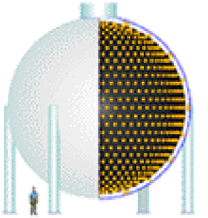


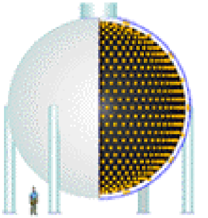
Short Baseline Neutrino Oscillations and MiniBooNE

Jonathan Link
Columbia University

Les Rencontres de Physique de la Vallée d’Aoste

March 10, 2003

A Little Neutrino Phenomenology



If neutrinos have mass then they may oscillate between flavors.

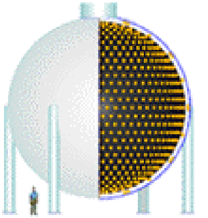
This mixing of flavors is governed by the MNS matrix which relates the mass eigenstates (ν_1, ν_2 and ν_3) to the flavor eigenstates.

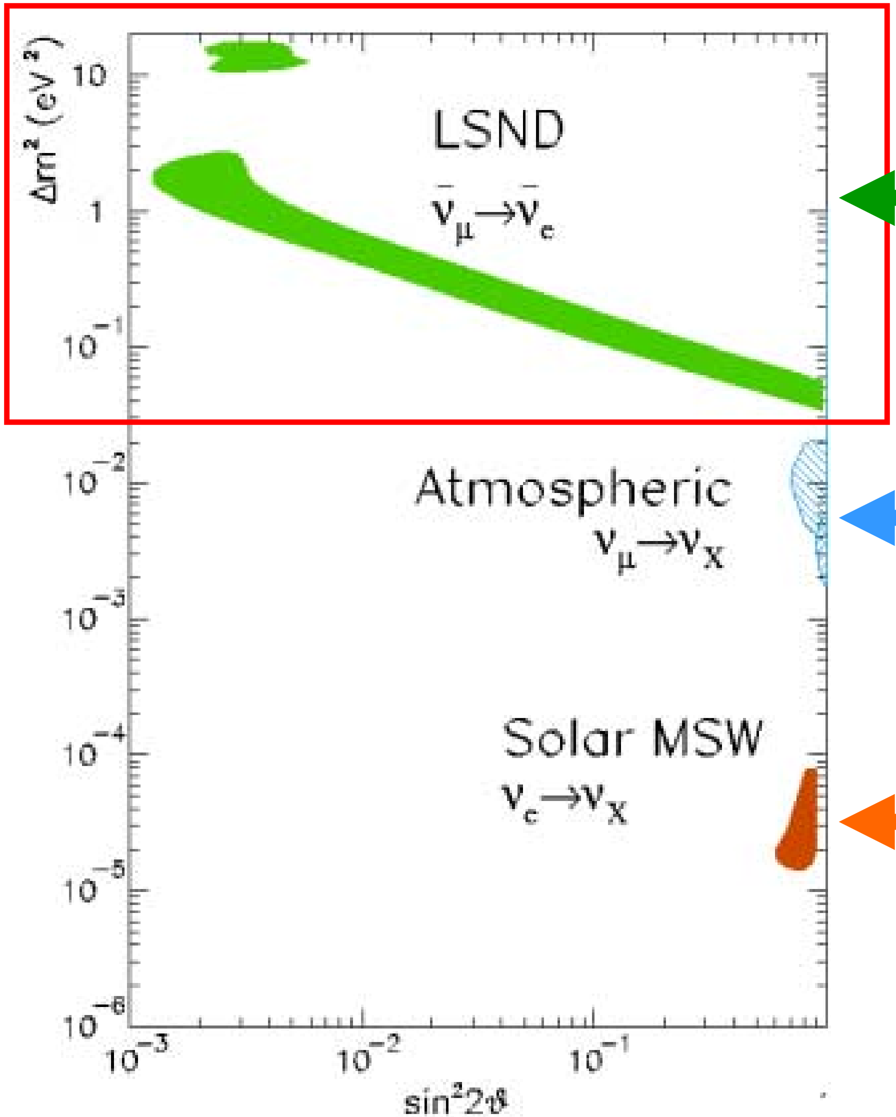
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

For oscillations involving just two neutrinos the oscillation probability simplifies to

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{12} \sin^2 (1.27 \Delta m_{12}^2 L / E_\nu)$$

Plenty of Evidence for Neutrino Mass



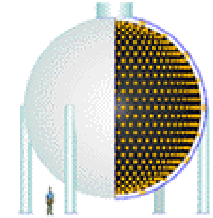


LSND – Uncorroborated

Atmospheric Neutrinos – Super-K, Soudan, Kamiokande, etc.

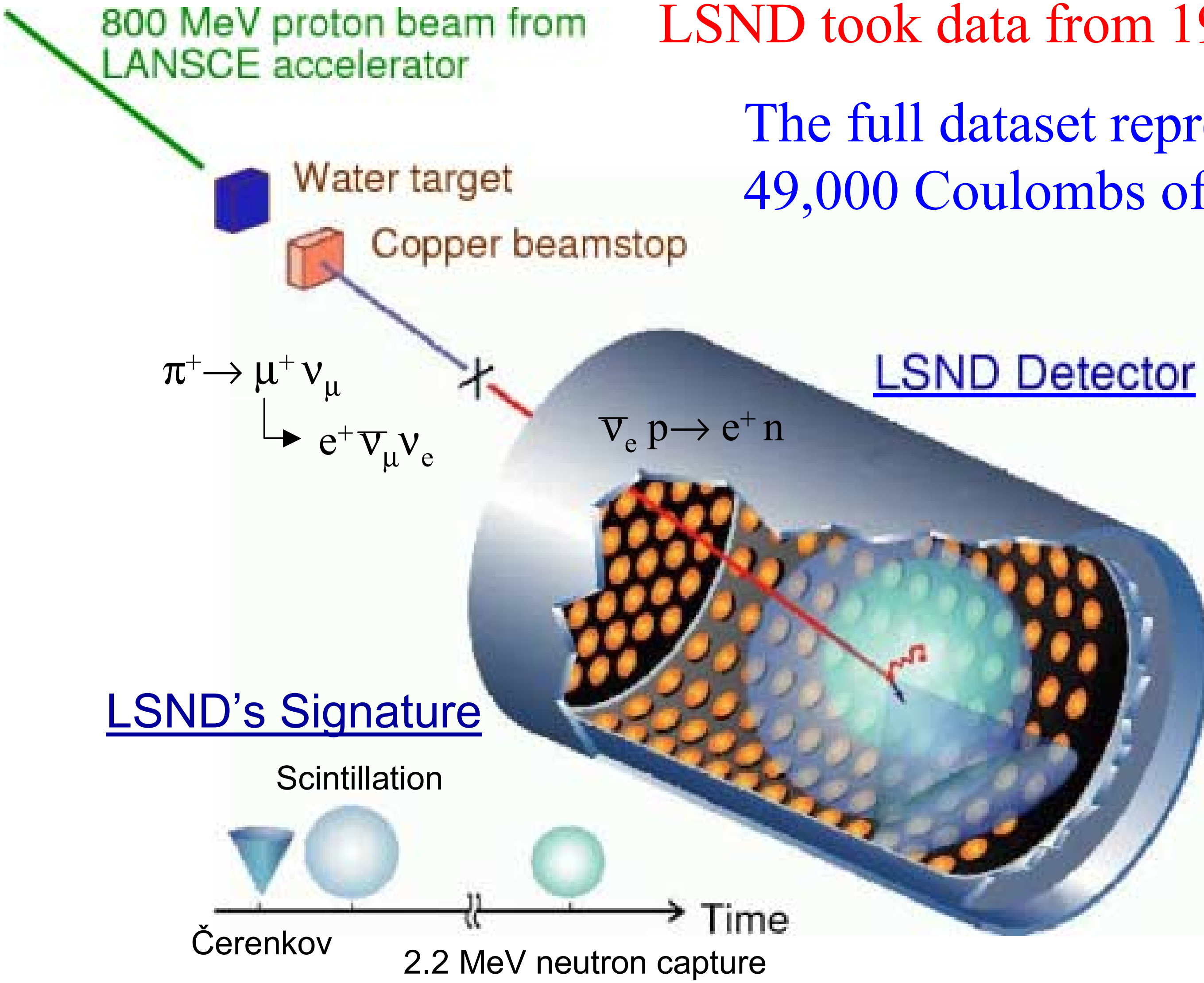
Solar Neutrinos – Recently nailed down by SNO

The LSND Experiment



LSND took data from 1993-98

The full dataset represents nearly 49,000 Coulombs of protons on target.

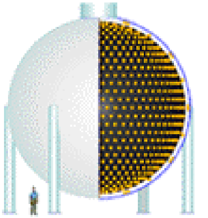


Baseline of 30 meters

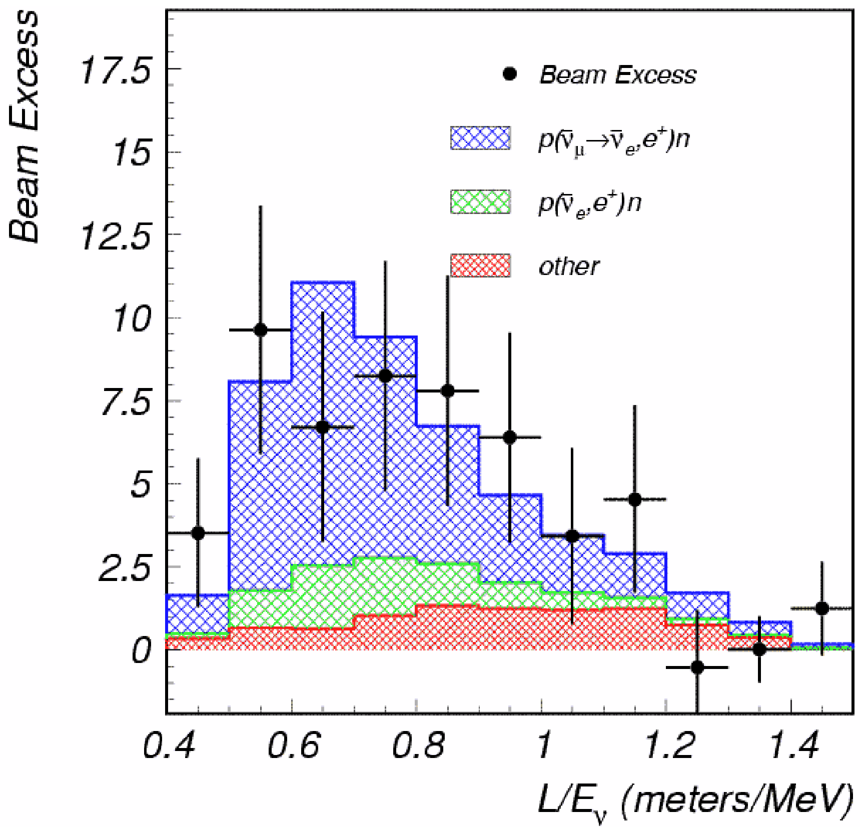
Energy range of 20 to 55 MeV

L/E of about 1m/MeV

LSND's Unexpected Result

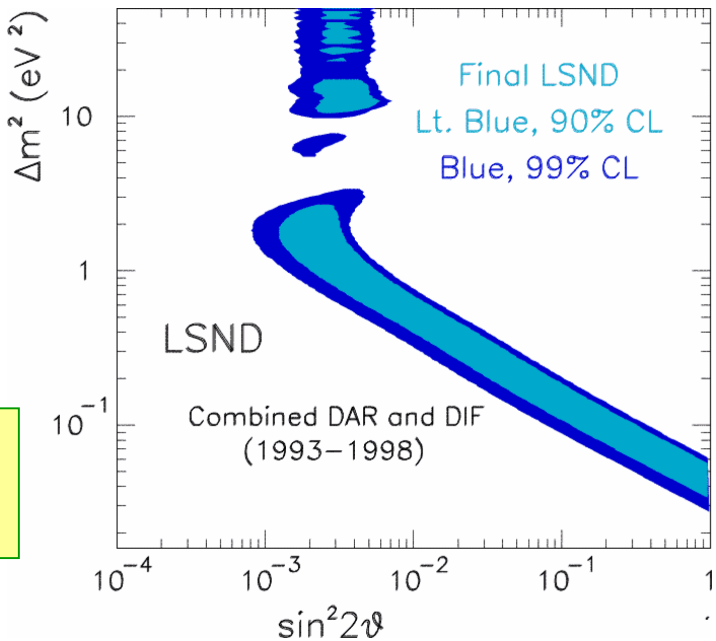


They looked for an excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam



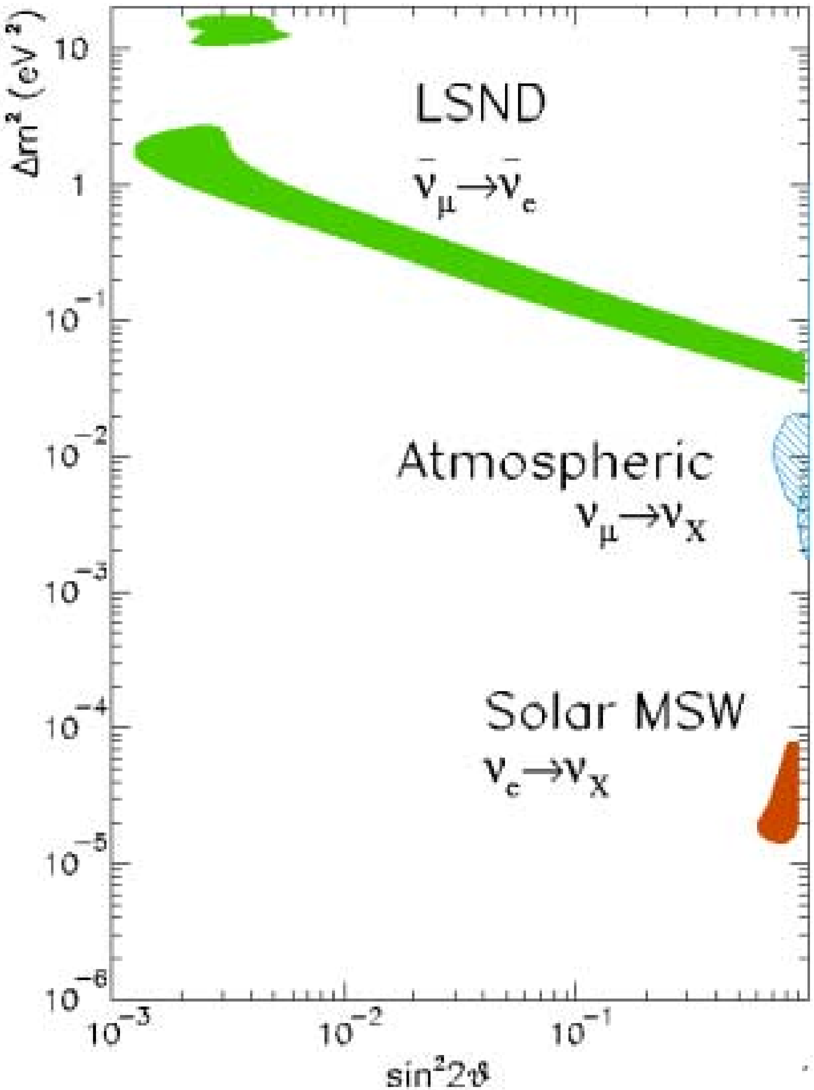
They found 87.9 ± 22.4 ± 6.0 events over expectation.

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



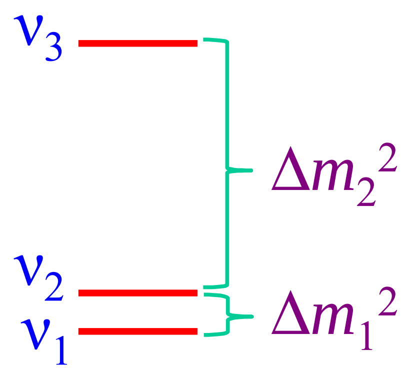
Decay in flight analysis ($\nu_\mu \rightarrow \nu_e$) oscillation probability of (0.10 ± 0.16 ± 0.04) %

Why is this Result Interesting?



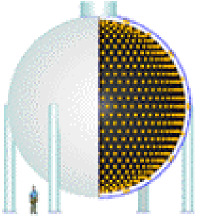
LEP found that there are only 3 light neutrinos that interact weakly.

Three neutrinos allow only 2 independent Δm^2 scales.



$$\Delta m_3{}^2 = \Delta m_1{}^2 + \Delta m_2{}^2$$

But there are experimental results in 3 Δm^2 regions!?!



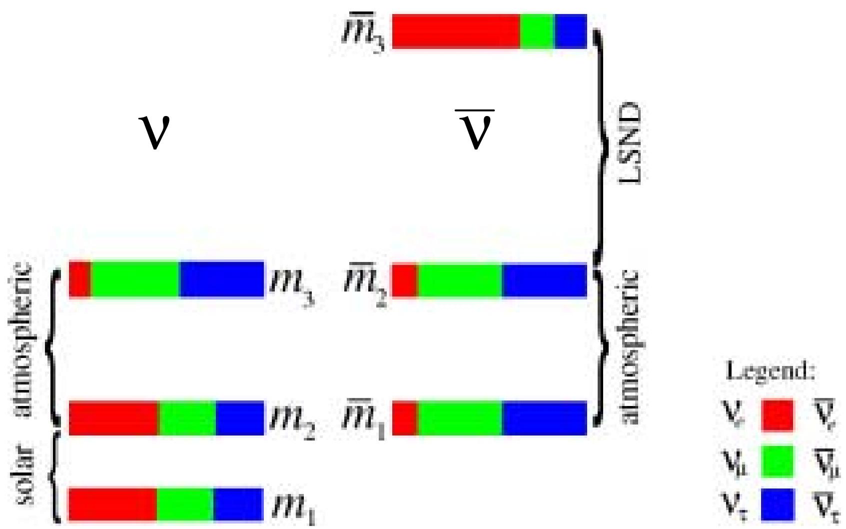
How Can We Fix the Things?

1. One or more of the experiments can be wrong.

2. Add a fourth sterile neutrino.
   Giving you three independent Δm^2 scales.
   (Not dead yet see Pas, Song, and Weiler *hep-ph*/0209373)

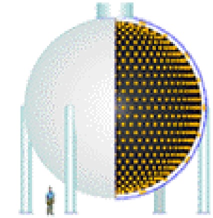
3. Violate CPT.
   Giving you different mass scales for ν and $\bar{\nu}$.

If MiniBooNE sees an LSND signal with ν we can rule this out, but if we don't then we need to run with $\bar{\nu}$!

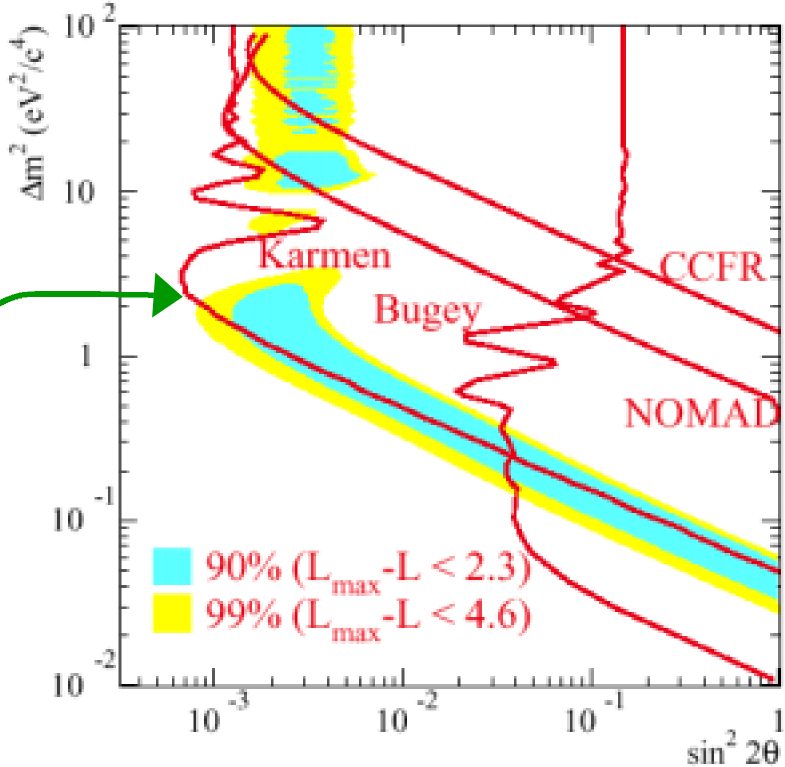


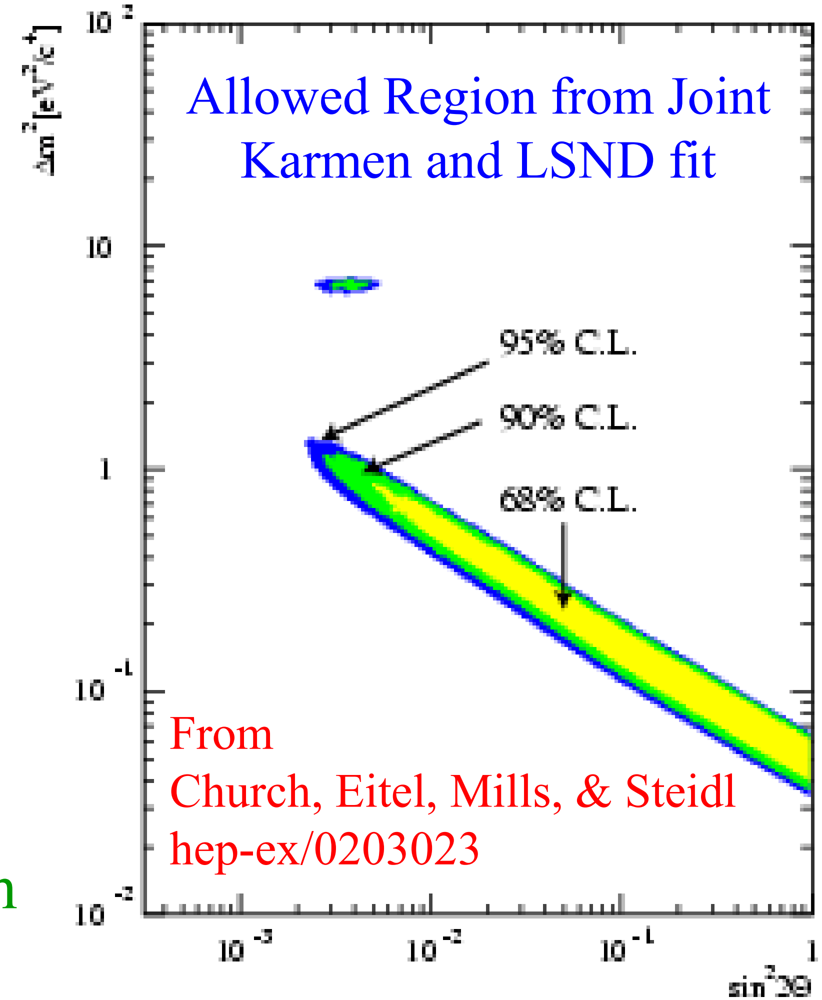
From Barenboim *et al.*, Phys.Lett.B534:106,2002

Other Related Data



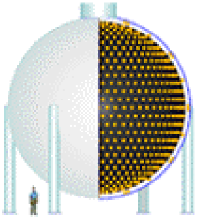
Several other experiments have looked for oscillations in this region.





The most restrictive limits come from the Karmen Experiment.

A Conclusive Experiment is Needed

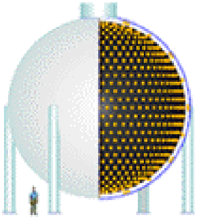


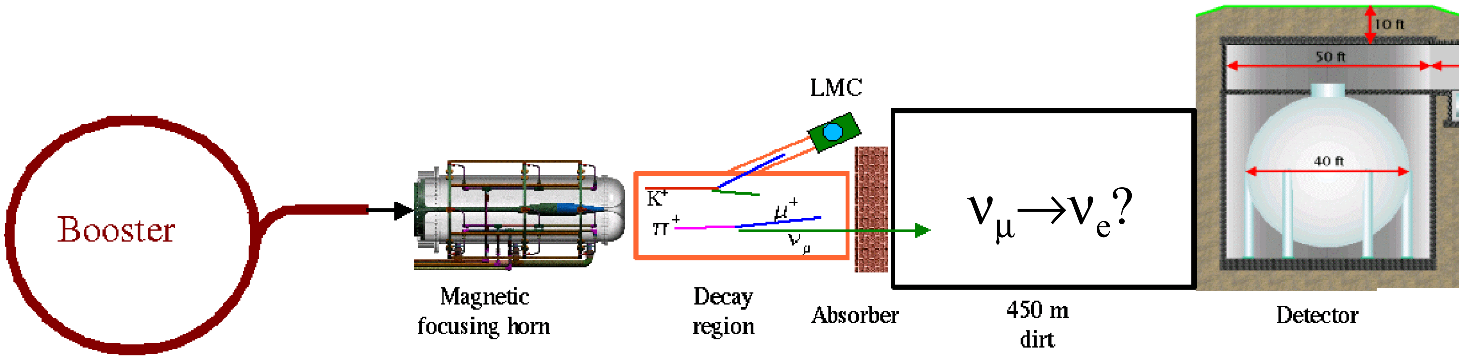
- With High Significance
  - At least 5σ over the entire LSND region (including systematic and statistical uncertainties)
  - Demonstrating expected energy dependence for oscillation
- Low and *Different* Systematics (Change the signature)
  - Change the beam to higher energy
  - Optimize detector for new signature
- High Statistics
  - An order of magnitude more events than LSND

The Booster Neutrino Experiment, BooNE, was formed.

It consists of about 60 scientists from 13 institutions.

The MiniBooNE Neutrino Beam





Start with an intense 8 GeV proton beam from the Booster.

In the Be target primarily pions are produced, but also some kaons.

- Charged pions decay almost exclusively as $\pi^\pm \rightarrow \mu^\pm \nu_\mu$.
- $K^\pm \rightarrow \pi^0 e^\pm \nu_e$, $K_L \rightarrow \pi^\pm e^\mp \nu_e$ and $\mu^\pm \rightarrow e^\pm \nu_e$ contribute ν_e's to background.

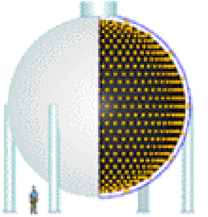
A toroidal field horn focuses the charged particles on the detector.

- Initially positive particles will be focused selecting ν.
- The horn current can be reversed to select $\bar{\nu}$.
- Increases neutrino intensity by an order of magnitude.

The horn is followed by a decay region.

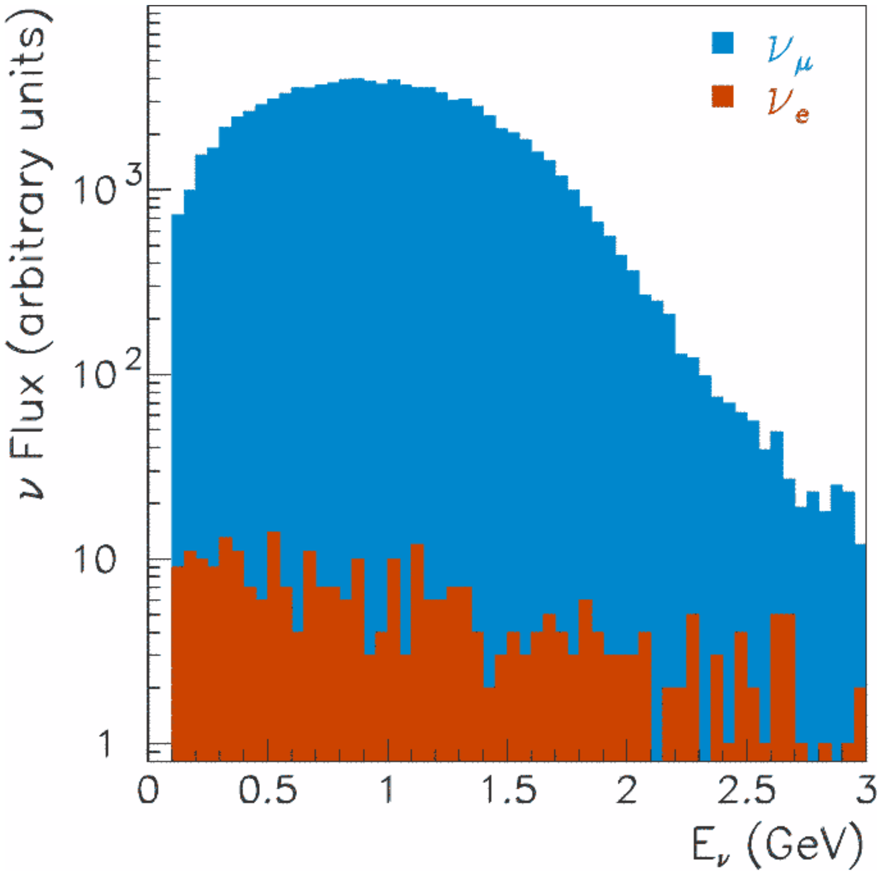
The decay region is followed by an absorber and 450 m of dirt, beyond which only the neutrino component of the beam survives.

Neutrino Flux at the Detector



The *L/E* is designed to be a good match to LSND at ~1 m/MeV.

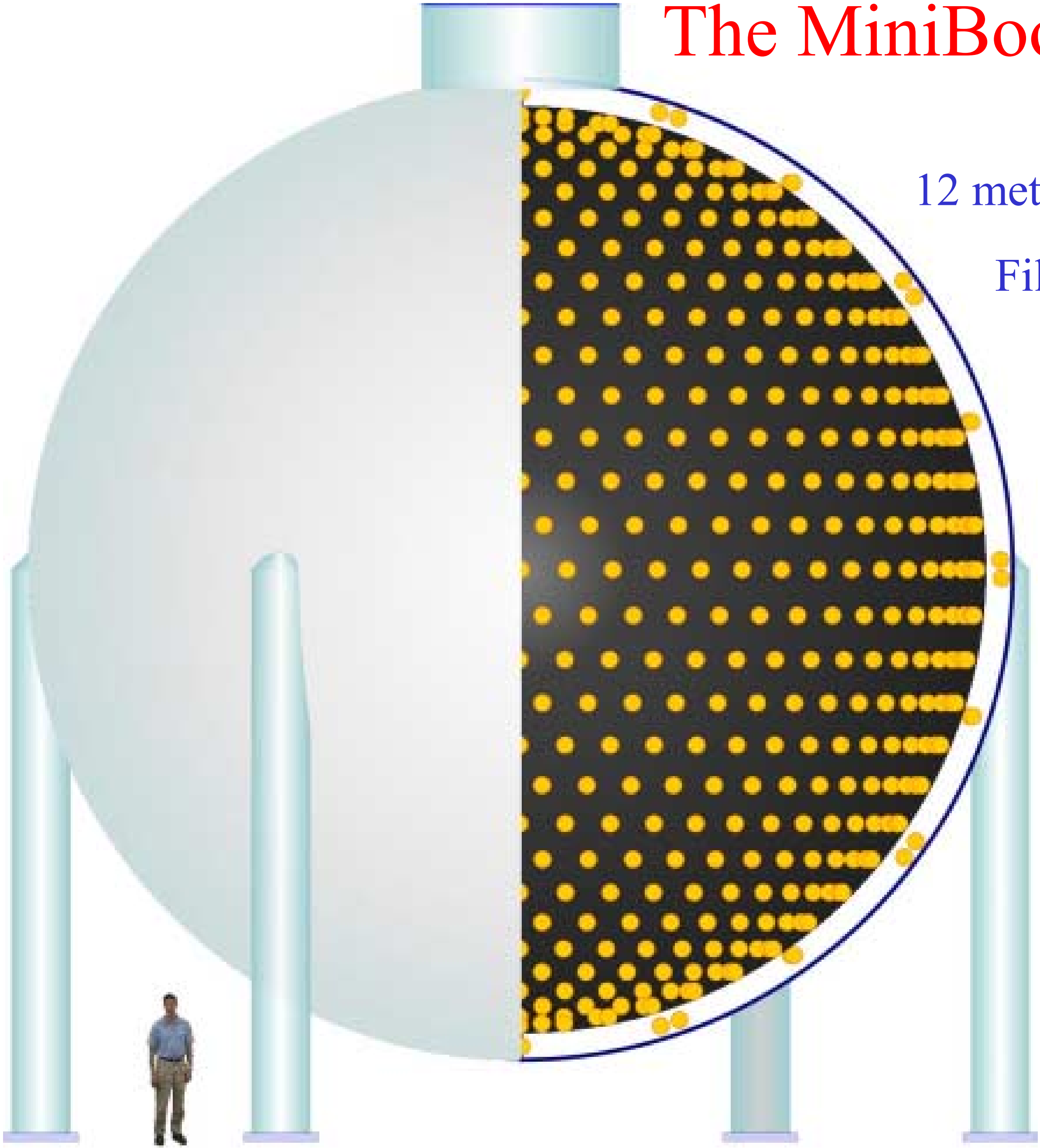
$$P_{oscillation} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L / E)$$

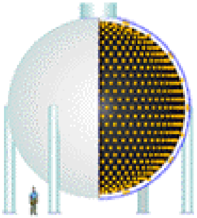


From beam simulations the expected intrinsic ν_e flux is small compared to the ν_μ flux.

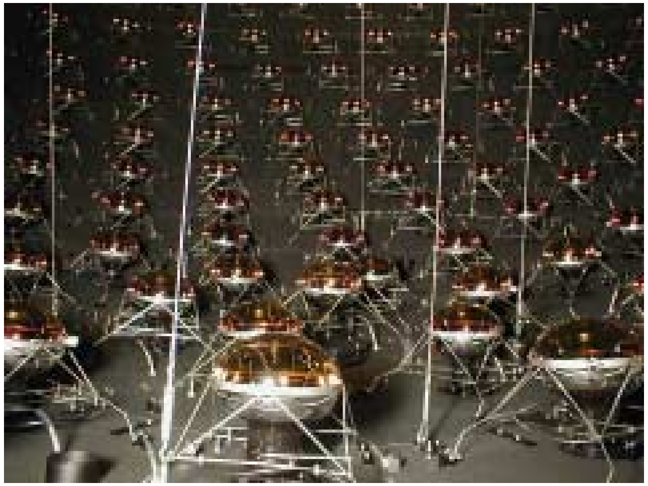
But the intrinsic ν_e flux is comparable in size to an LSND-like signal.

The MiniBooNE Detector

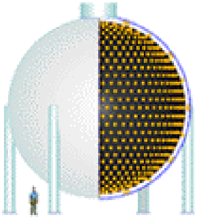




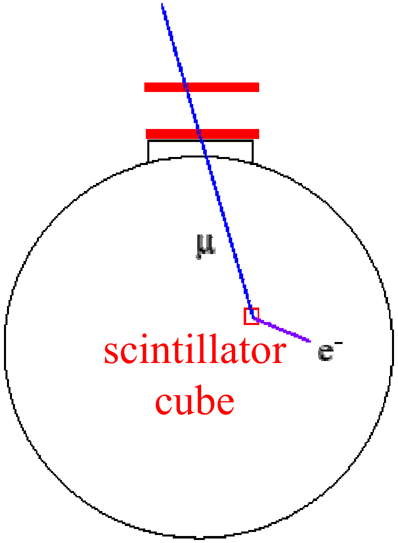
- 12 meter diameter sphere
- Filled with 950,000 liters of pure mineral oil — 20+ meter attenuation length
- Light tight inner region with 1280 photomultiplier tubes
- Outer veto region with 240 PMTs.



Calibration Systems

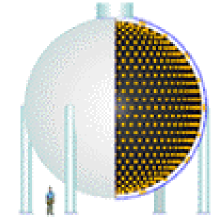


Laser flasks provide PMT charge and timing calibration and a means to monitor the oil attenuation length *in situ*.

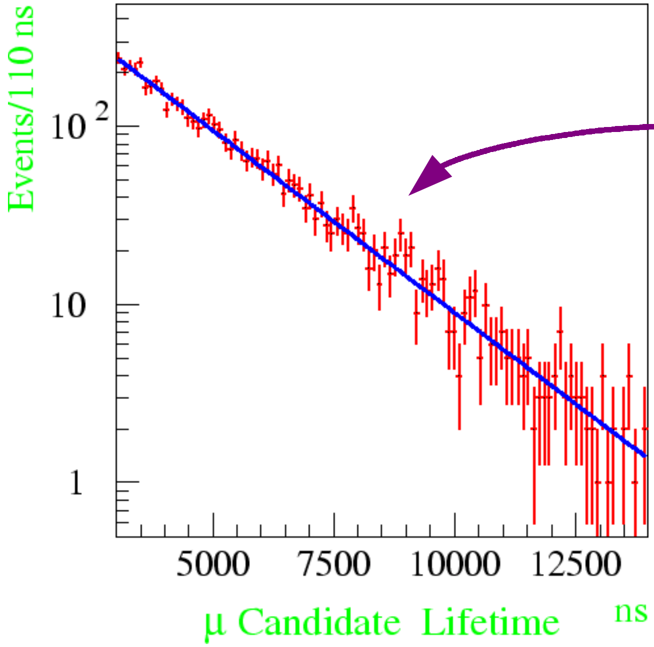


Muon tracker above detector and 7 optically isolated scintillator cubes in the detector provide cross checks for energy estimation and reconstruction algorithms.

Other Calibration Studies

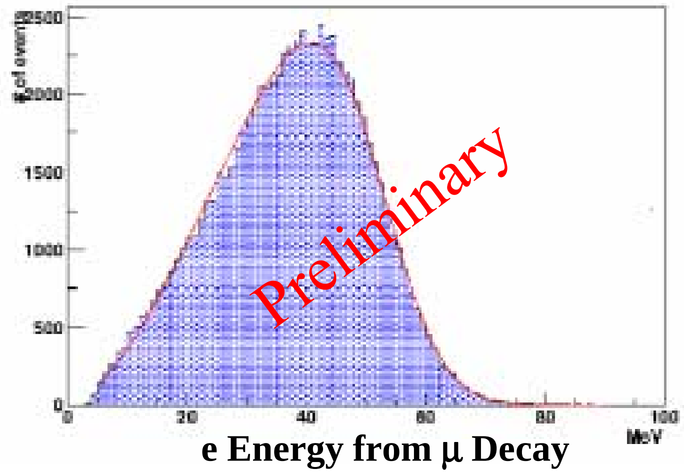


Cosmic Muons



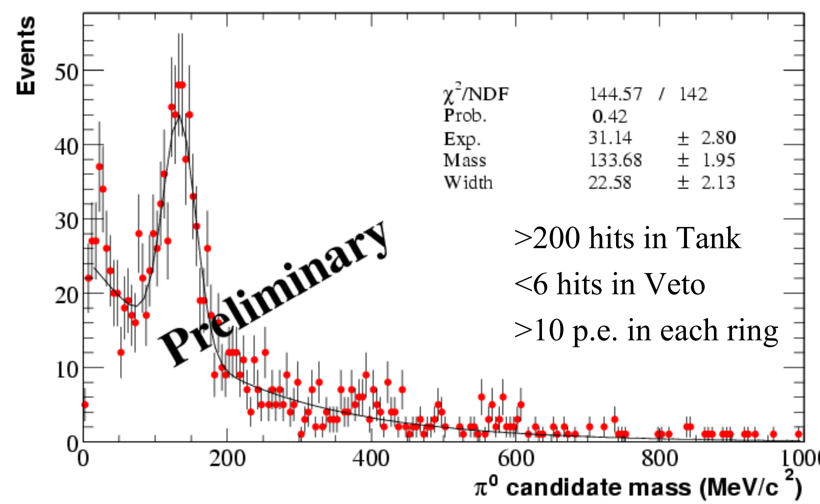
$\tau = 2.12 \pm 0.05\ \mu s$

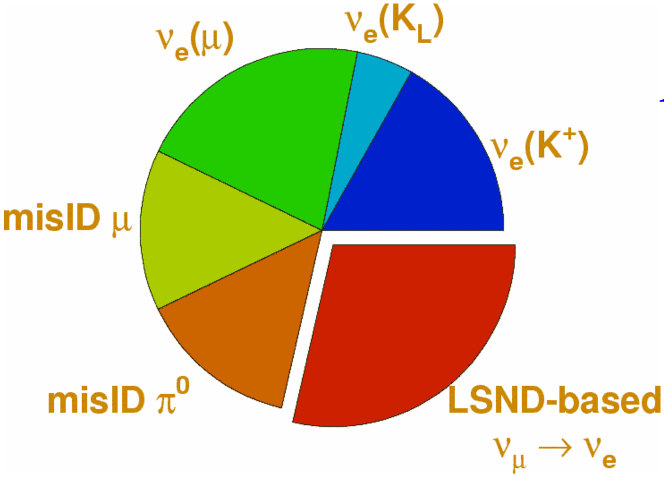
With 8% μ^- capture on carbon, expected μ lifetime in oil is 2.13 μs



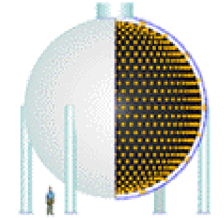
π^0 Mass

Can be used to check energy calibration at the relevant energy scale.

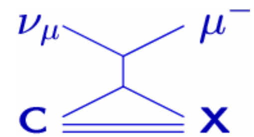




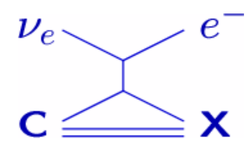
Approximate number of events expected in MiniBooNE with two years of running.



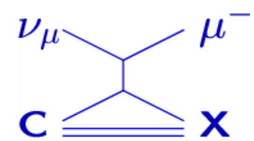
ν_μ Charged Current, Quasi-elastic — 500,000 events



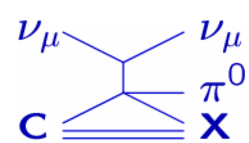
Intrinsic ν_e background: — 1,500 events



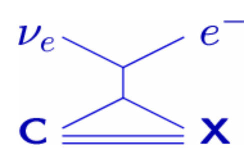
μ mis-ID background: — 500 events



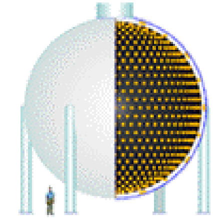
π^0 mis-ID background: (Neutral Current Interaction) — 500 events



LSND-like $\nu_\mu \to \nu_e$ signal: — 1,000 events



Particle Identification: μ, e, and π^0



Neutrino interactions in oil produce:

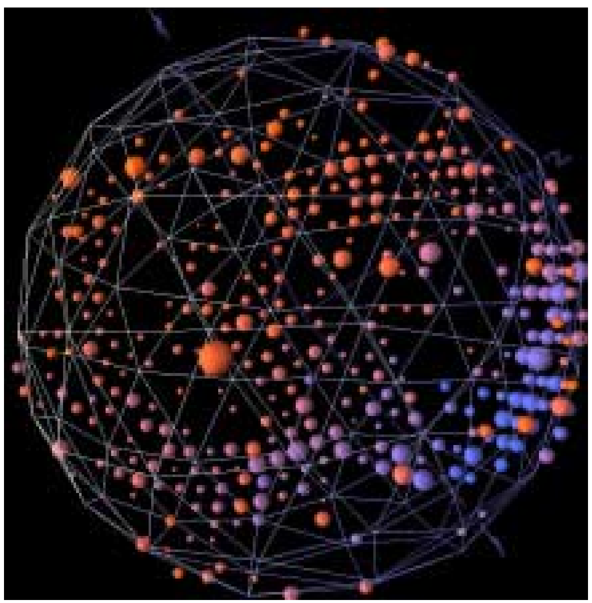
- Prompt Čerenkov light in a cone centered on the track.
- Delayed scintillation light distributed isotropically.

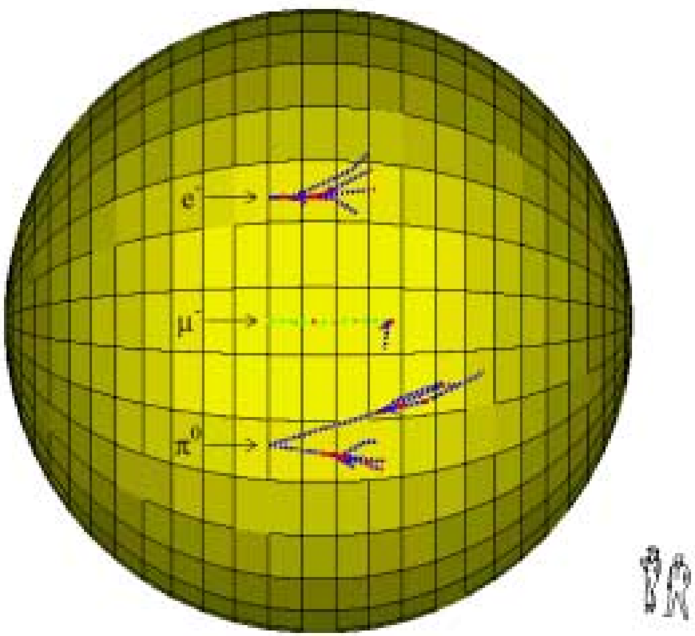
Čerenkov to scintillation ratio ~ 5 to 1

Particle ID is based on ring id, track length, ratio of prompt/late light.

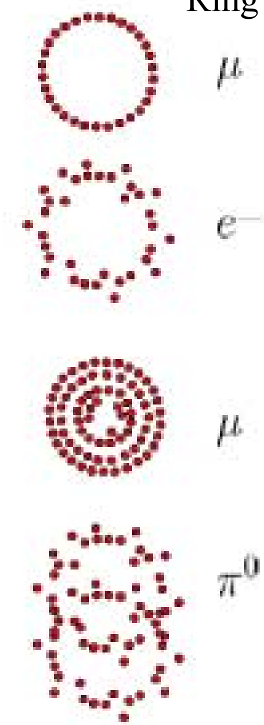
Fuzzy rings distinguish electrons from muons.

π^0 look like 2 electrons

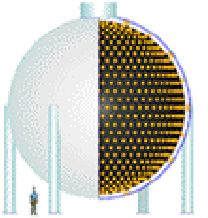




Ideal Ring



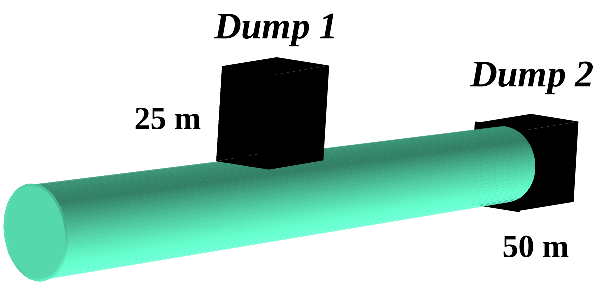
Understanding Backgrounds



All Backgrounds can be related to data measurements

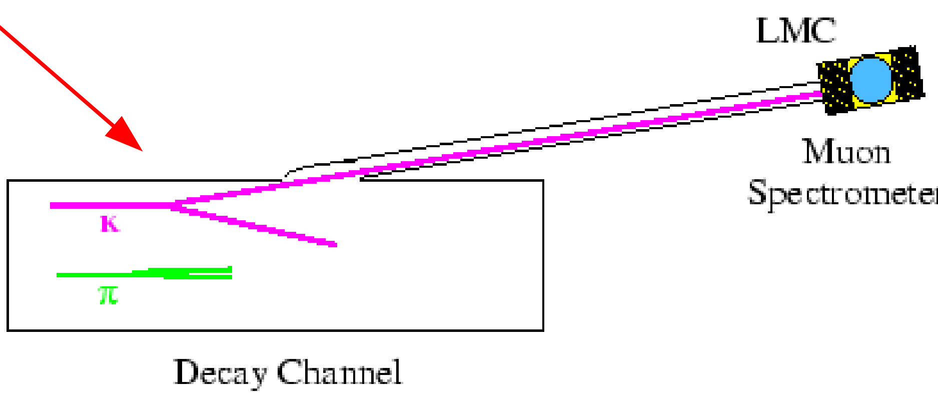
Intrinsic Beam Backgrounds

- ν_e from μ –decay
  - Directly tied to observed ν_μ rate
  - Quadratic decay pipe length dependence



Can change decay pipe length:
- ν_e from μ-decay $\propto L^2$
- ν_μ from π-decay $\propto L$
- ν_e from K-decay $\propto L^{<1}$

- ν_e from K–decay
  - Related to observed high E events
  - Beam surveys: BNL-910, HARP
  - “Little Muon Counters” (LMC)

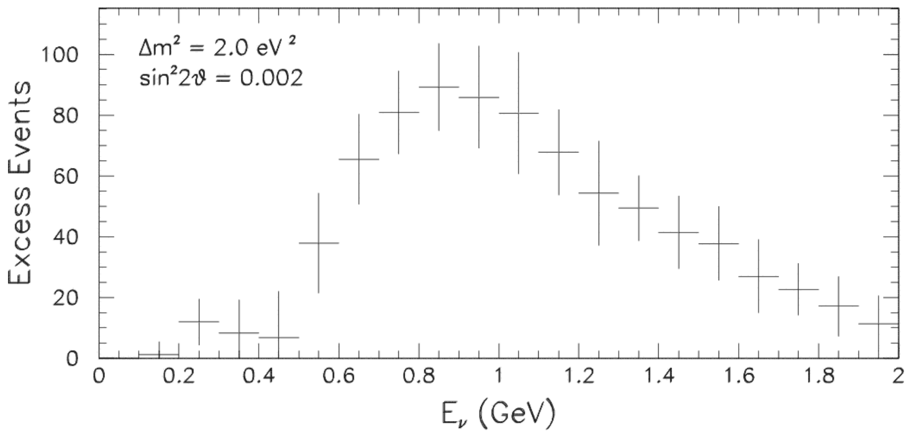


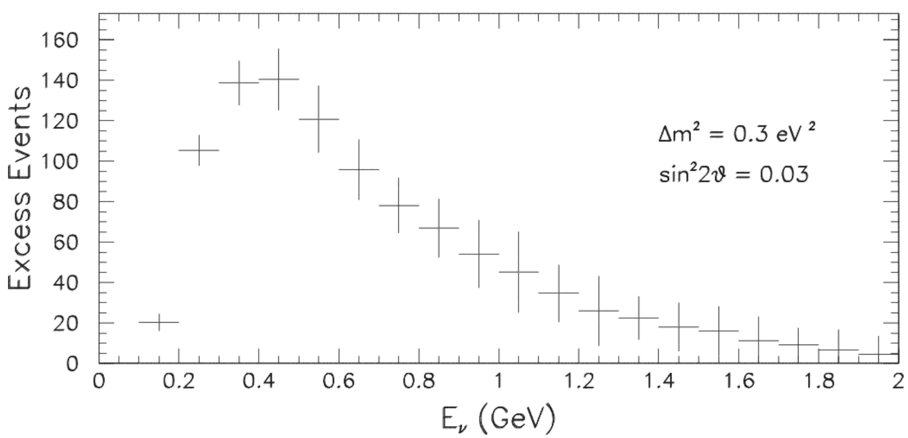
Mis-Identification

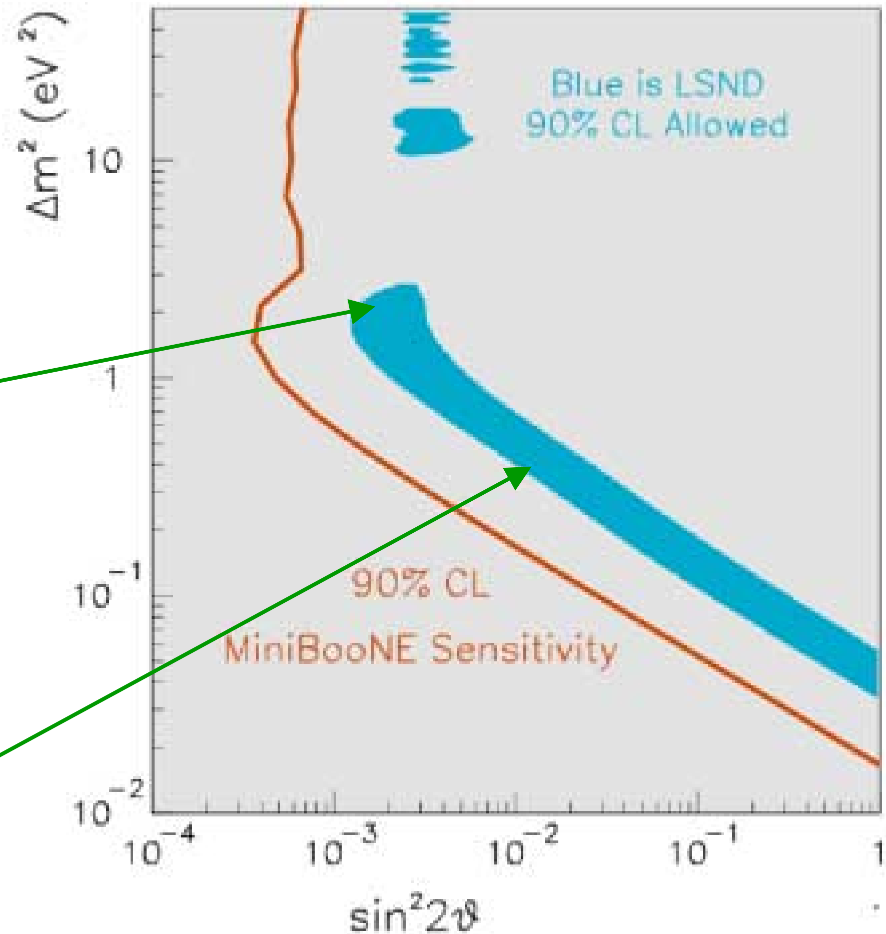
- Neutral current π^0 production
  - Scaled from the fraction that are properly reconstructed
- ν_μ mis-id’ed as ν_e’s
  - Scaled from the majority that are properly reconstructed

MiniBooNE Sensitivity to LSND

With 1×10^{21} protons on target MiniBooNE will completely cover the entire LSND signal region.

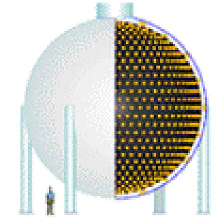


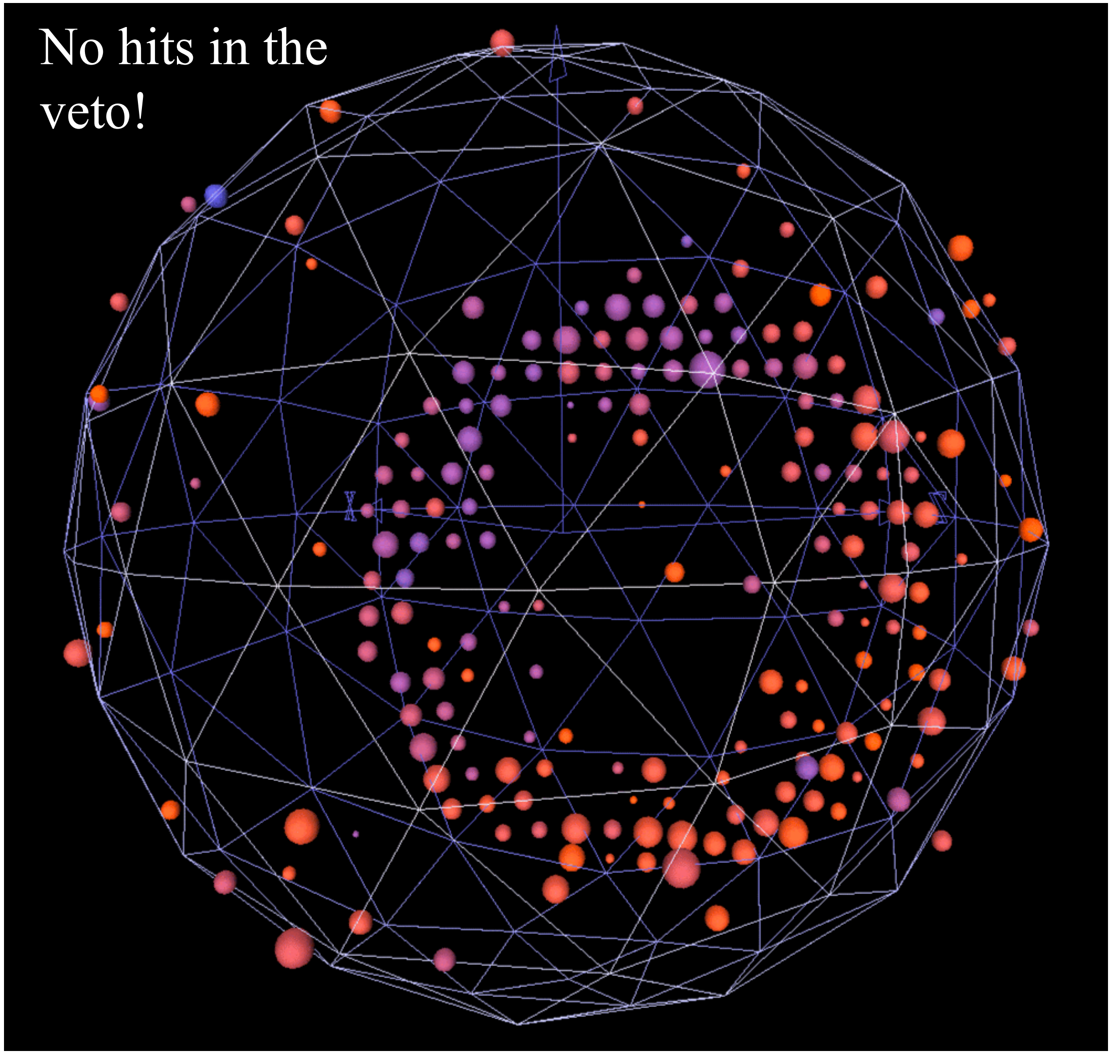




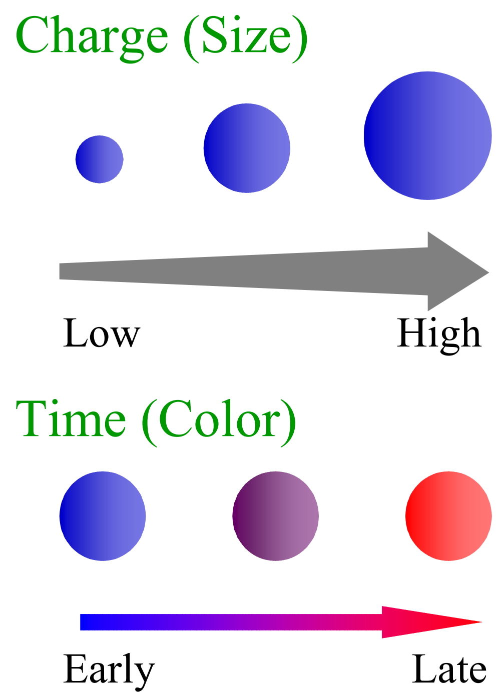
First Beam Event

We started taking beam data in late August.

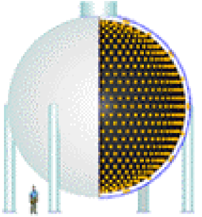




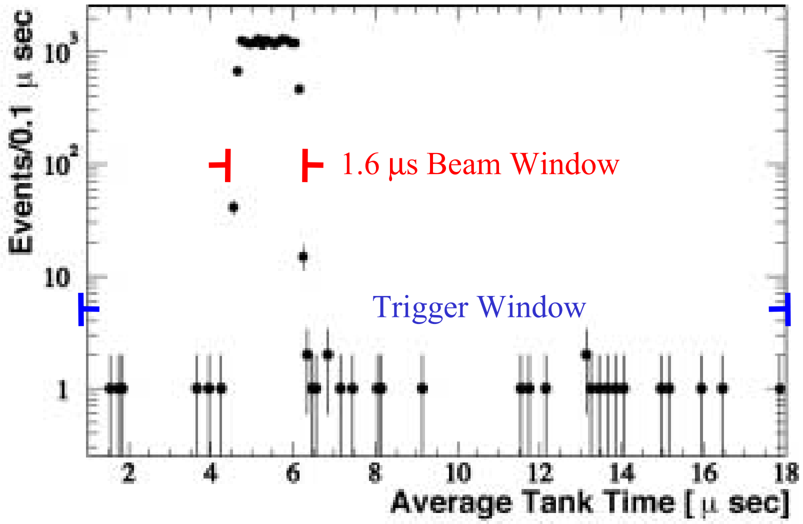
This is a typical event from the first few days of beam data.



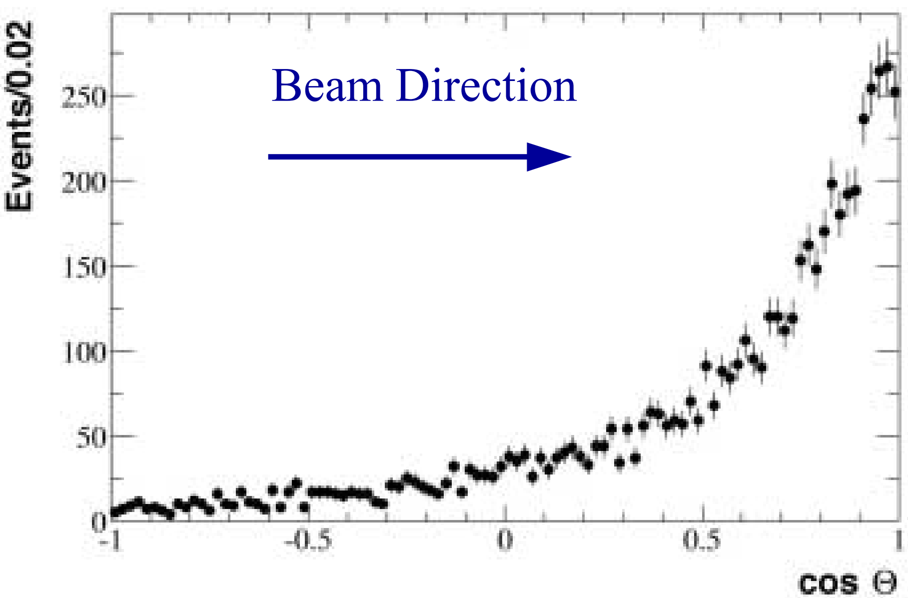
More on Beam Events



ν Candidate Time Profile



Reconstructed Lepton Direction Cosine

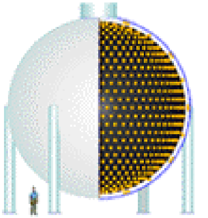


Required >200 hits in the Main Tank and <6 hits in the Veto.

Signal-to-noise ratio >5000!!!

Veto efficiency >99.9%

Current Status of Data Taking



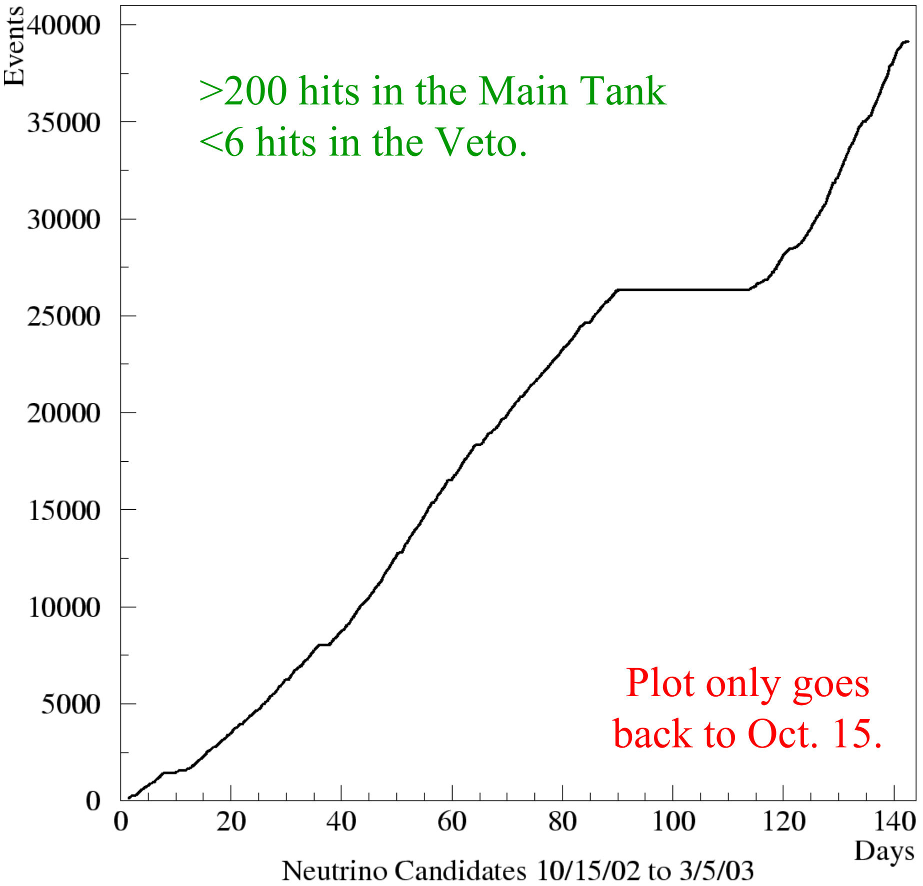
The Detector is working wonderfully.

- Greater than 98% of channels operational.
- DAQ dead time is less than 1%.

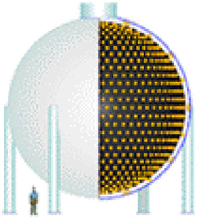
Booster performance is improving.

- Currently delivers 3×10^{16} p/hr.
- We need 8×10^{16} p/hr.

In the first 6 months of running we have recorder about 8% of our expected neutrino events.

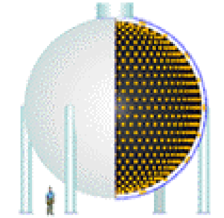


Conclusions and Outlook



- We began taking beam data in September 2002.
- We will take at least 5×10^{20} protons on target in ν mode.
- With this data we should be able to confirm or rule out the full high Δm^2 oscillation range of LSND (CPT conserving).
- If no signal is seen in ν mode, $\bar{\nu}$ running is needed to investigate CPT violation.
- We will also study several other physics topics such as
  - Cross Sections
  - Supernova neutrinos
  - Exotics
- Possible upgrade to BooNE, a two detector experiment to carefully measure Δm^2 and look for ν_μ disappearance.

The BooNE Collaboration



The BooNE Collaboration

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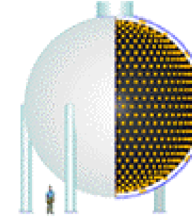
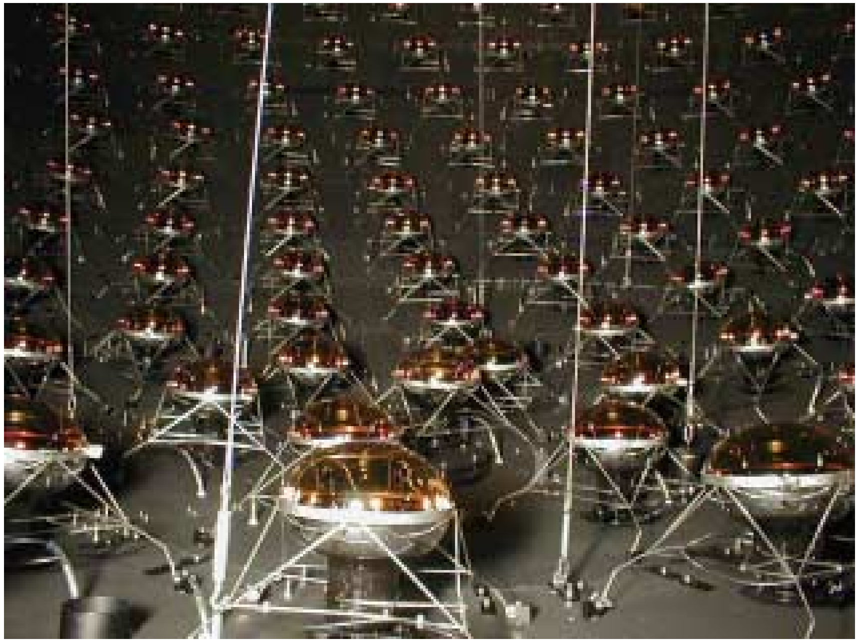
Inside the MiniBooNE Detector

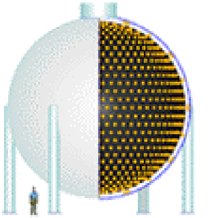




PMTs at the bottom of the detector just before sealing up the inner region.

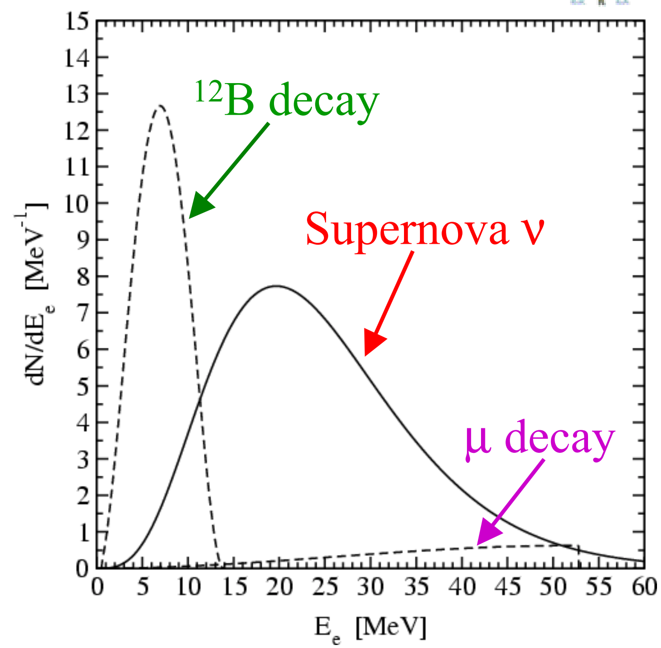
View of the Veto Region as the first oil is added to the detector.

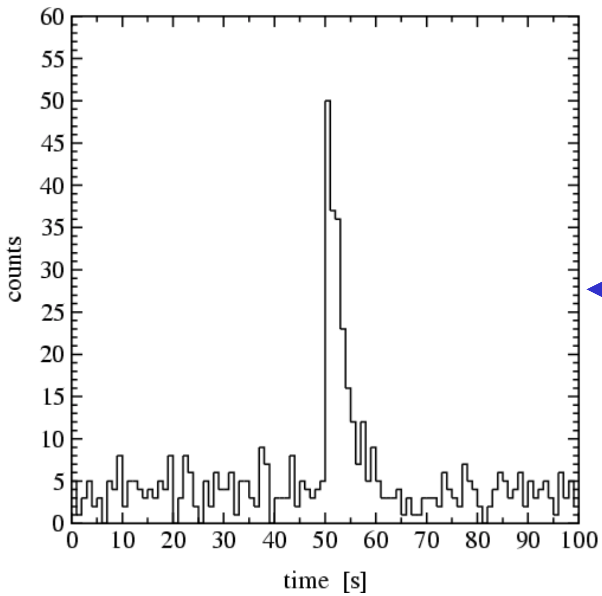
MiniBooNE as a Supernova ν Detector



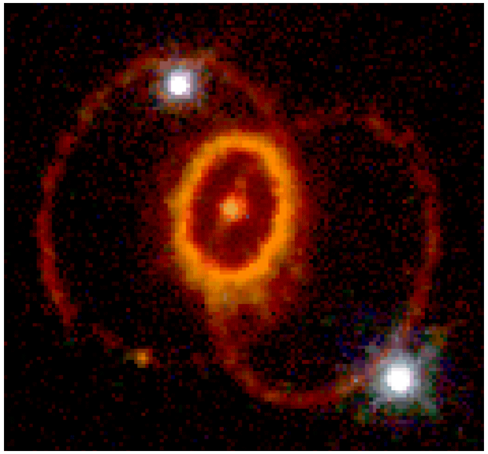
For a Supernova within 10 Kpc MiniBooNE expects to see at least 200 ν interactions in a 10 second period.

From Sharp, Beacom, and Formaggio
Phys. Rev. D66:013012,2002





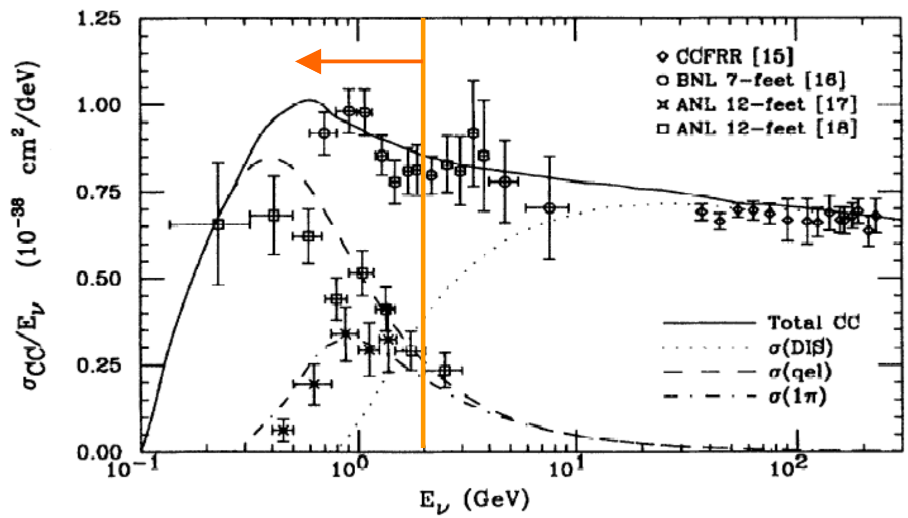
How the supernova signal might look as a function of time.



Cross Sections and Exotics

The ν cross sections are not well measured in our energy range.

Oscillation probability is small enough that we can ignore it in ν_μ cross section measurements.



From Lipari *et al.*, PRL 74, 4384

Exotics:

Look for things that may not have been conceived of yet

Neutrino Magnetic Moment (Very Small in SM)

The Karmen Timing Anomaly

(see paper by Case, Koutsoliotas, and Novak, Phys. Rev. D65:077701, 2002)

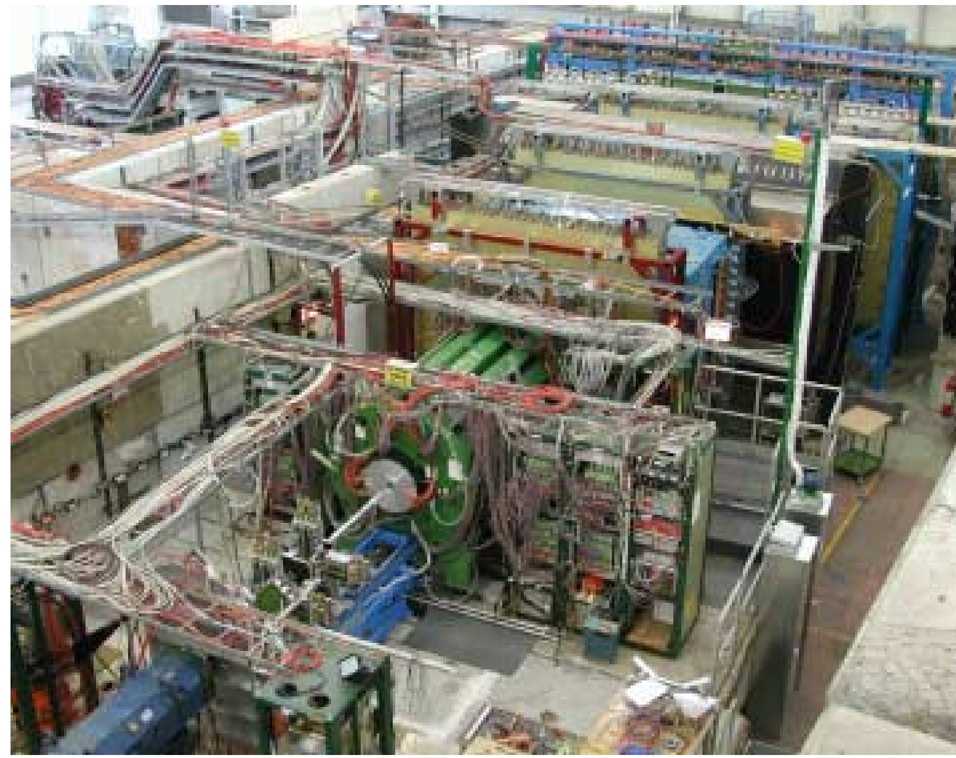
Beam Survey Experiments

Experiments E910 at Brookhaven and HARP at CERN are studying K and π production with medium energy proton beams on beryllium.

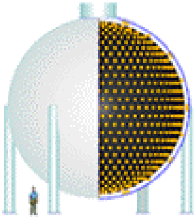
HARP took data using our target with 8 GeV protons.

These data sets are still being analyzed.

The results will be the primary input to our neutrino flux simulations.



The HARP Experiment at CERN



Oscillation Analysis Plan

We intend to do a blind analysis.

This means that we will not look at any thing that might give away the final result. (i.e. no electron neutrino events!)

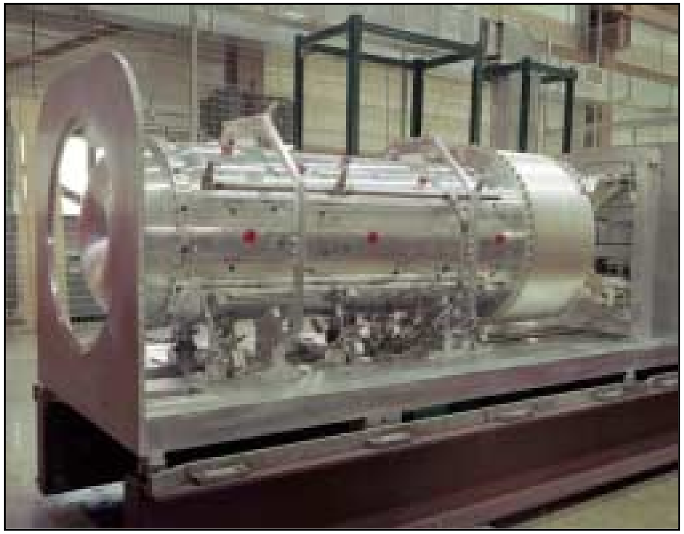
Currently this means that we can fully study fewer that 5% of our events. This fraction will increase as we learn more about our data.

We generate some distributions from all events (online) that can not provide information about neutrino types.

The MiniBooNE Horn

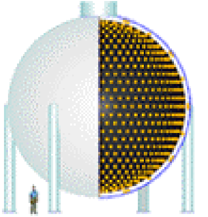
The horn generates a toroidal magnetic field that focus off axis charged particles (of one charge) in the forward direction.

- The horn pulses at 5 Hz
- Each 170 kilo-amp pulse lasts for 150 micro seconds
- Design lifetime of 200 million pulses (Tested with 10+ million pulses)
- Designed to maximize neutrino flux from 0.5 GeV to 1 GeV
- Increases neutrino flux at the detector by a factor of 10.

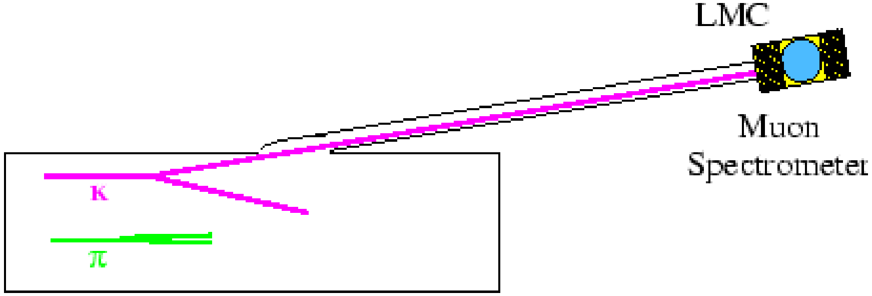


MiniBooNE horn during assembly

The Little Muon Counter (LMC)

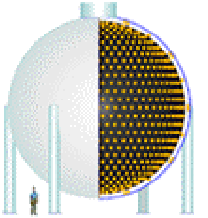


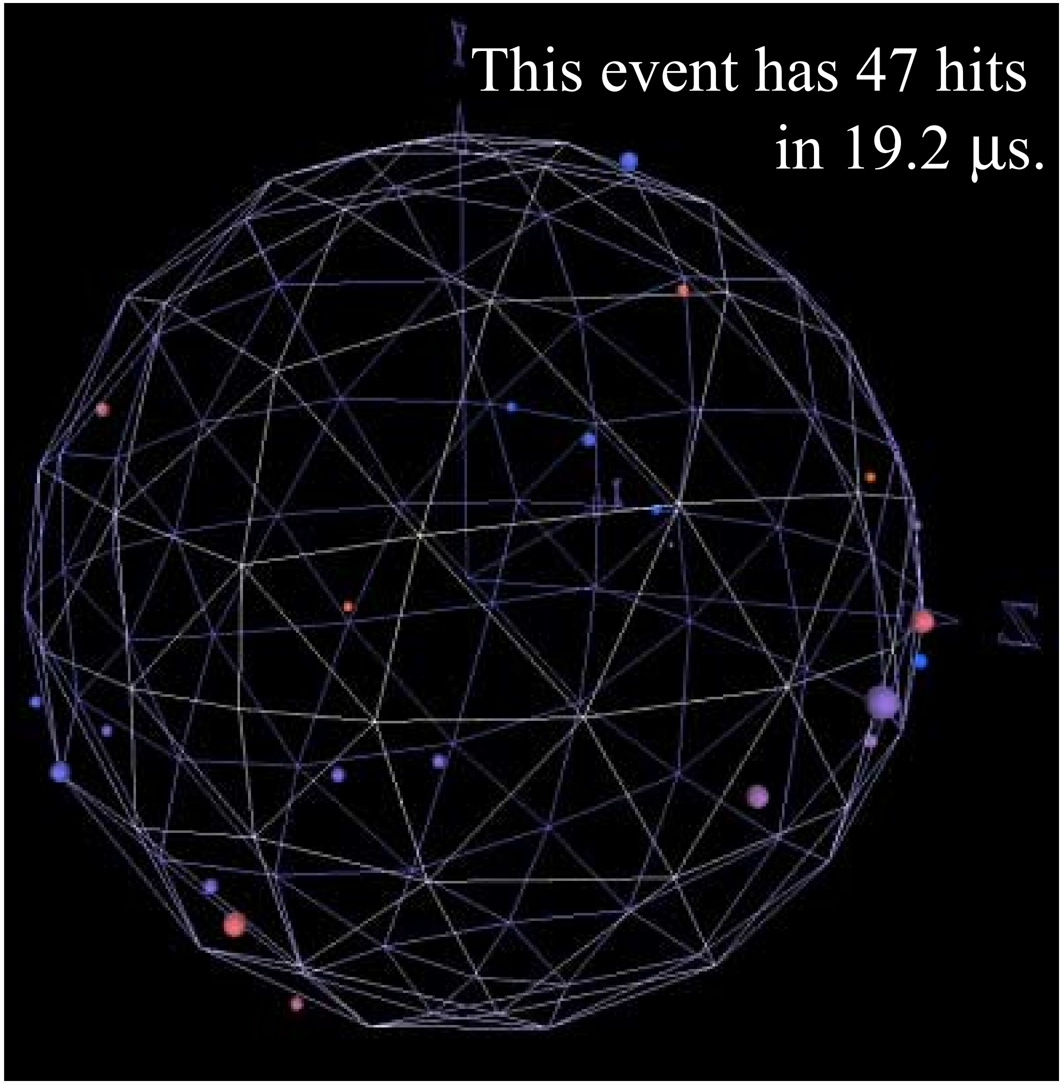
- Detects muons at an angle of 7° from the beam center.
- At this angle all muons are from kaon decays.
- Gives us a data point on kaons in our own beamline.

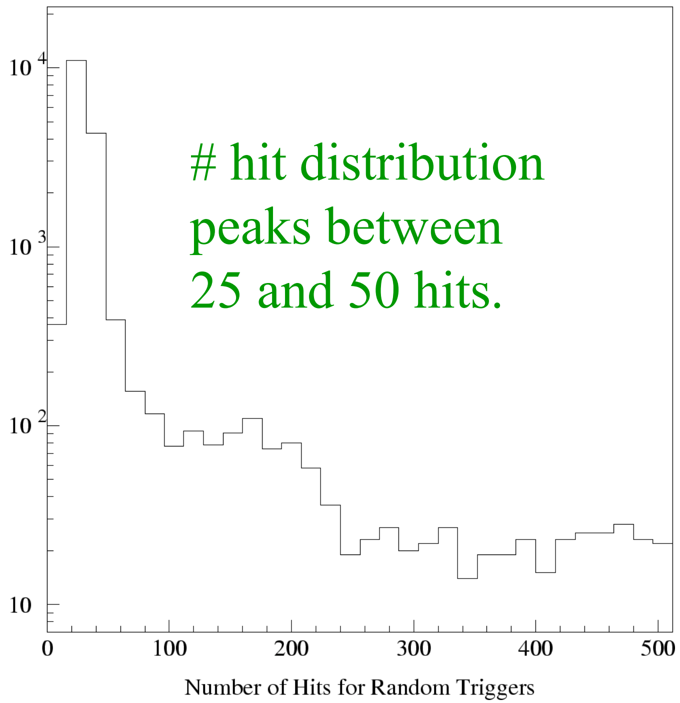


The LMC drift pipe during construction

Typical Dark Noise in MiniBooNE







Mean per tube dark noise rate is only 1.2 kHz!

More on LSND's Analysis…

Examples of backgrounds people worry about…

Can these events be neutrons in coincidence with an e-like interaction?

- neutrons produced in the beam will sometimes capture
- but also will knock into the nucleus producing multiple γ's $\rightarrow$ the "smoking gun" is an excess of multiple γ events.

Events with one associated γ: 49.2 ± 9 events
Events with > 1 associated γ: -2.8 ± 1.7 events

Estimated background from neutrons in the beam: < 2 events

Can these events be from $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$?

- The $\bar{\nu}_\mu$ come the neutrino has to have > 105 MeV
  - It had to be produced by decay-in-flight (not DAR)
  - The CC probability is small until well above threshold
- You have to mis-identify the muon!

Estimated background from $\bar{\nu}_\mu$: < 5 events

The spatial distribution of the excess

- If the excess is due to oscillations, then the distribution will look similar the ν_e beam events. (solid black line)
- If the events are due to background, then you expect asymmetries in the distribution…