LARGE EXTRA DIMENSIONS SEARCHES IN DUNE

DAVID VANEGAS FORERO

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In coll. with A. Sousa, E. Fernandez-M, S. Rosauro

Motivation

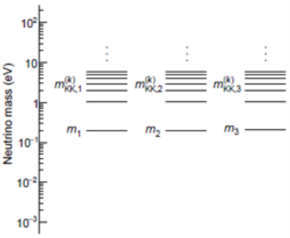
- From the model point of view:
  - Extra space-time dimensions were originally introduced to “alleviate” the so called hierarchy problem, i.e. the large difference between the electroweak and the GUT (or even the Planck) energy scales. N. Arkani-Hamed et. al, PLB429, 1998
  - Models with large extradimensions can also accommodate non-zero neutrino masses, specifically, of the Dirac type which are naturally small. N. Arkani-Hamed et. al, PRD65, 1998 & K. R. Dienes et. al, NPB557, 1999
- From the phenomenological point of view:
  - The LED model turns out to be pretty testable at neutrino oscillation experiments (Davoudiasl et. al. 2002, Machado et. al. 2011).
  - MINOS (2016) experiment (PRD94) set a constrain to the LED compactification radius: $R < 0.45\,\mu m$ at 90% of C.L. when the lightest neutrino mass $m_0 \to 0$.

Model signatures/consequences

$m_i^{(0)} = f(m_0, R)$,
$m_0 \equiv$ absolute neutrino mass

LED 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 ($R \equiv$ compactification radius), from the four dimensional (brane) point of view, the right-handed neutrino appears as an infinite tower of sterile neutrinos or Kaluza-Klein (KK) modes.



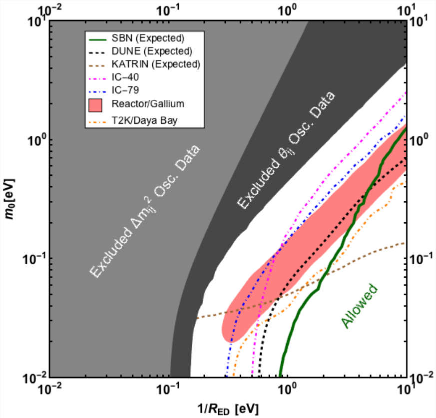
Phenomenological consequences:

- The sterile-active mixings 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).

Prior studies

At neutrino oscillation experiments

- SBN program: G. Stenico, DVF & O.L.G Peres arxiv:1808.05450



$R \equiv$ compactification radius
$m_0 \equiv$ absolute neutrino mass

- DUNE FD-only: Berryman et. al. arxiv:1603.00018
- IceCUBE: A. Esmaili et. al. arxiv:1409.3502
- Daya Bay & T2K data: Di Lura et. al. arxiv:1411.5330
- Reactor anomaly: P.A.M Machado et. al. arxiv:1107.2400

So far, MINOS is the only experimental collaboration that has constrained R with data. Thus, MINOS sensitivity will be our reference.

Vacuum probabilities

Three-active neutrino oscillation probability:

$$P_{\nu_\alpha \to \nu_\beta} = \left| \sum_{k=1}^{3} U^*_{\alpha k} U_{\beta k} \exp\left(-i \frac{m_k^2}{2E}\right) \right|^2$$

LED oscillation probability, n-KK modes:

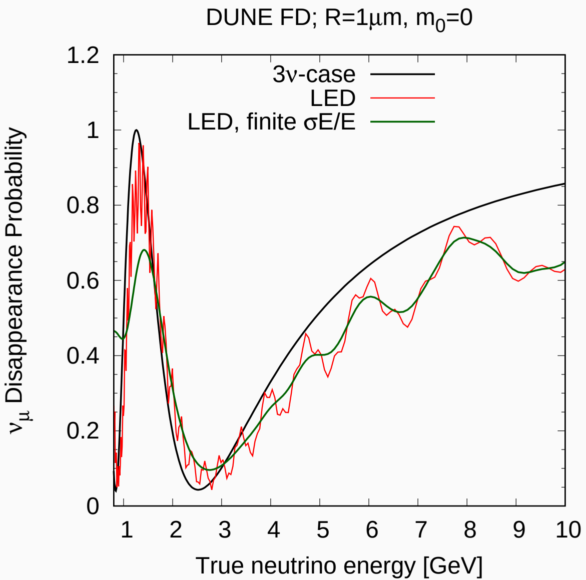
$$P_{\nu_\alpha \to \nu_\beta} = \left| \sum_{k=1}^{3} \sum_{n=0}^{\infty} U^*_{\alpha k} U_{\beta k} \left(L_k^{0n}\right)^2 \exp\left(-i \frac{\left(\lambda_k^{(n)}\right)^2}{2ER^2}\right) \right|^2$$

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

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

Four free parameters m_1^D, m_2^D, m_3^D, and R in the theory, which can be reduced to m_0 and R .
For $n = 0$ and $m^D R \ll 1$, 3ν-flavor phenomenology must be satisfied Davoudiasl et. al 2002.

Main features



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

- 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 (2016).
- Sensitivity analyses for several osc. Exps (Machado et. al 2011), IceCube (Esmaili et. al. 2014), DUNE (Berryman et. al 2016... "revamped" for DUNE FD TDR & ND CDR), and SBN (Stenico, DVF, Peres 2018).

Previous DUNE setup

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

Information considered in the analysis:

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

Systematics

T. Alion et. al. arxiv:1606.09550 $\rightarrow$ First GLoBES files release.

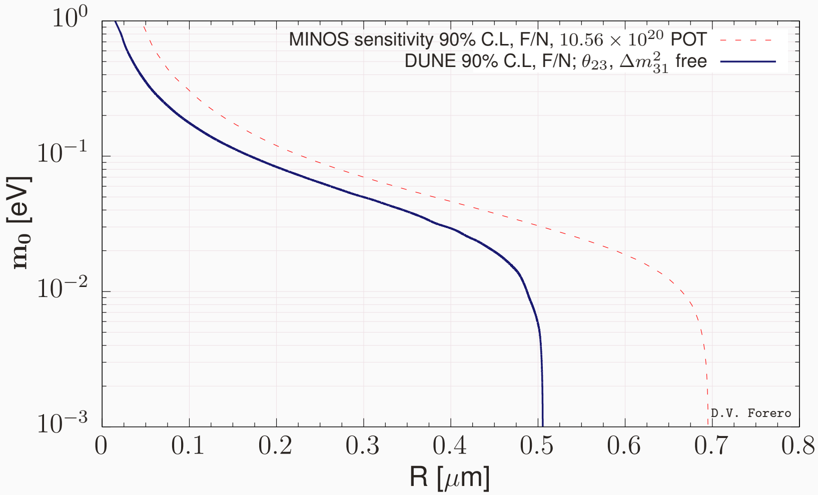
- Signal normalization systematical errors:
  $\sigma(\nu_e) = 0.02$, $\sigma(\bar{\nu}_e) = 0.02$, $\sigma(\nu_\mu) = 0.05$, $\sigma(\bar{\nu}_\mu) = 0.05$.
- Background normalization systematical errors:
  $\sigma(\nu_\mu) = 0.05$, $\sigma(\nu_e) = 0.05$, $\sigma(\nu_\tau) = 0.2$, $\sigma(\bar{\nu}_e) = 0.05$ & $\sigma(NC_{dis}) = 0.1$.
- At this point, bin-to-bin uncorrelated systematics (or SHAPE syst.) not included!

Fluxes

- The “Optimized Engineered Nov2017”.

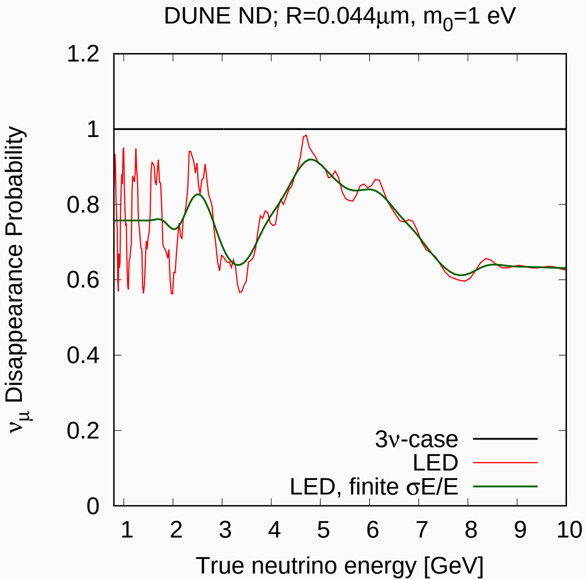
DUNE Sensitivity to LED; 300 kt-MW-years of exposure

DUNE TDR arxiv:2002.03005



Thanks to S. De Rijck we can show MINOS sensitivity result (Asimov data).

How sensitive is the ND?



- Reduction of survival probability, noticeable departure from 1.
- Appearance of modulations and fast oscillations to Kaluza-Klein states.
- These shape-like features can be exploited at the analysis level.

Using ND information [previous DUNE setup]

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.

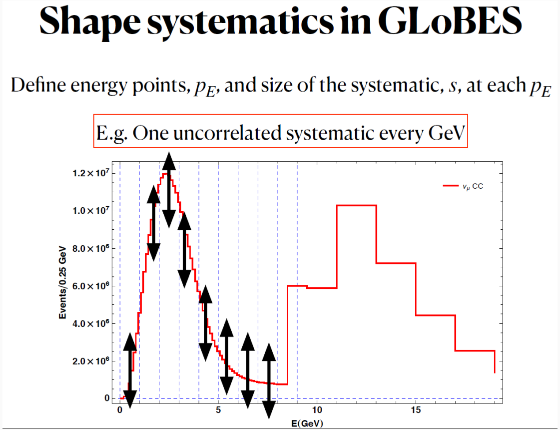
Fluxes

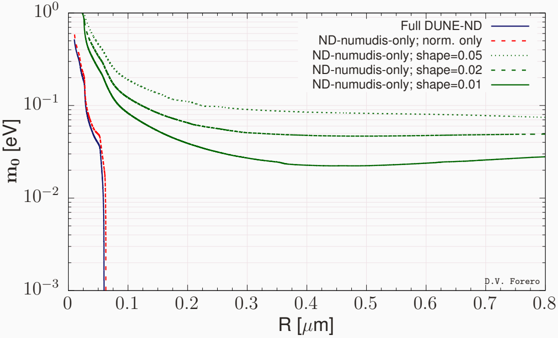
- The “Optimized Engineered Nov2017” for ND.

DUNE ND-only Sensitivity to LED; 0.5 Kt-MW-yrs of exposure

The importance of the shape systematics

DUNE ND CDR, arxiv:2103.13910





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Work in progress...

Current DUNE setup

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

Information considered in the analysis:

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

Systematics

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

- Signal normalization systematical errors: $\sigma(\nu_e) = 0.02$, $\sigma(\bar{\nu}_e) = 0.02$, $\sigma(\nu_\mu) = 0.05$, $\sigma(\bar{\nu}_\mu) = 0.05$.
- Background normalization systematical errors: $\sigma(\nu_\mu) = 0.05$, $\sigma(\nu_e) = 0.05$, $\sigma(\nu_\tau) = 0.2$, $\sigma(\bar{\nu}_e) = 0.05$ & $\sigma(NC_{dis}) = 0.1$.
- bin-to-bin uncorrelated systematics (or SHAPE syst.) included, as explained in slide 9.

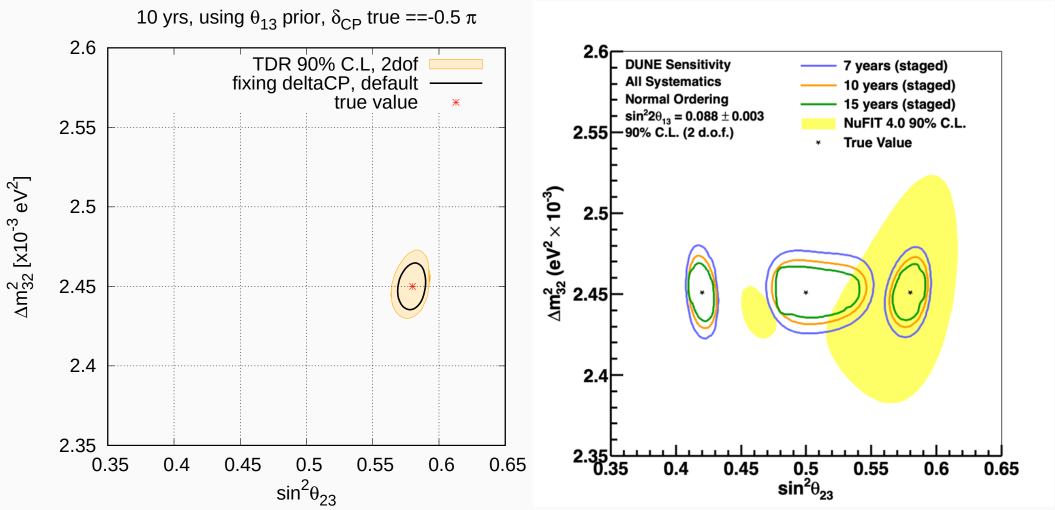
Fluxes

- The "Optimized Engineered Nov2017".

Estimating the level of the ‘shape’ systematics

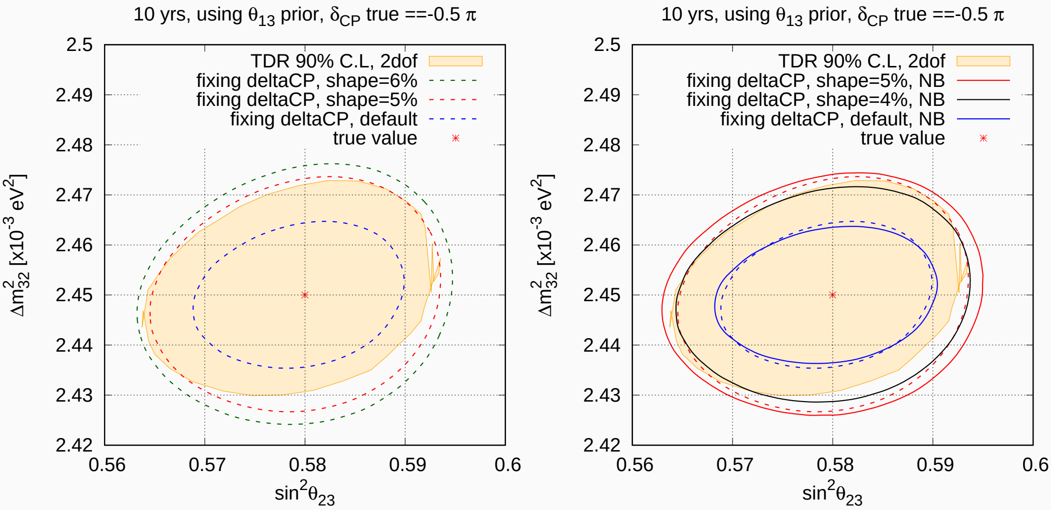
Atmospheric plane, the importance of the shape systematics

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



Estimating the level of the ‘shape’ systematics

ZOOMING IN the Atmospheric plane, when using TDR binning result quoted as ‘NB’



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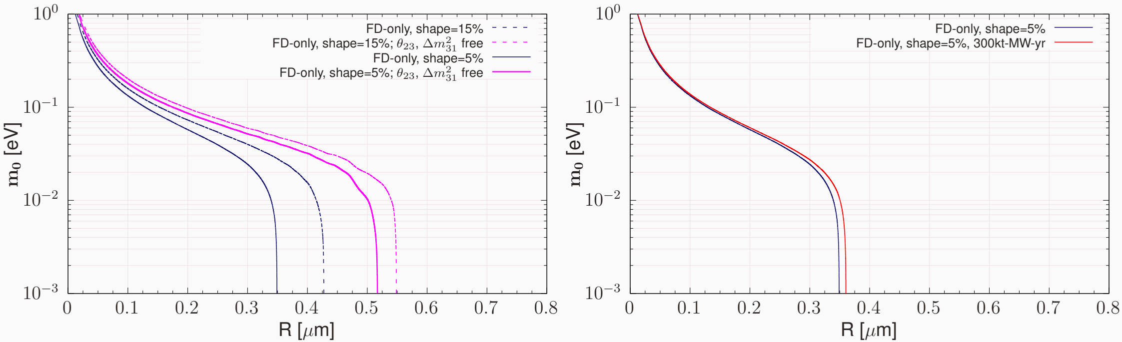
DUNE Sensitivity to LED, preliminary results

FD-Only, with TDR binning & 2 KK modes

624 kt-MW-years of exposure $\equiv$ 10 yrs (staged). DUNE 90% of C.L for 2 d.o.f:



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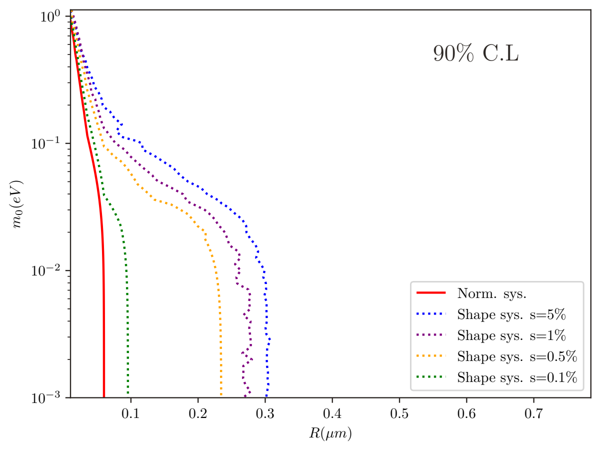
Towards a two-detector fit [previous DUNE setup]

First results for 2 KK modes, with the old binning

Includding a shape-like systematic error in the signal (uncorrelated between detectors) in the ND.



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Summary

- The LED model (N. Arkani-Hamed et. al, PLB429, 1998) turns out to be pretty testable at neutrino oscillation experiments (Davoudiasl et. al 2002).
- Neutrino oscillations within this LED model provide unique features that can be explored in parallel to the search for a sterile neutrino oscillation at the eV energy-scale in the economical '3+1' scenario.
- Long-baseline experiments detecting neutrinos at high energies, and with a percent-level energy resolution, are good candidates for LED probes.
- In particular, combining information from near and far detectors allows to probe lighter and heavier KK modes simultaneously. Therefore, a two-detector analysis with realistic systematics is very promising for future LED searches.
- Neutrino oscillation experiments provide a competitive, model independent constrain to R, which is complementary to other searches, for instance in neutrinoless double beta decay experiments, in core collapse supernovae, at colliders like the LHC, and in kinematical tests (Basto et. al 2012).

THANK YOU FOR YOUR ATTENTION!

Back up

Near Future Plans

- To understand the departures from 3-flavor results in arxiv:2006.16043, FIG. 26 obtained when estimating of the level of systematics, using GLoBES files (first procedure).
- To implement covariance matrices for the 2-detector analysis including LED (second procedure).
- First procedure is considered as a cross check of the second one, at least for the FD-only sensitivity to LED.

A comment on the degrees of freedom

Possible approaches

MINOS Approach:

- m_1^D, m_2^D, m_3^D and R are free parameters.
- Do not assume Δm_{j1}^2 to be known, so they are free.
- This is the correct approach for a single experiment without considering external measurements.

Alternative approach from Basto et. al. (PLB **718** (2013)) arxiv:1205.6212:

(Also followed in Berryman et. al. (PRD **94** (2016)) arxiv:1603.00018)

- For a given hierarchy, one can use the 'known Δm_{j1}^2' to reduce the d.o.f from 4 to 2: $m_0 \equiv m_1^D (m_3^D)$ for NO(IO) and R.
- This assume Δm_{j1}^2 to be known or within some small range, for instance 1σ range from global fits or PDG.
- External measurements, added as penalties to the χ^2, can be included.

Both approaches produce the same sensitivity when Δm_{j1}^2 are free in the fit.

We followed the 2[nd] approach also let the atmospheric parameters to float free in the analysis.