



Constraining Extra-Dimensions with Hyper-K, DUNE, and JUNO

Ngoc Tran⁽¹⁾, Son Cao⁽²⁾

(1) Kyoto University, Japan

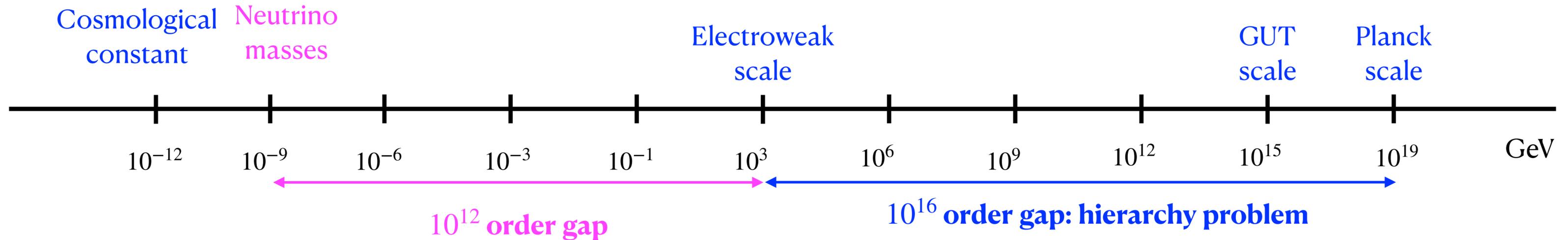
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1. Introduction



o Arkani-Hamed - Dimopoulos - Dvali (1998) and Randall - Sundrum (1999) introduce **Large Extra Dimension (LED)** models with **d** extra dimensions

o In LED models: $M_f^{d+2} = \frac{M_{Pl}^2}{R^d}$

- M_f : fundamental Planck scale (true scale)
- M_{Pl} : Planck scale (effective scale)
- R : radius of extra dimension

o Fundamental scale can be suppressed to electroweak scale by the **volume of the LEDs**

o What about neutrino case?

- **Seesaw mechanism**: lightness of neutrino masses is explained by introducing heavy Majorana mass term (\sim GUT scale)
- Applying **LED idea** to neutrino without introducing heavy Majorana mass

1. Introduction

○ Assumptions:

- **4D spacetime** is a **brane** embedded in a larger **(4+d)D spacetime (bulk)**
- All SM fields including **3 active neutrinos** are **restricted** to the **4D brane**
- Single fields under SM including **right-handed sterile neutrinos** propagate in the **(4+d)D bulk**
- One of the extra dimensions is **compactified** on a **circle of radius R** much larger than the others so we can use **5D treatment**
- 5D fermions can be **decomposed** into a **tower of infinite Kaluza-Klein modes (KK sterile neutrino modes)**

$$\psi_L(x, y) = \frac{1}{\sqrt{2\pi R}} \sum_{n=-\infty}^{+\infty} \psi_L^{(n)}(x) \sin \frac{ny}{R}, \quad \psi_R(x, y) = \frac{1}{\sqrt{2\pi R}} \sum_{n=-\infty}^{+\infty} \psi_R^{(n)}(x) \cos \frac{ny}{R}$$

1. Introduction

- In the present of LED, neutrino mixing is defined as: $\nu_{\alpha L} = \sum_{i=1}^3 U_{\alpha i} \sum_{n=0}^{\infty} W_{in} \nu_{iL}^{(n)}$
 - $U \equiv U_{PMNS}$: ordinary 3×3 PMNS mixing matrix
 - $\nu_{iL}^{(n)}$: mass eigenstate with mass $m_i^{(n)} = \lambda_i^{(n)}/R \approx n/R$, where $\lambda_i^{(n)}$ are the solutions of transcendental equation: $\lambda_i^{(n)} - \pi(m_i R)^2 \lambda_i^{(n)} \cot(\pi \lambda_i^{(n)}) = 0$
 - Components of mixing matrix W: $W_{in}^2 = \frac{2}{1 + \pi^2(m_i R)^2 + \lambda_i^{(n)2}/(m_i R)^2}$
- Neutrino oscillation probability

$$P_{\alpha\beta} = \left| \sum_{i=1}^3 \sum_{n=0}^{\infty} U_{\alpha i}^* U_{\beta i} W_{in}^2 \times \exp\left(i \frac{\lambda_i^{(n)2} L}{2ER^2}\right) \right|^2$$

- **Compared to 3-flavor case**, this model requires **2 extra parameters**: lightest active mass m_0 and extra dimension radius R

1. Introduction

○ **LED affects the “standard oscillation”:**

- **(1) Decrease survival probability of active neutrinos:** Active neutrinos can oscillate into invisible KK modes which reduce the probability.

- **(2) New oscillation frequency:**

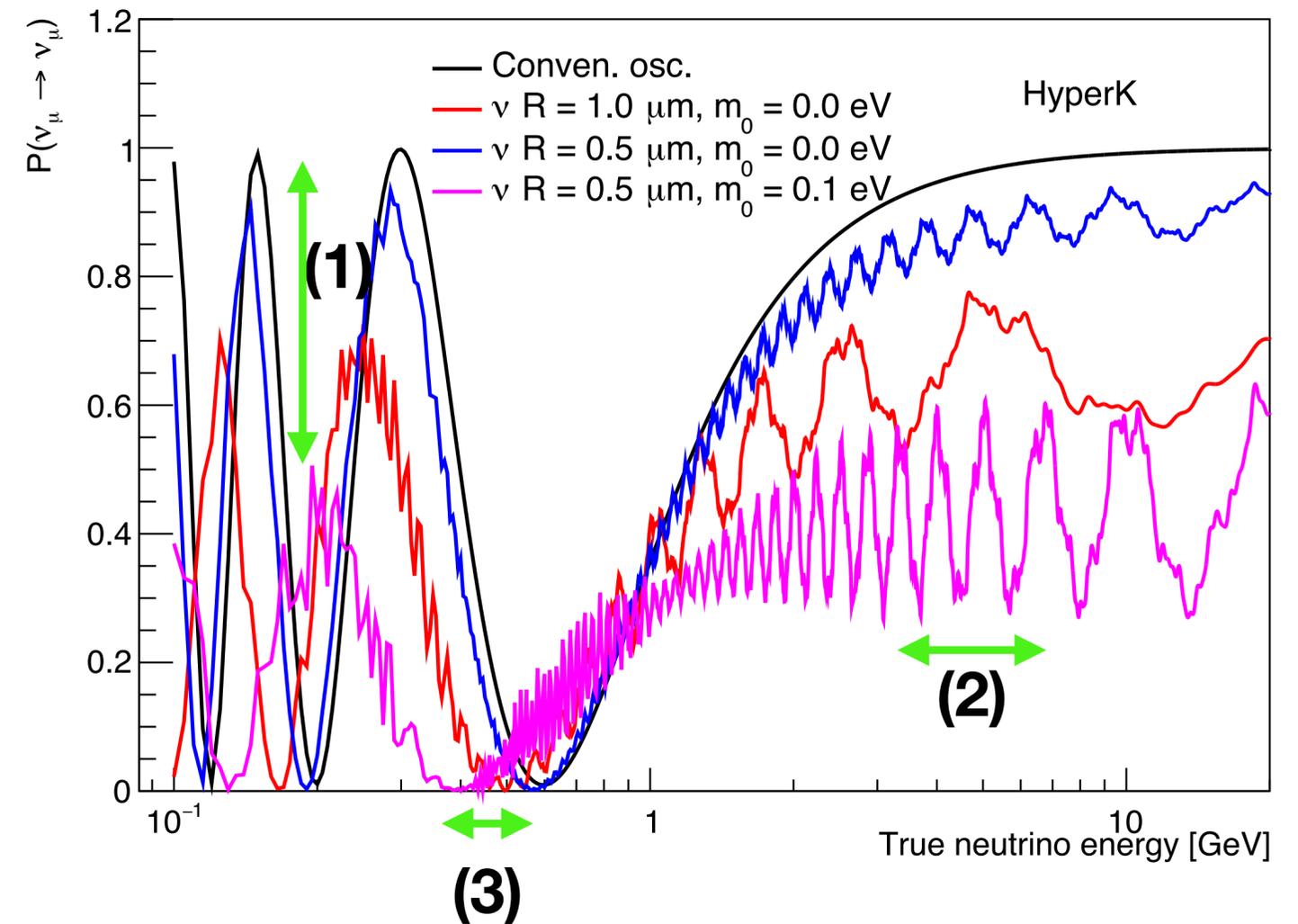
In 3ν oscillation scenario: $\omega = \frac{\Delta m_{ij}^2 L}{2E}$,

In LED oscillation scenario: $\omega_n = \frac{\Delta n^2 L}{2ER^2}$

If R is large enough, light KK modes can produce fast extra oscillation which can be observed

- **(3) Displacement of oscillation peaks:** In 3ν

oscillation, $\sin^2 \frac{\Delta m_{ij}^2 L}{2E}$ gets minima at specific L/E. Interference with KK modes shifts these minima



We can probe LED effects at neutrino oscillation experiments

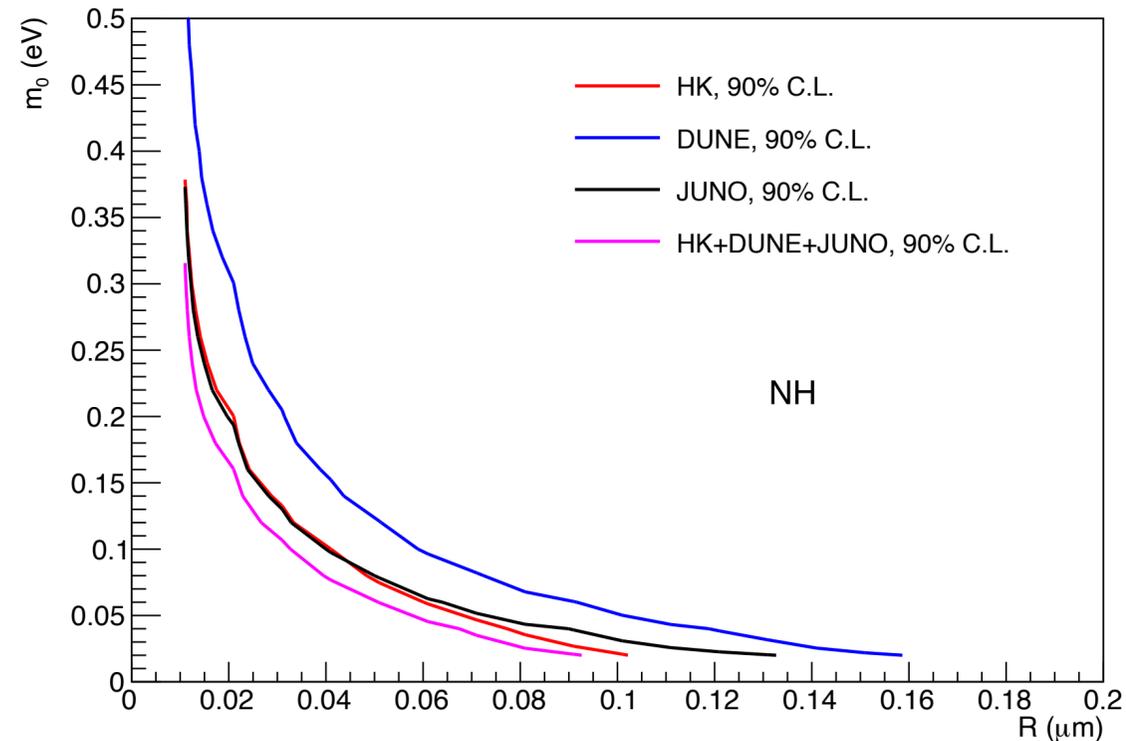
2. Current constraint on LED from neutrino oscillation experiments

Exp.	NH	IH
DayaBay + MINOS/MINOS+ + KATRIN (arXiv:2207.02790v1)	$R < 0.2 \mu m$	$R < 0.1 \mu m$
JUNO + TAO @3% shape uncertainty (arXiv:2112.00379v2)	$R < 0.81 \mu m$	$R < 0.142 \mu m$
MINOS (arXiv:1608.06964v3)	$R < 0.45 \mu m$	
KATRIN (arXiv:1205.6212v2)		$R < 0.2 \mu m$

3. Hyper-K, DUNE, and JUNO experimental setups

	JUNO	Hyper-K	DUNE
Baseline (km)	52.5	295	1285
Matter density <i>g/cm³</i>	2.6	2.6	2.85
Detector mass (kt)	20	187	40
Exposure	6 years	10 years (1:3)	10 years (1:1)
Power	26.6 GWth	1.3 MW	1.2 MW

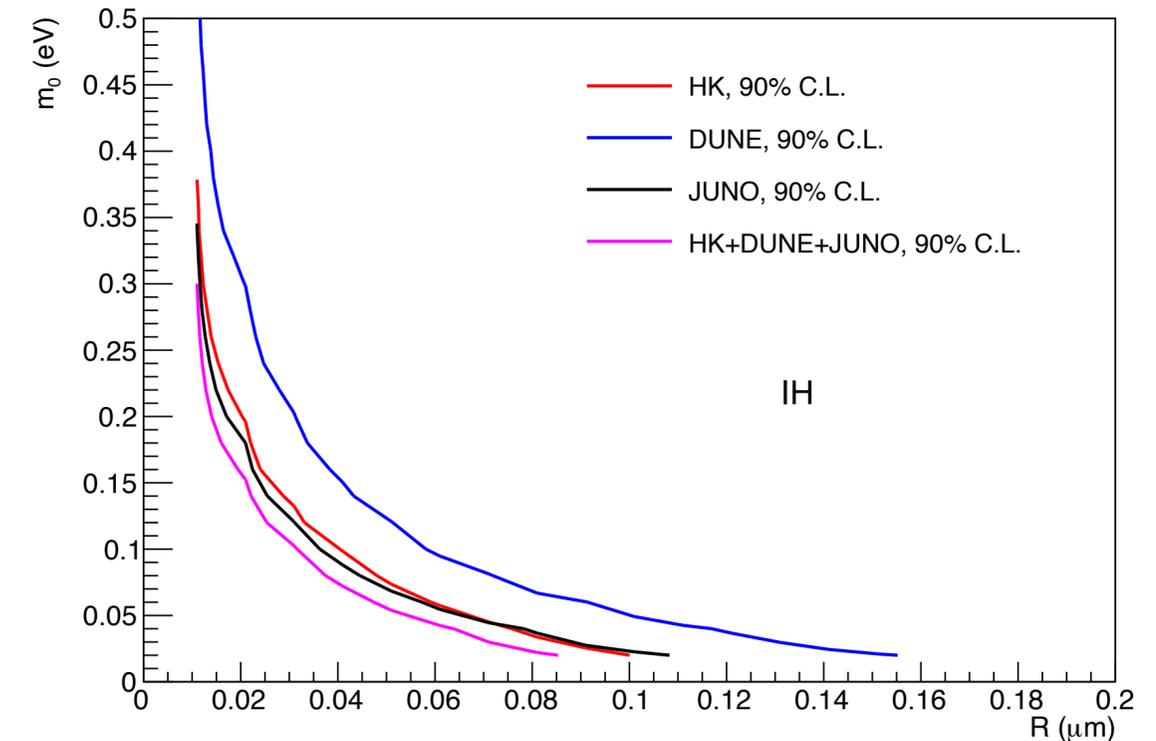
4. Constraining LED with Hyper-K, DUNE, and JUNO



NH vs IH

$$m_0 = 0$$

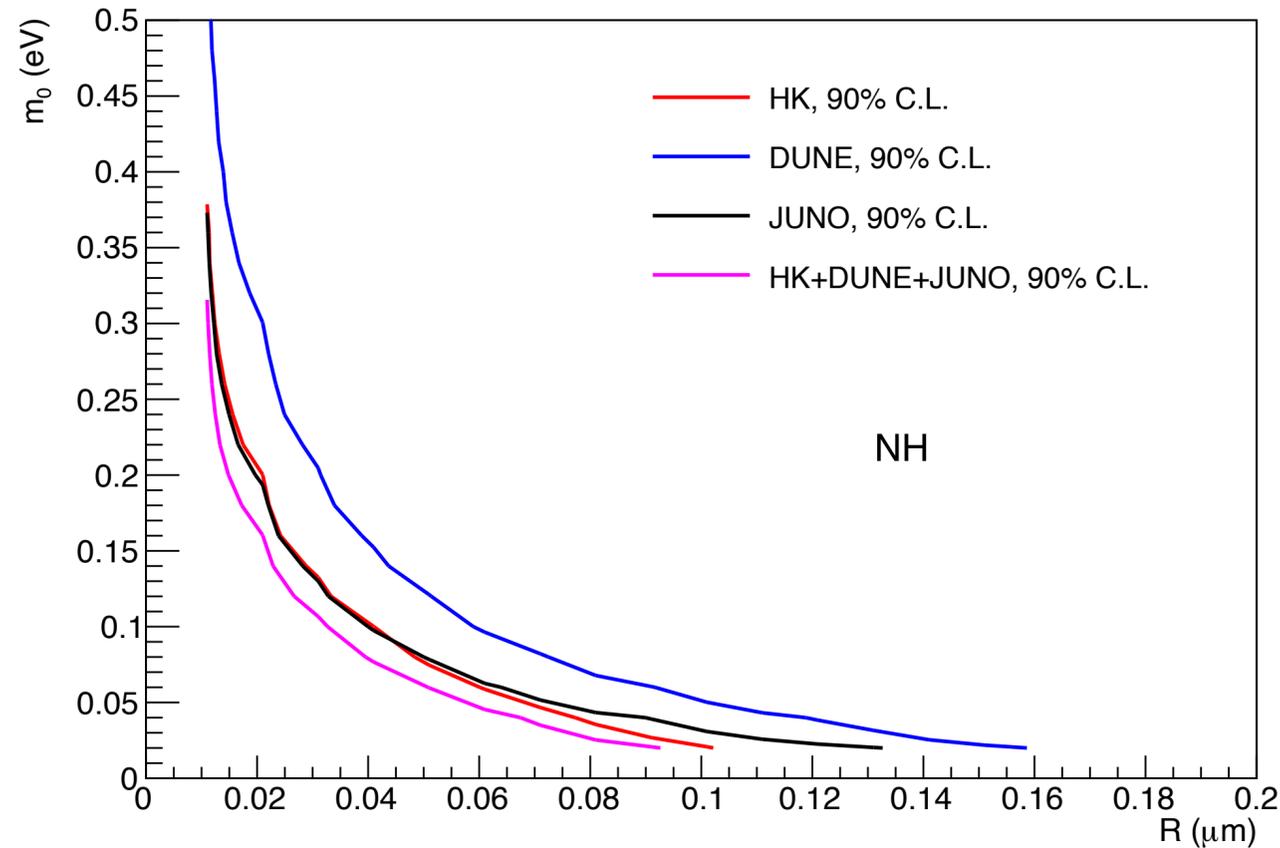
$$R \rightarrow 0$$



Exp.	HK	DUNE	JUNO	Combined
NH	$R < \sim 0.1 \text{ um}$	$R < \sim 0.16 \text{ um}$	$R < 0.13 \text{ um}$	$R < 0.95 \text{ um}$
IH	$R < \sim 0.1 \text{ um}$	$R < \sim 0.16 \text{ um}$	$R < 0.11 \text{ um}$	$R < 0.85 \text{ um}$

- No significant difference between NH and IH for accelerator experiments
- IH gives a bit better constraint than NH for reactor experiment

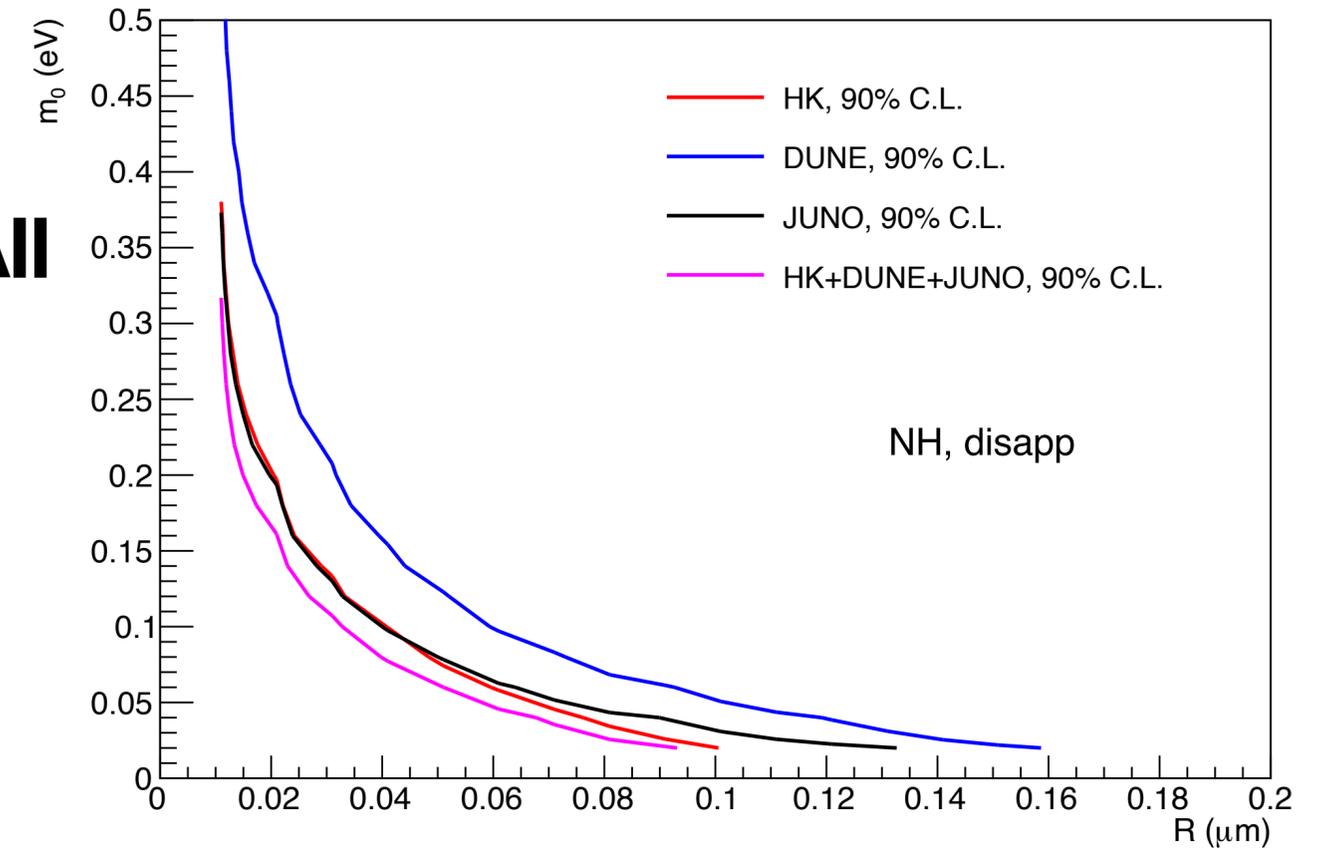
4. Constraining LED with Hyper-K, DUNE, and JUNO



Disapp vs All

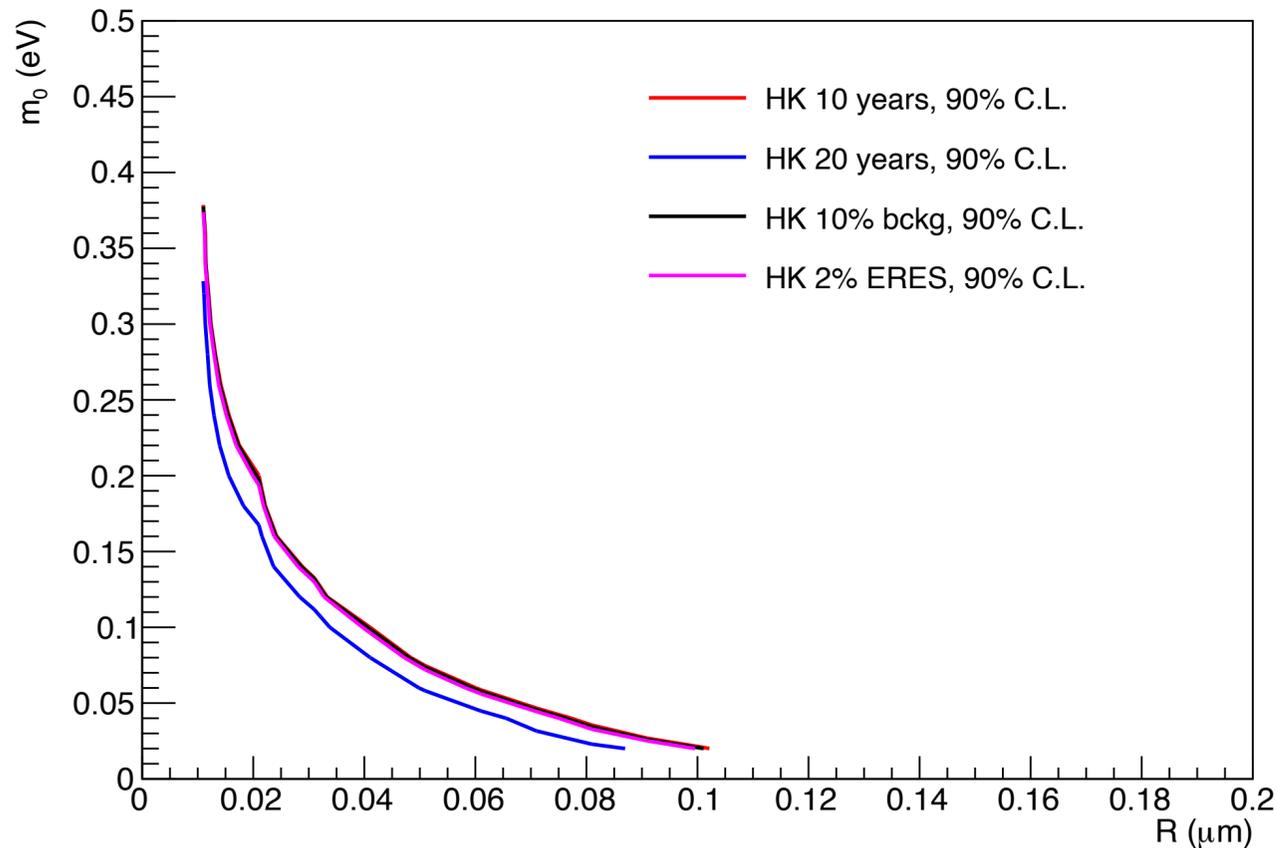
$$m_0 = 0$$

$$R \rightarrow 0$$

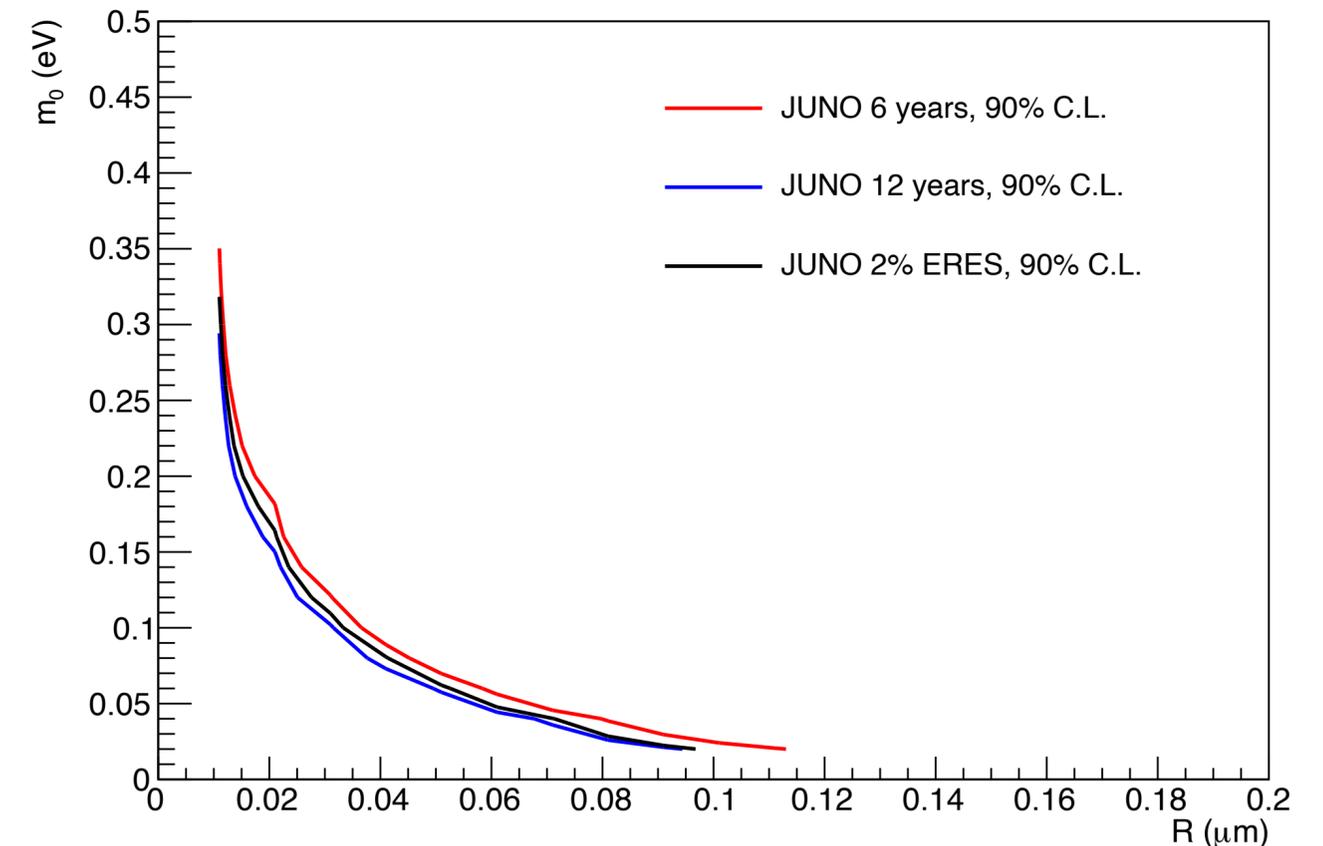


- Disappearance data leads the constraint on LED
- Appearance plays only a minor supporting role
- This reflects that LED effects alter the survival probability more directly (first-order effect), while appearance requires flavor transitions across towers, which are second-order suppressed

4. Constraining LED with Hyper-K, DUNE, and JUNO



Impact of Improved Statistics and Detector Performance



- Doubling exposure yields only marginal improvement, indicating sensitivity saturation under current analysis framework.
- Energy resolution and background reduction do not significantly enhance constraints for Hyper-K, however slightly improve for JUNO, suggesting the limiting factor lies in the oscillation structure itself.

5. Conclusions

- Hyper-K and DUNE show similar sensitivity to LED between NH and IH:
 $R < \sim 0.1 \mu m$, indicating little hierarchy dependence in the accelerator-based experiments.
- JUNO gives slightly better constraint on LED for IH than NH, and provides the comparable constraint on LED as Hyper-K and DUNE, likely due to its superior energy resolution, huge statistics, and sensitivity to fast oscillation patterns induced by LED.
- The combined limit does not significantly improve over single experiments, possibly due to differing systematics or inconsistent sensitivities between channels.
- Increasing statistics or decreasing energy resolution and backgrounds do not significantly affect the constraint

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Thank you very much for your attention

LED models

1. ADD (1998): Arkani-Hamed - Dimopoulos - Dvali

- Propose large but compact extra dimensions (LEDs)
- Gravity propagates in all extra dimensions, while SM particles are confined to a 4D brane
- Explain the hierarchy problem by lowering the fundamental Planck scale to electroweak scale by the volume of the extra dimensions

2. RS (1999): Randall - Sundrum

- Propose warped extra dimensions rather than large and flat
- RS1: two 4D branes (Planck brane & TeV brane) with a warped extra dimension
- RS2: a simple brane with an infinite extra dimension but exponentially decaying metric
- Solve hierarchy problem by warping

NH vs IH

- NH: $m_0 \equiv m_1 < m_2 \ll m_3$, IH: $m_0 \equiv m_3 \ll m_1 < m_2$
- $U_{\mu 1} = -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta}$, $U_{\mu 2} = c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta}$, $U_{\mu 3} = s_{23}c_{13}$
- $U_{e1} = c_{12}c_{13}$, $U_{e2} = s_{12}c_{13}$, $U_{e3} = s_{13}e^{-i\delta}$
- For $\nu_\mu \rightarrow \nu_\mu$: $A_{\mu\mu}^{(LED)} \propto \sum_i \xi_i^2 |U_{\mu i}|^2$ ($\xi_i = \sqrt{2}m_i R$) is of the same order for **NH** (mainly driven by $\xi_3 \sim m_3$, $m_0 \equiv m_1 < m_2 \ll m_3$) and **IH** (mainly driven by $\xi_2 \sim m_2$, $m_0 \equiv m_3 \ll m_1 < m_2$)
- For $\bar{\nu}_e \rightarrow \bar{\nu}_e$: $A_{\mu\mu}^{(LED)} \propto \sum_i \xi_i^2 |U_{ei}|^2 = \sum_{i=1,2} \xi_i^2 |U_{ei}|^2 + \xi_3^2 \sin^2 \theta_{13}$

NH: Contribution from $\xi_3^2 \sin^2 \theta_{13}$ ($U_{e3} = s_{13}e^{-i\delta}$) is small

IH: Contribution mainly from ξ_1^2, ξ_2^2 ($U_{e1} = c_{12}c_{13}$, $U_{e2} = s_{12}c_{13}$) are large

App vs. Disapp

o In LED models:

- Right-handed neutrino lives in a higher-dimensional spacetime (bulk)
- After compactification, it appears in 4D as a tower of KK sterile neutrinos (KK modes) with mass: $m_n \approx n/R$
- The standard active neutrino couples to each KK mode with a small mixing $\theta_n \propto m_D/m_n$

o In disappearance channels:

- Neutrinos oscillate into sterile KK states => decreases as leading order:

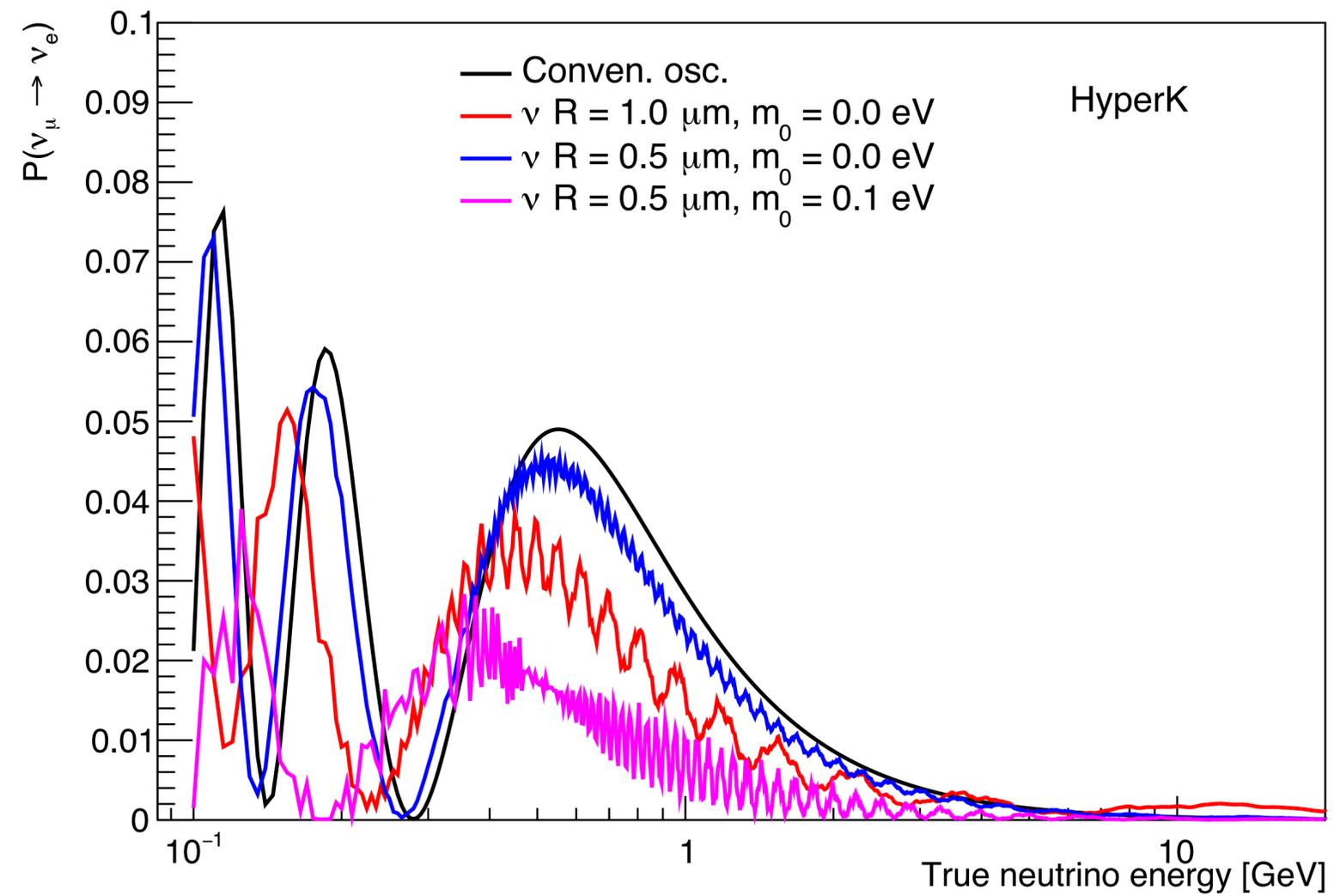
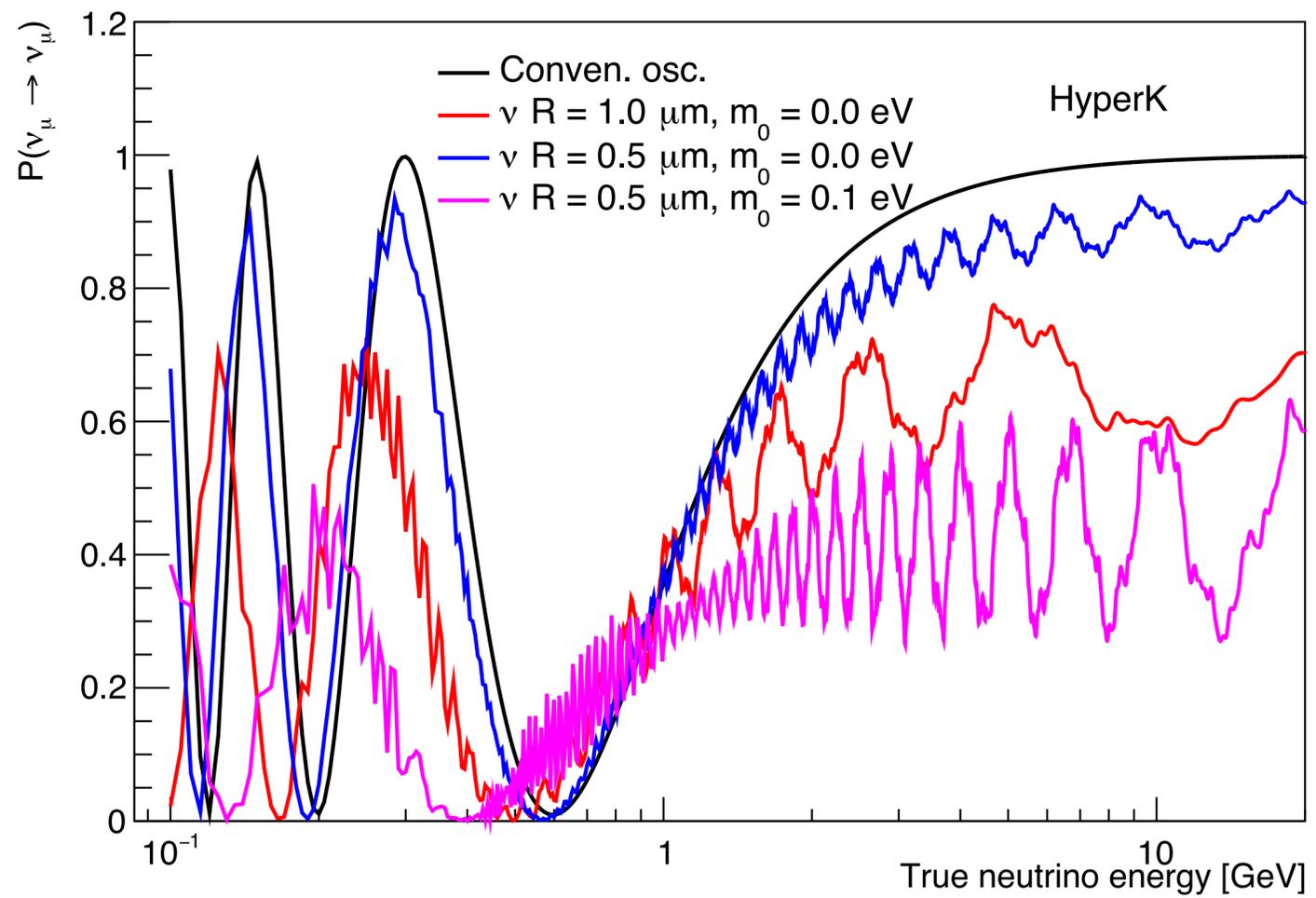
$$\nu_\mu \xrightarrow{\theta_n} \nu_n \quad \Rightarrow \quad A \sim \theta_n^\mu \propto m_D^\mu/m_n \approx m_D^\mu R/n$$

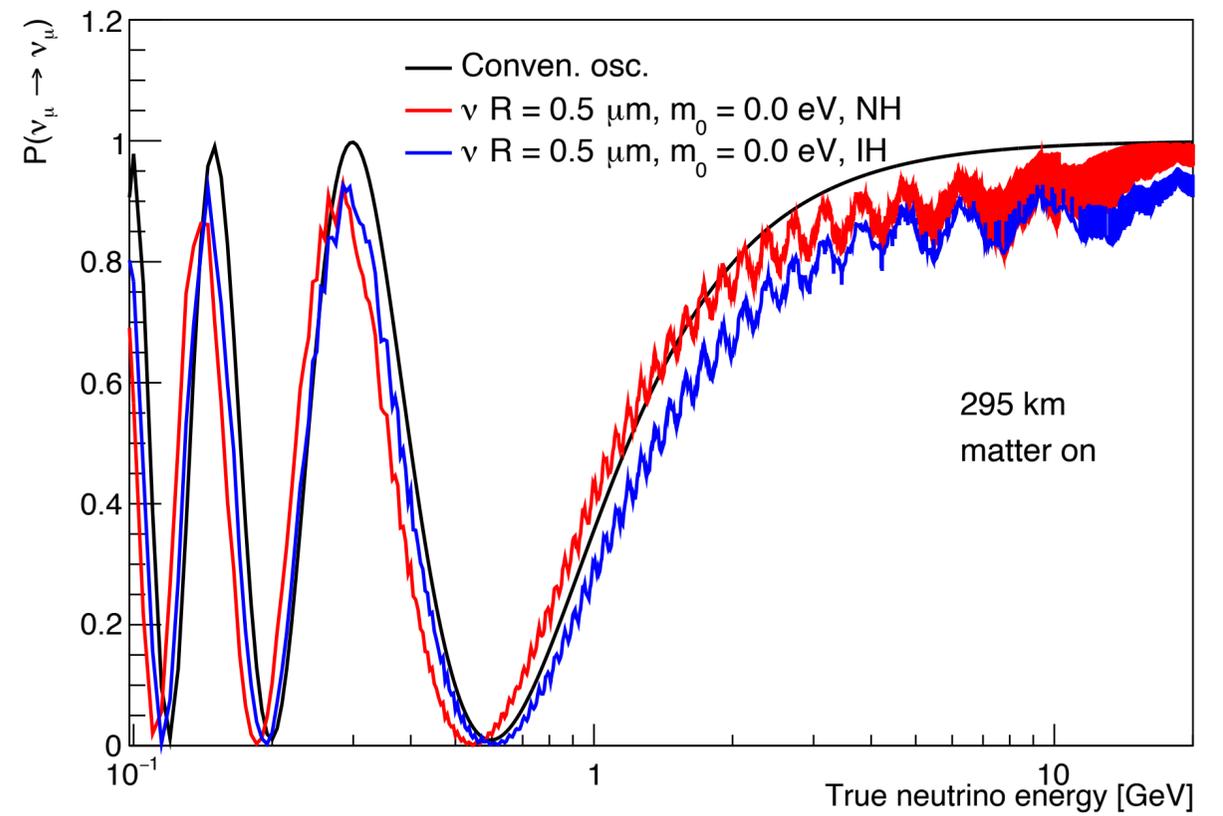
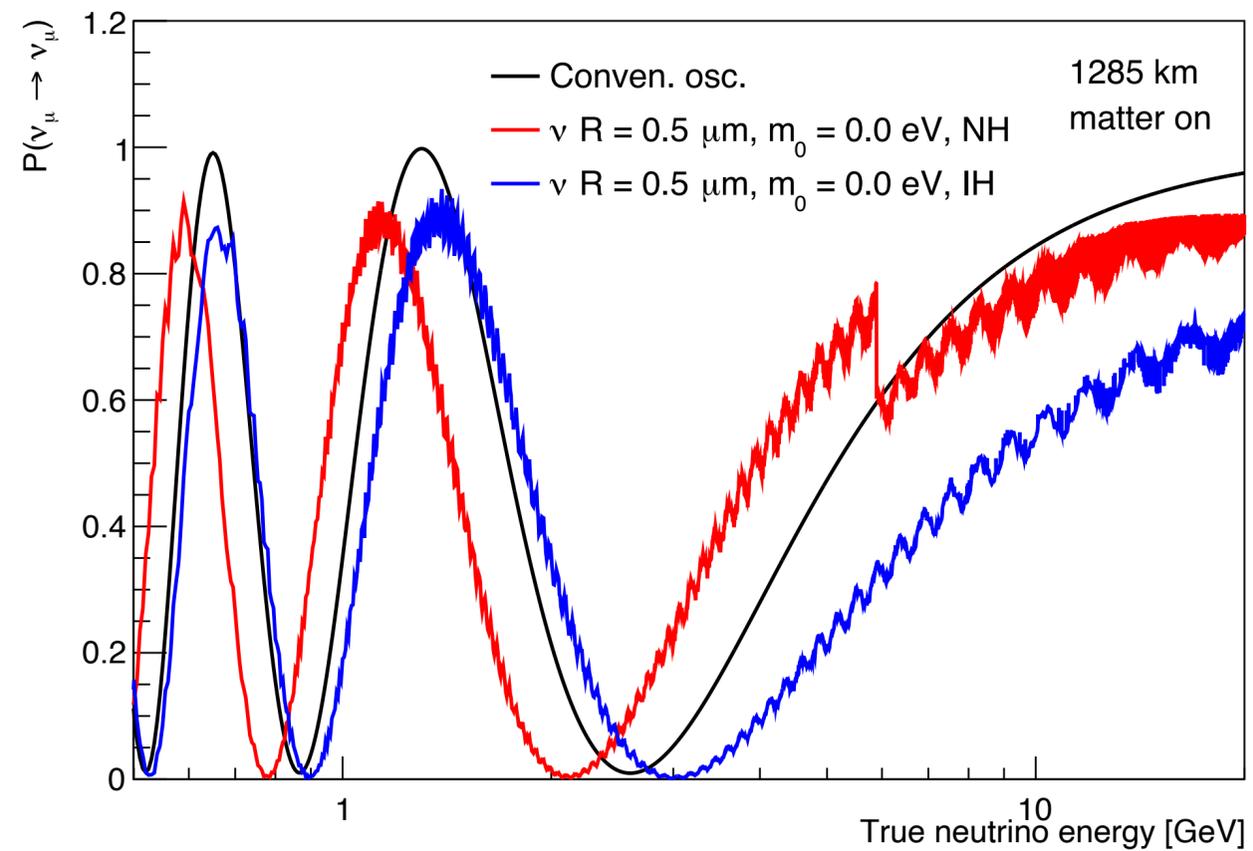
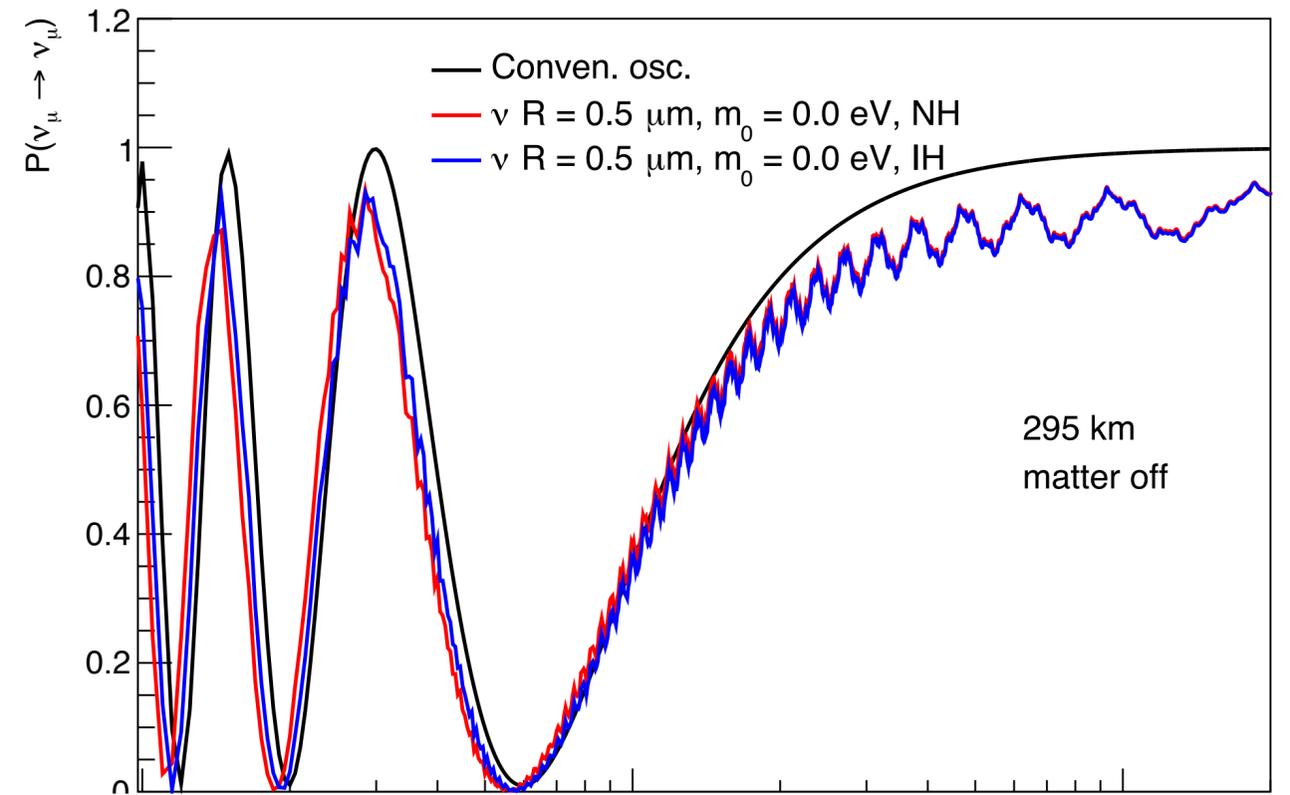
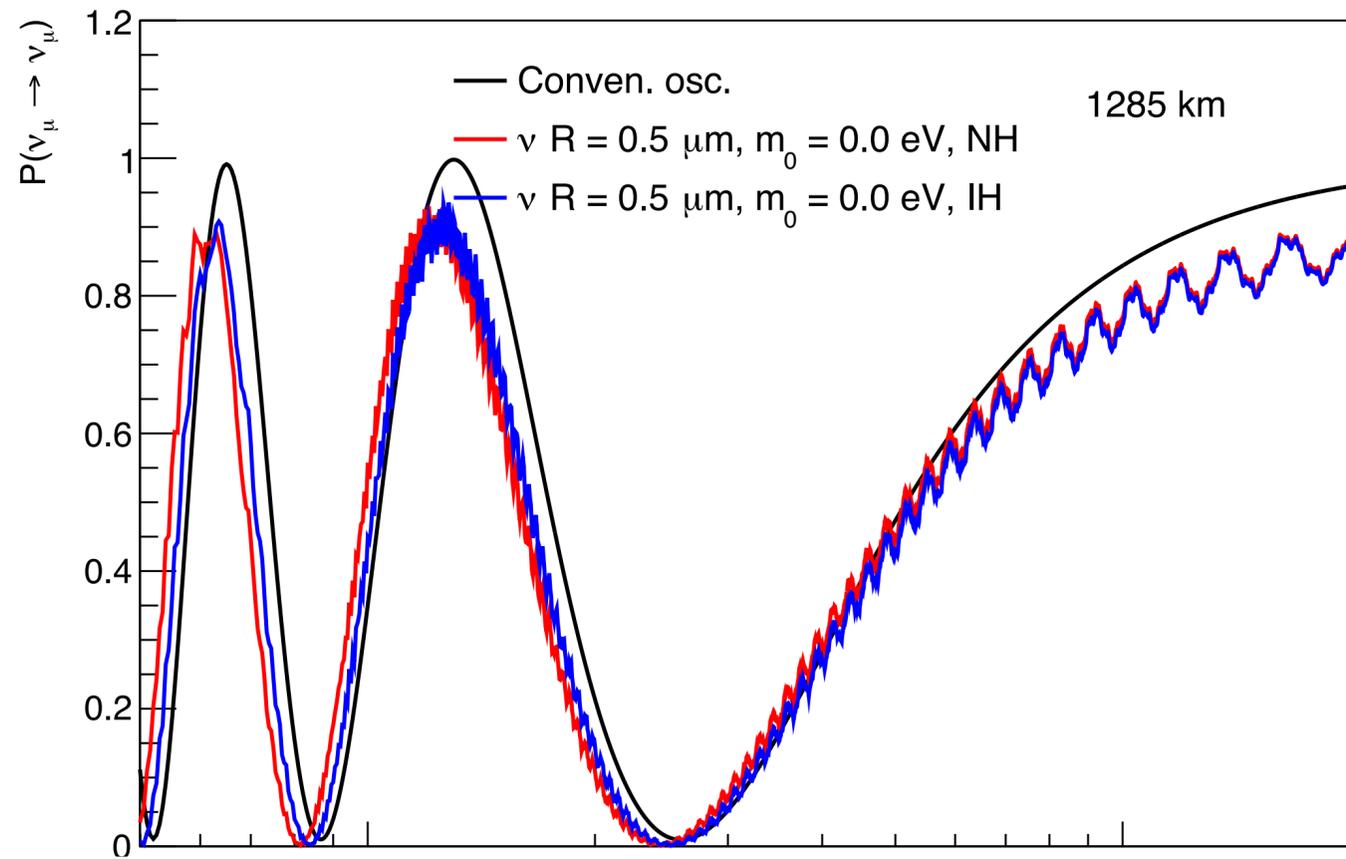
- High statistics $P \sim 1$

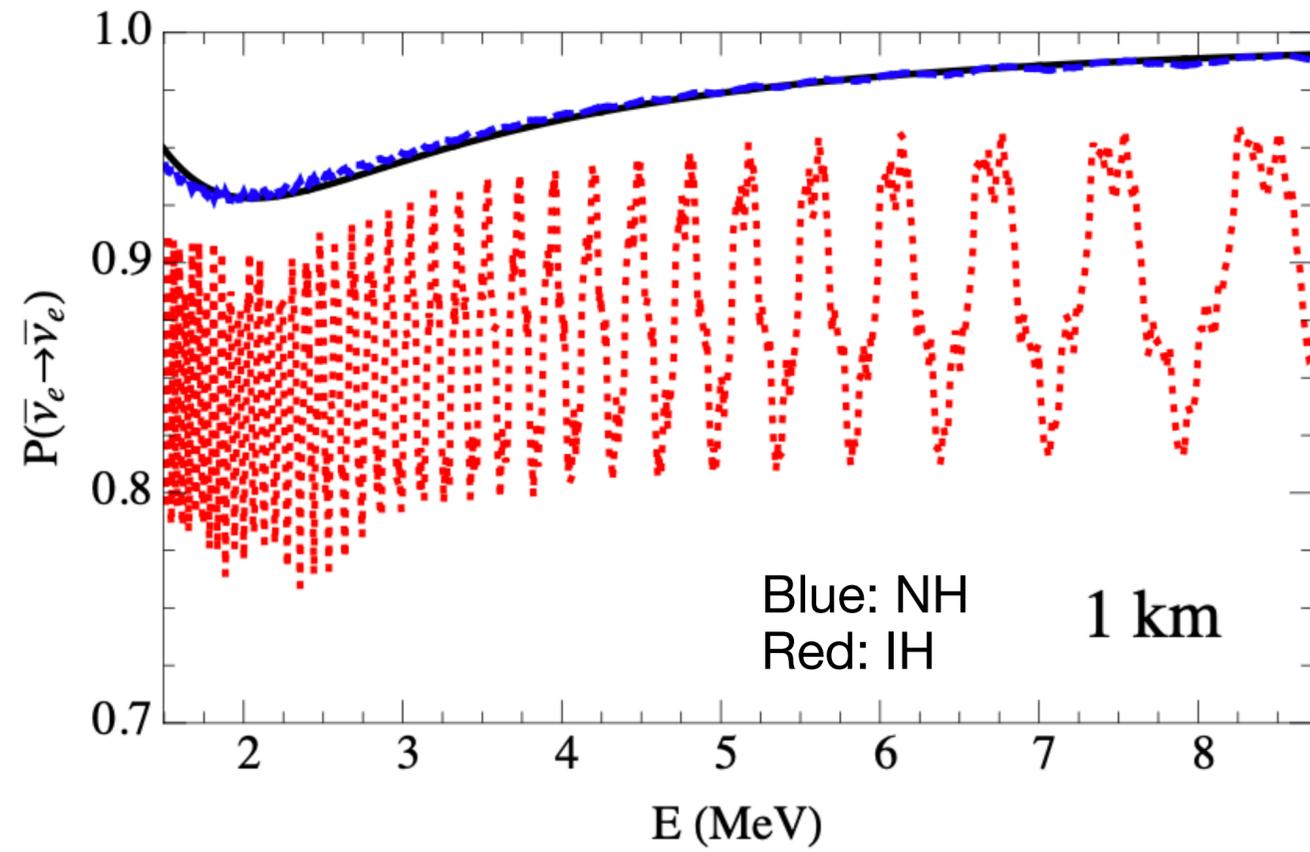
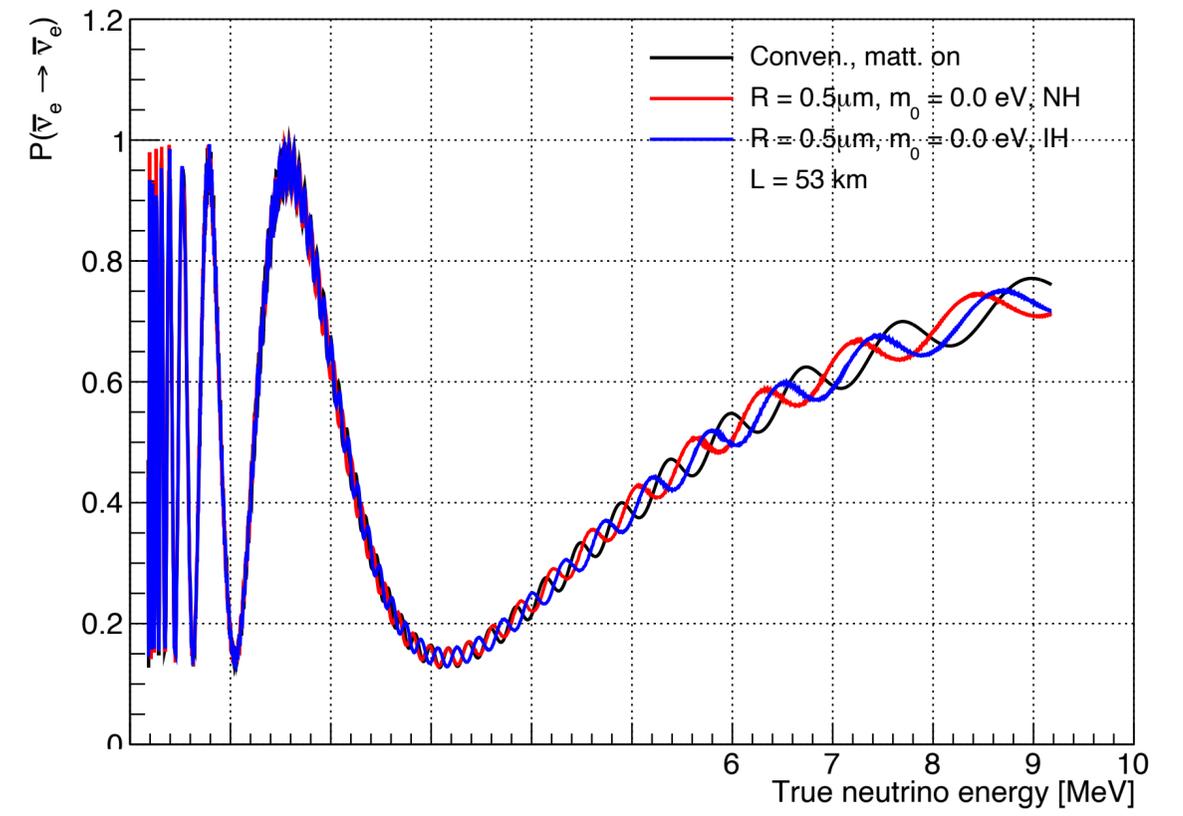
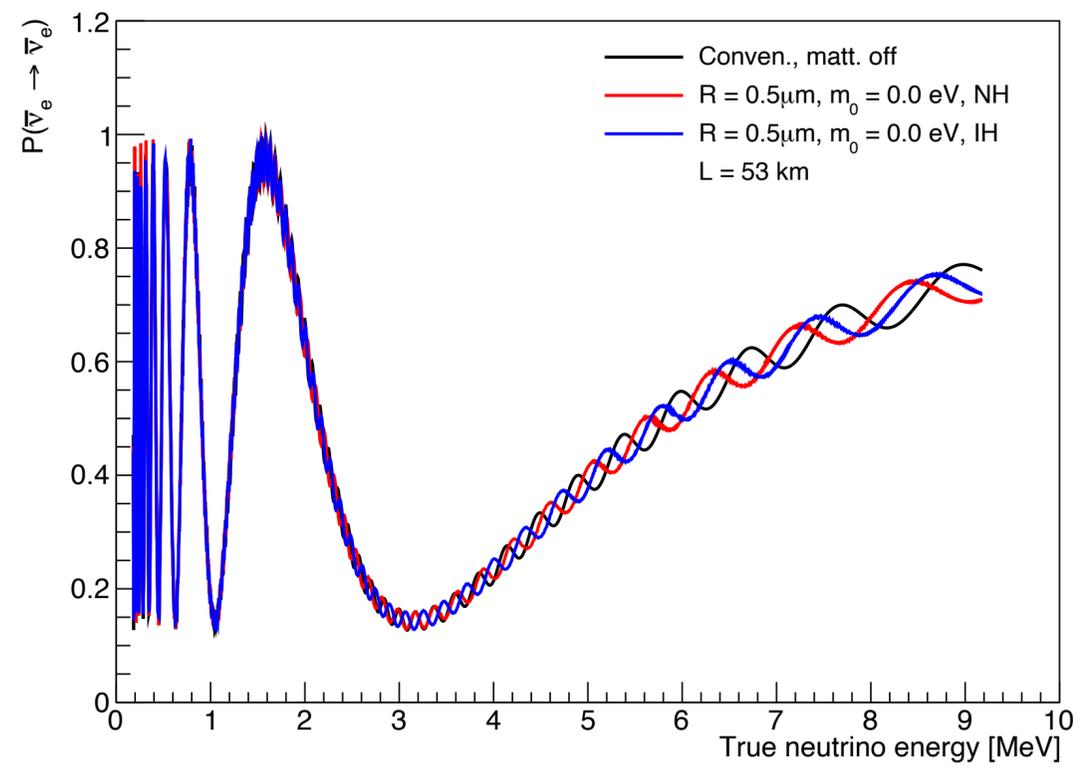
o In appearance channels:

- Low statistics $P \sim 0.1$

- Decreases as second order: $\nu_\mu \xrightarrow{\theta_n} \nu_n \xrightarrow{\theta'_n} \nu_e \quad \Rightarrow \quad A \sim \theta_n^\mu \cdot \theta_n^e \approx m_D^\mu m_D^e (R/n)^2$







- DUNE 13 years 1:1
- LE: low energy beam (2-3 GeV)
- ME: medium energy beam (> 4 GeV)

Neutrino Mass Hierarchy	Marginalization Assumption	Channel	Beam used	Bounds on R_{ED} [μm] (90% C.L.)
NH	All six std. osc. parameters free	$\nu_\mu \rightarrow \nu_e$	LE	0.69
			LE \oplus ME	0.72
		$(\nu_\mu \rightarrow \nu_e) \oplus (\nu_\mu \rightarrow \nu_\tau)$	LE	0.68
			LE \oplus ME	0.68
		$(\nu_\mu \rightarrow \nu_e) \oplus (\nu_\mu \rightarrow \nu_\tau) \oplus (\nu_\mu \rightarrow \nu_\mu)$	LE	0.47
			LE \oplus ME	0.41
	θ_{23}, δ_{13} free	$(\nu_\mu \rightarrow \nu_e) \oplus (\nu_\mu \rightarrow \nu_\tau) \oplus (\nu_\mu \rightarrow \nu_\mu)$	LE	0.23
			LE \oplus ME	0.24
IH	All six std. osc. parameters free	$\nu_\mu \rightarrow \nu_e$	LE	0.53
			LE \oplus ME	0.53
		$(\nu_\mu \rightarrow \nu_e) \oplus (\nu_\mu \rightarrow \nu_\tau)$	LE	0.48
			LE \oplus ME	0.46
		$(\nu_\mu \rightarrow \nu_e) \oplus (\nu_\mu \rightarrow \nu_\tau) \oplus (\nu_\mu \rightarrow \nu_\mu)$	LE	0.36
			LE \oplus ME	0.34
	θ_{23}, δ_{13} free	$(\nu_\mu \rightarrow \nu_e) \oplus (\nu_\mu \rightarrow \nu_\tau) \oplus (\nu_\mu \rightarrow \nu_\mu)$	LE	0.25
			LE \oplus ME	0.26

Table 2: The table shows the bounds on R_{ED} [μm] (as read off from Fig. 8) beyond which LED is excluded at 90% C.L. for $m_0 \simeq 0.001$ eV.