



fct

Fundação
para a Ciência
e a Tecnologia



REPÚBLICA
PORTUGUESA

COMPETE
2020

PORTUGAL
2020



UNIÃO EUROPEIA
Fundo Europeu
de Desenvolvimento Regional

Heavy Neutrino-Antineutrino Oscillations at the FCC-ee

Bruno M. S. Oliveira in collaboration with Stefan Antusch and Jan Hajer

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

LLP2024

Fourteenth workshop of the Long-Lived Particle Community

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

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

Neutrinos are unique:

Colourless

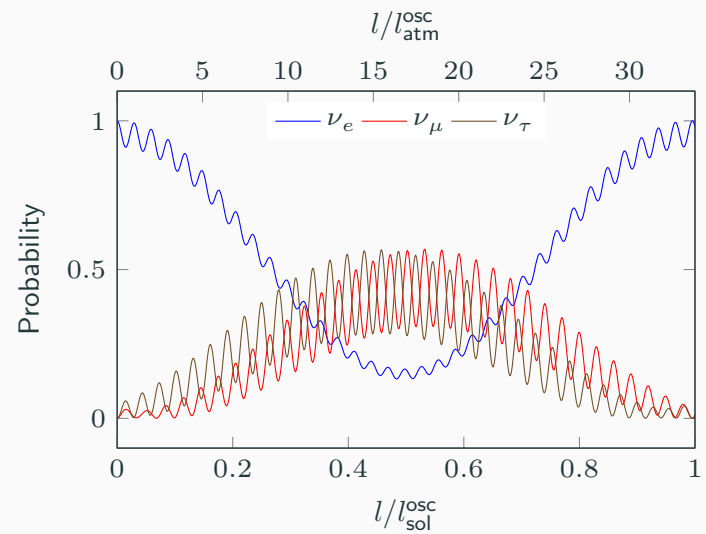
Neutral

Only left-chiral

Massless

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

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



Neutrinos are unique:

Colourless

Neutral

Only left-chiral

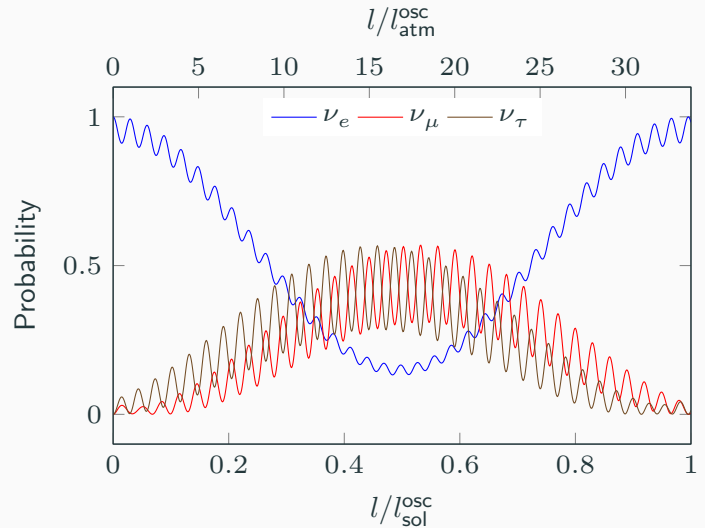
Massless

Unable to explain neutrino flavour oscillations

Standard Model of Particle Physics with Neutrino Masses

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

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



Neutrinos aren't so unique:

Colourless

Neutral

Only left-chiral

Massless

Explains neutrino flavour oscillations

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)

Dirac Mass Lagrangian:

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

Conserves lepton number (LNC)

Light Neutrinos ν :

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

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)

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)

Light Neutrinos ν :

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

Majorana Mass Lagrangian:

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

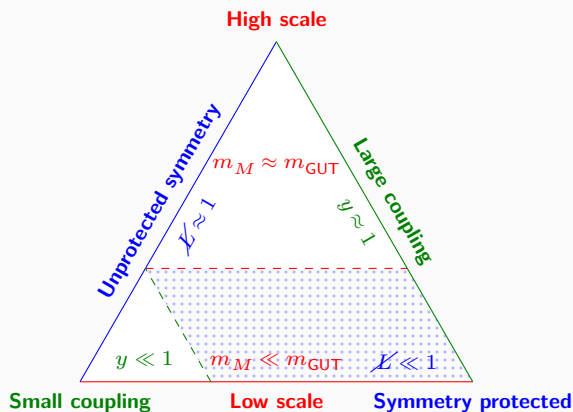
Violates lepton number (LNV)

Left-Right Mixing:

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

Heavy Neutrinos n :

$$M_n \simeq M_M^R$$



Dirac Mass Lagrangian:

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

Conserves lepton number (LNC)

Light Neutrinos ν :

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

Majorana Mass Lagrangian:

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

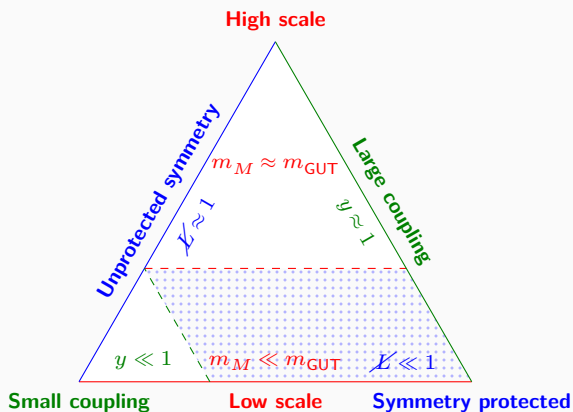
Violates lepton number (LNV)

Left-Right Mixing:

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

Heavy Neutrinos n :

$$M_n \simeq M_M^R$$



Two neutrinos:

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

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

Symmetric limit

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

Mild symmetry breaking

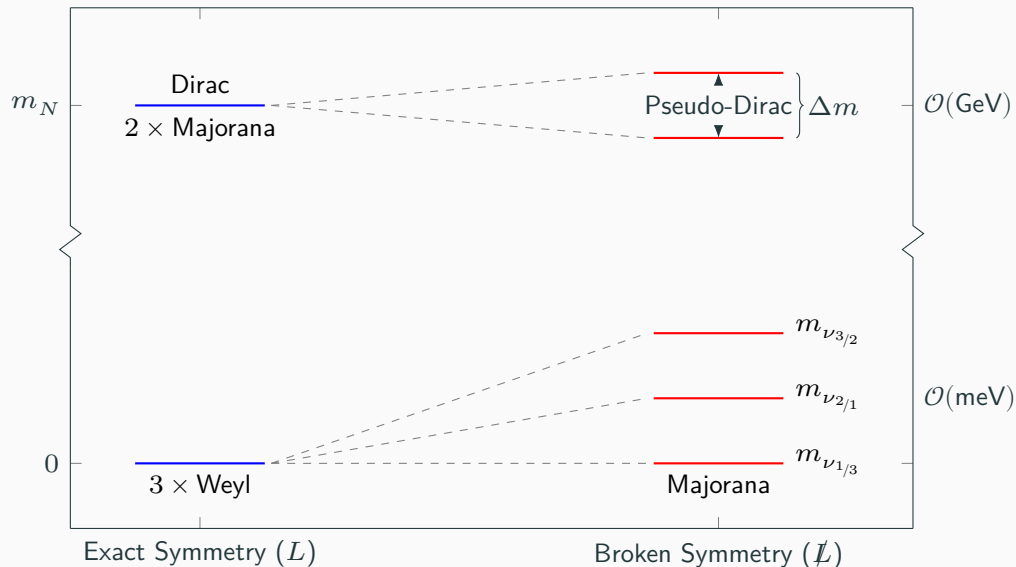
$$M = \begin{pmatrix} 0 & m_D^T & \mu_D^T \\ m_D & \mu'_M & m_M \\ \mu_D & m_M & \mu_M \end{pmatrix}$$

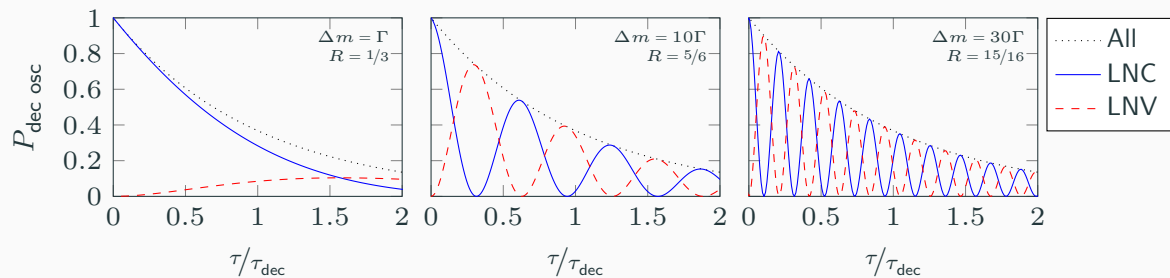
$\mu_D, \mu_M, \mu'_M \ll m_M$

Large symmetry breaking

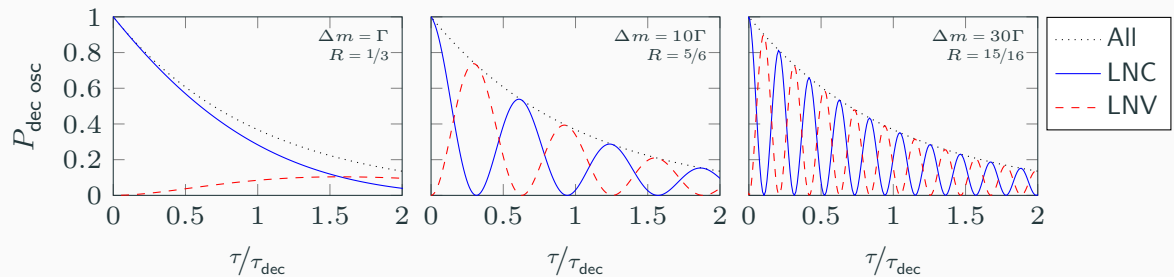
$$M = \begin{pmatrix} 0 & m_D^T & \hat{m}_D^T \\ m_D & \hat{m}'_M & m_M \\ \hat{m}_D & m_M & \hat{m}_M \end{pmatrix}$$

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





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



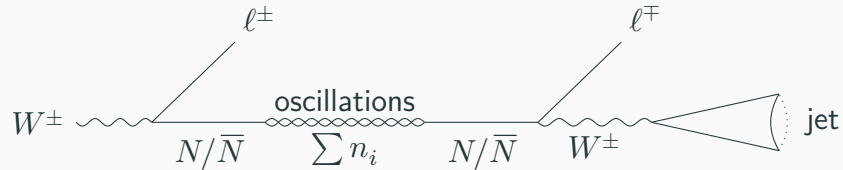
$$P_{\text{dec osc}}^{\text{LNC/LNV}}(\tau) = \left[P_{\text{decay}}(\tau) = \Gamma e^{-\Gamma\tau} \right] \times \left[P_{\text{osc}}^{\text{LNC/LNV}}(\tau) = \frac{1}{2} [1 \pm e^{-\lambda} \cos(\Delta m \tau)] \right]$$

Time-integrated behaviour:

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

Detecting Lepton Number Violation

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



LNV **can** be directly measured

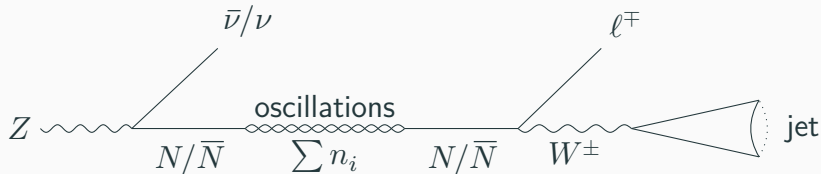
Detecting Lepton Number Violation

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



LN**V** **can** be directly measured

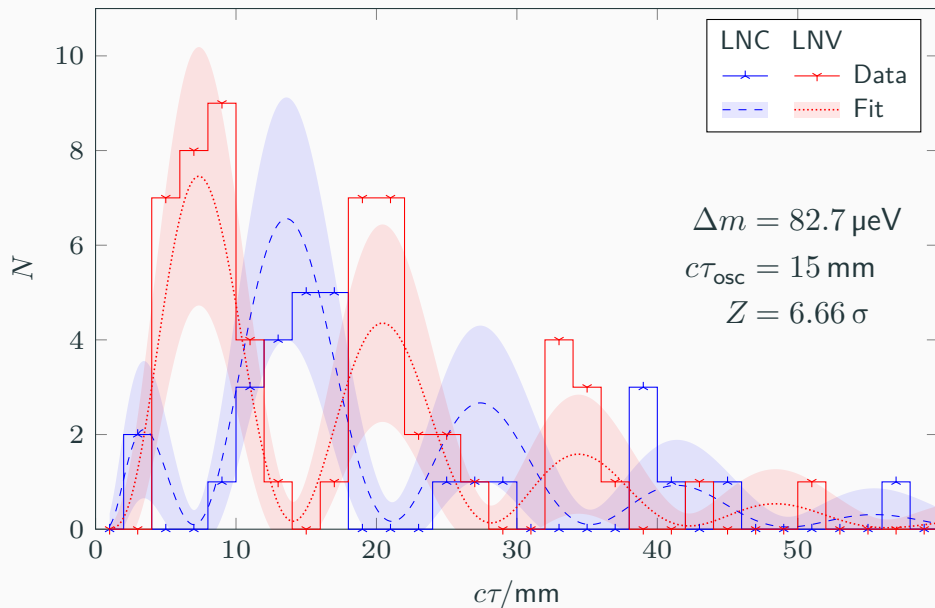
Z decay (FCC- ee 's Z Pole):



LN**V** **cannot** be directly measured



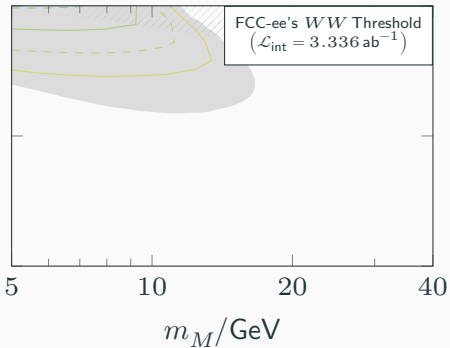
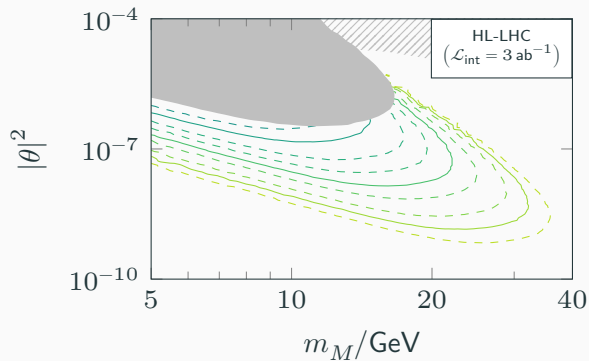
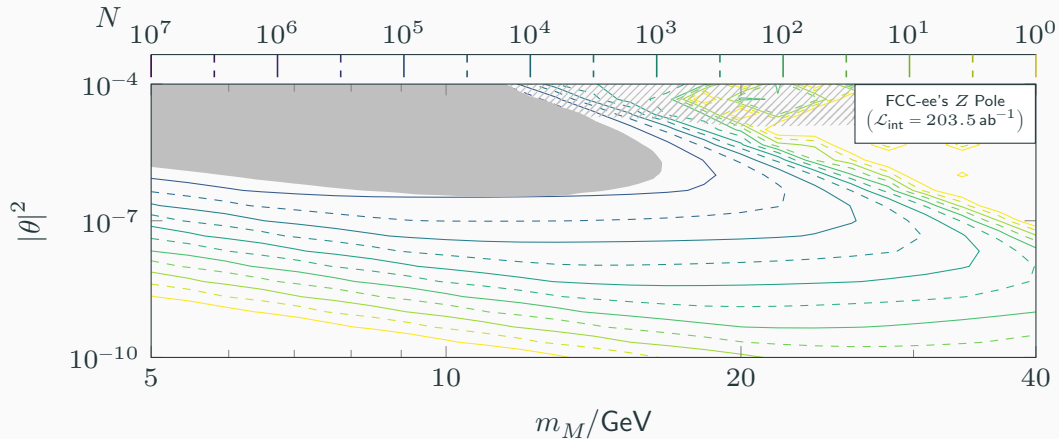
Must be **induced** from final state observables

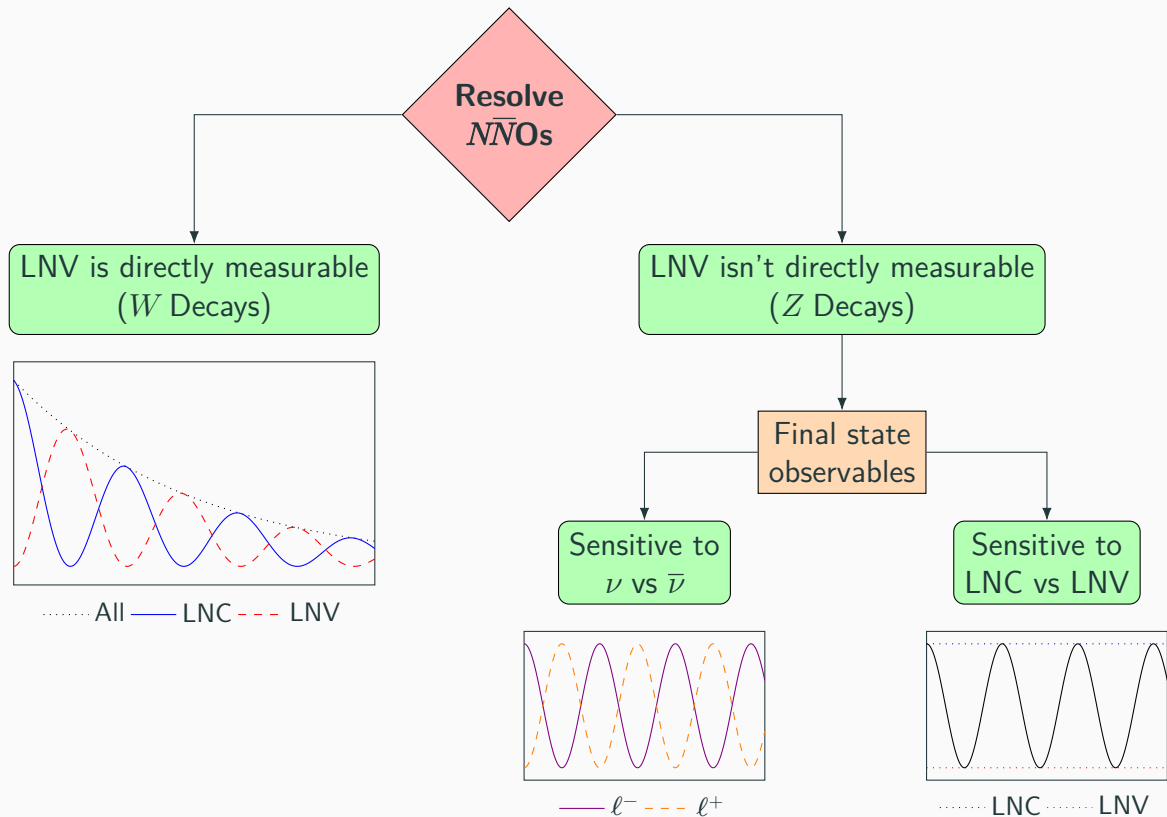


Group LNC/LNV events \Rightarrow **Fit** oscillations \Rightarrow **Analyse** significance

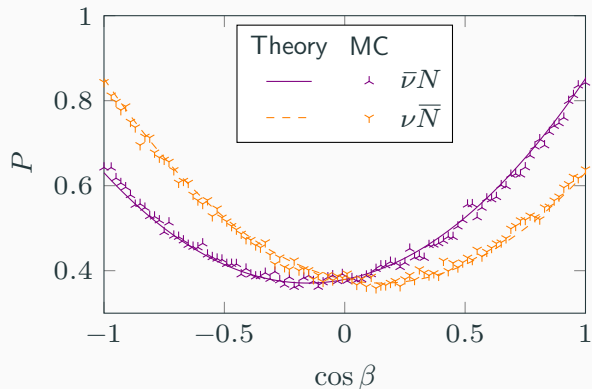
HL-LHC:
 Capable of resolving $\bar{N}\bar{N}$ Os Luminosity \Rightarrow Narrow frequency spectrum

Detecting Heavy Neutral Leptons

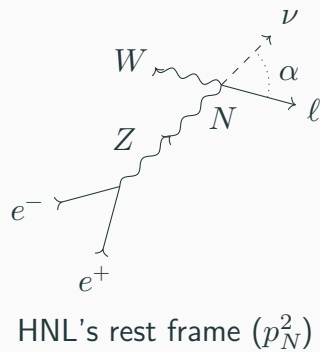
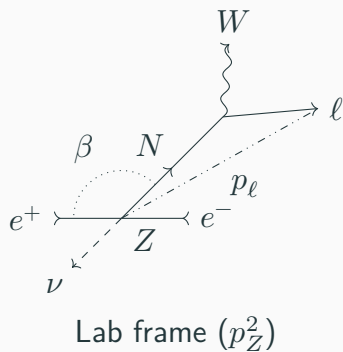
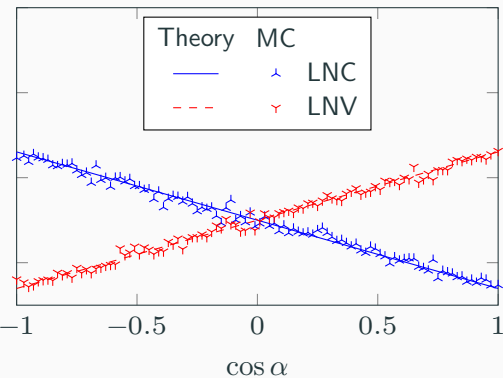




Forward-Backward Asymmetry

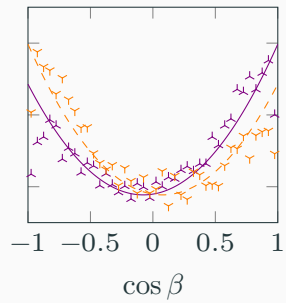
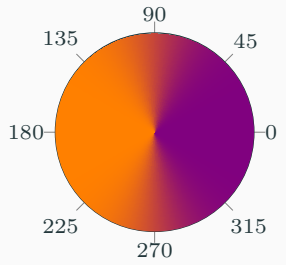


Opening Angle Asymmetry



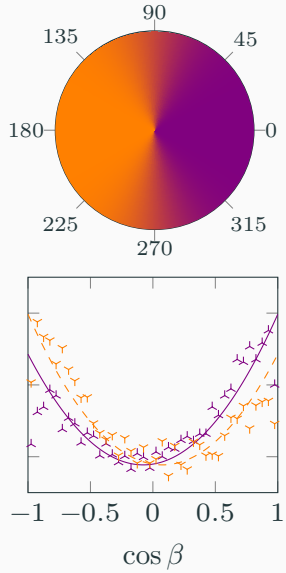
Forward-Backward Asymmetry [2308.07297]

Dirac-like:

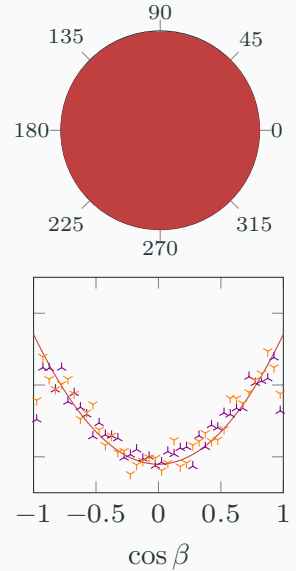


Forward-Backward Asymmetry [2308.07297]

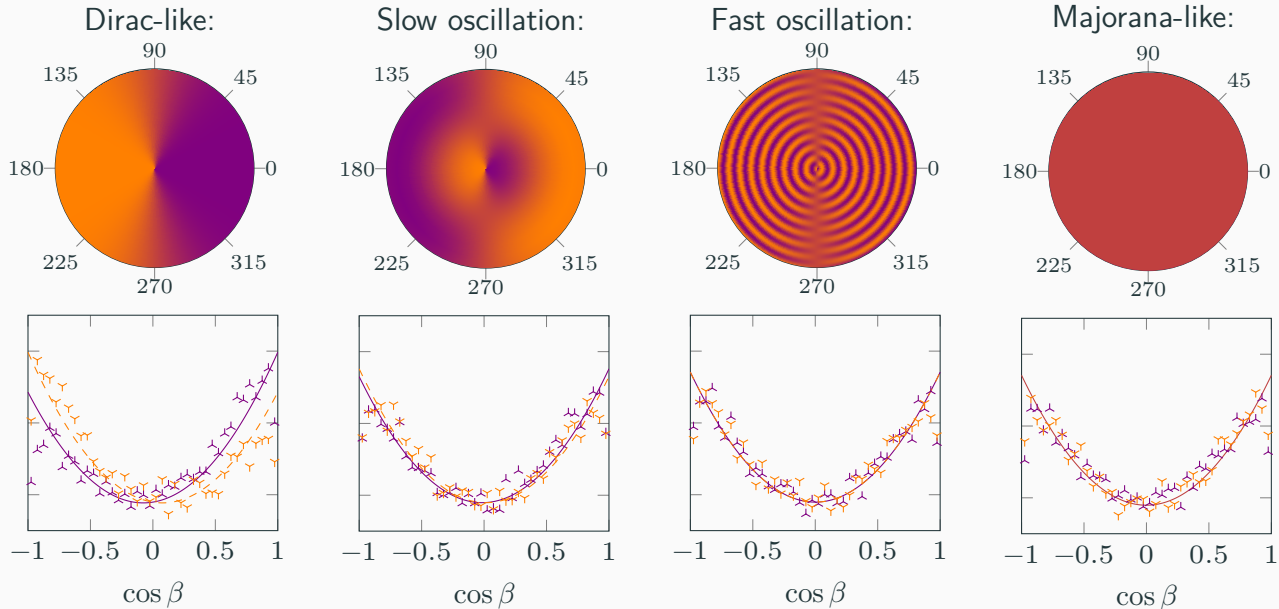
Dirac-like:



Majorana-like:



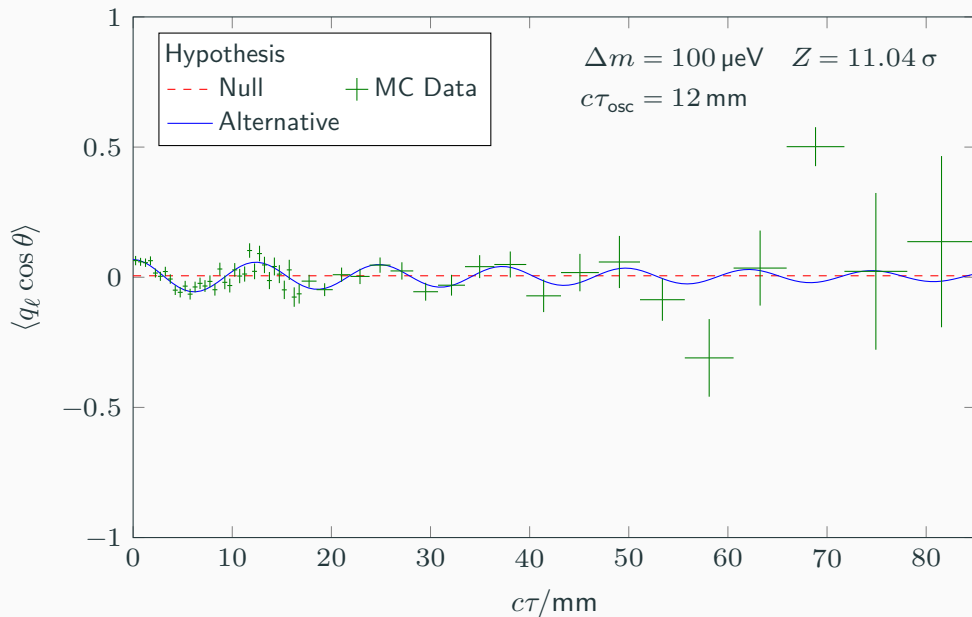
Forward-Backward Asymmetry [2308.07297]



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

$$P_N^\pm(\cos \beta) := \frac{P_N^D(\cos \beta) \pm P_{\bar{N}}^D(\cos \beta)}{2}$$

$$\Delta P_{\text{osc}}(\tau) := P_{\text{osc}}^{\text{LNC}}(\tau) - P_{\text{osc}}^{\text{LNV}}(\tau)$$

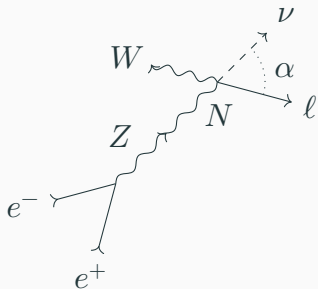
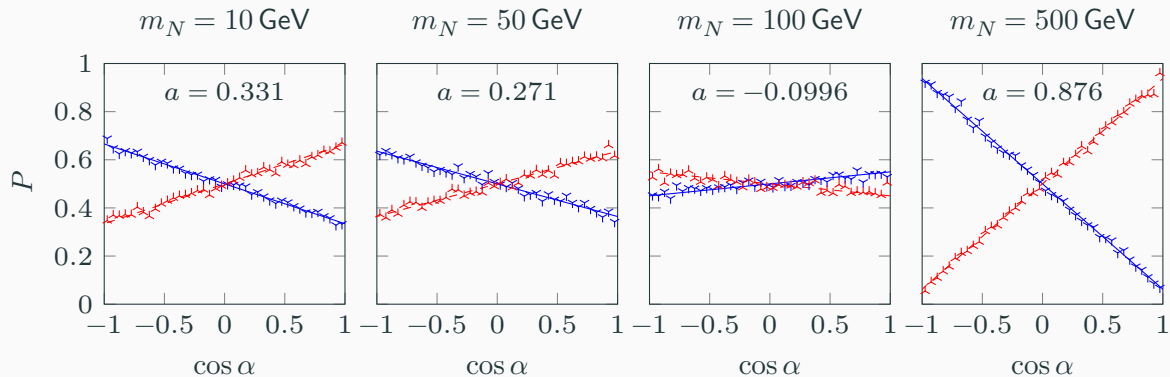


FCC- ee 's Z Pole run will outperform HL-LHC in the resolution of $N\bar{N}$ Os



Model-independent signal of LNV

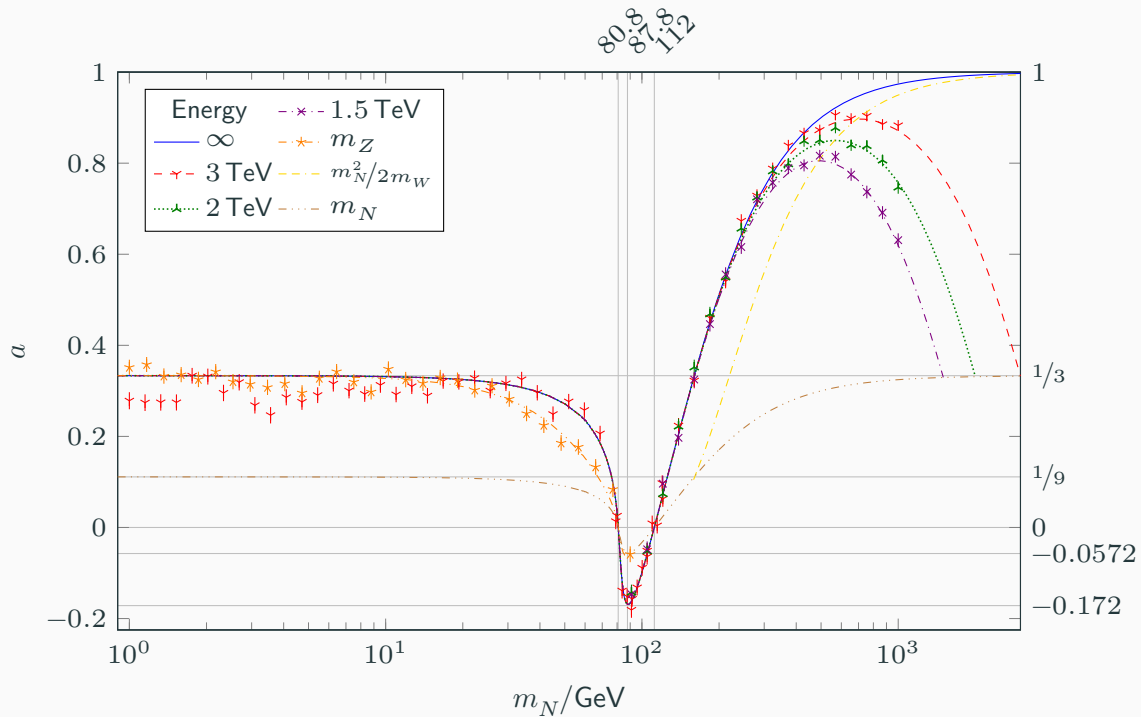
Opening Angle Asymmetry [Preliminary]



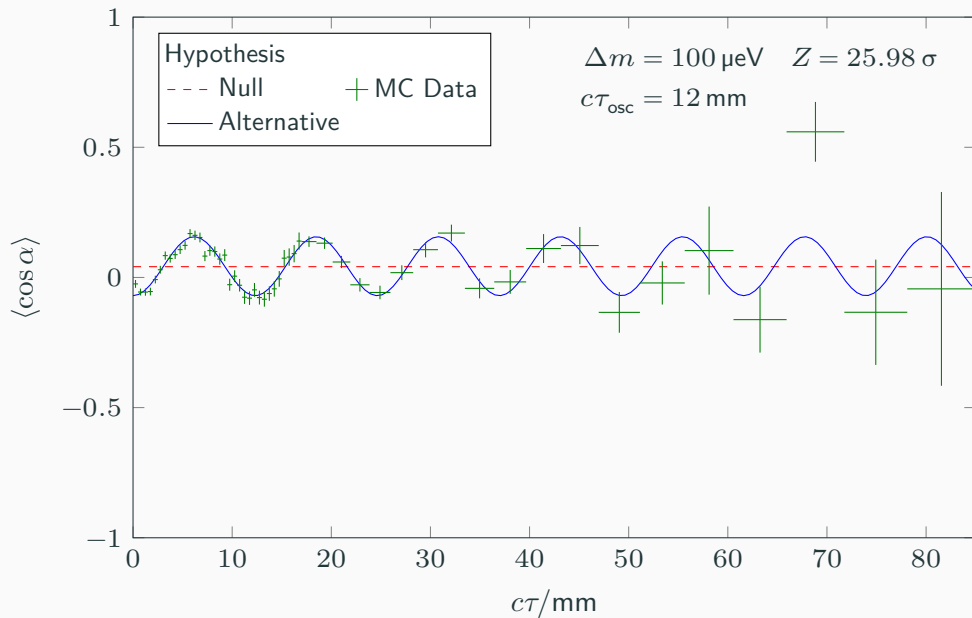
$$d\sigma_{\text{LNC/LNV}} \propto (\sigma_0 \mp \sigma_1 \cos \alpha) d\cos \alpha$$

$$P_{\text{LNC/LNV}}^M(\alpha) = \frac{1}{2}(1 \mp a \cos \alpha) \quad a = \frac{\sigma_1}{\sigma_0}$$

Opening Angle Asymmetry [Preliminary]



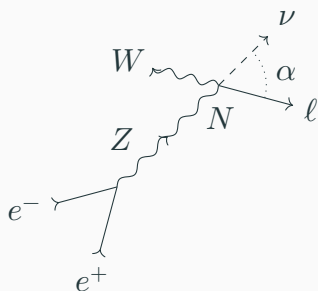
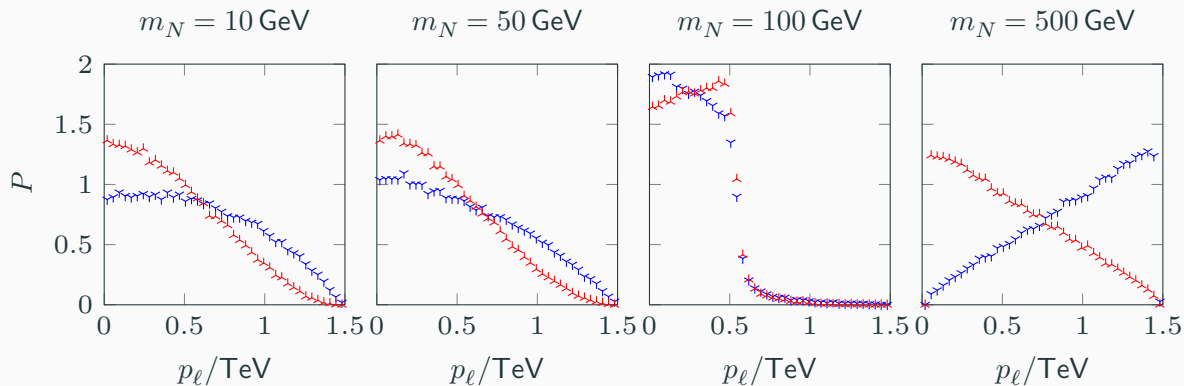
Resolving Heavy Neutrino-Antineutrino Oscillations [Preliminary]



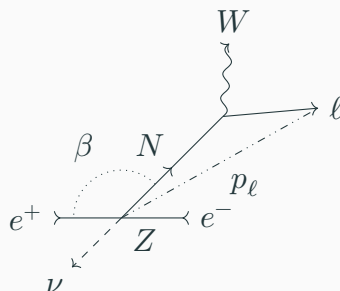
More sensitive to $\overline{N\bar{N}}$ O's than $\cos \beta$

Challenging to measure

Outgoing Lepton Momentum [2202.06703, Preliminary]



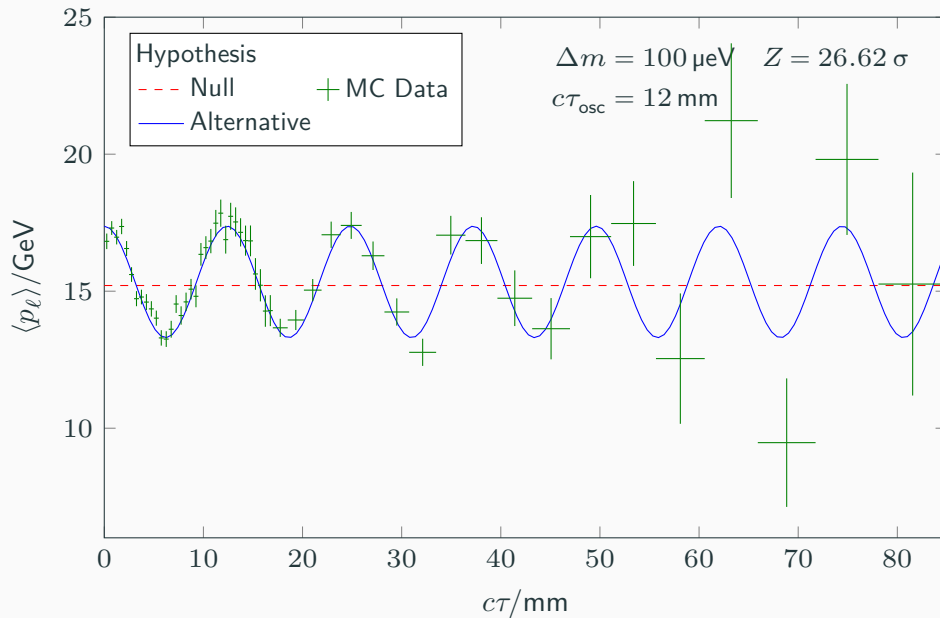
Lab frame (p_Z^2)



HNL's rest frame (p_N^2)

$$P_{\text{LNC/LNV}}^M(p_\ell) \sim P_{\text{LNC/LNV}}^M(\alpha)$$

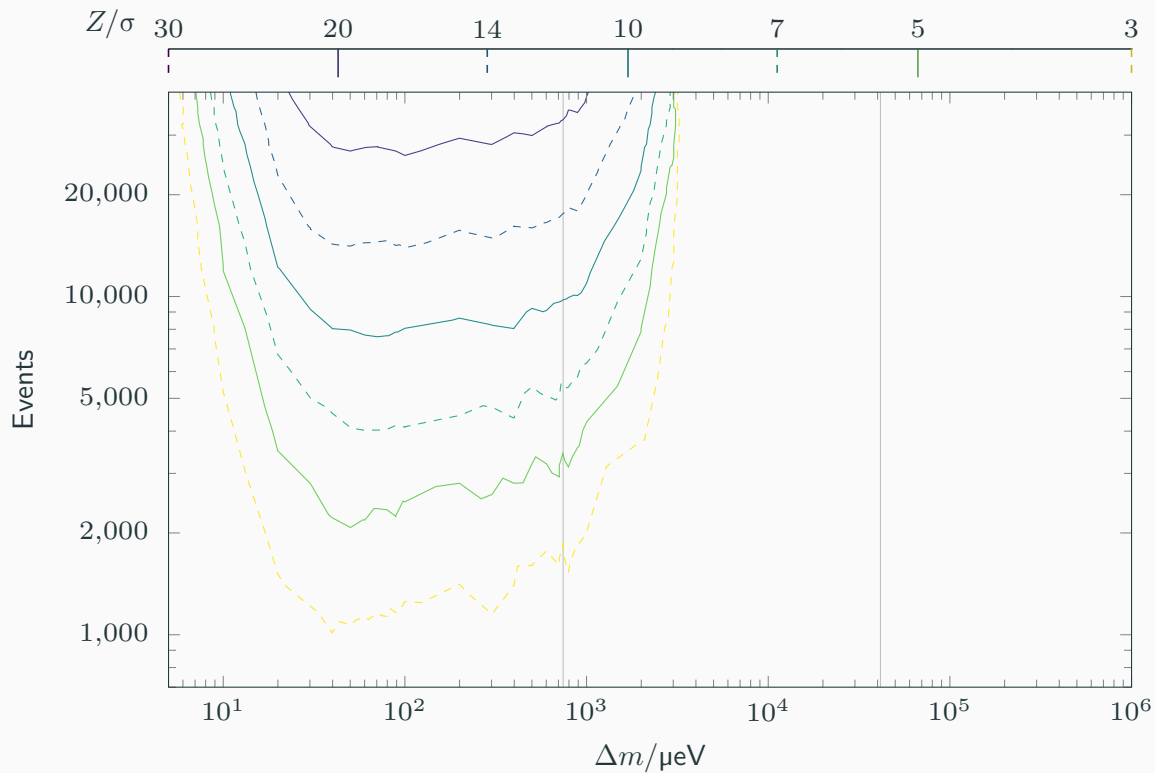
Resolving Heavy Neutrino-Antineutrino Oscillations [Preliminary]



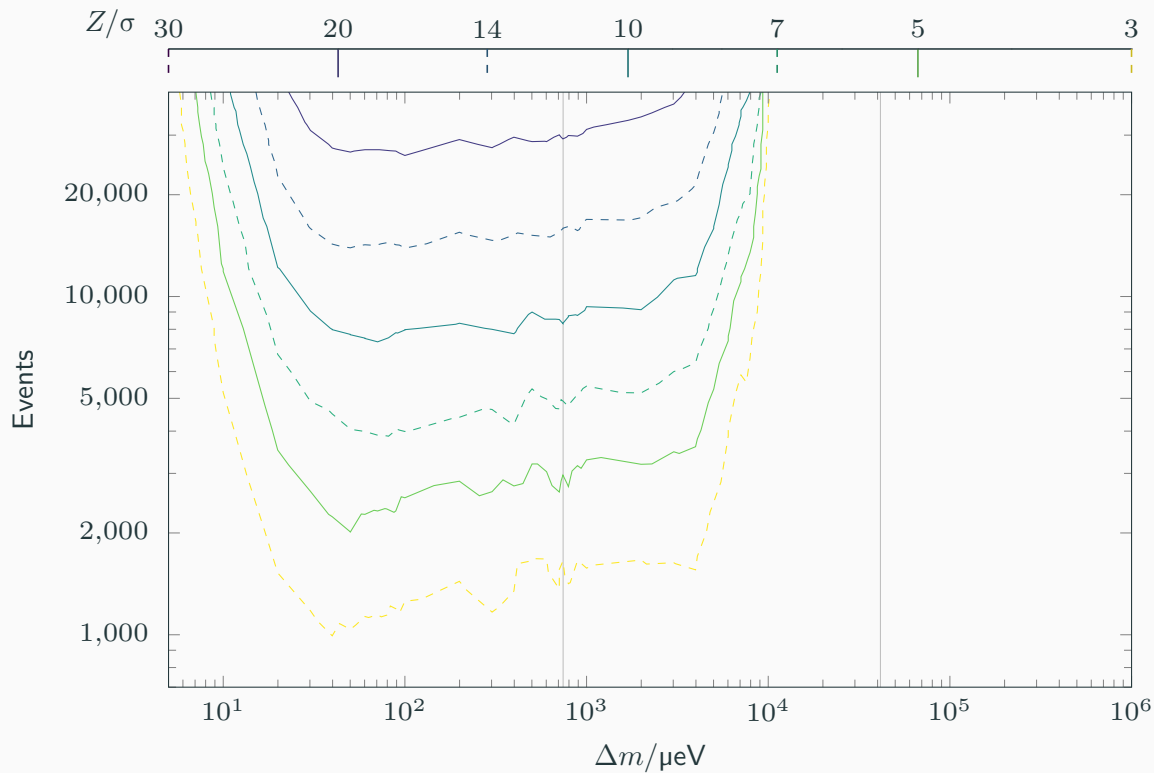
Equally sensitive to $N\bar{N}$ Os as $\cos \alpha$

Straightforward to measure

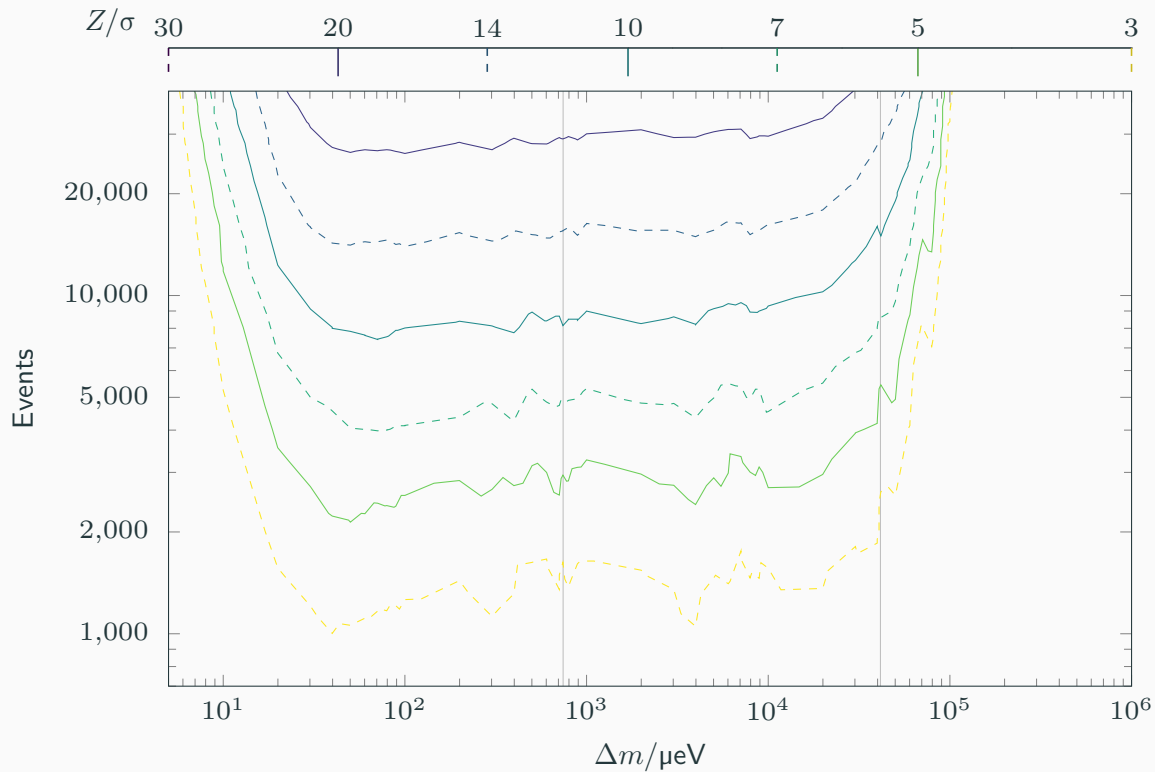
$m_M = 14 \text{ GeV}$ and $|\theta|^2 = 9 \times 10^{-8}$ (Vertex uncertainty = $300 \mu\text{m}$)



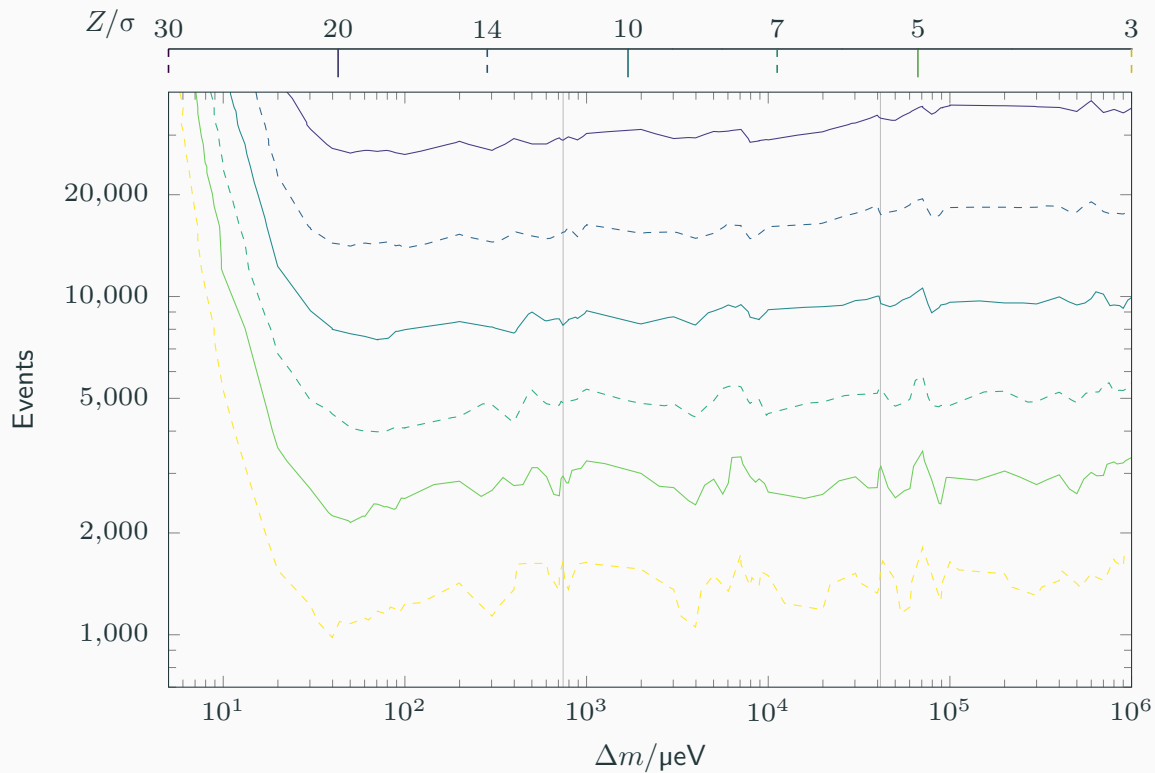
$m_M = 14 \text{ GeV}$ and $|\theta|^2 = 9 \times 10^{-8}$ (Vertex uncertainty = $100 \mu\text{m}$)



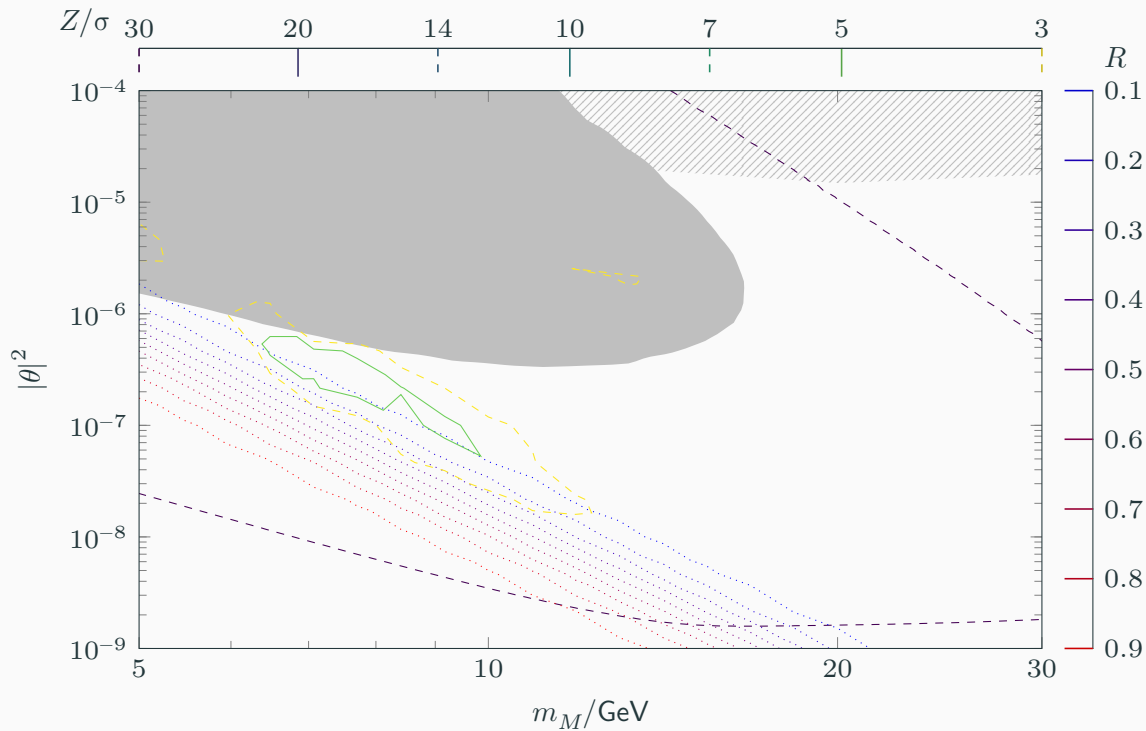
$m_M = 14 \text{ GeV}$ and $|\theta|^2 = 9 \times 10^{-8}$ (Vertex uncertainty = $10 \mu\text{m}$)



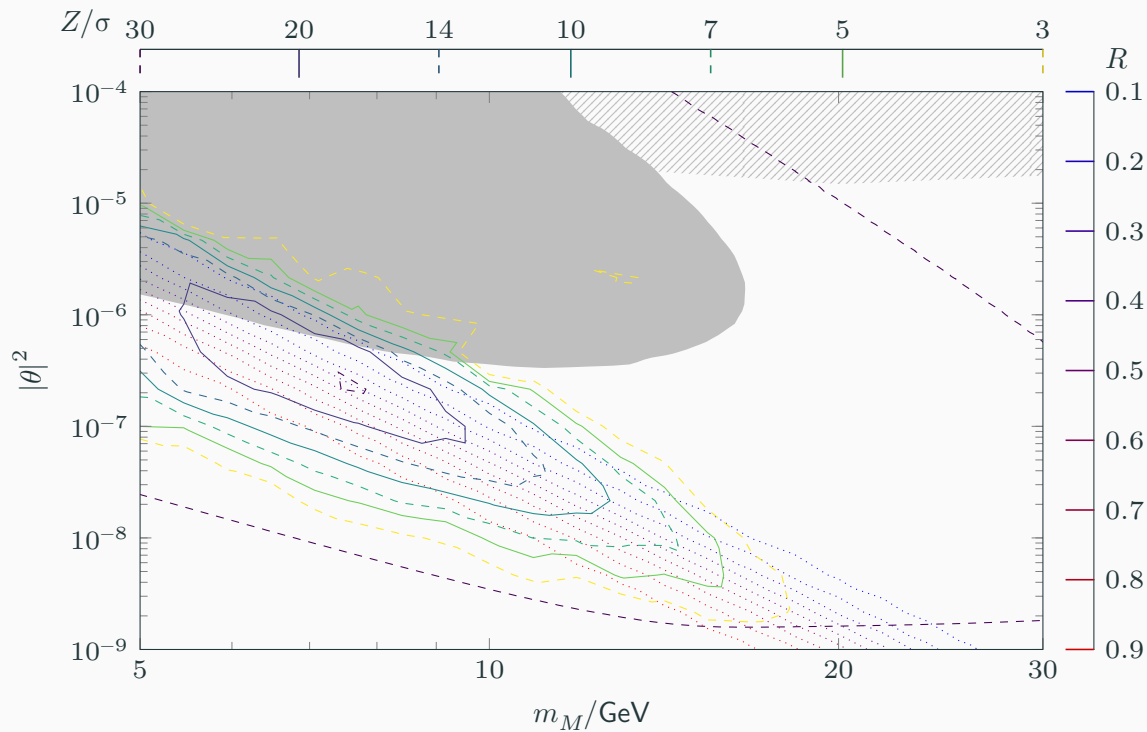
$m_M = 14 \text{ GeV}$ and $|\theta|^2 = 9 \times 10^{-8}$ (Perfect vertex reconstruction)



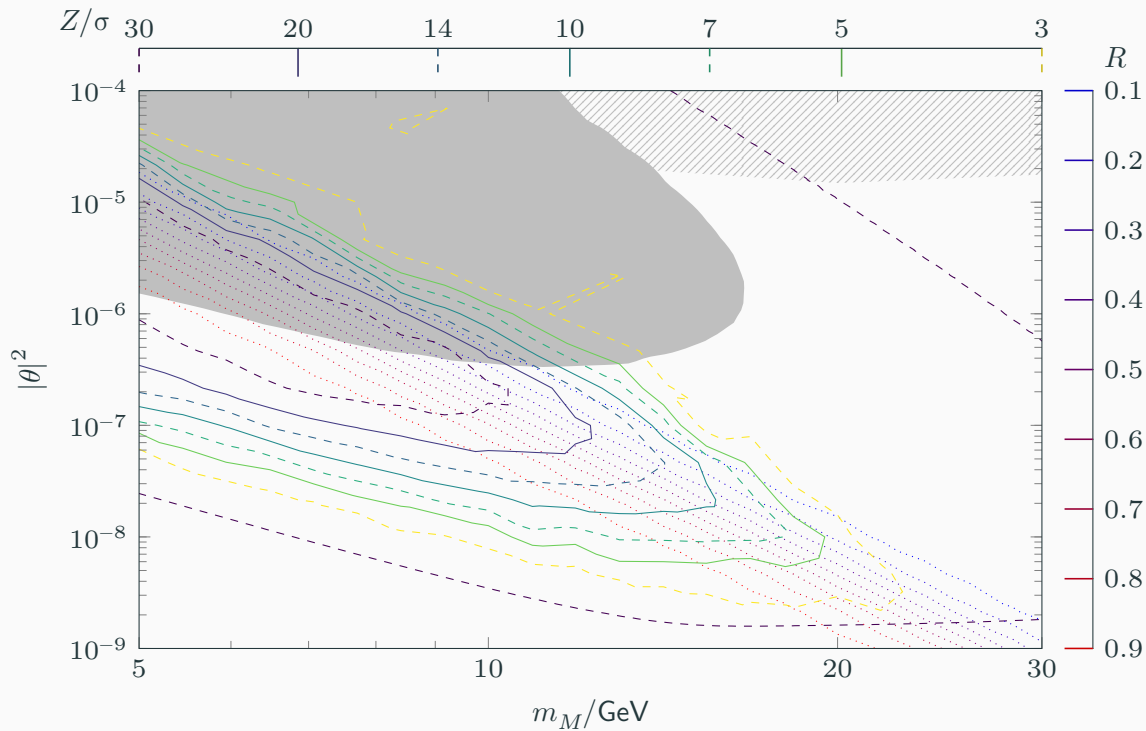
$$\Delta m = 1 \mu\text{eV} \quad (c\tau_{\text{osc}} = 1240 \text{ mm})$$



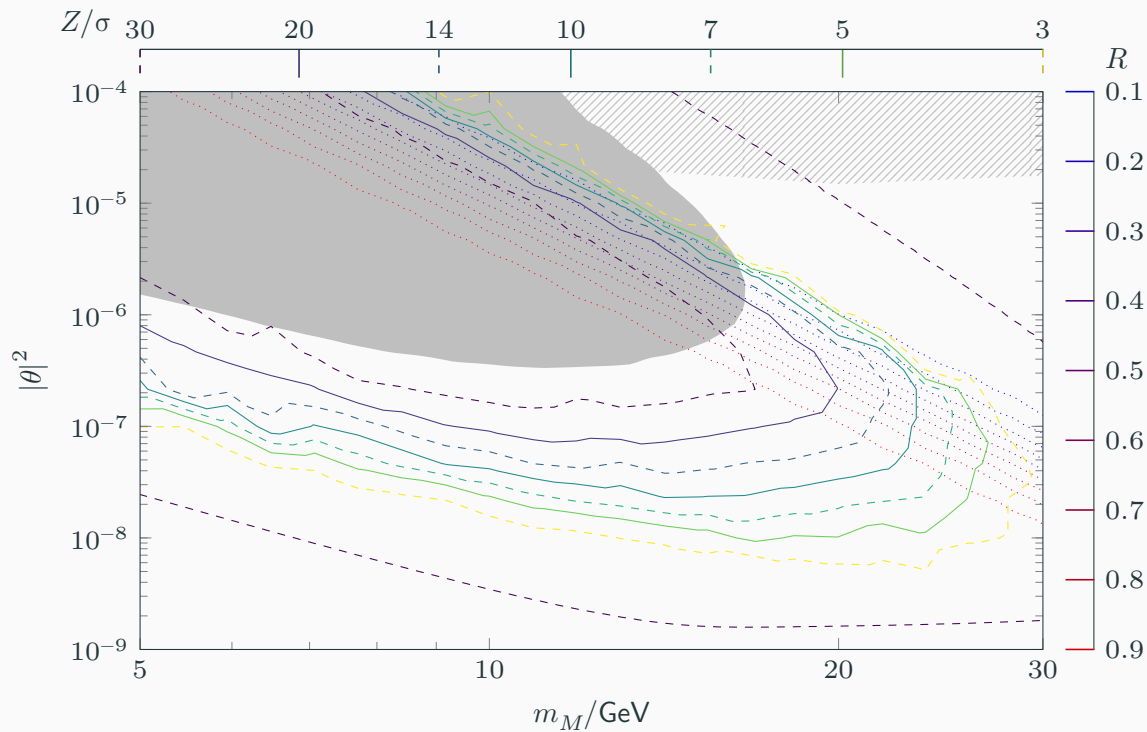
$$\Delta m = 3 \mu\text{eV} \quad (c\tau_{\text{osc}} = 413 \text{ mm})$$



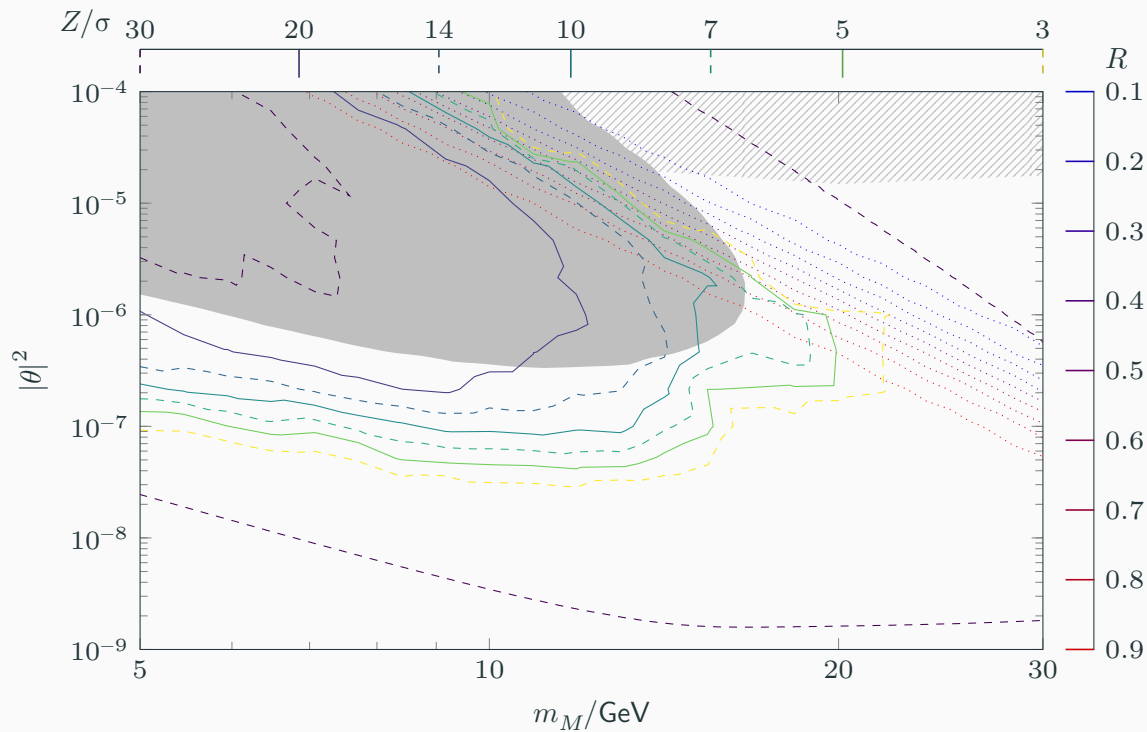
$\Delta m = 10 \mu\text{eV}$ ($c\tau_{\text{osc}} = 124 \text{ mm}$)



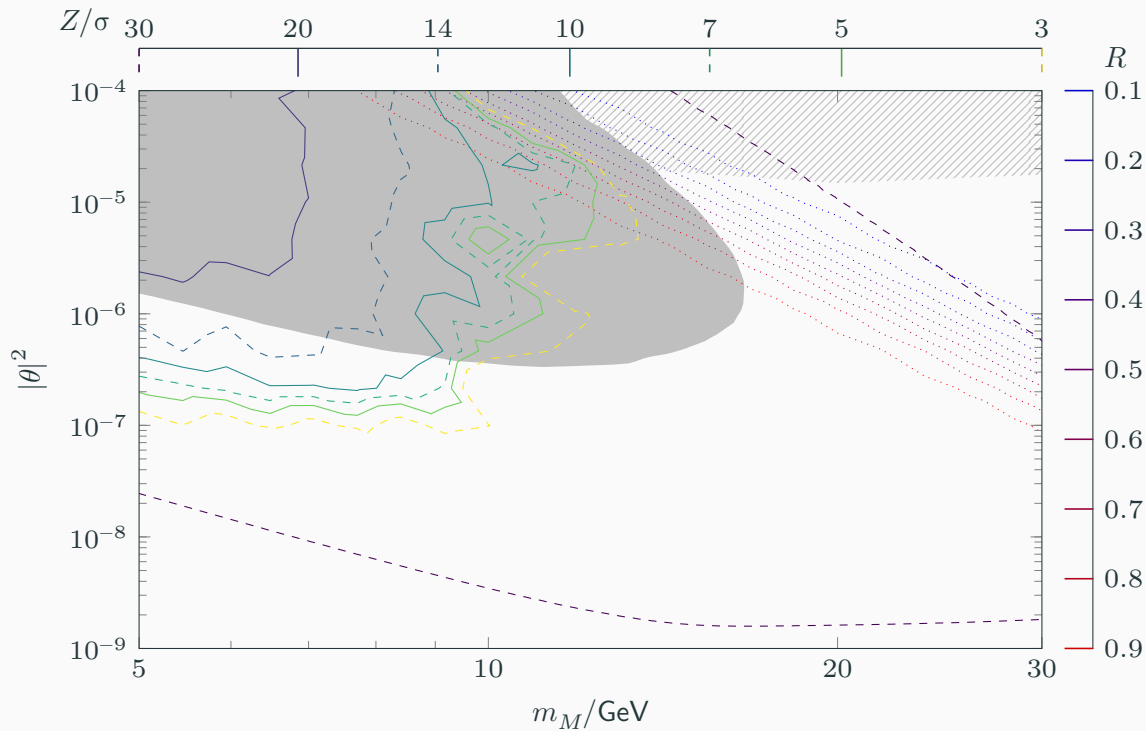
Inverted linear seesaw: $\Delta m = 743 \mu\text{eV}$ ($c\tau_{\text{osc}} = 1.67 \text{ mm}$)

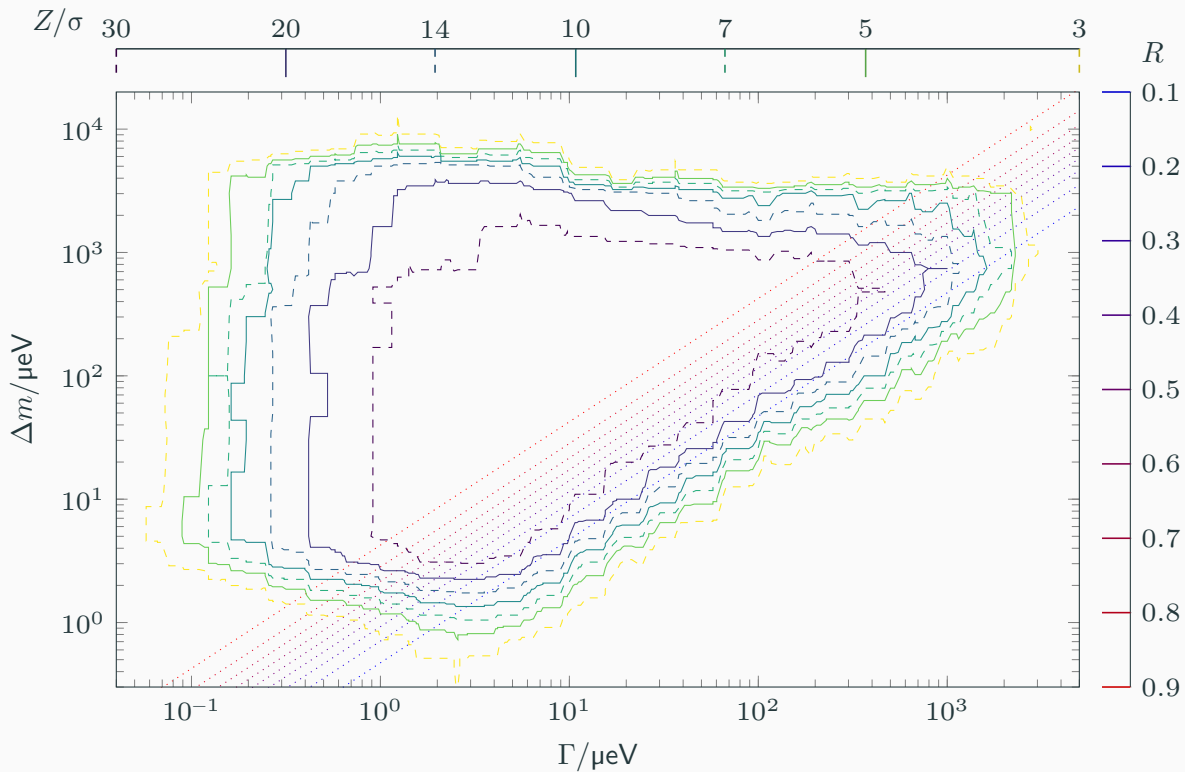


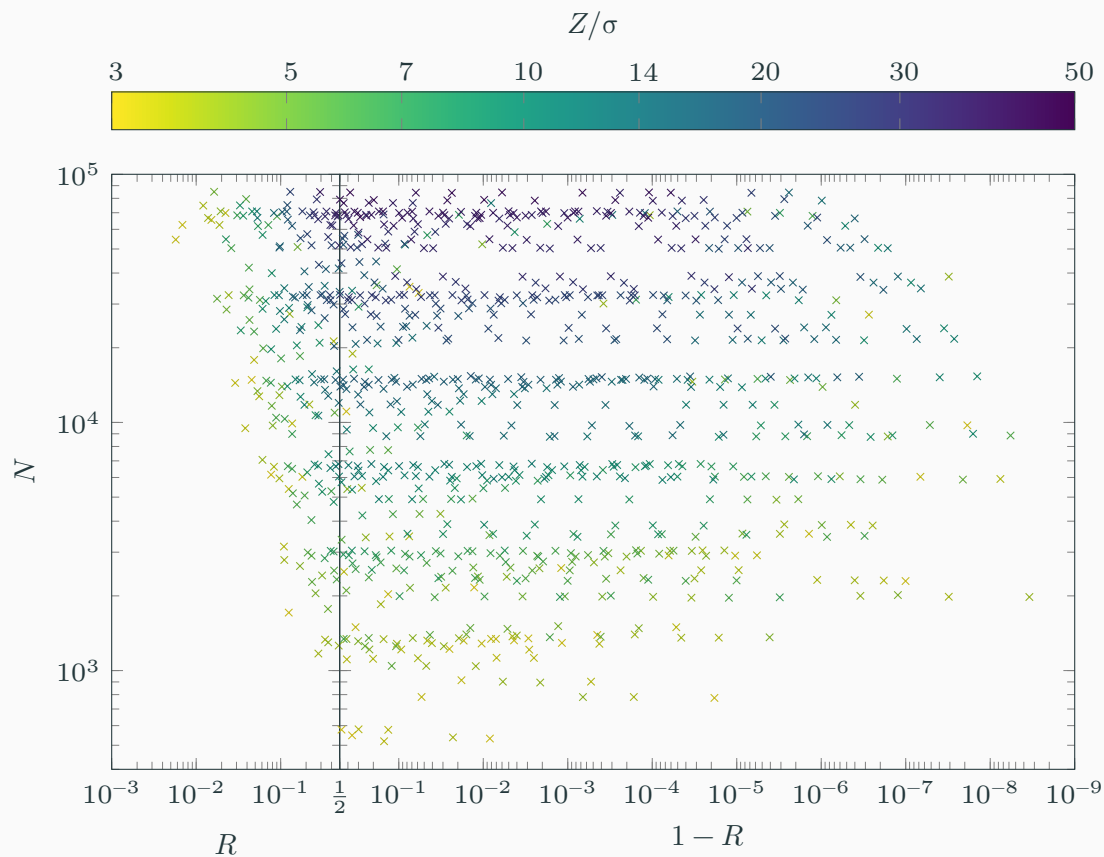
$\Delta m = 3 \text{ meV}$ ($c\tau_{\text{osc}} = 413 \mu\text{m}$)

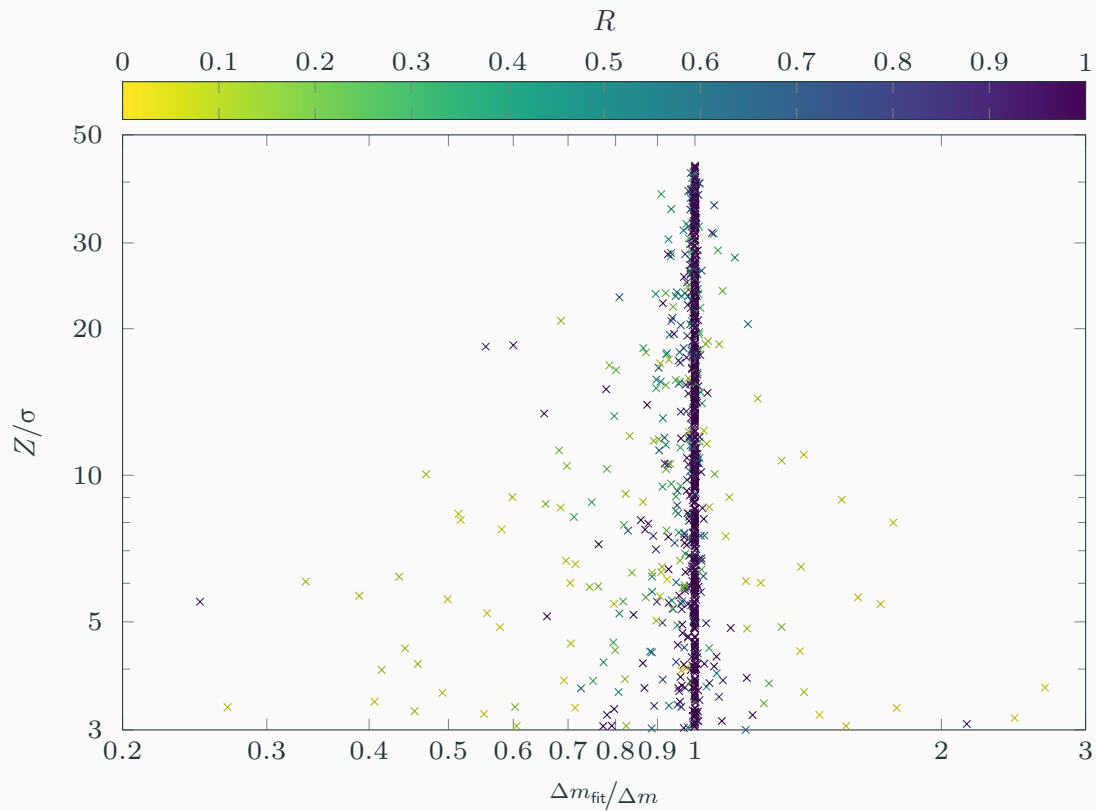


$$\Delta m = 5 \text{ meV} \quad (c\tau_{\text{osc}} = 0.258 \text{ } \mu\text{m})$$









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



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

HL-LHC (W decay)

LNV can be measured directly



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

FCC- ee (Z decay)

LNV can be detected in final state observables



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

Number of events + Interplay of oscillation and decay



Oscillations can be resolvable

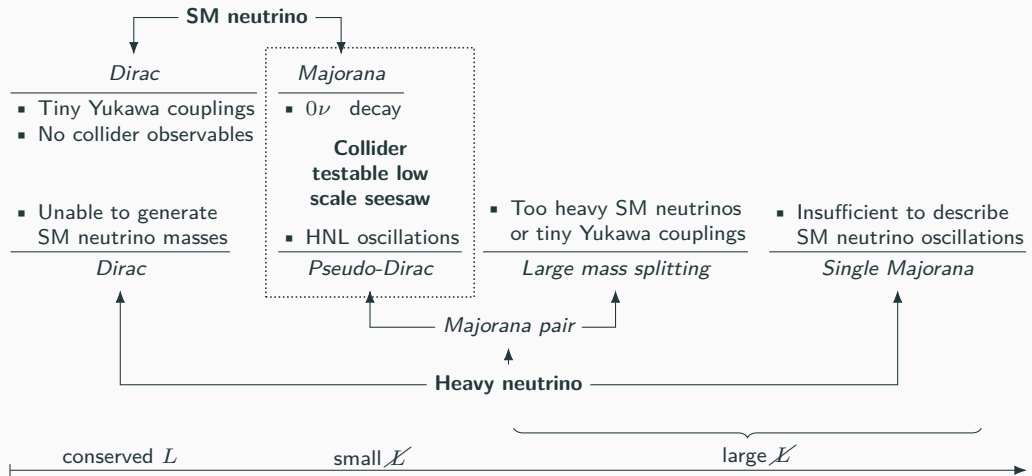


Understand neutrino mass generation + Detect LNV

More on [2308.07297] and [Preliminary]

Bibliography

- Stefan Antusch and Johannes Roszkopp. '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 Roszkopp. '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 Roszkopp. '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 Roszkopp. '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'. (2024). In progress.



Linear Seesaw

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

$$M_\nu = \mu_D \otimes \theta + \theta \otimes \mu_D \\ \{|\mu_D||\theta| \pm |\mu_D^*\theta|, 0\}$$

$$\Delta m = \Delta m_\nu = 2|\mu_D^*\theta|$$

Inverse Seesaw

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

$$\mu_M(\theta \otimes \theta) \\ \{\mu_M|\theta|^2, 0, 0\}$$

$$m_\nu|\theta|^{-2} = |\mu_M|$$

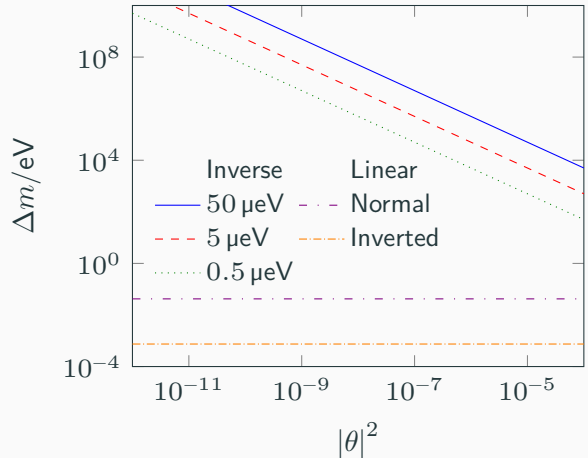
Seesaw Independent

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

$$0 \\ \{0, 0, 0\}$$

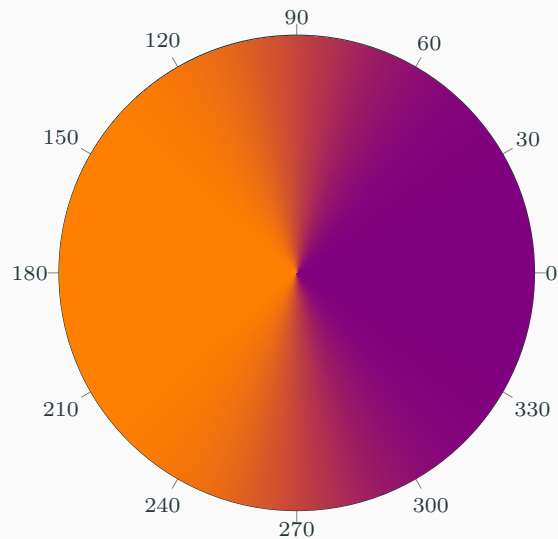
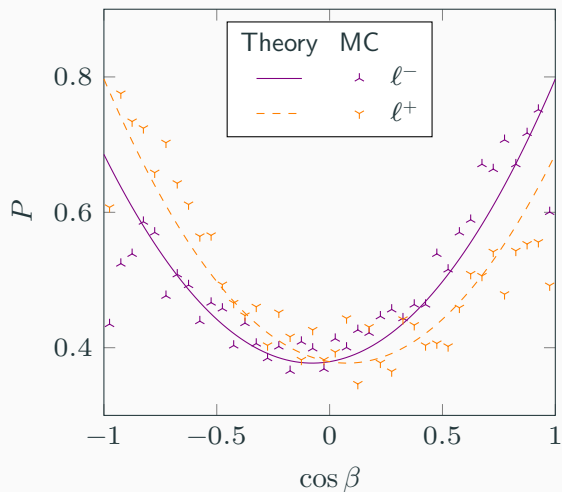
$$|\mu'_M|$$

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



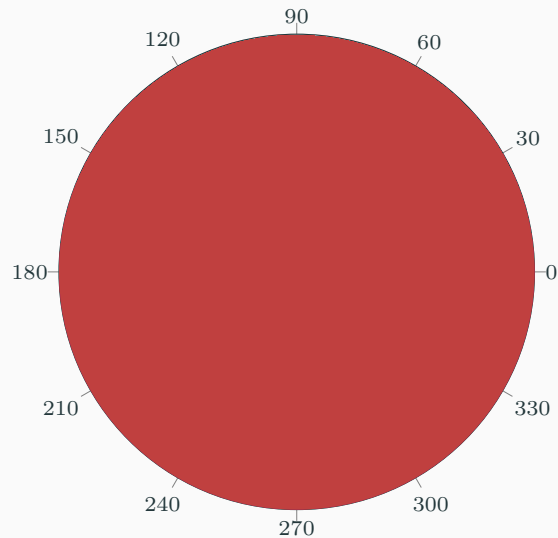
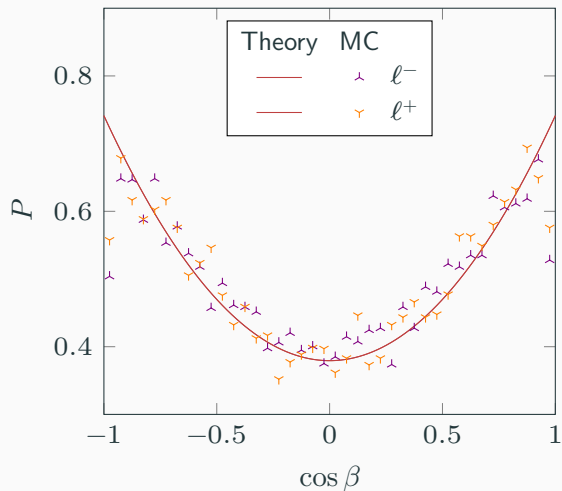
Pure Dirac HNL:

$$P_{\ell^{\mp}}(\beta) = P_{N/\bar{N}}^D(\beta) = \frac{3m_Z^2 [\gamma_{L/R}(1 + \cos\beta)^2 + \gamma_{R/L}(1 - \cos\beta)^2] + m^2 \sin^2\beta}{2m_Z^2 + m^2}$$



Single Majorana HNL:

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



Phenomenological Symmetry Protected Seesaw Scenario (pSPSS)

Two Majorana DOF described by six additional parameters

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

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

Light neutrinos are Majorana particles



No Lepton Number

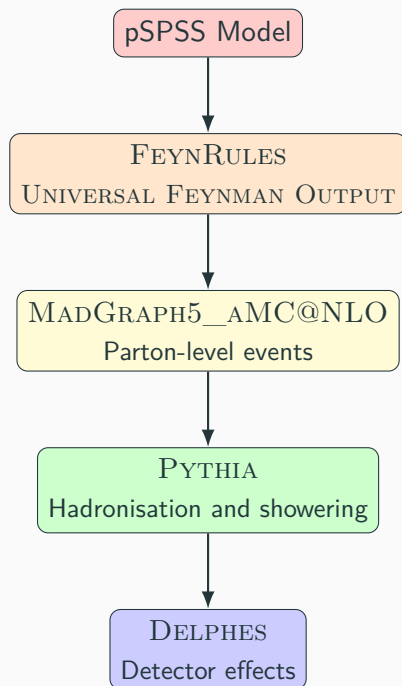
Left-chiral interaction + Small masses



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



Model light neutrinos as Dirac fields



	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

$$\begin{array}{lll}
 Z: & m_M = 14 \text{ GeV} & (\theta_e, \theta_\mu, \theta_\tau) = (0, 3, 0) \times 10^{-4} & \Gamma = 22.6 \mu\text{eV} \\
 WW: & m_M = 5.5 \text{ GeV} & (\theta_e, \theta_\mu, \theta_\tau) = (0, 1, 0) \times 10^{-3} & \Gamma = 2.05 \mu\text{eV} \\
 LHC & m_M = 14 \text{ GeV} & (\theta_e, \theta_\mu, \theta_\tau) = (0, 3.162\,28, 0) \times 10^{-4} & \Gamma = 13.8 \mu\text{eV}
 \end{array}$$

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

Null hypothesis

Oscillations are absent in the data

Alternative hypothesis

Oscillations are present in the data

Agreement between hypothesis and data

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

$$P_{\text{hyp}} = \prod_{\text{bins}} P_{\text{hyp}}^{\text{bin}}$$

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

$$P_{\text{hyp}} = \prod_{\text{events}} P_{\text{hyp}}^{\text{event}}$$

Compare hypothesis

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

Significance

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