Updated MiniBooNE Results

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Outline

• MiniBooNE Experiment Description
• MiniBooNE’s Neutrino Results
• MiniBooNE’s Anti-neutrino Results
• Next Steps and Summary
This signal looks very different from the others...

- Much higher $\Delta m^2 = 0.1 - 10 \text{ eV}^2$
- Much smaller mixing angle
- Only one experiment!

In SM there are only 3 neutrinos

- Three distinct neutrino oscillation signals, with $\Delta m^2_{solar} + \Delta m^2_{atm} \neq \Delta m^2_{LSND}$
- For three neutrinos, expect $\Delta m^2_{21} + \Delta m^2_{32} = \Delta m^2_{31}$

The three oscillation signals cannot be reconciled without introducing Beyond Standard Model Physics
This signal looks very different from the others...
- Much higher $\Delta m^2 = 0.1 - 10 \text{ eV}^2$
- Much smaller mixing angle
- Only one experiment!

In SM there are only 3 neutrinos

$\Delta m_{23}$
$\Delta m_{13}$

$\nu_e \rightarrow \nu_X$

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Atmospheric

Solar MSW

Oscillation Status After LSND

This signal looks very different from the others...
- Much higher $\Delta m^2 = 0.1 - 10 \text{ eV}^2$
- Much smaller mixing angle
- Only one experiment!
Oscillation explanation of LSND in conjunction with the atmospheric and solar oscillation results needed more than 3 ν’s.

Models developed with 1 or more sterile ν’s (or other new physics models).

Simplified 3+2 Models for ν_μ → ν_e:
2 independent Δm^2
3 mixing parameters
1 Dirac CP phase
It was important to check LSND what was left to MiniBooNE

(Booster Neutrino Experiment)
MiniBooNE Setup

Keep L/E same as LSND while changing systematics, energy & event signature

\[ P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E) \rightarrow \text{Two neutrino fits} \]

**LSND:**
- \( E \sim 30 \text{ MeV} \)
- \( L \sim 30 \text{ m} \)
- \( L/E \sim 1 \)

**MiniBooNE:**
- \( E \sim 500 \text{ MeV} \)
- \( L \sim 500 \text{ m} \)
- \( L/E \sim 1 \)

Neutrino mode: search for \( \nu_\mu \rightarrow \nu_e \) appearance with 6.5E20 POT \( \rightarrow \) assumes CP/CPT conservation

Antineutrino mode: search for \( \bar{\nu}_\mu \rightarrow \bar{\nu}_e \) appearance with 5.66E20 POT \( \rightarrow \) direct test of LSND
MiniBooNE Detector:
- 12 m diameter sphere
- 950000 liters of oil (CH₂)
- 1280 inner PMTs
- 240 veto PMTs

Detector Requirements:
- Detect and Measure Events: Vertex, $E_{\nu}$
- Separate $\nu_\mu$ events from $\nu_e$ events.
Čerenkov rings provide primary means of identifying products of $\nu$ interactions in the detector.

$\nu_\mu \ n \rightarrow \mu^- \ p$

$\nu_e \ n \rightarrow e^- \ p$

Multi-ring (e.g. $\pi^0 \rightarrow \gamma \gamma$)

$\nu_\mu \ p \rightarrow \nu_\mu \ p \ \pi^0$

$\pi^0 \rightarrow \gamma \gamma$
Energy Calibration

Tracker system

15% E resolution at 53 MeV

MiChel electrons

δm ~ 20%

π^0 photon energies

Tracker & Cubes

Through-going cosmics

Visible energy range of oscillation signal
Booster Flux at MiniBooNE

Neutrino-Mode Flux

\[ \pi^+ \rightarrow \mu^+ \nu_\mu \quad E_{\text{avg}} \sim 0.8 \text{ GeV} \]

- \( \nu_\mu \)
- \( \bar{\nu}_\mu \)
- \( \nu_e \)
- \( \bar{\nu}_e \)

\( K^+ \rightarrow \mu^+ \nu_\mu \)

\( \sim 6\% \ \bar{\nu} \)

Antineutrino-Mode Flux

\[ \pi^- \rightarrow \mu^- \bar{\nu}_\mu \quad E_{\text{avg}} \sim 0.6 \text{ GeV} \]

- \( \nu_\mu \)
- \( \bar{\nu}_\mu \)
- \( \nu_e \)
- \( \bar{\nu}_e \)

\( K^- \rightarrow \mu^- \bar{\nu}_\mu \)

\( \sim 18\% \ \nu \)

Subsequent decay of the \( \mu^+ (\mu^-) \) produces \( \bar{\nu}_e (\nu_e) \) intrinsics \( \sim 0.5\% \)

neutrino mode: \( \nu_\mu \rightarrow \nu_e \) oscillation search

antineutrino mode: \( \bar{\nu}_\mu \rightarrow \bar{\nu}_e \) oscillation search

Appearance experiment: it looks for an excess of electron neutrino events in a predominantly muon neutrino beam
**νₑ, νₑ Event Rate Predictions**

\[ \text{Events Rate} = \text{Flux} \times \text{Cross-sections} \times \text{Detector response} \]

- External measurements (HARP, etc)
- νₑ rate constrained by neutrino data
- νµ rate constrained by neutrino data
- External and MiniBooNE Measurements
  \[\pi^0, \Delta \rightarrow N\gamma, \text{dirt, and intrinsic}\]
- νₑ constrained from data
- Detailed detector simulation and PID
- Checked with neutrino data and calibration sources

- A. A. Aguilar-Arevalo et al., “Measurement of νₑ and νµ induced neutral current single \(\pi^0\) production cross sections on mineral oil at \(E_n \sim 1 \text{ GeV}\)”, Phys. Rev. D81, 013005 (2010).
Neutrino Mode MiniBooNE Results (2009)

- 6.5E20 POT collected in neutrino mode
- E > 475 MeV data in good agreement with background prediction
  - Energy region has reduced backgrounds and maintains high sensitivity to LSND oscillations.
  - A two neutrino fit rules out LSND at the 90% CL assuming CP conservation.
- E < 475 MeV, statistically large (6σ) excess
  - Reduced to 3σ after systematics, shape inconsistent with two neutrino oscillation interpretation of LSND.
Excess of 129 +/- 43 (stat+sys) events is consistent with magnitude of LSND oscillations.

Published PRL 102,101802 (2009)
Reminder of Some Pre-unblinding Choices

We are using energy range $E_{\nu} > 475$ MeV in oscillation analysis.

Why is the 200-475 MeV region unimportant for oscillation search?
- Large backgrounds from mis-ids reduce S/B.
- Many systematics grow at lower energies.
- Most importantly, not a region of L/E where LSND observed a significant signal
Neutrino Mode MiniBooNE Results (2009): Limit

Neutrino Exclusion Limits: 6.5E20 POT

(E>475 MeV)
Several possible explanations have been put forth by the physics community, attempting to reconcile the MiniBooNE neutrino mode result with LSND and other appearance experiments…

- 3+2 with CP violation
  [Maltoni and Schwetz, hep-ph/0705.0107; G. K., NuFACT 07 conference]
- Anomaly mediated photon production
  [Harvey, Hill, and Hill, hep-ph/0708.1281]
- New light gauge boson
- Neutrino decay
  [hep-ph/0602083]
- Extra dimensions
  [hep-ph/0504096]
- CPT/Lorentz violation
  [PRD(2006)105009]
- …

\[ \nu_\mu \rightarrow \nu_e \neq \bar{\nu}_\mu \rightarrow \bar{\nu}_e ? \]
We have collected about $\sim 1/5$ the number of interactions as in neutrino mode

- Similar number of protons on target so far in two modes
- The flux per proton on target is lower ($\sim \times 1.5$) in $\nu$ mode
- The cross section is lower ($\sim \times 3$) in $\bar{\nu}$ mode
- Background types and relative rates are similar for neutrino and antineutrino mode.
  - except inclusion of 15.9% wrong-sign neutrino flux component in antineutrino mode
- Fit analysis and errors are similar.
\( \nu_e, \bar{\nu}_e \) Background Predictions After Reconstruction and Selection

Neutrino 6.5x10^{20} POT

AntiNeutrino 5.66x10^{20} POT

\( E_{\nu}^{QE} = \) Reconstructed neutrino energy (MeV)
First Anti-neutrino Mode Results (2009): 3.4E20 POT

- 3.4E20 POT collected in anti-neutrino mode
- From 200-3000 MeV excess is 4.8 +/- 17.6 (stat+sys) events.
- Statistically small excess in 475-1250 MeV region
  - Only antineutrino’s allowed to oscillate in fit
  - Limit from two neutrino fit excludes less area than sensitivity due to fit adding a LSND-like signal to account for wiggle
  - Stat error too large to distinguish LSND-like from null
- No significant excess E < 475 MeV.

<table>
<thead>
<tr>
<th>$E_\nu$ [MeV]</th>
<th>200-475</th>
<th>475-1250</th>
</tr>
</thead>
<tbody>
<tr>
<td>total background</td>
<td>60.29</td>
<td>57.78</td>
</tr>
<tr>
<td>$\nu_e$ intrinsic</td>
<td>17.74</td>
<td>43.23</td>
</tr>
<tr>
<td>$\nu_\mu$ induced</td>
<td>42.54</td>
<td>14.55</td>
</tr>
<tr>
<td>NC $\pi^0$</td>
<td>24.60</td>
<td>7.17</td>
</tr>
<tr>
<td>NC $\Delta\rightarrow N\gamma$</td>
<td>6.58</td>
<td>2.02</td>
</tr>
<tr>
<td>Dirt</td>
<td>4.69</td>
<td>1.92</td>
</tr>
<tr>
<td>CCQE</td>
<td>2.86</td>
<td>1.24</td>
</tr>
<tr>
<td>other</td>
<td>3.82</td>
<td>2.20</td>
</tr>
<tr>
<td>LSND best fit</td>
<td>4.33</td>
<td>12.63</td>
</tr>
</tbody>
</table>

Published PRL 103,111801 (2009)
First Anti-neutrino Mode Results (2009): 3.4E20 POT

Anti-Neutrino Exclusion Limits: 3.4E20 POT
New Anti-neutrino mode results: $5.66 \times 10^{20}$ POT
(70% more data)
Data Checks

- Beam and Detector low level stability checks; beam stable to 2%, and detector energy response to 1%.
- $\bar{\nu}_\mu$ rates and energy stable over entire antineutrino run.
- Independent measurement of $\pi^0$ rate for antineutrino mode.
- Measured dirt rates are similar in neutrino and antineutrino mode.
- Measured $\nu$ wrong sign component stable over time and energy.
- Checked off axis rates from NuMI beam.
- Above 475 MeV, about two thirds of the electron (anti)neutrino intrinsic rate is constrained by simultaneous fit to $\bar{\nu}_\mu$ data.
- New SciBooNE neutrino mode $K^+$ weight = $0.75 \pm 0.05$ (stat) $\pm 0.30$ (sys).
- One third of electron neutrino intrinsic rate come from $K^0$, where we use external measurements and apply 30% error.
  - Would require $>3\sigma$ increase in $K^0$ normalization, but shape does not match well the excess.
Signal Prediction

- Assuming only right sign oscillates ($\bar{\nu}_\mu$)
- Need to know wrong sign vs right sign
- We measure it
- $\bar{\nu}_\mu$ CCQE gives more forward peaked muon
Oscillation Fit Method

• Maximum likelihood fit:

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

• Simultaneously fit
  – $\nu_e$ CCQE sample
  – High statistics $\nu_\mu$ CCQE sample

• $\nu_\mu$ CCQE sample constrains many of the uncertainties:
  – Flux uncertainties
  – Cross section uncertainties (CCQE process)
The following three distinct samples are used in the oscillation fits:

1. **Background** to $\nu_e$ oscillations
2. $\nu_e$ Signal prediction (dependent on $\Delta m^2$, $\sin^2 2\theta$)
3. $\nu_\mu$ CCQE sample, used to constrain $\nu_e$ prediction (signal+background)

\[
-2 \ln(L) = (x_1 - \mu_1, \ldots, x_n - \mu_n) M^{-1} (x_1 - \mu_1, \ldots, x_n - \mu_n)^T + \ln(\det(M))
\]

$M_{ij} =$ full syst+stat covariance matrix at best fit prediction

logL calculated using both datasets ($\nu_e$ and $\nu_\mu$ CCQE), and corresponding covariance matrix
New Anti-neutrino mode results: 5.66E20 POT

<table>
<thead>
<tr>
<th></th>
<th>200-475 MeV</th>
<th>475-1250 MeV</th>
<th>200-3000 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>119</td>
<td>120</td>
<td>277</td>
</tr>
<tr>
<td>MC (stat+sys)</td>
<td>100.5 ± 14.3</td>
<td>99.1 ± 13.9</td>
<td>233.8 ± 22.5</td>
</tr>
<tr>
<td>Excess (stat)</td>
<td>18.5 ± 10.0 (1.9σ)</td>
<td>20.9 ± 10.0 (2.1σ)</td>
<td>43.2 ±15.3 (2.8σ)</td>
</tr>
<tr>
<td>Excess (stat+sys)</td>
<td>18.5 ± 14.3 (1.3σ)</td>
<td>20.9 ± 13.9 (1.5σ)</td>
<td>43.2 ± 22.5 (1.9σ)</td>
</tr>
</tbody>
</table>

![Graph showing Events/MeV vs. $E^\text{QE}_\nu$ (GeV)]

- Data (stat err.)
- $\nu_e$ from $\mu^{+/−}$
- $\nu_e$ from $K^{+/−}$
- $\nu_e$ from $K^0$
- $\pi^0$ misid
- $\Delta \rightarrow N\gamma$
- dirt
- other
- other
- Constr. Syst. Error

$>$475 MeV
Testing the Null Hypothesis

- Model independent.
- At null look at the $\chi^2$ distribution of fake experiments (thrown from null error matrix).

<table>
<thead>
<tr>
<th>Energy</th>
<th>chi2/NDF</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>E &gt; 475 MeV</td>
<td>26.8/14.9</td>
<td>3.0%</td>
</tr>
<tr>
<td>E &gt; 200 MeV</td>
<td>33.2/18.0</td>
<td>1.6%</td>
</tr>
</tbody>
</table>

E > 475 MeV

E > 475 MeV
### Comparison to LSND

<table>
<thead>
<tr>
<th>$E_{\nu}(QE)$ [MeV]</th>
<th>200-475</th>
<th>475-1250</th>
<th>1250-3000</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC Background</td>
<td>100.5</td>
<td>99.1</td>
<td>34.2</td>
</tr>
<tr>
<td>Data</td>
<td>119</td>
<td>120</td>
<td>38</td>
</tr>
<tr>
<td>Excess</td>
<td>$18.5 \pm 14.3$</td>
<td>$20.9 \pm 13.9$</td>
<td>$3.8 \pm 5.8$</td>
</tr>
<tr>
<td>LSND Best Fit</td>
<td>7.6</td>
<td>22.0</td>
<td>3.5</td>
</tr>
<tr>
<td>Expectation from $\nu$ low-E excess</td>
<td>11.6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>LSND + Low-E</td>
<td>19.2</td>
<td>22.0</td>
<td>3.5</td>
</tr>
</tbody>
</table>

- Errors quoted here are stat+sys.
- Excess consistent with the expectation from LSND and adding the low energy excess scaled for neutrinos (wrong-sign).
- Expected 67 events at low energy (200-475 MeV) if neutrino low E excess is due to a Standard Model NC gamma-ray mechanism, e.g. Axial Anomaly.
• Results for $5.66\times10^{20}$ POT.
• Maximum likelihood fit.
• Only antineutrinos allowed to oscillate.
• $E > 475$ MeV region is free of effects of low energy neutrino excess. This is the same official oscillation region as in neutrino mode.
• Results published.

Accepted by PRL
• Results for 5.66E20 POT
• Maximum likelihood fit.
• Null excluded at 99.4% with respect to the two neutrino oscillation fit.
• Best Fit Point
  \((\Delta m^2, \sin^2 2\theta) = (0.064 \text{ eV}^2, 0.96)\)
  \(\chi^2/\text{NDF} = 16.4/12.6\)
  \(P(\chi^2) = 20.5\%\)
Oscillation Fit with $E_\nu > 200$ MeV

- Results for $5.66e20$ POT.
- Does not include effects (subtraction) of neutrino low energy excess.
- Maximum likelihood fit method.
- Null excluded at 99.6% with respect to the two neutrino oscillation fit (model dependent).
- Best Fit Point ($\Delta m^2$, $\sin^2 2\theta$) = (4.42 eV$^2$, 0.0066)  
  $\chi^2$/NDF = 20.4/15.3,  $P(\chi^2)$ = 17.1%
L/E Plot

- Data used for LSND and MiniBooNE correspond to $20 < E_\nu < 60 \text{ MeV}$ and $200 < E_\nu < 3000 \text{ MeV}$, respectively.
- Oscillation probability is event excess divided by the number of events expected for 100% $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transformation.
- $L$ is reconstructed distance travelled by the antineutrino from the mean neutrino production point to the interaction vertex; $E_\nu$ is the reconstructed antineutrino energy.

The data points include both statistical and systematic errors.
Comparison of $\nu_e$ and $\bar{\nu}_e$ Appearance Results

Neutrino $\nu_e$ Appearance Results (6.5E20POT)

Antineutrino $\bar{\nu}_e$ Appearance Results (5.66E20POT)
Summary of Results

• The MiniBooNE $\nu_e$ and $\bar{\nu}_e$ appearance picture starting to emerge is the following:

1) Neutrino Mode:
   a) $E < 475$ MeV: An unexplained $3\sigma$ electron-like excess.
   b) $E > 475$ MeV: A two neutrino fit rules out LSND at the 98% CL.

2) Anti-neutrino Mode:
   a) $E < 475$ MeV: A small $1.3\sigma$ electron-like excess.
   b) $E > 475$ MeV: An excess that is $3.0\%$ consistent with null. Two neutrino oscillation fits consistent with LSND at 99.4% CL relative to null.
Future MiniBooNE Running

Signal significance could continue to significantly grow up to $15 \times 10^{20}$ POT where it is $3.7 \sigma$.

MiniBooNE Collaboration requested $15 \times 10^{20}$ POT to complete the run in current configuration.

Essentially no gain from statistics after.
Future Prospects

- **Need more statistics**
  - MiniBooNE is running to double antineutrino data set for a total of \(\sim 10 \times 10^{20}\) POT by Spring 2011.
  - If signal continues at current rate, two neutrino best fit will be \(\sim 3\sigma\) (with \(>8 \times 10^{20}\) POT).
  - Requested \(\sim 15 \times 10^{20}\) POT to achieve \(\sim 4\sigma\) evidence.

- **There are follow on experiments at FNAL and elsewhere**
  - \(\mu\)Boone has CD-1 approval.
  - BooNE (LOI). A MB-like near detector at 200 m (when MiniBooNE finished in current configuration).
  - Proposal (Carlo Rubia) for two detector LAr detector at CERN PS ring.
  - Various other ideas (DAEdALUS or accelerator at few km distance from Gd-loaded SK, etc).
  - Ideas involving NOvA near detector(s).
Thank you!
Backup Slides
- MiniBooNE uses $E_\nu > 475$ MeV region for oscillation fits.
- Energy region where LSND-type signal is expected.
- If $E_\nu < 475$ MeV:
  - Large backgrounds
  - Big systematics
  - Not sensitive to LSND oscillation signal
Very stable throughout the run.

**Beam and Data Stability**

\[ \nu/POT = (102.1 \pm 0.1) \times 10^{-17} \]
\[ \bar{\nu}/POT = (20.6 \pm 0.1) \times 10^{-17} \]
\[ \chi^2/ndf = 841.67/863 \]
\[ \chi^2/ndf = 478.19/498 \]
Energy Scale Stability

Michel electron mean energy is within 1% since the start of data taking.
Background Prediction

<table>
<thead>
<tr>
<th></th>
<th>200-475</th>
<th>475-1250</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^\pm$</td>
<td>13.45</td>
<td>31.39</td>
</tr>
<tr>
<td>$K^\pm$</td>
<td>8.15</td>
<td>18.61</td>
</tr>
<tr>
<td>$K^0$</td>
<td>5.13</td>
<td>21.2</td>
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<tr>
<td>Other $\nu_e$</td>
<td>1.26</td>
<td>2.05</td>
</tr>
<tr>
<td>NC $\pi^0$</td>
<td>41.58</td>
<td>12.57</td>
</tr>
<tr>
<td>$\Delta \rightarrow N\gamma$</td>
<td>12.39</td>
<td>3.37</td>
</tr>
<tr>
<td>dirt</td>
<td>6.16</td>
<td>2.63</td>
</tr>
<tr>
<td>$\nu_\mu$ CCQE</td>
<td>4.3</td>
<td>2.04</td>
</tr>
<tr>
<td>Other $\nu_\mu$</td>
<td>7.03</td>
<td>4.22</td>
</tr>
<tr>
<td>Total</td>
<td>99.45</td>
<td>98.08</td>
</tr>
</tbody>
</table>
Background Prediction

- Intrinsic $\nu_e$

External measurements

- HARP p+Be for $\pi^\pm$

- Sanford-Wang fits to world $K^+/K^0$ data

MiniBooNE data constrained

Published PRD 79, 072002 (2009)
Background Prediction

Neutral Current $\pi^0$

MiniBooNE NC $\pi^0$ measurement

Constrains radiative decays as well

Published PRD 81, 013005 (2010)
Background Prediction

Neutral Current $\pi^0$

Published PLB 664, 41 (2008)
Background Prediction

Use MiniBooNE NC $\pi^0$ measurement to constrain

$\Delta \rightarrow N\gamma$
Background Prediction

Dirt Events

- Events at high radius pointing toward center
- Low energy depositions

MiniBooNE measurement
## Background Uncertainties

- **Unconstrained $\nu_e$ background uncertainties**

- **Propagate input uncertainties from either MiniBooNE measurement or external data**

<table>
<thead>
<tr>
<th>Uncertainty (%</th>
<th>200-475MeV</th>
<th>475-1100MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+$</td>
<td>0.4</td>
<td>0.9</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>3</td>
<td>2.3</td>
</tr>
<tr>
<td>$K^+$</td>
<td>2.2</td>
<td>4.7</td>
</tr>
<tr>
<td>$K^-$</td>
<td>0.5</td>
<td>1.2</td>
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<tr>
<td>$K^0$</td>
<td>1.7</td>
<td>5.4</td>
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<tr>
<td>Target and beam models</td>
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<td>3</td>
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<tr>
<td>Cross sections</td>
<td>6.5</td>
<td>13</td>
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<tr>
<td>NC pi0 yield</td>
<td>1.5</td>
<td>1.3</td>
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<tr>
<td>Hadronic interactions</td>
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<td>0.2</td>
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<tr>
<td>Dirt</td>
<td>1.6</td>
<td>0.7</td>
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<tr>
<td>Electronics &amp; DAQ model</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>OM</td>
<td>8</td>
<td>3.7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>13.43</strong></td>
<td><strong>16.02</strong></td>
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<tr>
<td>Electronics &amp; DAQ model</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>Optical Model</td>
<td>8</td>
<td>3.7</td>
</tr>
<tr>
<td>Total</td>
<td>13.43</td>
<td>16.02</td>
</tr>
</tbody>
</table>

- Uncertainty determined by varying underlying cross section model parameters ($M_A$, Pauli blocking, …)

- Many of these parameters measured in MiniBooNE
### Background Uncertainties

<table>
<thead>
<tr>
<th>Uncertainty (%)</th>
<th>200-475MeV</th>
<th>475-1100MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+$</td>
<td>0.4</td>
<td>0.9</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>3</td>
<td>2.3</td>
</tr>
<tr>
<td>K$^+$</td>
<td>2.2</td>
<td>4.7</td>
</tr>
<tr>
<td>K$^-$</td>
<td>0.5</td>
<td>1.2</td>
</tr>
<tr>
<td>K$^0$</td>
<td>1.7</td>
<td>5.4</td>
</tr>
<tr>
<td>Target and beam models</td>
<td>1.7</td>
<td>3</td>
</tr>
<tr>
<td>Cross sections</td>
<td>6.5</td>
<td>13</td>
</tr>
<tr>
<td>NC pi0 yield</td>
<td>1.5</td>
<td>1.3</td>
</tr>
<tr>
<td>Hadronic interactions</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Dirt</td>
<td>1.6</td>
<td>0.7</td>
</tr>
<tr>
<td>Electronics &amp; DAQ model</td>
<td>7</td>
<td>2</td>
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</tbody>
</table>

-Uncertainty in light creation, propagation and detection in the detector.
Other $\bar{\nu}_e$ kinematic distributions for 5.66E20 POT

**Visible Lepton Energy**

- Data points with error bars
- MiniBooNE data
- Total expected background
- $\bar{\nu}_e$ and $\nu_e$ background
- $\bar{\nu}_\mu$ and $\nu_\mu$ background

$\chi^2$/NDF = 23.8/13 shape only

**Reconstructed Lepton Angle wrt Beam**

- Data points with error bars
- Total expected background
- $\bar{\nu}_e$ and $\nu_e$ background
- $\bar{\nu}_\mu$ and $\nu_\mu$ background

$\chi^2$/NDF = 13.6/11 shape only
Background $\bar{\nu}_e$ Evis distributions for 5.66E20 POT
- Use frequentist approach.
- Generate fake data experiments on grid of $(\sin^2 2\theta, \Delta m^2)$ points.
- At each point find the cut on likelihood ratio for X% confidence level such that X% of experiments below cut
- Fitting two parameters, so naively expect $\chi^2$ distribution with 2 degrees of freedom, in reality at null it looks more like 1 degree of freedom.

Drawing Contours
Oscillation Fit with $E_\nu > 200$ MeV (include low $E_\nu$ $\nu$-mode effects)

- Results for $5.66e20$ POT.
- Assume simple scaling of neutrino low energy excess; subtract 11.6 events from low energy region (200-475 MeV).
- Maximum likelihood fit method.
- Null excluded at 99.6% with respect to the two neutrino oscillation fit (model dependent).
- Best Fit Point ($\Delta m^2$, $\sin^2 2\theta$) = (4.42 eV$^2$, 0.0066)
  $\chi^2$/NDF= 21.6/15.3, $P(\chi^2)$ = 13.7%.