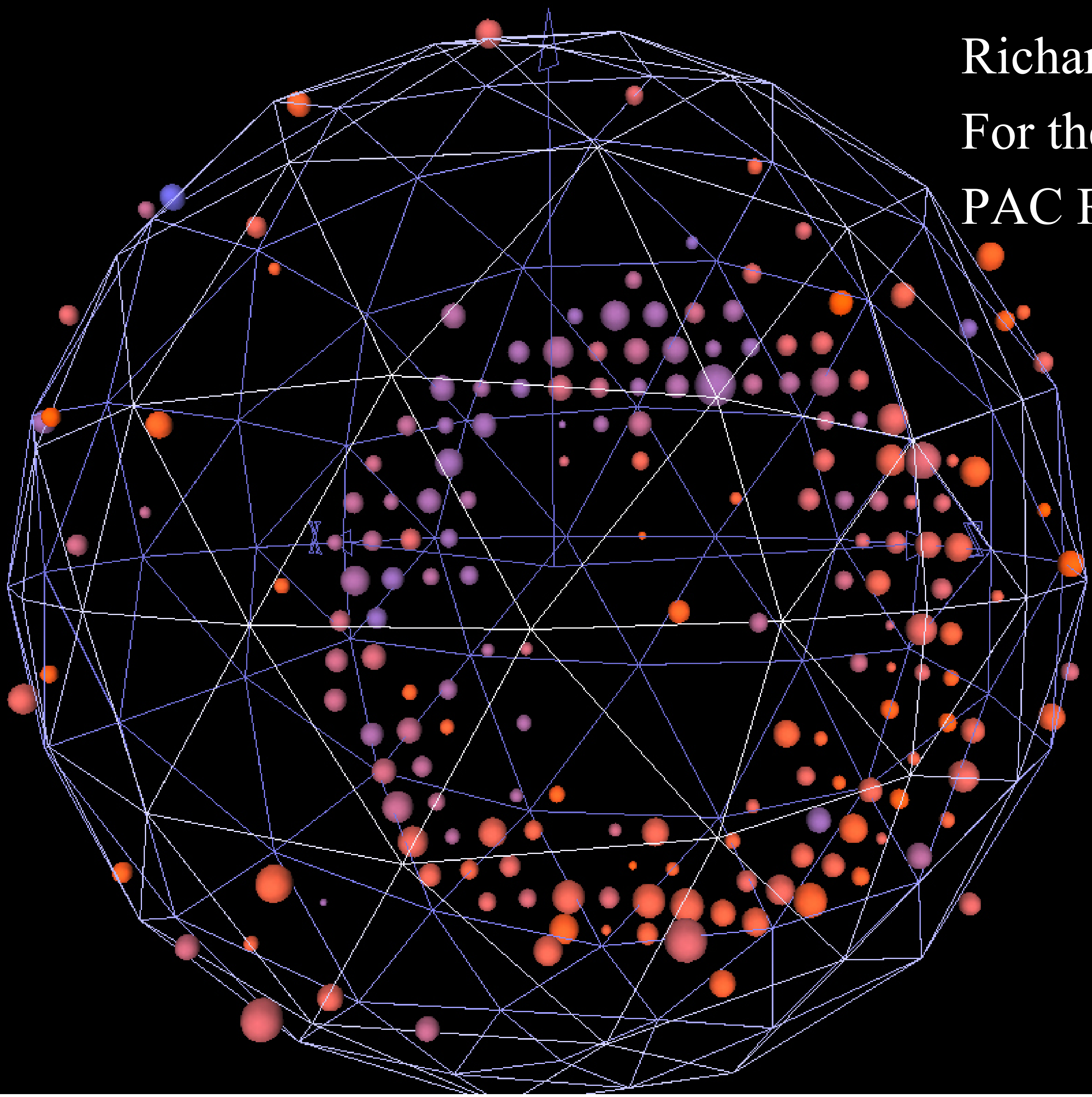
MiniBooNE Request for More Antineutrino Running



Richard Van de Water
For the MiniBooNE Collaboration
PAC Review, March 5, 2009

Outline

1. The neutrino and antineutrino electron appearance results.
   - Difference at low energy.
2. The need for more running.
3. Logistics of continued running.
4. Conclusions and Request.

MiniBooNE Anti-neutrino Run

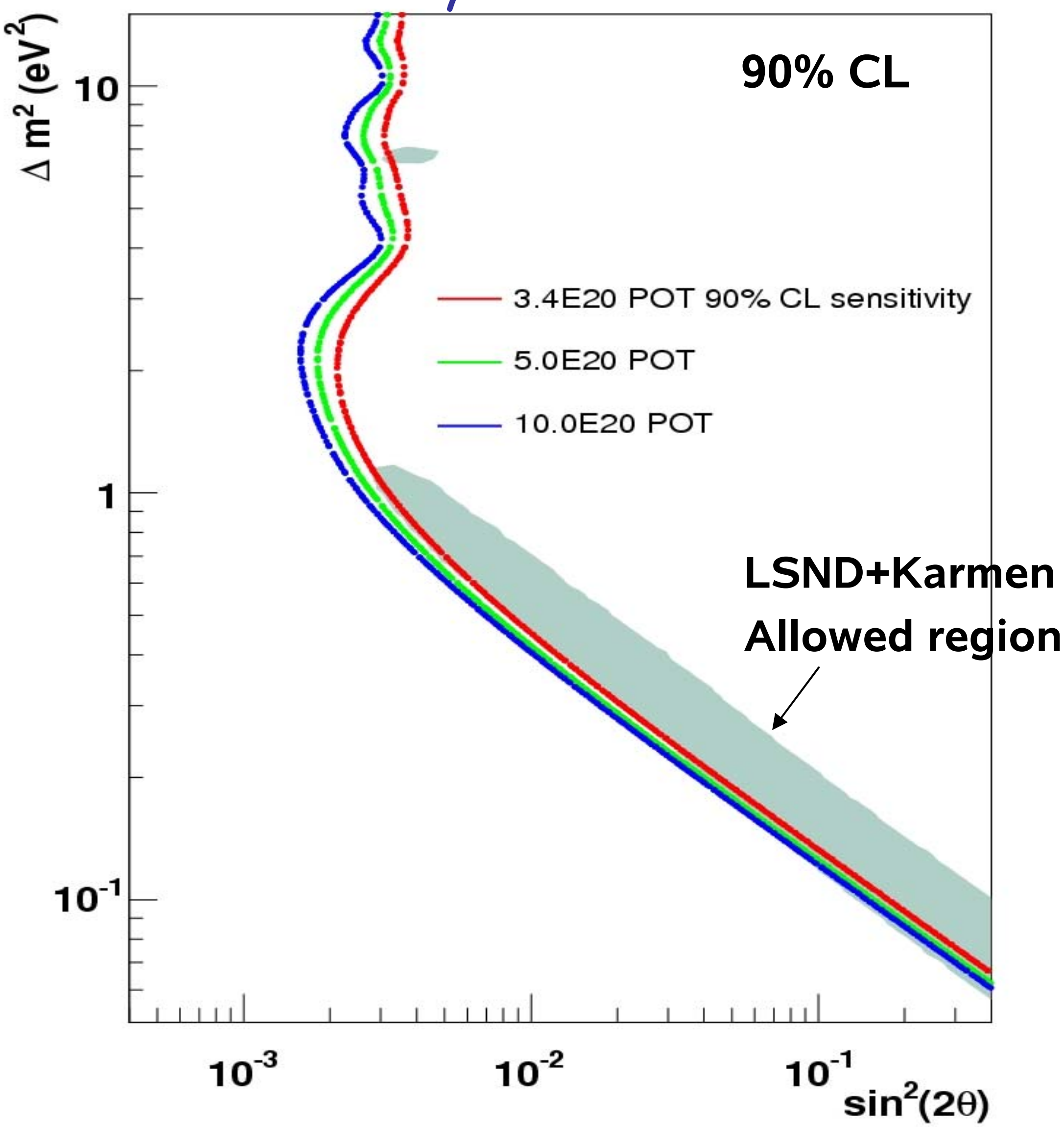
In November 07 Physics Advisory Committee (Fermilab) recommended MiniBooNE run to get to a total of 5×10^{20} POT in anti neutrino mode.

Provides direct check of LSND result.

Provides additional data set for low energy excess study.

Collected ~3.4×10^{20} POT so far.
Oscillation data set "blinded".
Box opened Oct 22, 2008, results made public early December.

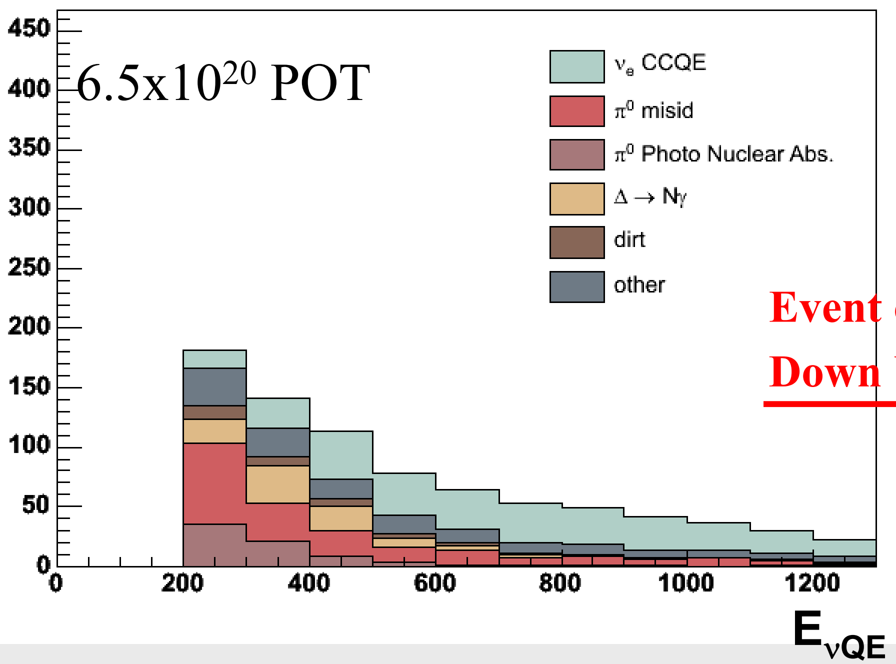
Sensitivity with E > 200 MeV



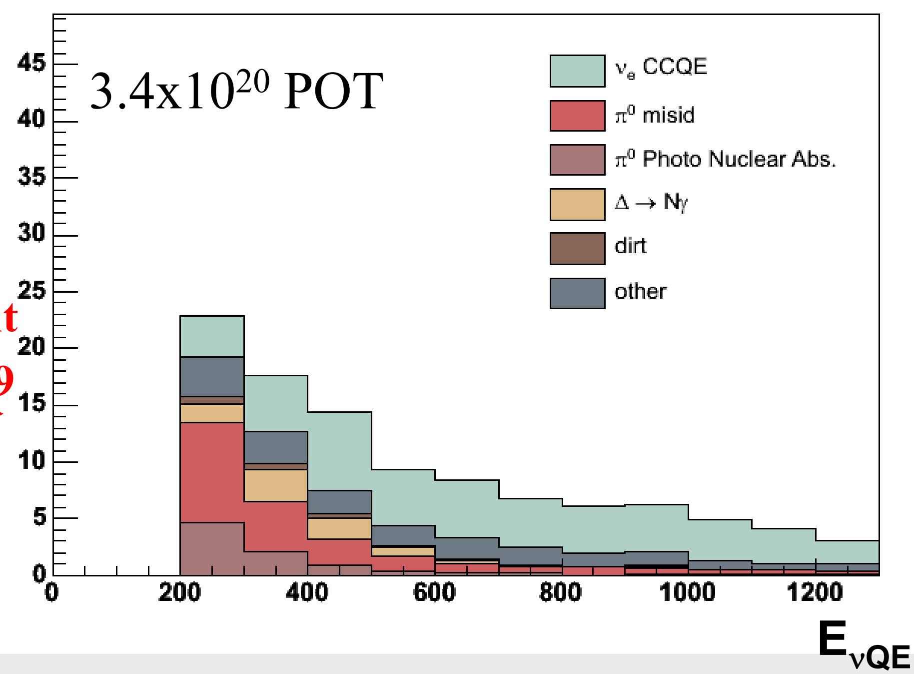
Comparing Neutrino/Antineutrino Low Energy ν_e Candidates

Background breakdown is very similar between neutrino and antineutrino mode running

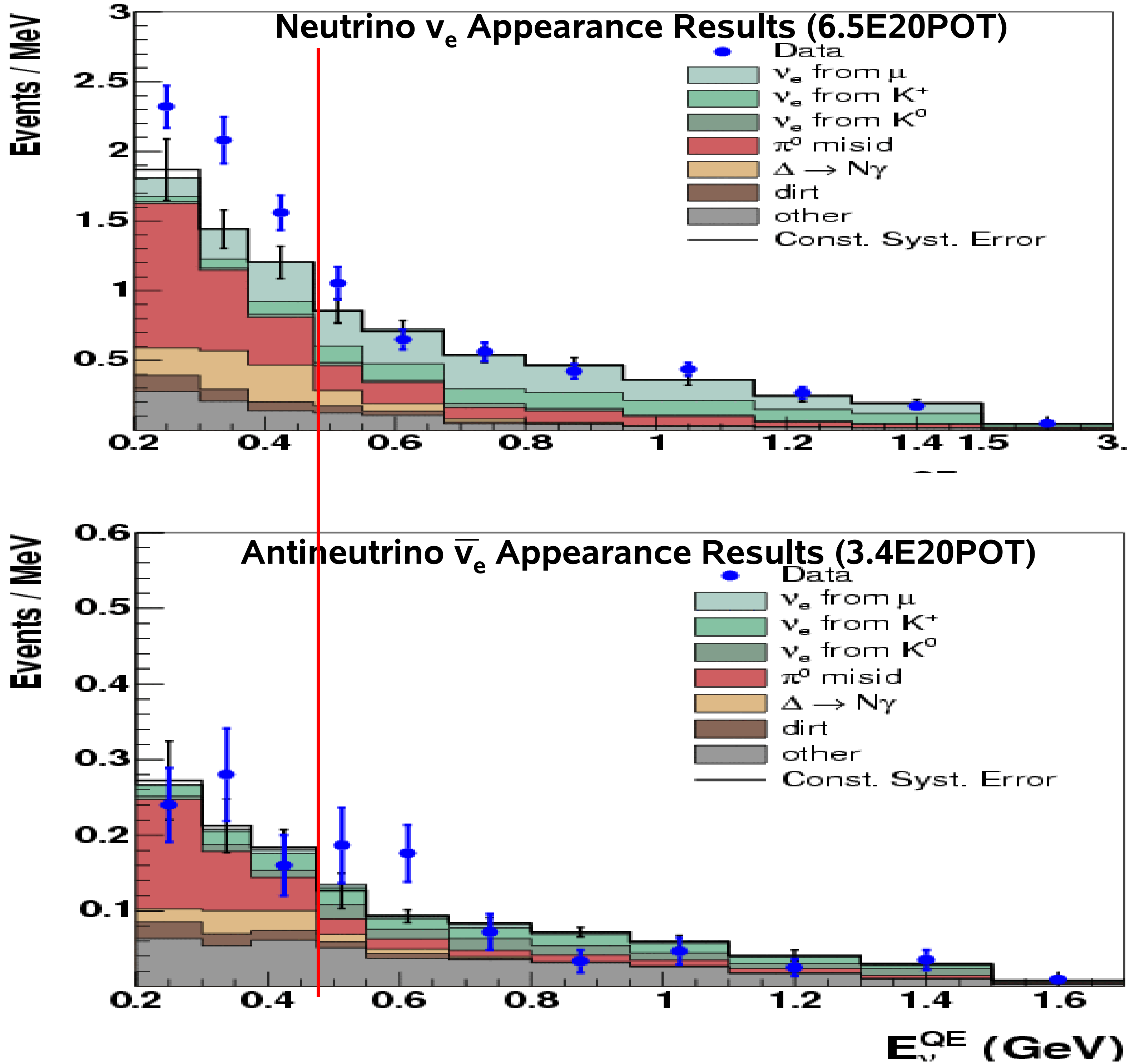
Neutrino



AntiNeutrino

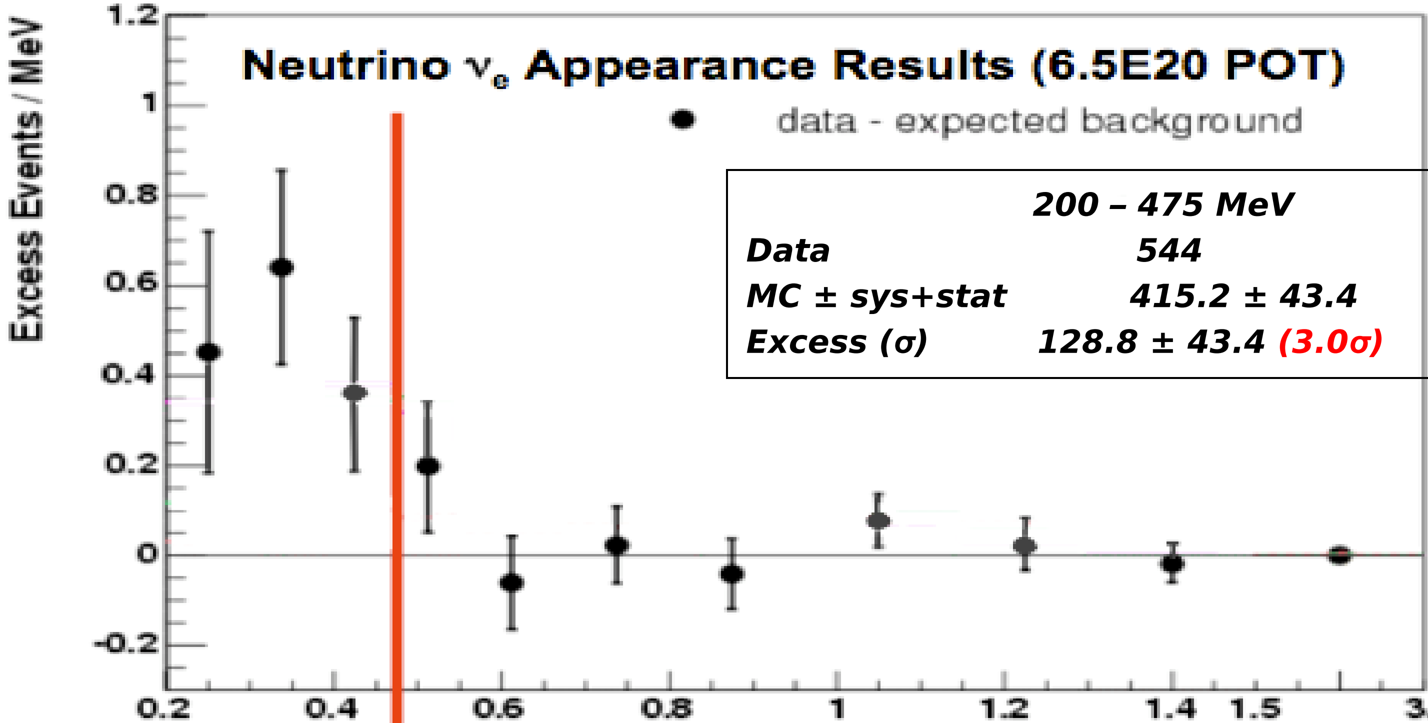


- Various background/signal hypotheses for the neutrino excess can have measurably different effects in the two modes:
  - Backgrounds at low energy, expect an excess >20 events.
  - Two neutrino oscillations produce ~13 events at higher energy.

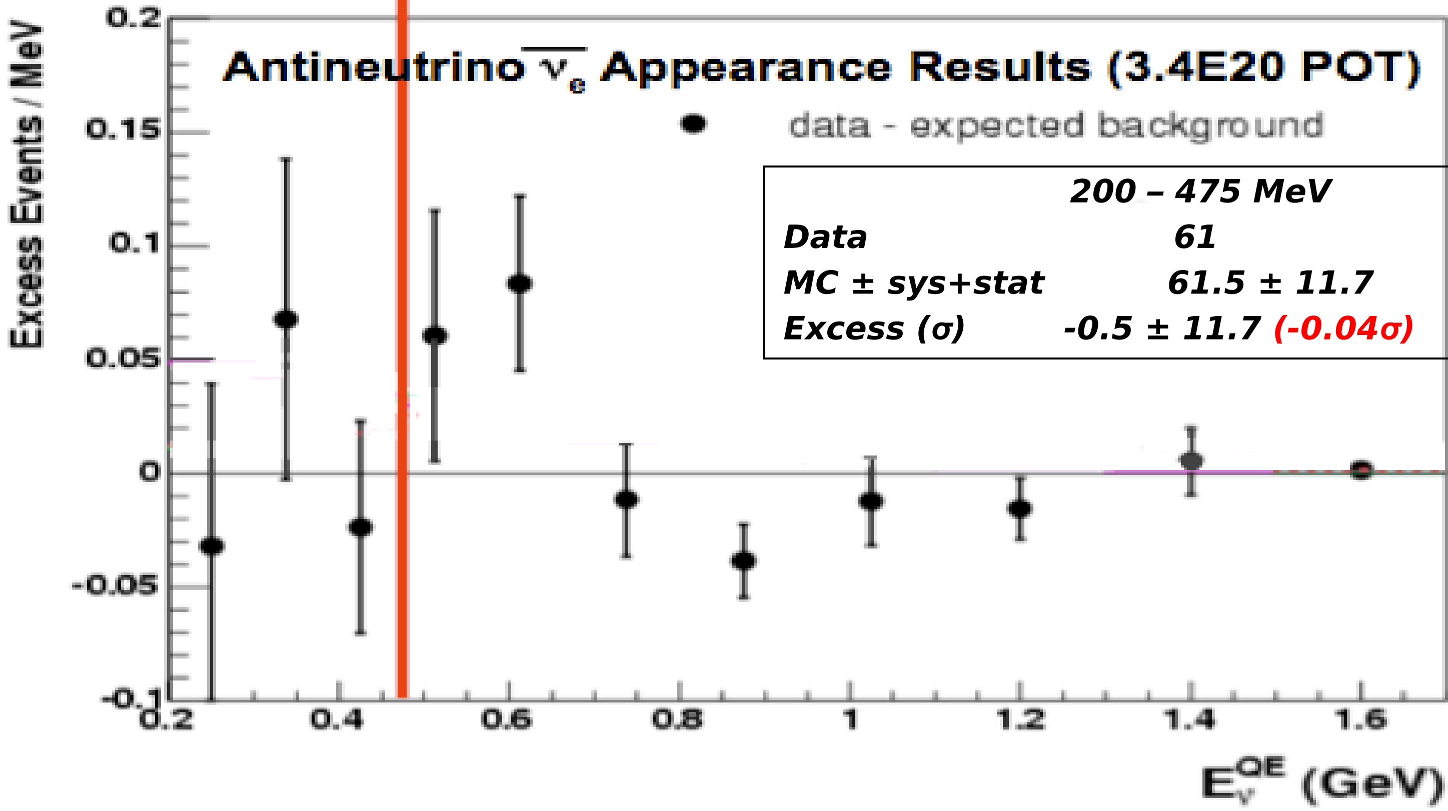


Neutrino ν_e Appearance Results (6.5E20POT)
Events / MeV
Data
ν_e from μ
ν_e from K^+
ν_e from K^0
π^0 misid
$\Delta \rightarrow N\gamma$
dirt
other
Const. Syst. Error
0.2 0.4 0.6 0.8 1 1.2 1.4 1.5 3.
Antineutrino $\overline{\nu}_e$ Appearance Results (3.4E20POT)
Events / MeV
Data
ν_e from μ
ν_e from K^+
ν_e from K^0
π^0 misid
$\Delta \rightarrow N\gamma$
dirt
other
Const. Syst. Error
0.2 0.4 0.6 0.8 1 1.2 1.4 1.6
E_ν^{QE} (GeV)

s Alamos



	200 – 475 MeV	475 - 1250 MeV
Data	*544*	*408*
MC ± sys+stat	*415.2 ± 43.4*	*385.9 ± 35.7*
Excess (σ)	*128.8 ± 43.4 (3.0σ)*	*22.1 ± 35.7 (0.6σ)*



	200 – 475 MeV	475 – 1250 MeV
Data	*61*	*61*
MC ± sys+stat	*61.5 ± 11.7*	*57.8 ± 10.0*
Excess (σ)	*-0.5 ± 11.7 (-0.04σ)*	*3.2 ± 10.0 (0.3σ)*

Expectation for Low Energy Excess

		$\bar{\nu}$	ν
200-475 MeV	*Data*	*61*	*544*
	MC ± sys+stat (constr.)	*61.5 ± 11.7*	*415.2 ± 43.4*
	Excess (σ)	*-0.5 ± 11.7 (-0.04σ)*	*128.8 ± 43.4 (3.0σ)*

$\nu / \bar{\nu}$ POT Ratio = 0.52

$\nu / \bar{\nu}$ Flux (per proton) Ratio = 0.55

How consistent are excesses in neutrino and antineutrino mode under different underlying hypotheses as the source of the low energy excess in neutrino mode?

- **Scales with POT (68 excess events)**
- **Scales with Kaon rate at low energy (40 events)**
- **Equal NC cross section for neutrinos and antineutrinos (37 excess events)**
- **Scales as π^0 background (20 excess events)**
- **Scales with background (20 excess events)**
- **Scales as the rate of Charged-Current interactions (20 excess events)**
- **Scales with neutrinos (not antineutrinos) (7 excess events)**

Comparison with Neutrino Low E Excess

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

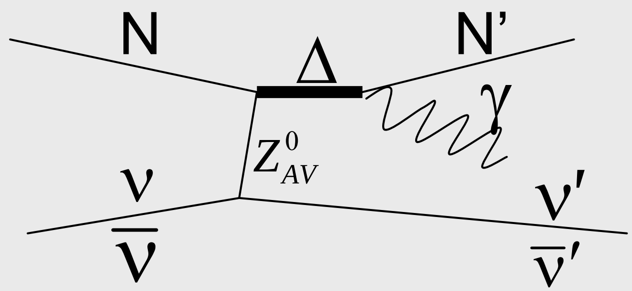
	Stat Only	Correlated Syst	Uncorrelated Syst	#Events
Same ν,$\bar{\nu}$ NC	0.1%	0.1%	6.7%	37
NC π^0 scaled	3.6%	6.4%	21.5%	20
POT scaled	0.0%	0.0%	1.8%	68
Bkgd scaled	2.7%	4.7%	19.2%	21
CC scaled	2.9%	5.2%	19.9%	20
Low-E Kaons	0.1%	0.1%	5.9%	40
ν scaled	38.4%	51.4%	58.0%	7

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 that where the low-energy excess comes from neutrinos in the beam (no contribution from anti-neutrinos).

Currently in process of more careful consideration of correlation of systematics in neutrino and antineutrino mode... results coming soon!

NC Processes with E_γ>200MeV and No Mesons

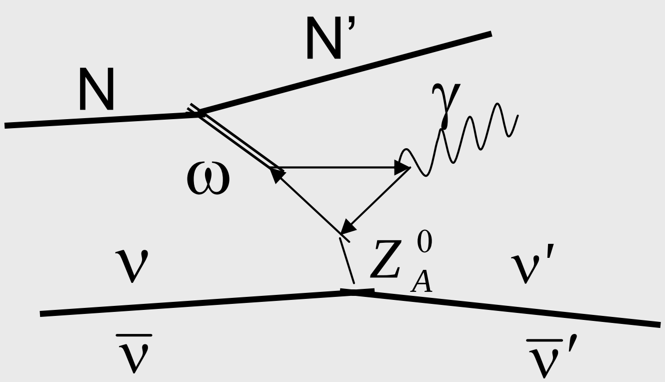


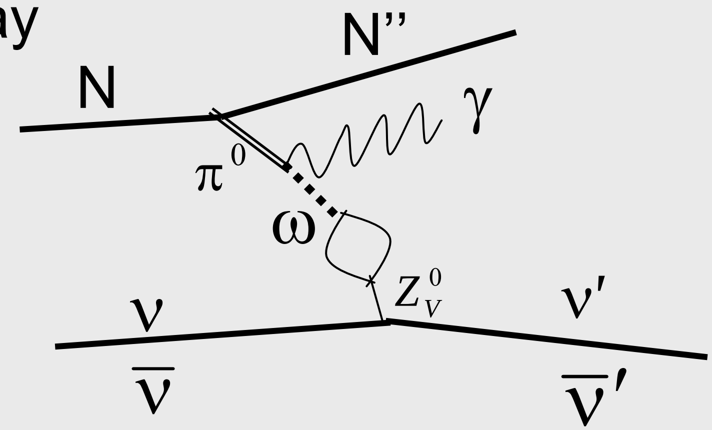
Radiative Delta Decay

in our MC

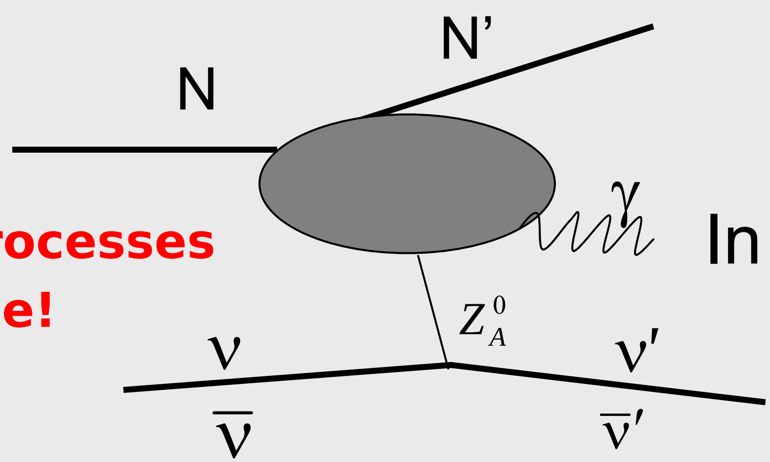
$(G^2\alpha/\alpha_S)$ α_S order 1

Axial Anomalies
(pure neutral current)
(Harvey, Hill, Hill, 0708.1281)





Other PCAC
(Goldman, Jenkins)

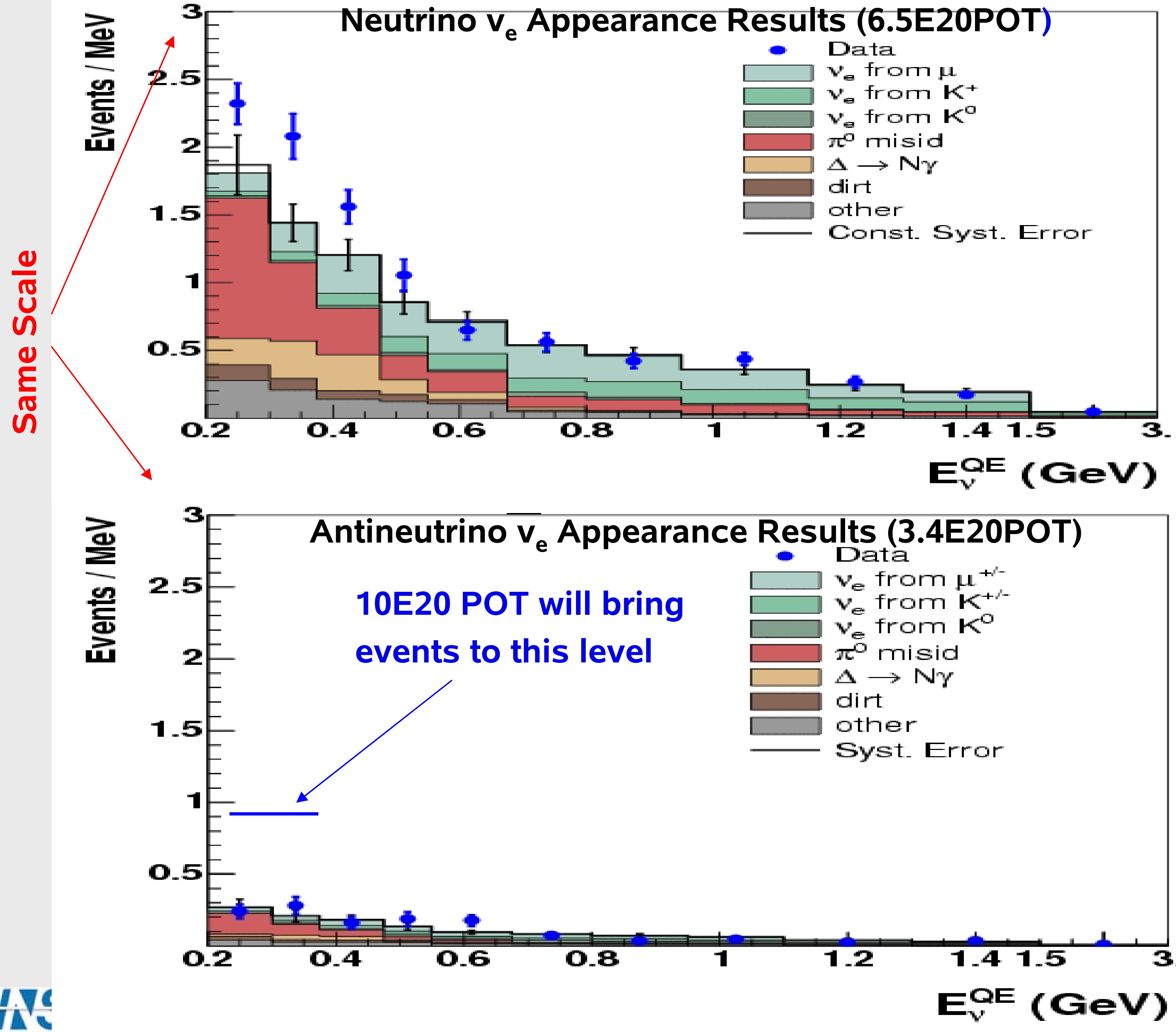


In General

Should see these processes in antineutrino mode!

Current and Future AntiNeutrino Running

- Continue running antineutrino mode till summer 2009 shutdown, plan to collect a total of ~5.3E20 POT (50% more data).
  - Will perform neutrino - antineutrino ratio analysis with extra data, where most systematic errors will cancel.
- More data and new experiments will be required to fully understand the low energy excess.
  - Request antineutrino running for a total of 10E20 POT.
- Doubling of antineutrino data will improve oscillation sensitivity, and background rejection from combined neutrino and antineutrino analysis
  - Presently observed neutrino – antineutrino difference would become more significant! Hard to reconcile with Standard Model!!


Same Scale
Neutrino ν_e Appearance Results (6.5E20POT)
Events / MeV
Data
ν_e from μ
ν_e from K^+
ν_e from K^0
π^0 misid
$\Delta \rightarrow N\gamma$
dirt
other
Const. Syst. Error
E_ν^{QE} (GeV)
Antineutrino ν_e Appearance Results (3.4E20POT)
Events / MeV
Data
ν_e from $\mu^{+/-}$
ν_e from $K^{+/-}$
ν_e from K^0
π^0 misid
$\Delta \rightarrow N\gamma$
dirt
other
Syst. Error
10E20 POT will bring
events to this level
E_ν^{QE} (GeV)

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	475-1250	200-475	475-1250
Flux from π^+/μ^+ decay	0.4	0.7	1.8	2.2
Flux from π^-/μ^- decay	3.3	2.2	0.1	0.2
Flux from K^+ decay	2.3	4.9	1.4	5.7
Flux from K^- decay	0.5	1.1	-	-
Flux from K^0 decay	1.5	5.7	0.5	1.5
Target and beam models	1.9	3.0	1.3	2.5
ν cross section	6.4	12.9	5.9	11.9
NC π^0 yield	1.7	1.6	1.4	1.9
Hadronic interactions	0.5	0.6	0.8	0.3
External interactions (dirt)	2.4	1.2	0.8	0.4
Optical model	9.8	2.8	8.9	2.3
Electronics & DAQ model	9.7	3.0	5.0	1.7
Total (unconstrained)	*16.3*	*16.2*	*12.3*	*14.2*
Statistical Error	*12.8*	*13.2*	*4.9*	*5.1*

Expect large cancellation of systematic errors in ratio analysis.

Antineutrino statistical error will dominate.

Improvements in Hypothesis Rejection (assuming no excess present)

5E20 POT

Hypothesis	Expec. # of $\bar{\nu}$ Events	Cor. Syst. Err.
Same σ	55.8	0.0%
π^0 Scaled	29.1	3.9%
POT Scaled	101.3	0.0%
BKGD Scaled	31.4	2.6%
CC Scaled	30.6	3.0%
Kaon Scaled	59.6	0.0%
Neutrino Scaled	10.1	49.5%

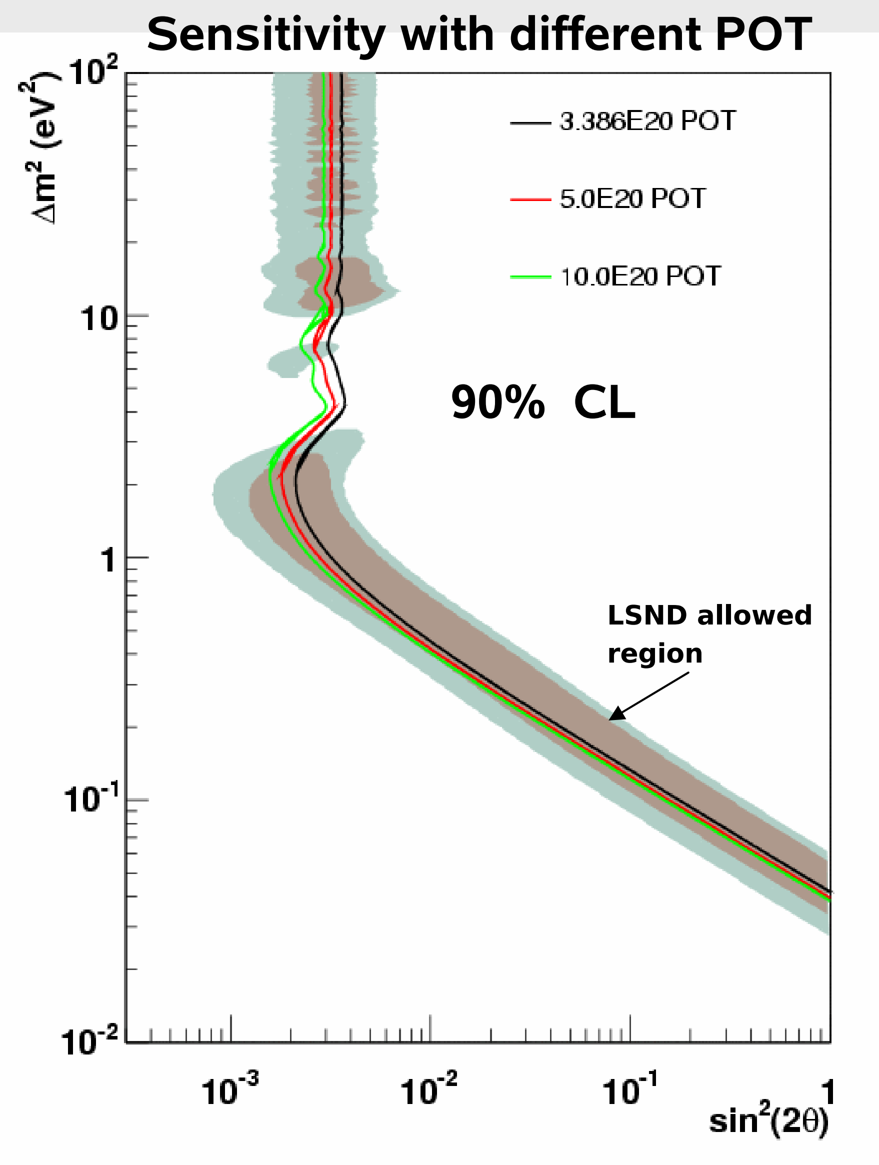
10E20POT

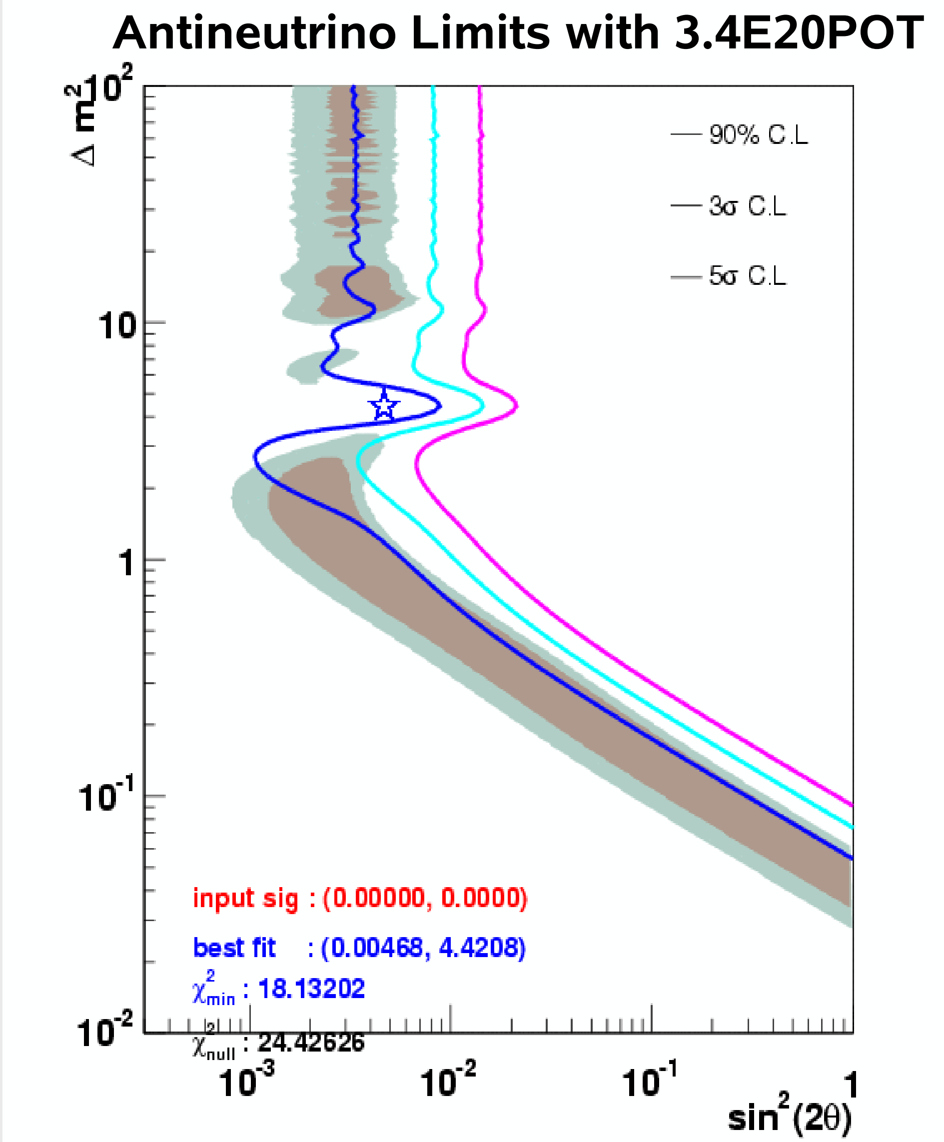
Hypothesis	Expec. # of $\bar{\nu}$ Events	Cor. Syst. Err.
Same σ	111.6	0.0%
π^0 Scaled	58.2	1.4%
POT Scaled	202.5	0.0%
BKGD Scaled	62.7	0.8%
CC Scaled	61.2	1.0%
Kaon Scaled	119.1	0.0%
Neutrino Scaled	20.1	44.1%

Will be able to reject background hypothesis at > 98% CL

Slightly Improved Oscillation Sensitivity (E>200 MeV)

However, our current limits are worse than expected sensitivity.
If upward fluctuation, then extra data will improve limits.

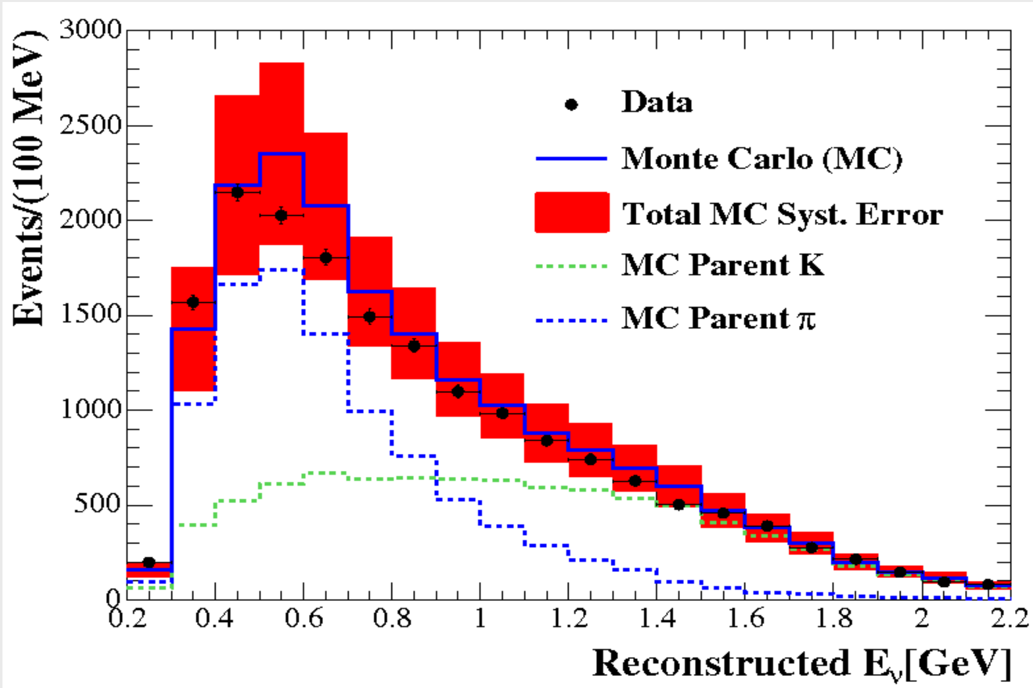




With 10E20POT, expected LSND signal = 44 +/- 15 +/- 21 events (1.7 sigma)

NuMI ν_μ and ν_e Data (neutrino mode)

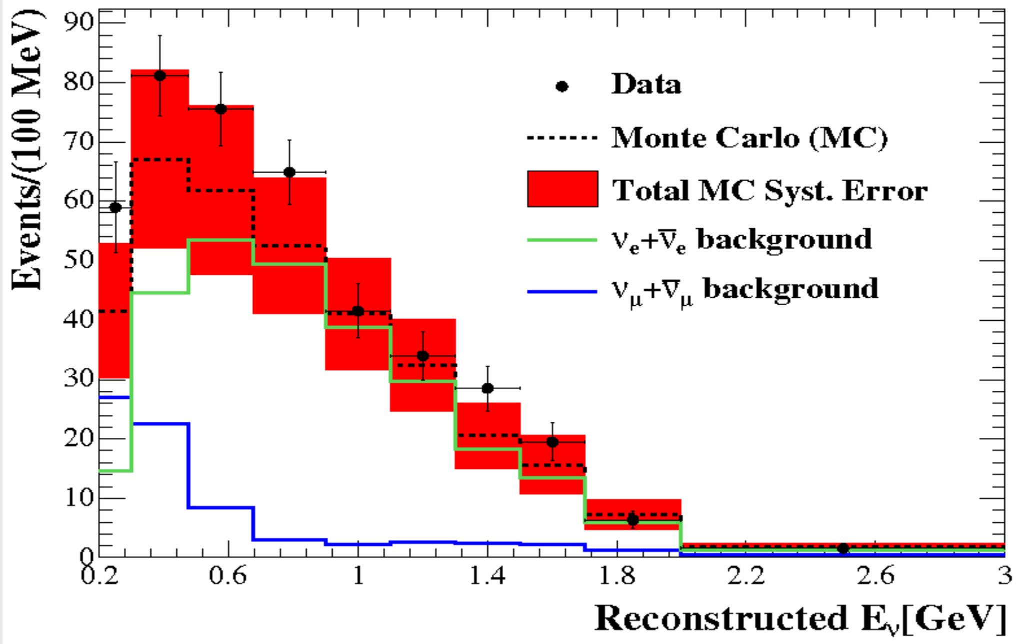
ν_μ CCQE sample



arXiv:0809.2447v1
Submitted to PRL

Good agreement between data and Monte Carlo:the MC is tuned well.
x3 more data available.

ν_e CCQE sample



Very different backgrounds compared to MB (Kaons vs Pions)

Currently working on ν_e appearance analysis (muon constraint will reduce sys errors).

NuMI will run in antineutrino mode 2009-2010, comparison with nu-mode will be interesting.

POT Projections for Extra 5E20 POT totaling 10E20 POT in antinu mode)

Booster runs at 7 Hz, we currently get ~1.5Hz

Rate increase	proton/hr	proton/week	protons/year	Years to 5E20 POT
Nominal	2.2E16	3.2E18	1.5E20	3.3
50% increase	3.3E16	5.3E18	2.3E20	2.2
100% increase	4.4E16	6.4E18	3.0E20	1.7
Maximum increase	7.5E16	10.7E18	4.6E20	1.1

Run will take three years. With some proton gains/improvements, maybe two.

Collaboration List

Proposal for More MiniBooNE Antineutrino Data Taking

W. Barletta[7], B. Brown[3], L. Bugel[7], J. M. Conrad[7], Z. Djurcic[2], B. T. Fleming[10], R. Ford[3], F. G. Garcia[3], G. T. Garvey[6], J. Grange[4], J. A. Green[6], G. Karagiorgi[7], T. Katori[7], T. Kobilarcik[3], W. C. Louis[6], W. Marsh[3], G. B. Mills[6], J. Monroe[7], C. D. Moore[3], V. Nguyen[7], P. Nienaber[9], Z. Pavlovic[6], H. Ray[4], B. P. Roe[8], R. Schirato[6], M. H. Shaevitz[2], I. Stancu[1], R. Tayloe[5], K. Terao[7], R. Van de Water[6]*, D. H. White[6], L. Winslow[7], G. P. Zeller[6],

(The MiniBooNE Collaboration)

[1] *University of Alabama; Tuscaloosa, AL 35487*

[2] *Columbia University; New York, NY 10027*

[3] *Fermi National Accelerator Laboratory; Batavia, IL 60510*

[4] *University of Florida; Gainesville, FL 32611*

[5] *Indiana University; Bloomington, IN 47405*

[6] *Los Alamos National Laboratory; Los Alamos, NM 87545*

[7] *Massachusetts Institute of Technology; Cambridge, MA 02139*

[8] *University of Michigan; Ann Arbor, MI 48109*

[9] *Saint Mary's University of Minnesota; Winona, MN 55987*

[10] *Yale University; New Haven, CT 06520*

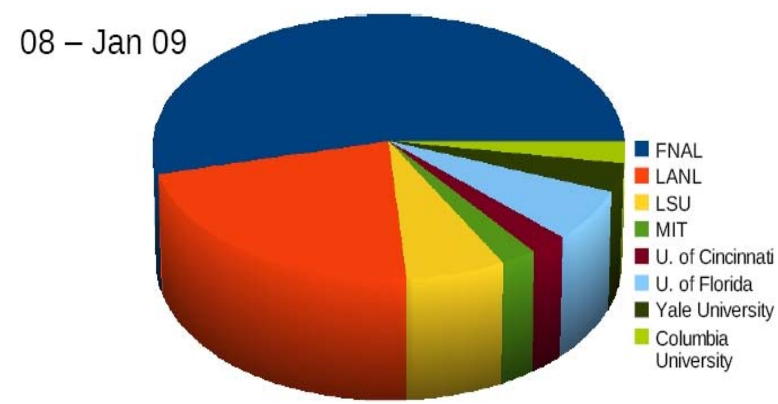
(Dated: March 4, 2009)

* Spokesperson

About 1/3 of the collaboration remains. Should increase to About 1/2 with addition of students and postdocs.

Core of beam and detector experts remain onsite. Spare horn and electronics available.

Have implemented remote shift capability. Allows collaboration to fulfill shift quota with minimal travel and disruption. Can hire local students to perform shifts (good HEP learning experience).



Conclusions and Request

- **NEUTRINO MODE:**
- MiniBooNE rules out a simple two neutrino $\nu_\mu \rightarrow \nu_e$ appearance-only model as an explanation of the LSND excess at 98% CL. (Phys. Rev. Lett. 98, 231801 (2007), arXiv:0704.1500v2 [hep-ex])
- A 128.8 +/- 43.4 event (3.0σ stat+sys, 6.4σ stat)) excess of electron or gamma-ray events are observed in the low energy range from 200 < E_ν < 475MeV (accepted by PRL, arXiv:0812.2243 [hep-ex]).
- **ANTI-NEUTRINO MODE:**
  - MiniBooNE is inconclusive on oscillations, need more data.
  - No low energy excess is observed similar to neutrino mode, which disfavors many types of backgrounds/signal processes (e.g. HHH Axial Anomaly).
- Whether a background or beyond the SM signal, more antineutrino data is crucial to firm up results.
  - If a background, important to understand for next generation long baseline experiments.
- MiniBooNE requests further running in antineutrino mode to collect 5E20 POT, for a total of 10E20 POT in antineutrino mode.

Current MiniBooNE Publication List

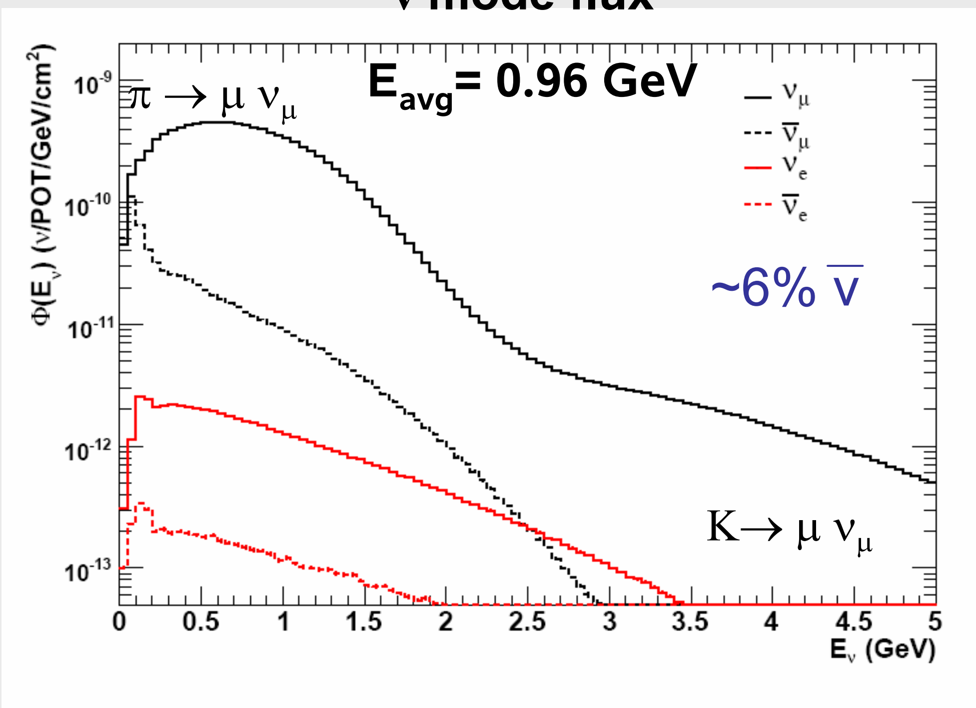
- A.A. Aguilar-Arevalo, et al., "A Search for Electron AntiNeutrino Appearance at the $\Delta m^2 \sim 1$ eV^2 Scale", to be submitted to Phys. Rev. Lett.
- A.A. Aguilar-Arevalo, et al., "A Search for Muon Neutrino and Antineutrino disappearance in MiniBooNE", to be submitted to Phys. Rev. Lett.
- A.A. Aguilar-Arevalo, et al., "Unexplained Excess of Electron-Like Events from a 1-GeV Neutrino Beam", arXiv:0812.2243 [hep-ex], accepted by Phys. Rev. Lett.
- P. Adamson et al., "First Measurement of ν_μ and ν_e Events in an Off-Axis Horn-Focused Neutrino Beam", arXiv:0809.2446 [hep-ex], submitted to Phys. Rev. Lett.
- A.A. Aguilar-Arevalo et al., "The MiniBooNE Detector", arXiv:0806.4201 [hep-ex], Nucl. Instr. Meth. A599: 28-46, 2009
- A.A. Aguilar-Arevalo et al., "The Neutrino Flux Prediction at MiniBooNE", arXiv:0806.1449 [hep-ex], submitted to Phys. Rev. D.
- A.A. Aguilar-Arevalo et al., "Compatibility of high Δm^2 ν_e and ν_e-bar Neutrino Oscillation Searches", arXiv:0805.1764 [hep-ex], Phys. Rev. D. 78, 012007 (2008)
- A.A. Aguilar-Arevalo et al., "First Observation of Coherent π0 Production in Neutrino Nucleus Interactions with Ev<2 GeV", arXiv:0803.3423 [hep-ex], Phys. Lett. B. 664, 41 (2008)
- A.A. Aguilar-Arevalo et al., "Constraining Muon Internal Bremsstrahlung As A Contribution to the MiniBooNE Low Energy Excess", arXiv:0706.3897 [hep-ex]
- A.A. Aguilar-Arevalo et al., "Measurement of Muon Neutrino Quasi-Elastic Scattering on Carbon", arXiv:0706.0926 [hep-ex], Phys. Rev. Lett. 100, 032301 (2008)
- A.A. Aguilar-Arevalo et al., "A Search for Electron Neutrino Appearance at the $\Delta m^2 \sim 1$ eV^2 Scale", arXiv:0704.1500 [hep-ex], Phys. Rev. Lett. 98, 231801 (2007)

BACKUP SLIDES

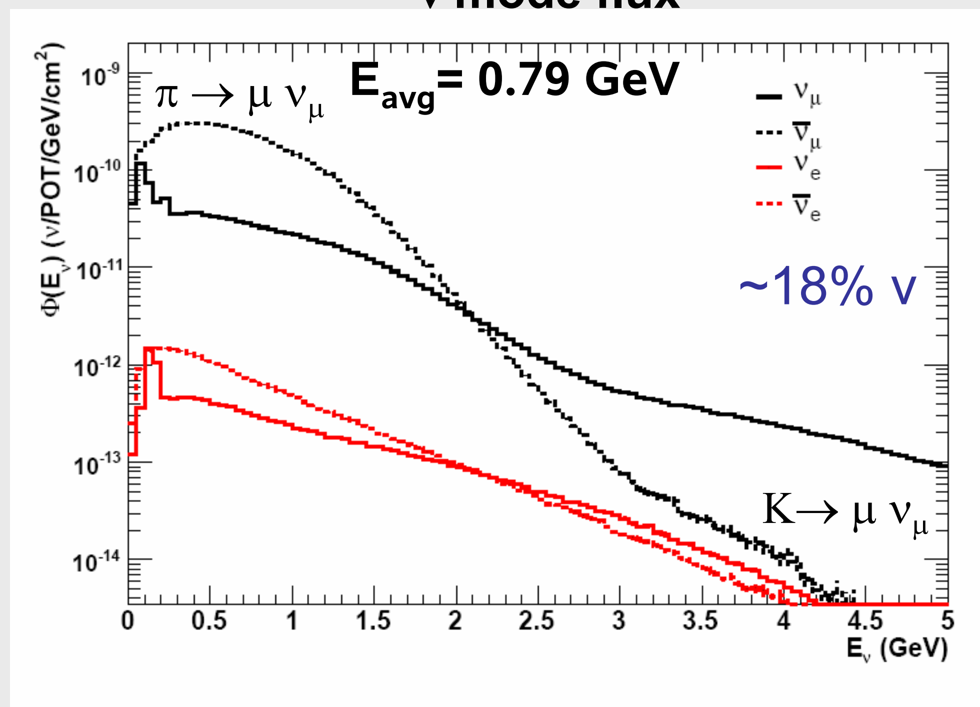
MiniBooNE experiment

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

ν mode flux



$\bar{\nu}$ mode flux

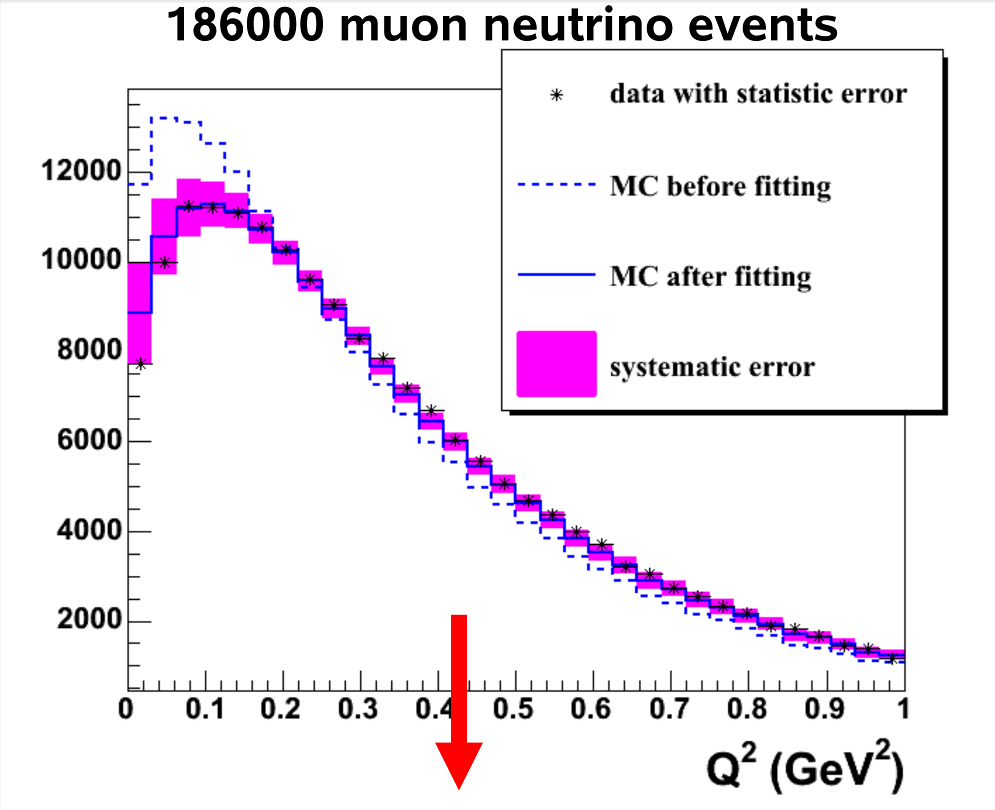


Subsequent decay of the **μ+ (μ-)** produces ν_e ($\bar{\nu}_e$) intrinsics ~0.5%

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))



From Q^2 fits to MB ν_μ CCQE data:

- M_A^{eff} -- effective axial mass
- κ -- Pauli Blocking parameter

From electron scattering data:

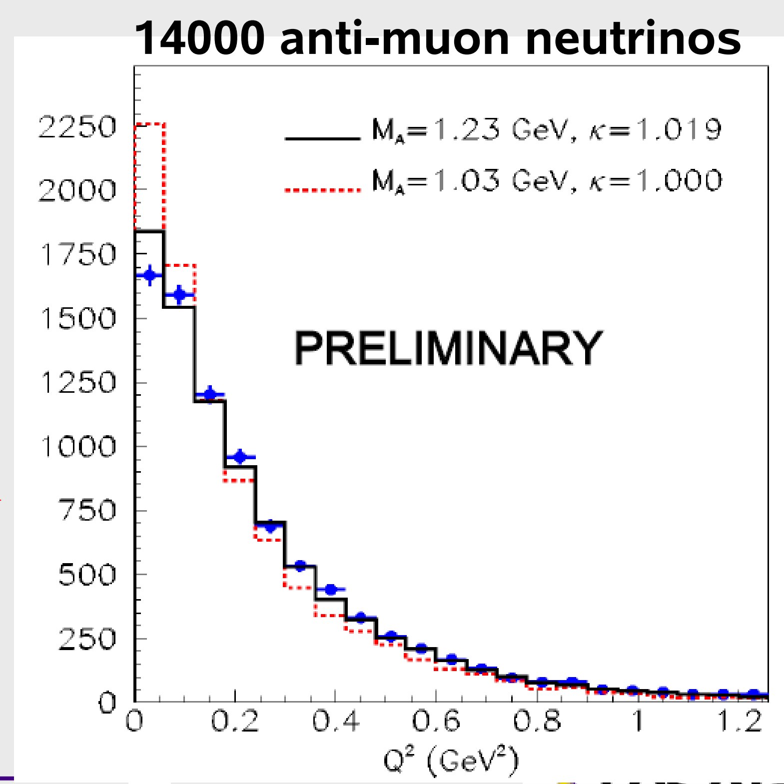
- E_b -- binding energy
- p_f -- Fermi momentum

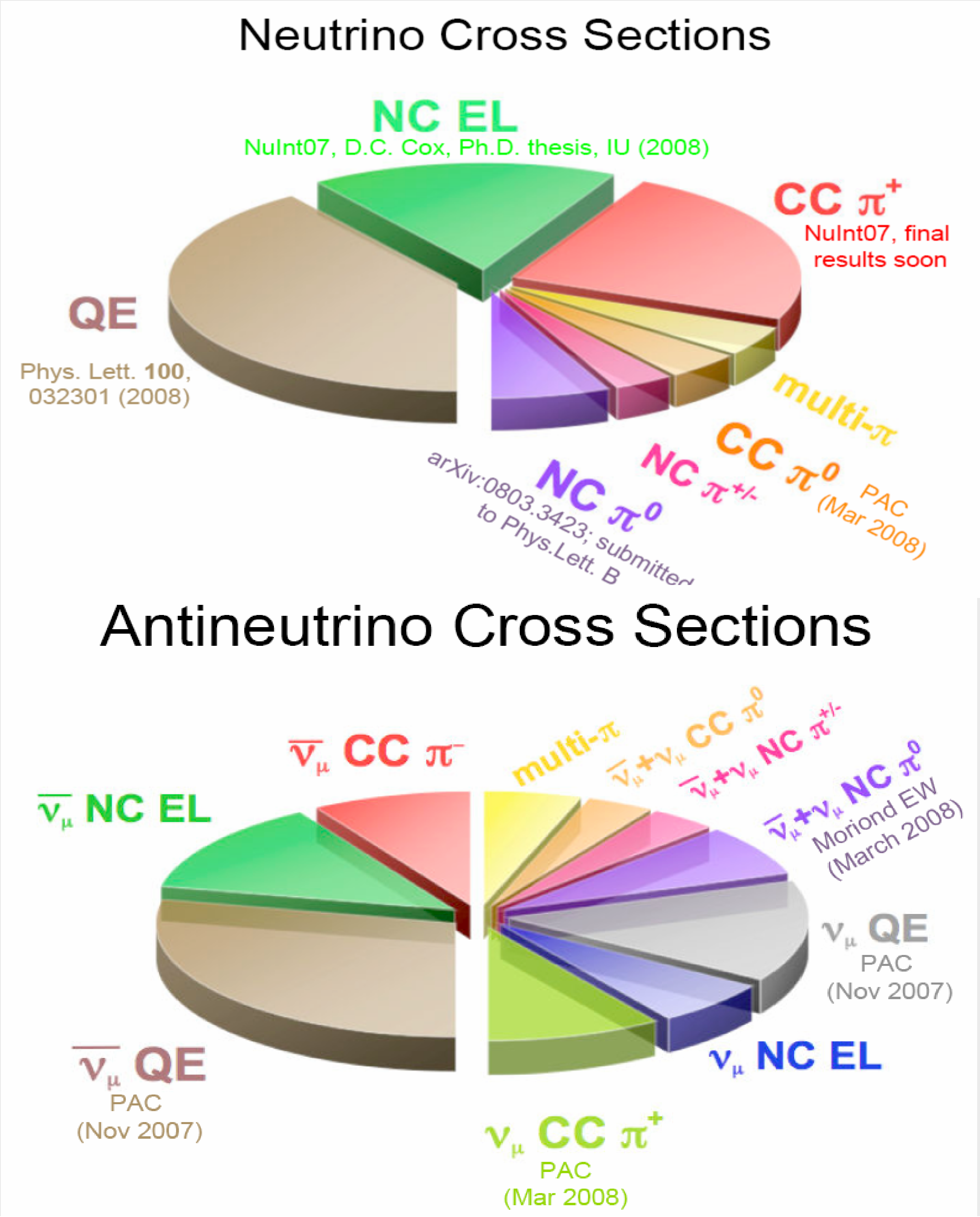
Fermi Gas Model describes CCQE ν_μ data well

M_A = 1.23+-0.20 GeV

κ = 1.019+-0.011

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

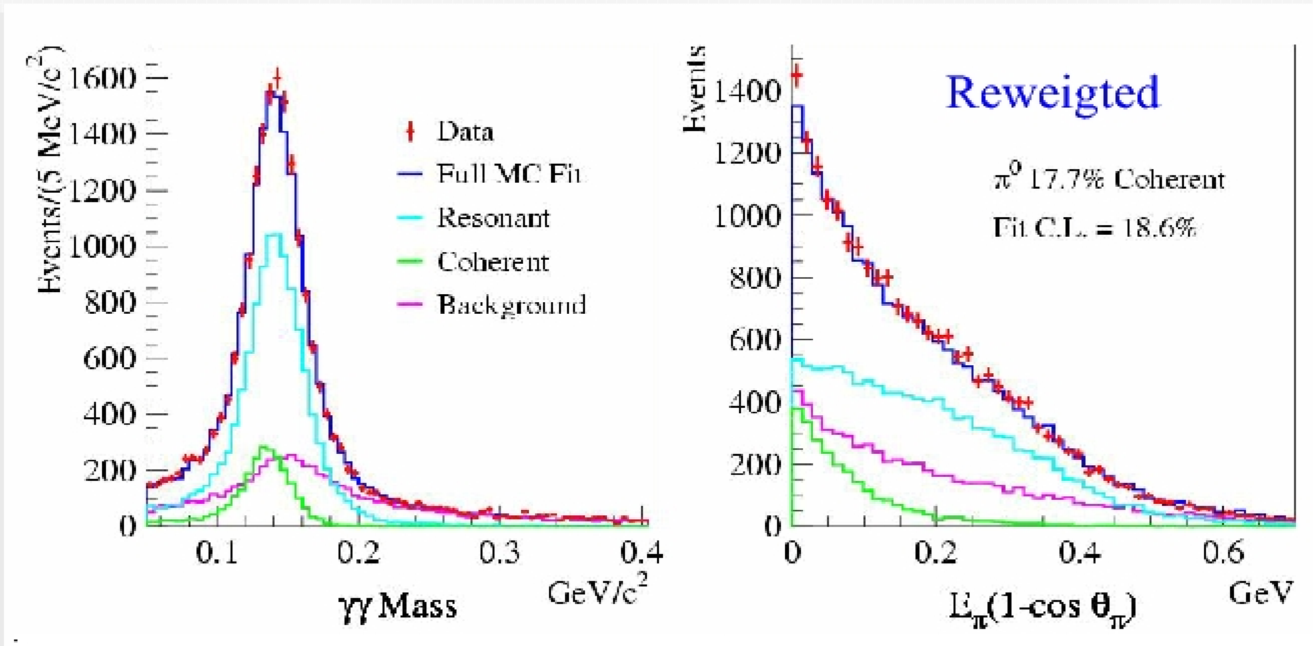




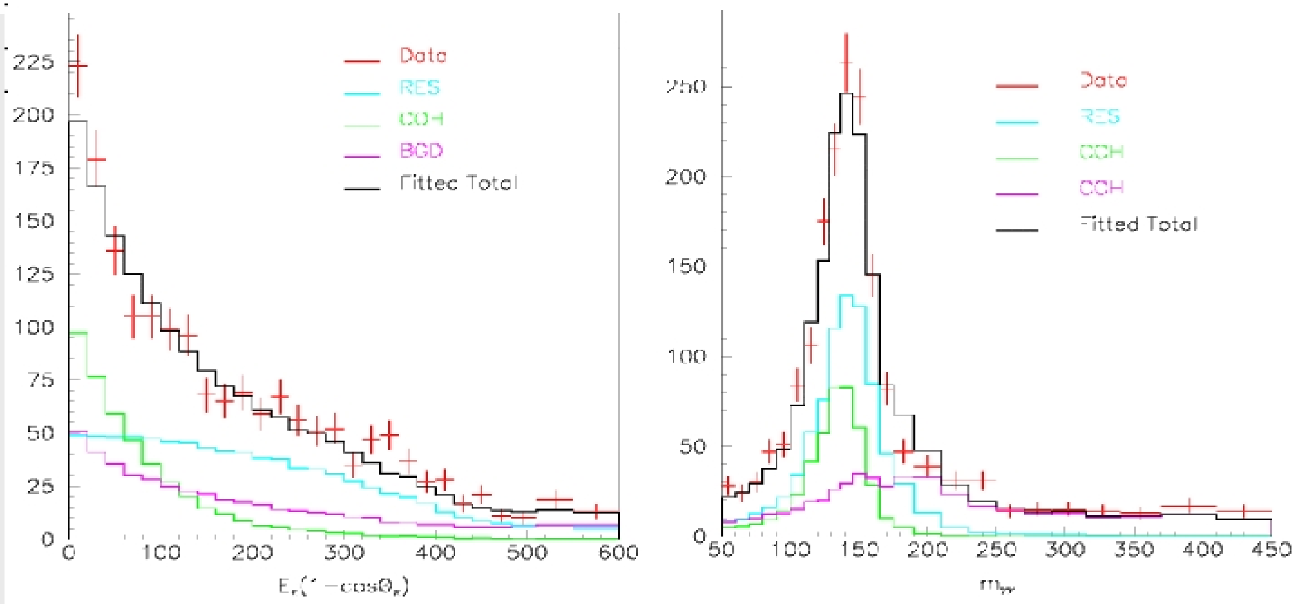
Similar backgrounds. However, anti-neutrino mode has sizable neutrino contribution

Neutral Current π^0: Good Data/MC agreement

Neutrino



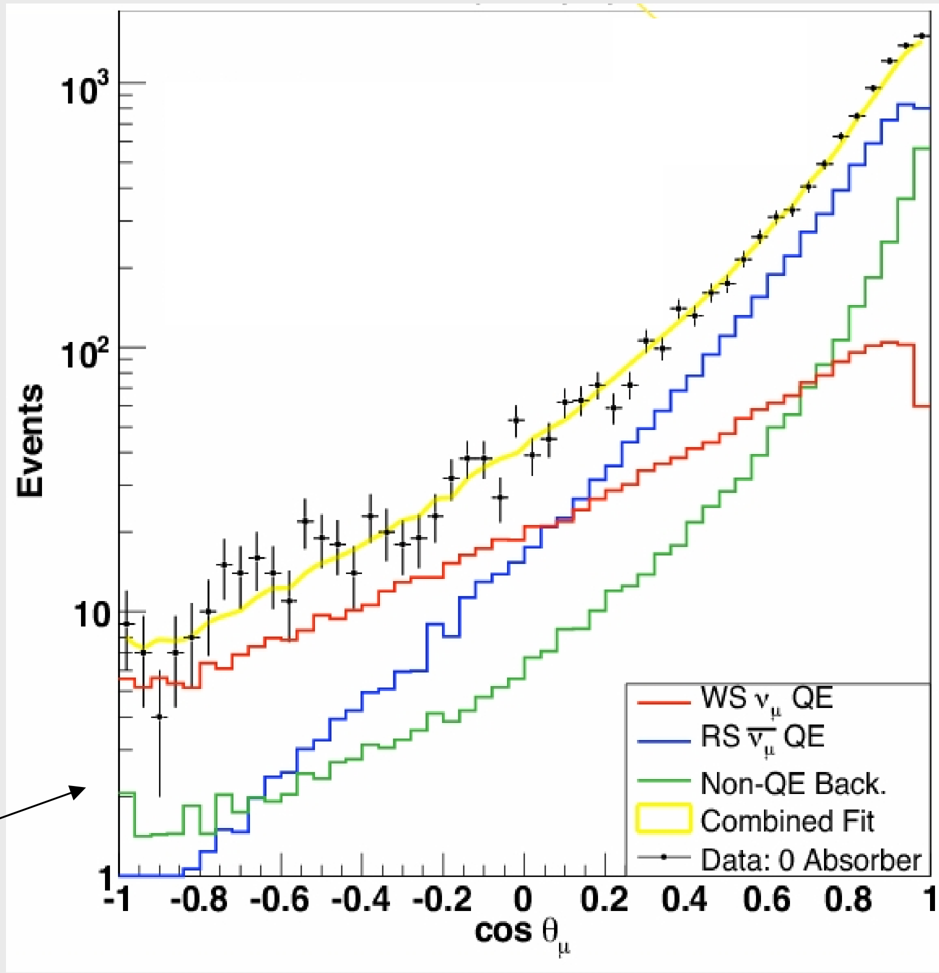
Antineutrino



Antineutrino Analysis

1. Flux estimated from HARP (pi-).
2. Cross sections from fits to neutrino Q^2.
3. Same reconstruction and PID.
4. Need to deal with wrong sign (neutrinos in antinu mode about ~30%).

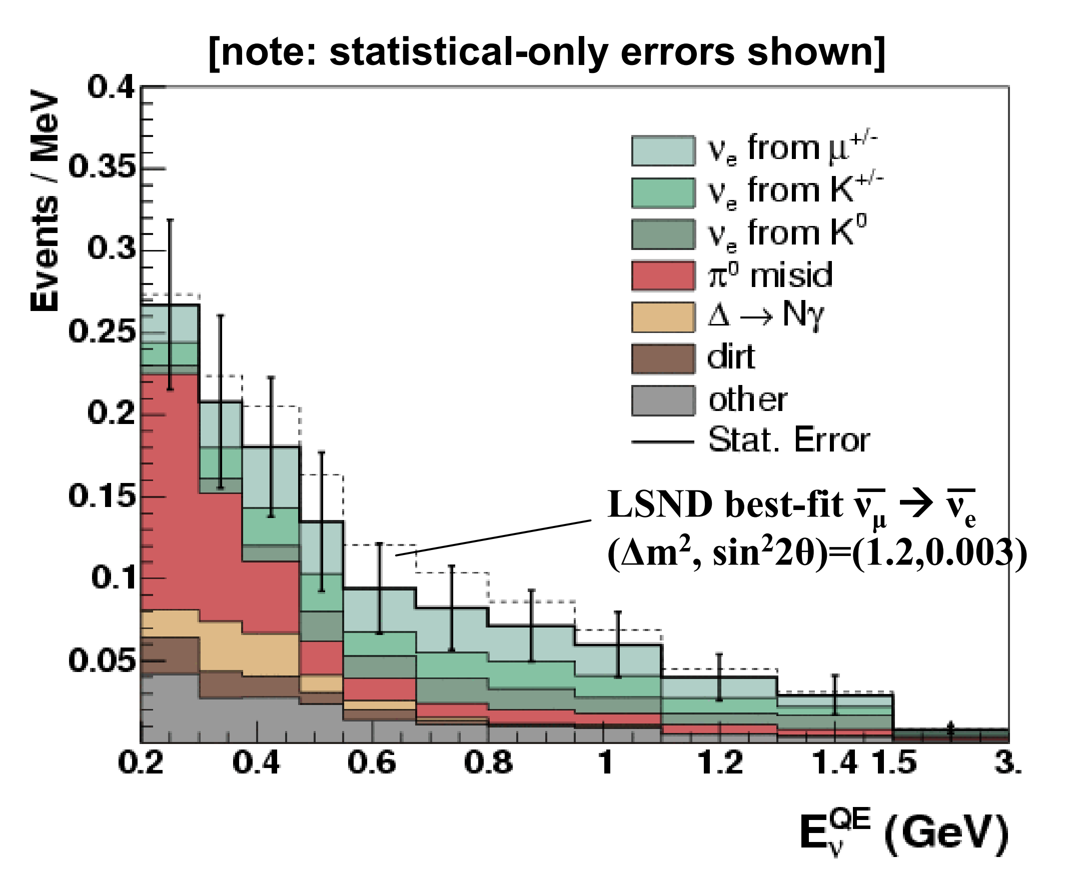
Angular fits to Muon data in good agreement with MC.



MiniBooNE $\bar{\nu}_e$ appearance analysis

Background composition for $\bar{\nu}_e$ appearance search (3.386e20 POT):

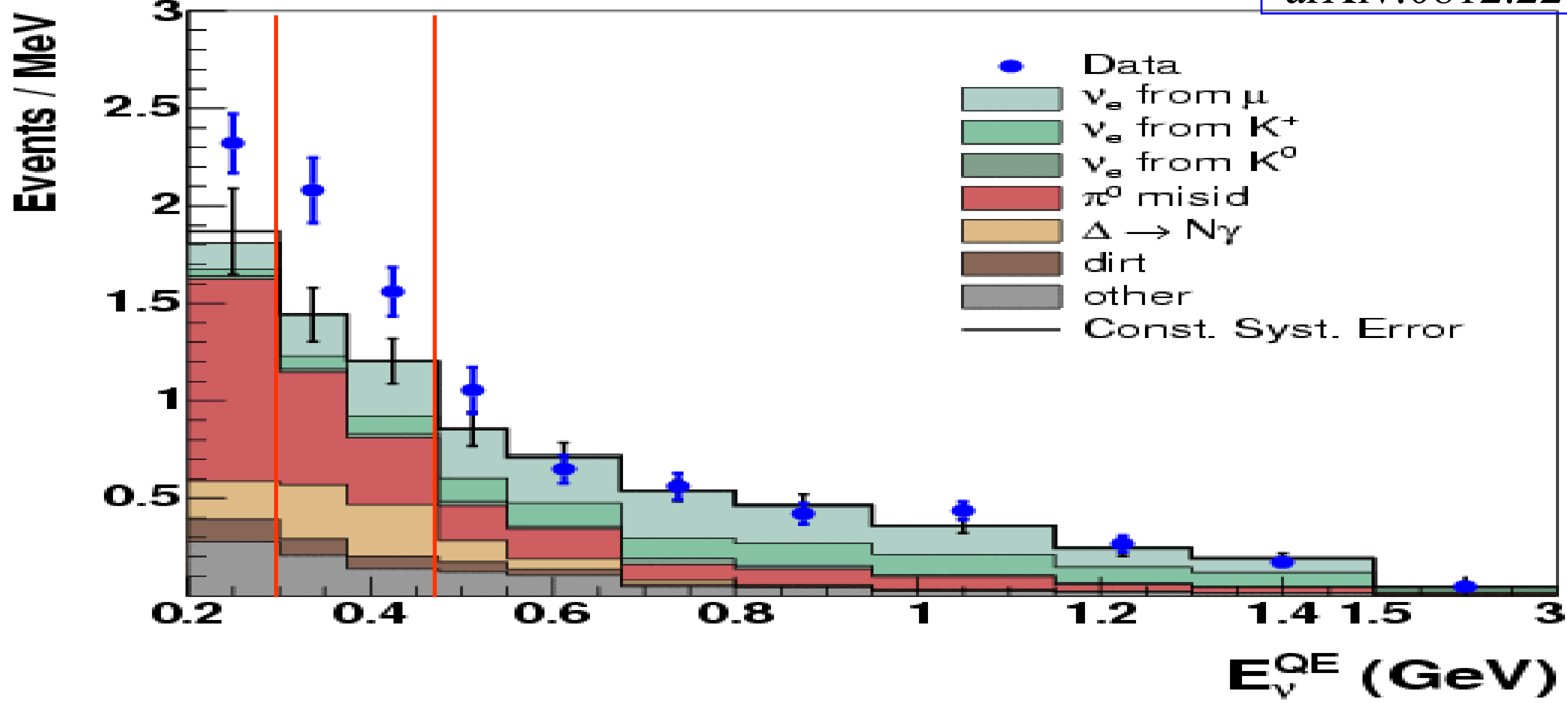
N_{events}	200-475 MeV	475-1250 MeV
intrinsic ν_e	17.74	43.23
from $\pi^\pm/\mu^\pm$	8.44	17.14
from $K^\pm$, K^0	8.20	24.88
other ν_e	1.11	1.21
mis-id ν_μ	42.54	14.55
CCQE	2.86	1.24
NC π^0	24.60	7.17
Δ radiative	6.58	2.02
Dirt	4.69	1.92
other ν_μ	3.82	2.20
Total bkgd	60.29	57.78
LSND best fit	4.33	12.63



Systematic errors similar to neutrino mode. Statistical errors dominate

New Neutrino Results

submitted to PRL
arXiv:0812.2243 [hep-ex]



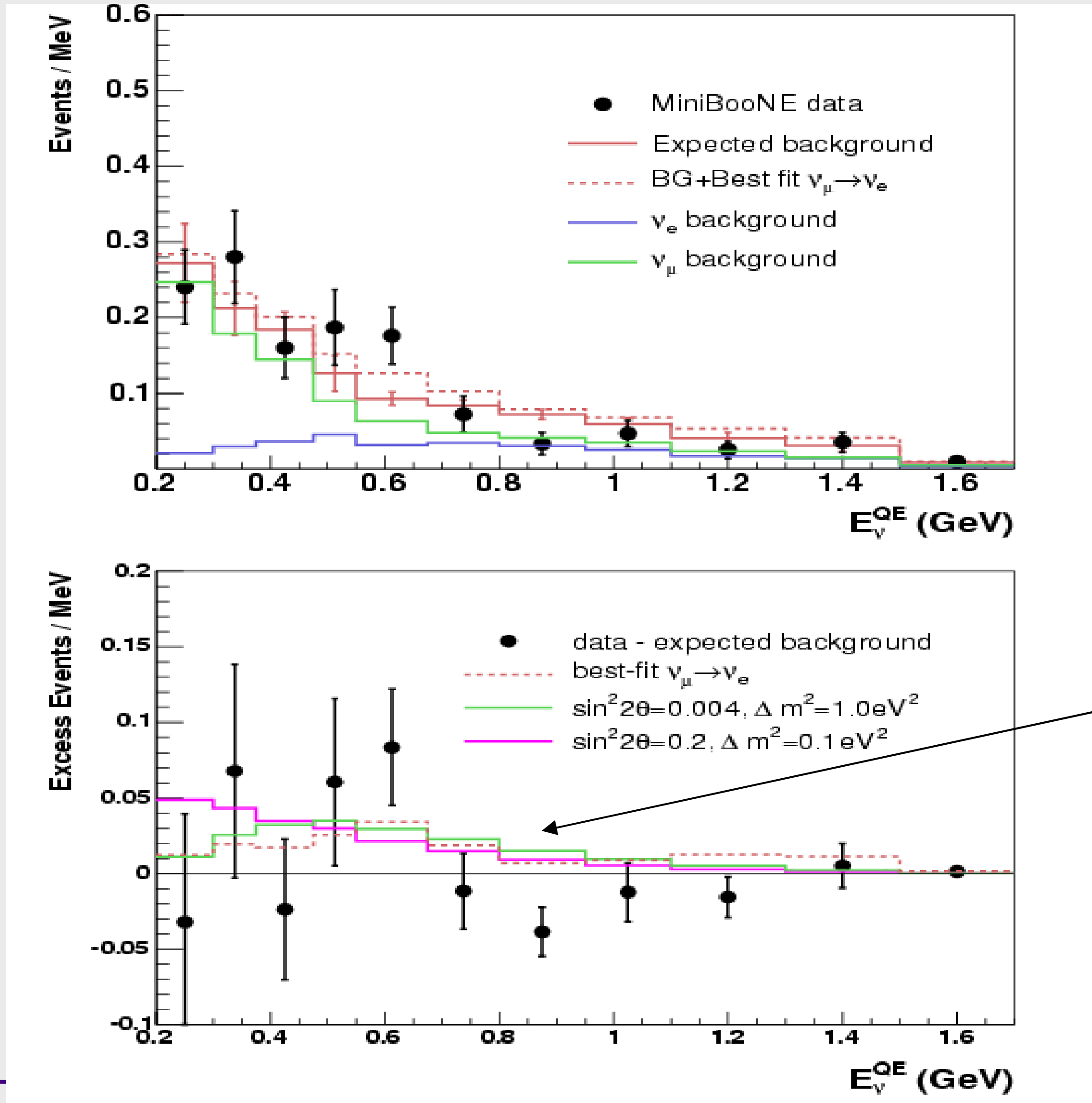
MC background prediction includes statistical and systematic error

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

"other" mostly muon mid-ID's

The excess at low energy remains significant!

Antineutrino Oscillation fit (>200 MeV) consistent with LSND and Null



NULL

χ^2(dof) 24.5(19)

χ^2-prob 17.7%

Best Fit

χ^2(dof) 18.1(17)

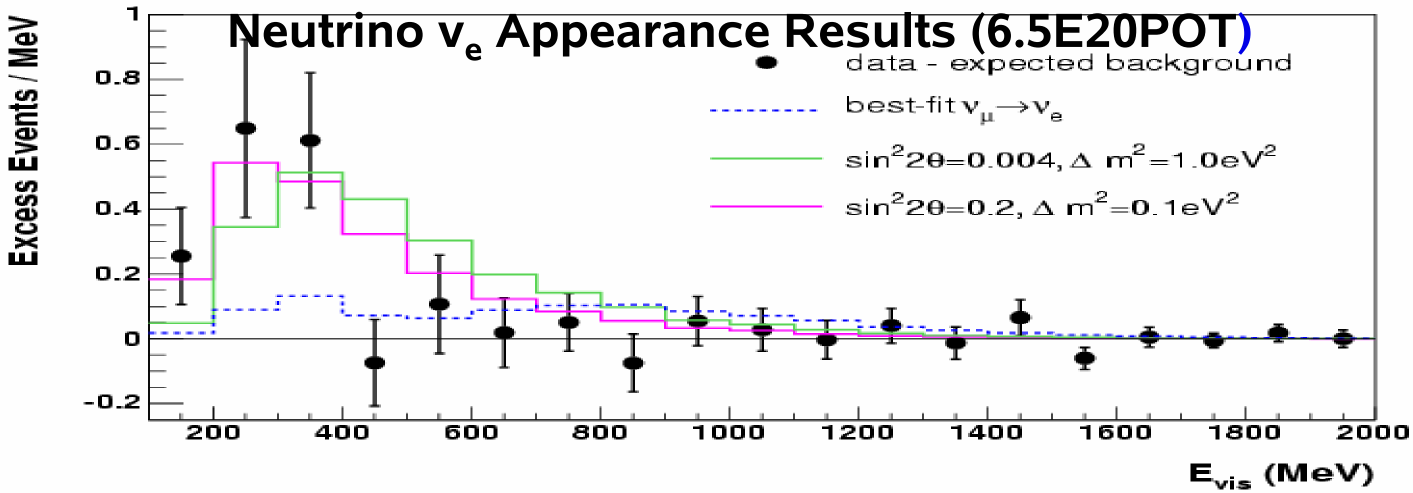
χ^2-prob 37.8%

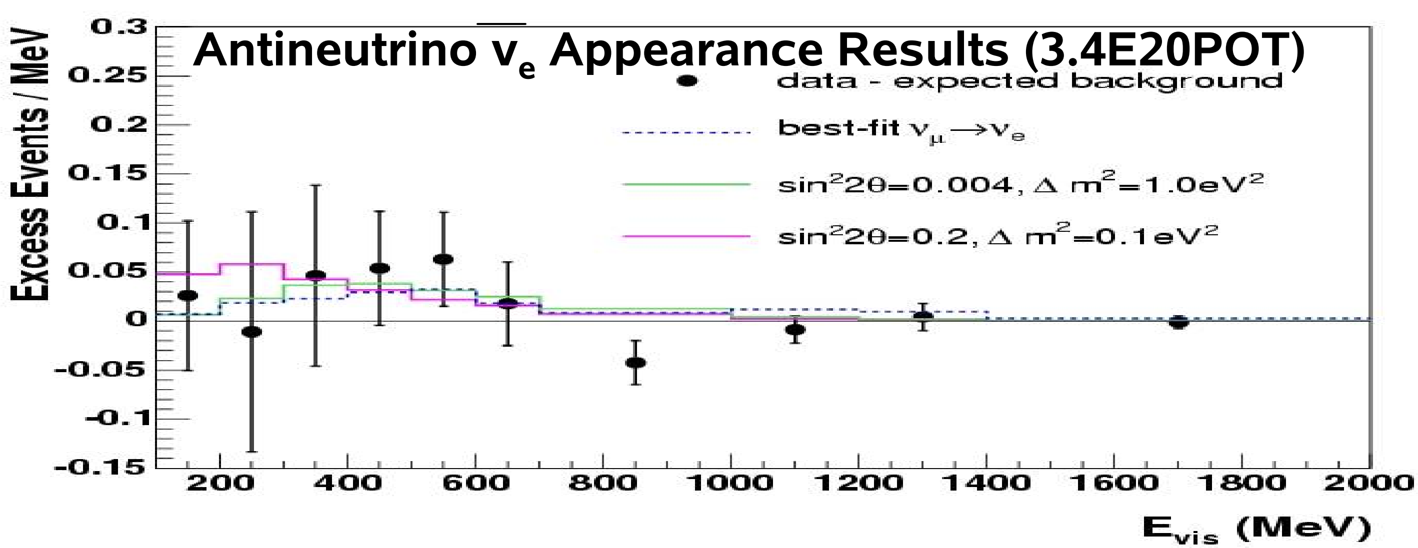
Fit yields 18+/-13 events, consistent with expectation from LSND.

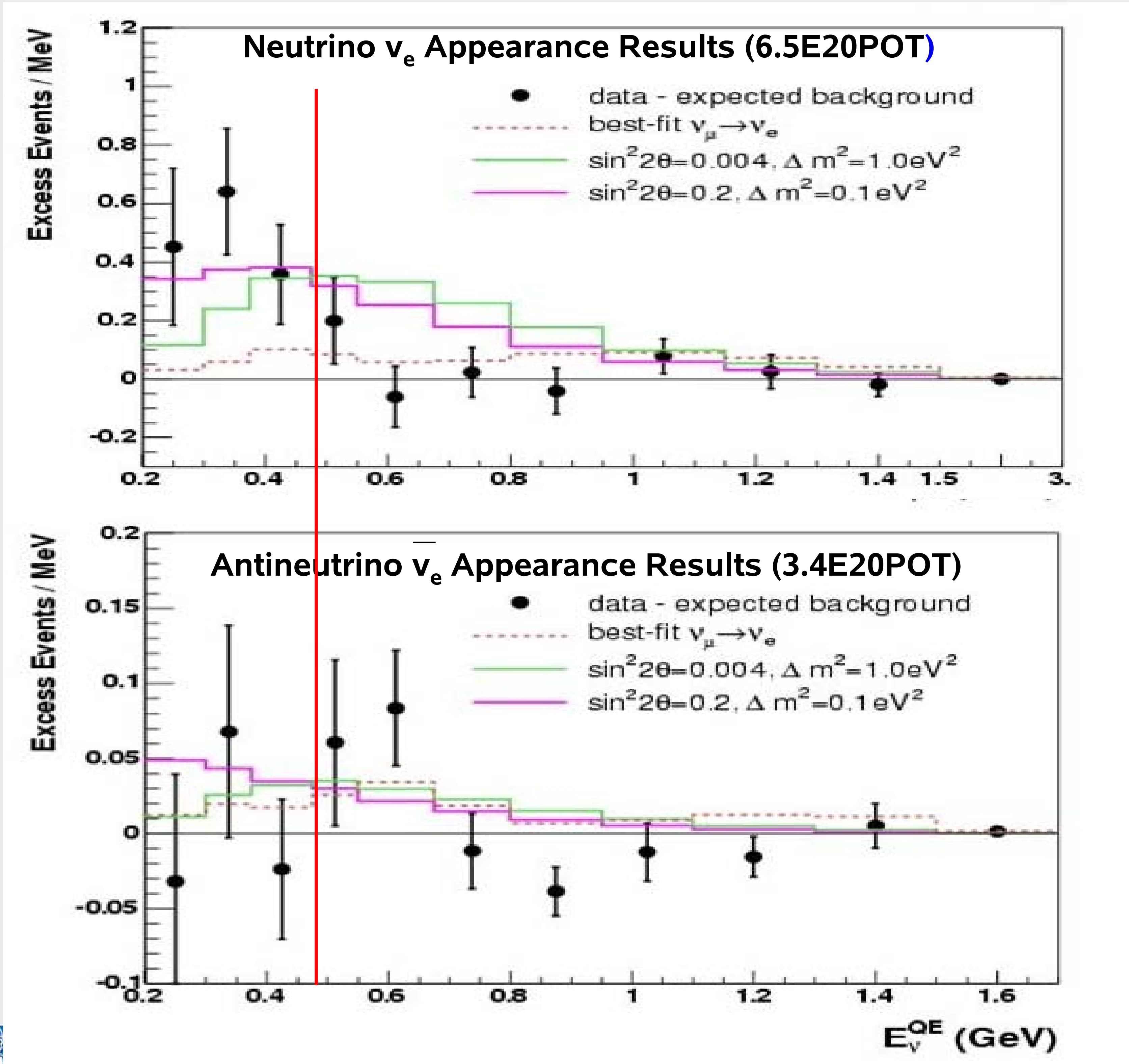
However, not conclusive due to large errors.

Complementary information: $E_{visible}$

Excess distribution as a function of $E_{visible}$ and Comparison with possible signal predictions:






Neutrino ν_e Appearance Results (6.5E20POT)
data - expected background
best-fit $\nu_\mu \rightarrow \nu_e$
$\sin^2 2\theta = 0.004, \Delta m^2 = 1.0 eV^2$
$\sin^2 2\theta = 0.2, \Delta m^2 = 0.1 eV^2$
Excess Events / MeV
Antineutrino $\bar{\nu}_e$ Appearance Results (3.4E20POT)
data - expected background
best-fit $\nu_\mu \rightarrow \nu_e$
$\sin^2 2\theta = 0.004, \Delta m^2 = 1.0 eV^2$
$\sin^2 2\theta = 0.2, \Delta m^2 = 0.1 eV^2$
Excess Events / MeV
E_ν^{QE} (GeV)

Alamos

Implications for low energy excess

200-475 MeV		$\bar{\nu}$	ν
	Data	*61*	*544*
	MC ± sys+stat (constr.)	*61.5 ± 11.7*	*415.2 ± 43.4*
	Excess (σ)	*-0.5 ± 11.7 (-0.04σ)*	*128.8 ± 43.4 (3.0σ)*

- Performed 2-bin χ^2 test for each assumption
- Calculated χ^2 probability assuming 1 dof

$$\chi^2 = \sum_{i,j} \left(D_i - \left(B_i + S_i\right)\right) M_{ij}^{-1} \left(D_j - \left(B_j + S_j\right)\right)$$

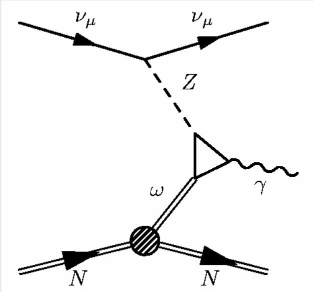
$$i, j = \nu, \bar{\nu} \text{ 200-475MeV bin}$$

The underlying signal for each hypothesis, S, was allowed to vary (thus accounting for the possibility that the observed signal in neutrino mode was a fluctuation up, and the observed signal in antineutrino mode was a fluctuation down), and an absolute χ^2 minimum was found.

- Three extreme fit scenarios were considered:
  - Statistical-only uncertainties
  - Statistical + fully-correlated systematics ← **Closest to true errors**
  - Statistical + fully-uncorrelated systematics

In process of performing neutrino/antineutrino comparison with correct handling of systematic errors.

Possible Explanations for the Low-Energy Excess



- A simple beam induced or reconstruction background **NO**
- Anomaly Mediated Neutrino-Photon Interactions at Finite Baryon Density: Jeffrey A. Harvey, Christopher T. Hill, & Richard J. Hill, arXiv:0708.1281 **NO (but what about interference?)**
- 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**
- Can connect with LSND, but not simple 2 neutrino model.