Neutrino Oscillations and Lorentz Violation Results from MiniBooNE

Outline:
- LSND
  - signal for $\nu$ oscillations
  - sidereal analysis and LV
- Tandem Model
- MiniBooNE
  - experiment, analysis, $\nu$ results
  - LV results
The LSND Result

The LSND experiment observed an excess of $\bar{\nu}_e$ events in beam of $\bar{\nu}_\mu$

$$87.9 \pm 22.4 \pm 6.0 \ (4\sigma)$$

consistent with $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations.

However, this result, with large $\Delta m^2$, does not fit in a 3 generation neutrino model (given results from other oscillation experiments) since $\Delta m_{12}^2 + \Delta m_{13}^2 + \Delta m_{23}^2 = 0$

If LSND is correct $\Rightarrow$ new physics.
- additional (sterile) neutrinos
- a different model for oscillations
Review: Sidereal variation in the LSND signal

- In AK, MM, PRD70, 076002, a short-baseline approximation for neutrino oscillations (allowing for sidereal variation) was developed.
- In PRD72, 076004 we (with LSND collaboration) reported the results of a search for sidereal variation in the LSND signal...

\[(h_{\text{eff}})_{ab} = |\vec{p}| \delta_{ab} + \frac{(\tilde{m}^2)_{ab}^*}{2|\vec{p}|} + \frac{1}{|\vec{p}|} \left[-(a_L)^\mu P_\mu - (c_L)^{\mu\nu} P_\mu P_\nu \right]_{ab}^*.\]

\[P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e} \approx \frac{|(h_{\text{eff}})\bar{\nu}_\mu |^2 L^2}{(\hbar c)^2}.\]

\[P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e} \approx \frac{L^2}{(\hbar c)^2} \left[ (C)\bar{\nu}_\mu + (A_s)\bar{\nu}_\mu \sin \omega_T \theta \right.\]
\[+ (A_c)\bar{\nu}_\mu \cos \omega_T \theta + (B_s)\bar{\nu}_\mu \sin 2\omega_T \theta\]
\[+ (B_c)\bar{\nu}_\mu \cos 2\omega_T \theta \bigg]^2,\]

all are \(f(a_L, c_L\text{ and } \nu \text{ beam direction in sun-centered frame})\)
Sidereal variation in the LSND signal

- LSND sidereal variation, results:
  consistent with no sidereal variation...

Null hypothesis tests

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<td>sidereal</td>
<td>GM</td>
<td>sidereal</td>
<td>GM</td>
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<td># of events</td>
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<td>Pearson’s $\chi^2$:</td>
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<td>$N_{\text{bins}}$</td>
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<td>0.066</td>
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<tr>
<td>$P(\text{KS})$</td>
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<td>0.386</td>
<td>0.604</td>
<td>0.010</td>
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<td>Beam-on/beam-off tests</td>
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<td>$D_n$</td>
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<tr>
<td>$P(\text{KS})$</td>
<td>0.432</td>
<td>0.864</td>
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</table>
Sidereal variation in the LSND signal

- LSND sidereal variation, results:
  extraction of SME parameter combinations.

- allowed regions include sidereal variations (non-zero $A_s$, $A_c$)

- extracted parameter square-sum:

$$\|(C)_{\bar{e}\bar{\mu}}\|^2 + \frac{1}{2}\|(A_s)_{\bar{e}\bar{\mu}}\|^2 + \frac{1}{2}\| (A_c)_{\bar{e}\bar{\mu}} \|^2$$

$$= 9.9 \pm 2.3 \pm 1.4 \times 10^{-19} \text{GeV}^2,$$

- (noted by AK, MM before this analysis)

- regardless of sidereal variation, if the SME is used to explain LSND then, $a_L$ or $E \times c_L \sim 10^{-19} \text{GeV}$ (~ expected Planck-scale effects)
A “global model” of $\nu$ oscillations (with the SME)

- The biggest challenge in constructing a global model of $\nu$ oscillations within the SME is the E-dependence. SK-atmospheric and KAMLAND report an L/E dependence... How to model with $E^0$ and $E^1$ terms?

$$h_{\text{eff}} = \frac{1}{E}[(a_L)^\mu p_\mu - (c_L)^\mu\nu p_\mu p_\nu].$$

- AK, MM noted that the mixed energy dependence in the coeffs can lead to a LV “see-saw” mechanism that occurs in certain energy ranges (“pseudomass”)

- the “bicycle-model”

$$(h_{\text{bicycle}})_{ab} \rightarrow \begin{pmatrix} \tilde{c} & \tilde{a} & \tilde{a} \\ \tilde{a} & 0 & 0 \\ \tilde{a} & 0 & 0 \end{pmatrix}$$
The “tandem model”

- start with bicycle model

- add additional $m^2$ term which generates a 2nd seesaw...

- 3 parameters, rotationally invariant

- explain solar, atmospheric, KamLAND, LSND

- only 3 parameters (remember, standard 3$\nu$ has 4-6)

- no MSW needed for solar

- prediction for MiniBooNE (among others)
oscillation probabilities

solar neutrino oscillations

long-baseline anti-ν oscillations

short-baseline ν/anti-ν oscillations
MiniBooNE experimental strategy

- Test the LSND observation via $\nu_\mu \rightarrow \nu_e$ appearance.
- Keep $L/E$ same, change beam, energy, and systematic errors

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 (1.27\Delta m^2 L/E)$$

neutrino energy (E):

- MiniBooNE: ~500 MeV
- LSND:   ~30 MeV

baseline (L):

- MiniBooNE: ~500 m
- LSND:   ~30 m

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**Diagram**:
- Booster
- Primary beam: (protons)
- Secondary beam: (mesons)
- Tertiary beam: (neutrinos)
- Target and horn
- Decay region
- Absorber
- Dirt
- Detector

$(\pi^+ \rightarrow \nu_\mu \rightarrow \nu_e ??)$
MiniBooNE Collaboration

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MiniBooNE beam: total $\nu$ flux

- mean energy $\sim$800MeV
- $\nu_e/\nu_\mu = 0.5\%$
ν Events in MiniBooNE
- Recall: search for ν_e in a ν_µ beam

- signature of a ν_e reaction (signal): electron

- need to distinguish from backgrounds (due to ν_µ reactions) that consist of a muon or π^0

- ν interaction products create (directed, prompt) Cerenkov light and (isotropic, delayed) scintillation light

- pattern and timing of the detected light allows for event identification (and position, direction, energy meas.)
ν interactions in detector:
- predicted ν events and fractions from event generator*
- extensively tuned using MiniBooNE data

predicted # ν events in data set (no efficiency corrections)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Events</th>
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<tbody>
<tr>
<td>CC quasilelastic</td>
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</tr>
<tr>
<td>NC elastic</td>
<td>150k</td>
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<tr>
<td>CC π⁺</td>
<td>180k</td>
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<tr>
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<tr>
<td>CC/NC DIS, multi-π</td>
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<tr>
<td>all channels</td>
<td>810k</td>
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<tr>
<td>ν osc. events</td>
<td>~1k</td>
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</table>

*NUANCE (D. Casper, NPS, 112 (2002) 161)
oscillation analysis: strategy
- need accurate, efficient particle identification algorithm to separate (signal) electron-like events from ubiquitous (background) muon, pion events

- To avoid experimenter bias, this was done with “blind” procedure, signal data set kept in “box” until algorithms set.

Two algorithms were used:
- “track-based” (TB)
  Uses direct reconstruction of particle types and likelihood ratios for particle-ID
- “boosted decision trees” (BDT)
  Set of low-level variables combined with BDT algorithm -> PID “score”

- In the end, the TB analysis had slightly better sensitivity, so is used for primary results. BDT analysis is a powerful “double-check”
oscillation analysis: backgrounds

intrinsic-$\nu_e$ backgrounds (from $\nu_e$ produced at $\nu$ source)

- $\mu \rightarrow \nu_e$: (indirectly) measured in $\nu_\mu$ CCQE events via $\pi$-decay chain
- $\pi \rightarrow \nu_e$: 
- $K \rightarrow \nu_e$: measured in high-energy $\nu_\mu, \nu_e$ CCQE (from Kaons), extrapolate to low-E

“mis-ID” backgrounds (mainly from $\nu_\mu$)

- CC Inclusive: includes CCQE, measured, simulated
- NC $\pi^0$: measured, simulated
- NC $\Delta \rightarrow N\gamma$: constrained in data, simulated
- NC coherent, radiative $\gamma$: calculated, negligible
- Dirt: $\nu$ interactions outside tank, simulated, measured
- beam-unrelated events, measured, very small

correlated errors on all backgrounds are considered
oscillation analysis: box-opening

With...
- algorithms finalized,
- cuts determined,
- backgrounds predicted,
- the neutrino oscillation box was opened

on March 26, 2007
oscillation analysis: results

track-based analysis:
- $E_\nu > 475\text{MeV}$ cut for oscillation analysis region
- no sign of an excess in the analysis region
- visible excess at low $E$

No evidence for $\nu_\mu \rightarrow \nu_e$ appearance in the analysis region

$\chi^2_{\text{null}} - \chi^2_{\text{best}} = 0.94$
oscillation analysis: results

**track-based analysis:**
Counting Experiment: $475 < E_\nu < 1250$ MeV
data: 380 events
expectation: $358 \pm 19$ (stat) $\pm 35$ (sys)
significance: $0.55 \sigma$

No evidence for $\nu_\mu \rightarrow \nu_e$ appearance in the analysis region
oscillation analysis: results

Limit curves:
solid: TB, primary result
dashed: BDT

- MiniBooNE and LSND incompatible at a 98% CL for all $\Delta m^2$ under a $2\nu$ mixing hypothesis
oscillation results: low-energy region

Track-based analysis
$E_ν$ distributions:

For:
$300 < E_ν < 475$ MeV
$96 \pm 17 \pm 20$ events
Excess: $3.7\sigma$

The energy-dependence of excess is not consistent with $ν_μ \rightarrow ν_e$ appearance assuming standard energy dependence

$$P(ν_μ \rightarrow ν_e) = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$
Continuing work to understand low-energy region

- We continue to work to characterize and to determine the source of the event excess in the low-energy region ($E_\nu < 475 \text{MeV}$)

It may be...
- detector or analysis problems
- a background (and of importance for other experiments searching for $\nu_\mu \rightarrow \nu_e$ appearance)
- new physics

Working on all of these... new results soon

- NEW! this energy bin
Sidereal Analysis of MiniBooNE data

- Proceeding analogously to LSND sidereal analysis...
- better “coverage” than LSND data of sidereal day

300<\text{E}_\nu<475\text{MeV} MiniBooNE data
Sidereal Analysis, Preliminary results

300<\E<475\text{MeV}:

- sidereal: Pearson's $\chi^2 = 79.5/73$ (P=0.28)
- GM: Pearson's $\chi^2 = 72.8/73$ (P=0.49)

475<\E<1250\text{MeV}:

- sidereal: Pearson's $\chi^2 = 77.2/84$ (P=0.69)
- GM: Pearson's $\chi^2 = 76.4/84$ (P=0.71)

- actual chi2 tests performed with more bins (~5 events bin)
- final sidereal analysis will extract allowed regions or limits on SME parameters
Tandem model prediction

- Using MiniBooNE (public) data that includes detector efficiency effects, we calculated oscillation signal as predicted by tandem model. Recall prediction:
Tandem model prediction

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Summary

- MiniBooNE rules out (to 98%CL) the LSND result interpreted as
\( \nu_\mu \rightarrow \nu_e \) oscillations described with standard L/E dependence

This eliminates the following interpretations of LSND:
- \( \bar{\nu}_\mu \rightarrow \bar{\nu}_e \) oscillations with (w/"standard" assumptions of CPT, E-dependence)
- \( \nu_\mu \rightarrow \nu_e \) via a single sterile neutrino (""")

- The as-yet-unexplained deviation of MiniBooNE data from prediction at low-energy could be a background ... Currently working on this with very high priority.

... Or perhaps, new physics
- final sidereal analysis to come
- more work on tandem model
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- Thanks to AK for workshop and collaboration!
Summary

- Much credit due to Teppei Katori, please see his poster this evening!
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