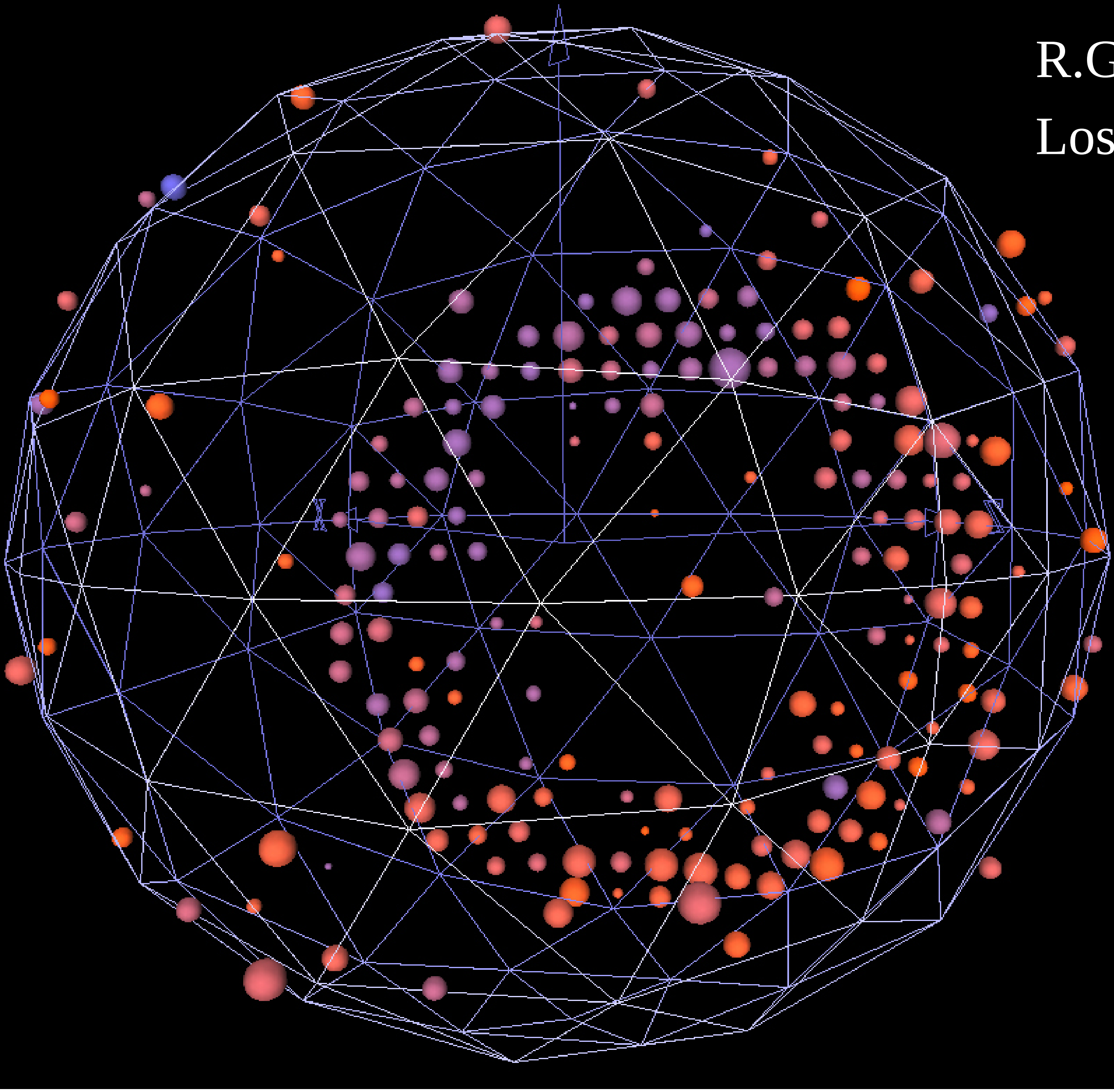
Searching for Physics Beyond Standard Model with Neutrinos



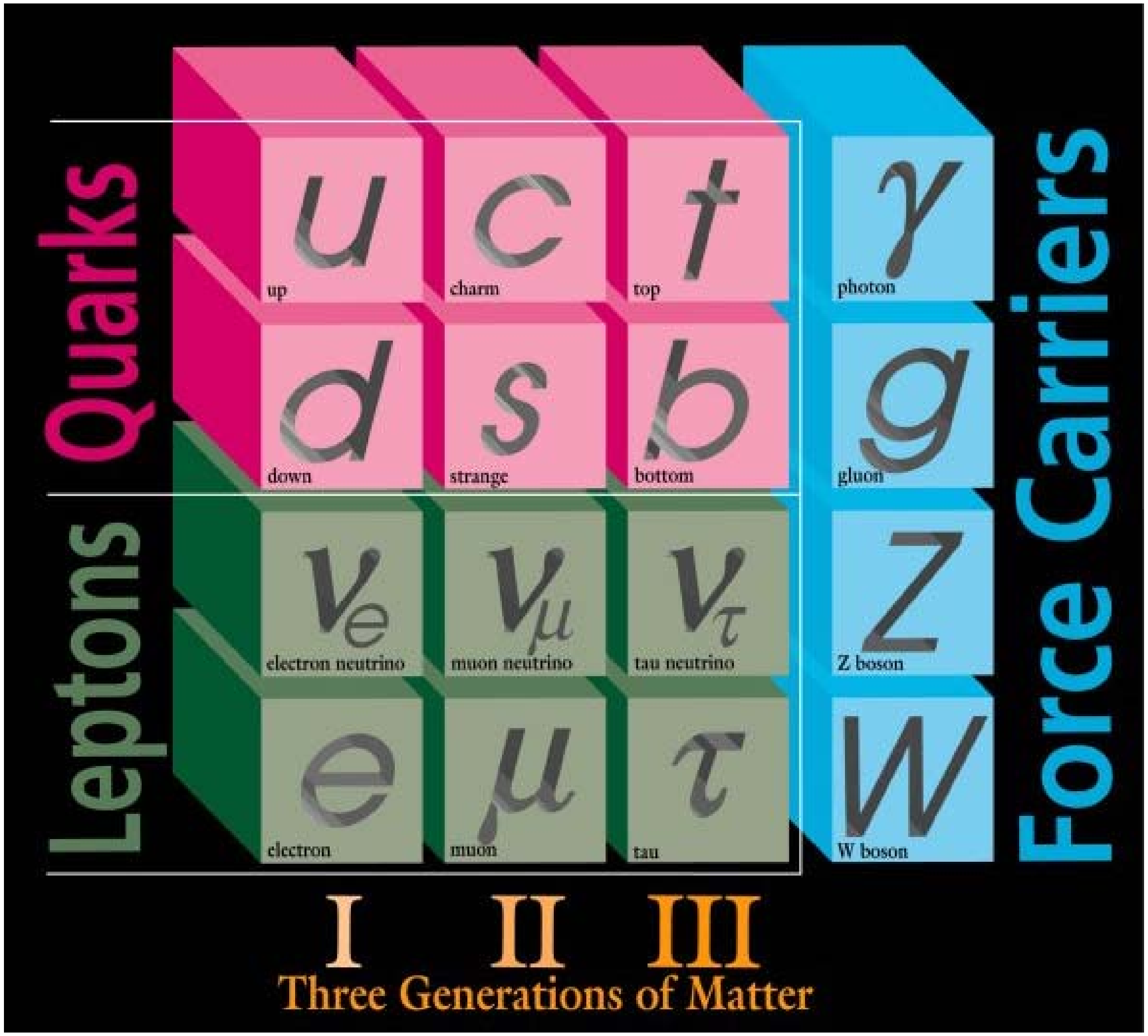
R.G. Van de Water

Los Alamos National Laboratory

Outline

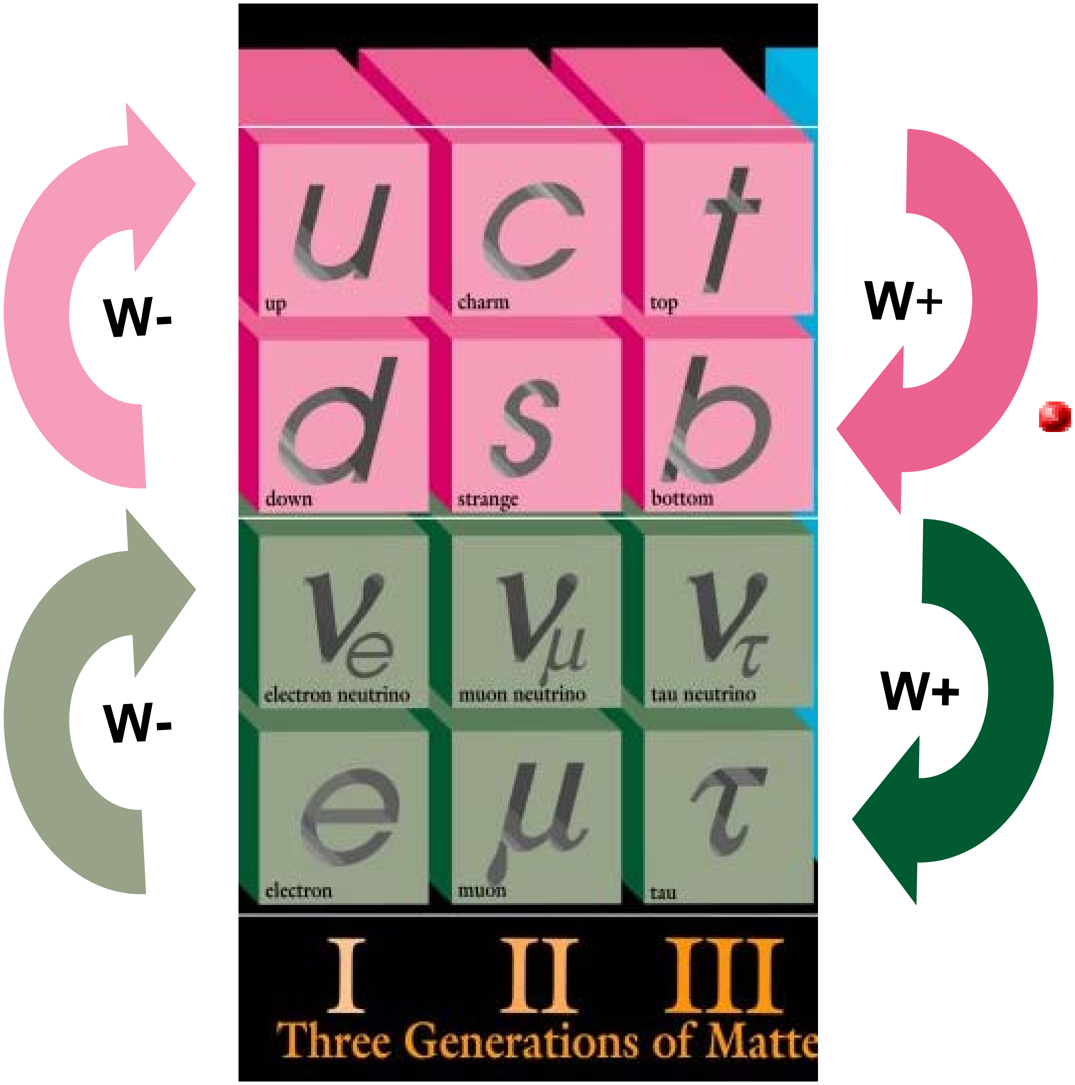
- Neutrino Oscillations, Mass, and other Properties
- MiniBooNE: A Test of the LSND Signal
- Future Neutrino Experiments: BooNE & OscSNS

The Standard Model building blocks...

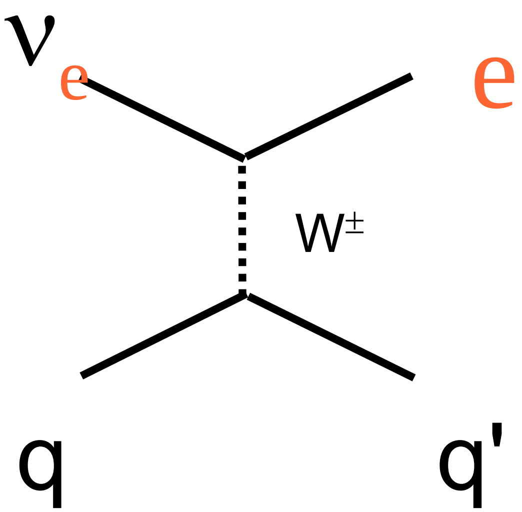


- Force carriers
  - photons ⇔ electromagnetic
  - gluons (g) ⇔ strong force
  - W, Z bosons ⇔ weak force
  - no inclusion of gravity...yet
- Quarks
  - Feel all the forces
  - Other than gluons, only particles that experience the strong force
- Leptons
  - Charged leptons
    - Feel EM and weak
  - Neutrinos
    - Interact ONLY via weak force

The weak force...force of transmutation



- Makes the weak interaction truly a force of transmutation
  - The CC channel converts neutrinos into their charged alter egos
  - Converts -1/3 charge quarks into +2/3 counterparts
- Incidentally, CC also proves that we have three distinct neutrino flavors



Charged Current

Three Salient Features of Neutrinos

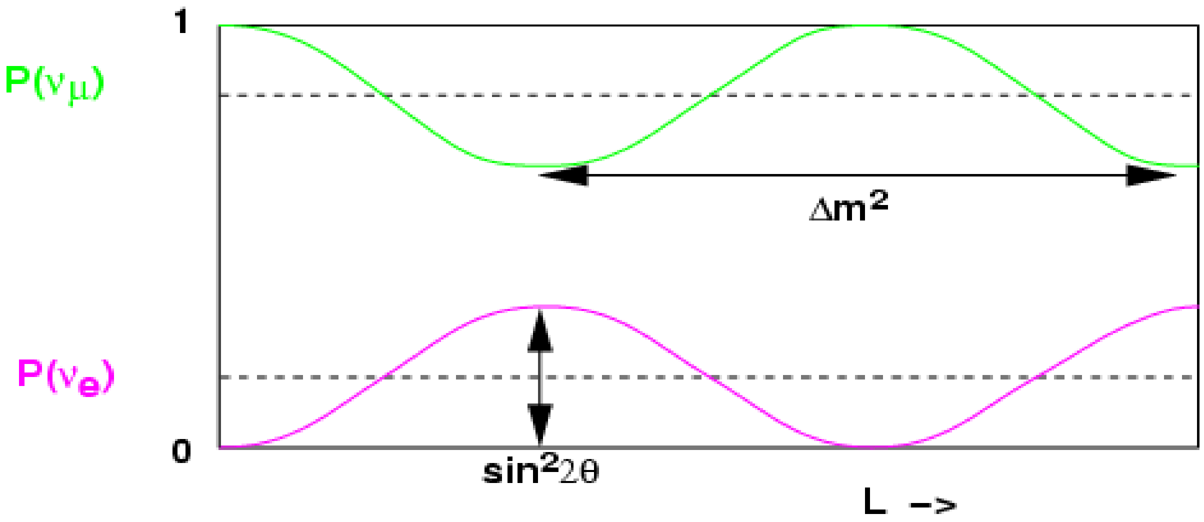
- Neutrinos interact very weakly with matter
- Neutrinos (& photons) dominate the universe in terms of number of particles
- Neutrinos undergo oscillations

Neutrino Oscillations

Weak Eigenstates = **Eigenstates of Propagation**

$\nu_\mu = \cos\Theta\ \nu_1 + \sin\Theta\ \nu_2$

$\nu_e = -\sin\Theta\ \nu_1 + \cos\Theta\ \nu_2$



$$P_{\nu_\mu \to \nu_e} = \sin^2(2\Theta)\ \ \sin^2(1.27\ \Delta m^2\ L/E_\nu)$$

$\Delta m^2 = m_2^2 - m_1^2$ in eV², L in meters, E_ν in MeV

For oscillations to occur, neutrinos must have mass!

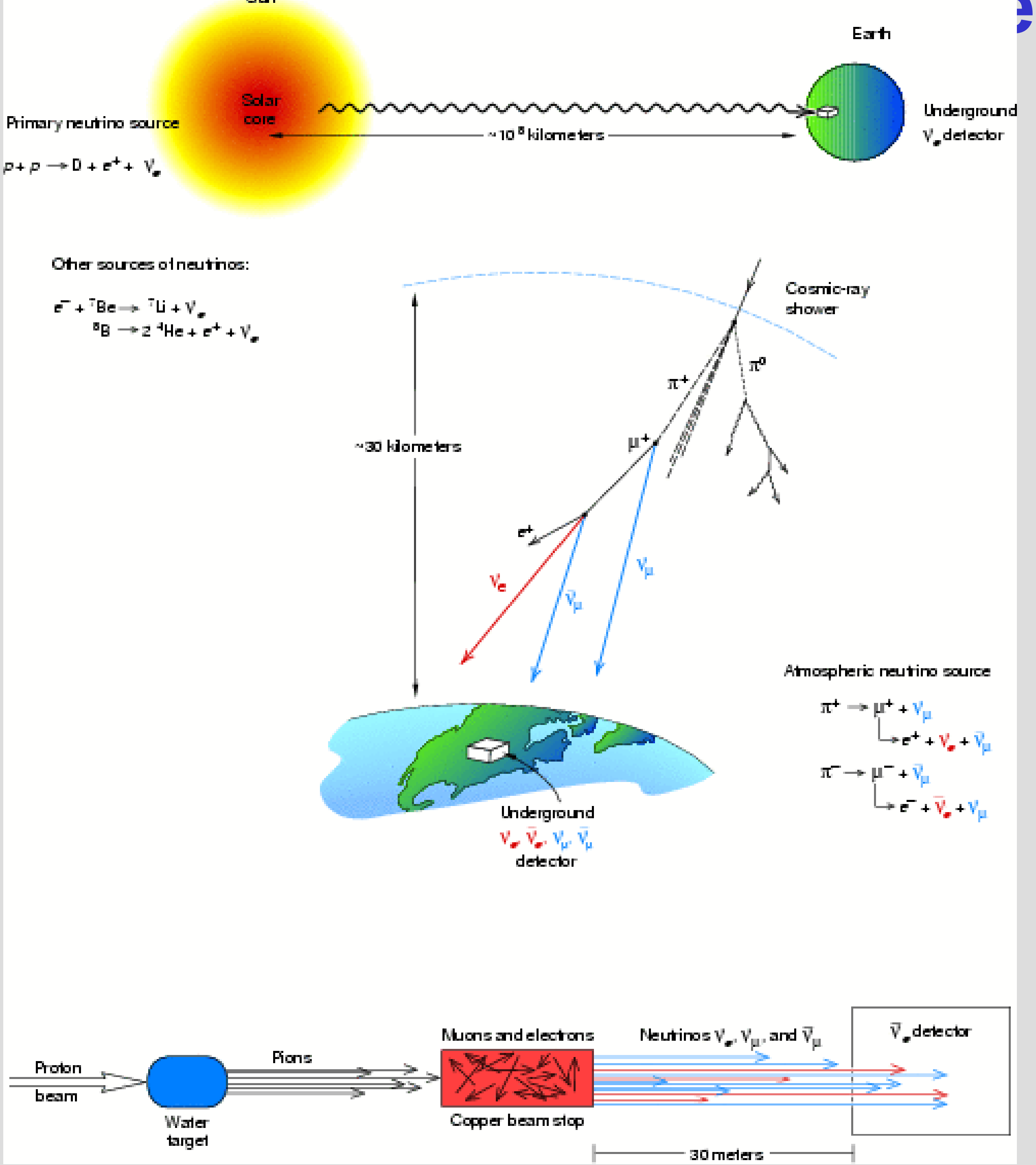
Probability of Neutrino Oscillations

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\Sigma_i\Sigma_j\,|U_{\alpha i}\,U^*_{\beta i}\,U^*_{\alpha j}\,U_{\beta j}|\,\sin^2(1.27\Delta m_{ij}{}^2 L/E_\nu)$$

As N increases, the formalism gets rapidly more complicated!

N	$\#\Delta m_{ij}{}^2$	$\#\theta_{ij}$	#CP Phases
2	1	1	0
3	2	3	1
6	5	15	10

Neutrino Oscillations Have Been O ed!

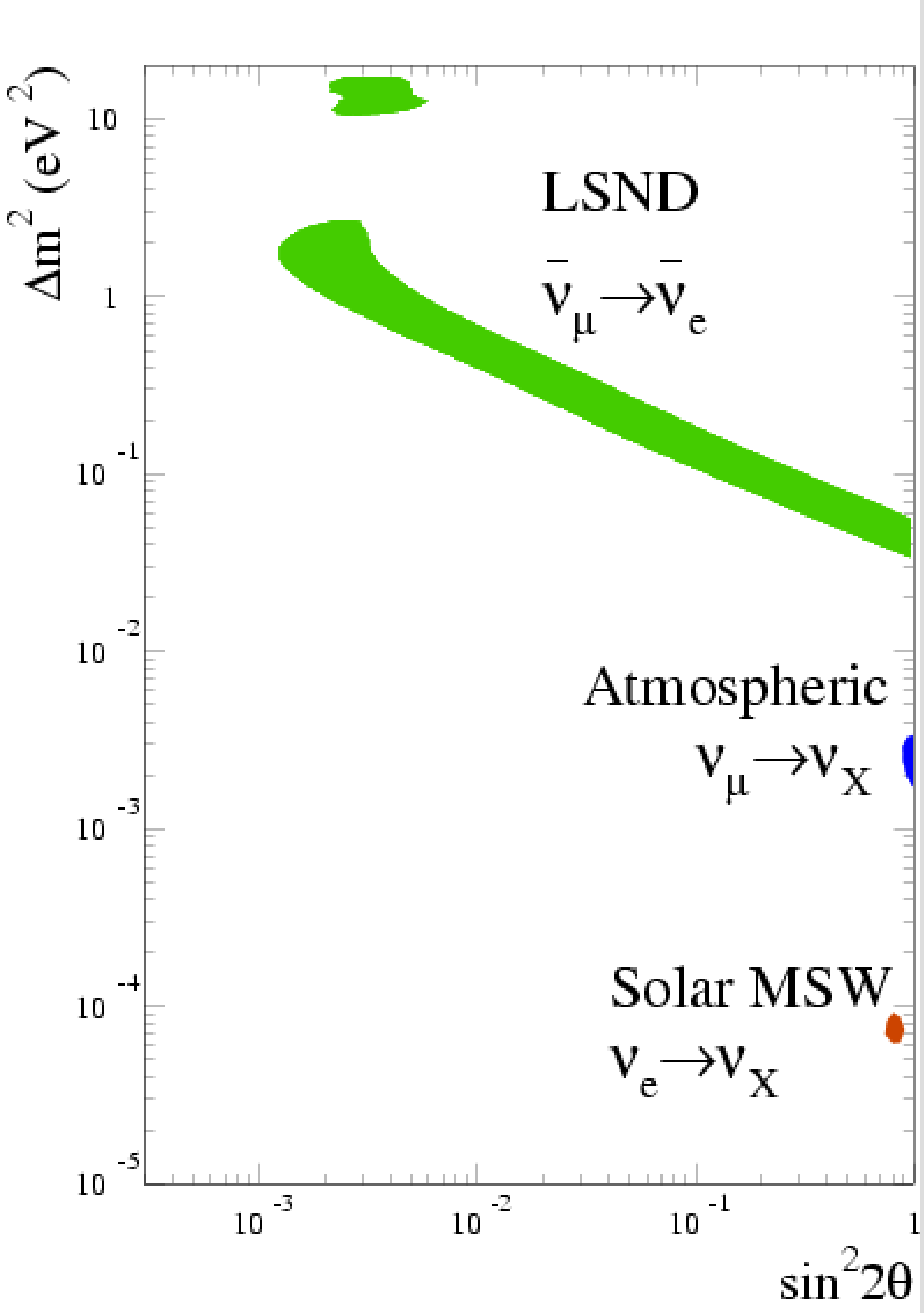


SuperK, SNO, KamLAND

SuperK, K2K, MINOS

LSND?

Current State of Neutrino Oscillation Evidence

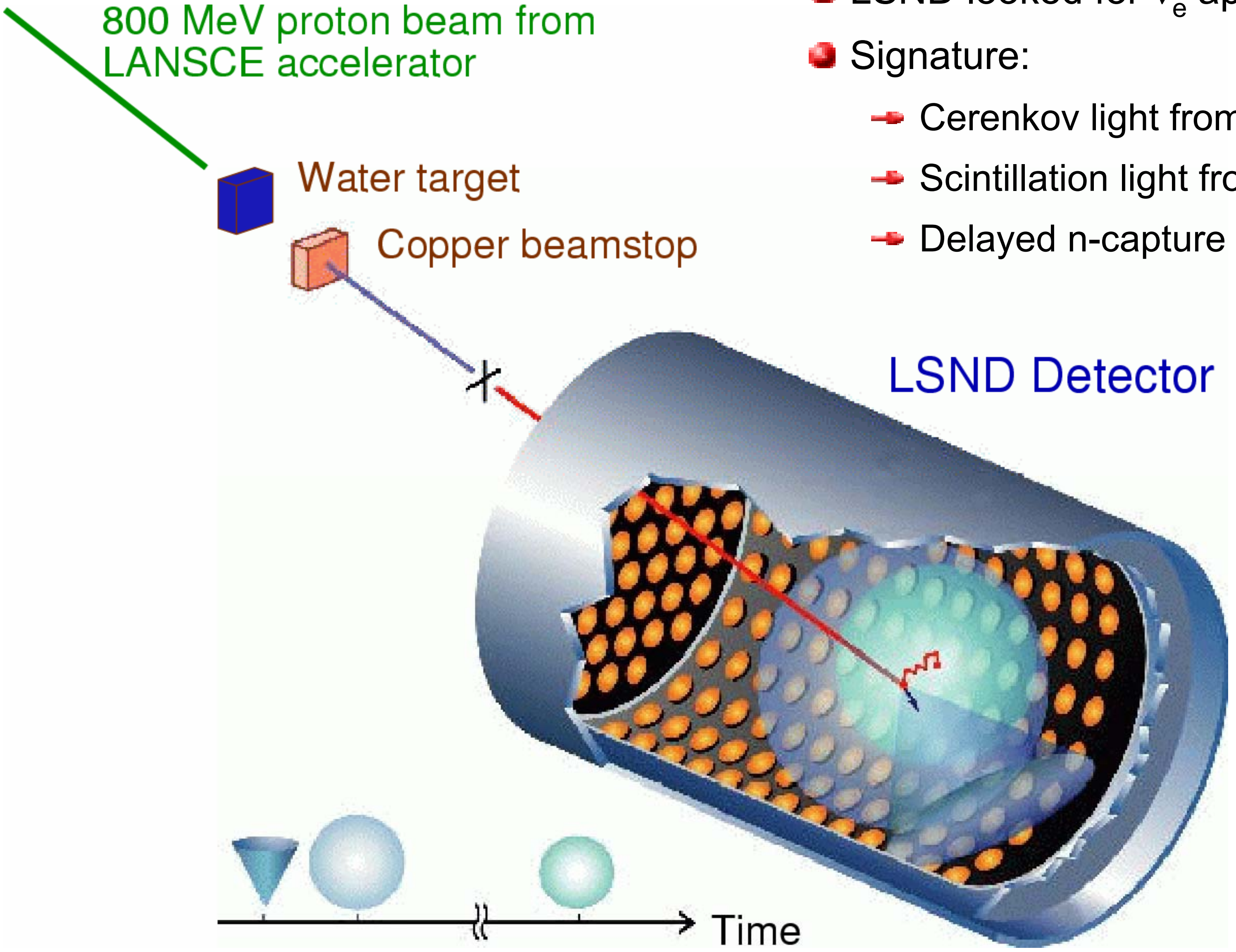


3-ν oscillations require
$\Delta m_{12}^2 + \Delta m_{23}^2 = \Delta m_{13}^2$
and cannot explain the data!

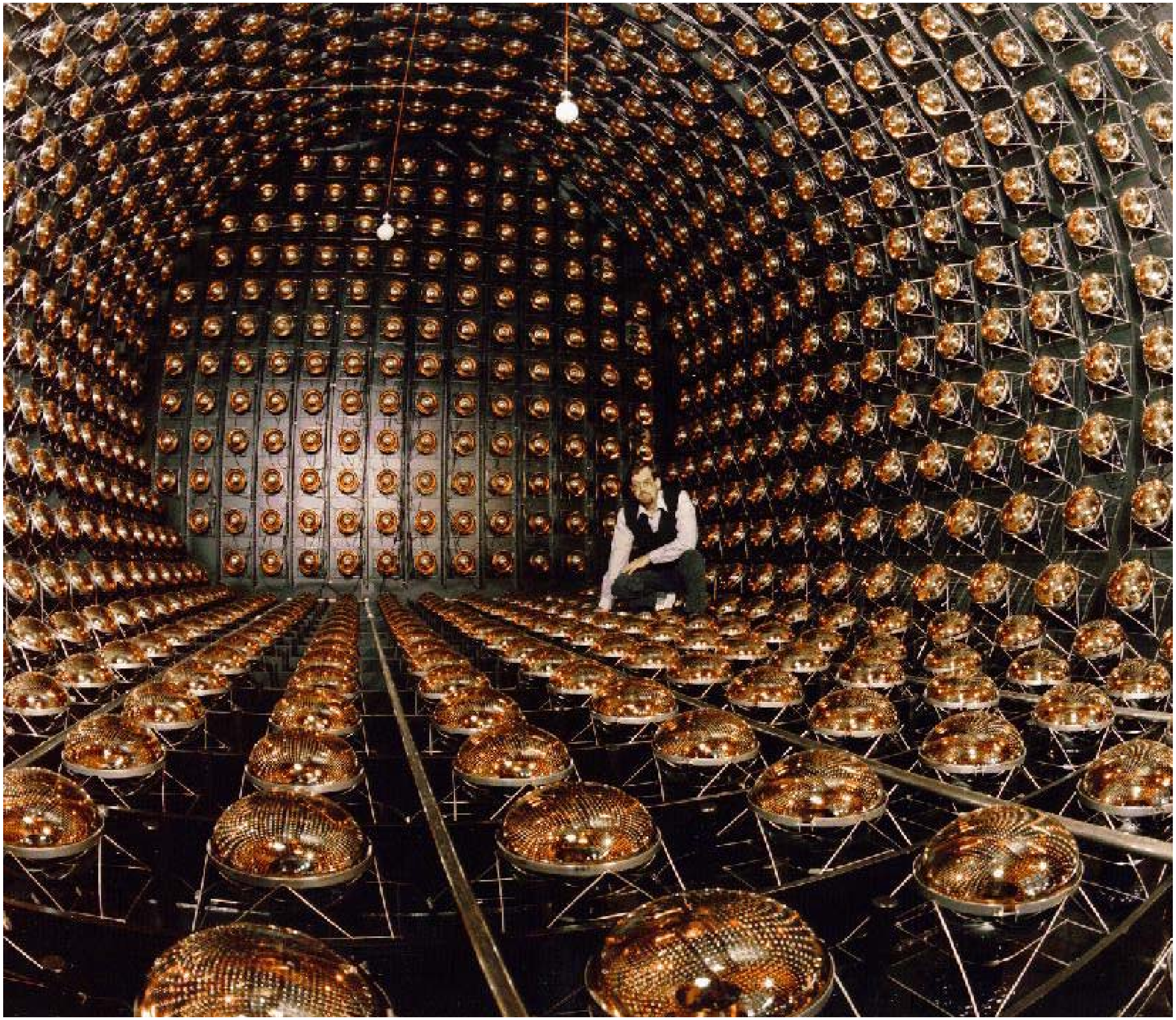
Expt.	Type	Δm^2 (eV^2)	$\sin^2 2\theta$
LSND	$\overline{\nu}_\mu$–>$\overline{\nu}_e$	~1	~3×10^{-3}
Atm.	ν_μ–>ν_x	~2×10^{-3}	~1
Solar	ν_e–>ν_x	~8×10^{-5}	~0.8

The Liquid Scintillator Neutrino Detector at LANL

- LSND looked for $\overline{\nu}_e$ appearing in a $\overline{\nu}_\mu$ beam
- Signature:
  - Cerenkov light from e^+ (CC)
  - Scintillation light from nuclear recoil
  - Delayed n-capture (2.2 MeV)



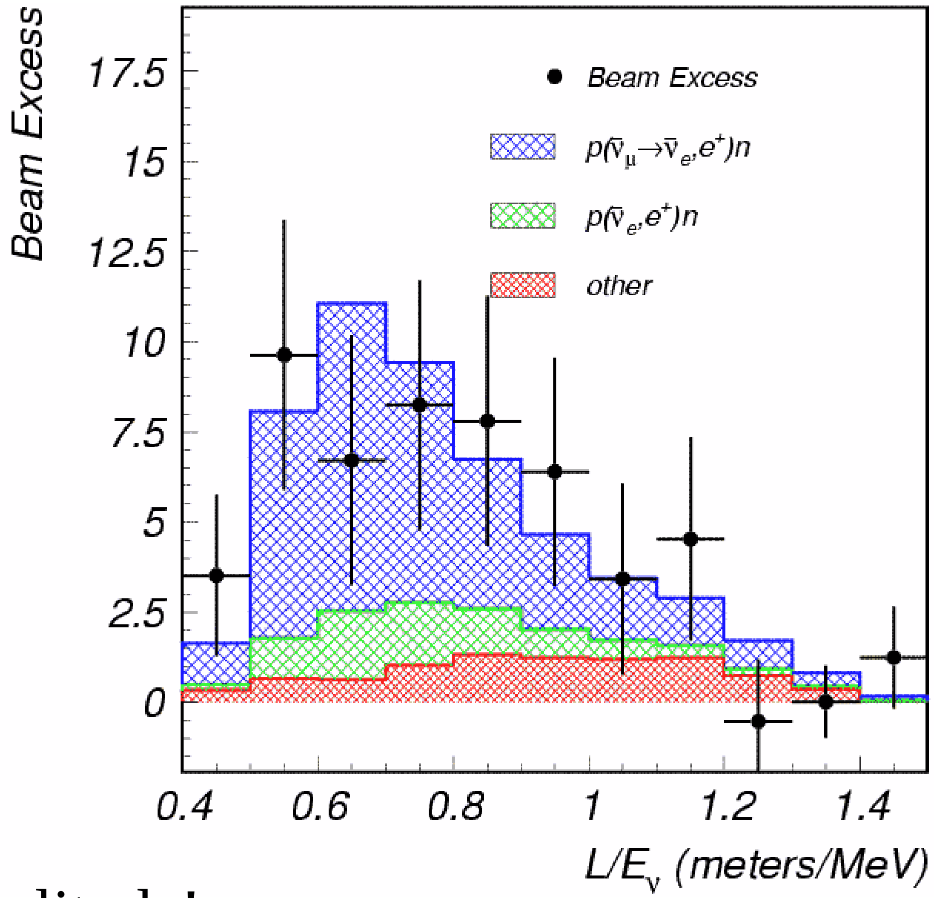
Picture of LSND photomultipliers (used later in MB)



Evidence for Oscillations from LSND

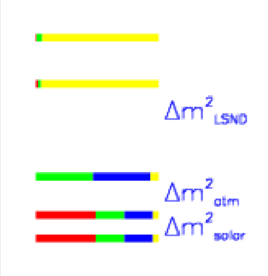
- LSND found an excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam
- Signature: Cerenkov light from e^+ with delayed n-capture (2.2 MeV)
- Excess: 87.9 ± 22.4 ± 6.0 (3.8σ)
- Under a two neutrino mixing hypothesis:

$$\begin{aligned} P(\bar{\nu}_\mu \to \bar{\nu}_e) &= \sin^2(2\theta)\sin^2\left(\frac{1.27\ L\,\Delta m^2}{E}\right) \\ &= 0.245 \pm 0.067 \pm 0.045\ \% \end{aligned}$$



Extremely small mixing amplitude!

If LSND Excess Confirmed: Physics Beyond the Standard Model!

3+2 Sterile Neutrinos  	Sorel, Conrad, & Shaevitz (PRD70(2004)073004) **Explain Pulsar Kicks?** **Explain R-Process in Supernovae?** **Explain Dark Matter?**
MaVaNs & 3+1 Sterile Neutrino	Hung (hep-ph/0010126) Kaplan, Nelson, & Weiner (PRL93(2004)091801) **Explain Dark Energy?**
CPT Violation	Barger, Marfatia, & Whisnant (PLB576(2003)303) **Explain Baryon Asymmetry in the Universe?**
Quantum Decoherence	Barenboim & Mavromatos (PRD70(2004)093015)
Lorentz Violation	Kostelecky & Mewes (PRD70(2004)076002) Katori, Kostelecky, Tayloe (hep-ph/0606154)
Extra Dimensions	Pas, Pakvasa, & Weiler (PRD72(2005)095017)
Sterile Neutrino Decay	Palomares-Ruiz, Pascoli, & Schwetz (JHEP509(2005)48)

Current Urgent Questions in ν Physics

- 1. What is the absolute neutrino mass scale?
- 2. What are all of the neutrino mixing angles?
- 3. Are neutrinos Majorana or Dirac type?
- 4. Do light, sterile neutrinos exist?
- 5. Do sterile neutrinos explain the dark matter of the universe?
- 6. Is CP violated in the neutrino sector?
- 7. Is CPT or Lorentz Invariance violated in the neutrino sector?

Sterile Neutrinos in the Standard Model Gauge Group

- With spontaneous symmetry breaking, Dirac neutrino mass terms of type,

$$\mathrm{m}_D \bar{\nu}_L \nu_R$$

- Neutrino mass implies ν_R exits!
- ν_R has the quantum numbers of the vacuum, thus sterile with respect to the standard model gauge interactions!
- SM with neutrino mass now looks like,

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \sim (3,2)(1/3), \qquad d_R \sim (3,1)(-2/3), \qquad u_R \sim (3,1)(4/3):$$

$$\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \sim (1,2)(-1), \qquad e_R \sim (1,1)(-2), \qquad \nu_R \sim (1,1)(0)$$

- Open question as to mass of sterile states. Look for Active-Sterile neutrino oscillations.

MiniBooNE: A Test of the LSND Evidence for Oscillations: Search for $\nu_\mu \to \nu_e$

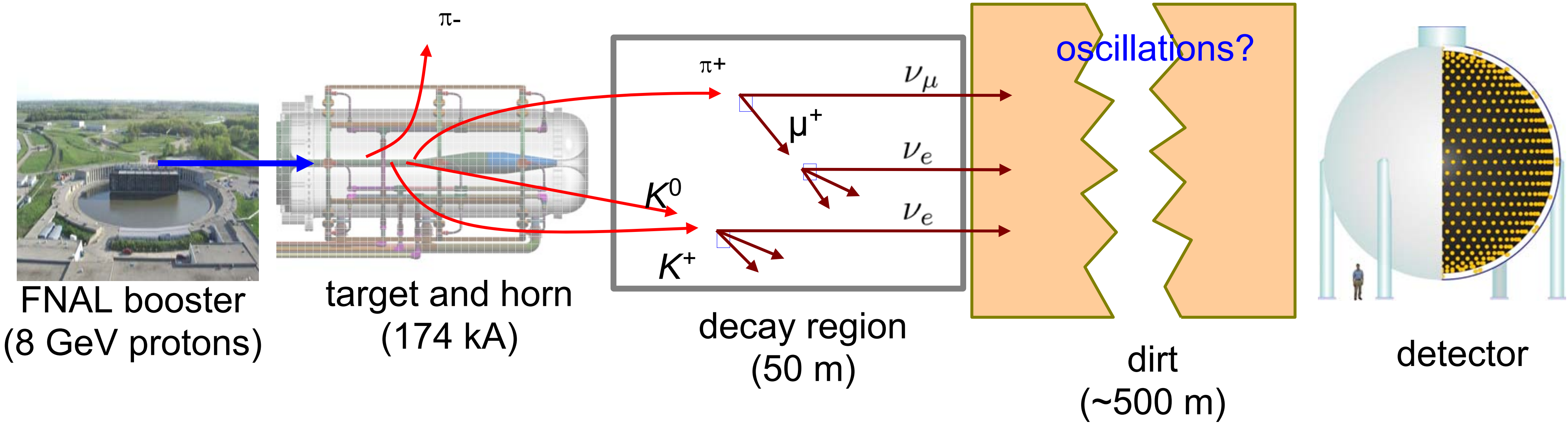
Completely different systematic errors than LSND

Much higher energy than LSND

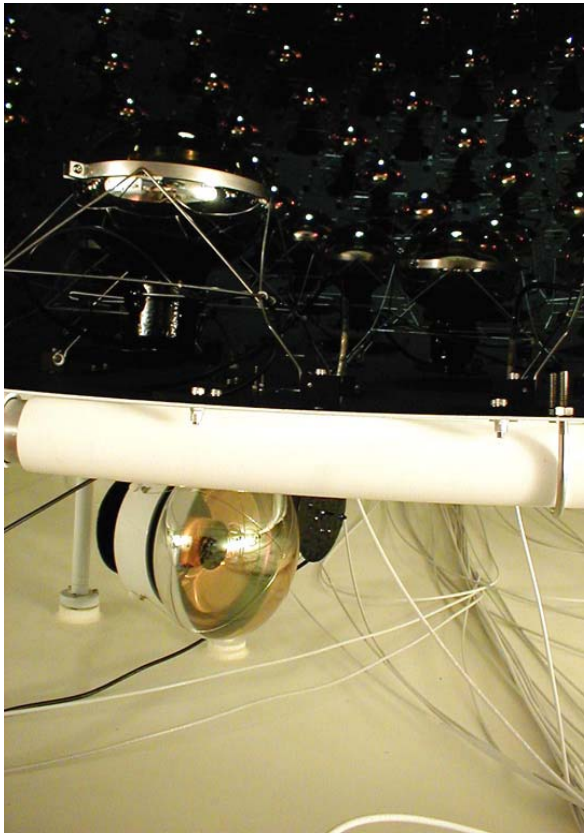
Blind Analysis

Alabama, Bucknell, Cincinnati, Colorado, Columbia, Embry-Riddle, Fermilab, Indiana, Los Alamos, LSU, Michigan, Princeton, St. Mary's, Virginia Tech, Yale

The MiniBooNE design strategy

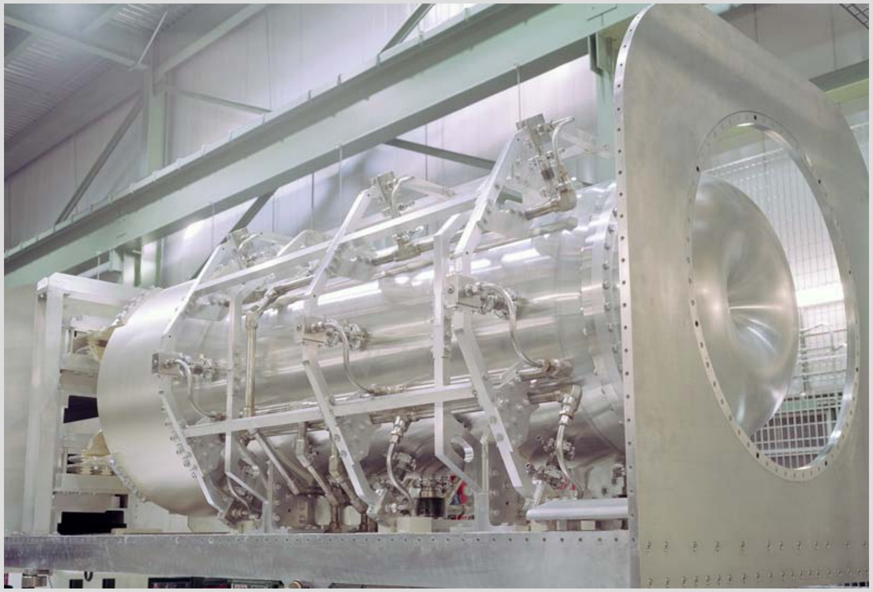


- Start with 8 GeV proton beam from FNAL Booster
- Add a 174 kA pulsed horn to gain a needed x 6
- Low intrinsic nue background
- *Place detector to preserve LSND L/E:*
  MiniBooNE: (500 m) / (700 MeV)
  LSND: (30 m) / (50 MeV)
- *Detect ν interations in 800T pure mineral oil detector*
  - *1280 8” PMTs provide 10% coverage of fiducial volume*
  - *240 8” PMTs provide active veto in outer radial shell*



MiniBooNE extracts beam from the 8 GeV Booster

Delivered to a 1.7 λ Be target



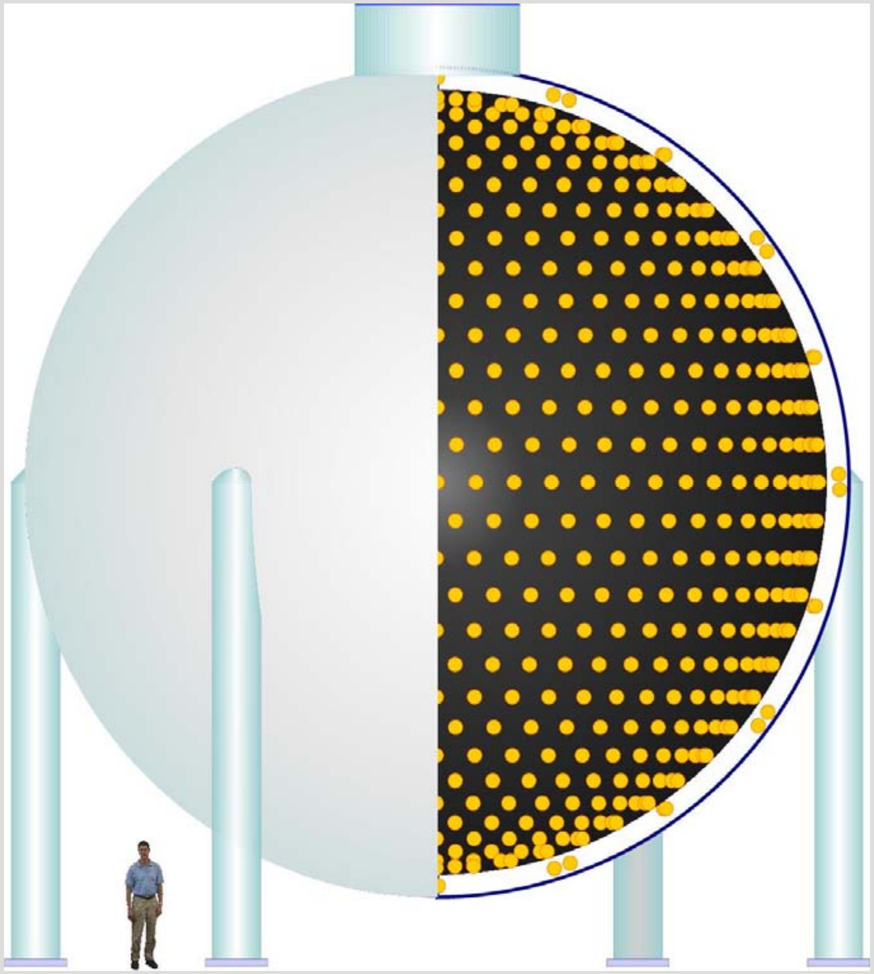
4 $\times 10^{12}$ protons per 1.6 μs pulse delivered at up to 5 Hz.

6.3 $\times 10^{20}$ POT delivered.

Results correspond to $(5.58 \pm 0.12) \times 10^{20}$ POT

within a magnetic horn (2.5 kV, 174 kA) that (increases the flux by ×6)

The MiniBooNE Detector



- 541 meters downstream of target
- 3 meter overburden
- 12.2 meter diameter sphere

  (10 meter “fiducial” volume)

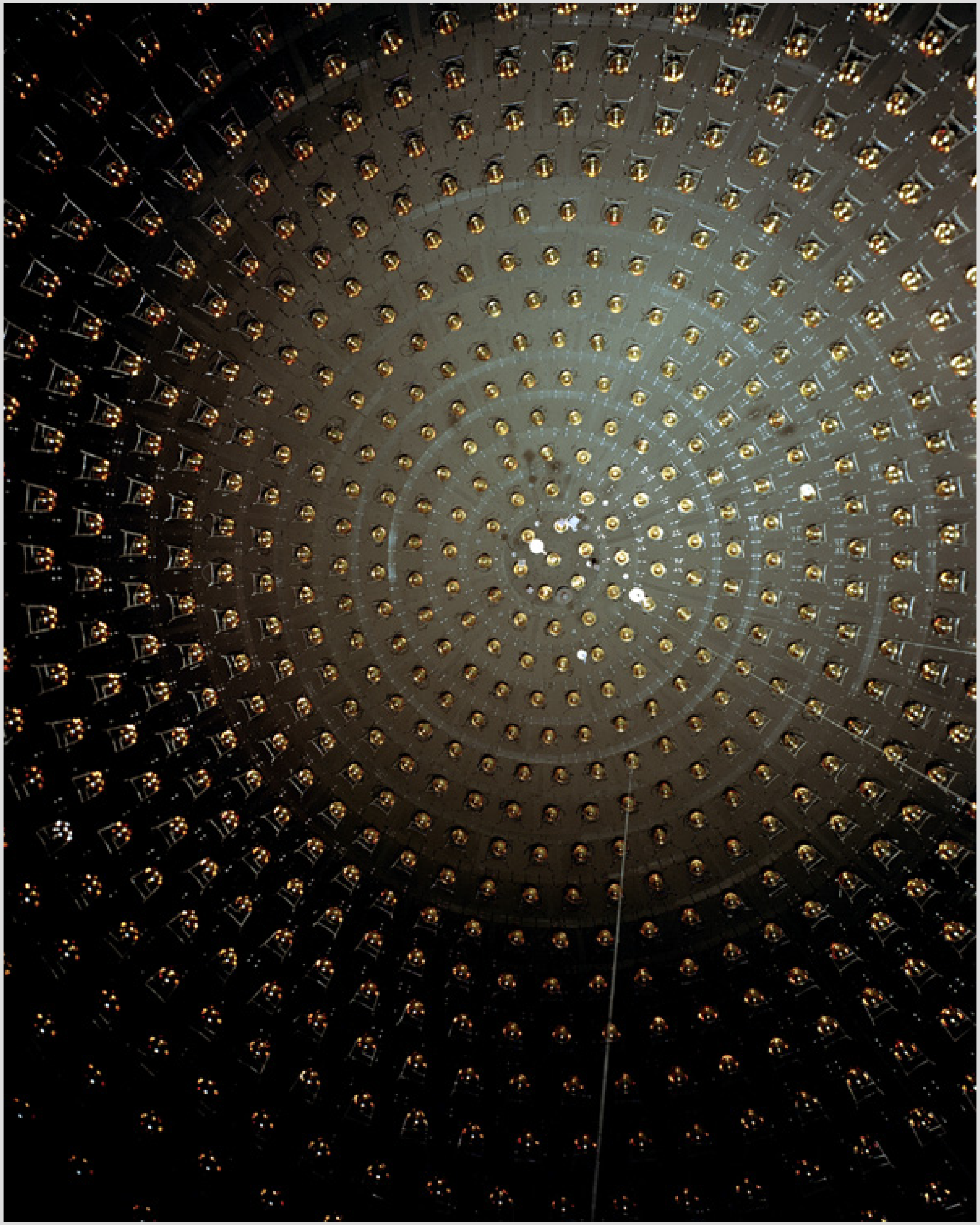
  - Filled with 800 t

    of pure mineral oil (CH_2)

    (Fiducial volume: 450 t)
  - 1280 inner phototubes,

    240 veto phototubes
  - Simulated with a GEANT3 Monte Carlo

MiniBooNE Detector Tank



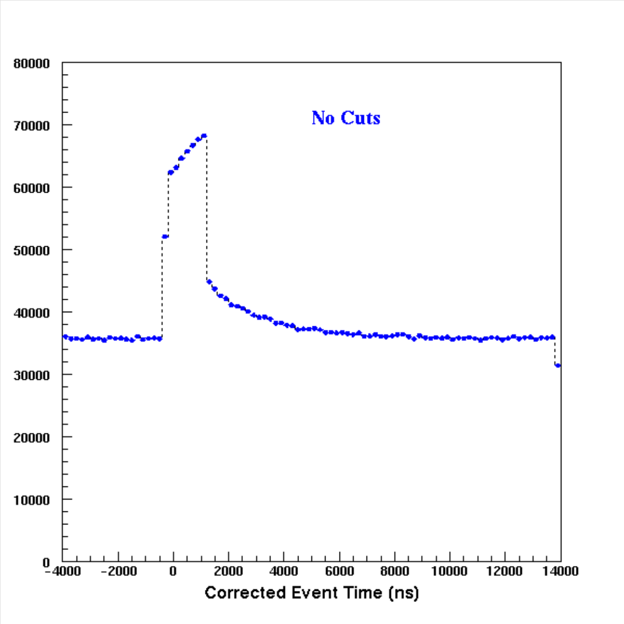
10% Photocathode coverage

Two types of
Hamamatsu Tubes:
R1408, R5912

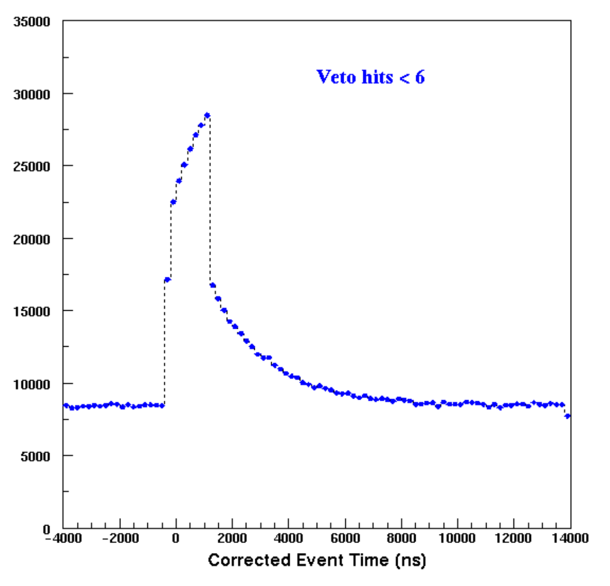
Charge Resolution:
1.4 PE, 0.5 PE

Time Resolution
1.7 ns, 1.1ns

Events in the Beam Time Window

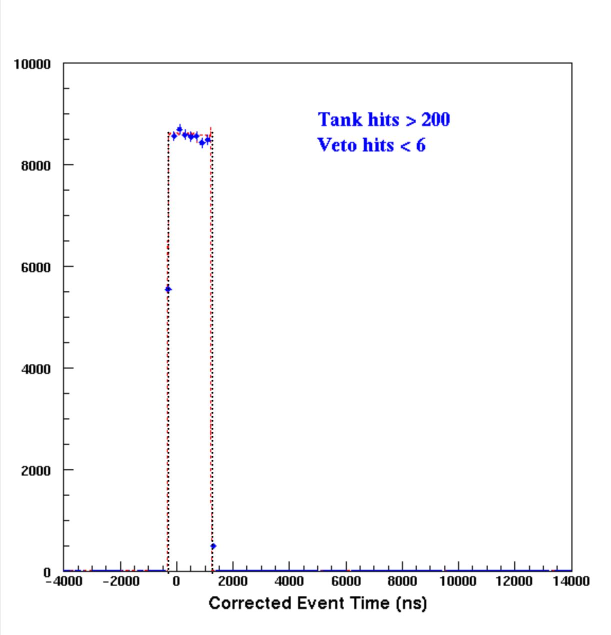


Raw data



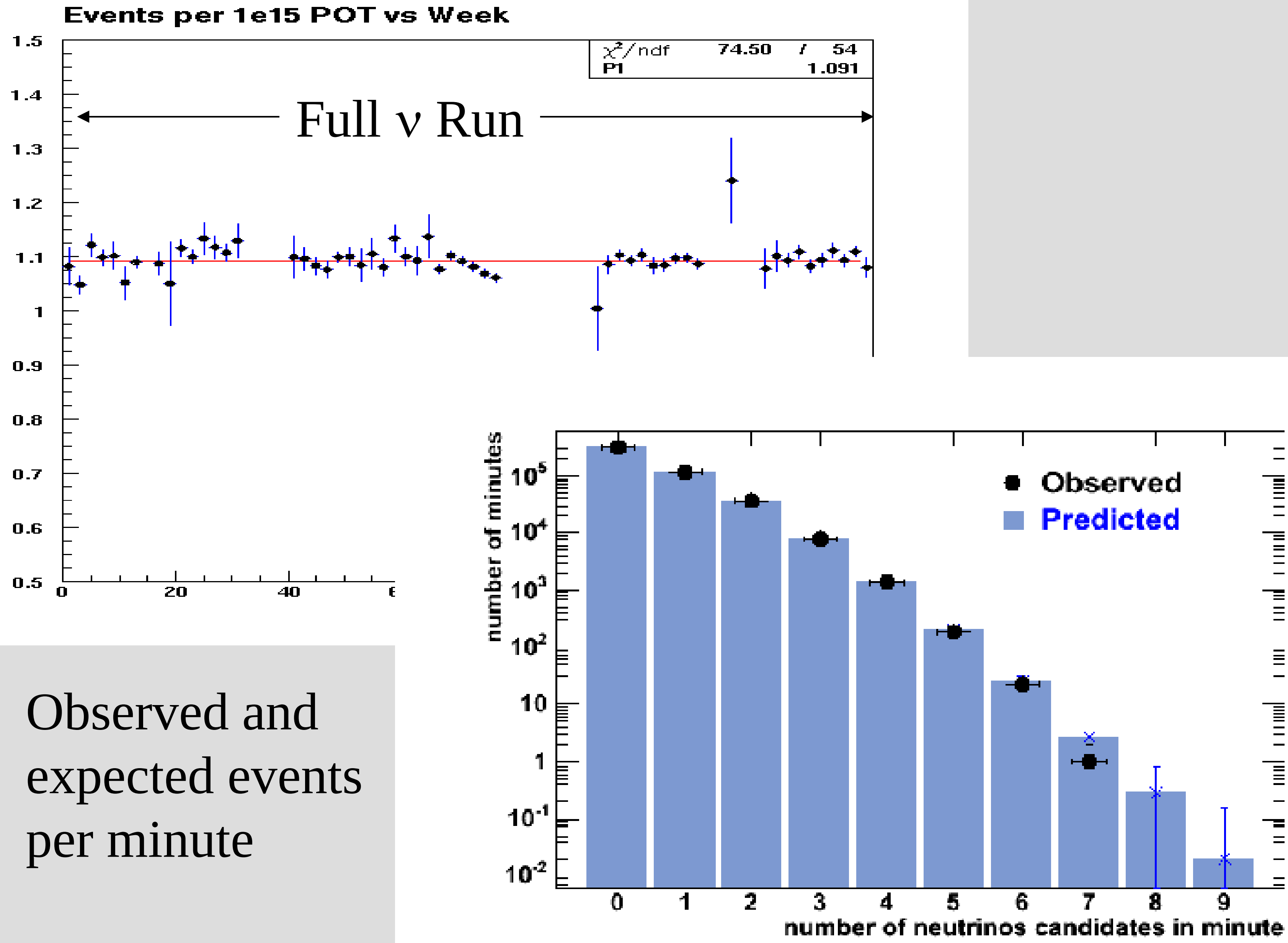
Veto<6 removes through-going cosmics

This leaves
" Michel electrons"
($\mu \rightarrow \nu_\mu \nu_e e$) from cosmics



Tank Hits > 200
(equivalent to energy)
removes Michel electrons,
which have
52 MeV endpoint

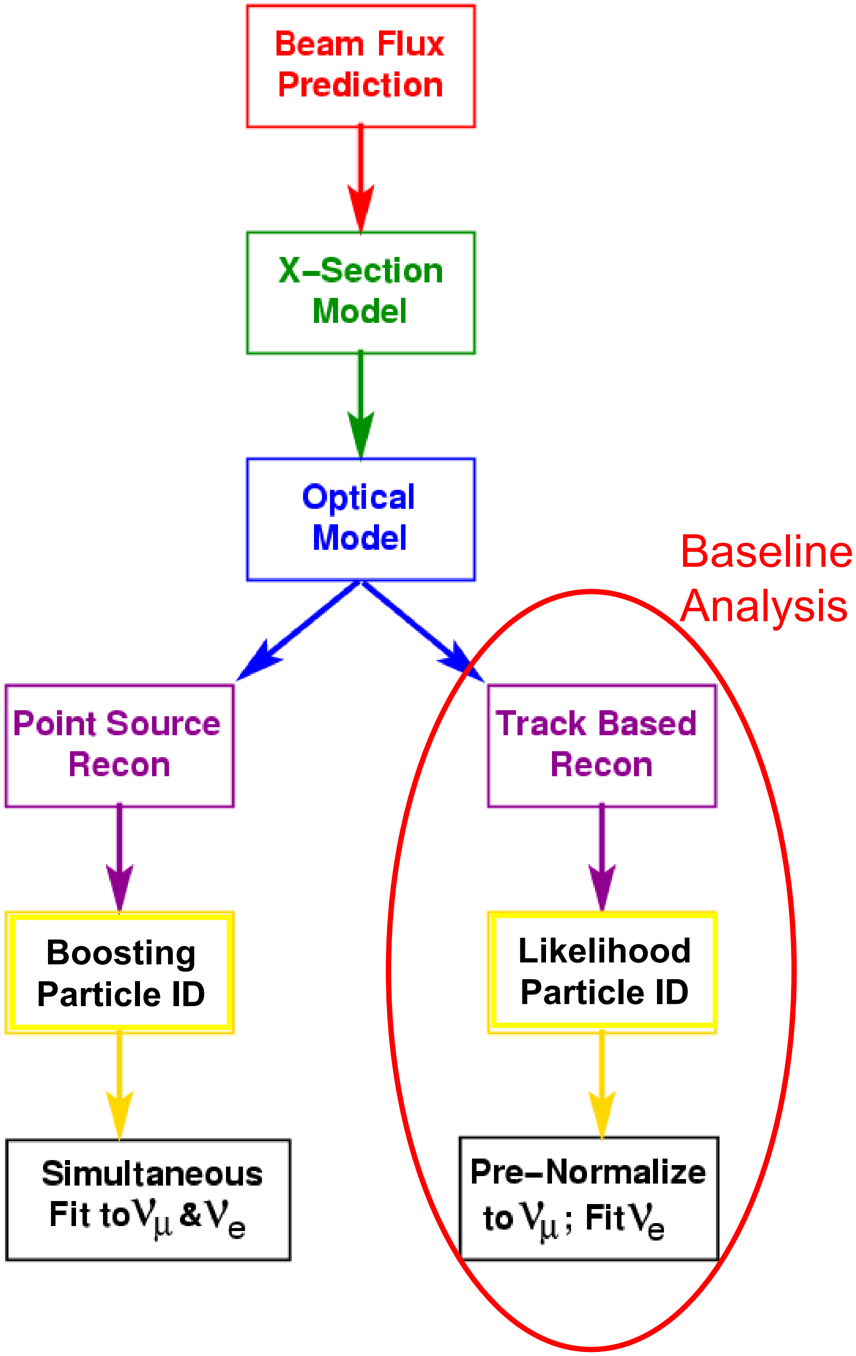
Stability of running:



Observed and expected events per minute

MiniBooNE analysis structure

- Start with a Geant 4 flux prediction for the ν spectrum from π and K produced at the target
- Predict ν interactions using the Nuance cross section parameterization
- Pass final state particles to Geant 3 to model particle and light propagation in the tank
- Starting with event reconstruction, independent analyses:
  - Boosted Decision Tree (BDT)
  - Track Based Likelihood (TBL)
- Develop particle ID/cuts to separate signal from background
- Fit reconstructed E_ν spectrum for oscillations



Beam Flux Prediction

X–Section Model

Optical Model

Point Source Recon

Boosting Particle ID

Simultaneous Fit to ν_μ & ν_e

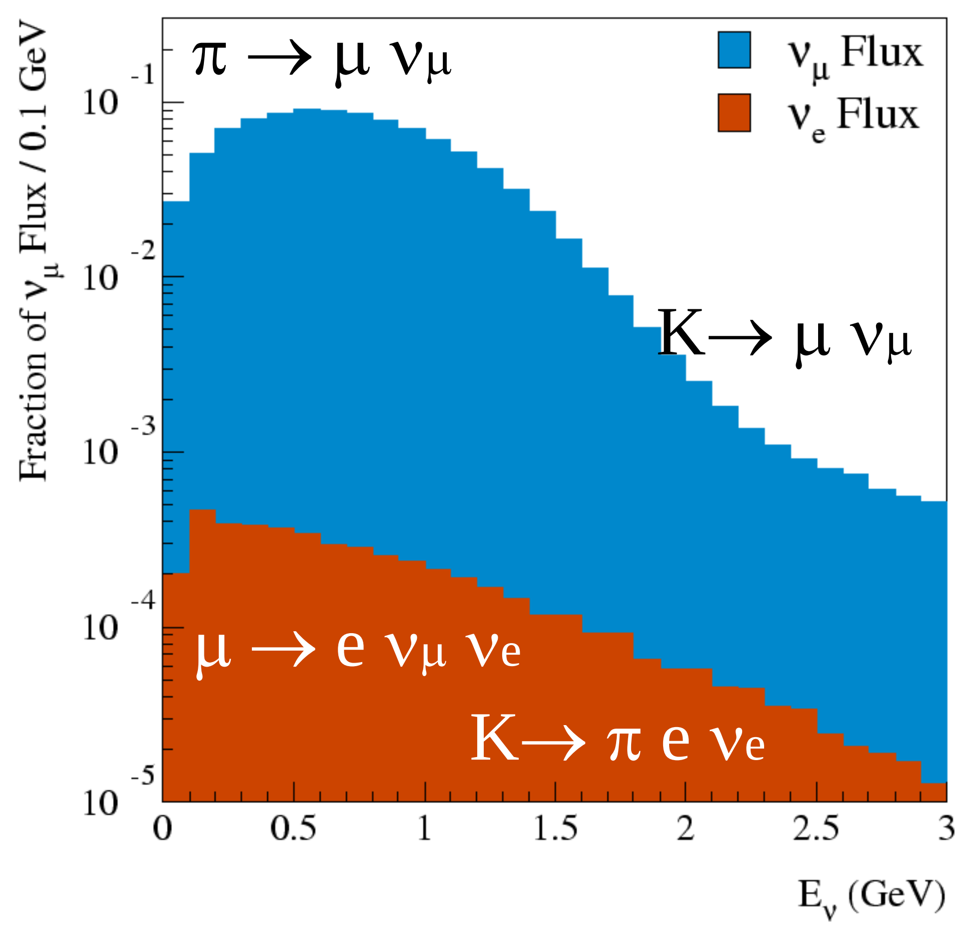
Track Based Recon

Likelihood Particle ID

Pre–Normalize to ν_μ ; Fit ν_e

Baseline Analysis

Neutrino Flux from GEANT4 Simulation



"Intrinsic" $\nu_e + \bar{\nu}_e$ sources:

$\mu^+ \rightarrow e^+ \ \nu_\mu \ \nu_e$ (52%)

$K^+ \rightarrow \pi^0 e^+ \nu_e$ (29%)

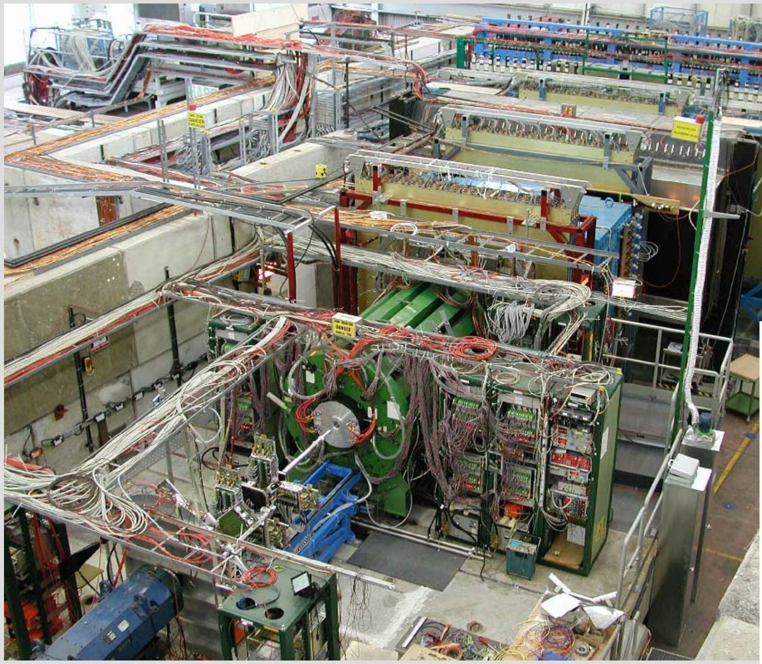
$K^0 \rightarrow \pi \ e \ \nu_e$ (14%)

Other (5%)

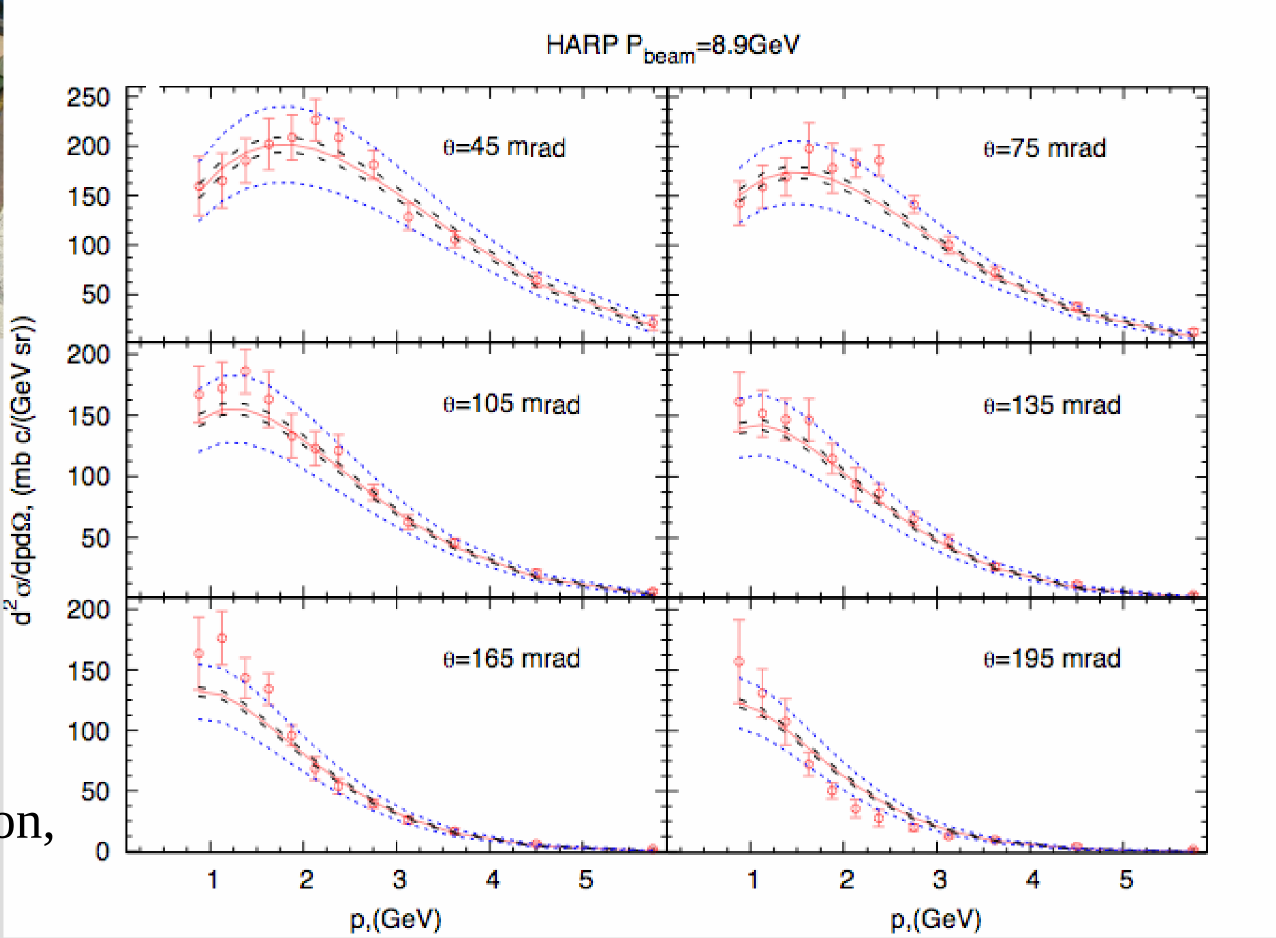
$\nu_e/\nu_\mu = 0.5\%$

Antineutrino content: 6%

Modeling Production of Secondary Pions



- HARP (CERN)
  - 5% λ Beryllium target
  - 8.9 GeV proton beam momentum

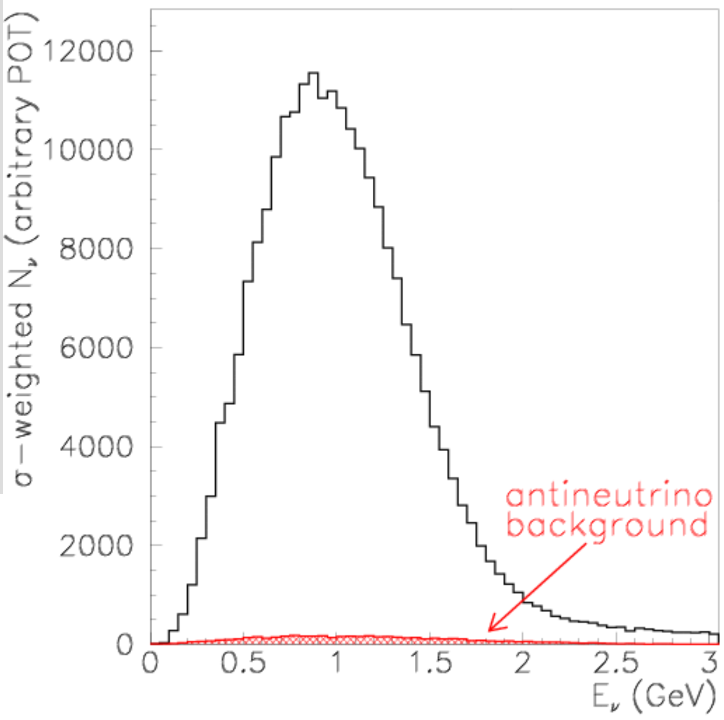


Data are fit to a Sanford-Wang parameterization.

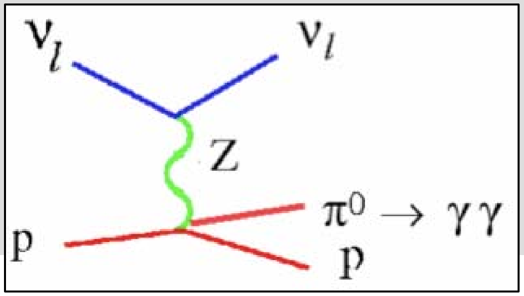
HARP collaboration,
hep-ex/0702024

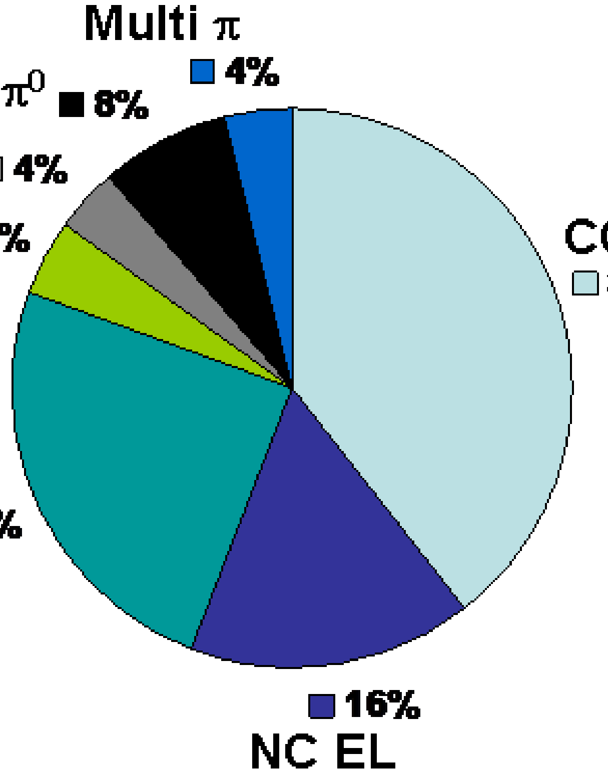
Predicted event rates before cuts (NUANCE Monte Carlo)

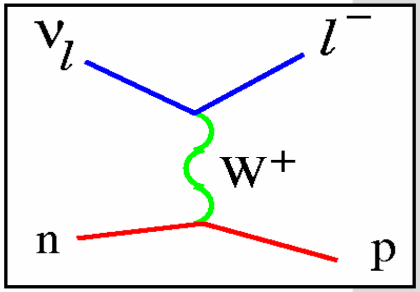
D. Casper, NPS, 112 (2002) 161

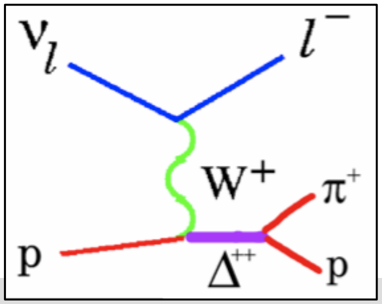


Event neutrino energy (GeV)

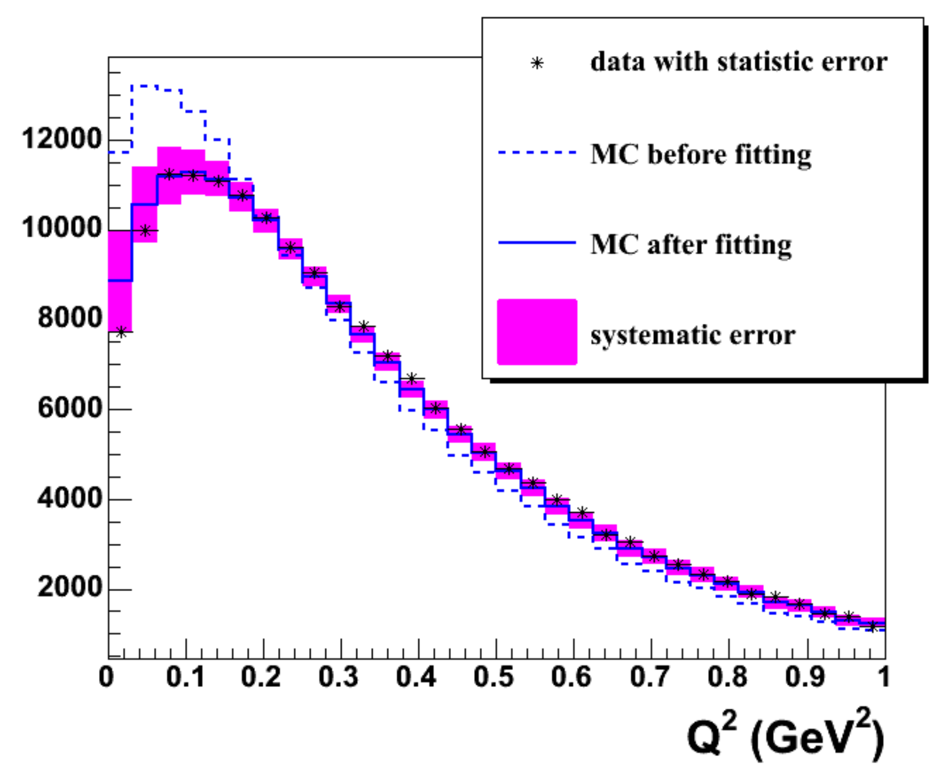








CCQE Scattering



From Q^2 fits to MB ν_μ CCQE data:

M_A^{eff} -- effective axial mass

E_{lo}^{SF} -- Pauli Blocking parameter

From electron scattering data:

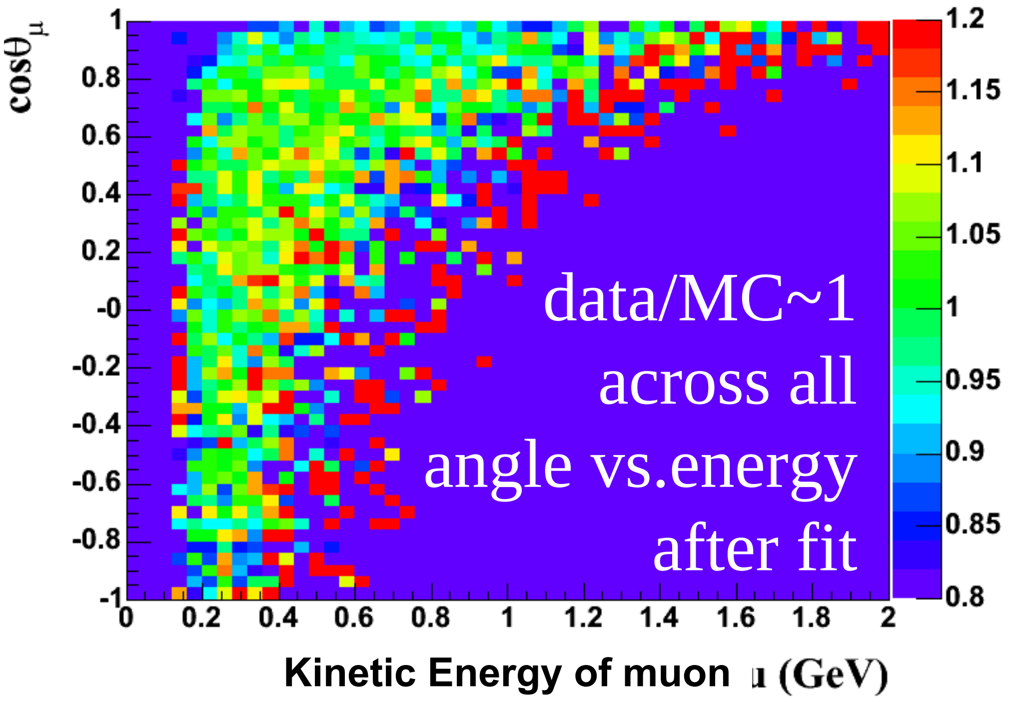
E_b -- binding energy

p_f -- Fermi momentum

Model describes CCQE ν_μ data well

M_A = 1.23+-0.20 GeV

E_{lo} = 1.019+-0.011



data/MC~1

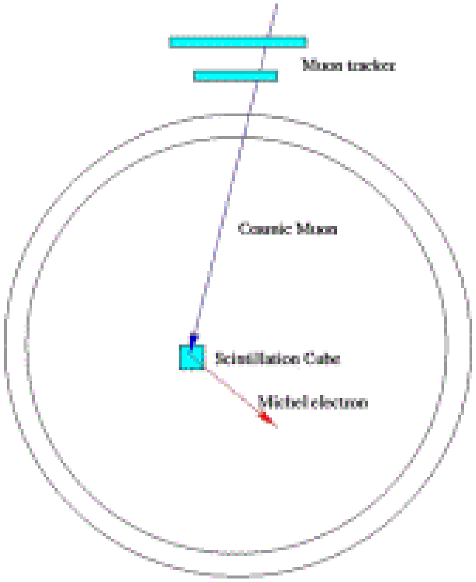
across all

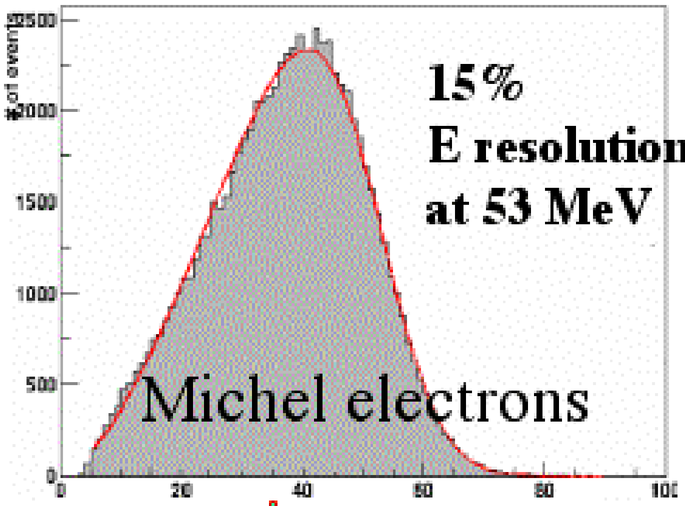
angle vs.energy

after fit

Calibration Sources

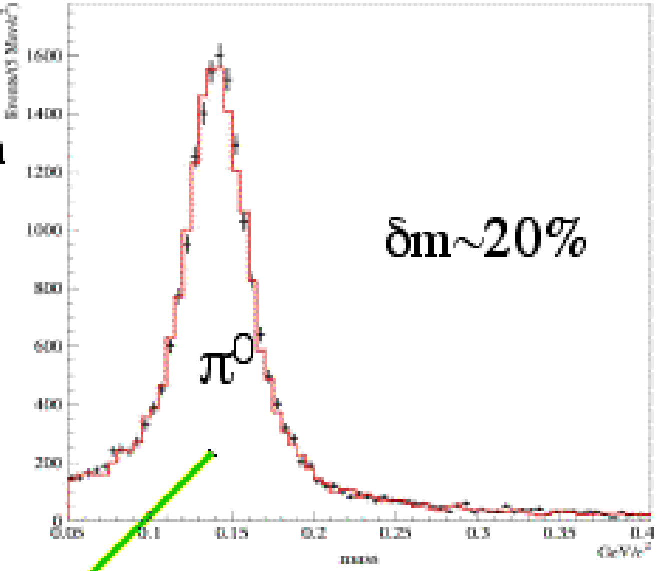
Tracker system





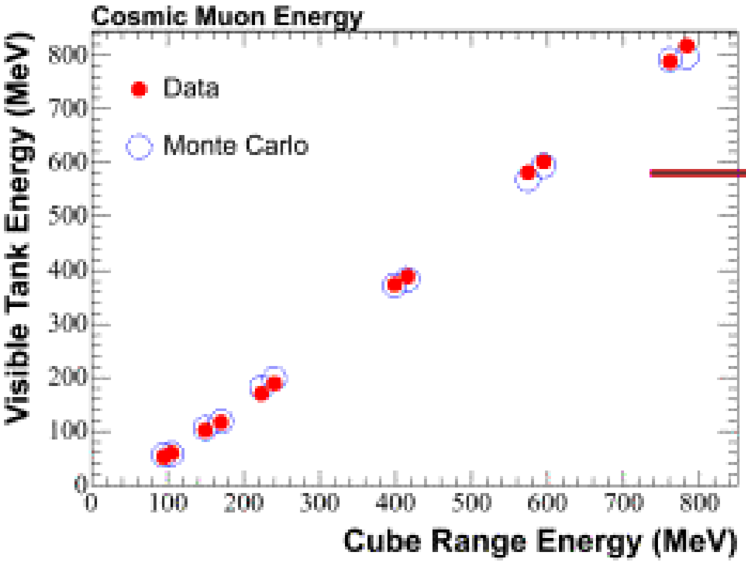
15%
E resolution
at 53 MeV

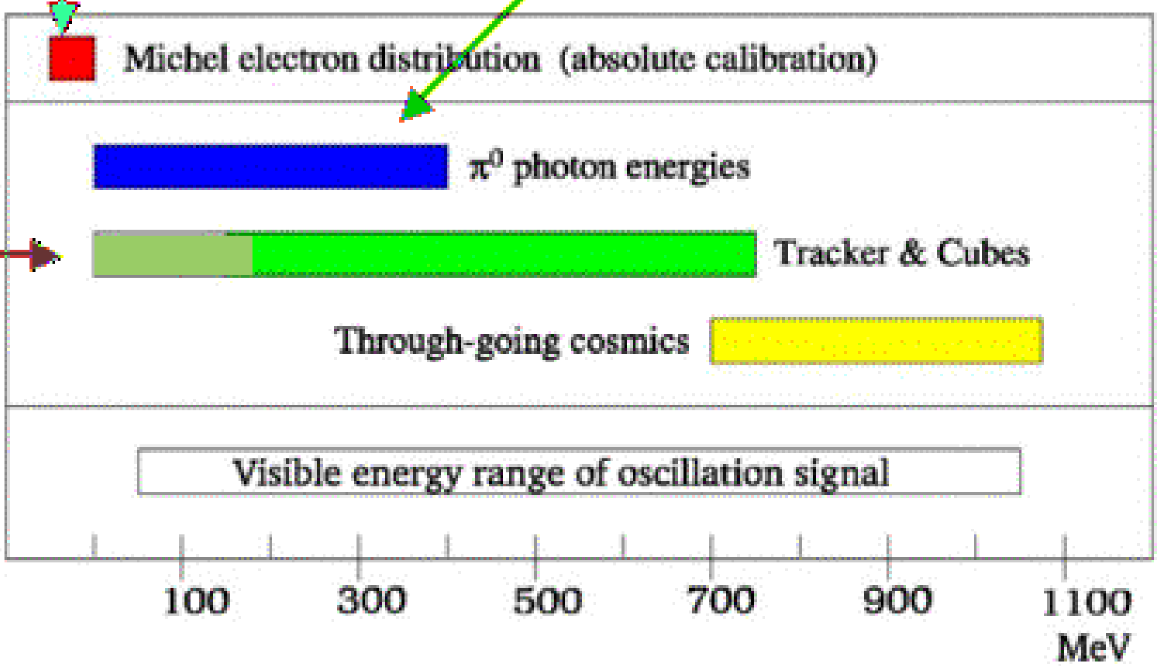
Michel electrons



$\delta m \sim 20\%$

π^0





🟥 Michel electron distribution (absolute calibration)

π^0 photon energies

Tracker & Cubes

Through-going cosmics

Visible energy range of oscillation signal

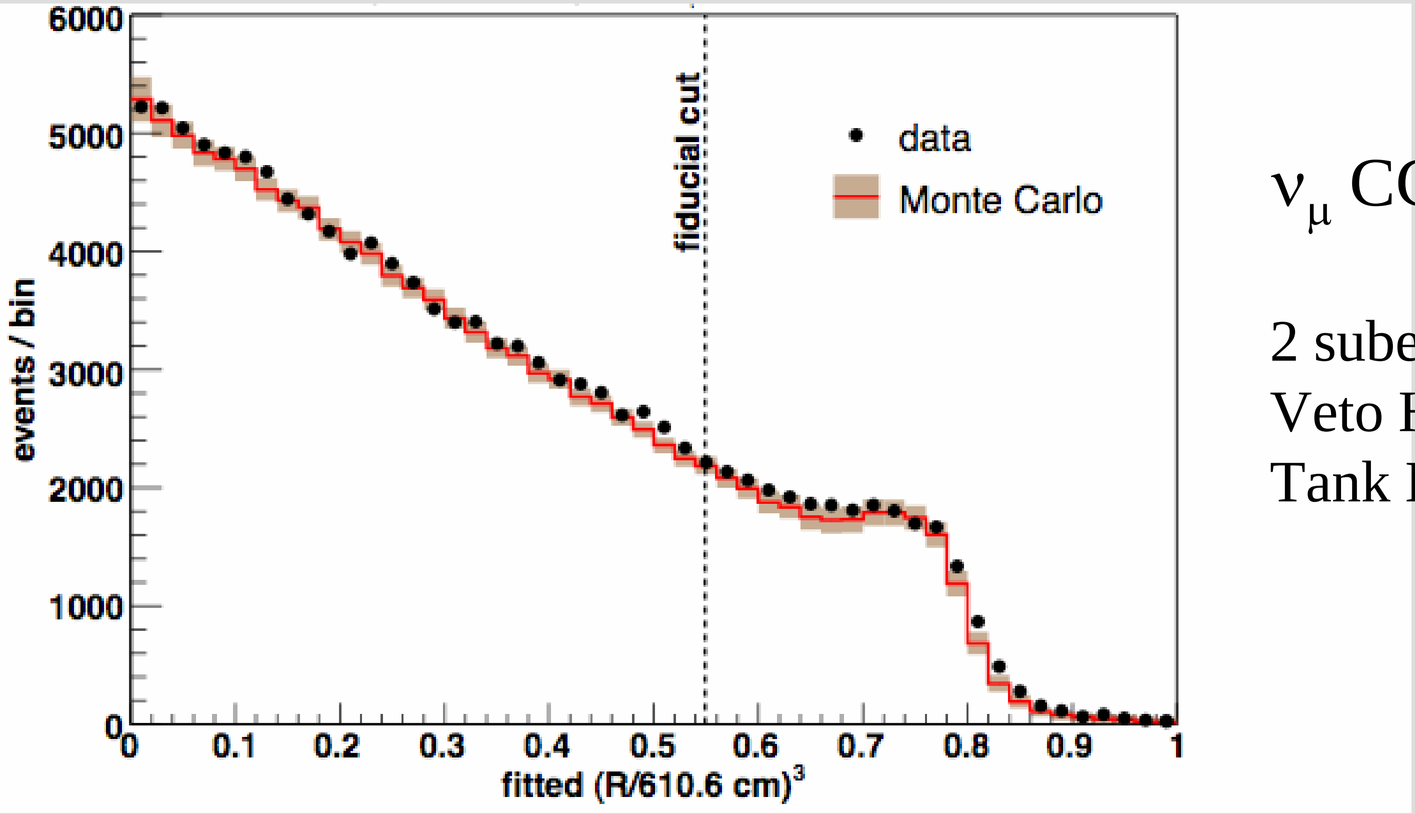
Each event is characterized by 7 reconstructed variables:

vertex *(x,y,z)*, time, energy, and direction $(\theta,\phi)\Leftrightarrow(U_x, U_y, U_z)$.

Resolutions: vertex: 22 cm

direction: 2.8°

energy: 11%



ν_μ CCQE events

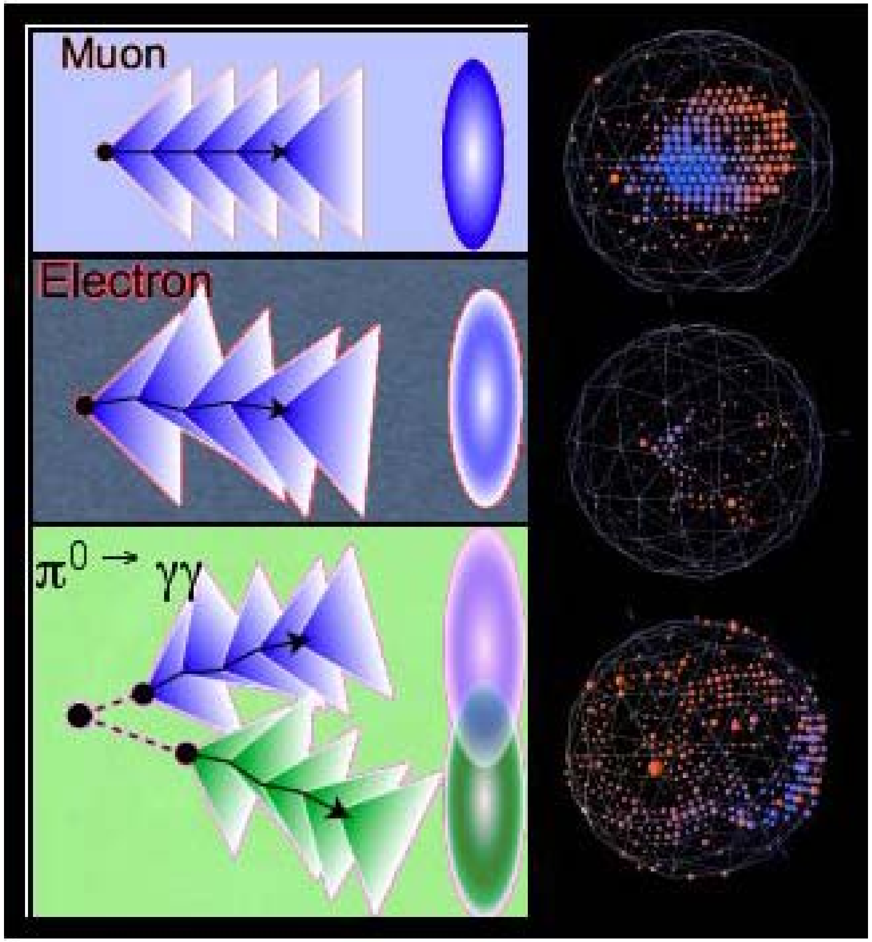
2 subevents
Veto Hits<6
Tank Hits>200

Three types of particles are reconstructed:

Muons:
Produced in most CC events.
Usually 2 subevent or exiting.

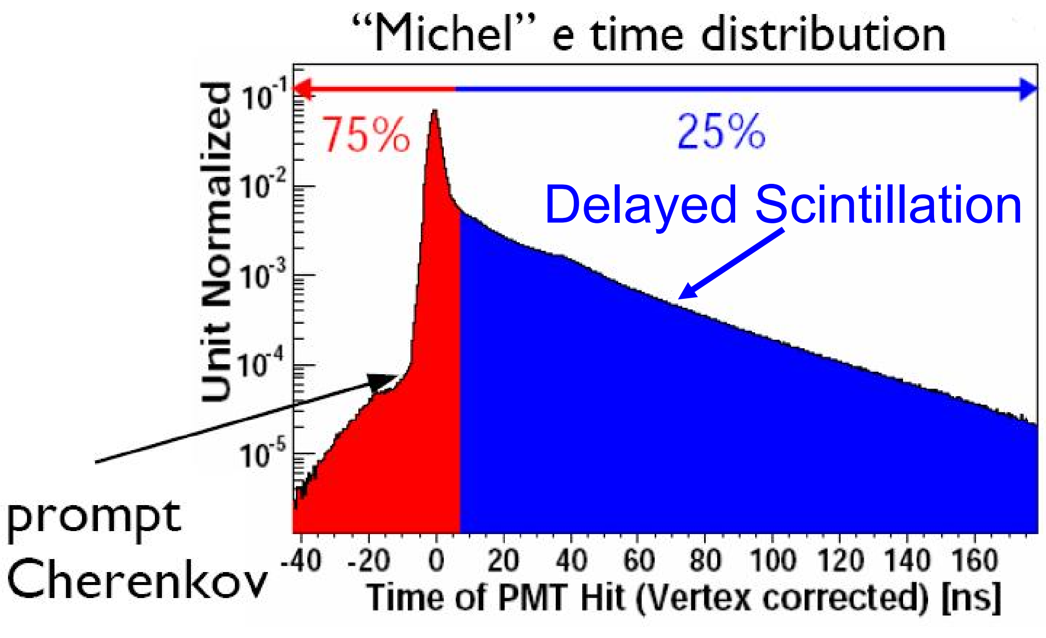
Electrons:
Tag for $\nu_\mu \rightarrow \nu_e$ CCQE signal.
1 subevent

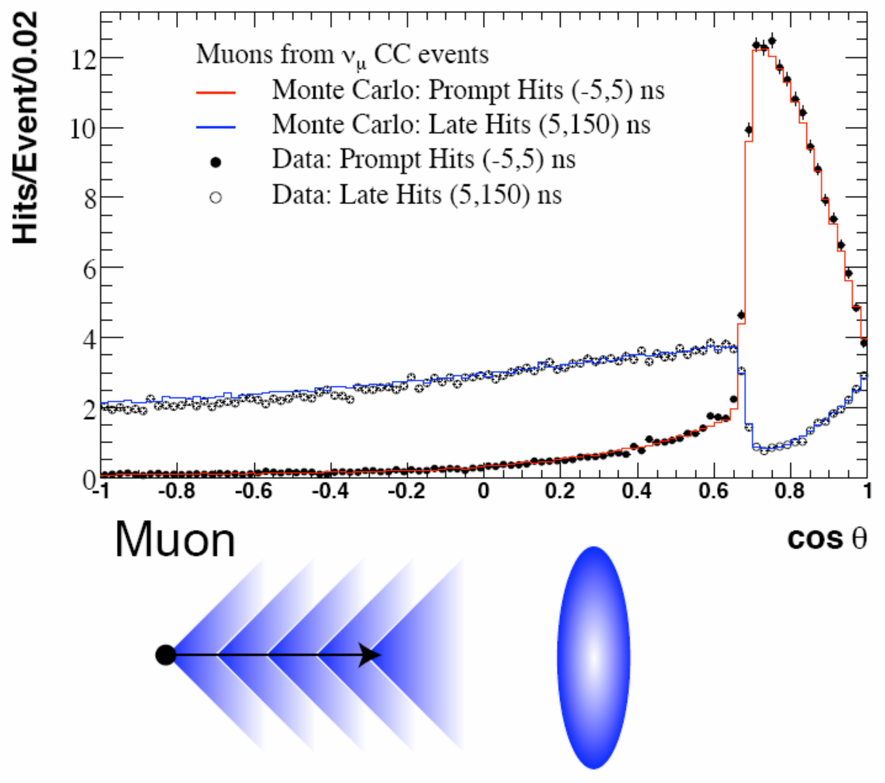
π^0s:
Can form a background if one photon is weak or exits tank.
In NC case, 1 subevent.

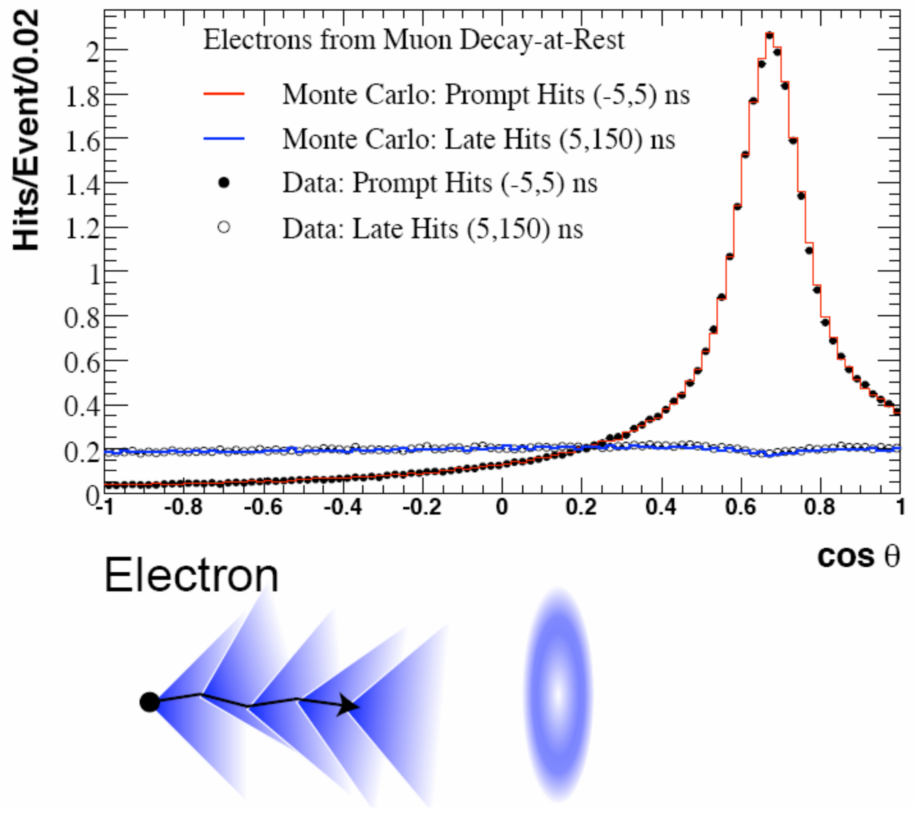


Event Reconstruction

- Use energy deposition and timing of hits in the phototubes
  - Prompt Cherenkov light
    - Highly directional with respect to particle direction
    - Used to give particle track direction and length
  - Delayed scintillation light
    - Amount depends on particle type







Cuts Used to Separate ν_μ events from ν_e events

Compare observed light distributions to fit prediction:

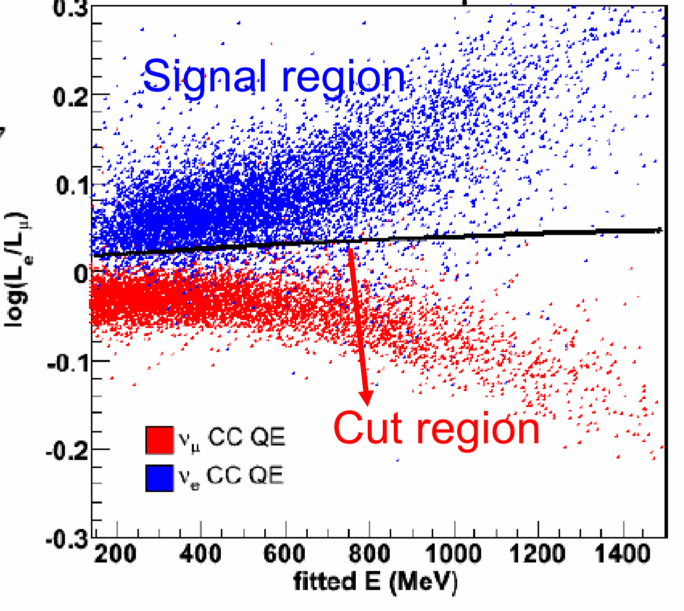
TBL Analysis

Apply these likelihood fits to three hypotheses:

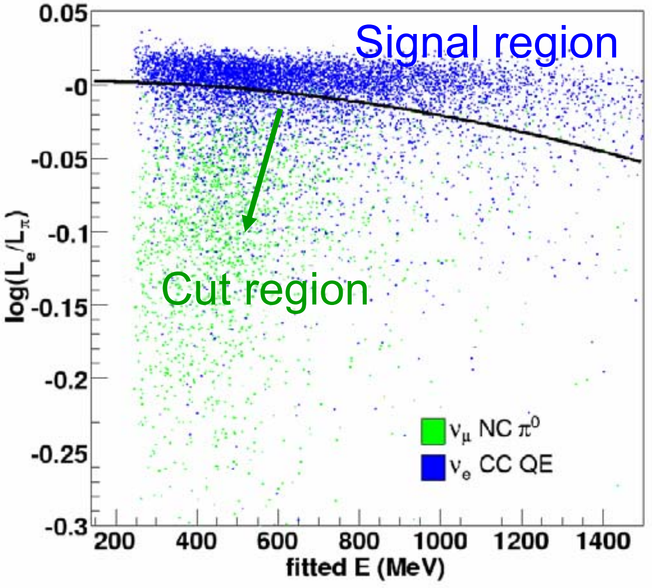
- **single electron track L_e**
- **single muon track L_μ**
- **two electron-like rings (π^0 event hypothesis) L_π**

Combine three cuts to accomplish the separation: $L_{e\mu}$, $L_{e\pi}$, and 2-track mass

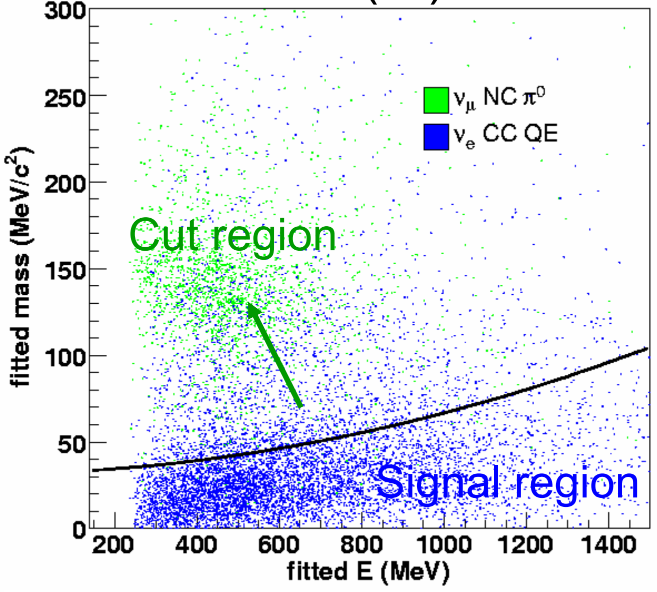
Likelihood e/μ cut



Likelihood e/π cut



Mass(π^0) cut



Blue points are signal ν_e events

Red points are background ν_μCC QE events

Green points are background ν_μ NC π^0 events

Summary of Track Based cuts

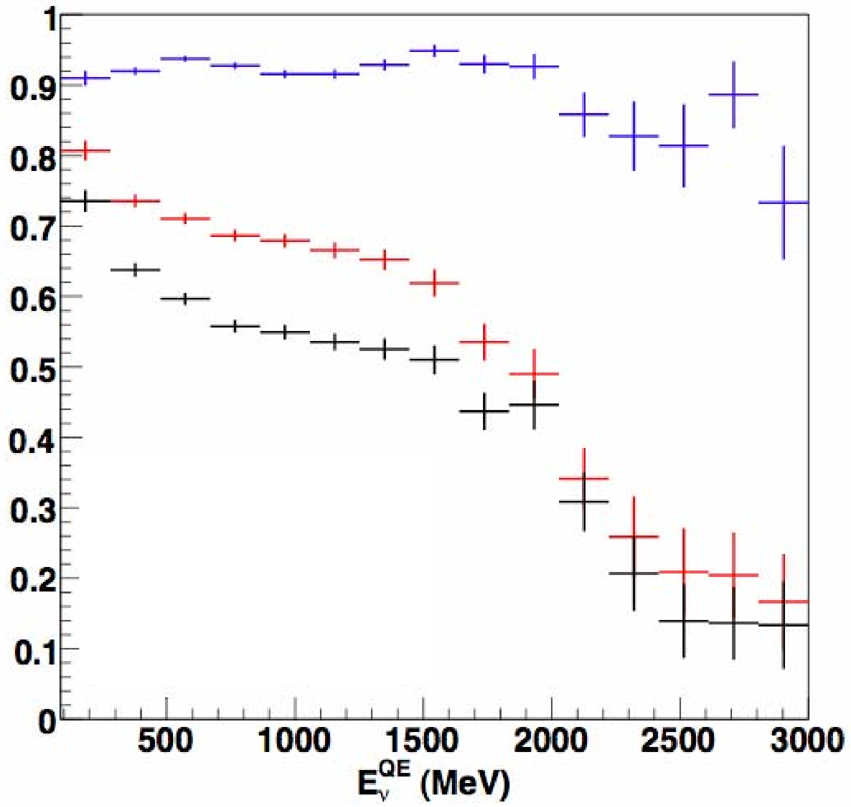
“Precuts” +

$\mathrm{Log}(L_e/L_\mu)$

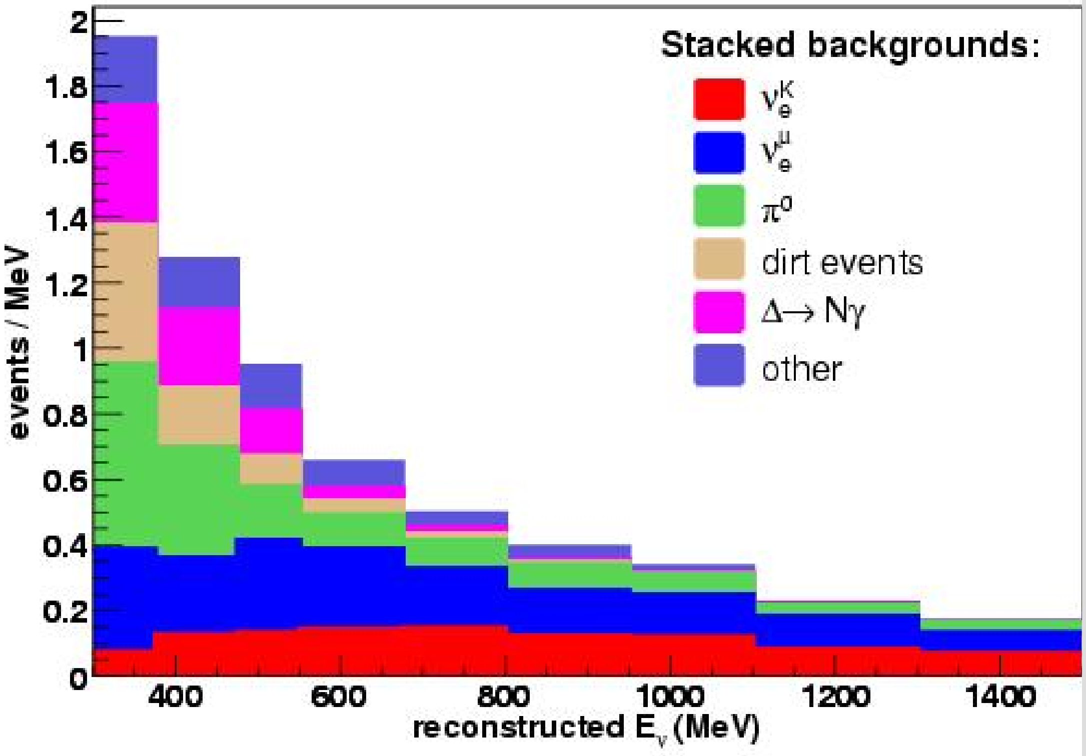
$+ \mathrm{Log}(L_e/L_\pi)$

+ invariant mass

Efficiency:

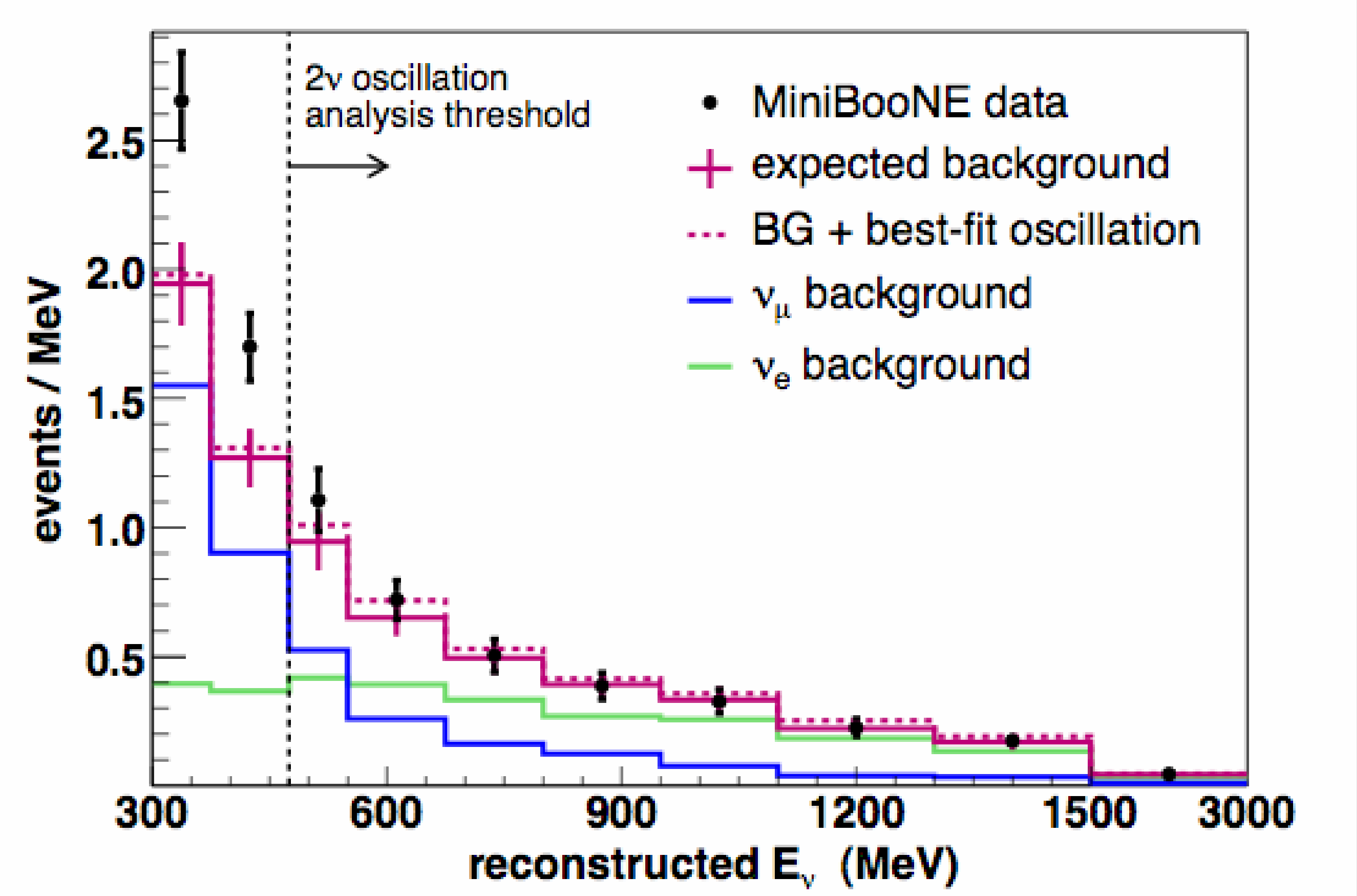


Backgrounds after cuts



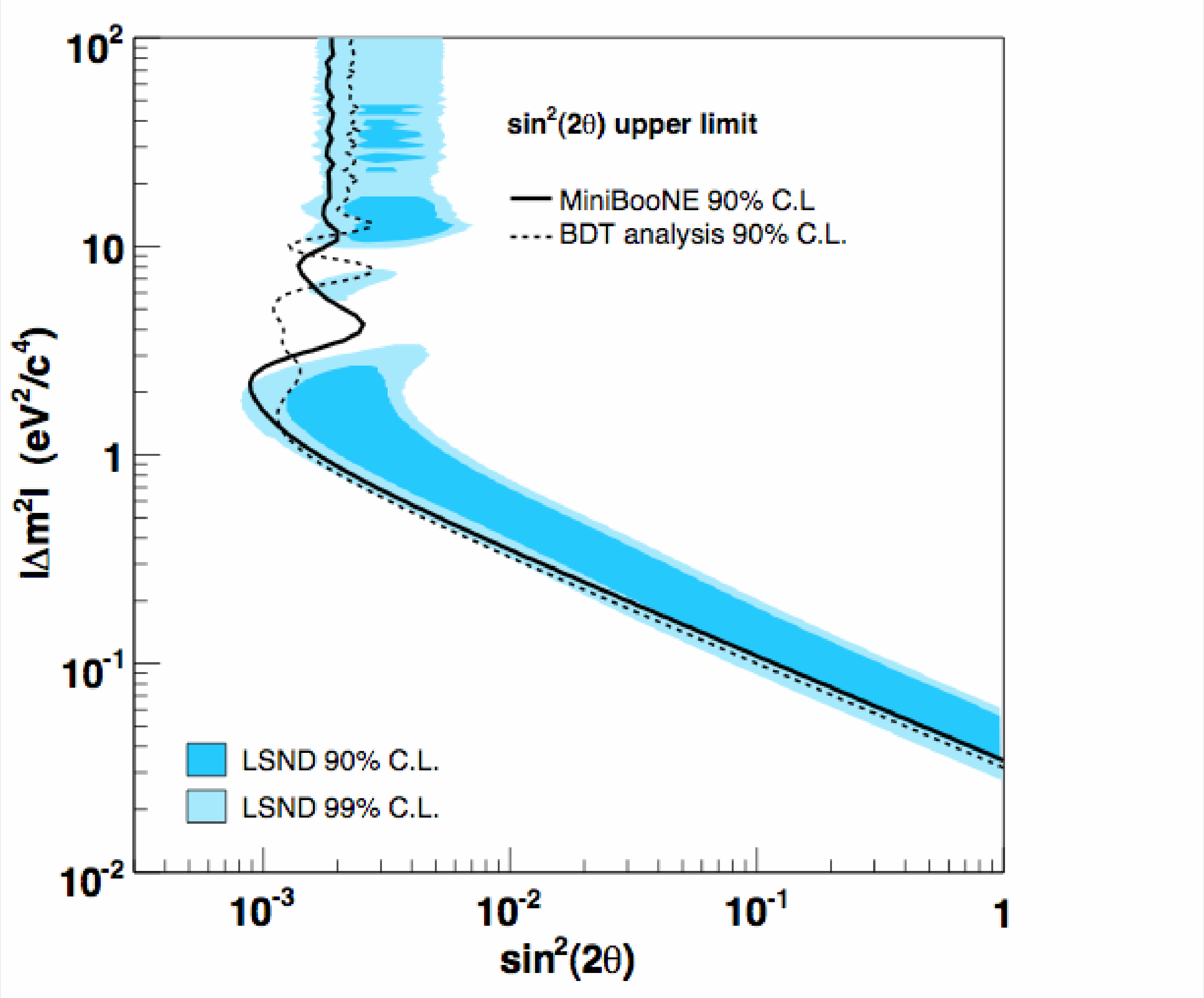
Source of Uncertainty On ν_e background	Track Based error in %		Checked or Constrained by MB data
Flux from π^+/μ^+ decay	6.2	√	√
Flux from K^+ decay	3.3	√	√
Flux from K^0 decay	1.5	√	√
Target and beam models	2.8	√	
ν-cross section	12.3	√	√
NC π^0 yield	1.8	√	
External interactions (“Dirt”)	0.8	√	
Optical model	6.1	√	√
DAQ electronics model	7.5	√	

The Track-based $\nu_\mu \rightarrow \nu_e$ Appearance-only Result:



$475 < E_\nu^{QE} < 1250$ MeV : data: 380 events, MC: 358 ±19 ±35 events, 0.55 σ

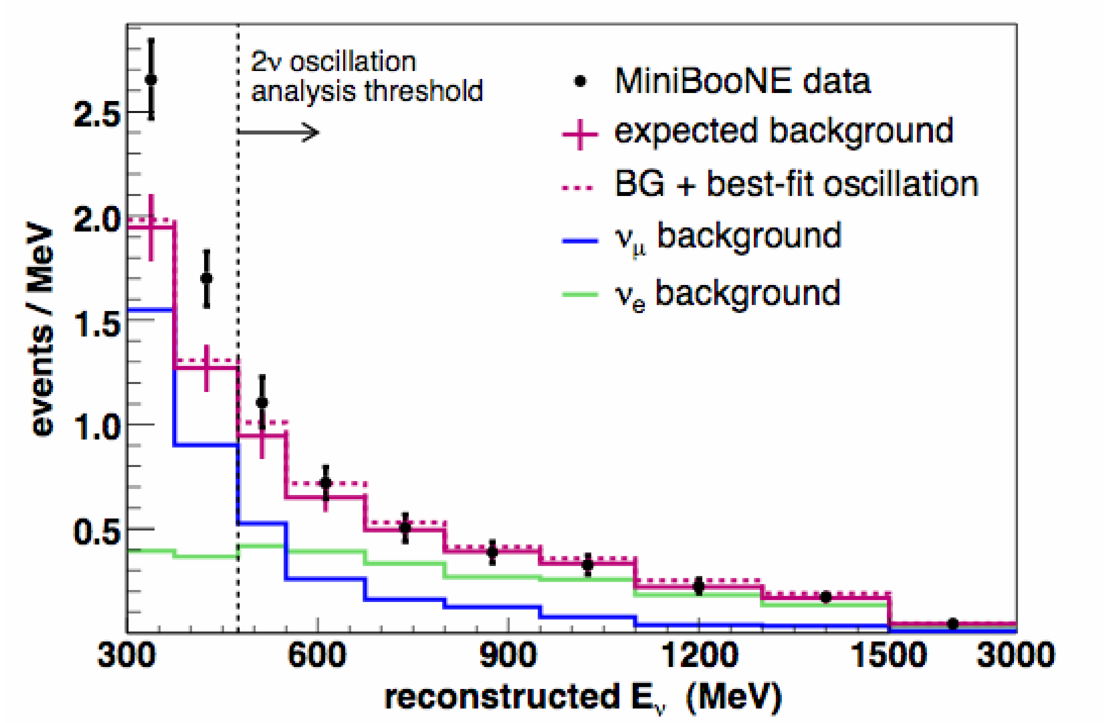
The result of
the $\nu_\mu \rightarrow \nu_e$ appearance-only analysis
is a <u>limit</u> on oscillations:



Simple 2-neutrino oscillations excluded at 98% C.L.

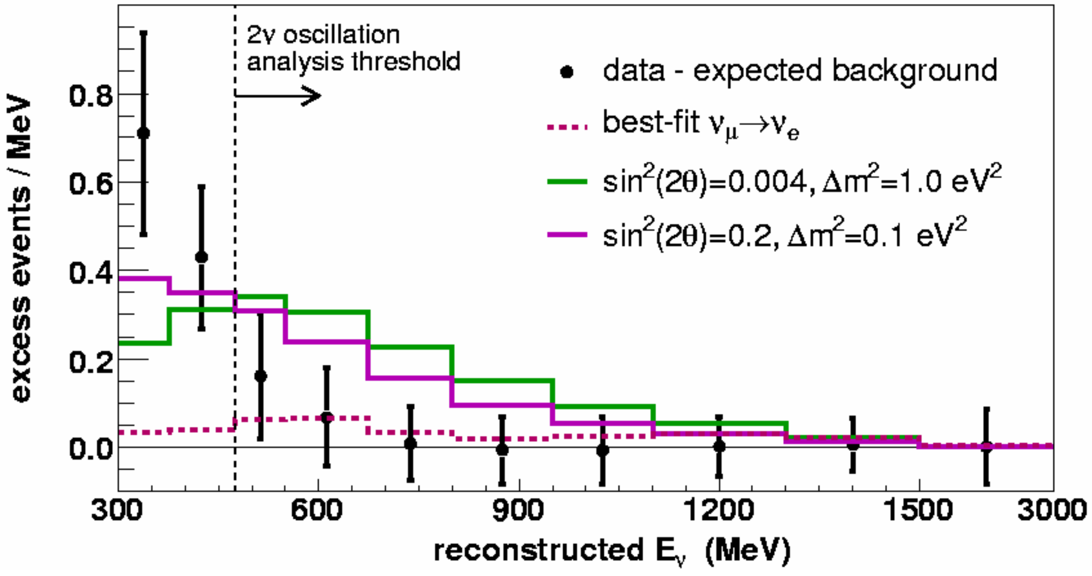
Energy fit: $475 < E_\nu^{QE} < 3000$ MeV

But an Excess of Events Observed Below 475 MeV



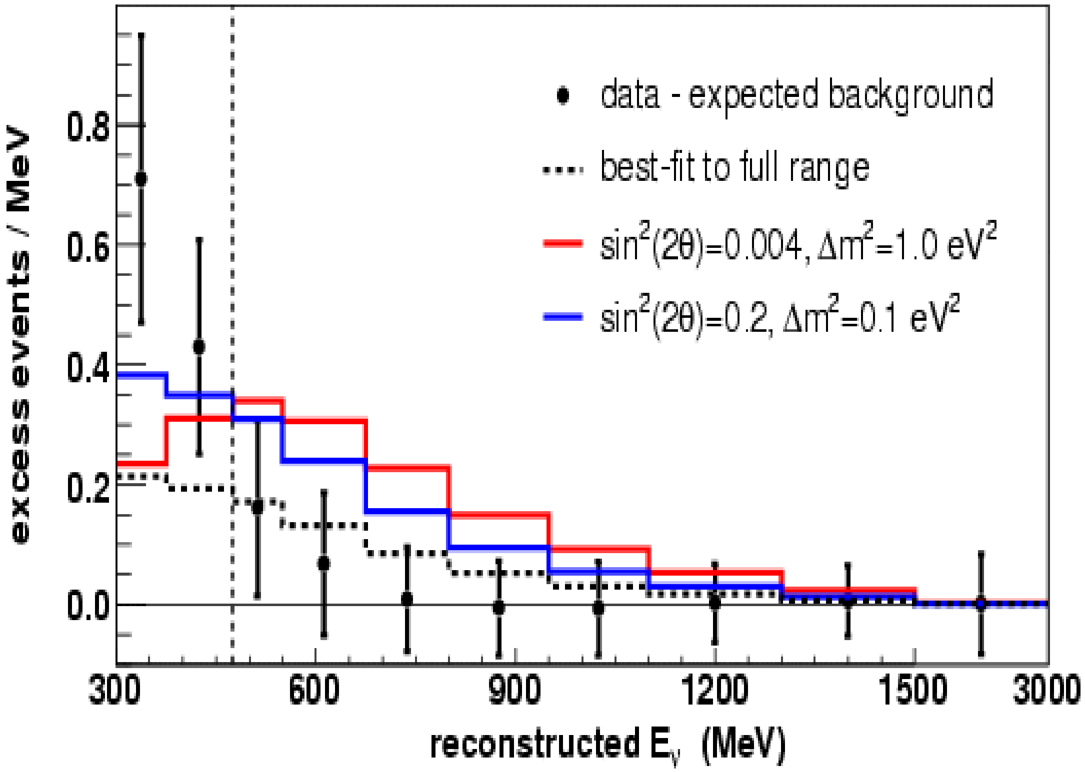
$96 \pm 17 \pm 20$ events above background, for $300 < E_\nu^{QE} < 475$MeV

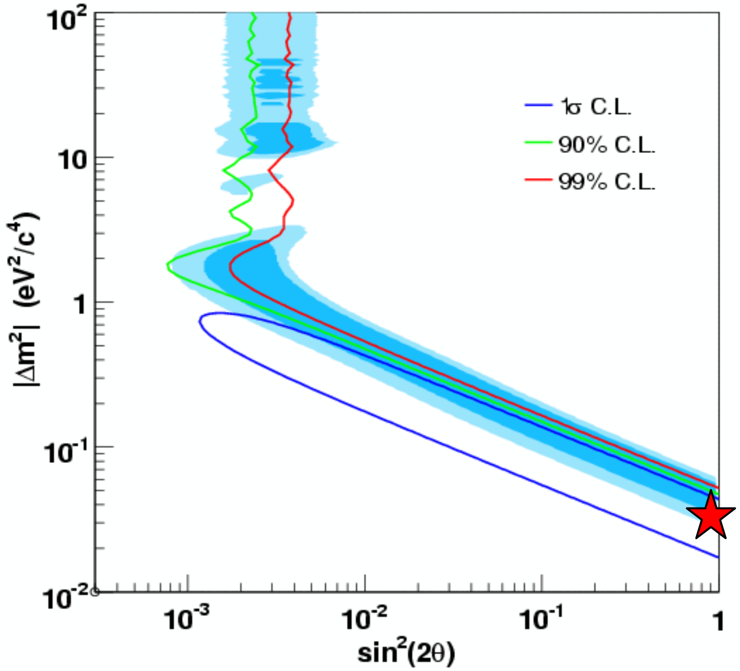
Deviation: $3.7\ \sigma$



Excess Distribution
inconsistent with
a 2-neutrino oscillation model

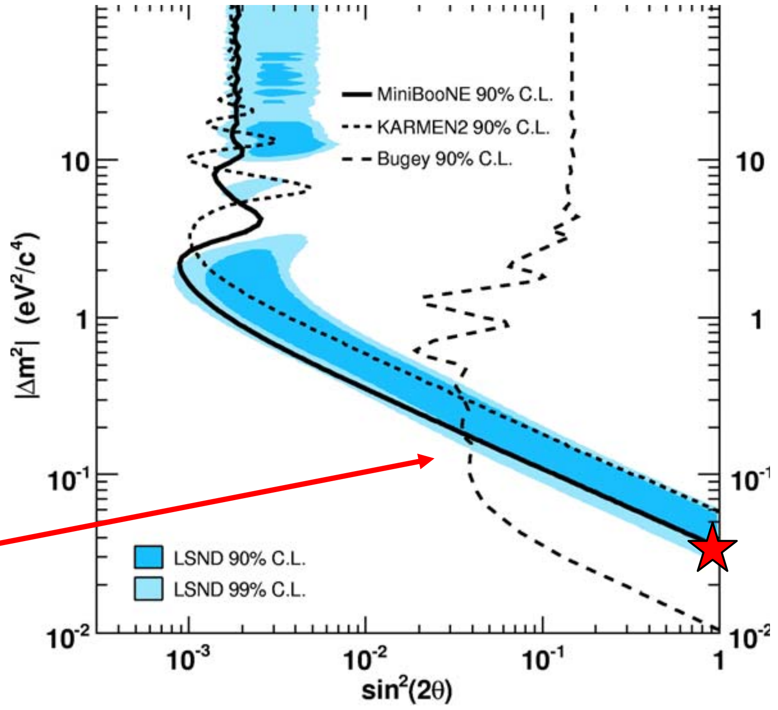
2-neutrino Oscillation Fits for 300 – 3000 MeV





Best Fit (dashed):
$(\sin^2 2\theta, \Delta m^2) = (1.0, 0.03\ \mathrm{eV}^2)$
χ^2 Probability: 18%

This best fit is not probable but also ruled out by the Bugey reactor experiment.



Going Beyond the First Result

Investigations of the Low Energy Excess

- Possible detector anomalies or reconstruction problems
- Incorrect estimation of the background
- New sources of background
- New physics including exotic oscillation scenarios, neutrino decay, Lorentz violation, …….

Any of these backgrounds or signals could have an important impact on other future oscillation experiments.

Status of Low Energy ν_e Candidate Analysis Since Oscillation Publication

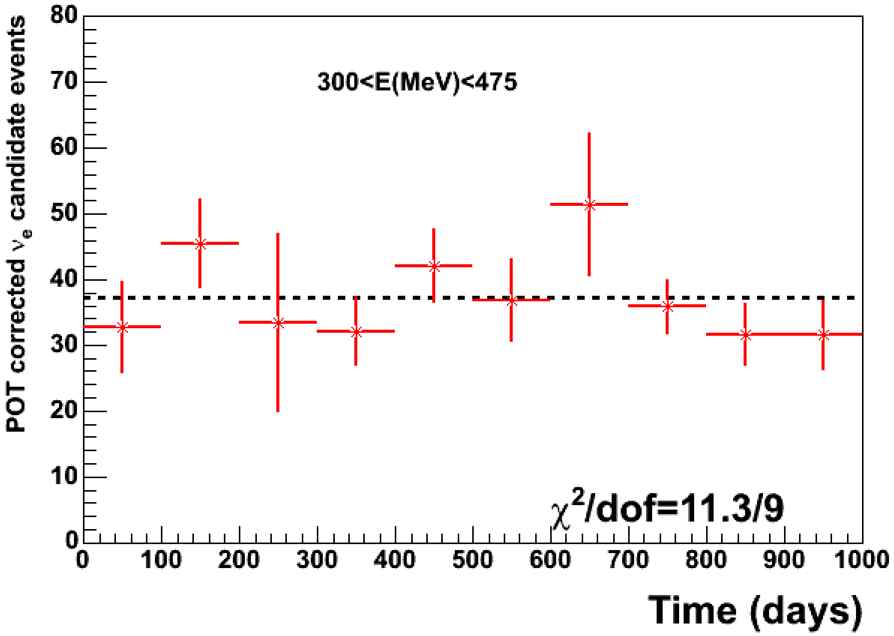
- Have observed a ~4 sigma excess down to 200 MeV (including systematic errors).
- Confirmed excess is electromagnetic (electron or gamma-ray), i.e. particle ID is working at low energy. MiniBooNE has no ability to distinguish gammas from electrons
- Events have normal reconstruction, e.g. Visible energy, radius, x,y,z, beam angle, run time, etc.
- Major sources of backgrounds all look well modelled, e.g. dirt, radiative delta decay, mis-ID pions and muons.
- Working on possible new sources of single gamma-rays.
- Currently analyzing neutrinos from NuMI source, horn-off, and anti-neutrino data sets.

Detector Anomalies or Reconstruction Problems

No Detector anomalies found

- Example: rate of electron candidate events is constant (within errors) over course of run

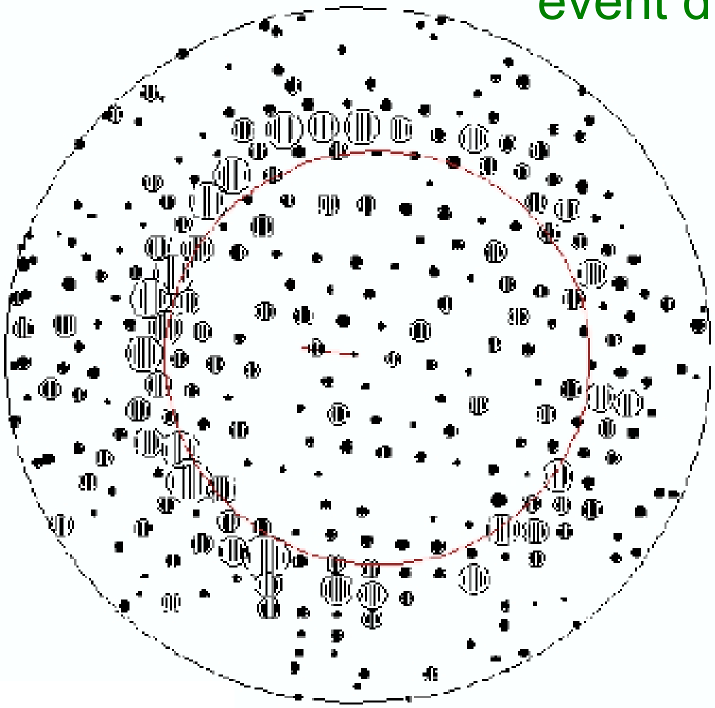
event/POT vs day, 300<Enu<475 MeV



No Reconstruction problems found

- All low-E electron candidate events have been examined via event displays, consistent with 1-ring events

example signal-candidate event display

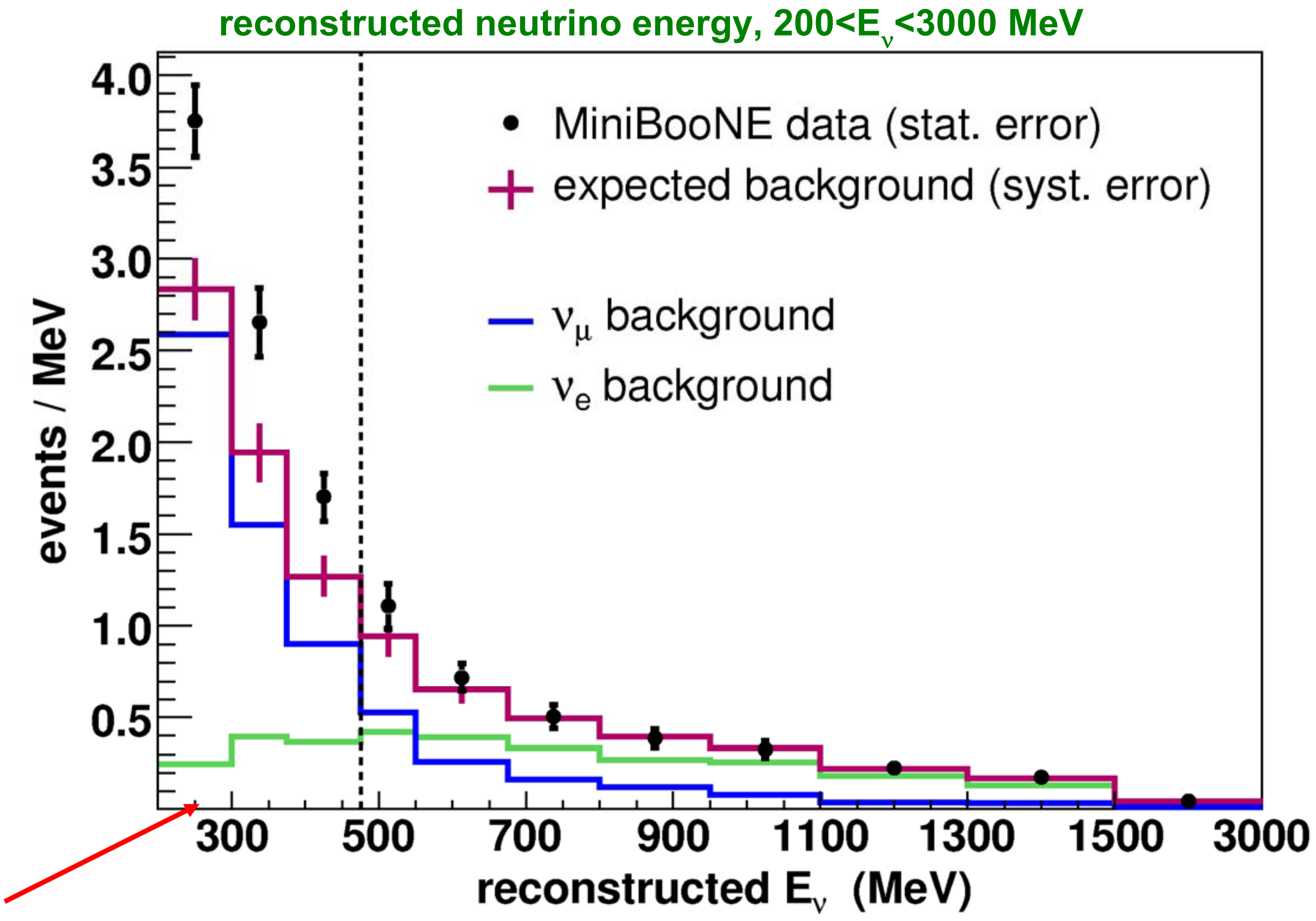


Signal candidate events are consistent with single-ring neutrino interactions

⇒ But could be either electrons or photons

New Result for 200 – 300 MeV Bin

Excess persists below 300 MeV but background is also rising



New low
energy bin

Background Estimates

E_ν^{QE} [MeV]	200-300	300-475	475-1250	
total background	284±25	274±21	358±35	(syst. error)
ν_e intrinsic	26	67	229	
ν_μ induced	258	207	129	
NC π^0	115	76	62	
NC $\Delta \rightarrow N\gamma$	20	51	20	
Dirt	99	50	17	
other	24	30	30	
Data	375±19	369±19	380±19	(stat. error)
Data-MC	91±31	95±28	22±40	(stat+syst)

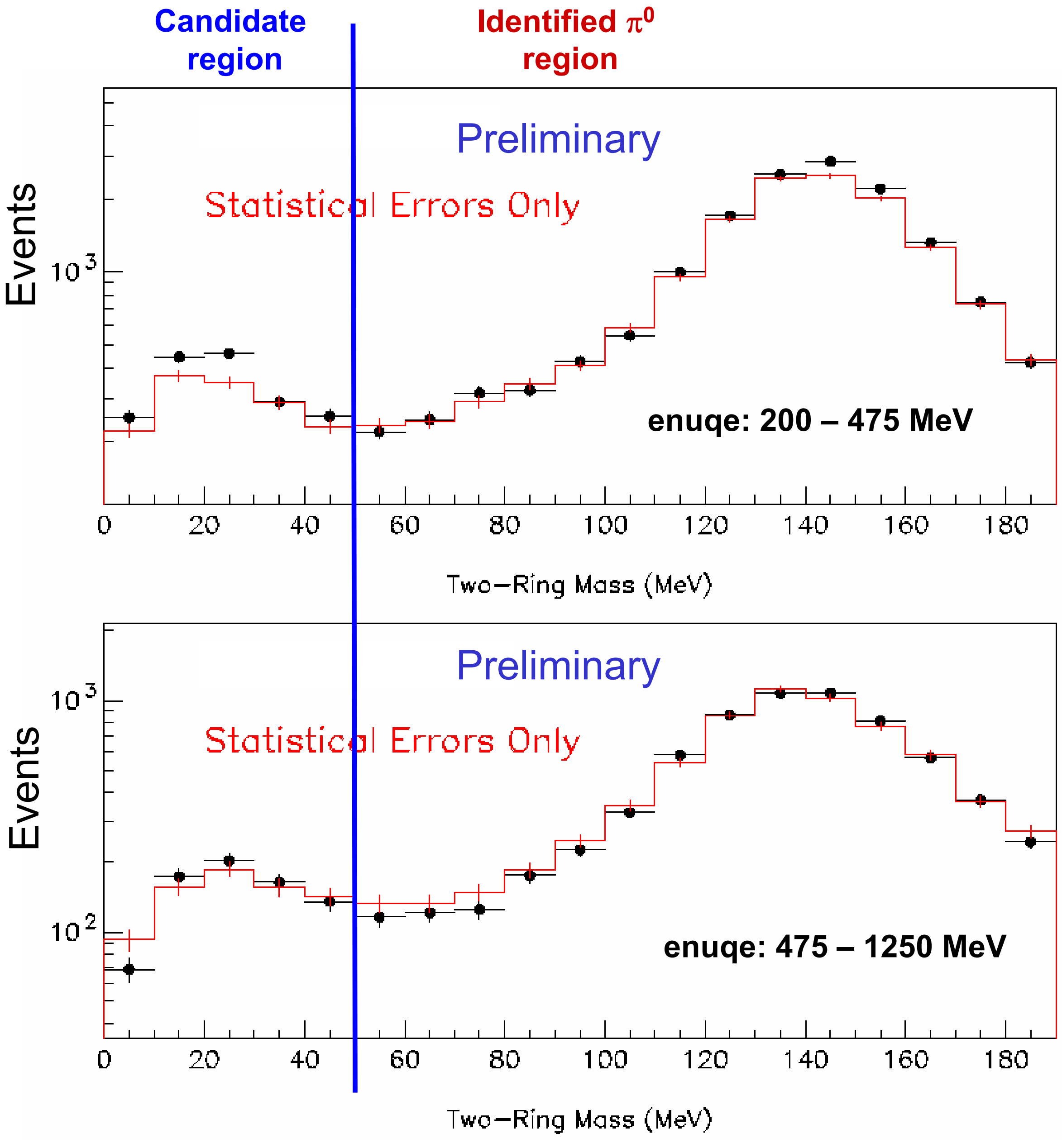
“Dirt Background”
ν interactions outside of the detector that mainly give a single gamma from π^0 decay

- NC π^0 largest
- Dirt background significant
- NC $\Delta \rightarrow N\gamma$ falling off
- Intrinsic ν_e negligible

- Three main:
  - NC π^0
  - Dirt bkgnd
  - NC $\Delta \rightarrow N\gamma$
- Intrinsic ν_e small

- Intrinsic ν_e largest
- NC π^0 significant
- Others small

How Well Does the NC π^0 Constraint Work?

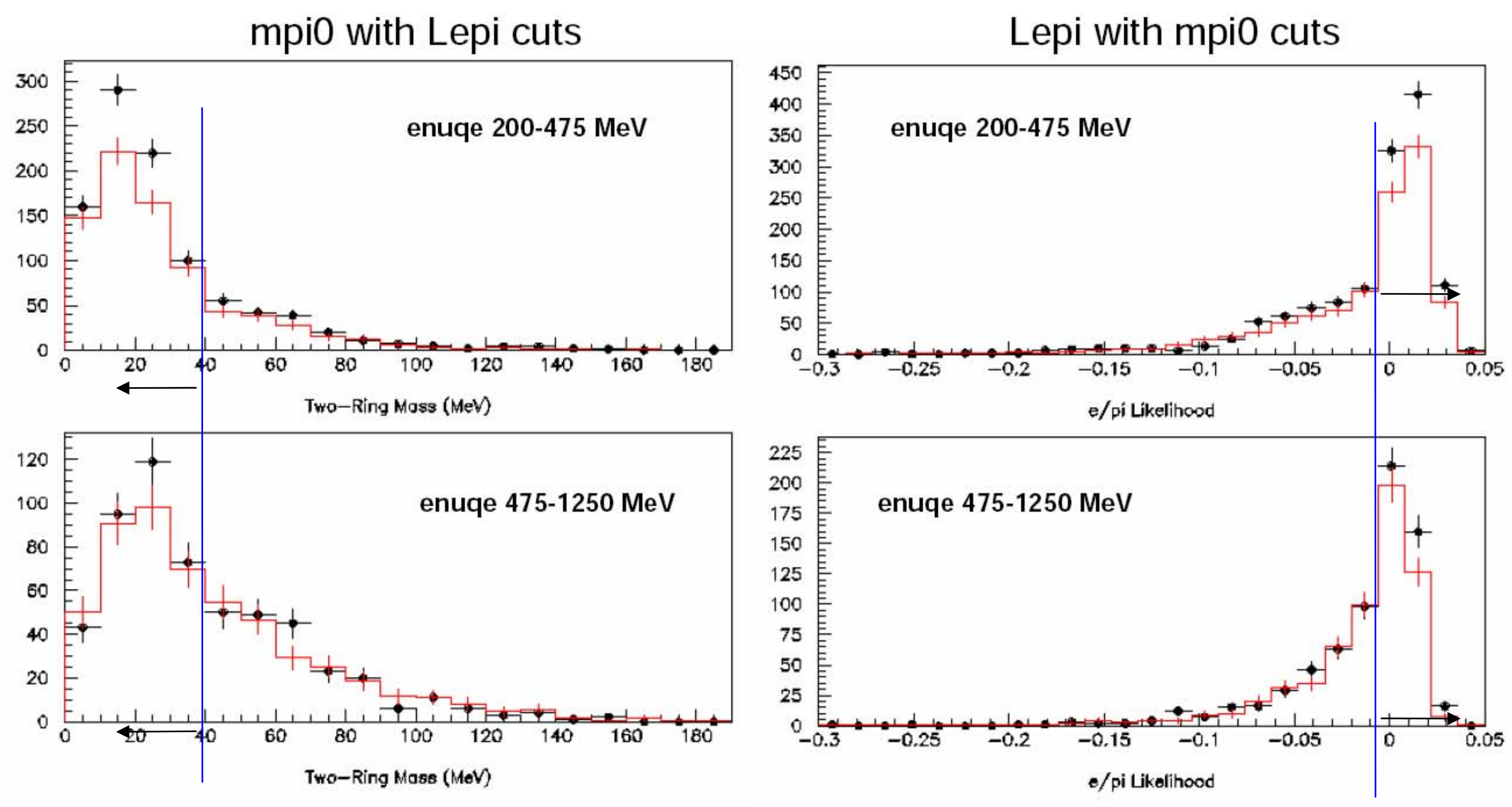


Results after removing the mass and $L_{e\pi}$ cut

- Good agreement in “Identified π^0 region”
- Excess for low energy sample clearly observed below 50 MeV
- Excess cannot be explained by simply scaling up the π^0 and Rad-Δ background

Black points: Data
Red histogram: Prediction

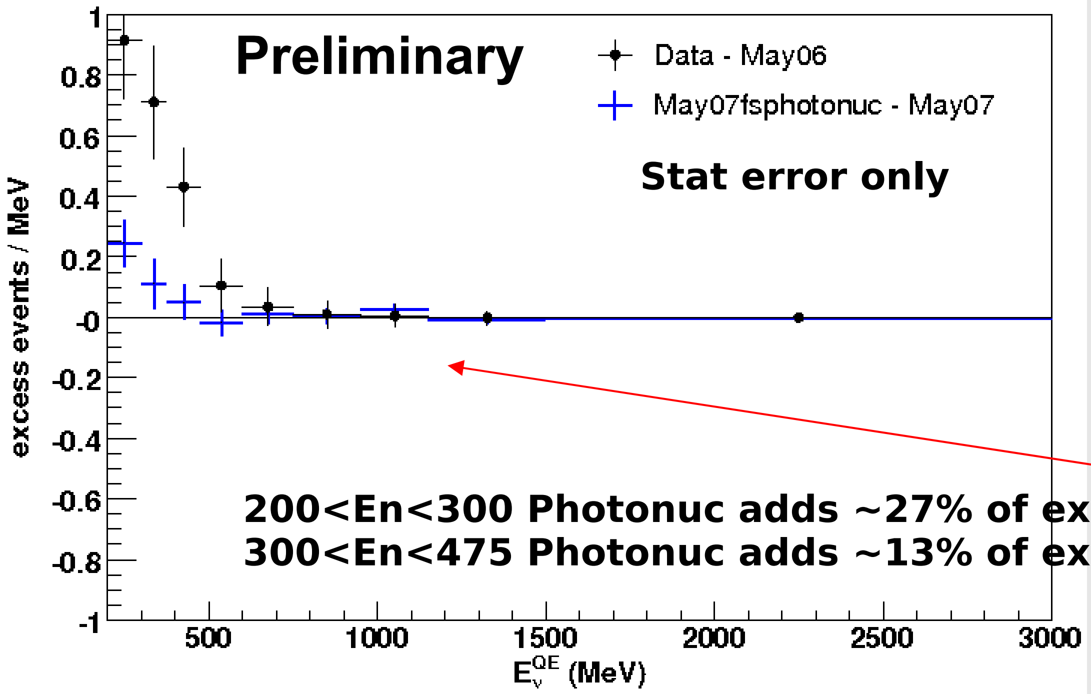
Particle Identification



No major discrepancy in Particle Identification

Possible Sources of Additional Single Gamma Backgrounds

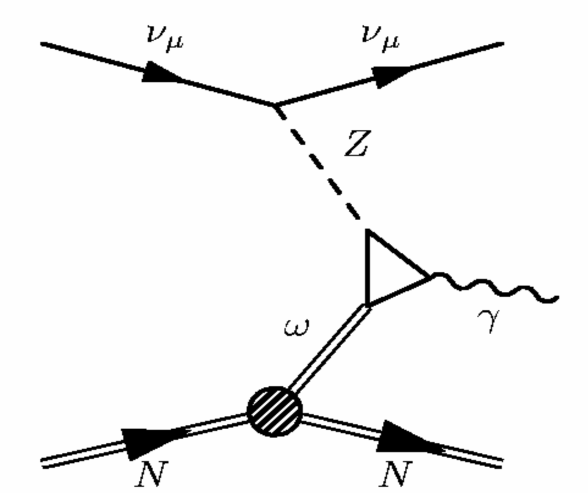
Since MiniBooNE cannot tell an electron from a single gamma, any process that leads to a single gamma in the final state can be a background



200<En<300 Photonuc adds ~27% of excess
300<En<475 Photonuc adds ~13% of excess

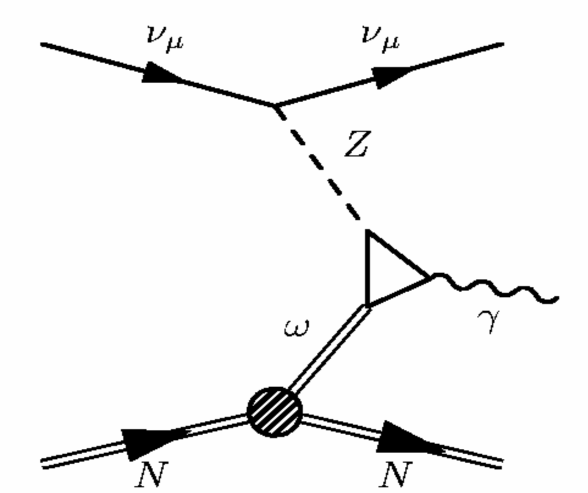
- Processes that remove/absorb one of the gammas from a ν_μ-induced NC $\pi^0 \rightarrow \gamma\gamma$
  - Photonuclear absorption was missing from our GEANT3 detector Monte Carlo
    - But tends to give extra final state particles.
    - Reduces size of excess
    - Systematics being calculated
    - No effect above 475 MeV

- ν processes that produce a final state single gamma
  - Example: “Anomaly mediated neutrino-photon interactions at finite baryon density.”
    - Standard Model process
      $\Rightarrow$ Under active investigation, prediction of
      ~140 $(g_\omega/10)^4$ events, where g_ω is 10 to 30.
    - Can use photon energy to check prediction.
      (Harvey, Hill, and Hill, arXiv:0708.1281[hep-ph])



Is the Low-Energy Excess Due to a Signal?

- Anomaly Mediated Neutrino-Photon Interactions at Finite Baryon Density (arXiv:0708.1281: Jeffrey A. Harvey, Christopher T. Hill, Richard J. Hill)
- CP-Violation 3+2 Model: Maltoni & Schwetz, arXiv:0705.0107
- Extra Dimensions 3+1 Model: Pas, Pakvasa, & Weiler, Phys. Rev. D72 (2005) 095017
- Lorentz Violation: Katori, Kostelecky, & Tayloe, Phys. Rev. D74 (2006) 105009
- CPT Violation 3+1 Model: Barger, Marfatia, & Whisnant, Phys. Lett. B576 (2003) 303



M. Sorel, et. al. hep-ph/0305255

3+2 Analysis

Idea: If light sterile neutrinos (ν_s) exist, then:

Includes CP phase; $\phi = -\phi$ for antineutrinos

$\nu_\mu \rightarrow \nu_s \rightarrow \nu_e$

$$\begin{aligned} P(\nu_\alpha \rightarrow \nu_\beta) = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2 \sin^2 x_{41} + 4|U_{\alpha 5}|^2|U_{\beta 5}|^2 \sin^2 x_{51} + \\ 8|U_{\alpha 5}||U_{\beta 5}||U_{\alpha 4}||U_{\beta 4}| \sin x_{41} \sin x_{51} \cos(x_{54} - \phi_{54}) \end{aligned}$$

$\nu_\mu \rightarrow \nu_s$

$\nu_e \rightarrow \nu_s$

$$\begin{aligned} P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - 4[(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2)(|U_{\alpha 4}|^2 \sin^2 x_{41} + |U_{\alpha 5}|^2 \sin^2 x_{51}) + \\ +|U_{\alpha 4}|^2|U_{\alpha 5}|^2 \sin^2 x_{54}] \end{aligned}$$

With SBL approximation $\Delta m_{solar}=0$, $\Delta m_{ATM}=0$, and $x_{ij}= \Delta m_{ij}L/4E$

Experimental constraints from:

LSND, KARMEN, NOMAD, MB, CCFR, CDHS, CHOOZ, BUGEY (+ atm constraint)

appearance experiments ($\nu_\mu \rightarrow \nu_e$)

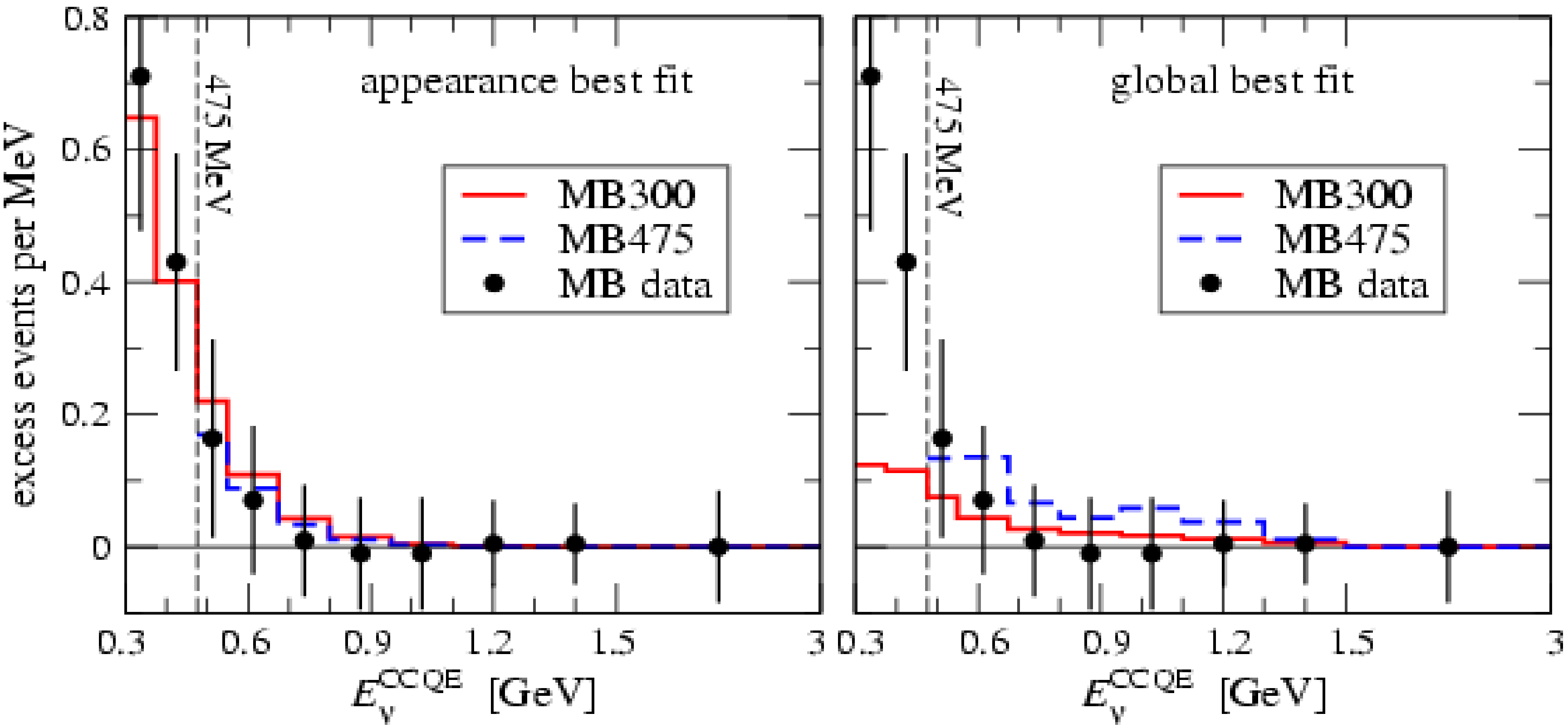
disappearance experiments ($\nu_\mu \not\rightarrow \nu_\mu$ or $\nu_e \not\rightarrow \nu_e$)

(ν_μ disappearance Constraint)

3+2 models can produce differences between neutrino and antineutrino appearance rates!

Analysis by Maltoni & Schwetz [hep-ph/0705.0107]

3+2 Global Fit Results



3+2 neutrino models:

- provide a **good fit** to LSND and the recent MB data
- can **account for the low energy** event **excess in MB**

However:

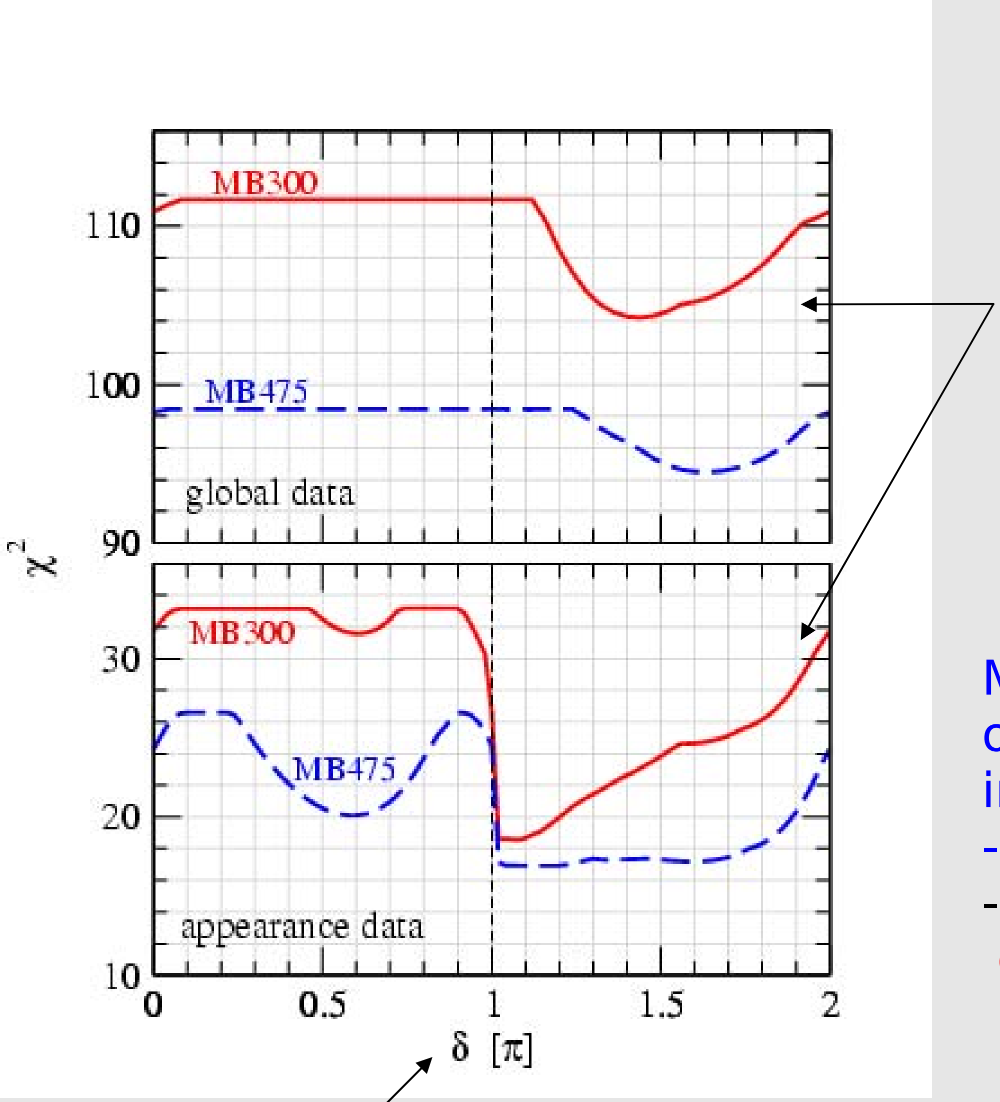
- there is significant **tension between appearance and disappearance data**

Note: analysis done without full MiniBooNE error matrix

MB will perform full analysis, G. Karagiorgi.

3+2 Model CP Phase Fits

Has CP violation been observed?



Improved fits with CP phase included!

MiniBooNE antineutrino oscillation analysis will be interesting.

-could see LSND oscillations

-may need more antineutrino data for decent sensitivity!

CP conserving value

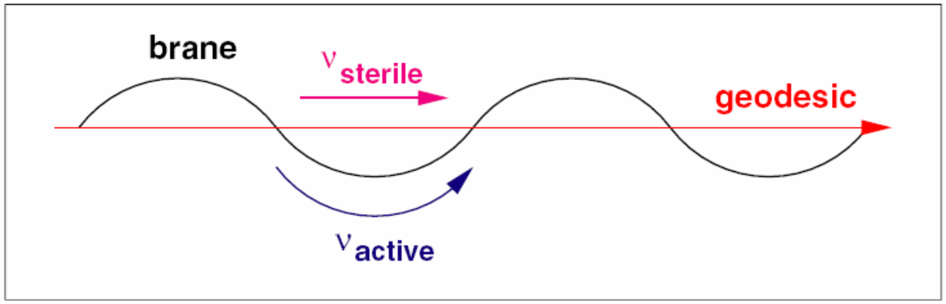
Sterile Neutrinos That Take Shortcuts in Extra Dimensions

- Prior to MiniBooNE's first result, it was put forward that sterile neutrinos can take shortcuts in extra dimensions.

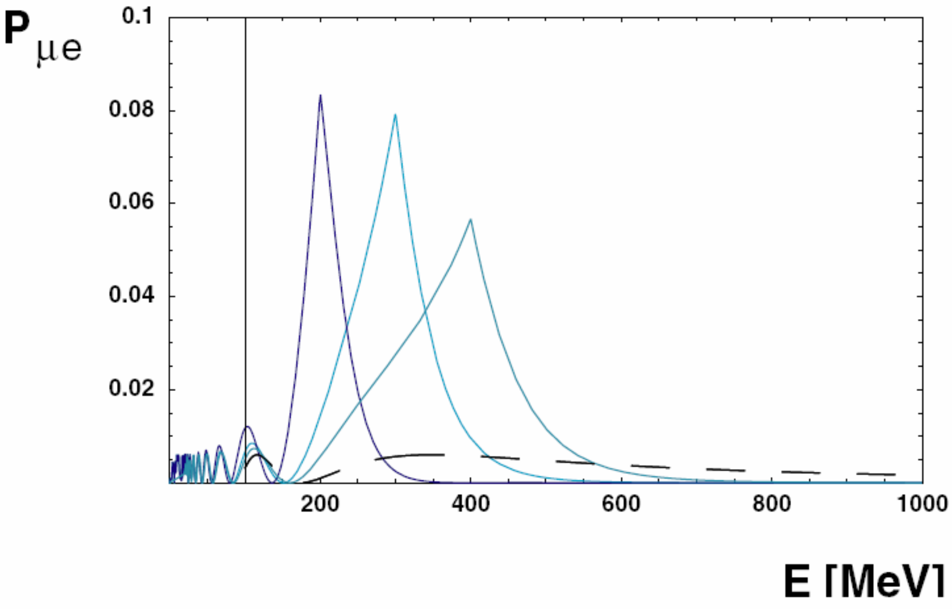
(Päs, Pakvasa, Weiler, Phys.Rev. D72 095017, 2005)

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

Schematic representation of a periodically curved brane in Minkowski spacetime.



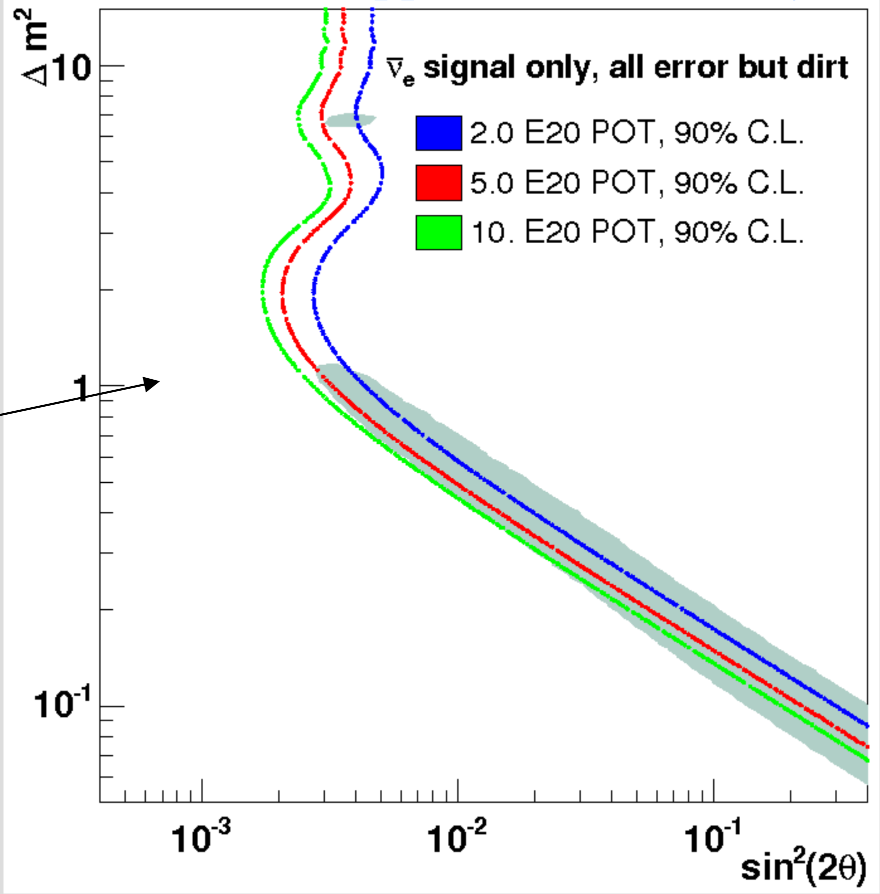
Oscillation probabilities for MiniBooNE as a function of the neutrino energy.



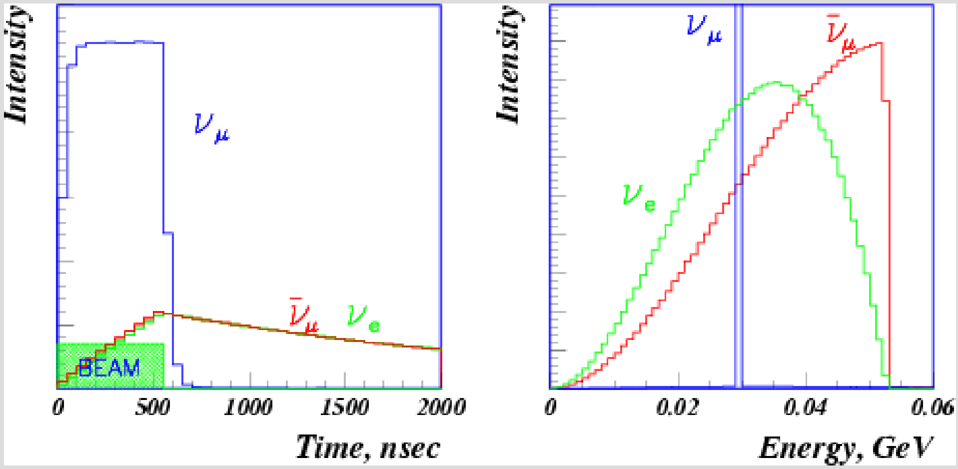
Future Work

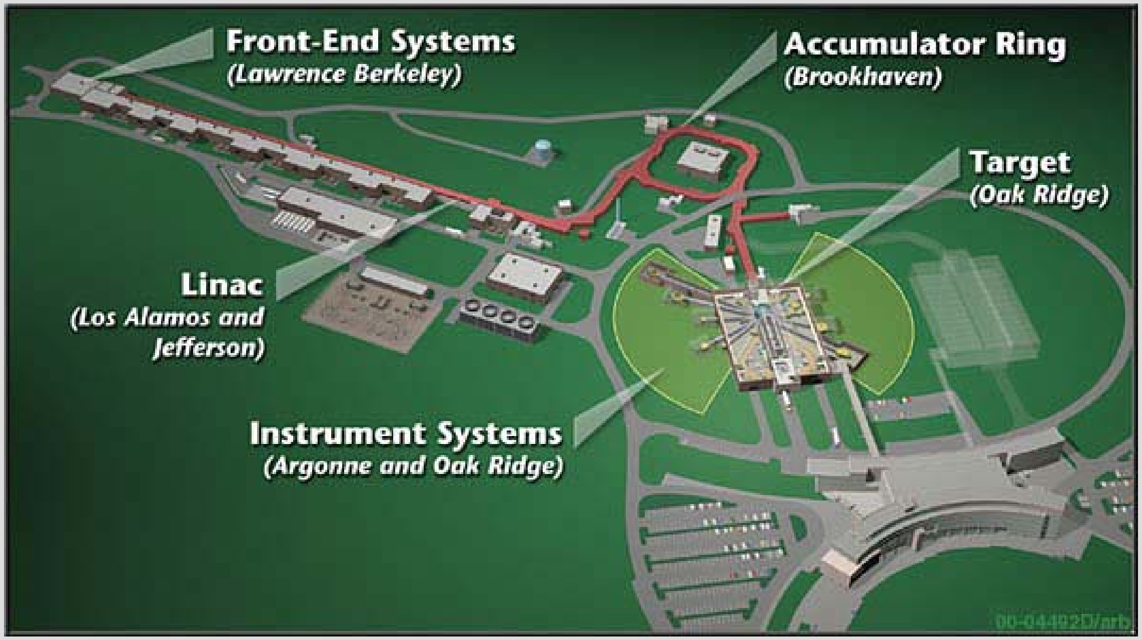
- Understand the low-energy excess of events!
- Analyze antineutrino data, NuMI ν in MiniBooNE data, & SciBooNE data.
- Approved to run two more years to collect enough antineutrino data to test LSND with antineutrinos.
- If low-energy excess is consistent with a signal, new experiments at FNAL (BooNE) and/or SNS (OscSNS) will be proposed to explore physics Beyond the Standard Model.

Anti-nue Appearance Sensitivity



OscSNS at ORNL: A Smoking Gun Measurement of Active-Sterile Neutrino Oscillations





SNS: ~1 GeV, ~1.4 MW

$\bar{\nu}_\mu$ -> $\bar{\nu}_e$ $\Delta(L/E) \sim 3\%$; $\bar{\nu}_e\, p$ -> $e^+ n$

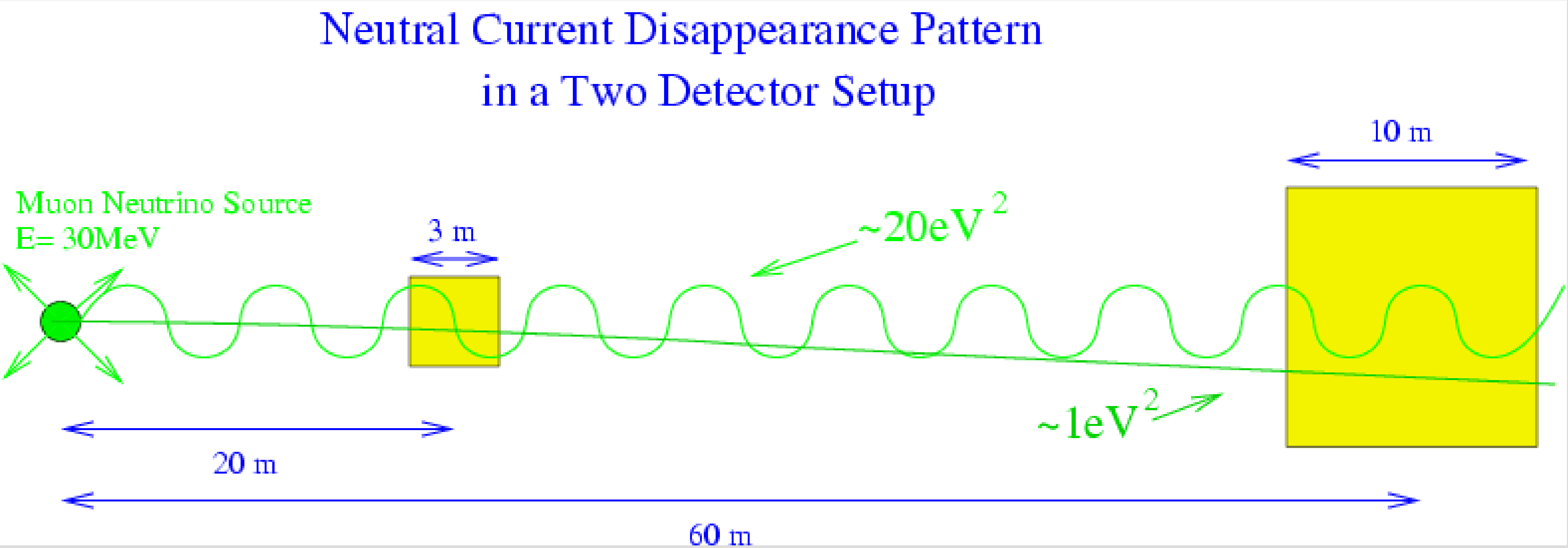
ν_μ -> ν_s $\Delta(L/E) < 1\%$; **Monoenergetic ν_μ** ; $\nu_\mu\, C$ -> $\nu_\mu\, C^*(15.11)$

OscSNS would be capable of making precision measurements of ν_e appearance & ν_μ disappearance and proving, for example, the existence of sterile neutrinos! (see Phys. Rev. D72, 092001 (2005)). Flux shapes are known perfectly and cross sections are known very well.

Search for Sterile Neutrinos with OscSNS Via Measurement of NC Reaction:

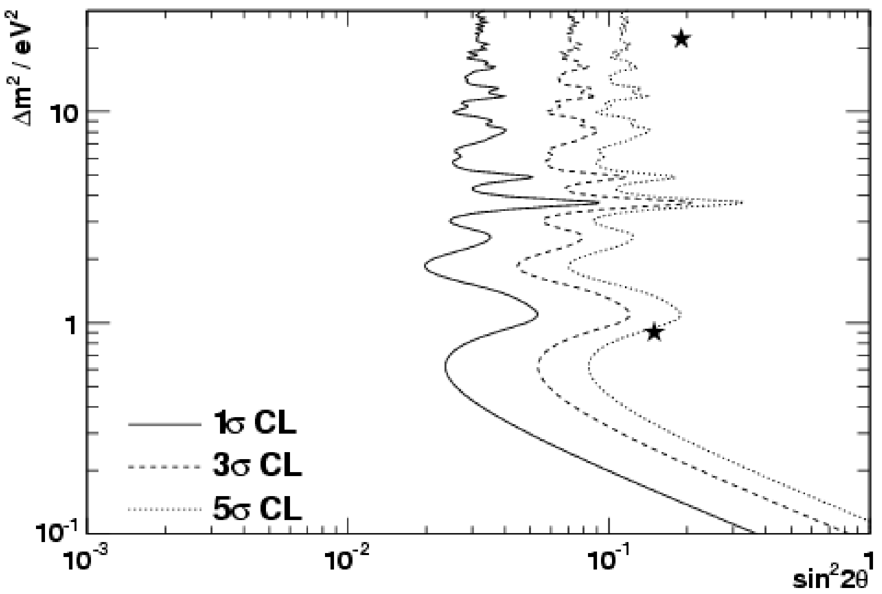
$\nu_\mu \, C \rightarrow \nu_x \, C^*(15.11)$

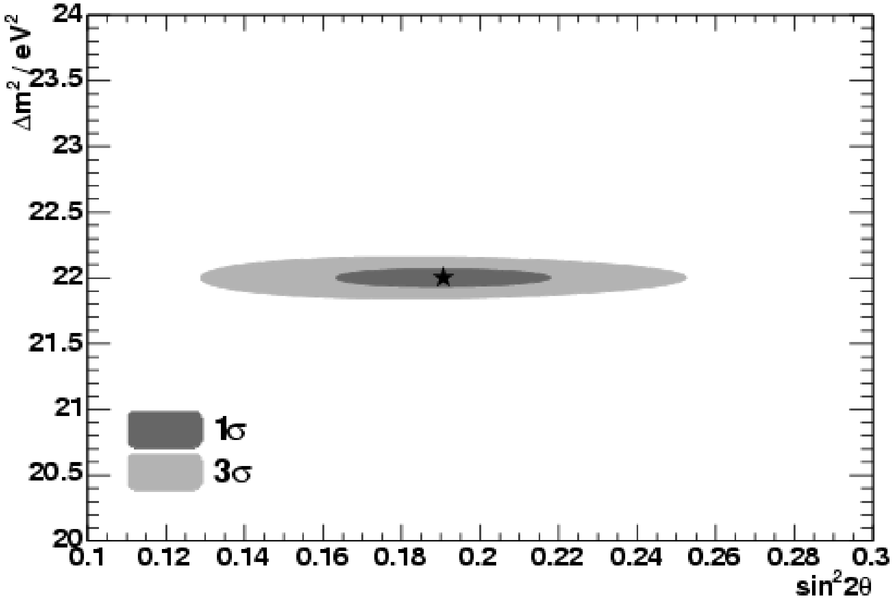
Garvey et al., Phys. Rev. D72 (2005) 092001

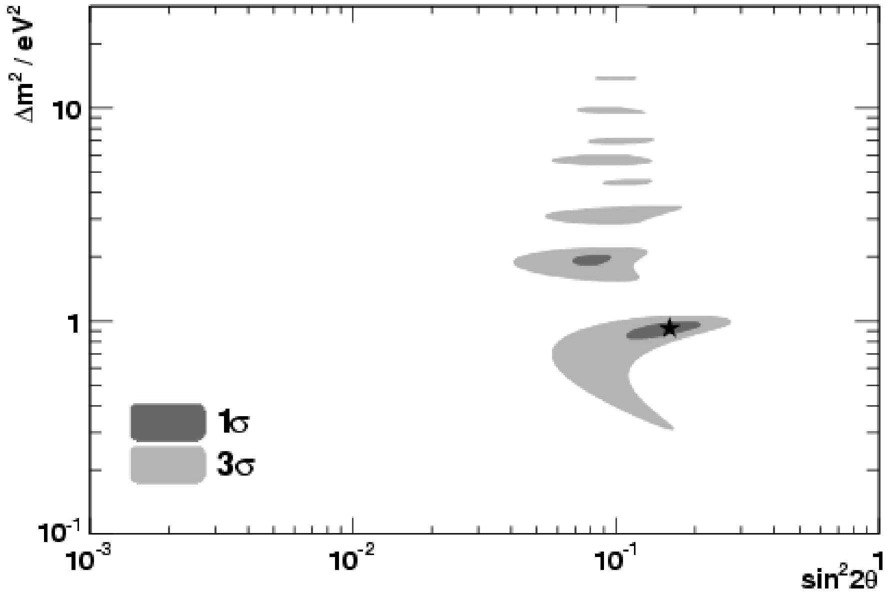


Measurement of 3+2 Model with OscSNS

Garvey et al., Phys. Rev. D72 (2005) 092001







Conclusions

- Despite recent progress, many basic properties of neutrinos are still unknown and the possibility of future surprises remains strong.

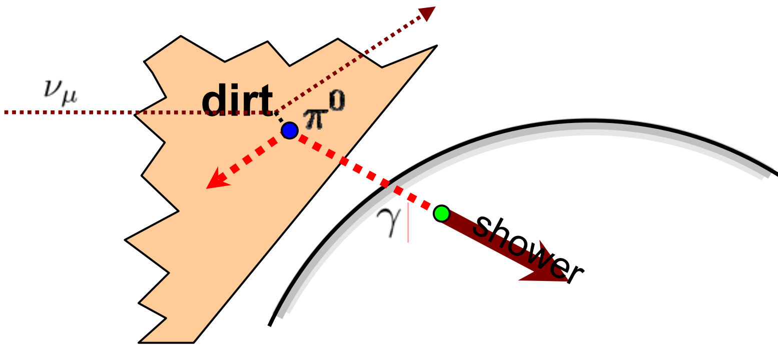
- MiniBooNE rules out a simple $\nu_\mu \rightarrow \nu_e$ appearance-only model as an explanation of the LSND excess at 98% CL.
  (Phys. Rev. Lett. 98, 231801 (2007), arXiv:0704.1500v2 [hep-ex])

- However, more events are observed than expected in the lower energy range from $200 < E_\nu^{QE} < 475$MeV.

- This unexplained deviation is under intense investigation

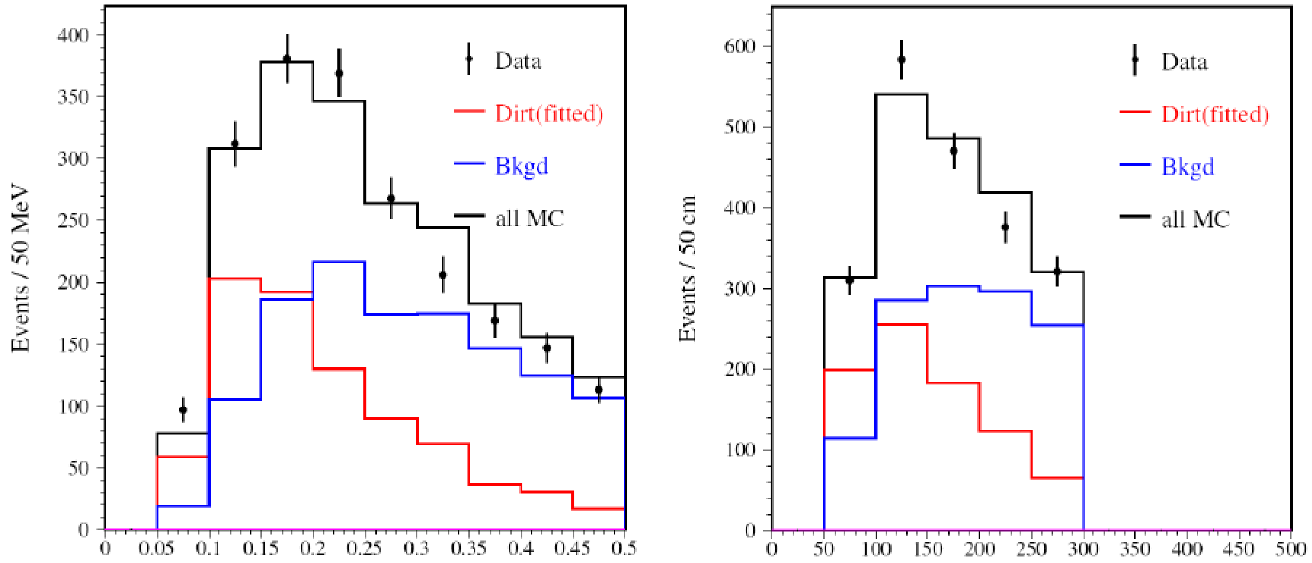
Backup Slides

"Dirt" background



- dirt background is due to ν interactions outside detector creating neutrals that enter tank
- **measured** in "dirt-enhanced" samples:
    - before box-opening, fit predicted: 1.00±0.15
    - in different (open) sample, a fit says that meas/pred is 1.08±0.12.
- shape of visible E and distance-to-wall distributions are well-described by MC

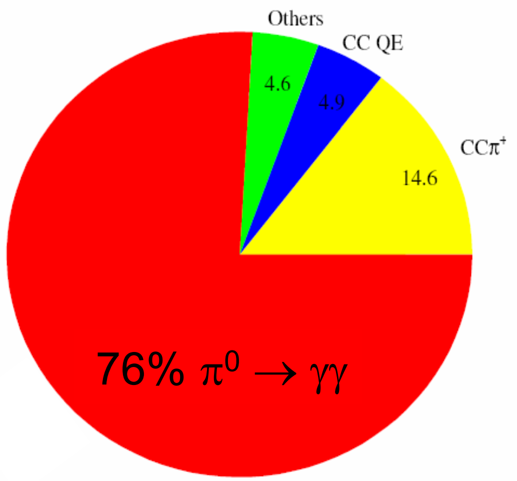
results from dirt-enhanced fits



visible energy (GeV)

dist to tank wall along track (cm)

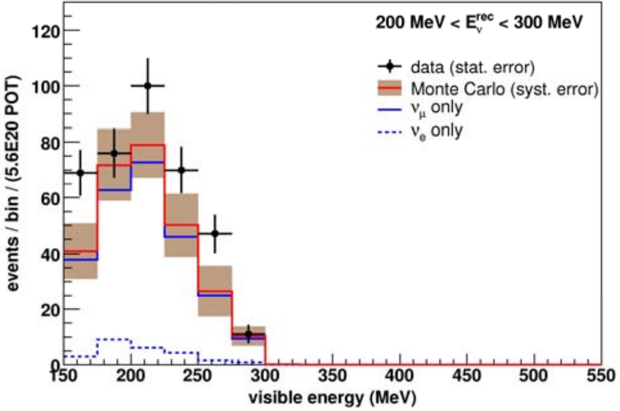
Event Type of Dirt Events

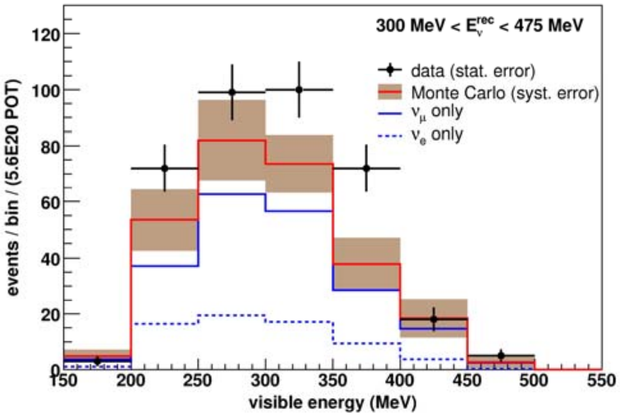


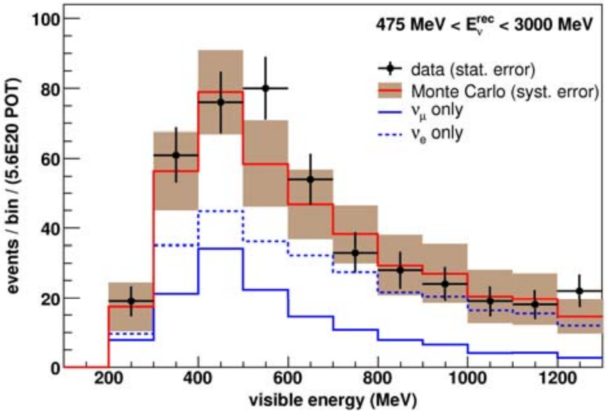
Visible Energy and cosθ of Events

200<E_ν<300 MeV **300<E_ν<475 MeV** **475<E_ν<3000 MeV**

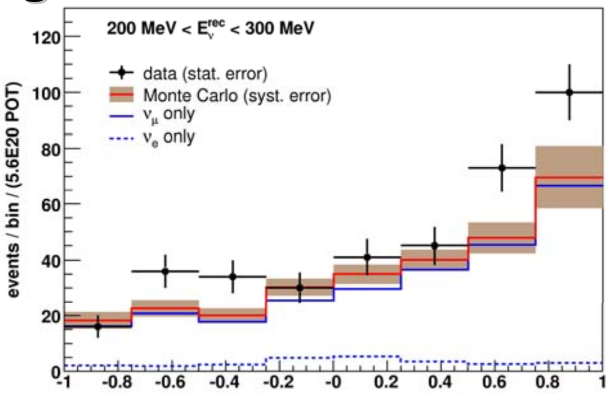
Visible energy



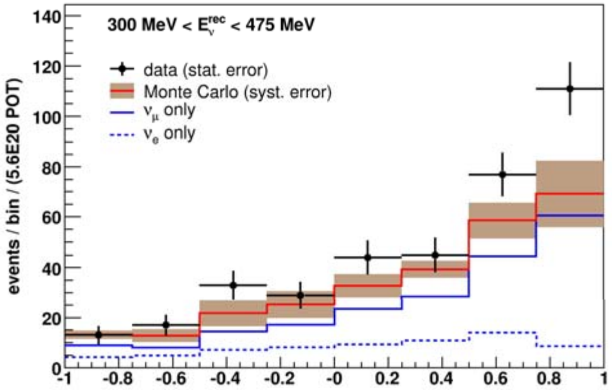




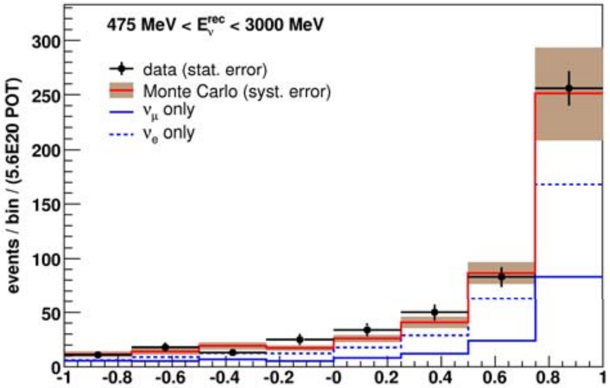
Angle



cosθ



cosθ



cosθ

-Low Energy: Excess distributed among visible E, cos Θ bins.

-High Energy:Predicted background agrees with data.