Baseline dependence of active-sterile neutrino mixing in the presence of extra-dimensional shortcuts

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Dark Matter at the Crossroads

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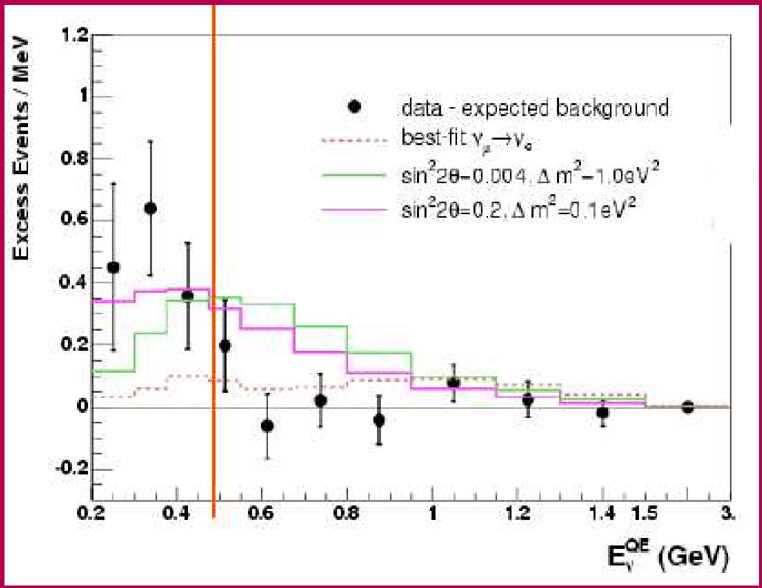
Motivation

- LSND observed a 3.8σ excess of $\bar{\nu}_e$ events in a pure $\bar{\nu}_\mu$ beam.
- MiniBooNE sees excess only in the low energy regime:



- can be explained by active-sterile neutrino oscillations.

Bulk Shortcuts

Mechanisms for bulk shortcuts:

- Self-gravity effects in the presence of matter localized on the brane imply extrinsic brane curvature.
- Thermal or quantum fluctuations lead to brane bending.
- The extra dimension can be warped asymmetrically, i.e. warp factors can shrink the space dimensions x parallel to the brane but leave the time and bulk dimension t and u unaffected

$$ds^2 = dt^2 - \sum_{i=1}^{3} a^2(t) e^{-2k|u|} \left(dx^i\right)^2 - du^2,$$

Active-Sterile Oscillation Probability

Schrödinger equation in flavor space

$$i\frac{d}{dt}\begin{pmatrix}\nu_a(t)\\ \nu_s(t)\end{pmatrix} = H_F \begin{pmatrix}\nu_a(t)\\ \nu_s(t)\end{pmatrix}$$

With the Hamiltonian (flavor basis)

$$H_F = E + \frac{\Sigma m^2}{4E} + \frac{\delta m^2}{4E}\begin{pmatrix}-\cos 2\theta & \sin 2\theta\\ \sin 2\theta & \cos 2\theta\end{pmatrix},$$

and

$$|\,\nu_\alpha\,\rangle = \sum_{i=1}^{2} U^*_{\alpha i}|\,\nu_i\,\rangle, \quad U = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}.$$

With sterile ν's travelling in the bulk $\longrightarrow$ effective Hamiltonian:

$$H'_F = \frac{\delta m^2}{4E}\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} - E\frac{\epsilon}{2}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}.$$

with the *shortcut parameter*: $\epsilon \simeq (t_{brane} - t_{bulk})/t_{brane} \simeq \delta t/t \simeq \delta z/z$

Resonant energy condition

$$E_{res} = \sqrt{\frac{\delta m^2 \cos 2\theta}{2\epsilon}},$$

Flavor oscillation probability

$$P_{as} = \sin^2(2\tilde{\theta})\sin^2(\delta H D/2)$$

$$\sin^2(2\tilde{\theta})\frac{\sin^2(2\theta)}{\sin^2(2\theta) + \cos^2(2\theta)\left[1 - (E/E_{res})^2\right]^2}$$

$$\delta H = \frac{\delta m^2}{2E}\sqrt{\sin^2(2\theta) + \cos^2(2\theta)\left[1 - (E/E_{res})^2\right]^2}$$

Resonance plot

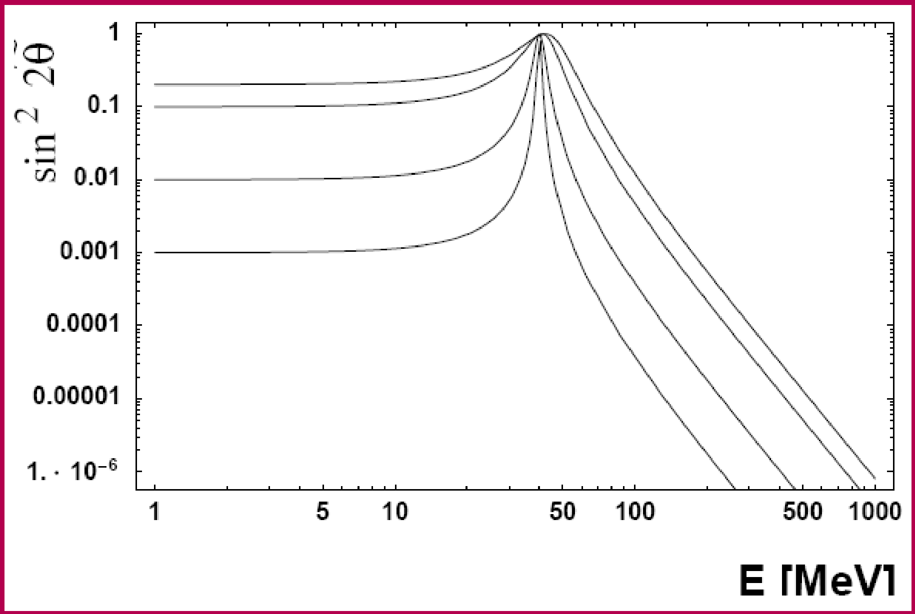
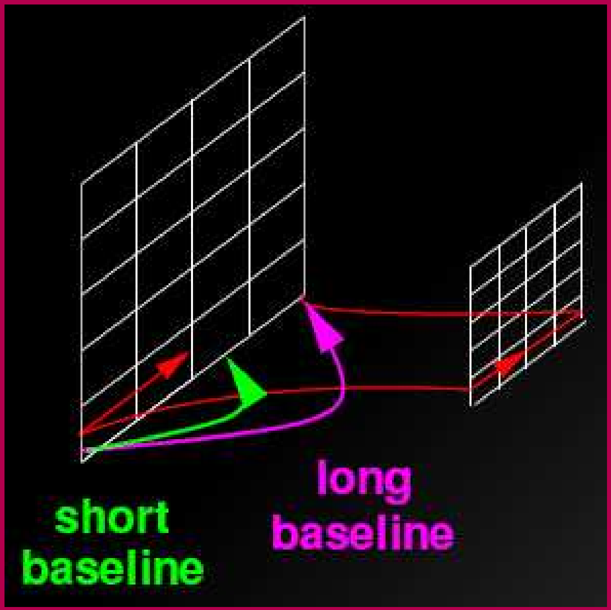


Figure 1: Oscillation amplitude $\sin^2 2\tilde{\theta}$ as a function of the neutrino energy E_ν , for a resonance energy of $E_{res} = 40MeV$. The different curves correspond to different values for the standard angle, $\sin^2 2\theta = 0.2, 0.1, 0.01, 0.001$ (from above).

Neutrino shortcuts



$$ds^2 = dt^2 - \sum_{i=1}^{3} a^2(t) e^{-2k|u|} \left(dx^i\right)^2 - du^2,$$

Geodesic equations:

$$\frac{d^2 x^\mu}{d\lambda^2} + \Gamma^\mu_{\alpha\beta} \frac{dx^\alpha}{d\lambda} \frac{dx^\beta}{d\lambda} = 0,$$

or by component

$$\begin{aligned}
\frac{d^2 t}{d\lambda^2} &= 0 \\
\frac{d^2 x}{d\lambda^2} - 2k \frac{dx}{d\lambda} \frac{du}{d\lambda} &= 0 \\
\frac{d^2 u}{d\lambda^2} + k e^{-2ku} \left(\frac{dx}{d\lambda} \right)^2 &= 0.
\end{aligned}$$

Boundary conditions:

$$\left.\frac{du}{dt}\right|_{t=0} \mapsto \text{Lorentz invariance violation in the bulk}$$

$$u(x=0)=0 \qquad , \qquad u(x=L)=0.$$

Geodesic:

$$u(x)=\frac{1}{2k}\ln\left[1+k^2x\,(L-x)\right].$$

Travel time in the bulk:

$$t^{bulk}(L):=\int_0^L \frac{dx}{1+k^2x\,(L-x)}=\frac{2}{k\sqrt{1+\left(\frac{kL}{2}\right)^2}}\,\text{arcsinh}\,\frac{kL}{2}.$$

Neutrino geodesic

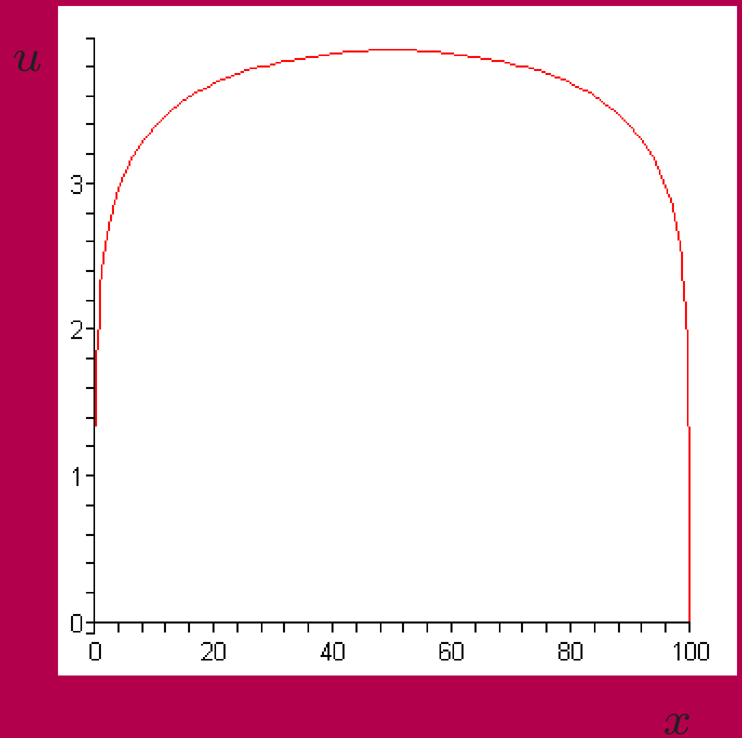
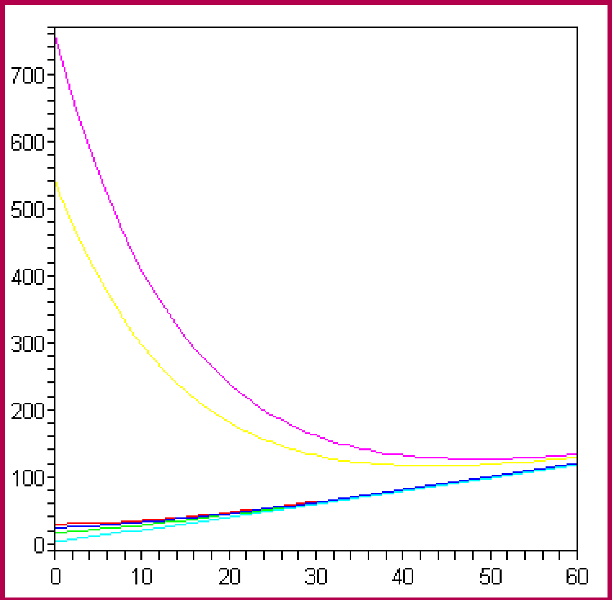


Figure 2: Sterile neutrinos travel path in the extra dimension for a travel distance L=100m as measured on the brane, and a warp factor k=1.

t



u

Figure 3: Travel time (in natural units where c=1) as a function of the penetration distance u into the extra dimension. Shown are the cases for the baseline distances $L = 17.7m, 25m, 30m, 540m, 750m$ (from top to bottom as measured on the brane), corresponding to the setups of KARMEN, BUGEY, LSND, MiniBooNE and CDHS. For $L \lesssim 2/k$ (blue line) the simple approximation of a rectangular propagation path breaks down and the minimal action is obtained for the sterile neutrino propagating on the brane.

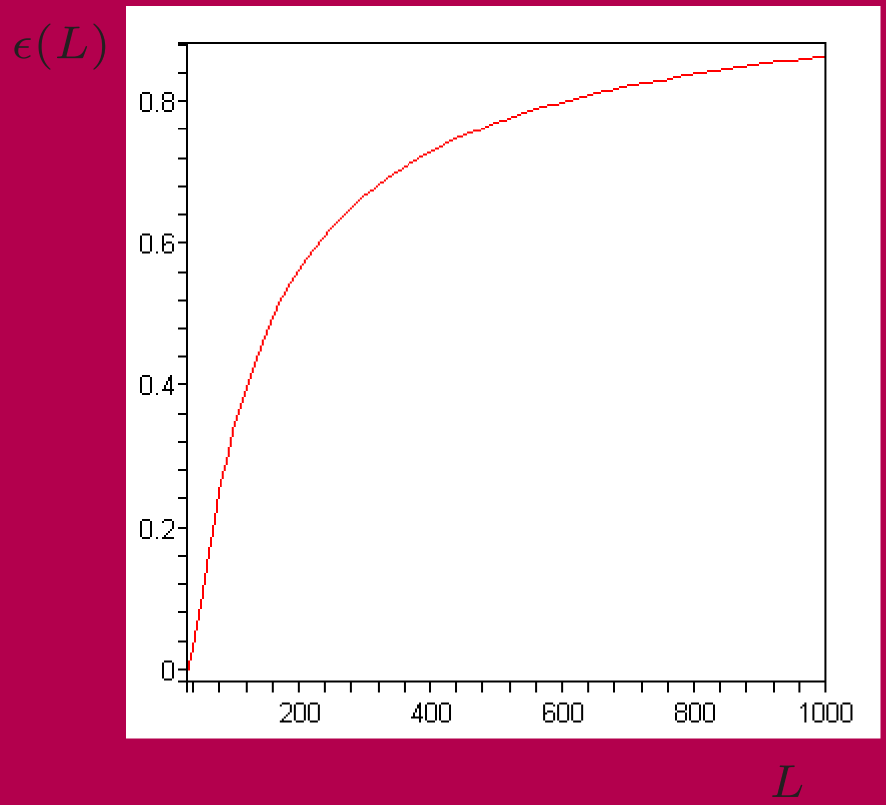


Figure 4: The relative difference between the travel time for SM neutrinos and sterile neutrinos.

Conclusions

- Bulk shortcuts can arise naturally in extra dimensional theories
- Bulk shortcuts affect neutrino mixing and imply a new resonance
- All LSND, MiniBooNE high AND low E data may be explained if shortcut effect is baseline dependent
  - Fits to BOTH LSND and MiniBooNE are work in progress by Barger, Huber, Learned, Marfatia, Päs, Pakvasa, Weiler. However there seem to be complications re the width of the resonance peak and bounds from large baseline experiments.

Thank you!