Investigating CPT violation with sterile neutrino fits

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LSND

LSND result: Observed allowed region of $\Delta m^2$ not consistent with known mass splittings.

A 3$^{rd}$ mass splitting solves this problem

$\Delta m^2_{\text{solar}} \sim 10^{-5} \text{ eV}^2$

$\Delta m^2_{\text{atm}} \sim 10^{-3} \text{ eV}^2$

$\Delta m^2_{\text{LSND}} \sim 1 \text{ eV}^2$
Sterile neutrinos

Don’t interact through the weak force but can still oscillate with other neutrinos

Assume $\Delta m^2_{\text{sterile}}$ is much greater than $\Delta m^2_{\text{atm}}$ and $\Delta m^2_{\text{solar}}$ so only fit to one $\Delta m^2$ and one mixing parameter.

(So when we say 3+1 we really mean a 2 neutrino fit)

\[
P(\nu_\alpha \rightarrow \nu_{\beta \neq \alpha}) = \sin^2 2\theta_{\alpha\beta} \sin^2[1.27(L/E)] \text{ (Appearance)}
\]

\[
P(\nu_\alpha \rightarrow \nu_\alpha) = \sin^2 2\theta_{\alpha\alpha} \sin^2[1.27(L/E)] \text{ (Disappearance)}
\]
**CP and CPT Violation**

3+1 and 3+2 fits usually assume **CPT conservation** ($P_{\text{dis}}^\nu = P_{\text{dis}}^\bar{\nu}$)

Occasionally introduce **CP violation** ($P_{\text{app}}^\nu \neq P_{\text{app}}^\bar{\nu}$) for better fits. CP violation is already known to occur in the weak interaction.

**CP violation** can NOT explain ($P_{\text{dis}}^\nu \neq P_{\text{dis}}^\bar{\nu}$)

**CPT violation** would be bad for physics! It is one of the key principles of quantum field theory.

If observed, some lack of symmetry between $P_{\text{dis}}^\nu$ and $P_{\text{dis}}^\bar{\nu}$ could possibly be explained by new physics, such as a new type of interaction, which may save **CPT conservation**
MINOS Preliminary

MINOS favoring $\Delta m^2$ around 0.01 to $\sim 0.4 \text{ eV}^2$.

For $\nu$, the best fit value from MINOS and other atmospheric experiments is known to lie at $\sim 3 \times 10^{-3} \text{ eV}^2$ with maximal mixing ($\sim 1$)

MINOS $\nu_\mu$ 90%

Global $\nu$ 90%
MINOS – 3+1 Fit

Preliminary 3+1 fits indicate a preferred $\Delta m^2_{41}$ around 0.5 eV$^2$

Don’t have $E_{\text{true}}$ and $L_{\text{true}}$ information per event (data not yet released)

<table>
<thead>
<tr>
<th>$\chi^2$</th>
<th>dof</th>
<th>Probability</th>
<th>$\Delta m^2_{41}$</th>
<th>$\sin^2 2\theta_{\mu\mu}$</th>
<th>$\chi^2$</th>
<th>dof</th>
<th>Probability</th>
<th>$\Delta m^2_{41}$</th>
<th>$\sin^2 2\theta_{\mu\mu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.8</td>
<td>5</td>
<td>57.9%</td>
<td>0.469</td>
<td>0.646</td>
<td>3.4</td>
<td>5</td>
<td>63.9%</td>
<td>0.467</td>
<td>0.535</td>
</tr>
</tbody>
</table>
Fitting to (preliminary) MINOS data

MINOS data & fit from Fermilab wine and cheese (Jeff Hartnell – May 2009) plus some 3+1 fits
Best fit:

<table>
<thead>
<tr>
<th></th>
<th>$\chi^2$</th>
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<th>Probability</th>
<th>$\Delta m^2_{41}$</th>
<th>$\sin^2 2\theta_{\mu e}$</th>
<th>$\sin^2 2\theta_{\mu\mu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before MINOS</td>
<td>87.9</td>
<td>103</td>
<td>86%</td>
<td>0.91</td>
<td>0.0043</td>
<td>0.350</td>
</tr>
<tr>
<td>With MINOS</td>
<td>92.26</td>
<td>110</td>
<td>89%</td>
<td>0.912</td>
<td>0.0044</td>
<td>0.405</td>
</tr>
</tbody>
</table>

MINOS data fits in nicely with previous $\bar{\nu}$ fit

Experiments included in fit:
- MINOS
- LSND
- Miniboone $\bar{\nu}_e$
- KARMEN
- Bugey
- Chooz

$\bar{\nu}$ only fit
v only fit

From Karagiorgi et al. 2009 (arxiv:0906.1997v1)

Experiments included in fit:

Miniboone $\nu_e$

NOMAD

NuMI

CCFR84

CDHS

Best fit: $\chi^2$  dof  Probability  $\Delta m^2_{41}$  $\sin^2 2\theta^e_{\mu e}$  $\sin^2 2\theta^\mu\mu$

90.5  90  47%  0.190  0.0310  0.0310

Looks different from $\bar{\nu}$ fit
Global 3+1 fit all experiments

Experiments included in fit:

$\bar{\nu}$ experiments:
MINOS, LSND, Miniboone $\bar{\nu}_e$, KARMEN, Bugey, Chooz

$\nu$ experiments: Miniboone $\nu_e$, NOMAD, NuMI, CCFR84, CDHS, atmospheric constraint

<table>
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<th>dof</th>
<th>Probability</th>
<th>$\Delta m^2_{41}$</th>
<th>$\sin^2 2\theta_{\mu e}$</th>
<th>$\sin^2 2\theta_{\mu\mu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before MINOS</td>
<td>197.4</td>
<td>196</td>
<td>46%</td>
<td>0.920</td>
<td>0.0025</td>
<td>0.130</td>
</tr>
<tr>
<td>After MINOS</td>
<td>196.2</td>
<td>203</td>
<td>62%</td>
<td>0.403</td>
<td>0.0130</td>
<td>0.0904</td>
</tr>
</tbody>
</table>
Global fit – CPT Violating

Allows $\Delta m^2$ to vary separately for neutrinos and antineutrinos

Not yet allowing mixing parameters to vary separately

Best fit:

$\chi^2$ 189.8

dof 204

Probability 75%

$\Delta m^2$ 0.255

$\Delta m^2_{\text{bar}}$ 0.402

$\sin^22\theta_{\mu e}$ 0.0188

$\sin^22\theta_{\mu\mu}$ 0.0899
Best fit not along line

No 90% CL points along line either
3+2 Fit to MINOS

Best fit values:

<table>
<thead>
<tr>
<th>$\chi^2$</th>
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<th>Probability</th>
<th>$\Delta m^2_{41}$</th>
<th>$\Delta m^2_{51}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.4</td>
<td>3</td>
<td>33%</td>
<td>0.463</td>
<td>0.467</td>
</tr>
</tbody>
</table>

Second $\Delta m^2$ not favored

Don’t have near detector data or good energy info. It’s possible things will change
Coming Soon...

Full event sample for MINOS

Allow Mixing parameters to vary separately too for CPT violating fits

Including the new MiniBooNE $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance data