MiniBooNE: Status and Prospects

Eric Prebys, FNAL/BooNE Collaboration

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Outline

- State of neutrino mixing measurements
  - Without LSND
  - LSND and Karmen
- Experiment
  - Beam
  - Detector
  - Calibration and cross checks
  - Analysis
- Resent Results
- Future Plans and outlook
  - Anti-neutrino running
  - Path to oscillation results

Theory of Neutrino Oscillations

- Neutrinos are produced and detected as *weak eigenstates* (ν_e, ν_μ, or ν_τ).
- These can be represented as *linear combination of mass eigenstates*.
- If the above matrix is not diagonal *and* the masses are not equal, then the net weak flavor content will *oscillate* as the neutrinos propagate.
- **Example:** if there is mixing between the ν_e and ν_μ:

Flavor eigenstates → $$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$ ← Mass eigenstates

then the probability that a ν_e will be detected as a ν_μ after a distance *L* is:

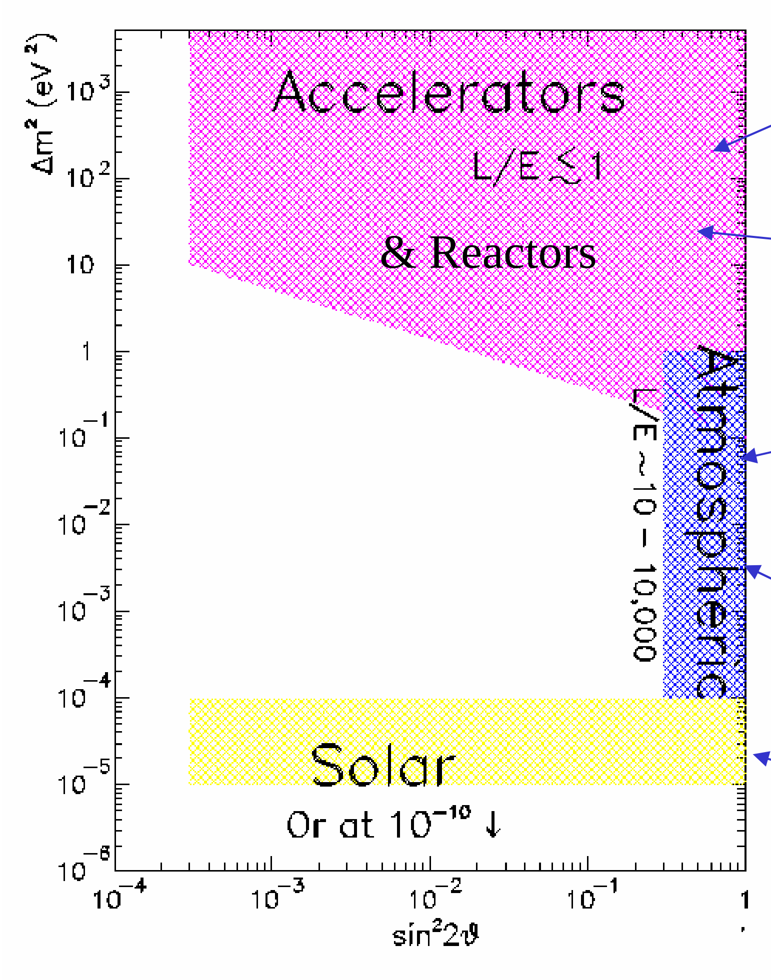
$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2\left(1.27 \bullet \Delta m^2 \bullet \frac{L}{E}\right)$$

- Δm^2: $m_2^2 - m_1^2$ (in eV^2)
- L: Distance in *km*
- E: Energy in GeV

Only measure *magnitude* of the *difference* of the squares of the masses.

Probing Neutrino Mass Differences

Different experiments probe different ranges of $\frac{L}{E}$ ← Path length, ← Energy



Accelerators use π decay to *directly* probe $\nu_\mu \rightarrow \nu_e$

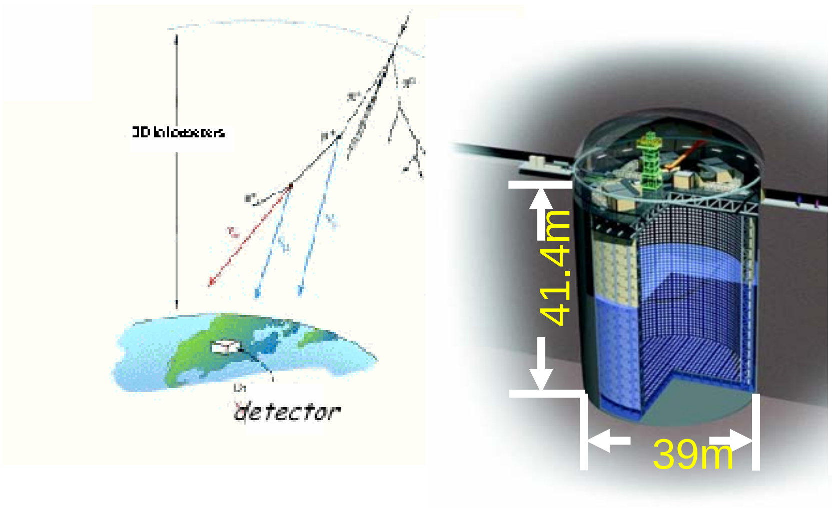
Reactors use use *disappearance* to probe $\nu_e \rightarrow$?

Cerenkov detectors directly measure ν_μ and ν_e content in atmospheric neutrinos. Fit to $\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$ mixing hypotheses

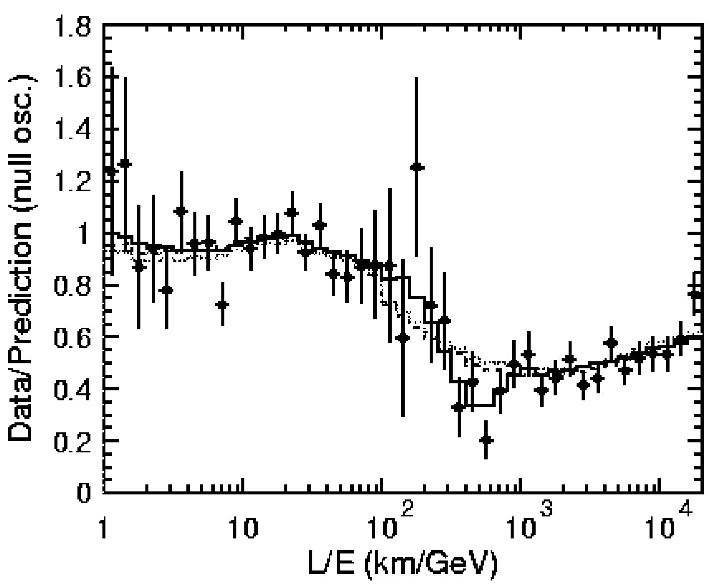
Also probe with "long baseline" accelerator and reactor experiments

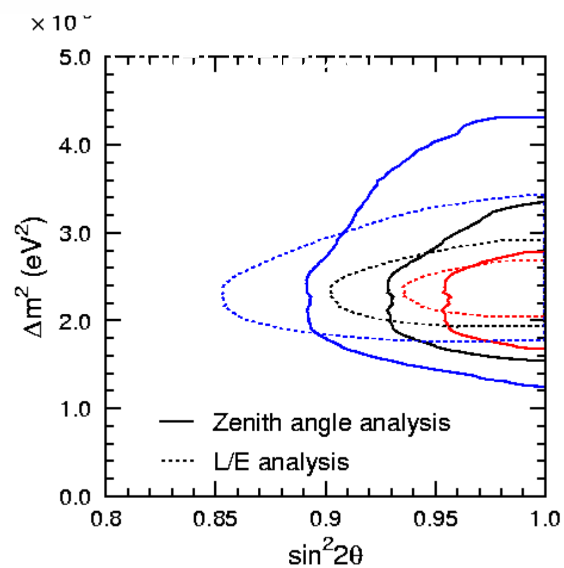
Solar neutrino experiments typically measure the disappearance of ν_e.

SuperKamiokande Atmospheric Result



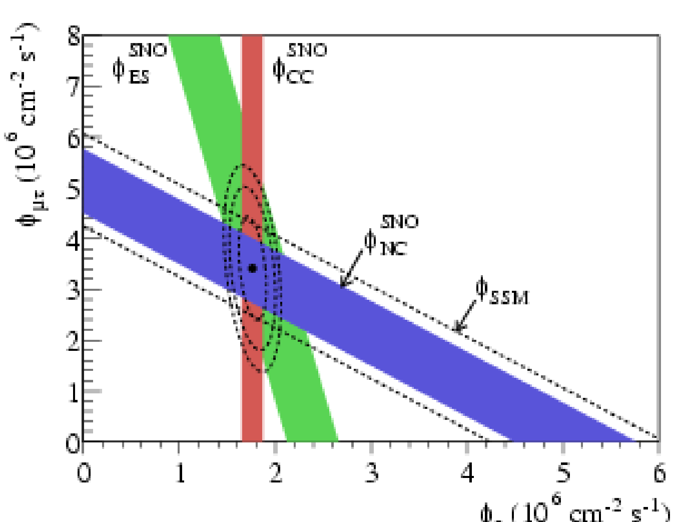
- Huge water Cerenkov detector can directly measure ν_μ and ν_e signals.
- Use azimuthal dependence to measure distance traveled (through the Earth)
- Positive result announced in 1998.
- Consistent with $\nu_\mu \leftrightarrow \nu_\tau$ mixing.

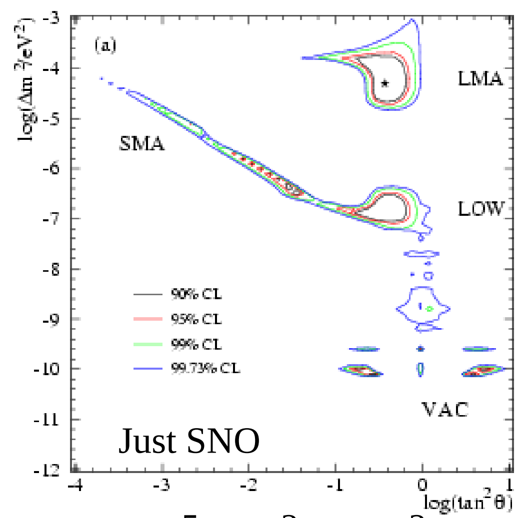


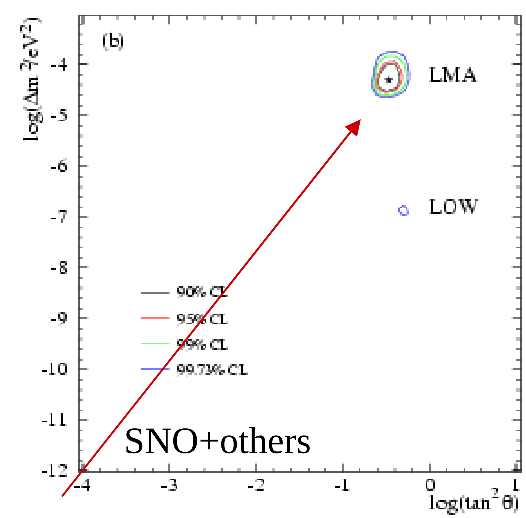


SNO Solar Neutrino Result

- Looked for Cerenkov signals in a large detector filled with heavy water.
- Focus on ^8B neutrinos
- Used 3 reactions:
  - $\nu_e + d \rightarrow p + p + e^-$: only sensitive to ν_e
  - $\nu_x + d \rightarrow p + n + \nu_x$: equally sensitive to ν_e, ν_μ, ν_τ
  - $\nu_x + e^- \rightarrow \nu_x + e^-$: 6 times more sensitive to ν_e than ν_μ, ν_τ *d*
- Consistent with initial full SSM flux of ν_e's mixing to ν_μ, ν_τ



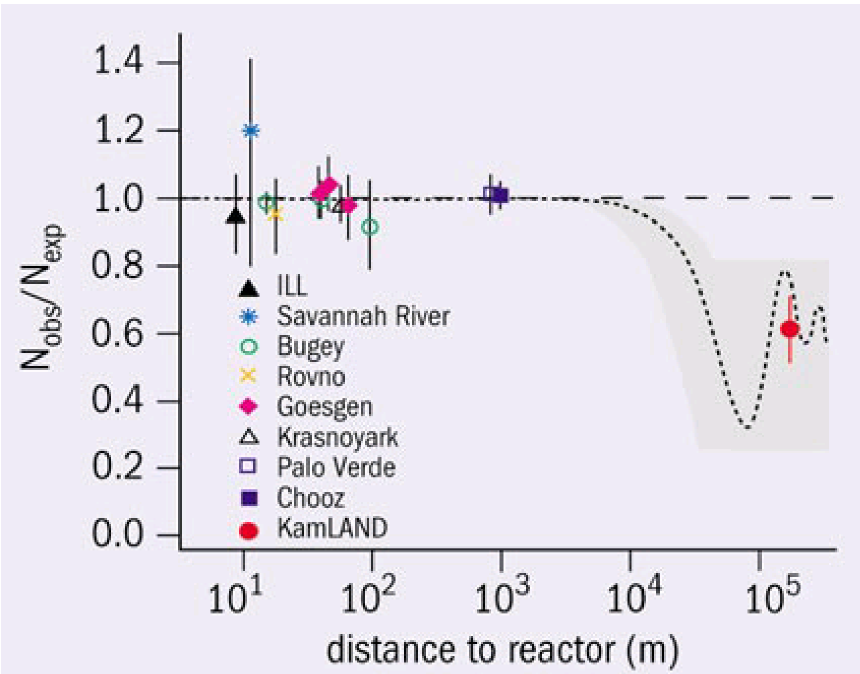


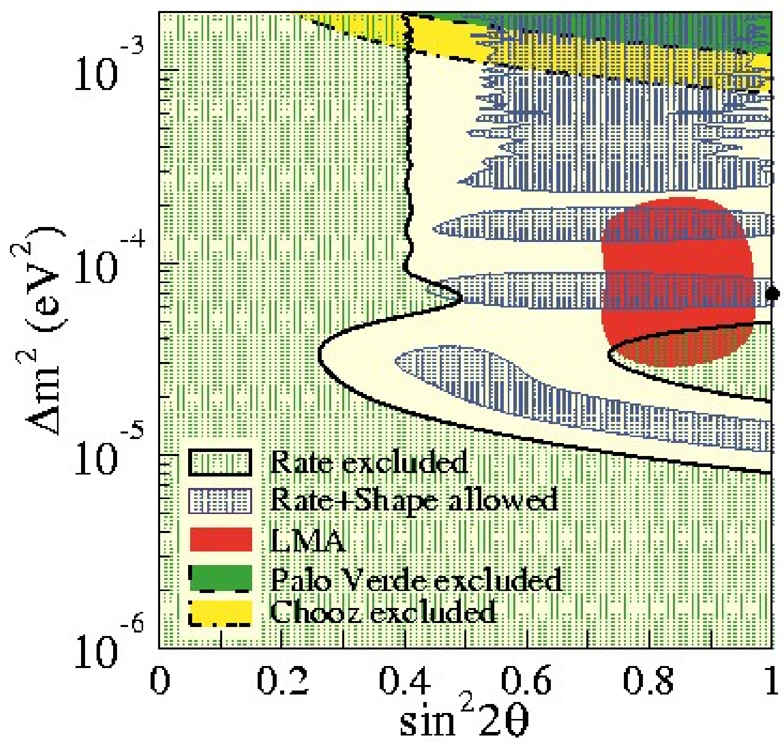


$$\text{Favor}: \Delta m^2 \approx 5\times10^{-5}\,\text{eV}^2; \tan^2\theta \approx .34$$

Reactor Experimental Results

- Single reactor experiments (Chooz, Bugey, etc). Look for ν_e disappearance: all negative
- KamLAND (single scintillator detector looking at ALL Japanese reactors): ν_e disappearance consistent with mixing.



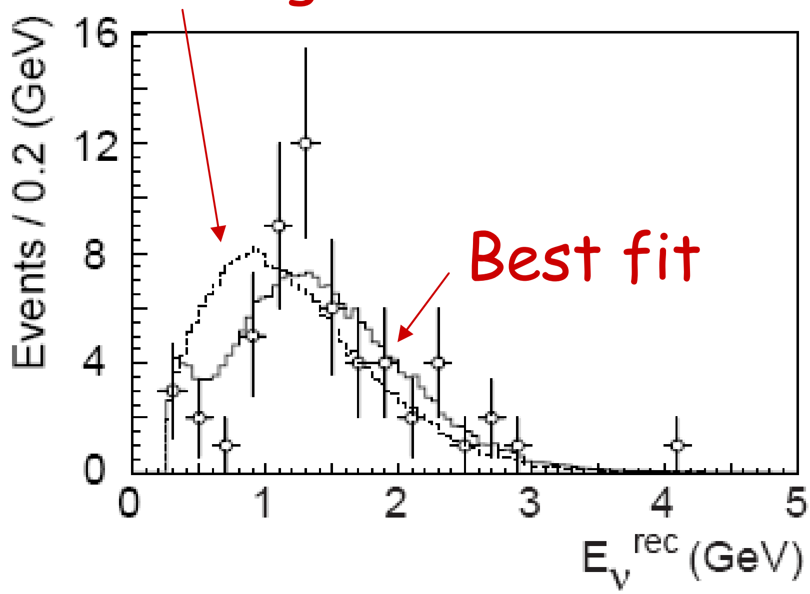


K2K

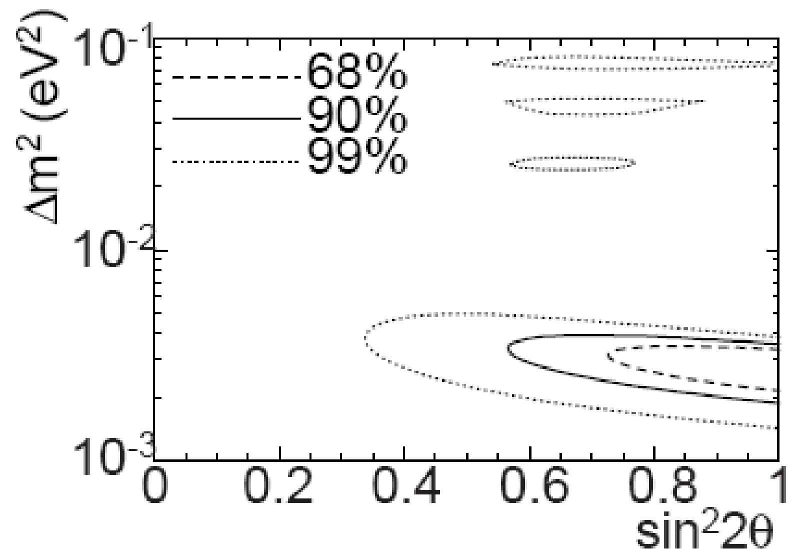
- First "long baseline" accelerator experiment
  - Beam from KEK PS to Kamiokande, 250 km away
  - Look for ν_μ disappearance (atmospheric "problem")
  - Results consistent with mixing

No mixing

Best fit



Allowed Mixing Region



Three Generation Mixing (Driven by experiments listed)

- General Mixing Parameterization

CP violating phase

$$\begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12}-s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12}-s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12}-s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12}-s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

QUARKS

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

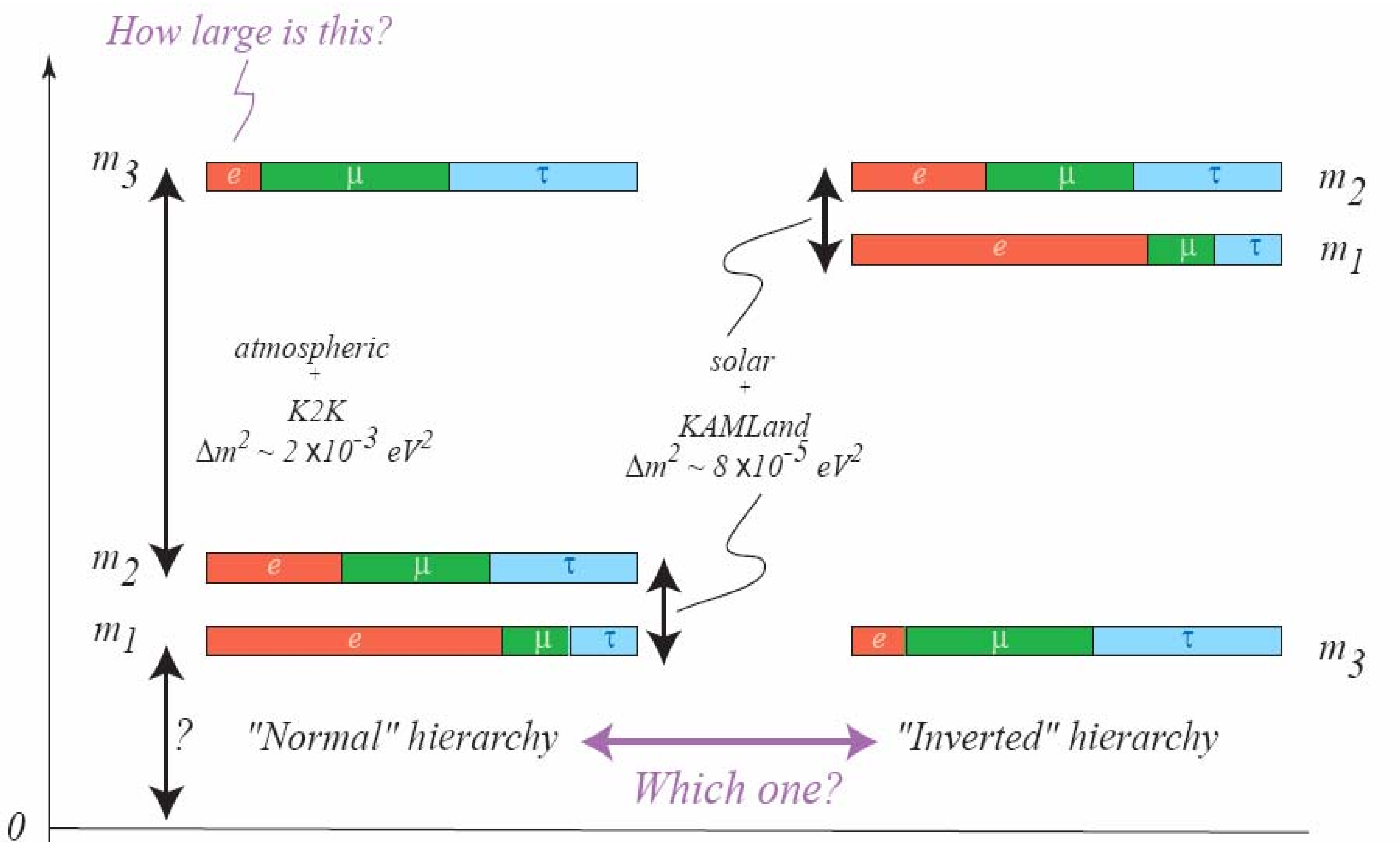
- *Almost diagonal*
- *Third generation weakly coupled to first two*
- *"Wolfenstein Parameterization"*

NEUTRINOS

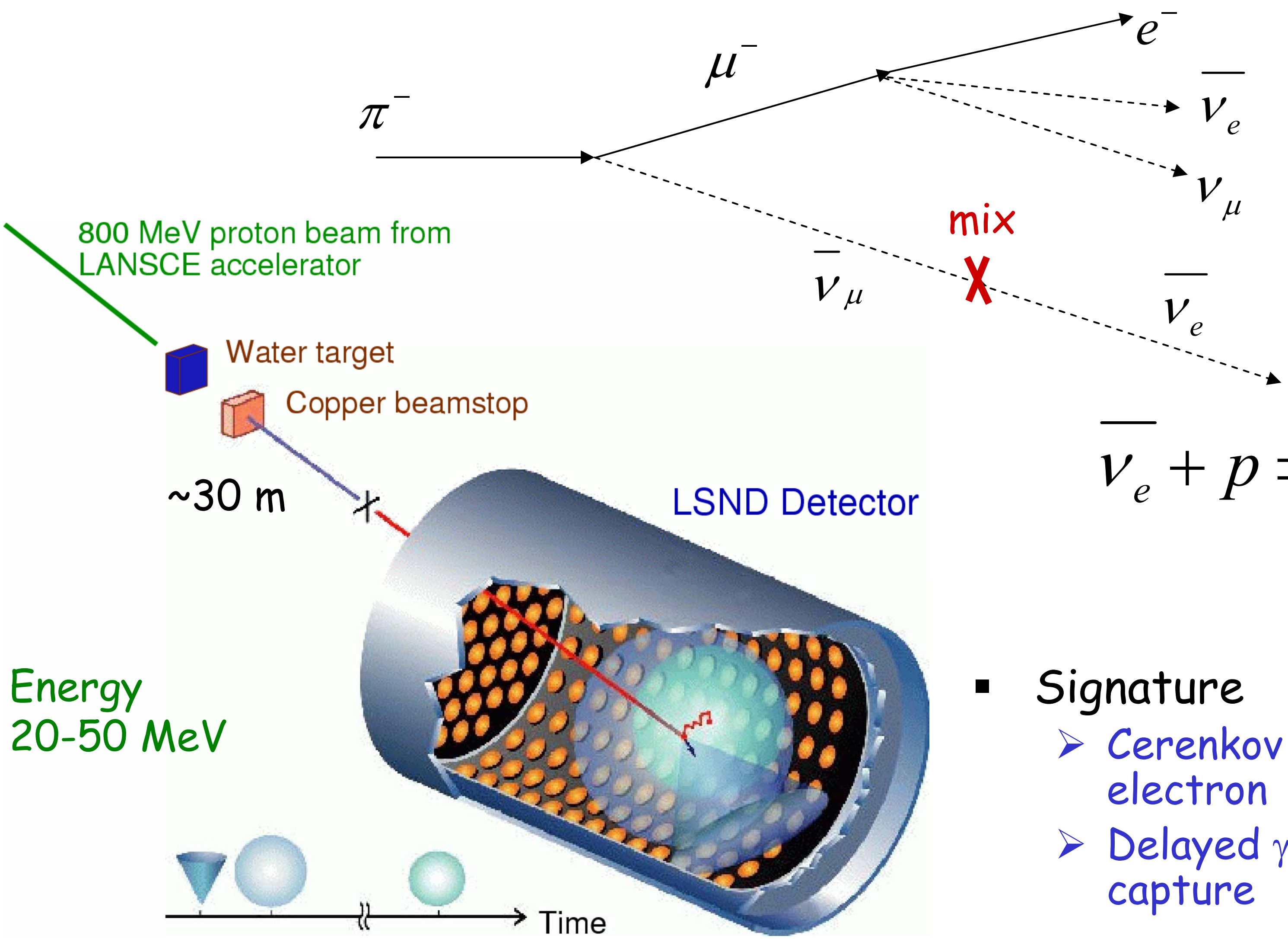
$$U_{MNSP} \sim \begin{pmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

- *Mixing large*
- *No easy simplification*
- *Think of mass and weak eigenstates as totally separate*

Best Three Generation Picture



The LSND Experiment (1993-1998)

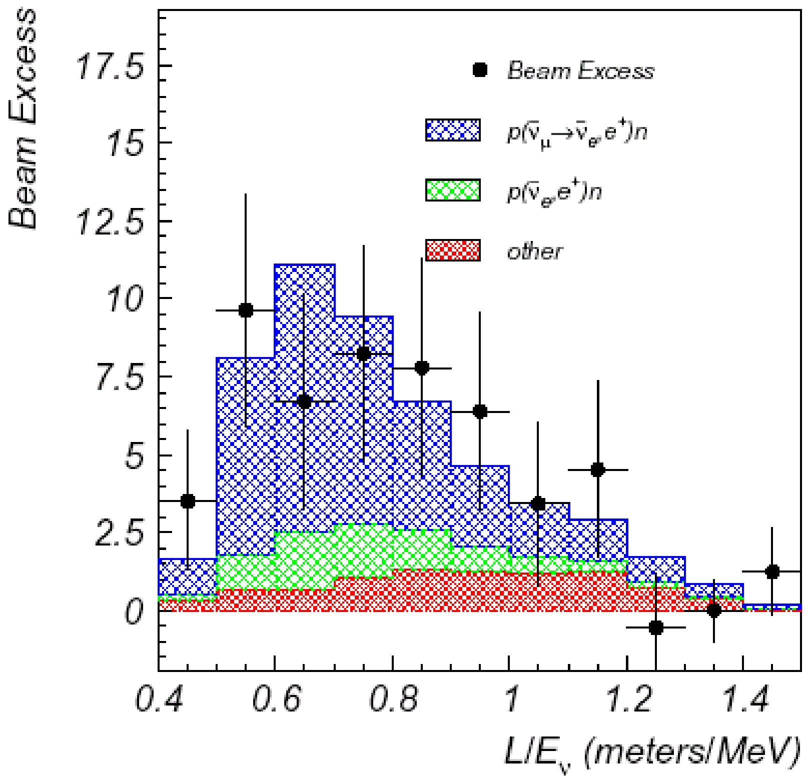


$$\bar{\nu}_e + p \Rightarrow e^+ + n$$

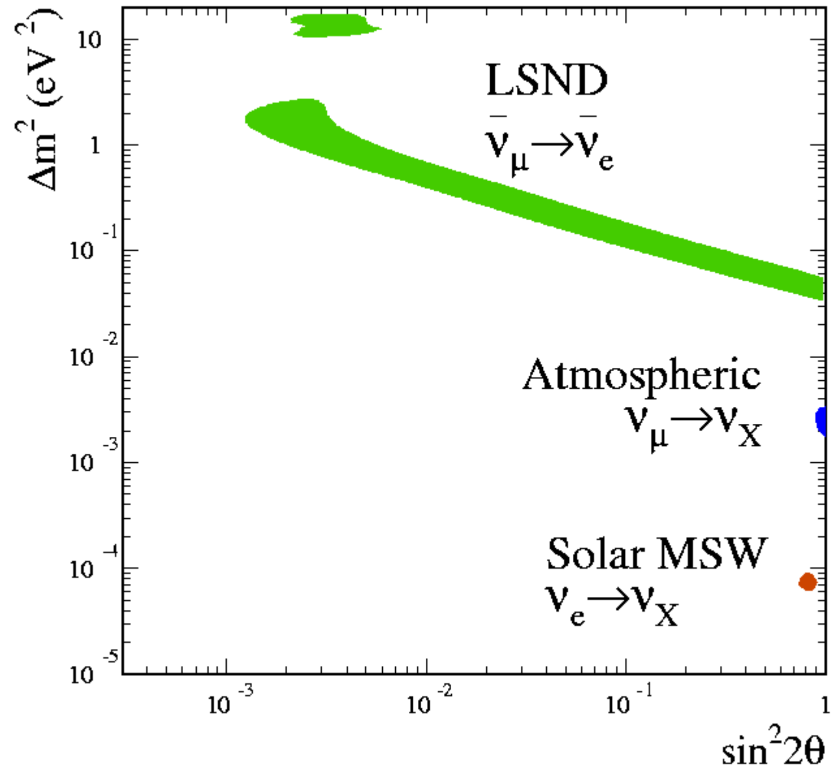
- Signature
  - Cerenkov ring from electron
  - Delayed γ from neutron capture

LSND Result

Excess Signal:



Best fit:

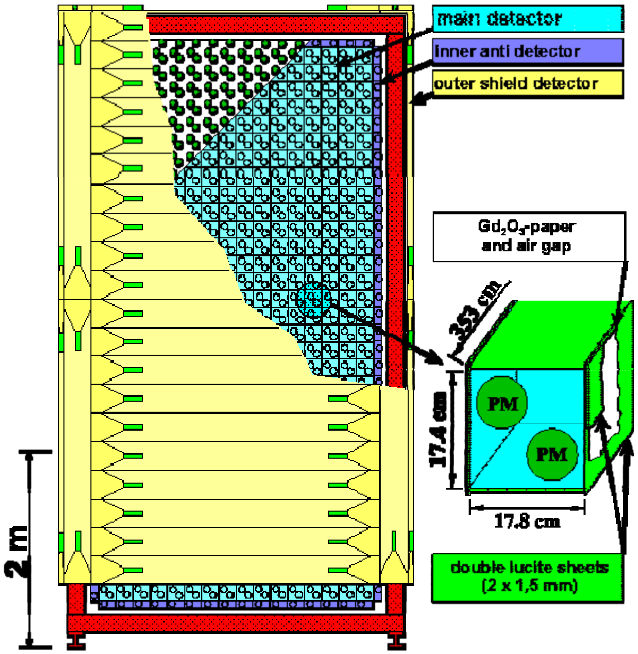


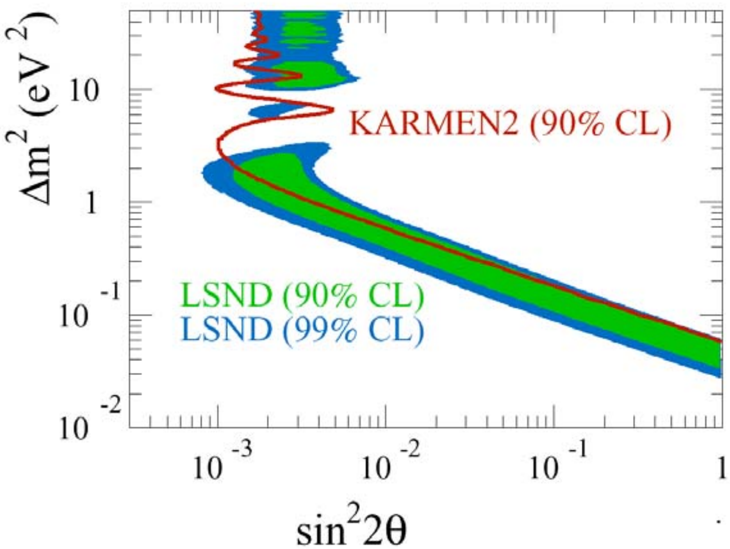
- Only exclusive appearance result to date
- Problem: $\Delta m^2 \sim 1\ eV^2$ not consistent with other results with simple three generation mixing

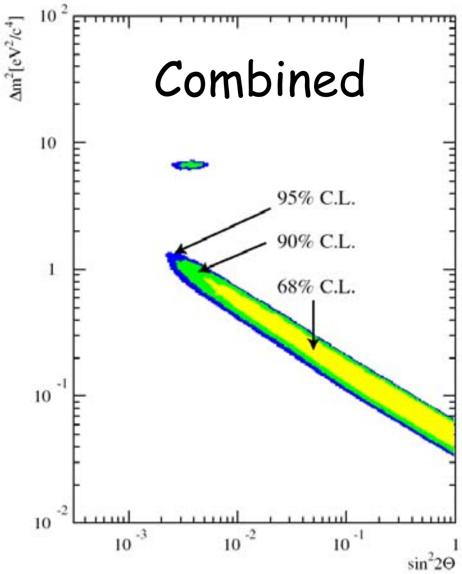
Possibilities

- 4 neutrinos?
  - We know from Z lineshape there are only 3 active flavors
  - Sterile?
- CP or CPT Violation?
- More exotic scenarios?
- LSND Wrong?
  - Can't throw it out just because people don't like it.

Karmen II Experiment: not quite enough





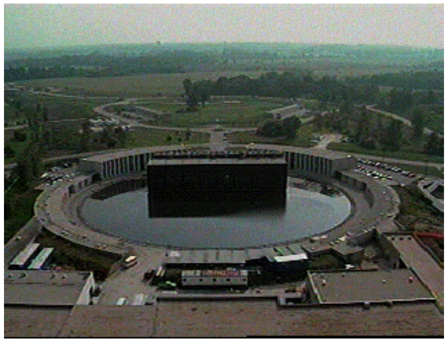


- Pulse 800 MeV proton beam (ISIS)
- 17.6 m baseline
- 56 tons of liquid scintillator
- Factor of 7 less statistical reach than LSND
- -> NO SIGNAL
- Combined analysis still leaves an allowed region

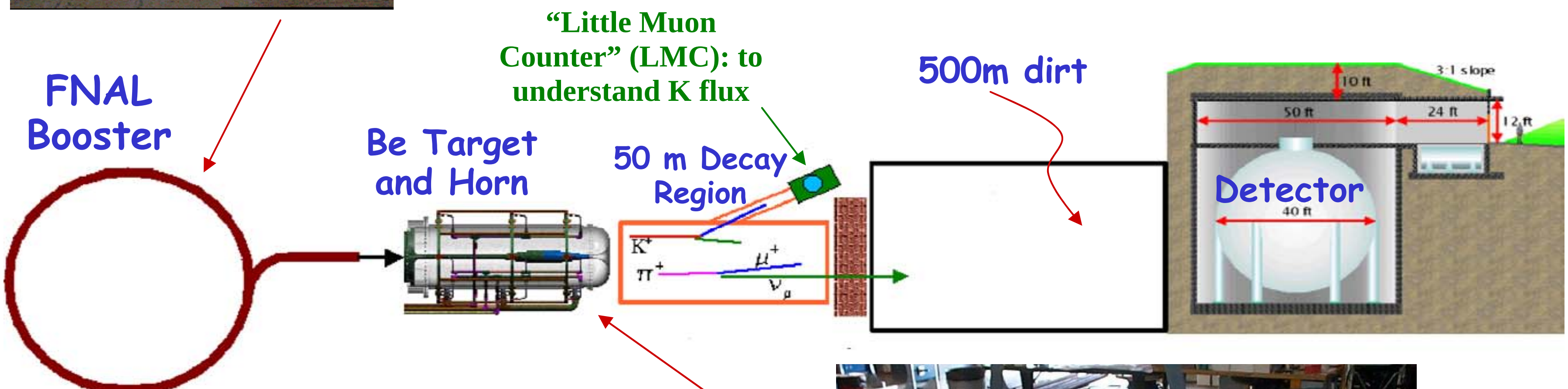
Role of MiniBooNE

- Boo(ster) N(eutrino) E(xperiment)
  - Full "BooNE" would have two detectors
- Primary Motivation: Absolutely confirm or refute LSND result
  - Optimized for L/E ~ 1
  - Higher energy beam -> Different systematics than LSND
- Timeline
  - Proposed: 12/97
  - Began Construction: 10/99
  - Completed: 5/02
  - First Beam: 8/02
  - Began to run concurrently with NuMI: 3/05
  - Presently ~7E20 proton on target in neutrino mode
    - More protons that all other users in the 35 year history of Fermilab combined!
  - Oscillation results: 2006

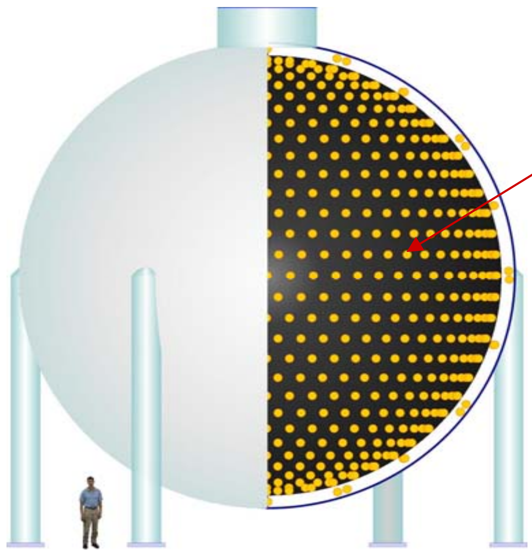
MiniBooNE Neutrino Beam (not to scale)



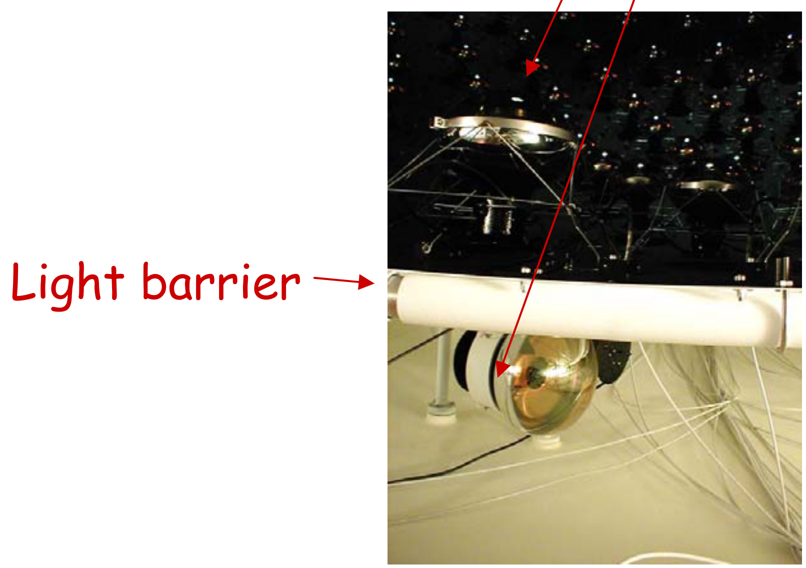
- 8 GeV Protons
  - ~ 7E16 p/hr max
  - ~ 1 detected neutrino/minute
  - L/E ~ 1



Detector

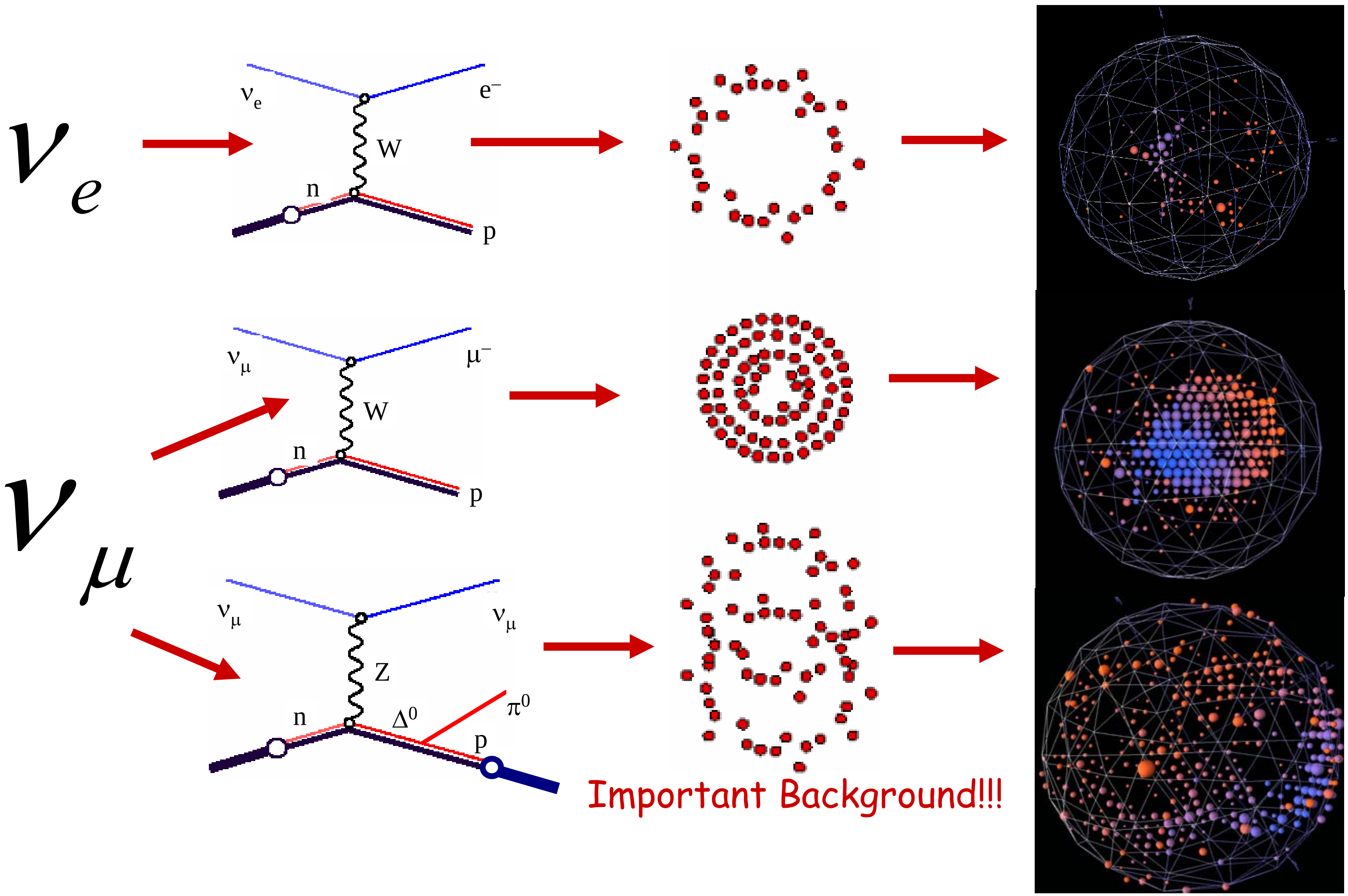


- 950,000 ℓ of pure mineral oil
- 1280 PMT's in inner region
- 240 PMT's outer veto region
- Light produced by Cerenkov radiation and scintillation



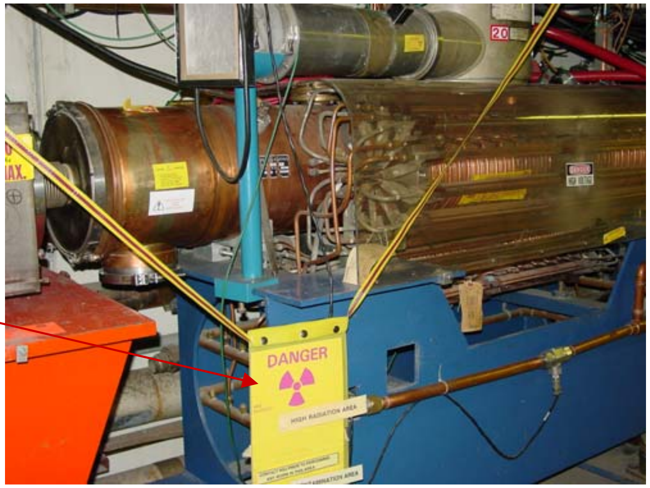
- Trigger:
  - All beam spills
  - Cosmic ray triggers
  - Laser/pulser triggers
  - Supernova trigger

Neutrino Detection/Particle ID



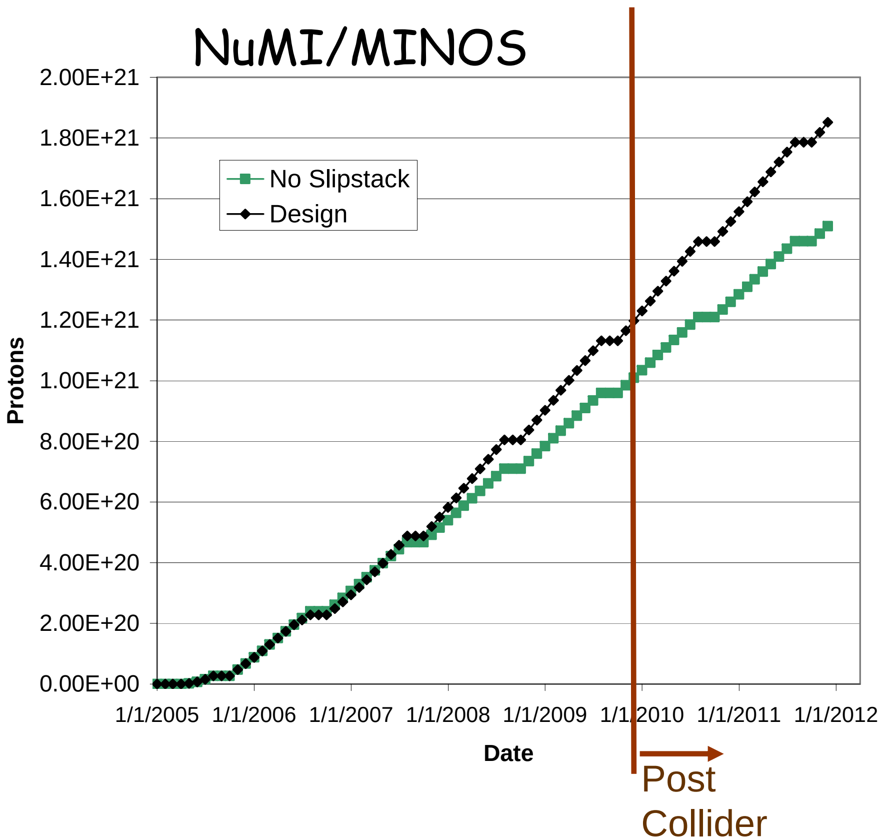
Delivering Protons

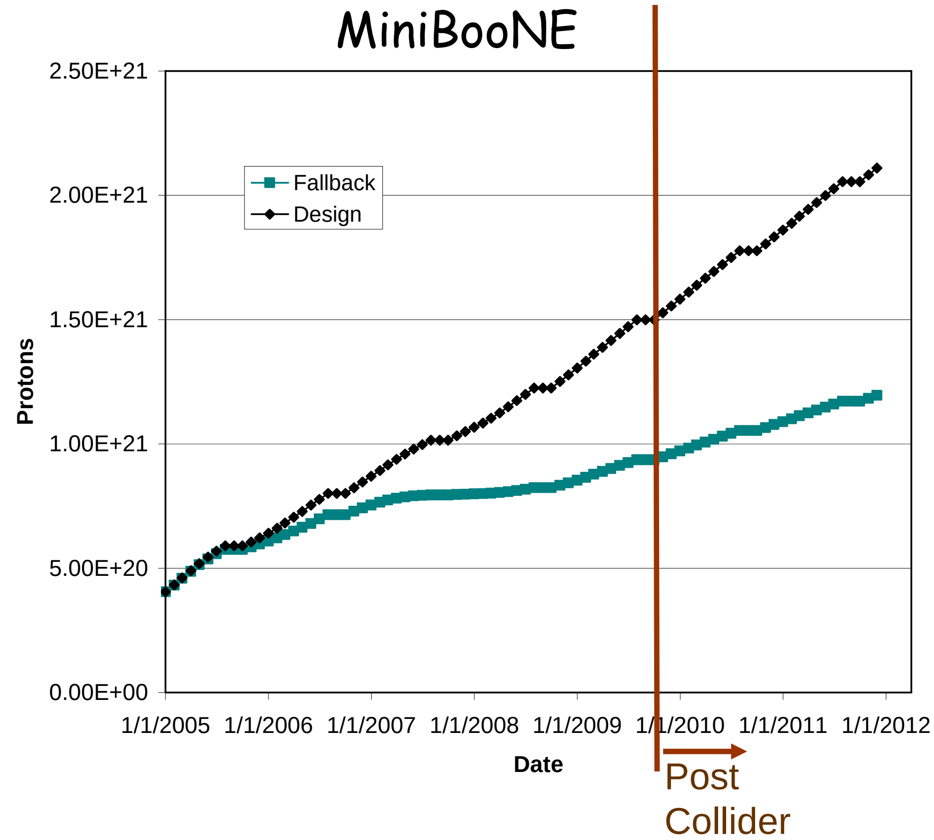
- Requirements of MiniBooNE greatly exceed the historical performance of the 30+ year old 8 GeV Booster, pushes…
  - Average repetition rate
  - Above ground radiation
  - Radiation damage and activation of accelerator components



- Intense Program to improve the Booster
  - Shielding
  - Loss monitoring and analysis
  - Lattice improvements (result of Beam Physics involvement)
  - Collimation system
- Very challenging to continue to operate 8 GeV line during NuMI/MINOS operation
  - Once believed imposible
  - Element of lab's "Proton Plan"
  - Goal to continue to deliver roughly 2E20 protons per years to the 8 GeV program for at least the next few years.

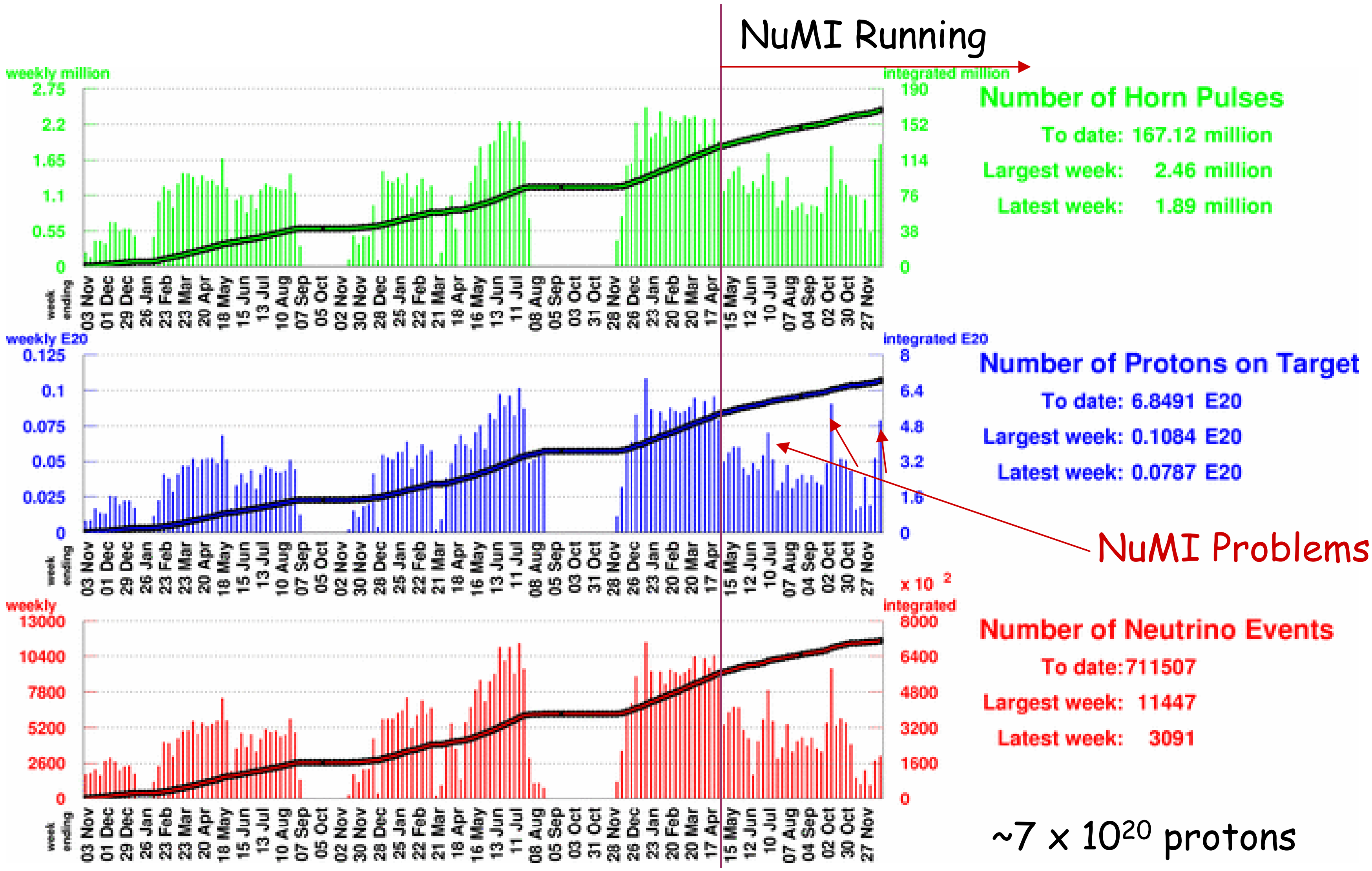
Running MiniBooNE with NuMI





- Note: these projections do *not* take into account the collider turning off in 2009
  - NuMI rates would go up at least 20%, possible higher
  - Major operational changes could make continued operation of 8 GeV line very difficult

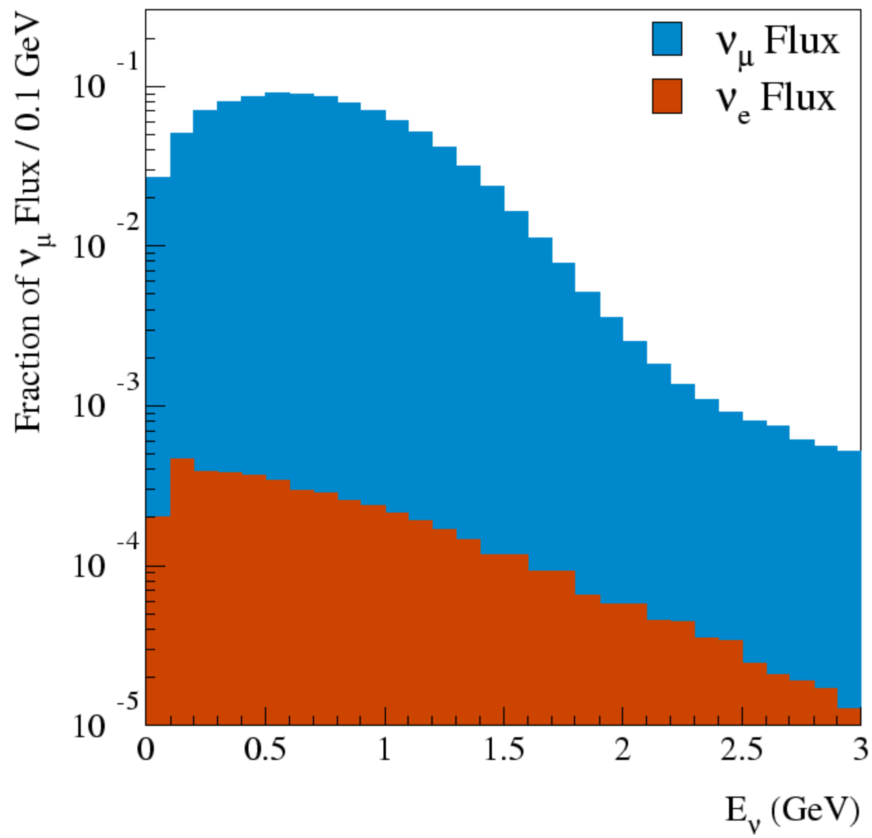
Beam to MiniBooNE



~7 x 10^{20} protons

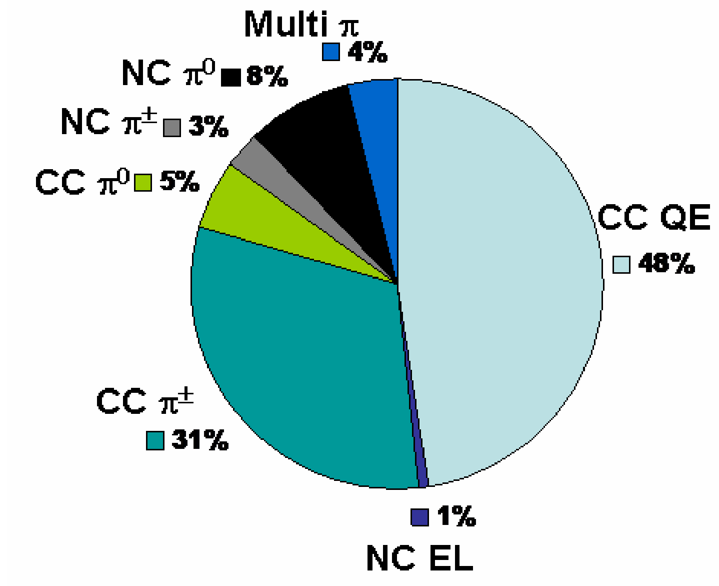
Analysis: Modeling neutrino flux

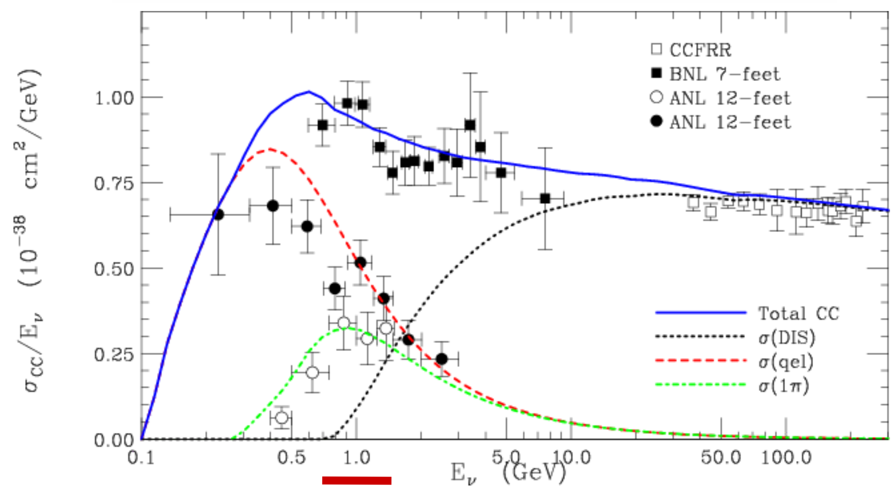
- Production
  - GEANT4 model of target, horn, and beamline
  - MARS for protons and neutrons
  - Sanford-Wang fit to production data for π and K
  - Mesons allowed to decay in model of decay pipe.
  - Retain neutrinos which point at target
  - Soon hope to improve model with data from the HARP experiment taken from a target identical to MiniBooNE



ν_μ Interactions

- Cross sections
  - Based on NUANCE 3 Monte Carlo
    - Use NEUT and NEUEN as cross checks
  - Theoretical input:
    - Llewellyn-Smith free neucleon cross sections
    - Rein-Sehgal resonant and coherent cross-sections
    - Bodek-Yang DIS at low-Q2
    - Standard DIS parametrization at high Q2
    - Fermi-gas model
    - Final state interaction model
- Detector
  - Full GEANT 3.21 model of detector
  - Includes detailed optical model of oil
  - Reduced to raw PMT hits and analyzed in the same way as real data

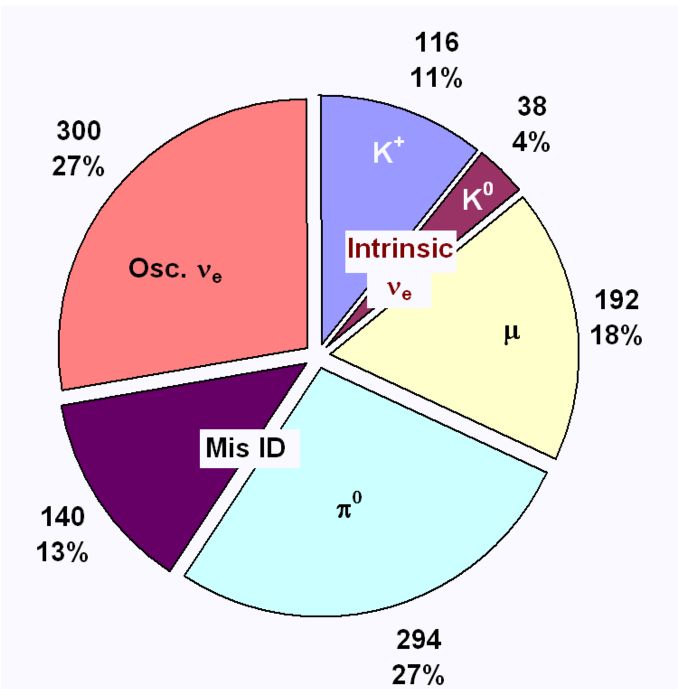


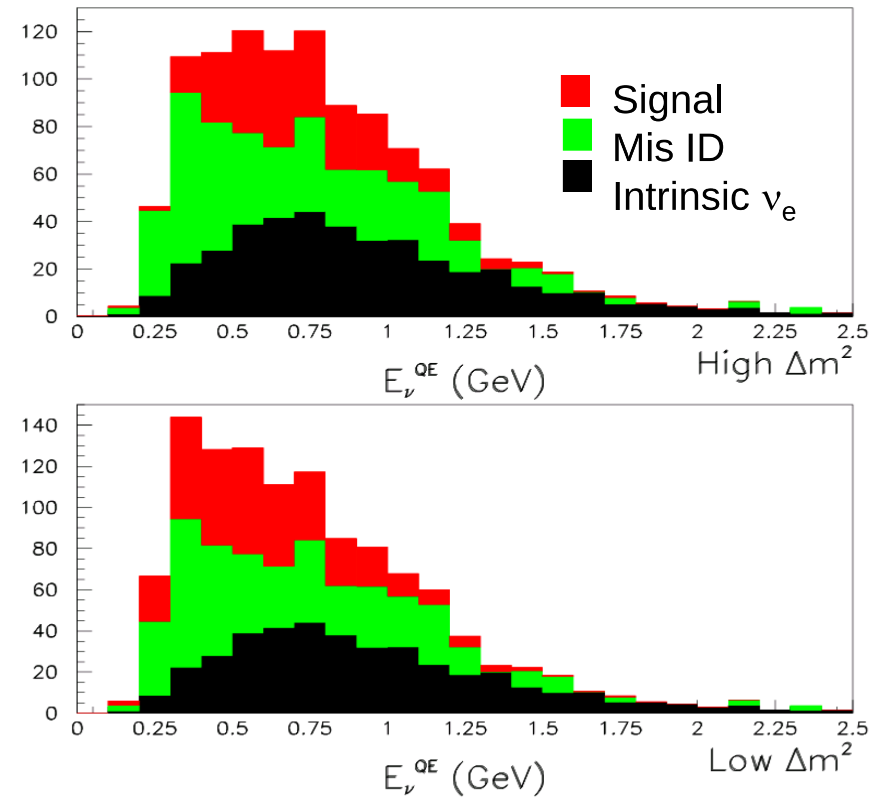


MiniBooNE

Background

- If the LSND best fit is accurate, only about a third of our observed rate will come from oscillations
- Backgrounds come from both intrinsic ν_e and misidentified ν_μ



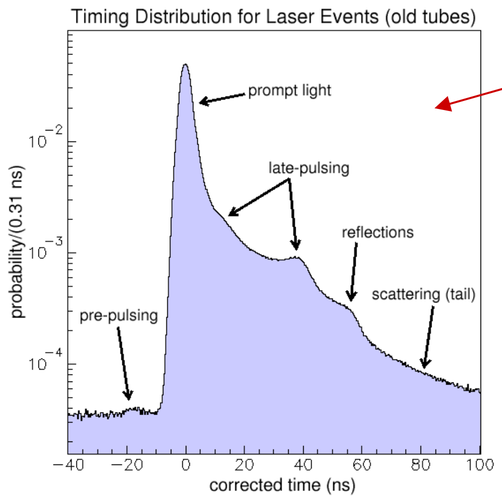


Energy distribution can help separate

Blindness

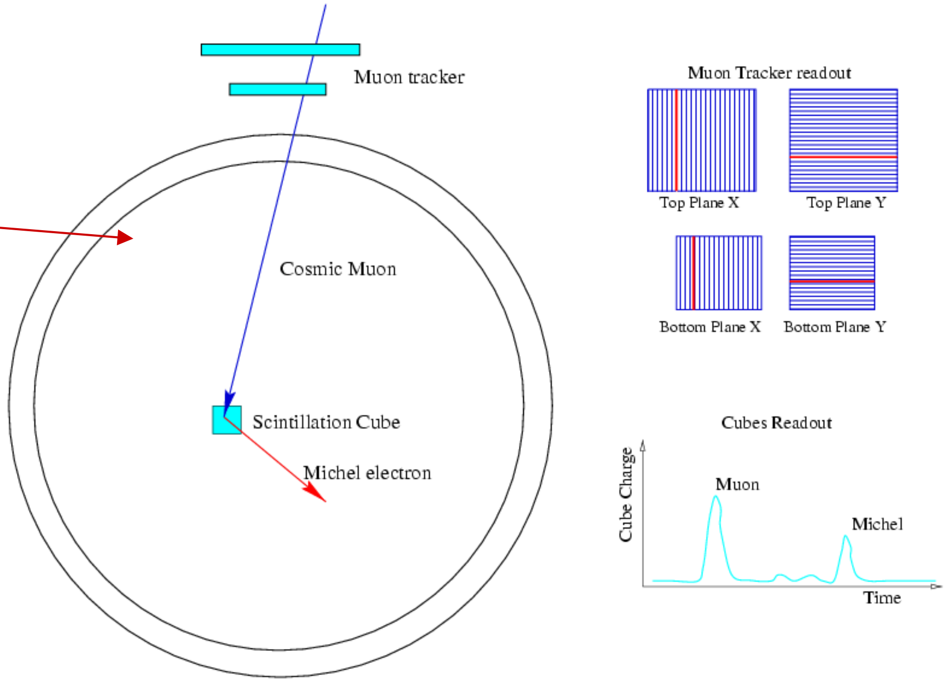
- Given the low signal to background ratio and the inherent difficulty of the analysis, there are many opportunities for unintentional bias
- Therefore, we consider a blind analysis essential
- General philosophy: guilty until proven innocent
- Events go "into the box" unless they are specifically tagged as being non-signal events, e.g
  - Muons
    - Single μ-like ring
    - Topological cuts
  - π^0
    - No Michel electron
    - Clear two-ring fit, both with E>40 MeV
- Will only look at remaining data when we are confident that we model the beam and detector well.
- Note: This still allows us to look at the majority of our data!

Characterizing the Detector



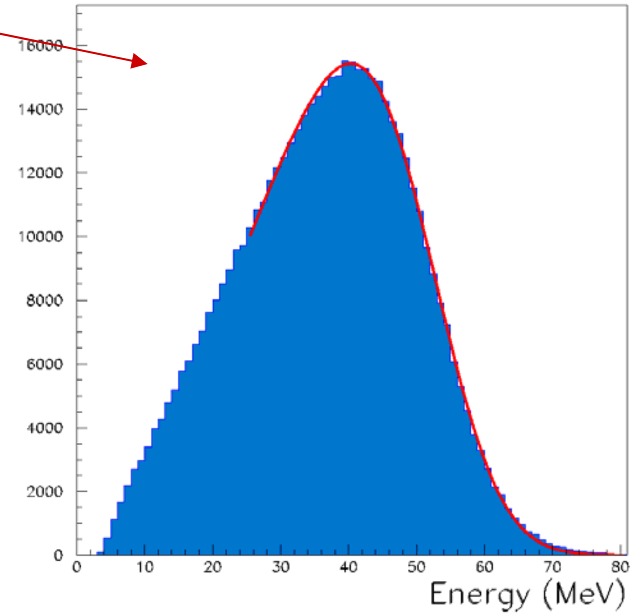
- Laser Calibration
  - ➢ Laser pulses illuminate one of 4 flasks which scatter light isotropically
  - ➢ Used to understand PMT response

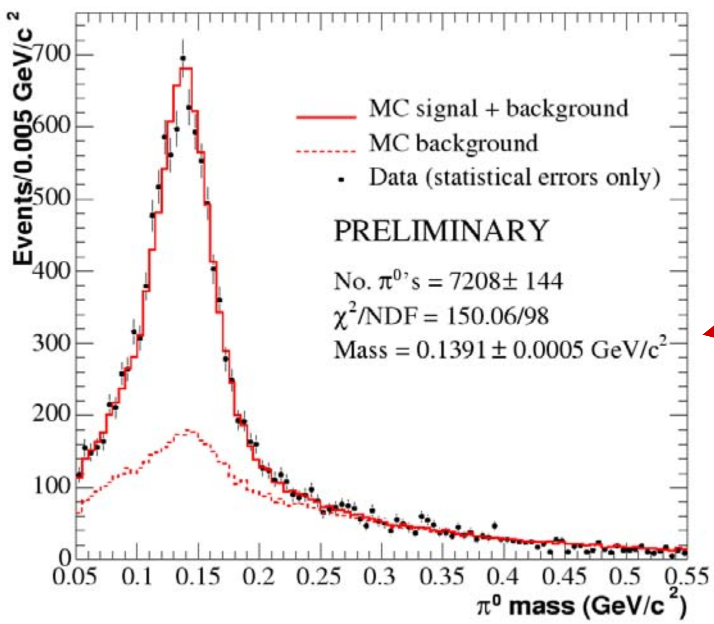
- Cosmic Muons
  - ➢ Muon Tracker used in conjunction with "cubes" to trigger on a particular endpoint (energy)
  - ➢ Vital in understanding energy scale



The Detector (cont'd)

- Electrons from muon decay (Michel electrons)
  - Vital for understanding signal events.

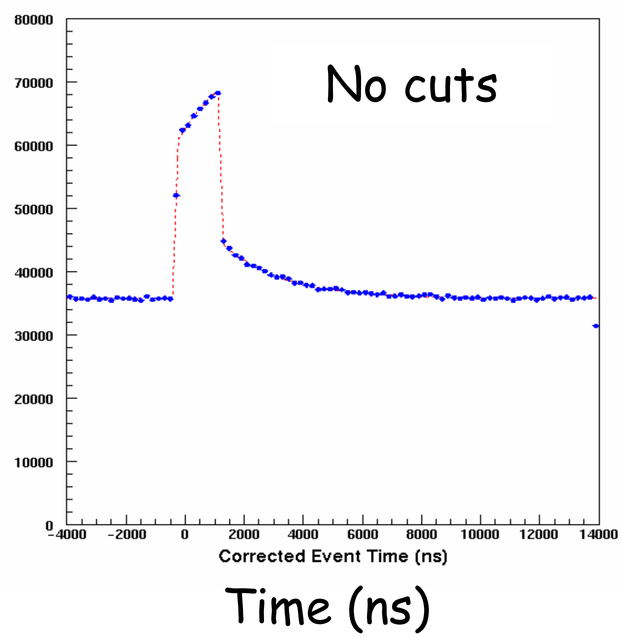


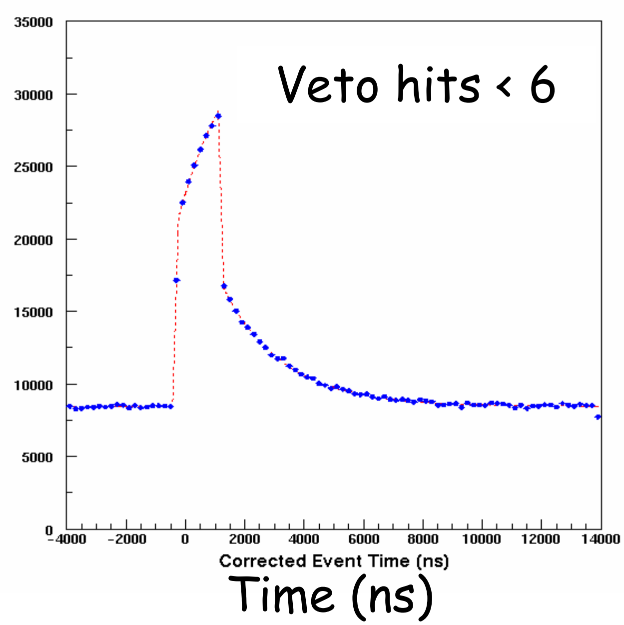


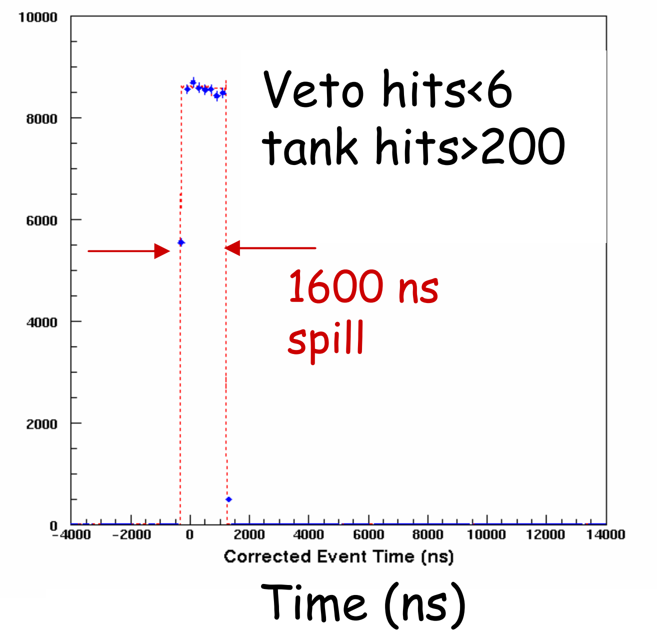
- π^0 Events
  - Help to understand higher energy ν_e
  - Help fix energy scale

Selecting Neutrino Events

- Collect data from -5 to +15 usec around each beam spill trigger.
- Identify individual "events" within this window based on PMT hits clustered in time.

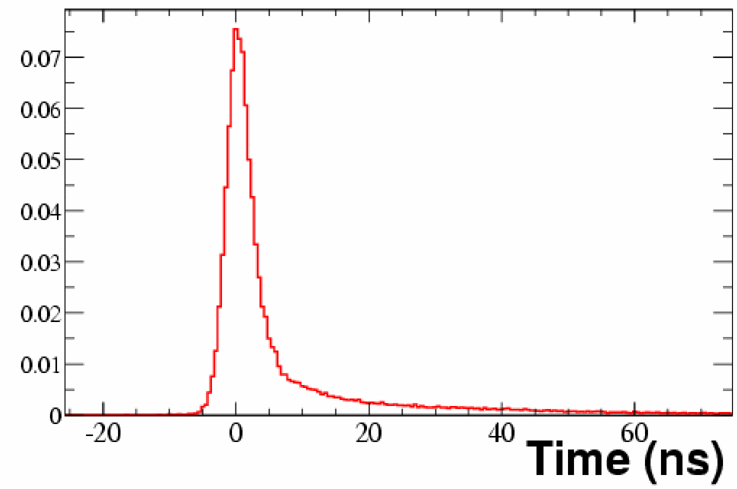


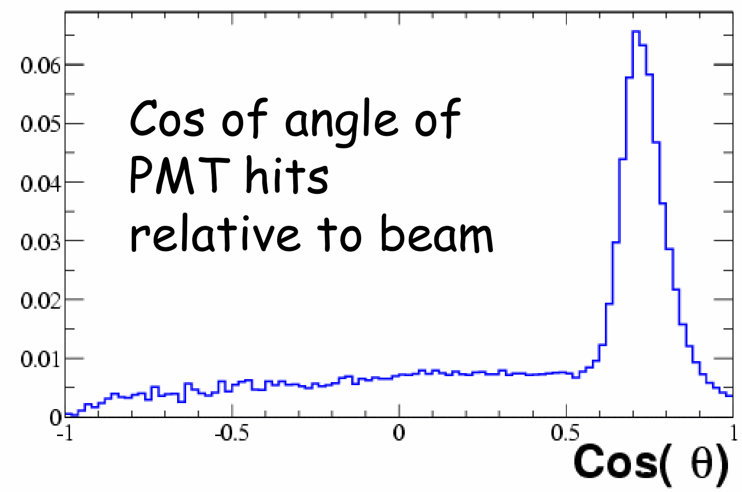




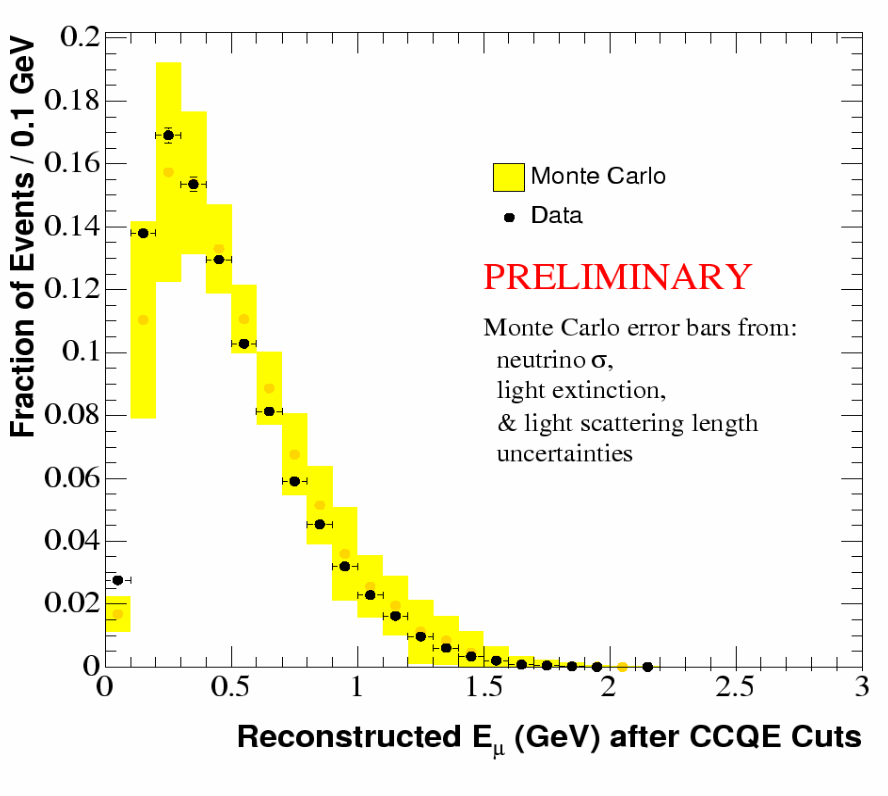
Muon Reconstruction

- Muon reconstruction is based on a fit to PMT's clustered in time
- Position and time of arrival are used to reconstuct the origin, direction and path length of the muon track segment

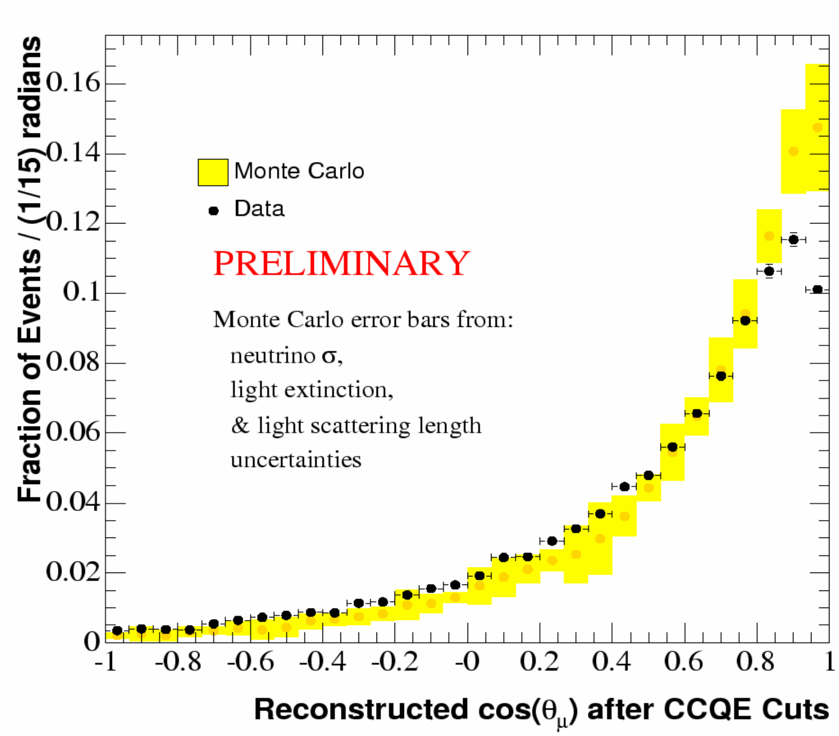




Charged Current Quasi-elastic Events

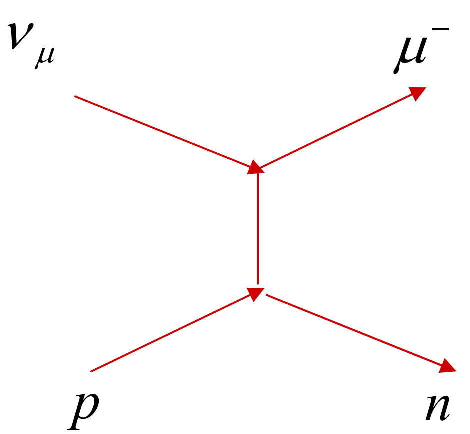


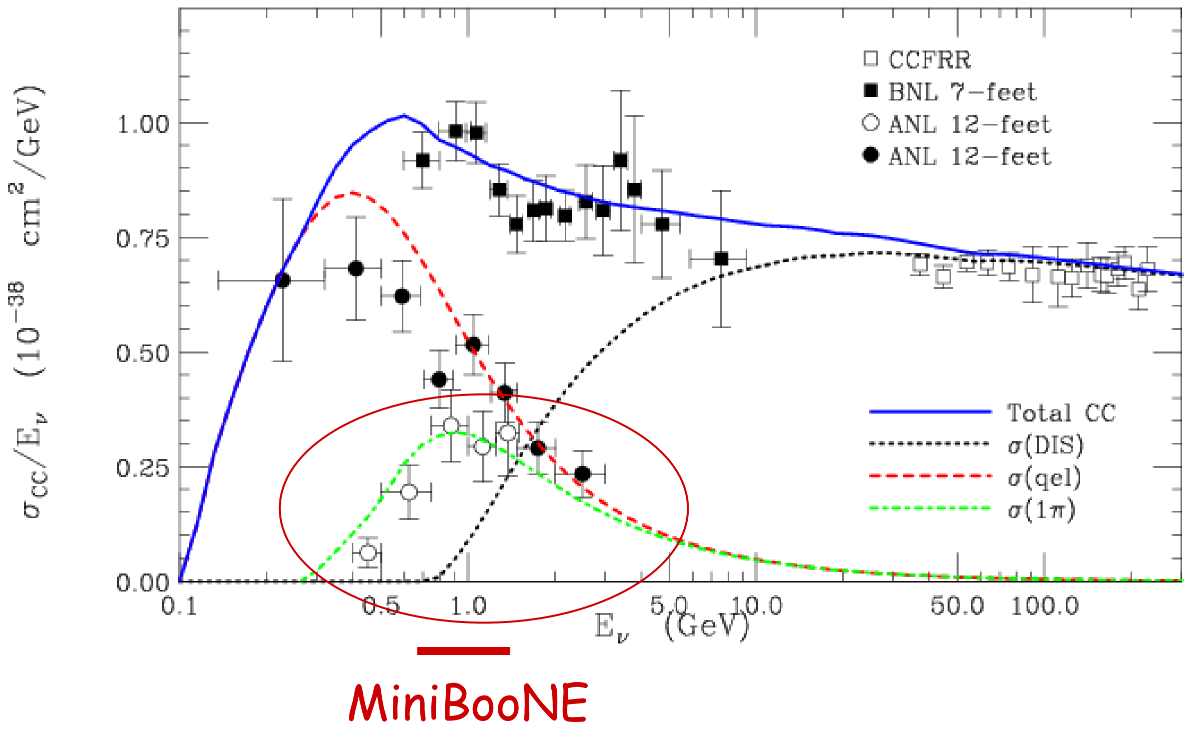
- Angular distribution

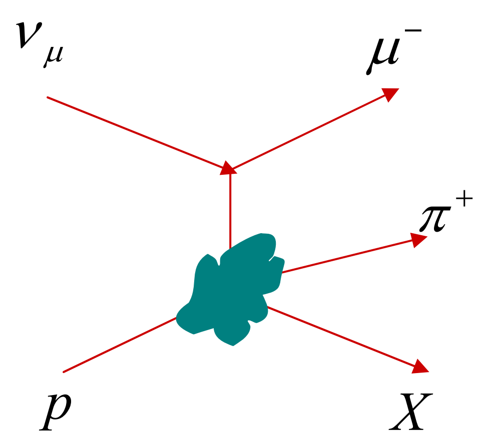


- Veto hits < 6
- Tank hits > 200
- PMT position/time fit consistent with muon

Recent Results: $\nu_\mu + X \Rightarrow X' + \mu + \pi^+$ (CCPiP)*





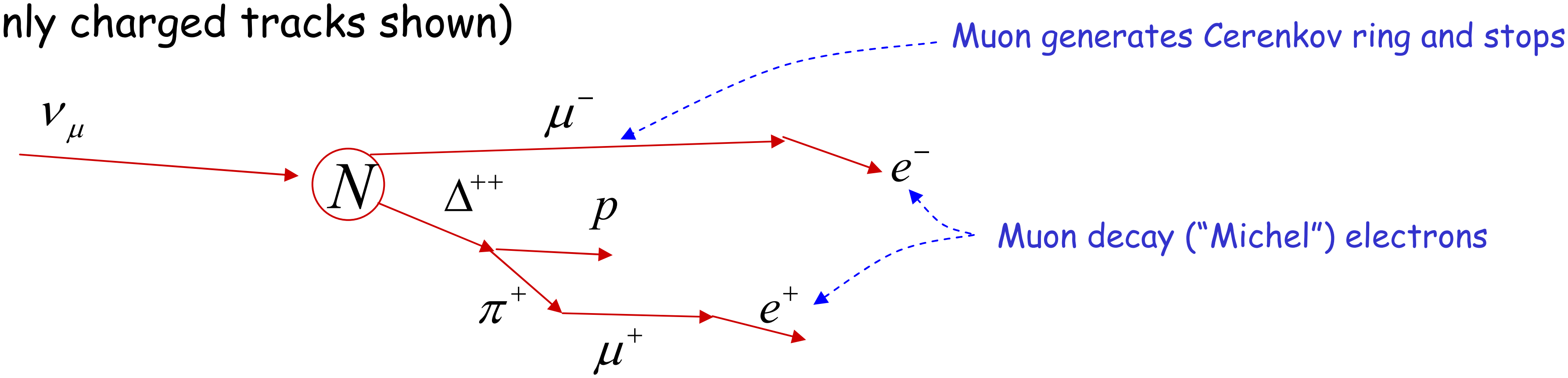


- Important for understanding backgrounds and nuclear cross sections.

*analysis by M. Wascko and J. Monroe

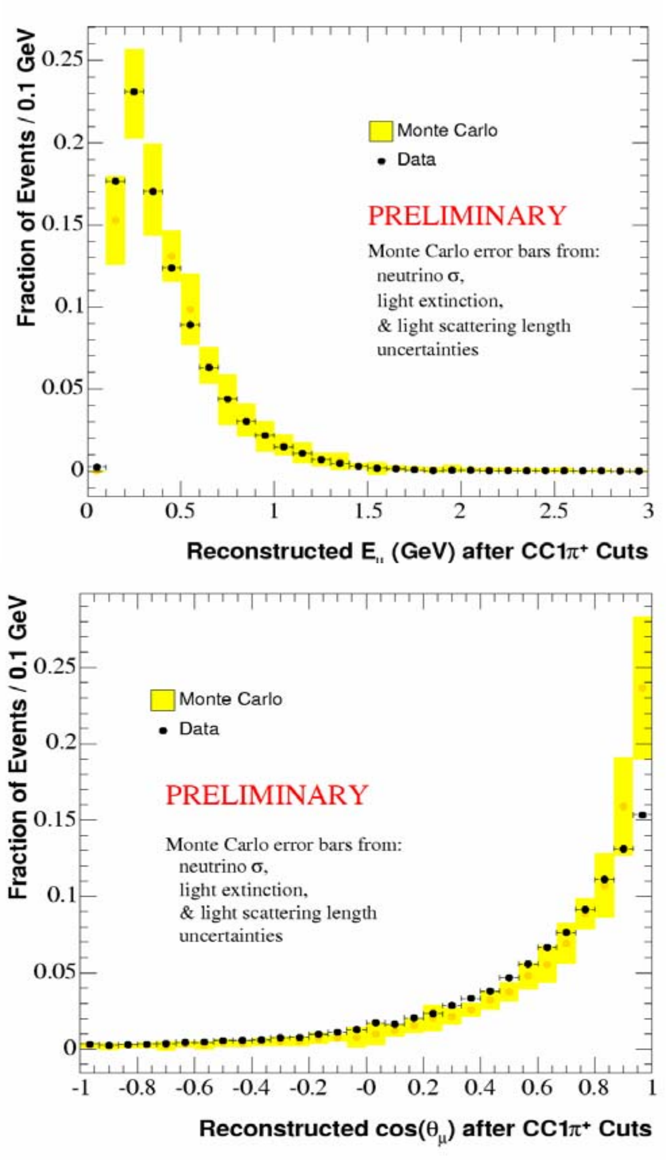
Signature of CCPiP Event

(only charged tracks shown)

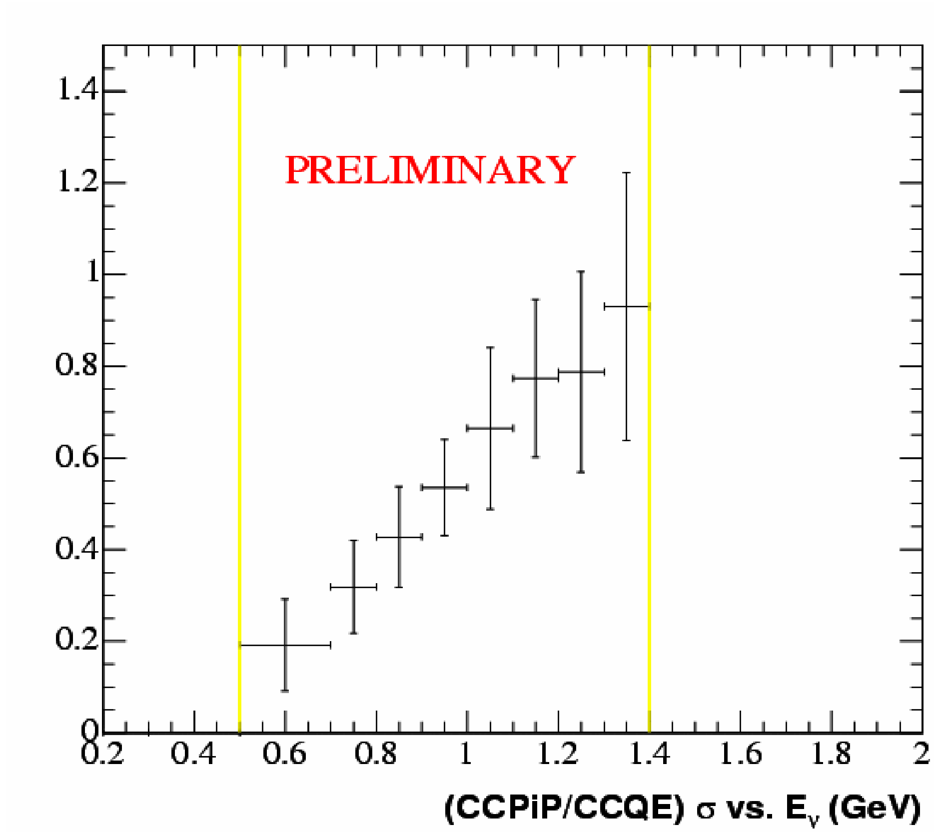


- Look for exactly three events:
  - First promptly with the beam
  - Second two within the ~15 usec trigger window
- First event consistent with CC muon
- Second two consistent with Michel decays.

CCPiP Results

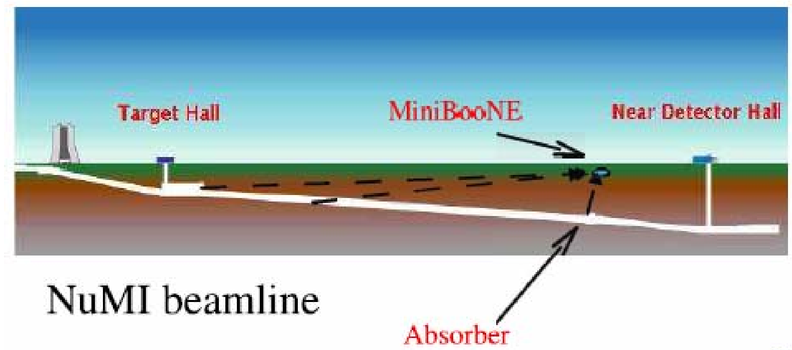


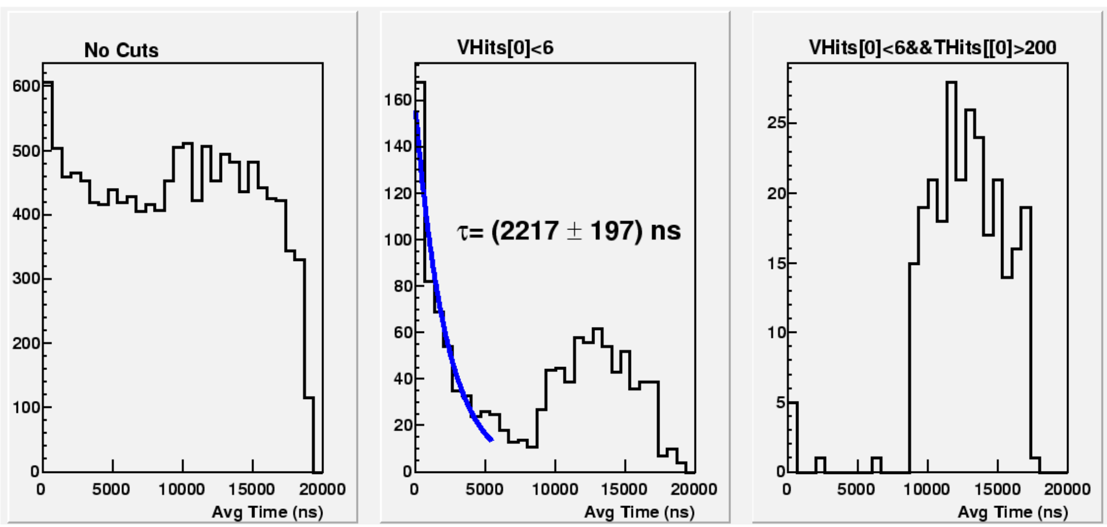
- CCPiP/CCQE ratio
- Corrected for efficiencies

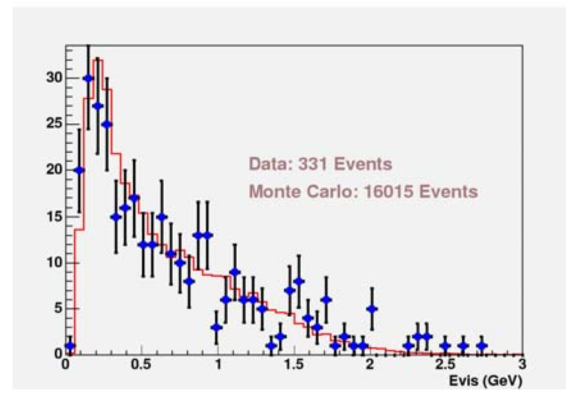


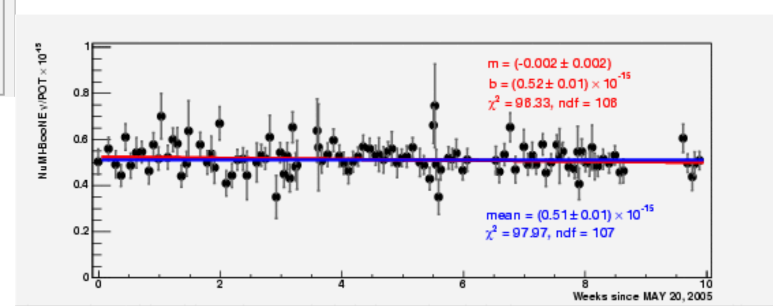
Additional Cross-checks: Neutrinos from NuMI beamline*

- NuMI decay pipe extends to almost just below the MiniBooNE detector







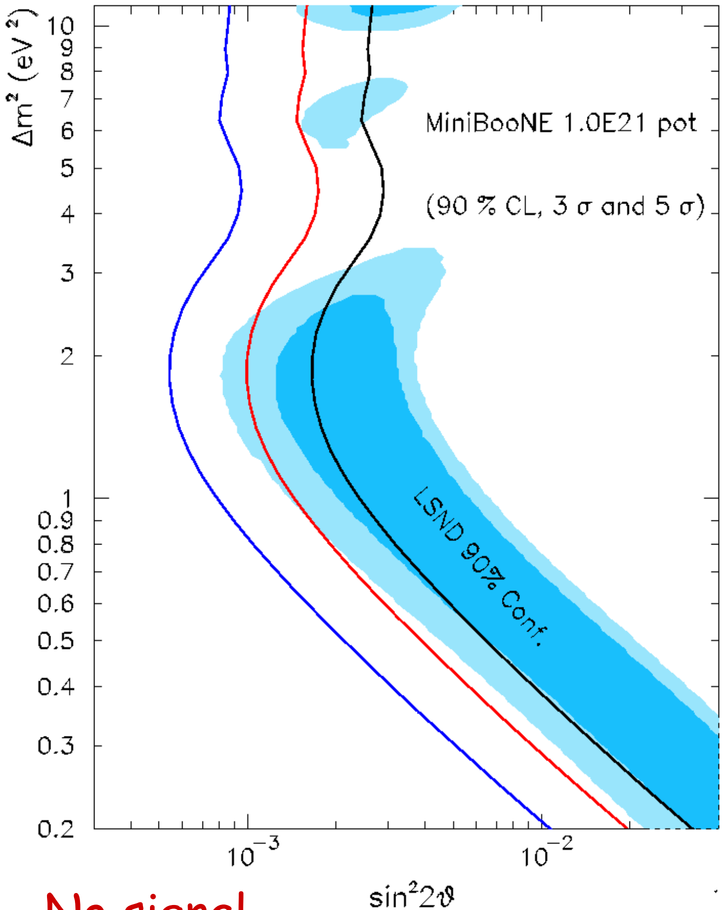


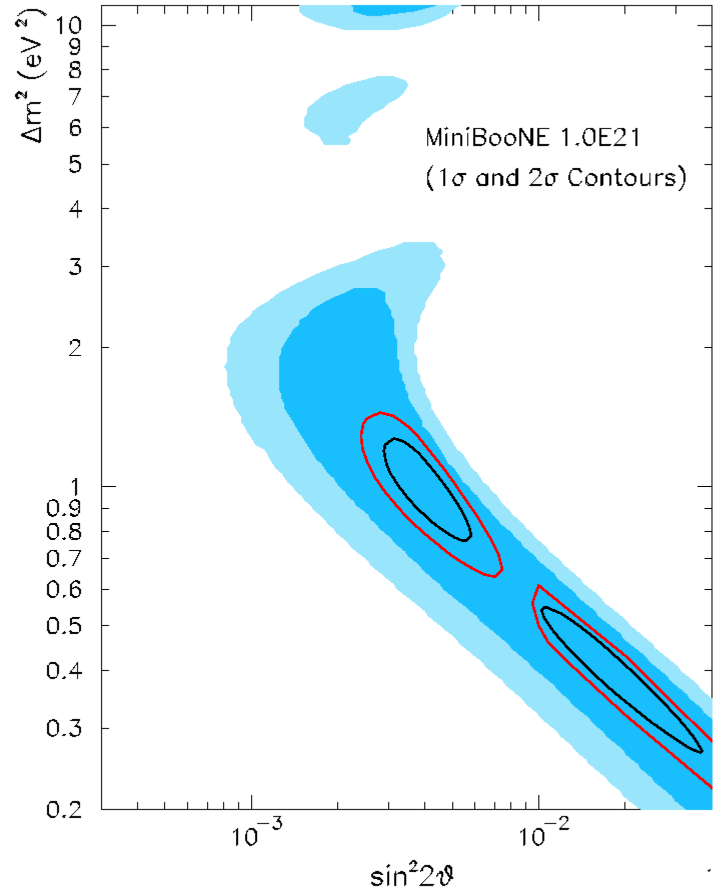
*primarily analysis of A. Aguilar

Path to "opening the box"

- Our present sample neutrino data is sufficient to release an oscillation result
  - We are not yet confident enough in our analysis to do so
- Continue to refine Monte Carlo until open box samples agree within errors
  - HARP data on MiniBooNE target an important constraint
- Generate systematic error matrix by varying all important production and optical model parameters ("Unisim Monte Carlo").
- When confident, practice on a fake oscillation signal.

Experimental Sensitivity

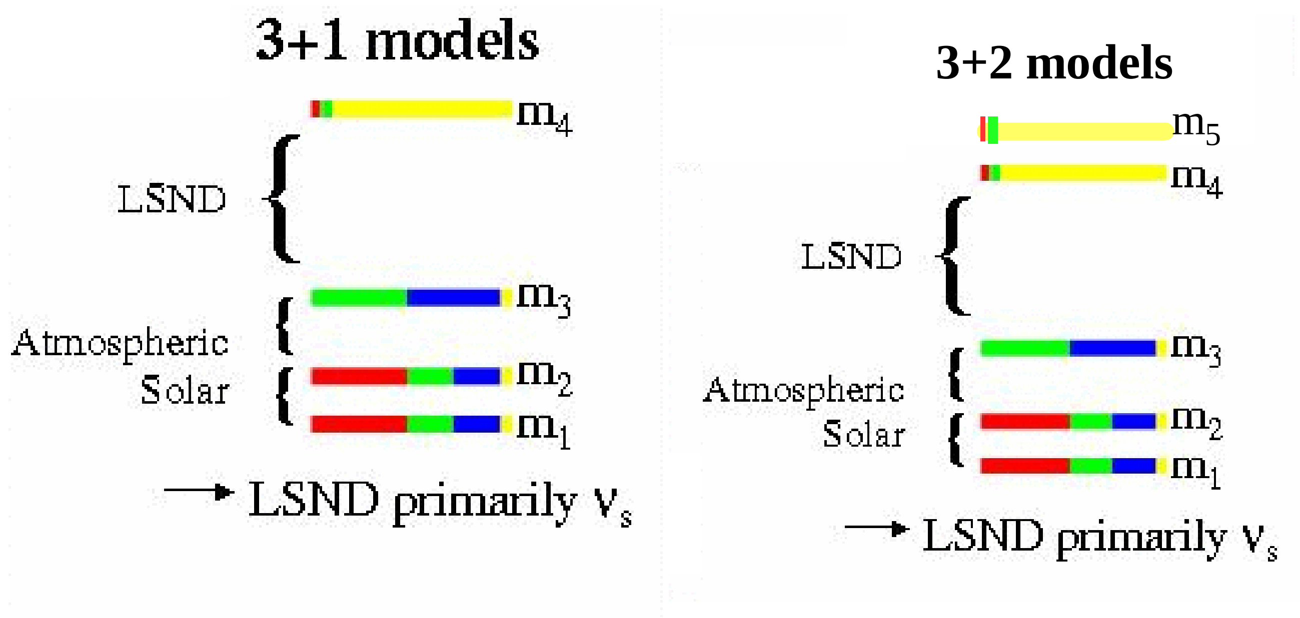




- No signal
  - Can exclude most of LSND at 5σ
- Signal
  - Can achieve good Δm^2 separation

Accommodating a Positive Signal

- We know from LEP that there are only 3 active, light neutrino flavors.
- If MiniBooNE confirms the LSND results, it might be evidence for the existence of sterile neutrinos



Everybody Loves a Mystery

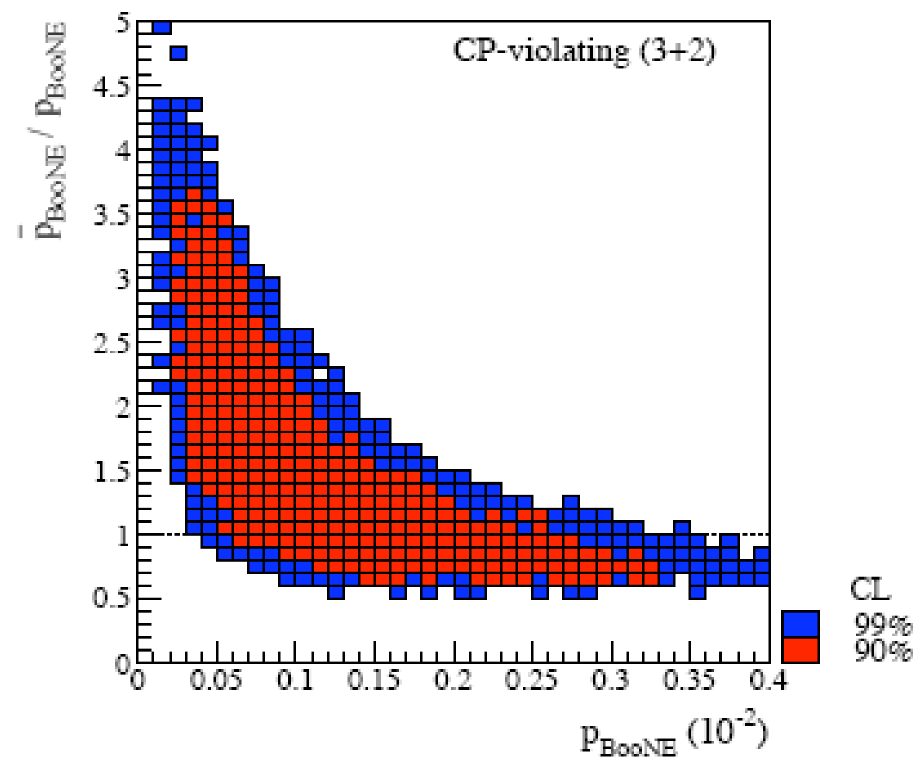
- 3+2 Sterile neutrinos
  - Sorel, Conrad, and Shaevitz (hep-ph/0305255)
- MaVaN & 3+1
  - Hung (hep-ph/0010126)
- Sterile neutrinos
  - Kaplan, Nelson, and Weiner (hep-ph/0401099)
    - Explain Dark Energy?
- CPT violation and 3+1 neutrinos
  - Barger, Marfatia & Whisnant (hep-ph/0308299)
    - Explain matter/antimatter asymmetry
- Lorentz Violation
  - Kostelecky & Mewes (hep-ph/0406035)
- Extra Dimensions
  - Pas, Pakvasa, & Weiler (hep-ph/0504096)
- Sterile Neutrino Decay
  - Palomares-Ruiz, Pascoli & Schwetz (hep-ph/0505216)

Near Future: MiniBooNE antineutrino running

As we speak, MiniBooNE is switching the horn polarity to run in antineutrino mode

- Inherently interesting
  - Not much anti-neutrino data
- Directly address LSND signal
- Important for understanding our own systematics and those of other experiments
- Problems:
  - Cross section not well known
  - Lower rate (about $\frac{1}{4}$)
  - Wrong sign background

Example of new physics:



Conclusions and Outlook

- MiniBooNE has been running for over three years, and continues to run well in the NuMI era
- The analysis tools are well developed and being refined to achieve the quality necessary to release the result of our blind analysis
- Recent results for CCQE and CCPiP give us confidence on our understanding of the detector and data.
- Look forward to many interesting results in 2006