Sterile neutrinos along the DUNE decay pipe

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Introduction

Sterile neutrinos: first hint - LSND (2001) - more $\bar{\nu}_e$'s than expected from $\bar{\nu}_\mu \to \bar{\nu}_e$. $\nu'_S s$ also currently provide a viable explanation for Ga anomaly and RAA

- Ga - Fewer neutrinos in the reaction $\nu_e +^{71} Ga \to e^- +^{71} Ge$ $\bar{R} = 0.844 \pm 0.031$ (gr. state model for Ge), all models for Ge excited states being very similar
- RAA - Fewer measured than theoretically expected antineutrinos from radioactive nuclides from reactors, $\bar{R} = 0.936 \pm^{0.024}_{0.023}$.

Possible solution: introduce one sterile neutrino (3+1 scenario) with

$$\Delta m^2_{41} \simeq \Delta m^2_{42} \simeq \Delta m^2_{43} = O(1eV^2) \;\; , \;\; sin^2 2\theta_{14} \sim 0.1$$

However (2209.00916)
Tension exists ($> 2\sigma$) between Ga and RAA's preferred values (b.f.)
$\Delta m^2_{41}(\mathrm{Ga}) \sim 2\Delta m^2_{41}(\mathrm{Reactor}) \quad \sin^2 2\theta_{14}(\mathrm{Ga}) \sim 3\sin^2 2\theta_{14}(\mathrm{Reactor})$

Introduction

Another source of tension (appearance/disappearance)

$$sin^2 2\theta_{e\mu} \simeq \frac{1}{4} sin^2 2\theta_{ee} sin^2 2\theta_{\mu\mu}$$

$$(sin^2 2\theta_{e\mu} = sin^2 2\theta_{14} sin^2 \theta_{24} \quad , \quad \theta_{ee} = \theta_{14} \quad , \quad \theta_{\mu\mu} \simeq \theta_{24})$$

- $sin^2 2\theta_{e\mu} \gtrsim 10^{-3}$ ν_e app (LSND, Karmen, ICARUS, ...) 99% CL
- $sin^2 2\theta_{ee} \sim (0.15 - 0.2)$ $\overset{(-)}{\nu_e}$ disapp (Ga, RAA), however in tension
- $sin^2 2\theta_{\mu\mu} \lesssim 10^{-2}$ ν_μ disapp, (Minos & Minos+, IceCube,...) 99% CL

However (2002.00301, PRL 125 (2020))
More recent new constraints on $sin^2 2\theta_{e\mu}$ slightly contradict LSND

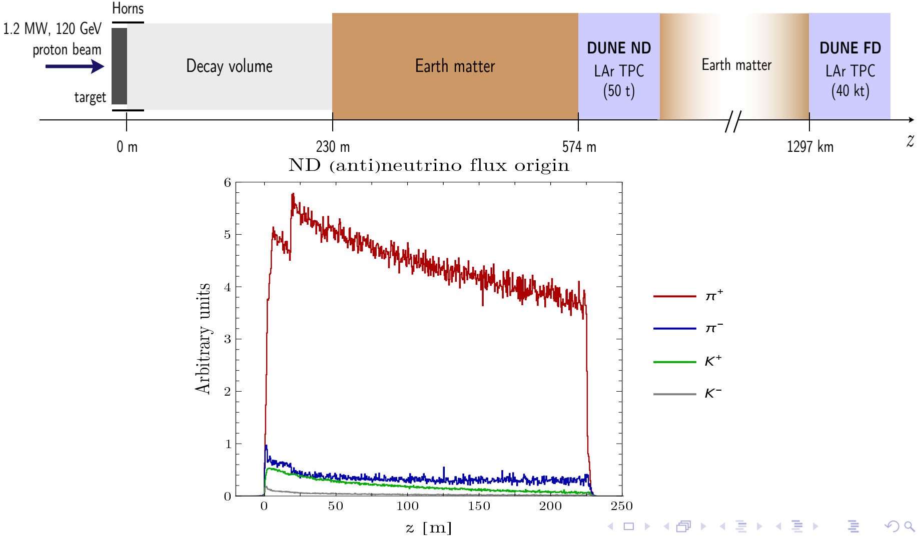
$$sin^2 2\theta_{e\mu} < 10^{-3} \ \ (99\% CL)$$

unless $\Delta m^2_{41} > 3eV^2 \Rightarrow$ tension with Ga, RAA

Hence sterile neutrino issue remains unsettled

Objective

In DUNE ν's are produced from meson decays along a decay pipe originated from proton collisions on a graphite target.



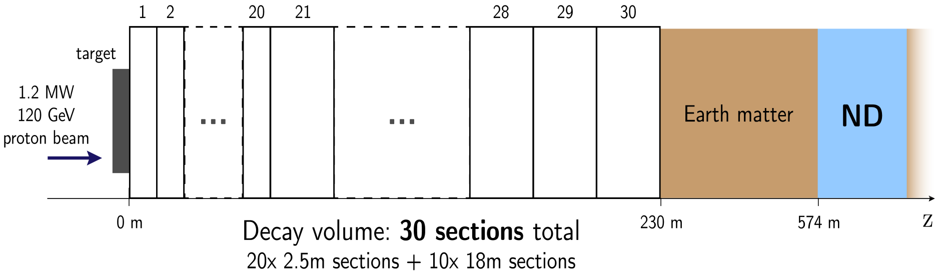
Objective

Our objective is to evaluate the effect of sterile neutrinos in DUNE ND and FD event rates. We used GLoBES

- GLoBES assumes a point-like source for each detector, clearly not valid for ND, but a routine weighting procedure circumvents this point-source restriction
- In (3+0) case, owing to the smallness of Δm^2' s, no oscillations occur up to the ND
- In (3+1) case, $\Delta m^2_{41} = O(0.1 - 1)\ eV^2$, so active/sterile oscillation length, $L_{osc} \sim L_{\text{decay pipe}}$
- Consequently sterile ν's will be produced via oscillations from active ones before reaching the ND
- Therefore in (3+1) case a point-source approximation would be erroneous and source-volume effects need to be explicitly taken into account

A Sterile Neutrino in DUNE - Basics

- To this end we conceptually divided the decay pipe into sections (30 of them) and associated each to a different point-source with its fixed baseline L
- Flux arriving at the ND from each section is passed to GLoBES as the flux of an independent experiment.



A Sterile Neutrino in DUNE - Basics

Some calculational details

- Hamiltonian
$$H^{\rm mat}_{\alpha\beta} = \frac{1}{2E}\left[U\, diag(0, \Delta m^2_{21}, \Delta m^2_{31}, \Delta m^2_{41})U^\dagger + diag(A_{CC}, 0, 0, A_{NC})\right]$$

- Oscillation probability
$$P_{\alpha\beta}(L,E) = \sum_{j,j'} \tilde{U}_{\beta j}\tilde{U}^*_{\alpha j}\tilde{U}^*_{\alpha j'}\tilde{U}^*_{\beta j'} \exp\left(-i\frac{\Delta\tilde{m}^2_{jj'}L}{2E}\right)\underbrace{\exp\left[-\frac{\sigma_E^2}{2E^2}\left(\frac{\Delta\tilde{m}^2_{jj'}L}{2E}\right)^2\right]}_{\rm low\ pass\ filter\ (LPF)}$$

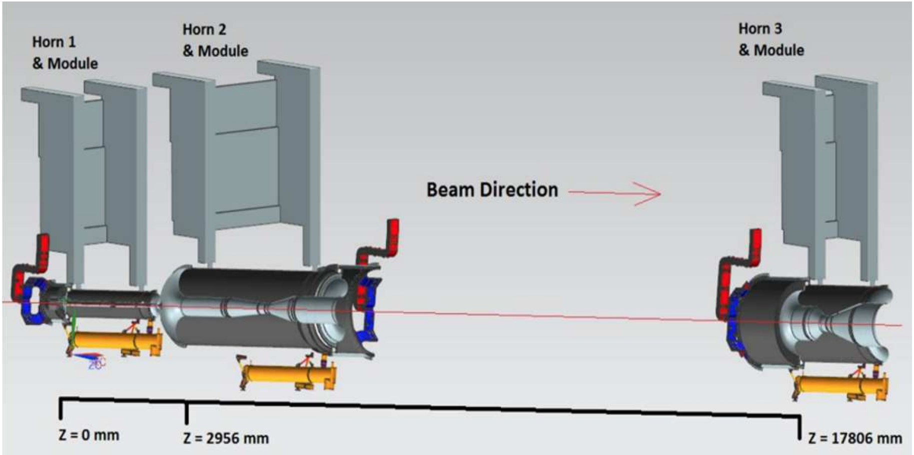
  LPF - to average over fast oscillations $\sigma_E = 0.125\ \mathrm{GeV}$

- For ND, oscillations to actives do not have time to occur. Moreover matter effects are negligible $\Rightarrow$ approximate expression OK

$$P^{SBL}_{\alpha\beta}(L,E) \simeq \delta_{\alpha\beta} - 2|U_{\alpha 4}|^2\left(\delta_{\alpha\beta} - |U_{\beta 4}|^2\right)\left[1 - \cos\left(\frac{\Delta m^2_{41}L}{2E}\right)\mathrm{LPF}\right]$$

A Sterile Neutrino in DUNE - Statistical Analysis

In 3+0 at ND one expects ν_μ (signal) from $\pi^+ \to \mu^+ \nu_\mu$ (horns in FHC).
Or $\bar{\nu}_\mu$ (signal) from $\pi^- \to \mu^- \bar{\nu}_\mu$ (horns in RHC).
However: background from contamination and misidentifications ($\overset{(-)}{\nu}_e$'s)



A Sterile Neutrino in DUNE - Statistical Analysis

In 3+0 case at FD: signal is $\overset{(-)}{\nu}_\mu$ and $\overset{(-)}{\nu}_e$ but bkg is also there as part of event rate.
We consider 3+1 case and follow DUNE simulation configurations.
Hence the analysis is based on the concept of 'rule':

Rule (event rate $\cup$ stat. analysis): $\supset$ signal, bkg, stat. analysis

Each of the 2 operation modes (FHC, RHC) unfolds into 2 rules
Hence consider 4 rules and their respective channels

- FHC signal ν_e (at ND this signal only possible in 3+1 case)
- RHC signal $\bar{\nu}_e$ (at ND this signal only possible in 3+1 case)
- FHC signal ν_μ
- RHC signal $\bar{\nu}_\mu$

All other channels in each of these rules are considered bkg (NB: rules are not 100% efficient, $\Rightarrow$ some $\bar{\nu}$'s in FHC and ν's in RHC)

A Sterile Neutrino in DUNE - Statistical Analysis

Definitions

$$\chi^2 = \chi^2_{\rm stat}(\omega, \omega_0, \zeta, \zeta') + \chi^2_{\rm prior}(\omega, \omega_0) + \sum_{k=1}^{26} \left(\frac{\zeta_k}{\sigma_k} \right)^2 + \sum_{r=1}^{4} \sum_{i=1}^{60} \left(\frac{\zeta'_{r,i}}{\sigma'} \right)^2$$

60 energy bins (i) in each rule (r) with $E \in [1.25, 18.0]$ GeV

Random parameters

- ω: $\Delta m^2_{21}, \Delta m^2_{32}, \theta_{12}, \theta_{13}, \theta_{23}, \rho_{ND}, \rho_{FD}$ (7 parameters, measured)
- ω_0: their central values
- $\theta_{34}, \delta_{14}, \delta_{24}$ unconstrained and either θ_{14}, θ_{24} unconst. (4 par.)
- $\zeta'_{r,i}$: shape (bin-to-bin uncorrelated) nuisance parameters ($\sigma' = 5\%$) (240 par.)
- ζ_k: normalization (nuisance) parameters (ND, FD fiducial volumes, fluxes, cross-sections), (26 par.) (2008.12769)

A Sterile Neutrino in DUNE - Statistical Analysis

Definitions (cont.)

$$\chi^2_{\mathrm{stat}} = 2\sum_{d=1}^{2}\sum_{r=1}^{4}\sum_{i=1}^{60}\left[T^d_{r,i} - O^d_{r,i}\left(1 - \ln\frac{O^d_{r,i}}{T^d_{r,i}}\right)\right]$$

$$\chi^2_{\mathrm{prior}} = \sum_{j=1}^{7}\left(\frac{\omega_j - (\omega_0)_j}{\sigma(\omega_j)}\right)^2$$

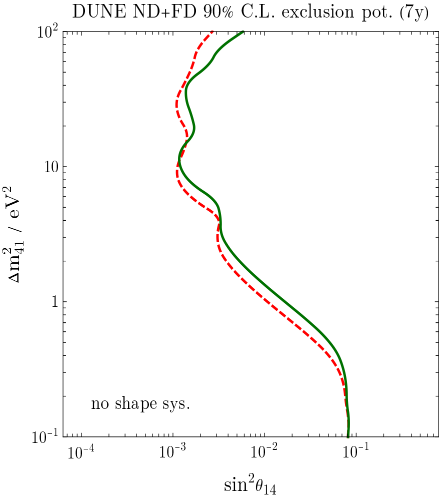
With test and observed event rates (for each detector d)

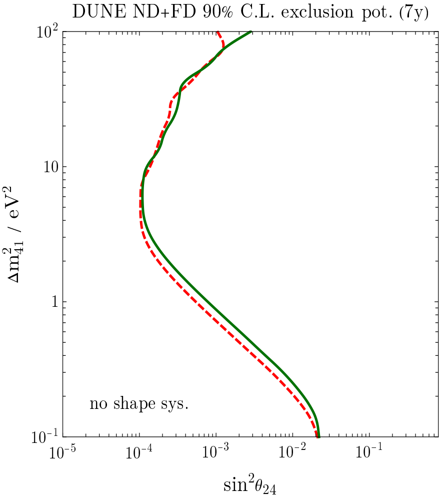
$$T^d_{r,i} = \sum_{\mathrm{c=s,b}} N^d_{r,c,i}(\omega)\left(1 + \zeta'_{r,c,i} + \sum_{(k)}\zeta\right) \quad , \quad O^d_{r,i} = \sum_{\mathrm{s,b}} N^d_{r,c,i}(\omega_0)$$

$\sum_{(k)}\zeta$ is restricted to those ζ_k parameters involved in d, c, r

Results

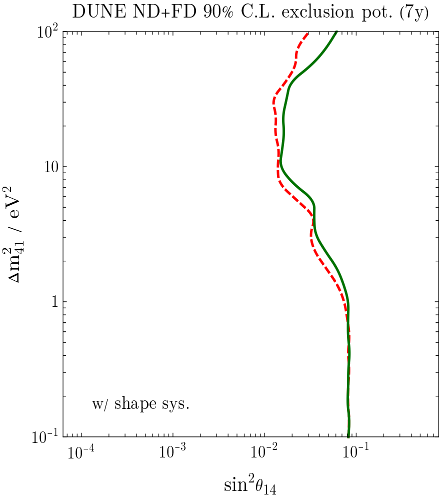
Sterile neutrino exclusion plots without shape systematics $\sigma' = 0$

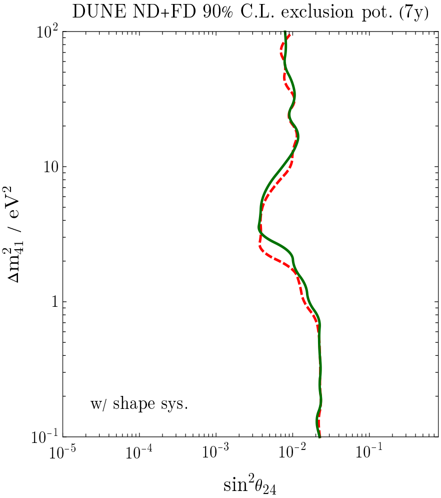




Results

Sterile neutrino exclusion plots with shape systematics $\sigma' \neq 0$





Conclusions

- We took into account both DUNE ND and FD event rates and energy shape systematics ($\sigma' = 5\%$)
- We considered the effect of a space distribution in the oscillation baseline for steriles instead of a single baseline
- Consequently, DUNE sterile neutrino exclusion reach is affected
- We find a slight decrease in DUNE's sensitivity, relevant for precision studies