1. Anomalies in Oscillation experiments
2. Updated MiniBooNE results
3. Resolution: The BooNE Proposal
Synopsis:

- A number of anomalies have appeared in neutrino data in E and L regions corresponding to a $\Delta m^2 \sim 1\ eV^2$

- Predominantly from single detector experiments...

- There is a possibility that some of the effects are due to oscillations between sterile neutrinos and active neutrinos

- A definitive two-detector experiment is warranted

- BooNE would be such an experiment
Motivation....

Anomalies in Neutrino Data
Excess Events from LSND still remain:

- LSND found an excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam.
- Signature: Cerenkov light from $e^+$ with delayed $n$-capture (2.2 MeV).
- Excess: $87.9 \pm 22.4 \pm 6.0 \ (3.8 \text{s})$.
- The data was analysed under a two neutrino mixing hypothesis*.

\[
P(\bar{\nu}_\mu \to \bar{\nu}_e) = \sin^2 (2\theta) \sin^2 \left( \frac{1.27 L \Delta m^2}{E} \right) = 0.245 \pm 0.067 \pm 0.045 \%
\]

KARMEN at a distance of 17 meters saw no evidence for oscillations $\rightarrow$ low $\Delta m^2$.

Motivation...
Inclusion of new beta decay estimates in reactor flux calculations
Increases expected flux

Best fit: $0.943 \pm 0.023$

$P_{osc} \sim 10\%$, $\Delta m^2 \sim 1 \text{ eV}^2$
Motivation....

Gallium Source Anomaly in $\nu_e$ Data

- Observed too few $\nu_e$ interactions observed from an electron capture source

Sterile Neutrinos at the Crossroads
Other data: KARMEN & LSND $\nu_e$ Disappearance Limit

$^{12}\text{C}(\nu_e,e^-)^{12}\text{N}_{GS}$

Not usually included in global fits

FIG. 4: The 95% $\nu_e$ disappearance limit from the Fukugita (EPT) fit (solid, black line) compared to the predicted sensitivity (dotted line). Also shown is the 68% (darker, shaded region) and 90% (lighter, shaded region) contours from the Gallium experiments. The dashed line is the Kolbe (CRPA) fit. The Gallium best fit point and the Reactor Anomaly best fit point are shown as the plus and cross symbols respectively. The Gallium best fit point is excluded at 3.6σ.
MiniBooNE Data
MiniBooNE looks for an excess of electron neutrino events in a predominantly muon neutrino beam

**Neutrino mode flux:**

- $\nu_\mu \rightarrow \nu_e$ oscillation search

**Antineutrino mode flux:**

- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation search

Sterile Neutrinos at the Crossroads
Meson production at the Proton Target

Pions(+-):

- MiniBooNE members joined the HARP collaboration
- 8 GeV proton beam
- 5% Beryllium target
- Spline fits were used to parameterize the data.

Kaons:

- Kaon data taken on multiple targets in 10-24 GeV range
- Fit to world data using Feynman scaling
- 30% overall uncertainty assessed
Data stability

- Very stable throughout the run

25m absorber

$\nu/\text{POT} = (102.1 \pm 0.1) \times 10^{-17}$

$\chi^2/\text{ndf} = 841.67/863$

$\bar{\nu}/\text{POT} = (20.6 \pm 0.1) \times 10^{-17}$

$\chi^2/\text{ndf} = 478.19/498$
We adjust the parameters of a Fermi Gas model to match our observed $Q^2$ distribution.

Fermi Gas Model describes CCQE

$$n_m \text{ data well}$$

$$M_{A,\text{eff}} = 1.23 \pm 0.20 \text{ GeV}$$

$$\kappa = 1.019 \pm 0.011$$

Also used to model $\nu_e$ and $\bar{\nu}_e$ interactions.

Benchmark Reaction: Charged Current Quasi Elastic (CCQE)

Normalizes our (flux × cross section)

Sterile Neutrinos at the Crossroads
Separating muon-like and electron-like events by using a likelihood ratio technique

\[ \log \left( \frac{L_e}{L_m} \right) > 0 \] favors electron-like hypothesis

Note: photon conversions are electron-like. This does not separate e/π⁰.

Separation is clean at high energies where muon-like events are long.

Analysis cut was chosen to maximize the \( \nu_\mu \rightarrow \nu_e \) sensitivity.
Reconstruction of NC $\pi^0$ events

Separating electrons from neutral current $\pi^0$s by using a likelihood ratio combined with the $\gamma\gamma$ invariant mass

Signal region

Sterile Neutrinos at the Crossroads
MiniBooNE Antineutrino Oscillation Results

- 8.58E20 POT (~50% more data than published and new K+ constraint from SciBooNE)
- Excess = 57.7+/-18.8+/-22.4 (200-3000 MeV)

Preliminary
July 2011
MiniBooNE Antineutrino Oscillation Results

Preliminary
July 2011
Fit to a 2-(anti)Neutrino Model

- Oscillations favored over background only hypotheses at 97.6% CL (model dependent)
- No assumption made about low energy excess
  - $P(\text{null}) = 10.1\%$
  - $P(\text{best fit}) = 50.7\%$
- Clearly a 2-neutrino model doesn’t describe the data very well
  - No $\nu$ disappearance included in fit

8.58E20 POT
Model Independent Comparison of LSND & MiniBooNE Antineutrino mode

Karmen reports no signal around L/E $\sim 0.5$

Preliminary
July 2011
8.58$\times$10$^{20}$ POT
And with MiniBooNE neutrino mode:

8.58×10^{20} \text{ POT}

Sterile Neutrinos at the Crossroads
Conclusions (I)

Excesses in $\nu_e (~3 \, \sigma)$ and $\bar{\nu}_e (~2.75 \, \sigma)$ above background are emerging in both neutrino mode and antineutrino mode in MiniBooNE.

Antineutrino mode: statistical errors dominate (more data?)

MiniBooNE plans has now accumulated almost $10^{21}$ protons on target in anti-neutrino mode and will continue until March, 2012.

Difficulties remain:

- We cannot determine whether or not the excess events are due to an oscillation phenomena because MiniBooNE has only one detector.
The solution: BooNE

- A MiniBooNE near detector at ~200 meters

- Accumulate a sufficient data sample for both neutrino and antineutrino modes in < 1 year

- will dramatically reduce errors in neutrino mode, the 3σ low energy excess has a ~ 6σ significance with statistical errors only.

- Many short runs for checking systematic effects would be possible, as was done for MINOS (e.g. 25 meter absorber and different horn currents).
A Proposal to Build a MiniBooNE Near Detector: BooNE

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Sterile Neutrinos at the Crossroads
Example: New Location at 200 meters

Existing detector location:

New near detector location:

Proton target location:

541 meters

200 meters

Sterile Neutrinos at the Crossroads
Neutrino Fluxes at Near and Far Locations

Sterile Neutrinos at the Crossroads
$\nu_\mu$ Charged Current Event Rates Near and Far

**Neutrino Mode:**
- Near (black): $1.0 \times 10^{20}$ POT
- Far (red): $6.462 \times 10^{20}$ POT

**Quasi elastic event rates**
Sterile Neutrinos at the Crossroads
BooNE Performance

- Use full MiniBooNE sensitivity machinery
  - Use identical detector response (fully correlated errors)
  - $1 \times 10^{20}$ POT per mode (2 $\times$ 0.5 years at current rates)
  - Reweight MC events for fluxes at 200 meters
  - Full oscillation analysis package applied
Near/Far Sensitivity for Several Distances

- 150 m: $0.6 \times 10^{20}$ POT
- 200 m: $1.0 \times 10^{20}$ POT
- 250 m: $1.5 \times 10^{20}$ POT
- 300 m: $2.0 \times 10^{20}$ POT

Near/Far comparison relatively insensitive to detector distance for roughly the same number of events.

- 200 meters gives similar flux shapes
Sensitivity with Near/Far Comparison

- Near/Far comparison sensitivity
  - Near location at 200 meter
    - $1 \times 10^{20}$ pot ~ 1 yr of running
  - Full systematic error analysis
    - Flux, cross section, detector response

Preferred by some fits

Sterile Neutrinos at the Crossroads
Sensitivity with Near/Far Comparison Anti-nu Mode

- Near/Far comparison sensitivity
  - Near location at 200 meter
    - $1 \times 10^{20}$ pot $\sim 1$ yr of running
  - Full systematic error analysis
    - Flux, cross section, detector response

Sterile Neutrinos at the Crossroads
Neutrino Disappearance Sensitivity with Detector at 200 Meters

Sterile Neutrinos at the Crossroads
Antineutrino Disappearance Sensitivity with Detector at 200 Meters

Preferred by some fits

Sterile Neutrinos at the Crossroads
Conclusions and Outlook

BooNE proposal:
- Cloning MiniBooNE at a near position following the $\bar{\nu}$ run
- Cost $\sim 10M\$ for new detector, 5M\$ reusing the existing MiniBooNE detector.
- Data can be accumulated in $< 1$ yr at present proton delivery rates
- Precision measurements of disappearance and appearance

Powerful addition to MicroBooNE/MiniBooNE running
- Photon/electron rates
- Nu/nubar disappearance and appearance ($\sim 5\sigma$ for both in some cases)
- Very little systematic error
Near Term Steps Towards BooNE

- Will present proposal to the Fermilab PAC early December, 2011
- Dust off MiniBooNE engineering designs
  - Would like to reproduce MiniBooNE as much as possible
  - May transfer old oil and/or electronics to new location in order to reduce any systematic changes
- Optimistic schedule would put turn-on (CD-4) in early FY2014

Sterile Neutrinos at the Crossroads
Sterile Neutrinos at the Crossroads
Sterile Neutrinos at the Crossroads
Can the anomalies be due to a more complicated oscillation picture?

Sterile neutrino models

3+2 → next minimal extension to 3+1 models

• 2 independent $\Delta m^2$
• 4 mixing parameters
• 1 Dirac CP phase which allows difference between neutrinos and antineutrinos

$\Delta m^2_{51} \sim 0.1-100 \text{ eV}^2$
$\Delta m^2_{41} \sim 0.1-100 \text{ eV}^2$
$\Delta m^2_{21} = \Delta m^2_{32} = \Delta m^2_{31} = 0$

Sterile Neutrinos at the Crossroads

Oscillation probability:

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = 4|U_{\mu 4}|^2|U_{e 4}|^2 \sin^2 x_{41} + 4|U_{\mu 5}|^2|U_{e 5}|^2 \sin^2 x_{51} +$$
$$+ 8 |U_{\mu 5}| |U_{e 5}| |U_{\mu 4}| |U_{e 4}| \sin x_{41} \sin x_{51} \cos(x_{54} \pm \phi_{45})$$
Cosmology Fits for the Number of Sterile Neutrinos

Motivation....

$3 + N_s = 0$

$m_\nu = 0$

$N_s = 1.6 \pm 0.9$

Hamann, Hannestad, Raffelt, Tamborra, Wong, PRL 105 (2010) 181301

$N_s = 0.64 \pm 0.4$


Sterile Neutrinos at the Crossroads
E\textgreater{}200\text{MeV}

- 8.58E20 POT antineutrino mode
- Oscillations favored over background only hypotheses at 94.2\% CL (model dependent)
- Subtract low energy excess assuming neutrinos in antinu mode contribute to excess (17 events)
  - P(null) = 28.3\%
  - P(best fit) = 76.5\%

Preliminary
July 2011
MiniBooNE Far/Near fluxes
Scaled by 1/r^2

Oscillation region

Sterile Neutrinos at the Crossroads
Sterile Neutrinos at the Crossroads
### $\bar{\nu}_e$ Background Uncertainties

<table>
<thead>
<tr>
<th>Uncertainty (%)</th>
<th>200-475MeV</th>
<th>475-1100MeV</th>
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<tr>
<td>$\pi^+$</td>
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<tr>
<td>$\pi^-$</td>
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<td>2.3</td>
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<tr>
<td>$K^+$</td>
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<td>$K^-$</td>
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<td>$K^0$</td>
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<tr>
<td>Total</td>
<td>13.4%</td>
<td>16.0%</td>
</tr>
</tbody>
</table>

- Unconstrained $\bar{\nu}_e$ background uncertainties
  - Biggest contributors:
    - Detector response
    - Cross sections

$(\bar{\nu}_\mu$ constrained error $\sim10\%)$