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Theoretische Physik III
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Sterile Neutrinos with Altered Dispersion Relations as an Explanation for the MiniBooNE, LSND, Gallium and Reactor Anomalies

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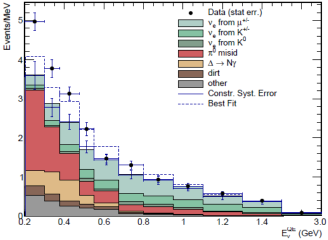
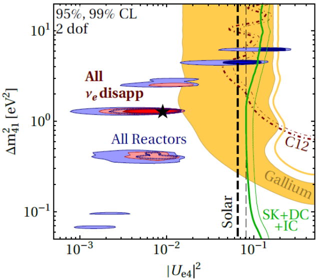
based on arXiv:1808.07460 (**D.D.**, P. Sicking, H. Päs, T.J. Weiler)

Talk @ WIN, Bari, 2019

- Anomalies in the Neutrino sector
  - MiniBooNE collaboration report 4.8σ excess, 6.1σ combined with LSND *[A. A. Aguilar-Arevalo et al., Phys. Rev. Lett. 121, 221801 (2018)]*
  - Disappearance in Reactor and Gallium experiments *[M. Dentler et al., JHEP 1808 (2018) 010]]*





- Hints towards a new $\Delta m^2 \approx 1\,\text{eV}^2$?

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- Atmospheric/accelerator experiments:

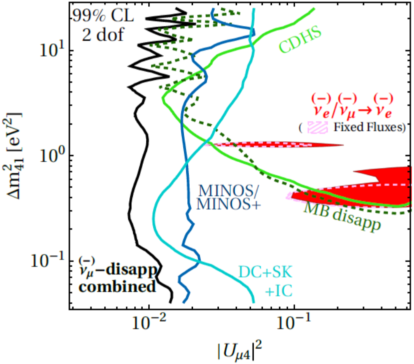

Figure: [M. Dentler et al., JHEP 1808 (2018) 010]

3+1 ν model

- CP invariant probability:

$$P_{\nu_\alpha \to \nu_\beta} \approx \delta_{\alpha\beta} - 4\sin^2\left(\frac{\Delta m^2_{\mathrm{LSND}} L}{4E}\right) \sum_j^3 U_{\alpha 4} U_{\beta 4} U_{\alpha j} U_{\beta j} \tag{1}$$

- Amplitudes: $\begin{cases} \sin^2 2\theta_{\alpha\alpha} = 4\,|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right) & \text{, disappearance} \\ \sin^2 2\theta_{\alpha\beta} = 4\,|U_{\alpha 4}|^2\,|U_{\beta 4}|^2 & \text{, appearance} \end{cases}$
- Relation between the amplitudes:

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

- Appearance Exp. require sizable $\sin^2 2\theta_{\mu e}$
- Disappearance Exp. constrain $\sin^2 2\theta_{\mu\mu}$ and $\sin^2 2\theta_{ee}$ to be small

What can we do about it?

- These equations hold for constant U
- Idea: $\Rightarrow$ Make U energy dependent!

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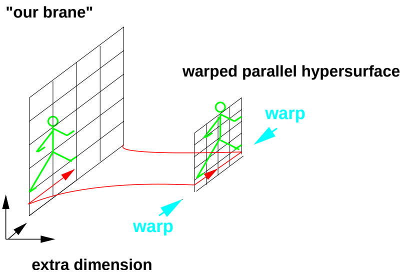
- Idea: $\Rightarrow$ Make U energy dependent!
  - Sterile states obtain Altered Dispersion Relation (ADR) $E^2 \neq |\vec{p}|^2 + m^2$ e.g. from warped extra dimensions *[H. Päs, S. Pakvasa, T.J. Weiler,Phys.Rev. D72 (2005) 095017];[* ***D.D.****, H. Päs, arXiv:1808.07734]*
  - geometrically induced $\Rightarrow \nu$ and $\overline{\nu}$ treated the same
  - $\Rightarrow$ Flavor-Hamiltonian picks up a potential term $V_{\text{eff}}(E)$



Is this a resonance?

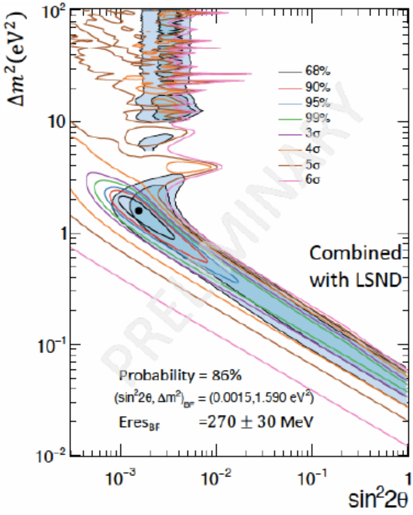


Figure: MSW-like probability. [En-Chuan Huang Neutrino2018]

3+1 ν + ADR

- Effective 2 flavor active-sterile oscillation
- $\lim_{E\to\infty} m_{\pm}^2 = \Delta m^2_{\mathrm{LSND}} \frac{1-\cos 2\theta}{2} = \mathrm{const}$
- $\Rightarrow$ Even above resonance there is still oscillation if L is large enough!
- Conflict with non-observation in atmospheric experiments! ✗

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- Conflict with non-observation in atmospheric experiments! ✗
- $\Rightarrow$ move to 3+3 ν models

Set-Up: 3+3 ν + ADR

$$H_{(\mathrm{F})} = \frac{1}{2E} U \begin{pmatrix} m_1^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & m_2^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & m_3^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & m_4^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & m_5^2 & 0 \\ 0 & 0 & 0 & 0 & 0 & m_6^2 \end{pmatrix} U^\dagger - \varepsilon E \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & & & \\ 0 & 0 & 0 & & V & \\ 0 & 0 & 0 & & & \end{pmatrix} \tag{3}$$

where

$$U = \underbrace{U_{12} U_{13} U_{23}}_{U_0} U_{14} U_{25} U_{36} \,,$$

$$\begin{aligned} & & \Delta m_{41}^2 &= \Delta m_{\mathrm{LSND}}^2 \,, \\ \Delta m_{51}^2 = \Delta m_{\mathrm{LSND}}^2 + \Delta m_{21}^2 &\rightarrow & \Delta m_{52}^2 &= \Delta m_{\mathrm{LSND}}^2 \,, \\ \Delta m_{61}^2 = \Delta m_{\mathrm{LSND}}^2 + \Delta m_{31}^2 &\rightarrow & \Delta m_{63}^2 &= \Delta m_{\mathrm{LSND}}^2 \,. \end{aligned} \tag{4}$$

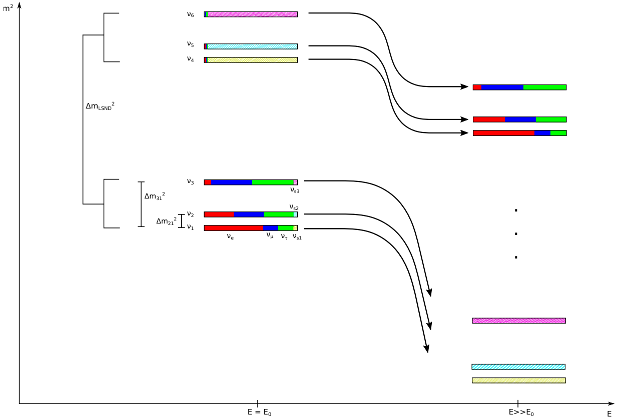

Figure: Schematic overview of mass eigenstates and their flavor content depending on the Energy E.

- Simplest choice: $V = \mathbb{1}$ not viable
  $\Rightarrow P_{\nu_\mu \to \nu_e} = 0$
- Choose three different potentials for each sterile state

$$V = \begin{pmatrix} 1 & & \\ & \kappa & \\ & & \xi \end{pmatrix} \tag{5}$$

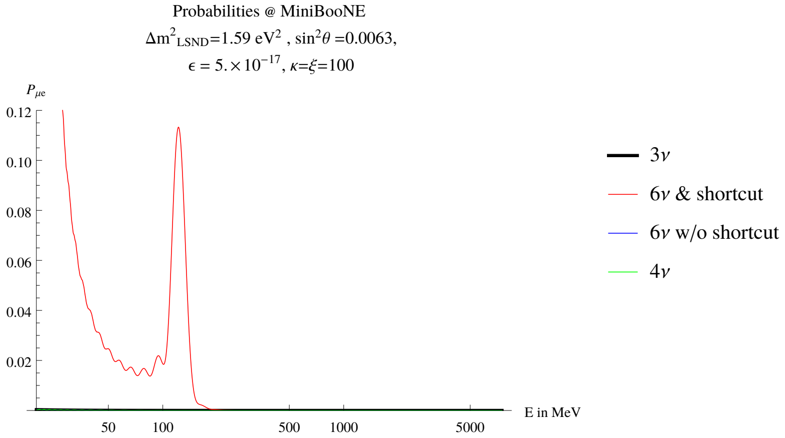

Figure: Probabilities P at MiniBooNE in the $\nu_\mu \to \nu_e$ channel.

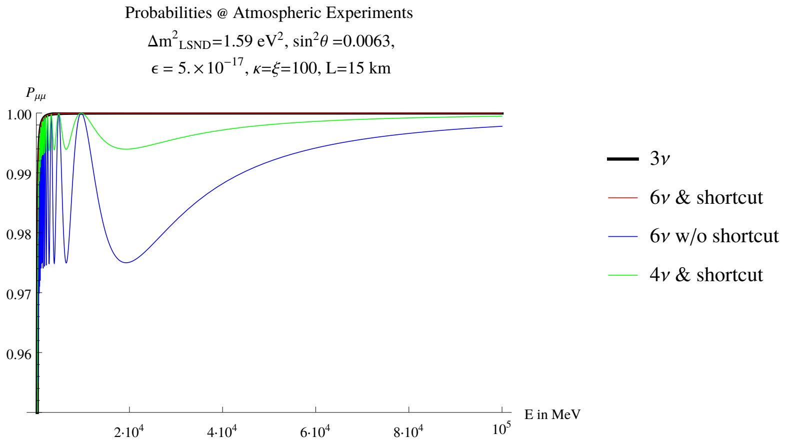

Figure: Probabilities *P* at atmospheric downward going ν experiments in the $\nu_\mu \to \nu_\mu$ channel.

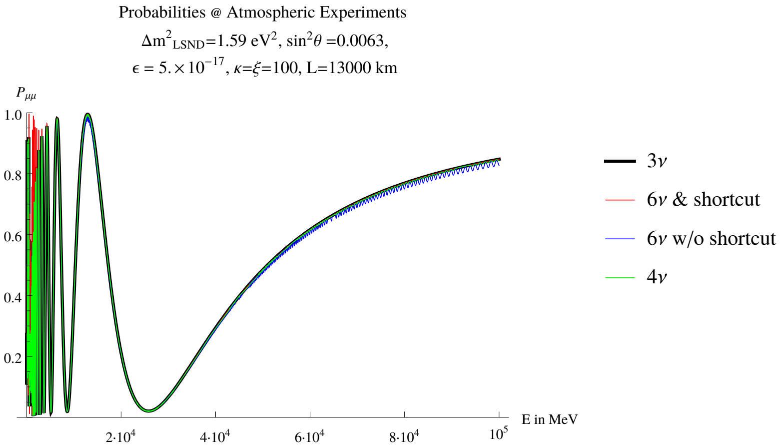

Figure: Probabilities P at atmospheric upward going ν experiments in the $\nu_\mu \to \nu_\mu$ channel.

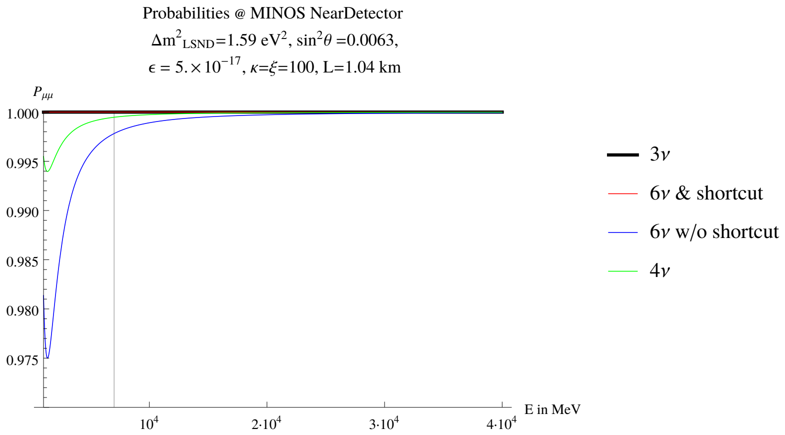

Figure: Probabilities P at MINOS NearDetector in the $\nu_\mu \to \nu_\mu$ channel.

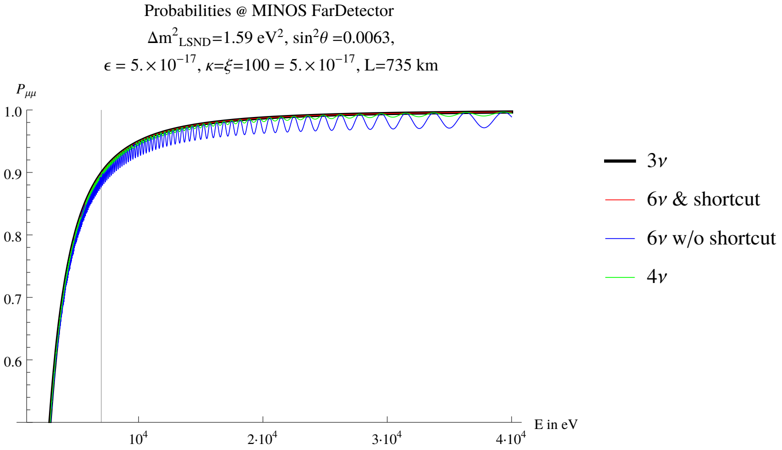

Figure: Probabilities P at MINOS FarDetector in the $\nu_\mu \to \nu_\mu$ channel.

Below the Resonance

- Evidence for $\overset{(-)}{\nu}_e$ disappearance at Reactor and Gallium experiments

- Look at ν_e disappearance channel in MeV range in our model:

$$P_{\nu_e \to \nu_e} = 1 - \sin^2 \left(\Delta m^2_{\mathrm{LSND}} \frac{L}{2E} \right) \sin^2 2\theta \qquad (6)$$

$\Rightarrow$ standard 3+1 ν probability!

Open Challenges

- Sub-GeV realm at atmospheric experiments: deviation from 3ν paradigm

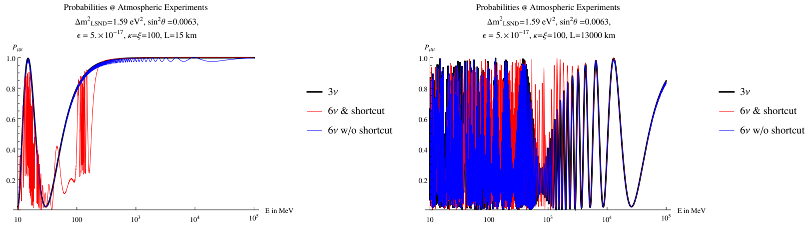

Figure: Probabilities at atmospheric experiments with highlights on the sub-GeV region.

- Low statistics for upward-going ν at SuperK at sub-GeV (e.g. [SuperK collaboration, Phys.Rev. D91 (2015) 05219])
- New analysis by the SuperK collaboration of the sub-GeV in the context of this model?

Conclusion

- Model with altered dispersion relation (origin e.g. extra dim.)
- 'Natural' 3+3 ν paradigm
- Set-Up with a common neutrino potential cannot explain atmospheric/accelerator and short-baseline results at the same time
- Set-Up with different potentials for each additional neutrino accommodates
  - LSND and MiniBooNE results
  - Atmospheric/Accelerator results
  - Gallium and Reactor results
- Sub-GeV region: We suggest an analysis of sub-GeV atmospheric data in the context of this model