Testing TeV Scale Gravity Theories with Public Neutrino Oscillation Data

Master's Thesis Defense

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Research conducted at: Technische Universität München

Outline

- Motivation: Beyond the Standard Model

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- Theory: ADD Model and Kaluza-Klein Towers

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- Results: Constraints on One and Two Extra Dimensions
- Summary and Outlook

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Motivates the search for a *natural* solution → **Large Extra Dimensions**

The ADD model proposes a solution to the Hierarchy Problem

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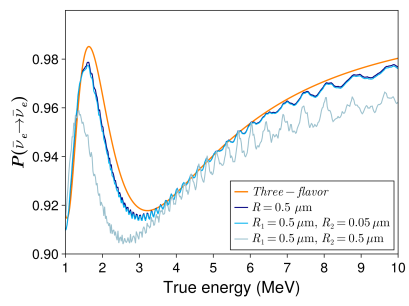
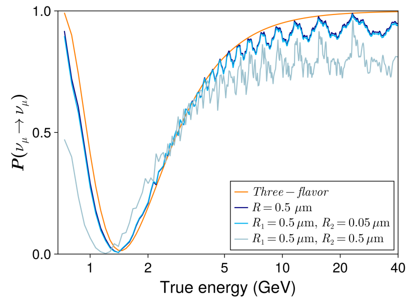
Its coupling to the Higgs is also diluted by the volume of the extra dimensions, naturally generating a tiny mass.

The Signature: Kaluza-Klein (KK) Towers

- Particles propagating in the extra dimension appear in our 4D world as a tower of massive states: the **Kaluza-Klein (KK) modes**.
- Sterile KK modes mix with the active neutrinos $(\nu_e, \nu_\mu, \nu_\tau)$.
- **Key Effect:** New, energy-dependent distortions in the neutrino survival probability.
    - Rapid "wiggles"
    - Overall suppression of event rate





The Signature: Effect of Topology

One Extra Dimension (1D)

The KK mass-squared spectrum is non-degenerate and relatively sparse.

$$m_n^2 = \frac{n^2}{R^2}$$

$n = 1, 2, 3, \ldots$

Two Extra Dimensions (2D)

The spectrum is much **denser** and highly **degenerate**.

$$m_{n_1,n_2}^2 = \frac{n_1^2}{R_1^2} + \frac{n_2^2}{R_2^2}$$

e.g., for a symmetric torus ($R_1 = R_2$), the states (1,2), (2,1) have the same mass.

KK Tower Structure

1 *Extra Dimension*
R

State (n)	Mass²
(1)	$1/R^2$
(2)	$4/R^2$
(3)	$9/R^2$
(4)	$16/R^2$
(5)	$25/R^2$

Sparse, evenly spaced.

2*D Symmetric*
$R_1 = R_2 = R$

State (n_1, n_2)	Mass²
(1,0), (0,1)	$1/R^2$
(1,1)	$2/R^2$
(2,0), (0,2)	$4/R^2$
(2,1), (1,2)	$5/R^2$
(2,2)	$8/R^2$

Denser & Degenerate.

2*D Asymmetric*
$R_1 = R = 10 \times R_2$

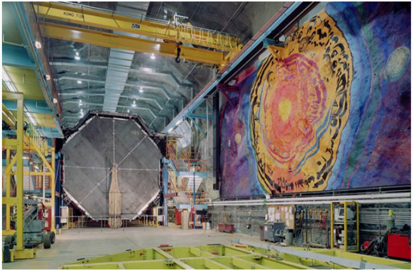
State (n_1, n_2)	Mass²
(1,0)	$1/R_1^2$
(2,0)	$4/R_1^2$
(3,0)	$9/R_1^2$
(10,0)	$100/R_1^2$
(0,1)	$100/R_1^2$

Moderate degeneracy.

Existing Experimental Data

Accelerator Neutrinos
MINOS/MINOS+

- Long-baseline (735 km) ν_μ disappearance experiment.
- Probes a different flavor channel at higher energies (GeV scale).



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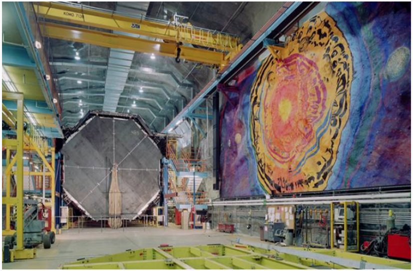
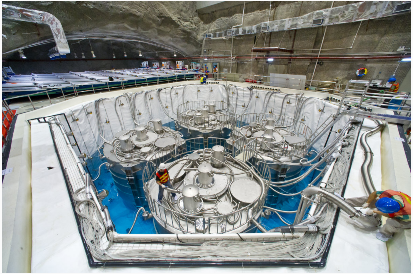
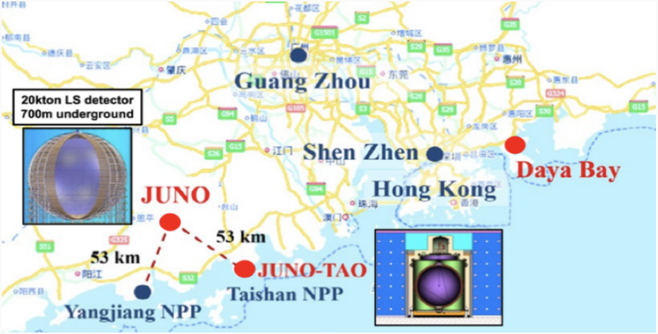


Reactor Neutrinos
Daya Bay

- Short-baseline ($\sim$1.5 km) $\bar{\nu}_e$ disappearance experiment.
- Provides a high-statistics measurement in the MeV energy range.



Future: JUNO & TAO



JUNO: The Precision Instrument

- Massive detector at a $\sim$53 km baseline.
- **Challenge:** Sensitivity limited by systematic uncertainties (flux, energy response).

TAO: The High-Resolution Calibrator

- Compact detector at a 30 m baseline.
- **Solution:** Precisely measures the *un-oscillated* spectrum as a reference.

Analysis Framework

1. **Software & Modeling**

Framework: `Newtrinos.jl` (Modular global neutrino analysis)

- **Forward Models:** Predict event spectra for each experiment.

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Method: All experimental likelihoods combined into a single Joint Likelihood.

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3. Final Constraint

Core Method: Profile Likelihood Analysis

- Scan physics parameters (e.g., Radius R).
- At each point, maximize likelihood over all nuisance parameters.

Projections: JUNO & TAO

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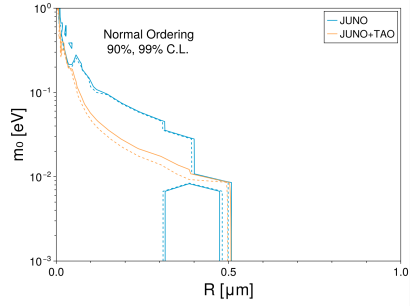
Normal Ordering: A Modest Improvement



TAO provides a slight tightening of

the allowed region.

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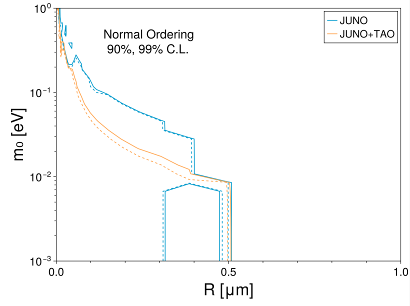

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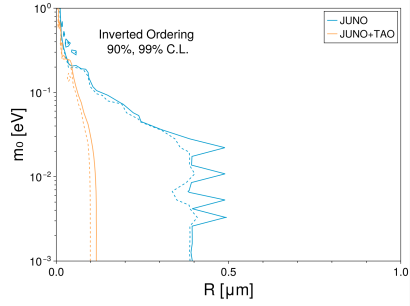
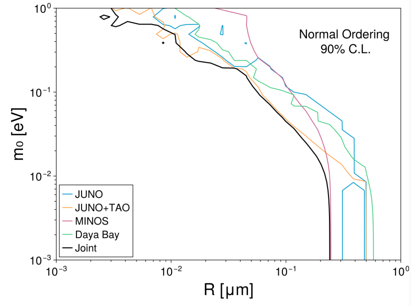
Inverted Ordering: A Dramatic Improvement



TAO's impact is huge, improving the limit on R by a factor of $\sim$4.

Joint Constraints



- MINOS drives the constraint.
- Final **Joint Limit:** $R < 0.2\,\mu\text{m}$ (90% C.L.).

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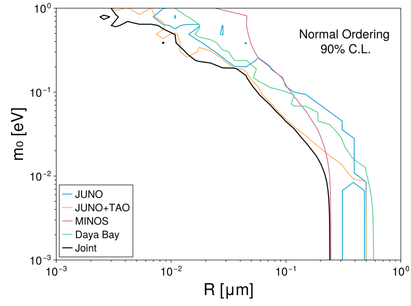

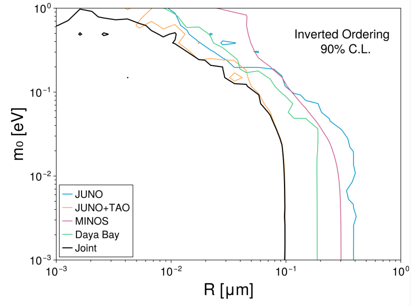

- MINOS drives the constraint.
- Final **Joint Limit:** $R < 0.2\,\mu m$ (90% C.L.).

- JUNO+TAO dominates.
- Final **Joint Limit:** $R < 0.1\,\mu m$ (90% C.L.).

2 Extra Dimensions: JUNO

Denser, more degenerate tower of KK states in **2D Symmetric** torus

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Stronger, more easily detectable distortion in the neutrino spectrum

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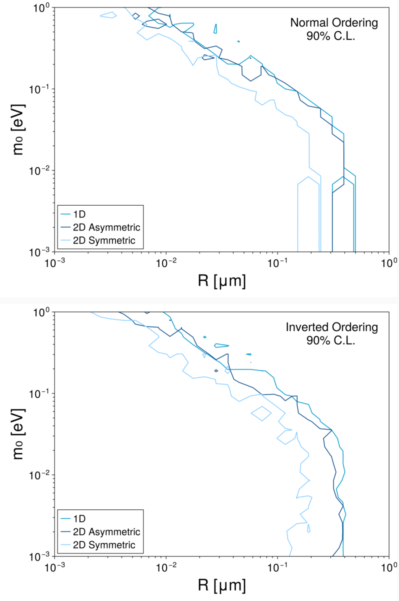
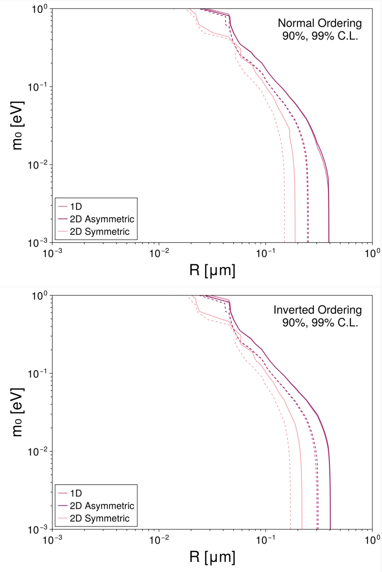
Twice as strong constraints as in the 1D case

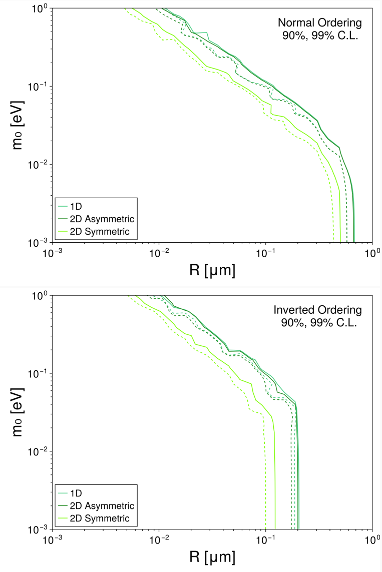


2 Extra Dimensions: MINOS & Daya Bay

MINOS



Daya Bay



Summary

- Explored tests of TeV-scale gravity with large extra dimensions using MINOS/MINOS+ and Daya Bay inputs together with JUNO/TAO *sensitivity forecasts*.
- The results *suggest* complementary strengths among the experiments, with the leading constraints varying based on the neutrino mass ordering.
- Sensitivity depends on compactification *topology*: 2D symmetric cases tended to yield tighter limits than 1D under the same settings, highlighting the importance of topology for BSM searches with neutrinos.

Outlook

- **Data/inputs**
  - Revisit with real JUNO/TAO data following the August 2025 commissioning.
- **Methodology**
  - Systematic study of KK truncation and alternative regularisations (e.g., smooth cutoffs, analytic tail) to bound scheme dependence.
- **Physics extensions**
  - Exploration of a wider range of 2D anisotropies (R_2/R_1).
  - Inclusion of complementary channels/experiments (e.g., DUNE, Hyper-K) for different L/E leverage and cross-checks.

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Backup — ADD and the Hierarchy Problem

Gravity dilution in n extra dimensions

$$M_{\mathrm{Pl}}^2 \;=\; M_*^{\,n+2}\, V_n \qquad \text{with} \qquad V_n = (2\pi R)^n$$

$$\Rightarrow \quad M_{\mathrm{Pl}}^2 \;=\; M_*^{\,n+2}\,(2\pi R)^n$$

- If the fundamental ($(4+n)$-D) gravity scale is $M_* \sim \mathcal{O}(\mathrm{TeV})$, a large compactification volume V_n boosts the observed M_{Pl} in 4D, explaining why gravity *appears* weak.

Backup — Small Neutrino Masses from a Bulk RH Neutrino

Brane–bulk Yukawa and volume suppression

$$\lambda_{4\mathrm{D}} \;=\; \frac{\lambda_{(4+n)}}{\sqrt{V_n\, M_*^n}}$$

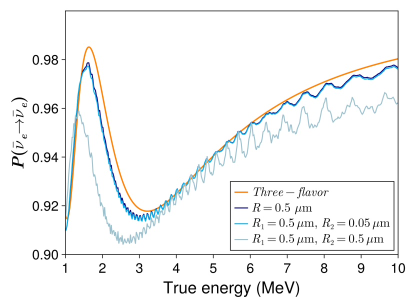
$$m_D \;=\; \lambda_{4\mathrm{D}}\, v \;\simeq\; \frac{\lambda_{(4+n)}\, v}{\sqrt{V_n\, M_*^n}} \;\approx\; \lambda\, v \left(\frac{M_*}{M_{\mathrm{Pl}}}\right)$$

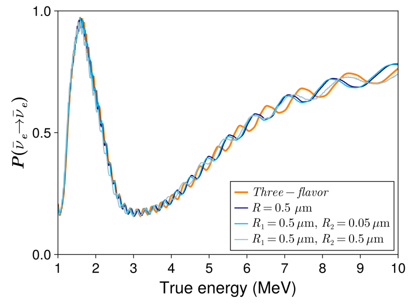
- The zero-mode wavefunction normalization over V_n suppresses the effective 4D Yukawa, giving naturally tiny Dirac masses without fine-tuning.

KK tower and oscillation signature

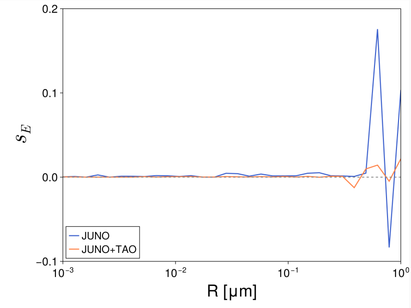
$$m_n^2 \;=\; m_0^2 + \frac{n^2}{R^2} \qquad (n = 1, 2, \dots)$$

Backup — Oscillation Patterns

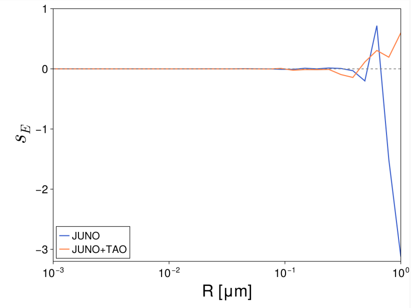




Backup — Energy Scale Pulls



Normal Ordering



Inverted Ordering

Backup — χ^2 vs N_{KK} (Daya Bay)