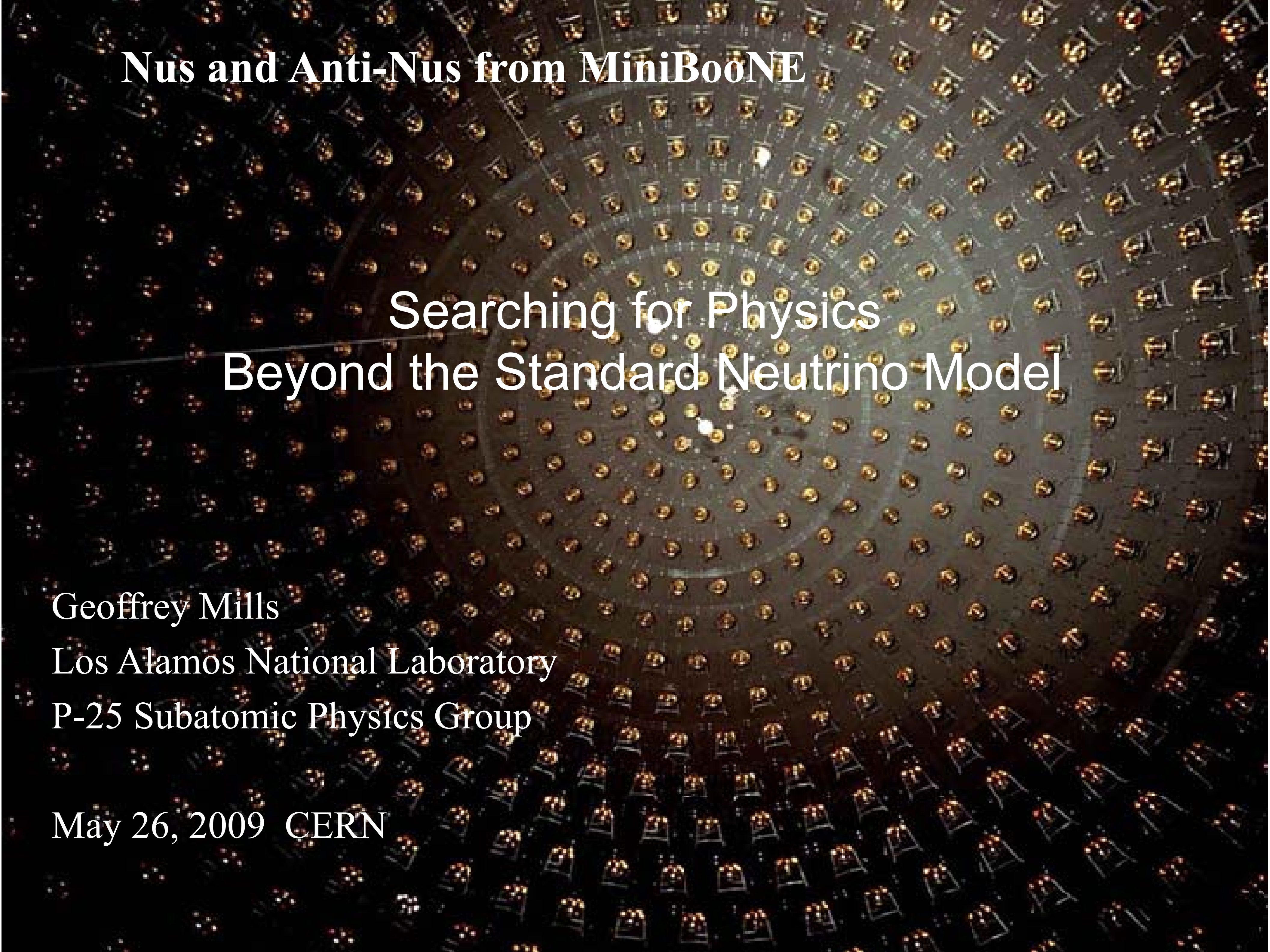


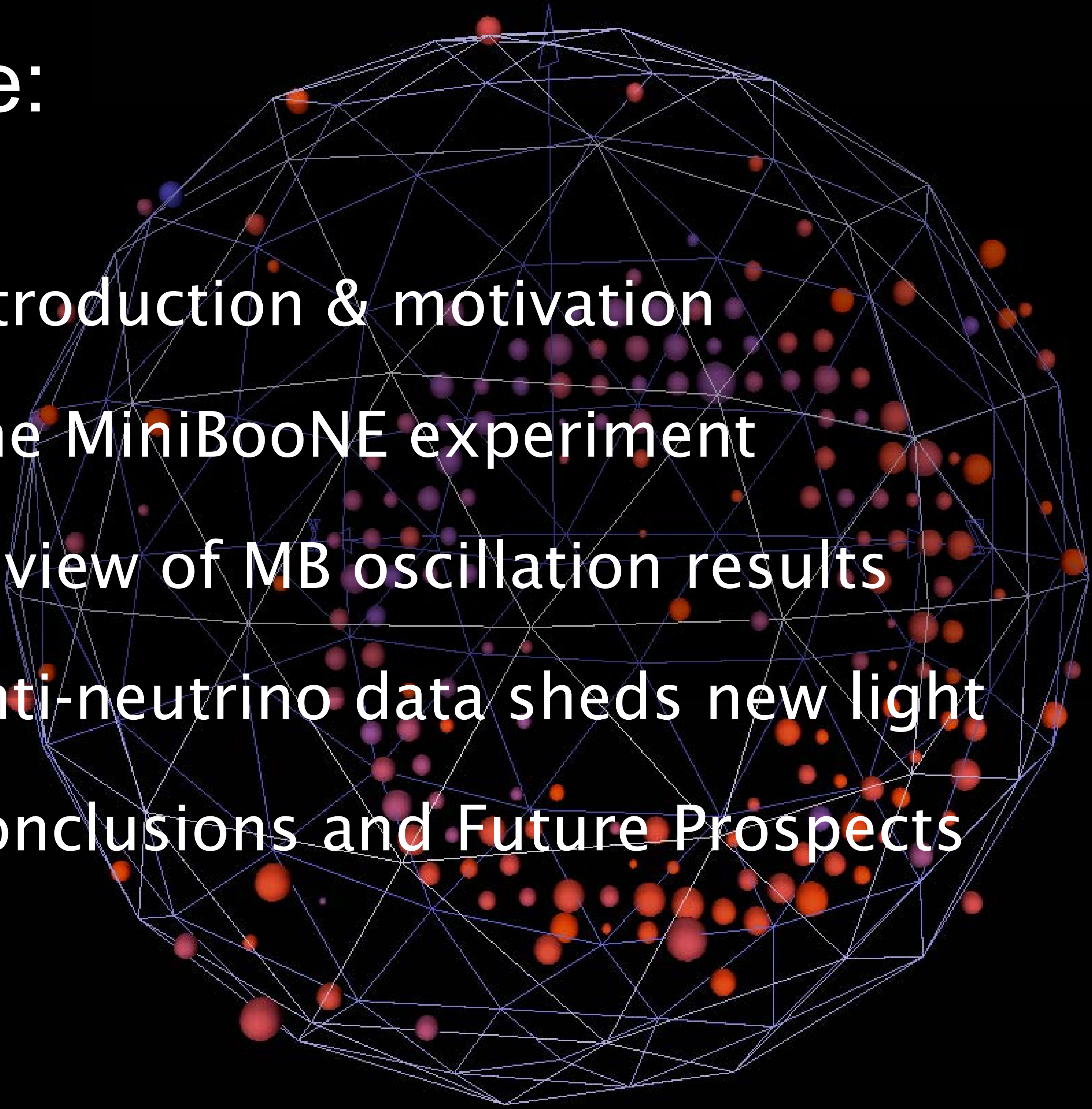
Nus and Anti-Nus from MiniBooNE

Searching for Physics Beyond the Standard Neutrino Model

Geoffrey Mills
Los Alamos National Laboratory
P-25 Subatomic Physics Group

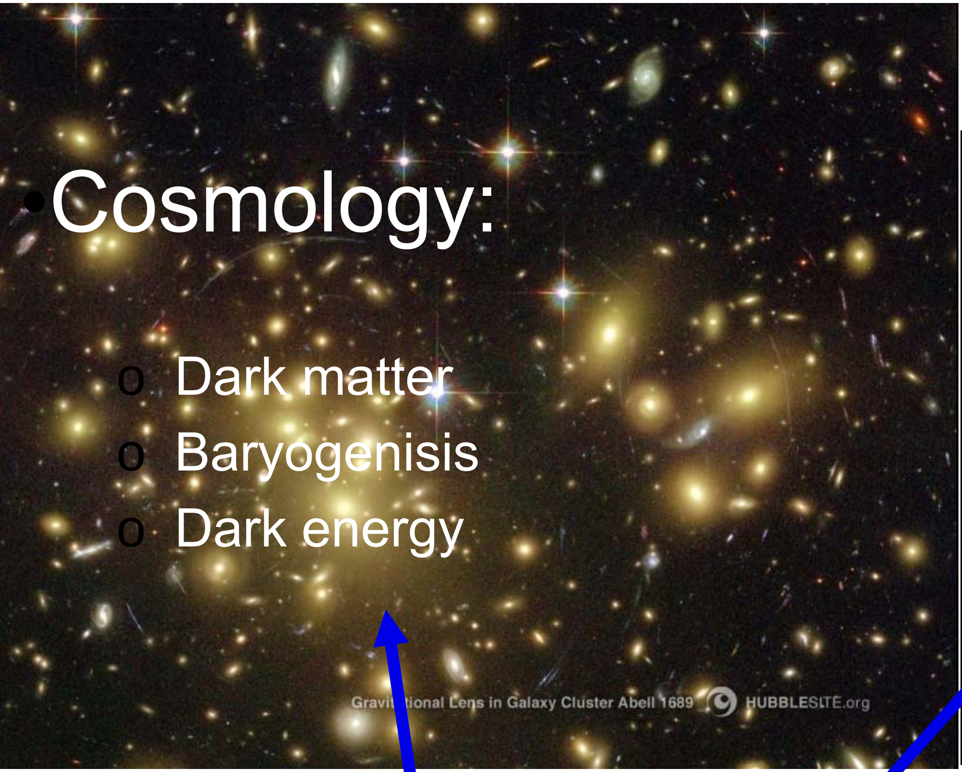
May 26, 2009 CERN

Outline:

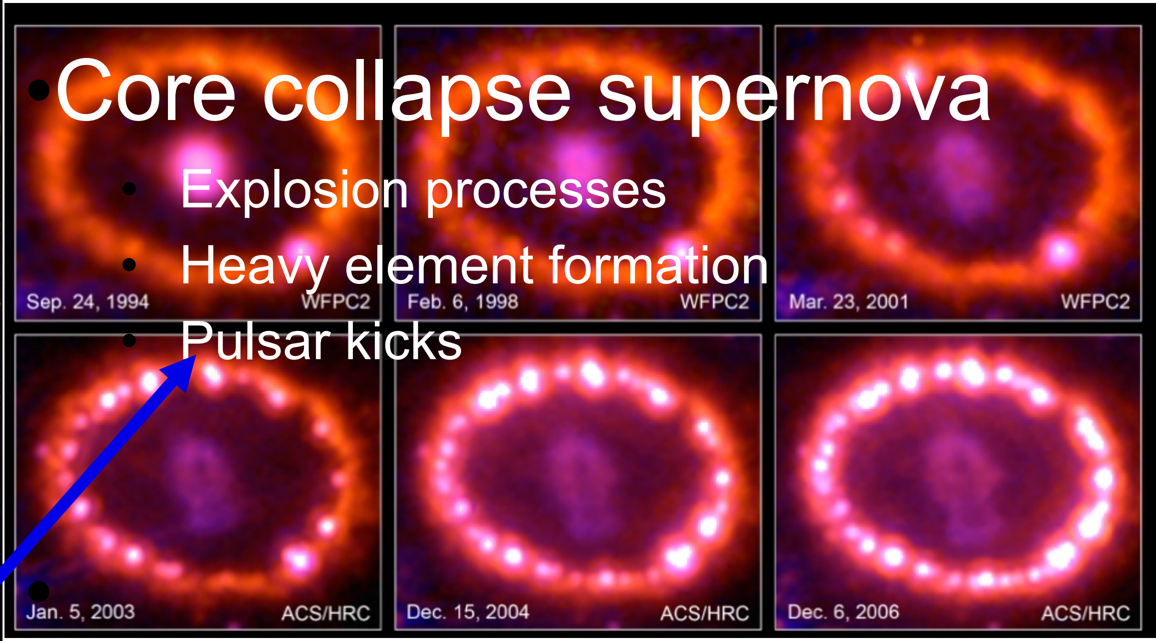


1. Introduction & motivation
2. The MiniBooNE experiment
3. Review of MB oscillation results
4. Anti-neutrino data sheds new light
5. Conclusions and Future Prospects

Motivation: astrophysics and cosmology

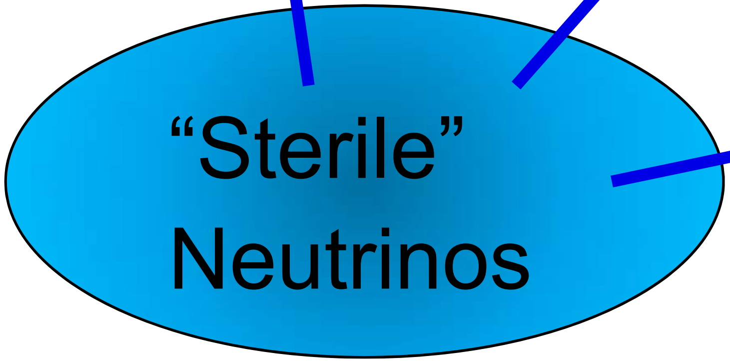


- Cosmology:
  - Dark matter
  - Baryogenisis
  - Dark energy



- Core collapse supernova
  - Explosion processes
  - Heavy element formation
  - Pulsar kicks

- Galaxies:
  - Structure formation
  - Dark galactic halo



“Sterile” Neutrinos

(“Sterile” means *very, very* weakly interacting)

Possible signatures of sterile νs in the lab:

- Nearly impossible to detect directly
  - *If the neutrino is the "ghost particle", the sterile neutrino is the "shadow of the ghost"*

- Possible active-sterile neutrino oscillations
  - Possible CP violation

- Possible decays to other particles
  - Heavy neutral leptons

There is no experimental proof that they exist, however they pose a daunting challenge to experimentalists!

Neutrino oscillations

- The oscillation patterns between the 3 known active neutrino species have been demonstrated by a number of experiments over the last two decades:
  - SNO, Kamland
  - Super-K, K2K, MINOS

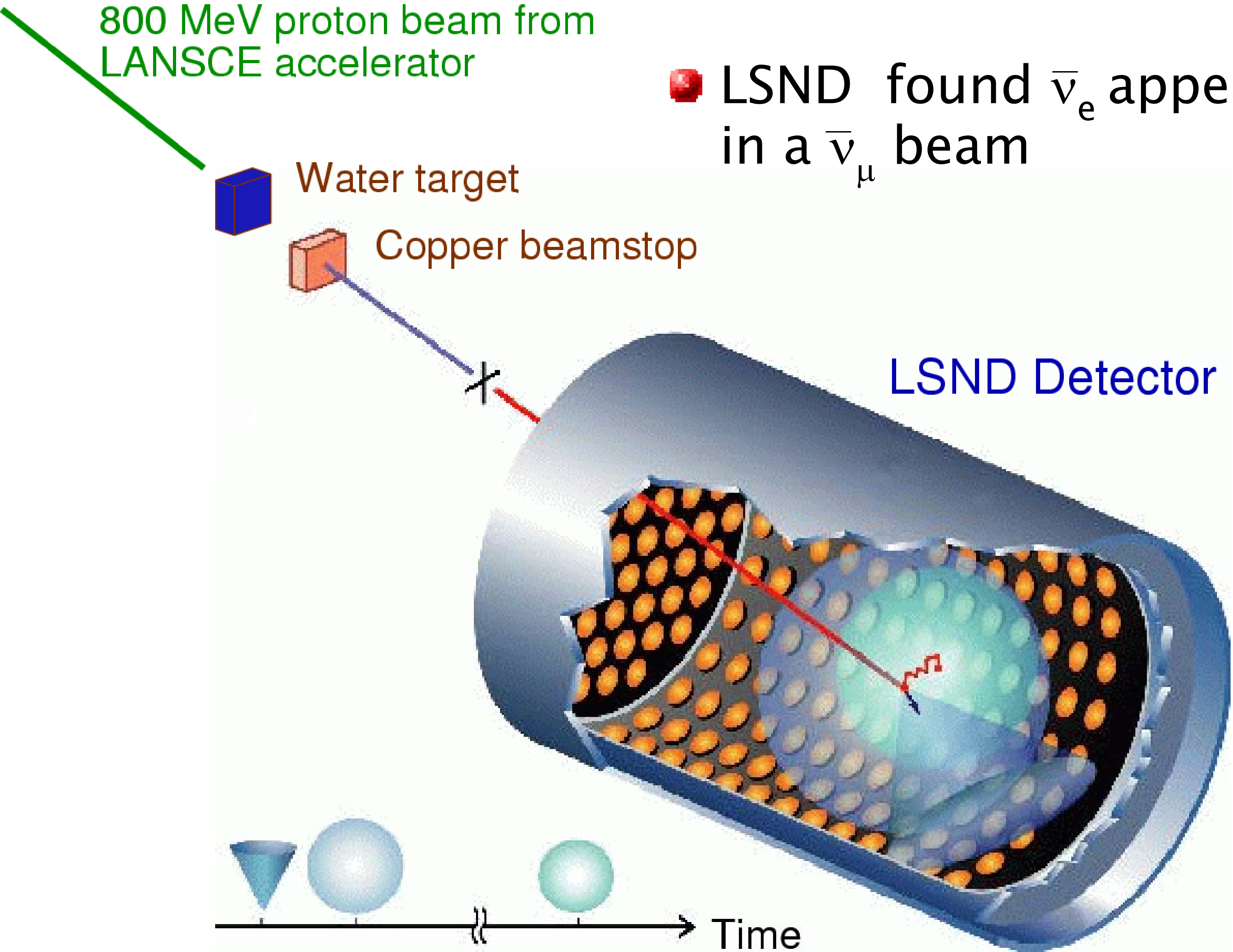
- Armed with that knowledge, measurements of neutrino behavior outside the standard 3 generations of active neutrinos indicate new physics:
  - LSND indicates that new physics may be operating

- Interpretations of such a non-standard result probe some deep theoretical issues, for example:
  - Light sterile neutrinos, neutrino decays, CP and/or CPT violation, Lorentz invariance, Extra dimensions

The investigation of neutrino oscillations at the <1% level is unique in its physics reach

The Liquid Scintillator Neutrino Detector at LANL

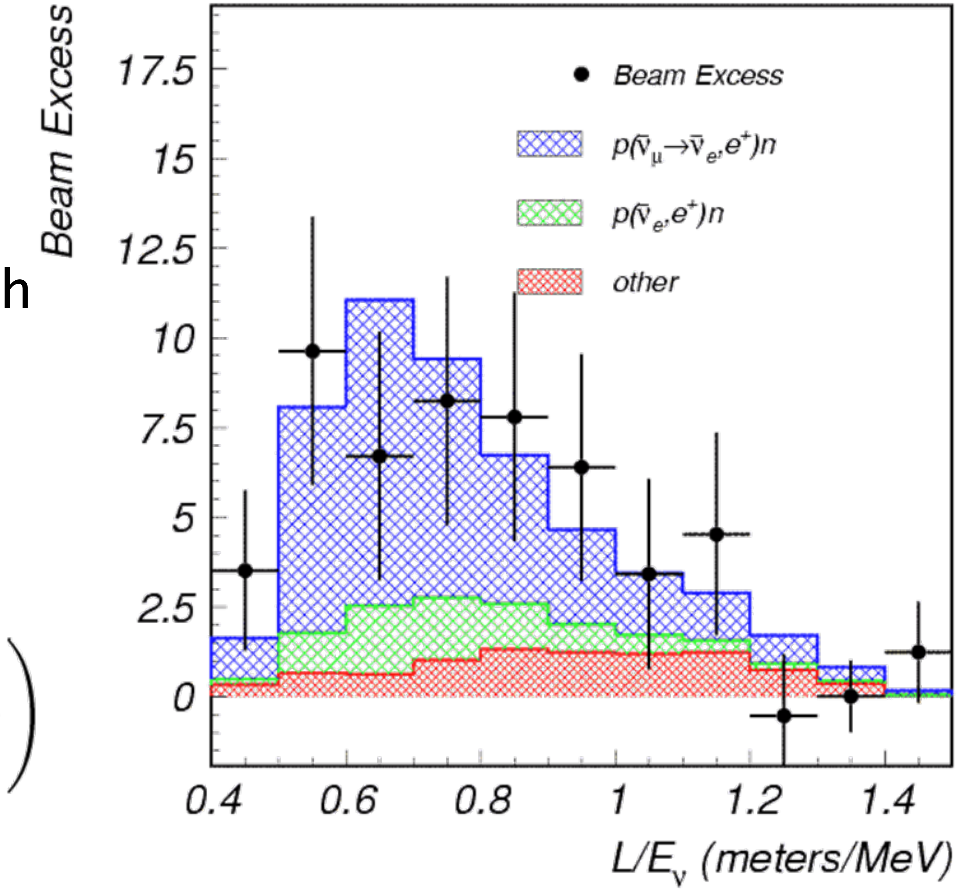
- LSND found $\bar{\nu}_e$ appearing in a $\bar{\nu}_\mu$ beam



Excess Events from LSND

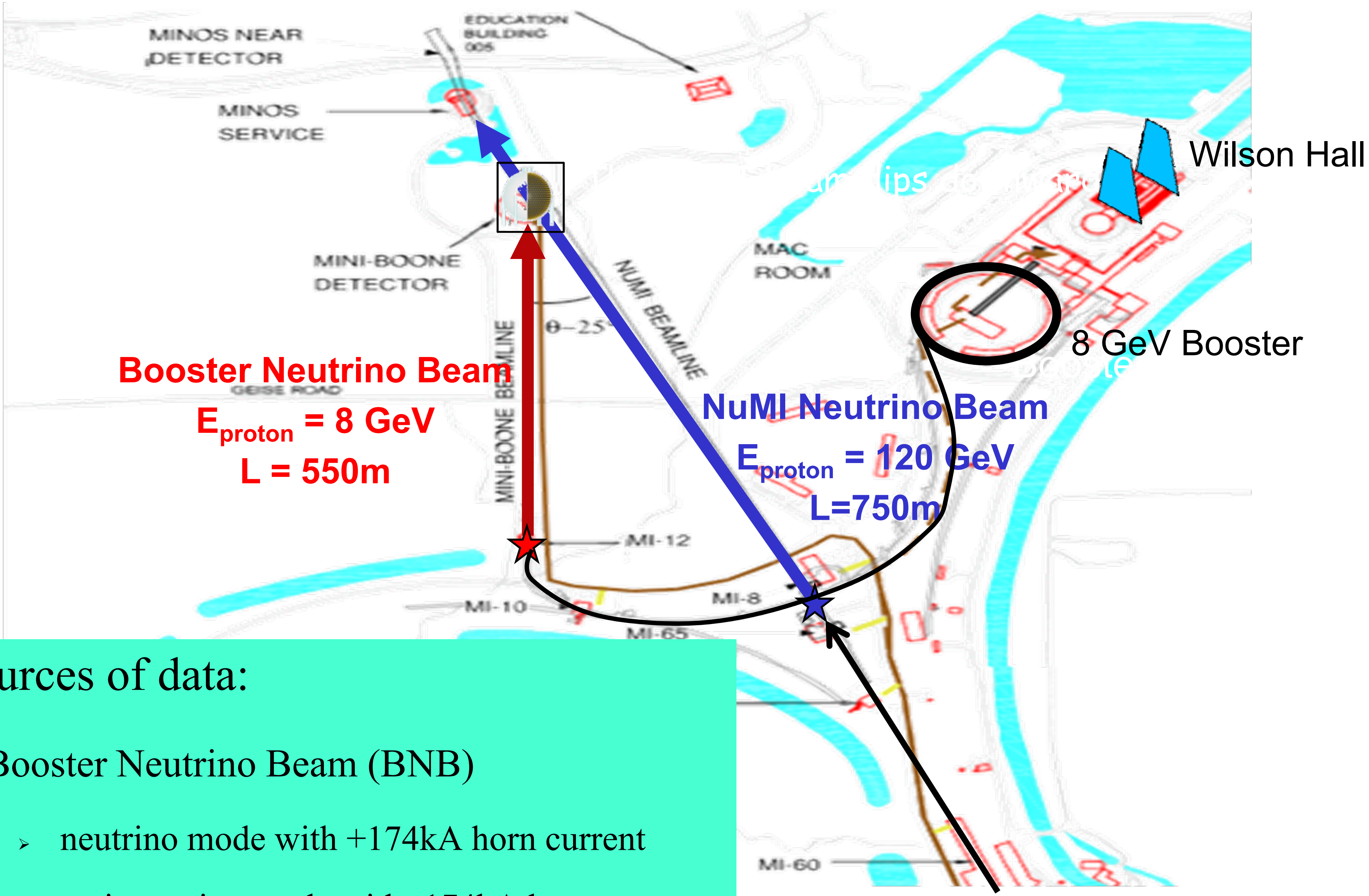
- LSND found an excess of $\overline{\nu}_e$ in $\overline{\nu}_\mu$ beam
- Signature: Cerenkov light from e^+ with delayed n-capture (2.2 MeV)
- Excess: 87.9 ± 22.4 ± 6.0 (3.8σ)
- *The data was analysed under a two neutrino mixing hypothesis**

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



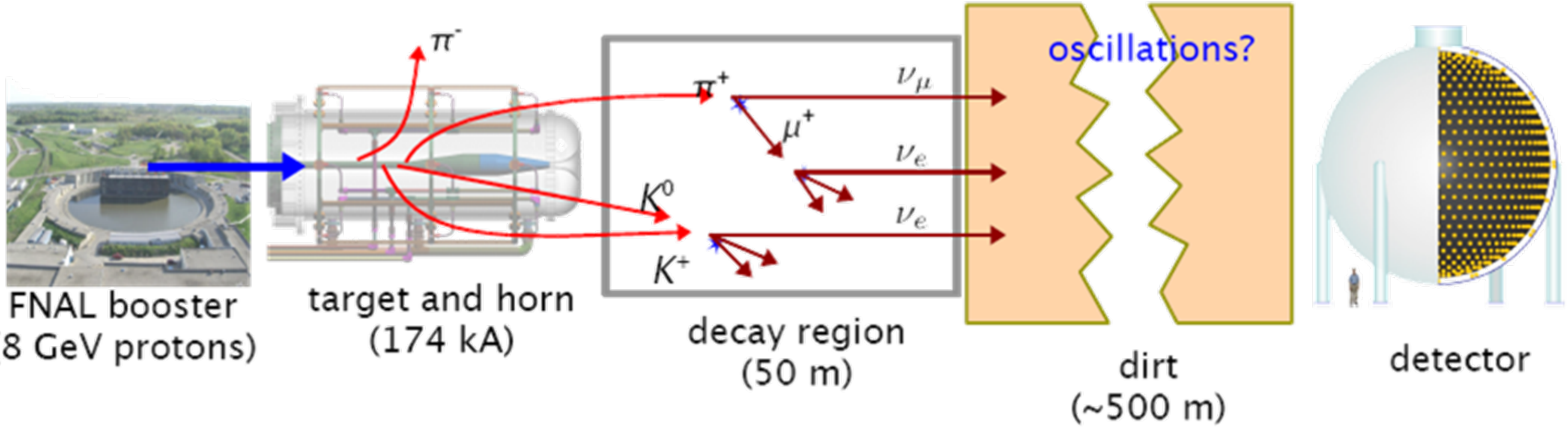
*at least 5 neutrinos are required to accommodate all experiments

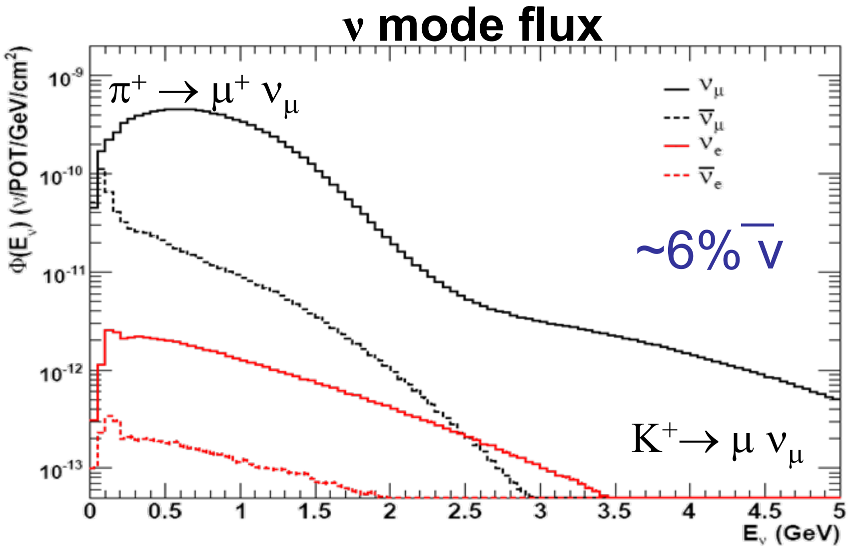
MiniBooNE: Neutrino beams at Fermilab

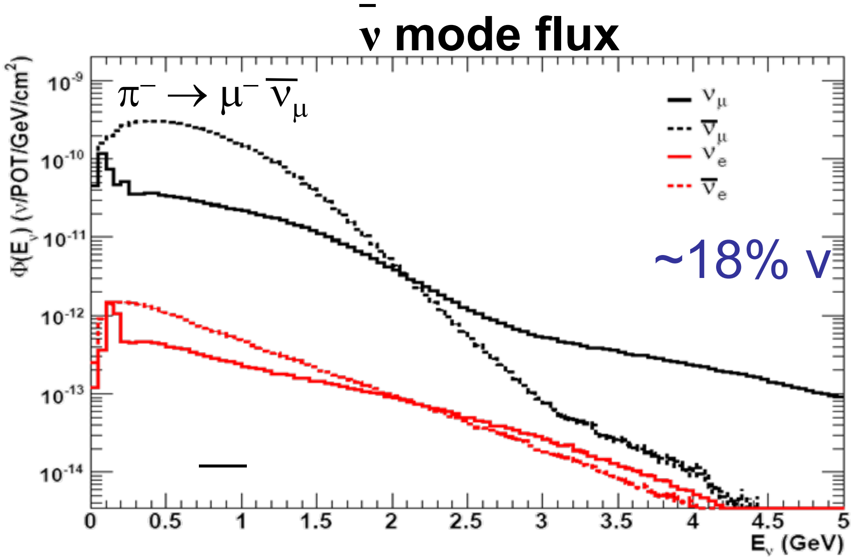


- 3 sources of data:
  - Booster Neutrino Beam (BNB)
    - neutrino mode with +174kA horn current
    - anti-neutrino mode with -174kA horn current
  - Neutrinos from the NUMI Beam

Appearance experiment: it looks for an excess of electron neutrino events in a predominantly muon neutrino beam



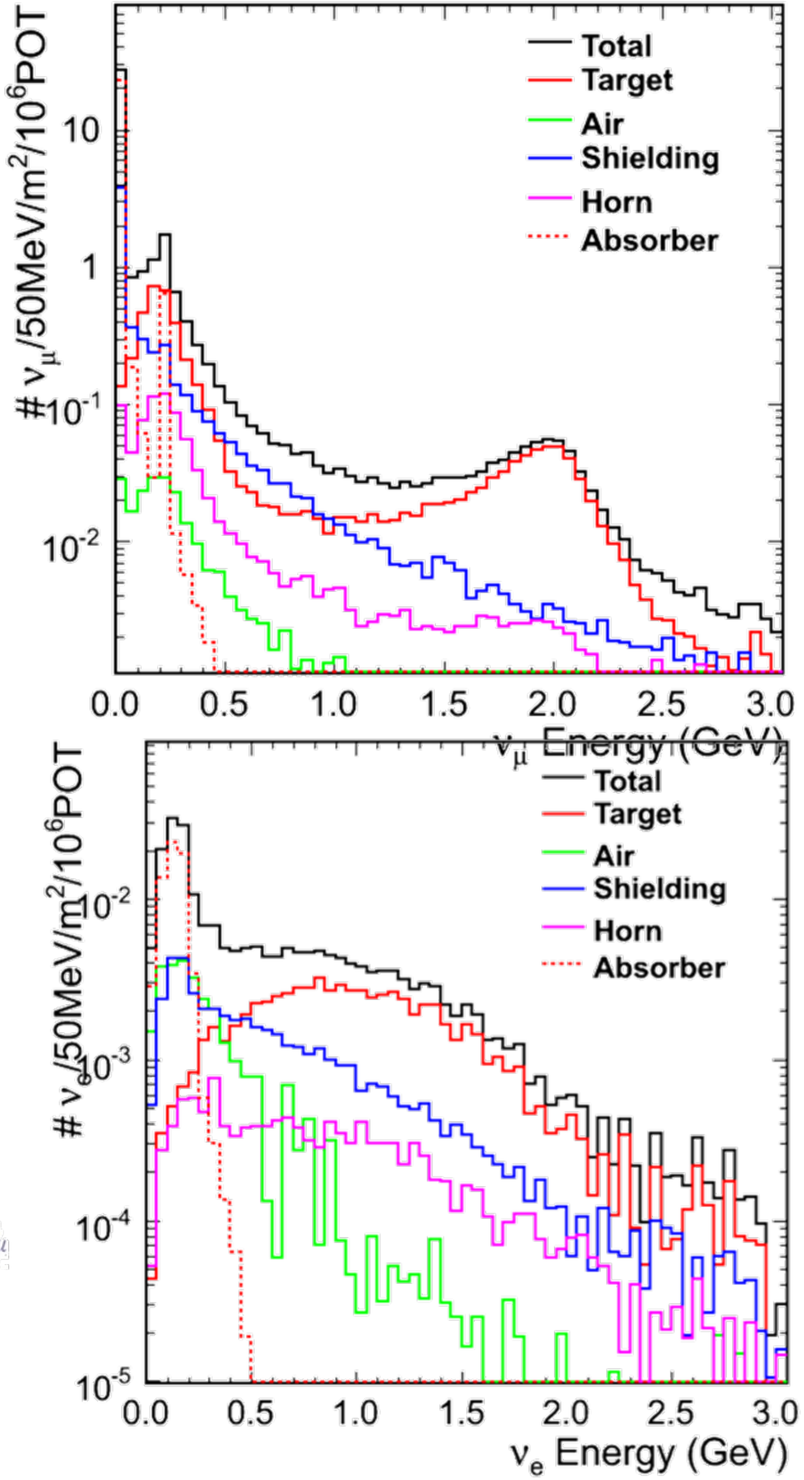




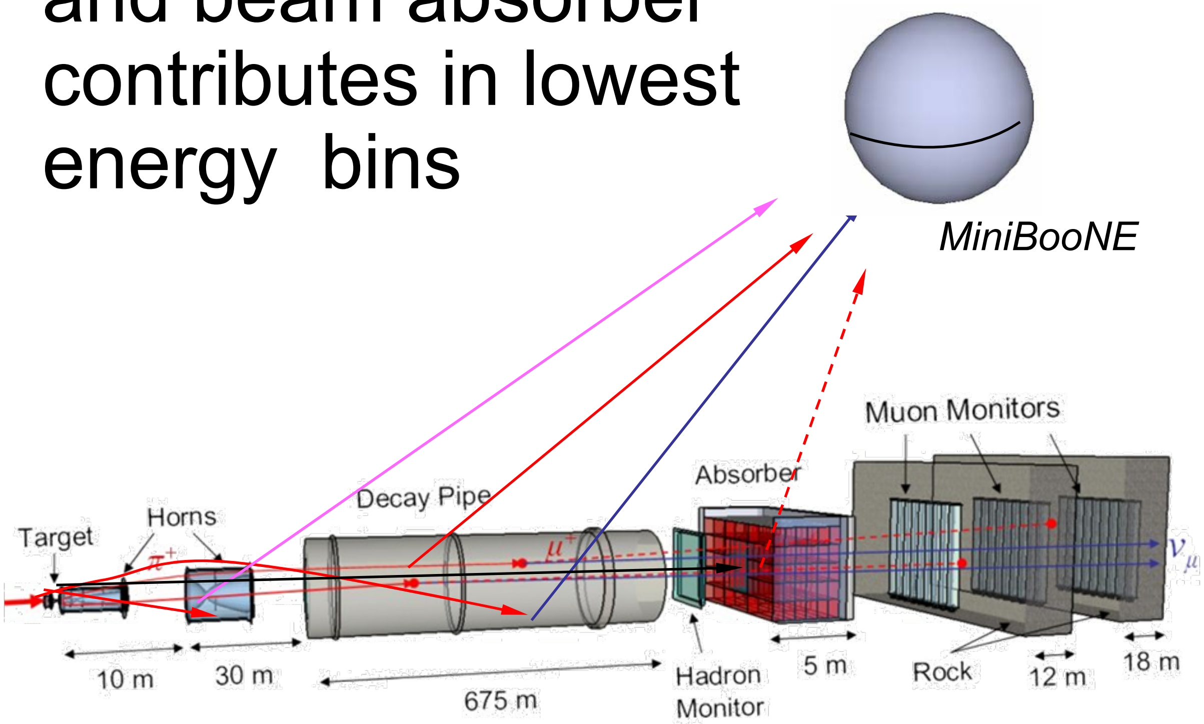
neutrino mode: $\nu_\mu \rightarrow \nu_e$ oscillation search

antineutrino mode: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation search

Neutrino Sources along the NuMI Beam Line

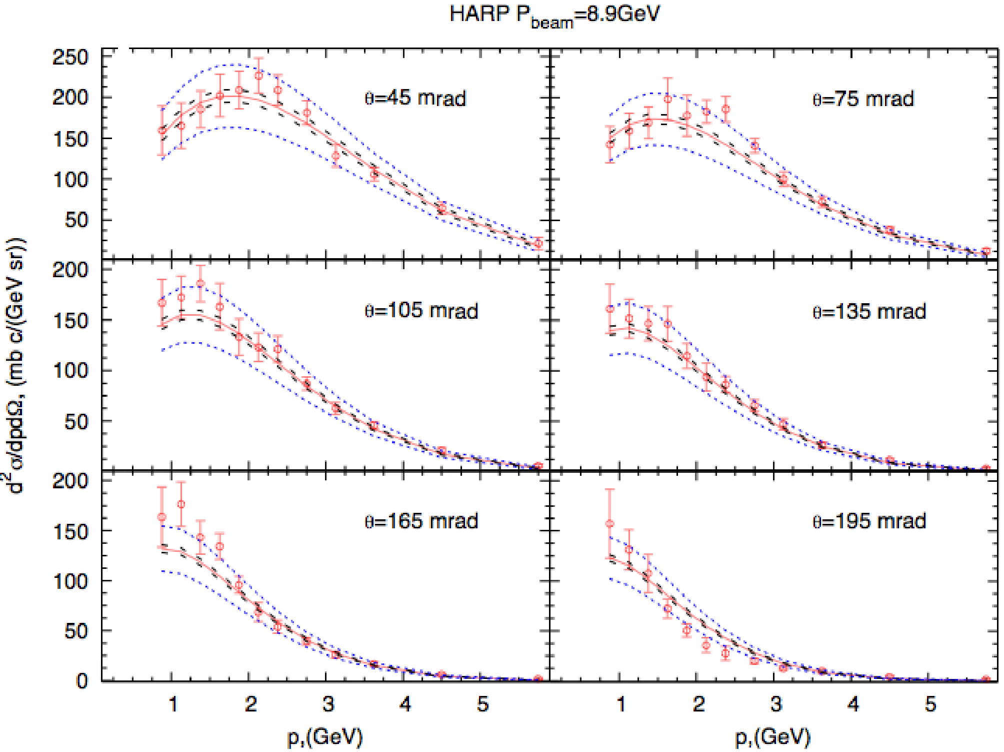


- Higher energy neutrinos mostly from particles created in target
- Interactions in shielding and beam absorber contributes in lowest energy bins



Meson production at the Proton Target

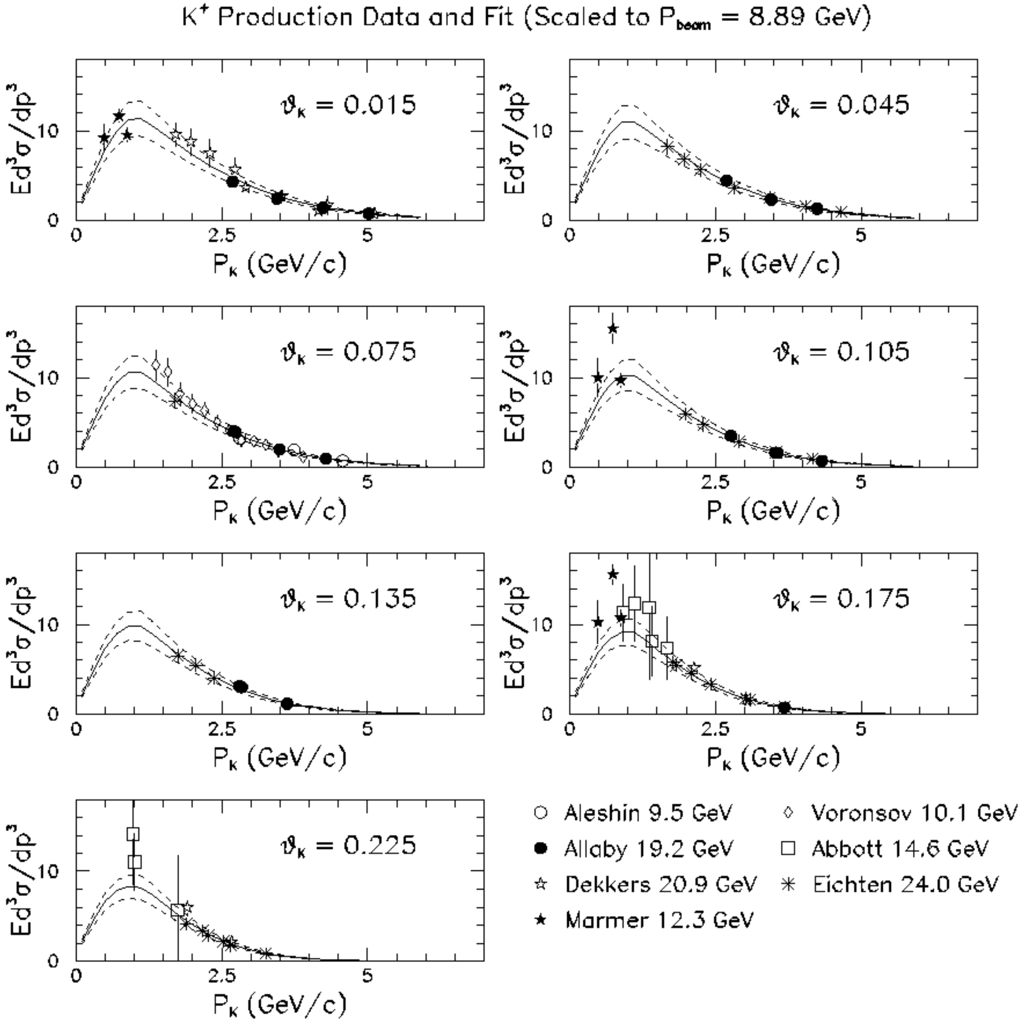
Pions(+/-):



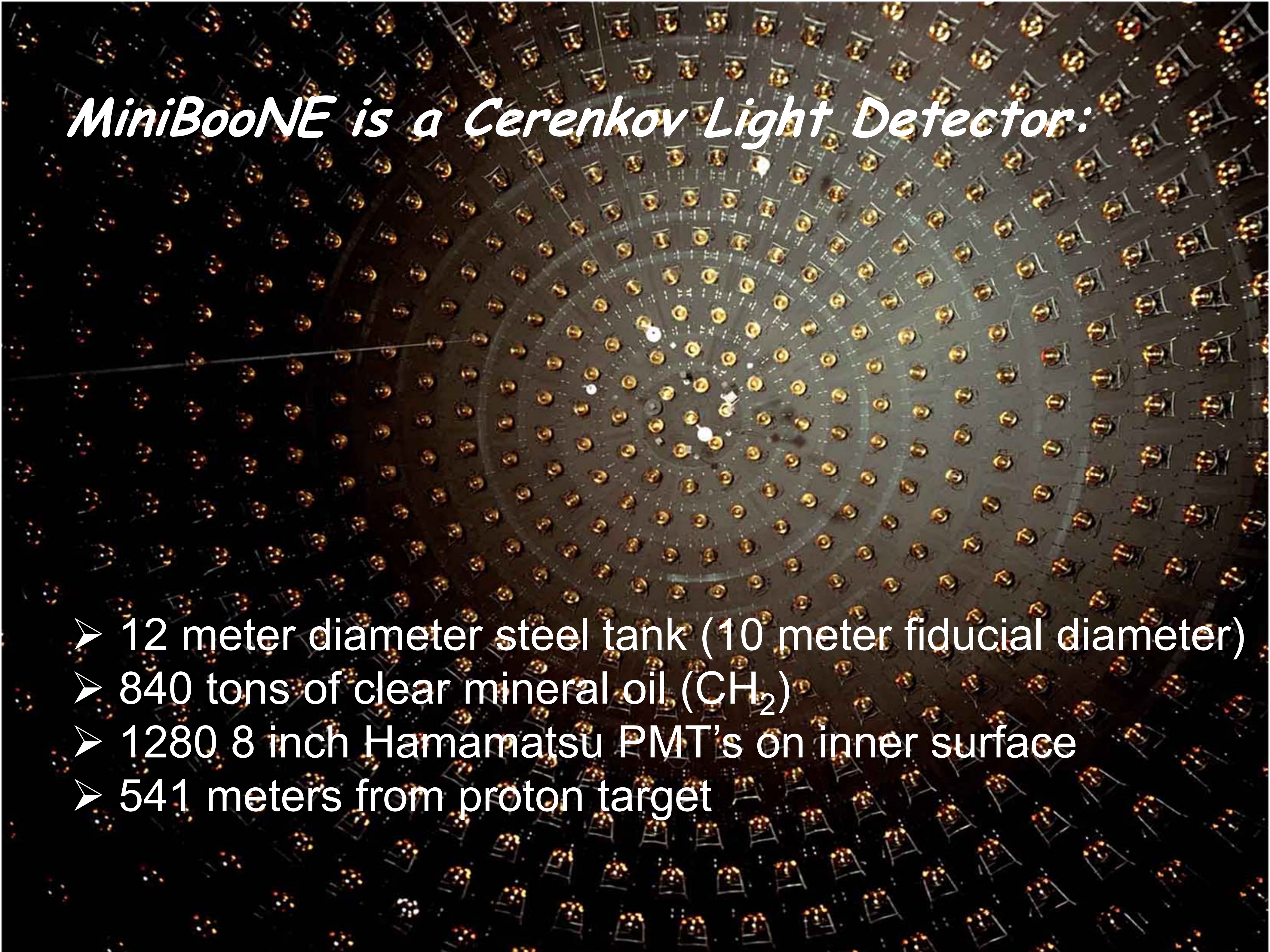
HARP collaboration, hep-ex/0702024

- MiniBooNE members joined the HARP collaboration
  - 8 GeV proton beam
  - 5% Beryllium target
- Spline fits were used to parameterize the data.

Kaons:



- Kaon data taken on multiple targets in 10-24 GeV range
- Fit to world data using Feynman scaling
- 30% overall uncertainty assessed



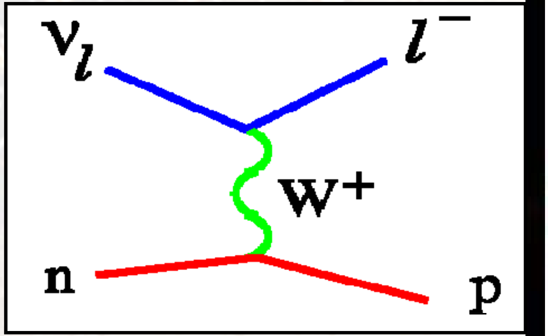
MiniBooNE is a Cerenkov Light Detector:

- 12 meter diameter steel tank (10 meter fiducial diameter)
- 840 tons of clear mineral oil (CH_2)
- 1280 8 inch Hamamatsu PMT's on inner surface
- 541 meters from proton target

Pattern of Cerenkov Light Gives Event Type

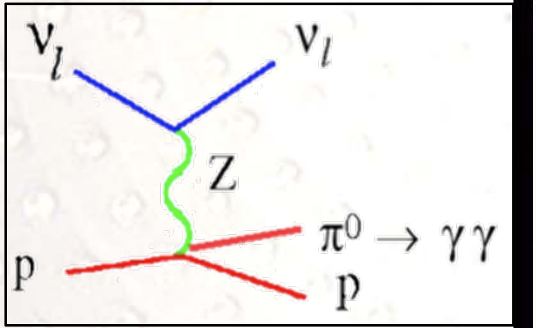
The main types of particles neutrino events produced:

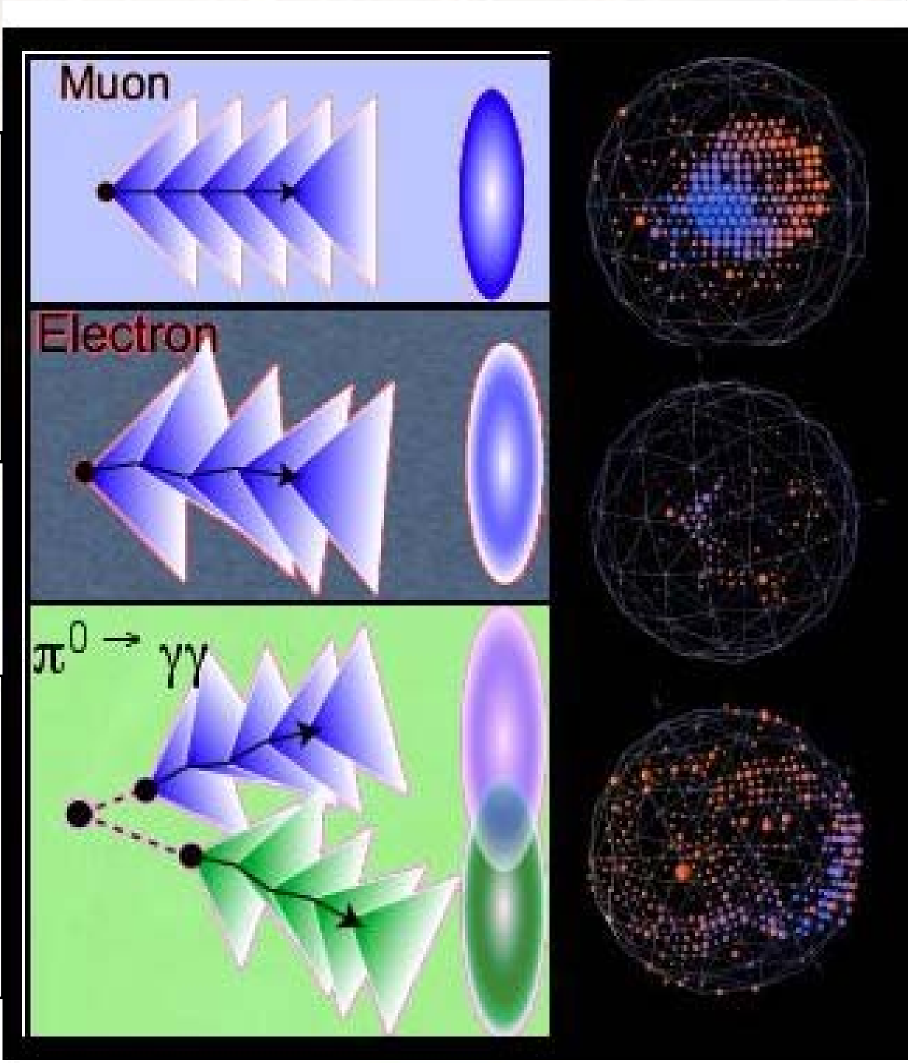
Muons (or charged pions):
Produced in most CC events.
Usually 2 or more subevents
or exiting through veto.



Electrons (or single photon):
Tag for $\nu_\mu \rightarrow \nu_e$ CCQE signal.
1 subevent

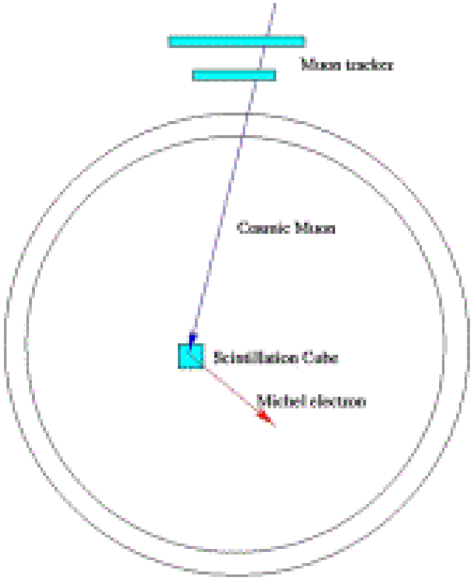
π^0s:
Can form a background if one
photon is weak or exits tank.
In NC case, 1 subevent.

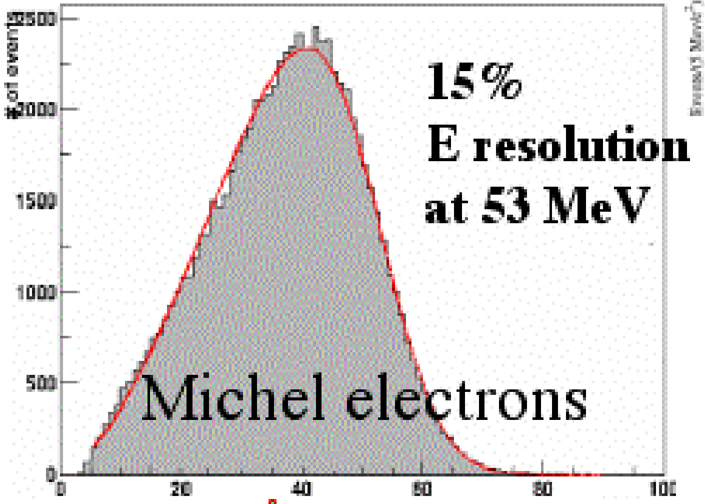




Calibration Sources

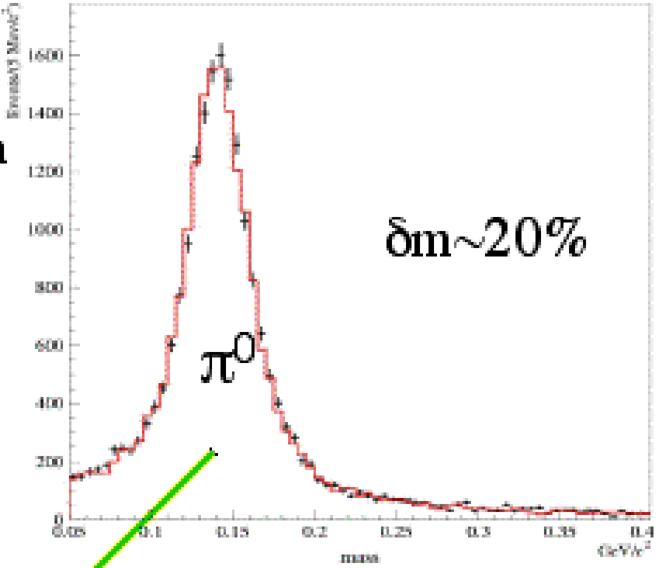
Tracker system



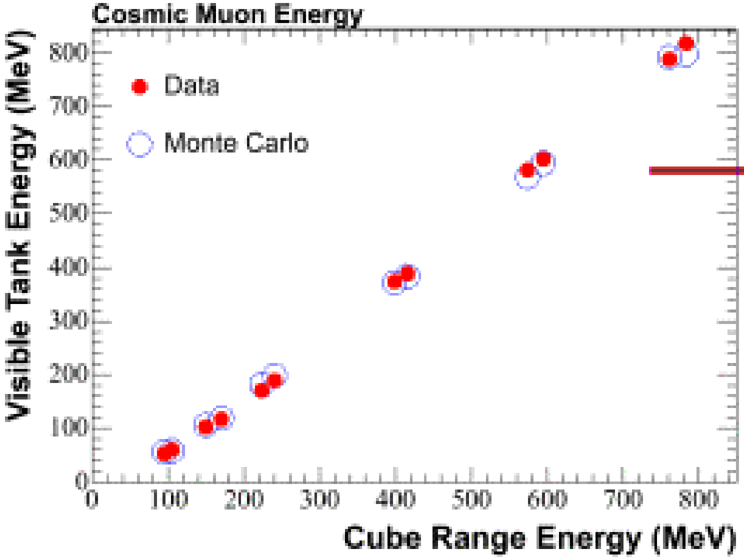


15%
E resolution
at 53 MeV

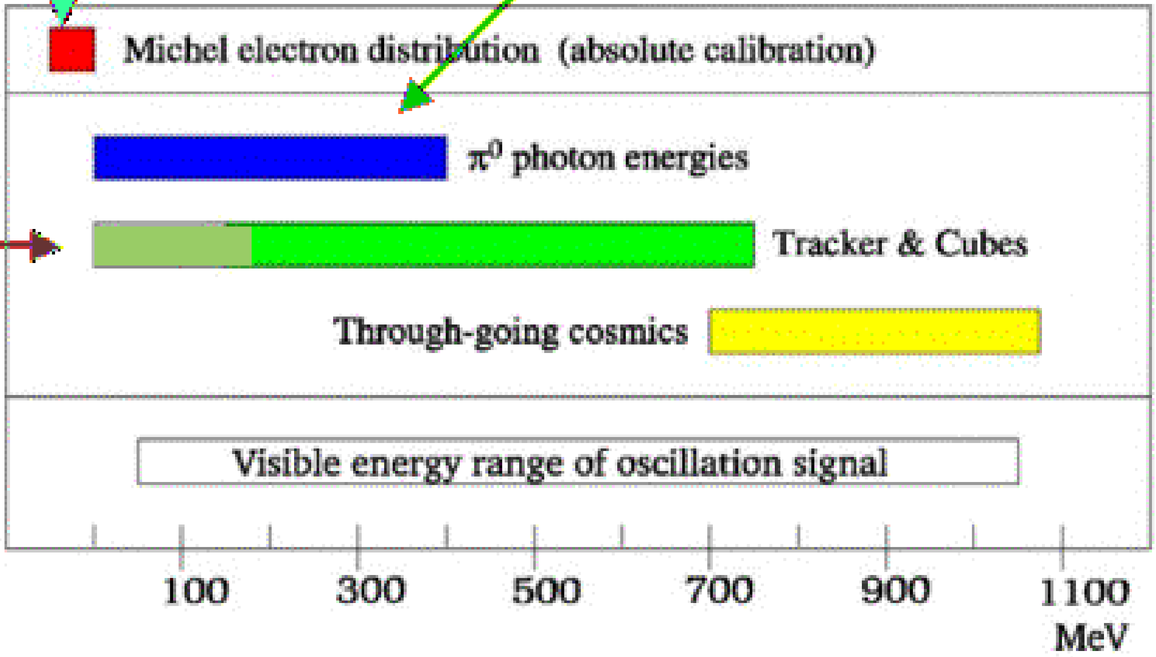
Michel electrons



δm~20%



Cosmic Muon Energy



🟥 Michel electron distribution (absolute calibration)

π^0 photon energies

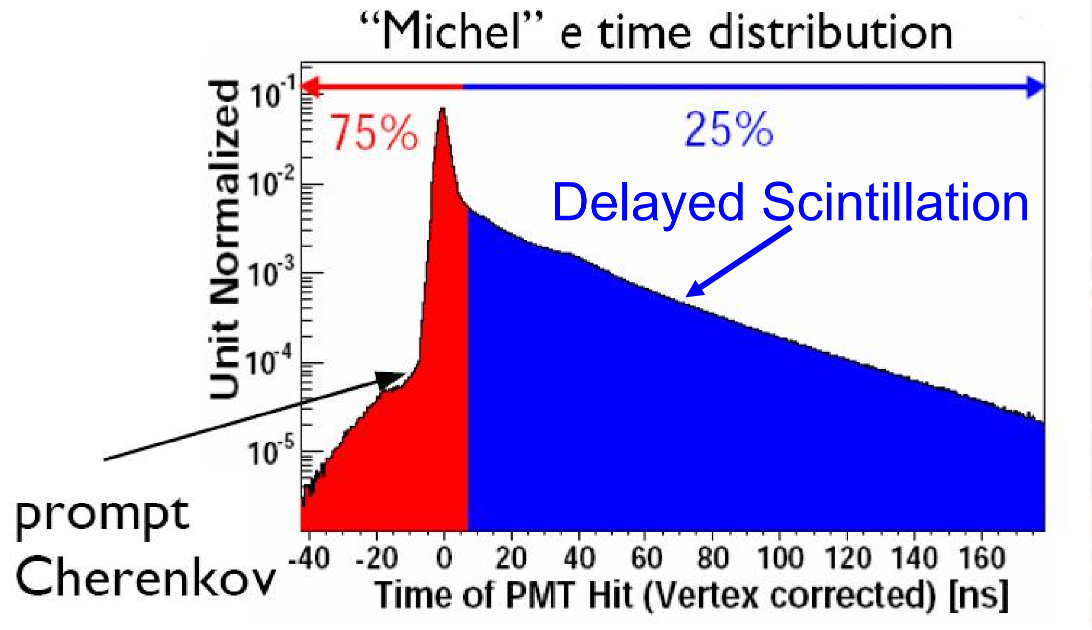
Tracker & Cubes

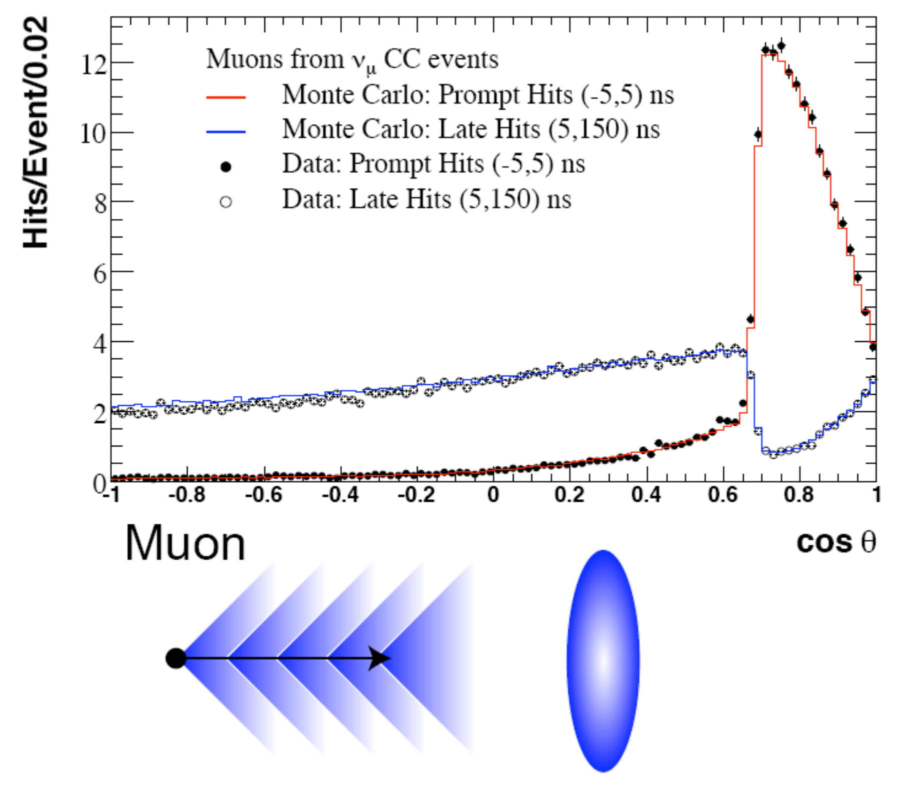
Through-going cosmics

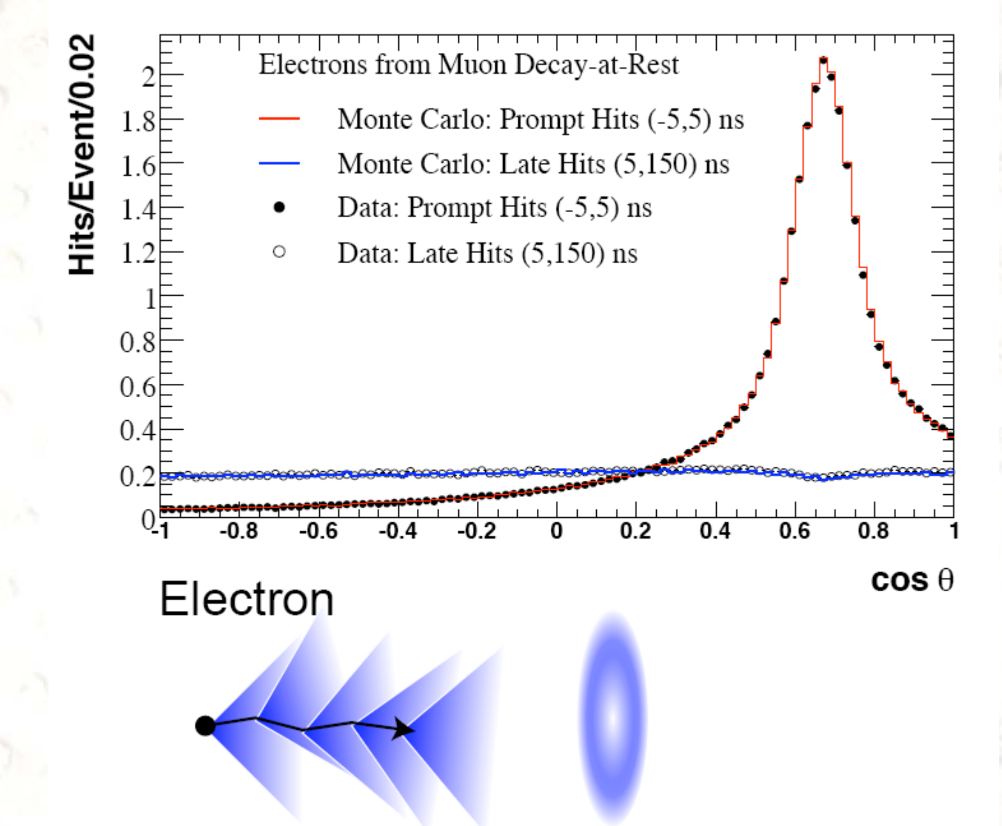
Visible energy range of oscillation signal

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

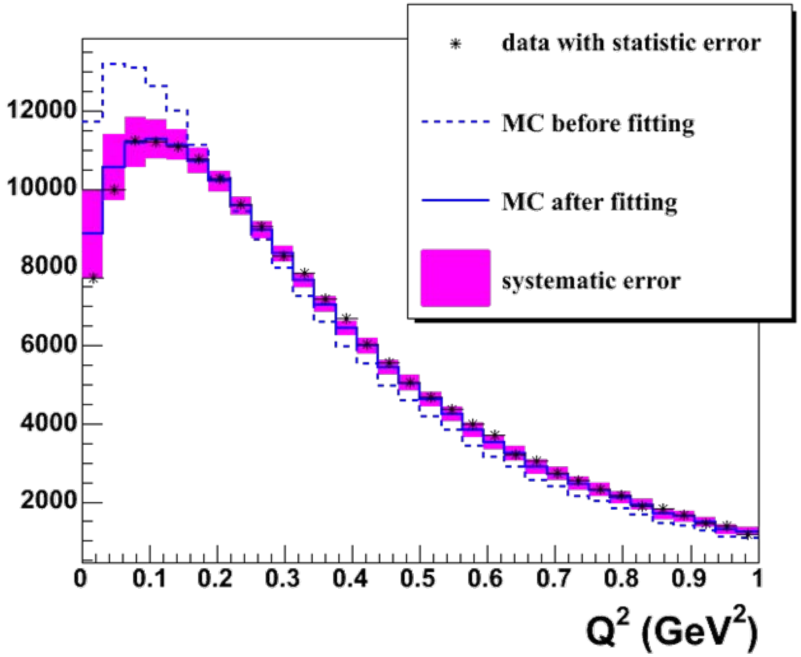




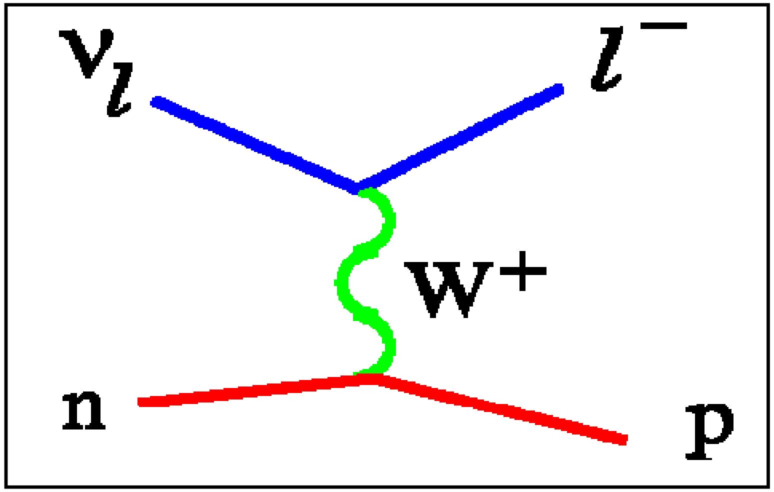


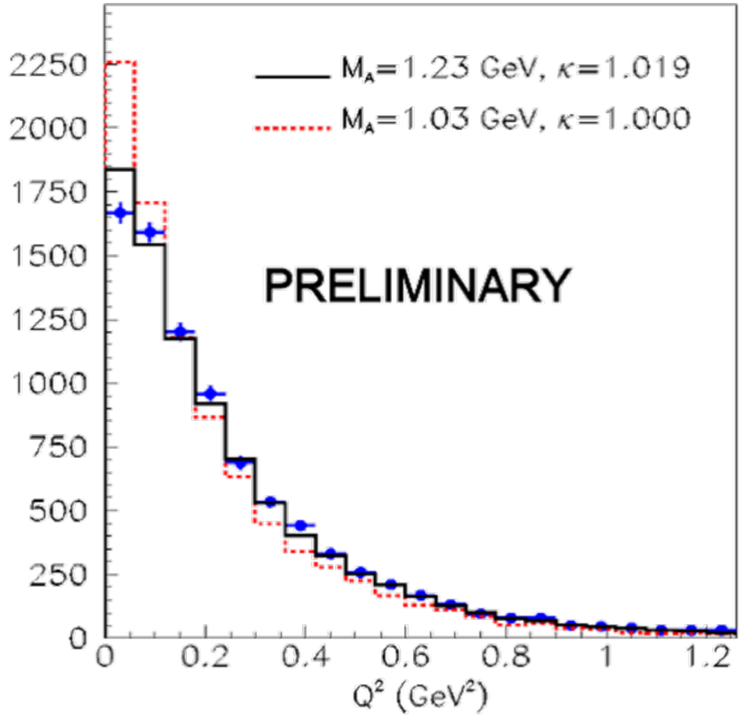
Benchmark Reaction: Charged Current Quasi Elastic (CCQE)

Normalizes our (flux ***x*** cross section)



186000 muon neutrino events





14000 anti-muon neutrinos

We adjust the parameters of a Fermi Gas model to match our observed Q^2 Distribution.

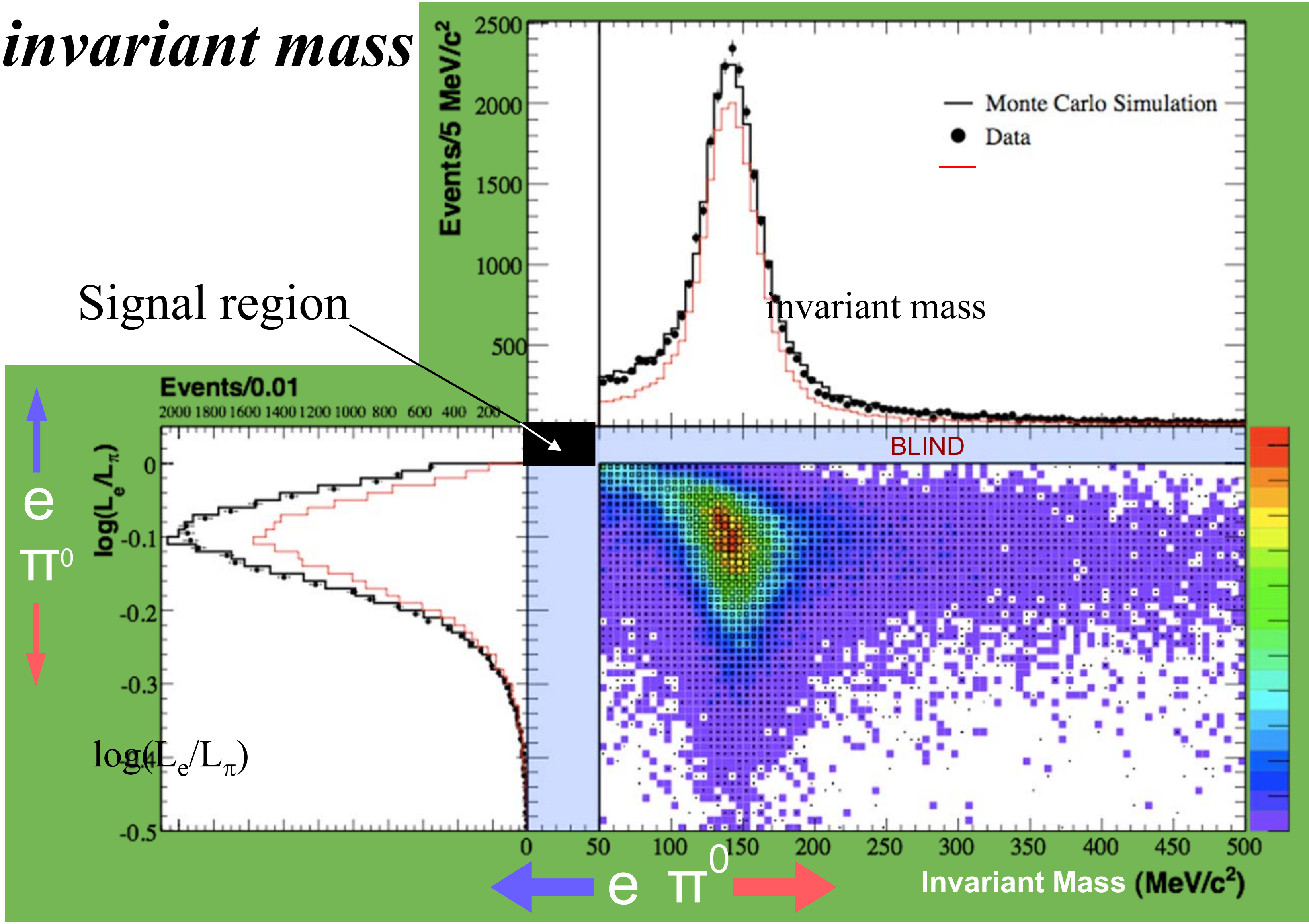
Fermi Gas Model describes CCQE ν_μ data well

$M_{A,eff}$ = 1.23+-0.20 GeV

κ = 1.019+-0.011 —

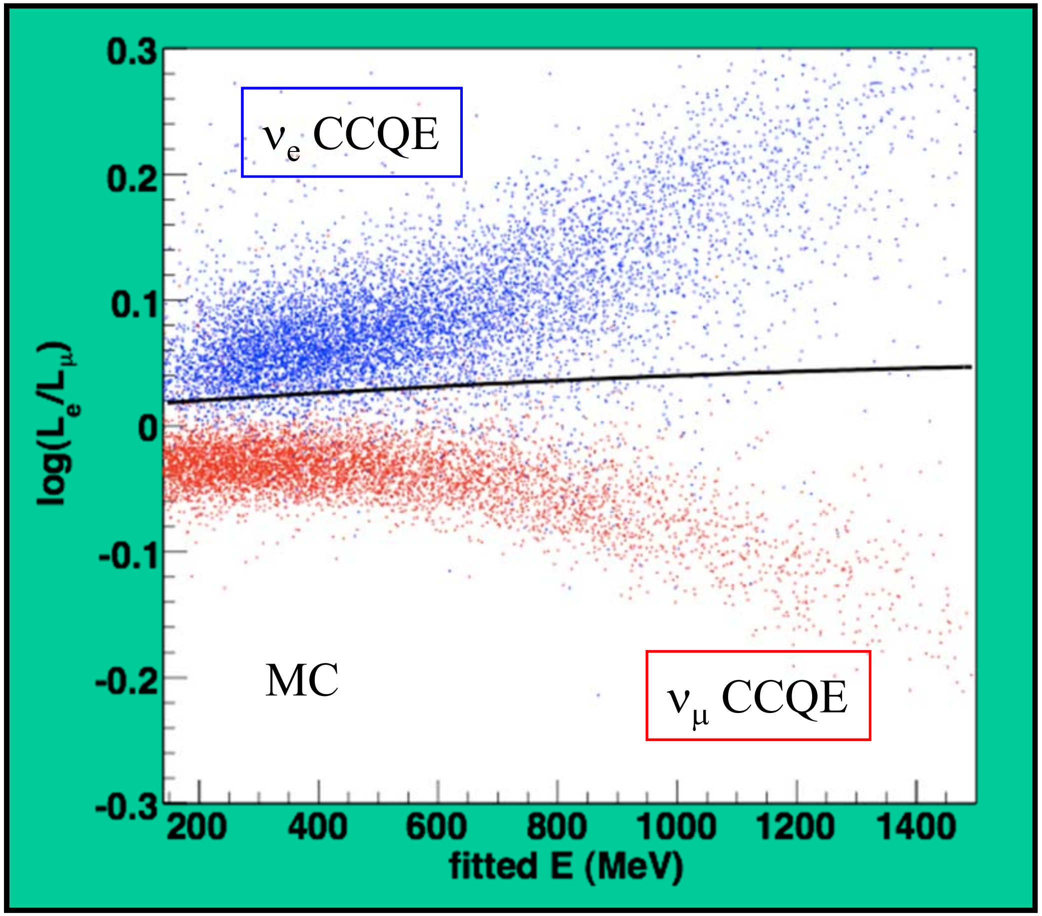
Also used to model ν_e and ν_e interactions

Separating electrons from neutral current π^0s by using a likelihood ratio combined with the $\gamma\gamma$ invariant mass


Signal region

Separating muon-like and electron-like events by using a likelihood ratio technique

$\log(L_e/L_\mu) > 0$ favors electron-like hypothesis



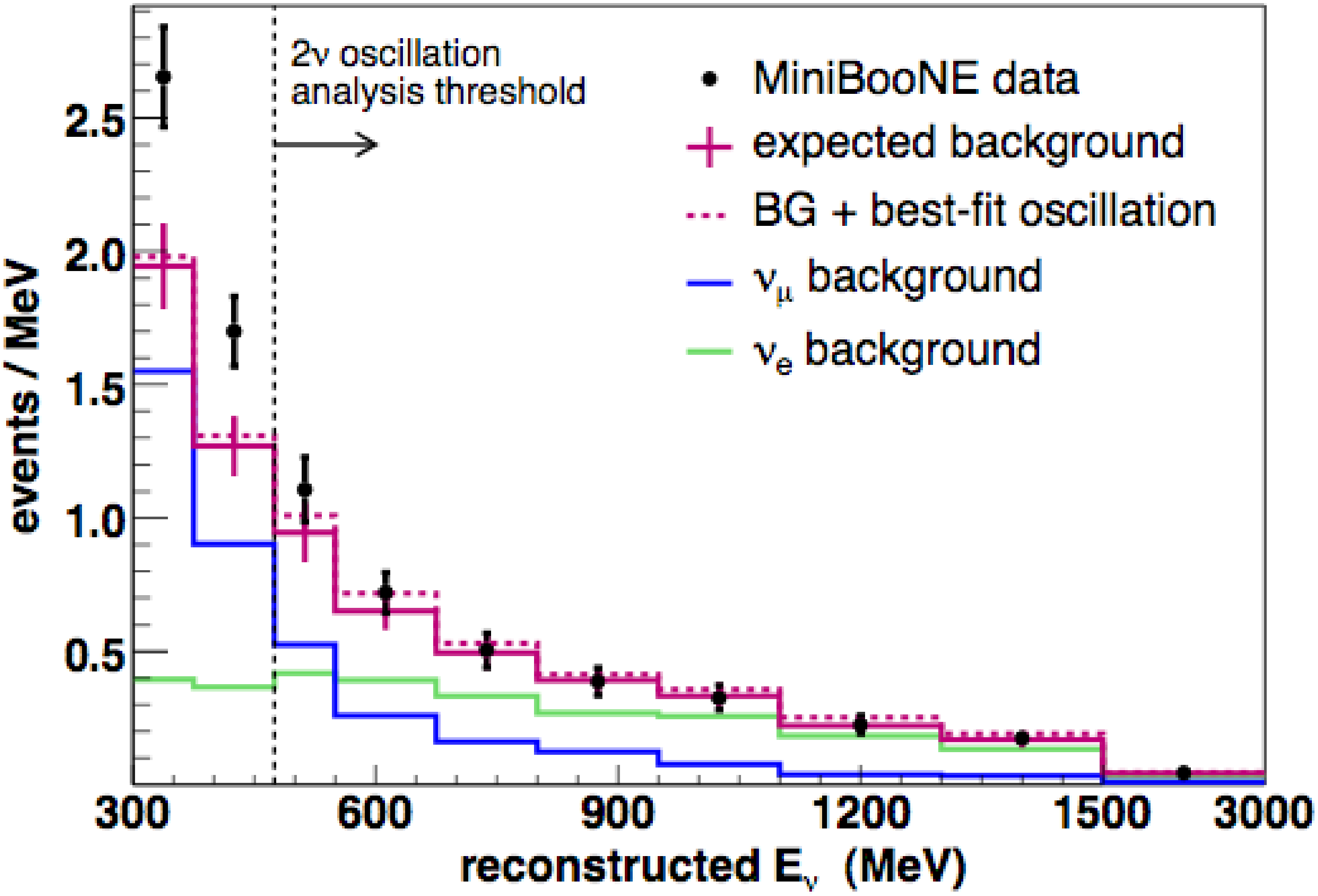
Note: photon conversions are electron-like.
This does not separate e/π^0.

Separation is clean at high energies where muon-like events are long.

Analysis cut was chosen to maximize the $\nu_\mu \rightarrow \nu_e$ sensitivity

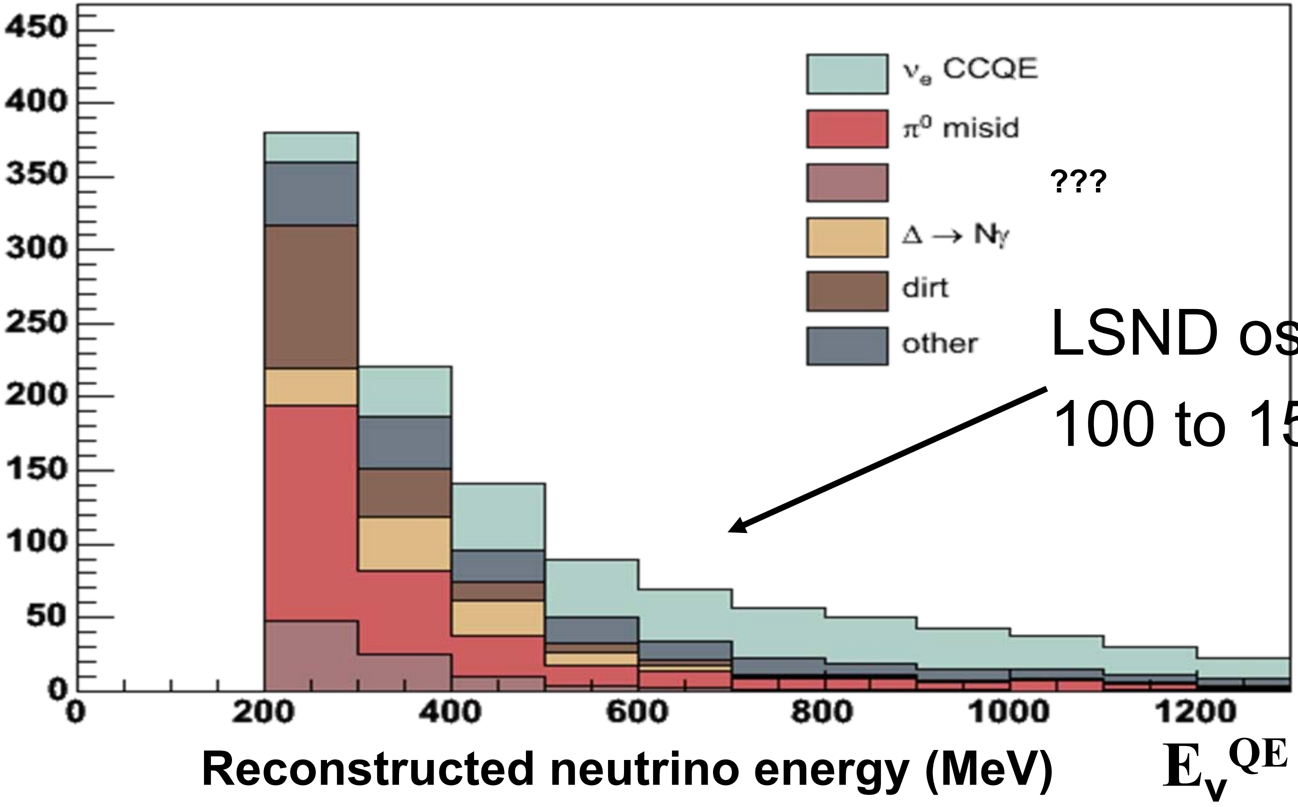
MiniBooNE ν_e Candidate Events

Reminder: Old 2007 Analysis



ν_e Event Rate Predictions: *Old 2007 Analysis*

ν_e Backgrounds after PID cuts (Monte Carlo)



LSND oscillations adds 100 to 150 ν_e events

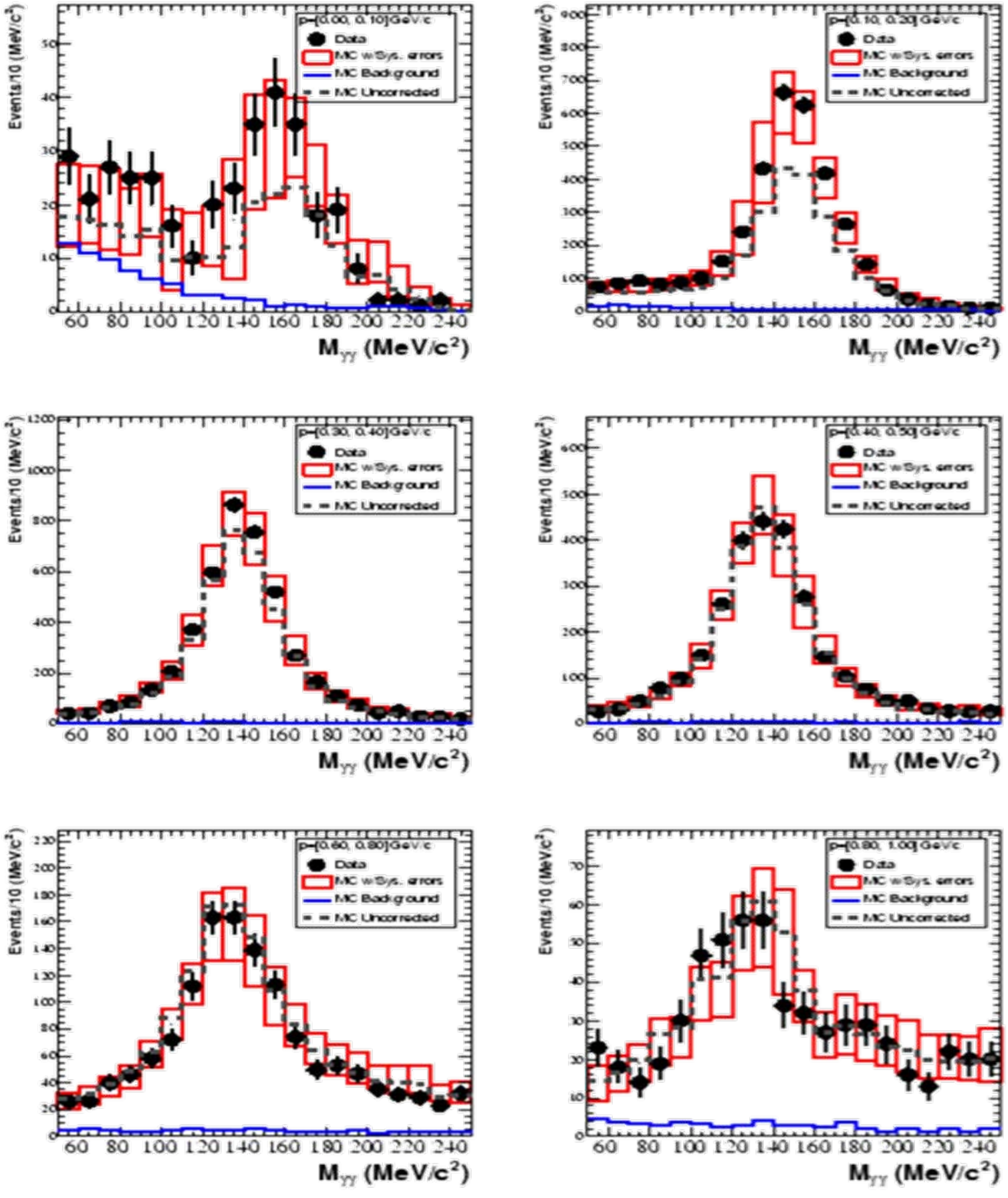
Improvements in the Analysis (since April 2007)

- Check many low level quantities (PID stability, etc)
- Rechecked various background cross-section and rates (π^0, $\Delta \to N\gamma$, etc.)
- Improved π^0 (coherent) production incorporated.
- Better handling of the radiative decay of the Δ resonance
- Photo-nuclear interactions included.
- Developed cut to efficiently reject "dirt" events.
- Analysis threshold lowered to 200 MeV, with reliable errors.
- Systematic errors rechecked, and some improvements made (i.e. flux, $\Delta \to N\gamma$, etc).
- Additional data set included in new results:

  Old analysis: 5.58×10^{20} protons on target.
  New analysis: 6.46×10^{20} protons on target.

Benchmark Neutral Current: NC π^0

- Fit invariant mass peak in each momentum range
- Normalizes NC reaction rates, e.g. $\Delta \rightarrow N\gamma$



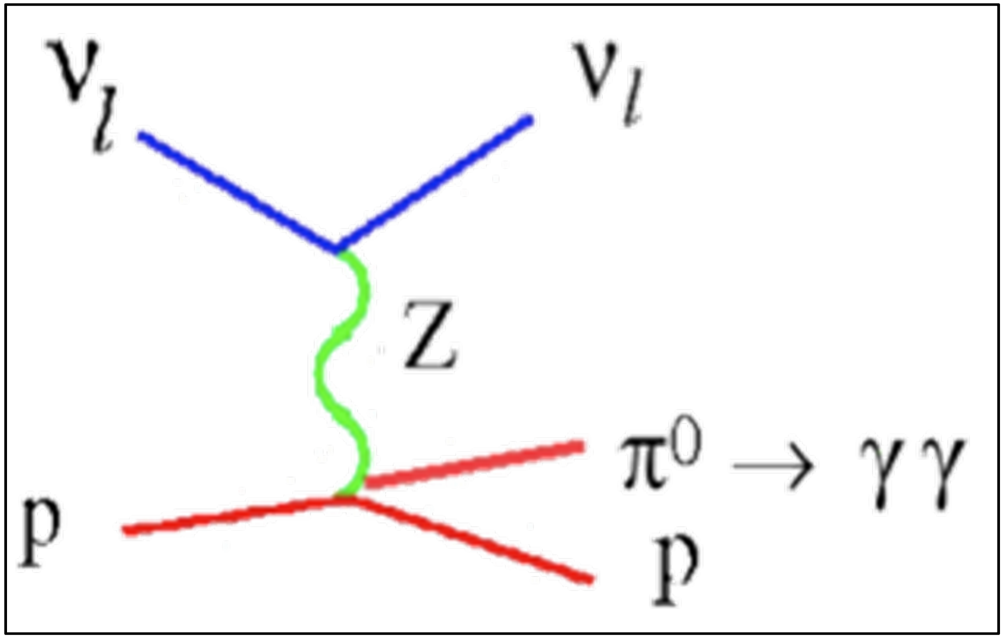
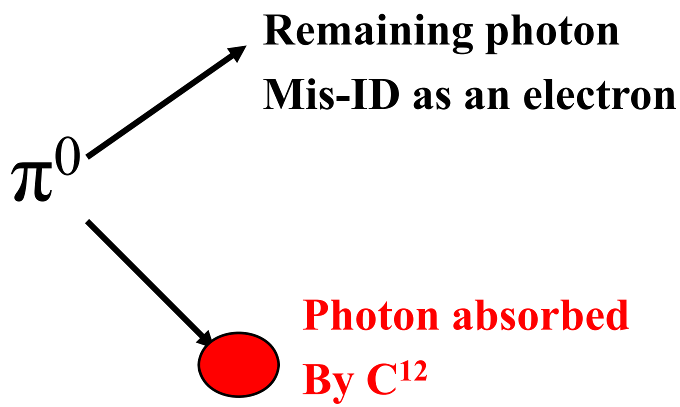


Photo-nuclear absorption of π^0 photon

A single γ is indistinguishable from an electron in MiniBooNE

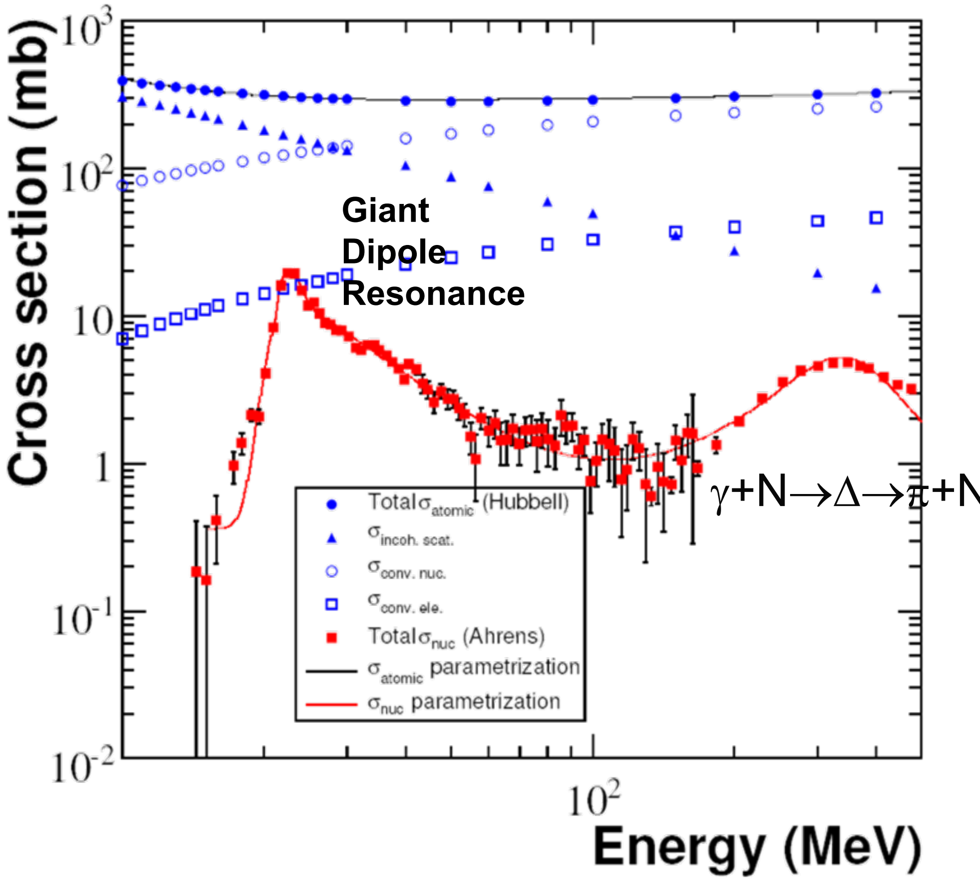

π^0

Remaining photon
Mis-ID as an electron

Photon absorbed
By C^{12}

Photonuclear processes can remove ("absorb") one of the gammas from NC $\pi^0 \rightarrow \gamma\gamma$ event

- *Total photonuclear absorption cross sections on Carbon well measured.*

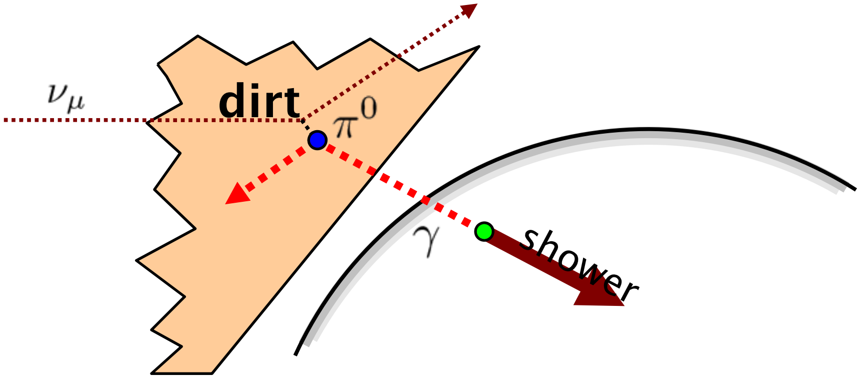


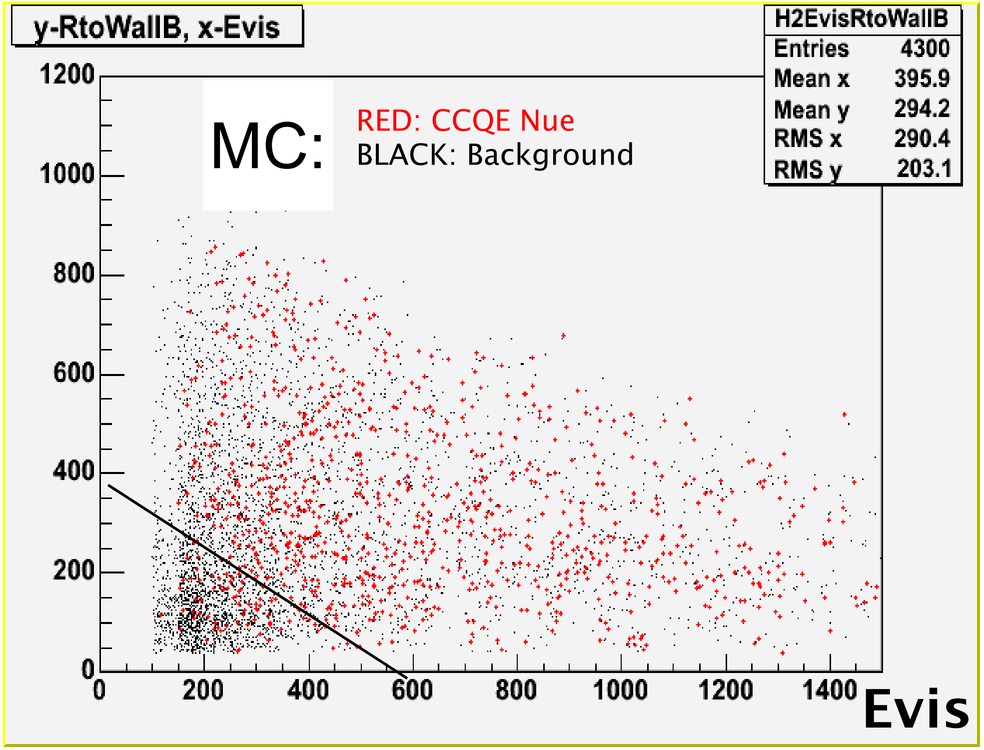
Photonuclear absorption recently added to our GEANT3 detector Monte Carlo.

- *Extra final state particles carefully modelled*
- *Reduces size of excess*
- *Systematic errors are small.*
- *No effect above 475 MeV*

External Events (“dirt”)

There is a significant background of photons from events occurring outside the fiducial volume (“Dirt” events)



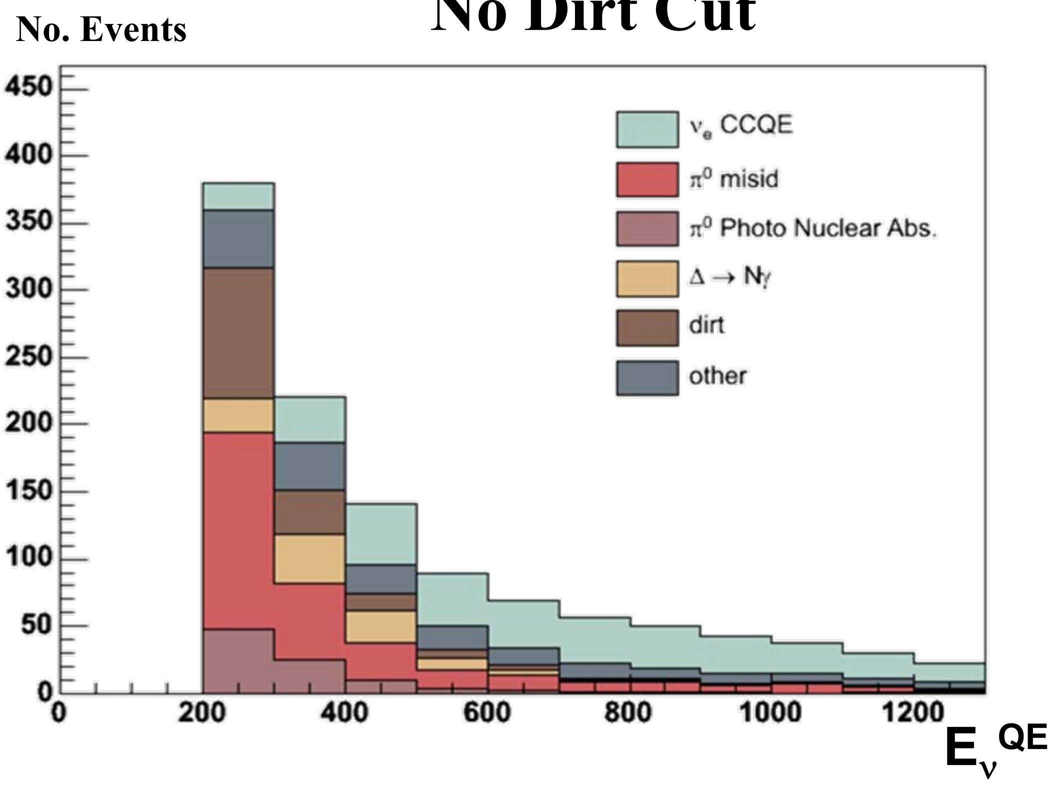


- occur at large radius
- inwardly directed
- low energy

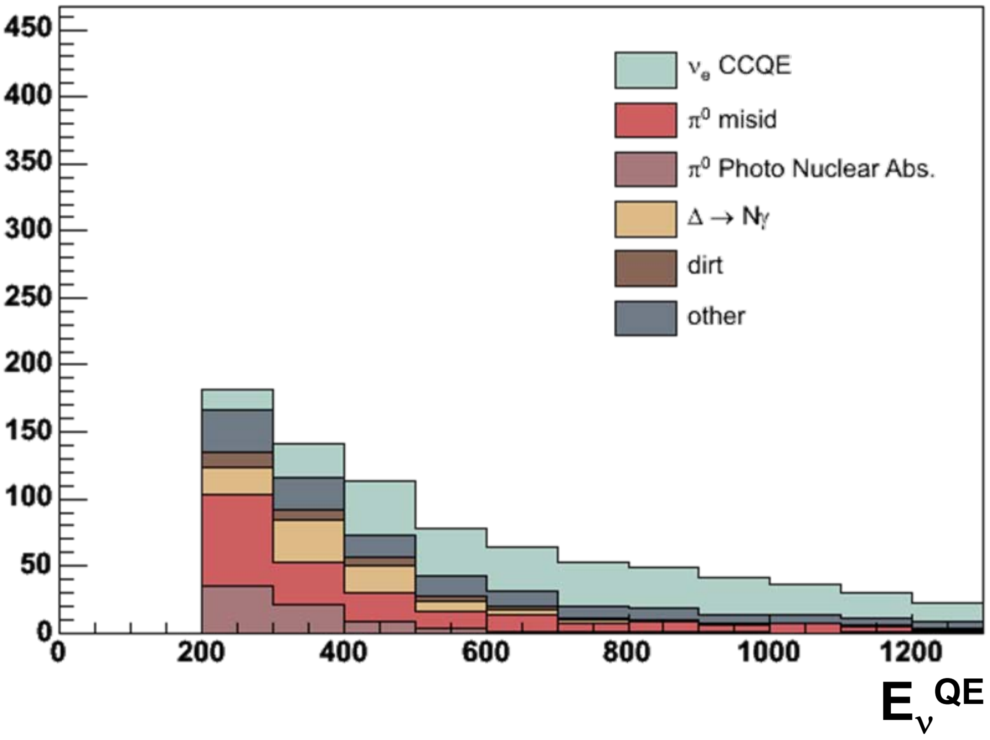
The background can be largely eliminated with and energy dependent fiducial cut

Effects of the Dirt Cut

No Dirt Cut



With Dirt Cut

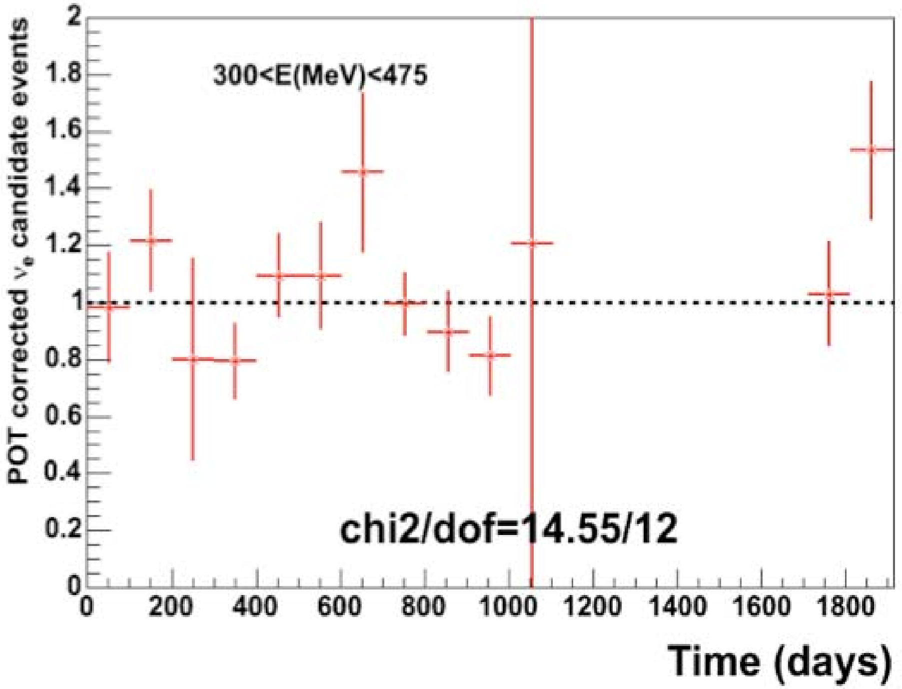


- The dirt cut:
  - significantly reduce dirt background by ~80%,
  - reduce pion background by ~40%
  - reduce electron/gamma-rays by ~20%.

Detector Anomalies or Reconstruction Problems

No Detector anomalies found

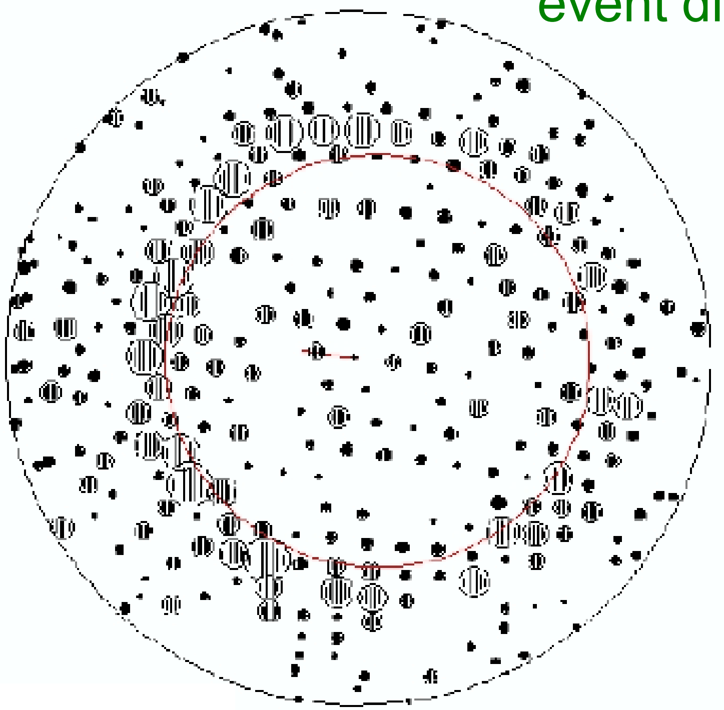
- Example: rate of electron candidate events is constant (within errors) over course of run



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

$\Rightarrow$ But could be either electrons or photons

ν_e-like Background Predictions

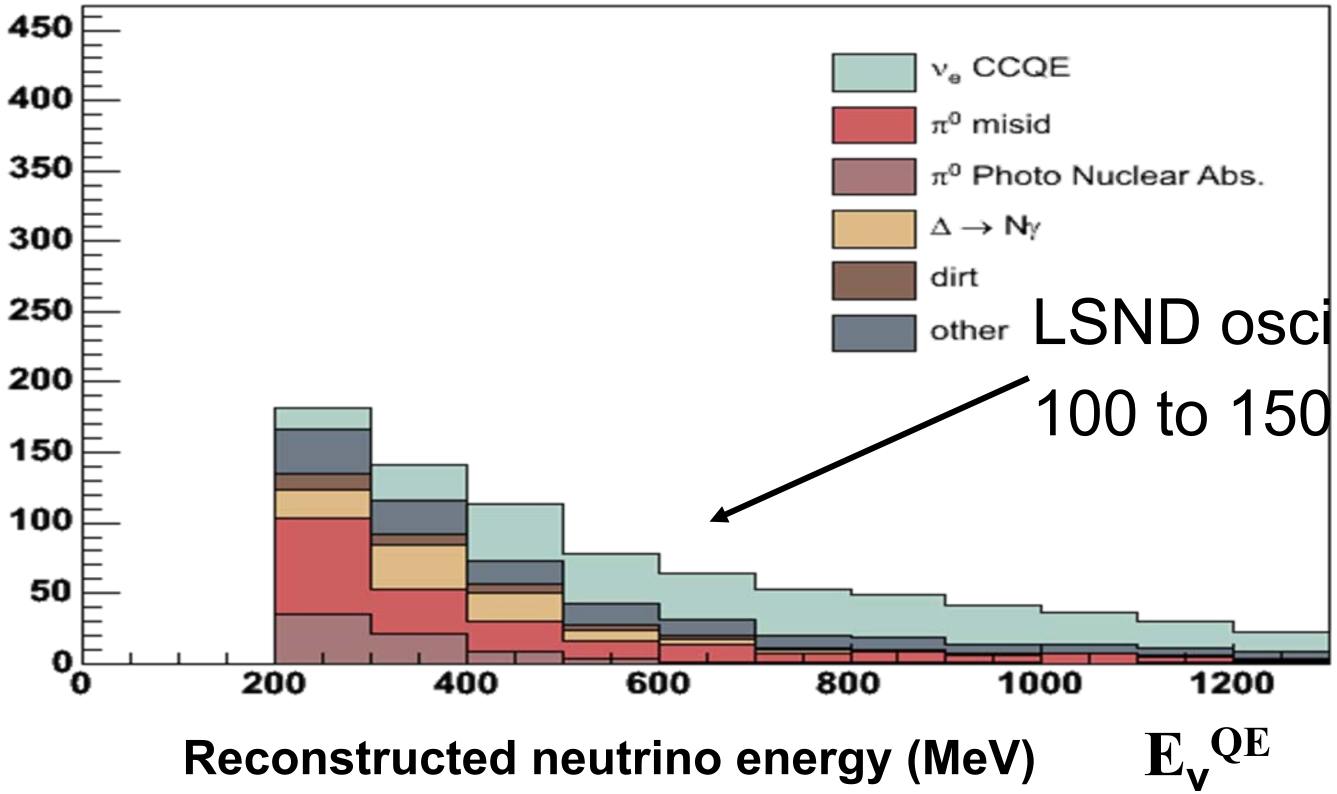
#Events = Flux x Cross-section x Detector response

- ✓ External measurements (HARP, etc)
- ✓ ν_μ rate constrained by neutrino data

- ✓External and MiniBooNE measurements
- ✓-π^0, delta and dirt backgrounds constrained from data.

- ✓Detailed detector simulation checked
- ✓with neutrino data and calibration sources.

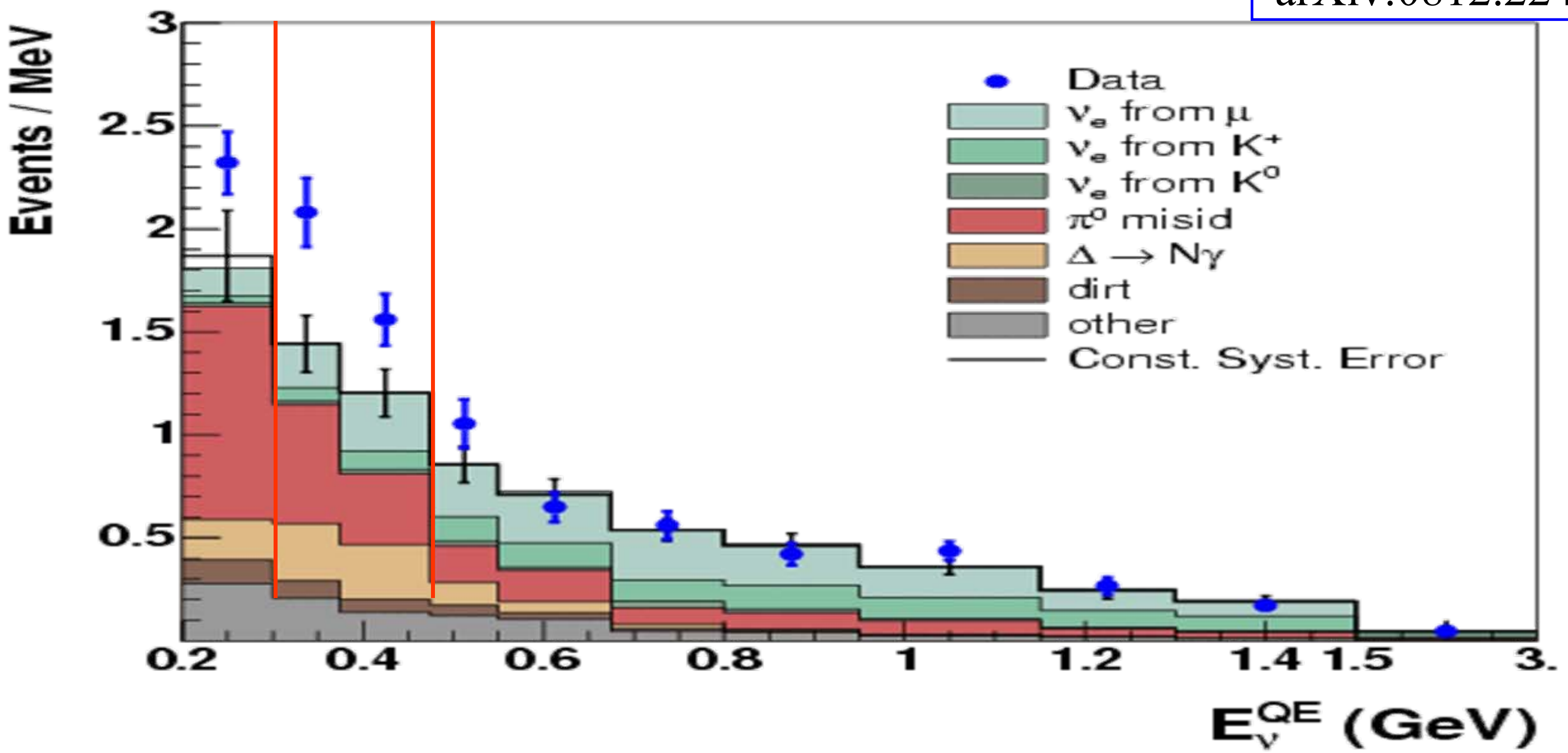
ν_e Backgrounds after PID cuts (Monte Carlo)



LSND oscillations adds 100 to 150 ν_e events

New ν Results

submitted to PRL
arXiv:0812.2243 [hep-ex]

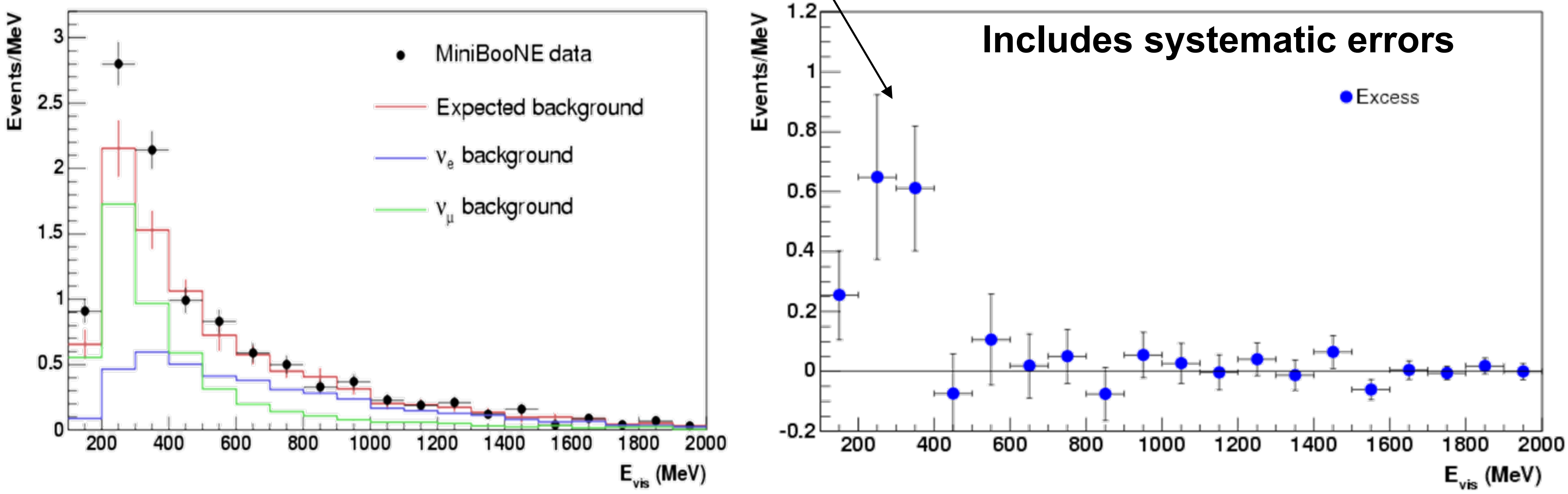


E_ν [MeV]	200-300	300-475	475-1250
total background	186.8±26	228.3±24.5	385.9±35.7
ν_e intrinsic	18.8	61.7	248.9
ν_μ induced	168	166.6	137
NC π^0	103.5	77.8	71.2
NC $\Delta \rightarrow N\gamma$	19.5	47.5	19.4
Dirt	11.5	12.3	11.5
other	33.5	29	34.9
Data	232	312	408
Data-MC	45.2±26	83.7±24.5	22.1±35.7
Significance	1.7σ	3.4σ	0.6σ

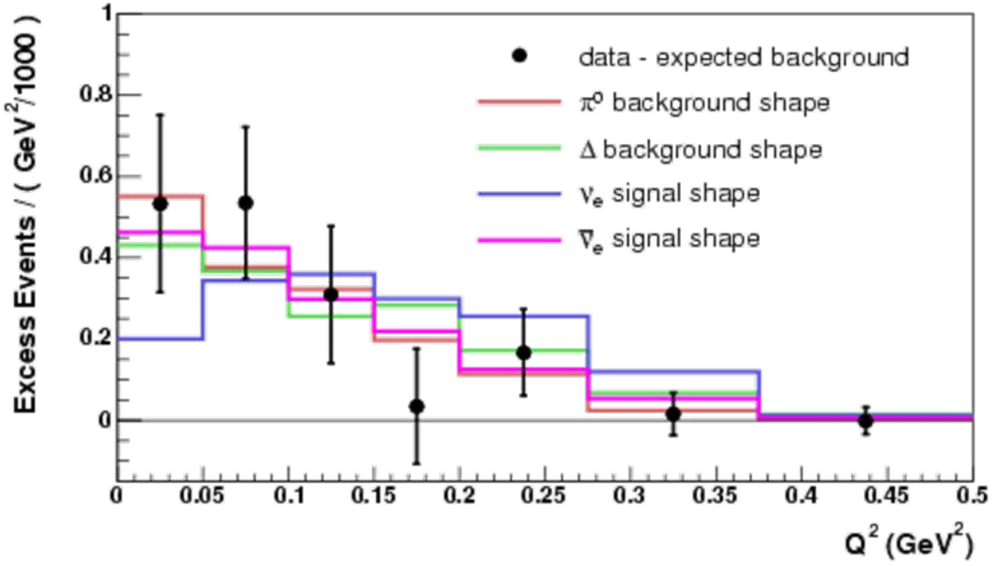
The excess at low energy has >3.0σ significance (~6σ statistical)

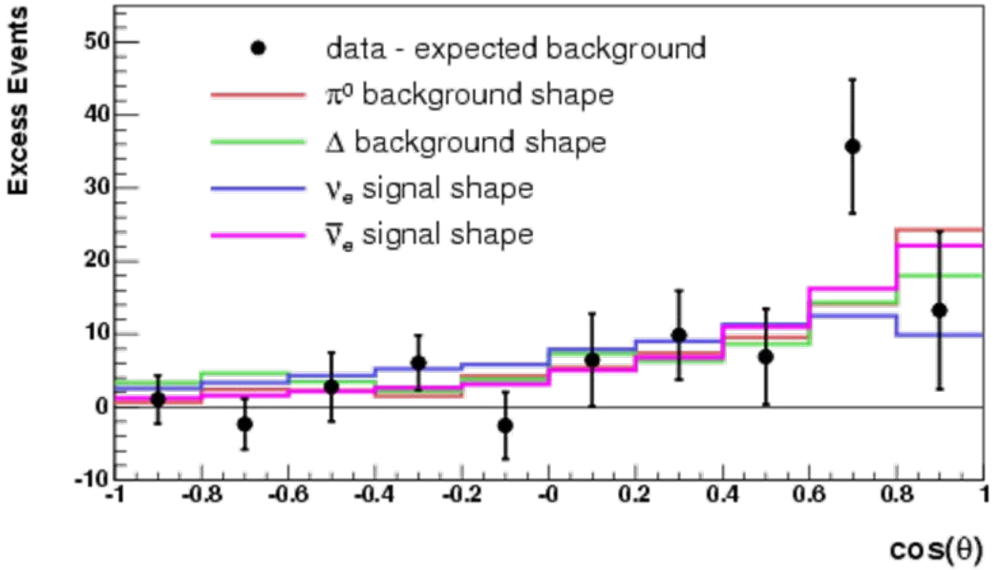
Reconstructed Visible Energy (E_e)

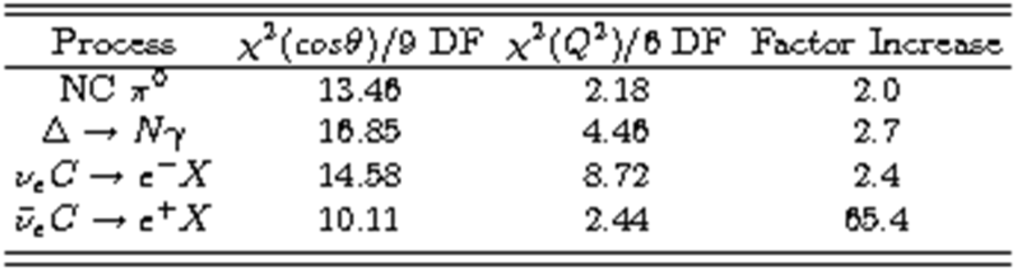
excess primarily $E_e < 400$ MeV



Reconstructed Q^2 and Cos(θ) Distribution Shapes







Process	$\chi^2(cos\theta)$/9 DF	$\chi^2(Q^2)$/6 DF	Factor Increase
NC π^0	13.46	2.18	2.0
$\Delta \rightarrow N\gamma$	16.85	4.46	2.7
$\nu_e C \rightarrow e^- X$	14.58	8.72	2.4
$\bar{\nu}_e C \rightarrow e^+ X$	10.11	2.44	65.4

However ,individual processes require >5σ increase to account for excess.

Excess shape is consistent with CC or NC scattering…

Anti-nu's

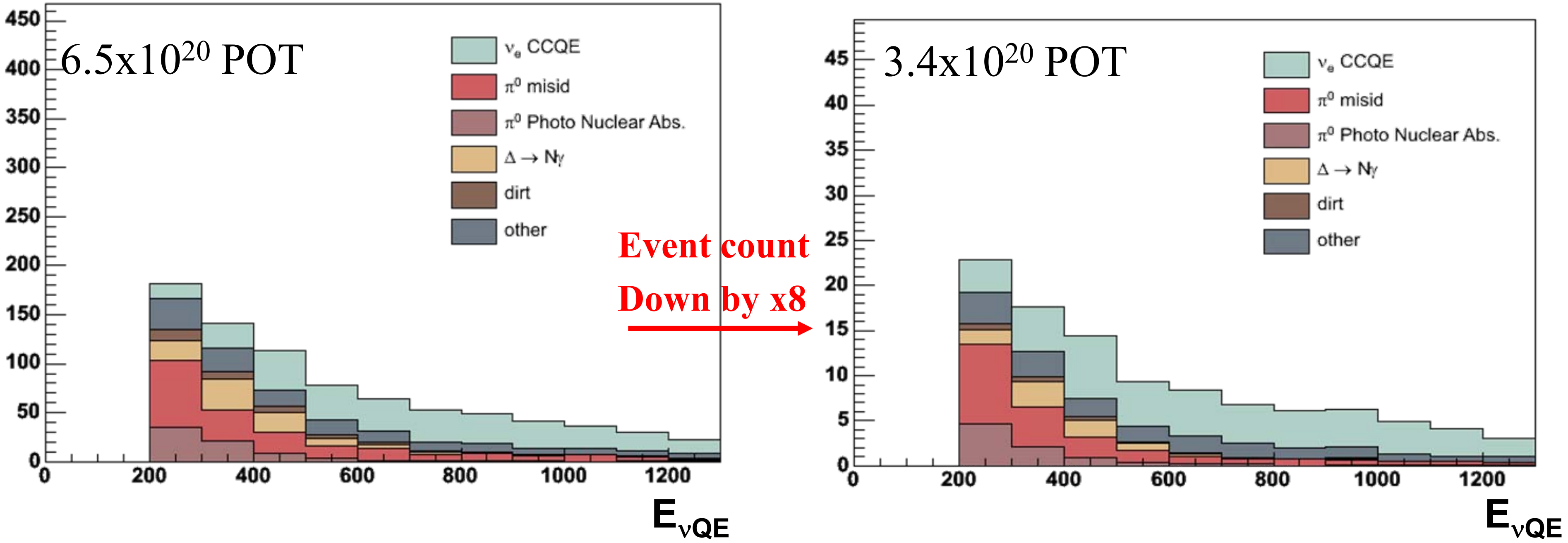
The Electron-like Anti-Neutrino Data

- Analysis nearly identical to neutrino mode
- Main difference is much larger "wrong-sign" contribution

Comparing Neutrino/Antineutrino Electron-like Event Rates

Background breakdown is very similar between neutrino and antineutrino mode running

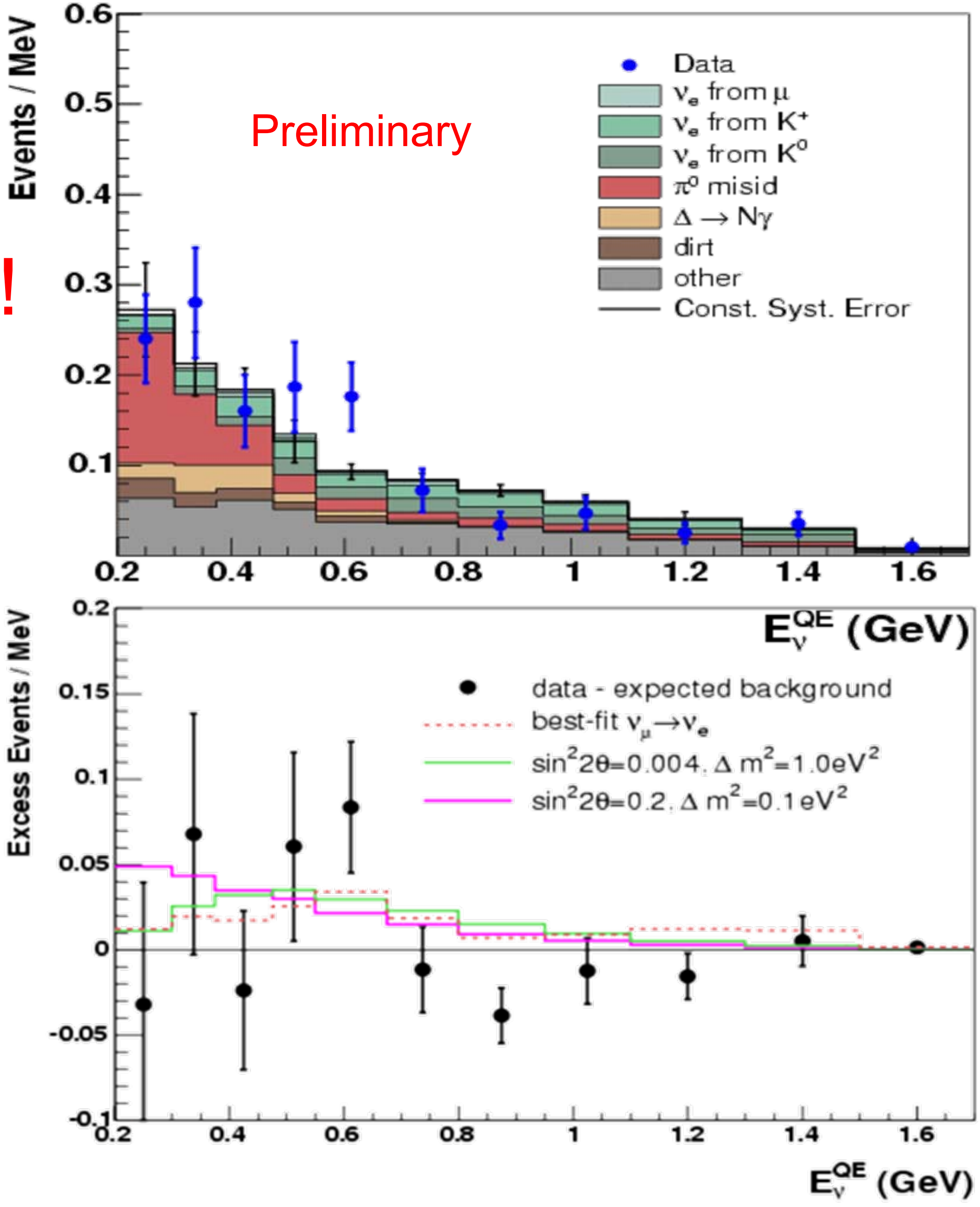
Neutrino **AntiNeutrino**



Event count Down by x8

- Various background/signal hypotheses for the excess can have measurably different effects in the two modes:
  - Backgrounds at low energy, expect an excess a few 10’s of events.
  - Two neutrino oscillations produce ~13 events at higher energy.
- Can compare the two modes to test some of the hypotheses.

Antineutrino Results (3.39e20POT)

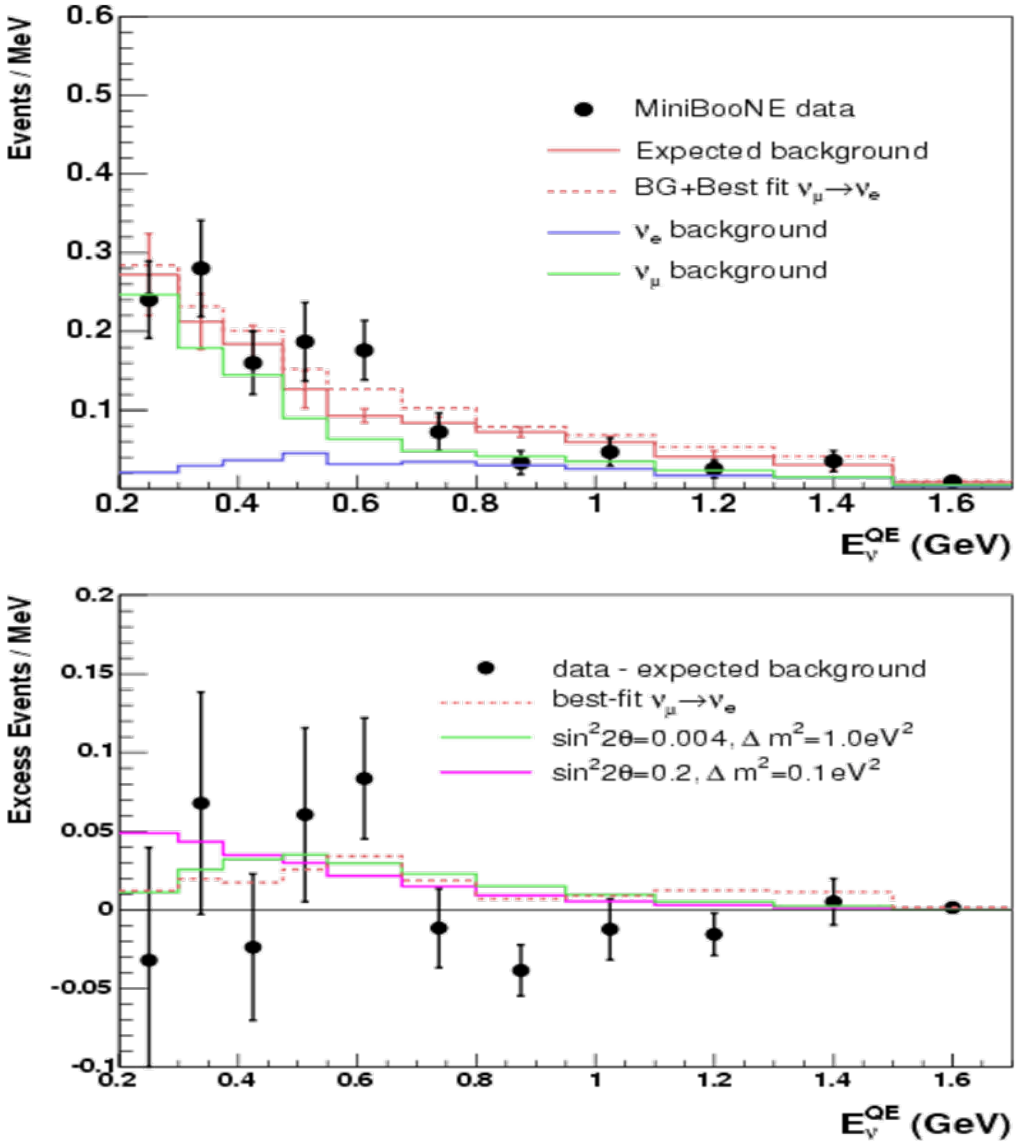


Surprise!

No low energy excess!

The statistics are not yet sufficient to test LSND directly, however we should have seen ~40 event excess if the H^3 anomaly was the cause of the low energy excess.

Oscillation fit (>200 MeV) consistent with LSND or Null Hypothesis



Fit yields 18+/-13 events, consistent with expectation from LSND.
However, not conclusive due to large errors.

Comparing Neutrino and Anti-Neutrino Data

Events summary (constrained syst + stat uncertainty)

E_ν^{QE} range (MeV)		$\bar{\nu}$ mode (3.386e20 POT)	ν mode (6.486e20 POT)
300-475	Data	37	312
	MC ± sys ± stat	34.3 ± 5.9 ± 4.4	228.3 ± 15.1 ± 19.3
	Excess ± sys ± stat	2.7 ± 5.9 ± 4.4 (0.4σ)	83.7 ± 15.1 ± 19.3(3.4σ)
200-475	**Data**	**61**	**544**
	MC ± sys ± stat	**61.5 ± 7.8± 8.7**	**415.2 ± 20.4 ± 38.3**
	Excess ± sys ± stat	**-0.5 ± 7.8± 8.7 (-.04σ)**	**128.8 ± 20.4 ± 38.3(3.0σ)**
475-1250	Data	61	408
	MC ± sys ± stat	57.8 ± 7.6± 6.5	385.9 ± 19.6± 29.8
	Excess ± sys ± stat	3.2 ± 7.6± 6.5(0.3σ)	22.1 ± 19.6± 29.8(0.6σ)

Tests of Background Sources

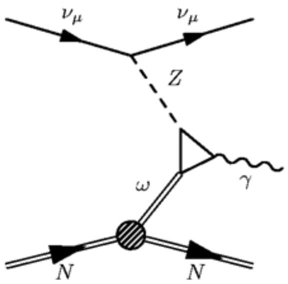
Maximum χ^2 probability from fits to ν and $\bar{\nu}$ excesses in 200-475 MeV range

	Stat Only	Correlated Syst	Uncorrelated Syst	#Events	
Same $\nu,\bar{\nu}$ NC	0.1%	0.1%	6.7%	37	
~~NC π^0 scaled~~	~~3.6%~~	~~6.4%~~	~~21.5%~~	~~20~~	>5σ
POT scaled	0.0%	0.0%	1.8%	68	
~~Bkgd scaled~~	~~2.7%~~	~~4.7%~~	~~19.2%~~	~~21~~	>3σ
~~CC scaled~~	~~2.9%~~	~~5.2%~~	~~19.9%~~	~~20~~	>3σ
Low-E Kaons	0.1%	0.1%	5.9%	40	
ν scaled	38.4%	51.4%	58.0%	7	

Same ν and $\bar{\nu}$ NC cross-section (HHH axial anomaly), POT scaled, Low-E Kaon scaled: strongly disfavored as an explanation of the MiniBooNE low energy excess!

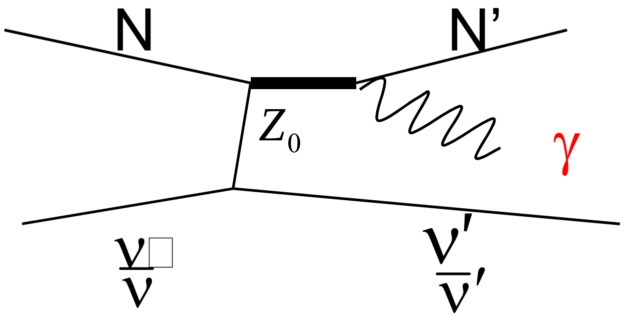
The most preferred model is one where the low-energy excess comes from neutrinos in the beam (no contribution from anti-neutrinos).

Possible Explanations for the ν_e & $\bar{\nu}_e$ Low-Energy Events

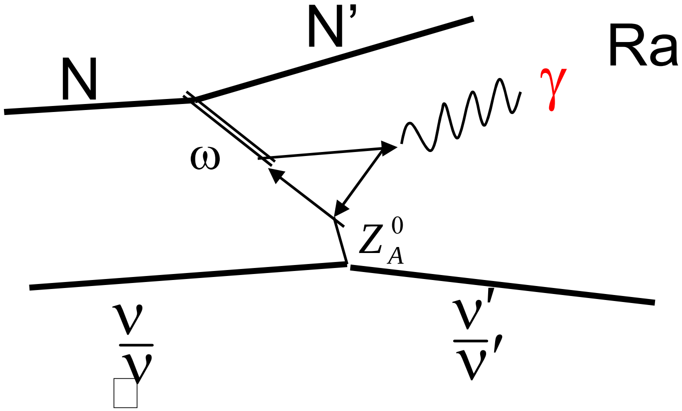


- Axial Anomaly :Jeffrey A. Harvey, Christopher T. Hill, & Richard J. Hill, Phys. Rev. Lett. 99, (2007) 261601 **NO**
- CP-Violation 3+2 Model: Maltoni & Schwetz, arXiv:0705.0107; T. Goldman, G. J. Stephenson Jr., B. H. J. McKellar, Phys. Rev. D75 (2007) 091301 **(YES?)**
- Extra Dimensions 3+1 Model: Pas, Pakvasa, & Weiler, Phys. Rev. D72 (2005) 095017 **NO**
- Lorentz Violation: Katori, Kostelecky, & Tayloe, Phys. Rev. D74 (2006) 105009 **YES?**
- CPT Violation 3+1 Model: Barger, Marfatia, & Whisnant, Phys. Lett. B576 (2003) 303 **YES?**
- New Gauge Boson with Sterile Neutrinos: Ann E. Nelson & Jonathan Walsh, arXiv:0711.1363 **NO**

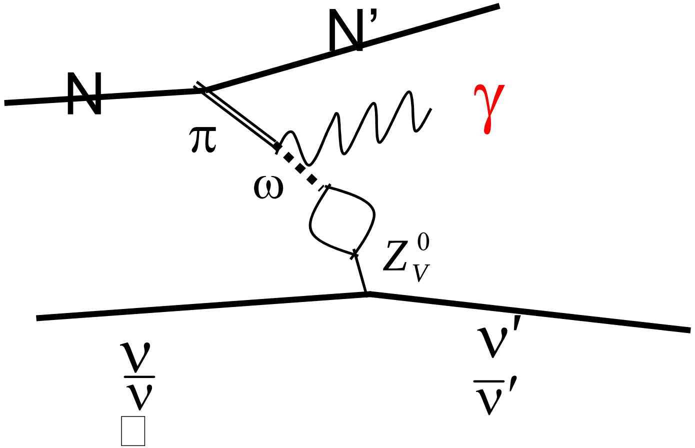
Backgrounds: Order(α x NC) , single photon FS



Radiative Delta Decay

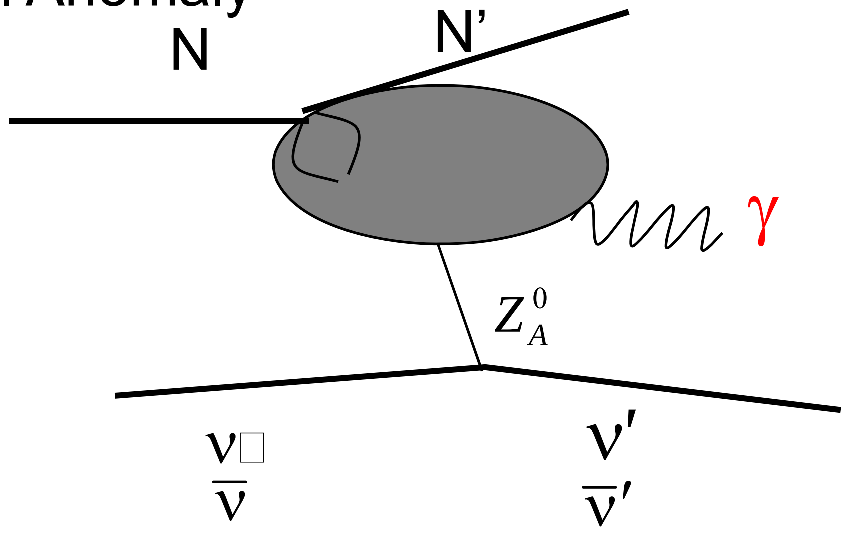


Axial Anomaly



Other PCAC

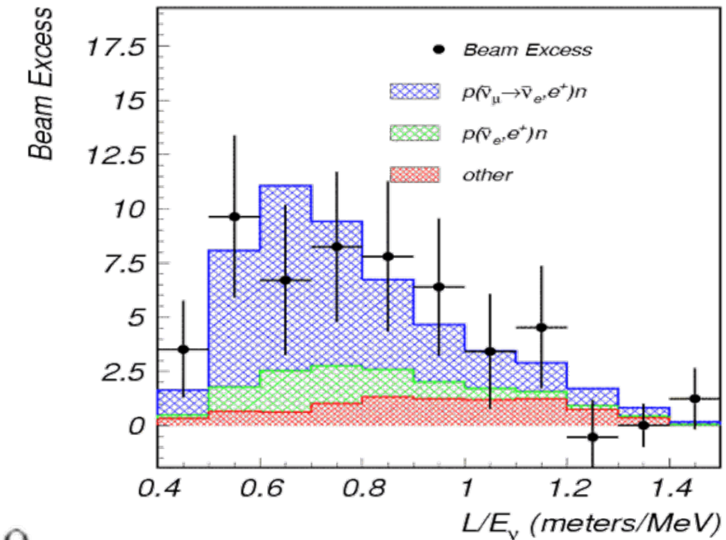
All order ($G^2\alpha\alpha_S$)



So far we have not found a process to account for the $\nu, \bar{\nu}$ difference.

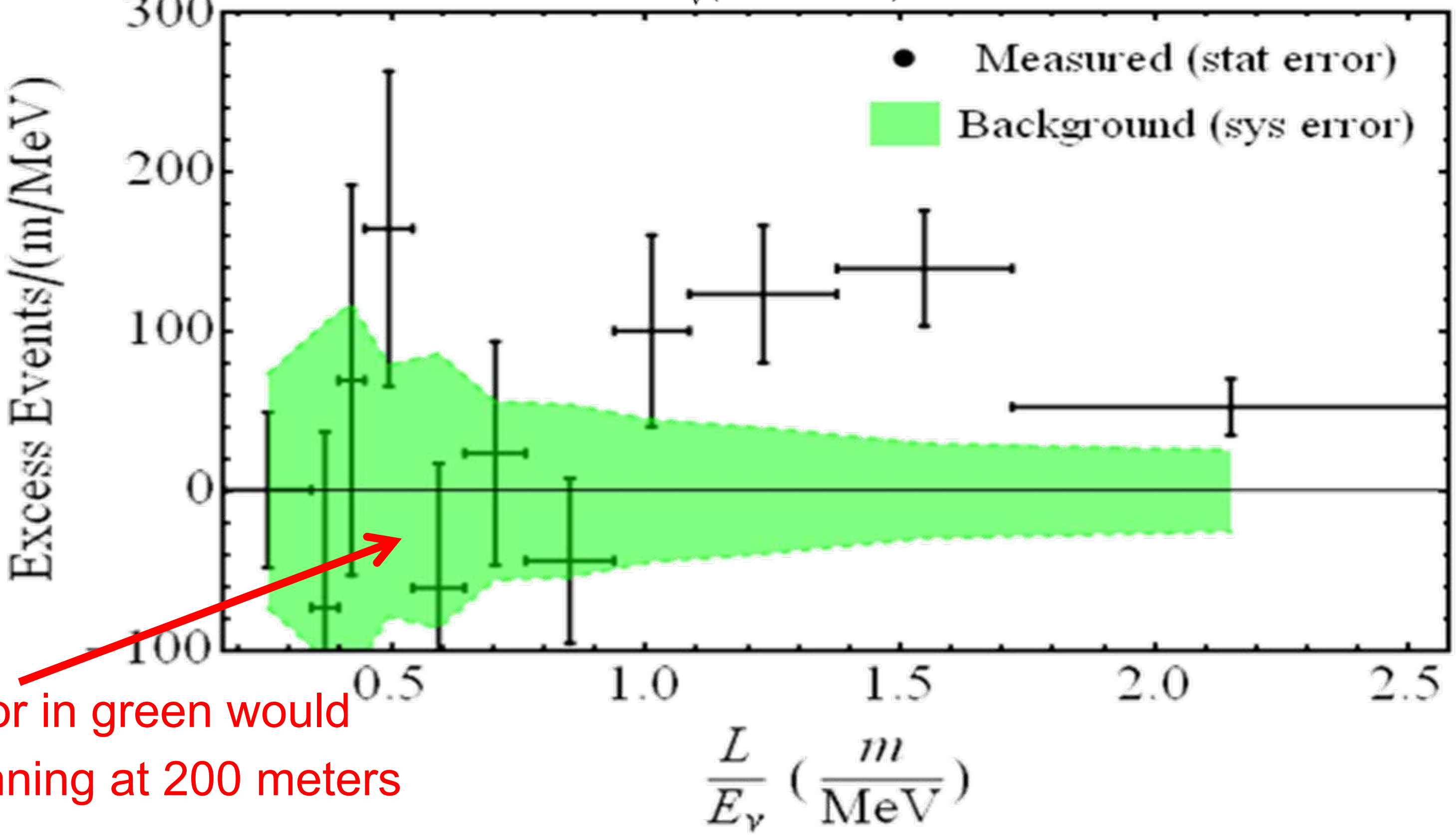
MiniBooNE and LSND Comparison

LSND
(anti-neutrino)



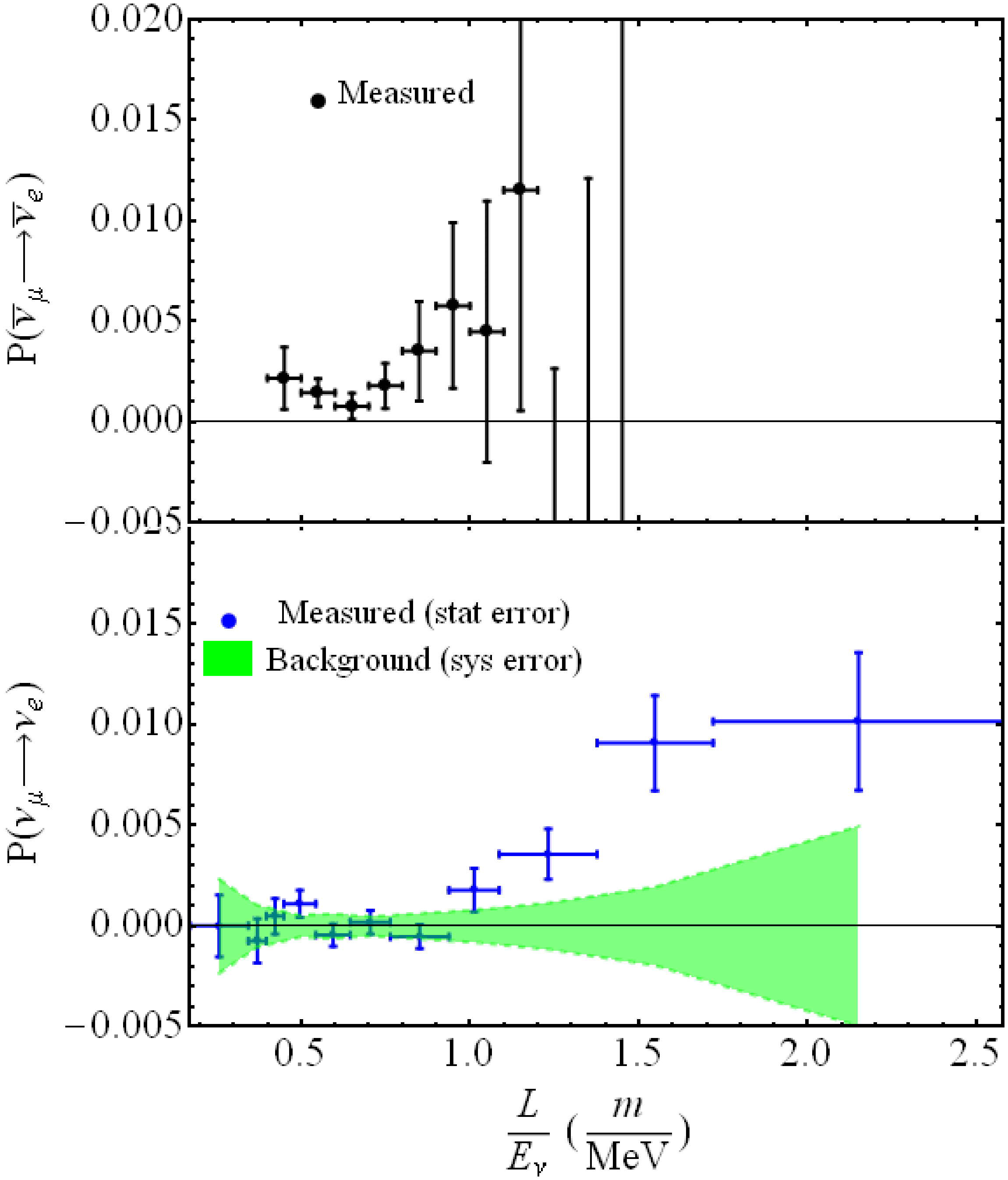
L/E ~ neutrino proper time
(in rest frame of neutrino)

MiniBooNE
(neutrino)



The systematic error in green would
disappear after running at 200 meters

LSND and MiniBooNE oscillation probabilities



LSND and MiniBooNE oscillation probabilities

My own attempts to reconcile
Data:

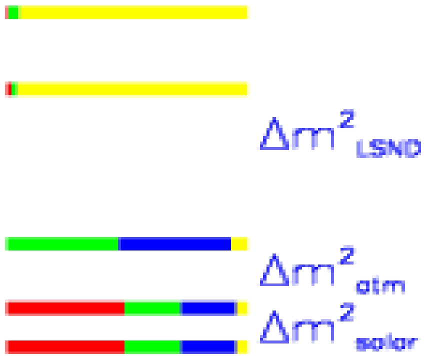
"high-low" solution

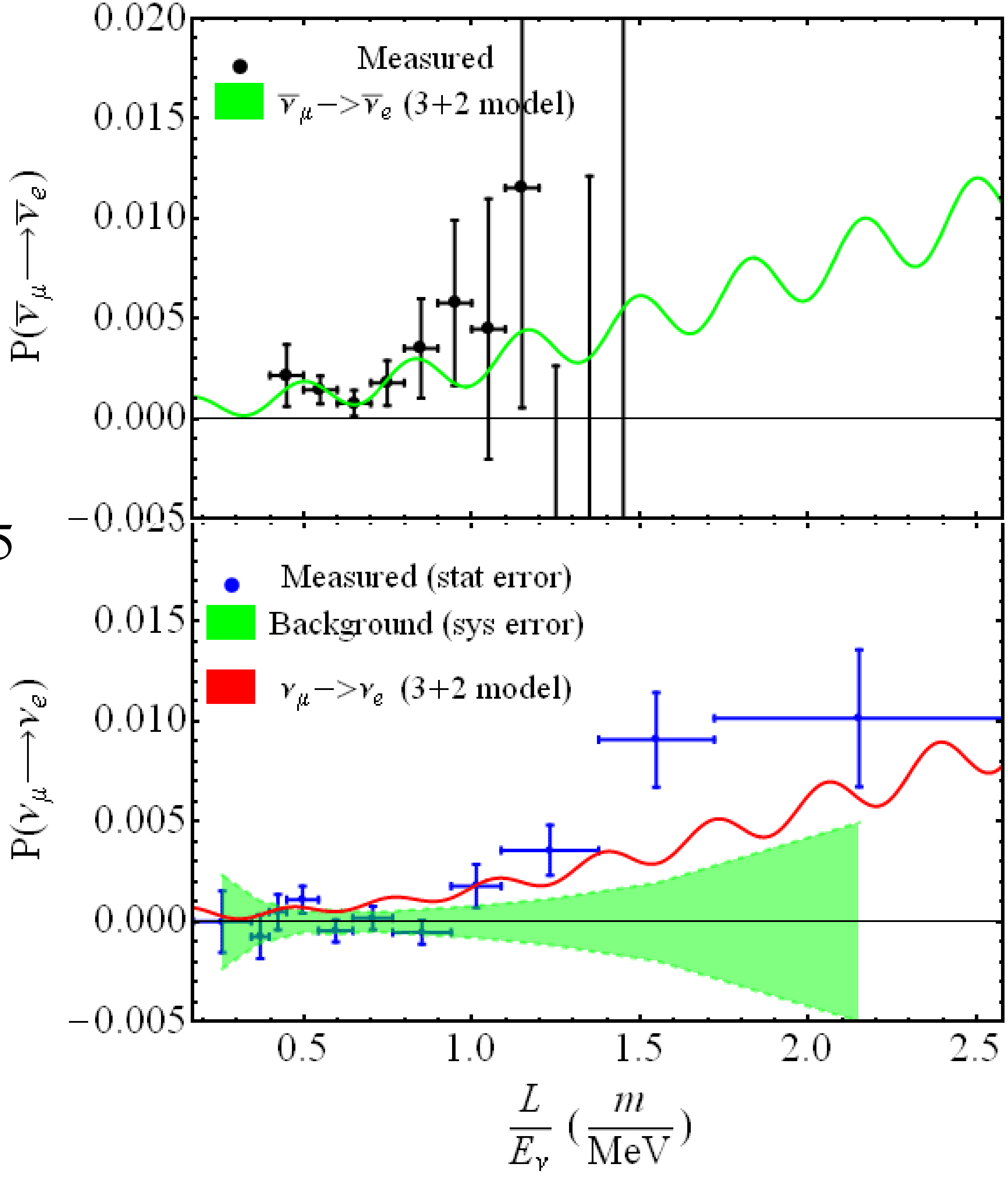
3+2 model (suggestive)

$$\Delta m_a^2 = 7.5\ \text{eV}^2, P_a = 0.015$$

$$\Delta m_b^2 = 0.25\ \text{eV}^2, P_b = 0.065$$

$$\phi_{CP} = 1.3\ \text{rad}$$





LSND and MiniBooNE oscillation probabilities

My own attempts to reconcile Data:

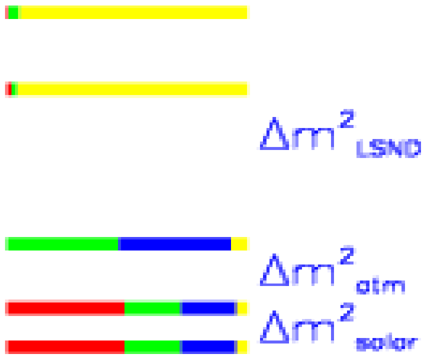
“low-low” solution

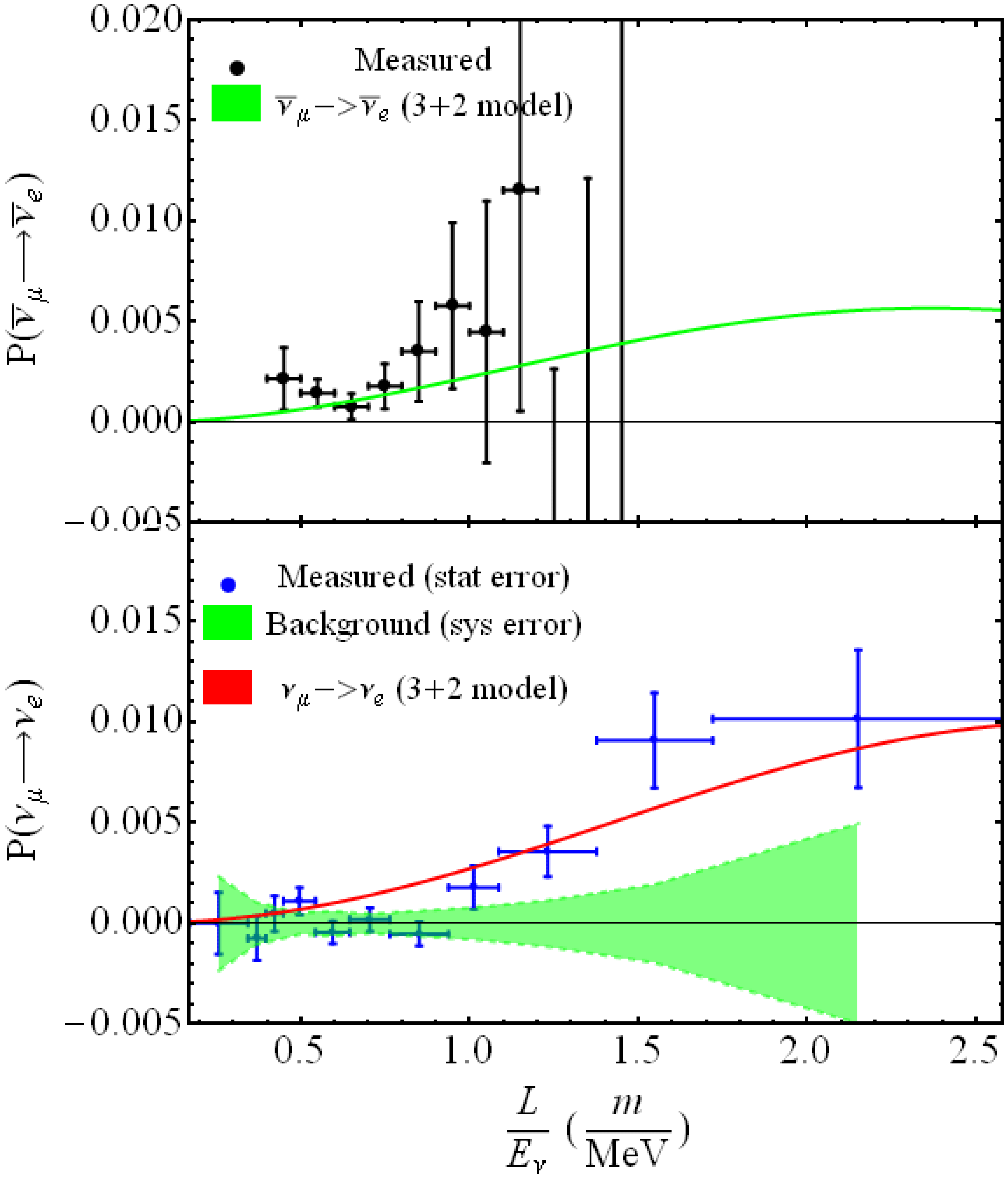
3+2 model (suggestive)

$$\Delta m_a^2 = 0.5\ \text{eV}^2, P_a = 0.04$$

$$\Delta m_b^2 = 0.25\ \text{eV}^2, P_b = 0.025$$

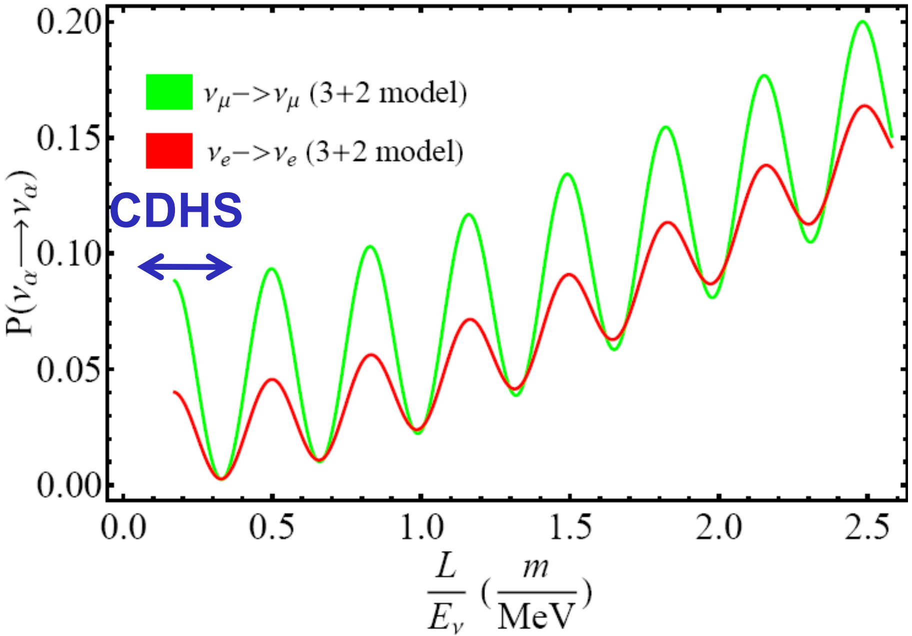
$$\phi_{CP} = \frac{\pi}{2}\ \text{rad}$$

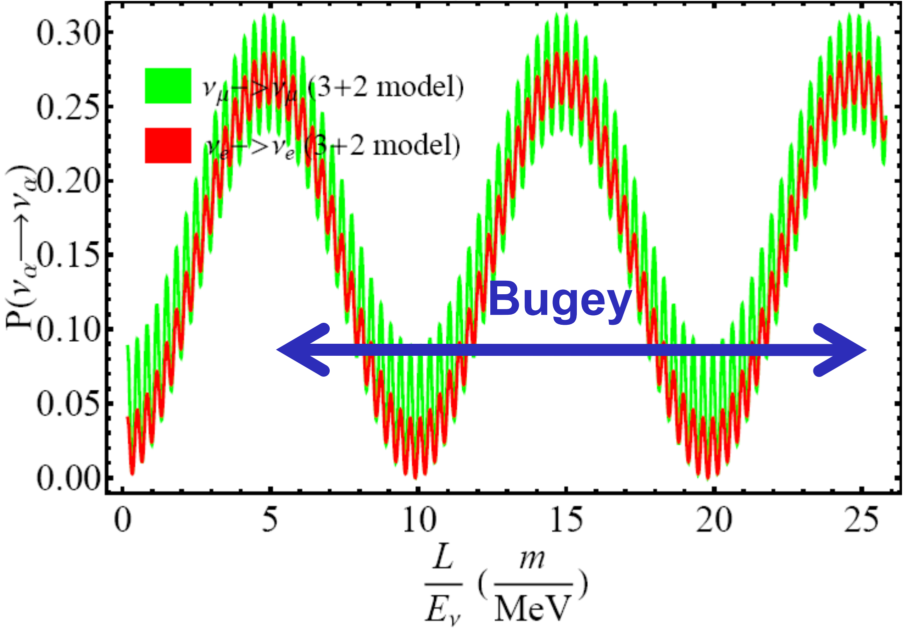




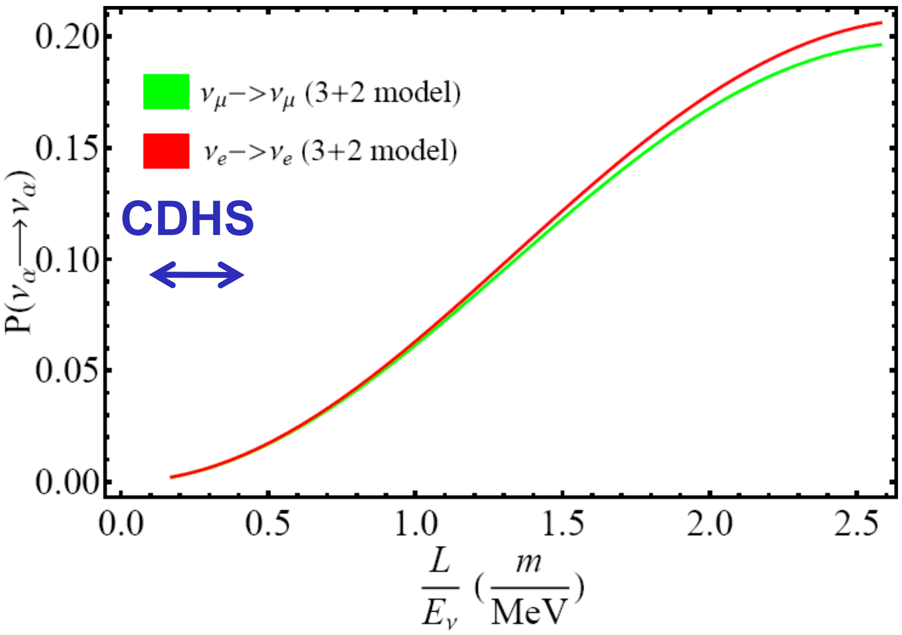
Disappearance oscillation probabilities

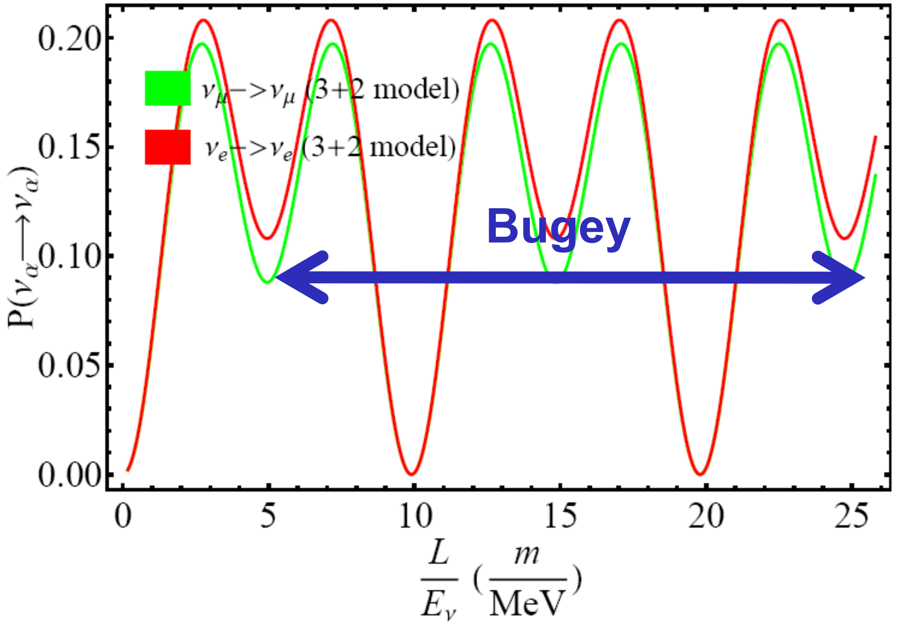
"high-low" 3+2 example





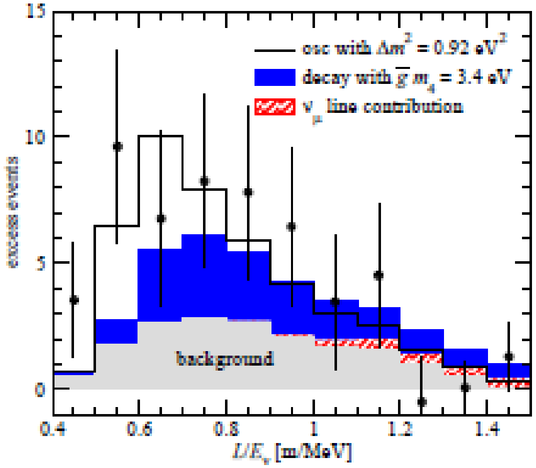
"low-low" 3+2 example



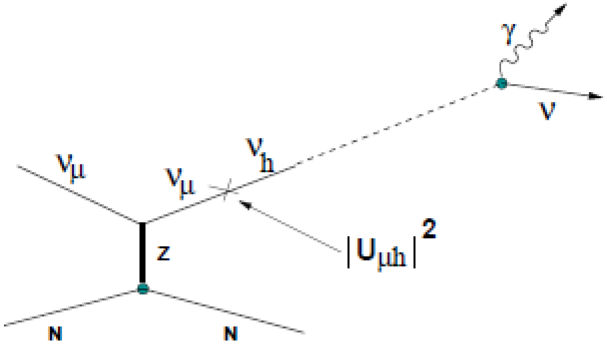


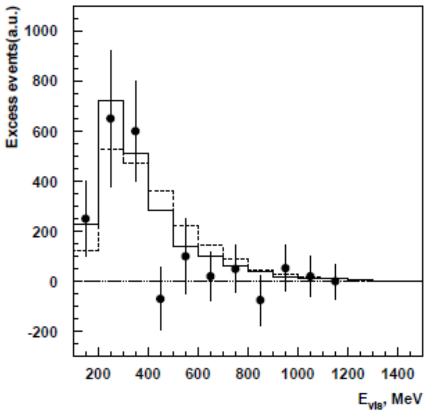
Neutrino Decays?

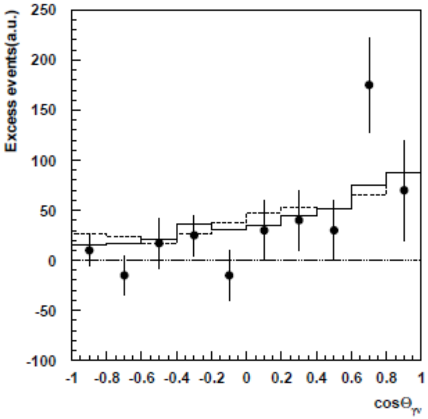
- With the addition of heavy sterile neutrinos the effects of sterile neutrino decays become important
- The combined effect has been shown to separately accommodate LSND and MiniBooNE results
  - arXiv:hep-ph/050521:



  - arXiv:0902.3802:







Future Work

- We plan to continue running in antineutrino mode until the summer 2009 shutdown and collect a total of ~5.3E20 POT (50% more data)
- We will perform combined neutrino/antineutrino analysis with the extra data, some systematic errors will cancel.
- Approved for antineutrino and/or neutrino running for another 0.5 E21 POT.

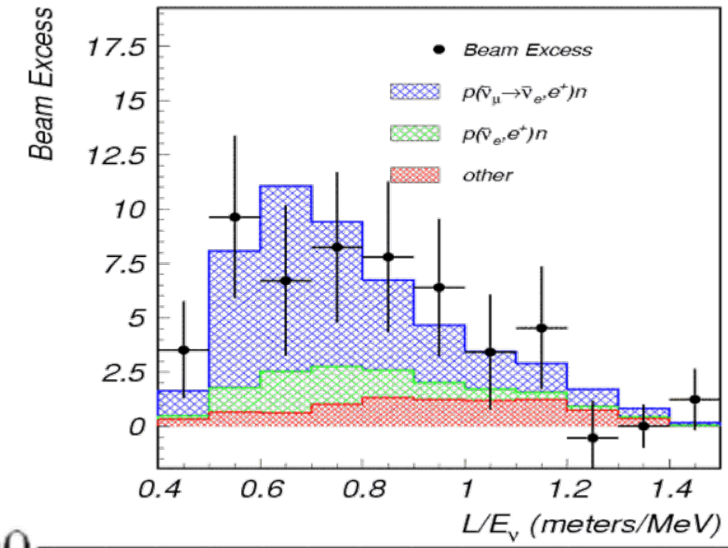
Resolving the Low Energy Excess

- Moving the MiniBooNE detector to 200m (~4M$) (or building a new detector at 200m (~$8M$))
  - Accumulate a sufficient data sample in < 1 year
  - will dramatically reduce systematic errors (low energy excess is ~ 6 sigma significance with statistical errors only.
  - Can study L dependence of excess: backgrounds scale as 1/L**2, oscillation signal as $\sin^2$(L/E), and decay as L/E.

- MicroBooNE:
  - is a 70 ton liquid argon time projection chamber planned for the booster neutrino beamline
  - can differentiate single gamma-rays from electrons (MiniBooNE cannot do this)

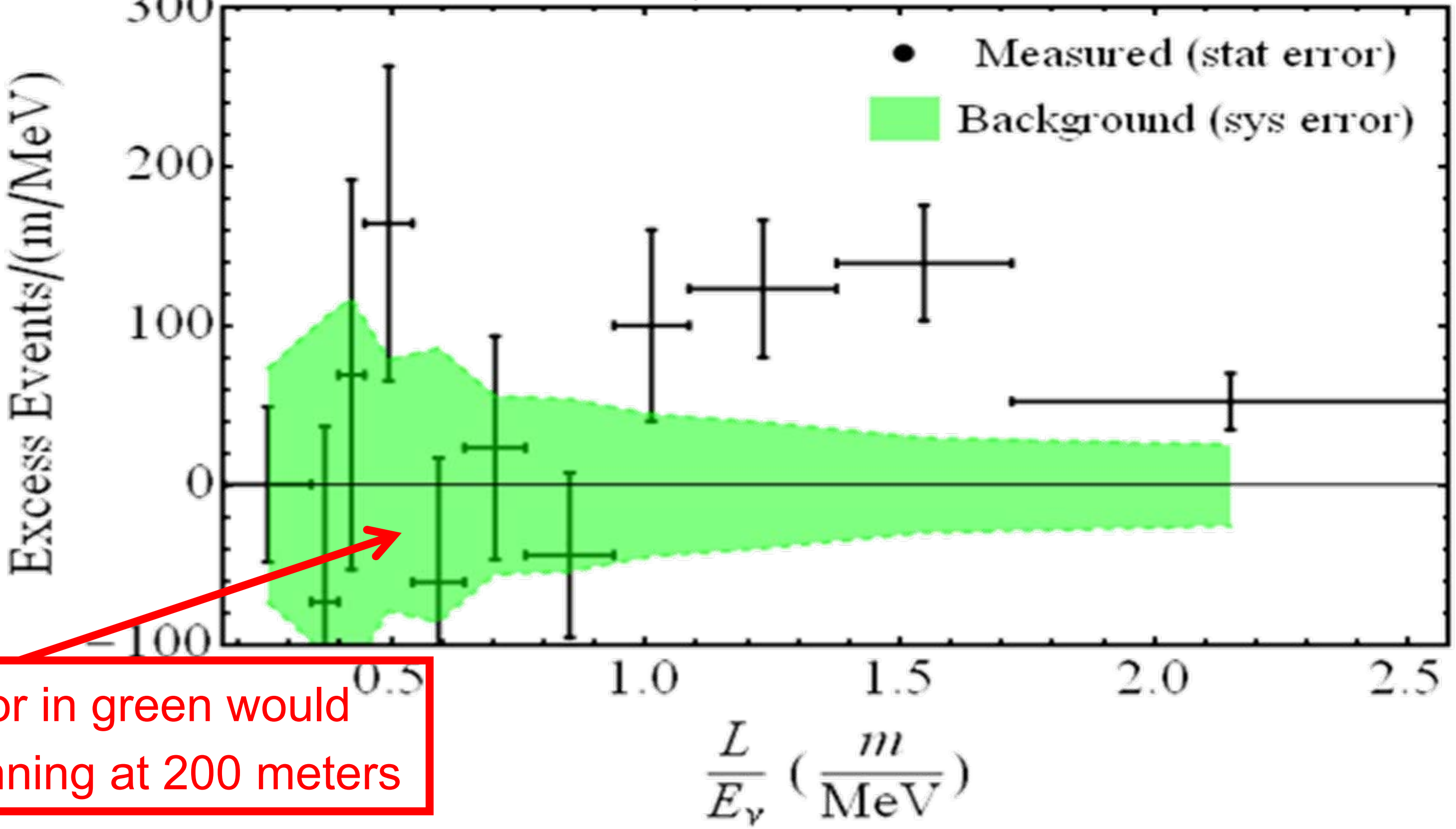
MiniBooNE at 200 meters

LSND
(anti-neutrino)



L/E ~ neutrino proper time
(in rest frame of neutrino)

MiniBooNE
(neutrino)



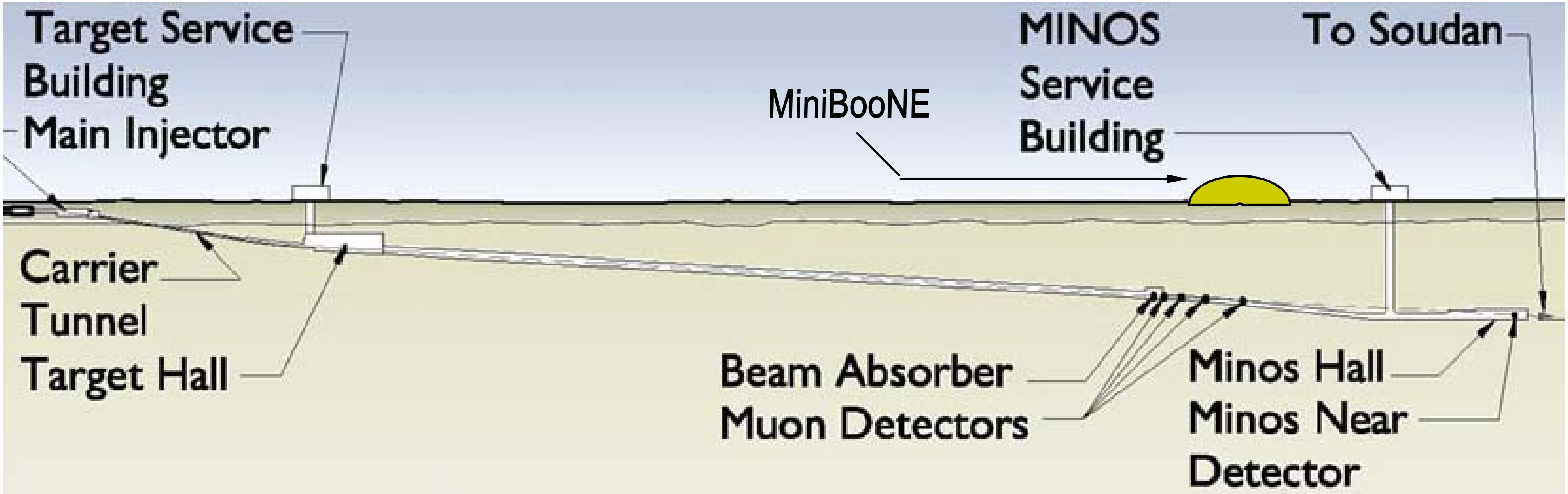
The systematic error in green would
disappear after running at 200 meters

Conclusions for BNB Data

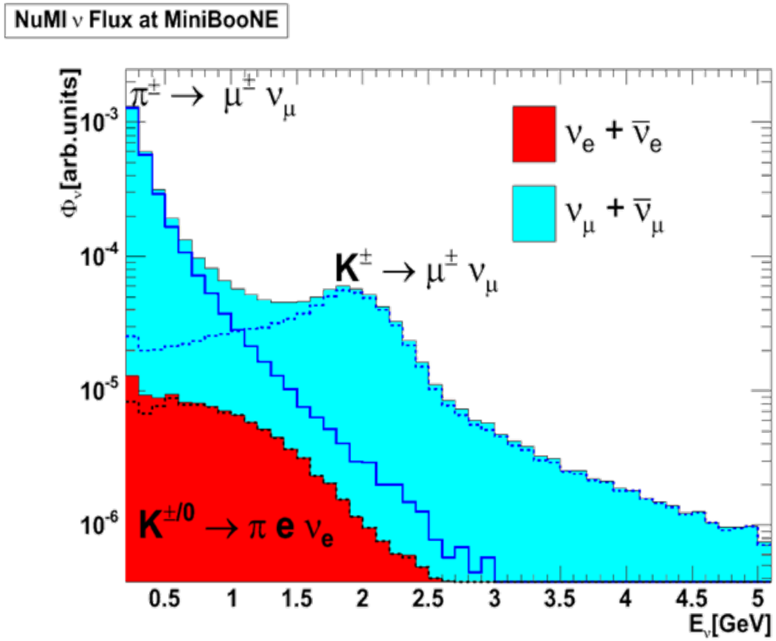
- An unexplained excess of 128.8 ± 20.4 ± 38.3 (3.0σ total, 6.4σ stat)) electron-like events are observed in the low energy range from $200 < E_v < 475$MeV (submitted to PRL, arXiv:0812.2243 [hep-ex]).
- *No low energy excess is observed* similar to neutrino mode, which disfavors many types of backgrounds/signal processes (e.g. HHH Axial Anomaly).
- The low energy excess is important to next generation long baseline neutrino experiments (T2K, NOvA, DUSEL-FNAL).
- If the low energy excess is due to new physics (complicated oscillations, sterile neutrinos, neutrino decay, etc), it would be a major discovery.
- We believe that this is an experimental question and that a combination of running MiniBooNE in a near position and data from the planned MicroBooNE detector will resolve the question.

NuMI Beam Data

NuMI Events in MiniBooNE



The beam at MiniBooNE from NuMI is significantly enhanced in ν_e from K decay because of the 110 mrad off-axis position. MiniBooNE is 745m from NuMI target

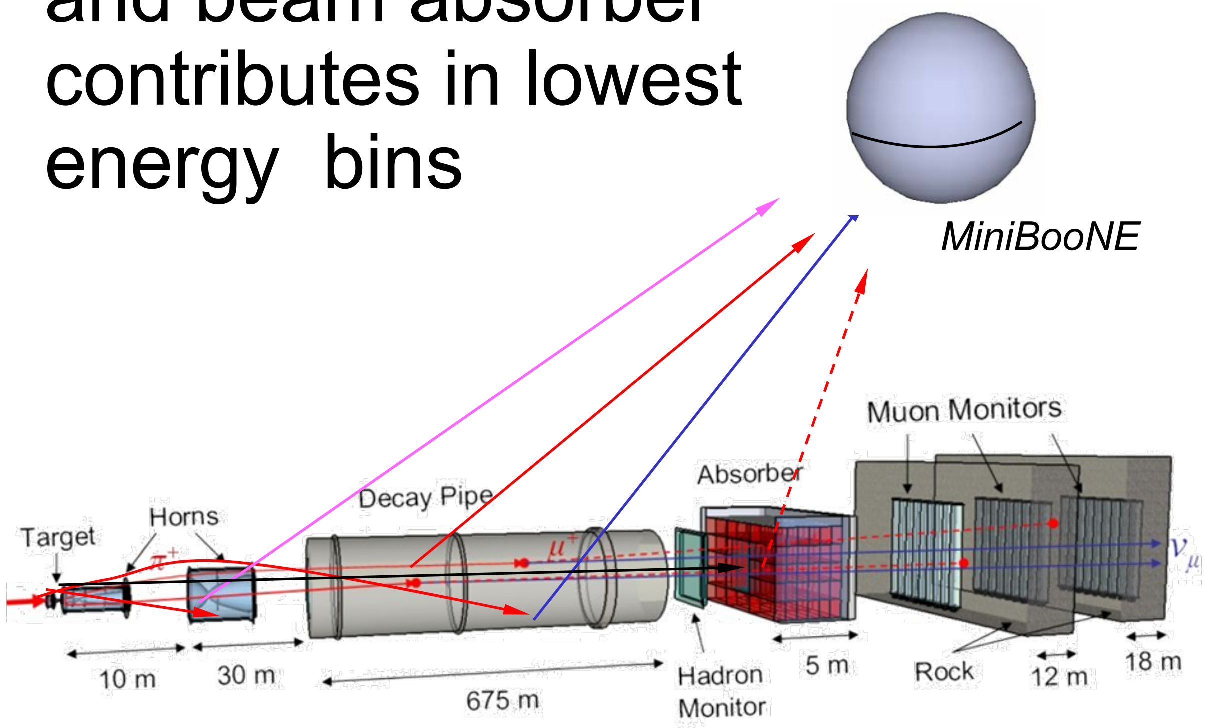


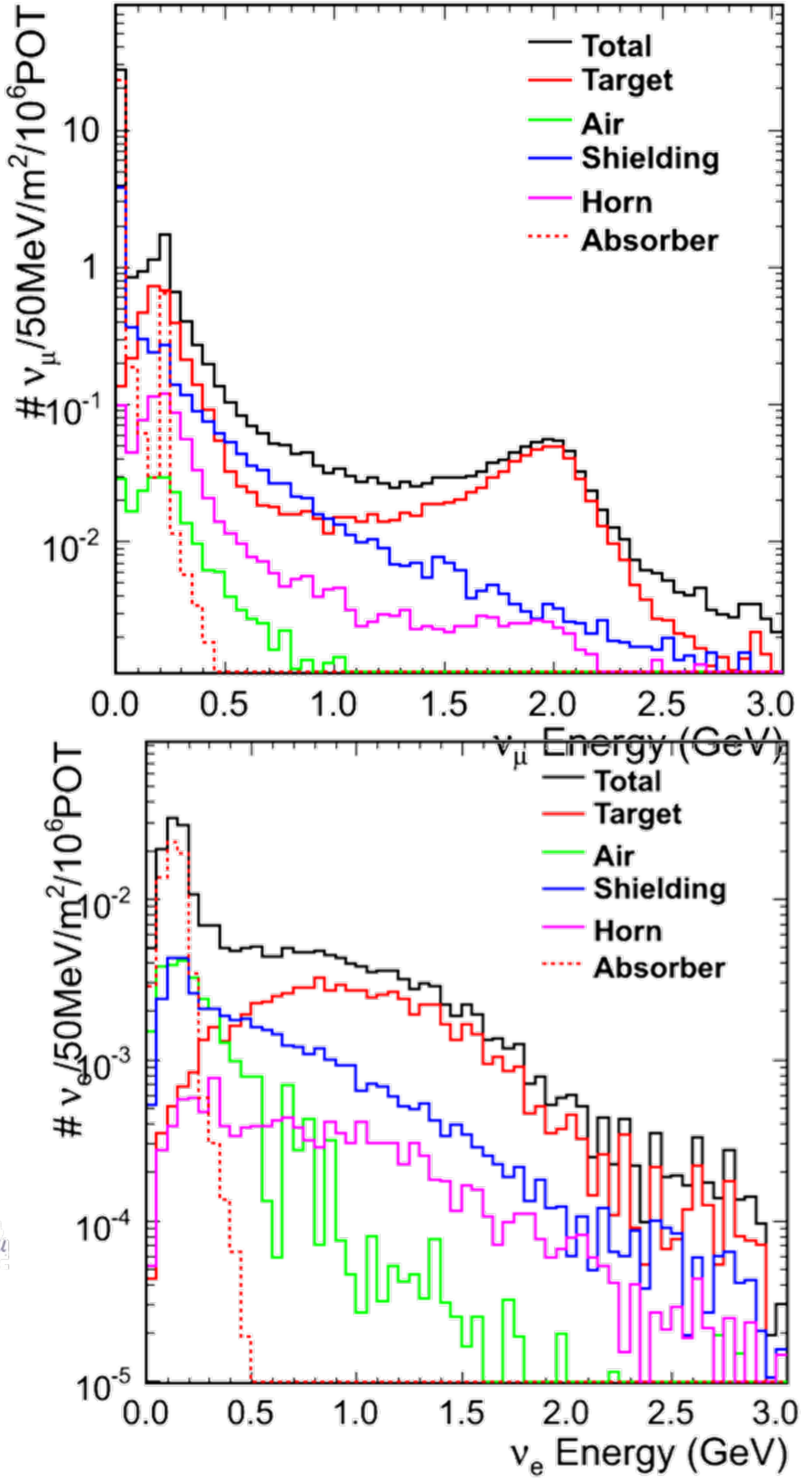
NuMI event rates:

ν_μ: 81% ν_e: 5% $\bar{\nu}_\mu$: 13% $\bar{\nu}_e$: 1%

Neutrino Sources along the NuMI Beam Line

- Higher energy neutrinos mostly from particles created in target
- Interactions in shielding and beam absorber contributes in lowest energy bins

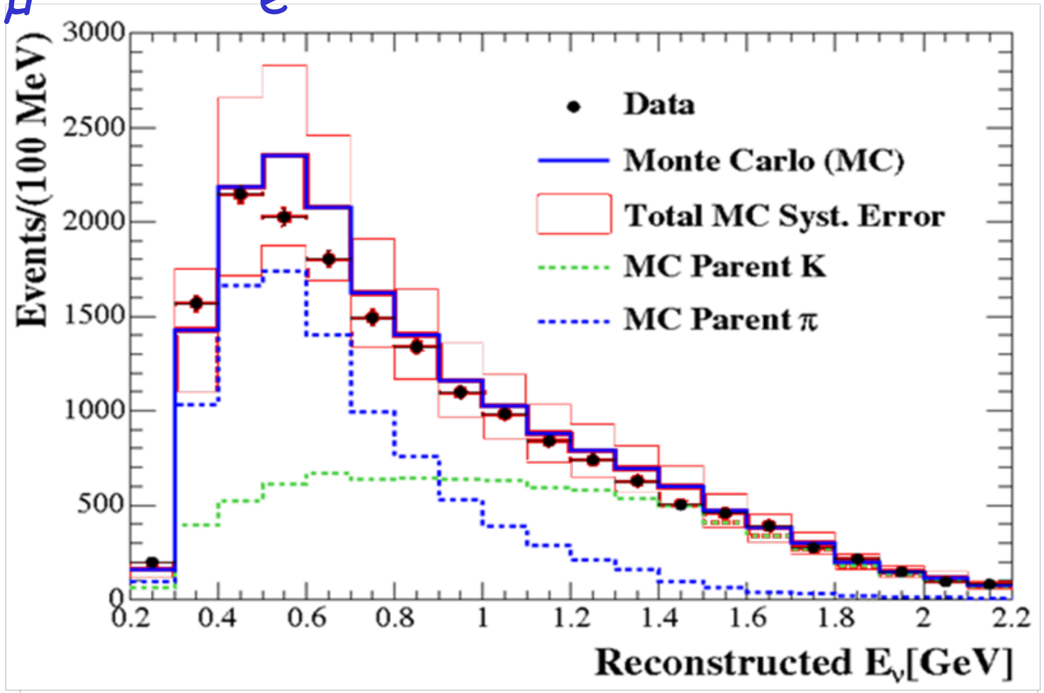




NuMI ν_μ and ν_e Data

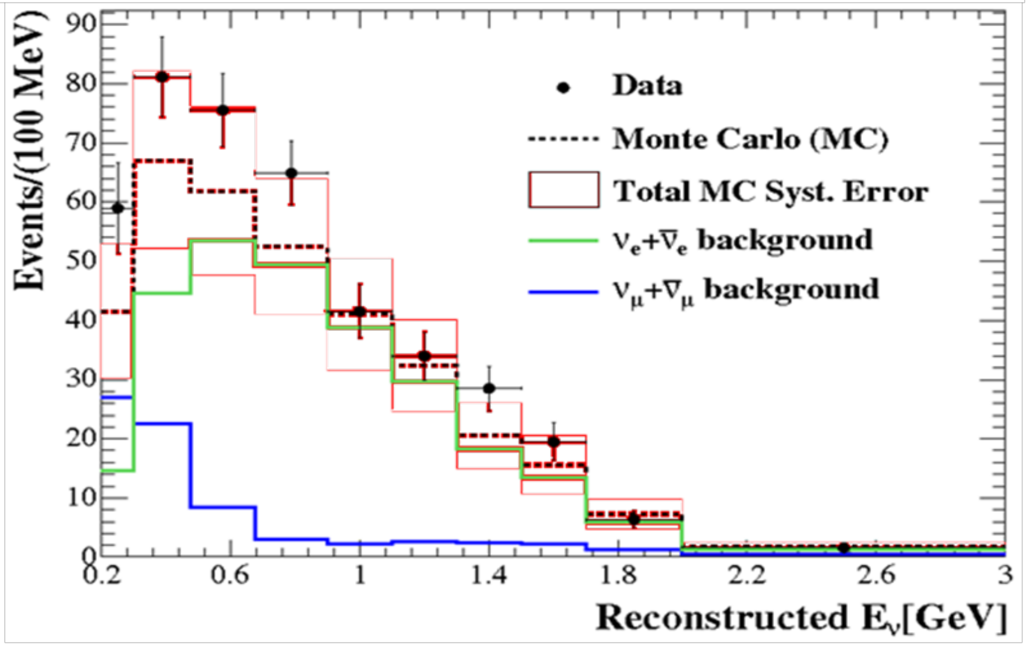
arXiv:0809.2447v1

ν_μ
CCQE
sample



Good agreement between data and Monte Carlo:the MC is tuned well.

ν_e
CCQE
sample



Very different backgrounds compared to MB (Kaons vs Pions)

Ongoing effort to reduce ν_e CCQE sample systematics

NuMI ν_e data shows a sizeable e-like excess but analysis is preliminary

Conclusions for NuMI Data

- Preliminary analysis of this data shows a large excess of electron-like events, but with large systematic errors owing to the preliminary nature of the analysis

- The analysis to constrain the nue background predictions to the numu data, hence reducing the systematic errors is nearly complete

- At the moment the excess appears to be too large to be explained by simple oscillations and be consistent the BNB low energy excess, so stay tuned….

Cosmic Gall

John Updike (1932 - 2009)

Neutrinos they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dust maids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall,
And, scorning barriers of class,
Infiltrate you and me! Like tall
And painless guillotines, they fall
Down through our heads into the grass.
At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed – you call
It wonderful; I call it crass.

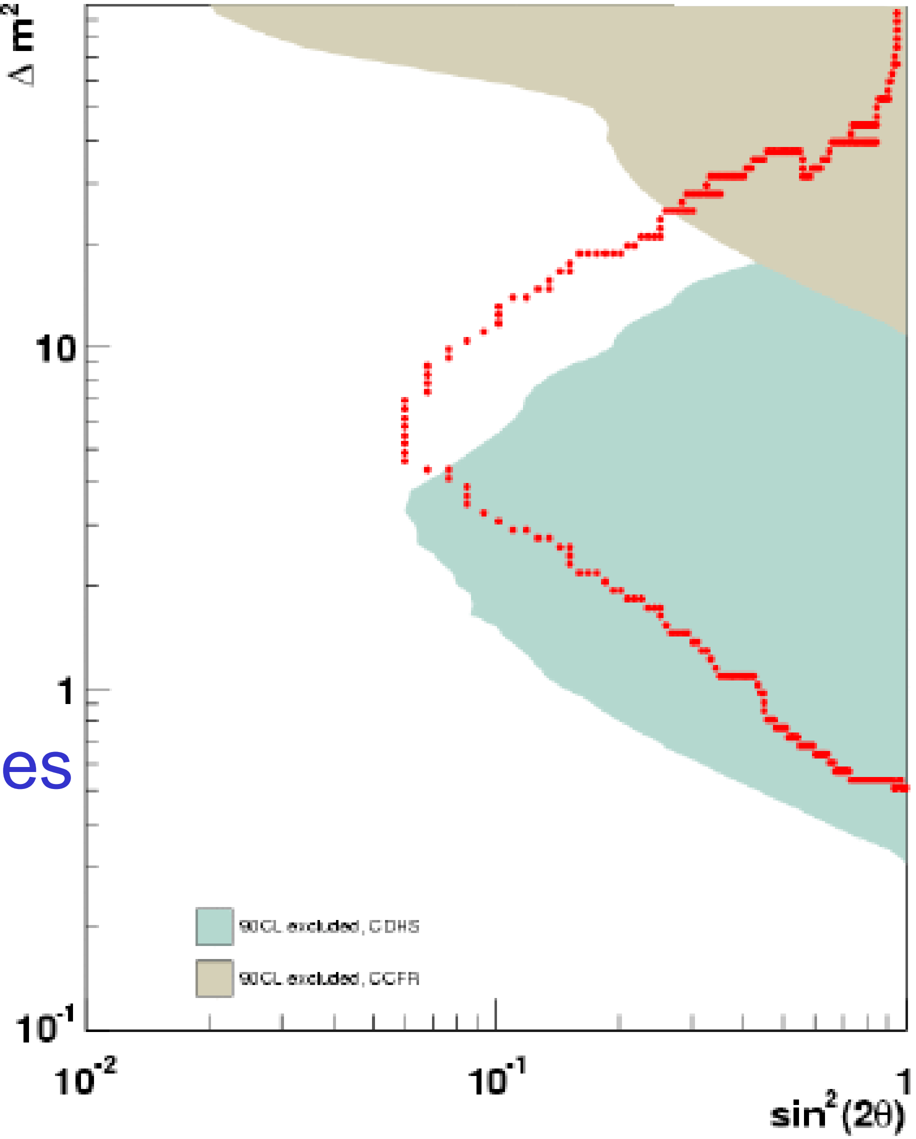
BACKUP SLIDES

Complete MiniBooNE ν_μ Disappearance Sensitivity

- MiniBooNE only 90% CL sensitivity

- CDHS CCFR 90% CL

Inclusion of SciBooNE as a near detector, dramatically improves the sensitivity by reducing flux and cross section uncertainties



Many oscillations models predict large muon disappearance.