Current Status of LSND and Reactor Anomalies and Future Prospects for Sterile Neutrino Searches

Steve Brice, Fermilab
25 June 2012
Current Indications of Tension in the Standard 3 Neutrino Mixing Scheme

- Gallium: \(2.7\sigma\) evidence for \(\nu_e\) disappearance
- LSND: \(3.8\sigma\) evidence for anti-\(\nu_e\) appearance
- MiniBooNE: \(3.8\sigma\) evidence for \(\nu_e\) and anti-\(\nu_e\) appearance
- Reactor: \(3.0\sigma\) evidence for anti-\(\nu_e\) disappearance

- Can be interpreted as a 4\(^{th}\) neutrino state at eV scale mass

- Only 3 light, Weakly interacting neutrinos (LEP Z width)
- Oscillations with \(\Delta m^2_{\text{solar}}\) and \(\Delta m^2_{\text{atm}}\) are well established
- Therefore a 4\(^{th}\) light state must be sterile

- Many thanks to K.Heeger, T. Lasserre, L.Huillier, C.Polly, M.Shaevitz for material
Gallium Anomaly

- Calibration of the Gallium Solar $\nu$ Detectors
- e-capture sources
  - $^{51}$Cr (750 keV) & $^{37}$Ar (810 keV)

- The goal was to calibrate the production and extraction efficiency of the SAGE and GALLEX experiments

- Deficit observed
- $R_{\text{obs/pred}} = 0.86 \pm 0.05 \ (\sigma_{\text{Bahcall}})$
- $R_{\text{obs/pred}} = 0.76 \pm 0.085 \ (\sigma_{\text{Haxton}})$
Gallium Anomaly

- No-oscillation hypothesis disfavored at 2.7σ (PRC 83 065504, 2011)

- Was not treated as evidence for new physics until the other anomalies appeared
LSND

- Used 800 MeV protons from LAMPF at Los Alamos in the 1990’s
- Searched for anti-$\nu_e$ appearance in neutrino beam from pion decay at rest.

- Found an excess of anti-$\nu_e$ over background prediction
  - $87.9 \pm 22.4 \pm 6.0$ (3.8$\sigma$)
Keep L/E same as LSND while changing systematics, energy & event signature

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

Order of magnitude higher energy (~500 MeV) than LSND (~30 MeV)

Order of magnitude longer baseline (~500 m) than LSND (~30 m)
MiniBooNE Update

- 6.6 x 10^{20} POT in neutrino mode
  - No neutrino mode data added
- 11.3 x 10^{20} POT in anti-neutrino mode
  - Results updated in Kyoto with double the POT previously published
- Modest Improvements to the (anti-)nue analysis
  - *In situ* measurement of WS contamination in anti-ν beam
    Phys.Rev.D84,072005 (2011)
  - New SciBooNE constraint on intrinsic ν\textsubscript{e} from K+
  - Added error matrix for intrinsic ν\textsubscript{e} from K-
  - Improved smoothing algorithm used to assess systematics due to discriminator thresholds and PMT response
  - CCπ\textsuperscript{+} events (bkg for ν\textsubscript{μ} CCQE when π\textsuperscript{+} is absorbed) Q\textsuperscript{2} reweighting applied based on internal MB measurement
Neutrino mode 3+1 fits with all updates

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<table>
<thead>
<tr>
<th>ν mode</th>
<th>E &gt; 200 MeV</th>
<th>E &gt; 475 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$(null)</td>
<td>22.81</td>
<td>6.35</td>
</tr>
<tr>
<td>Prob(null)</td>
<td>0.5%</td>
<td>36.6%</td>
</tr>
<tr>
<td>$\chi^2$(bf)</td>
<td>13.24</td>
<td>3.73</td>
</tr>
<tr>
<td>Prob(bf)</td>
<td>6.12%</td>
<td>42.0%</td>
</tr>
</tbody>
</table>

Overall probability of bf 6%...not great, but also not terrible
**Anti-ν<sub>e</sub> CCQE signal candidates with 11.3e20 POT**

Higher stat anti-neutrino data is now much more consistent with what was observed in the data taken with a neutrino beam

* Systematic error after all other data constraints applied, e.g. ν<sub>μ</sub> CCQE, NC π<sup>0</sup>, dirt events, SciBooNE K<sup>+</sup>

<table>
<thead>
<tr>
<th>E&lt;sub&gt;ν&lt;/sub&gt;(QE) range</th>
<th>Data</th>
<th>Bkg ± stat ± syst*</th>
<th>Excess</th>
</tr>
</thead>
<tbody>
<tr>
<td>200-475 MeV</td>
<td>257</td>
<td>199.1 ± 14.1 ± 16.3</td>
<td>57.9 ± 21.6 (2.7σ)</td>
</tr>
<tr>
<td>475-1250 MeV</td>
<td>221</td>
<td>201.1 ± 14.2 ± 17.9</td>
<td>19.9 ± 22.8 (0.9σ)</td>
</tr>
<tr>
<td>200-1250 MeV</td>
<td>478</td>
<td>400.2 ± 20.0 ± 23.4</td>
<td>77.8 ± 30.8 (2.5σ)</td>
</tr>
</tbody>
</table>
Fitting anti-neutrino data to 2ν model

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<table>
<thead>
<tr>
<th>anti-ν mode</th>
<th>$E &gt; 200$ MeV</th>
<th>$E &gt; 475$ MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$(null)</td>
<td>16.3</td>
<td>7.59</td>
</tr>
<tr>
<td>Prob(null)</td>
<td>5.8%</td>
<td>26.4%</td>
</tr>
<tr>
<td>$\chi^2$(bf)</td>
<td>4.76</td>
<td>3.23</td>
</tr>
<tr>
<td>Prob(bf)</td>
<td>67.5%</td>
<td>50.2%</td>
</tr>
</tbody>
</table>

No tension
Comparing neutrino to anti-neutrino mode

6.7e20 POT neutrino mode

11.3e20 POT anti-neutrino mode

Excess: 146.3 ± 28.4 ± 40.2

Excess: 77.8 ± 20.0 ± 23.4
Simultaneous 3+1 fit to $\nu$ and anti-$\nu$ data

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- **WS accounted for properly**
- **Construction of correlated systematic error matrix**
- **E>200 MeV BF preferred at 3.6$\sigma$ over null**

<table>
<thead>
<tr>
<th></th>
<th>E &gt; 200 MeV</th>
<th>E &gt; 475 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$(null)</td>
<td>42.53</td>
<td>12.87</td>
</tr>
<tr>
<td>Prob(null)</td>
<td>0.1%</td>
<td>35.8%</td>
</tr>
<tr>
<td>$\chi^2$(bf)</td>
<td>24.72</td>
<td>10.67</td>
</tr>
<tr>
<td>Prob(bf)</td>
<td>6.7%</td>
<td>35.8%</td>
</tr>
</tbody>
</table>

* Simultaneous fit (E>200 MeV) with fully-correlated systematic to entire MB neutrino and anti-neutrino data

**Total Excess:** 240.3 +/- 34.5 +/- 52.6
MiniBooNE observes an excess of $\nu_e$ candidates in the 200-1250 MeV energy range in neutrino mode (3.0σ) and in anti-neutrino mode (2.5σ). The combined excess is $240.3 \pm 34.5 \pm 52.6$ events (3.8σ).

The event excess is concentrated in the 200-475 MeV region where NC $\pi^0$ and other processes leading to a single $\gamma$ dominate.

Higher statistics anti-$\nu$ data is now similar to the neutrino mode data.

It is not yet known whether the MiniBooNE excesses are due to oscillations, some unrecognized NC $\gamma$ background, or something else.
Reactor Neutrino Anomaly

\[ \nu \text{ emission:} \]
- Improved reactor neutrino spectra produces +3.5%
- Accounting for long-lived isotopes accumulating in reactors produces +1%
- PRC83, 054615 (2011)
- PRC84, 024617 (2011)

\[ \nu \text{ detection:} \]
- Reevaluation of \(\sigma_{\text{IBD}}\) Improved neutron life time measurements produces +1%

**Observed/predicted averaged event ratio**: \(R = 0.927 \pm 0.023 \ (3.0 \ \sigma)\)

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Interpreted as Oscillation with 4th State
Interpreted as Oscillation with 4th State

Rate Analysis

Rate + Shape Analysis

Plot from G.Mention et al arXiv:1101.2755
Counter Evidence for 4\textsuperscript{th} State

There are a number of results that are sensitive, but see no evidence for a 4\textsuperscript{th} neutrino state with $\sim$eV mass:

- CDHS and MiniBooNE searches for $\nu_\mu$ disappearance
- MiniBooNE search for $\bar{\nu}_\mu$ disappearance
- MINOS search for $\nu_\mu \rightarrow \nu_s$
- Karmen search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

It is hard (impossible?) to fit all data with a single oscillation hypothesis
Future Tests

• Need a definitive test(s) of the 4th neutrino hypothesis hinted at by the current anomalies

• Many tests proposed. They fall into three types:
  1) Detector <15 m from compact nuclear reactor
  2) Accelerator based short baseline
  3) Intense sources close to or in detector

• For definitive test would like oscillation evidence in E and L and redundant cross-checks

• See Sterile Neutrino White Paper
  • arXiv:1204.5379

• Upcoming report from Fermilab Short Baseline Working Group
Reactor Searches for 4\textsuperscript{th} State

- Get a ton scale detector 2-10m from a compact core

![Expected E spectrum deformation with anomaly best fit: $\Delta m^2 = 2.4 \, \text{eV}^2 \, \sin^2(2\theta) = 0.15$](image)

- Look for depleted rate and altered shape

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## Proposed Reactor Short Baseline Experiments

<table>
<thead>
<tr>
<th>Proposal</th>
<th>Reactor</th>
<th>Fuel (#fissions)</th>
<th>Core Size (m)</th>
<th>&lt;L&gt; (m)</th>
<th>Depth (mwe)</th>
<th>Status</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nucifer</td>
<td>Osiris</td>
<td>235U ON-OFF cycle</td>
<td>&lt;1</td>
<td>7</td>
<td>5</td>
<td>Data Taking</td>
<td>Non proliferation 1 m³ Gd-LS</td>
</tr>
<tr>
<td>Saclay</td>
<td>70 MW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mostly Rate + Shape?</td>
</tr>
<tr>
<td>Stereo</td>
<td>ILL</td>
<td>235U ON-OFF cycle</td>
<td>&lt;1</td>
<td>10</td>
<td>10</td>
<td>Proposal</td>
<td>2 m³ Gd-LS</td>
</tr>
<tr>
<td>Genoble</td>
<td>50 MW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Rate + Mostly shape</td>
</tr>
<tr>
<td>SCRAMM (Ca)</td>
<td>San-Onofre</td>
<td>235,238U</td>
<td>3x3.8</td>
<td>24</td>
<td>30</td>
<td>Proposal</td>
<td>2 m³ Gd-LS</td>
</tr>
<tr>
<td></td>
<td>3 GW PWR</td>
<td>239.241Pu</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mostly Rate + Shape</td>
</tr>
<tr>
<td>SCRAMM (Idaho)</td>
<td>ATR</td>
<td>235U ON-OFF cycle</td>
<td>&lt;1</td>
<td>12</td>
<td>15</td>
<td>Proposal</td>
<td>2 m³ Gd-LS</td>
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<tr>
<td></td>
<td>150 MW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Rate + Mostly shape</td>
</tr>
<tr>
<td>DANSS (Russia)</td>
<td>KNPP</td>
<td>235,238U</td>
<td>few</td>
<td>14</td>
<td>70</td>
<td>Being Built</td>
<td>Segmented detector 1 m³ Rate + Shape?</td>
</tr>
<tr>
<td></td>
<td>3 GW PWR</td>
<td>239.241Pu</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NIST (US)</td>
<td>NCNR</td>
<td>235U ON-OFF cycle</td>
<td>≈1</td>
<td>4-11</td>
<td>0</td>
<td>Proposal</td>
<td>Rate + Mostly shape</td>
</tr>
<tr>
<td></td>
<td>20 MW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Nu4 (Russia)</td>
<td>SM-3</td>
<td>235U ON-OFF cycle</td>
<td>0.35x0.42</td>
<td>6-12</td>
<td>10</td>
<td>Being Built</td>
<td>14 m³ Gd-LS</td>
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<tr>
<td></td>
<td>100 MW</td>
<td></td>
<td>0.42</td>
<td></td>
<td></td>
<td></td>
<td>Rate + shape</td>
</tr>
</tbody>
</table>

Table from T. Lasserre
Accelerator Based Short Baseline Search

• Wish (Requirements) list:-

  • Need significance at >5σ level
  • Would like to see effect in L and E
  • Would like to have redundant crosschecks within an experiment
  • Would like to see a consistent picture with appearance and disappearance

• Four experiment types:-

  • Accelerator isotope production with large detector close by
  • Pion/Kaon decay at rest (C.F. LSND, Karmen)
  • Pion decay in flight (C.F. MiniBooNE)
  • Low energy neutrino factory
# Accelerator Short Baseline Experiments

<table>
<thead>
<tr>
<th>Isotope Source</th>
<th>Disapp &amp; Appearance</th>
<th>Osc Channel 1</th>
<th>Osc Channel 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pion / Kaon Decay-at-Rest Source</td>
<td>Appearance &amp; Disapp</td>
<td>$\bar{\nu}_e \rightarrow \bar{\nu}_e$</td>
<td>OscSNS, CLEAR, DAEδALUS, KDAR</td>
</tr>
<tr>
<td>Accelerator $\nu$ using Pion Decay-in-Flight</td>
<td>Appearance &amp; Disapp</td>
<td>$\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$</td>
<td>MINOS+, MicroBooNE, LAr1kton+MicroBooNE, CERN SPS</td>
</tr>
<tr>
<td>Low-Energy $\nu$-Factory</td>
<td>Appearance &amp; Disapp</td>
<td>$\nu_e \rightarrow \nu_\mu$, $\bar{\nu}<em>e \rightarrow \bar{\nu}</em>\mu$, $\nu_\mu \rightarrow \nu_\mu$, $\nu_e \rightarrow \nu_e$</td>
<td>$\nu$STORM at Fermilab</td>
</tr>
</tbody>
</table>

Table from M. Shaevitz
• Test 4\textsuperscript{th} state hypothesis with \textasciitilde\text{MeV} (anti-)neutrino sources placed a few meters from large low background detector
  • Similar to the $^{51}$Cr calibrations of the SAGE and GALLEX solar $\nu$ detectors
  • Can use existing reactor/solar neutrino detectors
  • Can place source inside or just outside detector

• Can search for effect on energy spectrum and rate as a function of distance from source.

• Typically need compact MCi source
  • Technically non-trivial
  • e.g. $^{144}$Ce
# Proposals with Intense Radioactive Sources

<table>
<thead>
<tr>
<th>Type</th>
<th>channel</th>
<th>Background</th>
<th>Source</th>
<th>Production</th>
<th>Activity (Mci)</th>
<th>Proposal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$</td>
<td>$\nu_e e \rightarrow \nu_e e$</td>
<td>radioactivity (managable)</td>
<td>$^{51}\text{Cr}$</td>
<td>$n_{th}$ irradiation in Reactor</td>
<td>in, out &gt;3</td>
<td>Sage LENS</td>
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<tr>
<td></td>
<td></td>
<td>Solar $\nu$ (irreducible)</td>
<td></td>
<td>$^{37}\text{Ar}$</td>
<td>&gt;1</td>
<td>SOX SNO+</td>
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<tr>
<td></td>
<td></td>
<td>$5% E_{\text{res}}$</td>
<td></td>
<td>$n_{\text{fast}}$ irradiation in Reactor</td>
<td>in, out 5-10</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>15cm $R_{\text{res}}$</td>
<td></td>
<td></td>
<td></td>
<td>Ricochet (NC)</td>
</tr>
<tr>
<td>$\bar{\nu}_e$</td>
<td>$\bar{\nu}_e p \rightarrow e^+ n$</td>
<td>$E_{\text{th}}=1.8$ MeV $E_{\text{th}}=1.8$ MeV</td>
<td>$^{144}\text{Ce}$</td>
<td>spent nuclear fuel reprocessing</td>
<td>in, out 0.5</td>
<td>Daya-Bay</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(e$^+$,n) Coincidence</td>
<td></td>
<td>$^{90}\text{Sr}$</td>
<td>0.005-0.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$E_{\text{th}}=1.8$ MeV $E_{\text{th}}=1.8$ MeV</td>
<td></td>
<td>$^{106}\text{Rh}$</td>
<td>0.5</td>
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<tr>
<td></td>
<td></td>
<td>$5% E_{\text{res}}$</td>
<td></td>
<td>$^{42}\text{Ar}$</td>
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<tr>
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<td></td>
<td>15cm $R_{\text{res}}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table from T.Lasserre
Conclusions

• A number of intriguing hints at oscillations involving a 4\textsuperscript{th} \( \nu \) state

• No single hint is compelling

• Much experimental evidence is in tension with such a 4\textsuperscript{th} state

• Nonetheless the situation cannot be ignored

• Definitive experiments are needed in more than one experimental domain

• Many proposals are on the table and some would be definitive
MiniBooNE Detector

541 meters downstream of target
3 meter overburden of dirt
12 meter diameter sphere
Filled with 800 t of pure mineral oil
\((\text{CH}_2 -- \text{density } 0.86, n=1.47)\)
Fiducial volume: 450 t
1280 inner 8” phototubes 10% coverage,
240 veto phototubes
Neutrino and anti-neutrino analyses are identical

Start with pre-cuts

- No late time activity, removes Michel electrons, cuts ~80% of $\nu_\mu$ CCQE events
- Veto hits < 6, contained & not a cosmic
- Tank hits > 200 & visible E > 140 MeV, removes NC elastic bkgs
- Radius < 500 cm, far enough from PMTs to avoid area where light modeling becomes less certain
- R-to-wall backward cut, removes bkgs (mainly $\gamma$'s) from beam $\nu$ that interact in dirt outside the detector
Form sophisticated Q and T pdfs, and fit for track parameters under 3 hypotheses:
- The track is due to an electron
- The track is coming from a muon
- The "track" is a two-track (ring) π^0 event

Apply energy-dependent cuts on L(e/μ), L(e/π), and the π^0 mass

Plot remaining events versus E_{ν}(QE) and fit.
KS test 17.8% (29.5% if exclude absorber down period)

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>1st half Data</th>
<th>1st half MC</th>
<th>1st half Excess</th>
<th>2nd half Data</th>
<th>2nd half MC</th>
<th>2nd half Excess</th>
</tr>
</thead>
<tbody>
<tr>
<td>200-475</td>
<td>119</td>
<td>100.5±14.3</td>
<td>18.5 (1.3s)</td>
<td>138</td>
<td>100.0±14.1</td>
<td>38 (2.7s)</td>
</tr>
<tr>
<td>475-1250</td>
<td>120</td>
<td>99.1±14.0</td>
<td>20.9 (1.5s)</td>
<td>101</td>
<td>103.1±14.4</td>
<td>-2.2 (-0.2s)</td>
</tr>
</tbody>
</table>
* Note this plot assumes that the excess events in anti-neutrino mode come only from the anti-neutrino beam content, $P(\text{osc})$ at highest 3 $L/E$ bins would be reduced by 25% WS contamination were also included.
Can also compare to LSND $P(\text{osc})$
Maximum likelihood fit:

$$ -2 \ln(L) = (x_1 - \mu_1, ..., x_n - \mu_n) M^{-1} (x_1 - \mu_1, ..., x_n - \mu_n)^T + \ln(|M|) $$

\[ M = M_{om} + M_{xsec} + M_{flux} + M_{\pi^0} + M_{dirt} + M_{K^0} + \ldots \]

Simultaneously fit (FC-corrected)

- $\nu_e$ CCQE signal + high E $\nu_e$ sample
- High statistics $\nu_\mu$ CCQE sample

$\nu_\mu$ CCQE sample acts like a near detector, i.e. same flux as oscillation $\nu_e$ by definition, lepton universality + muon mass corrections fix relative cross-section

$\nu_\mu$ flux through detector ($\nu$ mode)

June 25 2012

Steve
**In situ** measurement of WS contamination in anti-$\nu$ beam \textit{Phys.Rev.D84,072005 (2011)}

- $\nu_\mu$ CCQE angular fit, and new constraint from $CC\pi^+$ rate...good agreement with expectation

New SciBooNE constraint on intrinsic $\nu_e$ from $K^+$
- Found $K^+$ production to be $0.85 \pm 0.12$ relative to prediction, consistent with prior MiniBooNE assessment of $1.00 \pm 0.30$
- Combined with world $K^+$ production data, reduces error on $K^+$ flux to 9% in MB $E\nu$ range
- Leading error on $K^+$ bkgs becomes $\sim20\%$ error from cross-section
Few other minor updates...

- Added error matrix for intrinsic $\nu_e$ from K-

- Improved smoothing algorithm that was being used to assess systematics due to discriminator thresholds and PMT response

- $CC\pi^+$ events (bkg for $\nu_\mu$ CCQE when $\pi^+$ is absorbed) $Q^2$ reweighting applied based on internal MB measurement... *Phys.Rev.D83,052007 (2011)*
- $5.66 \times 10^{20}$ POT $\rightarrow$ $11.3 \times 10^{20}$ POT
- higher statistics in anti-$\nu_e$ appearance
- ...and samples used for constraints
What can we say about low-E excess...

- Not a stat fluctuation, statistically $6\sigma$
- Unlikely to be intrinsic $\nu_e$, small bkg at low E
- NC $\pi^0$ background dominates
  - reduce significance to $3\sigma$
  - heavily constrained by NC $\pi^0$ in situ rate
- Region where single $\gamma$ backgrounds can contribute
- MB ties $\Delta \rightarrow N\gamma$ expected rate to be $\sim1\%$ of measured NC $\pi^0$ rate
  - Number of theory calculation for various single $\gamma$ processes
  - All find total cross-section within 20% of MiniBooNE's $\sim5 \times 10^{-42}$ cm$^2$/N
  - Would need nearly 300% change...

R. Hill, arXiv:0905.0291
Jenkins & Goldman, arXiv:0906.0984
Serot & Zhang, arXiv:1011.5913
Something to consider...

- This plot assumes CCQE-like reconstruction

\[ E_\nu = \frac{2(M_n - E_B)E_\mu - (E_B^2 - 2M_nE_B + m_\mu^2 + \Delta M^2)}{2 [(M_n - E_B) - E_\mu + p_\mu \cos \theta_\mu]} \]

- Additional participants other than the outgoing lepton and struck nucleon will cause events to reconstruct at lower \( E_\nu^{\text{QE}} \)
- This plot assumes CCQE-like reconstruction

\[ E_\nu = \frac{2(M_n - E_B)E_\mu - (E_B^2 - 2M_nE_B + m_\mu^2 + \Delta M^2)}{2 [(M_n - E_B) - E_\mu + p_\mu \cos \theta_\mu]} \]

- Additional participants other than the outgoing lepton and struck nucleon will cause events to reconstruct at lower \( E_\nu(QE) \)

- MiniBooNE finds a cross-section for \( \nu_\mu \) CCQE that is 20-30% higher than expected

- Number of theorists suggesting this could arise from multi-nucleon correlations, observed many years ago in e-scattering

- Could help explain why MB xsec is higher than free nucleon, differences between expts where event selection can depend on final state nucleons

Steve Brice  Fermilab
Comparison between models including np-nh

Martini et al.

Nieves et al.

Amaro et al.

Bodek et al.

QE \{ 
- only vector 
- only MEC 2p2h 

\[ \sigma (E_\nu, E_r) \text{[cm}^2 \text{]} \]

\[ \sigma (E_\nu, E_r) \text{[cm}^2 \text{]} \]

\[ \sigma (E_\nu, E_r) \text{[cm}^2 \text{]} \]

\[ \sigma (E_\nu, E_r) \text{[cm}^2 \text{]} \]
Relevant for oscillation analysis?

- Means a fraction of oscillated $\nu_e$ could be misreconstructed (similar to CC$\pi^+$ case)
- Could feed down help relax tension between low and mid range energies?
- Possible, but MiniBooNE corrects sig/bkg predictions based on the measured $\nu_\mu$ spectrum
- Studies where we double the $\pi^+$ absorption rate, and then retune sig/bkg predictions to match to CCQE...negligible impact
Account for neutrino low-E events

- Fits on prior page assume only anti-neutrinos are oscillating, but we know there is a low E excess in nu mode data.
- Simplest scaling is to assume that there should be an excess in the low energy region proportional to the WS content (21 events).

* E>200 MeV fits to full anti-neutrino statistics (11.3e20 POT)
## Reanalysis of Reactor Experiments

<table>
<thead>
<tr>
<th>result</th>
<th>Det. type</th>
<th>$\tau_n$ (s)</th>
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