Baseline–dependent neutrino oscillations in asymmetrically–warped spacetimes

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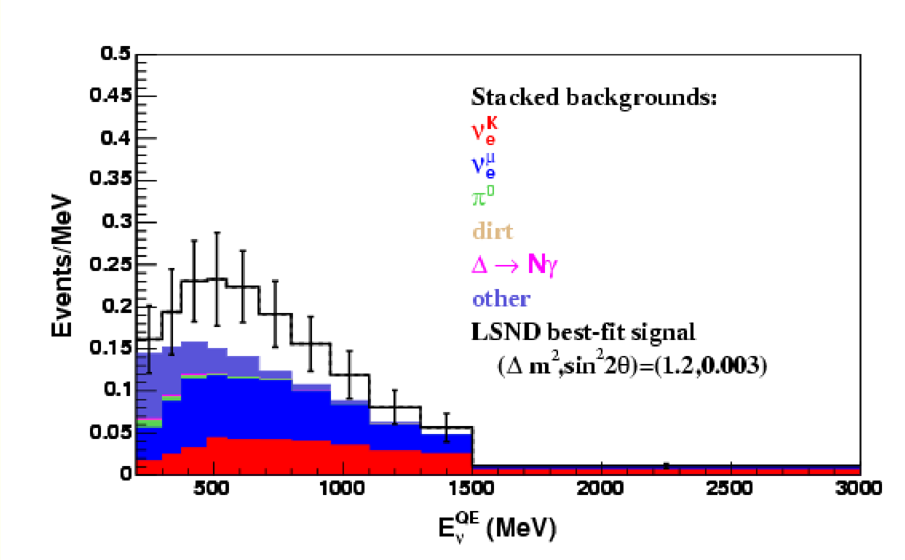
European Strategy for Future Neutrino Physics, CERN
01–03 October 2009

The LSND experiment

wherein a fourth neutrino is believed to exist

- LSND observed excess of $\bar{\nu}_e$ events in pure $\bar{\nu}_\mu$ beam



- with $\Delta m^2_\odot$ & $\Delta m^2_{\text{atm}} \Rightarrow 3\ \Delta m^2$'s $\Rightarrow$ 4 neutrinos
- LSND excess might hint towards deviations from usual oscillation mechanism...
  - oscillations into new "sterile" neutrinos?
  - extra dimensions? [SH, Micu, Päs, Weiler: arXiv:0906.0150 [hep-ph]]
  - CPT & Lorentz violation? [SH, Micu, Päs: arXiv:0906.5072 [hep-ph]]

- altered dispersion relations: "small", effective deviations from common energy–momentum–mass relation

$$E = \sqrt{p^2 + m^2} + V$$

- write Hamiltonian governing oscillations via

$$\begin{aligned} Ht &= H_{\text{diag}} t + \delta(Ht) \\ &= H_{\text{diag}} t + t\delta H + H\delta t \end{aligned}$$

- neutrino oscillations driven by three phase e^{-iHt} differences:
  - diag part H_{diag}: no influence on oscillation probability
  - common phase difference δH: non–degenerate neutrino masses $\Rightarrow$ standard flavour oscillations
  - unconventional phase difference δt: different travel times for different neutrino states

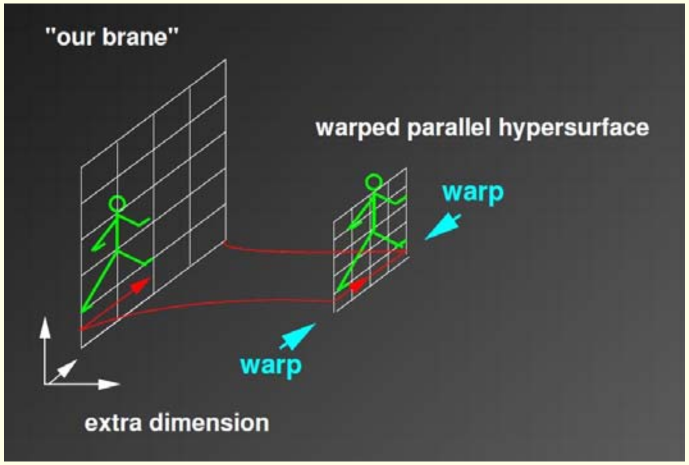
Warped spacetimes

wherein adr's are generated by means of spacetime geometry

- asymmetrically–warped 5D spacetime

$$ds^2 = dt^2 + e^{-2k|u|}dx_i dx^i - du^2$$

  - our Minkowskian brane located at $u = 0$
  - the deeper you dive into the bulk the more your spatial line element gets warped
  - greater warp = less travel time



- different travel times for neutrinos on brane & in bulk
  ⇒ phase difference δt in propagation

Neutrino oscillations in a brane–bulk scenario

- two–state active–sterile system with active neutrino confined to brane; sterile neutrino (gauge singlet) may propagate through bulk
- altered dispersion relations encapsulated in potential V prop to "shortcut parameter" $\epsilon \equiv \frac{\delta t}{t}$
- diagonalize Hamiltonian $H + V$ via new mixing angle expressible in terms of vacuum values

$$\tan 2\tilde{\theta} = \frac{\tan 2\theta}{1 - \frac{E^2}{E_{\text{res}}^2}} \qquad \text{with} \qquad E_{\text{res}} = \sqrt{\frac{\Delta m^2 \cos 2\theta}{2\epsilon}}$$

- resonant oscillations with three energy domains
  - $E \gg E_{\text{res}}$ oscillations suppressed $\tilde{\theta} \to 0$
  - $E = E_{\text{res}}$ maximal mixing $\tilde{\theta} = \frac{\pi}{4}$
  - $E \ll E_{\text{res}}$ vacuum oscillations $\tilde{\theta} \to \theta$

The Weights

wherein the ingredients for the osc prob are presented

- different modes = sterile's path intersecting the brane an n^{th} time at fixed baseline L
  $\Rightarrow$ replace $l = L/n$

- each mode = one possible path; QM: sum over all possible paths
  $\Rightarrow$ insert e^{iS_n}

- sort out geodesics which do not intersect at L
  $\Rightarrow$ insert measure Δn

- assume Gaußian distribution of initial momenta p_u about brane
  $\Rightarrow$ insert distribution with "inverse brane thickness" $\sigma \geq \frac{1}{2\Delta u}$

$$A(\nu_\mathrm{a} \to \nu_\mathrm{s}) = \sum_{n=1}^{\infty} \Delta n \; e^{iS_{cl}(n)} \, \frac{vn}{(n^2+v^2)^{3/2}} \left[\sqrt{\frac{2}{\pi}} \, \frac{\beta E}{\sigma} \, e^{-\frac{(\beta E v)^2}{2\sigma^2(n^2+v^2)}} \right] \sin 2\tilde{\theta}_n \; \sin \frac{L\delta\tilde{H}_n}{2}$$

The Near Zone

- resonance energy; shortcut parameter; "scaling variable" for mode n

$$\frac{E^2_{\text{res}}(n)}{\Delta m^2} = \frac{\cos 2\theta}{2\epsilon_n} \quad ; \quad \epsilon_n = 1 - \left(\frac{n}{v}\right) \operatorname{arcsinh}\left(\frac{v}{n}\right) \quad ; \quad v = \frac{kL}{2}$$

- experimentally relevant case: The Near Zone

$$\frac{E^2_{\text{res}}(n)}{\Delta m^2} \sim \frac{(\text{MeV})^2}{\text{eV}^2} \gg 1 \quad \Leftrightarrow \quad v \ll 1 \quad \text{id est} \quad L \ll k^{-1}$$

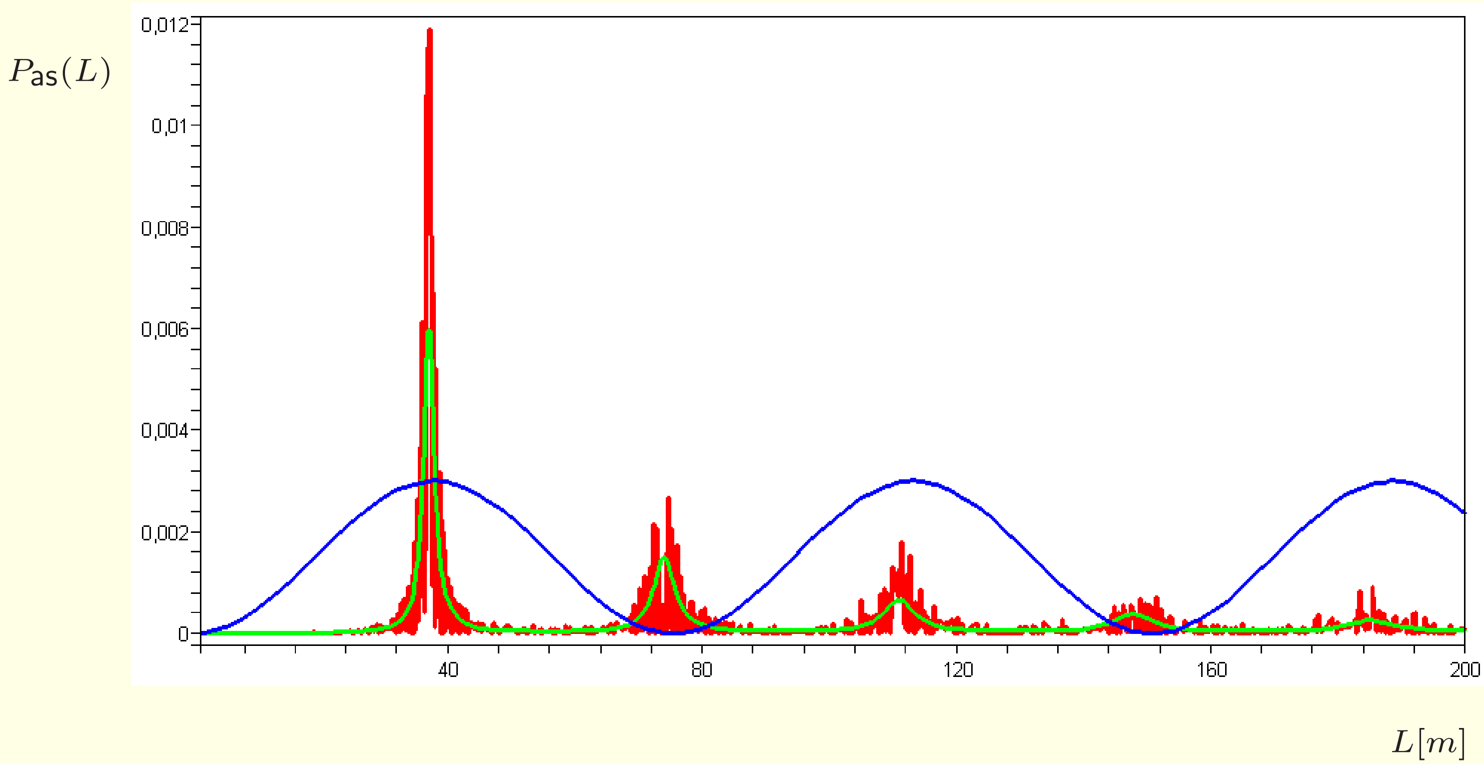
- Near Zone pheno: a novel "resonant product of L and E"

$$\frac{E^2}{E^2_{\text{res}}(n)} = \frac{(LE)^2}{n^2 (LE)^2_{\text{res}}} \qquad \text{with} \qquad (LE)_{\text{res}} = k^{-1}\sqrt{12\ \Delta m^2 \cos 2\theta}$$

The Near Zone II

wherein the osc prob is presented

- plot $P_{\text{as}}(L)$ using Near Zone pheno $\Rightarrow$ resonance peaks at different baselines $L = n(LE)_{\text{res}}/E$!



red – 5D osc prob; green – phase averaged 5D osc prob; blue – standard 4D osc prob
$\sin^2 2\theta = 0.003$, $k = 5/(10^8 \text{ m})$, $E = 15$ MeV, $\Delta m^2 = 64$ eV^2, and $\sigma = 100$ eV;

resonances found at multiples $L = n(LE)_{\text{res}}/E = 37n$ m, $n = 1, 2, 3 \ldots$

- three domains at hand
  - $LE \gg (LE)_{\text{res}}$ oscillations suppressed $\tilde{\theta} \to 0$
  - $LE = (LE)_{\text{res}}$ maximal mixing $\tilde{\theta} = \frac{\pi}{4}$
  - $LE \ll (LE)_{\text{res}}$ vacuum oscillations $\tilde{\theta} \to \theta$
- LSND resonant excess + LSND baseline $\Rightarrow$ resonance condition $LE = (LE)_{\text{res}}$ fulfilled $\Rightarrow$ explains resonant excess
- above LSND domain $LE \gg (LE)_{\text{res}}$: active & sterile neutrinos decouple $\Rightarrow$ no discernible traces of brane–bulk physics in atmospheric data
- below LSND domain $LE \ll (LE)_{\text{res}}$: vacuum oscillations prevail
- Final question:
  Is the LE resonance phenomenology indeed compatible with the world's oscillation data?