The MiniBooNE Experiment

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The MiniBooNE Collaboration

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Motivation: *The oscillation signal seen by LSND (Los Alamos)*

Neutrino Oscillations:

If neutrinos have mass, the weak eigenstates are mixtures of the mass eigenstates:

$$\nu_e = \cos\theta\, \nu_1 + \sin\theta\, \nu_2$$
$$\nu_\mu = -\sin\theta\, \nu_1 + \cos\theta\, \nu_2$$

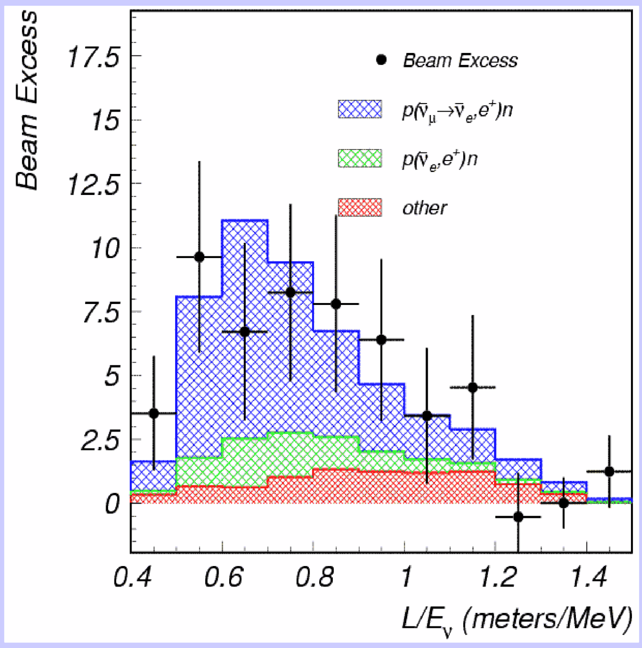
This implies that the weak eigenstates change flavors periodically with time as they propagate in space. The probability of observing a ν_e at a distance L from the creation point of a ν_μ of energy E is known as the “oscillation probability”:

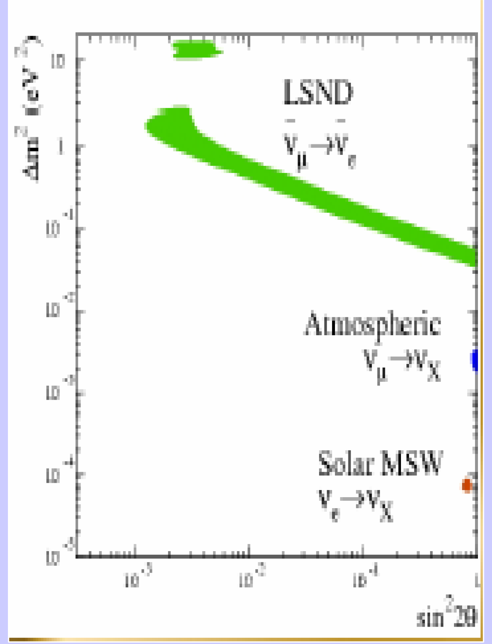
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta\, \sin^2\left(\frac{1.27\,\Delta m^2(\mathrm{eV}^2)\, L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

Statistical significance of the LSND signal:

LSND observed oscillations from μ^+ decay at rest. An excess of (87.9±22±6) events over its running period (1993-1997) corresponds to an oscillation probability which is different from 0 at the 3.3 σ level.

MiniBooNE will test this observation by keeping a similar L/E while changing the systematics of the measurement.





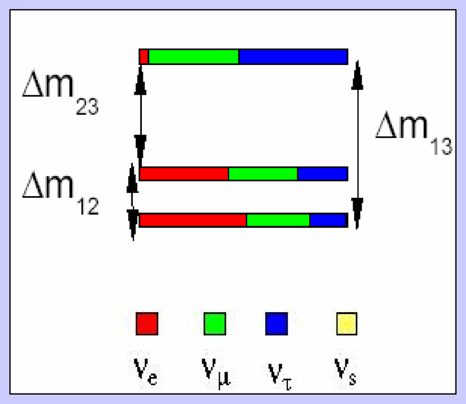
Solar, atmospheric, and accelerator (LSND) experiments, imply the existence of 3 Δm^2 values, which is only possible if more than 3 neutrinos exist! ν_e, ν_μ, ν_τ, ν_s ...

Left: The LSND signal and background L/E distributions. Right: Regions in parameter space allowed by the results of oscillation experiments. Note the 3 different scales of Δm^2 values.

Neutrino models

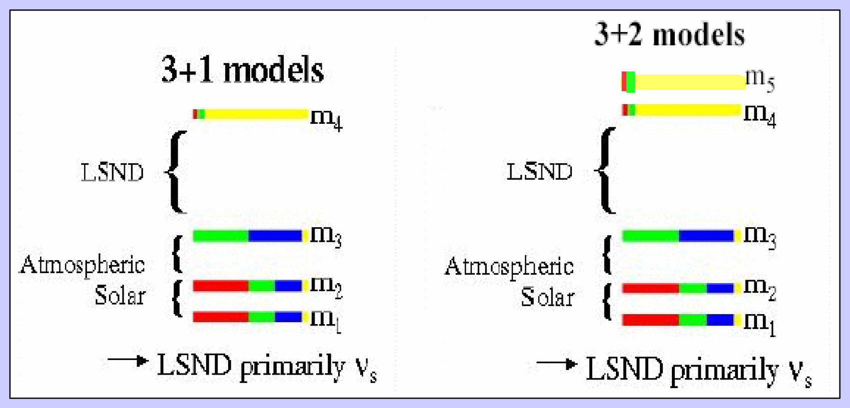
“3 neutrino” models

Accommodate one high and one low Δm^2 values.. The atmospheric oscillations are a combination of the other two. However is unattractive to other measurements.



Sterile Neutrino models:

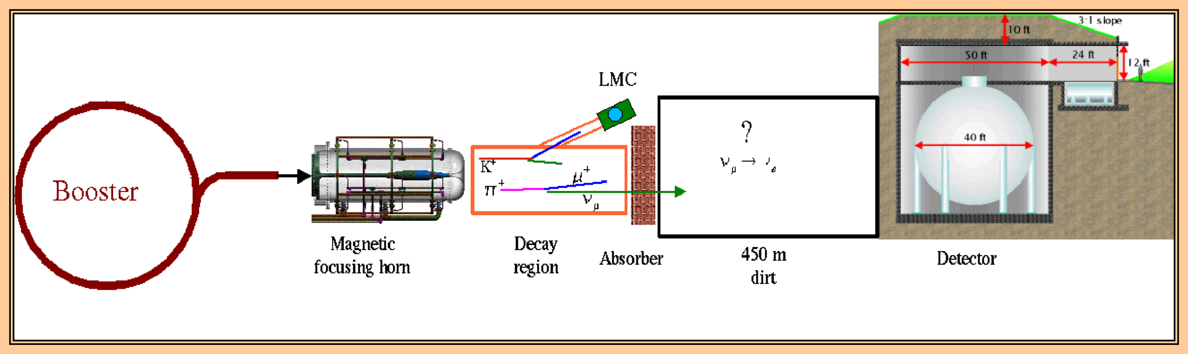
The most likely scenario that will accommodate the LSND signal includes one or more sterile (non-interacting) neutrinos. The diagram shows 3+1 and 3+2 mixing schemes that are possible in the case of a confirmed LSND signal.



The Neutrino Beam

Schematic of the experiment:

The FNAL Booster produces 8 GeV protons that interact in a thick beryllium target. The protons arrive in a 1.6 μs beam spill typically delivering ~4 x10^{12} protons per pulse at a rate of 3-4 Hz, with a beam uptime of ~88%.



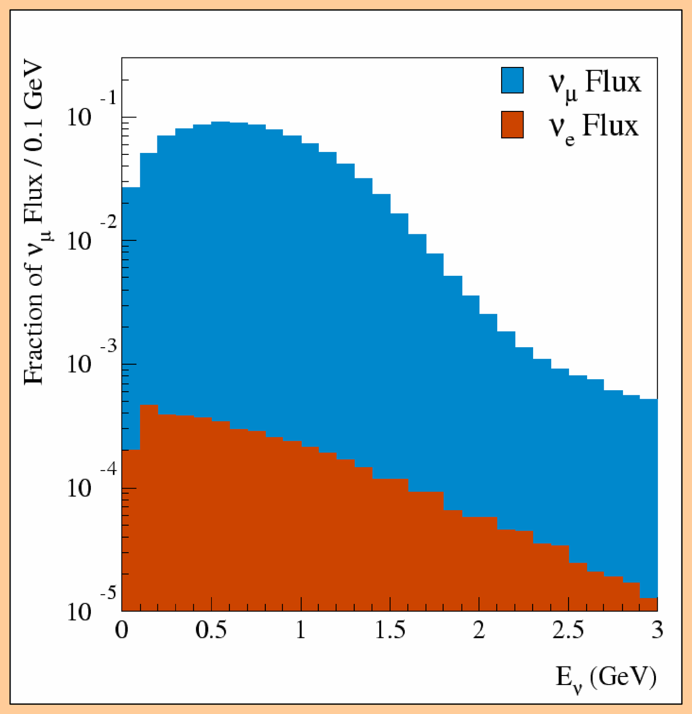
Positive and negative mesons are copiously produced. At the time of interaction a 170 kA current pulse feeds the Magnetic Horn, which then focuses the positive mesons and defocuses the negative ones. The mesons are allowed to decay in a 50 m long decay pipe, and the remaining neutrinos reach the detector. The question is... Do they oscillate?

The MiniBooNE Neutrino Flux:

In its current running mode, the MiniBooNE neutrino flux is composed primarily of ν_μ’s with a small component of ν_e’s . Neutrinos come primarily from the decay of π^+’s , and K^+’s that are produced in the target and focused by the horn. The Little Muon Counter (LMC) will provide us with an additional constraint on kaon production. Note that by changing the polarity of the horn, the experiment can be run in antineutrino mode and study CP violation in the neutrino sector.

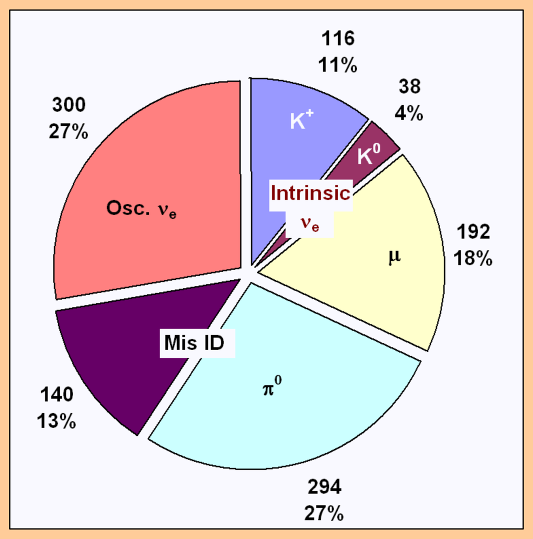
Neutrinos are produced in the decay chain of charged mesons :

$$\pi^+/K^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \overline{\nu_\mu} + \nu_e$$
$$K^+ \rightarrow \pi^0 + e^+ + \nu_e$$
$$K^L \rightarrow \pi^\pm + e^\mp + \overset{(-)}{\nu_e}$$



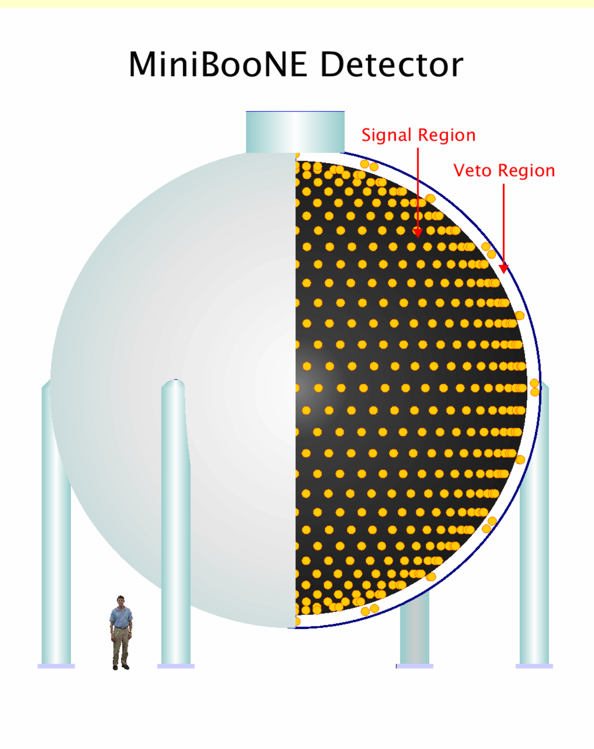
While nearly all the π^+’s decay producing a ν_μ because of their short lifetime, only a fraction of the μ^+ decay producing a ν_e .
Intrinsic ν_e’s coming from kaons are measured at low energy production experiments: HARP (CERN), E910 (Brookhaven).

Event Rate Prediction for an appearance search:



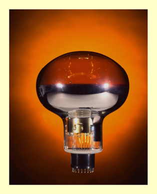
Shown here are the different sources of backgrounds for an appearance experiment in the scenario of LSND-like oscillations (numbers are for 1e21 P.O.T.). Beam intrinsic neutrinos from kaon decays and miss-identified neutral pions must be well understood.
Misidentified NC π^0 events are one of the most serious backgrounds for this search.

The Detector



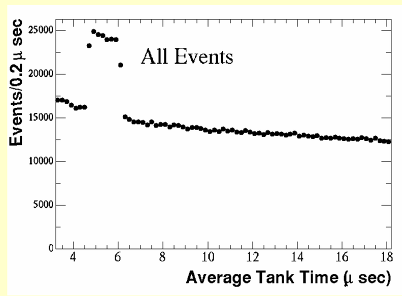
The MiniBooNE detector is a 12 m diameter spherical tank filled with mineral oil. Its inner walls are covered with 1280 8” photomultiplier tubes (PMT) that gather the light produced by the processes in the detector. A veto region with 240 PMT’s serves the purpose of eliminating the cosmic ray background reaching the detector. With ~3m of overburden, roughly, 10000 muons enter the tank every second, with ~2200 stopping in the oil volume.

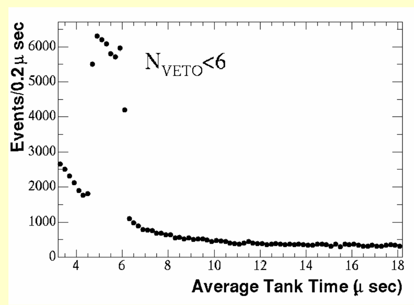
A MiniBooNE PMT

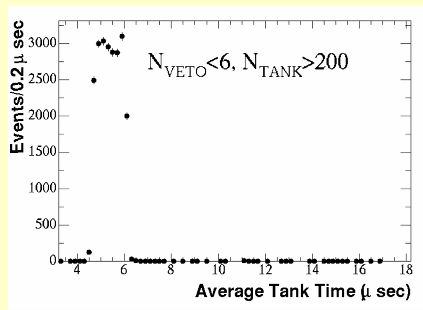


Beam events:

Beam events are easily isolated by simple low-level analysis cuts. The majority of cosmic ray activity is cut out by requiring that an event fires less than 6 PMT’s in the veto. Muons that enter the tank and do not exit will produce a Michel electron that will light less than 200 PMT’s in the tank. The additional requirement of events with more than 200 PMT’s in the tank ensures that we’re left with good neutrino candidate events (see plot sequence to the right)

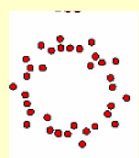
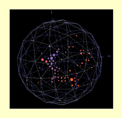


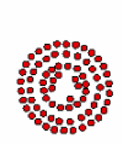
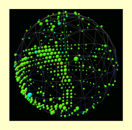


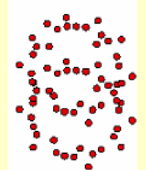
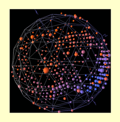


MiniBooNE as a Cherenkov detector:

Rings of different characteristics identify particles


Electron suffering multiple scattering



Muon Slowing down


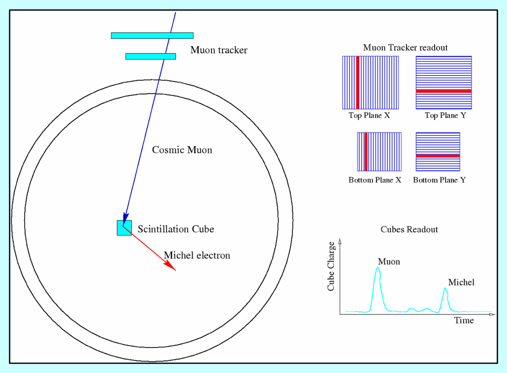

Pi0 decay into 2 photons


Particle identification is possible using the topology of the ring patterns. Cherenkov light (prompt) and scintillation light produced naturally in the oil (delayed and isotropic) are key to the identification algorithms.

The MiniBooNE Experiment (II)

Calibrating MiniBooNE

Muon Tracker Calibration System:

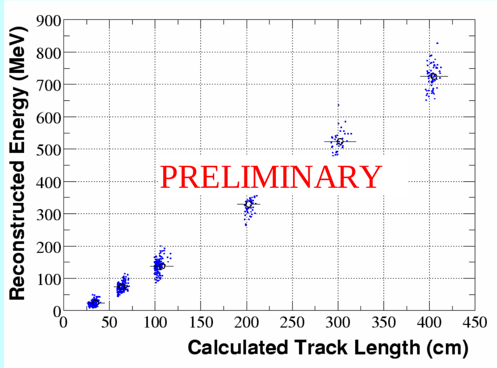


Top: Schematic of the muon tracking system. In red the scintillating strips that fire by the passage of a muon through them determine the entry position of the muon in the tank by geometry.

The muon calibration system employs cosmic ray muons that stop in scintillating cubes located inside the detector to provide the experiment with an independent source of energy calibration. The entry position of a cosmic muon is determined by a series of scintillating strips located at the "north pole" of MiniBooNE. The schematic on the left shows how the muon tracker strip system is used for this purpose.

Below: The muon reconstructed energy versus path length from its entry point to a scintillating cube. Shown is data for 6 scintillating cubes.

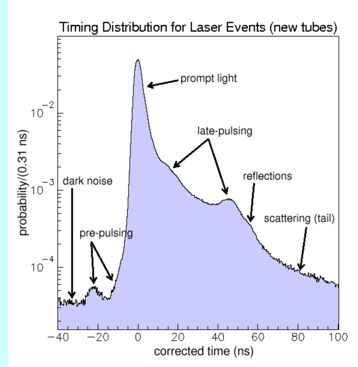
The linear relation between the energy reconstructed in the MiniBooNE detector and the muon track length, shown on the plot to the right, is expected for a minimally ionizing particle traversing the oil (hydrocarbon chain). Each data cluster corresponds to each of 6 (out of a total of 7) scintillating cubes located at different depths in MiniBooNE. Longer muon track length and energy are needed to reach the cubes at larger depth.

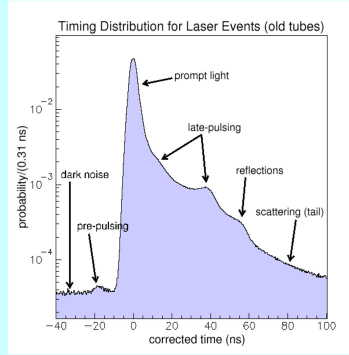


Laser calibration system:

A set of laser-fed flasks filled with Ludox are distributed inside the MiniBooNE tank. The purpose of this system is to study the PMT time response and the optical properties of the oil, the latter being one of the most important sources of systematic error in the experiment.

The plots show the time distributions of the PMT hits in laser events from a flask located at the center of the tank. MiniBooNE has a set of old PMT's inherited from LSND, and a set of new PMT's. They have a different time structure in laser events as seen in the plots.

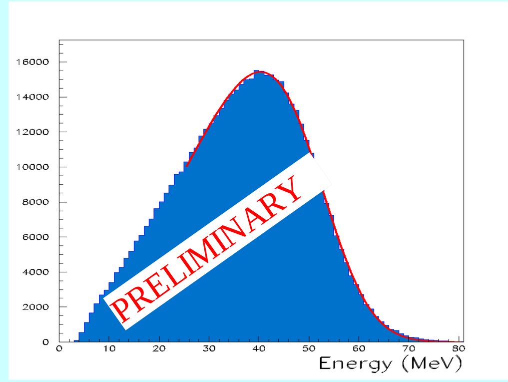




Features: The prominent peak is due to laser light. The width is due to the inherent time response of the PMT's. Pre- and post- pulsing peaks are known features of PMT's. A shoulder due to reflections from the wall and the faces of the PMT's is clear. The long tail is due to light scattering in the oil.

Electrons coming from muon decays in the detector have a characteristic spectrum whose endpoint provides a "candle" to calibrate the reconstruction algorithms used in MiniBooNE.

The plot to the right shows the Michel electron energy spectrum convolved with a Gaussian response function. The fit gives a resolution of 15% at 53 MeV.



MiniBooNE Physics Analyses:

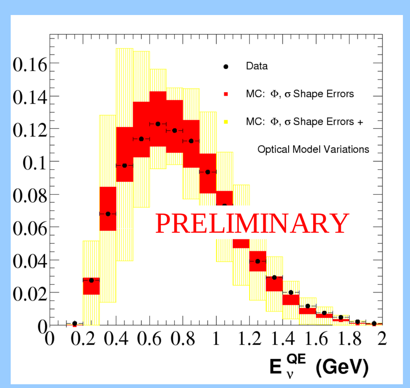
Charged Current Quasi-Elastic scattering:

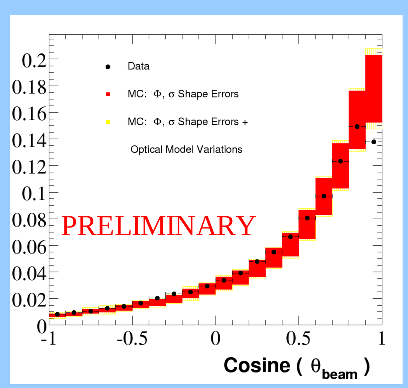
(Analysis by Jocelyn Monroe and Michel Sorel, Columbia University)

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

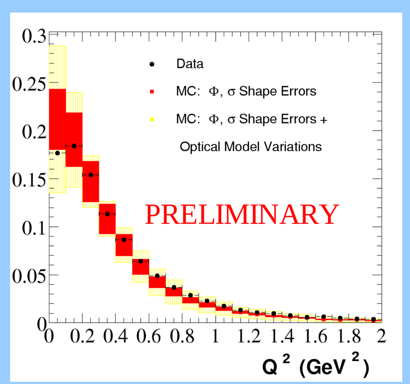
The neutrino energy and the 4-momentum transfer are calculated from the kinematics of the event by measuring the muon energy and scattering angle. The plots below show shape comparisons between data and Monte Carlo.

$$E_\nu = \frac{1}{2}\frac{M_p E_\mu - m_\mu^2}{M_p - E_\mu + \cos\theta_\mu \sqrt{E_\mu^2 - m_\mu^2}}$$

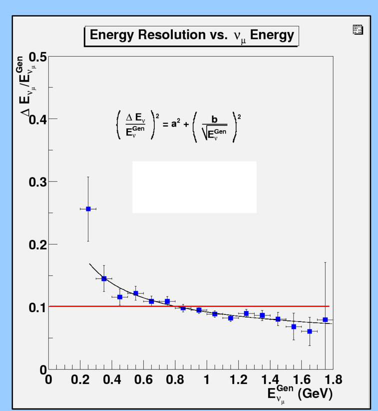




$$Q^2 = 2E_\nu E_\mu (1 - \beta_\mu \cos\theta_\mu) - m_\mu^2$$



The red bars correspond to 1σ flux (shape) and cross section errors added in quadrature. The yellow bars account for optical model uncertainties given by variations of the detector Optical Model parameters (added in quadrature).



Top left: Reconstructed neutrino energy distribution (relatively normalized)
Top Right: Reconstructed lepton scattering angle (relatively normalized)
Bottom Left: Reconstructed Q^2 distribution (relatively normalized).

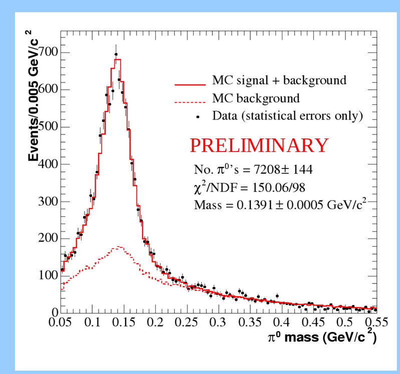
Left: The neutrino energy resolution for CCQE ν_μ events as predicted by our detector Monte Carlo.

Neutral Current π^0 events:

(Analysis by Jennifer Raaf, University of Colorado)

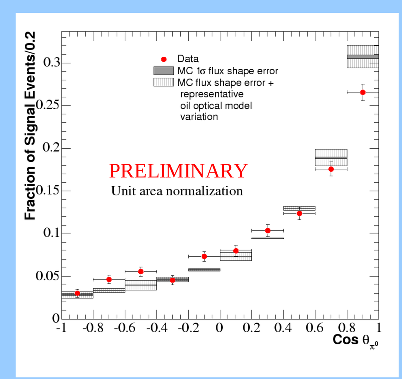
$$\nu_\mu + N \rightarrow \nu_\mu + N + \pi^0$$

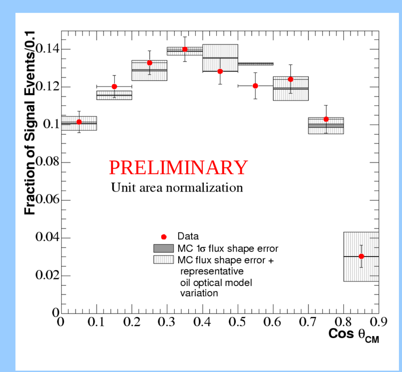
A π^0 decays promptly into two photons. These photons scatter off electrons in the mineral oil and the light emitted by the electrons reaches the PMT's. The energy and direction of the photons can be reconstructed and from it the kinematics of the original π^0.



The above figure shows the fit to the invariant π^0 mass distribution for a fraction of the data, which serves as an additional energy scale calibration source for electron-tyoe events. This method is used to extract the number of NC π^0 events (yields).

NC π^0 events represent a significant background to the $\nu_\mu \rightarrow \nu_e$ oscillation search in MiniBooNE. Understanding of these events is crucial!



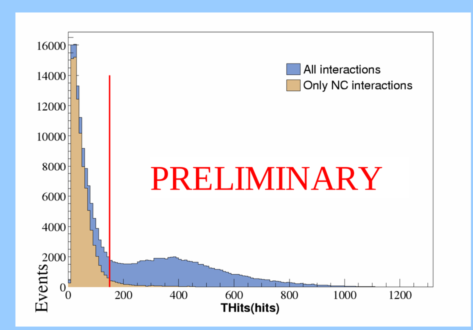


Top: Extracted π^0 yields in bins of the π^0 angle relative to beam direction. *Bottom*: Extracted yields in bins of the center of mass decay photon angle (plots are relatively normalized)

Neutral Current Elastic scattering:

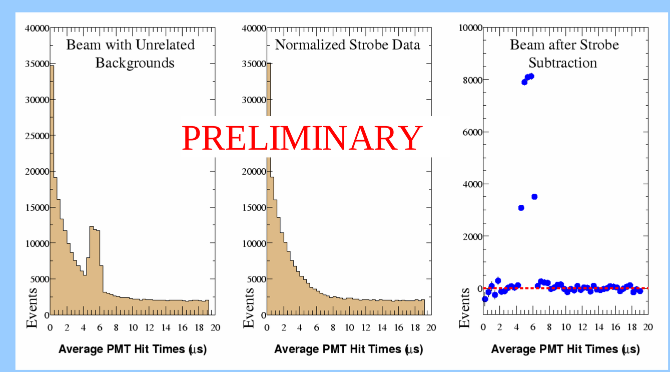
(Analysis by Chris Cox, Indiana University)

$$\nu_\mu + N \rightarrow \nu_\mu + N$$



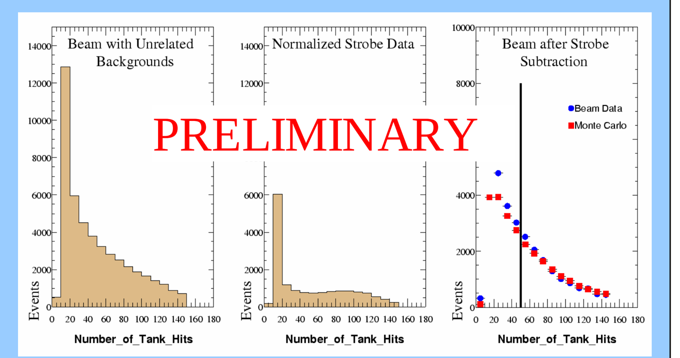
This type of events is characterized by a low number of PMT hits in the Tank.

Left: Distribution of the number of PMT hits for events with no secondary electrons and less than 6 hits in the veto. We see that the additional cut at about 150 tank hits isolates well this type of events.



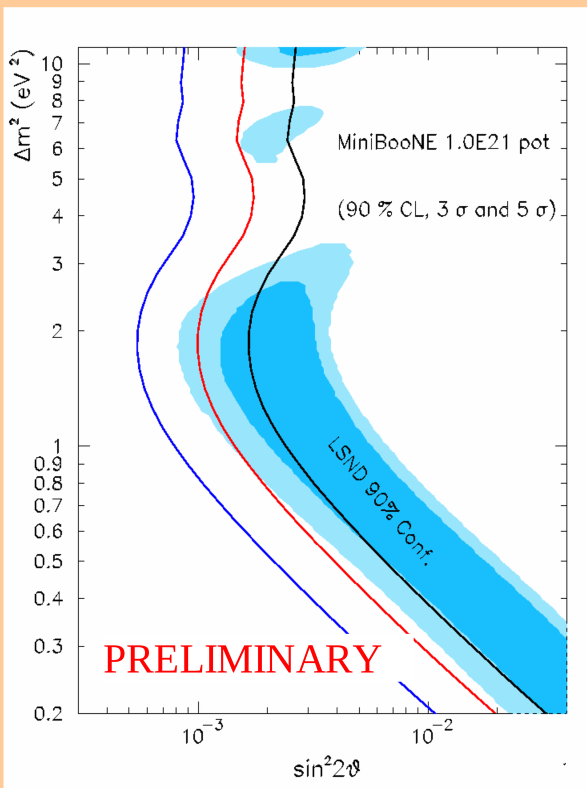
They are easily isolated with a suitable background subtraction. Note the 1.6 μs beam window.

Above: Average event time distributions. Michel electrons from cosmic muons stopping in the tank constitute the most important background to this sample. Here, a background subtraction is performed using uncorrelated beam events (strobe).



Sensitivity to appearance search

CASE 1: MiniBooNE with at null result:

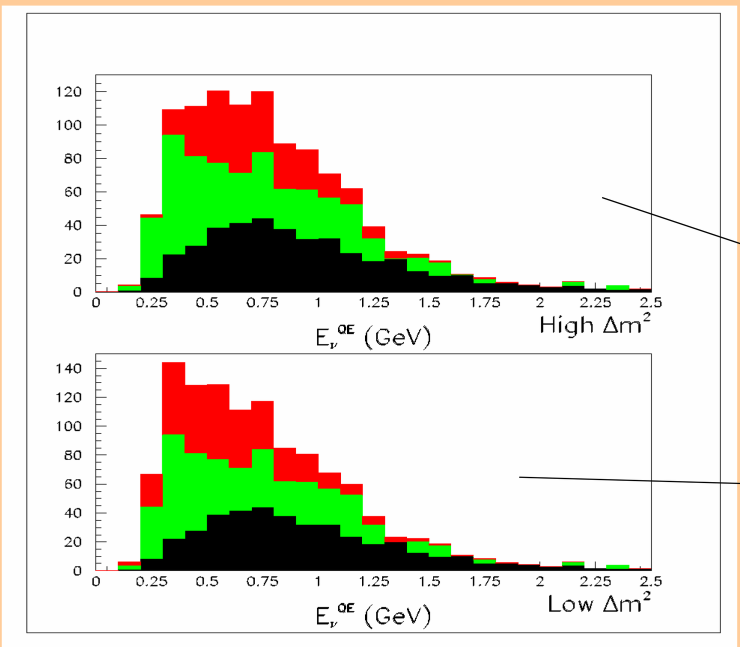


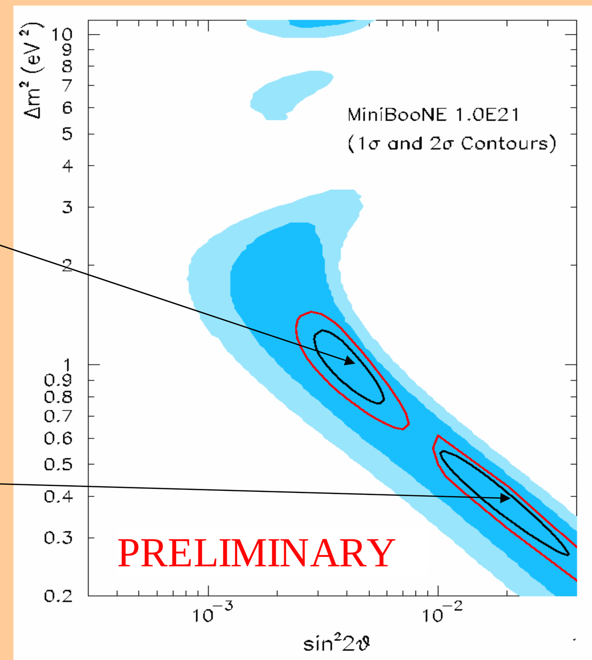
If no oscillations signal is observed, MiniBooNE requires 1e21 protons on target (P.O.T.) to definitively exclude the LSND 90% C.L. allowed region at the 3σ level (middle line).

Left: Updated oscillations sensitivity ($\nu_\mu \rightarrow \nu_e$) . Dark (light) blue is LSND 90% (99%) C.L. allowed region. MiniBooNE Collaboration Run Plan , Dec. 2003 §

§ http://www-boone.fnal.gov/publicpages/runplan.ps.gz

CASE 2: MiniBooNE sees a signal:





Left: The summed energy distribution of oscillation events and backgrounds for Δm^2 of 1 eV^2 (top) and 0.4 eV^2 (bottom). Black: intrinsic backgrounds; Green: ν_μ miss-ID background; Red: oscillation events.

Right: One and two sigma contours for an oscillation signal at Δm^2 of 1 eV^2 and 0.4 eV^2 .

If an oscillations signal is observed in any part of the allowed LSND region, MiniBooNE will be able to distinguish between a "low" or a "high" Δm^2 scenario from the shape of the neutrino energy distribution. This also requires that 1e21 P.O.T. be delivered to the experiment.

Final comments:

At current time we have collected ~3E20 P.O.T. The FNAL Linac and Booster have undergone significant improvements leading to record beam delivery rates to MiniBooNE in the past few weeks.
However, we need to reach 1E21 P.O.T to succeed in our physics goals.

Look out for our results on $\nu_\mu \rightarrow \nu_e$ oscillations sometime in 2005!

Stay tuned…