PROBING ACTIVE-STERILE NEUTRINO MIXING IN LED AND 3+1 SCENARIOS WITH DUNE

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OUTLINE

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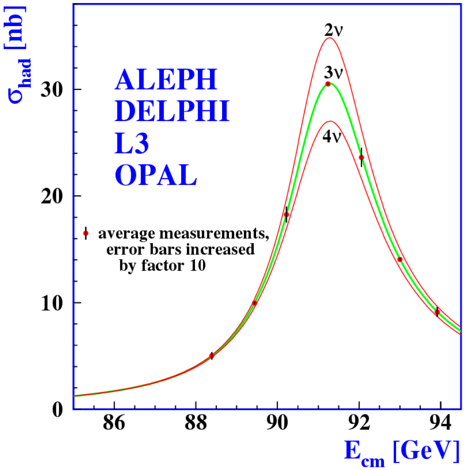
Three and only three active neutrinos: $N_\nu = 2.984 \pm 0.008$

Phys.Rept. 427 (2006) 257-454



- Extra flavor neutrino states have to be sterile!
- SBL anomalies motivate light sterile neutrino(s) with $\Delta m^2 \sim 1\text{eV}^2$
  - One economical extension is to introduce one extra sterile neutrino, 3+1 framework.
- Right-handed neutrinos (singlets under SM gauge group) can propagate in hypothesized extra space-time dimensions.
  - In a ‘vanilla’ LED model, similar phenomenology to that of light sterile neutrinos results.

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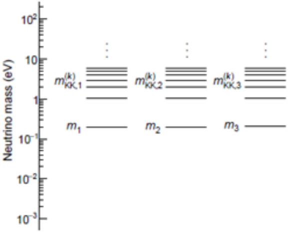
LED Model signatures/consequences

LED (3,3)-model (`Davoudiasl et. al 2002`) :

- In this model, three bulk right-handed neutrinos coupled (via Yukawas's) to the three active brane neutrinos.
- After compactification of the effective extra dimension, from the four dimensional (brane) point of view, the right-handed neutrino appears as an infinite tower of sterile neutrinos or Kaluza-Klein modes.



Phenomenological consequences:

- The active-sterile mixing and the new oscillation frequencies modify the active 3ν-oscillations therefore distorting the neutrino event energy spectrum.
- Departures from the standard oscillations due to the existence of LED can then be probed at neutrino oscillation experiments (Long & Short baselines).

Vacuum probabilities

LED oscillation probability, n-KK modes:

$$P_{\nu_\alpha \to \nu_\beta} = \left| \sum_{k=1}^{3} \sum_{n=0}^{\infty} U^*_{\alpha k} U_{\beta k} \left(L_k^{0n}\right)^2 \exp\left(-i \frac{\left(\lambda_k^{(n)}\right)^2}{2ER^2} L \right) \right|^2$$

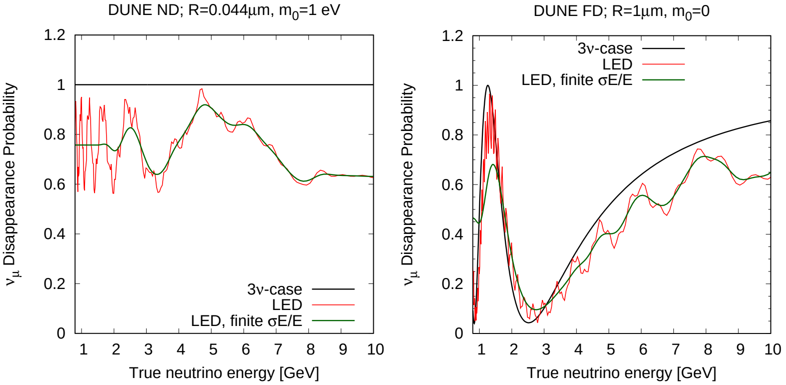
& $\lambda_k^{(n)}$ is obtained from $\boxed{\lambda_k^{(n)} - \pi (m_k^D R)^2 \cot\left(\pi \lambda_k^{(n)}\right) = 0}$ with $\boxed{\lambda_k^{(n)} \in [n, n+1/2]}$. We can then make the identification:

$$\boxed{m_k^{(n)} = \frac{\lambda_k^{(n)}}{R} \overset{n \gg 1}{\rightarrow} \frac{n}{R}}$$, and for the ‘modified’ mixing $\boxed{U_{\alpha k} L_k^{0n}}$

m_1^D, m_2^D, m_3^D, and R free parameters in the theory. However, for $n = 0$ and $m^D R \ll 1$, 3ν-flavor phenomenology must be satisfied (Davoudiasl et. al 2002), which reduces the dof to m_0 and R .

Main features

- Global reduction of survival probabilities, which is typically noticeable at high energies (Machado et. al 2011).
- Appearance of modulations and fast oscillations to Kaluza-Klein states.
- These shape-like features can be exploited at the analysis level. This have been done in MINOS (Phys.Rev.D 94 (2016) 11).



Most active (sterile) case corresponds to $n = 0$ ($n \gg 1$). The standard 3ν-neutrino oscillations are recovered in the limit $R \to 0$.

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The case of one light sterile state

3+1 sterile neutrino framework

DUNE-doc-1707-v1

Flavor and mass eigenstates are connected via:

$$\nu_\alpha = U^*_{\alpha i}\nu_i\,,\ \text{with} \quad \alpha = e, \mu, \tau, s$$

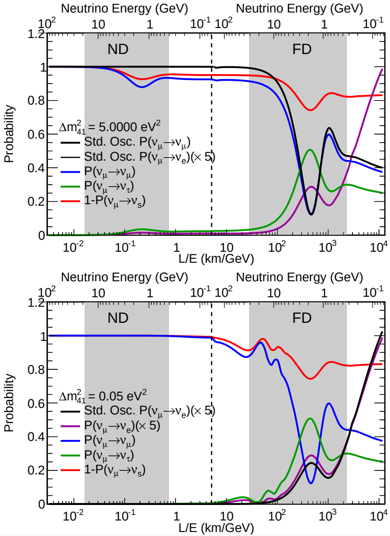
where U can be parametrized as:

$$U = O_{34}\,V_{24}\,V_{14}\,O_{23}\,V_{13}\,O_{12},$$

where O_{ij} (V_{ij}) denotes a real (complex) rotation.

How many new parameters we have included to the 3-flavor case?

- θ_{i4} new mixing angles.
- Three new splittings $\Delta m^2_{4k} \equiv m^2_4 - m^2_k$, with $k = 1, 2, 3$.
- Two new CP-violating phases: δ_{14} and δ_{24}.



The case of one light sterile state

Sterile appearance

By probability conservation we know $\sum_\alpha P_{\mu\alpha} = 1$ or

$$\sum_{\alpha=e,\mu,\tau} P_{\mu\alpha} = 1 - P_{\mu s} \,,$$

So, in the presence of s the $\sum_\beta P^{3\nu}_{\mu\beta} < 1$! Which is something that is experimentally exploited (NC measurements).

Working assumptions `Coloma, DVF, Parke arxiv:1707.05348`:

- We consider the sterile appearance channel, $P(\nu_\mu \to \nu_s)$.
- For simplicity, and without losing generality, we consider $\theta_{14} = 0$.
  This assumption implies that only one extra phase is physical, δ_{24}.

At the end, we are left with: θ_{34}, θ_{24}, δ_{24} and Δ_{41} extra parameters!

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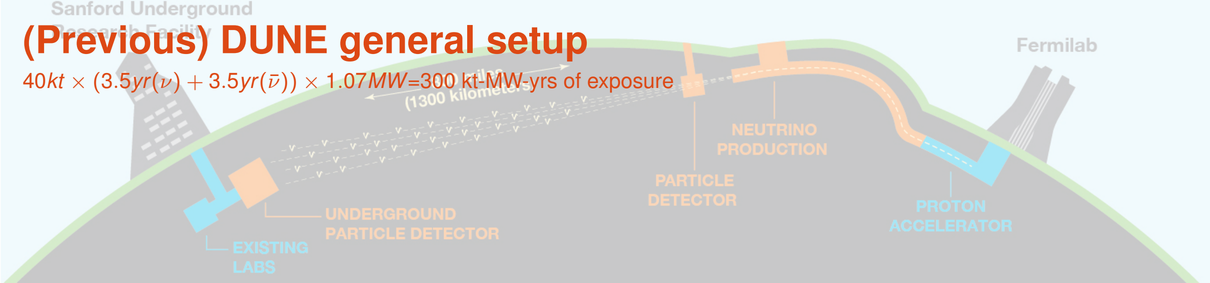
(Previous) DUNE general setup

$40kt \times (3.5yr(\nu) + 3.5yr(\bar{\nu})) \times 1.07MW$=300 kt-MW-yrs of exposure



T. Alion, et. al, arxiv:1606.09550

- CC ν and $\bar{\nu}$, (dis)appearance oscillation channels (& NC) included in the analysis.
- Initially, only FD information was considered, where ND fixed the flux normalization.
- Both FD & ND information is considered in the final analysis.

<u>Fluxes</u>: FHC & RHC “Optimized Engineered Nov2017”.

<u>xsection</u>: CC & NC “GENIE 2.8.4”.

<u>Energy reconstruction</u>

- Migration matrices accounting for the correspondence between E_ν and $E_{\rm rec}$.

<u>Efficiencies</u>

- Efficiencies function of $E_{\rm rec}$.

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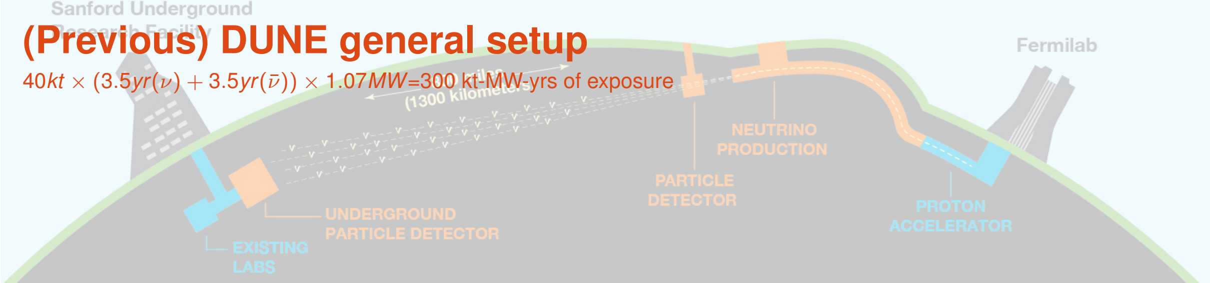

Systematical uncertainties

`T. Alion, et. al, arxiv:1606.09550` $\rightarrow$ 1st released GLoBES files

- Signal normalization syst. unc.:
  $\sigma(\nu_e) = \sigma(\bar{\nu}_e) = 0.02$, $\sigma(\nu_\mu) = \sigma(\bar{\nu}_\mu) = 0.05$,
- Background normalization syst. unc.:
  $\sigma(\nu_e) = \sigma(\bar{\nu}_e) = 0.05$, $\sigma(\nu_\mu) = 0.05$,
  $\sigma(\nu_\tau) = 0.2$ & $\sigma(NC_{dis}) = 0.1$.

- Systematical errors in GLoBES (implemented using pull method):
  - Total normalization uncertainties.
  - bin-to-bin uncorrelated systematics NOT included by default.

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ND-only LED Sensitivity

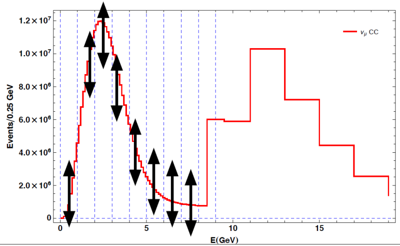
The importance of the bin-to-bin uncorrelated systematical (shape) uncertainties

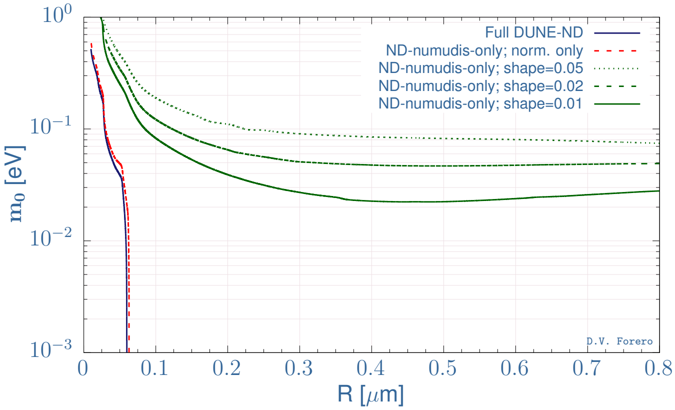
DUNE ND CDR, arxiv:2103.13910

Shape systematics in GLoBES

Define energy points, p_E, and size of the systematic, s, at each p_E

E.g. One uncorrelated systematic every GeV



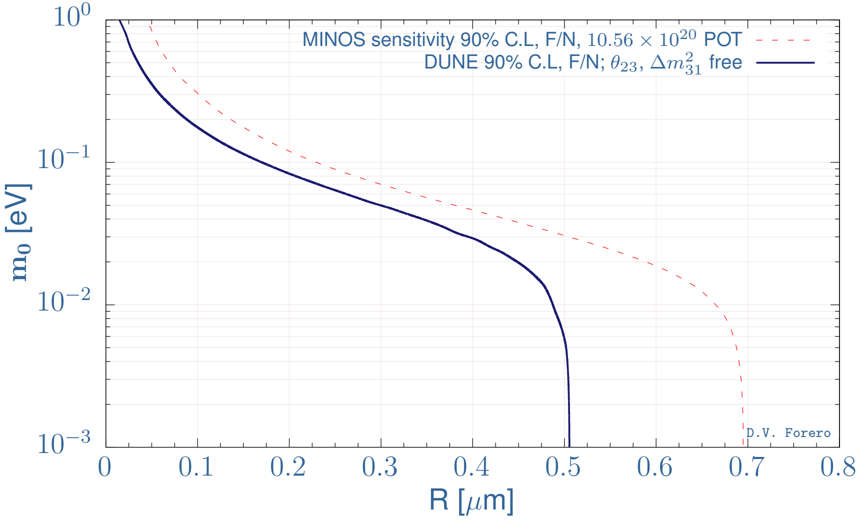


What is the best estimate of the shape uncertainties?

FD-only LED Sensitivity

300 kt-MW-yrs of exposure

DUNE TDR arxiv:2002.03005

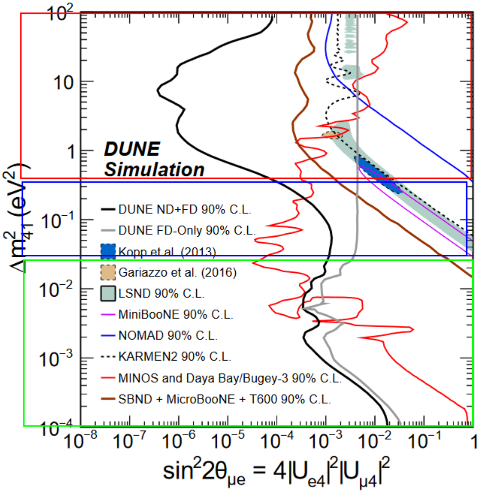


Sensitivity to light sterile mixing

ν_e CC App./Disapp.+ν_μ CC Disapp.

DUNE TDR arxiv:2002.03005

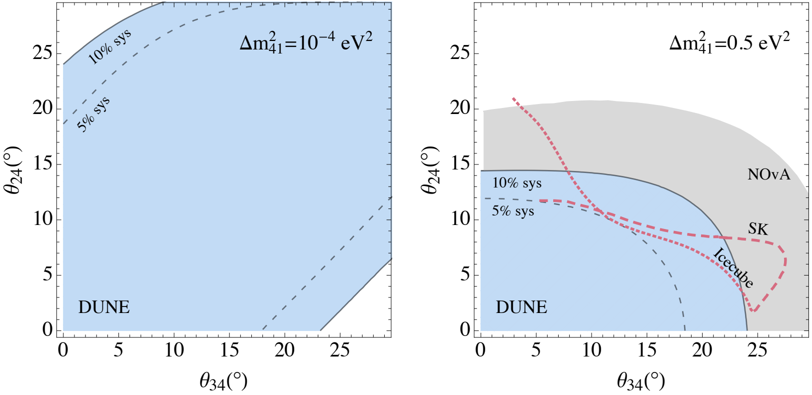
- Large Δm^2_{41} (ND-dominated)
  - ND oscillation
  - ND spectral distortions affect extrapolation to FD
  - Rapid oscillations at FD are average out
- Intermediate Δm^2_{41} (Counting Exp.)
  - No ND oscillations
  - Rapid oscillations at FD are average out
- Small Δm^2_{41} (FD-dominated)
  - FD oscillations, no ND oscillation
  - FD spectral distortions



FD-only sensitivity to light sterile mixing

NC analysis, minimizing over δ_{24}

Coloma, DVF, Parke arxiv:1707.05348



- Left: In the $\Delta_{41} \ll \Delta_{31}$ regime, $P_{\mu s} = 4|U_{\mu 3}|^2 |U_{s3}|^2 \sin^2 \Delta_{31}$. Cancellations: For $\delta_{24} = \pi$, when $|U_{s3}|^2 \approx 0$
- Right: In the $\Delta_{41} \gg \Delta_{31}$ regime, almost no δ_{24} impact, and therefore no cancellations.

Outline

Summary & conclusions

- In parallel to the standard physics program, several BSM physics searches can be pursued in DUNE. In this talk we have focus on two specific cases.
- DUNE experimental capabilities such as broad energy spectrum, energy resolution plus the discrimination power between NC and CC events, make DUNE a unique place to look for BSM signals, as shown here for the 3+1 and the LED scenarios.
- In both scenarios, particular spectral-like features can be exploited at the analysis level in a single simulation framework.
- Combining information from near and far detectors allows to probe a large part of the parameter space of the the 3+1 and the LED scenarios. Therefore, a two-detector analysis with realistic systematics is very promising for future BSM searches.
- Within the DUNE BSM physics WG both theorist and experimentalist have joint efforts to tackle open problems, developing common frameworks and tools, that will benefit the neutrino community as whole.

Thank you for your attention!

Back up

ND information

mass=67.2Tons; baseline=575m

Information considered in the analysis:

- Signal: CC, ν and $\bar{\nu}$, appearance and disappearance oscillation channels included in the analysis.
- Only ND information is considered.

Systematics See sterile section in TDR

Type of error	Value	affects	ND/FD correlated?
ND fiducial vol.	0.01	all ND events	no
FD fiducial vol.	0.01	all FD events	no
flux signal component	0.08	all events from signal comp.	yes
flux background component	0.15	all events from bckg comp.	yes
flux signal component n/f	0.004	all events from signal comp. in ND	no
flux background component n/f	0.02	all events from bckg comp. in ND	no
CC cross section (each flav.)	0.15	all events of that flavour	yes
NC cross section	0.25	all NC events	yes
CC cross section (each flav.) n/f	0.02	all events of that flavour in ND	no
NC cross section n/f	0.02	all NC events in ND	no

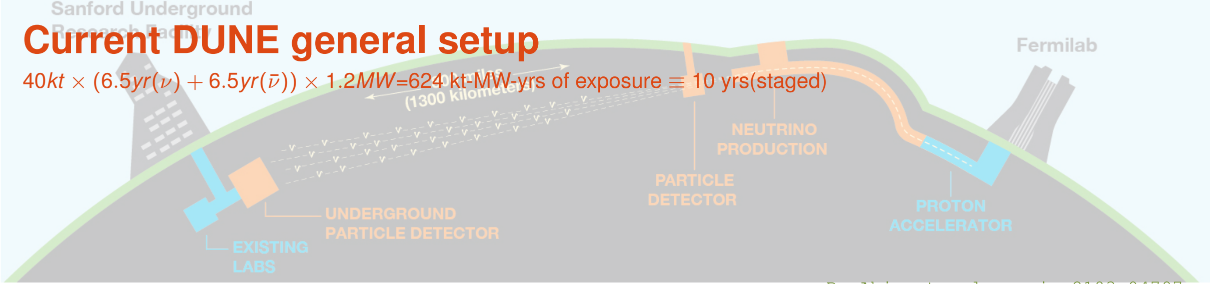
Table I. List of systematic errors assumed in the analysis.

Fluxes

- The “Optimized Engineered Nov2017” for ND.

Current DUNE general setup

$40kt \times (6.5yr(\nu) + 6.5yr(\bar{\nu})) \times 1.2MW$=624 kt-MW-yrs of exposure $\equiv$ 10 yrs(staged)



B. Abi, et. al, arxiv:2103.04797

- Signal: CC, ν and $\bar{\nu}$, (dis)appearance oscillation channels included in the analysis.
- BG: CC ν_τ, NC.
- Initially, only FD information was considered, where ND fixed the flux normalization.
- Both FD & ND information is considered in the final analysis.

Fluxes: FHC & RHC "Optimized Engineered Nov2017".

xsection: CC & NC "GENIE 2.8.4".

Energy reconstruction

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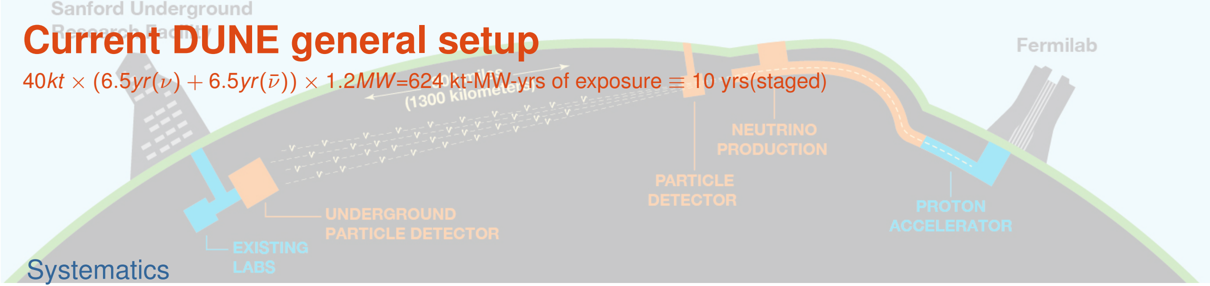


Systematics

B. Abi, et. al, arxiv:2103.04797 $\rightarrow$ Latest GLoBES files: $\boxed{E_{rec}\text{ binwidth= (TDR binwidth)/2}}$.

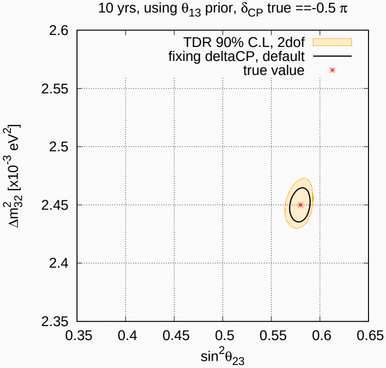
- Signal normalization systematical errors: $\sigma(\nu_e) = \sigma(\bar{\nu}_e) = 0.02$, $\sigma(\nu_\mu) = \sigma(\bar{\nu}_\mu) = 0.05$,
- Background normalization systematical errors: $\sigma(\nu_e) = \sigma(\bar{\nu}_e) = 0.05$, $\sigma(\nu_\mu) = 0.05$, $\sigma(\nu_\tau) = 0.2$ & $\sigma(NC_{dis}) = 0.1$.
- bin-to-bin uncorrelated systematics (named SHAPE syst.) now included.

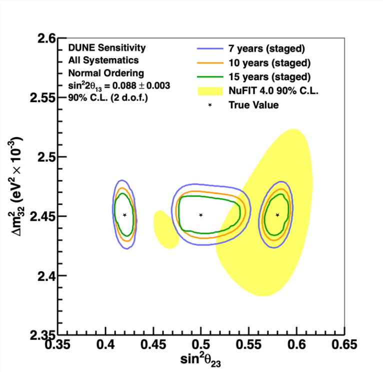
- Systematical errors in GLoBES (implemented using pull method):
  - Signal: Total normalization (norm) and shape uncertainty.
  - BG: Total normalization.
- Another possibility is to use the covariant method.

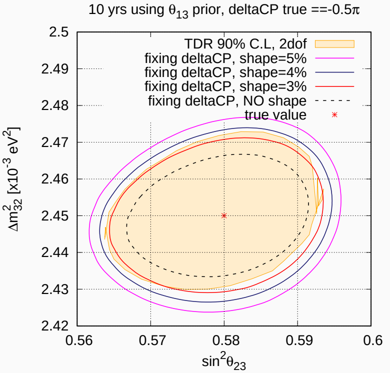
Estimating the level of the 'shape' systematics

Atmospheric plane, the importance of the shape systematics

LBL phys. Potential of the DUNE Exp. arxiv:2006.16043, FIG. 26







Light sterile neutrino

NC analysis

Simulation and analysis strategy

Coloma, DVF, Parke arxiv:1707.05348

- We assume that no sterile oscillations have taken place at the ND.
- Then one should look for a depletion in the number of NC events at the FD with respect to the (3-flavor) prediction.
- Signal:

$$\begin{aligned} N_{NC} &= N^{e}_{NC} + N^{\mu}_{NC} + N^{\tau}_{NC} \\ &= \phi_{\nu_\mu}\, \sigma^{NC}_{\nu} \{P(\nu_\mu \to \nu_e) + P(\nu_\mu \to \nu_\mu) + P(\nu_\mu \to \nu_\tau)\} \\ &= \phi_{\nu_\mu}\, \sigma^{NC}_{\nu} \{1 - P(\nu_\mu \to \nu_s)\}\ , \end{aligned}$$

- Background:
  $\nu_{e,\mu,\tau}$-CC events potentially misidentified as NC events.

Therefore, 'good' discrimination power between neutral-current and charged-current events is required!

DUNE neutrino oscillation experiment is therefore a good place to look for the 'depletion' of NC events at FD.