Testing the heavy decaying sterile neutrino solution to the LSND and MiniBooNE anomalies at DUNE near detector

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- the LSND and MiniBooNE anomalies
- the heavy decaying sterile neutrino scenario (HDSN)
- signature of a HDSN in the DUNE near detector
- results: expected sensitivity of the DUNE near detector

Work in progress with S. Sachi Chatterjee, G. Moreno and O. Miranda

Workshop on the Standard Model and Beyond
Mon Repos, Corfu, 29 August 2024

Introduction

All data from solar, atmospheric, reactor and accelerator neutrino experiments is successfully interpreted in terms of 3-flavour oscillations, except for a few anomalies

Oldest anomalies from the short-baseline accelerator experiments LSND and MiniBooNE remain unexplained. Could be due to $\nu_\mu \to \nu_e$ oscillations involving a fourth, light (eV-scale) neutrino, but strongly disfavoured by other experiments

Possible non-oscillation explanation: heavy (keV - MeV) sterile neutrino mixing with ν_μ and decaying to ν_e , thus mimicking the LSND and MiniBooNE excesses [Palomares-Ruiz et al. '05 - Dentler et al. '19 - de Gouvêa et al. '19]

This talk: possibility to test this scenario at the DUNE near detector

The LSND and MiniBooNE anomalies

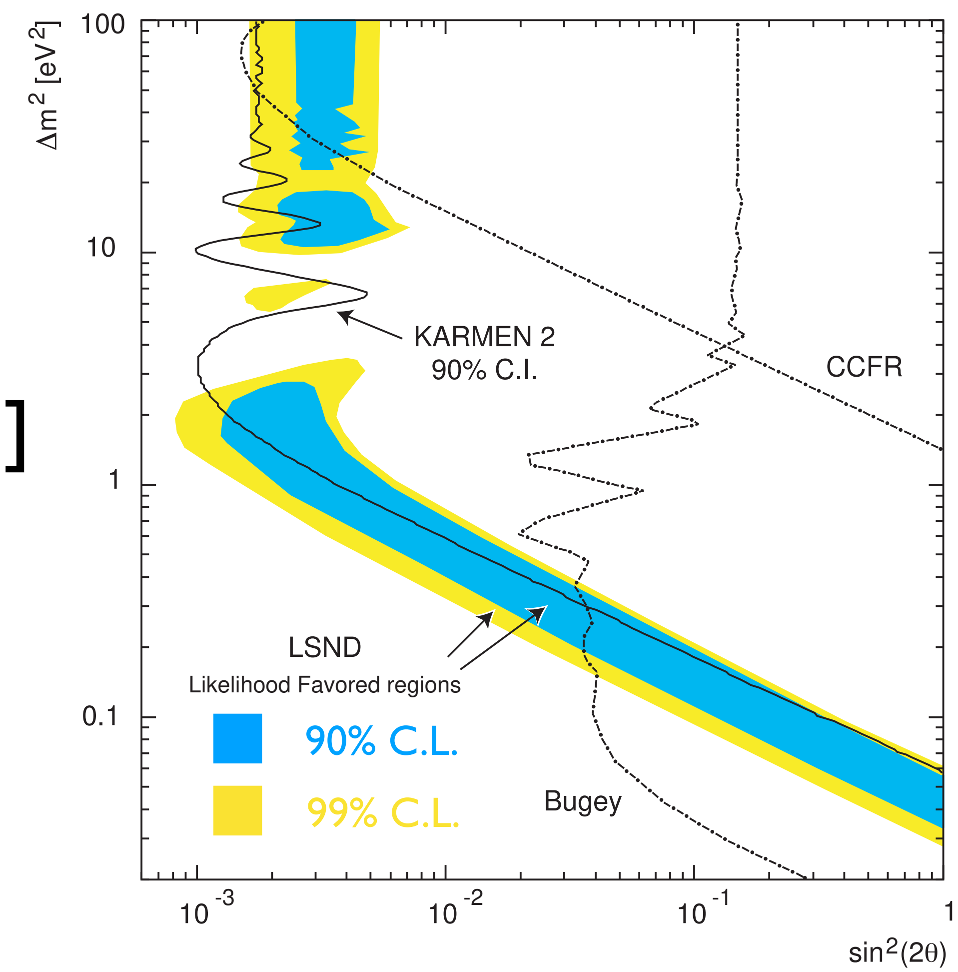
Short-baseline accelerator experiments [$\nu_e(\bar{\nu}_e)$ appearance in a $\nu_\mu(\bar{\nu}_\mu)$ beam]

LSND (1993-1998) [$\bar{\nu}_\mu$ beam, $L = 30\,\mathrm{m}$]

Excess of $\bar{\nu}_e$ events over background at 3.8 σ interpreted by LSND as $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations

Not observed by KARMEN

[LSND allowed region in the $(\sin^2 2\theta, \Delta m^2)$ plane (2-neutrino fit) - hep-ex/0203021]



$\sin^2 2\theta_{\mu e} \equiv 4|U_{e4}U_{\mu 4}|^2$

MiniBooNE (2002-2017) [ν_μ and $\bar{\nu}_\mu$, $L = 541\,\mathrm{m}$]

Designed to test the LSND anomaly with a different L but a similar L/E

2002-2012 : inconclusive/contradictory results

Full 2002-2019 data : excess of $\nu_e(\bar{\nu}_e)$ CC events both in the ν and $\bar{\nu}$ modes (4.8 σ in total), mainly in the low-energy region, consistent with LSND

→ suggests $\nu_\mu \to \nu_e \,/\, \bar{\nu}_\mu \to \bar{\nu}_e$ oscillations, but can't be explained within the 3-flavour framework

2002-2019 MiniBooNE results

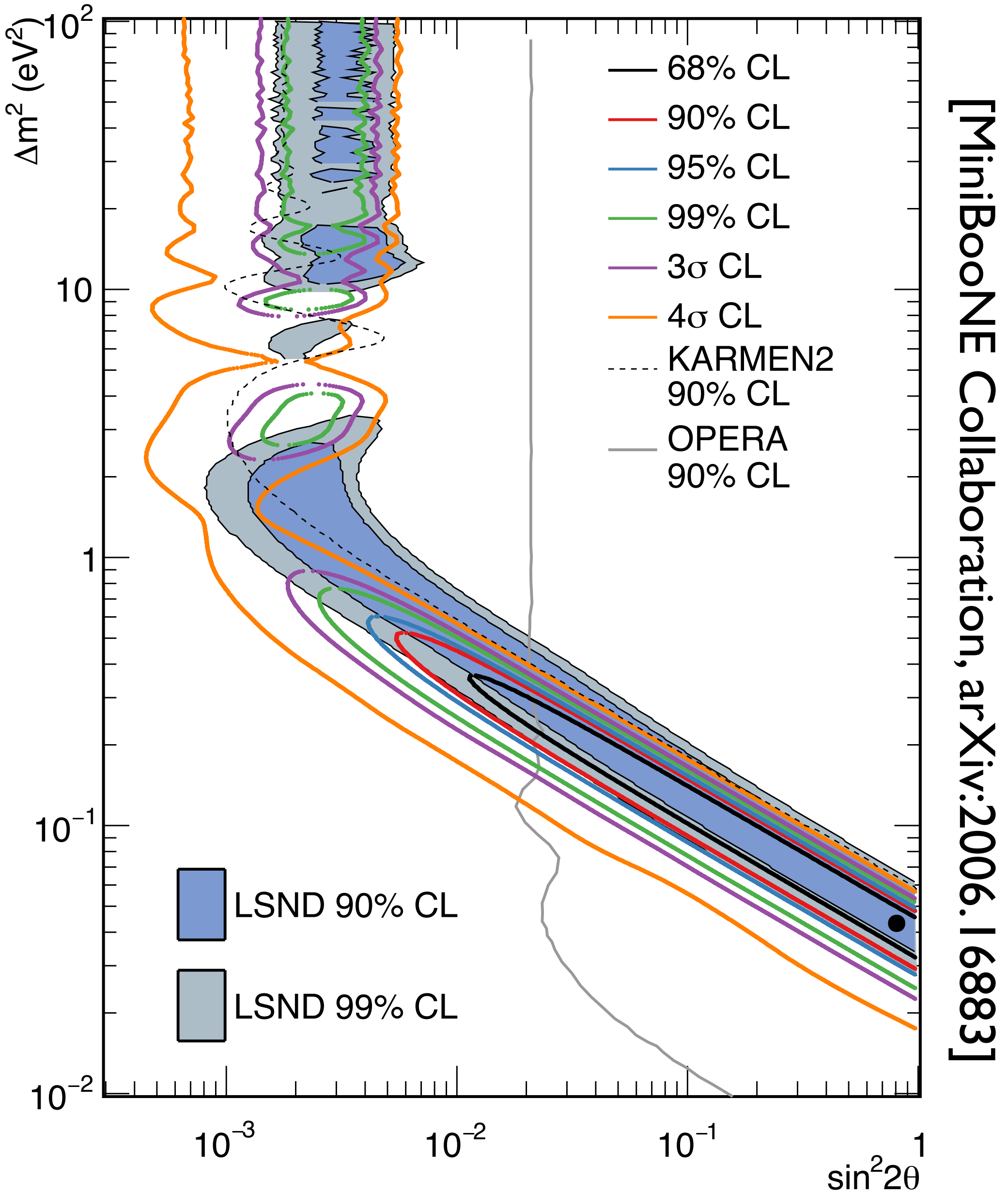


FIG. 20: MiniBooNE allowed regions for combined neutrino mode (18.75×10^{20} POT) and antineutrino mode (11.27×10^{20} POT) data sets for events with $200 < E_\nu^{QE} < 3000$ MeV within a two-neutrino oscillation model. The shaded areas show the 90% and 99% C.L. LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ allowed regions. The black point shows the MiniBooNE best fit point. Also shown are 90% C.L. limits from the KARMEN [26] and OPERA [27] experiments.

MiniBooNE + LSND excesses : 6.1 σ significance

Oscillation interpretation requires a 4th massive neutrino in the eV range

$$\Delta m^2_{41} \gtrsim 0.1\,\text{eV}^2, \quad \sin^2 2\theta_{\mu e} \approx (10^{-3} - 10^{-2})$$

However, this interpretation is essentially excluded by $\nu_\mu(\bar{\nu}_\mu)$ disappearance data :

- MINOS/MINOS+ (long-baseline oscillation experiment)
- IceCube (neutrino telescope located under the Antarctic ice: atmospheric neutrino data)

Quantifying the tension between appearance and disappearance data

[M. Dentler et al., arXiV:1803.10661]

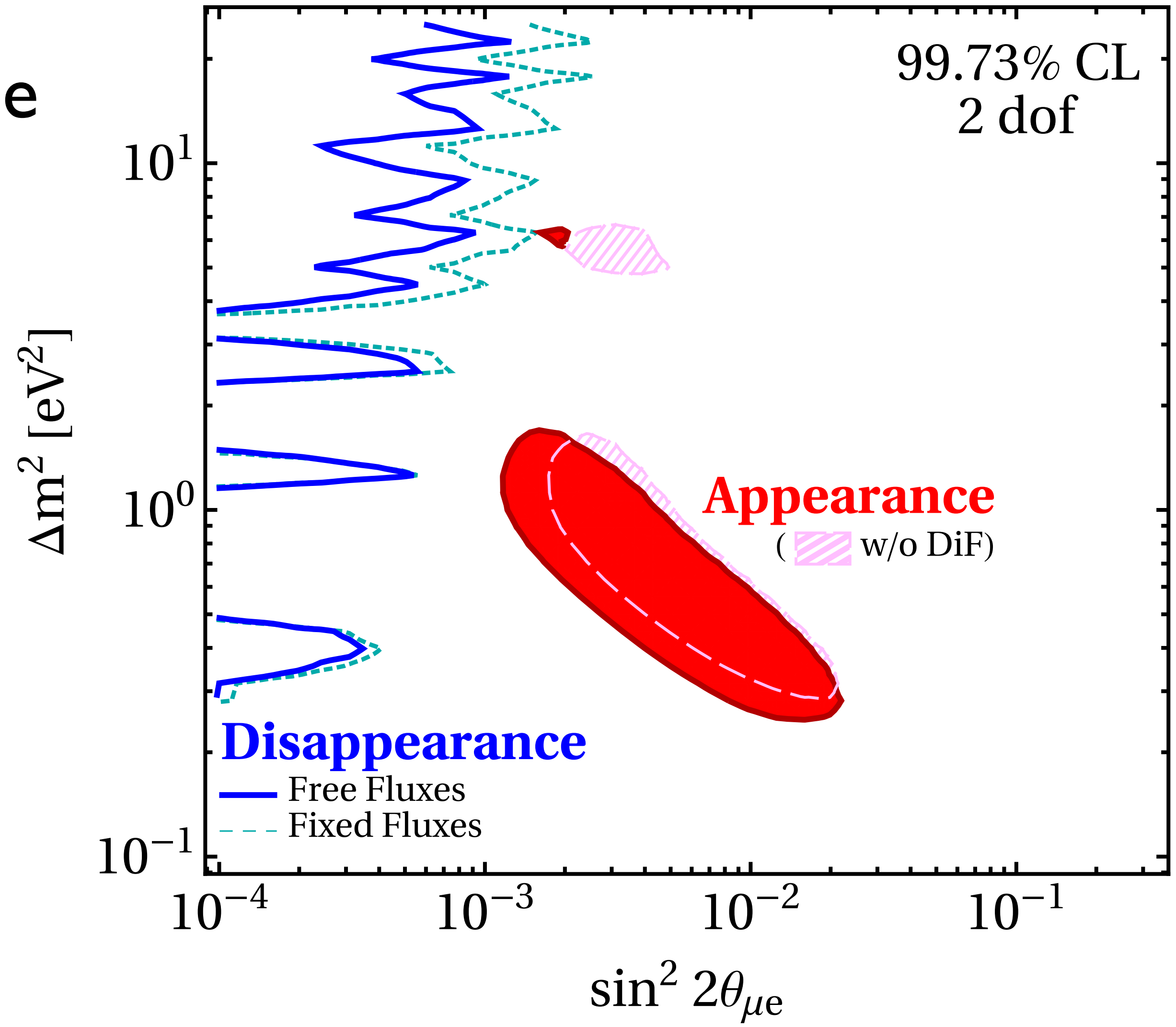
$(\sin^2 2\theta_{\mu e} \equiv 4|U_{e4}U_{\mu 4}|^2,\ \Delta m^2_{41})$ plane

red region is allowed at 3σ by appearance data

[pink hatched: without LSND DiF]

blue curve defines 3σ excluded region by disappearance data

[dashed = fixed reactor fluxes]



[M. Dentler et al., arXiV:1803.10661]

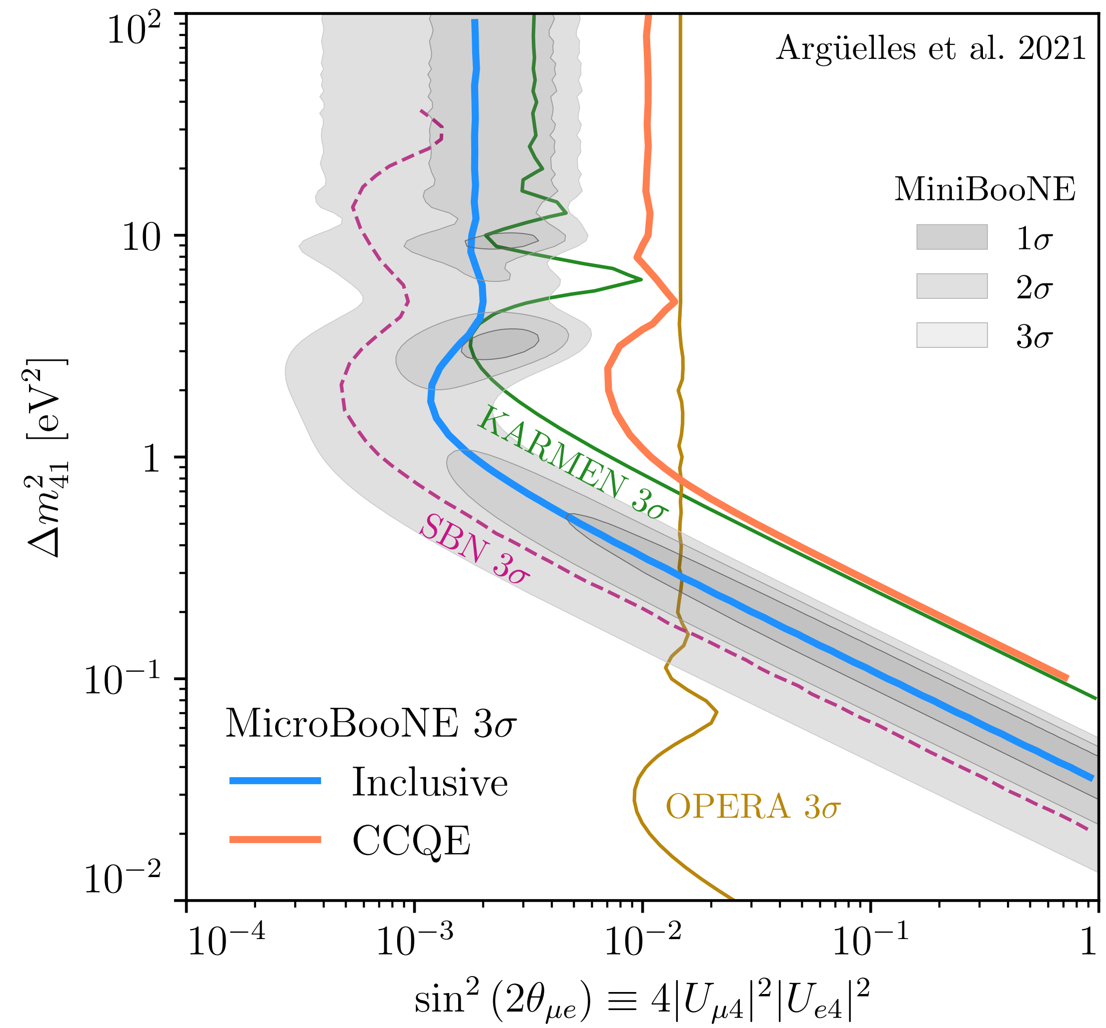
→ sterile neutrino interpretation of LSND and MiniBooNE data excluded at the 4.7 σ level

This tension persists for 2 sterile neutrinos [M. Maltoni at Neutrino 2018]

→ in addition, a light sterile neutrino is strongly disfavoured by cosmology

The short-baseline accelerator neutrino program (SBN) at Fermilab aims at testing the light sterile neutrino hypothesis. Consists of 3 Liquid Ar detectors with very good event reconstruction (while MiniBooNE cannot distinguish an e- from a photon): SBND (110 m), MicroBoone (470 m) and ICARUS (600 m)

First MicroBooNE results do not support the interpretation of the MiniBooNE excess as ν_e (which would produce e- via charged current), but the 2σ regions of the two experiments overlap



[C.A.Argüelles et al., arXiV:2111.10359]

FIG. 3. MicroBooNE constraints on sterile neutrino parameter space at 3σ C.L. (blue, Inclusive and orange, CCQE). For reference, we show the MiniBooNE 1-, 2-, and 3-σ preferred regions in shades of grey [42], the future sensitivity of the three SBN detectors (pink) [43], and existing constraints from KARMEN (green) [19] and OPERA (gold) [44].

→ if the LSND and MiniBooNE anomalies are real, must be explained by alternative, non-oscillation explanations

→ this talk: heavy decaying sterile neutrino (HDSN) scenario

Disclaimer: the MiniBooNE and especially LSND results have always been controversial. I do not claim that they are correct (there could be experimental errors and/or misunderstood backgrounds; experimentalists are in a better position than theorists to judge)

My claim is just that if these anomalies are real, the HDSN scenario provides a plausible explanation, which should therefore be tested at current or upcoming experimental facilities

Heavy decaying sterile neutrino (HDSN)

S. Palomares-Ruiz, S. Pascoli and T. Schwetz, arXiv:hep-ph/0505216
M. Dentler, I. Esteban, J. Kopp and P. Machado, arXiv:1911.01427
A. de Gouvêa, O.L.G. Peres, S. Prakash and G.V. Stenico, arXiv:1911.01447

Introduce a 4th neutrino mass eigenstate ν_4 with mass $10\,\mathrm{keV} \lesssim m_4 \lesssim 1\,\mathrm{MeV}$ which mixes only (or mainly) with ν_μ :

$$\nu_\alpha = \sum_{i=1}^4 U_{\alpha i}\nu_i \,, \qquad U_{\mu 4} \neq 0\,, \quad U_{e4} = U_{\tau 4} = 0$$

and decays to a ν_e and a very light, gauge singlet scalar

$$\mathcal{L} \ni -g\,\bar{\nu}_4 P_L \nu_e \phi + \mathrm{h.c.}$$

$\Rightarrow$ mimics LSND/MiniBooNE excess: some muon neutrinos from the flux decay to lower energy electron neutrinos

If neutrinos are Dirac, only $\nu_4 \to \nu_e \phi$ (and $\bar{\nu}_4 \to \bar{\nu}_e \phi$) is possible

If neutrinos are Majorana, both $\nu_4 \to \nu_e \phi$ and $\nu_4 \to \bar{\nu}_e \phi$ are possible

[$m_4 \lesssim 1\,\mathrm{MeV}$ avoids contraints from pion decay on $U_{\mu 4}$ and ensures that ν_4 is present in the LSND beam ($E \lesssim 50\,\mathrm{MeV}$ for most $\bar{\nu}_\mu$'s); $10\,\mathrm{keV} \lesssim m_4$ avoids constraints from leptonic meson decays for the $(gm_4, |U_{\mu 4}|)$ values required to explain the LSND and MB excesses]

Decay rate in the lab frame (including a Lorentz boost factor $1/\gamma_{\nu_4}$) :

Dirac case $\quad \Gamma_4^{\rm D} \equiv \Gamma(\nu_4 \to \nu_e \phi)|_{\rm Dirac} = \dfrac{|g|^2 m_4^2}{32\pi E_4} \qquad (E_4 = E_{\nu_\mu})$

Majorana case $\quad \Gamma(\nu_4 \to \nu_e \phi)|_{\rm Majorana} = \Gamma(\nu_4 \to \bar{\nu}_e \phi)|_{\rm Majorana} = \dfrac{|g|^2 m_4^2}{32\pi E_4}$

hence $\quad \Gamma_4^{\rm M} \equiv \Gamma(\nu_4 \to \nu_e \phi)|_{\rm Majorana} + \Gamma(\nu_4 \to \bar{\nu}_e \phi)|_{\rm Majorana} = 2\,\Gamma_4^{\rm D}$

Flavour transition probabilities depend on the fraction of ν_4's in the ν_μ beam (given by $|U_{\mu 4}|^2$) and of the fraction that have decayed before reaching the detector, i.e. $(1 - e^{-\Gamma_4 L})$. Given the baseline L , standard oscillations are negligible, while oscillations driven by $\Delta m^2_{41} > 10^8\,{\rm eV}^2$ average out

[one obtains the same formulae if one assumes that ν_4 is produced incoherently]

Survival (disappearance) probabilities:

$$P_{\mu\mu} = P_{\bar{\mu}\bar{\mu}} = (1 - |U_{\mu 4}|^2)^2 + |U_{\mu 4}|^4\, e^{-\Gamma_4 L}\,, \qquad P_{ee} = P_{\bar{e}\bar{e}} = 1$$

Appearance probabilities:

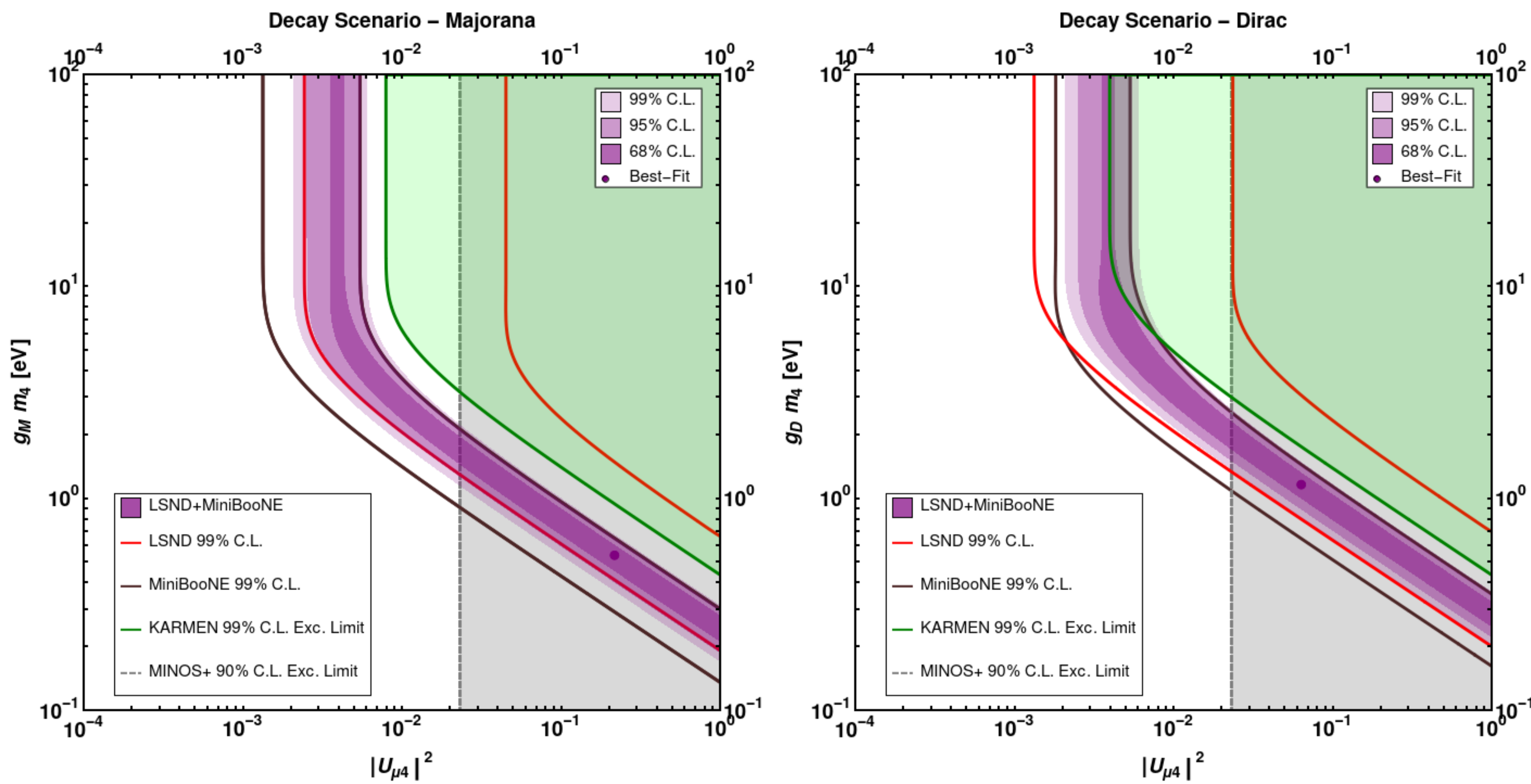
Dirac $\quad P_{\mu e} = P_{\bar{\mu}\bar{e}} = |U_{\mu 4}|^2 (1 - e^{-\Gamma_4^D L})$

Majorana $\quad P_{\mu e} = P_{\bar{\mu}\bar{e}} = P_{\mu\bar{e}} = P_{\bar{\mu}e} = \frac{1}{2}\,|U_{\mu 4}|^2 (1 - e^{-\Gamma_4^{\rm M} L})$

$$P_{\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta; L)\,, \quad P_{\bar{\alpha}\bar{\beta}} \equiv P(\bar{\nu}_\alpha \to \bar{\nu}_\beta; L)\,, \quad P_{\alpha\bar{\beta}} \equiv P(\nu_\alpha \to \bar{\nu}_\beta; L)\,, \quad \Gamma_4 = \Gamma_4^D \text{ or } \Gamma_4^M$$

The HDSN scenario can fit the LSND and MiniBooNE data…

[de Gouvêa, Peres, Prakash and Stenico, arXiv:1911.01447]

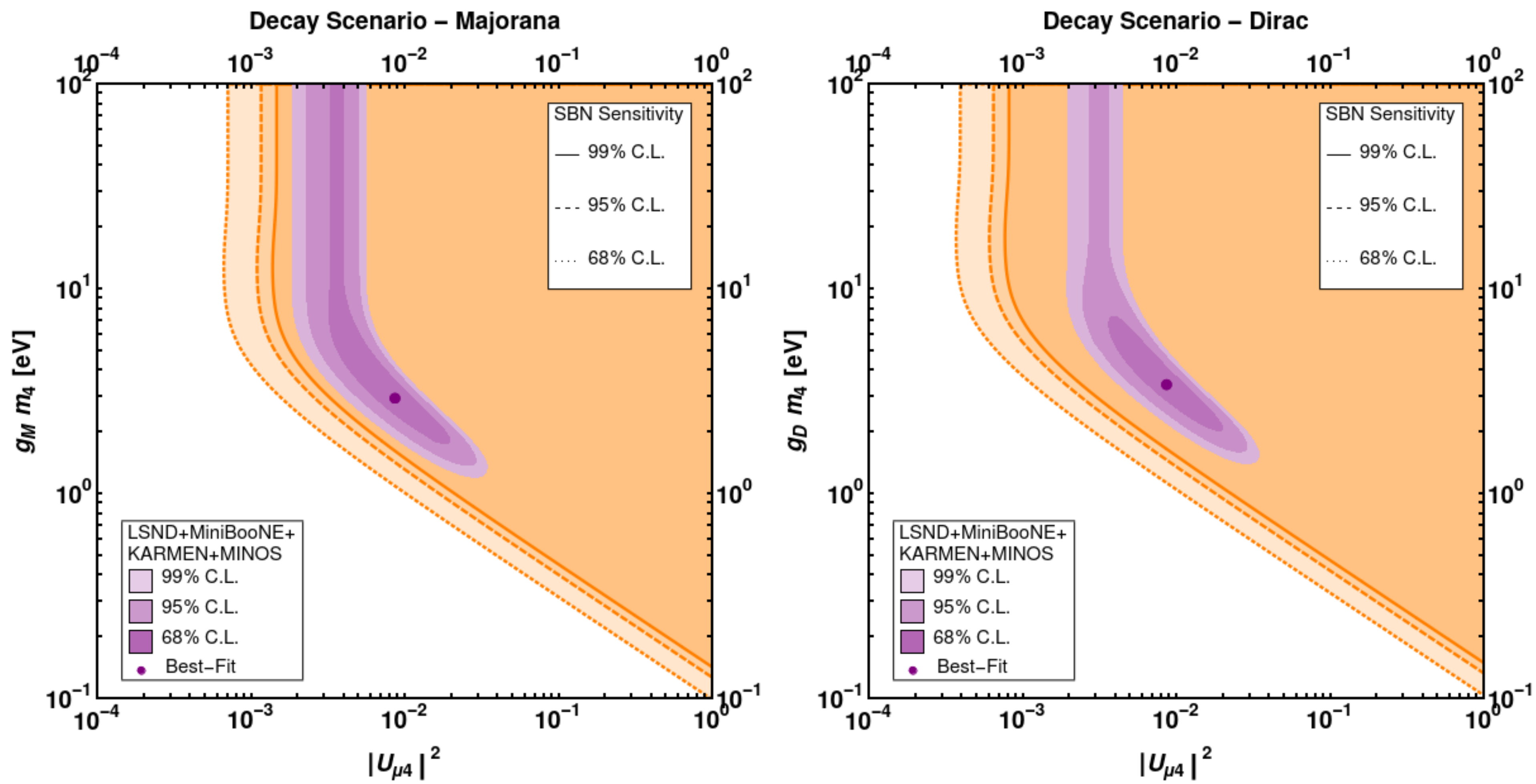


MINOS/MINOS+ upper bound $|U_{\mu4}|^2 < 2.3 \times 10^{-2}$ $(90\%\,\mathrm{C.L.})$

from $\nu_\mu\,(\bar{\nu}_\mu)$ disappearance searches (applies to both stable and unstable sterile neutrinos)

… and can also be tested by SBN

[de Gouvêa, Peres, Prakash and Stenico, arXiv:1911.01447]



Still interesting to probe a larger region of the HDSN parameter space

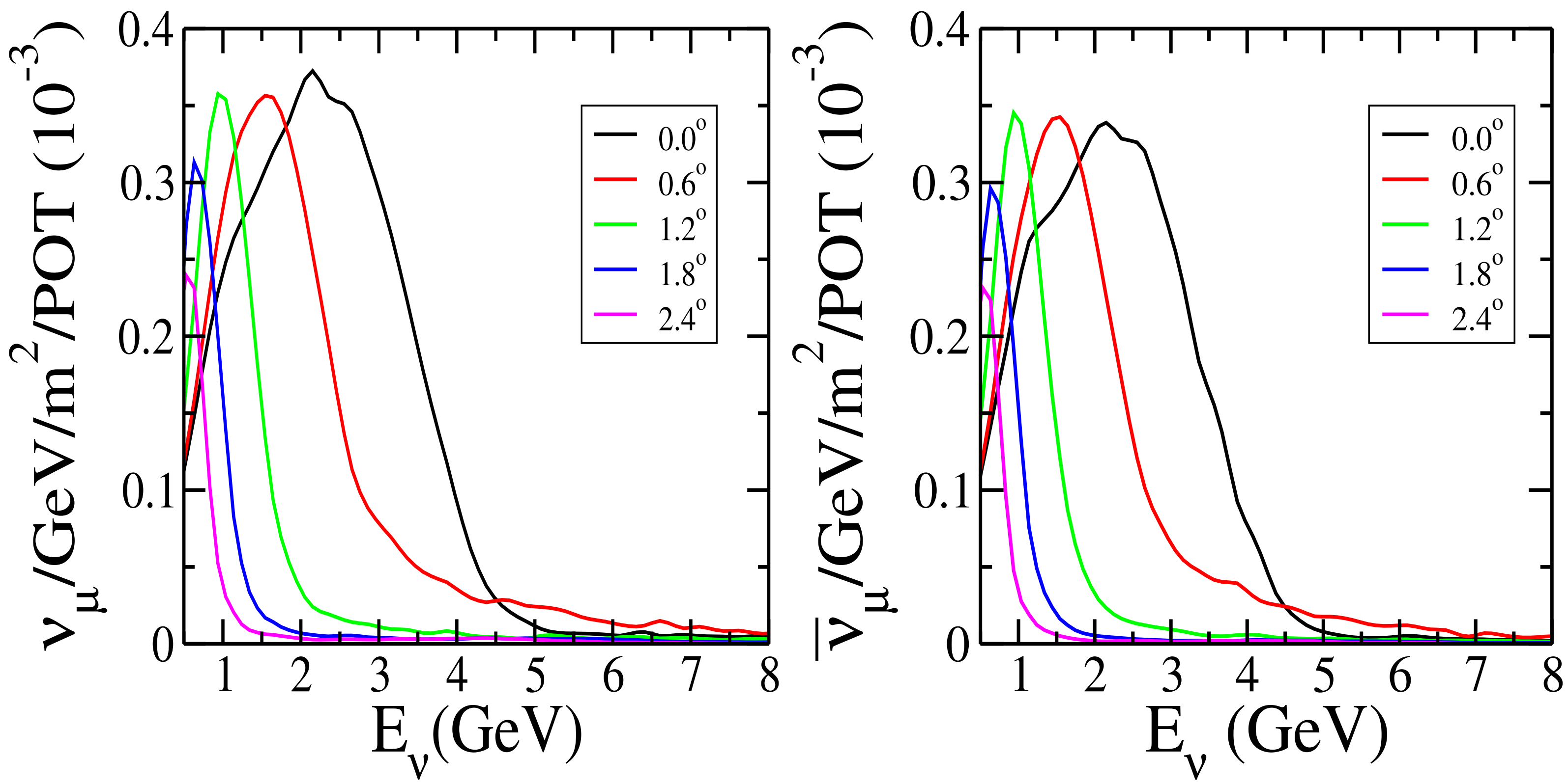
→ DUNE near detector

DUNE near detector (ND-LAr)

DUNE = long-baseline neutrino oscillation experiment (1300 km), whose main goals are to establish leptonic CP violation in the $\nu_\mu \to \nu_e$ channel and to determine the neutrino mass ordering using matter effects on oscillations

The DUNE near detector will consist of three components, one of which is a movable Liquid Argon detector (ND-LAr), which can be located either on the beam axis or at an off-axis position (up to 3.6° off axis)

The neutrino flux depends on the off-axis angle: peaks towards lower energies (and the total flux decreases) when the off-axis angle increases



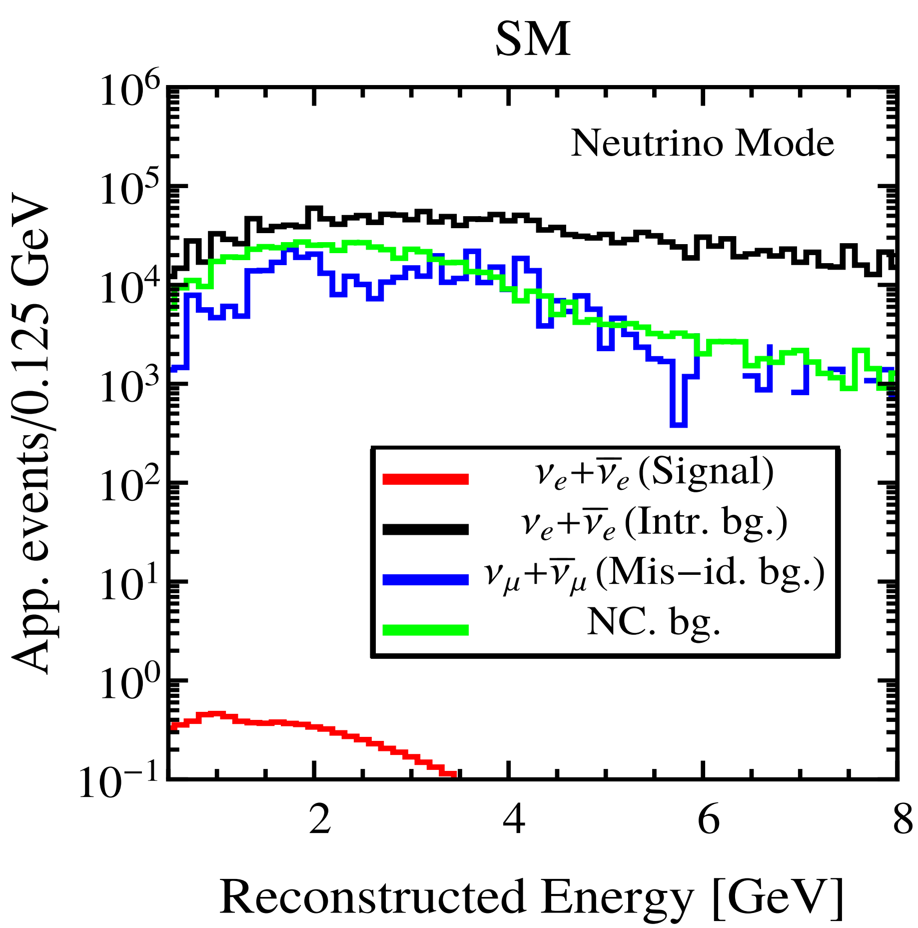
Near detector baseline: 574 m

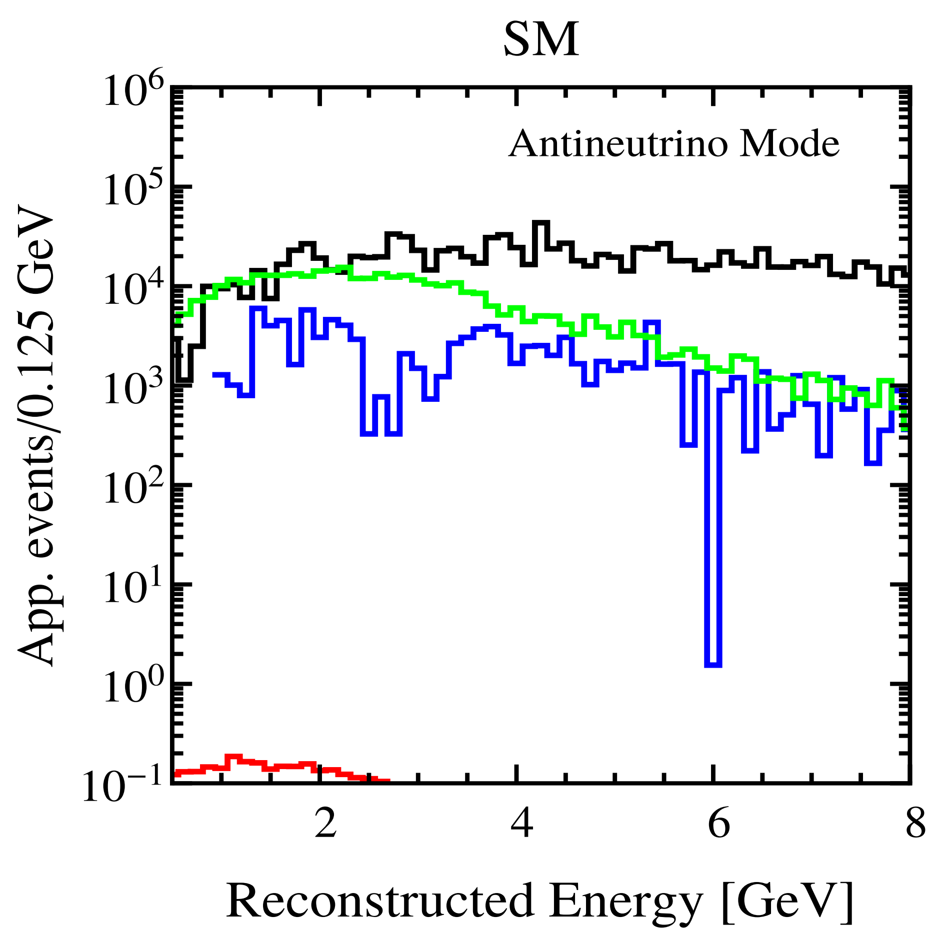
Appearance and disappearance events

We are interested in two types of events in ND-LAr:

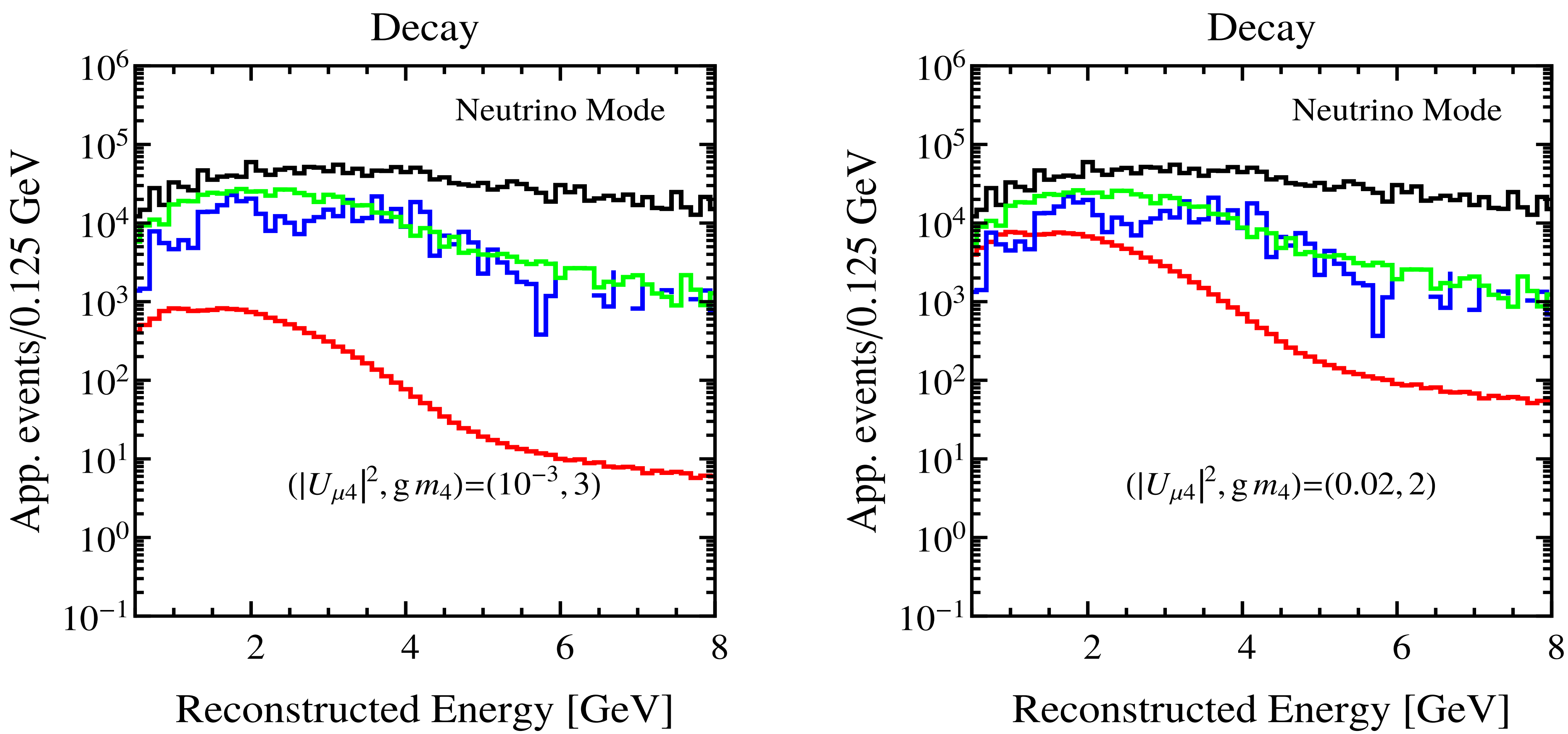
- appearance events: $\nu_\mu \to \nu_e$ $(\bar{\nu}_\mu \to \bar{\nu}_e)$, which produce an e- (e+) in the near detector [also $\nu_\mu \to \bar{\nu}_e$ $(\bar{\nu}_\mu \to \nu_e)$ in the Majorana case (HDSN)]
- disappearance events: $\nu_\mu \to \nu_\mu$ $(\bar{\nu}_\mu \to \bar{\nu}_\mu)$, which produce a positively (negatively) charged muon in the near detector

Number of appearance events as a function of the reconstructed neutrino energy (Standard Model case, running time 3.5 years):





Number of appearance events as a function of the reconstructed neutrino energy (HDSN, Dirac case, running time 3.5 years):

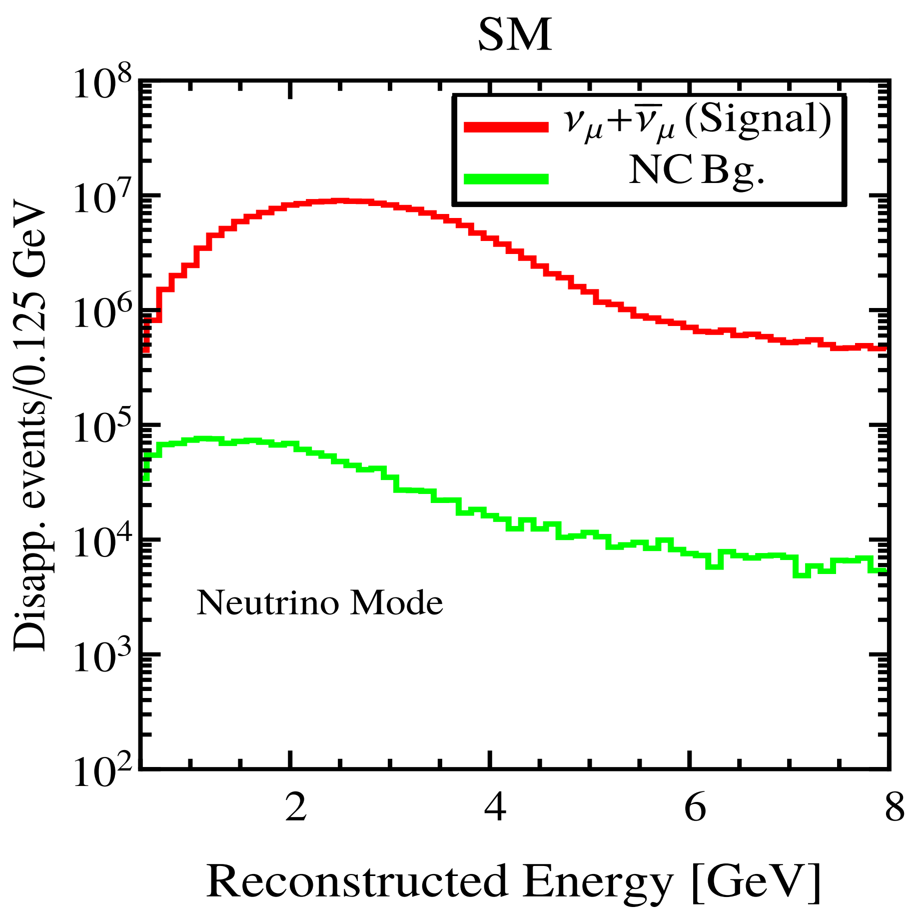


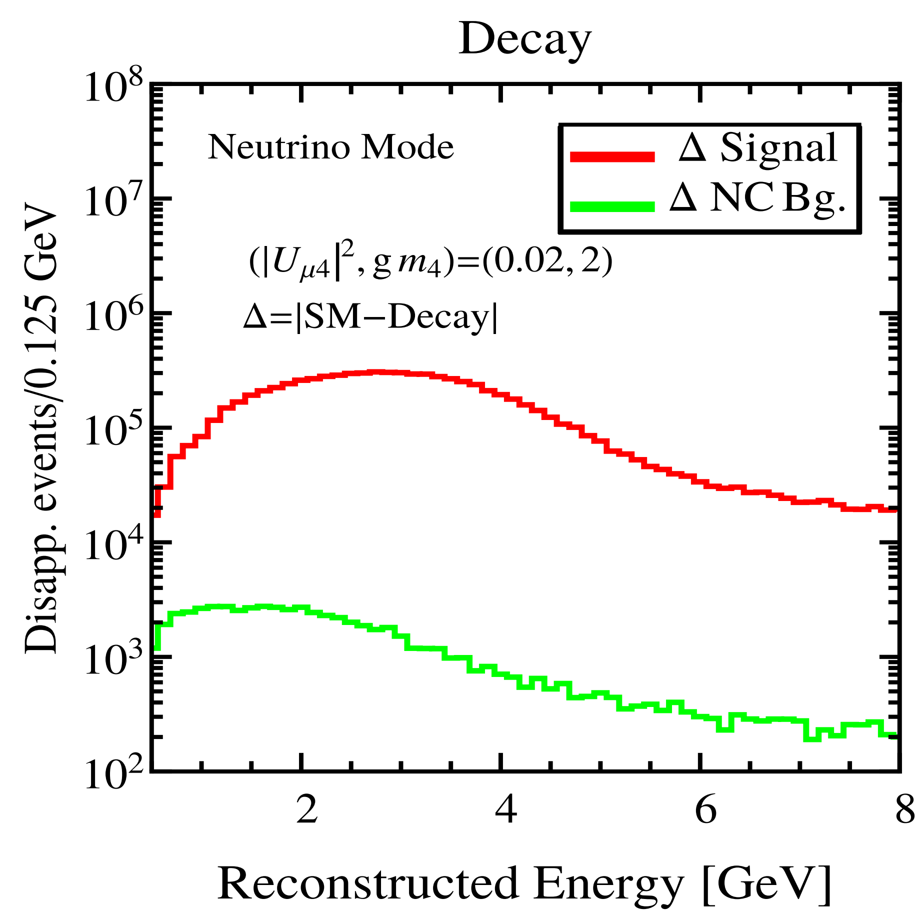
While the signal was negligible in the SM (baseline two short for oscillations to develop), it is now much more sizable due to the sterile neutrino decays

The signal increases with $|U_{\mu4}|^2$ and gm_4 , as $\Gamma_4 \propto (gm_4)^2$: the larger gm_4 , the larger the fraction of sterile neutrinos that have decayed

Backgrounds are also affected by sterile neutrino decays, but effect $\propto |U_{\mu4}|^2$

Number of disappearance events as a function of the reconstructed neutrino energy (Standard Model vs HDSN scenario [Dirac], running time 3.5 years):





Smaller impact of the HDSN scenario on the signal than in the appearance channel: departure from SM given by $P_{\mu\mu} \simeq 1 - 2|U_{\mu4}|^2$

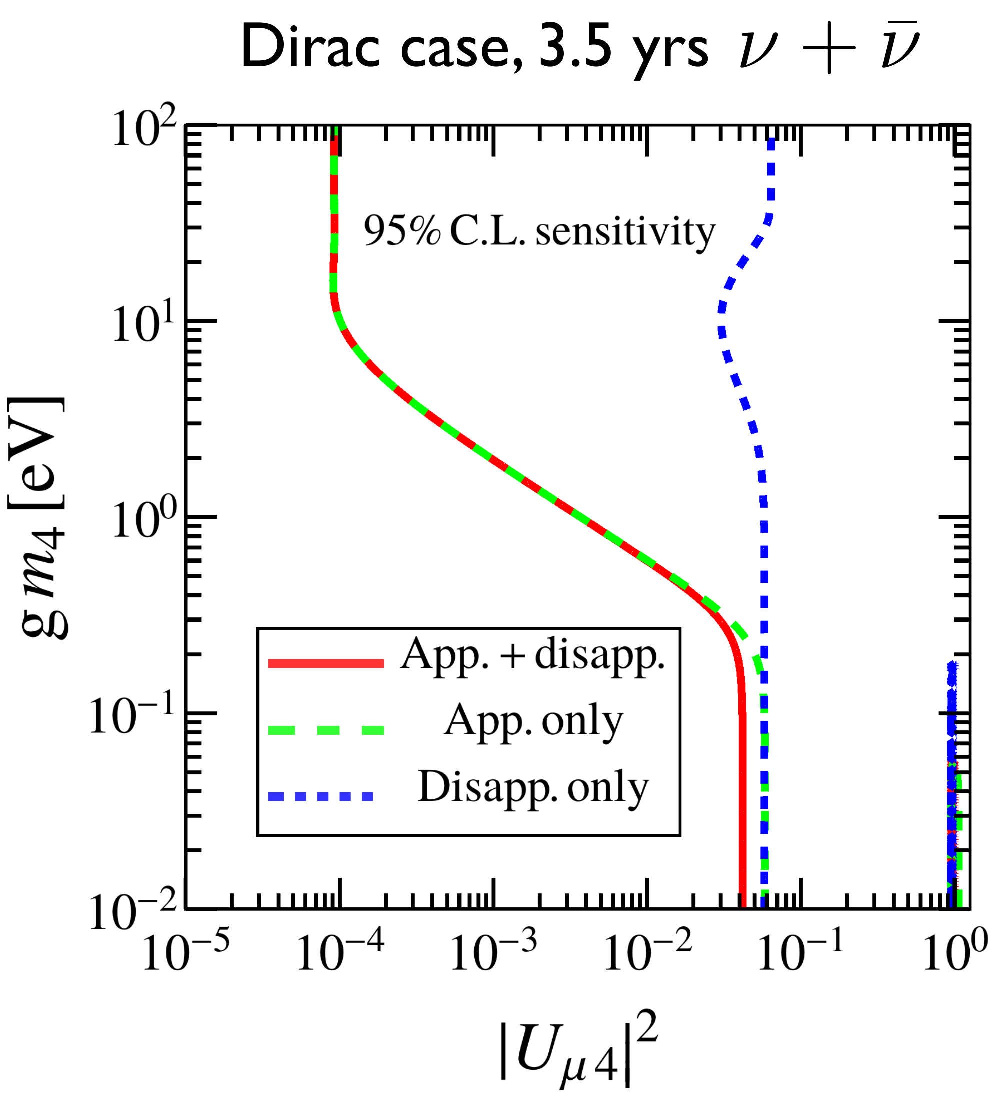
Sensitivity of the DUNE near detector to HDSN

DUNE near detector sensitivity to the HDSN parameters $(|U_{\mu 4}|^2, gm_4)$

Dominated by appearance events

$$P_{\mu e} = |U_{\mu 4}|^2 (1 - e^{-\Gamma_4^D L}) \qquad \Gamma_4 \propto (gm_4)^2$$

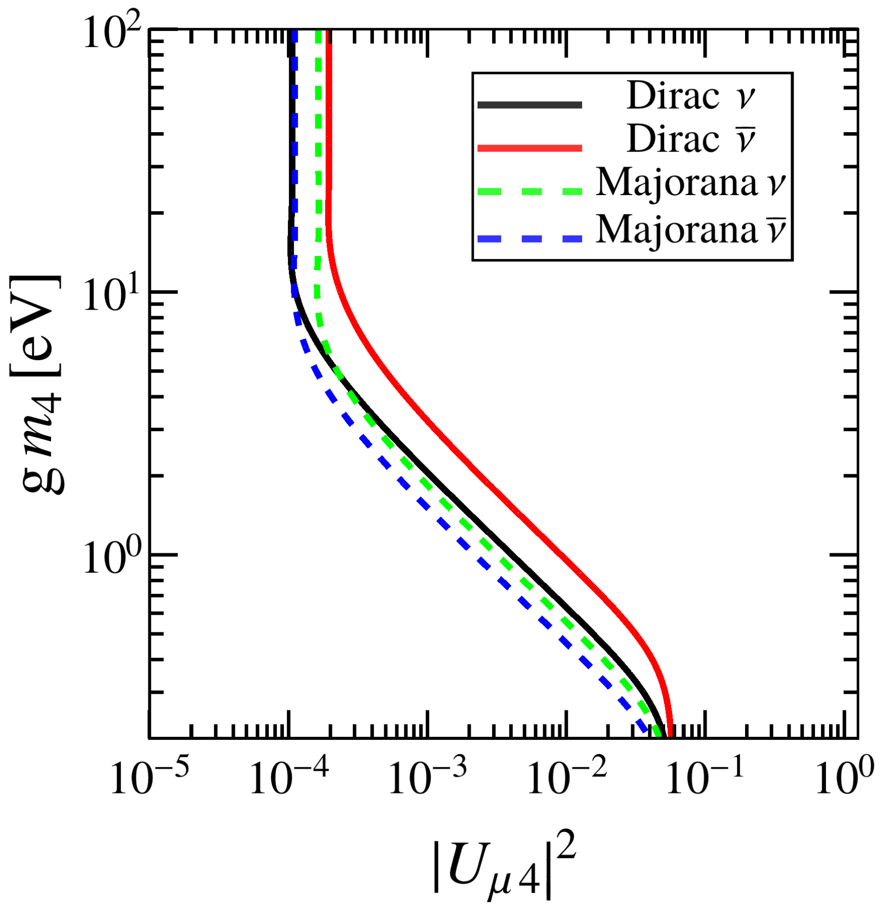
- large gm4 region: $\Gamma_4 L \gg 1$
  all sterile neutrinos have decayed
  $P_{\mu e} \simeq |U_{\mu 4}|^2$
- small/intermediate gm4 region:
  $\Gamma_4 L \ll 1 \;\Rightarrow\; P_{\mu e} \simeq |U_{\mu 4}|^2 \Gamma_4 L$
  sensitivity to $|U_{\mu 4}|^2$ decreases with gm4



Sensitivity of disappearance channel depends very weakly on gm4

$$P_{\mu\mu} = (1 - |U_{\mu 4}|^2)^2 + |U_{\mu 4}|^4 e^{-\Gamma_4 L} \simeq 1 - 2|U_{\mu 4}|^2$$

Dirac versus Majorana neutrinos



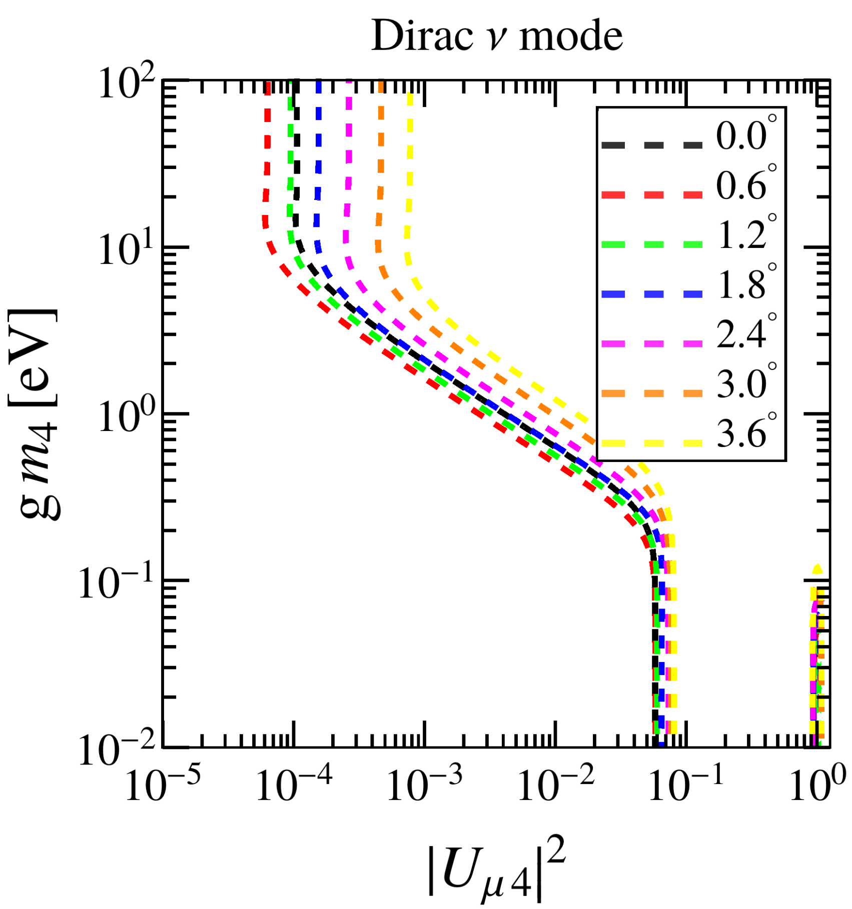
3.5 years of running either in neutrino or in antineutrino mode

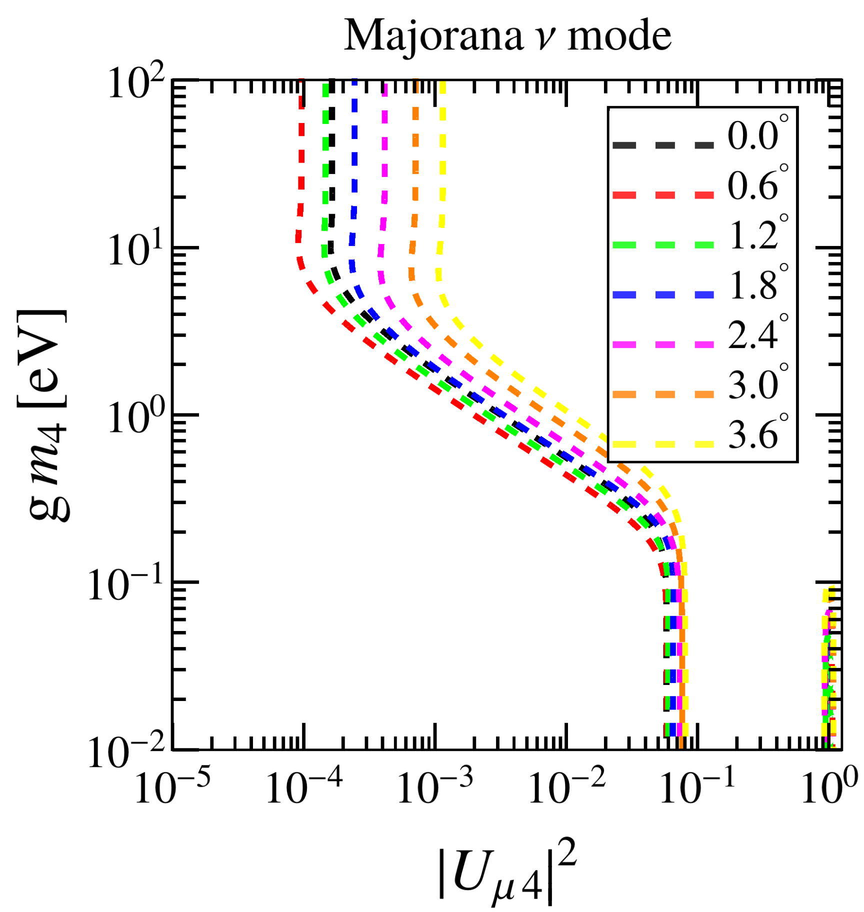
Differences due to the fact that charged current cross section smaller for $\bar{\nu}_e$

- Dirac ν_μ always decays to ν_e (and $\bar{\nu}_\mu \to \bar{\nu}_e$)
- Majorana $\nu_\mu(\bar{\nu}_\mu)$ decays 50% to ν_e, 50% to $\bar{\nu}_e$

and for smaller gm4 (for which only a fraction of the sterile neutrinos decay), to the fact that $\Gamma_4^M = 2\,\Gamma_4^D$

Do we gain something (better sensitivity) by moving the detector off axis ?

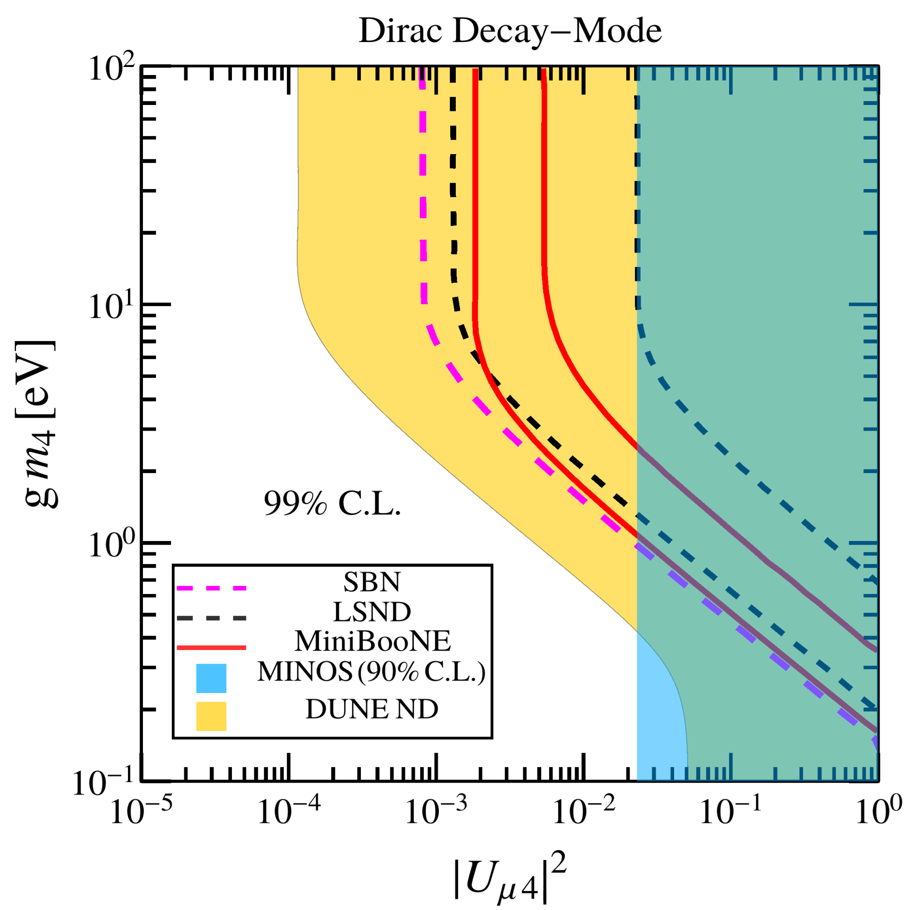


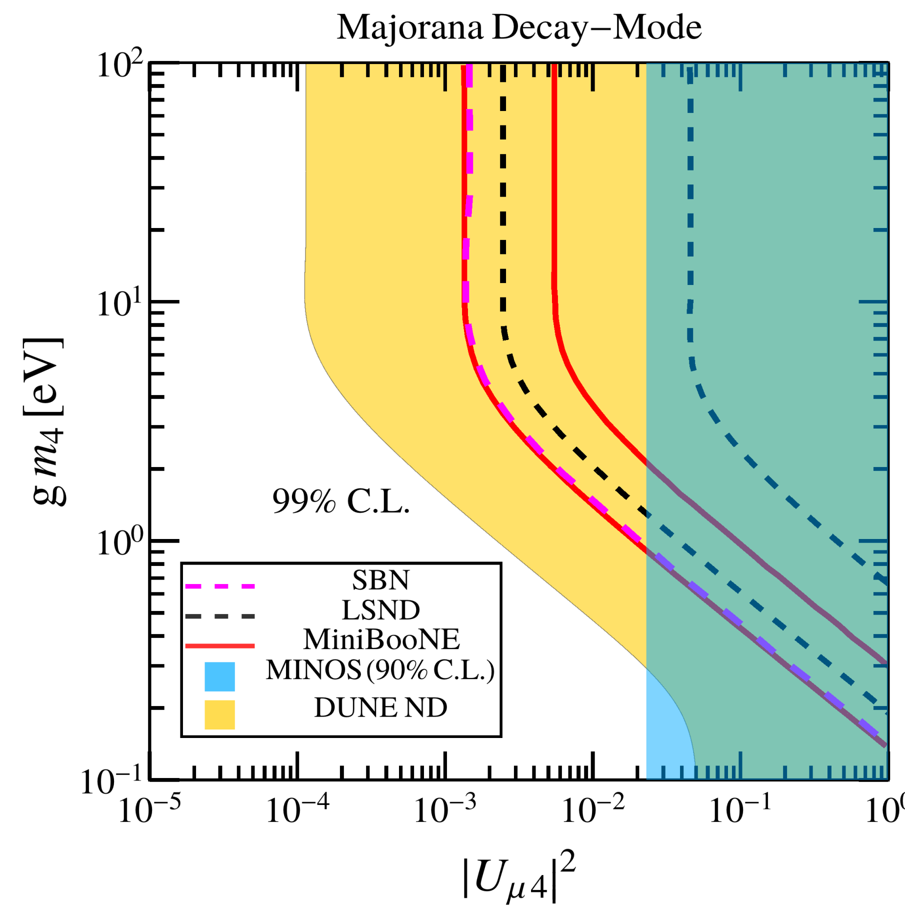


For off-axis angles > 1.2°, sensitivity to $|U_{\mu 4}|^2$ degrades due to the smaller flux (smaller statistics)

For off-axis angle 0.6°, small benefit at large gm4 due to the different energy dependence of the flux (more peaked) – also backgrounds depend on the off-axis angle

99% C.L. sensitivities to HDSN scenario for Dirac and Majorana neutrinos, running 3.5 + 3.5 years in neutrino and antineutrino modes





Much better sensitivity than SBN to the HDSN scenario

DUNE near detector can exclude the HDSN solution to the LSND and MiniBooNE anomalies at more than 99% C.L.

Combined neutrino and antineutrino modes ⇒ same sensitivity for Dirac or Majorana case at large gm_4, but better in Majorana case for intermediate gm_4

Conclusions

A heavy sterile neutrino can explain the long-standing LSND and MiniBooNE anomalies

The DUNE near detector ND-LAr can test the HDSN scenario with a much better sensitivity than the short-baseline neutrino program (SBN) at Fermilab ➞ might provide a crucial check if SBN observes some hint of ν_e appearance (even if not large enough to explain LSND/MiniBooNE)

Possibility to distinguish between Dirac and Majorana neutrinos in the HDSN scenario by running in the neutrino and antineutrino modes