MiniBooNE and shortcuts in extra dimensions: explaining the World neutrino data

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Outline

• Summary of neutrino data & LSND dilemma
• Neutrinos in extra dimensions
• Bulk shortcuts, neutrino oscillations & LSND
• MiniBooNE & the World neutrino data: Towards a realistic 3+1 neutrino fit
Summary of neutrino data

- $3 \Delta m^2$'s $\rightarrow$ 4 neutrinos!
- width of the Z-boson (LEP) $\rightarrow$ 3 neutrinos!
- $\rightarrow$ one sterile neutrino? (i.e. not coupling to the Z)
The LSND Dilemma

**LSND:** $\bar{\nu}_\mu - \bar{\nu}_e$ oscillations over $\Delta m^2 \simeq 1 \text{ eV}^2$

**2+2 spectrum:**
no oscillations of solar or atmospheric $\nu$'s into steriles → excluded!

**3+1 spectrum:** constraints from $\nu$ disappearance experiments

- **BUGEY bound** ($\nu_e \rightarrow \nu_\ell$): $\sin^2 2 \theta_{e\ell} = 4 U^2_{e4} (1 - U^2_{e4})$
- **CDHS bound** ($\nu_\mu \rightarrow \nu_\ell$): $\sin^2 2 \theta_{\mu\ell} = 4 U^2_{\mu4} (1 - U^2_{\mu4})$
- **LSND** ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$): $\sin^2 2 \theta_{\text{LSND}} = 4 U^2_{e4} U^2_{\mu4}$

LSND is doubly suppressed! $\sin^2 2 \theta_{\text{LSND}} \simeq \frac{1}{4} \sin^2 2 \theta_{e\ell} \sin^2 2 \theta_{\mu\ell}$ → excluded!
LSND:

- might be wrong
- may hint towards deviations from the usual oscillation mechanism
- may be a messenger of the mechanism of neutrino mass generation!
- extra dimensions? bulk shortcuts?
Large extra dimensions and neutrino masses

- No large scale $\rightarrow$ no seesaw suppression of neutrino masses

- However: string theories $\rightarrow$ singlet fermions in the bulk (e.g. superpartners of moduli fields) $\rightarrow \nu_R$

$\rightarrow$ small Dirac neutrino masses from volume-suppressed couplings to $\nu_R$ in the bulk:

$$m^D = \frac{vY}{\sqrt{2}V_\delta M^{4d}_{\delta d}} = v \frac{Y}{\sqrt{2}} M^{4d}_{\delta d}$$

suppression factor: $M^{4d}_{\delta d}/M^{4d}_{\delta d}$

Large extra dimensions and neutrino masses

What about:
Non-trivial brane properties?
Brane bending?
Asymmetrical warping?
3 mechanisms for bulk shortcuts:

- Gravitational self attraction due to brane matter
  
  H. Ishihara, 2000

- Thermal or quantum fluctuations

- Asymmetrically warped bulk dimension

\[ ds^2 = dt^2 - \alpha^2(u) dx^2 - du^2 \]

D.J.H. Chung & K. Freese, 1999

→ bulk shortcuts as a solution to the cosmological horizon problem
Brane bending or asymmetrical warping allows for apparent superluminal propagation!

How do bulk shortcuts affect neutrino oscillations?
consider bulk shortcuts:

Evolution factor in path integral: $\sim e^{iS}$ with $S = \int H dt$

Bulk signal gains a time shift $\Delta t$

$\Rightarrow$ Phase difference in evolution factor due to shortcut:

$\Delta S = \Delta \int H dt = H \Delta t \rightarrow \Delta H_{\text{eff}} T$

$\Rightarrow \Delta H_{\text{eff}} = H \Delta t / T$

Introduce shortcut parameter: $\epsilon \equiv (t_{\text{brane}} - t_{\text{bulk}})/t_{\text{brane}} = \Delta t / T$

Change in the Hamiltonian:

$\Rightarrow \Delta H_{\text{eff}} = H \Delta t / T \rightarrow \epsilon E$

(Päs, Pakvasa, Weiler, 2005)
Evolution equation in flavor space:

\[
\begin{align*}
\frac{d}{dt} \begin{pmatrix} \nu_a(t) \\ \nu_s(t) \end{pmatrix} &= H_F \begin{pmatrix} \nu_a(t) \\ \nu_s(t) \end{pmatrix} \\
\end{align*}
\]

Hamiltonian in the presence of bulk shortcuts:

\[
H_F = + \frac{\delta m^2}{4E} \begin{pmatrix} \cos 2\theta & - \sin 2\theta \\ - \sin 2\theta & - \cos 2\theta \end{pmatrix} + E \frac{\epsilon}{2} \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}
\]

⇒ A Resonance exists at 

\[
E_{\text{res}} = \sqrt{\frac{\delta m^2 \cos 2\theta}{2\epsilon}}
\]

→ choose \( E_{\text{res}} = 30\text{-}400 \text{ MeV} \leftrightarrow \epsilon \simeq 10^{-18} - 10^{-16} \)

(Päss, Pakvasa, Weiler, 2005)
The active-sterile oscillation probability

\[ P_{as} = \sin^2 2\tilde{\theta} \sin^2(\frac{\delta H D}{2}) \]

\[ \sin^2 2\tilde{\theta} = \left[ \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - A)^2} \right] \]

\[ \delta H = \frac{\delta m^2}{2E} \sqrt{(\cos 2\theta - A)^2 + \sin^2 2\theta} \]

\[ A = \left( \frac{E}{E_{\text{res}}} \right)^2 \]

Oscillations at \( E \gg E_{\text{res}} \) (CDHS) are suppressed!
CDHS bound not valid anymore! 3+1 spectrum allowed again! \( \rightarrow \) choose
\[ E_{\text{LSND}} < E_{\text{res}} \ll E_{\text{CDHS}} \] (Päs, Pakvasa, Weiler, 2005)
Scenario with low resonance energy

- $E_{\text{res}} = 33$ MeV
- $P_{\text{LSND}} > P_{\text{KARMEN}}$
- good (better) fit for LSND spectrum

- no signal at MiniBooNE!
- strongly enhanced $\nu_\mu$ depletion at SNS stopped $\pi$ source

(Päss, Pakvasa, Weiler, 2005)
Scenario with high resonance energy

- $E_{\text{res}} = 200$ MeV, 300 MeV, 400 MeV; $\sin^2 \theta_* = 0.1$; $\sin^2 2\theta = 0.45$; $\delta m^2 = 0.8$ eV$^2$

- good fit to LSND spectrum, $P_{\text{LSND}} > P_{\text{KARMEN}}$

- enhanced miniBooNE signal in the energy range 100-600 MeV

(Päs, Pakvasa, Weiler, 2005)
The MiniBooNE result:

- excludes standard neutrino oscillations as an explanation for LSND
- sees a $3.7 \sigma$ excess of $\nu_e$ events at low energies $< 475$ MeV (background?)
Realistic 3+1 fits: Good news

- Päs, Pakvasa, Weiler: 2-flavor approximation
- Barger, Huber, Learned, Marfatia, Päs, Pakvasa, Weiler: realistic 3+1 neutrino fits

standard $\nu$ oscillations vs $\nu$ shortcut scenario

(MiniBooNE $> 475$ MeV, LSND, KARMEN, CDHS, BUGEY)
preliminary fit courtesy by Patrick Huber
Bad news: Determination of the resonance energy

- best fit at $E_{\text{res}} = 33$ MeV
- MiniBooNE low-E anomaly: local minimum in the $E_{\text{res}} = 100 - 200$ MeV range

fit courtesy by Patrick Huber
Results of a 3-parameter fit: $\theta_{as}, \Delta m^2_{41}, E_{res}$

- standard neutrino oscillations are disfavored at 4 $\sigma$ level
- sterile neutrinos with a modified dispersion relation (shortcuts) are compatible at the 1 $\sigma$ level with all data (both MiniBooNE $> 300$ GeV and MiniBooNE $> 475$ GeV)
- the best-fit resonance energy lies in the small energy range
- large $E_{res}$ creates tension between
  - small active-sterile mixing $\rightarrow$ suppressed LSND signal
  - large active-sterile mixing $\rightarrow$ too much $\nu_e$ events in MiniBooNE high-E sample

**New data to come:**
- SciBooNE as a near detector
- anti-neutrino data
- detection of MINOS neutrinos
- lower energy data $> 100$ GeV

**If MiniBooNE low-E anomaly is confirmed with smaller error bars (work in progress):**
- switch on more mixing angles
- introduce a second sterile neutrino (maybe KK mode) with small mixing $\rightarrow$ large $E_{res}$ and small contribution to LSND and high-E MiniBooNE
Conclusions

• Bulk shortcuts can arise naturally in extra dimensional theories

• Bulk shortcuts affect neutrino mixing and imply a new resonance
  – Neutrino oscillations are suppressed for $E \gg E_{\text{res}}$
  – LSND becomes compatible with BUGEY and CDHS ($E_{\text{CDHS}} \gg E_{\text{res}}$)

• Excellent (only?) fit to the World’s neutrino data with 3 parameters: $\theta_{a.s.}, \Delta m_{41}^2, E_{\text{res}}$
  – More pronounced MiniBooNE low-E anomaly may require 2nd mixing angle or 2nd sterile neutrino
  – BBN and other cosmological bounds may be evaded
  – May explain Heidelberg-Moscow double beta decay claim?
  – Large signals expected in future MiniBooNE data (NEW DATA TO COME!), reactor, SNS, LENS experiments

• All simple realizations are causally stable but... if you are desparate to have a neutrino time machine I’ll get you one