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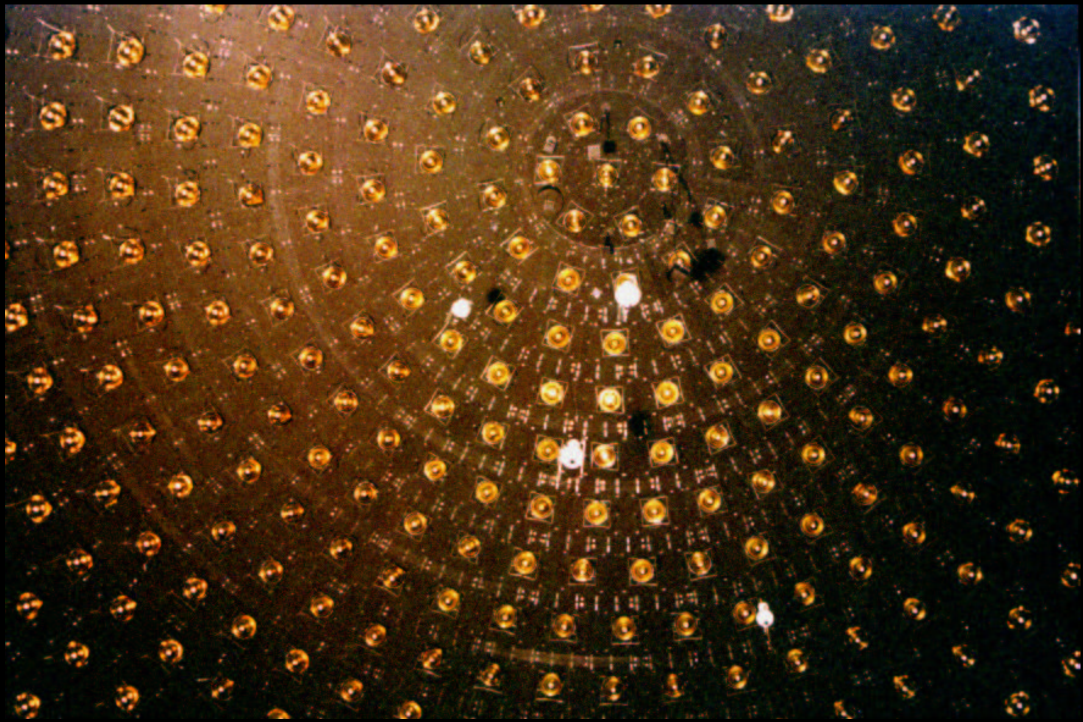
The Latest from MiniBooNE

- Context
  - ν oscillation primer
  - ν oscillation landscape
  - LSND
    - Implications
- Latest MiniBooNE news
  - Beam performance
  - Detector performance
  - Neutrino data
    - flux, cross section progress
- Updated Oscillation Sensitivity based on measured neutrino rates during first year of data



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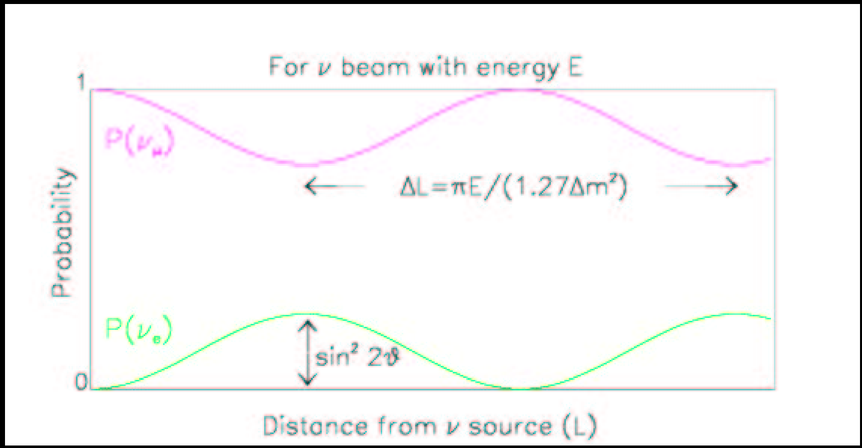
ν Oscillation Physics

$$P(\nu_a \rightarrow \nu_b) = \sin^2(2\theta)\sin^2\left(1.27\,\Delta m^2_{12}\,\frac{L}{E}\right)$$

- Oscillation probability between 2 states depends on:
  - Two fundamental parameters
    - $\Delta m^2 = m_1^2 - m_2^2$ - "period"
      - mass difference between states
    - $\sin^2 2\theta$ - "amplitude"
      - mixing between flavors
  - Two experimental parameters
    - L: distance from source to detector
    - E: Neutrino energy



- Two experiments in this example:
- ν_μ disappearance
  - $P(\nu_\mu \rightarrow \nu_\mu)$
- ν_e appearance
  - $P(\nu_\mu \rightarrow \nu_e)$

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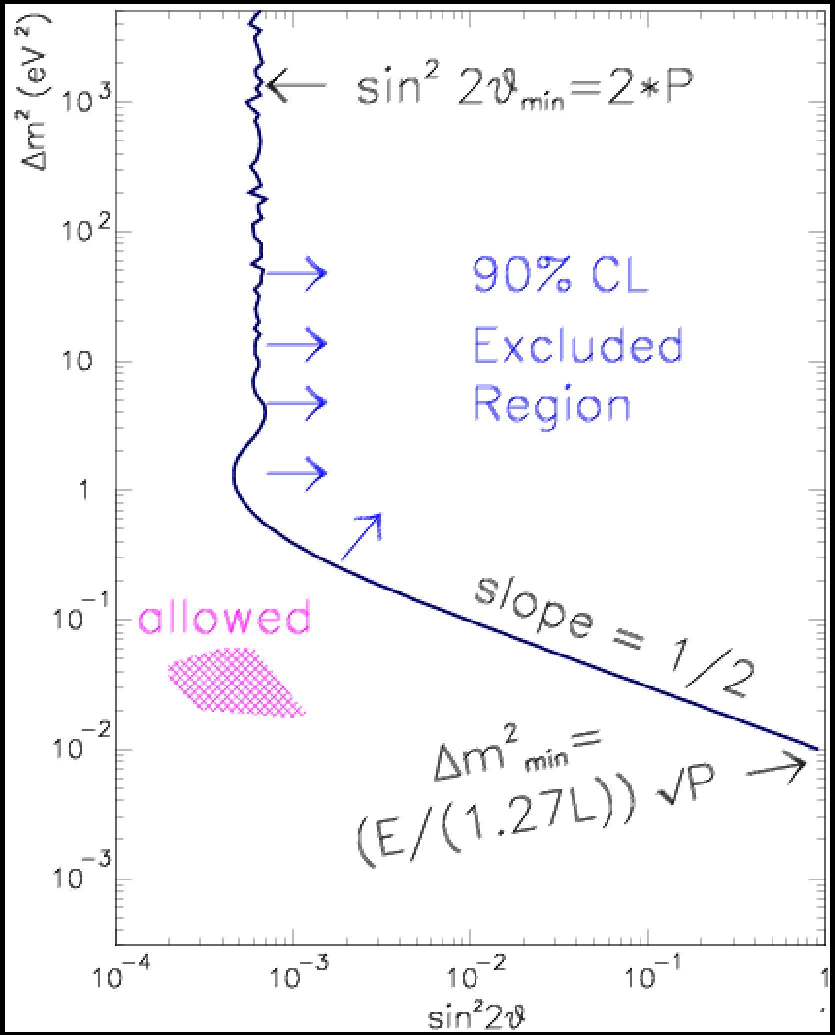
ν Oscillation Physics

$$P(\nu_a \to \nu_b) = \sin^2(2\theta)\sin^2\left(1.27\,\Delta m_{12}^2 \frac{L}{E}\right)$$

- L and E determine the Δm^2 sensitivity region
- $\sin^2 2\theta$ gives amplitude of oscillations
  - Small mixing ⇔ relatively few osc. events
  - Large mixing ⇔ relatively many osc. events
- Exclusion regions
  - Above and to the right excluded
  - Below and to the left cannot be ruled out
- Allowed regions shown by shaded areas specifying Δm^2 and $\sin^2 2\theta$



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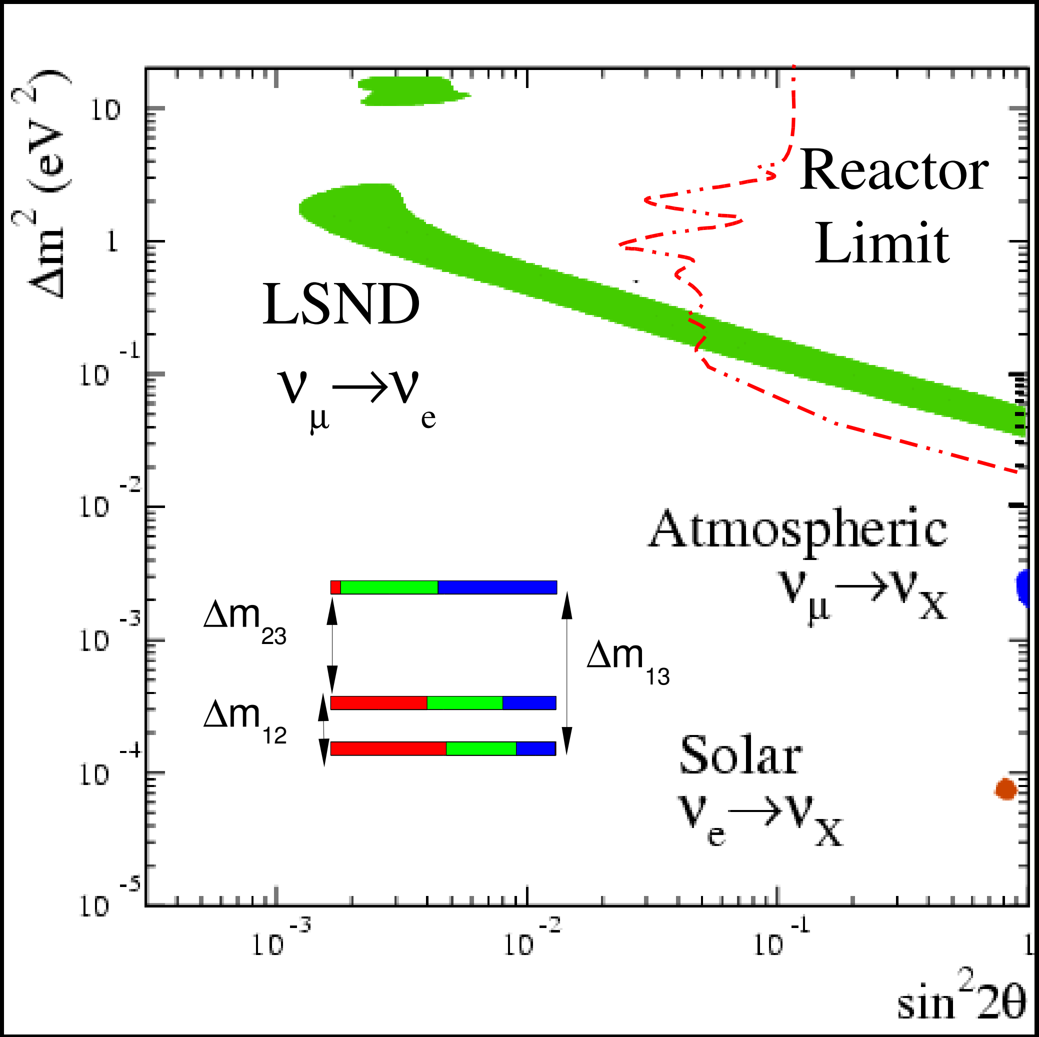
Current Oscillation Picture

- Solar neutrino "problem"
  - First studied by Homestake, SAGE, GALLEX, GNO, Kamiokande...
  - Resolved by SNO
  - Confirmed by KamLAND
- Atmospheric oscillation
  - first hints: IMB,Kamiokande
  - confirmed by Super-K, also seen by SOUDAN2, MACRO
  - K2K
- LSND
  - Yet to be confirmed
- Problem: The three oscillation regions are incompatible with three standard model neutrinos



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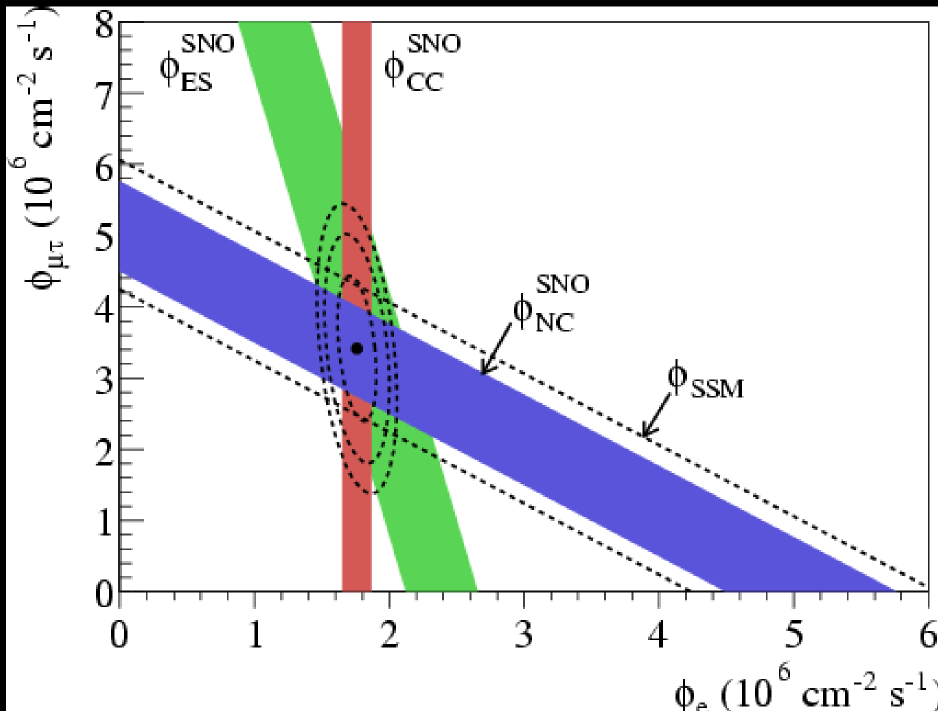
Solar ν Solution

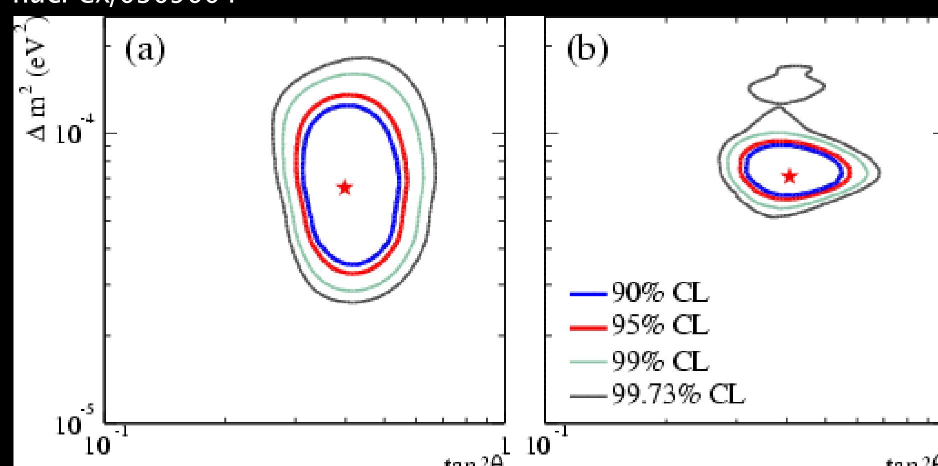


nucl-ex/0106015

- Sudbury Neutrino Observatory
  - sensitive to charged current (W exchange), elastic scattering, and neutral currents (Z exchange)
  - Measure rate of ν_e only with CC data
    - Deficit compared to SSM
  - Measured rate of all ν with ES,NC data
    - Observed total expected flux of ν from SSM!

- Solution: small mixing
  - $\theta \simeq 32^\circ$
- $\Delta m^2 = 8.2 \times 10^{-5} eV^2$
  - very low mass

nucl-ex/0309004



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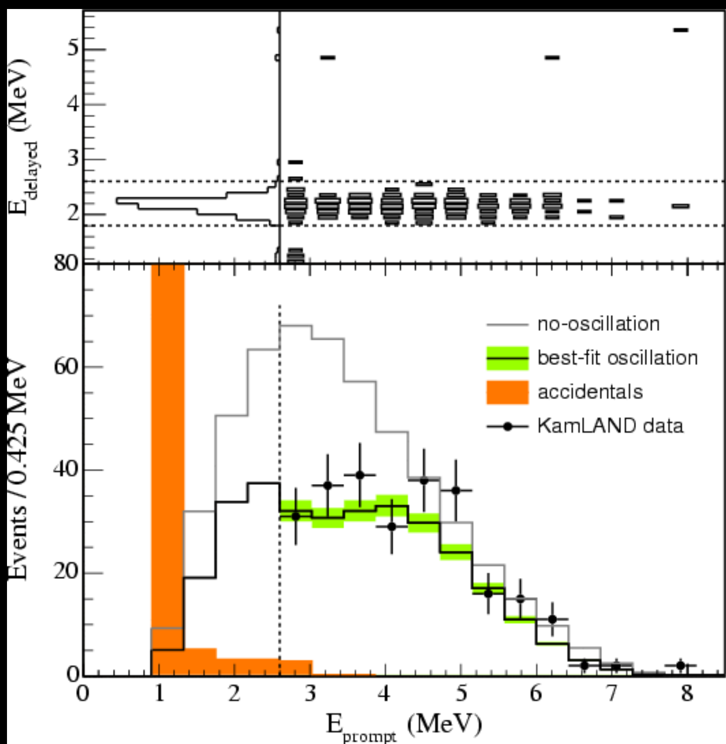
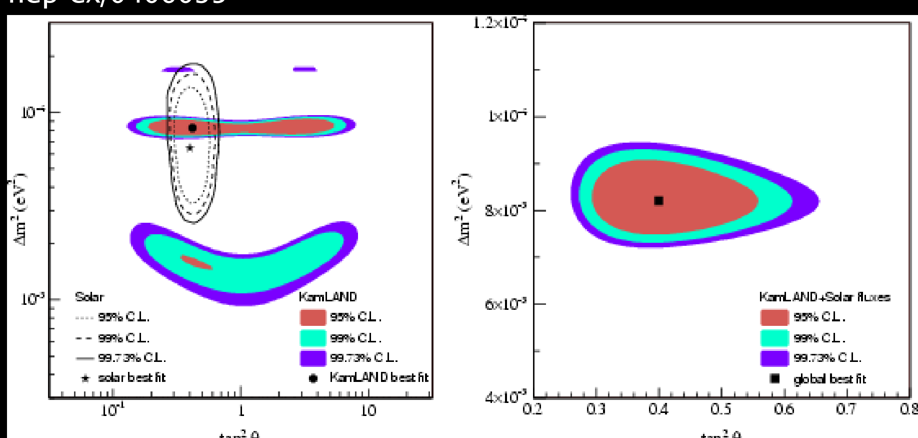
Solar Confirmation



hep-ex/0406035



- KamLAND observes reactor neutrinos from dozens of reactors in Japan and Korea
- Energy spectrum of observed events incompatible with simple rescaling of reactor spectrum
- Oscillation results confirm solar result
  - Better sensitivity to Δm^2
- $\bar{\nu}$ vs. ν

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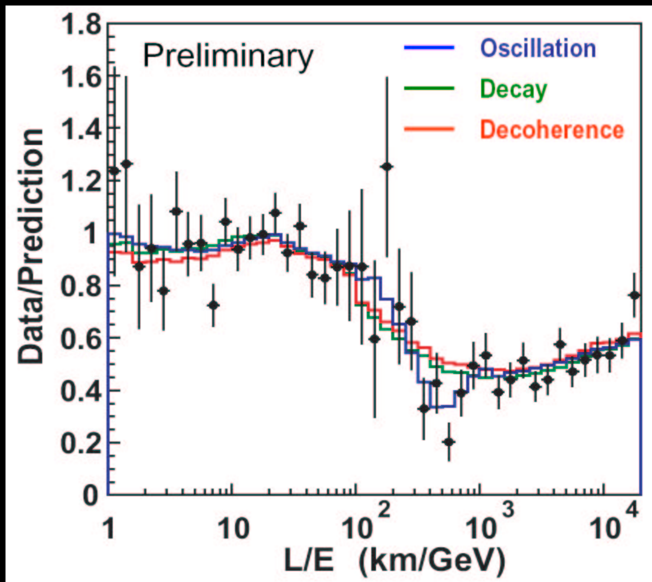
Atmospheric ν



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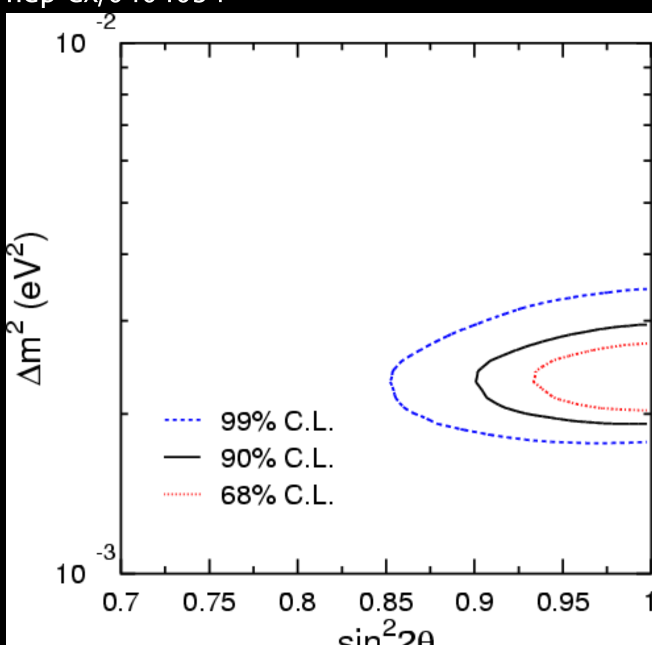

- Super-Kamiokande observes difference in fluxes of upward and downward going atmospheric neutrinos
- L/E distribution characteristic of oscillations
- Best fit to data:
  - Maximal mixing
  - $\Delta m^2 = 2.4\times10^{-3}eV^2$
  - ν_μ disappearance
    - $\nu_\mu\rightarrow\nu_\tau$ preferred over $\nu_\mu\rightarrow\nu_s$

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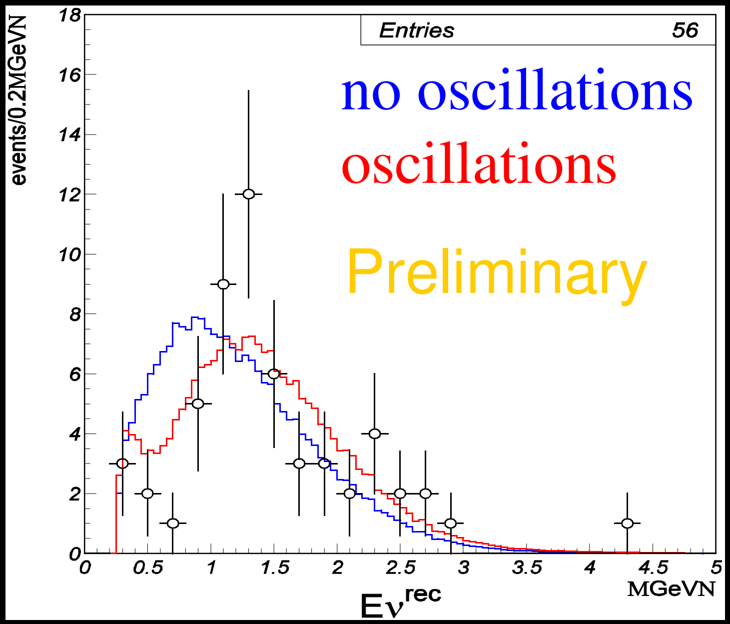
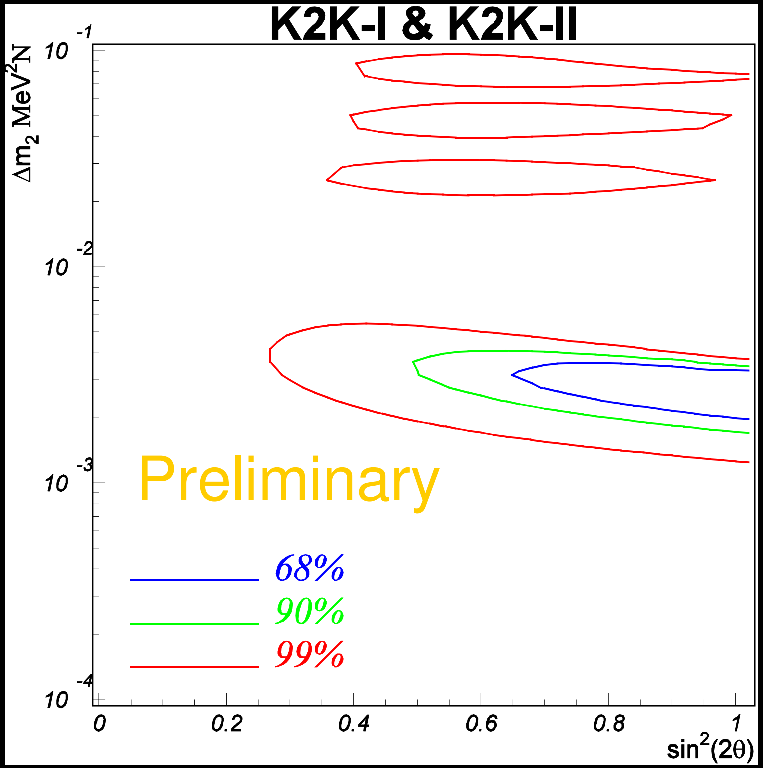
Confirmation of Atmospheric



- K2K send νs from KEK accelerator to Super-K
- Compare fluxes in near detectors (200m) to fluxes at Super-K (250km)

- 56 neutrino events are detected at Super-K, with energy spectrum consistent with the oscillation hypothesis



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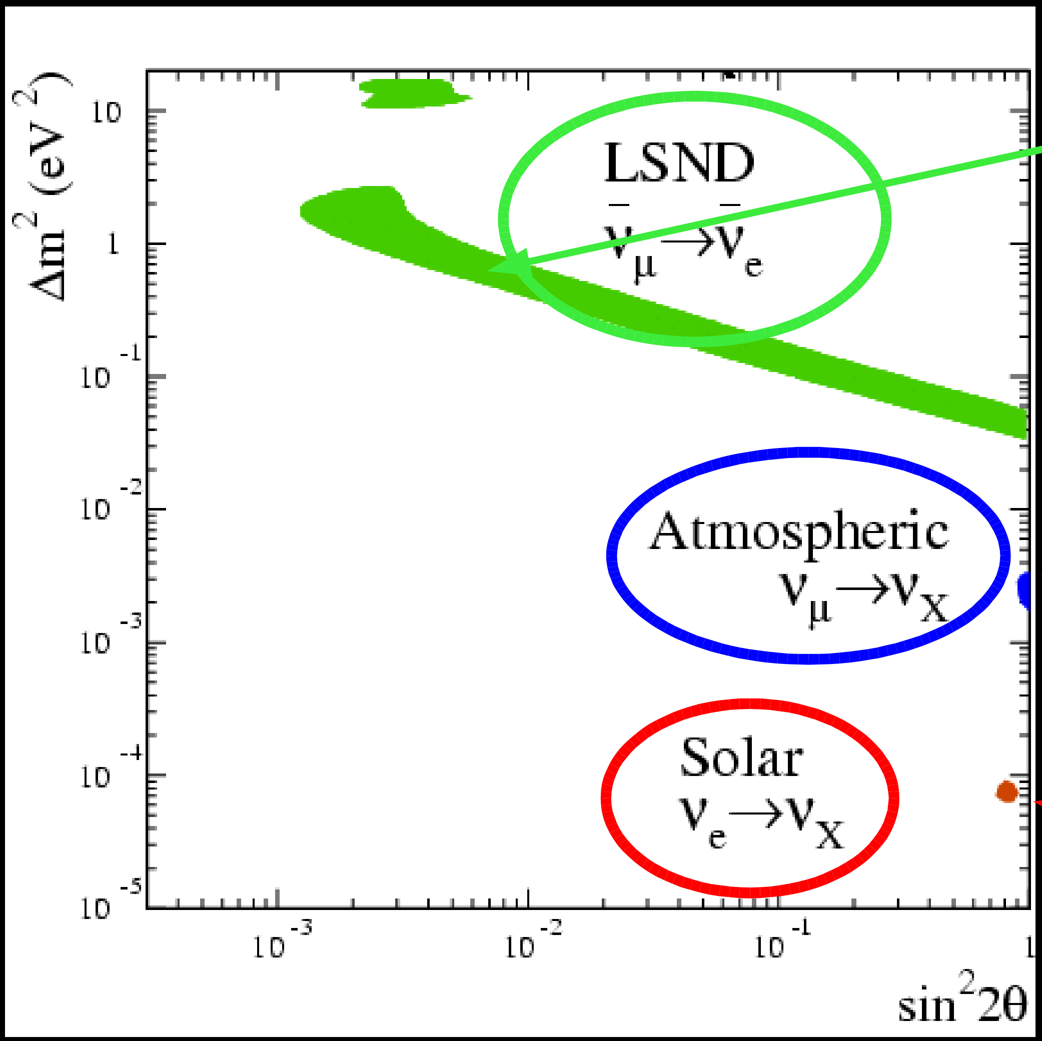
Current Oscillation Summary



LSND
$\Delta m^2 \sim 1 eV^2$
$\theta \sim 2°$

Atmospheric oscillations
$\Delta m^2 \sim 10^{-3} eV^2$
$\theta \sim 45°$

Solar oscillations
$\Delta m^2 \sim 10^{-5}$ eV^2
$\theta \sim 32°$

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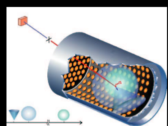
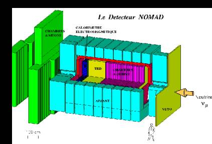
SBL Accelerator ν Expts

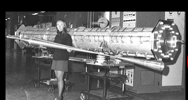
LSND: Liquid scintillator
~50MeV
30m



NOMAD:
Drift Chamber tracker, calorimeters
~25GeV, ~600m



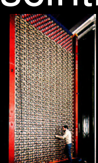
CDHS: iron calorimeter
~25GeV,
~900m

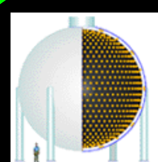


Neutrino Source

BASELINE

KARMEN:
Segmented scintillator
~50MeV
~17m

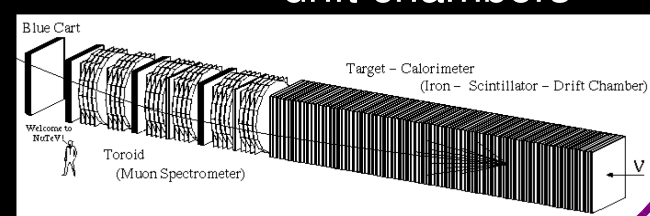




<1GeV
~500m

MiniBooNE:
Pure Mineral Oil

NuTeV:
tracker, calorimeter, spectrometer, drift chambers
20-350 GeV
0.9-1.4km



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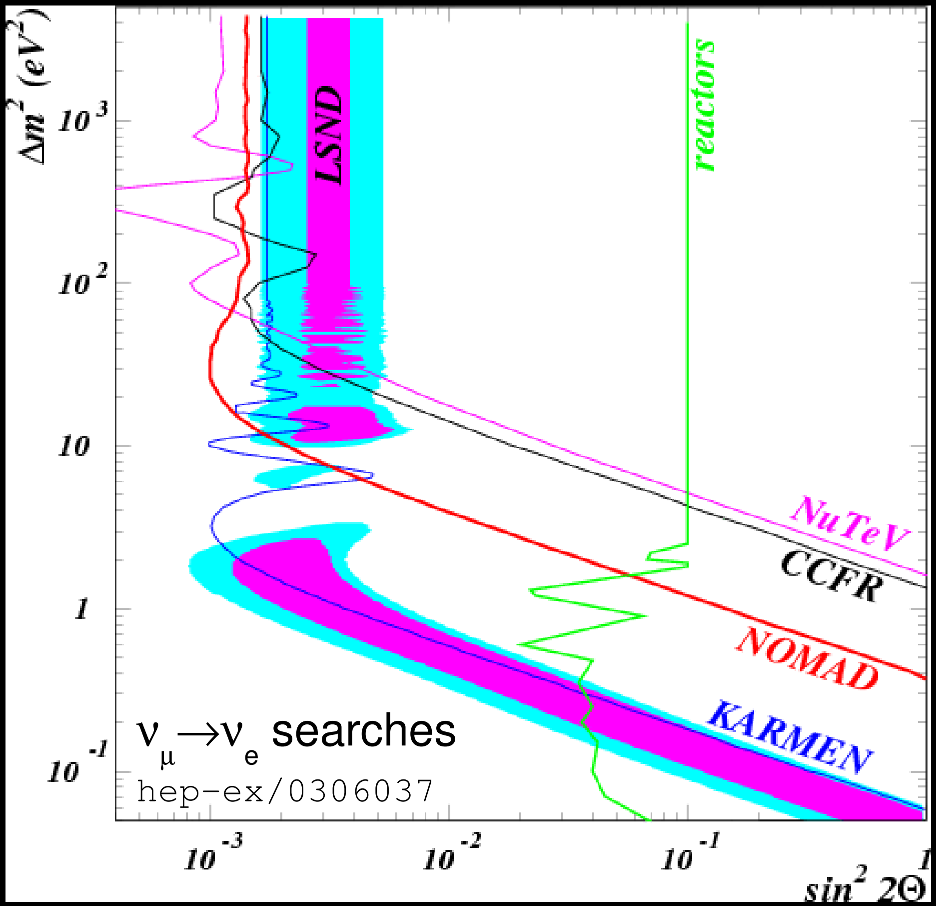
SBL $\nu_\mu \rightarrow \nu_e$ Oscillation Picture

- Oscillation physics at high Δm^2, $0.03 < E_\nu < 300$ GeV, 17m<L<1.4km
- Most sensitive searches shown here:
  - Positive Result
    LSND: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (1993-1998)
  - SBL oscillation NULL results:
    NuTeV, CCFR: $\nu_\mu \rightarrow \nu_{e,\tau}$ (1985→1997)
    NOMAD: $\nu_\mu \rightarrow \nu_{e,\tau}$ (1994-1998)
    KARMEN: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (1992-1999)
- Other expts with NULL results
  - LANL E645
  - BNL E734, E776
  - CERN
    - CHORUS
    - CDHS



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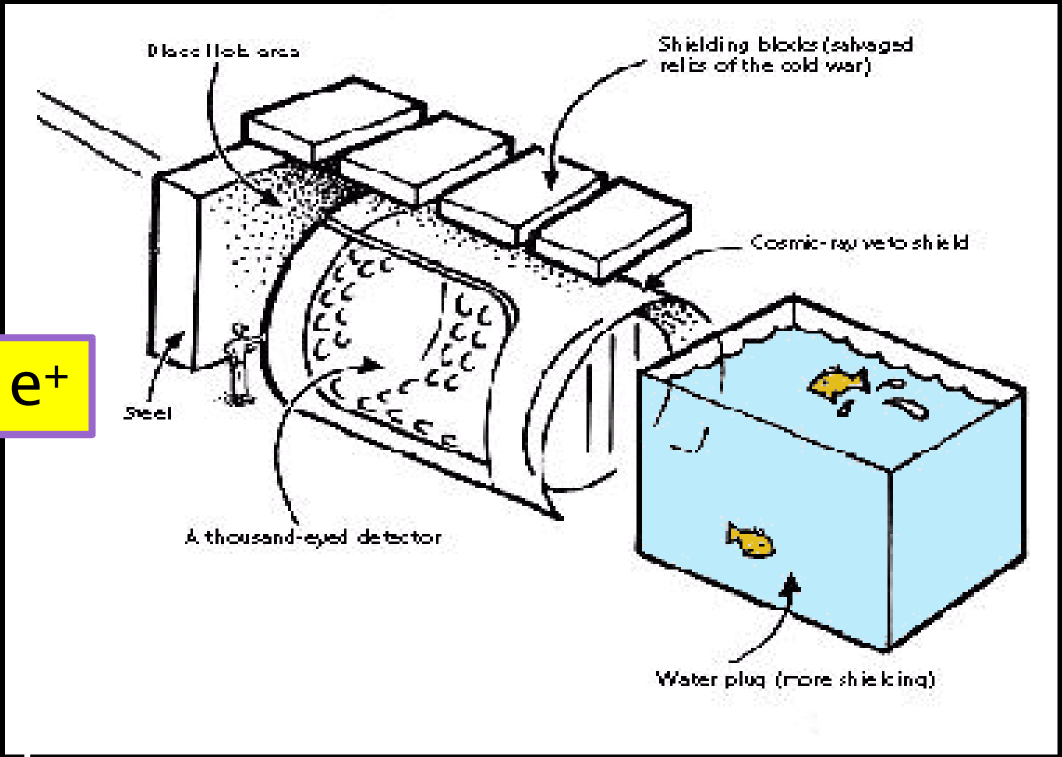
LSND

- The LSND Experiment at LANL (1993-1998)
- Baseline 30 m
- Beam mostly decay at rest
  - stopped $\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\hookrightarrow \bar{\nu}_\mu + \nu_e + e^+$



- 20MeV < E_ν < 55MeV
- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$?
  - Signal reaction: inverse β decay

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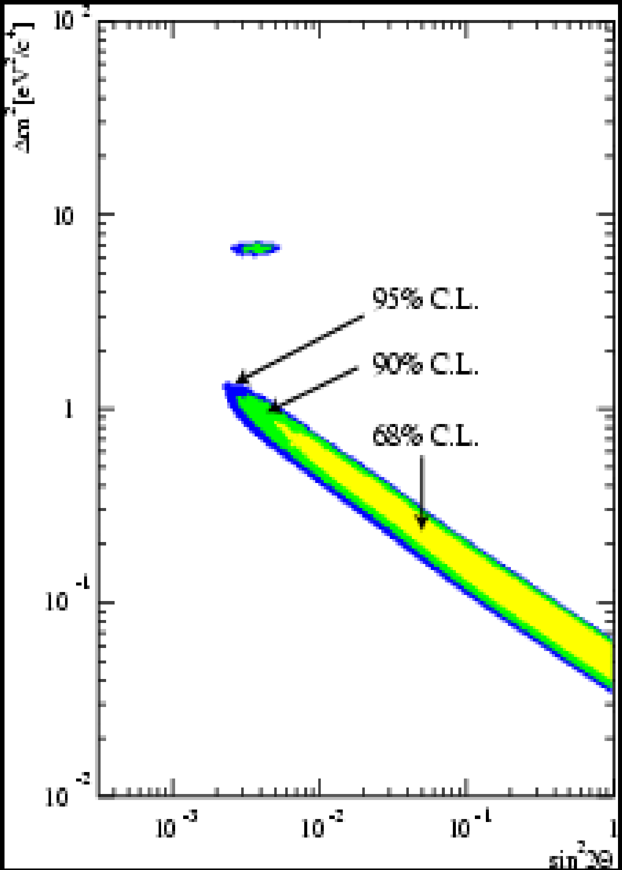
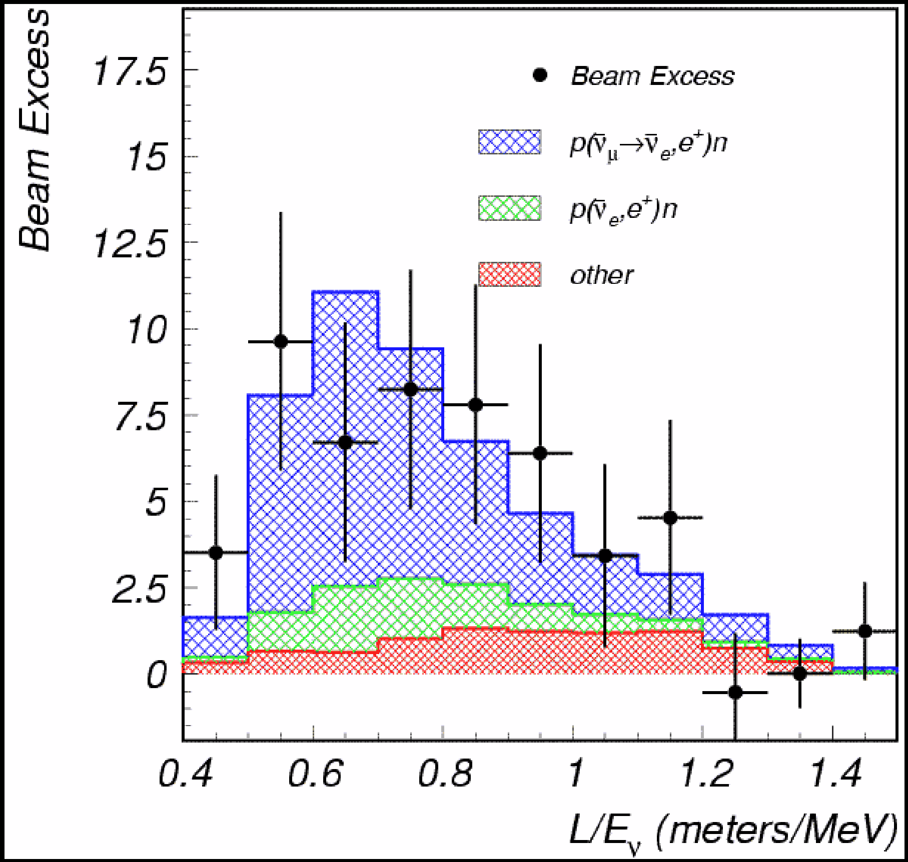
The LSND signal

3.8σ excess!

- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation probability:
  0.264±0.067±0.045%
- KARMEN2 and LSND collaborators performed joint analysis on both data sets - allowed regions remain!



hep-ex/0203023



hep-ex/0104049

- High statistical significance - not easily ruled out

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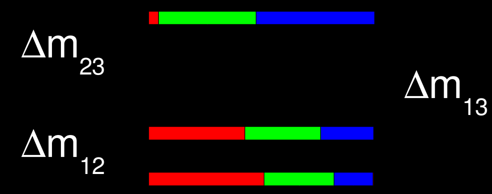
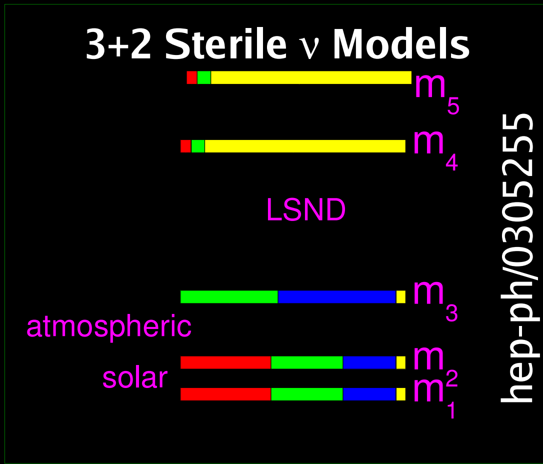
Interpreting LSND

- Not oscillations?
  - Anomalous muon decay: Ruled out by KARMEN2 at 90%CL (hep-ex/0302017)
- If it is oscillations, it indicates
  new physics beyond the standard model
- Sterile Neutrinos
  - (No weak coupling ⇐ invis. Z width)
  - $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_s \leftrightarrow \bar{\nu}_e$
  - 2+2 models (not quite?) ruled out
  - 3+1 models disfavored
  - 3+n models wide open (n>1)
    - CP violation
- Mass varying neutrinos (astro-ph/0309800)
- MiniBooNE can confirm or exclude LSND w/ 1E21 POT

Neutrino key: ν_e ν_μ ν_τ ν_s





The LSND signal has inspired fresh, new ideas.

MiniBooNE Collaboration

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P. Kasper, T. Kobilarcik, I. Kourbanis,
A. Malensek, W. Marsh, P. Martin, F. Mills,
C. Moore, P. Nienaber, E. Prebys,
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R. Imlay, W. Metcalf, S.A. Ouedraogo,
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A.O. Bazarko, P.D. Meyers, R.B. Patterson,
F.C. Shoemaker, H.A.Tanaka *Princeton*

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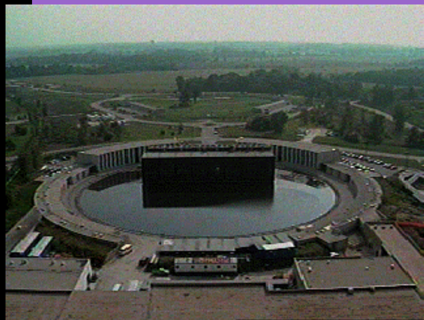
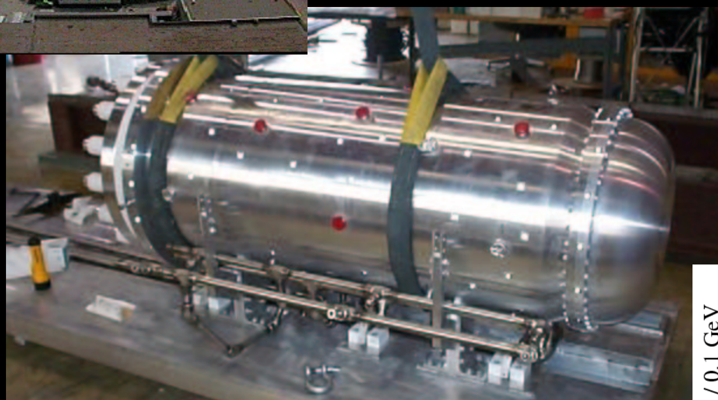
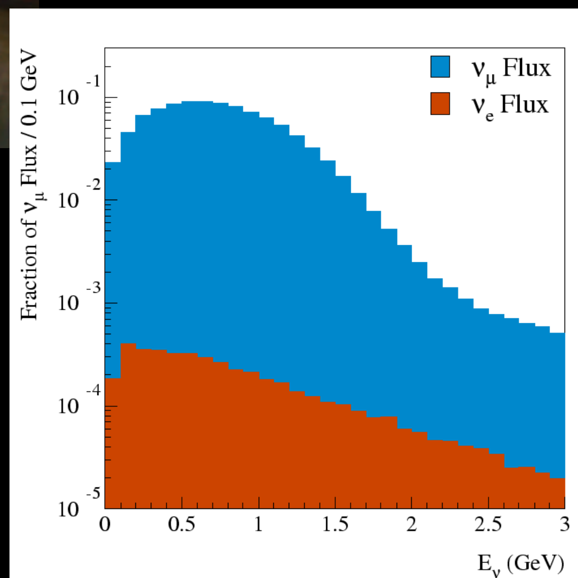
MiniBooNE Overview



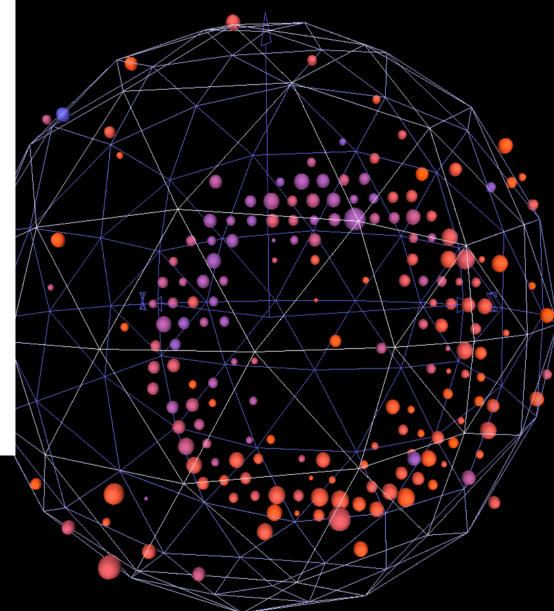
- 8 GeV protons from Booster
- Beryllium target



- Magnetic horn to focus mesons
  - Over 96M pulses - a world record!
  - Reversible polarity - $\bar{\nu}$ mode



- 50 m decay region
  - >99% pure ν_μ, $\bar{\nu}_\mu$ beam
- ~500 m dirt
  - $\nu_\mu \rightarrow \nu_e$?
- 800 ton mineral oil detector
  - 1520 PMTs (1280+240 veto)



The Horn

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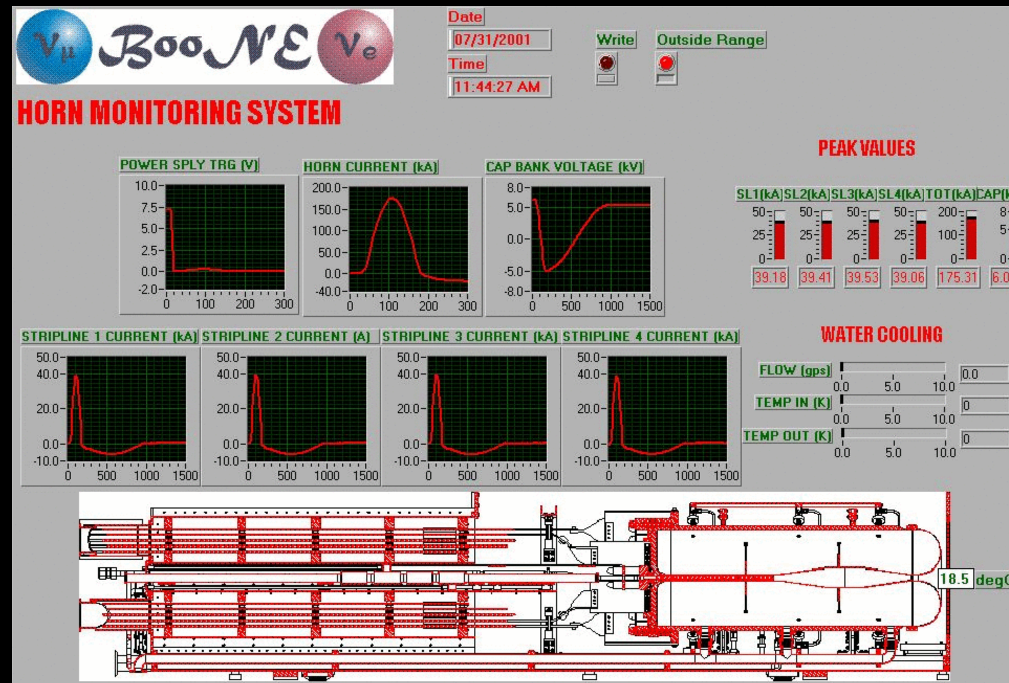
- Horn power supply tripped repeatedly beginning 9 days ago
- Problem within horn box, not power supply
- Cannot continue to run this horn
- Will remove and install spare horn during summer shutdown
- Expected 100-200 million pulses
- We are continuing to take data with the horn off



Beam Performance

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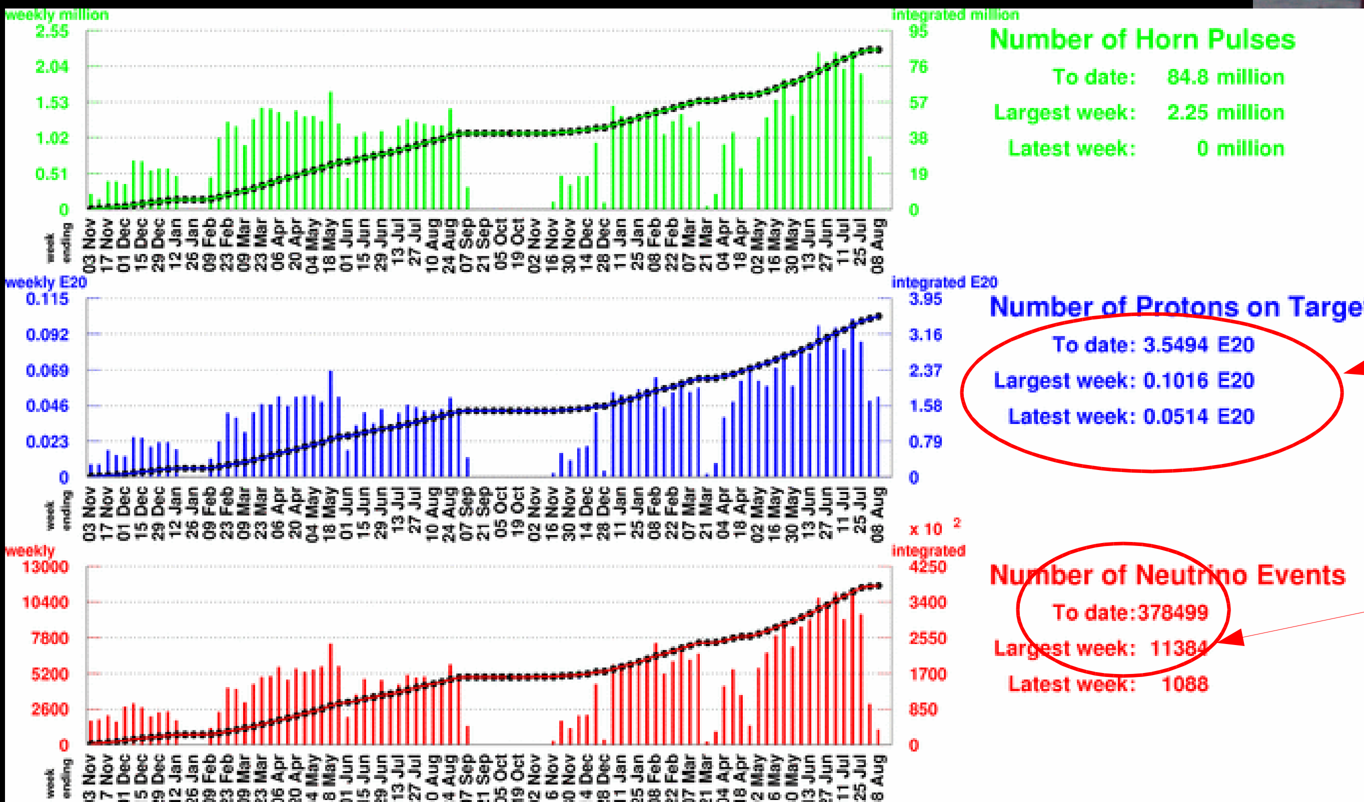
- MiniBooNE Design request (proposal):
  - 5Hz × 5E12ppp × 88% ≈ 8E16p/hr → 0.13E20 p/week
  - Near 75% for the past month



http://www-boone.fnal.gov/publicpages/progress_monitor.html

Setting new records

Already the largest data set at these energies - ever!

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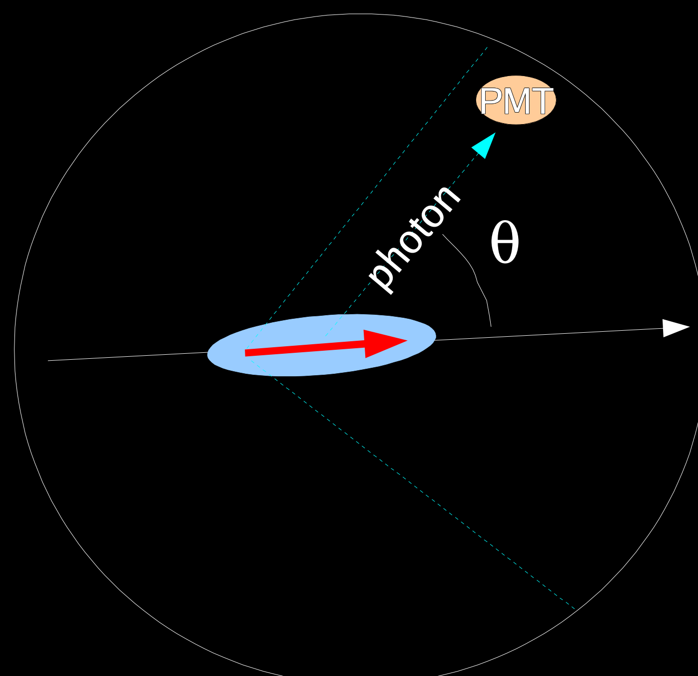
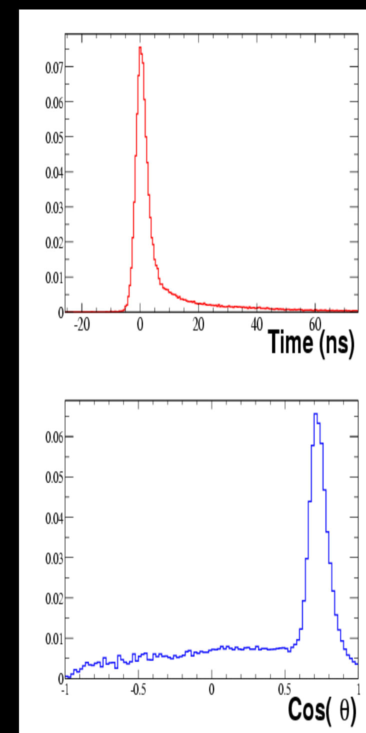
MiniBooNE Detector

- 800 tons of pure mineral oil
- 6m radius steel sphere
- 1520 8" PMTs
  - 1280 in main tank (sphere)
  - 240 in veto region (shell)





- ν reaction products cause Cherenkov and scintillation light emission in oil
- PMTs collect photons, record t,Q

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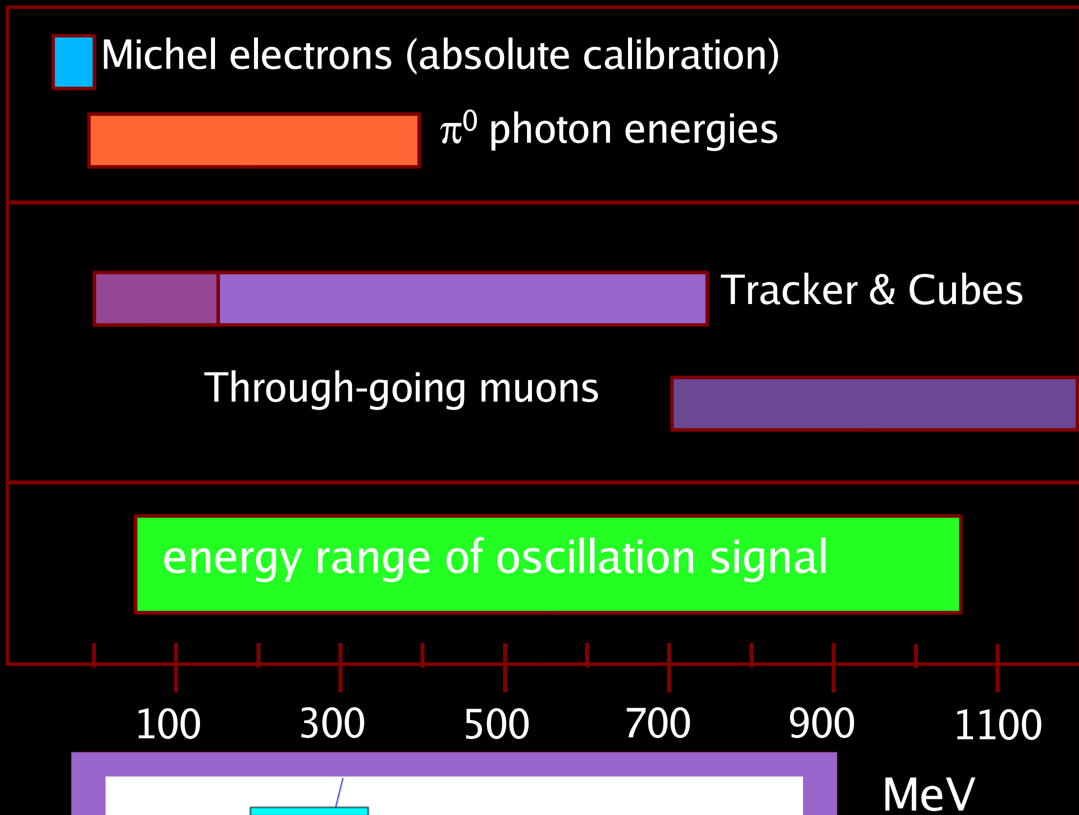
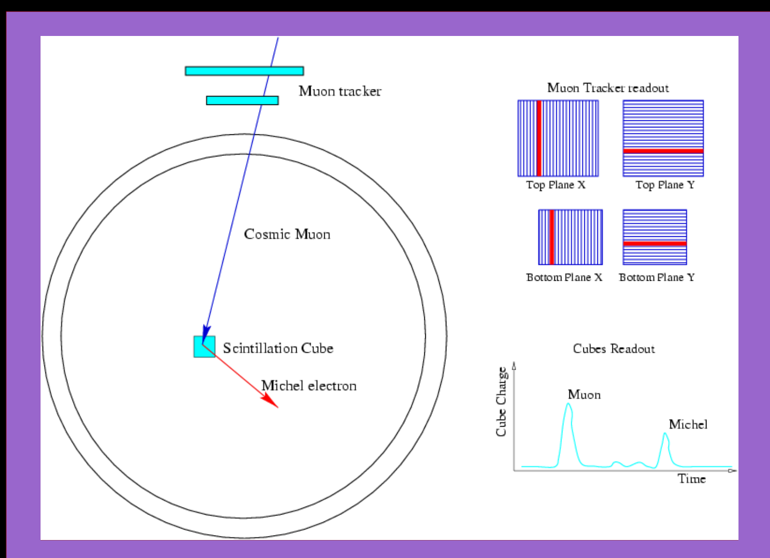
Detector Calibration





- Many calibration sources
- PMTs calibrated with laser system
- Calibration data samples that span oscillation signal energy range
- Electron data samples
  - Michel electrons
  - π^0 photons
- Cosmic Muons
  - Stopping, through-going

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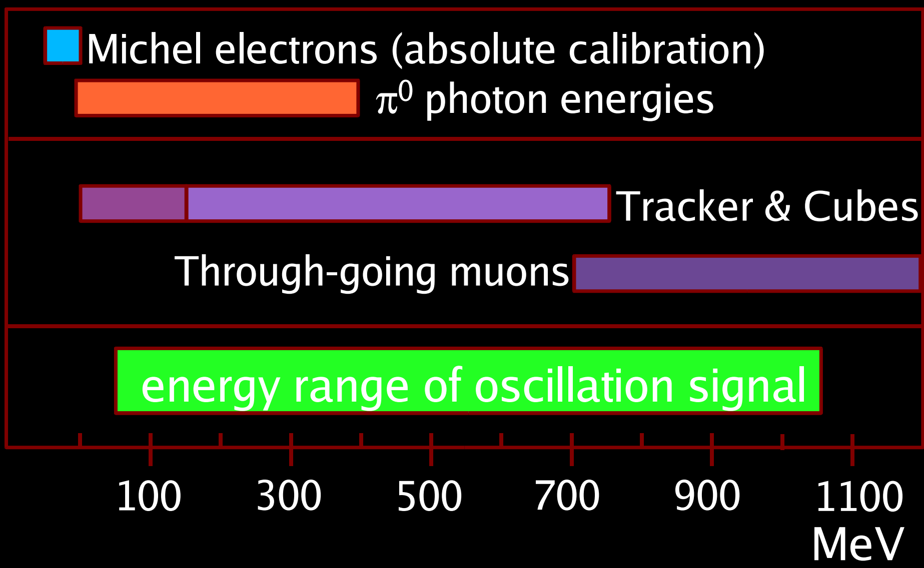
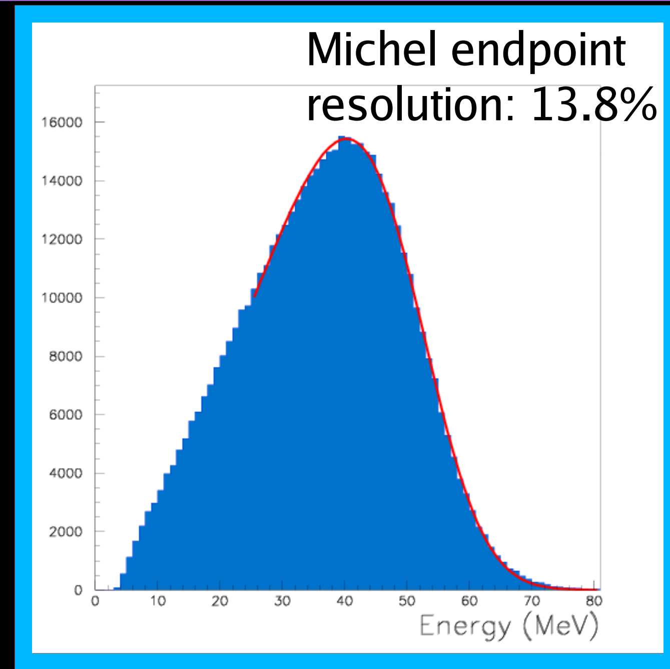
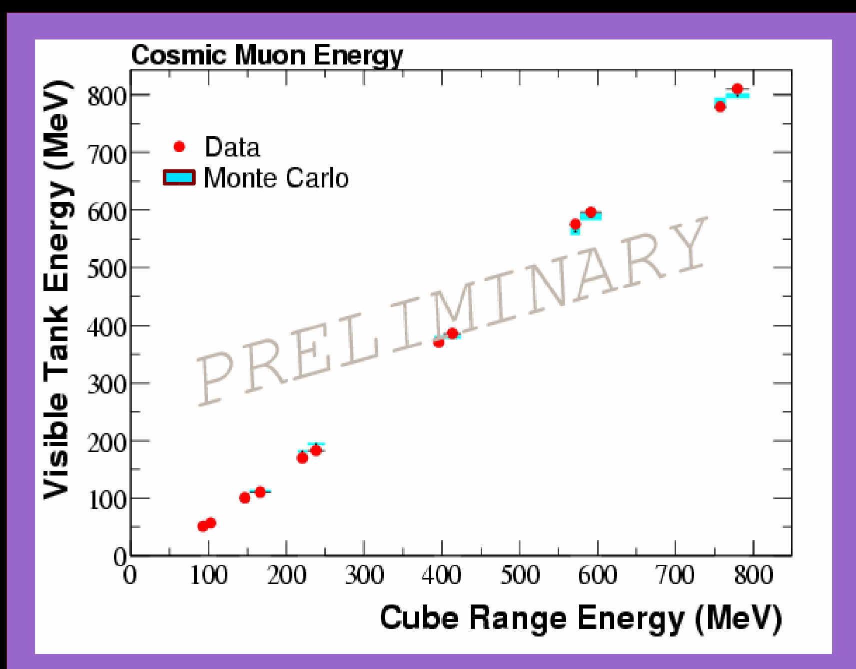
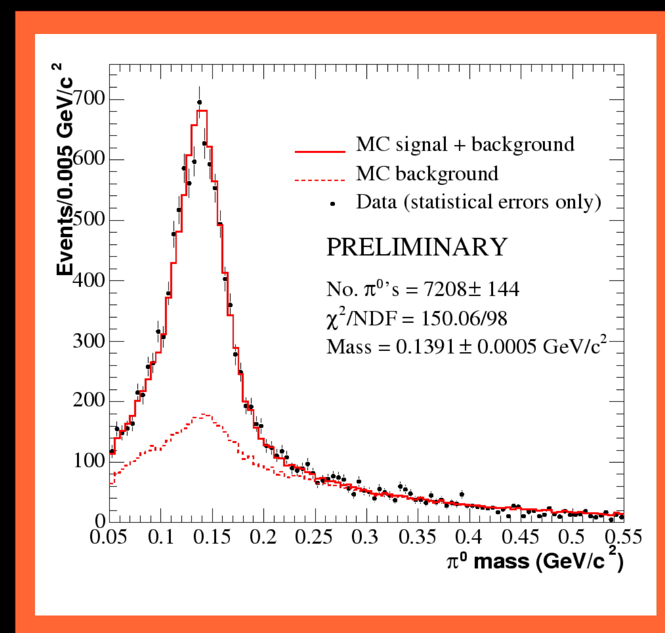
Detector is Calibrated









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Optics of Mineral Oil

Creation

- Čerenkov light
  - proportional to β
- Scintillation
  - dE/dx
  - time delay

Propagation

- Scattering (Rayleigh)
  - prompt
  - $1+\cos^2\theta$
  - λ^4
- Fluorescence
  - isotropic
  - time delay
  - spectrum
- Absorption

In Situ

- Michel electrons
- Cosmic muons
- Laser: diffuse light
- Laser: pencil beam

Ex Situ

- Scintillation (IUCF) w/p$^+$
- Scintillation (FNAL) w/μ
  - repeated w/p$^+$ (IUCF)
- Goniometry (Princeton)
- Fluorescence spectroscopy (FNAL)
- Time resolved spectroscopy (JHU)
- Attenuation (FNAL)
  - multiple devices

Work in progress...

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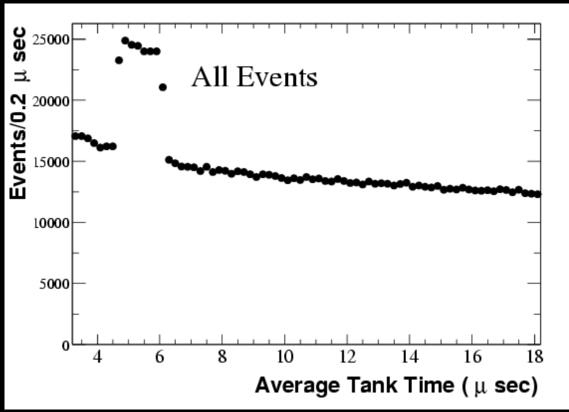
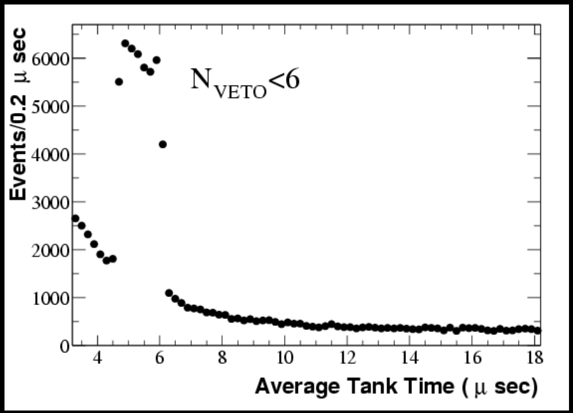
Neutrino Data

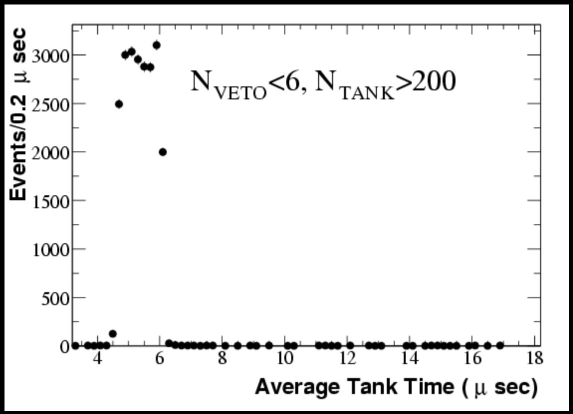
- Neutrino Candidate Cuts
  - <6 veto PMT hits
  - >200 tank PMT hits
- Beam spill (1.6μs) is clearly evident in all
  - simple cuts eliminate cosmic backgrounds



Beam and Cosmic BG



Beam and Michels



Beam only

Neutrino Data

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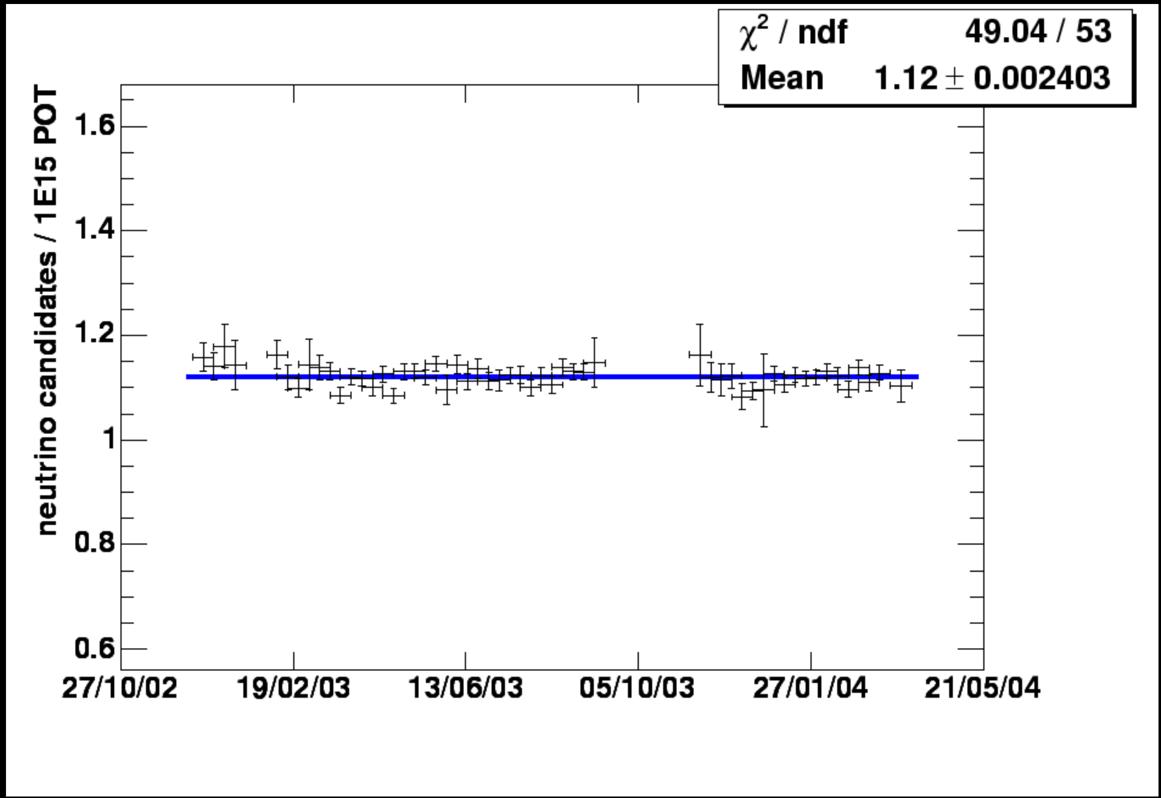
- Measured rate of neutrino candidates
  - Neutrino candidates ≡
    - >200 tank hits
    - <6 veto hits
- Constant rate over time
  - χ^2/d.o.f. = 49/53
- Tests performance of:
  - Tank DAQ
  - ACNET DAQ
  - Calibration stability
  - Data processing chain



Analysis HOWTO

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- Goal: ν_e appearance - measure excess above BG of ν_e events
- Start with external prediction for ν flux
  - All νs: ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$
- Add external prediction for cross sections
  - NUANCE, NEUGEN, NEUT, others...
- Input to detector Monte Carlo
  - Predict event rates, spectra in detector
    - Expected oscillation signal for different values of $\sin^2 2\theta$, Δm^2
      - ν_μ disappearance, ν_e appearance
    - Expected backgrounds for both
  - Calculate uncertainties
- Measure event rates, spectra
  - "Blind analysis" - be careful!
  - Use ν_μ data to understand ν_e backgrounds
  - Open box when we get the POT goal...

Blind analysis in action

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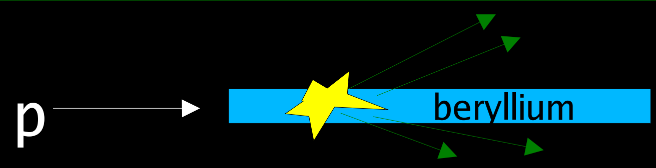
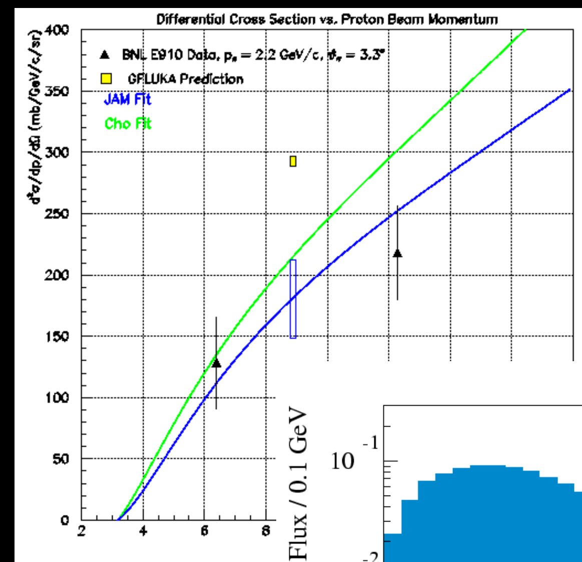
External Flux Prediction

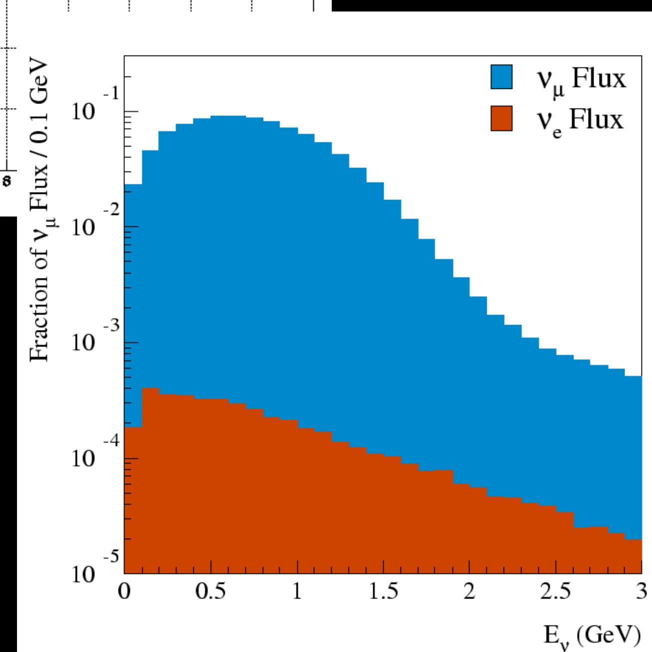


$\pi^+/K^+ \to \mu^+\nu_\mu$
$\hookrightarrow e^+\ \bar{\nu}_\mu \nu_e$

$K^+/K^0_L \to \pi e \nu_e$

- Meson production σ modelled as a function of p_p, p_π,
- Predictions based on π data:
  - **E910(BNL):** recent p data on Be target
    - 6.3, 12.4, 17.5 GeV/c beam momenta
  - **Near future:**
    - HARP (CERN): measure σ at 8.9 GeV/c
    - high statistics, MiniBooNE replica target
- Pion,kaon fluxes put into GEANT4 Monte Carlo
  - effects of horn
  - decay pipe
  - calculate ν flux at detector





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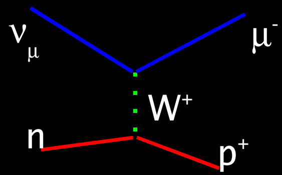
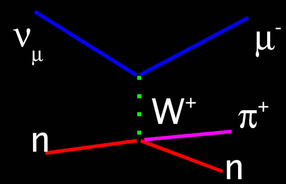
Event Rate Predictions

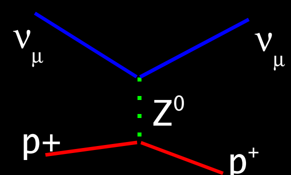
- >380,000 neutrino events and counting!
  - 148k CCQE



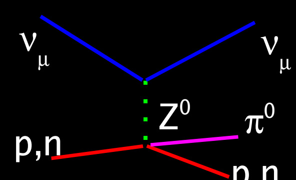
  - 94k CC $1\pi^\pm$



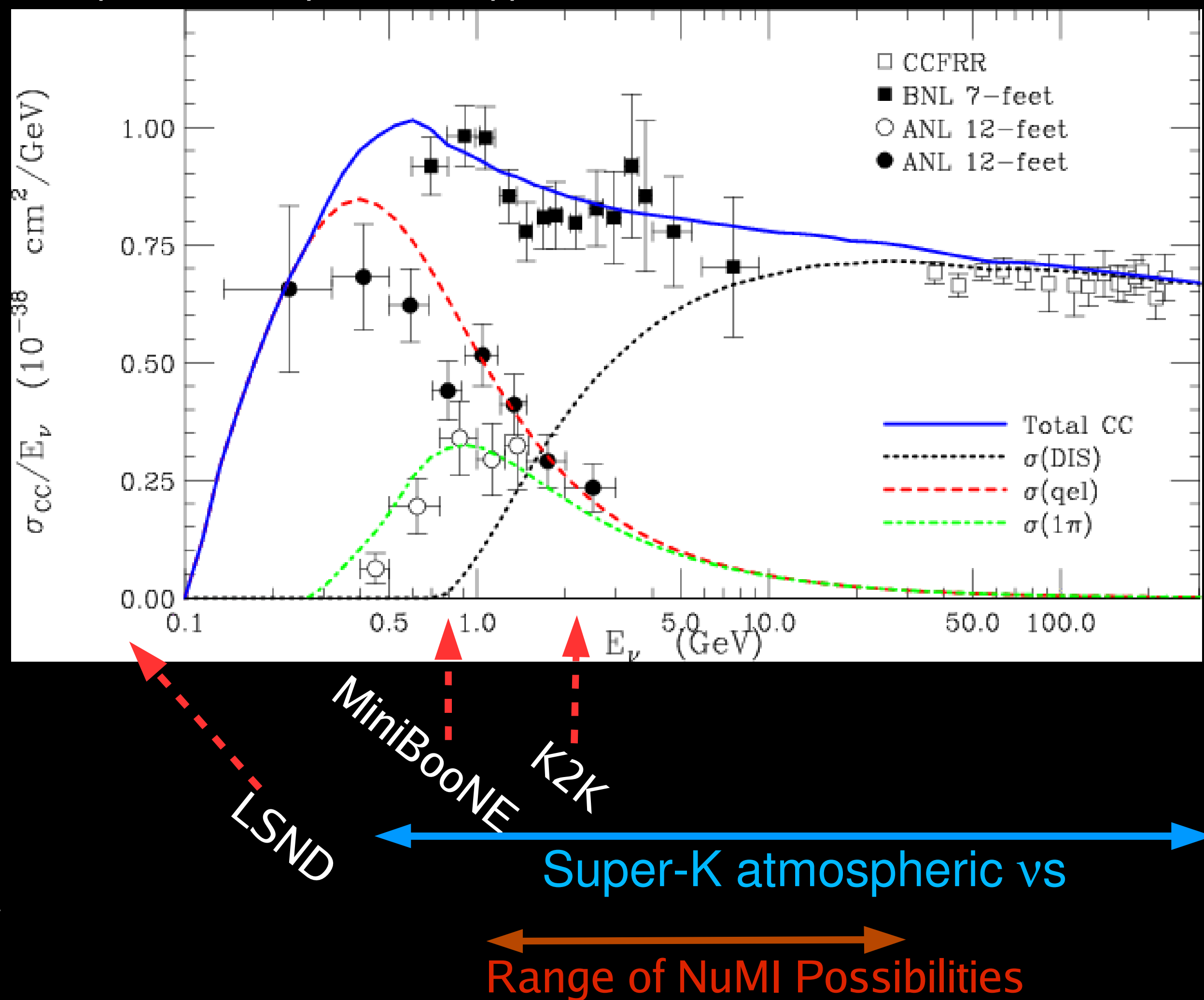
  - 60k NC E



  - 26k NC π^0



P. Lipari, Nucl. Phys. Proc. Suppl. 112, 274 (2002) (NuInt01)



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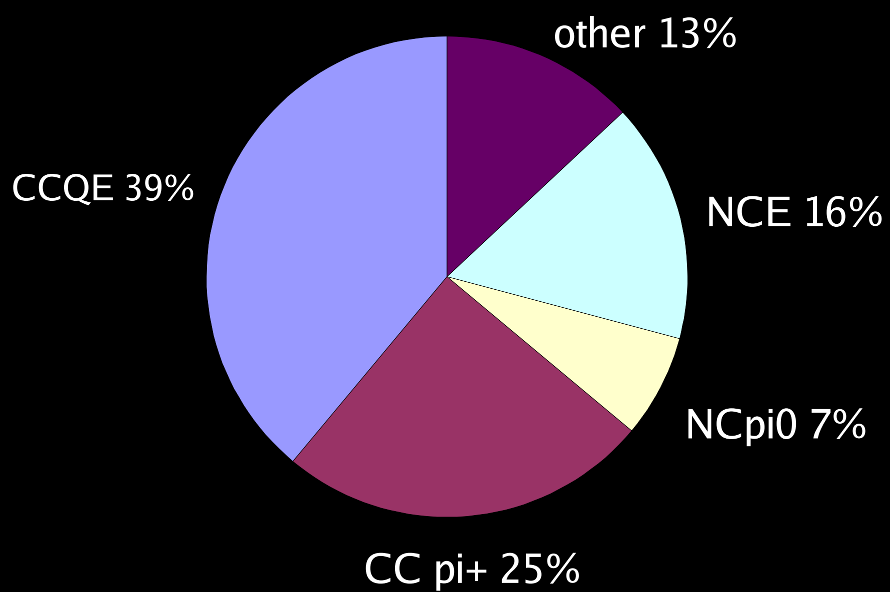
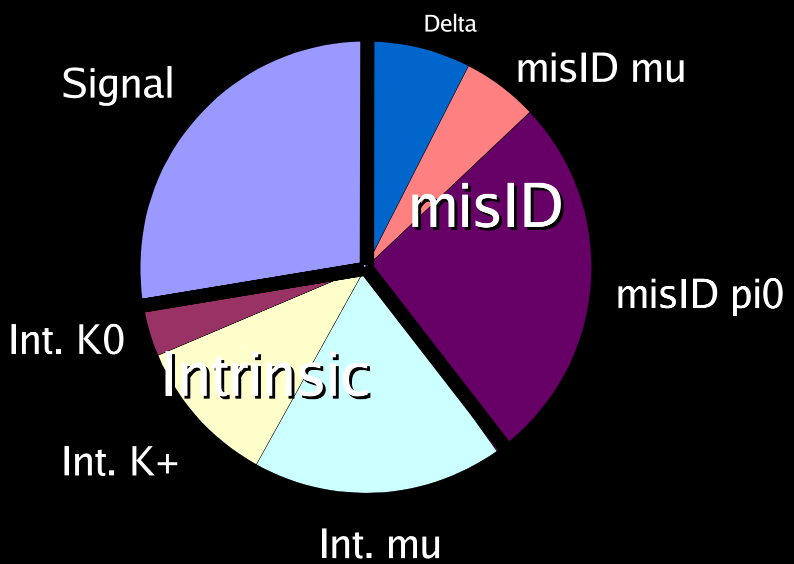
ν_μ and ν_e Event Rates



- ν_μ Event Analyses
- CCQE
  - Eν distribution
  - Q^2 reconstruction
- NC π^0
  - coherent fraction

- ν_e Appearance Analysis, 1E21
- Expect to see ~1000 ν_e CC QE
  - 300 oscillation signal events
  - 350 Intrinsic ν_e in beam
    - K^+, K^0, μ decay
  - 430 misID events
    - μ, π^0, Δ



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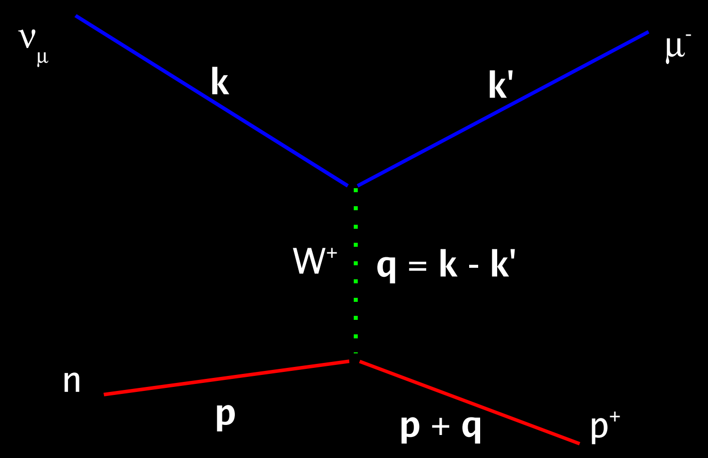
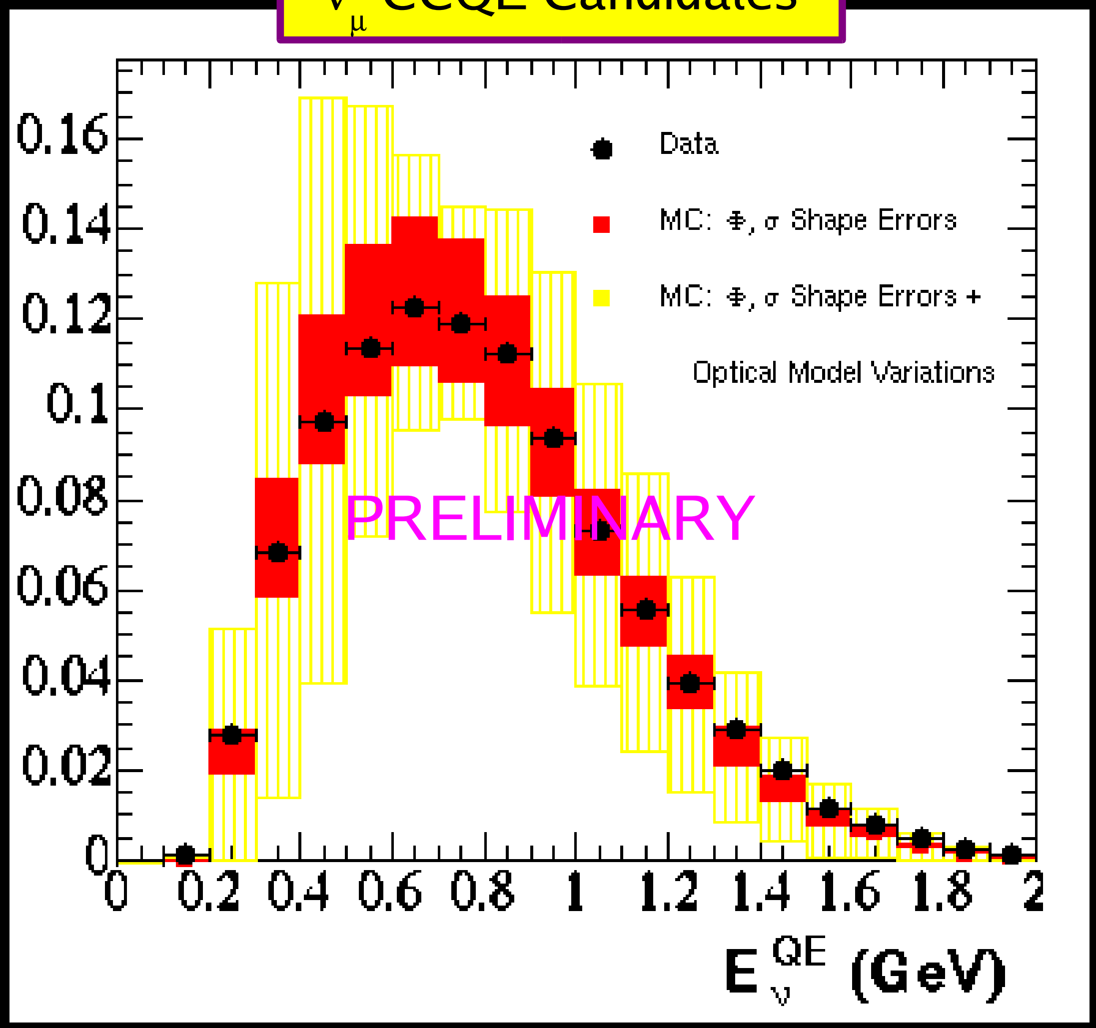
Observed ν Events



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

- Measure:
  - muon energy: ±10%
  - muon direction ±45mrad
- Calculate ν ("Missing") Energy
  - Neutrino energy res.: 15-20%

ν_μ CCQE Candidates



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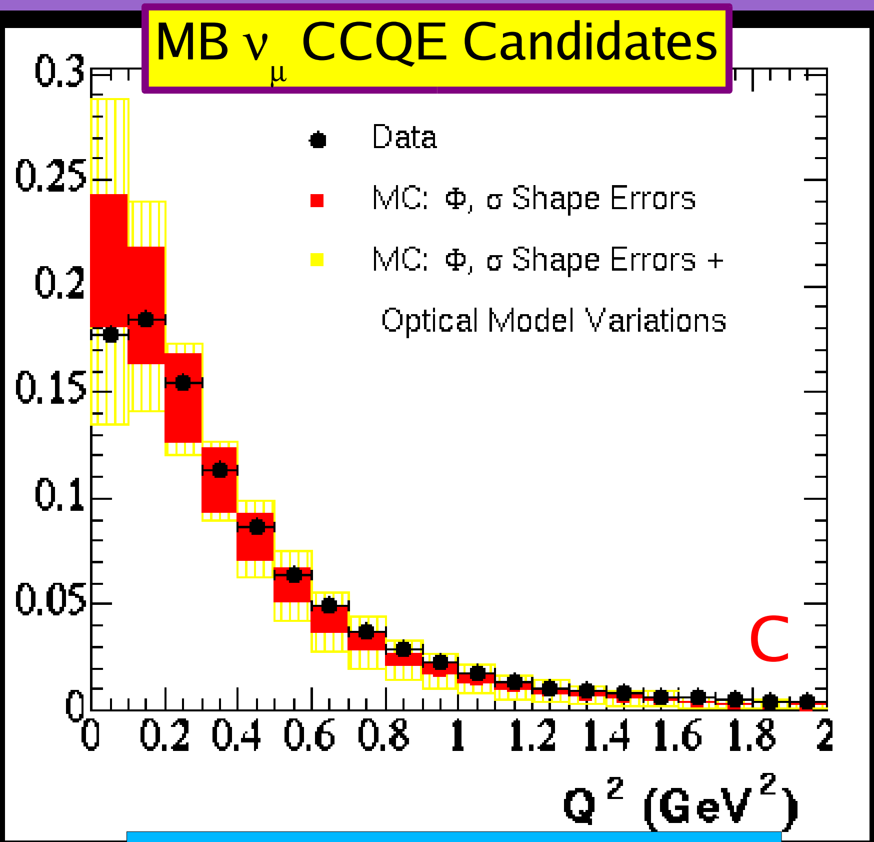
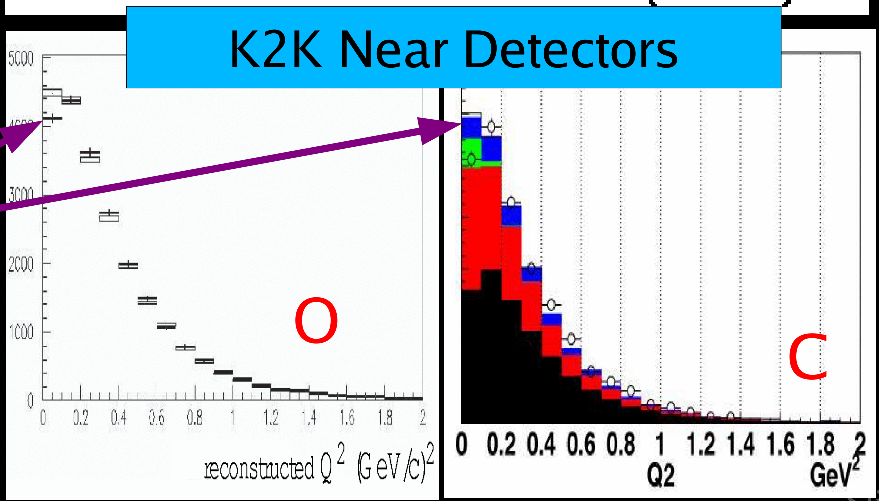
Neutrino Kinematics

- Nuclear effects important at MiniBooNE neutrino energies
  - Pauli blocking and simple nuclear effects included in NUANCE MC - neutrino simulation used by MiniBooNE
  - Reduction in low Q^2 rate previously observed by BEBC comparing Ne to D data sets
    P. Allport et al., Phys. Lett. B232, 417 (1989)
- Observed reduction exceeds Pauli blocking prediction
  - Nuclear shadowing?
  - Also observed by K2K near detectors





Rik Gran, NuInt04

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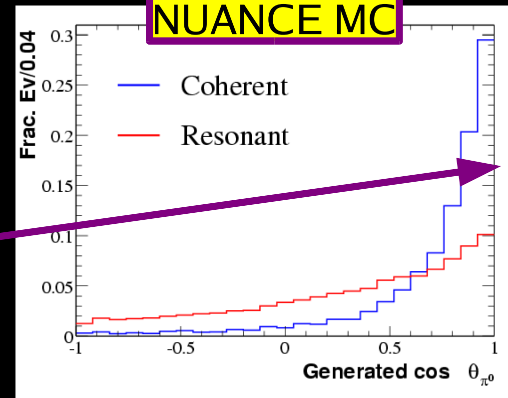
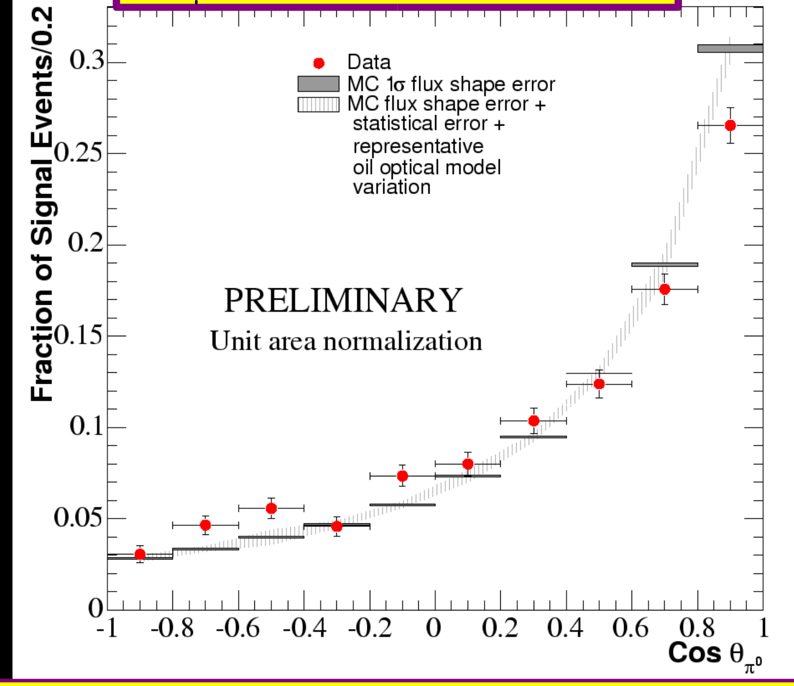
Measuring Cross Sections

- NC π^0: important background for MiniBooNE $\nu_\mu \rightarrow \nu_e$
- Coherent: ν scatters w/ whole nucleus
  - diffractive scattering, forward-peaked
  - NUANCE predicts ~20% of $\sigma(\nu_\mu N \rightarrow X\pi^0)$ at 1 GeV
  - competing models differ by 20X!
- No data published below 2 GeV
  - K2K near dets also have data

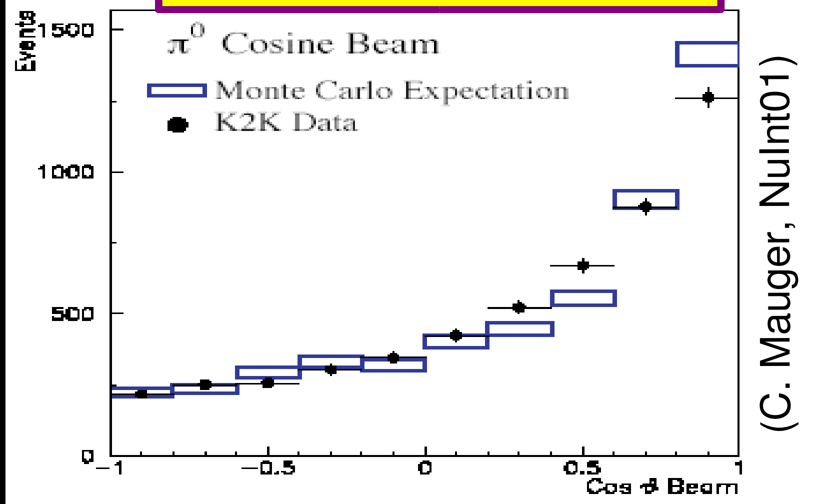
NUANCE MC



ν_μ NC π^0 Candidates



K2K NC π^0 Candidates



- Needed for Super-K $\nu_\mu \rightarrow \nu_\tau$ vs. $\nu_\mu \rightarrow \nu_s$

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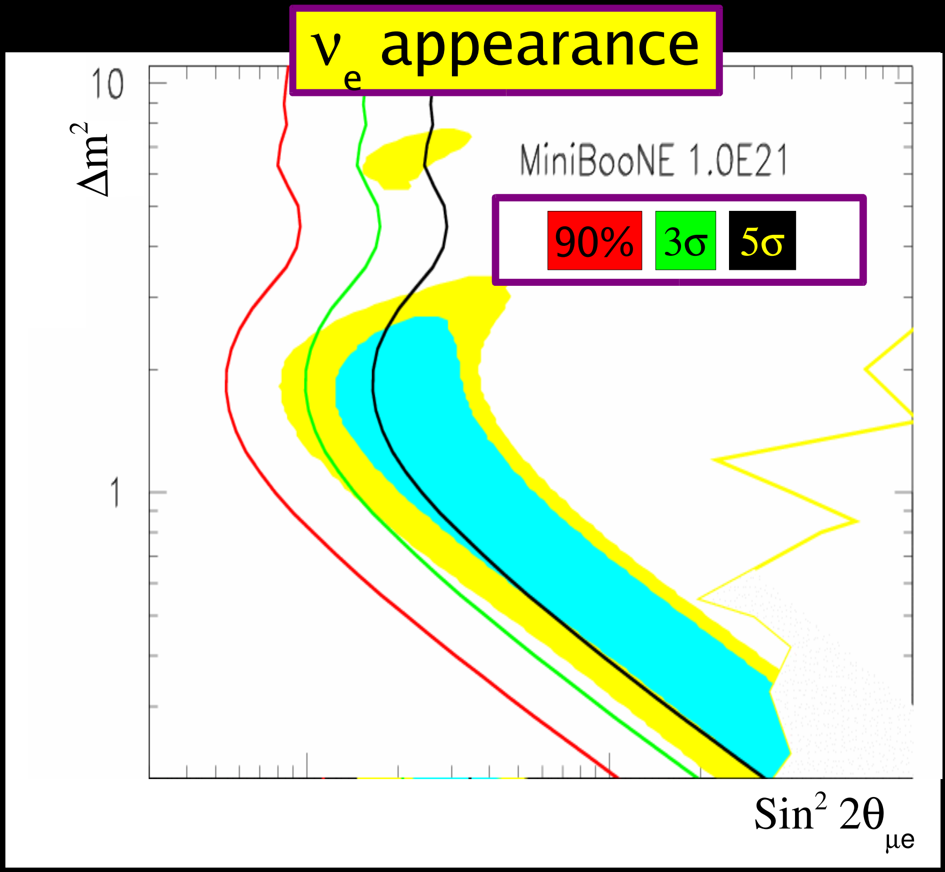
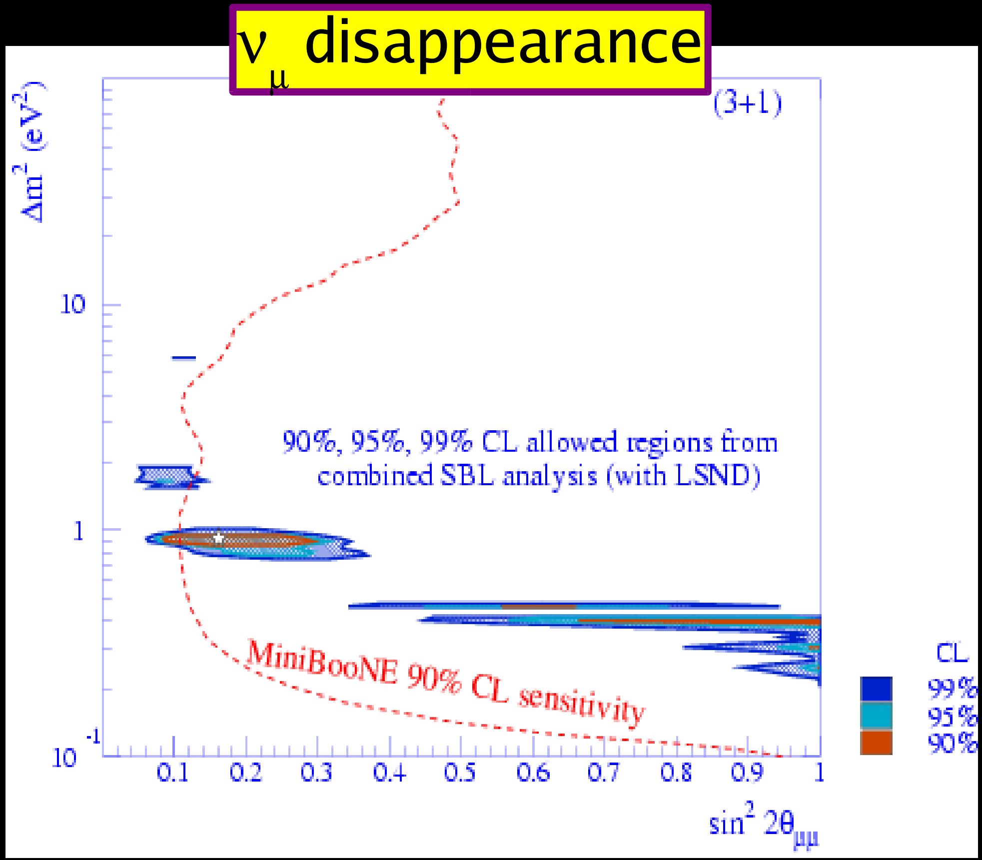
Oscillation Sensitivity

- Updated sensitivity based on measured rates in first year of data





www-boone.fnal.gov/publicpages/news.html

- Can exclude LSND at high statistical level only with 1E21 POT
- Sensitivity is statistics limited until >2E21 POT

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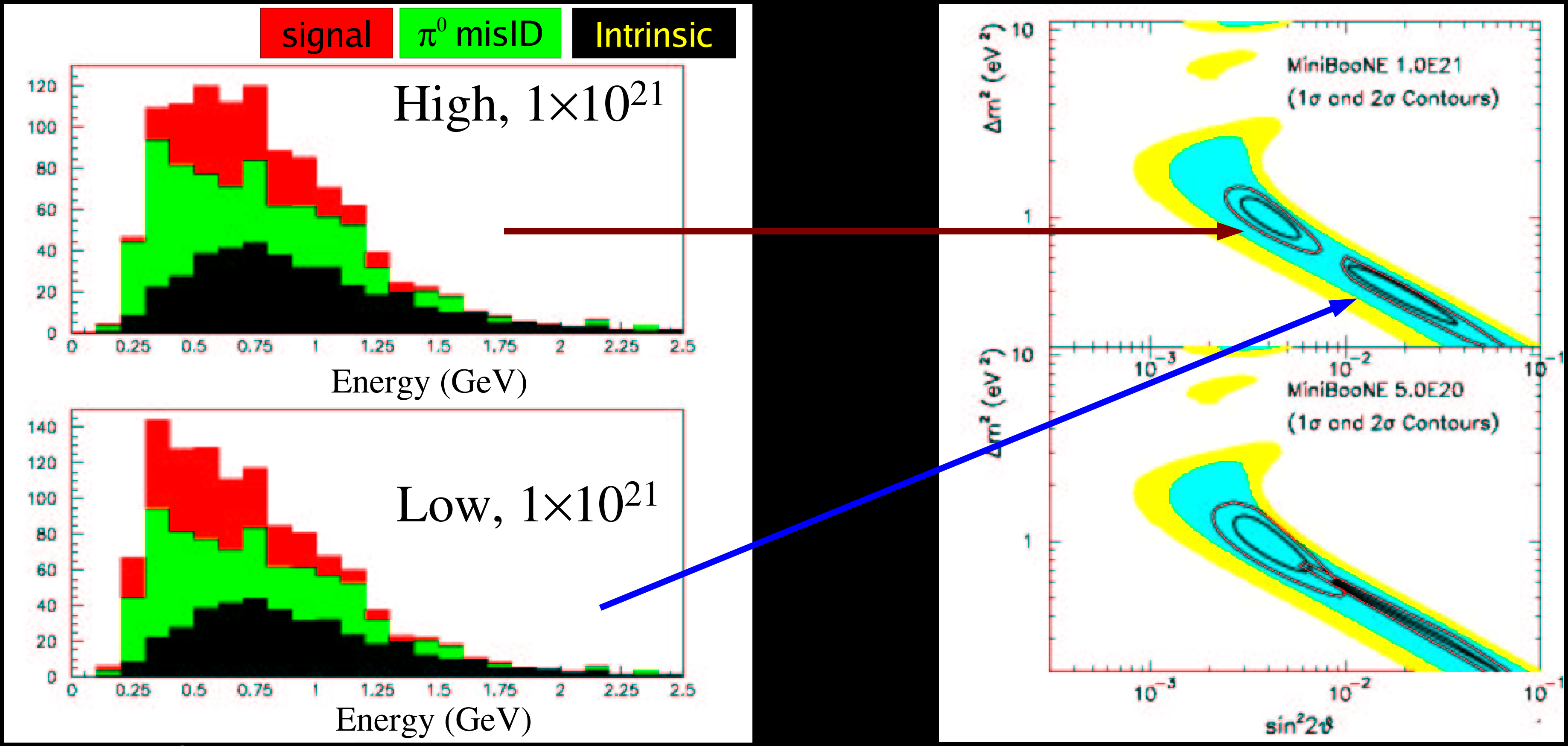
Measuring Δm^2



www-boone.fnal.gov/publicpages/news.html

- Can differentiate high and low Δm^2 regions with 1E21 POT
- High vs. low Δm^2 is important for near future experiments

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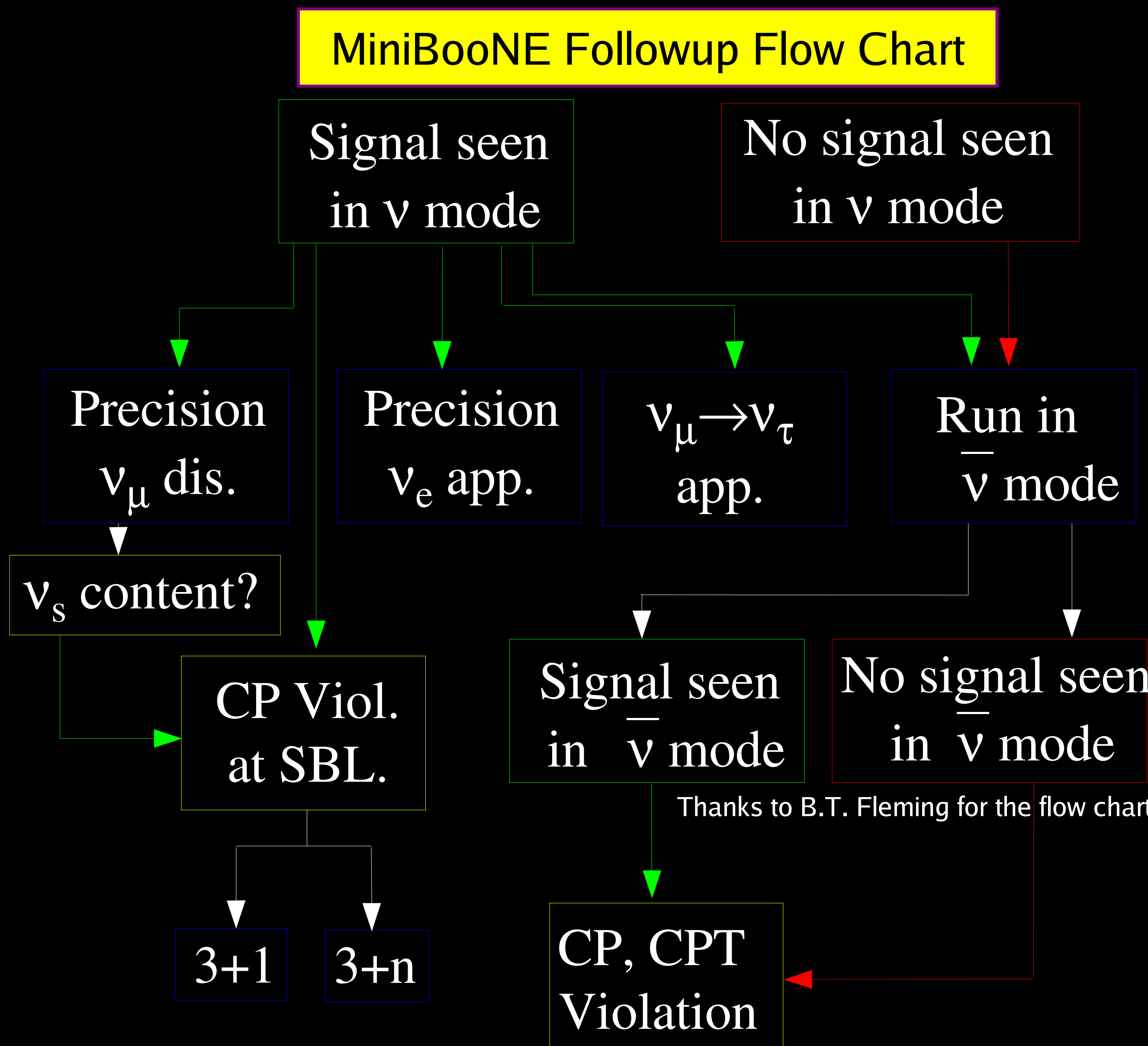
If LSND is Confirmed...



Thanks to B.T. Fleming for the flow chart

Conclusions

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- MiniBooNE data have already generated much interest in ν community
- HARP results will finalize flux predictions
  - pion and kaon rates
- Tank energy calibrations indicate good reconstruction, resolution
- Optical model being pursued vigorously
  - Parameters, uncertainties will soon incorporate vast program of measurements
- Currently running with horn off
  - Horn replacement planned for summer shutdown
- High statistics will allow important low energy cross section measurements
- ν_μ disappearance result coming soon!
- Will be fully ready to open $\nu_\mu \rightarrow \nu_e$ box with 1E21 POT
- Looking forward to $\bar{\nu}$ running!

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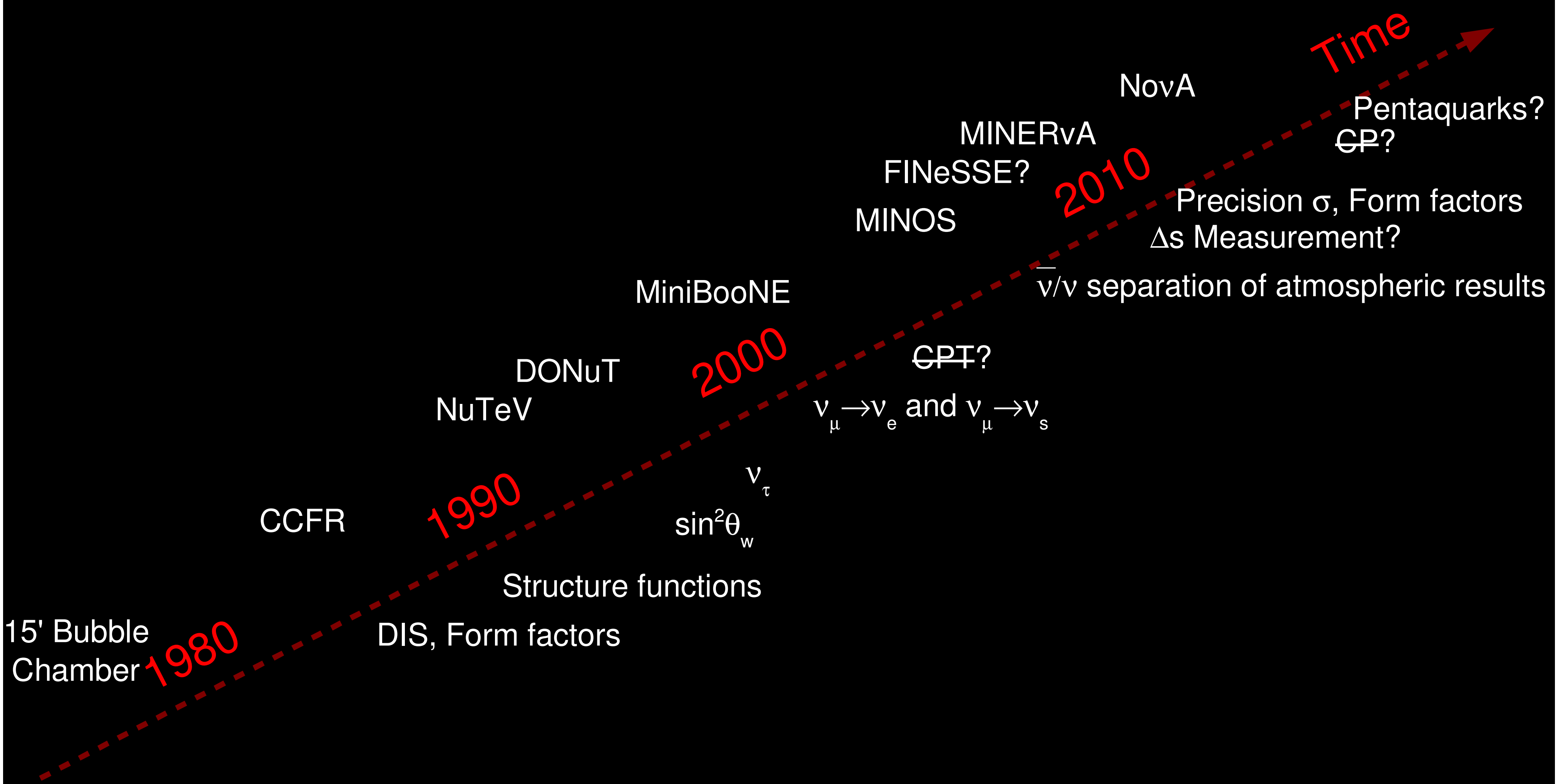
Parting Thought

MiniBooNE is one in a long line of great ν physics experiments at FNAL



We're working hard to ensure that the future matches our great past