

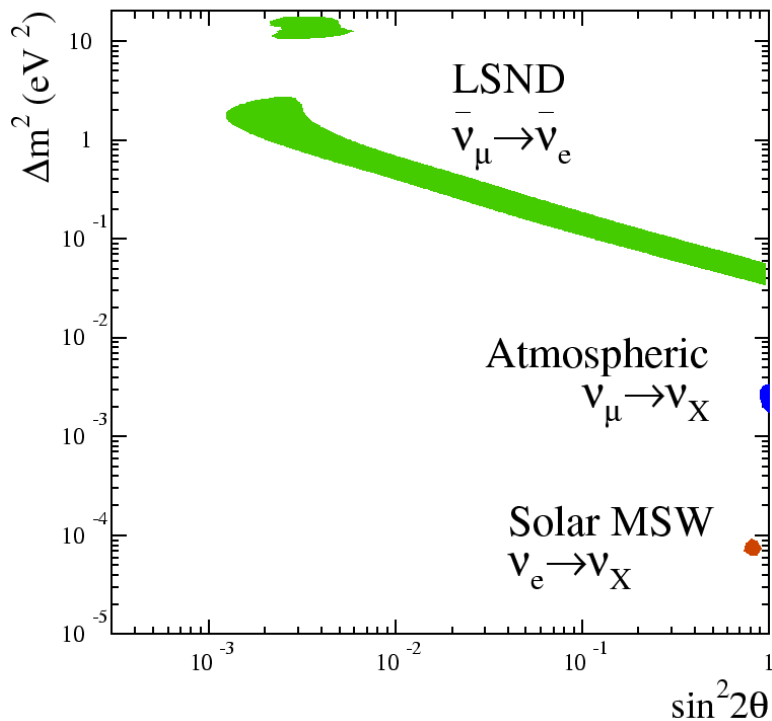
# MiniBooNE $\nu$ Oscillation Results

W.C. Louis, July 6, 2009

- **MiniBooNE Introduction**
- **Neutrino Oscillation Results**
- **NuMI Data Results**
- **Antineutrino Oscillation Results**
- **Disappearance Oscillation Results**
- **Future Experiments**

# *MiniBooNE was designed to test the LSND signal*

$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$



A 3 neutrino picture requires

$$\Delta m_{13}^2 = \Delta m_{12}^2 + \Delta m_{23}^2$$

↑  
increasing (mass)<sup>2</sup>



$\nu_3$

$$\Delta m_{23}^2 = m_2^2 - m_3^2$$

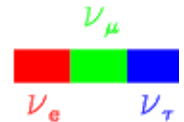


$\nu_2$

$$\Delta m_{12}^2 = m_1^2 - m_2^2$$



$\nu_1$



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

# MiniBooNE

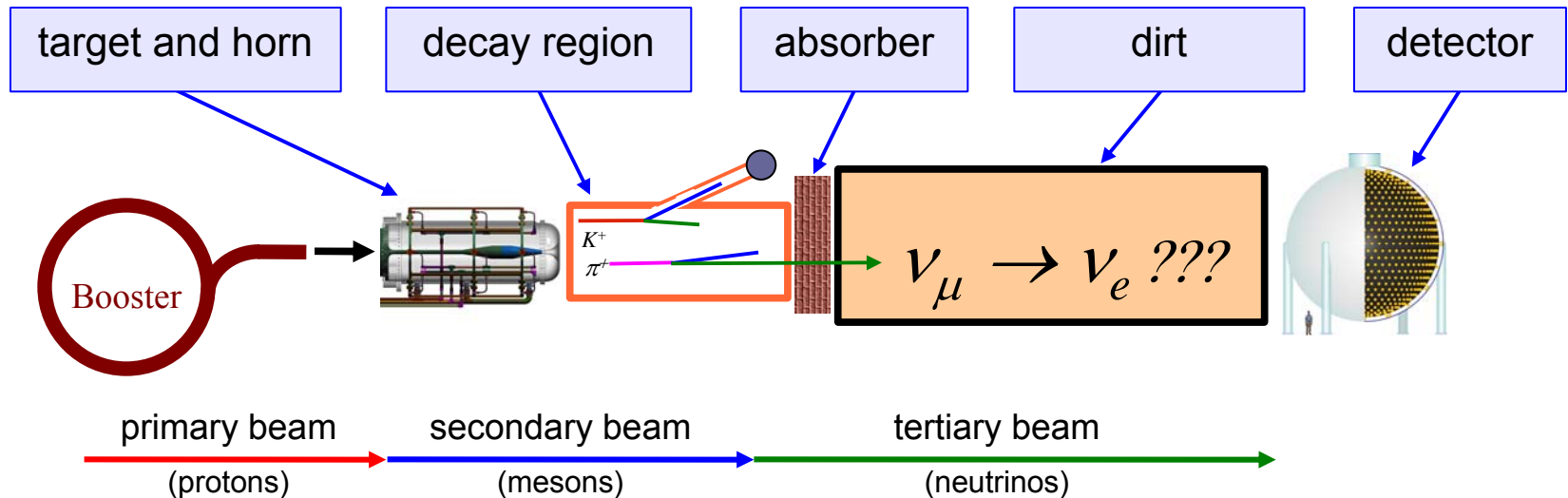


**Alabama, Bucknell, Cincinnati, Colorado,  
Columbia, Embry-Riddle, Fermilab, Florida,  
Illinois, Indiana, Los Alamos, LSU, MIT,  
Michigan, Princeton, Saint Mary's, Virginia  
Tech, Yale**

# MiniBooNE's Design Strategy

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

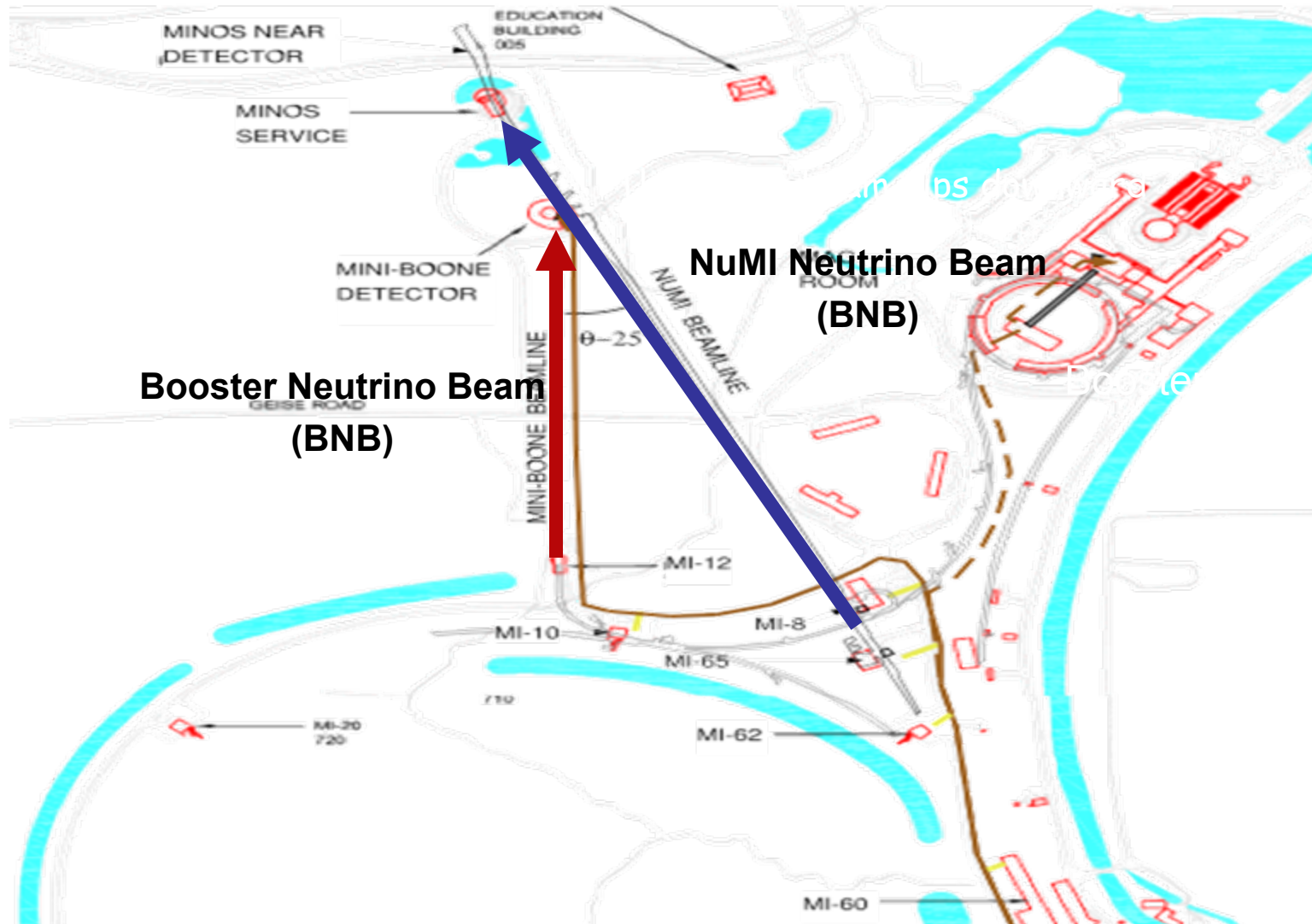
$$P(\nu_{\mu} \rightarrow \nu_e) = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$$



Order of magnitude  
higher energy (~500 MeV)  
than LSND (~30 MeV)

Order of magnitude  
longer baseline (~500 m)  
than LSND (~30 m)

# Neutrino beams at Fermilab



# $\nu_e$ Event Rate Predictions

$$\#Events = Flux \times Cross\text{-sections} \times Detector\ response$$

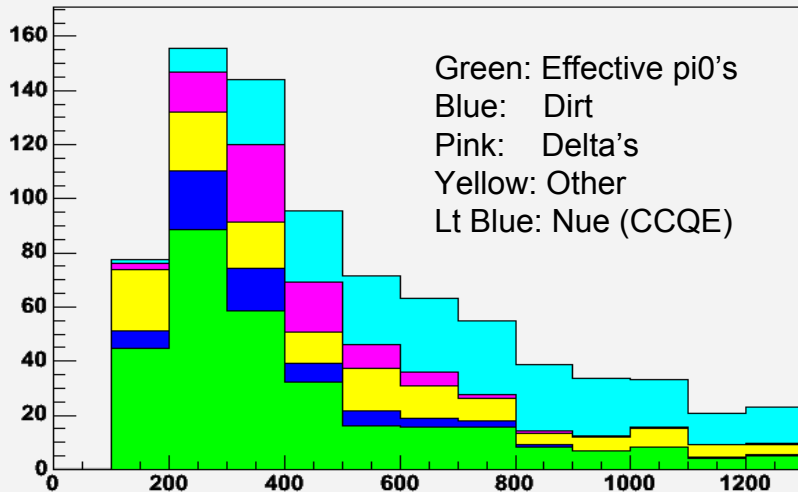
External measurements  
(HARP, etc)  
 $\nu_\mu$  rate constrained by  
neutrino data

External and MiniBooNE  
measurements  
 $-\pi^0$ , delta and dirt backgrounds  
constrained from data.

Detailed detector  
simulation checked  
with neutrino data and  
calibration sources.

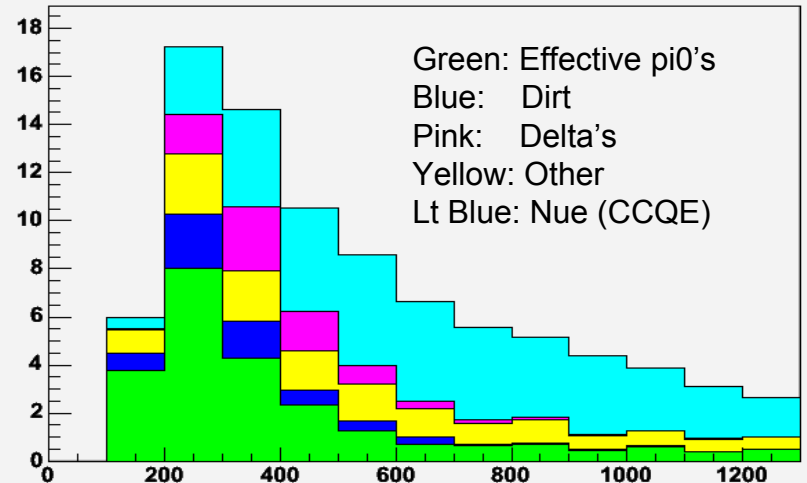
HEOneTrackEnueQE

## Neutrino

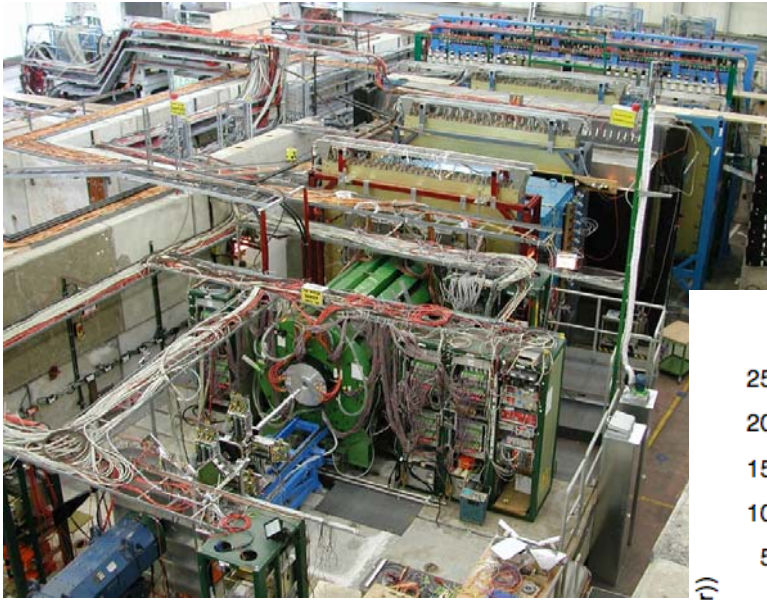


HEOneTrackEnueQE

## Antineutrino



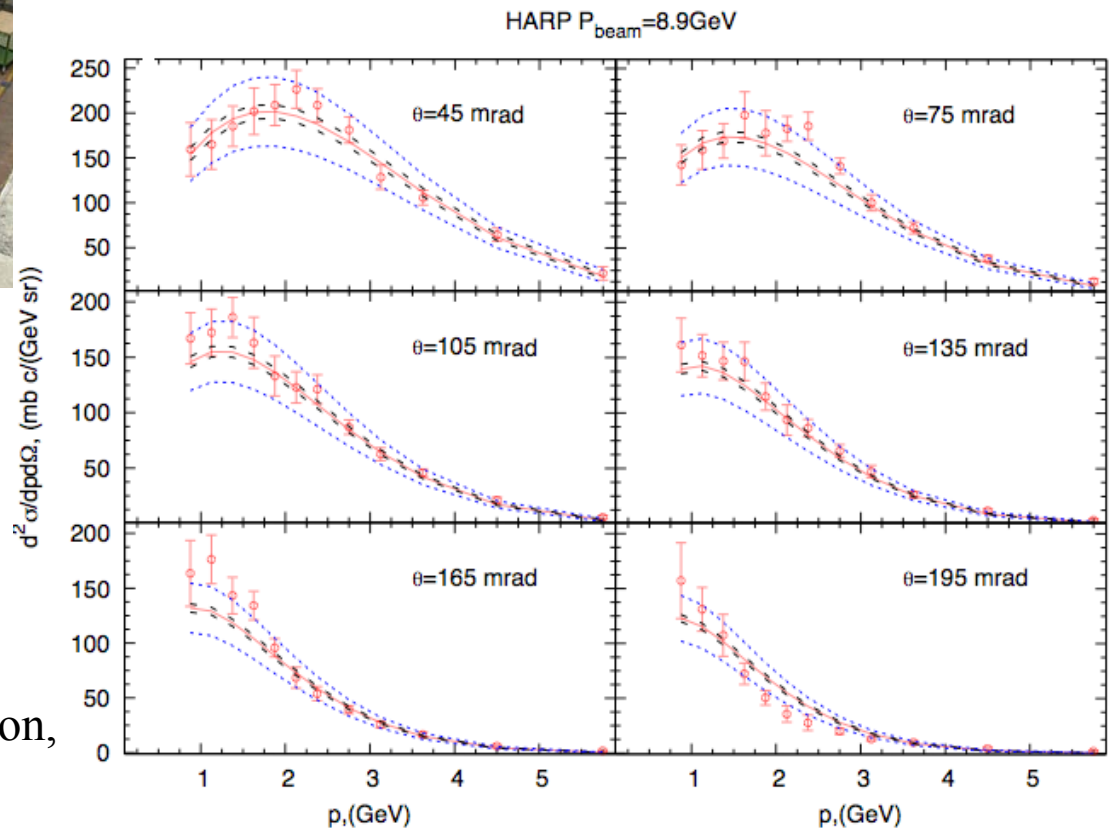
# Modeling Production of Secondary Pions



- HARP (CERN)
  - 5%  $\lambda$  Beryllium target
  - 8.9 GeV proton beam momentum
  - $\pi^+$  &  $\pi^-$

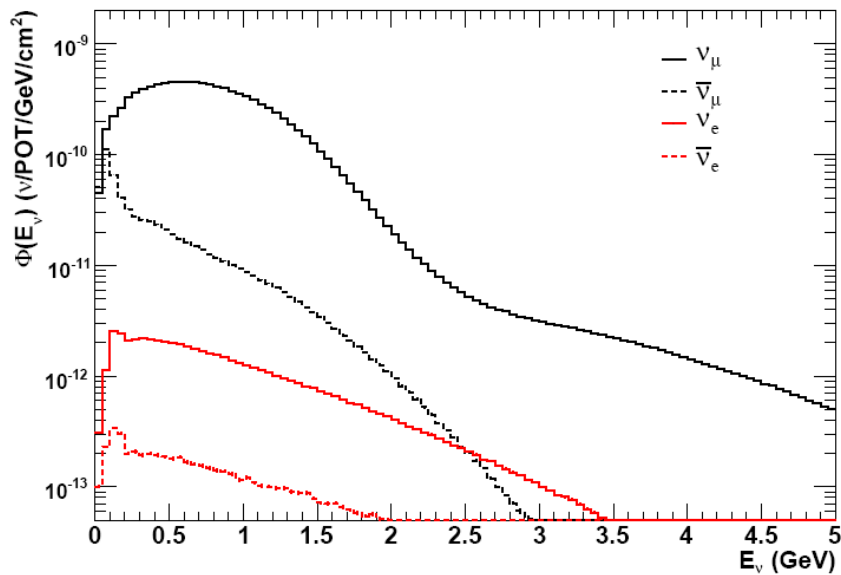
Data are fit to a Sanford-Wang parameterization.

HARP collaboration,  
hep-ex/0702024

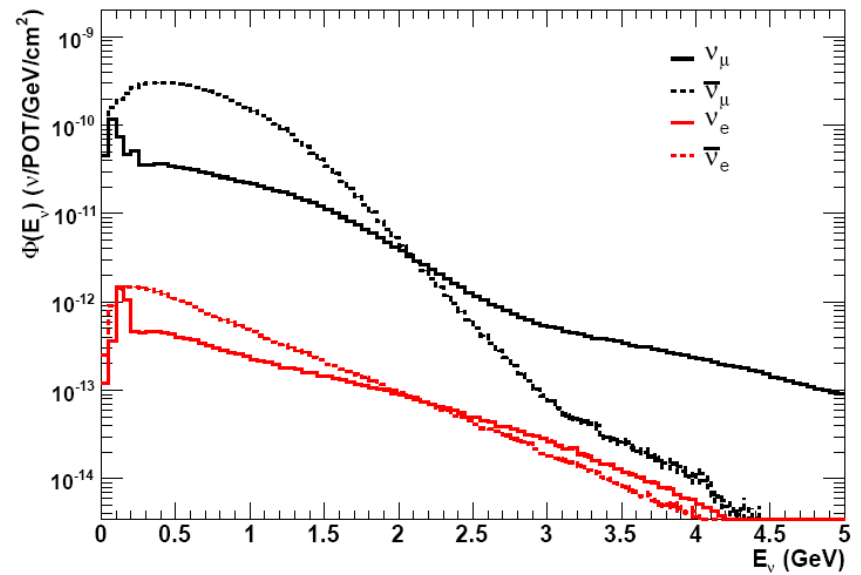


# Neutrino Flux from GEANT4 Simulation

## Neutrino-Mode Flux

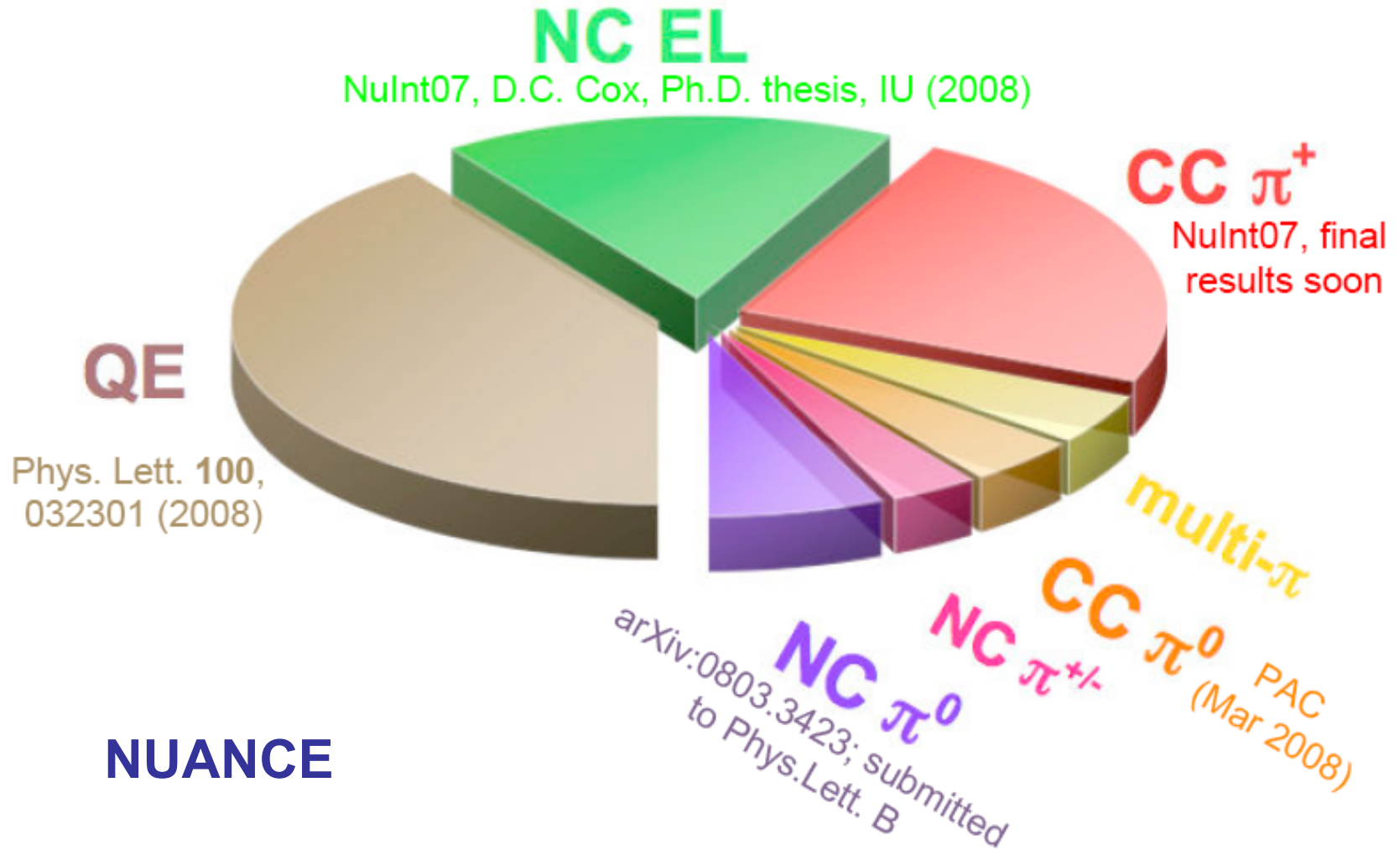


## Antineutrino-Mode Flux

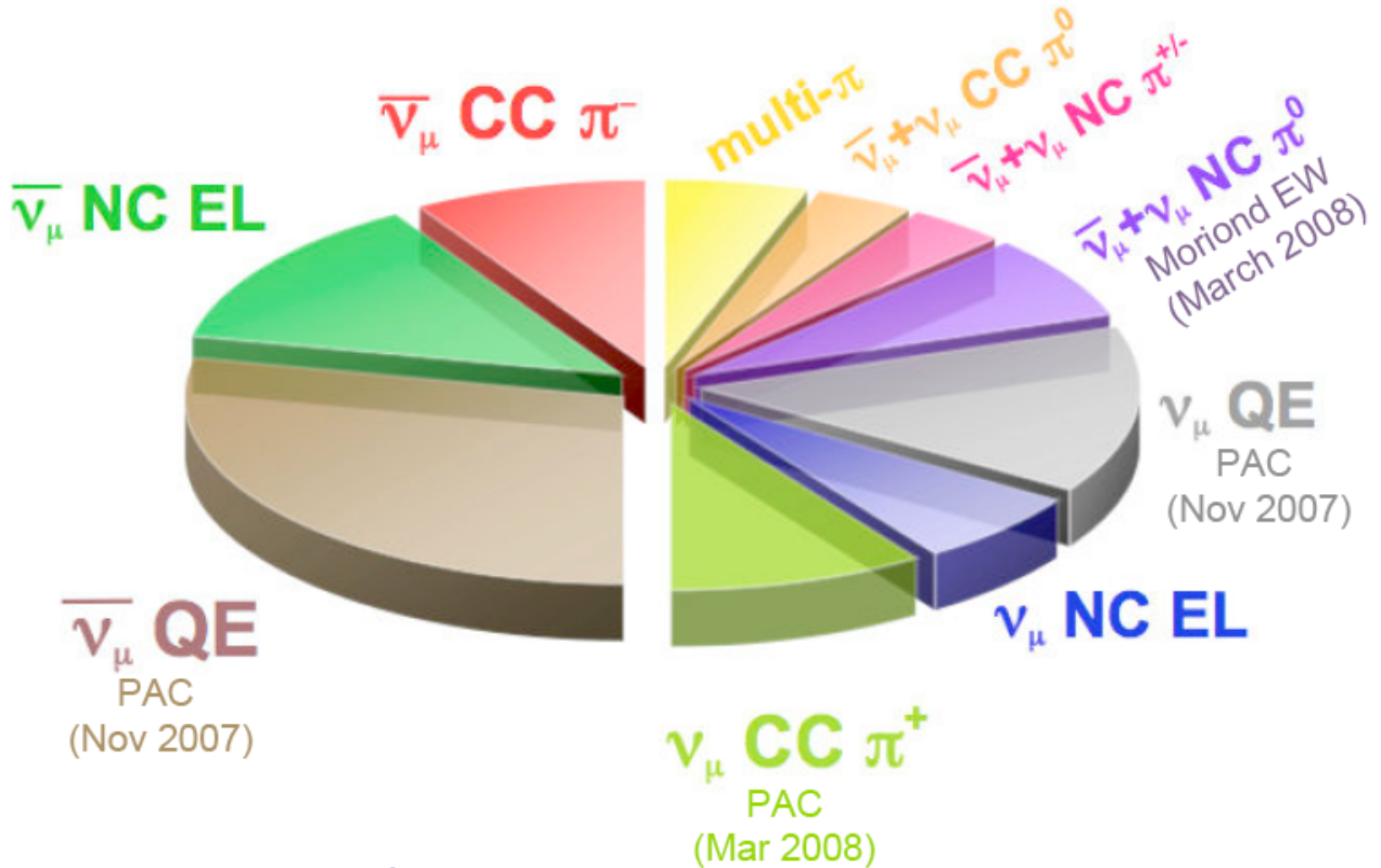


**Wrong-sign background is ~6% for Nu-Mode & ~18% for Antinu-Mode**  
**Intrinsic  $\nu_e$  background is ~0.5% for both Nu-Mode & Antinu-Mode**

# Neutrino Cross Sections



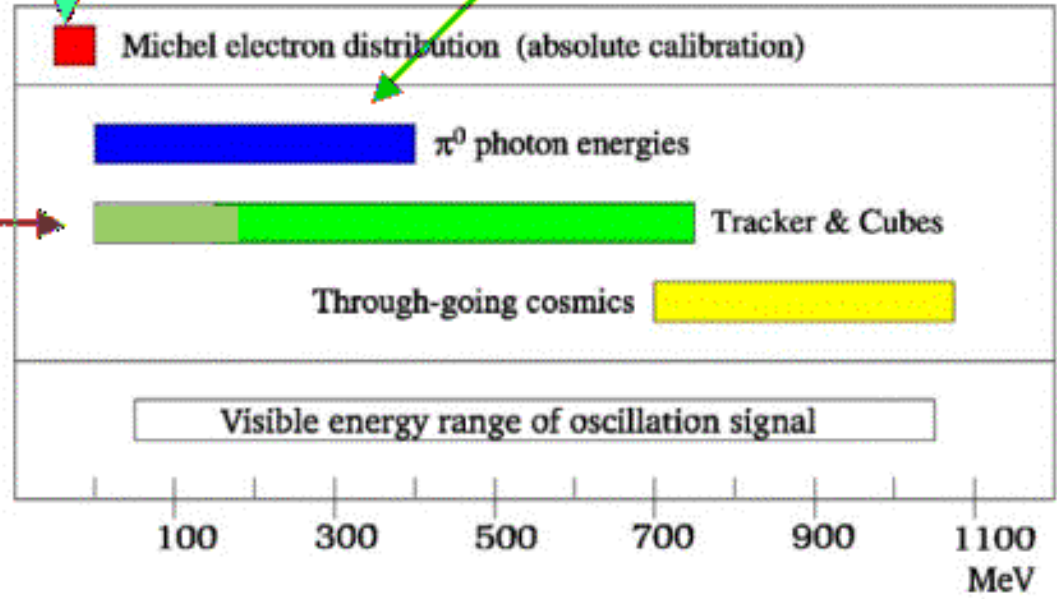
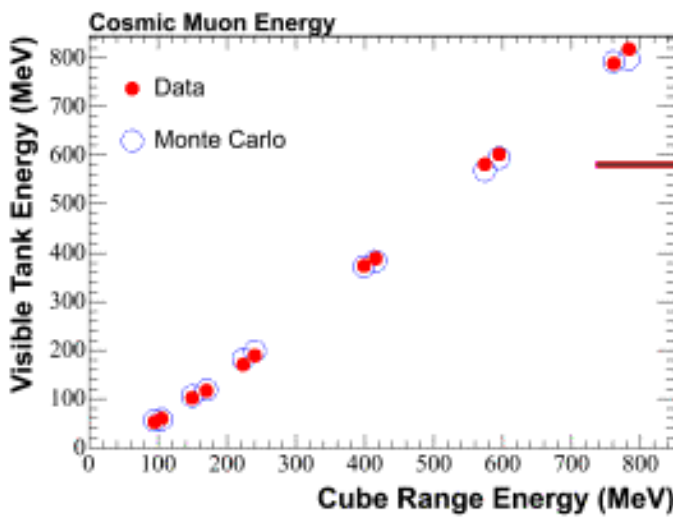
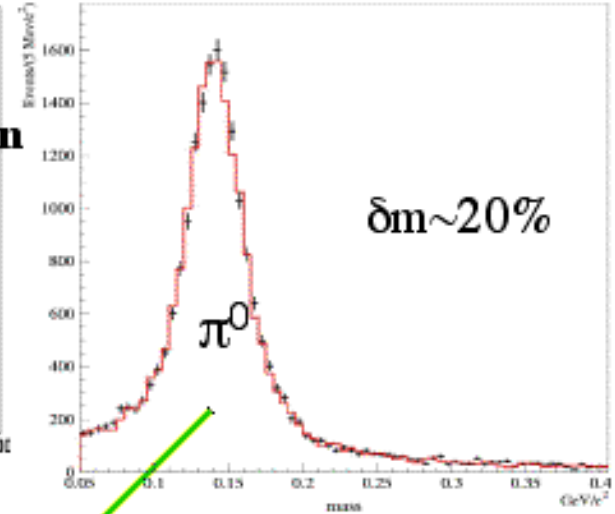
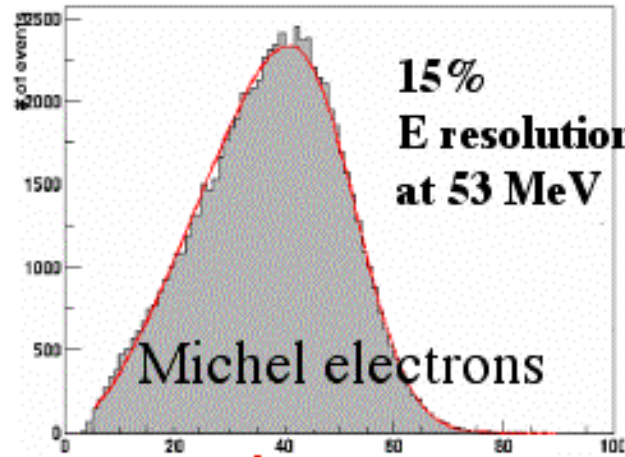
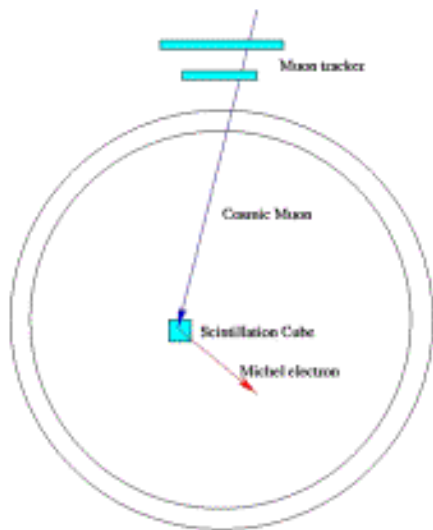
# Antineutrino Cross Sections



**NUANCE**

# Calibration Sources

## Tracker system



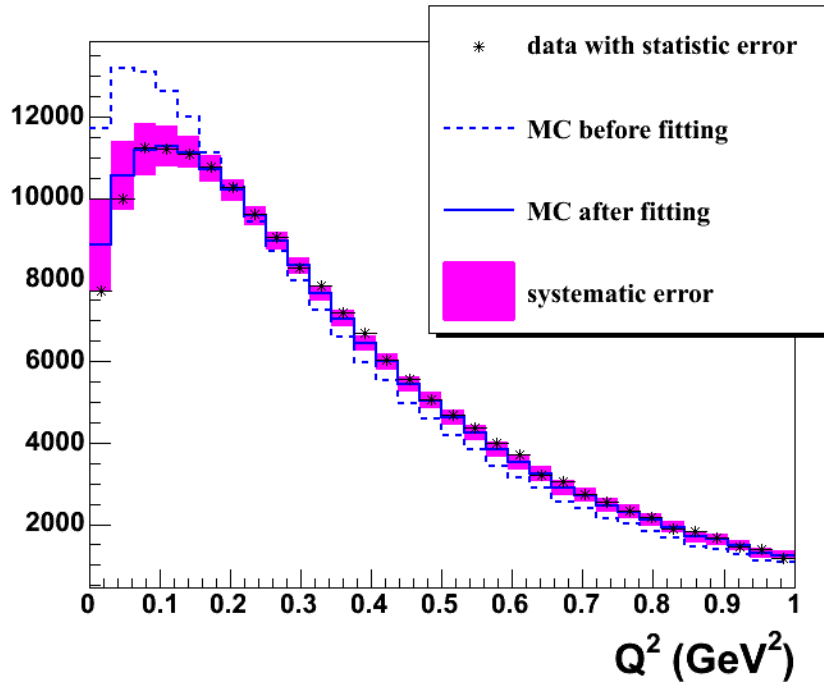
## *Neutrino Backgrounds*

<b>Background</b>	<b>200-300 MeV</b>	<b>300-475 MeV</b>	<b>475-1250 MeV</b>
$\nu_\mu$ CCQE	9.0	17.4	11.7
$\nu_\mu e \rightarrow \nu_\mu e$	6.1	4.3	6.4
NC $\pi^0$	103.5	77.8	71.2
$\Delta \rightarrow N\gamma$	19.5	47.5	19.4
External	11.5	12.3	11.5
Other	18.4	7.3	16.8
$\nu_e$ from $\mu$	13.6	44.5	153.5
$\nu_e$ from $K^+$	3.6	13.8	81.9
$\nu_e$ from $K_L$	1.6	3.4	13.5
<b>Total Bkgd</b>	<b>186.8+-26.0</b>	<b>228.3+-24.5</b>	<b>385.9+-35.7</b>

# $\nu_\mu$ CCQE Scattering

A. A. Aguilar-Arevalo et al., Phys. Rev. Lett. 100, 032301 (2008)

186000 muon neutrino events



From  $Q^2$  fits to MB  $\nu_\mu$  CCQE data:

$M_A^{\text{eff}}$  -- effective axial mass

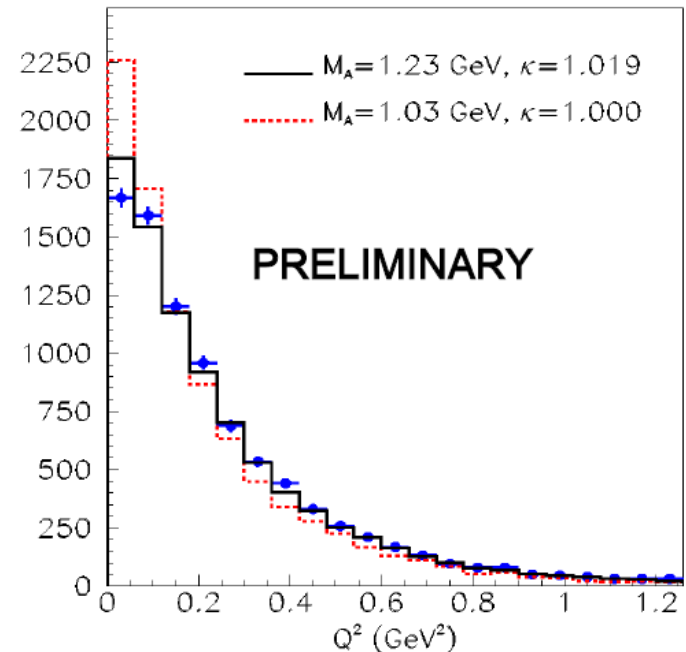
$\kappa$  -- Pauli Blocking parameter

From electron scattering data:

$E_b$  -- binding energy

$p_f$  -- Fermi momentum

14000 anti-muon neutrinos



Fermi Gas Model describes CCQE

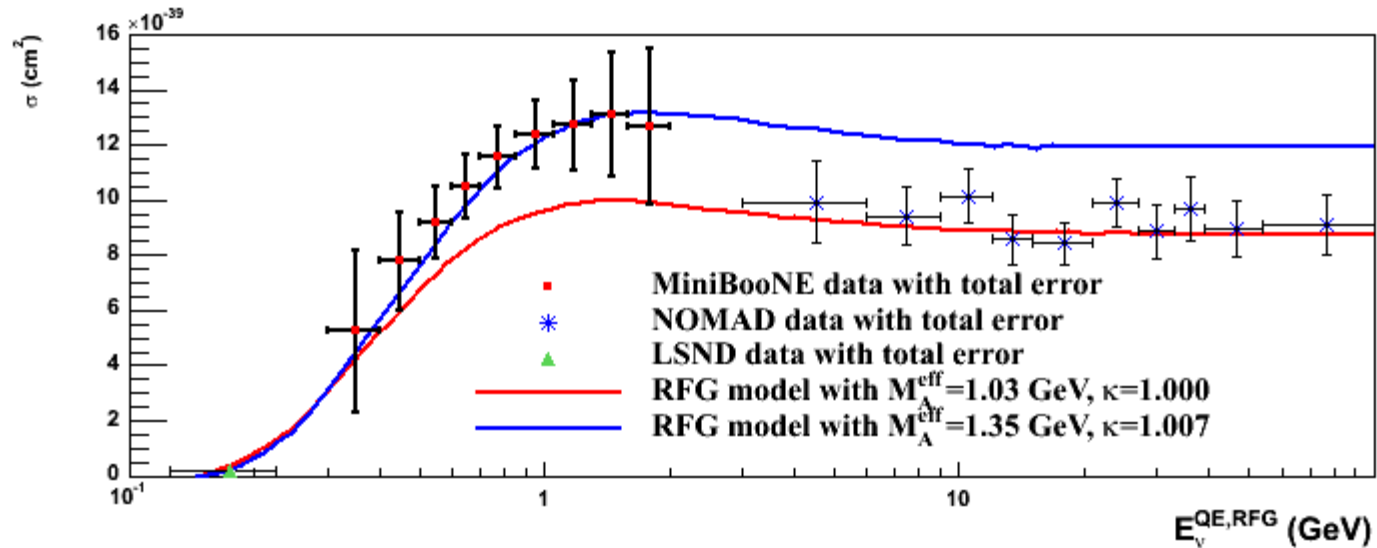
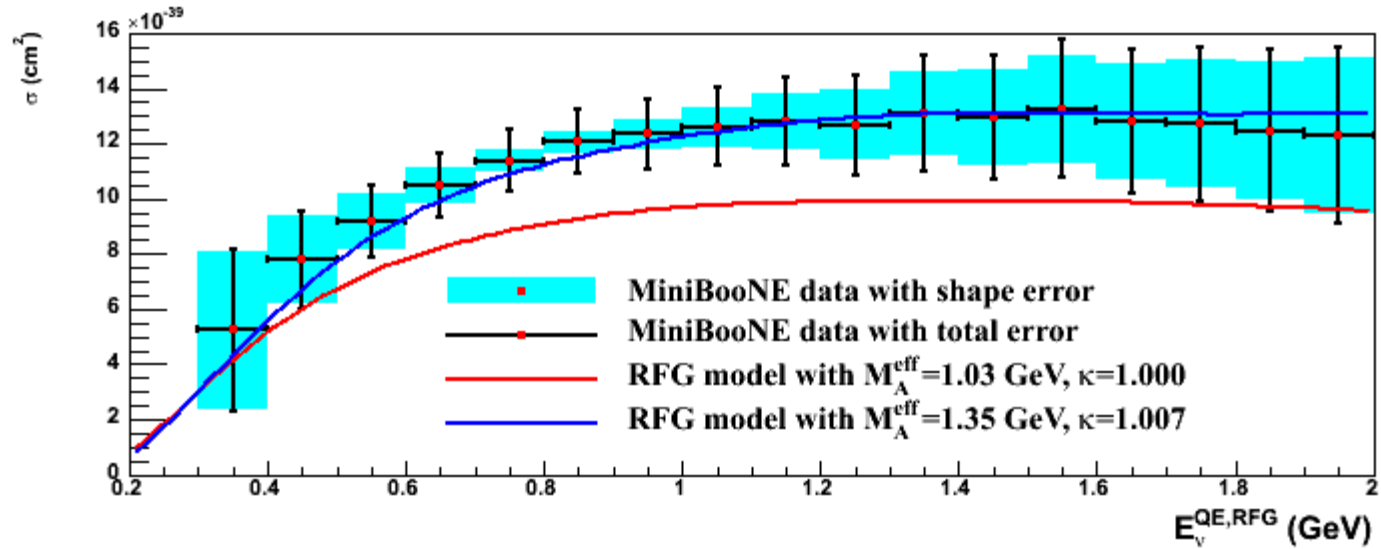
$\nu_\mu$  data well

$M_A = 1.23 \pm 0.20$  GeV

$\kappa = 1.019 \pm 0.011$

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

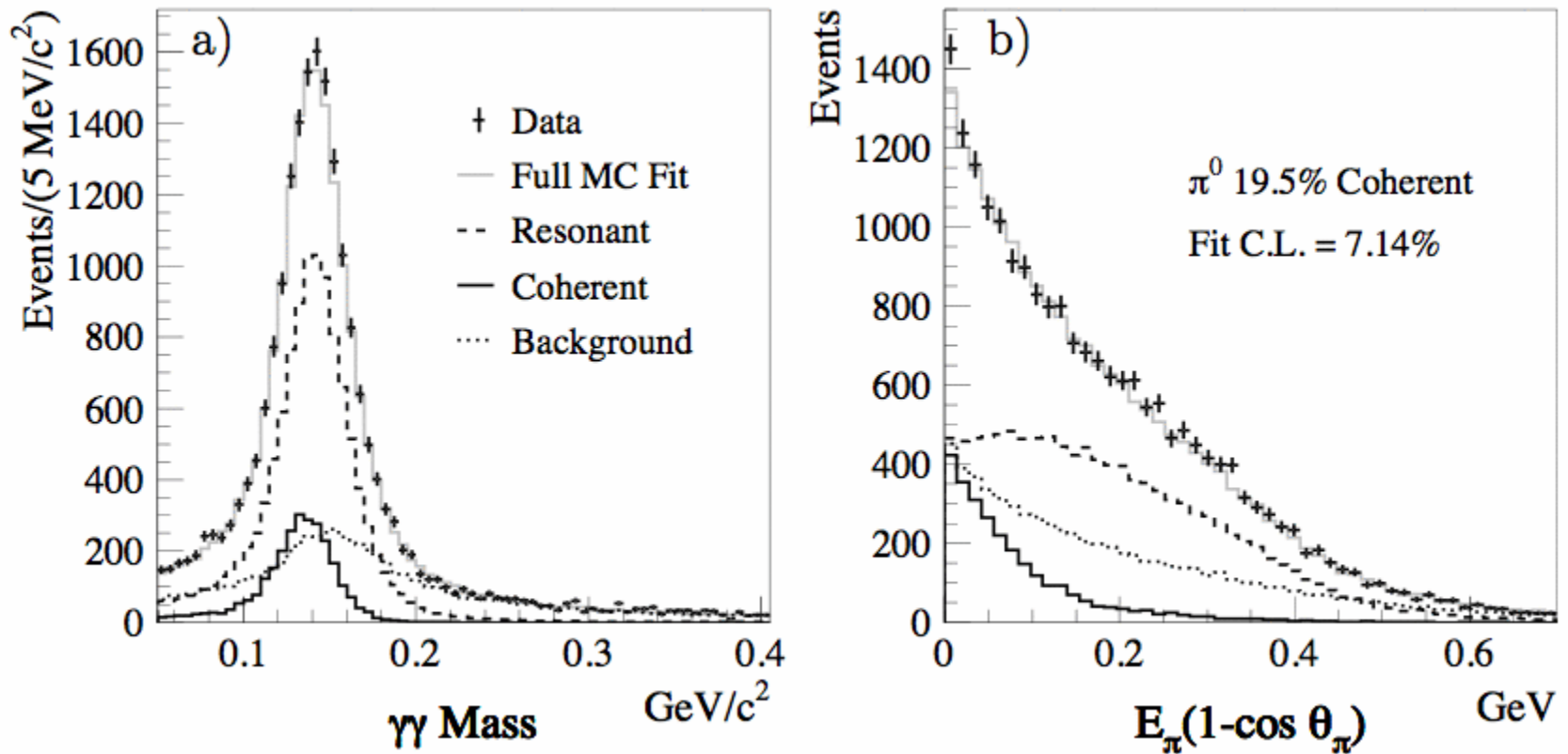
# $\nu_\mu$ CCQE Scattering



# *NC $\pi^0$ Scattering*

A. A. Aguilar-Arevalo et al., Phys. Lett. B 664, 41 (2008)

**coherent fraction=19.5 $\pm$ 1.1 $\pm$ 2.5%**



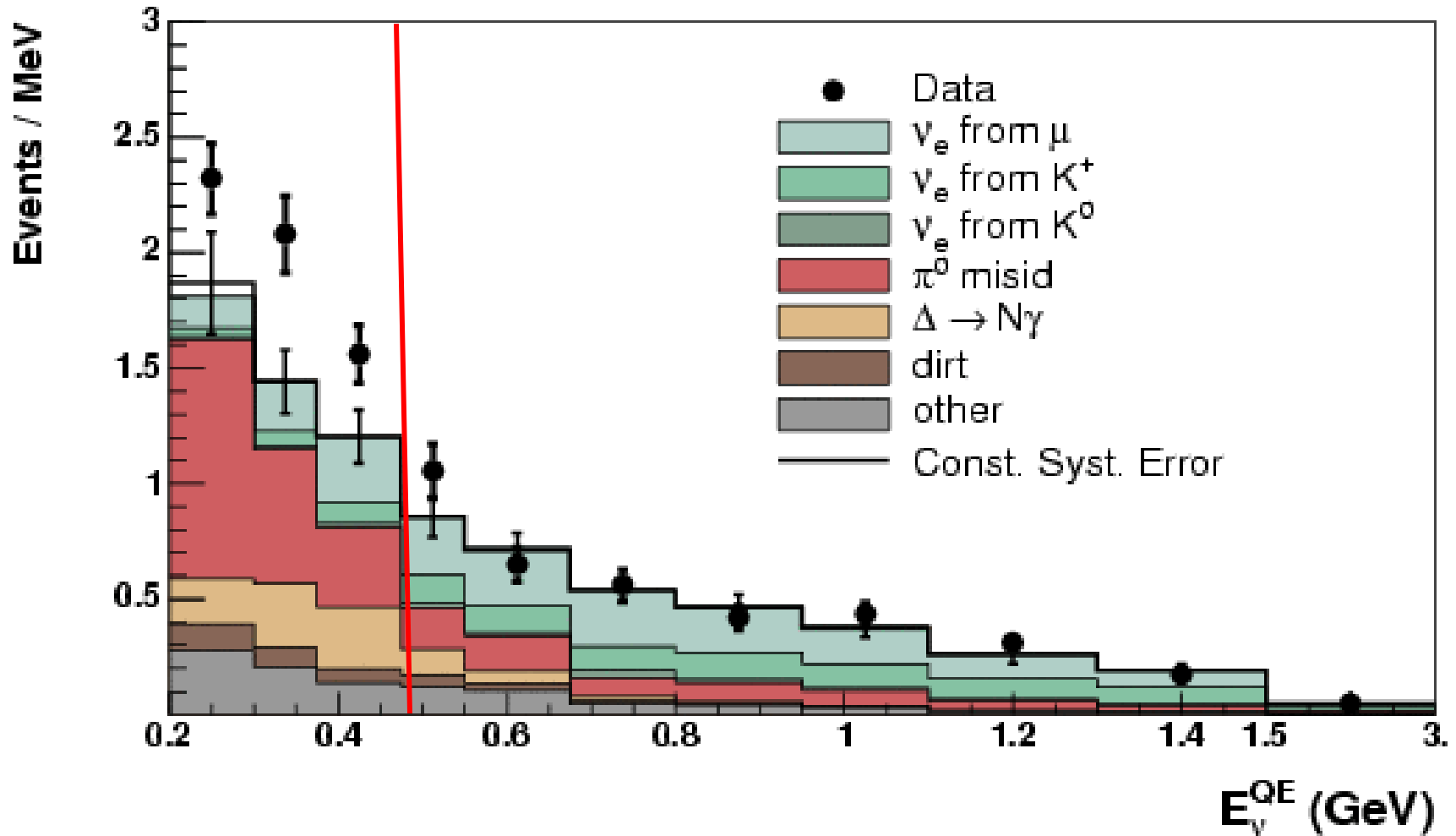
# MiniBooNE Neutrino Oscillation Results

- Results based on  $6.46 \times 10^{20}$  POT
- Approximately  $0.7 \times 10^6$  neutrino events recorded with tank hits  $>200$  & veto hits  $<6$
- Approximately  $1.5 \times 10^5$   $\nu_\mu$  CCQE events
- Approximately 375  $\nu_e$  CCQE events (intrinsic bkgd)
- Expect  $\sim 200$   $\nu_e$  CCQE events (LSND signal)

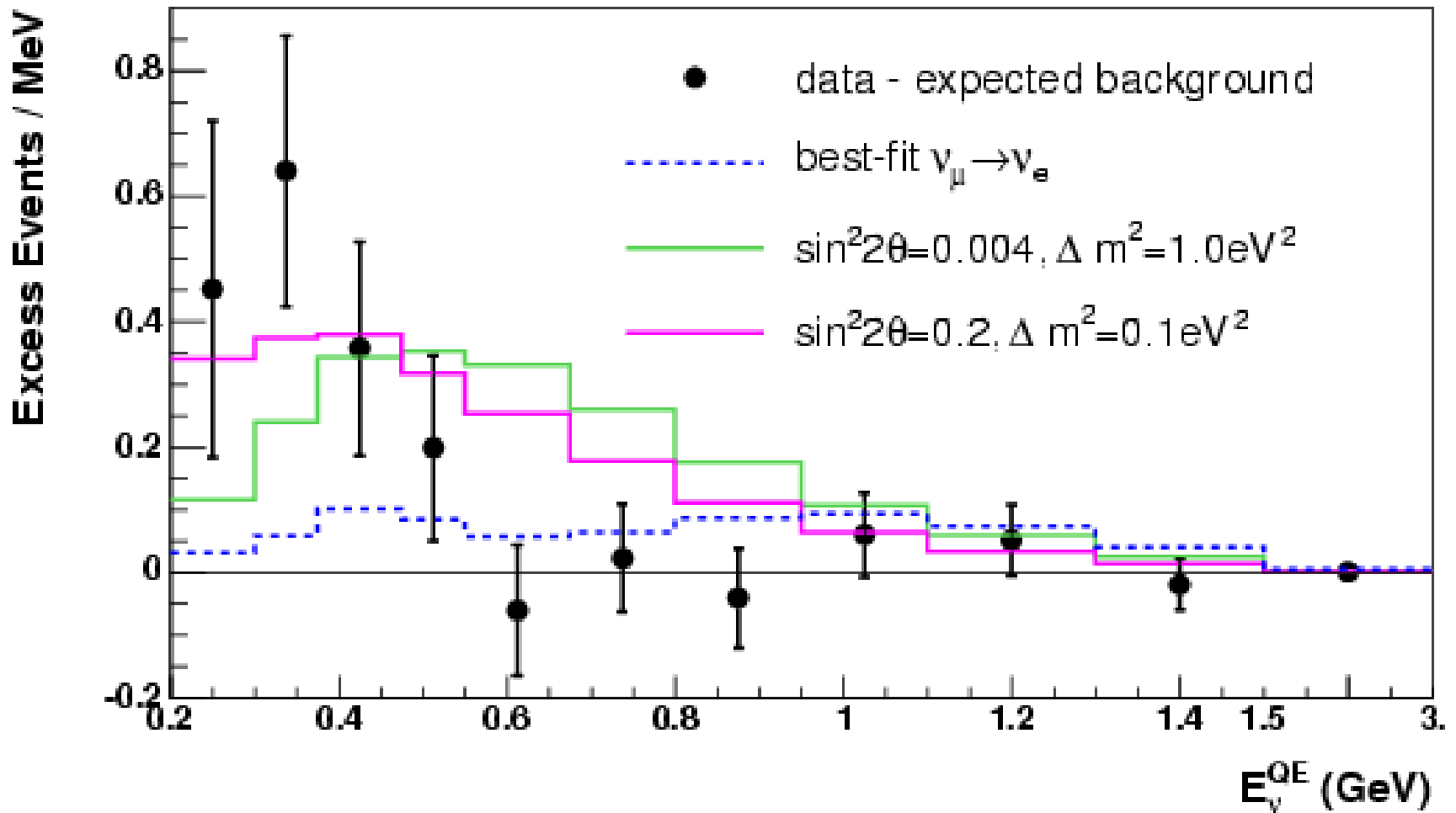
# *MiniBooNE observes a low-energy excess!*

A. A. Aguilar-Arevalo et al., Phys. Rev. Lett. 98, 231801 (2007);

A. A. Aguilar-Arevalo et al., arXiv: 0812.2243, submitted to Phys. Rev. Lett.



# Low-energy excess vs $E_\nu^{QE}$

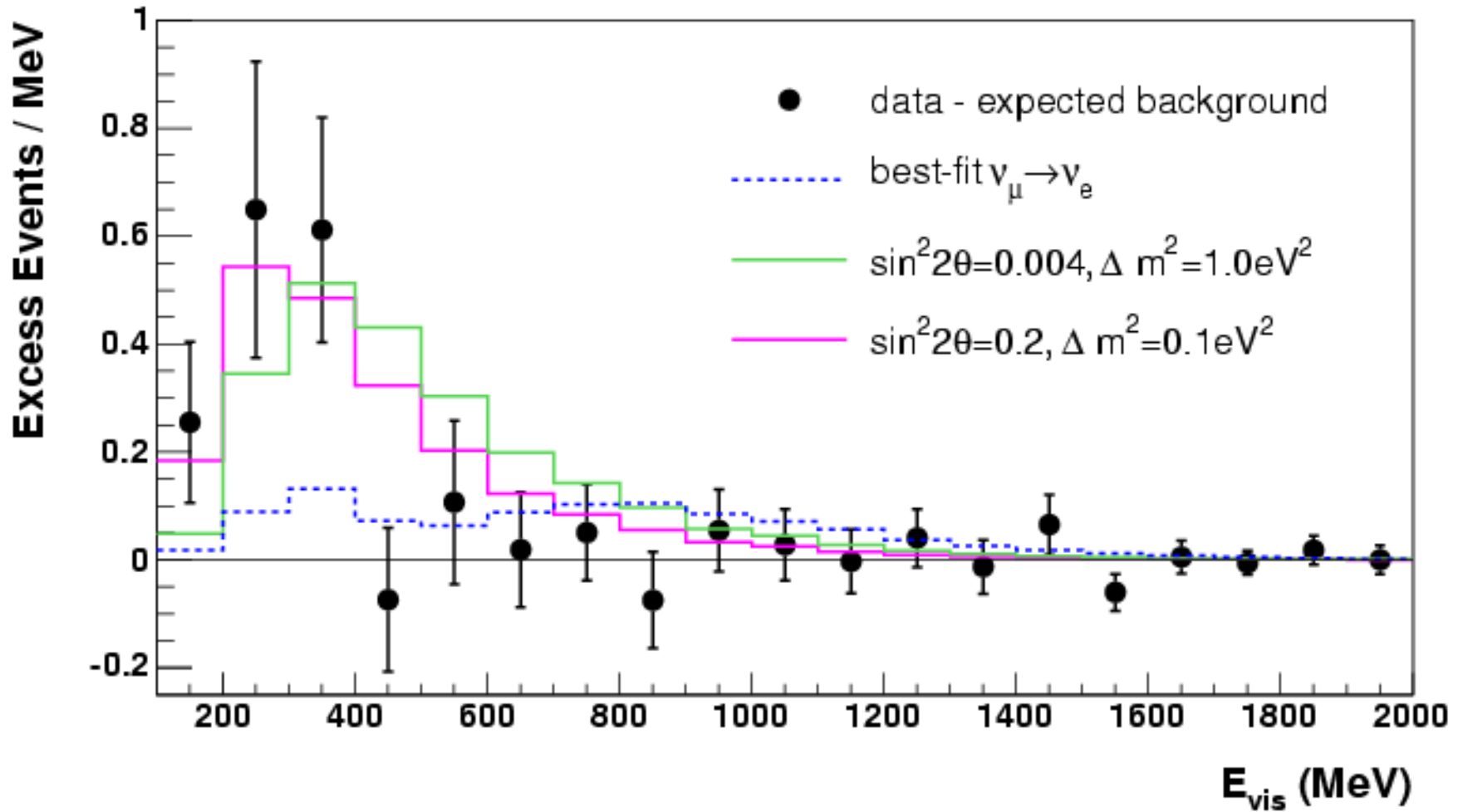


## *Number of Excess Events*

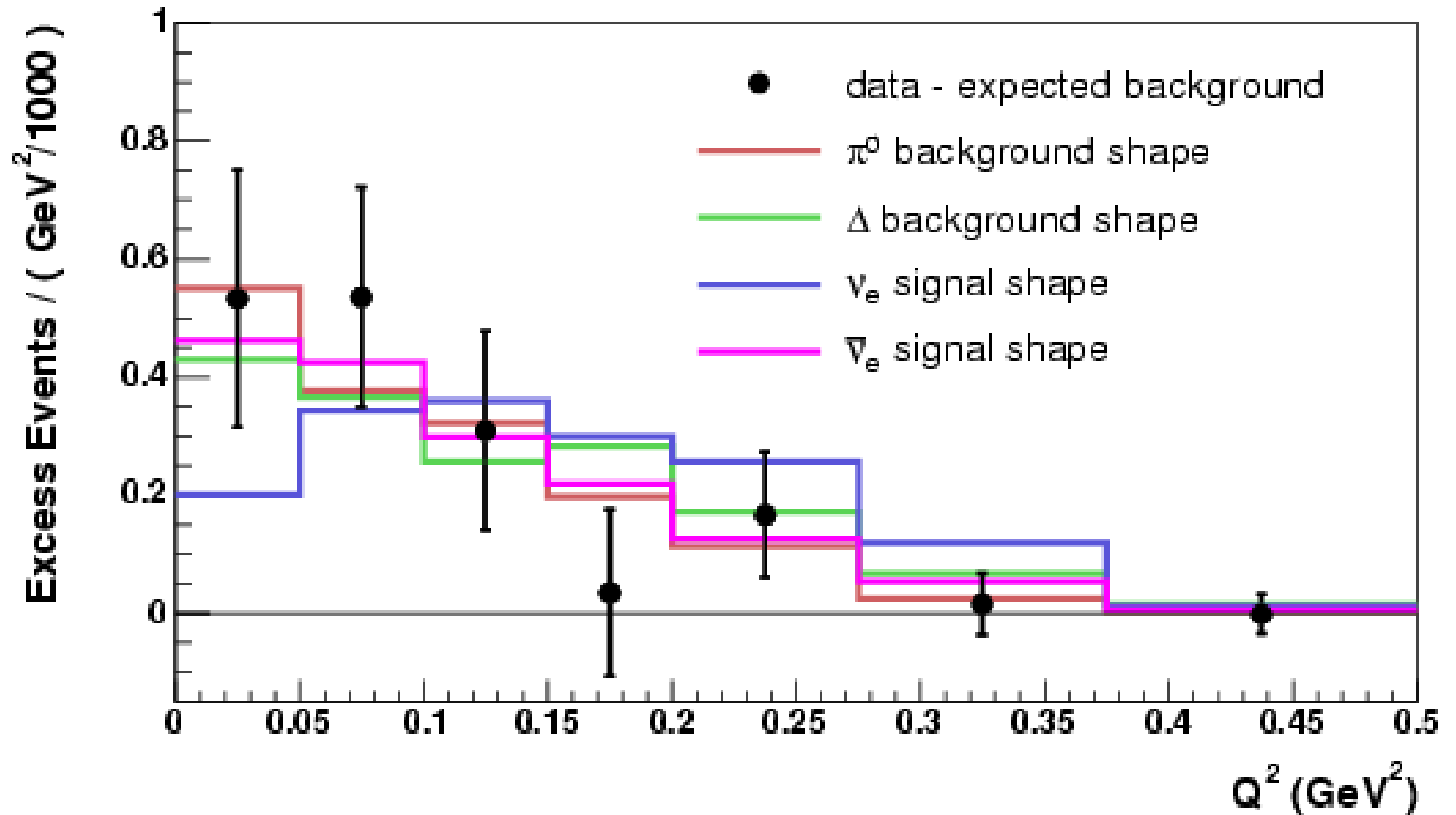
<b>Energy (MeV)</b>	<b>Data</b>	<b>Background</b>	<b>Excess</b>	<b>#<math>\sigma_{\text{tot}}</math></b>	<b>(#<math>\sigma_{\text{stat}}</math>)</b>
200-300	232	186.8 $\pm$ 26.0	45.2 $\pm$ 13.7 $\pm$ 22.1	1.7	(3.3)
300-475	312	228.3 $\pm$ 24.5	83.7 $\pm$ 15.1 $\pm$ 19.3	3.4	(5.5)
200-475	544	415.2 $\pm$ 43.4	128.8 $\pm$ 20.4 $\pm$ 38.3	3.0	(6.3)
475-1250	408	385.9 $\pm$ 35.7	22.1 $\pm$ 19.6 $\pm$ 29.8	0.6	(1.1)
200-1250	952	801.0 $\pm$ 58.1	151.0 $\pm$ 28.3 $\pm$ 50.7	2.6	(5.3)

# *Low-energy excess vs $E_{vis}$*

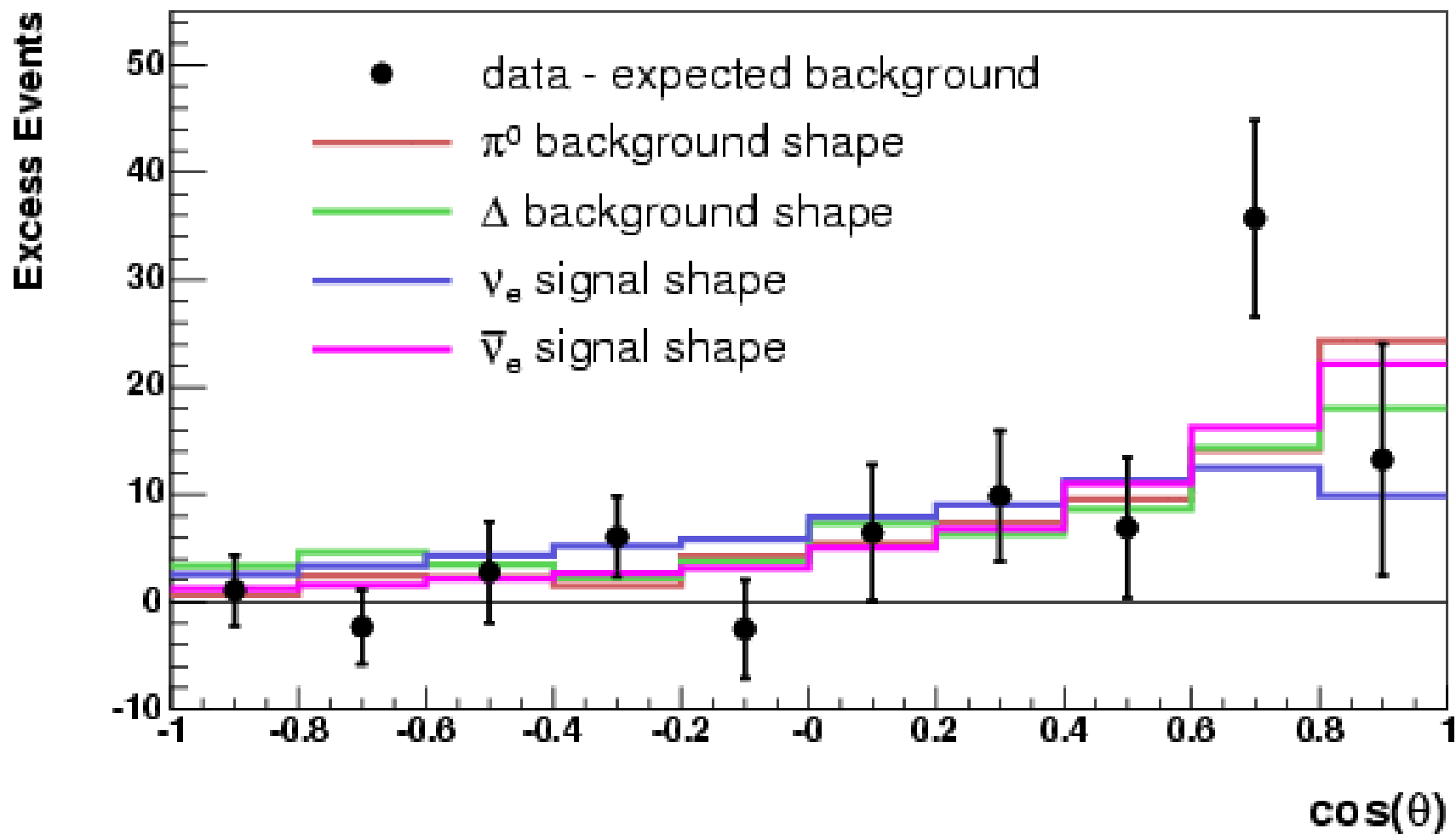
With  $E_{\nu}^{QE}$  Best Fit (3.14 eV<sup>2</sup>, 0.0017)



# *Low-energy excess vs $Q^2$*



# *Low-energy excess vs $\cos\theta$*

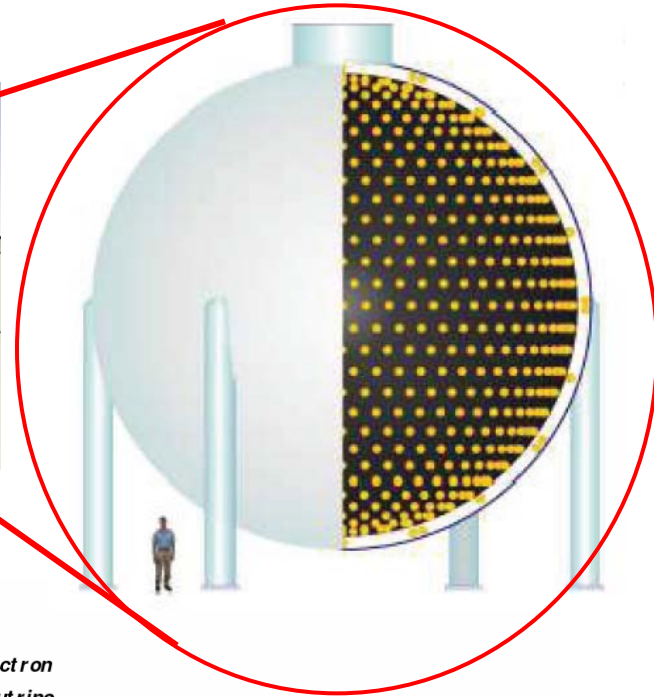
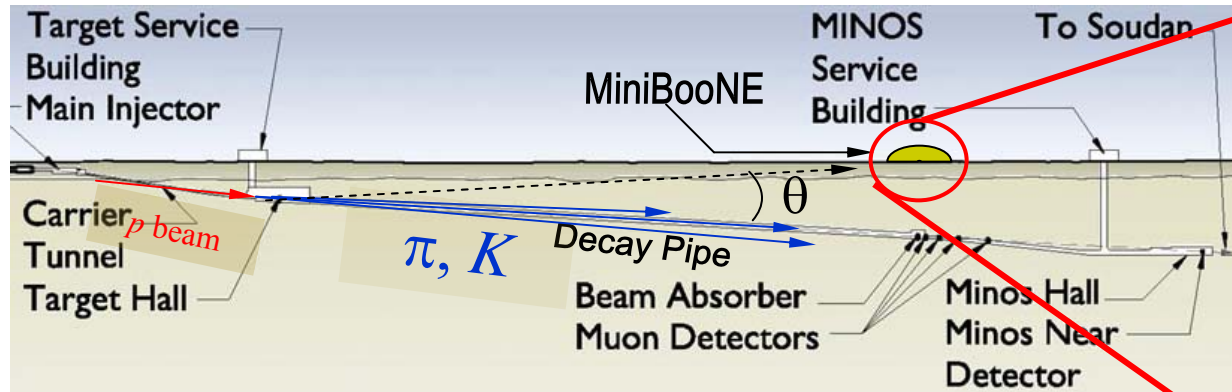


## *$\chi^2$ Values from Data/MC Comparisons*

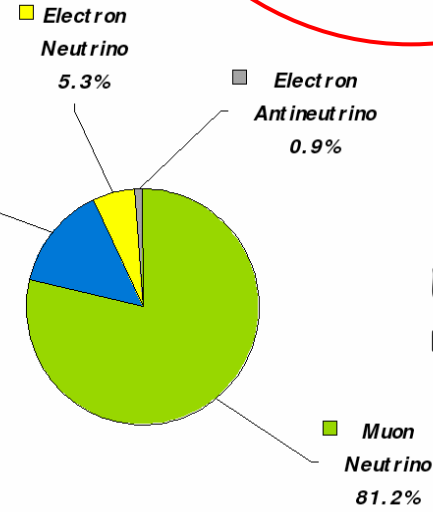
<b>Process</b>	<b><math>\chi^2(\cos\theta)/9</math> DF</b>	<b><math>\chi^2(Q^2)/6</math> DF</b>	<b>Factor Inc.*</b>
<b>NC <math>\pi^0</math></b>	<b>13.46</b>	<b>2.18</b>	<b>2.0</b>
<b><math>\Delta \rightarrow N\gamma</math></b>	<b>16.85</b>	<b>4.46</b>	<b>2.7</b>
<b><math>\nu_e C \rightarrow e^- X</math>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

**\* Any single bkgd would have to increase by  $>5\sigma$ !**

# Events from NuMI Directed at MiniBooNE



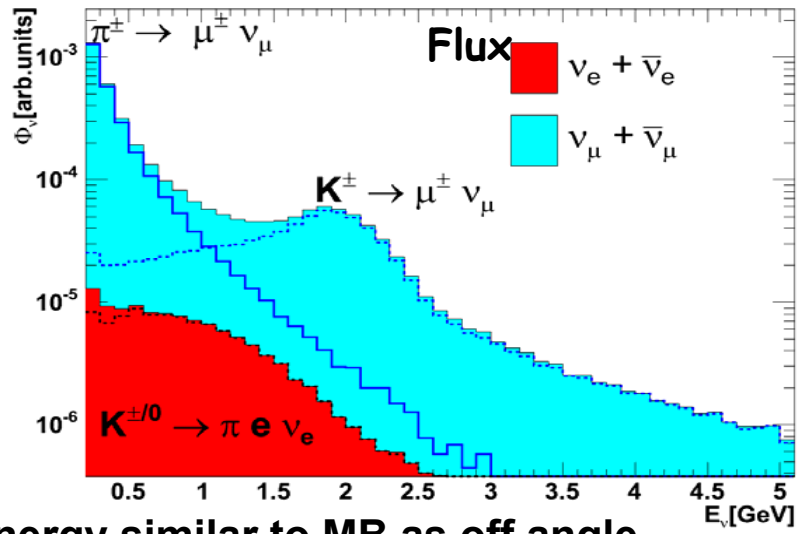
MiniBooNE detector is 745 meters downstream of NuMI target.  
 MiniBooNE detector is 110 mrad off-axis from the target along NuMI decay pipe.



MB ~0.5%

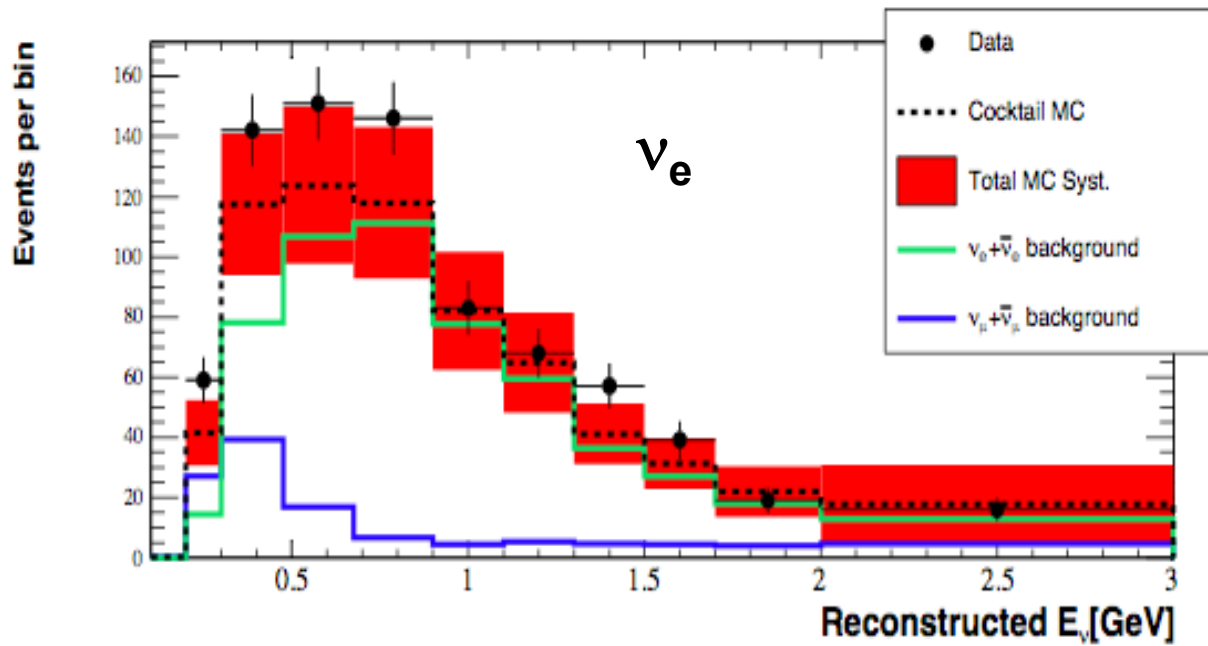
NuMI event composition at MB  
 $\nu_\mu$ -81%,  $\nu_e$ -5%,  $\bar{\nu}_\mu$ -13%,  $\bar{\nu}_e$ -1%

NuMI  $\nu$  Flux at MiniBooNE

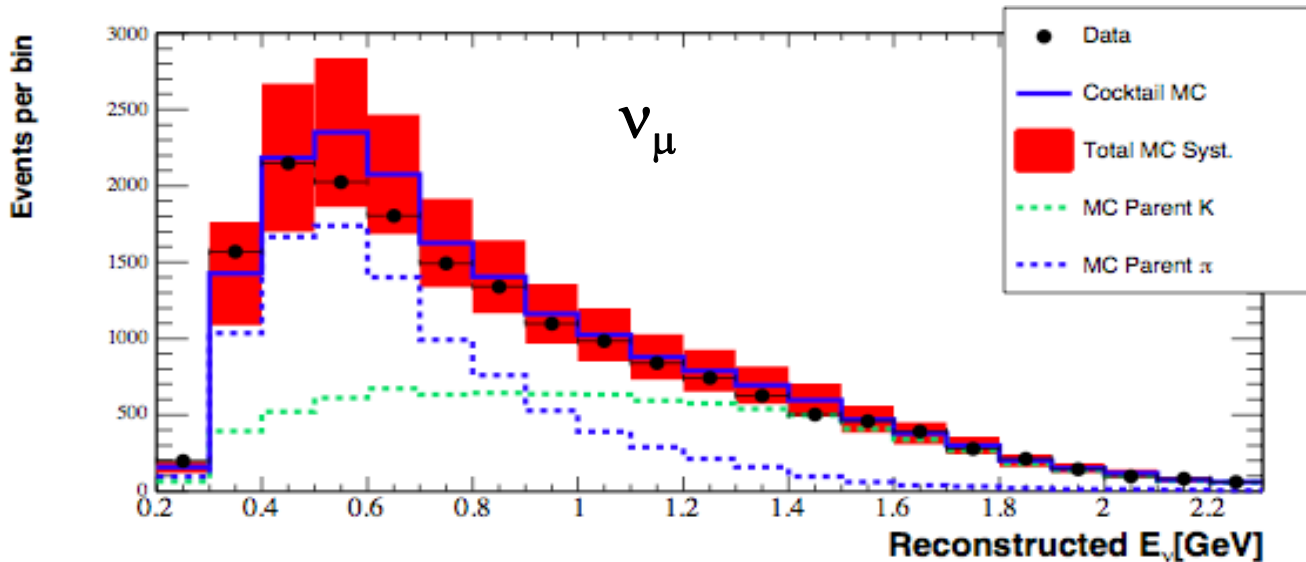


Energy similar to MB as off angle

# *Excess Also Observed in NuMI Data!*

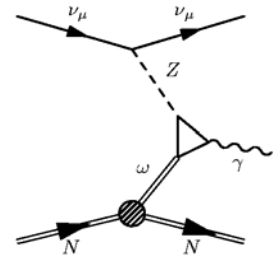


**Systematic errors  
will be reduced  
plus 3x as much  
data. Results soon!**



# *Possible Explanations for the Low-Energy Excess*

- **Anomaly Mediated Neutrino-Photon Interactions at Finite Baryon Density:** Jeffrey A. Harvey, Christopher T. Hill, & Richard J. Hill, arXiv:0708.1281
- **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.
- **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
- **New Gauge Boson with Sterile Neutrinos:** Ann E. Nelson & Jonathan Walsh, arXiv:0711.1363
- **Heavy Sterile Neutrino Decay:** S.N. Gninenko, arXiv:0902.3802
- **VSBL Electron Neutrino Disappearance:** Carlo Giunti & Marco Laveder, arXiv: 0902:1992
- **Soft Decoherence:** Yasaman Farzan, Thomas Schwetz, & Alexei Smirnov, arXiv: 0805.2098



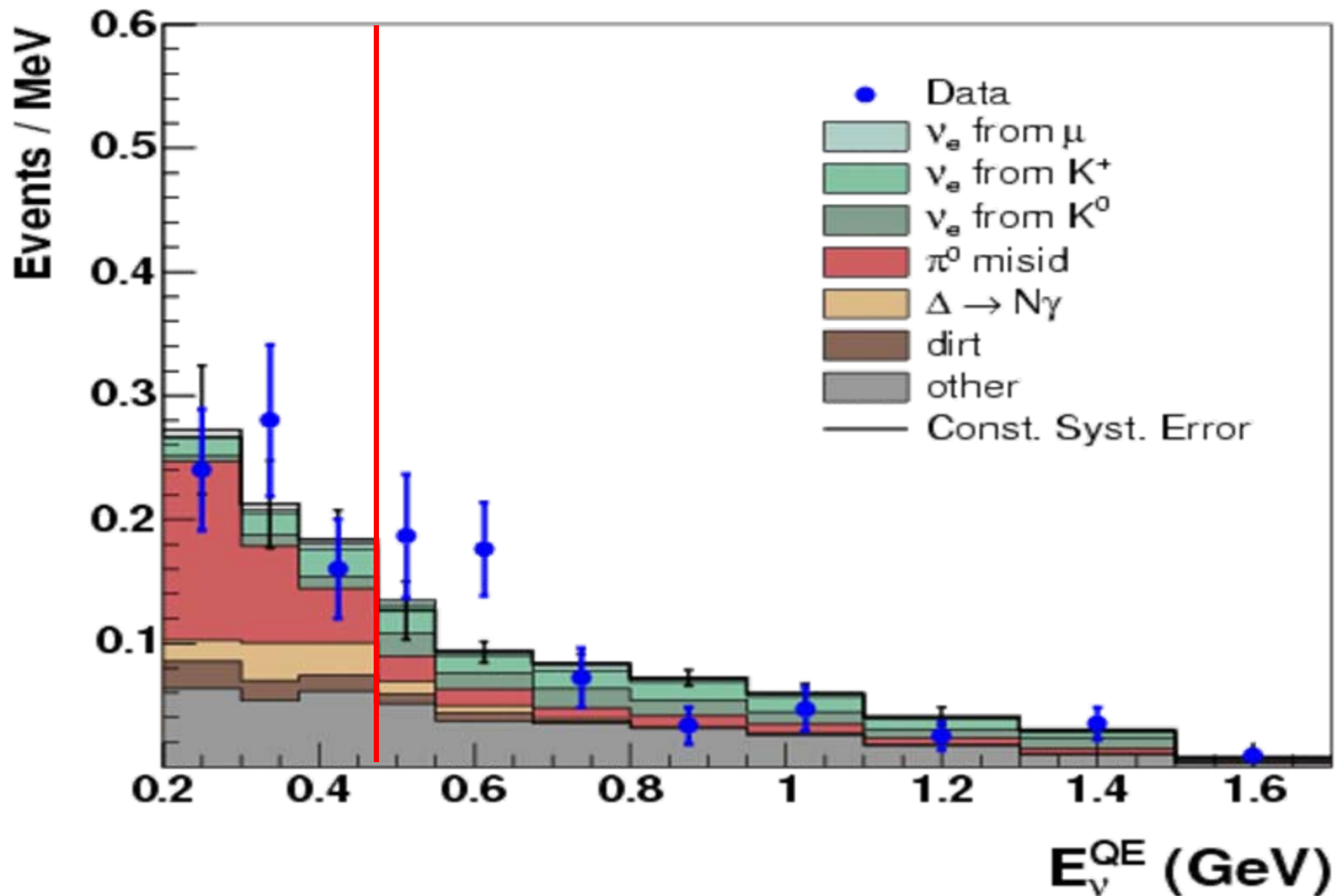
**Other data sets (NuMI, antineutrino, SciBooNE) may provide an explanation!**

# MiniBooNE Antineutrino Oscillation Results

- The antineutrino data sample is especially important because it provides direct tests of LSND and the low-energy excess, although statistics are **low** at present.
- The backgrounds at low-energy are almost the same for the neutrino and antineutrino data samples.
- First antineutrino results based on  $3.386E20$  POT. (Total collected so far  $\sim 5E20$  POT.)
- Approximately  $0.1 \times 10^6$  antineutrino events recorded. (An order of magnitude fewer antineutrino events than neutrino events.)
- Antineutrino analysis is the same as the neutrino analysis.

# *Antineutrino Results (3.39e20POT)*

$\chi^2(\text{dof}) = 24.5(19)$



# *Implications for Low-E Excess*

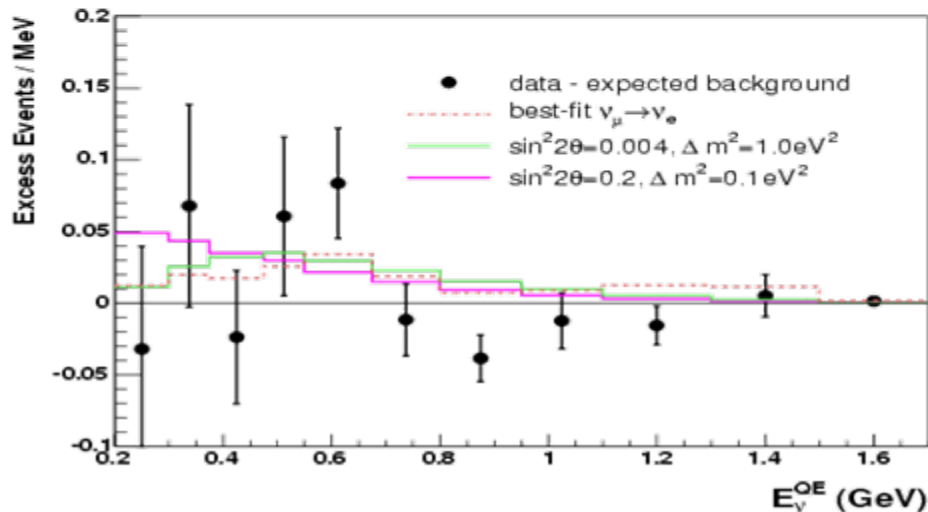
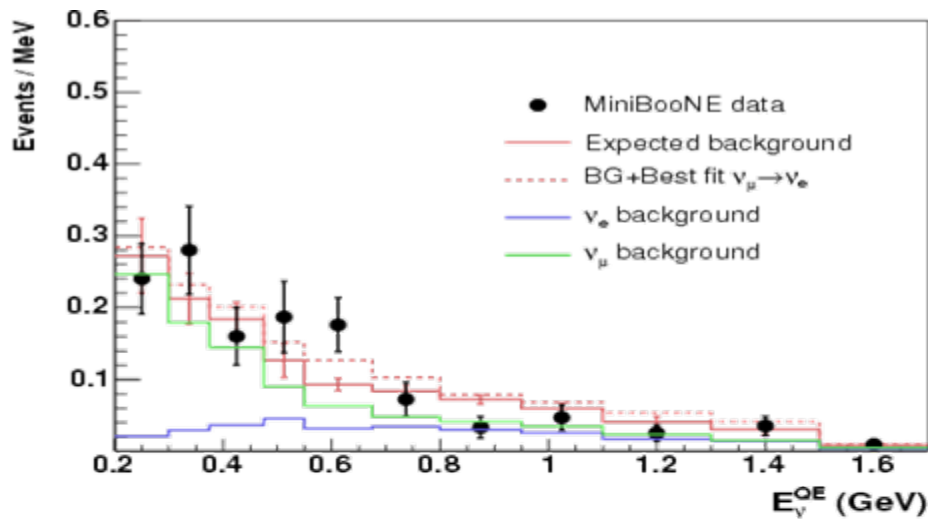
## *( $E < 475$ MeV)*

	<i>Antineutrino</i>	<i>Neutrino</i>
<i>Data</i>	<b>61</b>	<b>544</b>
<i>MC <math>\pm</math> sys+stat (constr.)</i>	<b><math>61.5 \pm 7.8 \pm 8.7</math></b>	<b><math>415.2 \pm 20.4 \pm 38.3</math></b>
<i>Excess (<math>\sigma</math>)</i>	<b><math>-0.5 \pm 7.8 \pm 8.7</math> (-0.04<math>\sigma</math>)</b>	<b><math>128.8 \pm 20.4 \pm 38.3</math> (3.0<math>\sigma</math>)</b>

<b>Hypothesis</b>	<b>Stat Only</b>	<b>Cor. Syst</b>	<b>Uncor. Syst</b>	<b>#<math>\bar{\nu}</math> Expec.</b>
Same $\nu, \bar{\nu}$ NC	0.1%	0.1%	6.7%	37.2
NC $\pi^0$ scaled	3.6%	6.4%	21.5%	19.4
POT scaled	0.0%	0.0%	1.8%	67.5
Bkgd scaled	2.7%	4.7%	19.2%	20.9
CC scaled	2.9%	5.2%	19.9%	20.4
Low-E Kaons	0.1%	0.1%	5.9%	39.7
* $\nu$ scaled	38.4%	51.4%	58.0%	6.7

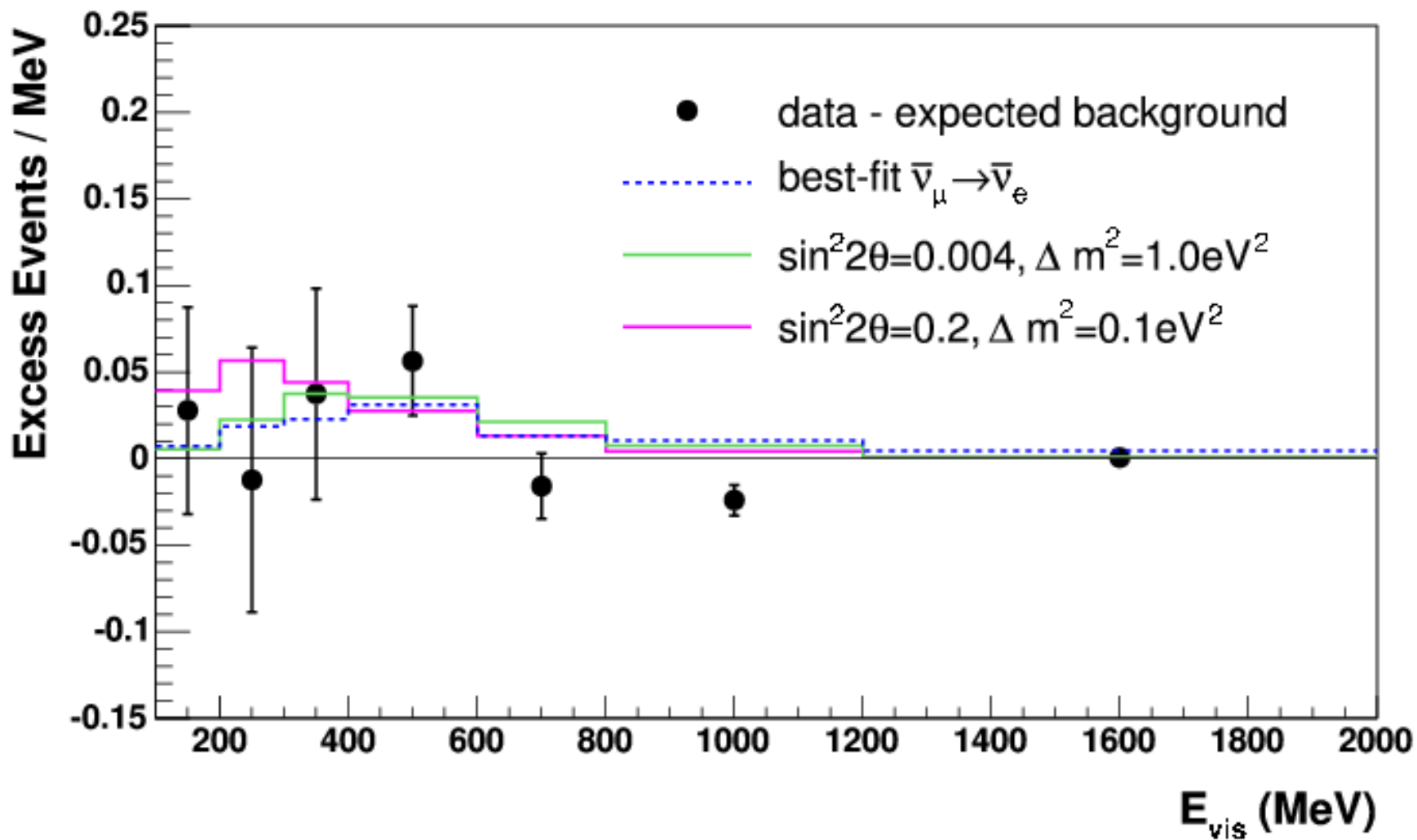
\* Best fit is where excess scales only with neutrino flux!

# Oscillation fit ( $>475$ MeV) consistent with LSND & Null



**Fit yields  $18.6 \pm 13.2$  events, consistent with expectation from LSND. However, not conclusive due to low statistics.**

## *Antineutrino Excess Events*



## *Antineutrino Statistics & Oscillation Fit*

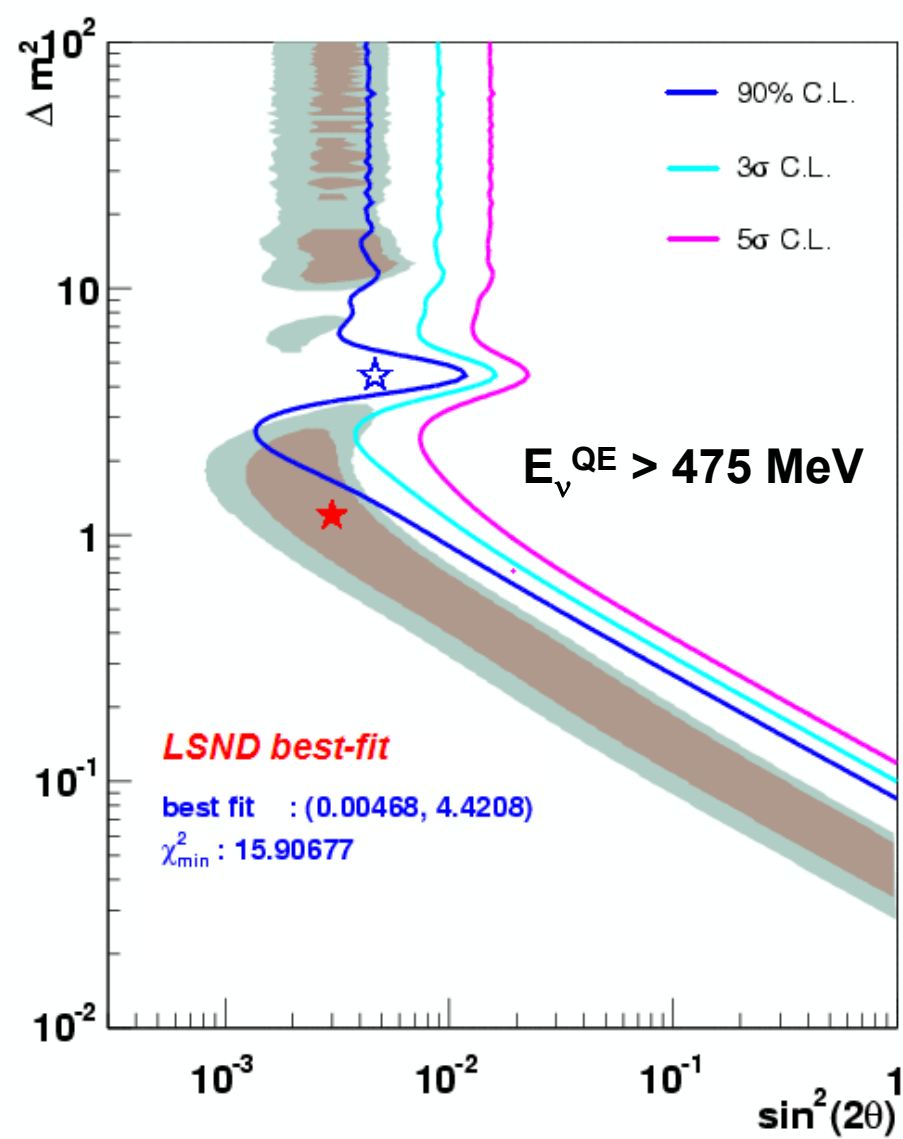
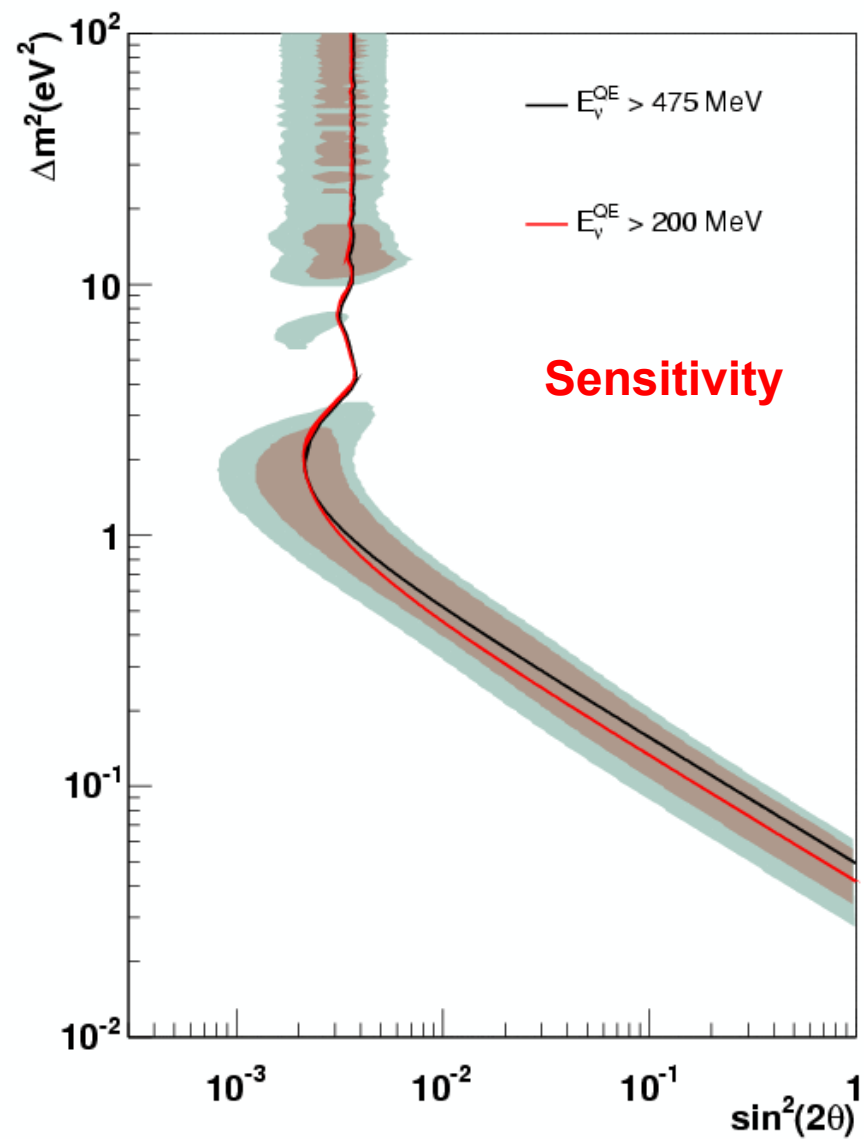
Energy (MeV)	Data	MC	Excess	
475-3000	83	77.4+-13.0	5.6+-13.0	(0.4 $\sigma$ )
Best Fit			18.6+-13.2	(1.4 $\sigma$ )
LSND Expect.			14.7	

$\chi^2$ Null	$\chi^2$ LSND	$\chi^2$ Best
22.19/16 (13.7%)	17.63/16 (34.6%)	15.91/14 (31.9%)

**Best fit:  $\Delta m^2 = 4.4 \text{ eV}^2$ ,  $\sin^2 2\theta = 0.004$**

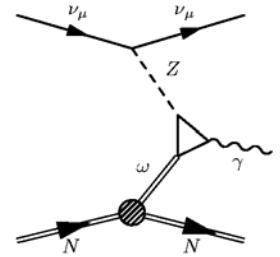
**LSND Best Fit:  $\Delta m^2 = 1.2 \text{ eV}^2$ ,  $\sin^2 2\theta = 0.003$**

# *Antineutrino Allowed Region*

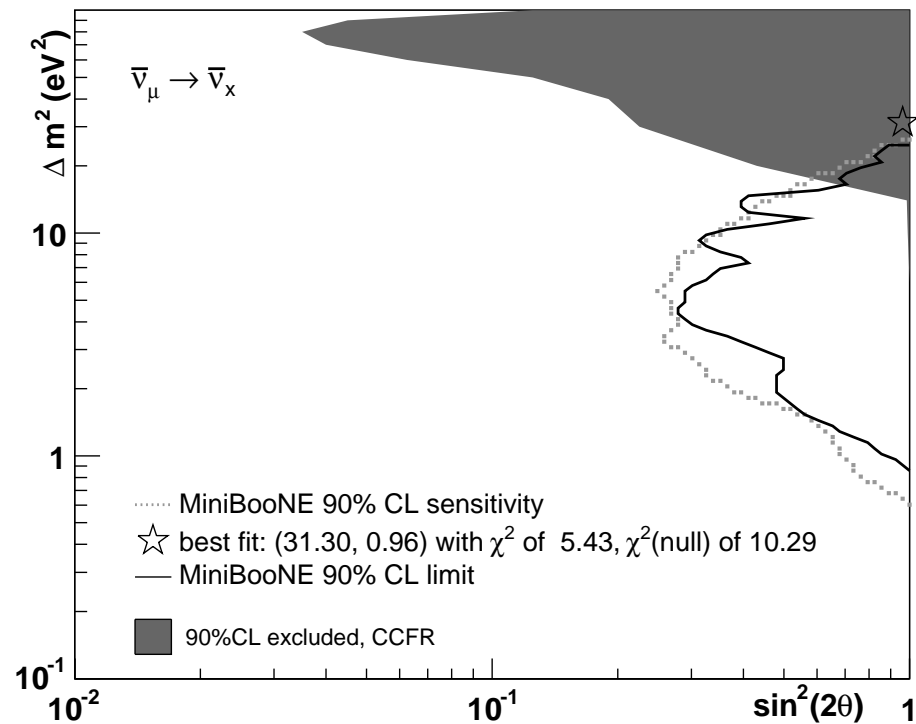
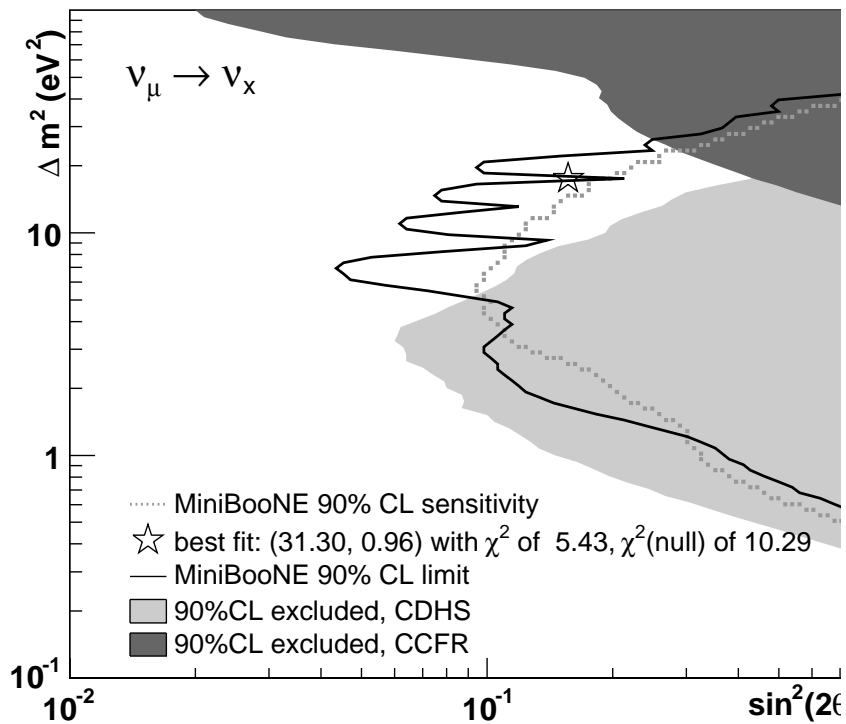


# Possible Explanations for the Low-Energy Excess

- 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 effects?)**
- 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**
- Heavy Sterile Neutrino Decay: S.N. Gninenko, arXiv:0902.3802 **YES**
- VSBL Electron Neutrino Disappearance: Carlo Giunti & Marco Laveder, arXiv: 0902:1992 **YES**
- Soft Decoherence: Yasaman Farzan, Thomas Schwetz, & Alexei Smirnov, arXiv: 0805.2098 **NO**

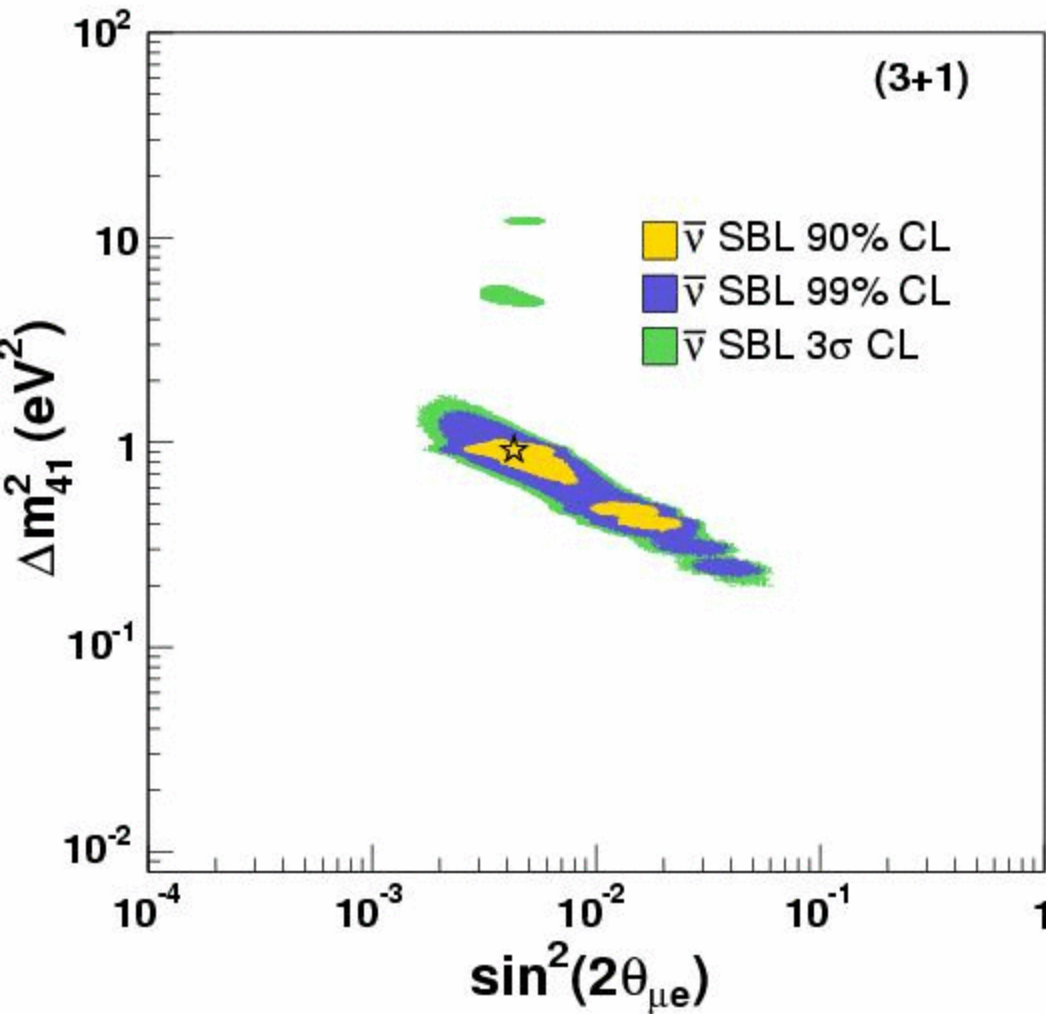


**Other data sets (NuMI, antineutrino, SciBooNE) may provide an explanation!**



**Improved results soon from MiniBooNE/SciBooNE Joint Analysis!**

## *Fit to World Antineutrino Data*



G. Karagiorgi et al.,  
arXiv:0906.1997

Best 3+1 Fit:

$$\Delta m^2 = 0.915 \text{ eV}^2$$

$$\sin^2 2\theta_{\mu e} = 0.0043$$

$$\chi^2 = 87.9/103 \text{ DOF}$$

$$\text{Prob.} = 86\%$$

**Predicts a  $\bar{\nu}_{\mu}$   
disappearance of  $\sim 35\%$**

# Future

- Collect more antineutrino data! ( $\sim 5E20$  POT at present &  $\sim 1E21$  POT by end of 2011) to study low-energy excess and LSND signal directly.
- Complete analysis of NuMI data with reduced systematic and statistical errors.
- Complete MiniBooNE/SciBooNE joint disappearance analysis.
- Understand apparent difference between neutrinos & antineutrinos! (CPT Violation?)
- Future experiments at FNAL (MicroBooNE & BooNE) should be able to determine whether the low-energy excess is due to a Standard Model process (e.g. interference of NC  $\gamma$  processes) or to Physics Beyond the Standard Model (e.g. sterile neutrinos with CP or CPT violation)

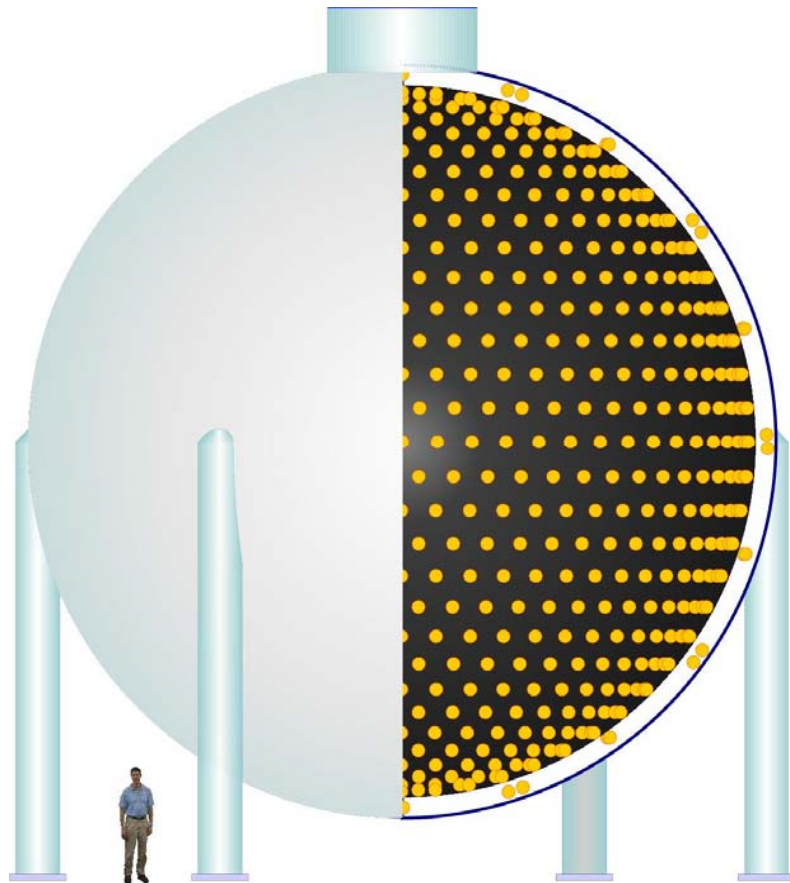
# Conclusions

- **MiniBooNE observes a low-energy excess of events in neutrino mode; the magnitude of the excess is what is expected from the LSND signal, although the energy shape is not very consistent with simple 2- $\nu$  oscillations.**
- **MiniBooNE so far observes no low-energy excess in antineutrino mode; this suggests that the excess may not be due to a Standard Model background. At present, the high-energy antineutrino data are consistent with both the LSND best-fit point ( $\chi^2=17.6/16$ , P=34.6%) & the null point ( $\chi^2=22.2/16$ , P=13.7%). **(LSND is alive & well.)****
- **All antineutrino data fit well to a simple 3+1 model! However, there is tension between neutrino & antineutrino data. (CPT Violation?)**
- **The low-energy excess ( $\sim 1\%$ ) is interesting in its own right and important for future long-baseline experiments (T2K, NOvA, DUSEL). Monte Carlos need improvement!**

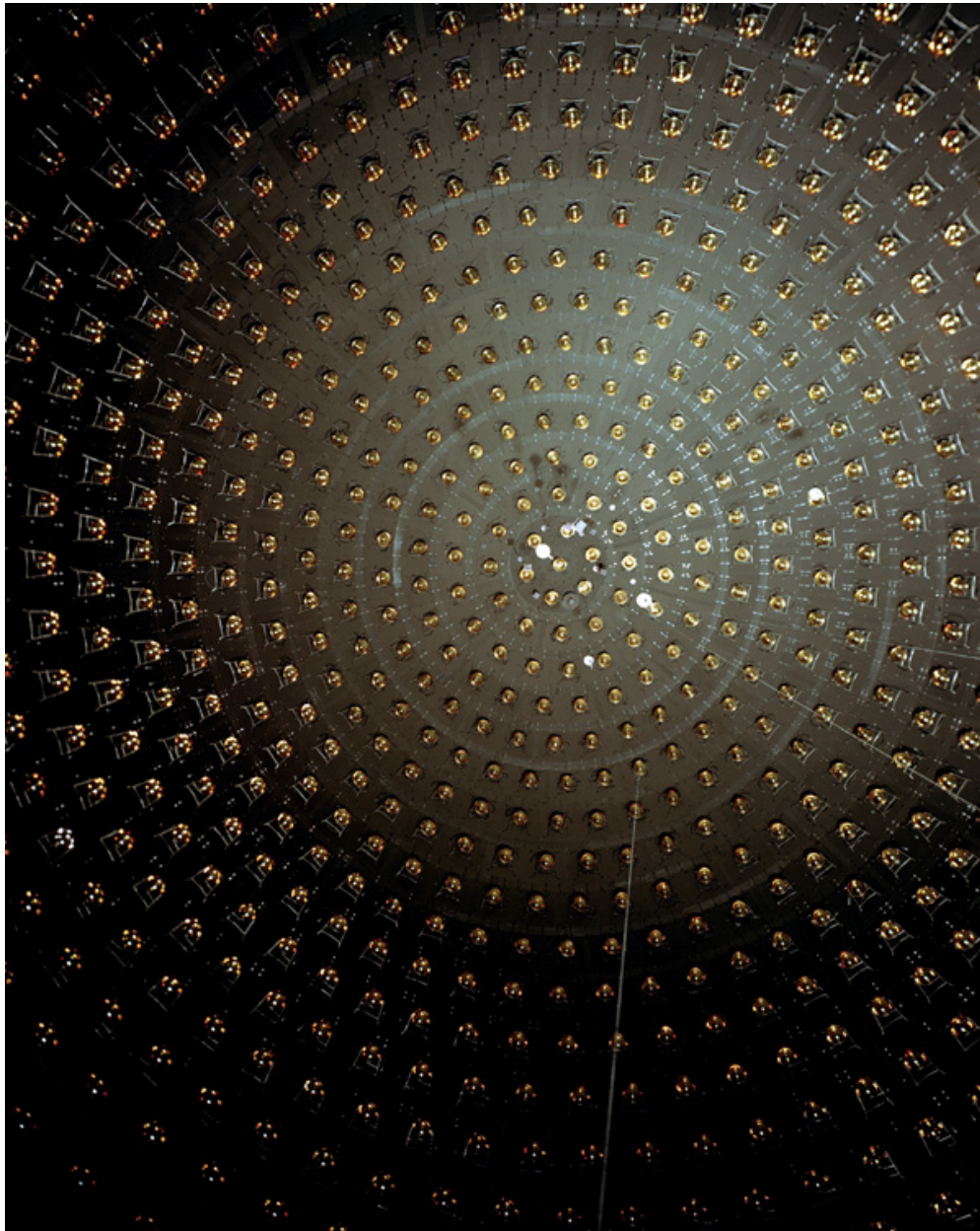
# Backup Slides



# *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 ( $\text{CH}_2$ )  
(Fiducial volume: 450 t)
- 1280 inner phototubes,  
240 veto phototubes
- Simulated with a GEANT3 Monte Carlo



10% Photocathode coverage

Two types of  
Hamamatsu Tubes:  
R1408, R5912

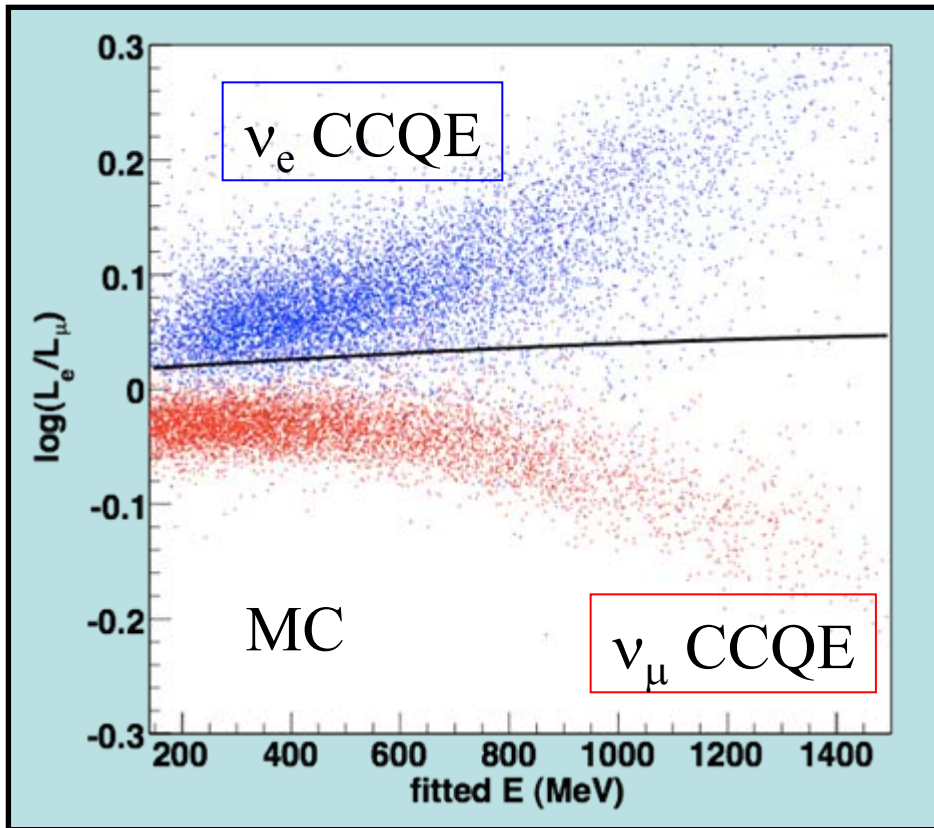
Charge Resolution:  
1.4 PE, 0.5 PE

Time Resolution  
1.7 ns, 1.1ns



# Rejecting “muon-like” events Using $\log(L_e/L_\mu)$

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



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

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

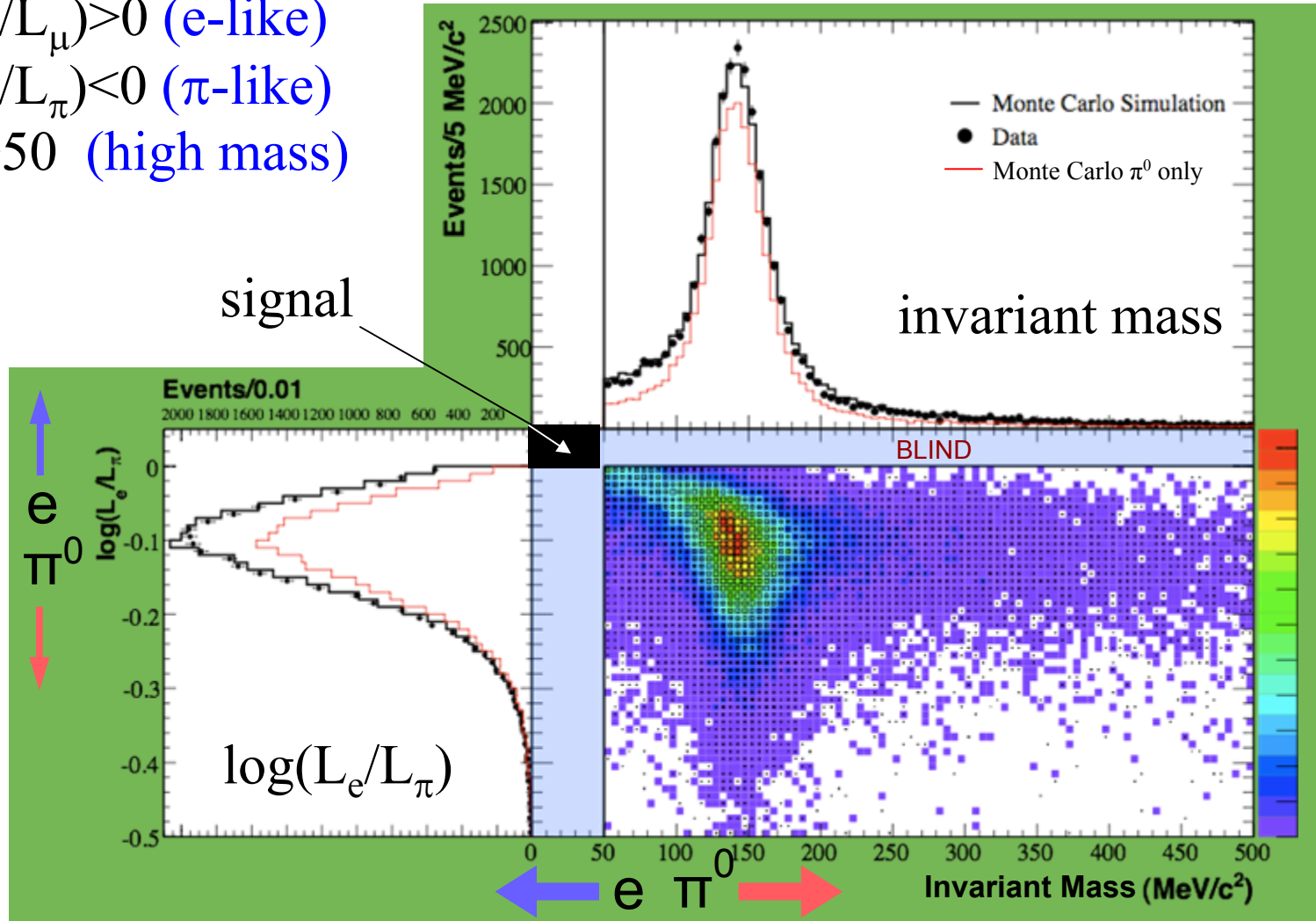
# Testing $e-\pi^0$ separation using data

1 subevent

$\log(L_e/L_\mu) > 0$  (e-like)

$\log(L_e/L_\pi) < 0$  ( $\pi$ -like)

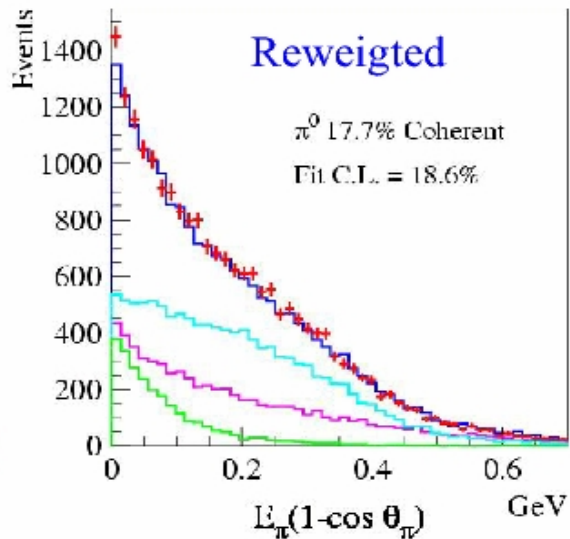
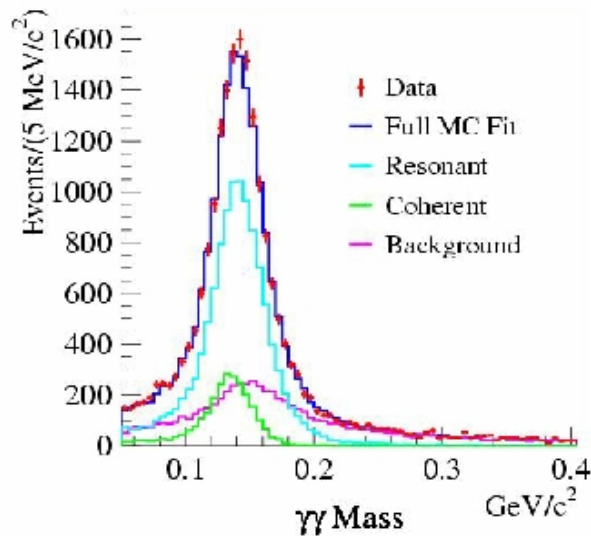
mass  $> 50$  (high mass)



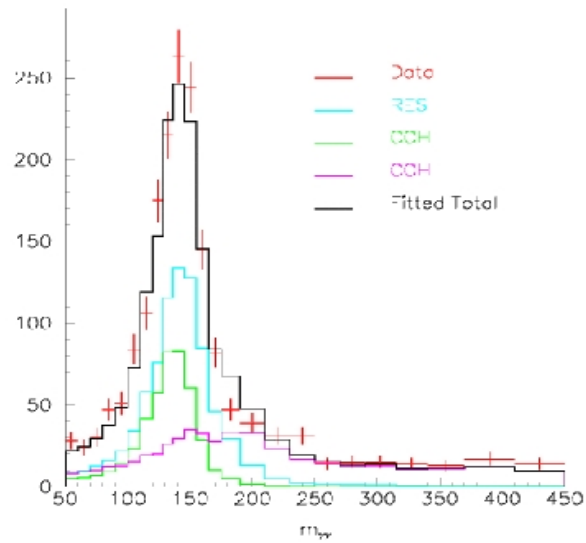
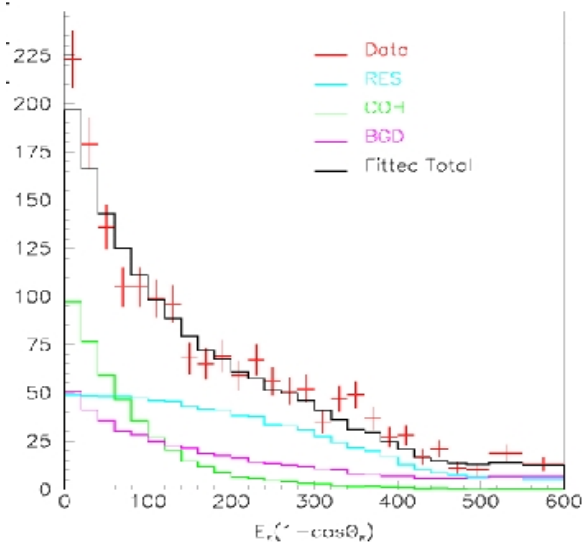
# Neutral Current $\pi^0$ Scattering

A. A. Aguilar-Arevalo et al., Phys. Lett. B 664, 41 (2008)

Neutrino



Antineutrino



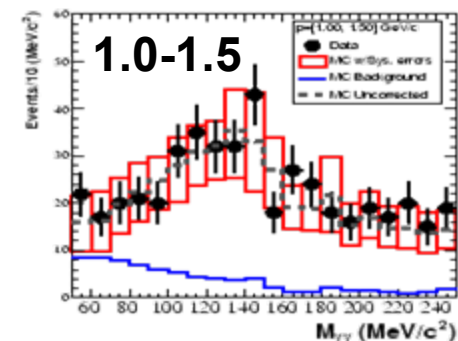
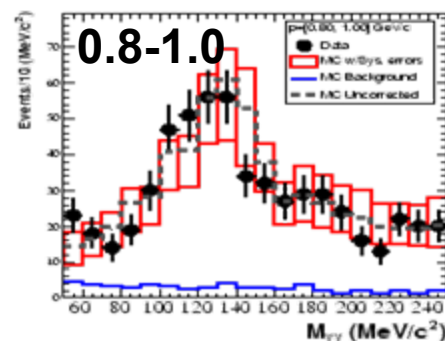
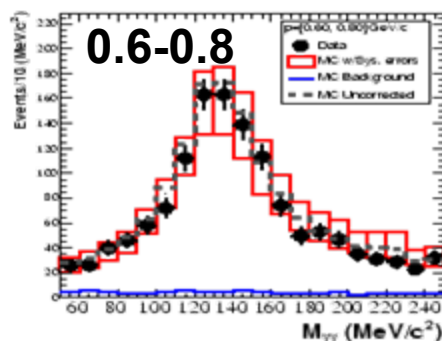
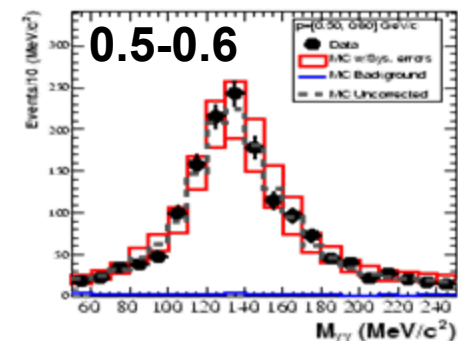
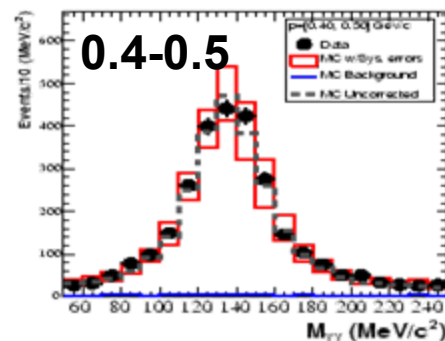
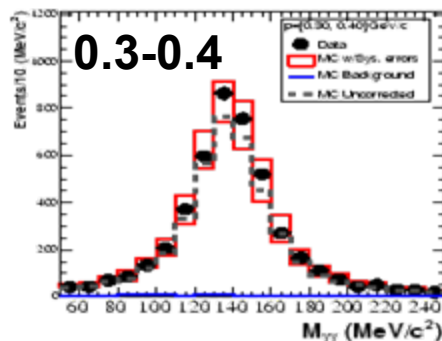
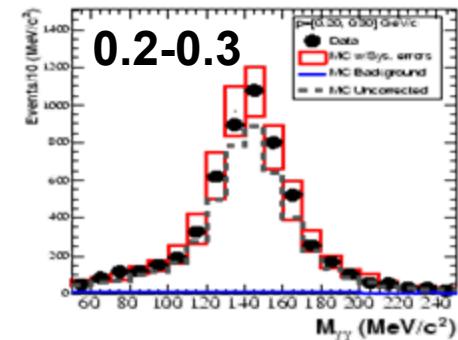
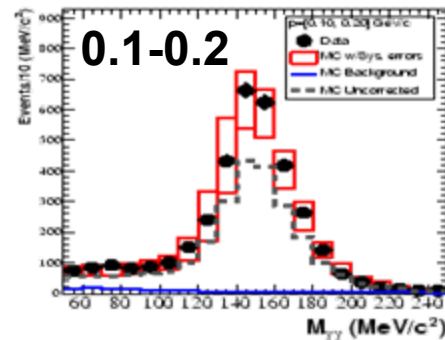
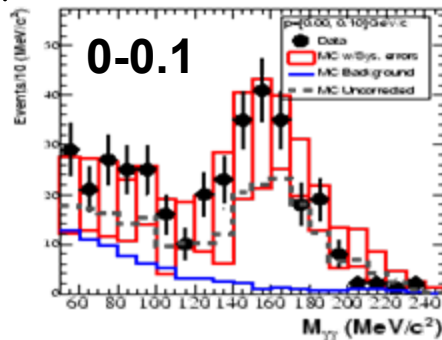
## *Recent Improvements in the Analysis*

- Check many low level quantities (PID stability, etc)
- Rechecked various background cross-section and rates ( $\pi^0$ ,  $\Delta \rightarrow N\gamma$ , etc.)
- Improved  $\pi^0$  (coherent) production incorporated.
- Better handling of the radiative decay of the  $\Delta$  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,  $\Delta \rightarrow N\gamma$ , etc).
- Additional data set included in new results:
  - Old analysis:  $5.58 \times 10^{20}$  protons on target.
  - New analysis:  $6.46 \times 10^{20}$  protons on target.

# *(Re)Measuring the $\pi^0$ rate versus $\pi^0$ momentum*

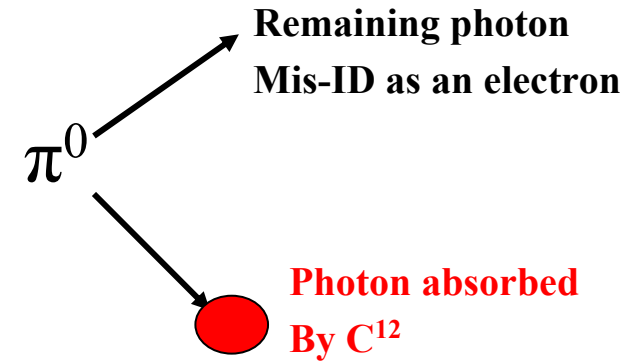
● Fit invariant mass peak in each momentum range

●  $\Delta \rightarrow N\gamma$  also constrained



# Photo-nuclear absorption of $\pi^0$ photon

**A single  $\gamma$  is indistinguishable from an electron in MiniBooNE**

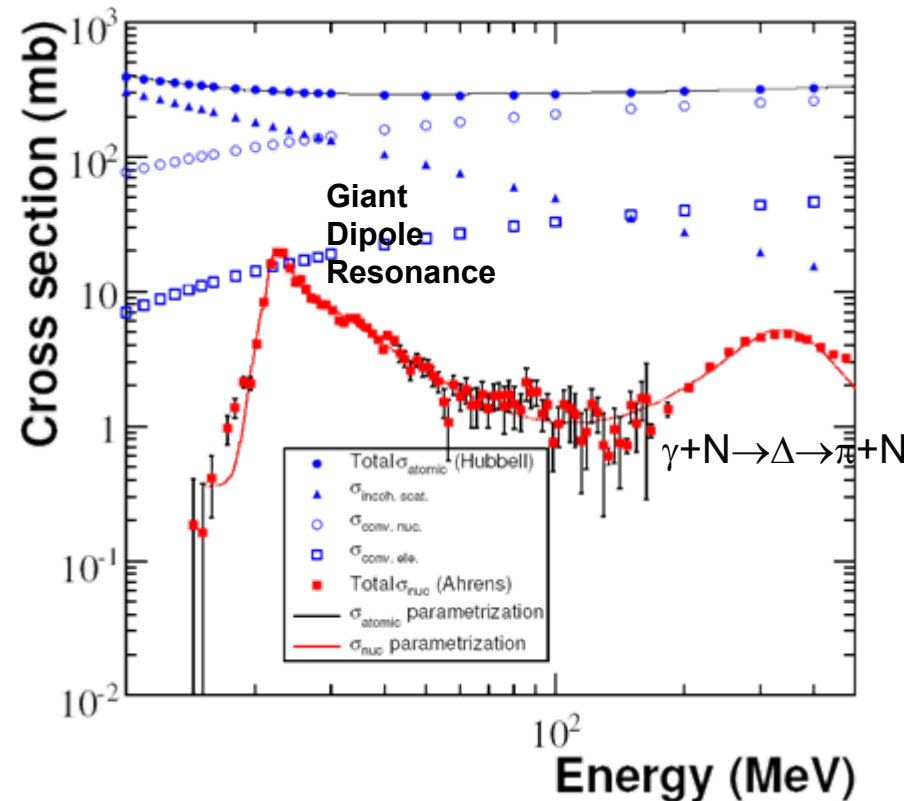


Photonuclear processes can remove ("absorb") one of the gammas from NC  $\pi^0 \rightarrow \gamma\gamma$  event

- Total photonuclear absorption cross sections on Carbon well measured.

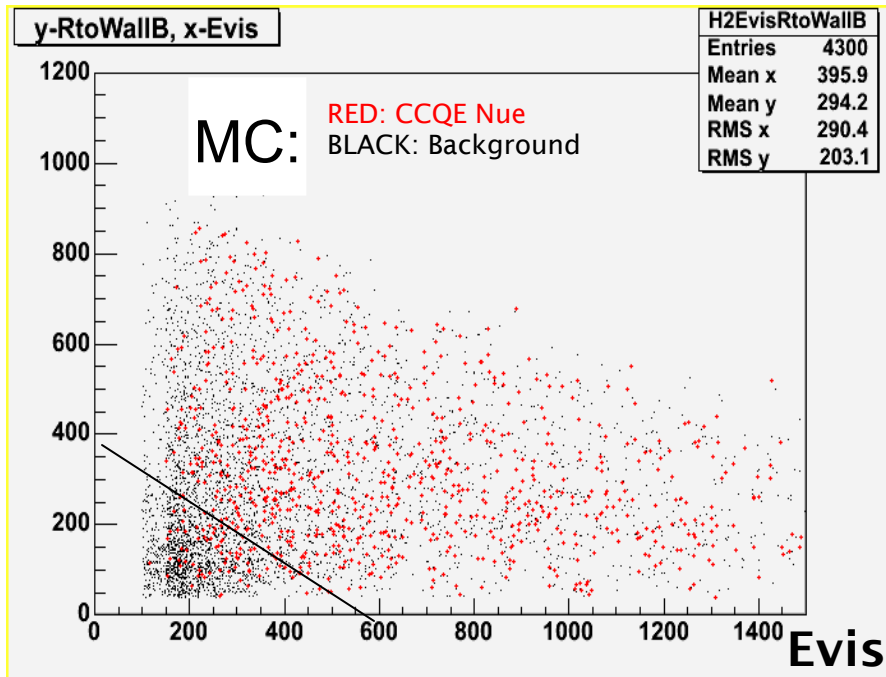
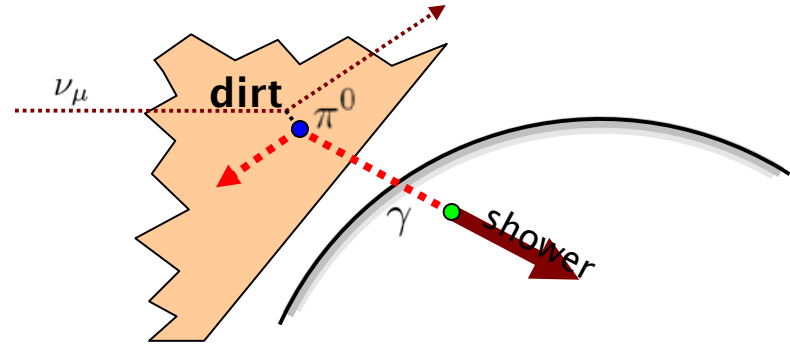
Photonuclear absorption recently added to our GEANT3 detector Monte Carlo.

- 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)

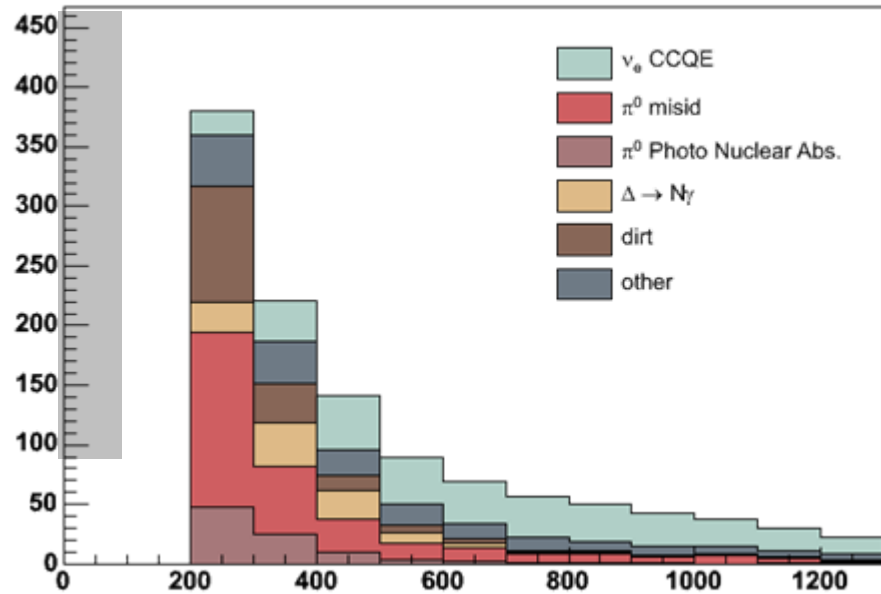


- occur at large radius
- inwardly directed
- low energy

**The background can be largely eliminated with an energy dependent fiducial cut (rtowallb)**

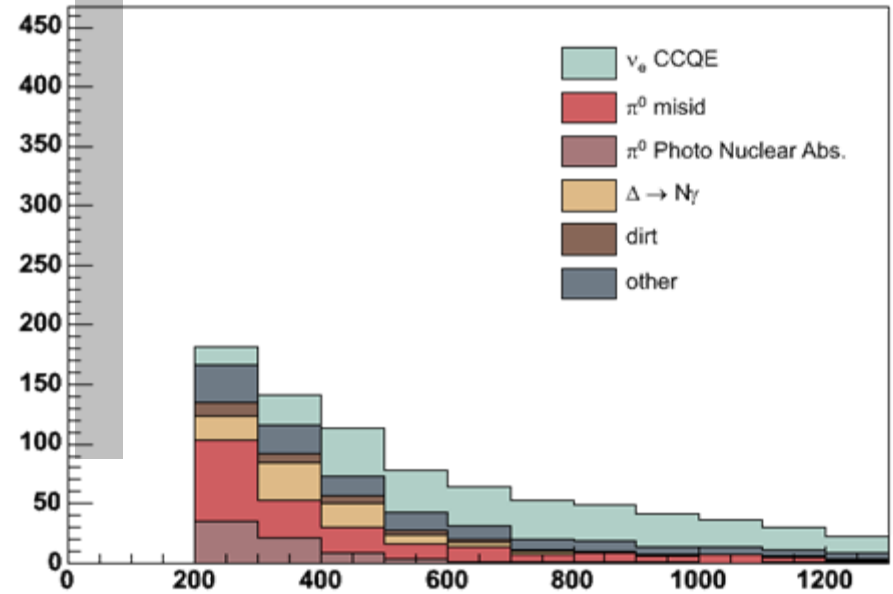
# Comparing Neutrino Low Energy $\nu_e$ Candidates with & without dirt cut

## Without Dirt Cut



$E_{\nu QE}$

## With Dirt Cut



$E_{\nu QE}$

## *Sources of Systematic Errors*

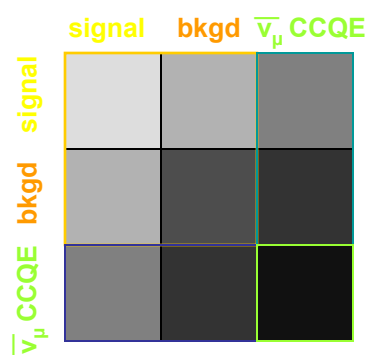
Source of Uncertainty On $\nu_e$ background	Track Based error in %		Checked or Constrained by MB data
	200-475 MeV	475-1250 MeV	
Flux from $\pi^+/\mu^+$ decay	1.8	2.2	✓
Flux from $K^+$ decay	1.4	5.7	✓
Flux from $K^0$ decay	0.5	1.5	✓
Target and beam models	1.3	2.5	✓
$\nu$ -cross section	5.9	11.8	✓
NC $\pi^0$ yield	1.4	1.8	✓
External interactions (“Dirt”)	0.8	0.4	✓
Detector Response	9.8	5.7	✓
DAQ electronics model	5.0	1.7	✓
Hadronic	0.8	0.3	✓
Total Unconstrained Error	13.0	15.1	

$\nu_\mu$  **CCQE events constrain ( $\phi \times \sigma$ ) !**

## *Fit method*

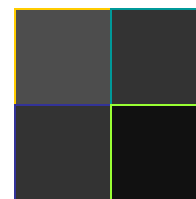
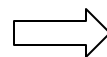
The following three distinct samples are used in the oscillation fits  
(fitting  $\nu_e$  &  $\bar{\nu}_\mu$  energy spectra)

1. **Background** to  $\nu_e$  oscillations
2.  $\nu_e$  **Signal** prediction (dependent on  $\Delta m^2$ ,  $\sin^2 2\theta$ )
3.  $\bar{\nu}_\mu$  **CCQE** sample, used to constrain  $\nu_e$  prediction (signal+background)



Syst+stat block-3x3 covariance matrix in  $E_\nu^{QE}$  bins  
(in units of events<sup>2</sup>) for all 3 samples

Matrix is actually 53x53 (in  $E_\nu^{QE}$  bins) !



collapsed to block-2x2 matrix ( $\bar{\nu}_e$  and  $\bar{\nu}_\mu$  CCQE)  
for  $\chi^2$  calculation

# *Low-energy excess vs $E_{vis}$*

With  $E_{vis}$  Best Fit (0.04 eV<sup>2</sup>, 0.96)

