Heavy Neutral Lepton Searches

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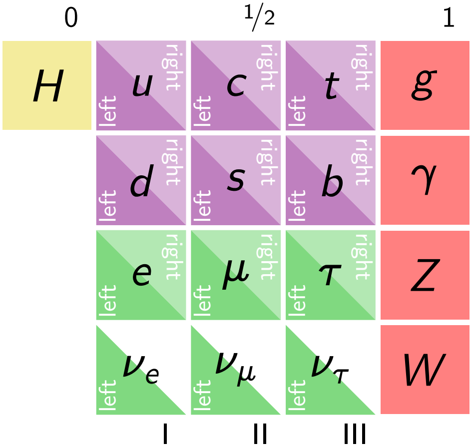
Fostering Swiss collaboration towards a future circular collider — Part 2

Fundação para a Ciência e a Tecnologia

Standard Model neutrinos

Standard Model particle content

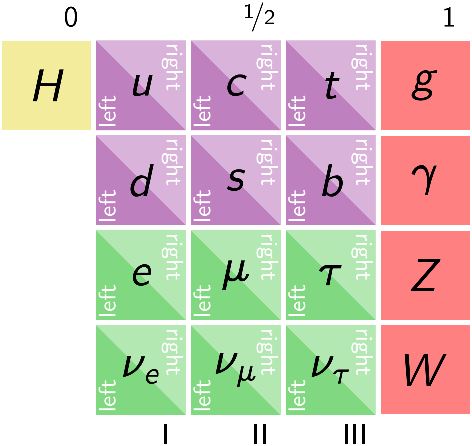


Neutrinos ν stand out

purely left-chiral and massless

Standard Model neutrinos

Standard Model particle content



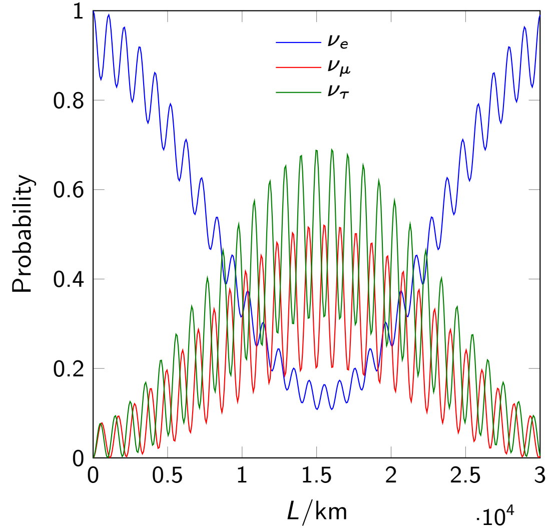
Neutrinos ν stand out

purely left-chiral and massless

Right-chiral or sterile Neutrinos would be

completely neutral under all SM symmetries

Observed neutrino flavour oscillations



Flavour oscillations are explained by

right-chiral neutrinos allowing mass terms

Seesaw models generating neutrino masses

Dirac mass

$$\mathcal{L}_D = -m_D \bar{\nu} N \,, \qquad m_D = v y$$

Majorana mass

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

Coupling strength is determined by

$$U \propto \theta = m_D / m_M$$

Majorana mass vanishes only if

lepton-number L is conserved

Majorana mass introduces

lepton number violation (LNV)

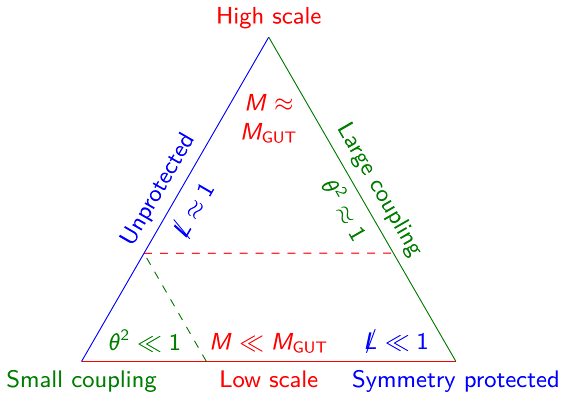
Neutrino oscillation pattern requires

at least two massive neutrinos

Neutrino mass matrix from two sterile neutrinos

$$M_\nu \propto \frac{m_{D,1}^T m_{D,1}}{m_{M,1}} + \frac{m_{D,2}^T m_{D,2}}{m_{M,2}}$$

Viable seesaw models



Neutrino masses are small for

- small θ
- large M
- symmetry ensuring cancellation

Symmetry protected seesaw

[1502.05915]

Lepton number-like symmetry

Generalizes the accidental lepton number of the SM

One simple choice of charges

	ℓ	N_1	N_2
L	$+1$	$+1$	-1

Other new fields

contribute further terms in the Lagrangian

Symmetric limit

$$\mathcal{L}_{\text{SPSS}}^{\text{sym}} = -\overline{N}_1^c m_M N_2 - \widetilde{H}^\dagger \overline{N}_1^c \ell_a y_{a1} + \text{h.c.}\,,$$

In the symmetry protected limit $y_{a2} \ll 1$

$$\Delta\mathcal{L}_{\text{SPSS}}^{y\ll 1} = -\widetilde{H}^\dagger \overline{N}_2^c \ell_a y_{a2} + \text{h.c.} + \dots\,,$$

Basis

$n = (\nu, N_4, N_5)$

Neutrino mass matrix

contains seesaw information

Symmetric limit

$$M_n^{\text{sym}} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^\mathsf{T} & 0 & m_M \\ 0 & m_M & 0 \end{pmatrix}$$

- Massless neutrinos
- Dirac HNL

Mild symmetry breaking

$$M_n^{\text{SPSS}} = \begin{pmatrix} 0 & m_D & \mu_D \\ m_D^\mathsf{T} & \mu_M' & m_M \\ \mu_D^\mathsf{T} & m_M & \mu_M \end{pmatrix}$$

- pseudo-Dirac HNL (2 related Majorana fermions with small Δm)
- phenomenology governed by small parameters μ

Large symmetry breaking

$$M_n^{\text{generic}} = \begin{pmatrix} 0 & m_D & \widehat{m}_D \\ m_D^\mathsf{T} & \widehat{m}_M' & m_M \\ \widehat{m}_D^\mathsf{T} & m_M & \widehat{m}_M \end{pmatrix}$$

- 2 Majorana HNLs with large Δm
- Large m_M or tiny θ

Special cases captured by the symmetry protected seesaw

[1502.05915]

Generic seesaw

All small parameter μ are nonzero

SM neutrinos masses

small and proportional the μ's

Special cases:

Linear seesaw μ

$$M_n = \begin{pmatrix} 0 & m_D & \mu_D \\ m_D^\intercal & 0 & m_M \\ \mu_D^\intercal & m_M & 0 \end{pmatrix}$$

Inverse seesaw μ_M

$$M_n = \begin{pmatrix} 0 & m_D & 0 \\ m_D^\intercal & 0 & m_M \\ 0 & m_M & \mu_M \end{pmatrix}$$

Seesaw independent term μ'_M

$$M_n = \begin{pmatrix} 0 & m_D & 0 \\ m_D^\intercal & \mu'_M & m_M \\ 0 & m_M & 0 \end{pmatrix}$$

SM Neutrino mass matrix:

$$M_\nu \propto \mu_D^\intercal \theta$$

$$M_\nu \propto \mu_M \theta^\intercal \theta$$

$$M_\nu = 0 \text{ at tree level}$$

HNL mass splitting:

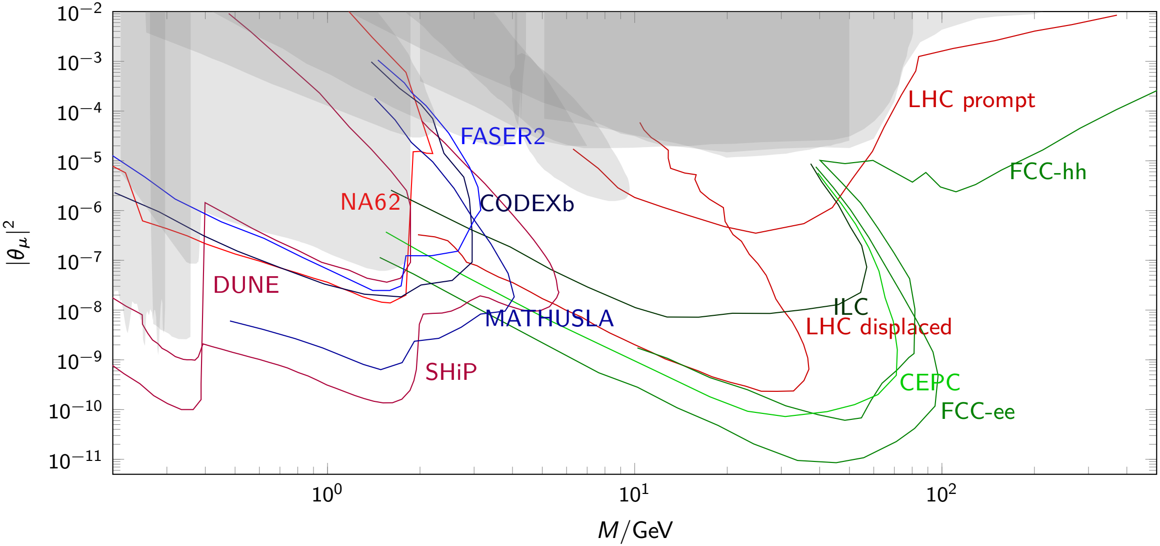
$$\Delta m \propto \Delta M_\nu$$

$$\Delta m \propto \frac{M_\nu}{|\theta^2|}$$

$$\Delta m \propto \mu'_M$$

Experimental prospects to find HNLs

Heavy neutral leptons (HNLs) at experiments

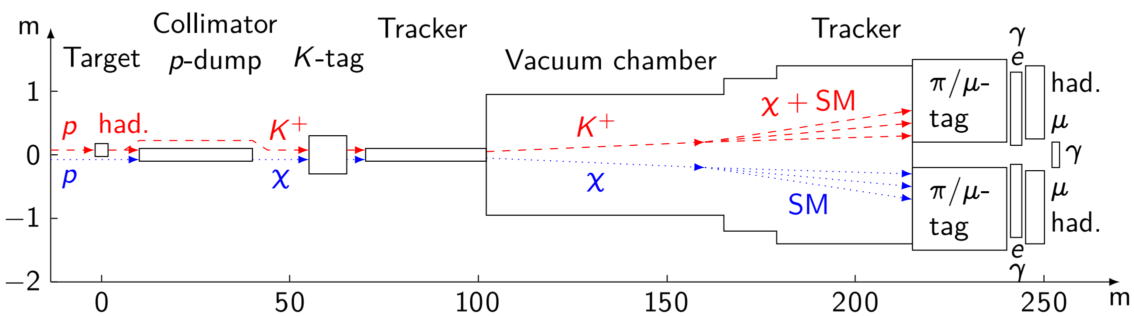


Fixed target experiments	Collider experiments	Long-lived signatures
Explore small masses	Explore large masses	interesting for FCC-ee

HNLs in NA62

Fixed target experiment in the North Area using the CERN SPS with the goal to

- measure the very rare kaon decay $K^+ \to \pi^+ \nu \overline{\nu}$
- 10 % measurement of the CKM parameter $|V_{td}|$

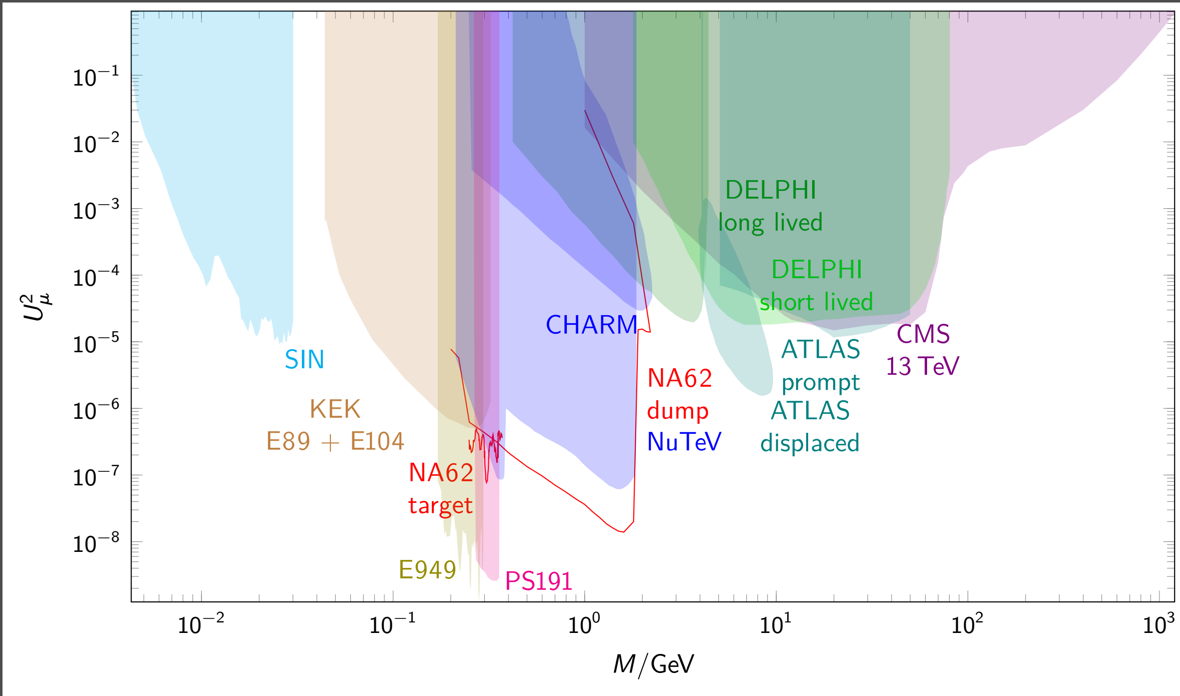


Hidden sectors at NA62

- it can also be used to search for hidden new physics χ such as a heavy neutrino
- Target mode
- only K^+ induced processes
- Dump mode
- D- and B-meson induced processes dominate

Exclusion potential of NA62

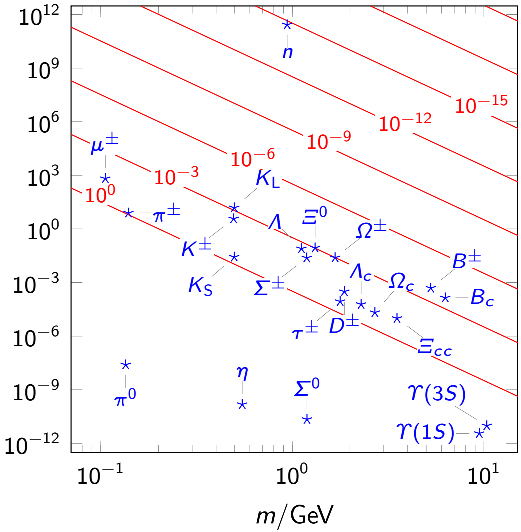
[1801.04207]

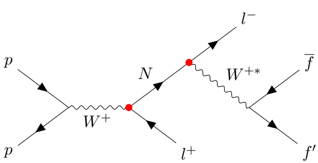


HNLs at the HL-LHC

[1903.06100]

HNL longevity $|\theta|^2(m, c\tau)$ vs. SM resonances

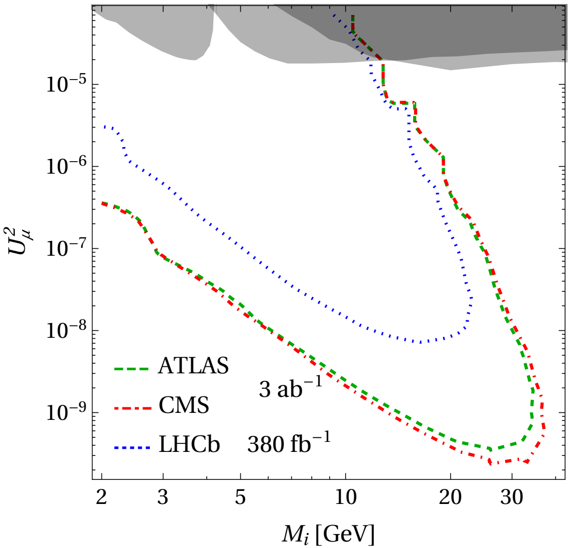




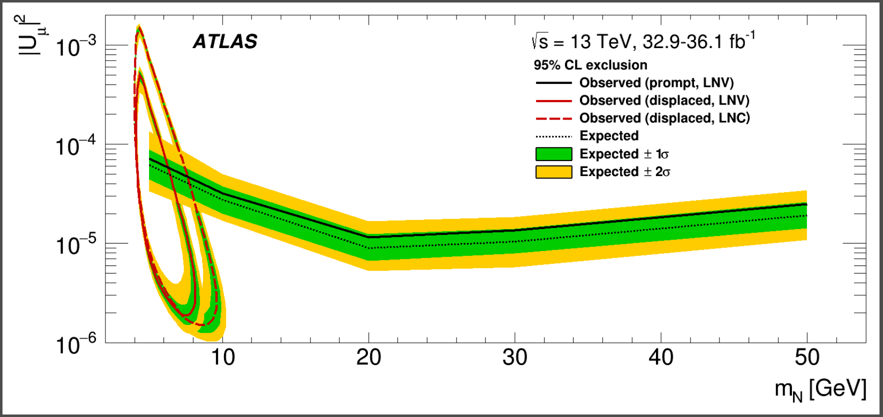
Search strategy

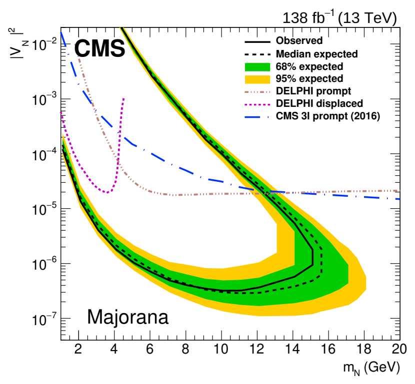
- trigger on first lepton
- search for secondary vertex

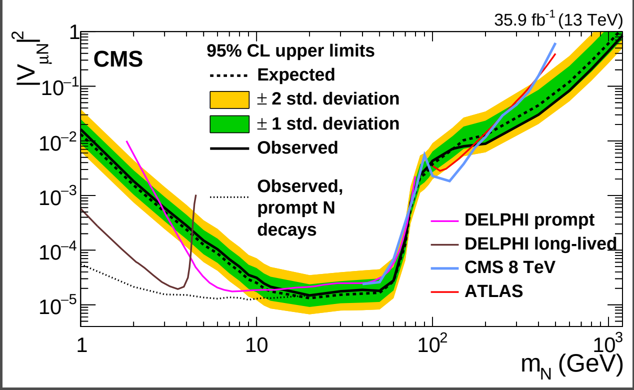
Maximal exclusion reach at the LHC



Prompt and displaced HNL searches at the LHC [1802.02965; 1905.09787; 2201.05578]

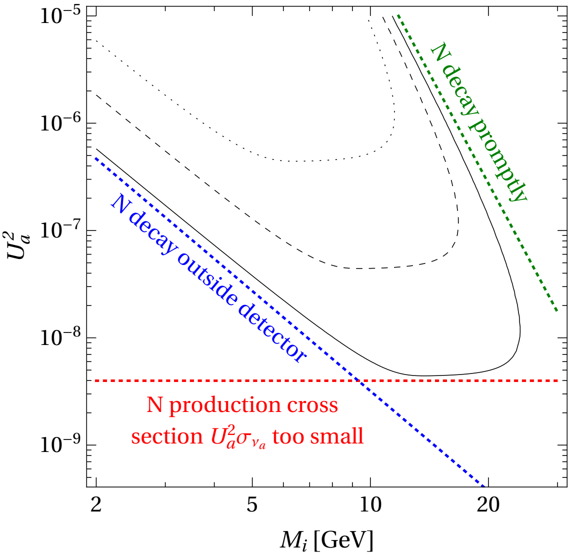






HNL sensitivity scaling in finite detectors

HNL sensitivity contours [1903.06100]



1 dim estimate for number of observed events

$$N_{obs} \simeq L\sigma_N \left[\exp\left(-\frac{l_0}{\lambda_N}\right) - \exp\left(-\frac{l_1}{\lambda_N}\right)\right]$$

- $\lambda_N = \frac{\beta\gamma}{\Gamma_N}$ $\qquad \Gamma_N \simeq 12\frac{|\theta|^2 M^5 G_F^2}{96\pi^3}$
- $\beta\gamma \simeq \frac{m_Z^2 - M^2}{2m_Z M}$ $\qquad$ (Z-boson at rest)

For $\lambda \gg l_1 \gg l_0$

$$N_{obs} \propto L|\theta|^4 \frac{M^5 l_1}{\beta\gamma}$$

For fixed mass and number of observed events

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

HECATE: a extension to the FCC-ee

[2011.01005]

Idea

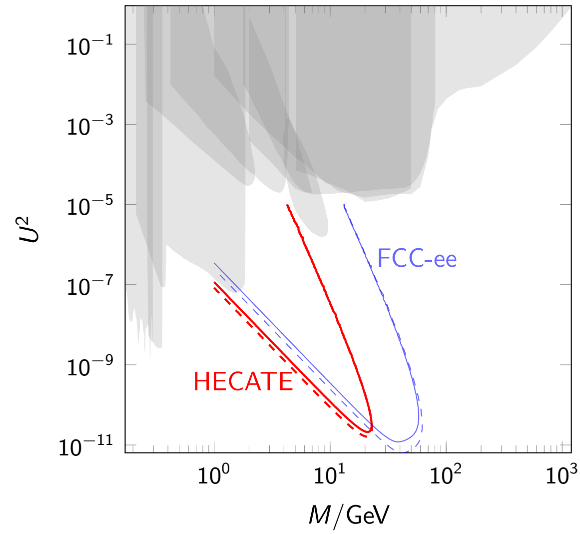
- Exploit the additional space surrounding the FCC-ee detectors in the FCC-hh caverns
- Build a 4π LLP detector

Layout

- Cover the cavern surface with $1\,\mathrm{m}^2$ scintilator plates / resistive plate chambers (RPCs)
- Assuming cylindrical caverns with $r = 15\,\mathrm{m}$ and $z \simeq 50\,\mathrm{m}$
- Results in ~ 6000 readout channels
- Minimum of two layers allows for timing
- Main detector serves as veto

Sensitivity calculation for spherical detector

$|\theta|^2$ sensitivity gain $\sqrt{\frac{l_1}{1.22\,\mathrm{m}}}$ with $l_1 = 15$–$25\,\mathrm{m}$

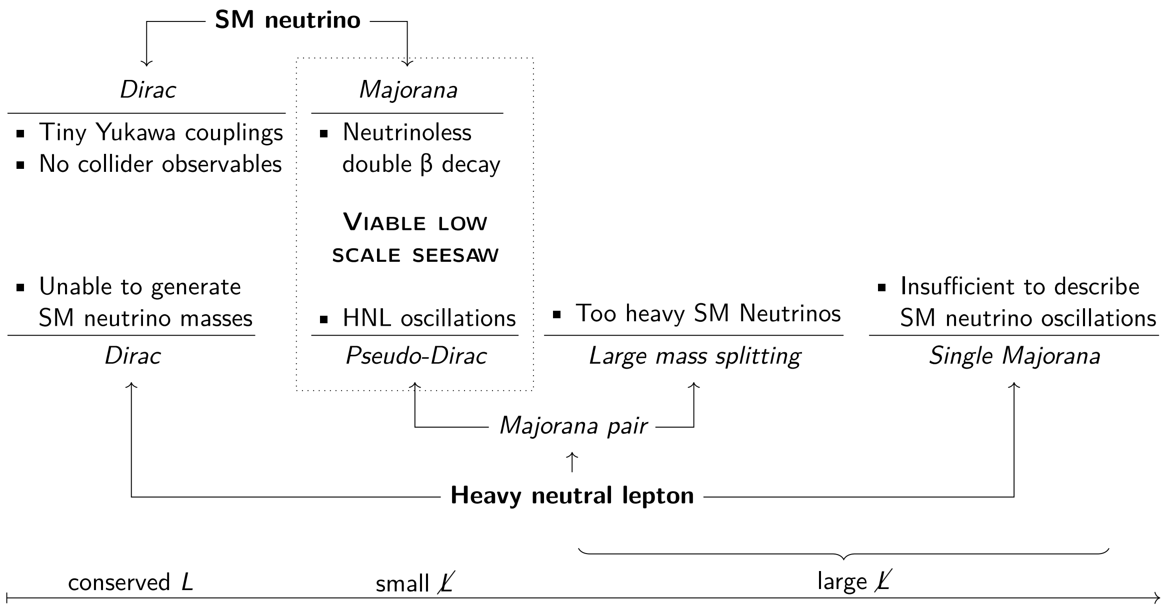


— $l_0 = 4\,\mathrm{m}$, $l_1 = 15\,\mathrm{m}$
- - - $l_0 = 4\,\mathrm{m}$, $l_1 = 25\,\mathrm{m}$

All efficiencies assumed to be 100 %

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

Are HNLs Majoran or Dirac Fermions?



Majorana and Dirac HNLs are

- not expected to be found at colliders
- insufficient benchmark points

pseudo-Dirac HNLs have unique phenomenology

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

Heavy neutrino antineutrino oscillations

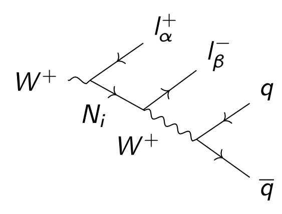
[1709.03797; 2012.05763]

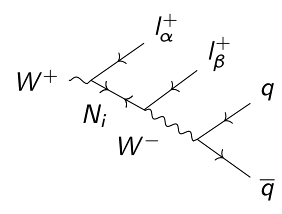
Oscillations

between LNC and LNV decays

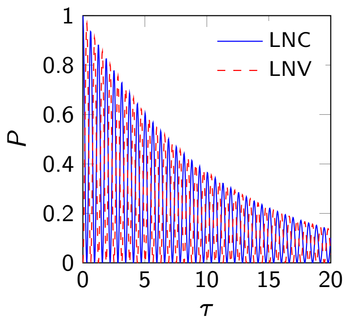
Mass splitting Δm

governs size of oscillations at leading order



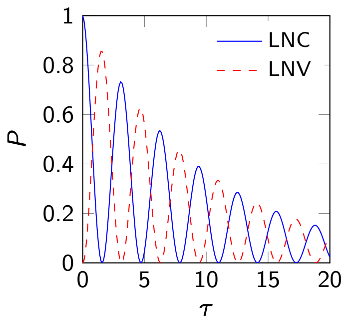


Short oscillation length



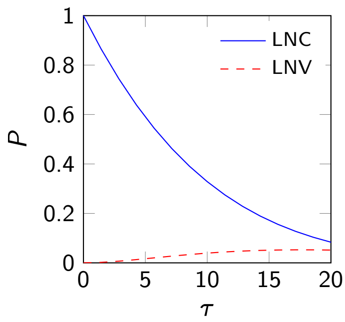
- Oscillations not resolvable
- Integrated effect $R_{ll} = N_{\text{LNV}}/N_{\text{LNC}} \approx 1$
- Majorana limit

Intermediate oscillation length



- $\Delta m/\Gamma \approx \mathcal{O}(1)$
- Oscillations potentially measurable

Long oscillation length

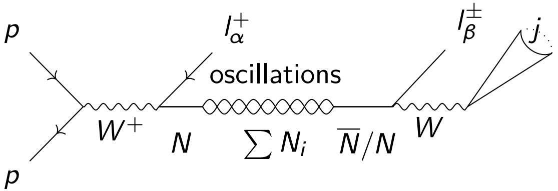


- LNV strongly suppressed
- LNV contribution not detectable
- Dirac limit

Heavy neutrino antineutrino oscillations at the LHC

[to appear soon]

Production, oscillation, and decay



Process

- Production of interaction eigenstates N or $\overline{N}$
- Mass splitting induced Δm oscillations between N_4 and N_5
- LNC decay into l^- or LNV decay into l^+

Idea

Observe heavy neutrino oscillations in long-lived decays

Simulation

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

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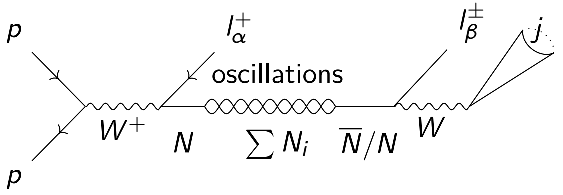
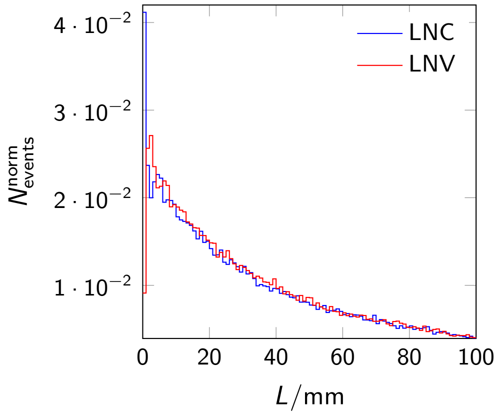


Lab frame



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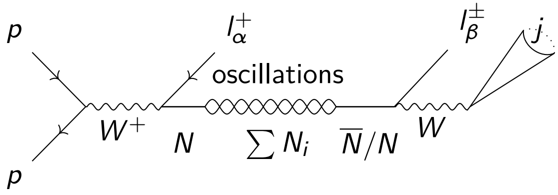
Observations

- No oscillations in the lab frame

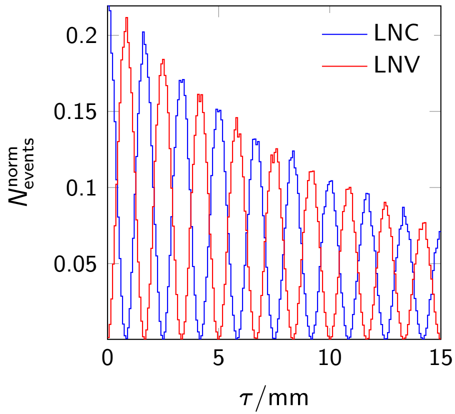
Heavy neutrino antineutrino oscillations at the LHC

[to appear soon]

Production, oscillation, and decay



Proper time frame



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Idea

Observe heavy neutrino oscillations in long-lived decays

Simulation

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

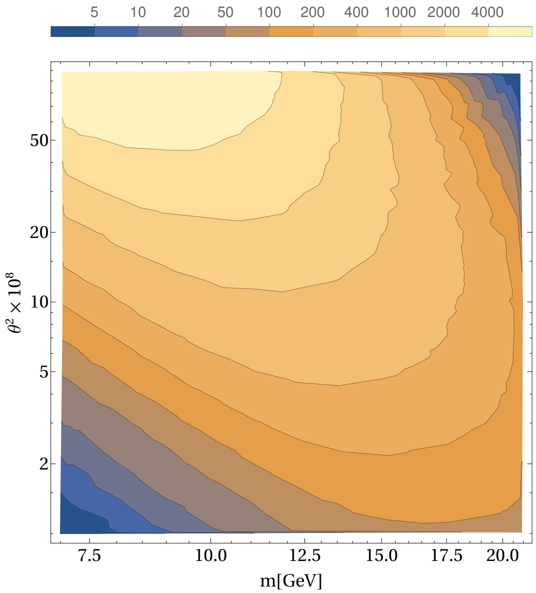
Observations

- No oscillations in the lab frame
- Oscillations appear in proper time frame
- It is crucial to reconstruct the boost factor γ
- Only processes without final neutrinos useful

Preliminary results

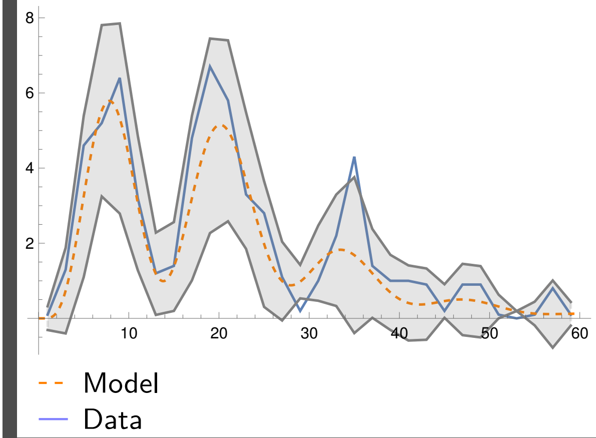
[to appear soon]

Event number for semi hadronic decays



Expected pattern for long lived particle searches

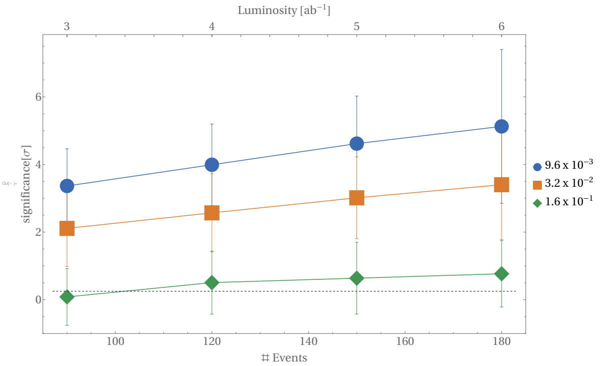
Example of oscillation reconstruction



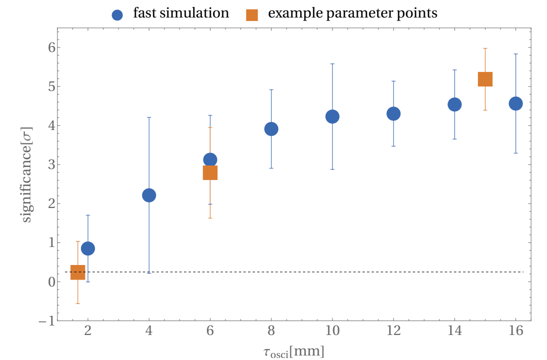
Preliminary results

- Large parts of the accessible parameter space are already excluded by LHC
- HL-LHC can measure some heavy neutrino oscillations with $5\,\sigma$
- Strong dependence on oscillation length

Significance as function of luminosity



Significance as function of oscillation length



Heavy neutrino antineutrino oscillations at FCC-ee

Future work in Basel

- Prospects to measure the amount of LNV at the FCC-ee
- Prospects to discover heavy neutrino antineutrino oscillations at FCC-ee

Obstacles

- Processes contain final state neutrinos
- Complete event reconstruction challenging

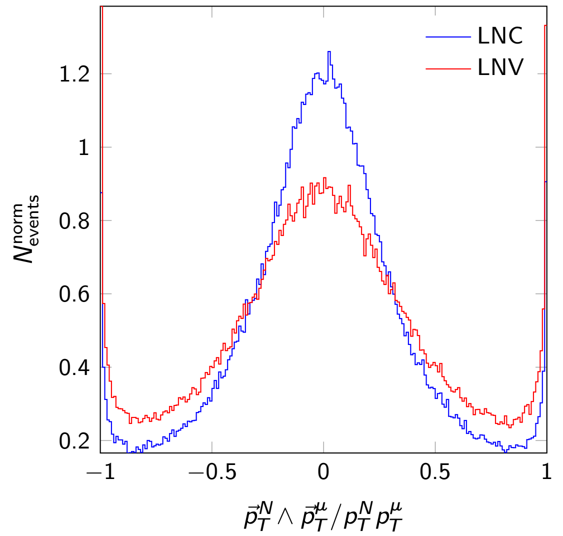
Ideas

- Exploit angular dependent variables

Tools we will publish

- Phenomenology symmetry protected seesaw model with minimal number of parameters
- FeynRules model file of this model describing pseudo-Dirac HNLs
- MadGraph patch for simulation of HNL oscillations
- Well motivated benchmark points

Spin correlation



Conclusion

- Low scale seesaw model predict pseudo-Dirac HNLs
- Pseudo-Dirac HNLs oscillate between LNC and LNV decays
- Displaced HNL oscillations are resolvable at the HL-LHC
- The symmetry protected seesaw captures the relevant physics in a simple model
- FCC-ee will probe a considerable larger part of the parameter space

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