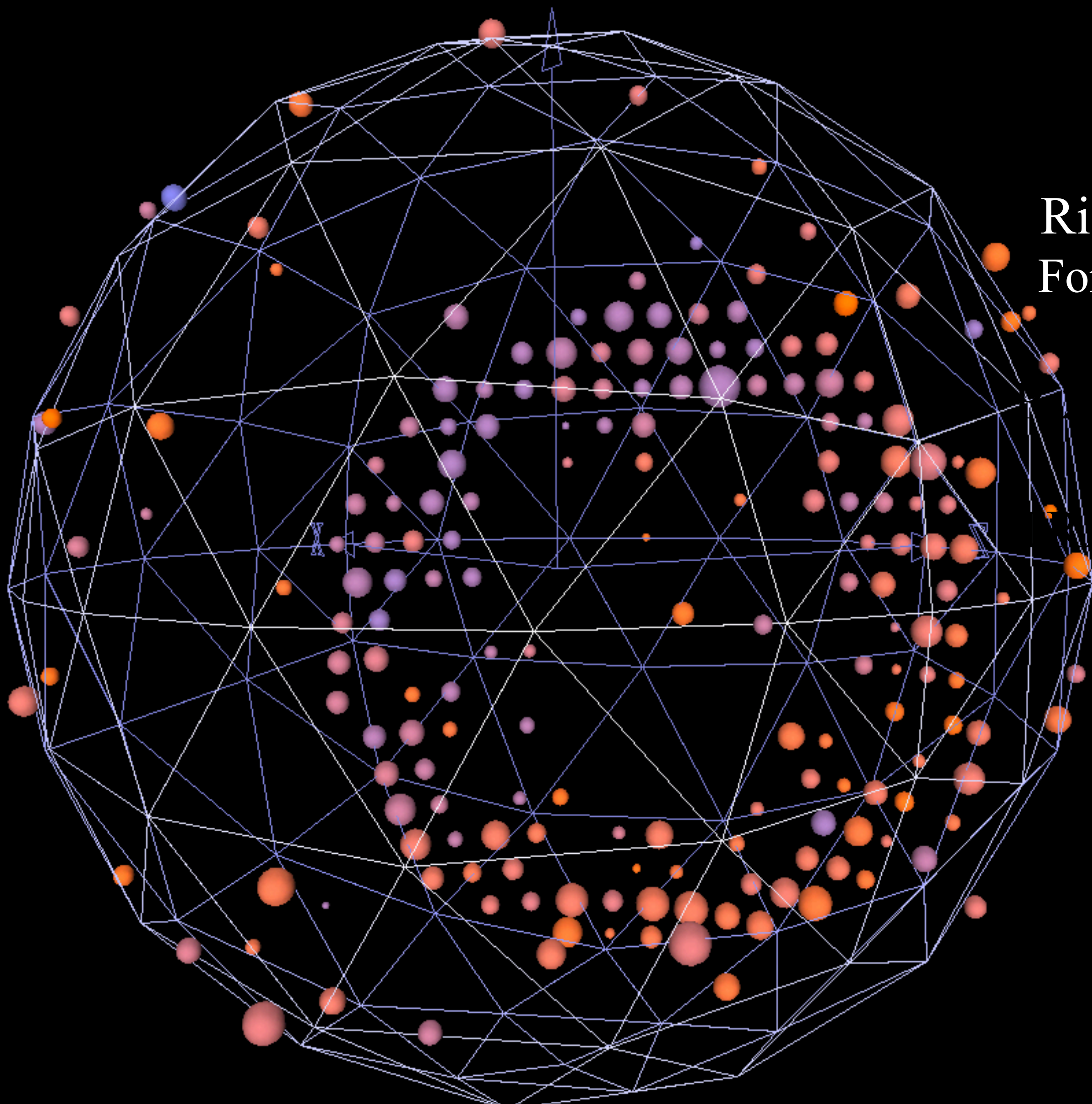
Updated Anti-neutrino Oscillation Results from MiniBooNE



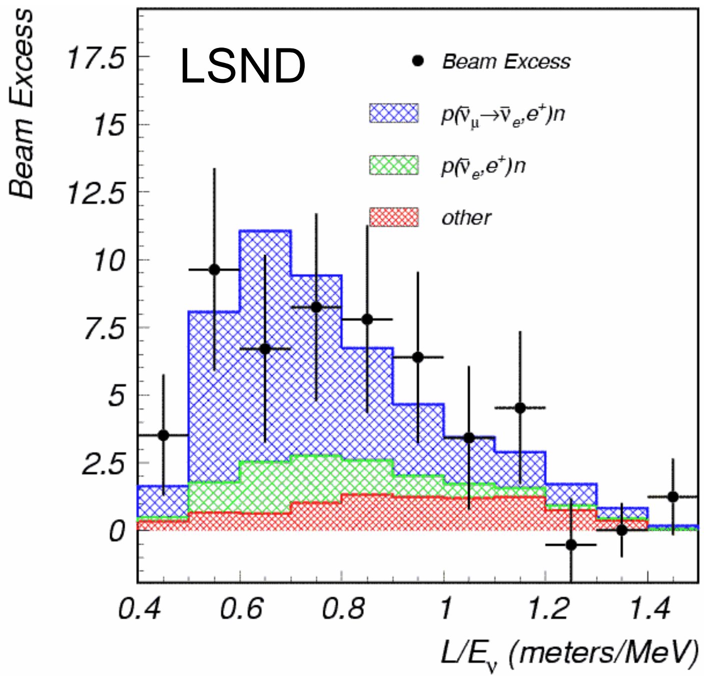
(Anti)Neutrino 2010
Athens, Greece
June 14, 2010

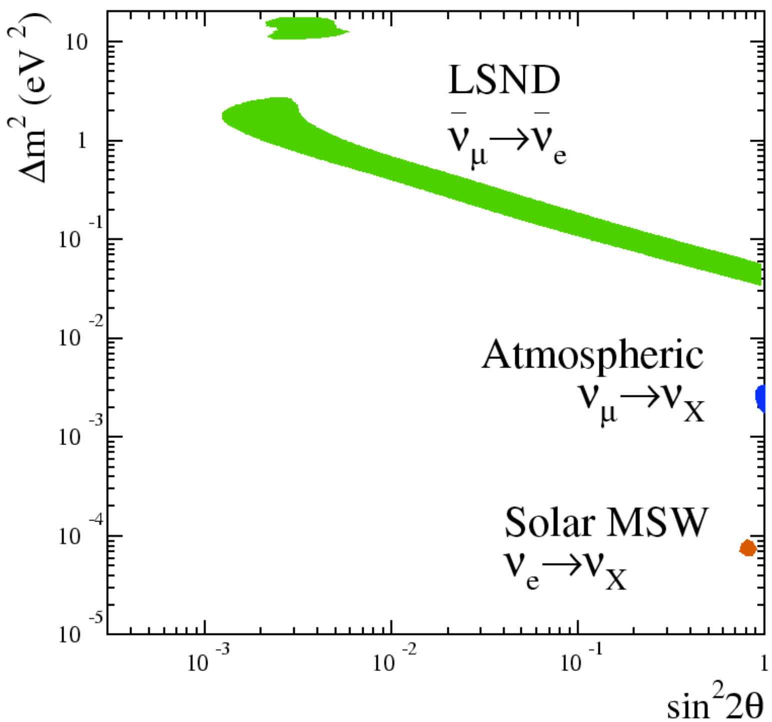
Richard Van de Water (LANL)
For the MiniBooNE collaboration

Introduction

- Presenting a review of the MiniBooNE oscillation results:
  - Motivation for MiniBooNE; Testing the LSND anomaly.
  - MiniBooNE design strategy and assumptions
  - Neutrino oscillation results; PRL 102,101802 (2009)
  - Antineutrino oscillation results; PRL 103,111801 (2009)
  - Updated Antineutrino oscillation results; ~70% more data
  - Summary and future outlook

Motivation for MiniBooNE: The LSND Evidence for Oscillations





LSND Saw an excess of $\overline{\nu}_e$:
87.9 ± 22.4 ± 6.0 events.

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

3.8 σ evidence for antineutrino $\overline{\nu}_u \longrightarrow \overline{\nu}_e$ oscillation.

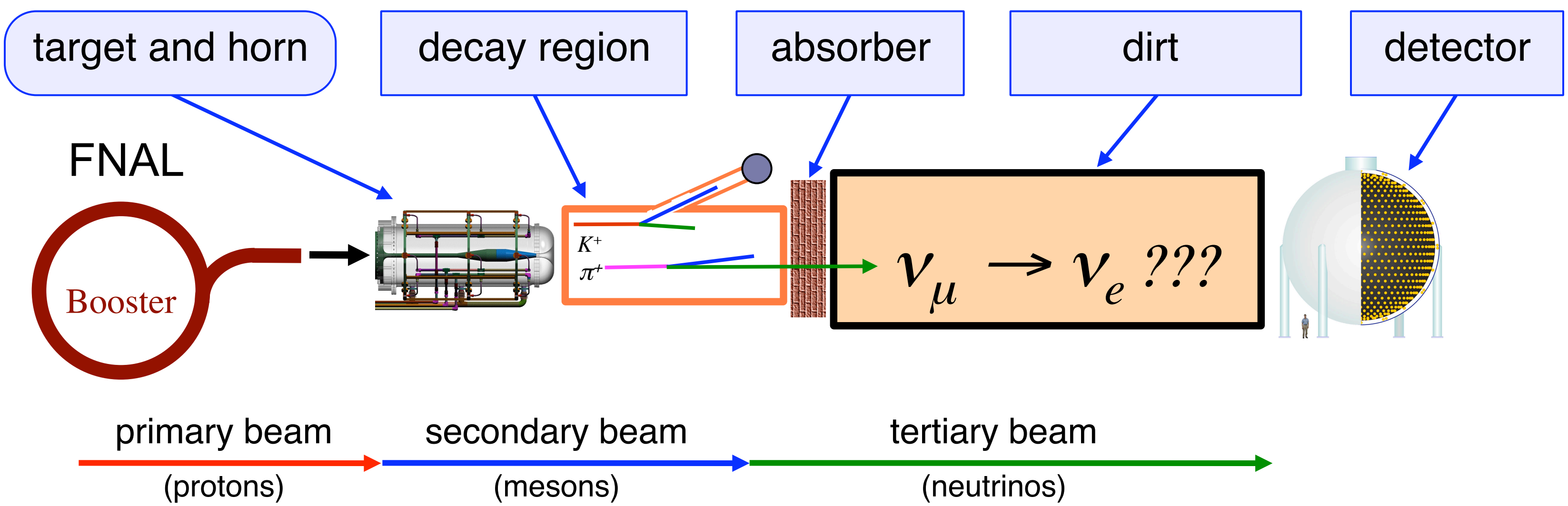
The three oscillation signals cannot be reconciled without introducing Beyond Standard Model Physics!

MiniBooNE was designed to test the LSND signal

Keep L/E same as LSND
while changing systematics, energy & event signature

$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$ ➔ Two neutrino fits

LSND:	E ~30 MeV	L ~30 m	L/E ~1
MiniBooNE:	E ~500 MeV	L ~500 m	L/E ~1



Neutrino mode: search for $\nu_\mu \to \nu_e$ appearance with 6.5E20 POT ➔ assumes CP/CPT conservation
Antineutrino mode: search for $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance with 5.66E20 POT ➔ direct test of LSND

FNAL has done a great job delivering beam!

$\overset{(-)}{\nu}_e$ *Event Rate Predictions*

#Events = Flux x Cross-sections x Detector response

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

External and MiniBooNE Measurements
π^0, $\Delta \longrightarrow N\gamma$, dirt, and intrinsic ν_e constrained from data.

Detailed detector simulation and PID
Checked with neutrino data and calibration sources.

- A. A. Aguilar-Arevalo et al., *"Neutrino flux prediction at MiniBooNE"*, Phys. Rev. D79, 072002 (2009).

- A. A. Aguilar-Arevalo et al., *"Measurement of Muon Neutrino Quasi-Elastic Scattering on Carbon"*, Phys. Rev. Lett. 100, 032301 (2008).
- A. Aguilar-Arevalo et al., *"First Observation of Coherent π^0 Production in Neutrino Nucleus Interactions with Neutrino Energy <2 GeV"*, Phys. Lett. 664B, 41 (2008).
- A. A. Aguilar-Arevalo et al., *"Measurement of the Ratio of the ν_u Charged-Current Single-Pion Production to Quasielastic Scattering with a 0.8 GeV Neutrino Beam on Mineral Oil"*, Phys. Rev. Lett. 103, 081801 (2009).
- A. A. Aguilar-Arevalo et al., *"Measurement of ν_u and $\underline{\nu_u}$ induced neutral current single π^0 production cross sections on mineral oil at E_n ~ 1 GeV"*, Phys. Rev. D81, 013005 (2010). (see talk by Martin Tzanov)
- A. A. Aguilar-Arevalo et al, "*Measurement of the ν_μ charged current π+ to quasi-elastic cross section ratio on mineral oil in a 0.8 GeV neutrino beam*". Phys.Rev. Lett. 103:081801 (2010). (see talk by Martin Tzanov)
- A. A. Aguilar-Arevalo et al, "*First Measurement of the Muon Neutrino Charged Current Quasielastic Double Differential Cross Section*", Phys. Rev, D81, 092005 (2010), arXiv: 1002.2680 [hep-ex]. (see talk by Morgan Wascko)

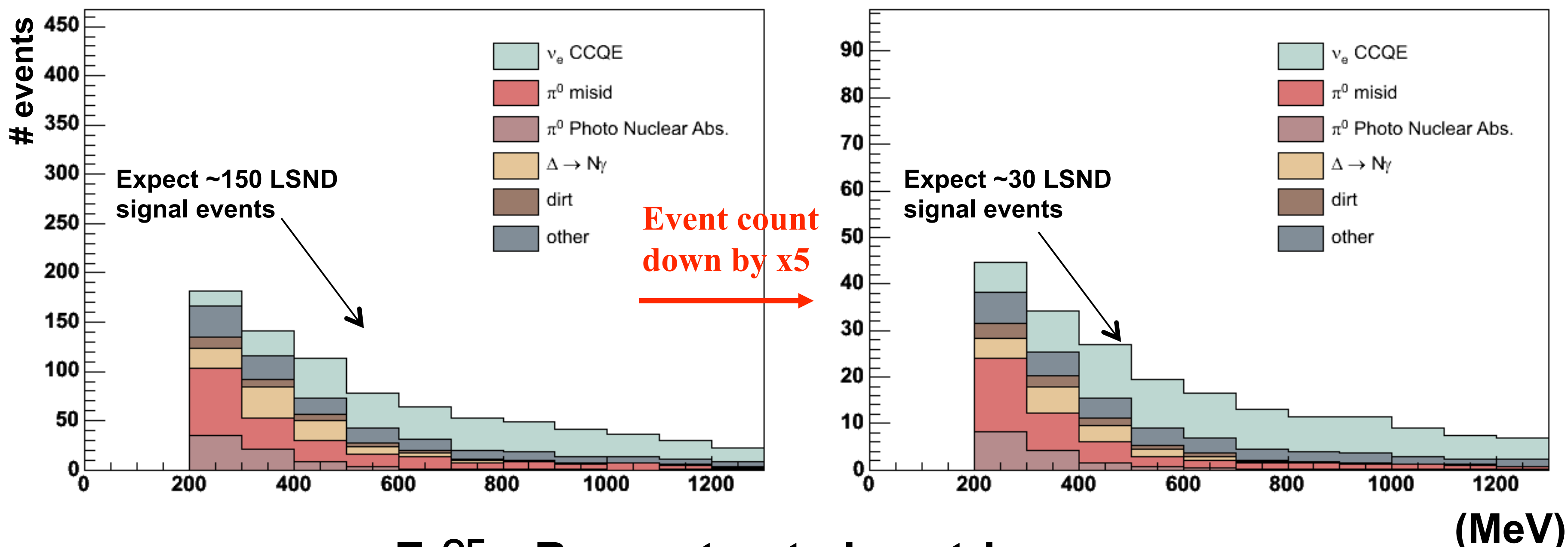
- A. A. Aguilar-Arevalo et al., *"The MiniBooNE Detector"*, Nucl. Instr. Meth. A599, 28 (2009).
- P. Adamson et al., *"Measurement of ν_u and ν_e Events in an Off-Axis Horn-Focused Neutrino Beam"*, Phys. Rev. Lett. 102, 211801 (2009).
- R.B. Patterson et al, "The Extended-Track Event Reconstruction for MiniBooNE", Nucl. Instrum. Meth. A608, 206 (2009).

$\overset{(-)}{\nu}_e$ *Event Rate Predictions for Appearance Analysis*

- Antineutrino rate down by a factor of 5 (reduced flux and cross section)
- Background types and relative rates are similar for neutrino and antineutrino mode.
    - except inclusion of 15.9% wrong-sign neutrino flux component in antineutrino mode (see poster by Joe Grange)
- Fit analysis and errors are similar.

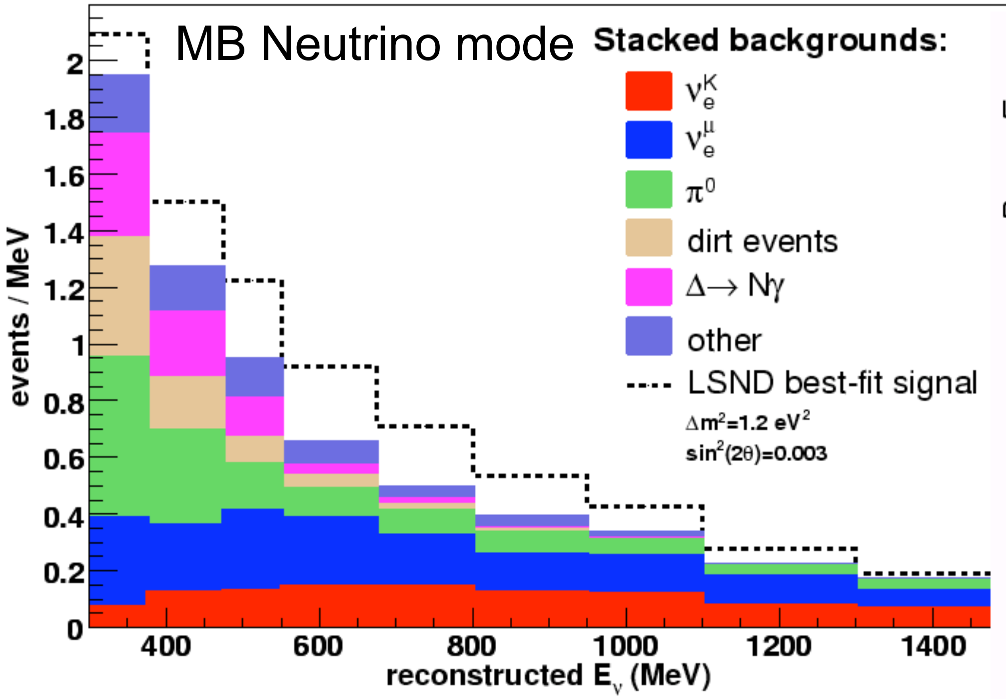
$\overset{(-)}{\nu}_e$ Backgrounds after PID cuts (Monte Carlo)

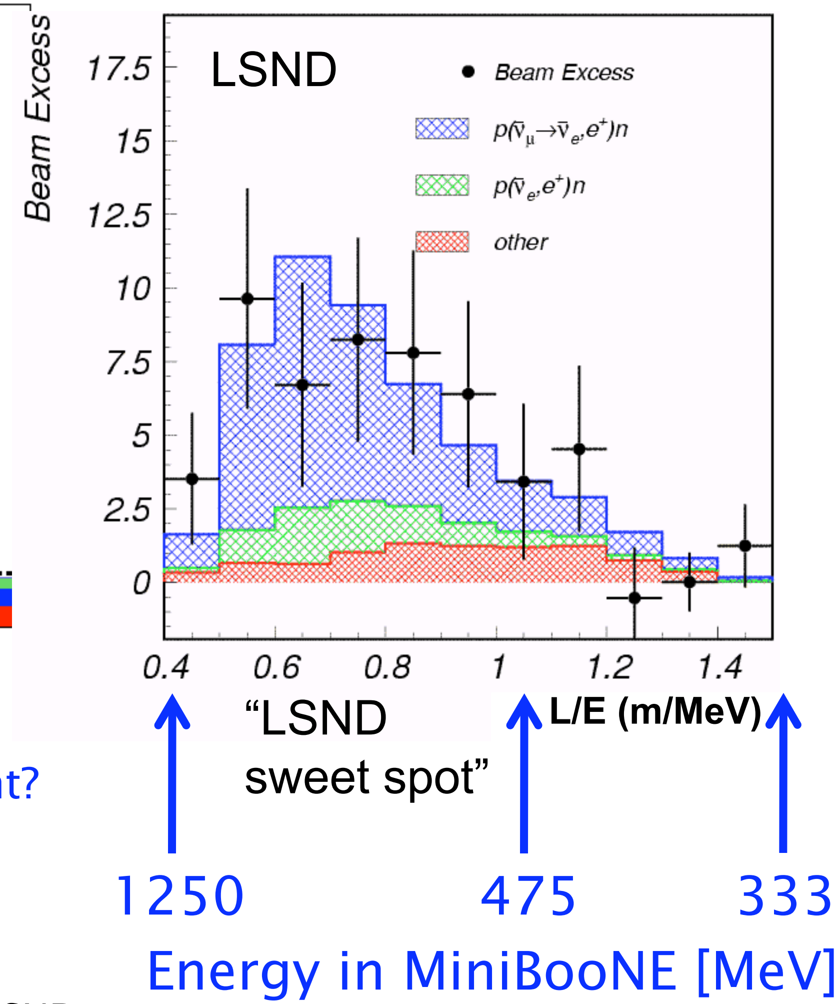
Neutrino 6.5x10^{20} POT **AntiNeutrino 5.66x10^{20} POT**



E_ν^{QE} = Reconstructed neutrino energy

Reminders of some pre-unblinding choices

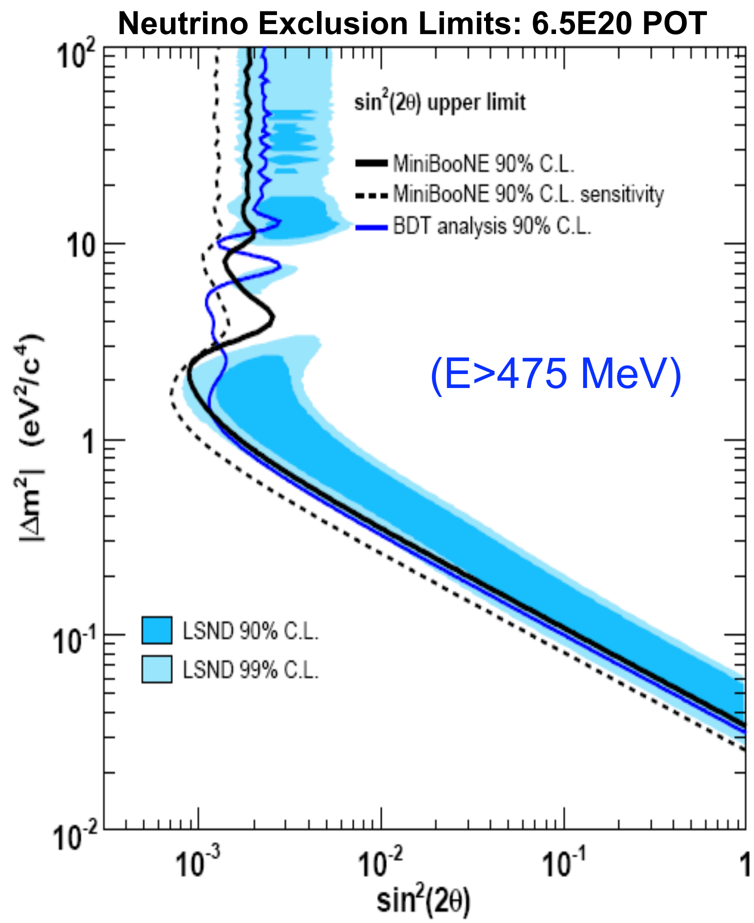




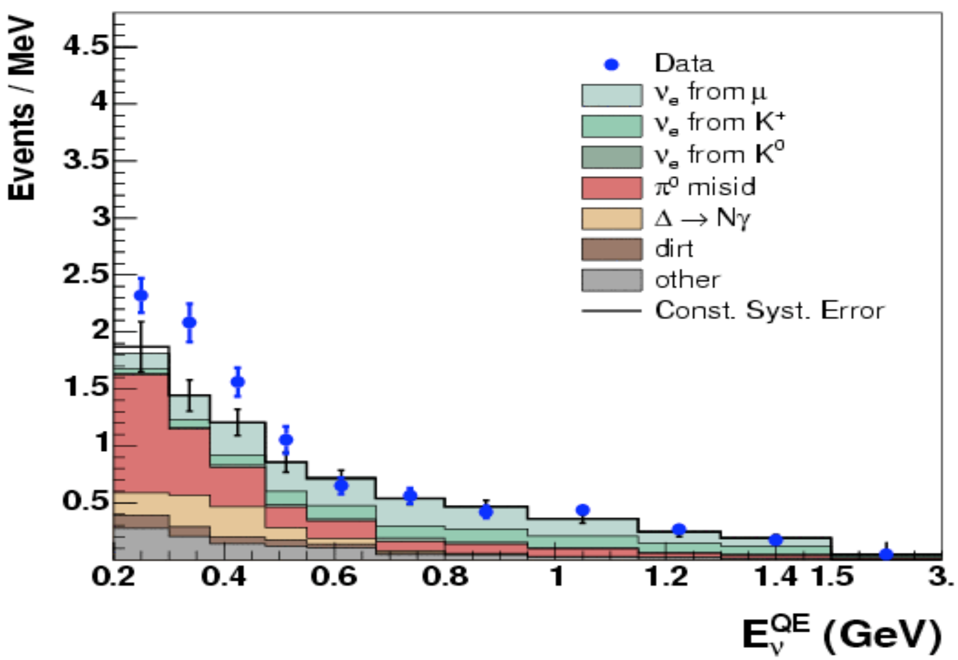
- Why is the 200-475 MeV region unimportant?
  - Large backgrounds from mis-ids reduce S/B.
  - Many systematics grow at lower energies, especially on signal.
  - Most importantly, not a region of L/E where LSND observed a significant signal!

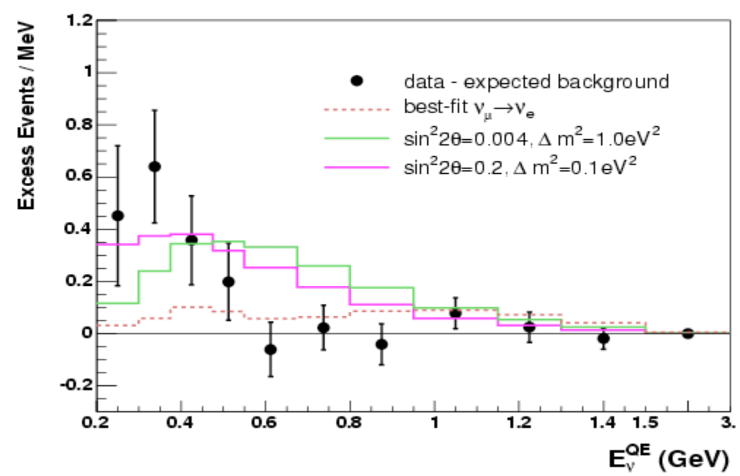
Neutrino mode MB results (2009)

- 6.5E20 POT collected in neutrino mode
- E > 475 MeV data in good agreement with background prediction
  - energy region has reduced backgrounds and maintains high sensitivity to LSND oscillations.
  - A two neutrino fit rules out LSND at the 90% CL assuming CP conservation.
- E < 475 MeV, statistically large (6σ) excess
  - Reduced to 3σ after systematics, shape inconsistent with two neutrino oscillation interpretation of LSND. Excess of 129 +/- 43 (stat+sys) events is consistent with magnitude of LSND oscillations.



Published PRL 102,101802 (2009)

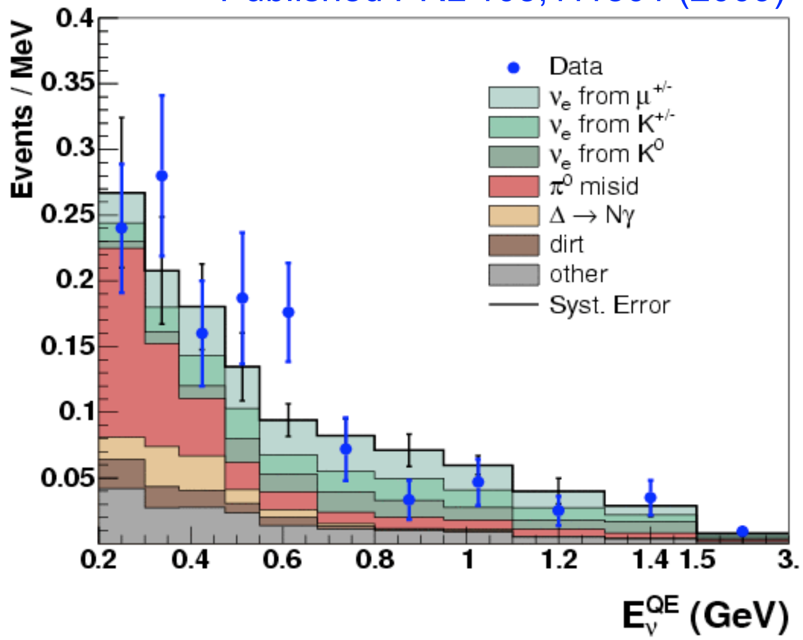


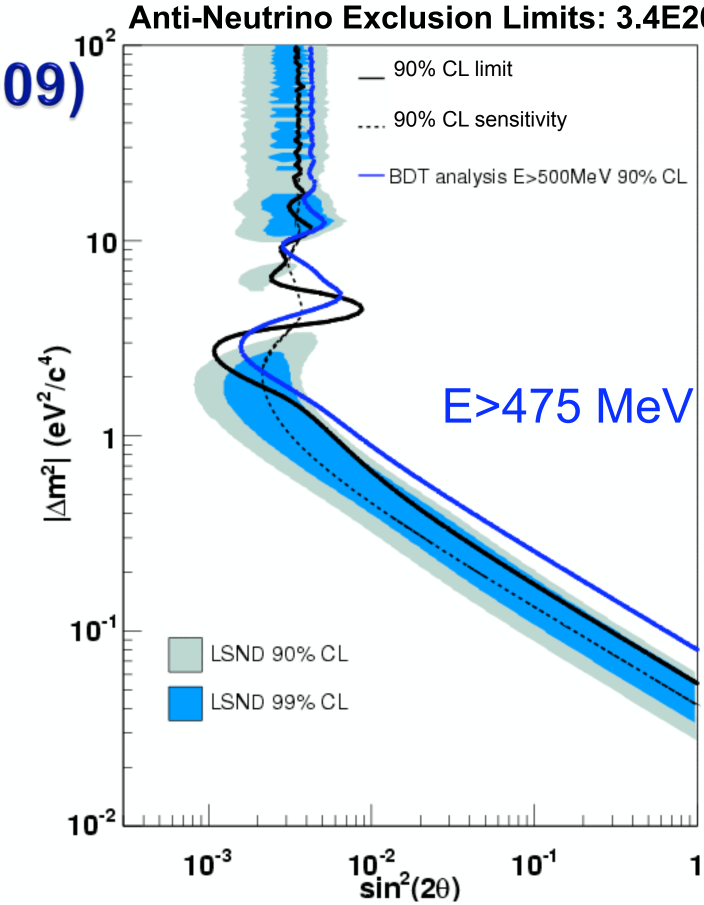


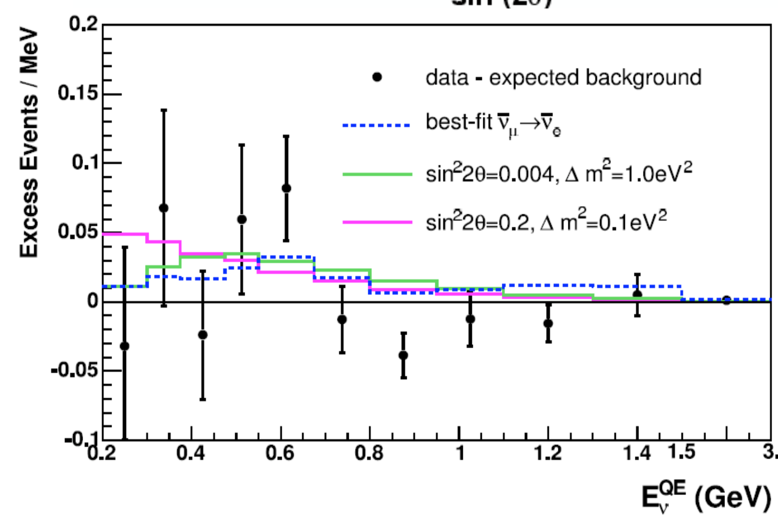
First Antineutrino mode MB results (2009)

- 3.4E20 POT collected in anti-neutrino mode
- From 200-3000 MeV excess is 4.8 +/- 17.6 (stat +sys) events.
- Statistically small excess (more of a wiggle) in 475-1250 MeV region
  - Only antineutrino's allowed to oscillate in fit
  - Limit from two neutrino fit excludes less area than sensitivity due to fit adding a LSND-like signal to account for wiggle
  - Stat error too large to distinguish LSND-like from null
- No significant excess E < 475 MeV.

Published PRL 103,111801 (2009)

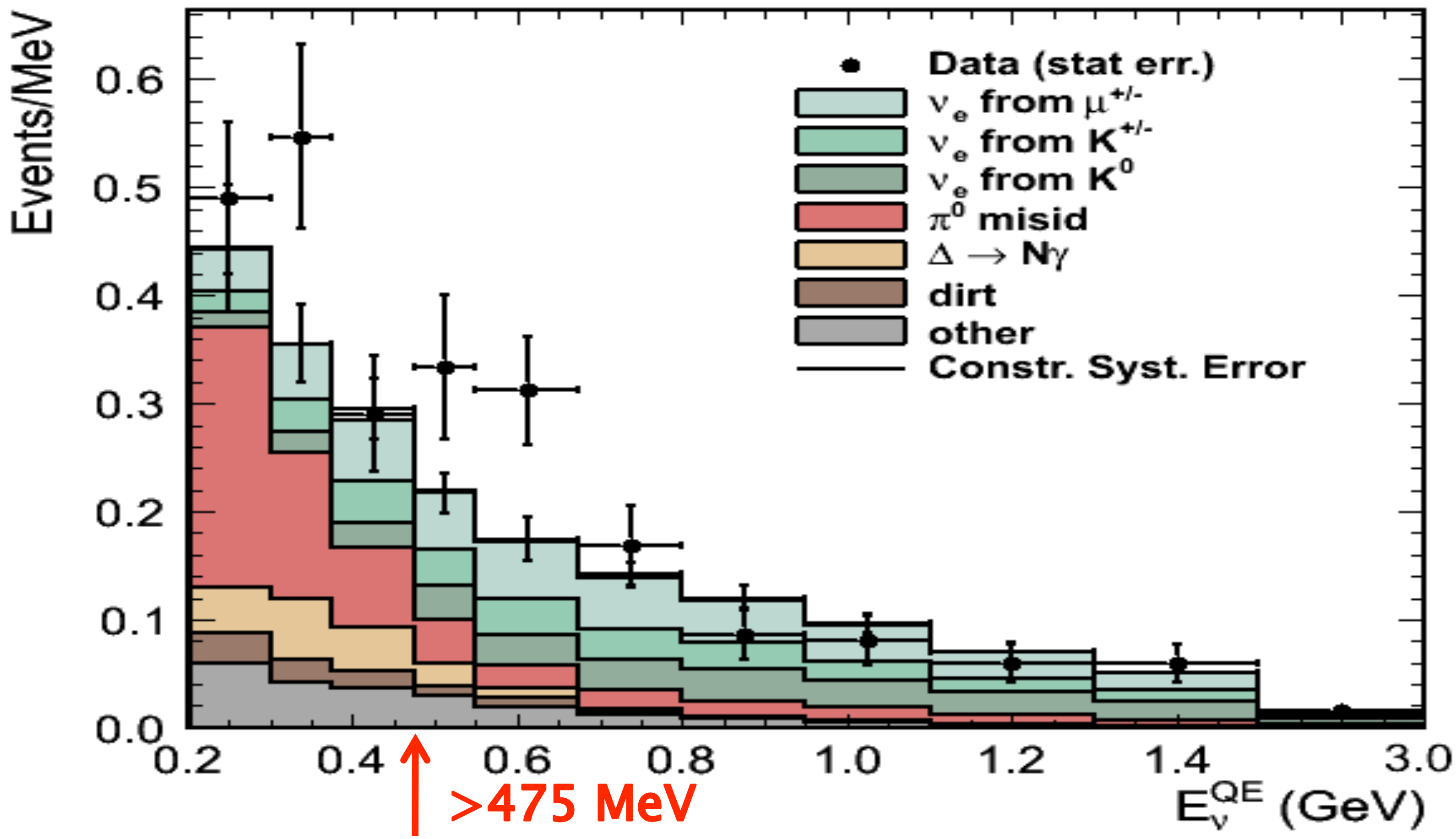






New Antinuetrino Result with 5.66E20 POT

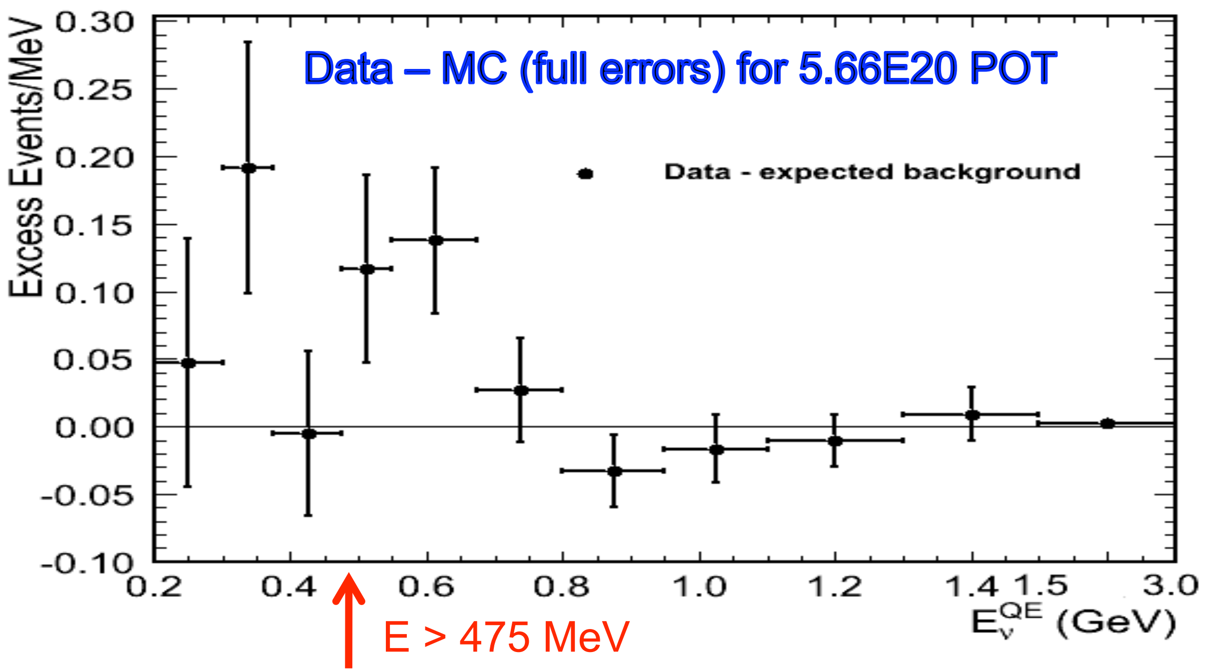
	200-475 MeV	475-1250 MeV	200-3000 MeV
Data	119	120	277
MC (stat+sys)	100.5 ± 14.3	99.1 ± 13.9	233.8 ± 22.5
Excess (stat)	18.5 ± 10.0 (1.9σ)	20.9 ± 10.0 (2.1σ)	43.2 ±15.3 (2.8σ)
Excess (stat+sys)	18.5 ± 14.3 (1.3σ)	20.9 ± 13.9 (1.5σ)	43.2 ± 22.5 (1.9σ)



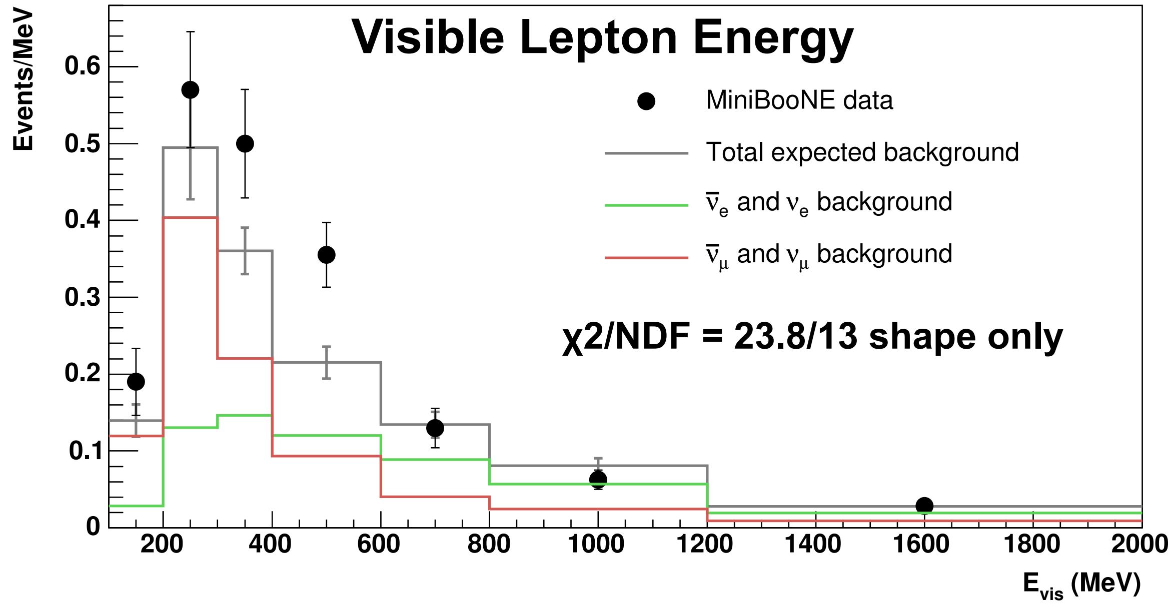
Testing the Null Hypothesis

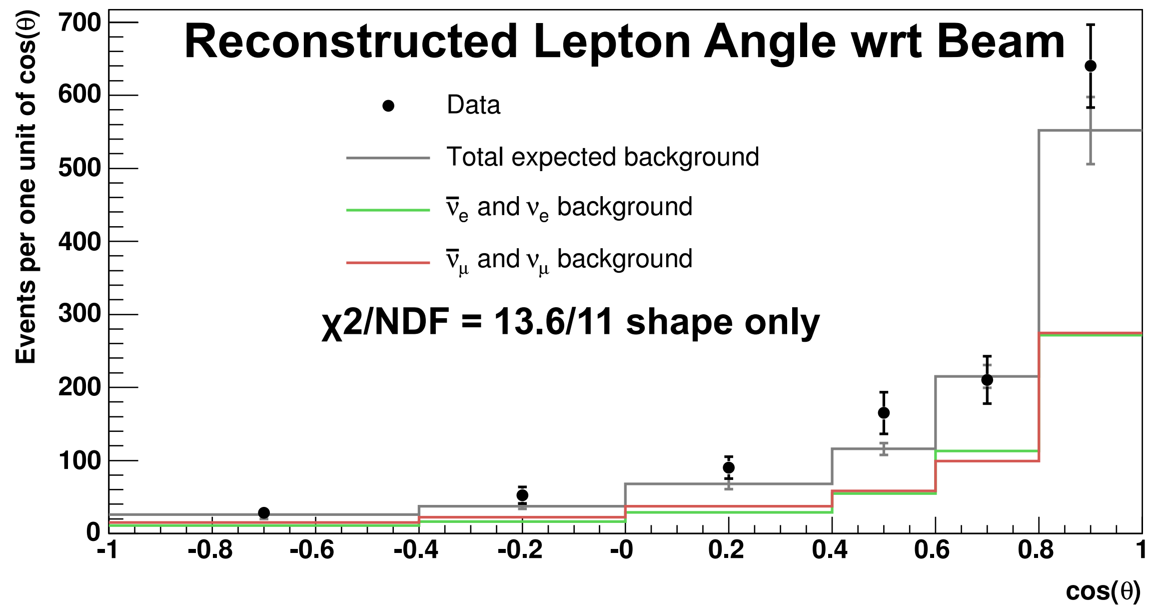
- Model independent.
- At null look at the χ^2 distribution of fake experiments (thrown from null error matrix).

	chi2/NDF	probability
E>475MeV	26.8/14.9	3.0%
E>200MeV	33.2/18.0	1.6%



Other $\bar{\nu}_e$ kinematic distributions for 5.66E20 POT





Data Checks for 5.66E20 POT (~70% more data)

- Beam and Detector low level stability checks; beam stable to 2%, and detector energy response to 1%.
- $\bar{\nu}_\mu$ rates and energy stable over entire antineutrino run.
- Latest $\bar{\nu}_e$ data rate is 1.9σ (stat) higher than 3.4E20POT data set.
- Independent measurement of π^0 rate for antineutrino mode.
- Measured dirt rates are similar in neutrino and antineutrino mode.
- Measured wrong sign component stable over time and energy.
- Checked off axis rates from NuMI beam **(see poster by Zelimir Djurcic)**.
- Above 475 MeV, about two thirds of the electron (anti)neutrino intrinsic rate is constrained by simultaneous fit to $\bar{\nu}_\mu$ data.
  - New SciBooNE neutrino mode K^+ weight = 0.75 ± 0.05(stat) ± 0.30(sys).
- One third of electron neutrino intrinsic rate come from K^0, where we use external measurements and apply 30% error.
  - Would require >3σ increase in K^0 normalization, but shape does not match well the excess.

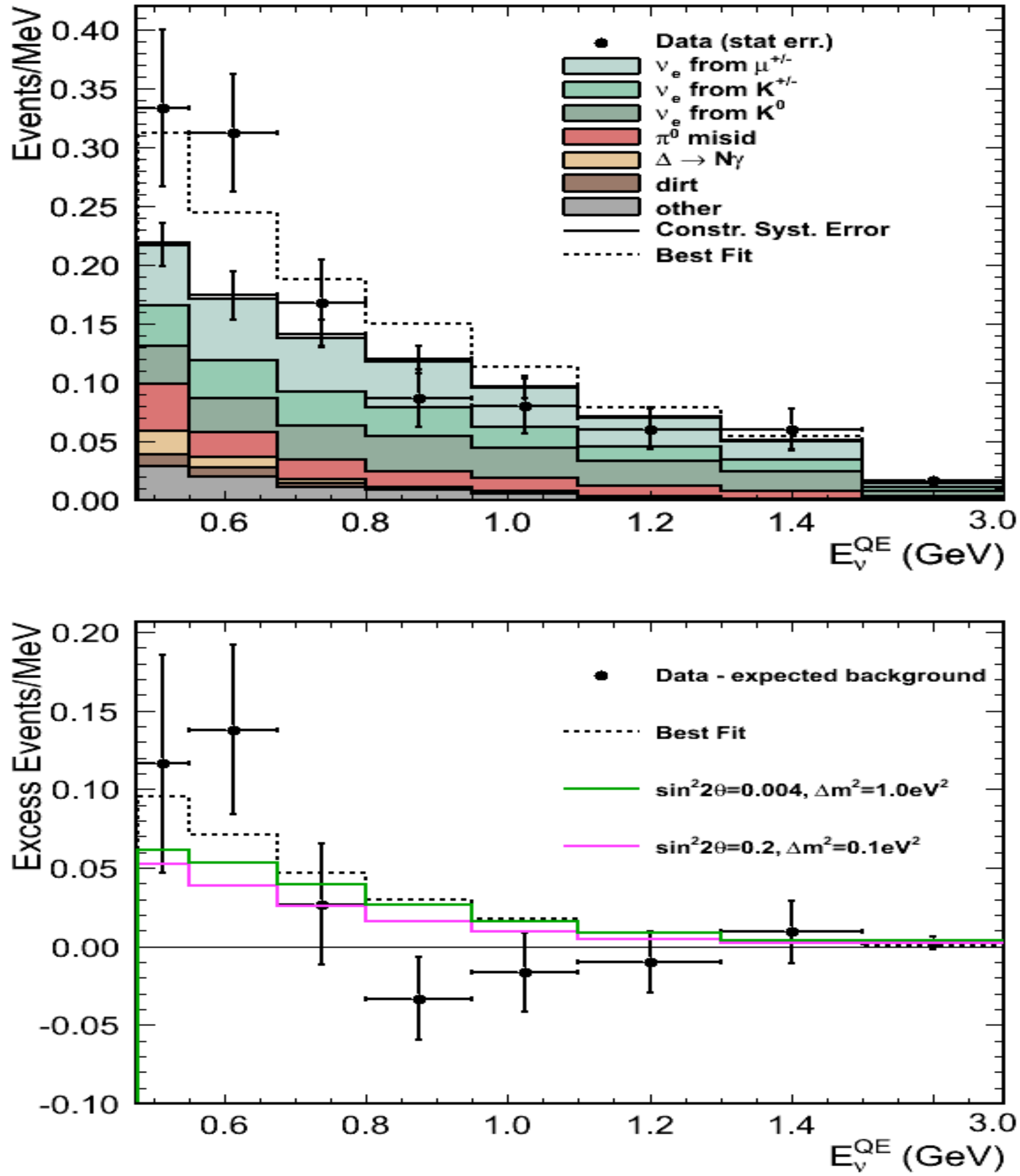
Comparison to LSND's best fit prediction and neutrino low energy expectation

	E_ν(QE) [MeV]		
	200-475	475-1250	1250-3000
MC Background	100.5	99.1	34.2
Data	119	120	38
Excess	18.5 ± 14.3	20.9 ± 13.9	3.8 ± 5.8
LSND Best Fit	7.6	22.0	3.5
Expectation from ν low-E excess	11.6	0	0
LSND + Low-E	19.2	22.0	3.5

- Errors quoted here are stat+sys.
- Excess consistent with the expectation from LSND and adding the low energy excess scaled for neutrinos (wrong-sign).
- Expected 67 events at low energy (200-475 MeV) if neutrino low E excess is due to a Standard Model NC gamma-ray mechanism, e.g. Axial Anomoly.

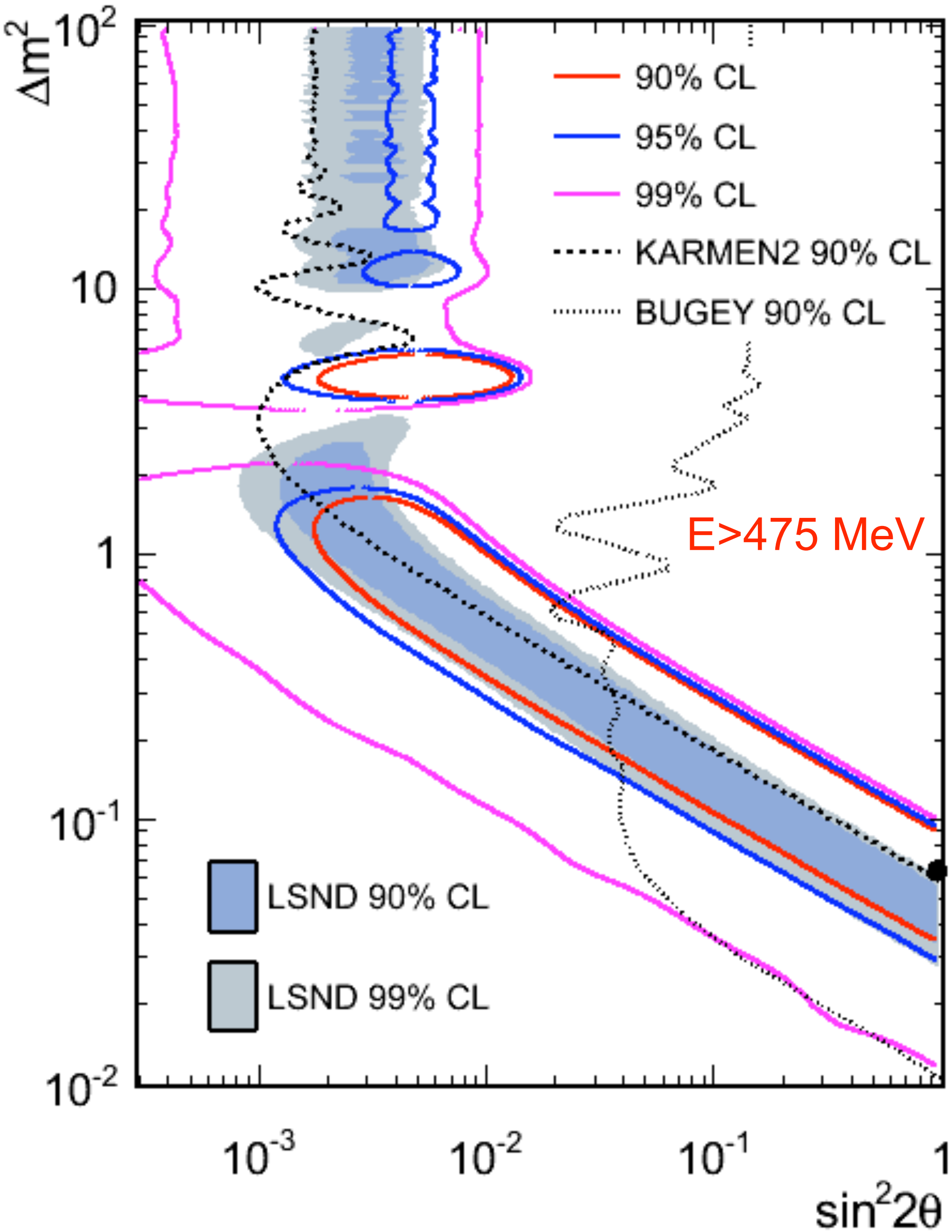
Updated Antineutrino mode MB results for E>475 MeV:
(official oscillation region)

- Results for 5.66E20 POT.
- Maximum likelihood fit.
- Only antineutrinos allowed to oscillate.
- E > 475 MeV region is free of effects of low energy neutrino excess. This is the same official oscillation region as in neutrino mode.
- Results to be published.



Updated Antineutrino mode MB results for E>475 MeV
(official oscillation region)

- Results for 5.66E20 POT
- Maximum likelihood fit.
- Null excluded at 99.4% with respect to the two neutrino oscillation fit.
- Best Fit Point
  (Δm^2, $\sin^2 2\theta$) =
  (0.064 eV^2, 0.96)
  χ^2/NDF= 16.4/12.6
  $P(\chi^2)$= 20.5%
- Results to be published.



Summary and Outlook:

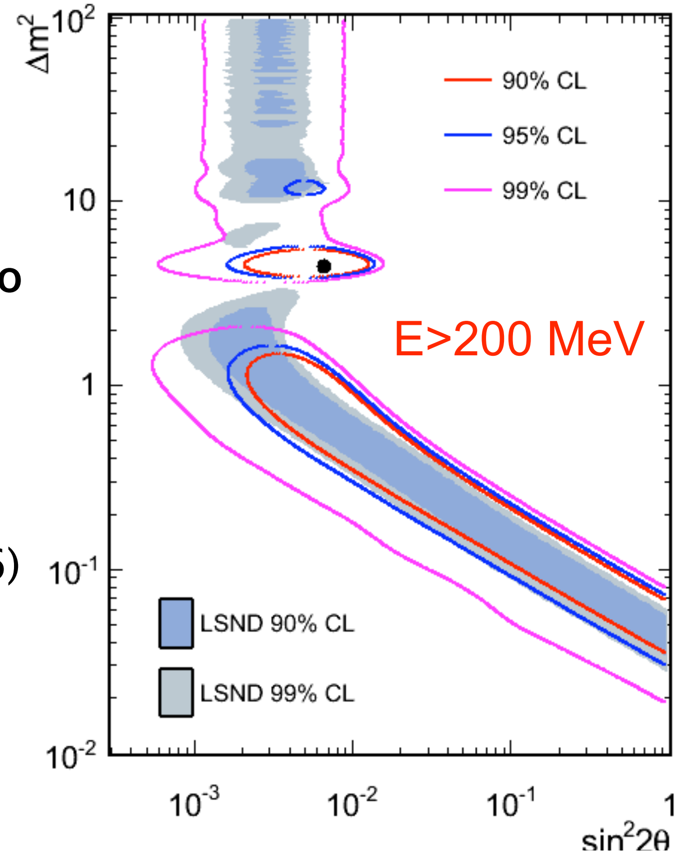
- The MiniBooNE ν_e and $\bar{\nu}_e$ appearance picture starting to emerge is the following:
    1) **Neutrino Mode**:
        a) E < 475 MeV: An unexplained 3σ electron-like excess.
        b) E > 475 MeV: A two neutrino fit is inconsistent with LSND at the 90% CL.
    2) **Anti-neutrino Mode**:
        a) E < 475 MeV: A small 1.3σ electron-like excess.
        b) E > 475 MeV: An excess that is 3.0% consistent with null. Two neutrino oscillation fits consistent with LSND at 99.4% CL relative to null.
- Clearly we need more statistics!
    - MiniBooNE is running to double antineutrino data set for a total of ~10×10^{20} POT.
    - If signal continues at current rate, statistical error will be ~4σ and two neutrino best fit will be >3σ.
- There are follow on experiments at FNAL
    - uBoone has CD-1 approval. See talk by *M. Soderberg*
    - BooNE (LOI). A MB-like near detector at 200 m. See poster by Geoff Mills.

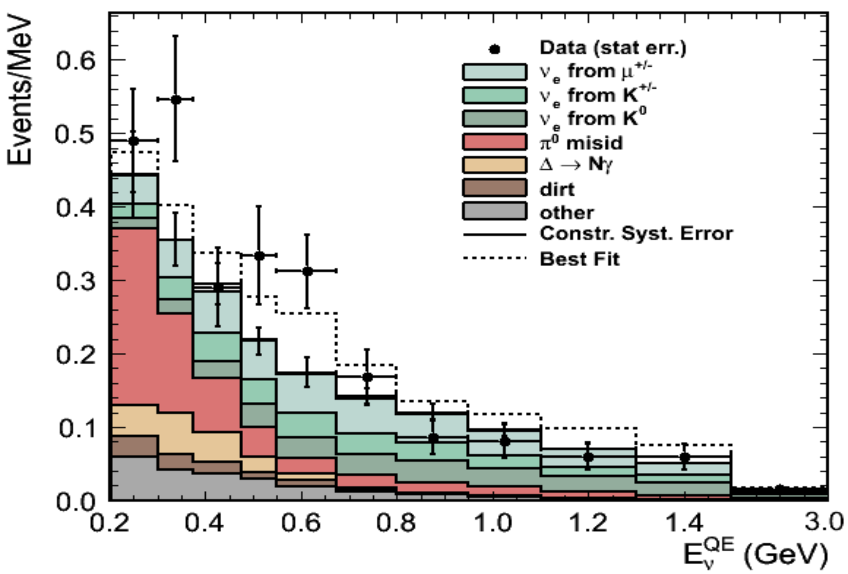
Backup Slides

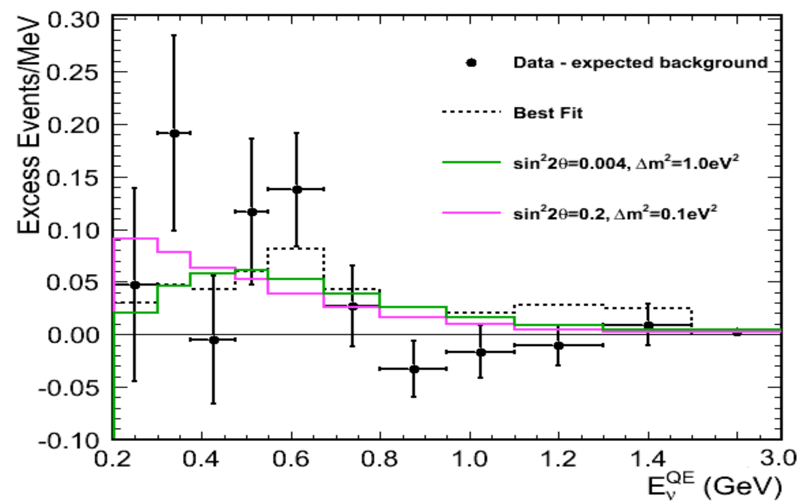
New Antineutrino mode MB results for E>200 MeV:

- Results for 5.66e20 POT.
- **Does not include effects (subtraction) of neutrino low energy excess.**
- Maximum likelihood fit method.
- Null excluded at 99.6% with respect to the two neutrino oscillation fit (model dependent).
- Best Fit Point (Δm^2, $\sin^2 2\theta$) = (4.42 eV^2, 0.0066)

  χ^2/NDF= 20.4/15.3, P(χ2)= 17.1%.

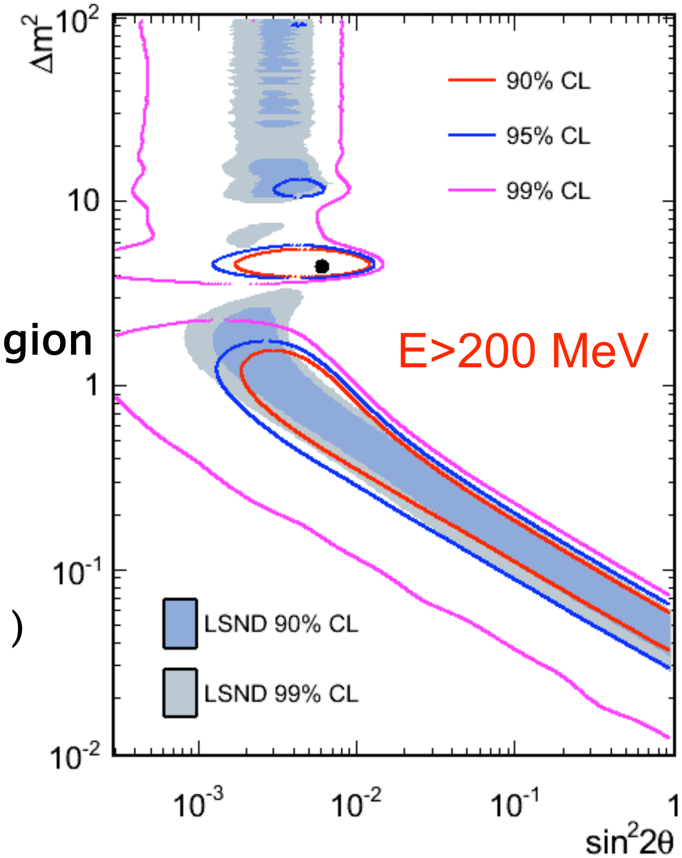


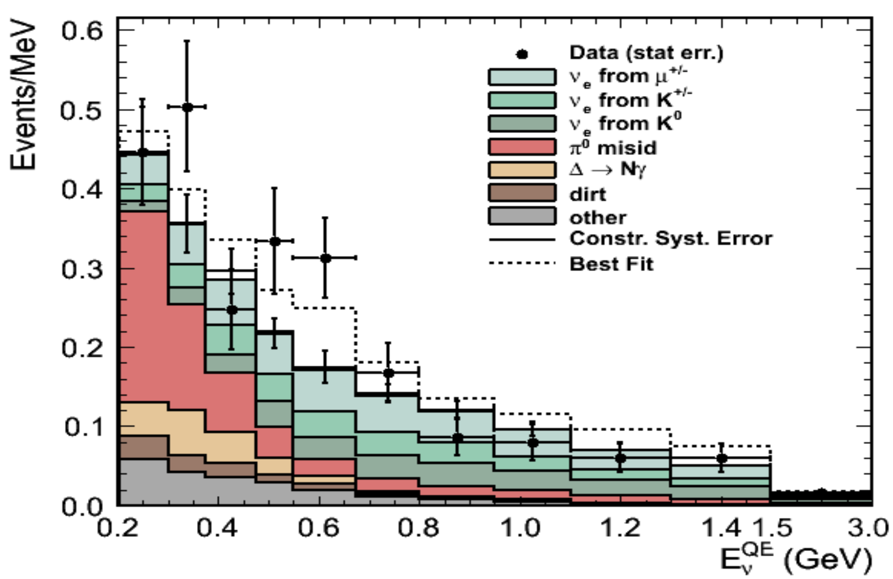


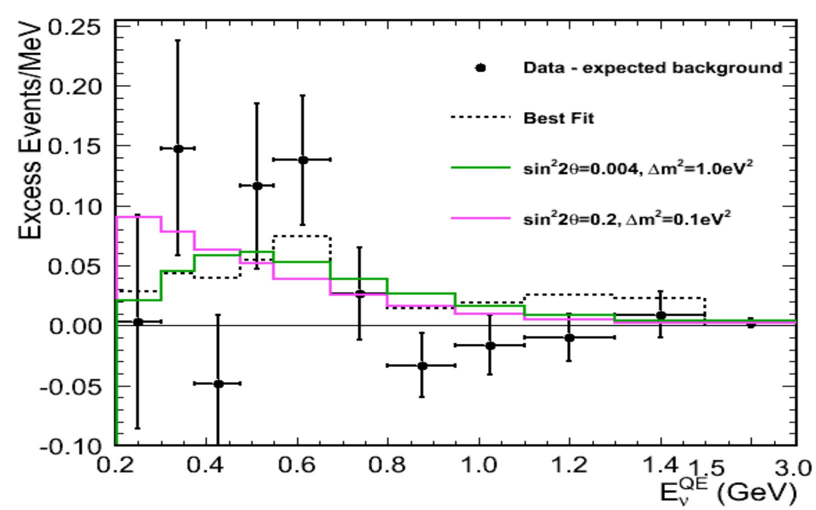


New Antineutrino mode MB results for E>200 MeV: Include low E Effects

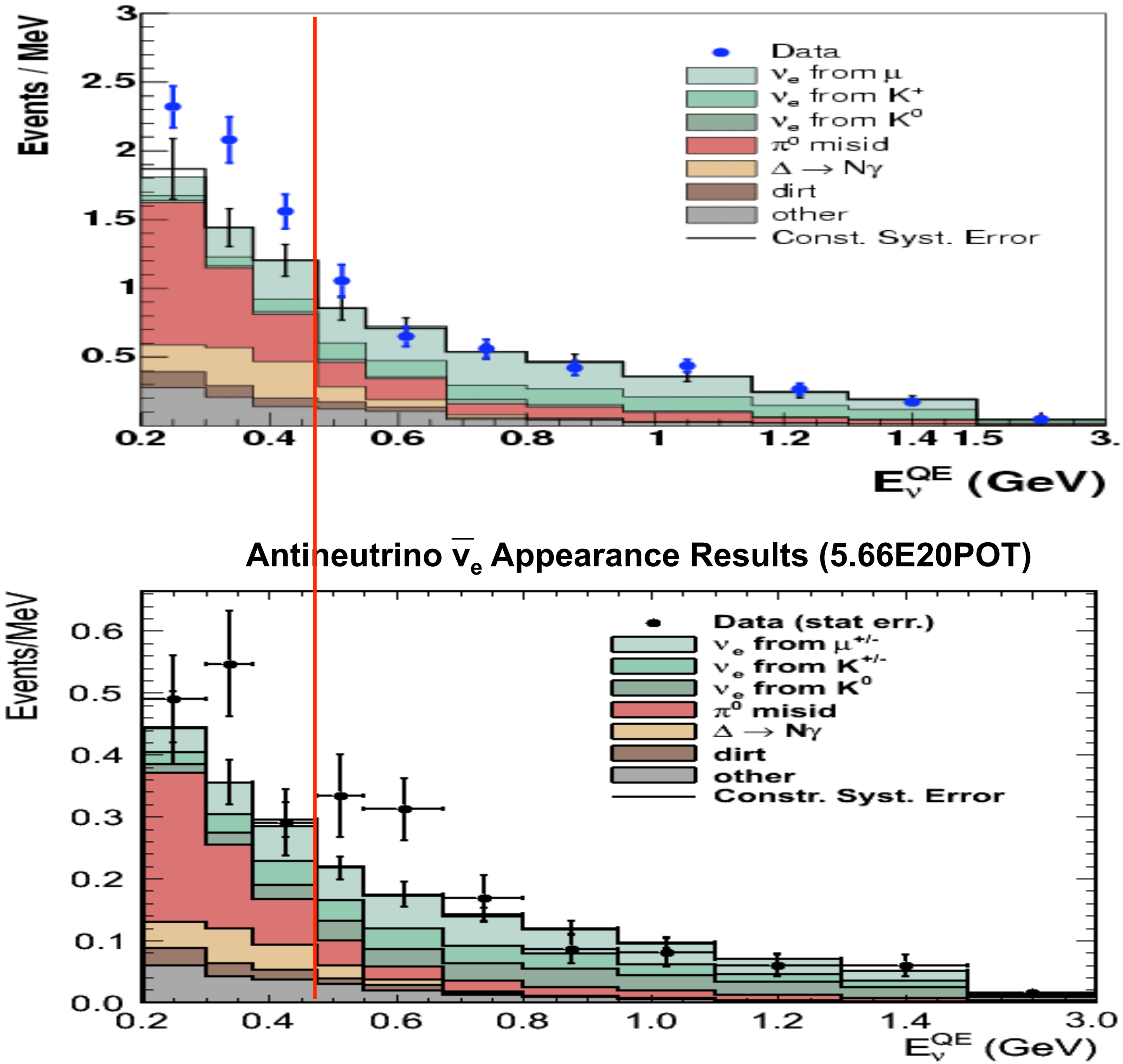
- Results for 5.66e20 POT.
- **Assume simple scaling of neutrino low energy excess; subtract 11.6 events from low energy region (200-475 MeV).**
- Maximum likelihood fit method.
- Null excluded at 99.6% with respect to the two neutrino oscillation fit (model dependent).
- Best Fit Point (Δm^2, $\sin^2 2\theta$) = (4.42 eV^2, 0.0061)
  χ^2/NDF= 21.6/15.3, P(χ2)= 13.7%.





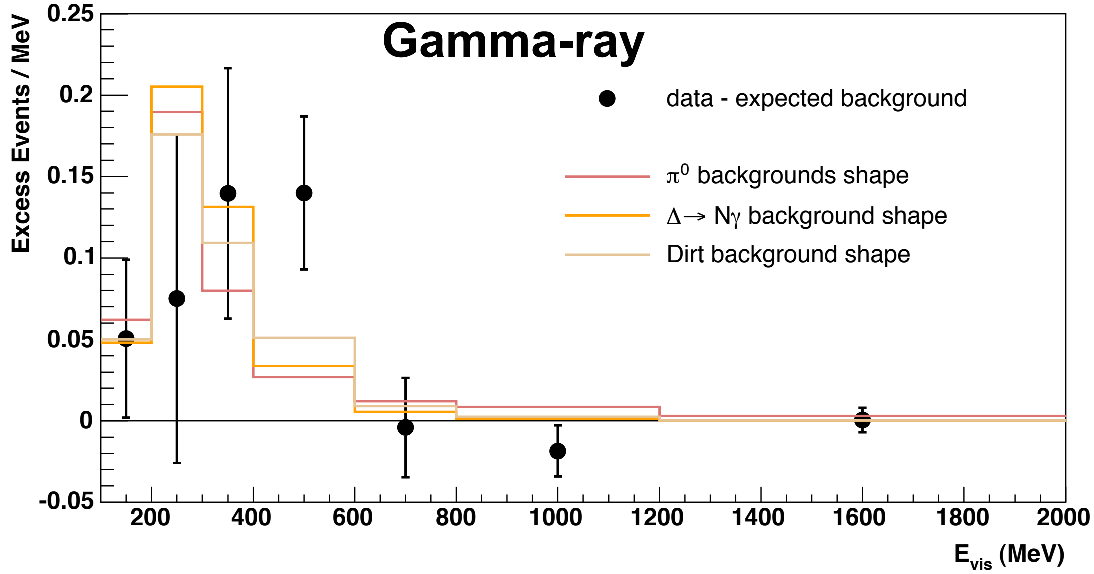


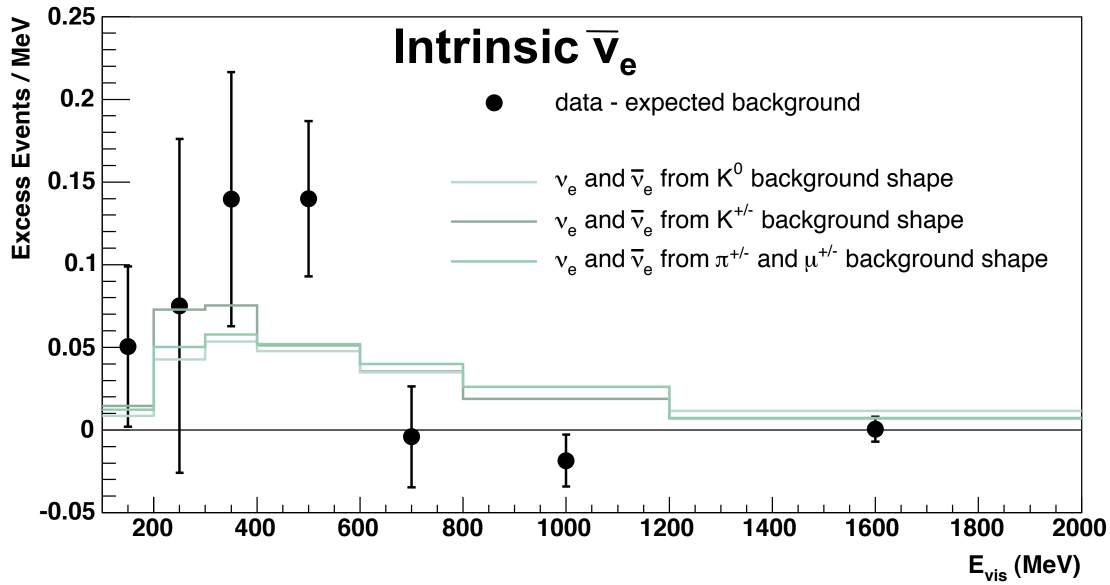
Neutrino ν_e Appearance Results (6.5E20POT)



Antineutrino $\bar{\nu}_e$ Appearance Results (5.66E20POT)

Background $\bar{\nu}_e$ Evis distributions for 5.66E20 POT

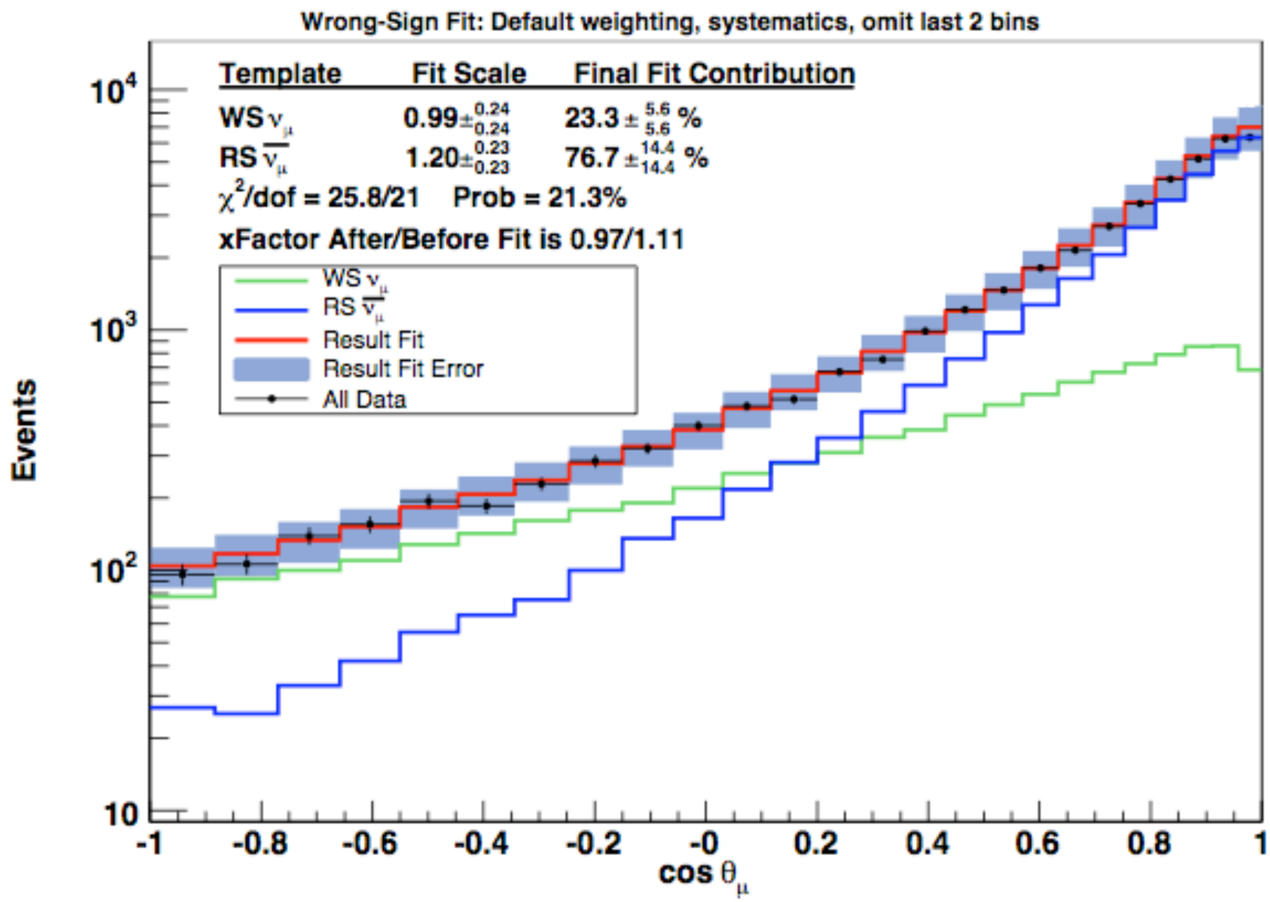




Background systematic uncertainties:
Many errors are similar between neutrino and antineutrino mode

Source	$\bar{\nu}$ mode uncer. (%)		ν mode uncer. (%)	
E_ν^{QE} range (MeV)	*200-475*	*475-1100*	*200-475*	*475-1100*
Flux from π^+/μ^+ decay	**0.4**	**0.9**	**1.8**	**2.2**
Flux from π^-/μ^- decay	**3.0**	**2.3**	**0.1**	**0.2**
Flux from K^+ decay	**2.2**	**4.7**	**1.4**	**5.7**
Flux from K^- decay	**0.5**	**1.2**	**-**	**-**
Flux from K^0 decay	**1.7**	**5.4**	**0.5**	**1.5**
Target and beam models	**1.7**	**3.0**	**1.3**	**2.5**
ν cross section	**6.5**	**13.0**	**5.9**	**11.9**
NC π^0 yield	**1.5**	**1.3**	**1.4**	**1.9**
Hadronic interactions	**0.4**	**0.2**	**0.8**	**0.3**
External interactions (dirt)	**1.6**	**0.7**	**0.8**	**0.4**
Optical model	**8.0**	**3.7**	**8.9**	**2.3**
Electronics & DAQ model	**7.0**	**2.0**	**5.0**	**1.7**
Total (unconstrained)	***13.5***	***16.0***	***12.3***	***14.2***

Wrong-sign Contribution Fits

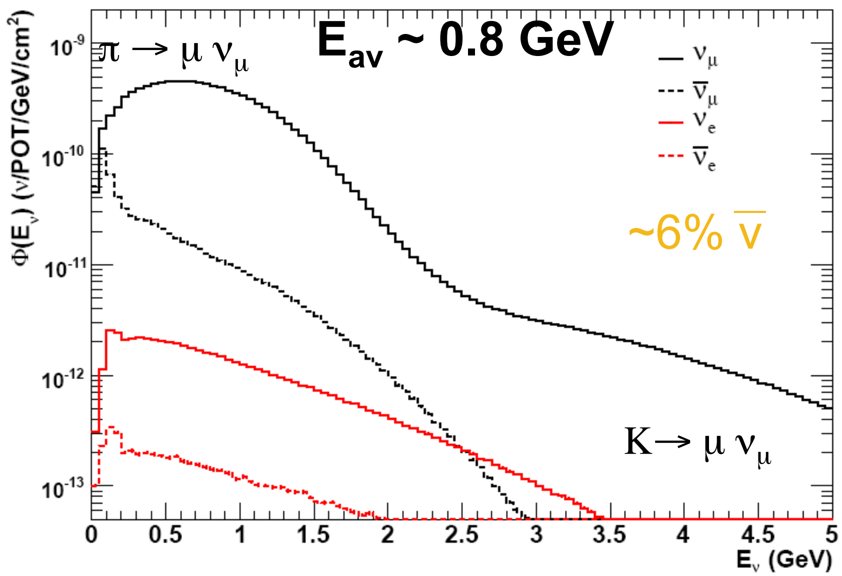


- Wrong-sign fit from angular distribution constrains WS
- Central value from fit used in background prediction
- Errors on WS flux and xsec propagated through osc analyses

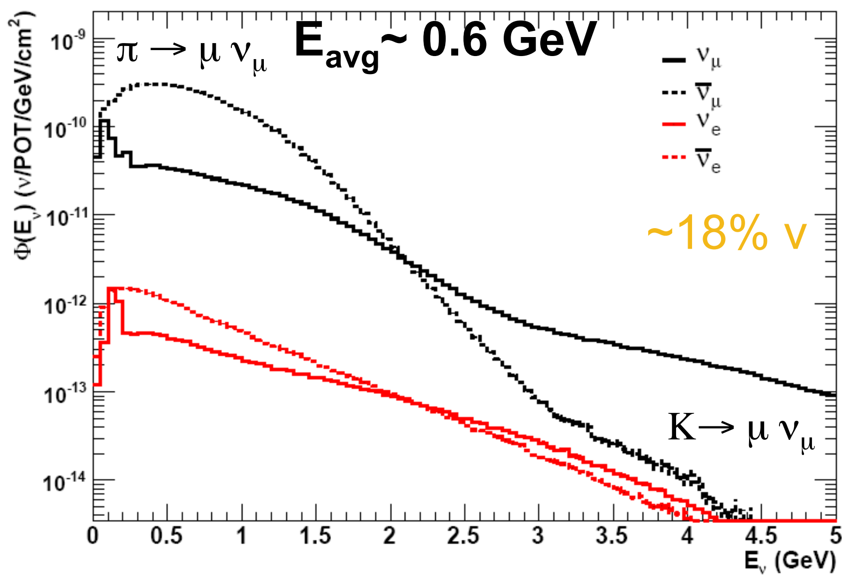
MiniBooNE Flux (Flux paper arXiv: 0806.1449)

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

ν mode flux



ν̄ mode flux

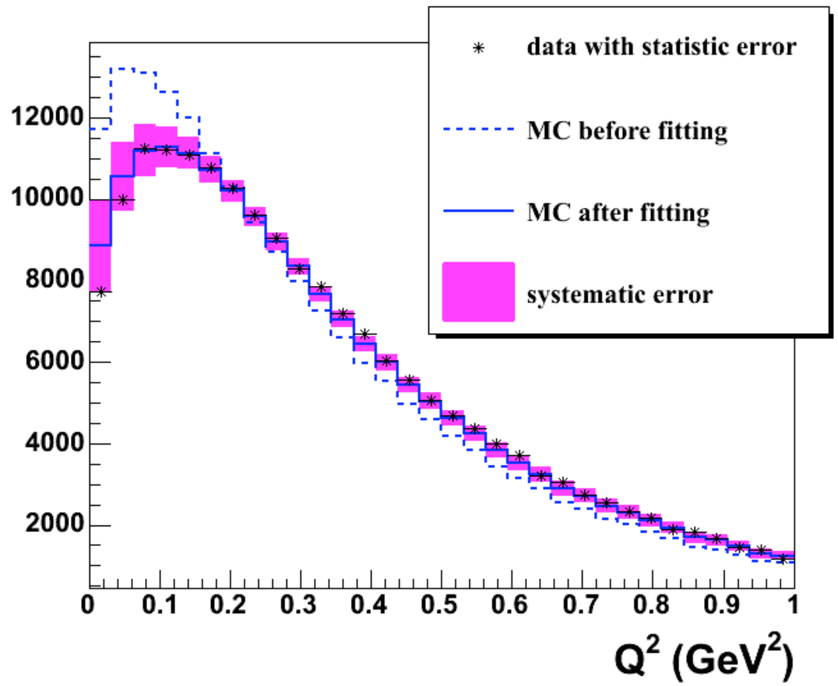


Subsequent decay of the **μ+ (μ-)** produces $\bar{\nu}_e$ (ν_e) intrinsics ~0.5%

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

CCQE Scattering *(Phys. Rev. Lett 100, 032301 (2008))*

186000 muon neutrino events



From Q^2 fits to MB ν_μ CCQE data:

M_A^{eff} -- effective axial mass

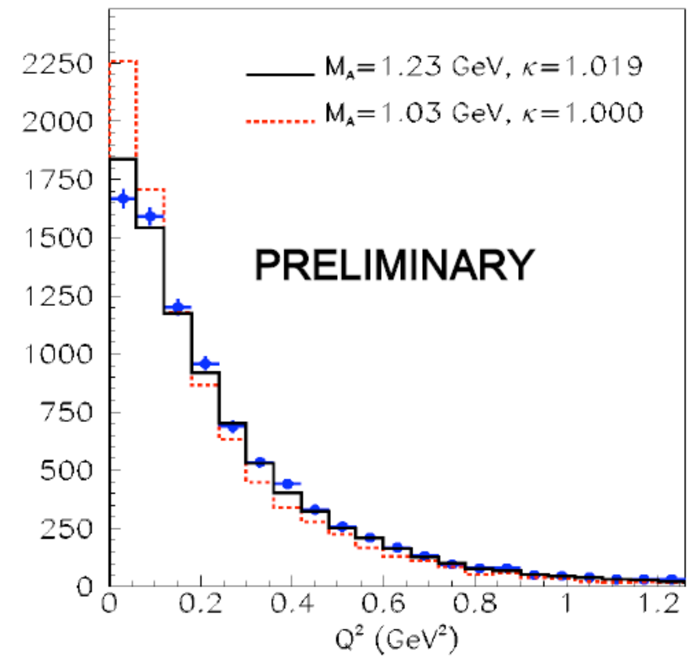
$\varkappa$ -- Pauli Blocking parameter

From electron scattering data:

E_b -- binding energy

p_f -- Fermi momentum

14000 anti-muon neutrinos



Fermi Gas Model describes CCQE ν_μ data well

$M_A = 1.23$+-0.20 GeV

$\varkappa = 1.019$+-0.011

Also used to model ν_e and $\overline{\nu}_e$ interactions