Searching for Physics Beyond the Standard Model with Neutrinos

Zelimir Djurcic
Physics Department
Columbia University

University of Virginia
February 13th, 2008
Outline

Neutrinos in the Standard Model of Particle Physics

What are neutrinos?
Why the neutrinos are important?
Oscillations?
ν oscillation landscape

Some of the Things I Worked on: MiniBooNE

Experiment Description
MiniBooNE’s First Results
MiniBooNE’s New Results!
What has MiniBooNE told us?

Conclusions and Next Steps
Neutrinos in the Standard Model

• Neutrinos are the only fundamental fermions with no electric charge
• Neutrinos only interact through the "weak force"
• Neutrinos are massless
• Neutrino interaction through W and Z bosons exchange is (V-A)
  - Neutrinos are left-handed (Antineutrinos are right-handed)
• Neutrinos have three types
  - Electron $\nu_e \rightarrow e$
  - Muon $\nu_\mu \rightarrow \mu$
  - Tau $\nu_\tau \rightarrow \tau$
Experiment shows that the neutrinos produced in muon interactions are different from neutrinos involved in interactions with electrons.

A third kind of particle, the tau, is heavier version of muon which is itself a heavier version of the electron. (It has its own neutrino as well.)

We have (at least) 3 kind of neutrinos:
the electron neutrino ($\nu_e$),
the muon neutrino ($\nu_\mu$),
and the tau neutrino ($\nu_\tau$).
Sterile $\nu$?

In colliders, $\nu$ “seen” only as missing energy

Invisible width of the $Z^0$ measured by LEP expts
Neutrino Cross Section: Very Small!

Weak interactions are weak because of the massive W and Z boson exchange

\[ \sigma_{\text{weak}} \propto G_F^2 \propto \left(1/M_W \text{ or } M_Z \right)^4 \]

\[ G_F = \frac{\sqrt{2}}{8} \left( \frac{g_W}{M_W} \right)^2 = 1.166 \times 10^{-5} / \text{GeV}^2 \quad (g_W \approx 0.7) \]

For 100 MeV Neutrinos:

\[ \sigma(\nu e) \sim 10^{-42} \text{ and } \sigma(\nu n) \sim 10^{-39} \text{ cm}^2 \]

compared to \( \sigma(pp) \sim 10^{-24} \text{ cm}^2 \)

A neutrino has a good chance of traveling through 3 million earths before interacting at all!

Mean free path length in steel \( \sim 10^{13} \text{ meters!} \)

Hundreds of billions of neutrinos from the sun pass through every square inch of you each second!

Need big detectors and lots of \( \nu \text{'s}! \)
Detecting neutrinos is very challenging!

**Must have:**
- Intense sources
- Large detectors
  - Many target atoms
- Patience

Many neutrinos traverse, but very few interact.
Continuous Beta Spectrum

Continuous beta spectrum was the first hint that there is an extra particle in the beta decay reaction: 

\[ n \rightarrow p + e^{-} + ? \]

Bohr: At the present stage of atomic theory, however, we may say that we have no argument, either empirical or theoretical, for upholding the energy principle in the case of β-ray disintegrations.
Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the $^6\text{Li}$ and $^7\text{Li}$ nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...
First Detection of (Reactor) Neutrinos

In 1953 Fred Reines and Clyde Cowan (LANL) in an experiment at Hanford nuclear reactor have detected anti-neutrinos from fission products. They confirmed their result in 1956 at Savannah River reactor where background conditions were much better.

F. Reines and C. Cowan at the Control Center of the Hanford Experiment (1953)
That was difficult experiment since cross section of anti-neutrino interaction with matter is incredibly small ($\sim 6 \times 10^{-44} \text{ cm}^2$ or $\sim 10^{20}$ times smaller than typical nuclear cross sections)

\[ V + p \rightarrow e^+ + n \]

Detector was placed 11 m from the reactor and 12 m under the ground level. Neutrino interactions were observed by coincidence of prompt positron signal and delayed $\text{Cd}(n,\gamma)$ capture with the rate of $\sim 3$ events / hour and with signal/background ratio of $\sim 3/1$

→ Nobel Prize to F. Reines for anti-neutrino detection in 1995
they collected data for ~ a year
recording flashes of light produced by impact of neutrinos from the nearby reactor ...

ghostly particle ($\nu_e$) had become a tangible reality
this ground breaking experiment changed the role the $\nu_e$ was to play in physics
$\nu_e$ not just the by-product of beta decay but would be used to expand our understanding of the subatomic world

June 14, 1956
Dear Professor Pauli,
We are happy to inform you that we have definitely detected neutrinos...
Fred Reines
Clyde Cowan

won the Nobel Prize for detection of the $\nu_e$ (1995)
Sources of neutrinos: artificial and natural

- ✔ Nuclear Reactors (power stations, ships)
- ✔ Particle Accelerator
- ✔ Earth’s Atmosphere (Cosmic Rays)
- ✔ Earth’s Crust (Natural Radioactivity)
- ✔ Sun
- ✔ Supernovae (star collapse) SN 1987A
- ✔ Astrophysical Accelerators
- ✔ Big Bang (here 330 ν/cm³)

Indirect Evidence
In the standard model, neutrinos are massless.

But it's difficult to confirm this!

Direct mass searches yield limits:
• $\nu_e$: tritium decay: $m < 2$ eV
• $\nu_\mu$: pion decay: $m < 170$ keV
• $\nu_\tau$: tau decay: $m < 18.2$ MeV

Compare to hadron masses: (larger than neutrino mass limits)
• pions ~ 140 MeV
• kaons ~ 500 MeV
• protons ~ 1 GeV
• neutrons ~ 1 GeV

Can learn about neutrino mass with indirect searches.

Use quantum mechanics $\rightarrow$ Neutrino Oscillations
Cosmological Implications

- Neutrinos important for heavy element production in supernova
- Light neutrinos affect galactic structure formation

Why Neutrino Mass Matters?

The fact that neutrino masses are so much smaller than other particles ⇒ See-Saw Mechanism

\[ \mathcal{L}^{D+M} = \mathcal{L}_L^M + \mathcal{L}_R^M + \mathcal{L}^D \]

\[ = - \frac{1}{2} \left( \bar{\nu}_L \nu_R \right) \begin{pmatrix} m_L \\ m_D \\ m_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_D \\ \nu_R \end{pmatrix} + \text{h.c.} \]

Set of very light neutrinos

Set of heavy sterile neutrinos

Structure formation

\[ \Omega_\nu < \sim 0.02 \]

\[ \Omega_\nu > 0.003 \]

Super-Kamiokande

Universe contains 330 active \( \nu/cm^3 \) (410 \( \gamma/cm^3 \)), from Big Bang (if sterile \( \nu \) → most abundant Particle in the Universe).

Heavy RH neutrino

Typical Dirac Mass
**Neutrino Oscillations?**

Mass (objects with definitive mass plane wave) and flavor states (objects that participate in weak interaction) are not identical.

\[ |\nu_\ell\rangle = \sum_i U_{\ell i} \cdot |\nu_i\rangle \]

**Simplified Model: only two neutrino mix**

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu
\end{pmatrix} =
\begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix}
\]

A neutrino created as one specific flavor might later be detected as a neutrino of a different flavor.

Why? Neutrinos propagate as mass eigenstates.
Oscillation Probability

\[ |\nu_\mu(t)\rangle = -\sin \theta \, |\nu_1\rangle + \cos \theta \, |\nu_2\rangle \]

\[ e^{-iE_1t} \quad e^{-iE_2t} \]

\( \Delta m^2 \) is the mass squared difference between the two neutrino states

\[ \theta \text{ is the mixing angle} \]

\[ P_{osc} = |\langle \nu_e | \nu_\mu(t) \rangle|^2 = \sin^2 2\theta \, \sin^2 1.27 \, \left( \frac{\Delta m^2 L}{E} \right) \]

Distance from point of creation of neutrino beam to detection point

E is the energy of the neutrino beam
sometimes the waves are in-phase

wave 1

wave 2

wave 1 + wave 2

sometimes they are out of phase

\[ \nu \mu - \text{begins to fade} \]
Example of quantum mechanics at work!
The observation of neutrino oscillations where one type of neutrino can change (oscillate) into another type implies:

1. Neutrinos have mass

and

2. Lepton number (electron, muon, tau) is not conserved

\( \nu_e \rightarrow \nu_\mu, \nu_\mu \rightarrow \nu_\tau, \nu_e \rightarrow \nu_\tau \)

This phenomena cannot be explained within the Standard Model of particle physics

→ Neutrino oscillations is the first indication of “new physics” outside the Standard Model.
In reality: 3 or more neutrinos! -> Neutrino mixing more complicated.
The case of only 3 neutrinos results is described by PMNS (Pontecorvo-Maki-Nakagawa-Sakata) matrix:

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau \\
\end{pmatrix}_L =
U_{e1} U_{e2} U_{e3}
U_{\mu1} U_{\mu2} U_{\mu3}
U_{\tau1} U_{\tau2} U_{\tau3}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3 \\
\end{pmatrix}
\]

Neutrino mass states

Can be parameterized as:

\[
U =
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13} e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-e^{i\alpha_1 / 2} & 0 & 0 \\
0 & e^{i\alpha_2 / 2} & 0
\end{pmatrix}
\]

Atmospheric angle Reactor angle and CP phase Solar angle Majorana phases
Consider searching for $\nu_\mu \rightarrow \nu_e$.

Disappearance:
Detect fewer $\nu_\mu$ events than expected.
Should have a characteristic energy signature – oscillation probability depends on $E$!

Appearance:
Detect more $\nu_e$ events than expected.
Oscillation depends on $E$: the events that disappeared in the blue plot are related to those appearing in the red plot.

Goal: Determine $\Delta m^2$, $\sin^2 2\Theta$.
If you see an oscillation signal with
\[ P_{\text{osc}} = P \pm \Delta P \]
then carve out an allowed region in \((\Delta m^2, \sin^2 2\theta)\) plane.

If you see no signal and limit oscillation with
\[ P_{\text{osc}} < P \text{ @90\%CL} \]
then carve out an excluded region in the \((\Delta m^2, \sin^2 2\theta)\) plane.

\[ P_{\text{osc}} = \sin^2 2\theta \sin^2 \left(1.27\Delta m^2 L / E\right) \]
**Solar ν Results**

- Solar Neutrino Oscillations Confirmed and Constrained
  - Many different exp’s see deficit
  - SNO experiments sees that total neutrino flux correct from sun but just changing flavor
  - Kamland experiment using reactor neutrinos confirms solar oscillations
  - Combination of experiments \(\Rightarrow\) Large Mixing Angle MSW Solution

---

**KamLAND Reactor Exp.**

- Events / 0.425 MeV
- \(E_{\text{prompt}}\) (MeV)

**Combination All Solar + KamLAND**

- \(\Delta m^2\) (eV²)
- \(\tan^2 \theta\)
Atmospheric ν Results

- Atmospheric neutrino oscillations definitively confirmed
  - "Smoking Gun" ⇒ Super-K flux change with zenith angle
  - Accelerator neutrino confirmation with KEK to Super-K exp. (K2K)
  - Confirmed by MINOS exp.
  - Value of $\Delta m^2$: $2.4 \times 10^{-3}$ eV$^2$
  - Mixing angle~45° (Maximal!)
Atmospheric ν Results

- Atmospheric neutrino oscillations definitively confirmed
  - “Smoking Gun” ⇒ Super-K flux change with zenith angle
  - Accelerator neutrino confirmation with KEK to Super-K exp. (K2K)
  - Confirmed by MINOS exp.
  - Value of $\Delta m^2$: $2.4 \times 10^{-3}$ eV$^2$
  - Mixing angle $\sim 45^\circ$ (Maximal!)

![Super-K (SK) Atmospheric Neutrino Experiment](image)

![K2K Accelerator Neutrino Exp.](image)

![Data Plot](image)
Mixing angle $\theta_{13}$ is not known ($\theta_{13} < 13^\circ$ @90% CL).
First experiment to address $\theta_{13}$: Double Chooz (France 09).
We now know:

1. Neutrinos have tiny masses

2. The neutrino types mix
We did see that there were multiple experiments confirming each other. However, one experiment produced an evidence for oscillations that stayed unconfirmed...
The LSND Experiment

LSND took data from 1993-98
- 49,000 Coulombs of protons
- L = 30m and 20 < E_ν < 53 MeV

Saw an excess of $\bar{\nu}_e$:
87.9 ± 22.4 ± 6.0 events.

With an oscillation probability of
(0.264 ± 0.067 ± 0.045)%.

3.8 $\sigma$ significance for excess.
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!

Kamioka, IMB, Super K, Soudan II, Macro, K2K
$\Delta m^2 = 2.4 \times 10^{-3} \text{ eV}^2$
Homestake, Sage, Gallex, Super-K
SNO, KamLAND
$\Delta m^2 = 8.2 \times 10^{-5} \text{ eV}^2$

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

LSND in conjunction with the atmospheric and solar oscillation results needed more than 3 $\nu$'s
⇒ Models developed with 2 sterile $\nu$'s or
⇒ Other new physics models
How can one get 3 distinct $\Delta m^2$?

- One of the experimental measurements is wrong
- One of the experimental measurements is not neutrino oscillations
  - Neutrino decay
  - Neutrino production from flavor violating decays
- Additional “sterile” neutrinos involved in oscillations
- CPT violation (or CP viol. and sterile $\nu$’s) allows different mixing for $\nu$’s and $\bar{\nu}$’s
MiniBooNE

(Booster Neutrino Experiment)
Search for $\nu_e$ appearance in $\nu_\mu$ beam

Use protons from the 8 GeV booster
$\Rightarrow$ Neutrino Beam
$\langle E_\nu \rangle \sim 0.7$ GeV

MiniBooNE Detector:
12m diameter sphere
950000 liters of oil (CH$_2$)
1280 inner PMTs
240 veto PMTs
Same L/E~0.8m/MeV as LSND!
$\nu_\mu \rightarrow \nu_e$ Oscillation Search

- Main $\nu_\mu$ flux from $\pi^+ \rightarrow \mu^+ \nu_\mu$
- Intrinsic $\nu_e$ flux from
  - $\mu^+ \rightarrow \nu_\mu e^+ \nu_e$
  - $K^+ \rightarrow \pi^0 e^+ \nu_e$
  - $K^0_L \rightarrow \pi^- e^+ \nu_e$

$\Rightarrow \nu_e / \nu_\mu \approx 0.5\%$

MiniBooNE Detector:
- 12m diameter sphere
- 950000 liters of oil (CH$_2$)
- 1280 inner PMTs
- 240 veto PMTs

Detector Requirements:
- Detect and Measure Events: Vertex, $E_\nu$ ...
- Separate $\nu_\mu$ events from $\nu_e$ events.
\( \nu_\mu \rightarrow \nu_e \) Oscillation Signal...

... is an excess of \( \nu_e \) events above expectation.

Understanding the expected events is therefore the key!

Need to know the neutrino fluxes:
- Electron neutrinos from \( \mu, K^+, \) and \( K^0 \) decay.
- Muon neutrinos can make background or oscillate to give a signal.

Need to know the \( \nu_\mu / e \) neutrino cross section vs. energy:
- Events = flux \( \times \) cross section.

Need to know the \( \nu_e \) reconstruction efficiency vs energy:
- Observed events = efficiency \( \times \) events.

Need to know the probability for \( \nu_\mu \) events to be mis-identified as \( \nu_e \) events. Events with single EM showers look like \( \nu_e \) events in MiniBooNE:
- Neutral current (NC) \( \pi^0 \) events are the main mis-id background.
- NC \( \Delta \) production followed by radiative decay, \( \Delta \rightarrow N\gamma \).
- Photons entering from outside detector ("Dirt" background).

MiniBooNE's Principle is to understand and calibrate the expected events from the observed non-signal events.
Start with a Geant4 flux prediction for the $\nu$ spectrum from $\pi$ and K produced at the target.

Predict $\nu$ interactions using the Nuance cross section parameterization.

Pass final state particles to Geant3 to model particle and light propagation in the tank.

Starting with event reconstruction, independent analyses:
- Boosted Decision Tree (BDT).
- Track Based Likelihood (TBL).

Develop particle ID/cuts to separate signal from background.

Fit reconstructed $E_\nu$ spectrum for oscillations.
Čerenkov rings provide primary means of identifying products of $\nu$ interactions in the detector.

- $\nu_\mu n \rightarrow \mu^- p$
- $\nu_e n \rightarrow e^- p$
- $\nu_\mu p \rightarrow \nu_\mu p \pi^0$
- $\pi^0 \rightarrow \gamma\gamma$

**Particle Identification**

**Muons**: $\nu_\mu n \rightarrow \mu^- p$

**Electrons**: $\nu_e n \rightarrow e^- p$

**Multi-ring** (e.g. $\pi^0 \rightarrow \gamma\gamma$)
Muon Identification
Signature:
$\mu \rightarrow e \nu_\mu \nu_e$
after $\sim 2\mu$sec

Animation
Each frame is 25 ns with 10 ns steps.

Charge (Size)

Low                   High

Time (Color)

Early                   Late
Analysis Method

Uses detailed, direct reconstruction of particle tracks, and ratio of fit likelihoods to identify particles.

Apply likelihood fits to three hypotheses:
- single electron track
- single muon track
- two electron-like rings ($\pi^0$ event hypothesis)

Form likelihood differences using minimized $-\log L$ quantities:
$\log(L_{e}/L_{\mu})$ and $\log(L_{e}/L_{\pi})$

Compare observed light distribution to fit prediction:
Does the track actually look like an electron?

---

Visible energy [MeV]

Blue points are signal $\nu_e$ events.
Green points are background $\nu_\mu$ NC $\pi^0$ events.

Red points are background $\nu_\mu$ CCQE events.
Two main categories of backgrounds: $\nu_\mu$ mis-ids and intrinsic $\nu_e$.

Expected Background Events

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Percentage</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$ mis-id</td>
<td>13%</td>
<td>6%</td>
</tr>
<tr>
<td>$\nu_e$ Selection requirements</td>
<td>20%</td>
<td>23%</td>
</tr>
<tr>
<td>Other</td>
<td>17%</td>
<td>20%</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>1%</td>
<td>62%</td>
</tr>
<tr>
<td>$\mu$</td>
<td>1%</td>
<td>3%</td>
</tr>
<tr>
<td>$K^0$</td>
<td>6%</td>
<td>47%</td>
</tr>
<tr>
<td>$K^\pm$</td>
<td>6%</td>
<td>20%</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>6%</td>
<td>132%</td>
</tr>
<tr>
<td>$\pi^0$</td>
<td>6%</td>
<td>37%</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>6%</td>
<td>1%</td>
</tr>
</tbody>
</table>

TBL analysis predicted backgrounds:

Total Expected Background = 358 events.

Example LSND Osc Signal = 163 events
($\Delta m^2 = 0.4\ eV^2, \sin^2 2\theta = 0.017$).
The Box Opening: What we found

Open the box and look into $E_{\nu}^{\text{QE}}$: Return the fit parameters.

Is there an oscillation signal?

The Track-based $\nu_\mu \rightarrow \nu_e$ appearance-only result:

Counting Experiment: $475 < E_{\nu}^{\text{QE}} < 1250$ MeV

Data: 380 events

Expectation: $358 \pm 19$ (stat) $\pm 35$ (sys) events

Significance: $0.55 \sigma$

Best Fit (dashed): $(\sin^2 2\theta, \Delta m^2) = (0.001, 4 \text{ eV}^2)$

Probability of Null Fit: 93%
Probability of Best Fit: 99%
Main Conclusion: The observed reconstructed energy distribution is inconsistent with a $\nu_\mu \rightarrow \nu_e$ 2-neutrino model.

Energy-fit analysis: Solid: Analysis I  
Dashed: Analysis II

Independent analyses are in good agreement.

The result of the $\nu_\mu \rightarrow \nu_e$ appearance-only analysis is a limit on oscillations.

Details:

96 ± 17 ± 20 events above background, for 300< $E_{\nu}^{QE}$ <475 MeV

Deviation: 3.7 $\sigma$

Background-subtracted:

Report the full range: 300< $E_{\nu}^{QE}$ <3000 MeV

Full Energy Range: Found Low E excess!
Full Energy Range Fit 300< $E_{\nu}^{QE}$< 3 GeV

Examples in LSND allowed range
- data - expected background
- best-fit to full range
- $\sin^2(2\theta)=0.004$, $\Delta m^2=1.0$ eV$^2$
- $\sin^2(2\theta)=0.2$, $\Delta m^2=0.1$ eV$^2$

Best Fit (dashed): $(\sin^22\theta, \Delta m^2) = (1.0, 0.03$ eV$^2)$
$\chi^2$ Probability: 18%

The best falls into region excluded by other Experiments (i.e. Bugey)
...the simplest models which would produce similar signals in LSND and MiniBooNE are ruled out.

There is a low energy excess observed: we are analyzing it vigorously.

The simplest explanation: it is some type of Standard Model background.

Alternative: it is a more complicated oscillation signal than originally expected.

Remember that LSND was an anti-neutrino experiment and MiniBooNE measurement was done with neutrinos. 
If neutrinos oscillate differently from anti-neutrinos, one might be able to explain difference between the MiNiboone and LSND signal → “CP Violation”. It is of great interest right now because of ...
Hard to generate a baryon asymmetry ($\Delta B \neq 0$) using quark matrix CP violation.

-> Use Heavy Sterile Neutrinos and Neutrino CP Violation.

Generate $\Delta L \neq 0$ in the early universe from CP (or CPT) violation in heavy neutrino N decays (only needs to be at the $10^{-6}$ level).

If $\nu$ oscillation violates CP, then quite likely so does N decay. In the See-Saw, these two CP violations have a common origin.

$$N \rightarrow L^- + ... \quad \text{and} \quad N \rightarrow L^+ + ...$$

Results: unequal number of leptons and anti-leptons. B-L processes then convert neutrino excess to baryon excess. Sign and magnitude $\sim$ correct to generate baryon asymmetry in the universe with $m_N > 10^9$ GeV and $m_\nu < 0.2$ eV.
Low Energy Excess
Investigation of observed low-energy excess

Lower the energy: to $E_{\nu}^{QE} = 200$ MeV!

Reconstructed $E_{\nu}^{QE}$: from $E_{\text{lepton}}$ ("visible energy") and lepton angle wrt neutrino direction

$$E_{\nu}^{QE} = \frac{1}{2} \frac{2M_p E_{\ell} - m_{\ell}^2}{M_p - E_{\ell} + \sqrt{(E_{\ell}^2 - m_{\ell}^2)\cos\theta_{\ell}}}$$
### Summary of estimated backgrounds vs data

<table>
<thead>
<tr>
<th>$E_{\nu}^{QE}$ [MeV]</th>
<th>200-300</th>
<th>300-475</th>
<th>475-1250</th>
</tr>
</thead>
<tbody>
<tr>
<td>total background</td>
<td>284±25</td>
<td>274±21</td>
<td>358±35</td>
</tr>
<tr>
<td>$\nu_e$ intrinsic</td>
<td>26</td>
<td>67</td>
<td>229</td>
</tr>
<tr>
<td>$\nu_\mu$ induced</td>
<td>258</td>
<td>207</td>
<td>129</td>
</tr>
<tr>
<td>NC $\pi^0$</td>
<td>115</td>
<td>76</td>
<td>62</td>
</tr>
<tr>
<td>NC $\Delta \rightarrow N\gamma$</td>
<td>20</td>
<td>51</td>
<td>20</td>
</tr>
<tr>
<td>Dirt</td>
<td>99</td>
<td>50</td>
<td>17</td>
</tr>
<tr>
<td>other</td>
<td>24</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Data</td>
<td>375±19</td>
<td>369±19</td>
<td>380±19</td>
</tr>
<tr>
<td>Data-MC</td>
<td>91±31</td>
<td>95±28</td>
<td>22±40</td>
</tr>
</tbody>
</table>

- **Low Energy**: largest backgrounds are $\nu_\mu$-induced, in particular:
  - NC $\pi^0$
  - NC $\Delta \rightarrow N\gamma$
  - Dirt

- **High Energy**: no significant excess with $\nu_e$ bkgd dominant

- Thoroughly Re-checked these processes last 6 months.

In addition, new processes being considered:
- $\nu_\mu$-induced NC $\pi^0$ with photonuclear absorption of $\pi^0$ photon
- new $\nu_\mu$-induced NC photon production (eg: hep-ex:0708.1281v2)
- new physics?
New Analysis:
Events from NuMI beamline
Fermilab Neutrino Beams
MINOS Experiment
L~700 km
E~2-5GeV

NuMI Beam

120 GeV protons ~ $3 \times 10^{13}$/pulse.

Primarily for the MINOS long baseline experiment.
**Off-axis Beam**

On-axis, neutrino energy more tightly related to hadron energy.

Off-axis, neutrino spectrum is narrow-band and 'softened'.

Easier to estimate flux correctly: all mesons decay to same energy $\nu$.

\[
E_\nu \approx \frac{\left(1 - \frac{m_\mu^2}{m_{\pi,K}^2}\right)E_{\pi,K}}{1 + \gamma^2 \theta^2}
\]

---

[Graphs showing energy distribution for different angles $\theta$.]

First Proposed by BNL-E889
Use off-axis trick for optimized $\nu_\mu \rightarrow \nu_e$ search.

**NOvA:**
- NuMI off-axis beam
- 810km baseline
- $14.5 \text{ mrad}; E_\nu \sim 2 \text{ GeV}$

**T2K:**
- J-PARC 50GeV proton beam
- Use SK as Far detector
- 295 km away
- $35 \text{ mrad}; E_\nu \sim 0.6 \text{ GeV}
**MiniBooNE detector is 745 meters downstream of NuMI target.**
**MiniBooNE detector is 110 mrad off-axis from the target along NuMI decay pipe.**

*Main trigger is an accelerator signal indicating a beam spill.*
*Information is read out in 19.2 μs interval covering arrival of beam.*
Higher energy neutrinos mostly from particles created in target.

Interactions in shielding and beam absorber contributes in lowest energy bins.

Plots show where the parent was created.
MiniBooNE

(Booster Neutrino Experiment)

becomes

An off axis neutrino experiment using Main Injector
Detector Operation and Event reconstruction

No high level analysis needed to see neutrino events

Events in DAQ window: no cuts

Removed cosmic ray muons: PMT veto hits < 6

Removed cosmic ray muons and $\mu$-decay electrons: PMT veto hits < 6 and PMT tank hits > 200

6-batch structure of MI about 10 $\mu$s duration reproduced.

Backgrounds: cosmic muons and decay electrons

$\rightarrow$ Simple cuts reduce non-beam backgrounds to $\sim 10^{-5}$
Events from NuMI detected at MiniBooNE

Neutrino interactions at carbon simulated by NUANCE event generator: neutrino flux converted into event rates.

**NuMI event composition at MB**

\[ \nu_\mu - 81\%, \nu_e - 5\%, \bar{\nu}_\mu - 13\%, \bar{\nu}_e - 1\% \]

**Event rates**

- **CCQE**: 39%
- **CC π^+**: 26%
- **NC π^0**: 9%
$\nu_\mu$ CCQE Analysis
Analysis of the $\nu_\mu$ CCQE events from NuMI beam

$\nu_\mu$ CCQE ($\nu+n \rightarrow \mu+p$) has a two "subevent" structure
(with the second subevent from stopped $\mu \rightarrow \nu_\mu \nu_e e$)

Event Selection:

**Subevent 1:**
- $T_{\text{hits}}>200$, $V_{\text{hits}}<6$
- $R<500$ cm
- $L_e/L_\mu < 0.02$

**Subevent 2:**
- $T_{\text{hits}}<200$, $Veto<6$
Visible E of $\mu$: final state interactions in $\nu_\mu$ CCQE sample

$\log(L_e/L_\mu) \times 0.02$

Data (stat errors only) compared to MC prediction for visible energy in the tank.

This sample contains 18000 events of which 70% are CCQE's.
Compare $\nu_\mu$ CCQE MC to Data: Parent Components

Beam MC tuned with MINOS near detector data.

Cross-section Monte Carlo tuned with MB measurement of CCQE pars $M_A$ and $\kappa$.

Visible energy in tank [GeV]

MC is normalized to data POT number!

arXiv:0706.0926 [hep-ex]
To evaluate Monte Carlo agreement with the data need estimate of systematics from three sources:

- Beam modeling: flux uncertainties.
- Cross-section model: neutrino cross-section uncertainties.
- Detector Model: describes how the light emits, propagates, and absorbs in the detector (how detected particle looks like?).
Add Systematic uncertainty to $\nu_\mu$ CCQE Monte Carlo

Predicted Pions are matching the data within systematics!

$\mu$ visible energy distribution

Outgoing $\mu$ angular distribution

Information about incoming $\nu$ wrt NuMI target direction.
$\nu_\mu$ CCQE sample: Reconstructed energy $E_v$ of incoming $\nu$

Reconstructed $E_v^{QE}$: from $E_{\text{lepton}}$ ("visible energy") and lepton angle wrt neutrino direction

$$E_v^{QE} = \frac{1}{2} \frac{2M_pE_\ell - m_\ell^2}{M_p - E_\ell + \sqrt{(E_\ell^2 - m_\ell^2)\cos \theta_\ell}}$$

Understanding of the beam demonstrated: 
MC is normalized to data POT number!
This is the first demonstration of the off-axis principle.

There is very good agreement between data and Monte Carlo: the MC tuned well.

Because of the good data/MC agreement in $\nu_\mu$ flux and because the $\nu_\mu$ and $\nu_e$ share same parents, the beam MC can now be used to predict:

- $\nu_e$ rate,
- mis-id backgrounds for a $\nu_e$ analysis.
$\nu_e$ CCQE Analysis
When we try to isolate a sample of $\nu_e$ candidates we find background contribution to it:

- $\pi^0$ ($\pi^0 \rightarrow \gamma\gamma$) and radiative $\Delta$ ($\Delta \rightarrow N\gamma$) events

Therefore, before analyzing $\nu_e$ CCQE we constrain the backgrounds by measurement in our own data.
Analysis of $\pi^0$ events from NuMI beam

Among the e-like mis-ids, $\pi^0$ decays which are boosted, producing 1 weak ring and 1 strong ring is largest source.

Strategy: Don’t try to predict the $\pi^0$ mis-id rate, measure it!
Measured rates of reconstructed $\pi^0$... tie down the rate of mis-ids

$\Delta$ decays to a single photon: with 0.56% probability:

What is applied to select $\pi^0$s
Event pre-selection:
1 subevent  
$T_{\text{hits}}>200$, $V_{\text{hits}}<600$  
$R<500$ cm

$log(L_e/L_\mu)>0.05$ (e-like)  
$log(L_e/L_\pi)<0$ ($\pi^0$-like)
Analysis of $\pi^0$ events from NuMI beam: $\pi^0$ mass

The peak is 135 MeV/c$^2$

Data

Monte Carlo

$\nu_e$ appear to be well modelled.

We declare good MC/Data agreement for $\pi^0$ sample going down to low mass region where $\nu_e$ candidates are showing up!

This sample contains 4900 events of which 81% are $\pi^0$ events: world second largest $\pi^0$ sample!
Before we further characterize data/MC agreement we have to account for the systematic uncertainties.

Data = 783 events.
Monte Carlo prediction = 662 events.
$\nu_e$ CCQE sample: Reconstructed energy $E_\nu$ of incoming $\nu$

$$E_{\nu}^{\text{QE}} = \frac{1}{2} \left( \frac{2M_pE_\ell - m_\ell^2}{2M_p - E_\ell + \sqrt{(E_\ell^2 - m_\ell^2)\cos\theta_\ell}} \right)$$
Summary of estimated backgrounds vs data $\nu_e$ CCQE sample

Looking quantitative into low energy and high energy region:

<table>
<thead>
<tr>
<th>$E_{\nu}^{\text{QE}}$ [MeV]</th>
<th>200-900</th>
<th>900-3000</th>
</tr>
</thead>
<tbody>
<tr>
<td>total background</td>
<td>$401 \pm 66$</td>
<td>$261 \pm 50$</td>
</tr>
<tr>
<td>$\nu_e$ intrinsic</td>
<td>311</td>
<td>231</td>
</tr>
<tr>
<td>$\nu_\mu$ induced</td>
<td>90</td>
<td>30</td>
</tr>
<tr>
<td>NC $\pi^0$</td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>NC $\Delta \rightarrow N\gamma$</td>
<td>14</td>
<td>1</td>
</tr>
<tr>
<td>Dirt</td>
<td>35</td>
<td>1</td>
</tr>
<tr>
<td>other</td>
<td>11</td>
<td>3</td>
</tr>
<tr>
<td>Data</td>
<td>$498 \pm 22$</td>
<td>$285 \pm 17$</td>
</tr>
<tr>
<td>Data-MC</td>
<td>$97 \pm 70$</td>
<td>$24 \pm 53$</td>
</tr>
<tr>
<td>Significance</td>
<td>1.40 $\sigma$</td>
<td>0.45 $\sigma$</td>
</tr>
</tbody>
</table>

At this point systematic errors are large: we cannot say much about the difference between low and high-E regions.

In the future we will reduce $\nu_e$ CCQE sample systematics constraining it with our large statistics $\nu_\mu$ CCQE sample.
Recall:
1) Distance to MiniBooNE:
   \( L \) (from NuMI source) \( \approx 1.4 \) \( L \) (from Booster beam source).

2) Neutrino Oscillation depends on \( L \) and \( E \) through \( L/E \) ratio.

Therefore, if an anomaly seen at some \( L \) in Booster beam data is due to oscillation it should appear at 1.4\( E \) in the NuMI beam data at MiniBooNE.

Will be published soon!
• Anomaly Mediated Neutrino-Photon Interactions at Finite Baryon Density (arXiv:0708.1281: Jeffrey A. Harvey, Christopher T. Hill, Richard J. Hill)

• CP-Violation 3+2 Model: Maltoni & Schwetz, arXiv:0705.0107


• Lorentz Violation: Katori, Kostelecky, & Tayloe, Phys. Rev. D74 (2006) 105009


Possible Sources of Single Gamma Backgrounds

Since MiniBooNE cannot tell an electron from a single gamma, any process that leads to a single gamma in the final state will be a background.

Example: “Anomaly mediated neutrino-photon interactions at finite baryon density.”
No quark vs. lepton cancellation in loop since only quarks can contribute
(Under active investigation)
(Harvey, Hill, and Hill, hep-ph0708.1281)

\[
\sigma = \frac{\alpha g_\omega^4 G_F^2 E_\nu^6}{480 \pi^6 m_\omega^4} \approx 2.2 \times 10^{-41} (E_\nu/\text{GeV})^6 (g_\omega/10.0)^4 \text{cm}^2
\]

if \( g_\omega \sim 10 \), and \( E_\nu \) were 700 MeV
this would produce a 115 event excess...
About the right level....
• Models with 3 active and 1 sterile neutrino (3+1) are excluded by various $\nu_e$ and $\nu_\mu$ disappearance measurements

• 3+2 models can give a good fit to appearance data but fit is discrepant with the disappearance results: Bugey, Chooz, PaloVerde, CDHS. (Appearance and disappearance incompatible at the 4$\sigma$ level) (Maltoni and Schwetz, hep-ph0705.0107)

• 3+2 models may also produce measurable effects in the Double Chooz experiment especially for the near detector (Bandyopadhyay and Choubey, hep-ph0707.2481)
But Wait, Here is More: SciBooNE
New Experiment on the Booster Neutrino Beamline
The SciBooNE detector: used at K2K in Japan

- **SciBar**: Fully active, CH$_2$ target (ran in K2K)
- **Muon Range Detector (MRD)**: 12 Fe plates, 13 scintillator planes range ~ 1 GeV
- **Electron Catcher (EC)**: 2.5 cm x 3 m scintillator strips, w/ multianode PMTs
The SciBooNE sees what MiniBooNE cannot

A CCQE event in SciBooNE:

Proton ID via dE/dx

Scibar hit eff > 99%

Muon Range Stack

\[ \nu_l \rightarrow l^- + W^+ \rightarrow n + p \]
The SciBooNE has good $\pi^0\rightarrow\gamma\gamma$ resolution.

SciBooNE is helpful for measuring beam content and cross sections...

Useful for both T2K, and MiniBooNE: new handle in low energy region $\rightarrow$ first analysis later this year.
Summary and Outlook
MiniBooNE is currently running with Booster antineutrino beam and is granted to run antineutrinos for several more years.

- Provides another low E data set and directly checks LSND.

MiniBooNE is collecting more data from NuMI beamline (different beam, another Low E data set).

SciBooNE is a near detector experiment now running that should make a (independent) cross check measurements.

Much interest in MiniBooNE results (New Physics Beyond Standard Model?).

More results Shortly...

“This could be the discovery of the century. Depending, of course, on how far down it goes.”
Backups
• Electron neutrino disappearance
  (Giunti and Laveder, hep-ph 0707.4593)
• Prompted by the deficit seen in the Ga
  exp’s source calibrations
• To fit the MiniBooNE data, postulate
  that the neutrino flux is off by $x1.48$
  and that electron neutrino disappearance
  probability is 0.59
• This model disagrees with the
  MiniBooNE constraints on the measured
  p0 background
• Lorentz Invariance Violation
  (Katori, Kostelecký, Tayloe, PRD
  74,1050009)
• Adding Lorentz invariance violating
  terms in the Hamiltonian that depend on
  neutrino flavor can produce interference
  terms for the neutrino propagation
• New oscillation phenomenology
• Osc length dependence on E*L
• Variation with sidereal position
Prior to MiniBooNE's first result, it was put forward that sterile neutrinos can take shortcuts in extra dimensions.


- A resonance in active-sterile neutrino oscillations arises from an increase in the path-length of active neutrinos relative to sterile neutrinos in the bulk.
  - Below the resonance, the standard oscillation formulas apply.
  - Above the resonance, active-sterile oscillations are suppressed.
  - A resonance energy in the range of 30–400 MeV allows an explanation of all neutrino oscillation data, including LSND data in a 3+1 model.
  - And this model can evade the problems with the Bugey and CDHS limits.

- This paper predicted that a significant oscillation signal would only be seen in MiniBooNE at low energy.
MiniBooNE has been running with Booster antineutrino beam and is granted to run antineutrinos for several more years.
- Statistics are less but background are smaller and somewhat different.
- Provides another low E data set and directly checks LSND.

MiniBooNE is collecting more data from NuMI beamline

SciBooNE is a near detector experiment now running that should be able to make a cross check of the intrinsic $\nu_e$'s from kaon decay.

"This could be the discovery of the century. Depending, of course, on how far down it goes"
Big Questions in Neutrino Oscillations

1. What is $\nu_e$ component in the $\nu_3$ mass eigenstate?  
   $\Rightarrow$ The size of the “little mixing angle”, $\theta_{13}$?  
   Only know $\theta_{13} < 13^0$

2. Is the $\mu - \tau$ mixing maximal?  
   $35^0 < \theta_{23} < 55^0$

3. What is the mass hierarchy?  
   Is the solar pair the most massive or not?

4. What is the absolute mass scale for neutrinos?  
   We only know $\Delta m^2$ values

5. Do neutrinos exhibit CP violation, i.e. is $\delta \neq 0$?
Since MiniBooNE cannot tell an electron from a single gamma, any process that leads to a single gamma in the final state will be a background.

Processes that remove/absorb one of the gammas from a $\nu_\mu$-induced NC $\pi^0 \rightarrow \gamma\gamma$

- These processes should be in the GEANT detector Monte Carlo but there might be exceptions or inaccurate rates
- Example: photonuclear absorption
- But tends to give extra final state particles

Explains some, but far from all of the excess.
Investigation of detector anomalies or problems

No Detector anomalies found
Example: rate of electron candidate events is constant (within errors) over course of run

No Reconstruction problems found
All low-E electron candidate events have been examined via event displays, consistent with 1-ring events

Signal candidate events are consistent with single-ring neutrino interactions
⇒ But could be either electrons or photons
Analysis of dirt events from NuMI beam

- “Dirt” background is due to ν interactions outside detector. Final states (mostly neutral current interactions) enter the detector.

- **Measured** in “dirt-enhanced” samples:
  - we tune MC to the data selecting a sample dominated by these events.

- “Dirt” events coming from outside deposit only a fraction of original energy closer to the inner tank walls.

- Shape of visible energy and event vertex distance-to-wall distributions are well-described by MC: good quantities to measure this background component.
Selecting the dirt events

Event pre-selection:
1 subevent
Thits>200, Vhits<600
R<500 cm

log($L_e/L_\mu$)>0.05 (e-like)
$E_e$<550 MeV
Distance-to-wall<250 cm
$m_\pi$<70 MeV/c$^2$ (not $\pi^0$-like)

Fits to dirt enhanced sample:
Uncertainty in the dirt rate is less than 20%.

We declare good MC/Data agreement for the dirt sample.
Analysis of the $\nu_e$ CCQE events from NuMI beam

$\nu_e$ CCQE ($\nu n \rightarrow e p$)

1 Subevent
   Thits > 200, Vhits < 6
   R < 500 cm, $E_e$ > 200 MeV

+ Likelihood cuts as shown below

$E_e$ > 200 MeV cut is appropriate to remove $\nu_e$ contribution from the dump that is hard to model.

Analysis of $\nu_e$ events: do we see data/MC agreement?

MC example plots here come from Booster beam MC
Energy Calibration

We have calibration sources spanning wide range of energies and all event types!

Michel electrons from $\mu$ decay:
- provide E calibration at low energy (52.8 MeV),
- good monitor of light transmission, electron PID

$\pi^0$ mass peak: energy scale & resolution at medium energy (135 MeV), reconstruction

Cosmic ray $\mu +$ tracker + cubes:
- energy scale & resolution at high energy (100-800 MeV), cross-checks track reconstruction

12% $E$ res at 52.8 MeV

Preliminary

Provides $\mu$ tracks of known length $\rightarrow E_{\mu}$
Observation and analysis of an off-axis beam.

Measurement of $\pi/K$ components of the NuMI beam.

The NuMI beam provides MiniBooNE with an independent set of neutrino interactions.

Enables a comparison of the Booster Neutrino Beam (BNB) with the NuMI neutrino beam (off axis):
- Similar energy spectrum.
- Proton target is further away (~746 m vs. 550 m)
- Very different background composition.
- Rich in $\nu_e$ flux → can study $\nu_e$ reactions in greater detail.