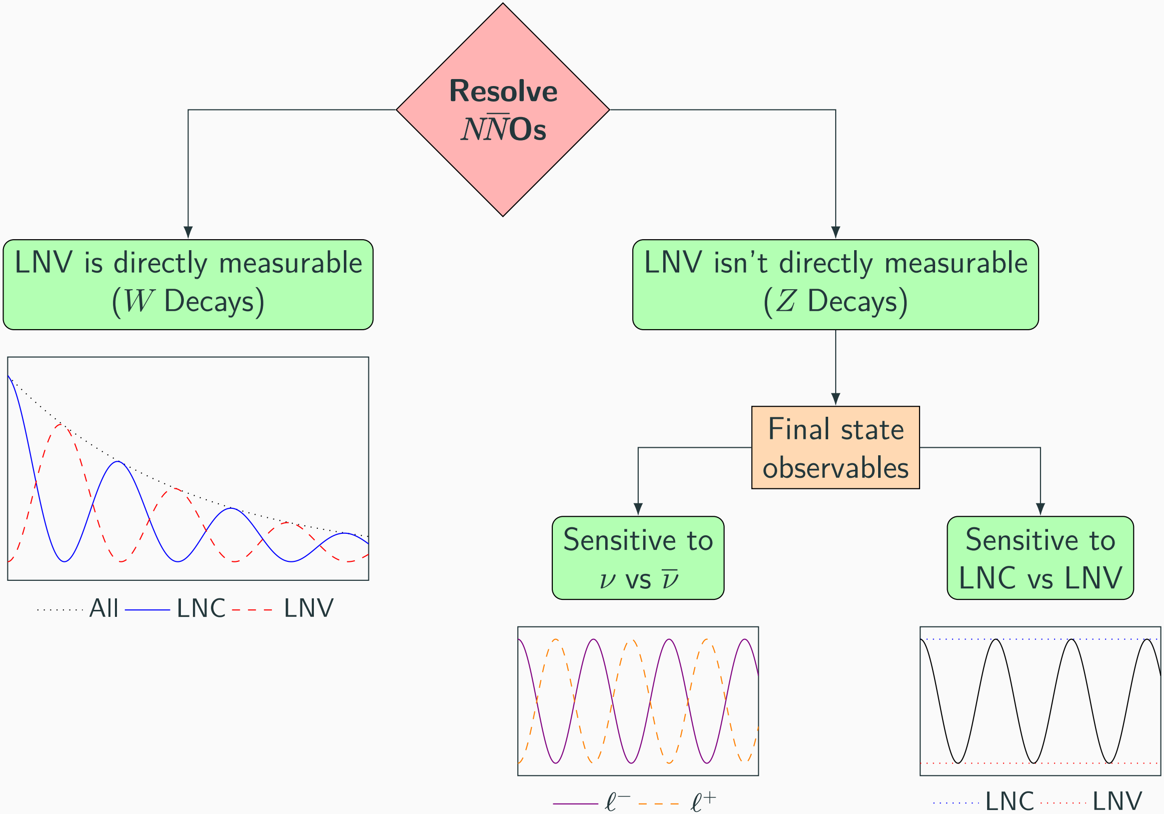
Capable of resolving $N\overline{N}$Os

Luminosity ⇒ Narrow frequency spectrum

Detecting Heavy Neutral Leptons

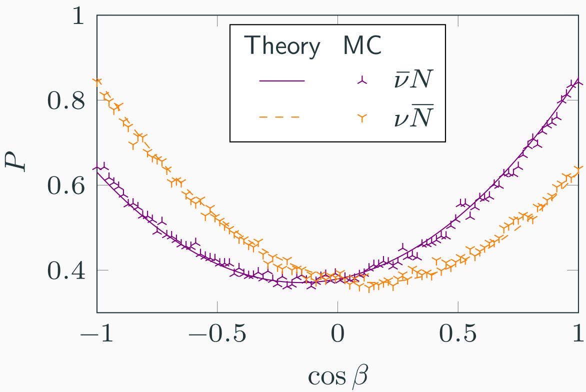


Resolving Heavy Neutrino-Antineutrino Oscillations [2212.00562, 2308.07297, Preliminary]

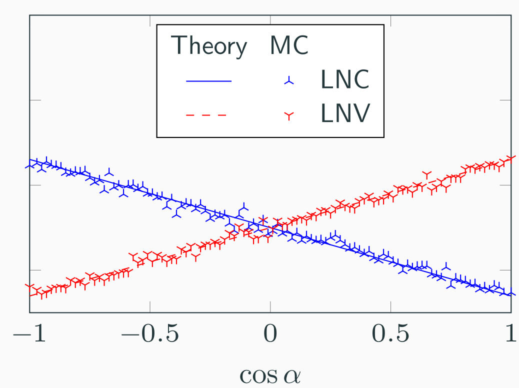


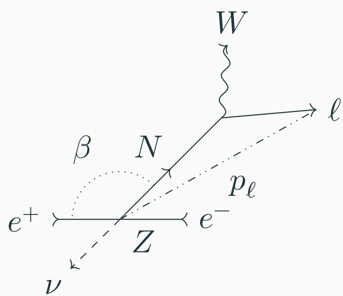
Final State Observables [2308.07297, Preliminary]

Forward-Backward Asymmetry

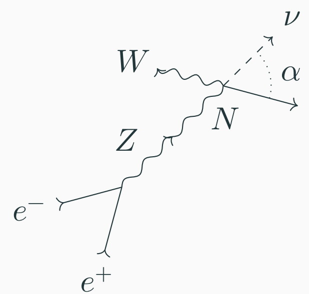


Opening Angle Asymmetry





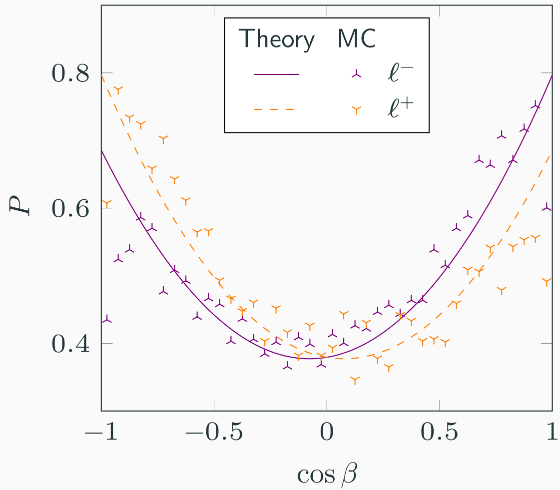
Lab frame (p_Z^2)

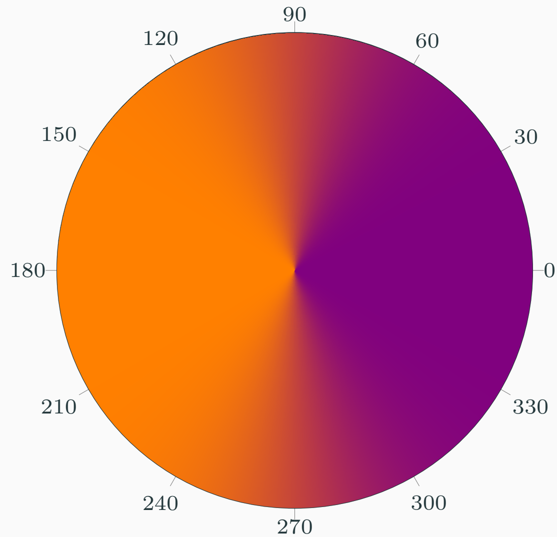


HNL's rest frame (p_N^2)

Pure Dirac HNL:

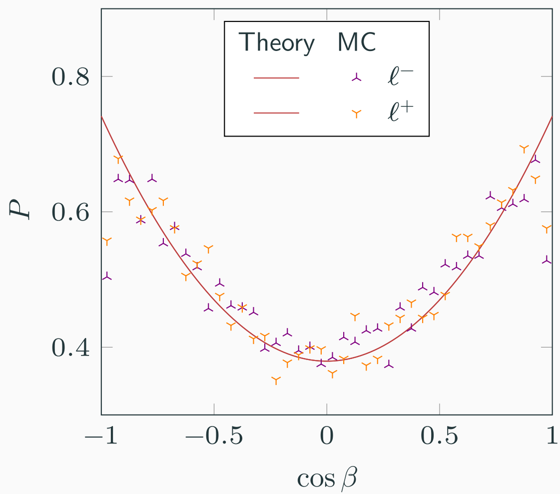
$$P_{\ell^\mp}(\beta) = P^D_{N/\overline{N}}(\beta) = \frac{3}{4}\frac{m_Z^2\left[\gamma_{L/R}(1+\cos\beta)^2 + \gamma_{R/L}(1-\cos\beta)^2\right] + m^2\sin^2\beta}{2m_Z^2 + m^2}$$

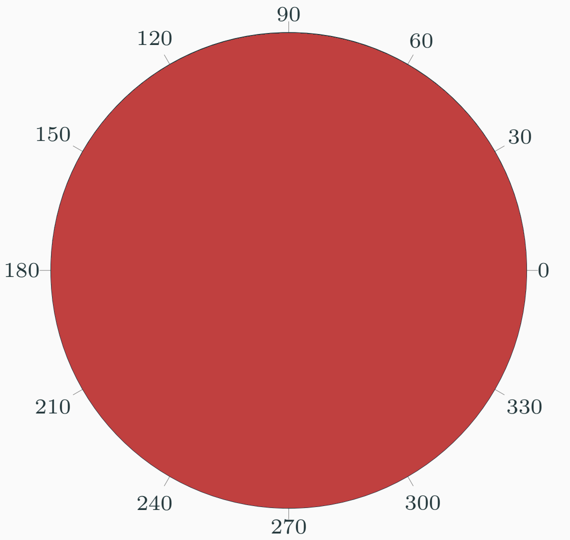




Single Majorana HNL:

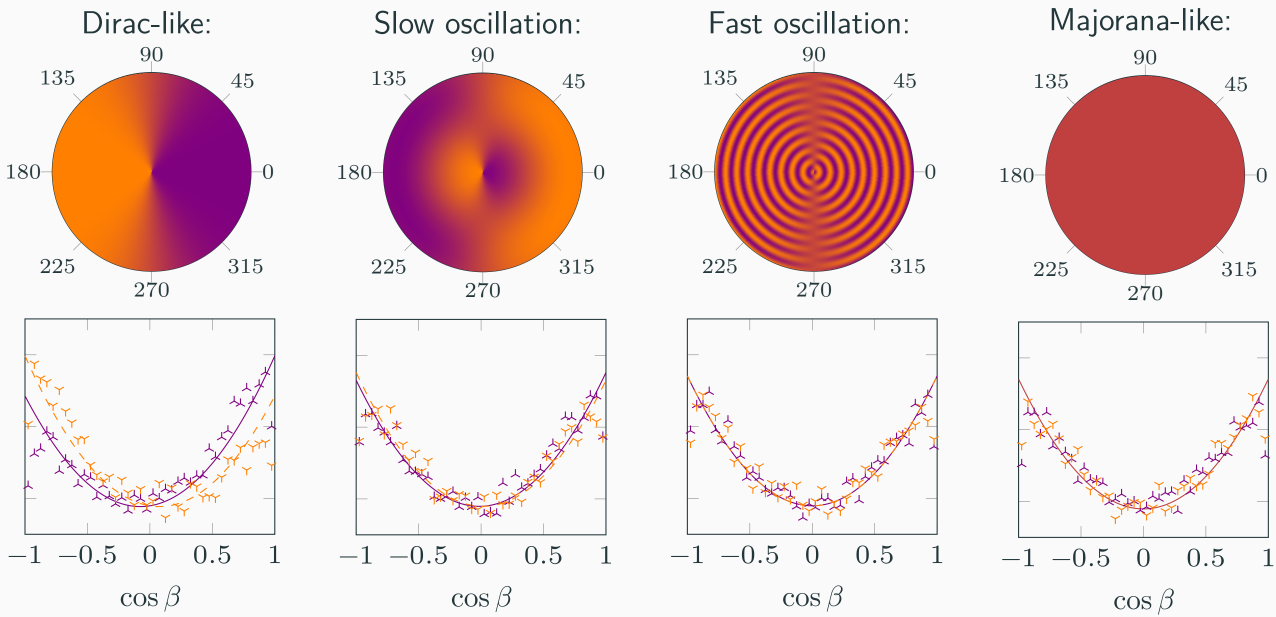
$$P_N^M(\cos\beta) = \frac{P_N(\cos\beta) + P_{\overline{N}}(\cos\beta)}{2} = \frac{3}{4}\frac{m_Z^2(1+\cos^2\beta) + m^2\sin^2\beta}{2m_Z^2 + m^2}$$

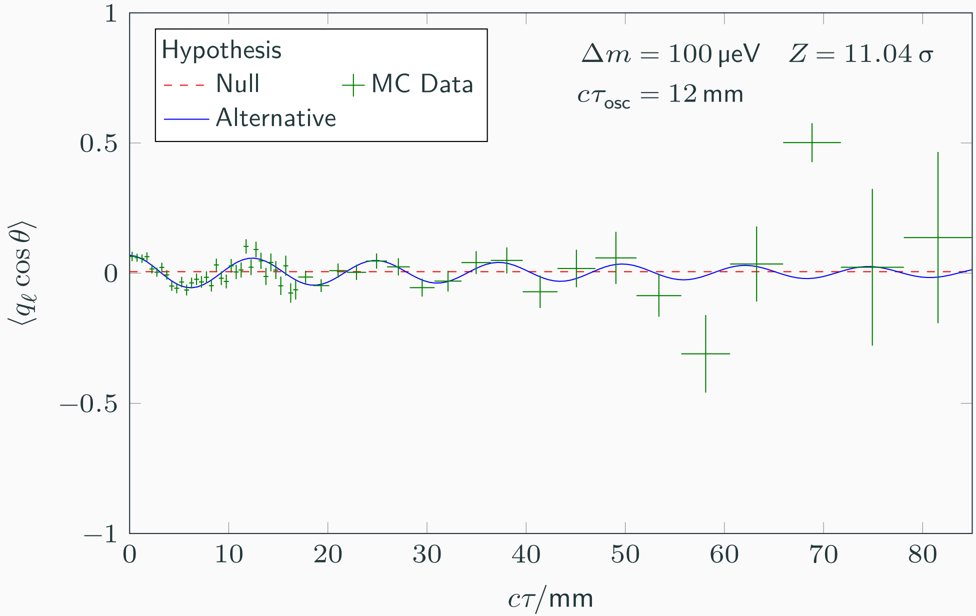




$$P_{\ell^{\mp}}(\tau, \cos\beta) = P_{\text{decay}}(\tau)\left[P_N^{+}(\cos\beta) \pm P_N^{-}(\cos\beta)\Delta P_{\text{osc}}(\tau)\right]$$

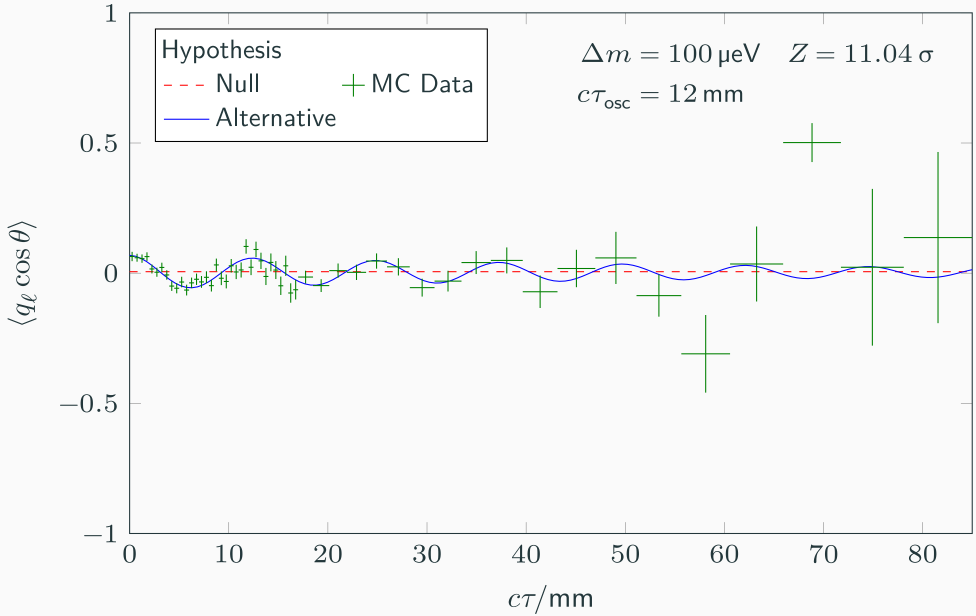
$$P_N^{\pm}(\cos\beta) := \frac{P_N^D(\cos\beta) \pm P_{\overline{N}}^D(\cos\beta)}{2} \qquad \Delta P_{\text{osc}}(\tau) := P_{\text{osc}}^{\text{LNC}}(\tau) - P_{\text{osc}}^{\text{LNV}}(\tau)$$





$\cos\beta$:
Distinguishes $Z \to \nu\overline{N}$ from $Z \to \bar{\nu}N$

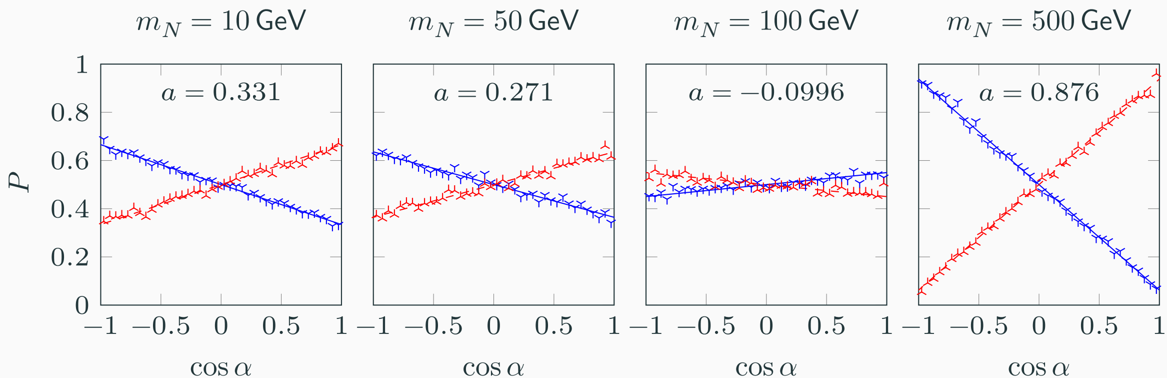
$q_\ell \cos\beta$:
Distinguishes LNC from LNV

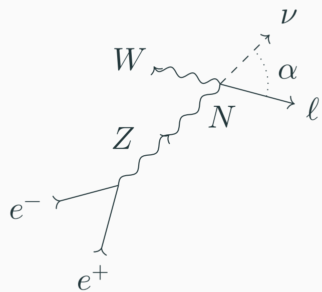


$\cos\beta$:
Distinguishes $Z \to \nu\overline{N}$ from $Z \to \bar{\nu}N$

$q_\ell \cos\beta$:
Distinguishes LNC from LNV

FCC-ee's Z Pole run will outperform HL-LHC in the resolution of $N\overline{N}$Os
$\Downarrow$
Model-independent signal of LNV

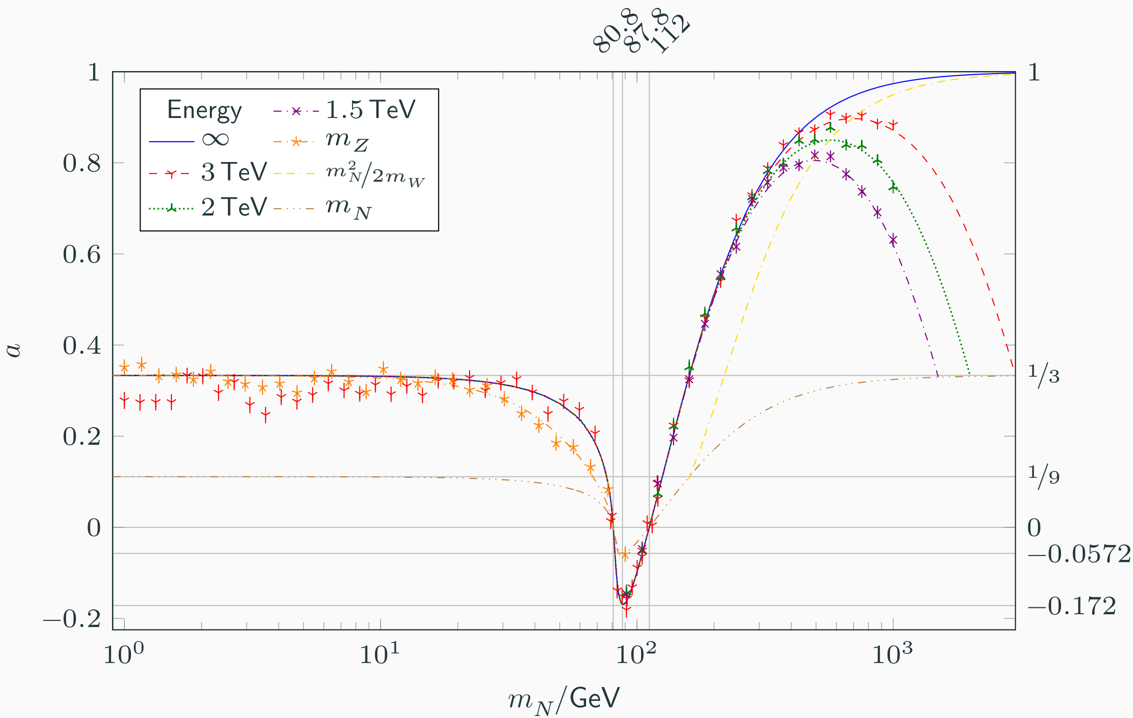


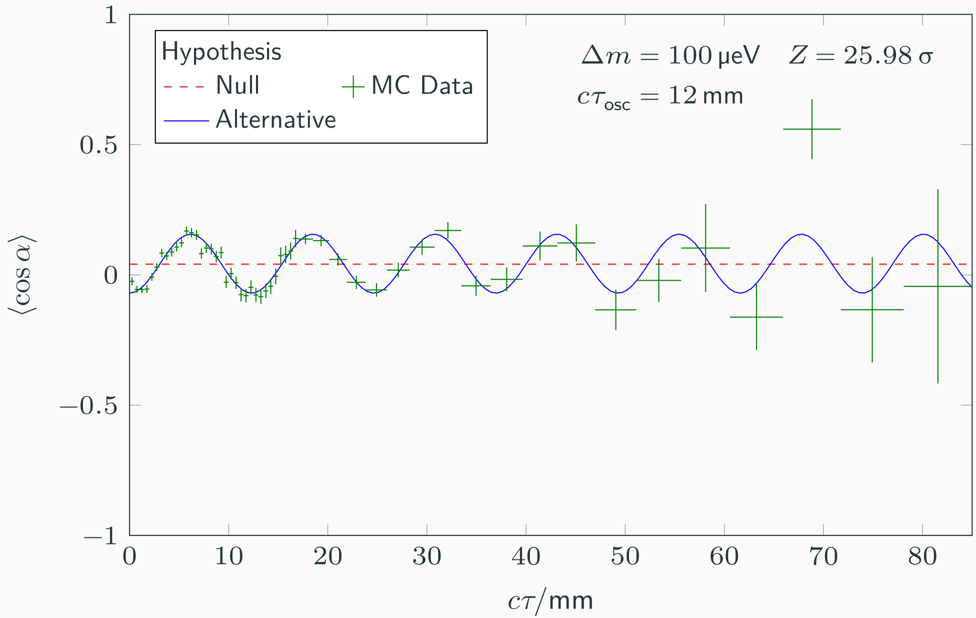


$$d\sigma_{\text{LNC}/\text{LNV}} \propto (\sigma_0 \mp \sigma_1 \cos\alpha)\, d\cos\alpha$$

$$P^M_{\text{LNC}/\text{LNV}}(\alpha) = \frac{1}{2}(1 \mp a\cos\alpha) \qquad a = \frac{\sigma_1}{\sigma_0}$$

Opening Angle Asymmetry [Preliminary]



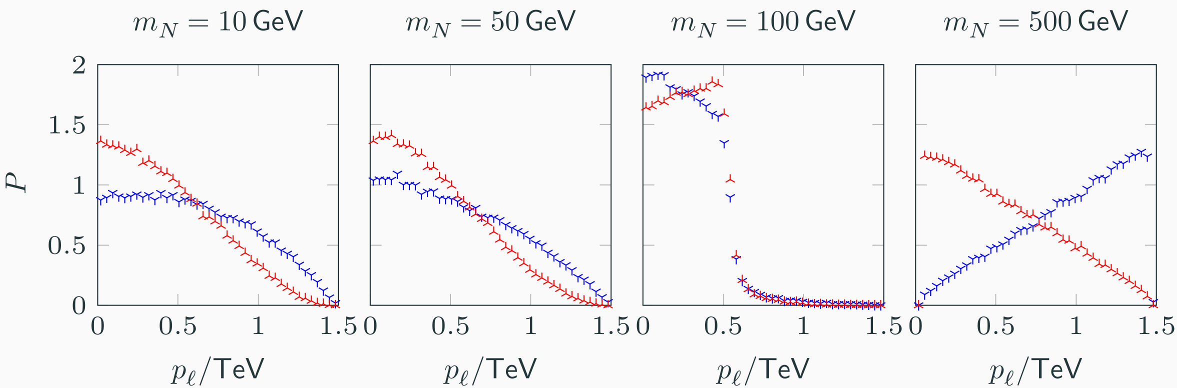


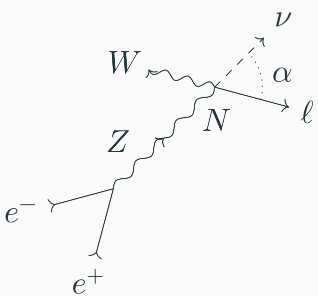
$\cos\alpha$:

More sensitive to $N\overline{N}$Os that $\cos\beta$

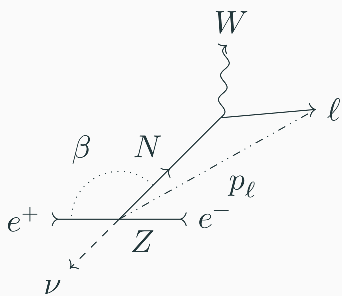
Challenging to measure

Opening Angle Asymmetry [Preliminary]



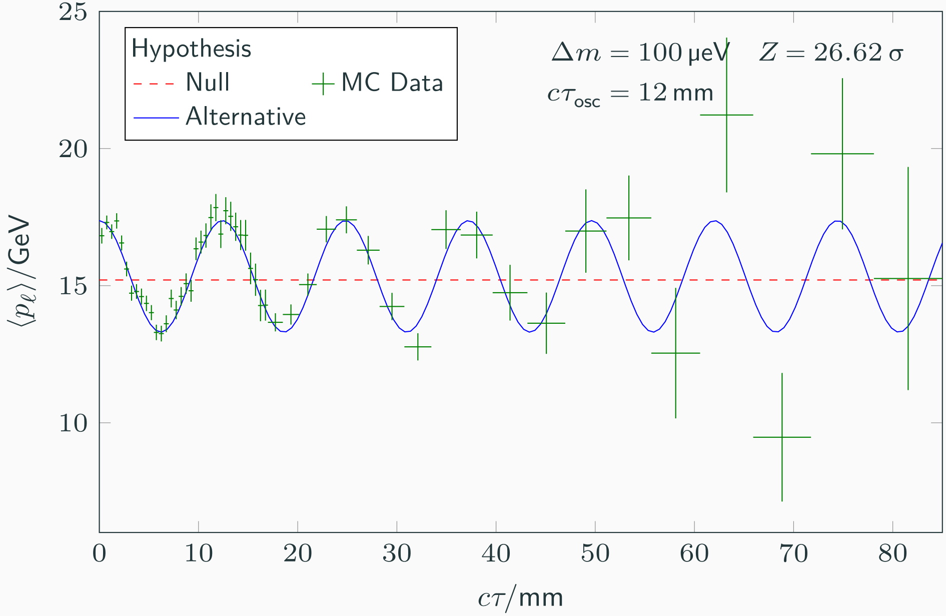


Lab frame (p_Z^2)



HNL's rest frame (p_N^2)

$$P^M_{\text{LNC}/\text{LNV}}(p_\ell) \sim P^M_{\text{LNC}/\text{LNV}}(\alpha)$$

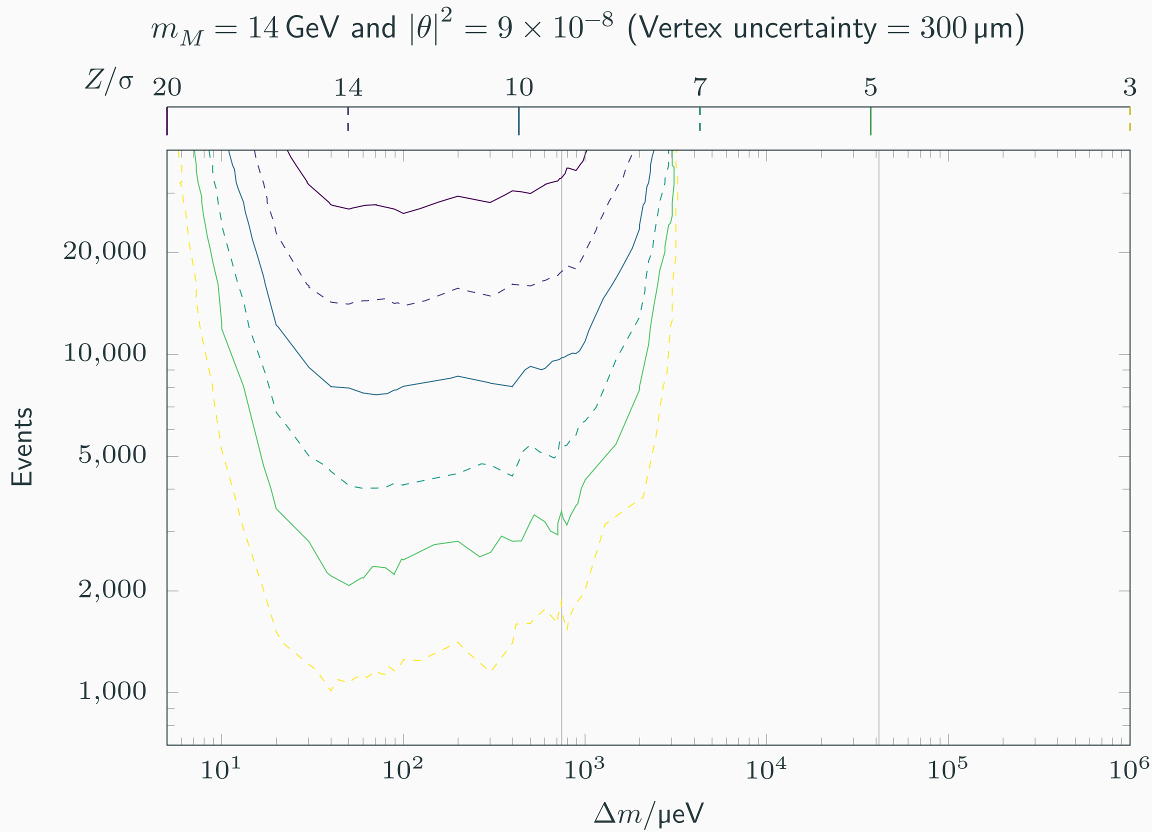


p_ℓ:

Equally sensitive to $N\overline{N}$Os as $\cos\alpha$

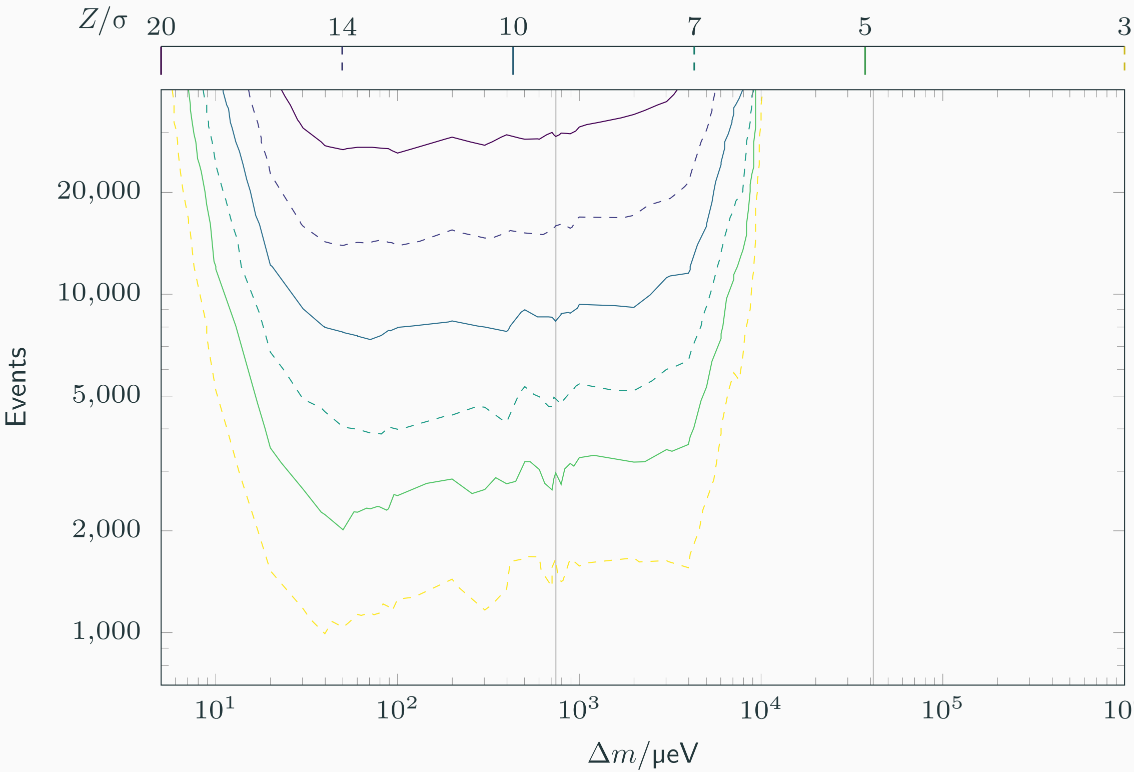
Straightforward to measure

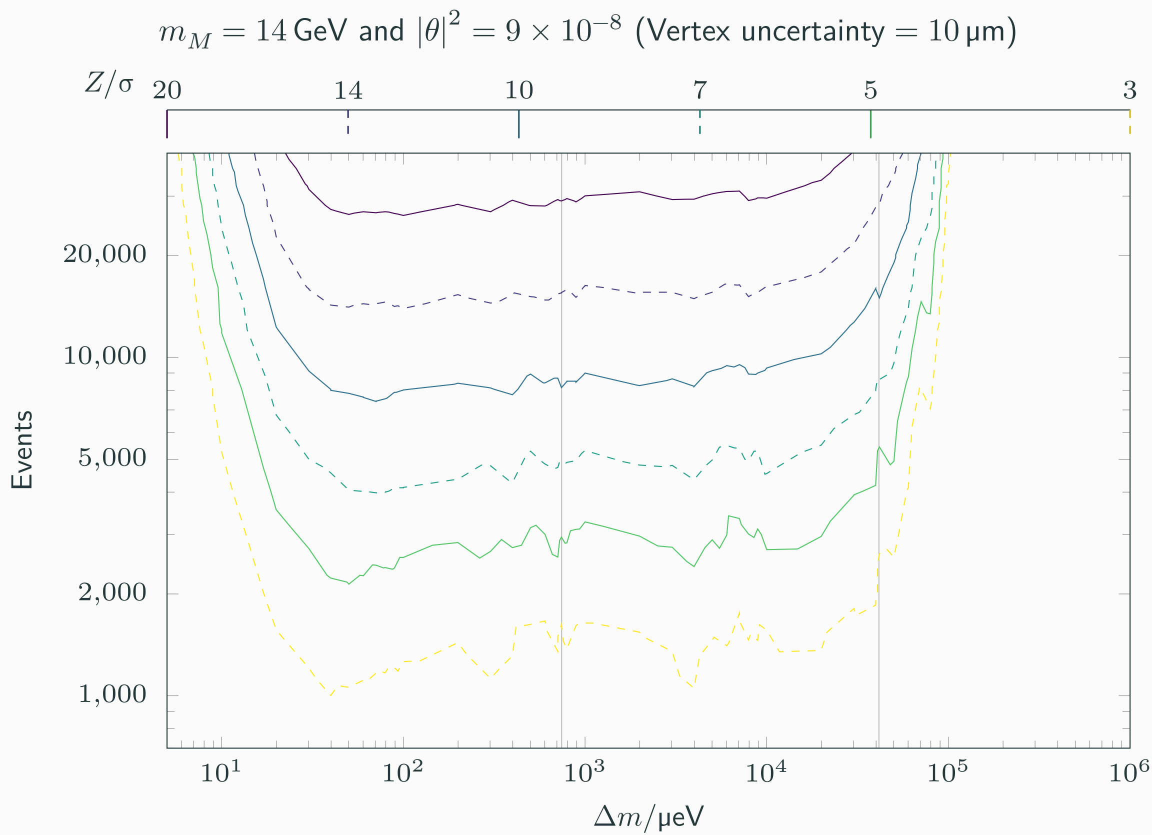
Results [Preliminary]



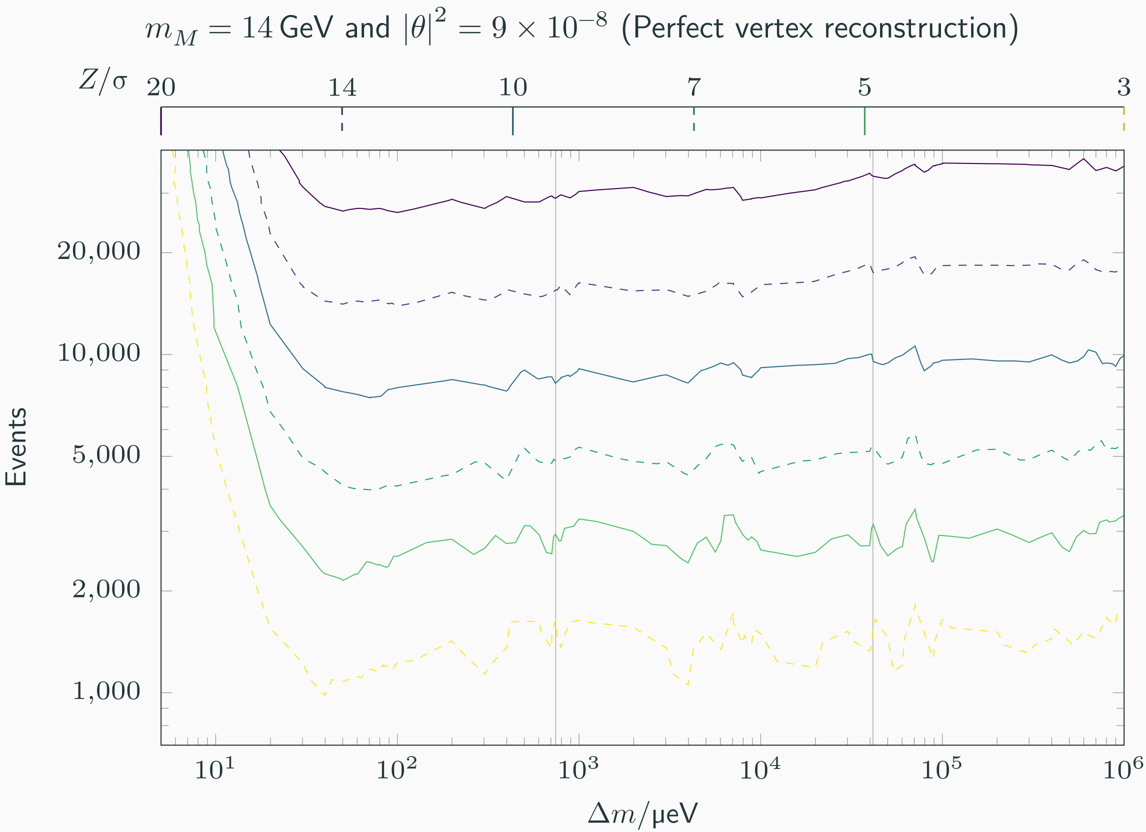
Results [Preliminary]

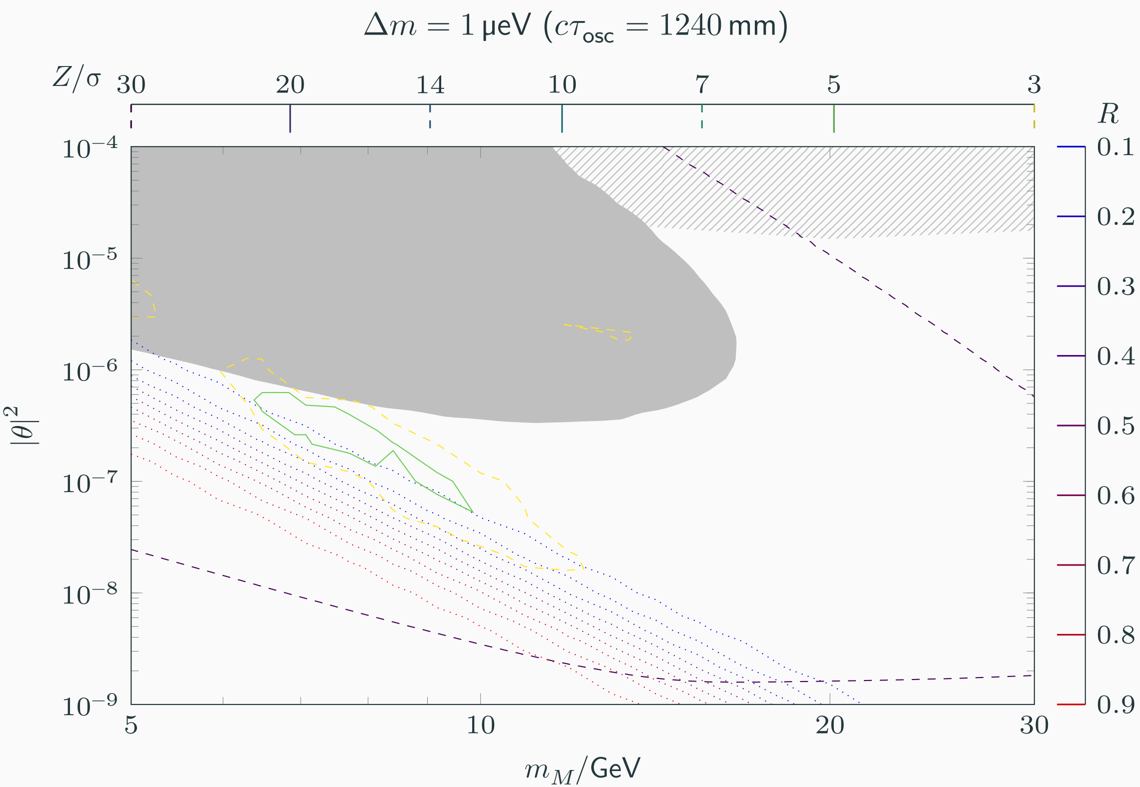
$m_M = 14\,\text{GeV}$ and $|\theta|^2 = 9 \times 10^{-8}$ (Vertex uncertainty $= 100\,\mu\text{m}$)

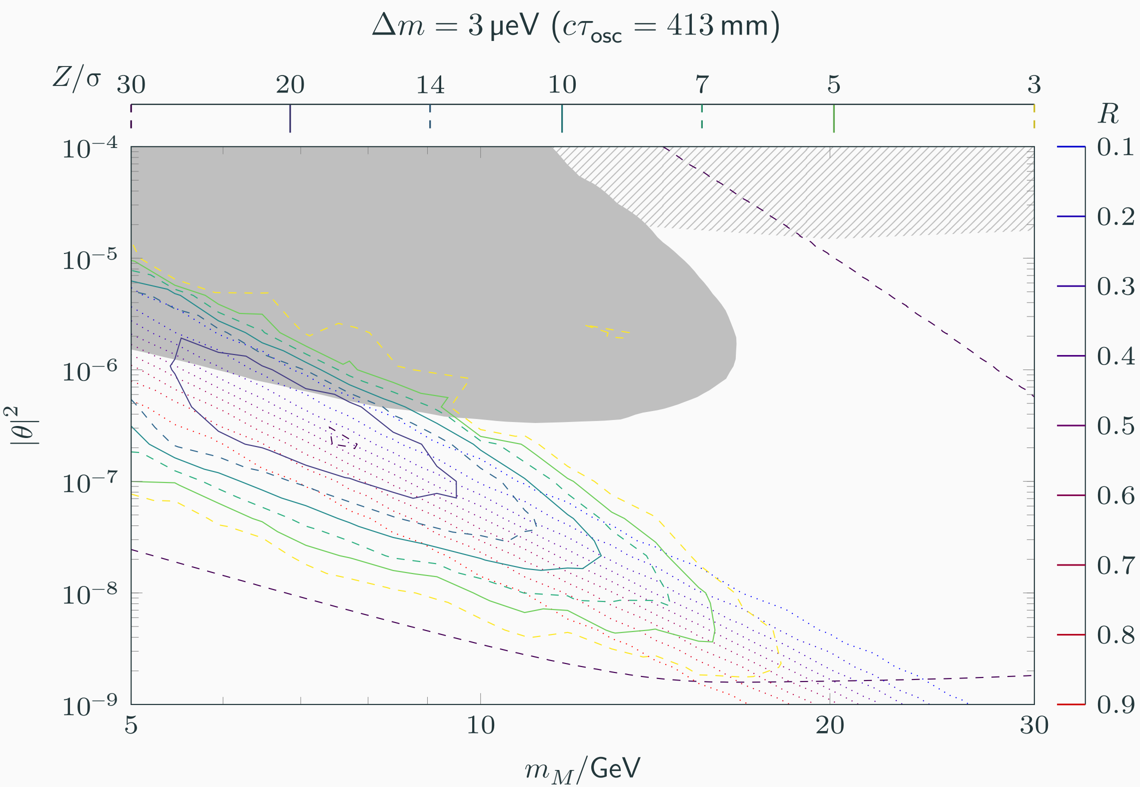



$m_M = 14\,\text{GeV}$ and $|\theta|^2 = 9 \times 10^{-8}$ (Vertex uncertainty = 10 µm)
Z/σ
20
14
10
7
5
3
20,000
10,000
5,000
2,000
1,000
Events
10^1
10^2
10^3
10^4
10^5
10^6
$\Delta m/\mu\text{eV}$

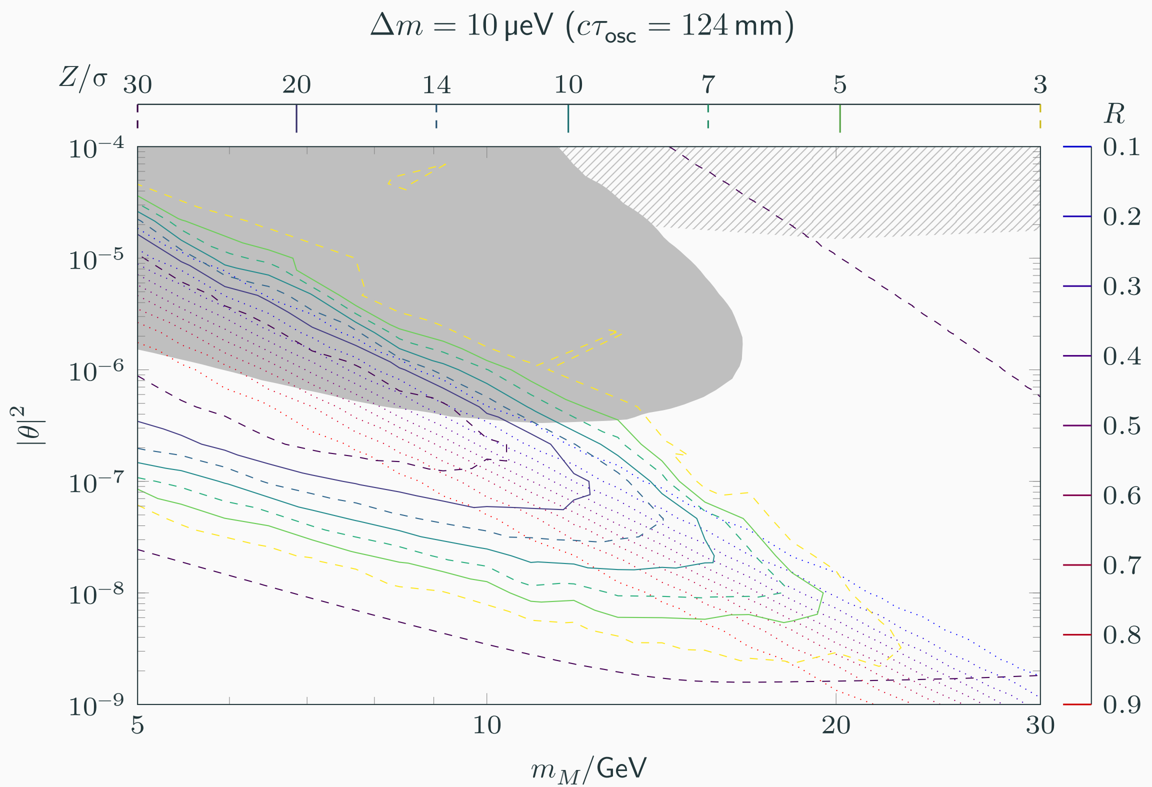
Results [Preliminary]

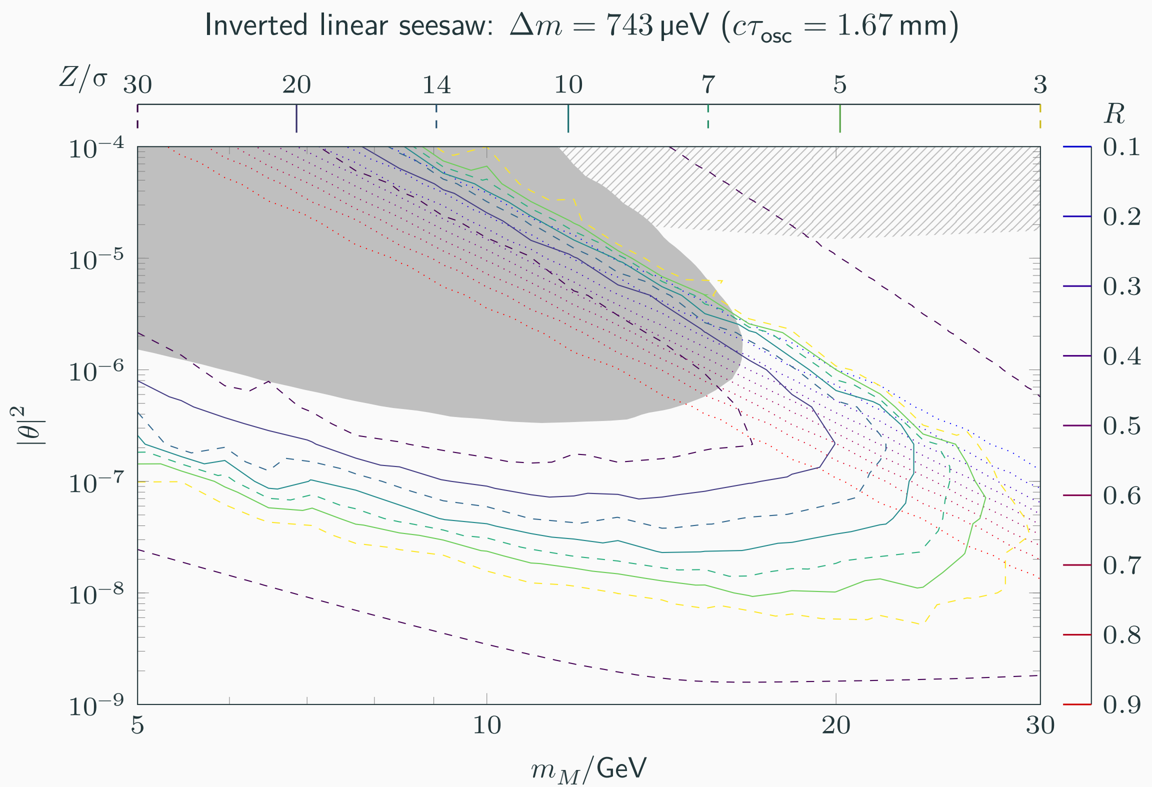



$\Delta m = 1\,\mu\text{eV}$ ($c\tau_{\text{osc}} = 1240\,\text{mm}$)
Z/σ
30
20
14
10
7
5
3
R
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
$|\theta|^2$
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
5
10
20
30
m_M/GeV


$\Delta m = 3\,\mu\text{eV}$ ($c\tau_{osc} = 413\,\text{mm}$)
Z/σ
30
20
14
10
7
5
3
R
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
$|\theta|^2$
5
10
20
30
m_M/GeV

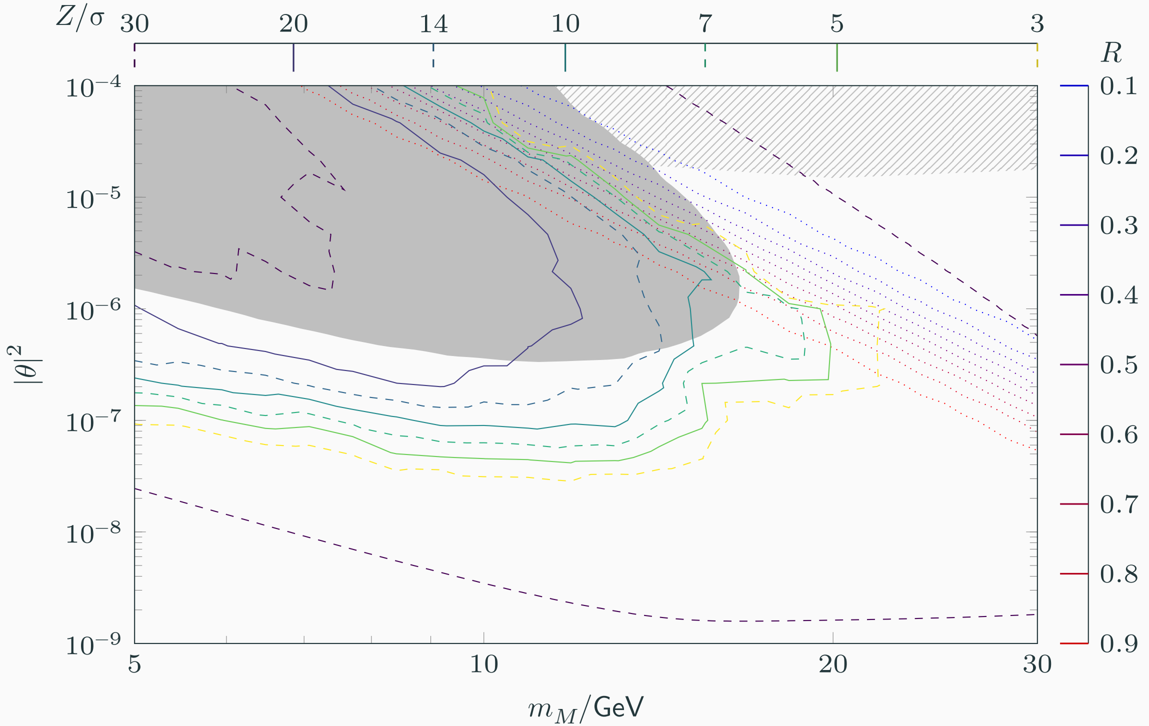
Results [Preliminary]



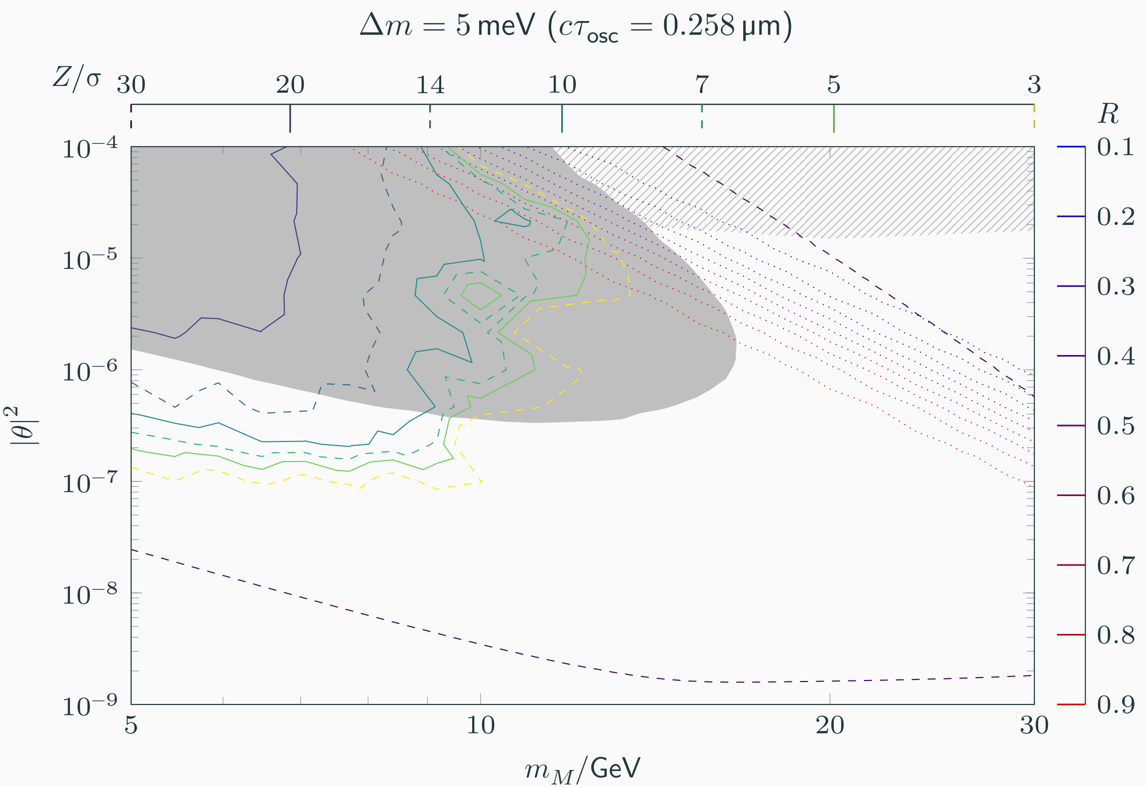

Inverted linear seesaw: $\Delta m = 743\,\mu\text{eV}$ ($c\tau_{\text{osc}} = 1.67\,\text{mm}$)
Z/σ
30
20
14
10
7
5
3
R
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
$|\theta|^2$
5
10
20
30
m_M/GeV

Results [Preliminary]

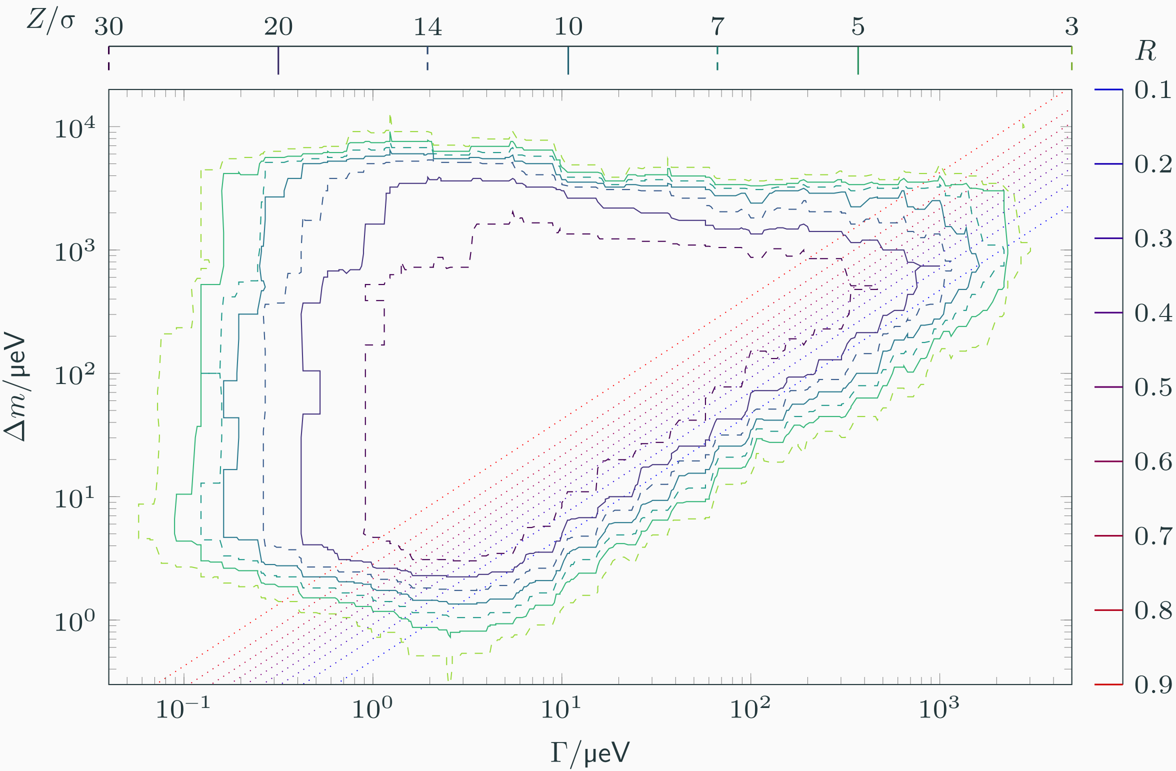
$\Delta m = 3\,\mathrm{meV}$ ($c\tau_{osc} = 413\,\mu\mathrm{m}$)

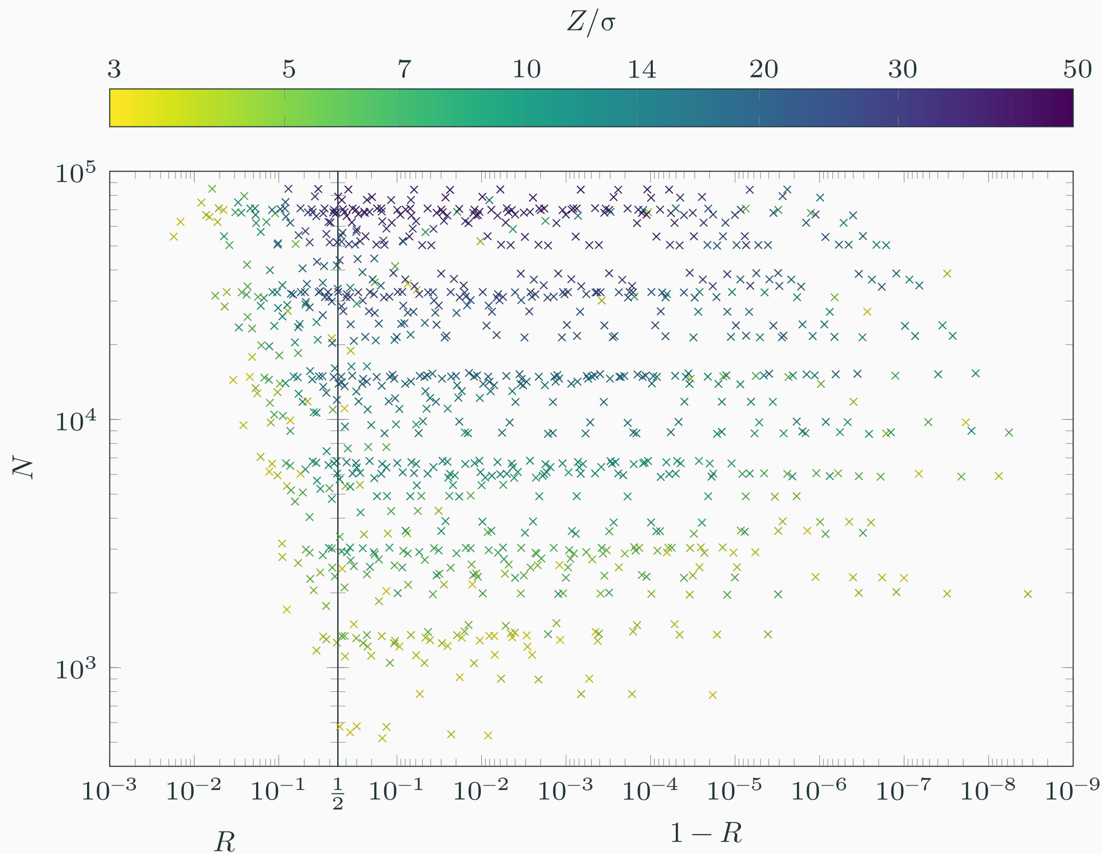


Results [Preliminary]

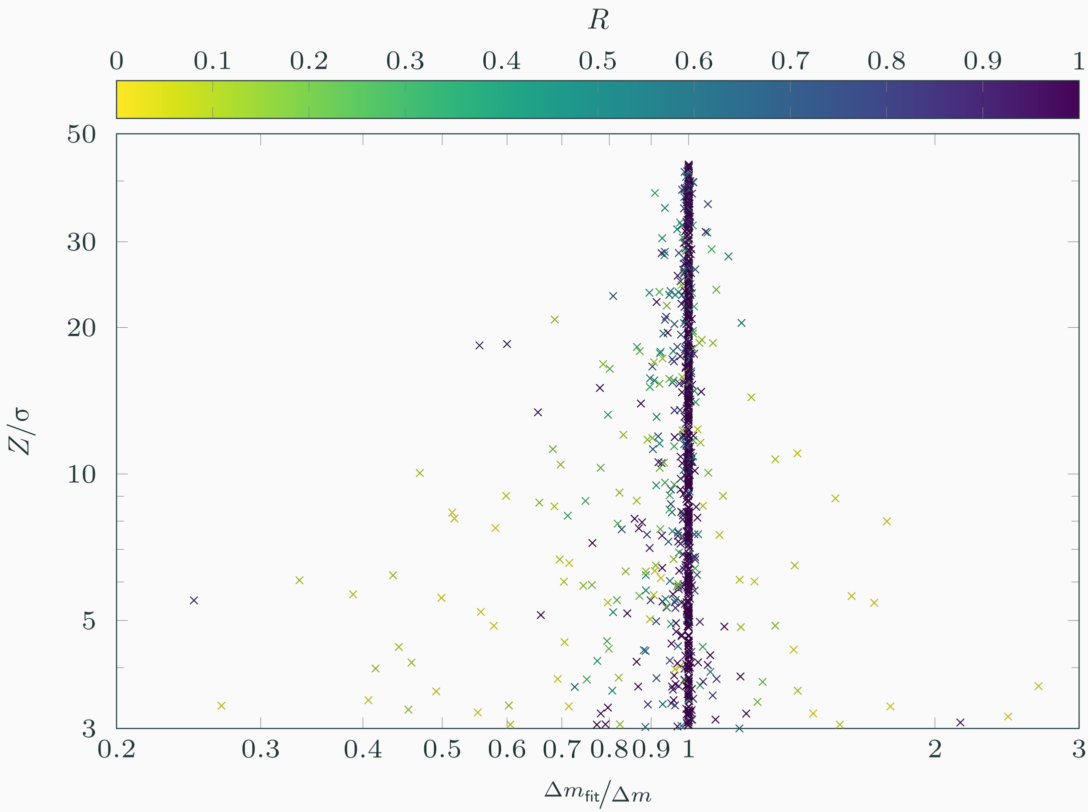


Results [Preliminary]




Z/σ
3
5
7
10
14
20
30
50
10^5
10^4
10^3
N
10^{-3} 10^{-2} 10^{-1} $\frac{1}{2}$ 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9}
R
$1 - R$

Results [Preliminary]



Conclusion

Collider-testable type I seesaw models predict pseudo-Dirac HNLs

$\Downarrow$

$N\overline{N}$Os between LNC and LNV

HL-LHC (W decay)

LNV can be measured directly

$\Downarrow$

$N\overline{N}$Os manifest as decaying oscillations

FCC-ee (Z decay)

LNV can be detected in final state observables

$\Downarrow$

$N\overline{N}$Os manifest as an oscillatory pattern

Number of events + Interplay of oscillation and decay

$\Downarrow$

Oscillations can be resolvable

$\Downarrow$

Understand neutrino mass generation + Detect LNV

Bibliography i

Stefan Antusch and Johannes Rosskopp. 'Heavy Neutrino-Antineutrino Oscillations in Quantum Field Theory'. In: *JHEP* 03 (2021), p. 170. DOI: 10.1007/JHEP03(2021)170. arXiv: 2012.05763 [hep-ph].

Alain Blondel, André de Gouvêa and Boris Kayser. 'Z-boson decays into Majorana or Dirac heavy neutrinos'. In: *Phys. Rev. D* 104.5 (2021), p. 055027. DOI: 10.1103/PhysRevD.104.055027. arXiv: 2105.06576 [hep-ph].

Krzysztof Mękała, Jürgen Reuter and Aleksander Filip Żarnecki. 'Heavy neutrinos at future linear e^+e^- colliders'. In: *JHEP* 06 (2022), p. 010. DOI: 10.1007/JHEP06(2022)010. arXiv: 2202.06703 [hep-ph].

Stefan Antusch, Jan Hajer and Johannes Rosskopp. 'Simulating lepton number violation induced by heavy neutrino-antineutrino oscillations at colliders'. In: *JHEP* 03 (2023), p. 110. DOI: 10.1007/JHEP03(2023)110. arXiv: 2210.10738 [hep-ph].

Stefan Antusch, Jan Hajer and Johannes Rosskopp. 'Beyond lepton number violation at the HL-LHC: resolving heavy neutrino-antineutrino oscillations'. In: *JHEP* 09 (2023), p. 170. DOI: 10.1007/JHEP09(2023)170. arXiv: 2212.00562 [hep-ph].

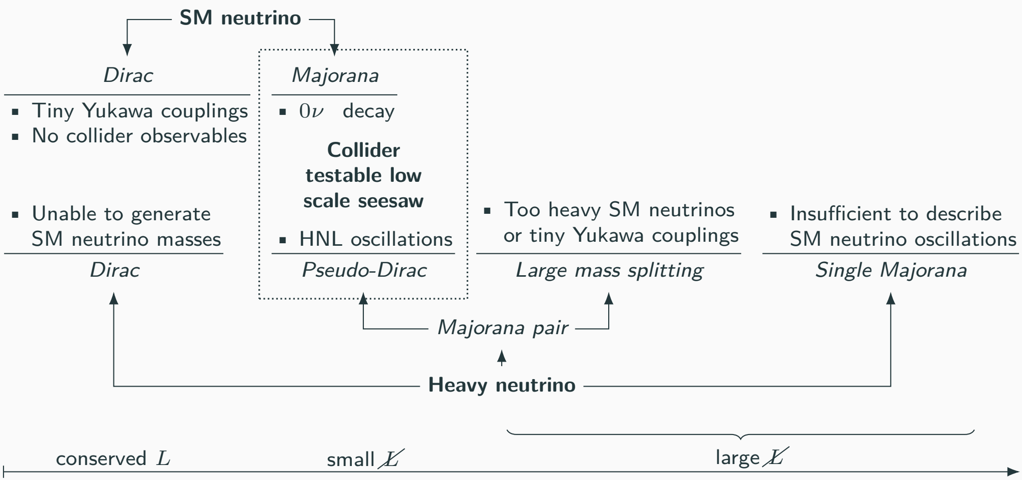
Stefan Antusch, Jan Hajer and Johannes Rosskopp. 'Decoherence effects on lepton number violation from heavy neutrino-antineutrino oscillations'. In: *JHEP* 11 (2023), p. 235. DOI: 10.1007/JHEP11(2023)235. arXiv: 2307.06208 [hep-ph].

Stefan Antusch, Jan Hajer and Bruno M. S. Oliveira. 'Heavy neutrino-antineutrino oscillations at the FCC-ee'. In: *JHEP* 10 (2023), p. 129. DOI: 10.1007/JHEP10(2023)129. arXiv: 2308.07297 [hep-ph].

Stefan Antusch, Jan Hajer and Bruno M. S. Oliveira. 'Discovering lepton number violation in distributions at the FCC-ee '. (June 2024). In progress.

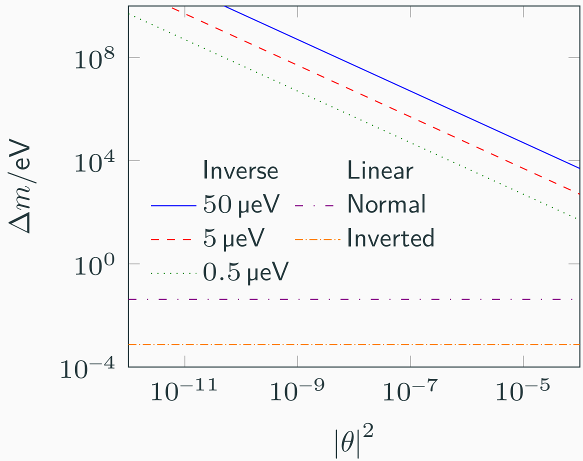
Jan Hajer. 'Measuring lepton number violation at colliders'. PLANCK2024. June 2024. URL: https://indico.cern.ch/event/1323379/contributions/5889385/.

Symmetry Protected Seesaw Scenarios [2210.10738]



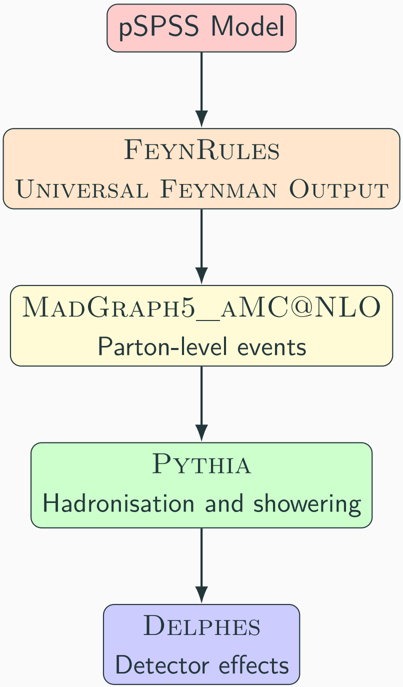
	Linear Seesaw	Inverse Seesaw	Seesaw Independent
$M =$	$\begin{pmatrix} 0 & m_D^T & \boldsymbol{\mu_D^T} \\ m_D & 0 & m_M \\ \boldsymbol{\mu_D} & m_M & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & m_M \\ 0 & m_M & \boldsymbol{\mu_M} \end{pmatrix}$	$\begin{pmatrix} 0 & m_D^T & 0 \\ m_D & \boldsymbol{\mu'_M} & m_M \\ 0 & m_M & 0 \end{pmatrix}$
$M_\nu =$	$\mu_D \otimes \theta + \theta \otimes \mu_D$	$\mu_M(\theta \otimes \theta)$	0
	$\{\lvert\mu_D\rvert\lvert\theta\rvert \pm \lvert\mu_D^* \theta\rvert, 0\}$	$\left\{\mu_M \lvert\theta\rvert^2, 0, 0\right\}$	$\{0, 0, 0\}$
$\Delta m =$	$\Delta m_\nu = 2\lvert\mu_D^* \theta\rvert$	$m_\nu \lvert\theta\rvert^{-2} = \lvert\mu_M\rvert$	$\lvert\mu'_M\rvert$

Seesaw	Hierarchy	Benchmark Model
Linear	Normal	$\Delta m_\nu = 42.3\,\text{meV}$
	Inverted	$\Delta m_\nu = 748\,\mu\text{eV}$
Inverse		$m_\nu = 0.5\,\text{meV}$
		$m_\nu = 5.0\,\text{meV}$
		$m_\nu = 50\,\text{meV}$



Simulation [2210.10738, 2308.07297]

Phenomenological Symmetry Protected Seesaw Scenario (pSPSS)



Two Majorana DOF described by six additional parameters

$$m_M \qquad (\theta_e, \theta_\mu, \theta_\tau) \qquad \Delta m \qquad \lambda$$

$$M_{4/5} \simeq m_M \left(1 + \frac{1}{2}|\theta|^2\right) \pm \frac{1}{2}\Delta m \quad \Gamma = \Gamma(m_M, \theta_e, \theta_\mu, \theta_\tau)$$

Light neutrinos are Majorana particles

$\Downarrow$

No Lepton Number

Left-chiral interaction + Small masses

$\Downarrow$

Approximate LNLS with $\nu \simeq \nu_L$ and $\bar{\nu} \simeq \nu_R$

$\Downarrow$

Model light neutrinos as Dirac fields

Event Reconstruction [2212.00562, Preliminary]

Run	Z Pole	WW Threshold
Simulated Events	309 965	47 937
Exactly one/three μ	−34 241	−14 009
Exactly one j	−1498	−2819
Displaced μ	−3964	−5107
Displaced j	−12 128	−4322
Vertex direction	−53	−3
N mass window	−40 534	−1709
Remaining events	217 547	19 968

Run	HL-LHC
Simulated Events	50 000
Exactly one prompt μ	−23 196
Exactly one displaced j	−21 652
Exactly one displaced μ	−1396
μ isolation	−838
Vertex direction	0
No prompt electron	0
W mass window	−111
N mass window	−1211
Remaining Events	1596

Z: $m_M = 14\,\text{GeV}$ $(\theta_e, \theta_\mu, \theta_\tau) = (0, 3, 0) \times 10^{-4}$ $\Gamma = 22.6\,\mu\text{eV}$

WW: $m_M = 5.5\,\text{GeV}$ $(\theta_e, \theta_\mu, \theta_\tau) = (0, 1, 0) \times 10^{-3}$ $\Gamma = 2.05\,\mu\text{eV}$

LHC $m_M = 14\,\text{GeV}$ $(\theta_e, \theta_\mu, \theta_\tau) = (0, 3.162\,28, 0) \times 10^{-4}$ $\Gamma = 13.8\,\mu\text{eV}$

The three muons in the WW diagram are correctly identified in 19 132 events

Statistical Analysis [2212.00562, Preliminary]

Null hypothesis
Oscillations are absent in the data

Alternative hypothesis
Oscillations are present in the data

Agreement between hypothesis and data

#Events: $$P_{\text{hyp}}^{\text{bin}} = \frac{N_{\text{hyp}}(\tau_{\text{bin}})^{N_{\text{bin}}!} e^{-N_{\text{hyp}}(\tau_{\text{bin}})}}{N_{\text{bin}}!} \qquad P_{\text{hyp}} = \prod_{\text{bins}} P_{\text{hyp}}^{\text{bin}}$$

Observable: $$P_{\text{hyp}}^{\text{event}} = \frac{1}{\sqrt{2\pi}\sigma_{\text{event}}} \exp\left\{-\frac{1}{2}\left(\frac{\mu_{\text{hyp}}(\tau_{\text{event}}) - \mu_{\text{event}}}{\sigma_{\text{event}}}\right)^2\right\} \qquad P_{\text{hyp}} = \prod_{\text{events}} P_{\text{hyp}}^{\text{event}}$$

Compare hypothesis

	No oscillations	Oscillations
Likelihood ratio (LR) $= P_{\text{null}} \times P_{\text{alt}}^{-1}$	1	0^+
Log Likelihood ratio (LLR) $= -2\log(\text{Likelihood ratio})$	0	$+\infty$

Significance
Likelihood of finding oscillations at a given LLR under the null hypothesis