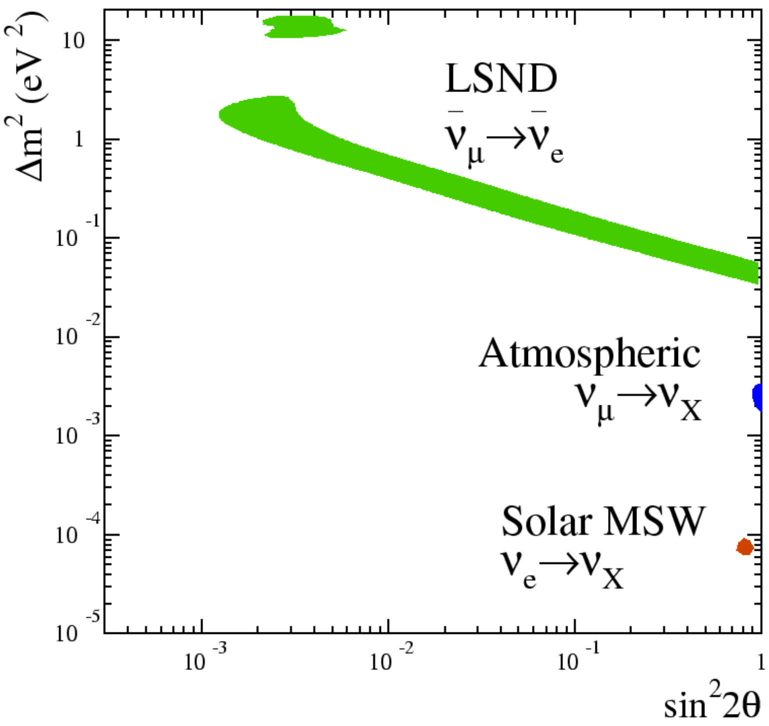
MiniBooNE ν Oscillation Results

W.C. Louis, Aspen Winter Conference, January 22, 2010

- MiniBooNE Introduction
- ν_e Appearance Oscillation Results
- NuMI Data Results
- $\bar{\nu}_e$ Appearance Oscillation Results
- Global 3+1 fits to World Data
- ν_μ & $\bar{\nu}_\mu$ Disappearance Oscillation Results
- Conclusions

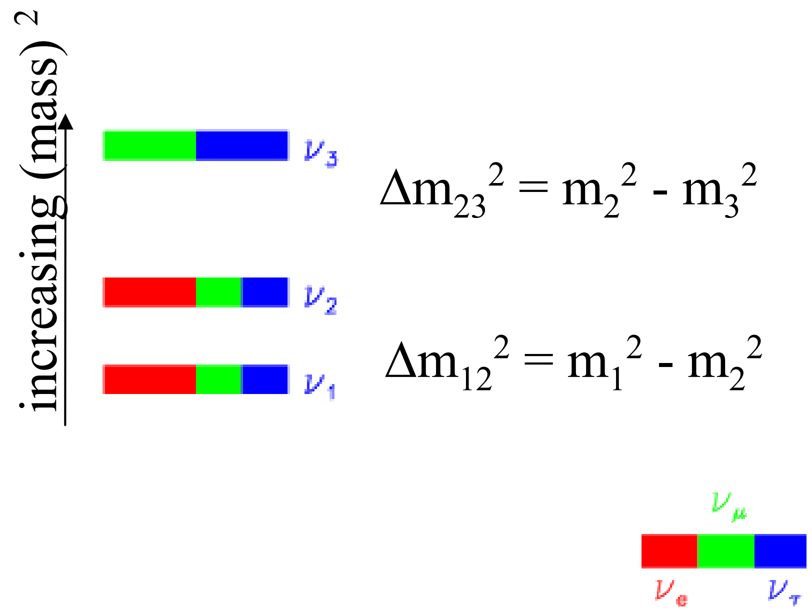
MiniBooNE was designed to test the LSND signal

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



A 3 neutrino picture requires

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

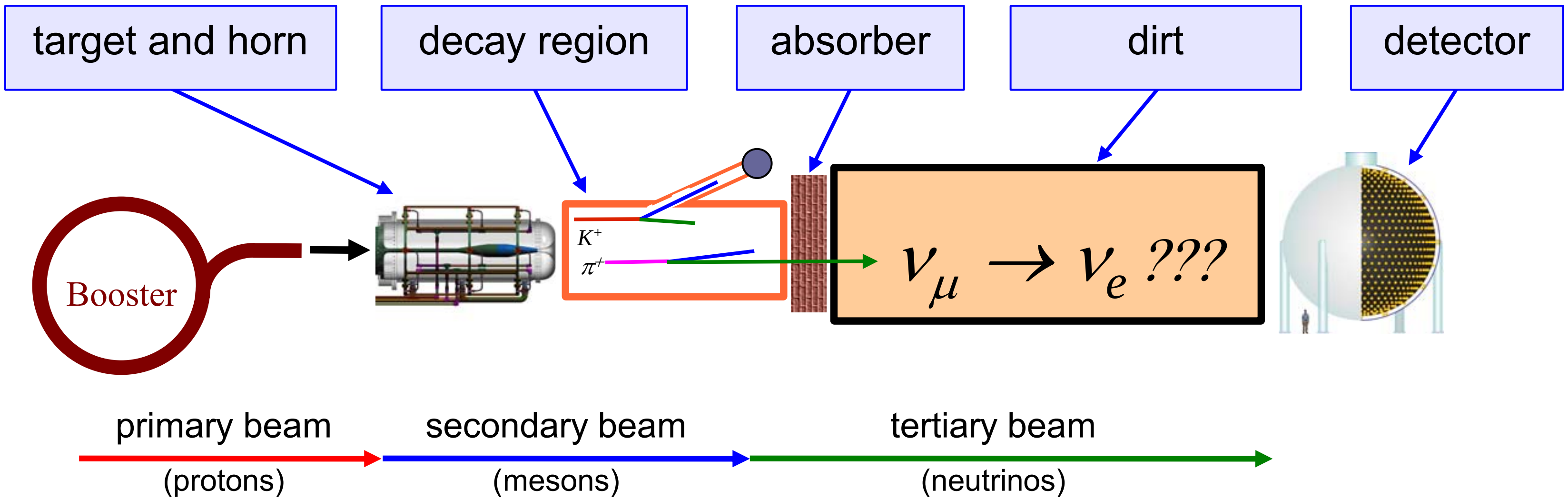


The three oscillation signals cannot be reconciled without introducing Beyond Standard Model Physics

MiniBooNE's Design Strategy

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

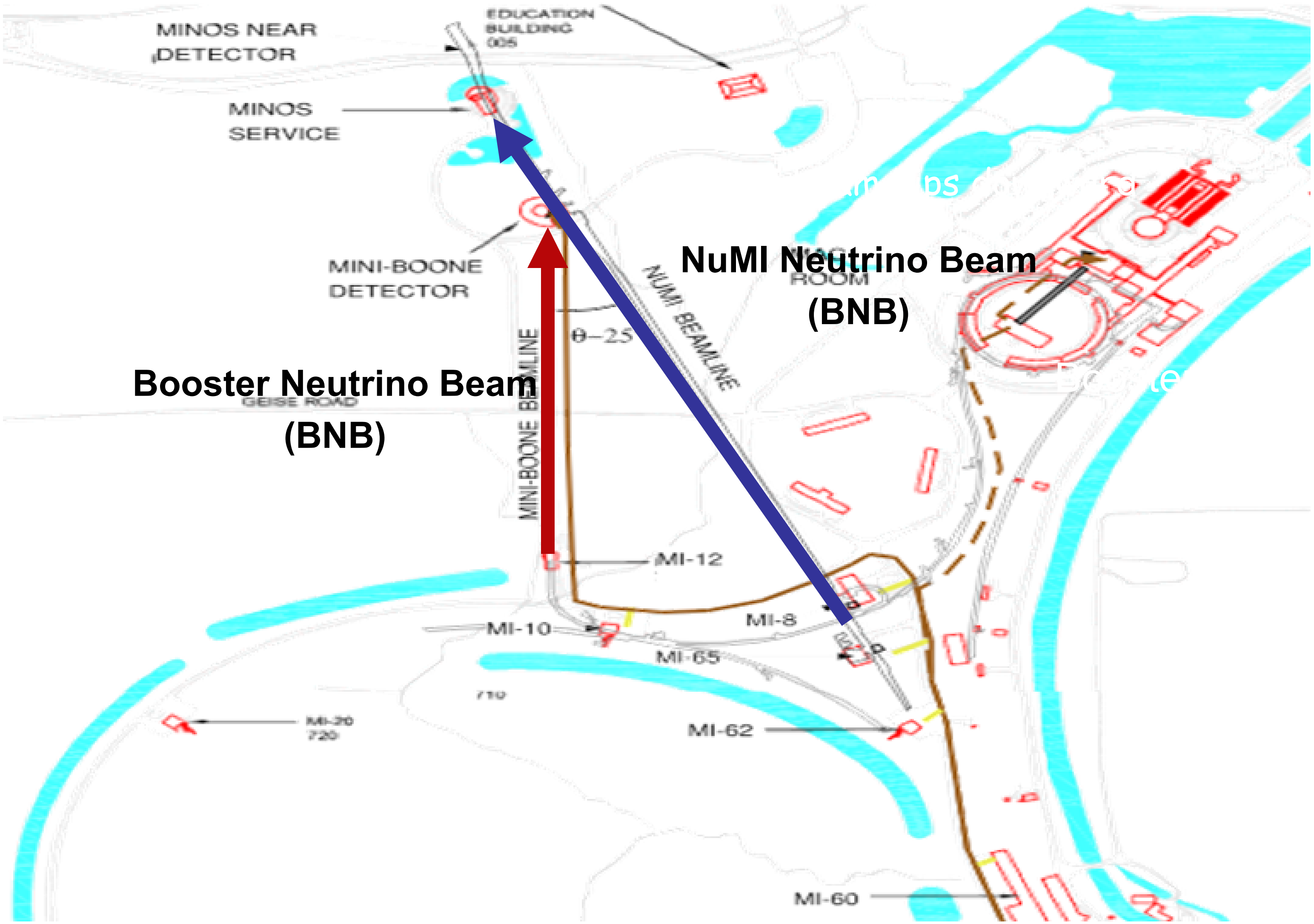
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2(1.27 \Delta m^2 L/E)$$



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



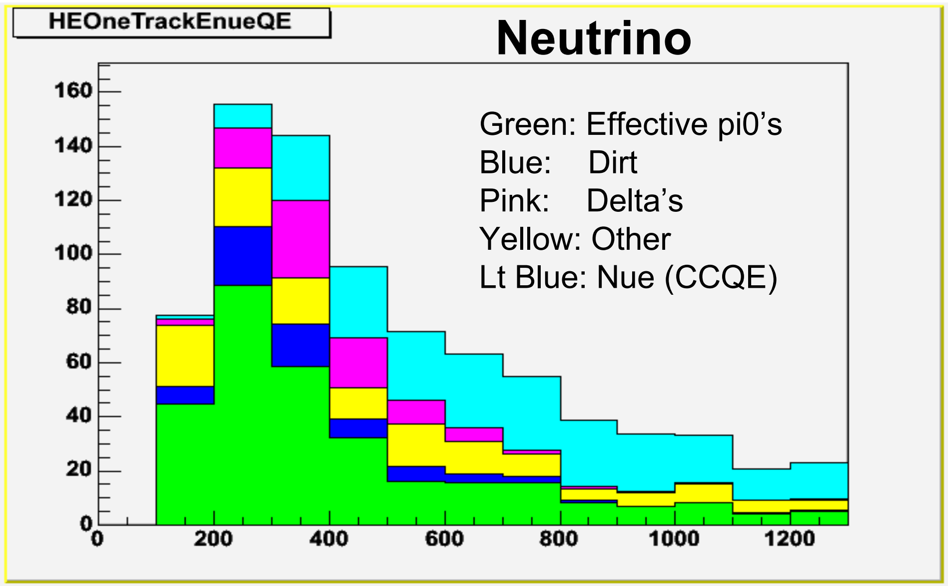
ν_e *Event Rate Predictions*

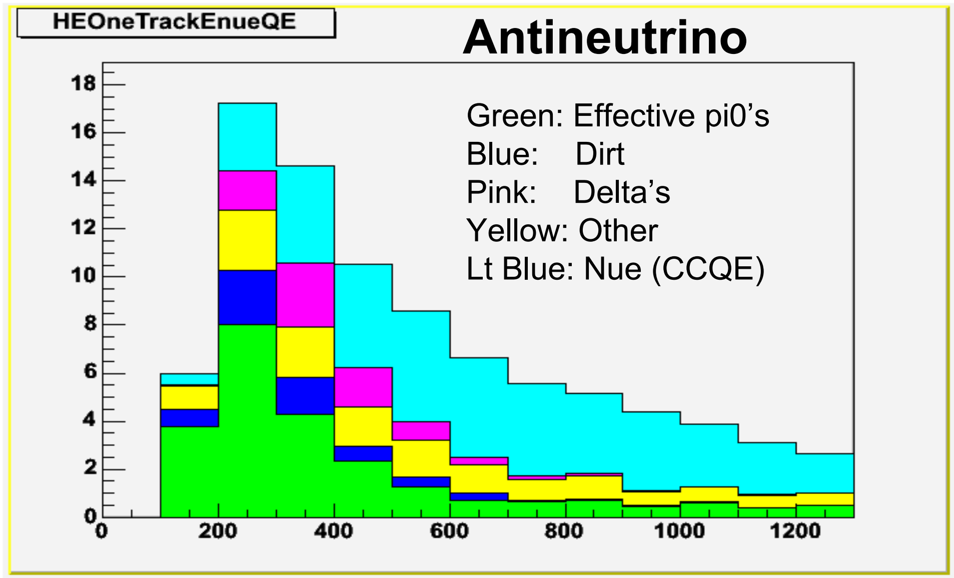
#Events = Flux x Cross-sections x Detector response

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

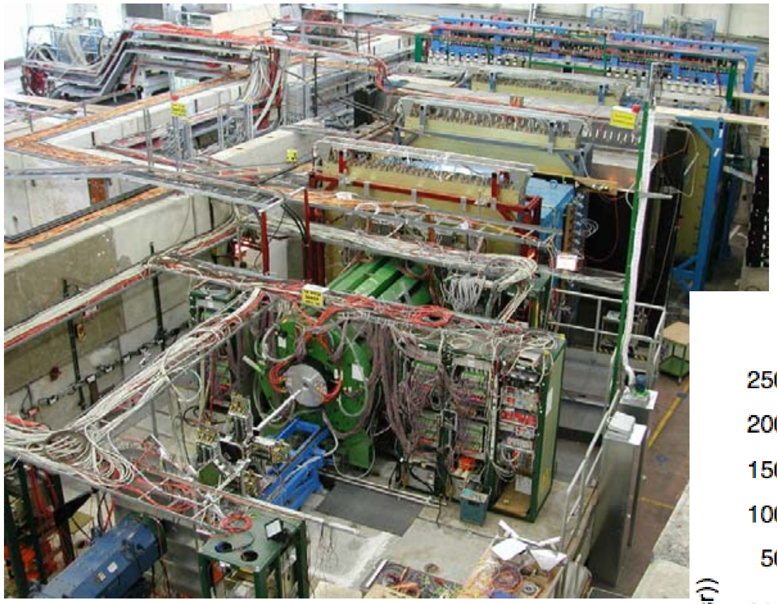
External and MiniBooNE measurements
-π^0, delta and dirt backgrounds constrained from data.

Detailed detector simulation checked with neutrino data and calibration sources.

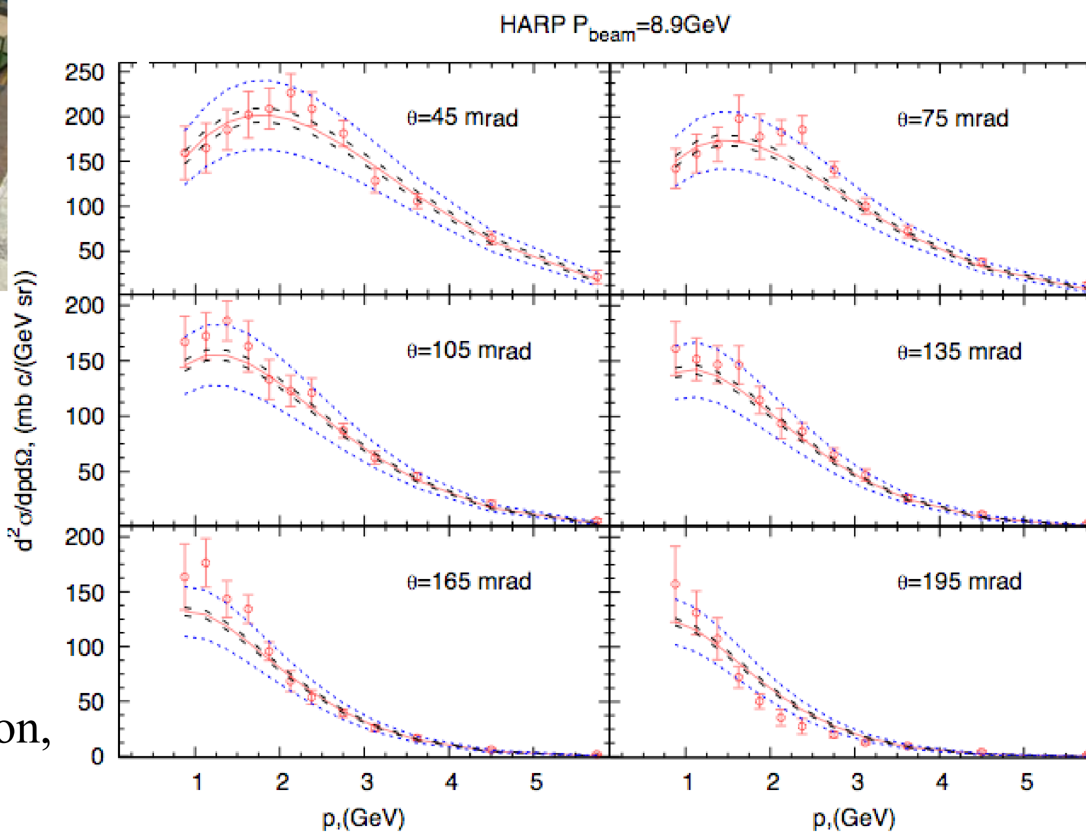




Modeling Production of Secondary Pions



- HARP (CERN)
  - 5% λ Beryllium target
  - 8.9 GeV proton beam momentum
  - π^+ & π^-

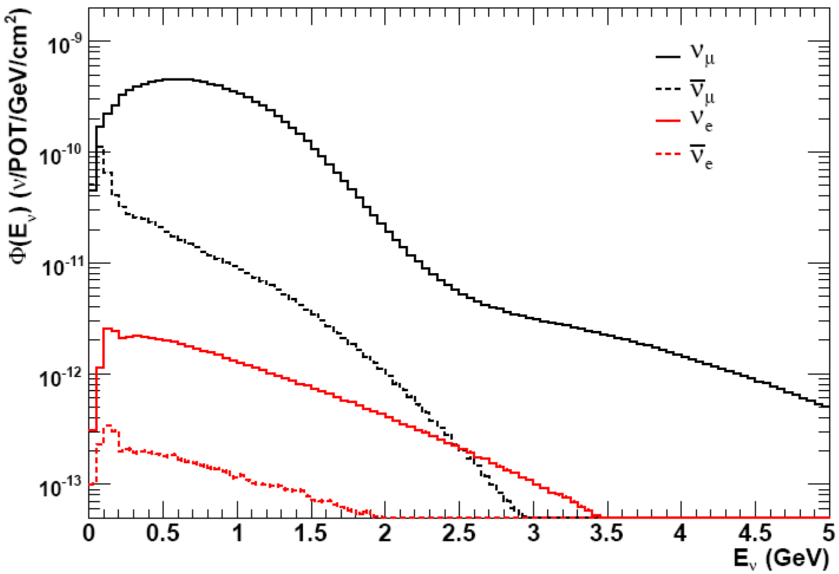


Data are fit to a Sanford-Wang parameterization.

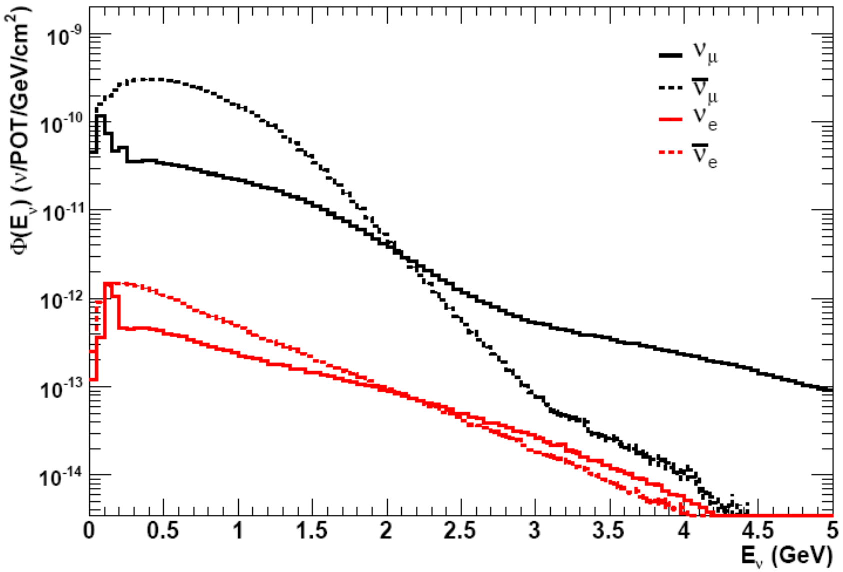
HARP collaboration, hep-ex/0702024

Neutrino Flux from GEANT4 Simulation

Neutrino-Mode Flux



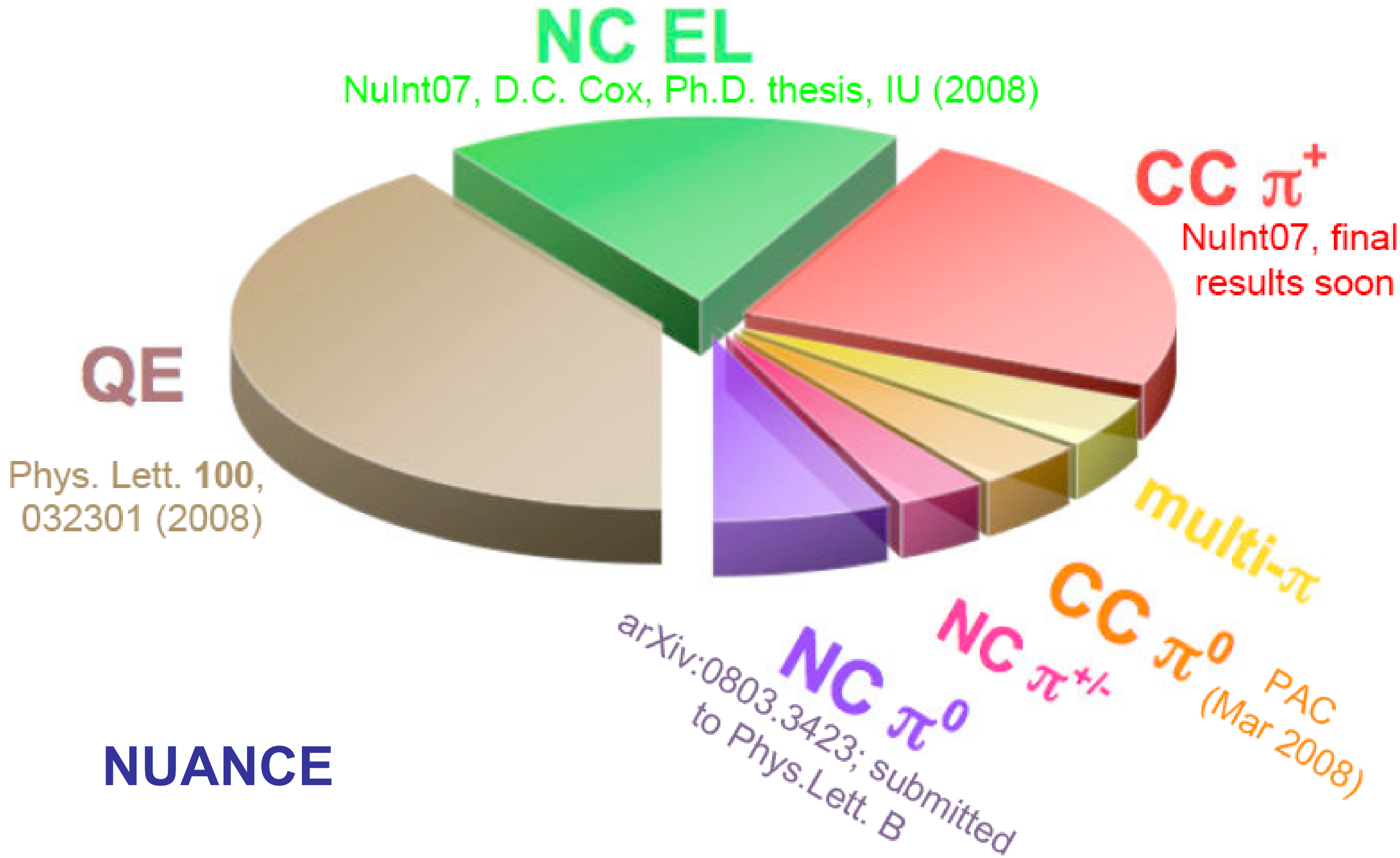
Antineutrino-Mode Flux



Wrong-sign background is ~6% for Nu-Mode & ~18% for Antinu-Mode

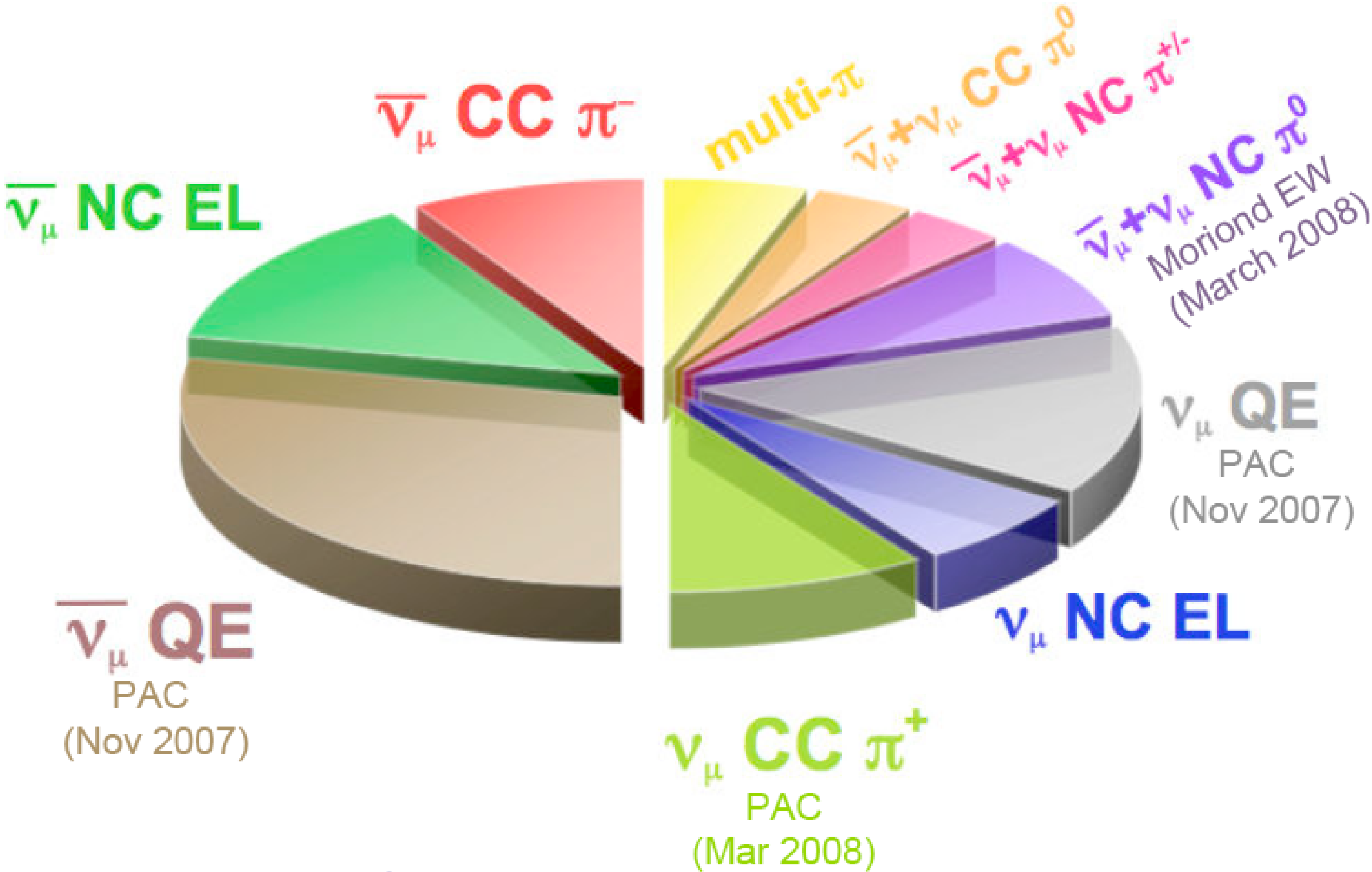
Instrinsic ν_e background is ~0.5% for both Nu-Mode & Antinu-Mode

Neutrino Cross Sections



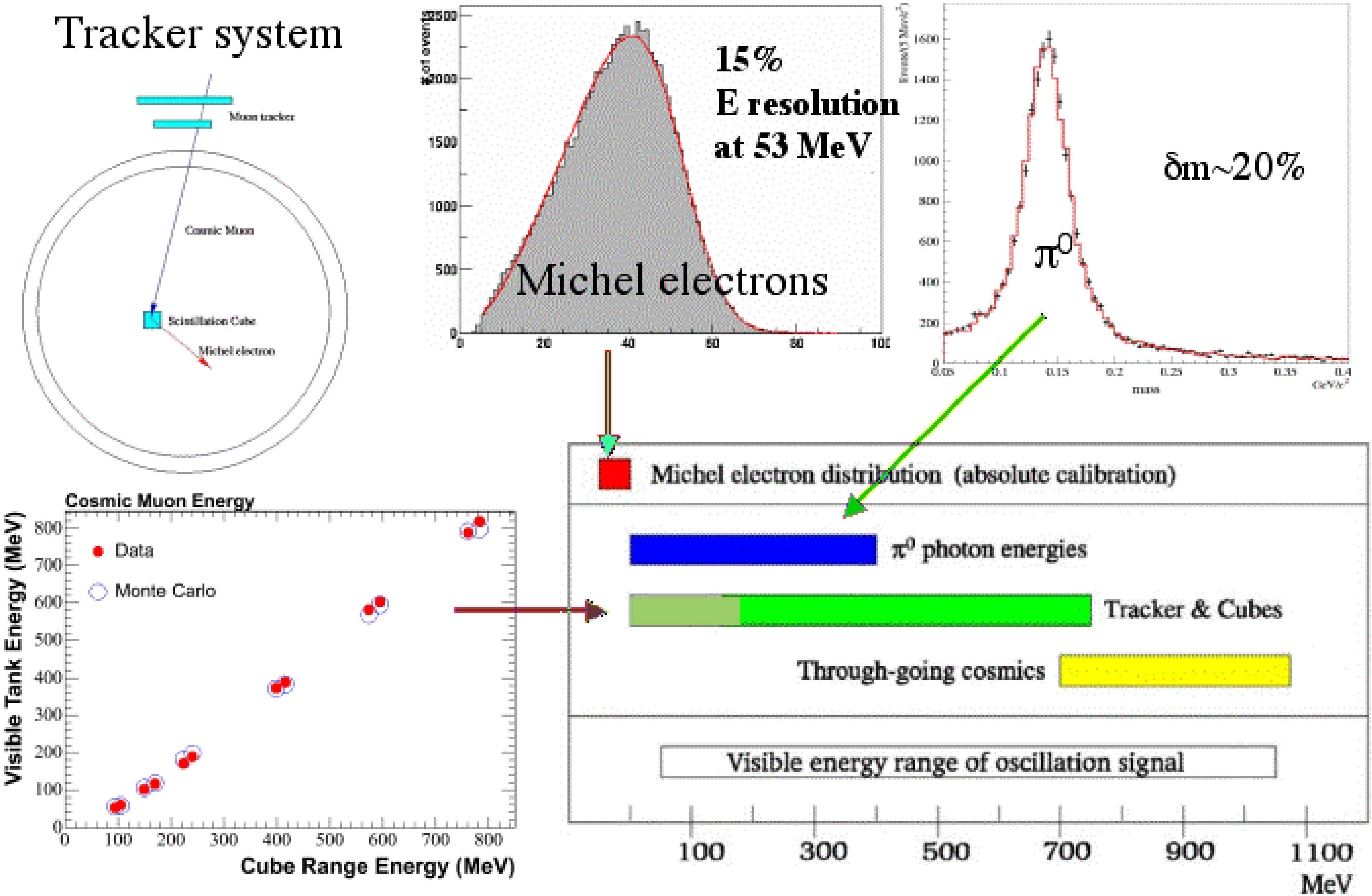
NUANCE

Antineutrino Cross Sections



NUANCE

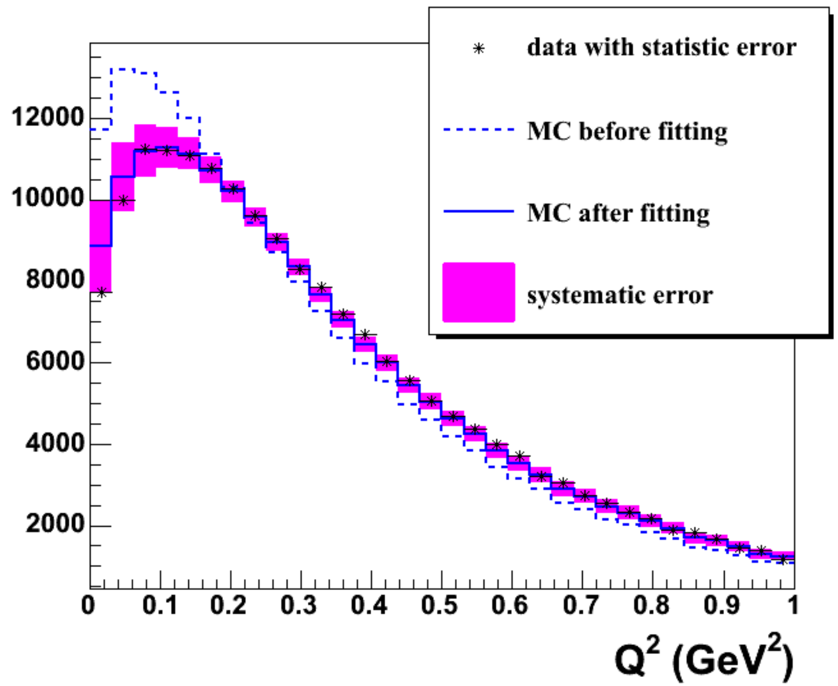
Calibration Sources



ν_μ CCQE Scattering

A. A. Aguilar-Arevalo et al., 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

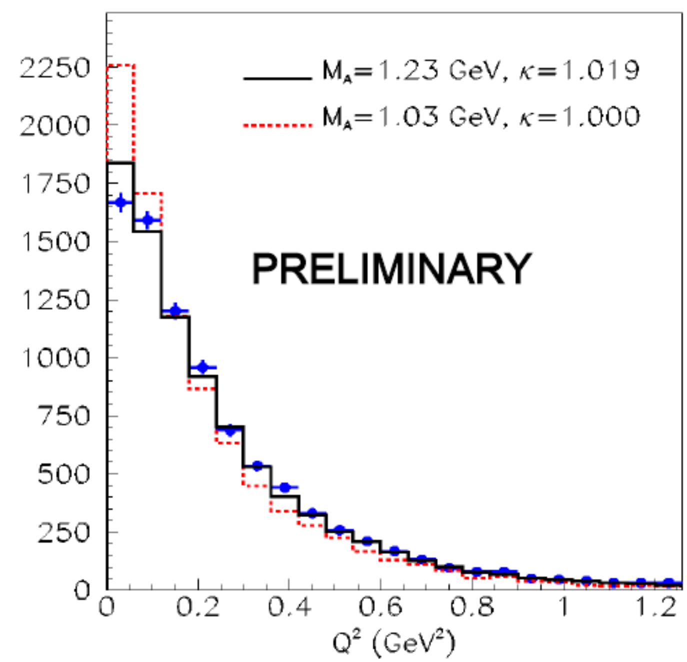
κ -- Pauli Blocking parameter

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

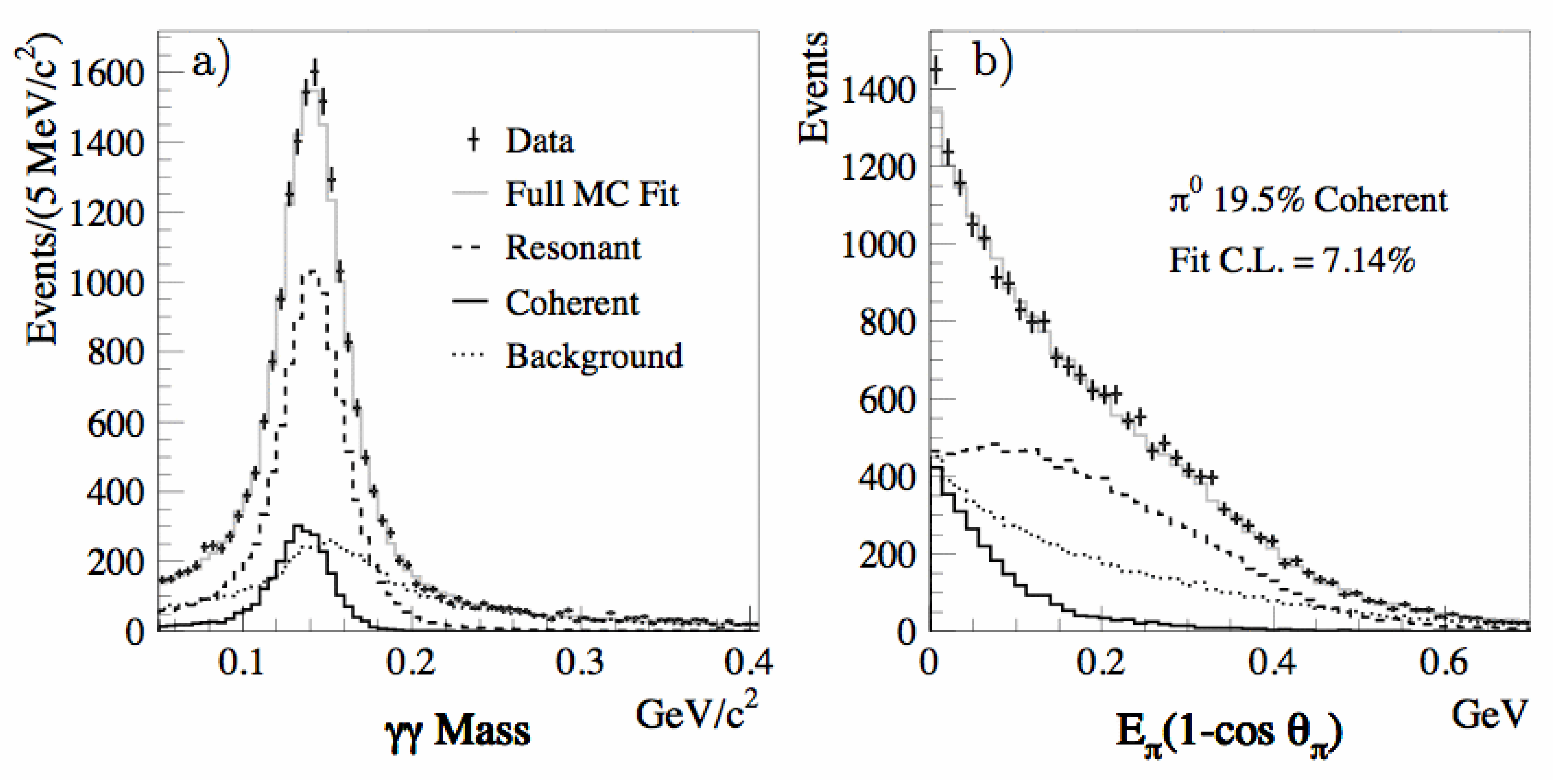
$\kappa = 1.019$+-0.011

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

NCpi0 Scattering

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

coherent fraction=19.5+-1.1+-2.5%

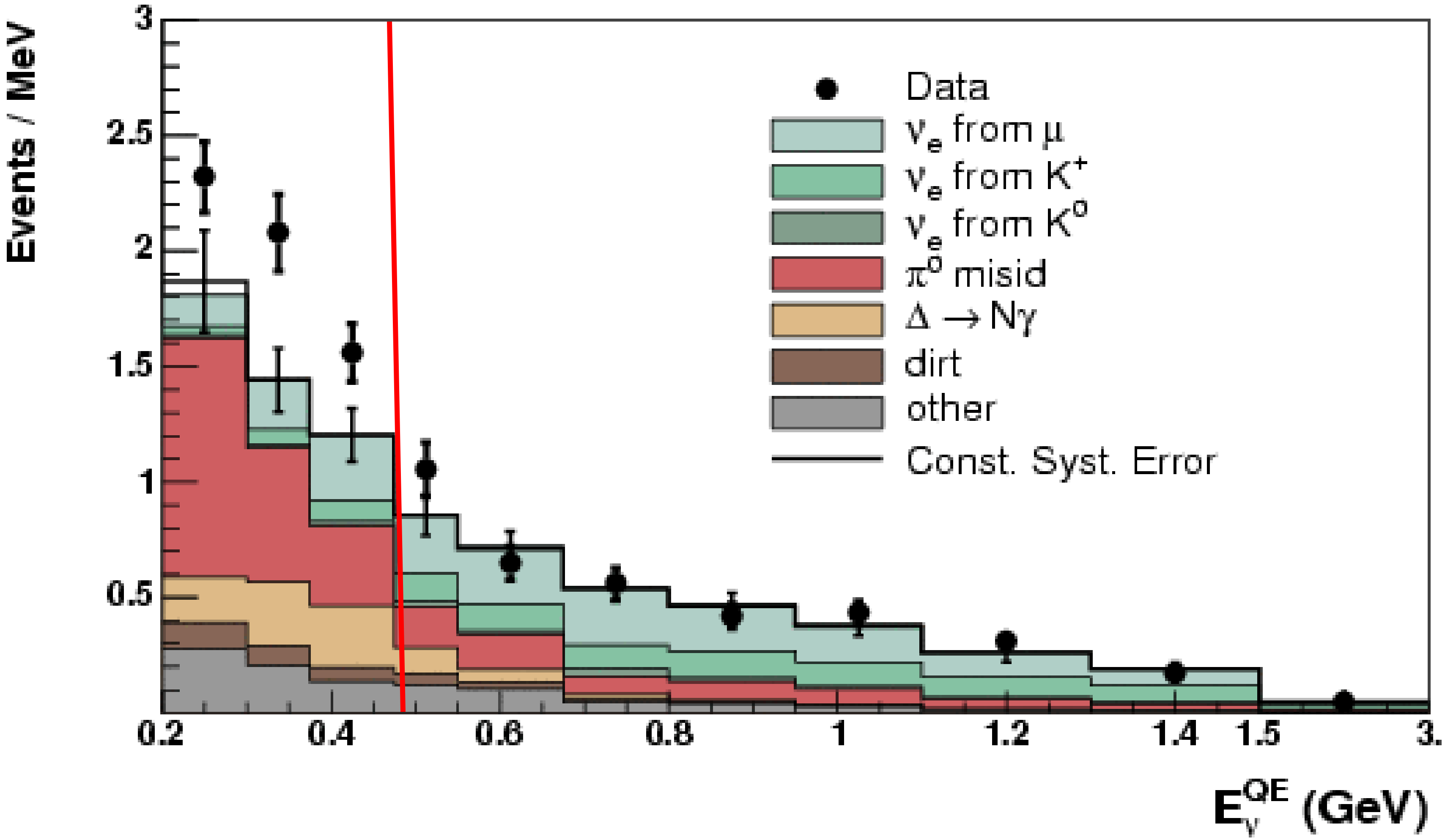


ν_e Appearance Oscillation Results

- Results based on 6.46 x 10^{20} POT
- Approximately 0.7×10^6 neutrino events recorded with tank hits >200 & veto hits<6
- Approximately 1.5×10^5 ν_μ CCQE events
- Approximately 375 ν_e CCQE events (intrinsic bkgd)
- Expect ~200 ν_e CCQE events (LSND signal)

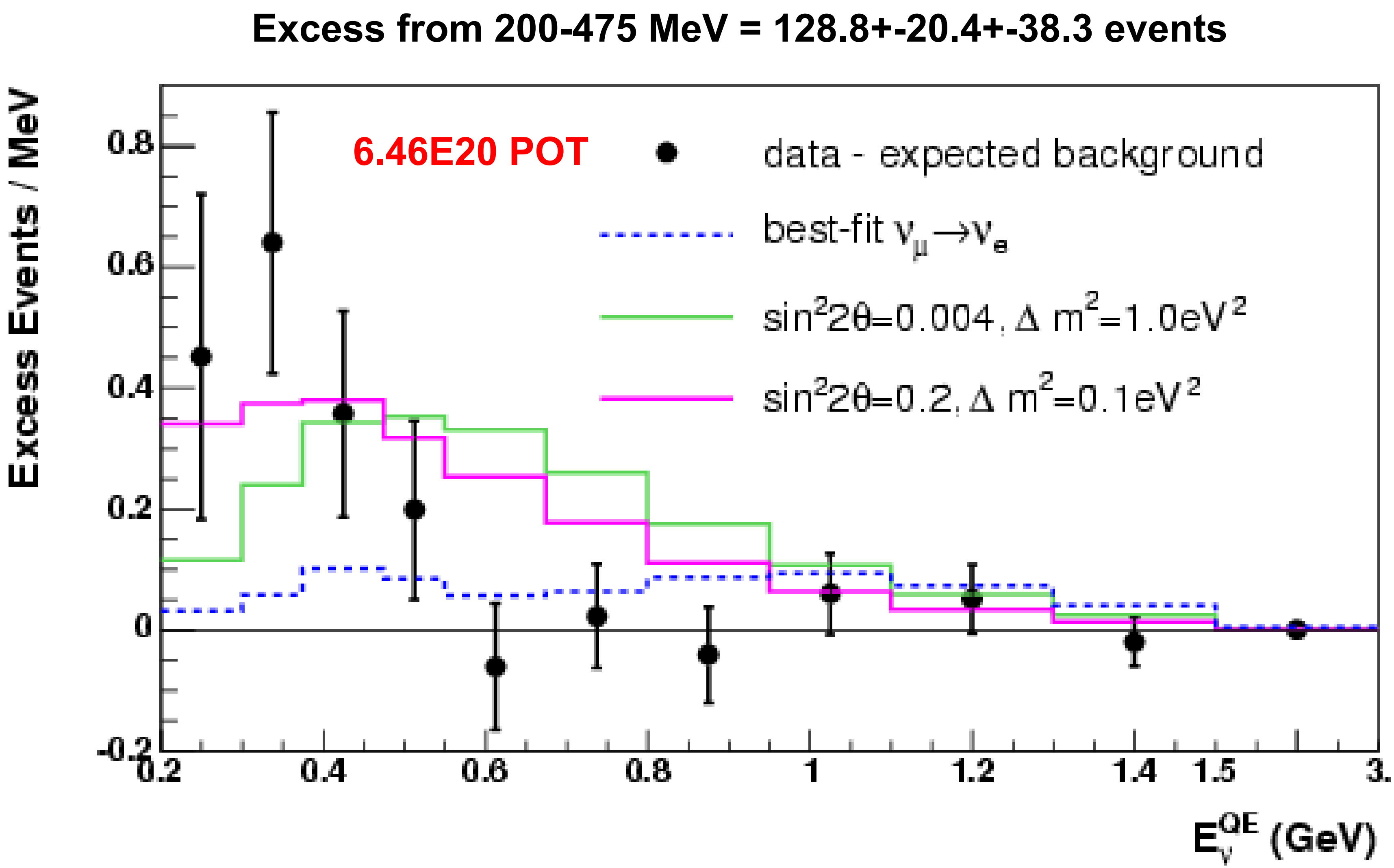
MiniBooNE observes a low-energy excess!

A.A. Aguilar-Arevalo et al., Phys. Rev. Lett. 98, 231801 (2007);
A.A. Aguilar-Arevalo et al., Phys. Rev. Lett. 102, 101802 (2009)



MiniBooNE ν_e appearance data show a low-energy excess

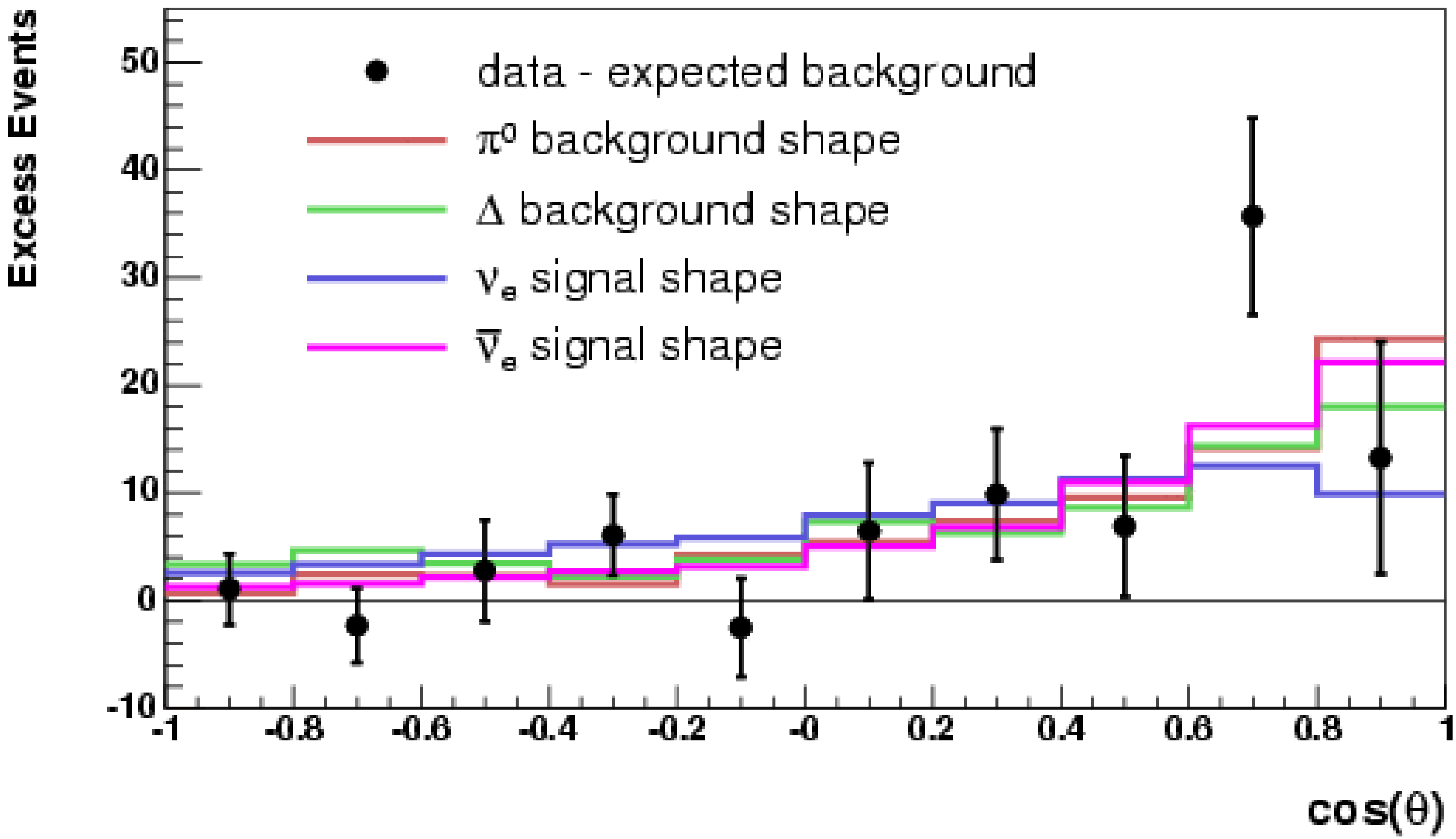
A.A. Aguilar-Arevalo et al., PRL 102, 101802 (2009)



Number of Excess Events

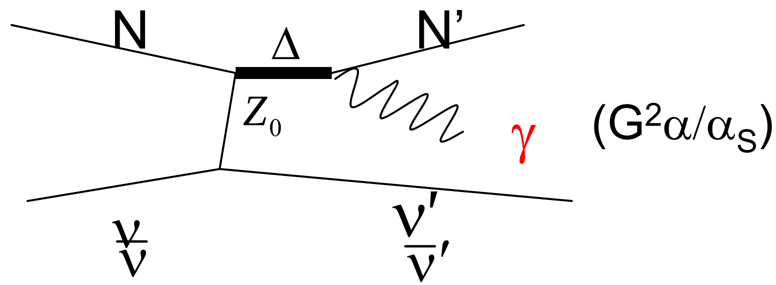
Energy (MeV)	Data	Background	Excess	$\#\sigma_{tot}$ ($\#\sigma_{stat}$)
200-300	232	186.8+-26.0	45.2+-13.7+-22.1	1.7 (3.3)
300-475	312	228.3+-24.5	83.7+-15.1+-19.3	3.4 (5.5)
200-475	544	415.2+-43.4	128.8+-20.4+-38.3	3.0 (6.3)
475-1250	408	385.9+-35.7	22.1+-19.6+-29.8	0.6 (1.1)
200-1250	952	801.0+-58.1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

Low-energy excess vs cosθ

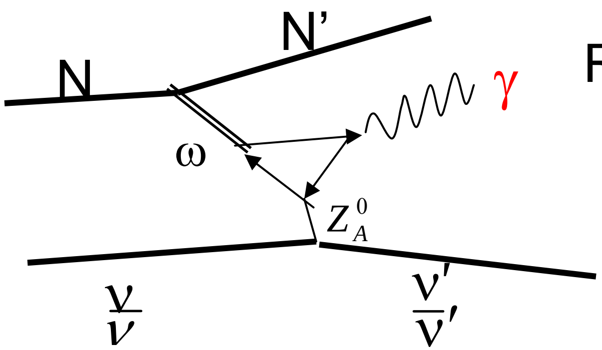


Backgrounds: Order ($G^2\alpha\alpha_s$) , single photon FS?

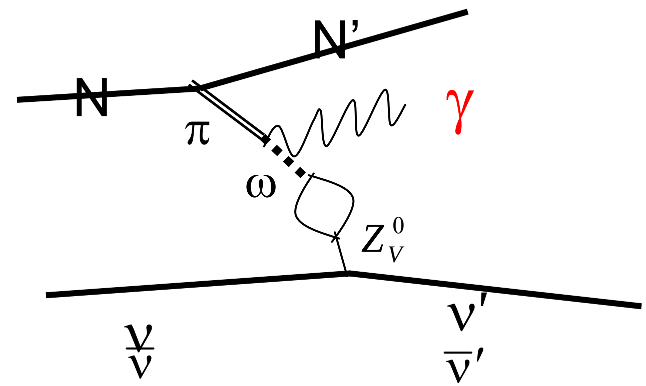
Dominant process accounted for in MC!



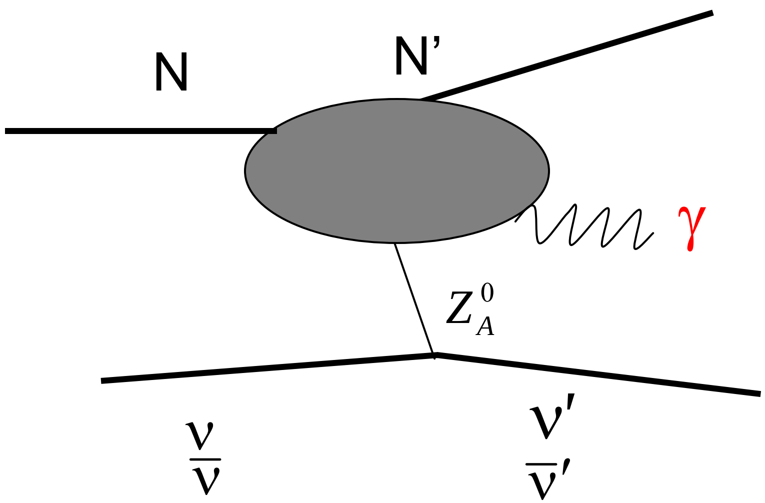
Radiative Delta Decay



Axial Anomaly



Other PCAC



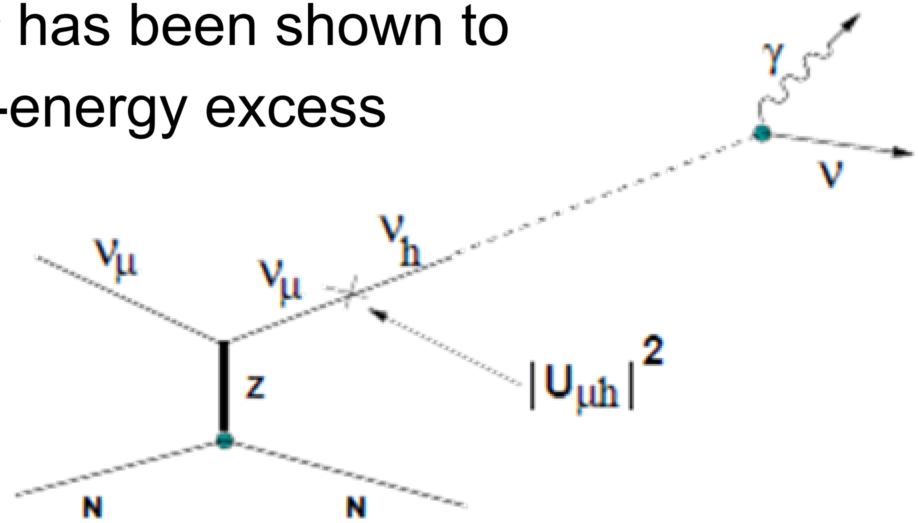
So far no one has found a NC process to account for the $\nu, \bar{\nu}$ difference & the ν low-energy excess. Work is in progress:

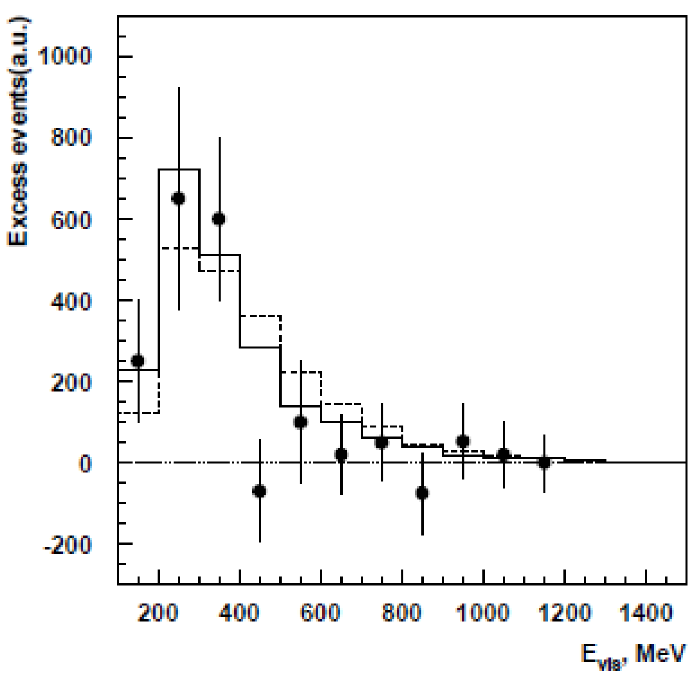
R. Hill, arXiv:0905.0291

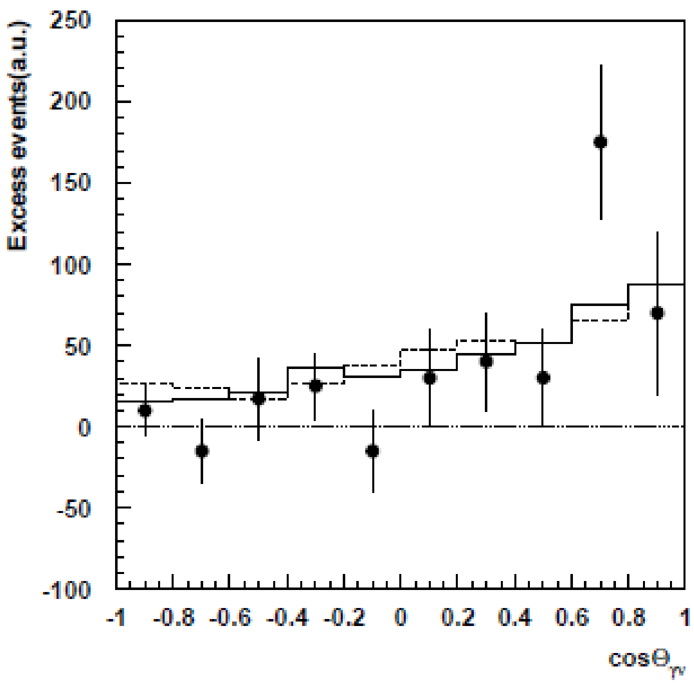
Jenkins & Goldman, arXiv:0906.0984

Sterile ν Decay?

- The decay of a ~500 MeV sterile ν has been shown to accommodate the MiniBooNE low-energy excess
  - **Gninenko, PRL 103, 241802 (2009)**

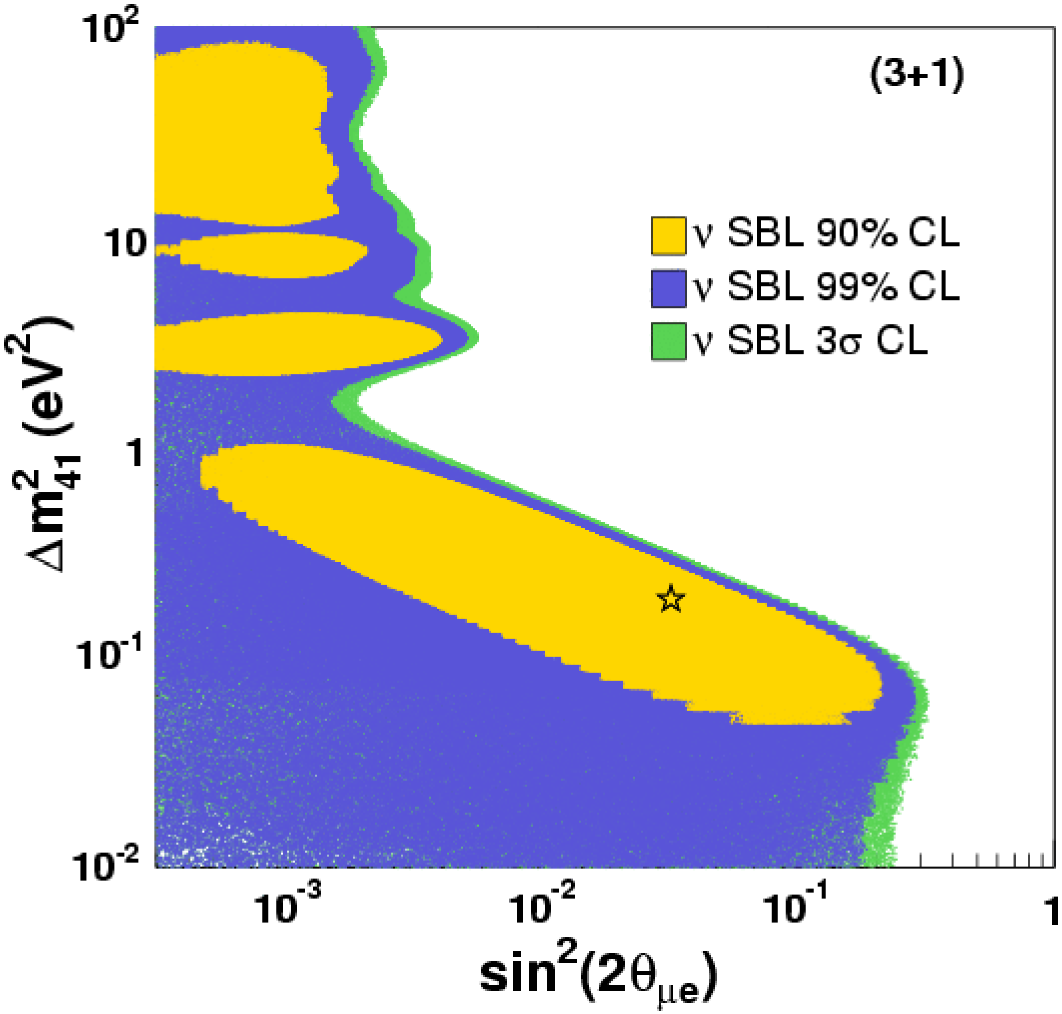






More Complicated ν Oscillations?

3+1 Global Fit to World Neutrino Data Only

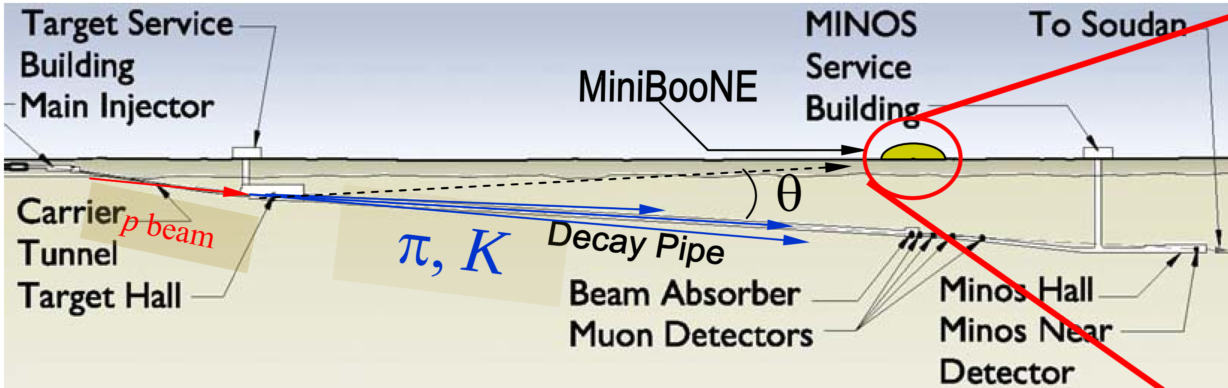


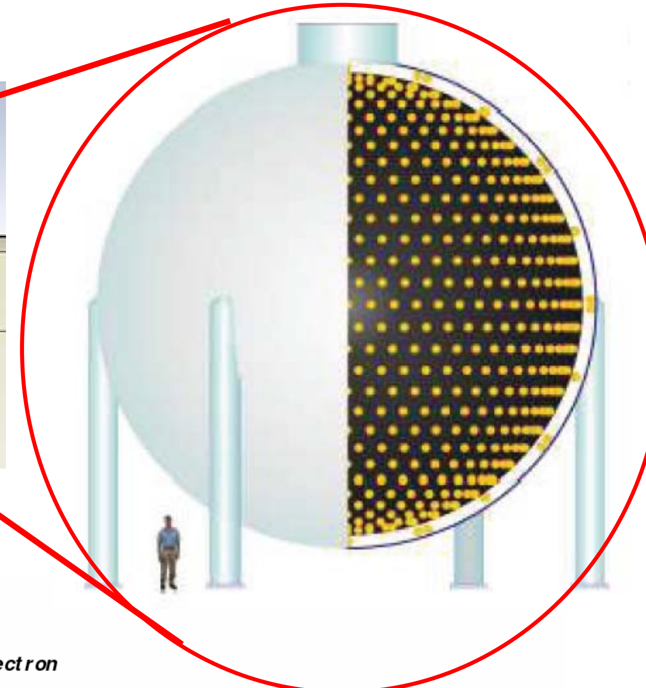
G. Karagiorgi et al., arXiv:0906.1997

Best 3+1 Fit:
$\Delta m_{41}^2 = 0.19$ eV^2
$\sin^2 2\theta_{\mu e} = 0.031$
$\chi^2 = 90.5/90$ DOF
Prob. = 46%

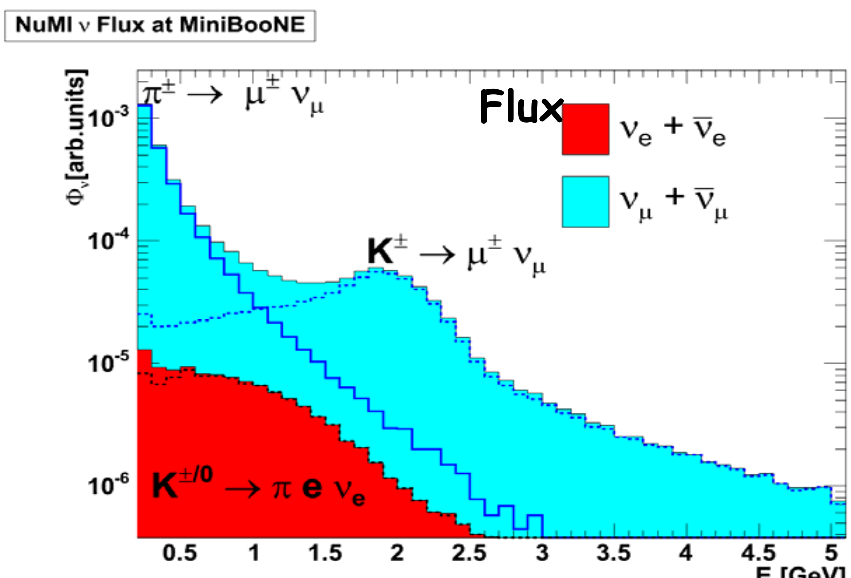
Predicts ν_μ & ν_e disappearance of $\sin^2 2\theta_{\mu\mu} \sim 3.1\%$ and $\sin^2 2\theta_{ee} \sim 3.4\%$

Events from NuMI Directed at MiniBooNE

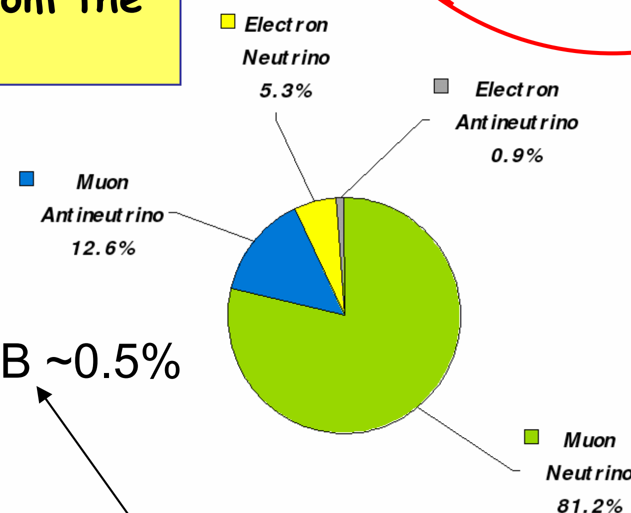




MiniBooNE detector is 745 meters downstream of NuMI target.
MiniBooNE detector is 110 mrad off-axis from the target along NuMI decay pipe.



Energy similar to MB as off angle



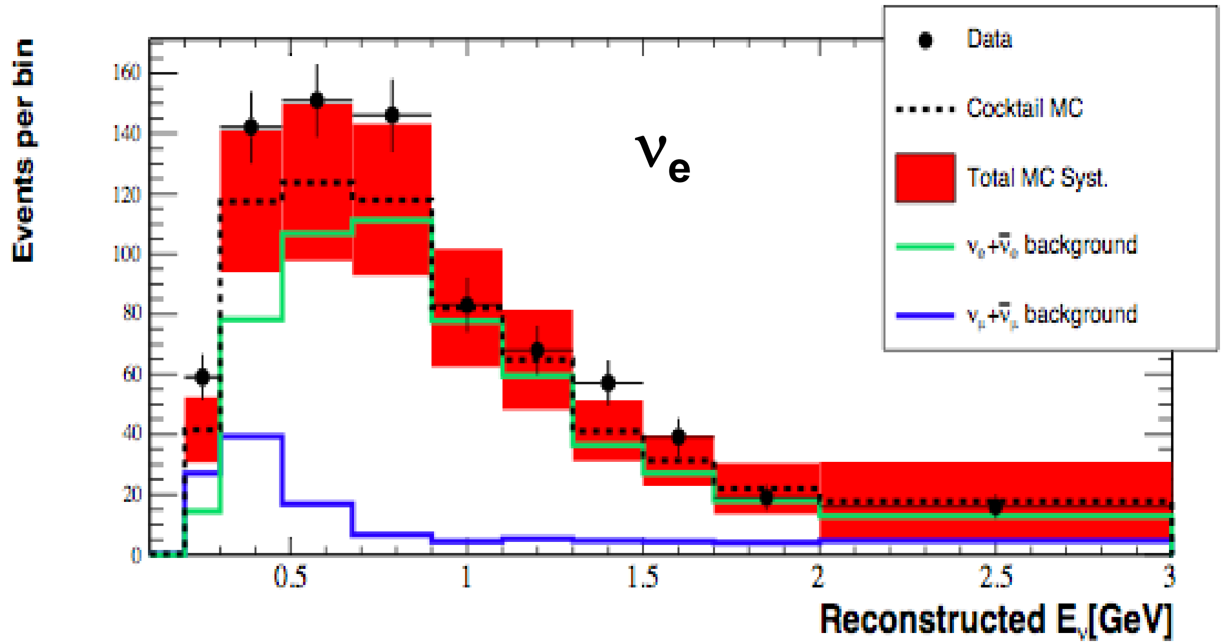
Event rates

MB ~0.5%

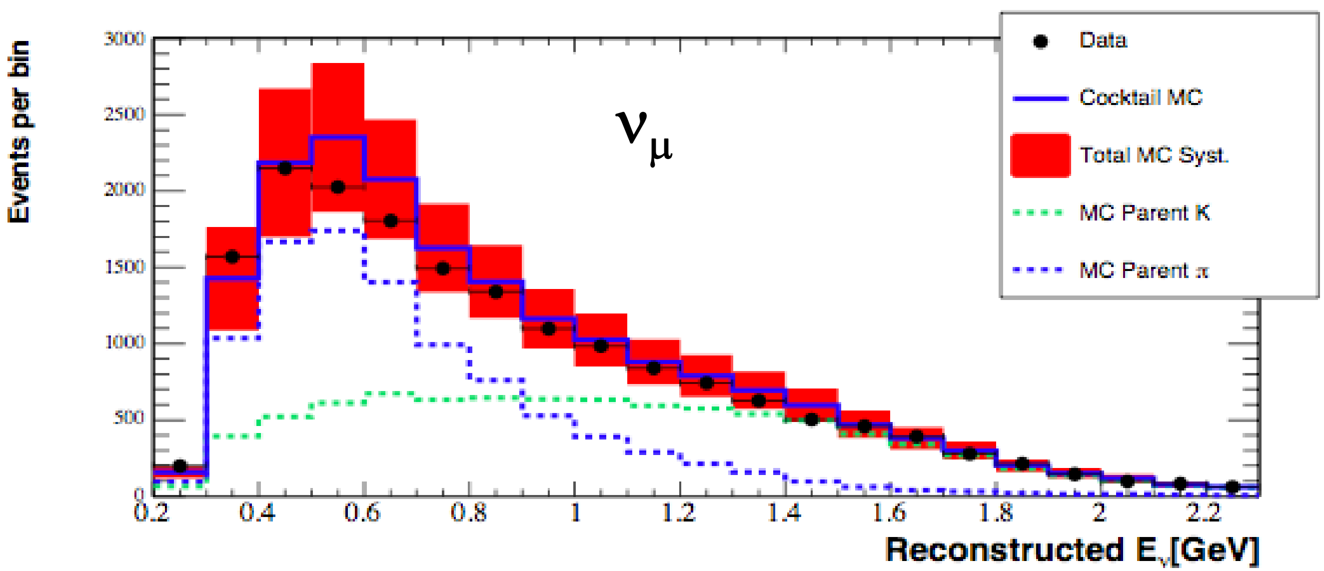
NuMI event composition at MB
ν_μ-81%, ν_e-5%, $\bar{\nu}_\mu$-13%, $\bar{\nu}_e$-1%

Excess Also Observed in NuMI Data!

P. Adamson et al., PRL 102, 211801 (2009)



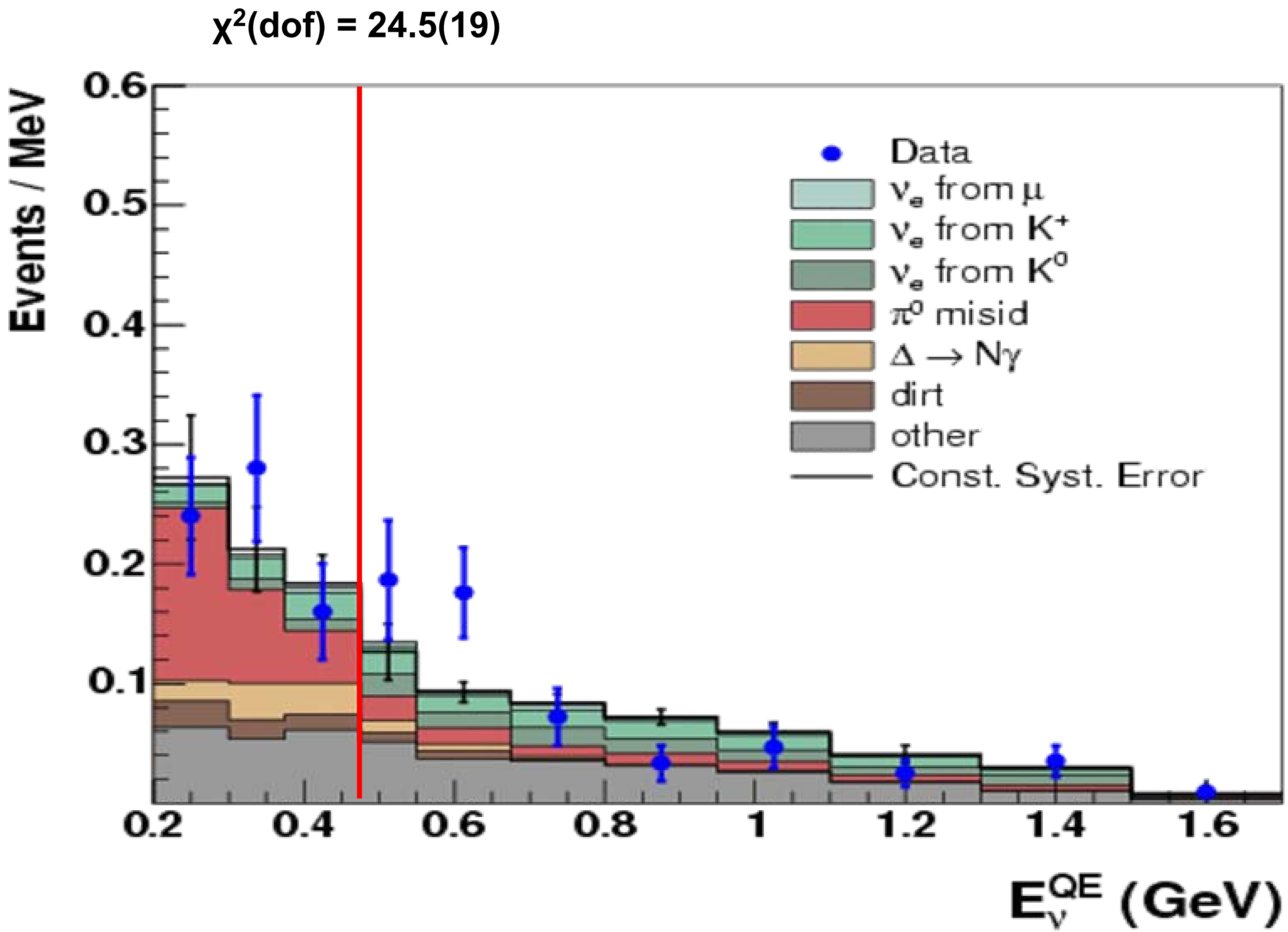
Systematic errors will be reduced plus 3x as much data.



$\bar{\nu}_e$ Appearance 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 ~ 5.5E20 POT.)
- Approximately 0.1×10^6 antineutrino events recorded. (An order of magnitude fewer antineutrino events than neutrino events.)
- Antineutrino analysis is the same as the neutrino analysis.

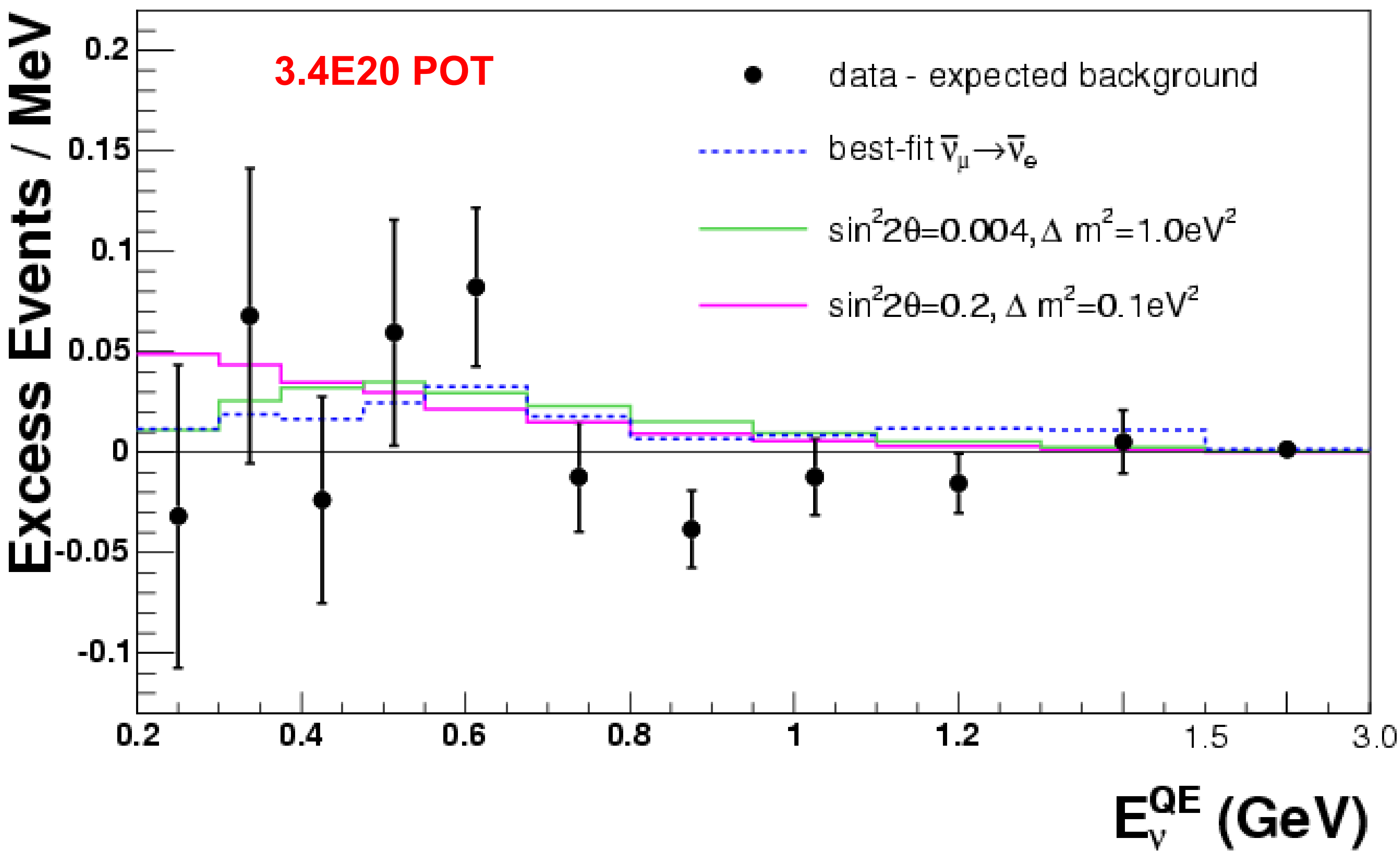
Antineutrino Results (3.39e20POT)



MiniBooNE $\bar{\nu}_e$ appearance data are inconclusive at present but are consistent so far with LSND

A.A. Aguilar-Arevalo et al., PRL 103, 111801 (2009)

Excess from 200-475 MeV = -0.5 ± 7.8 ± 8.7 events



Antineutrino Statistics & Oscillation Fit

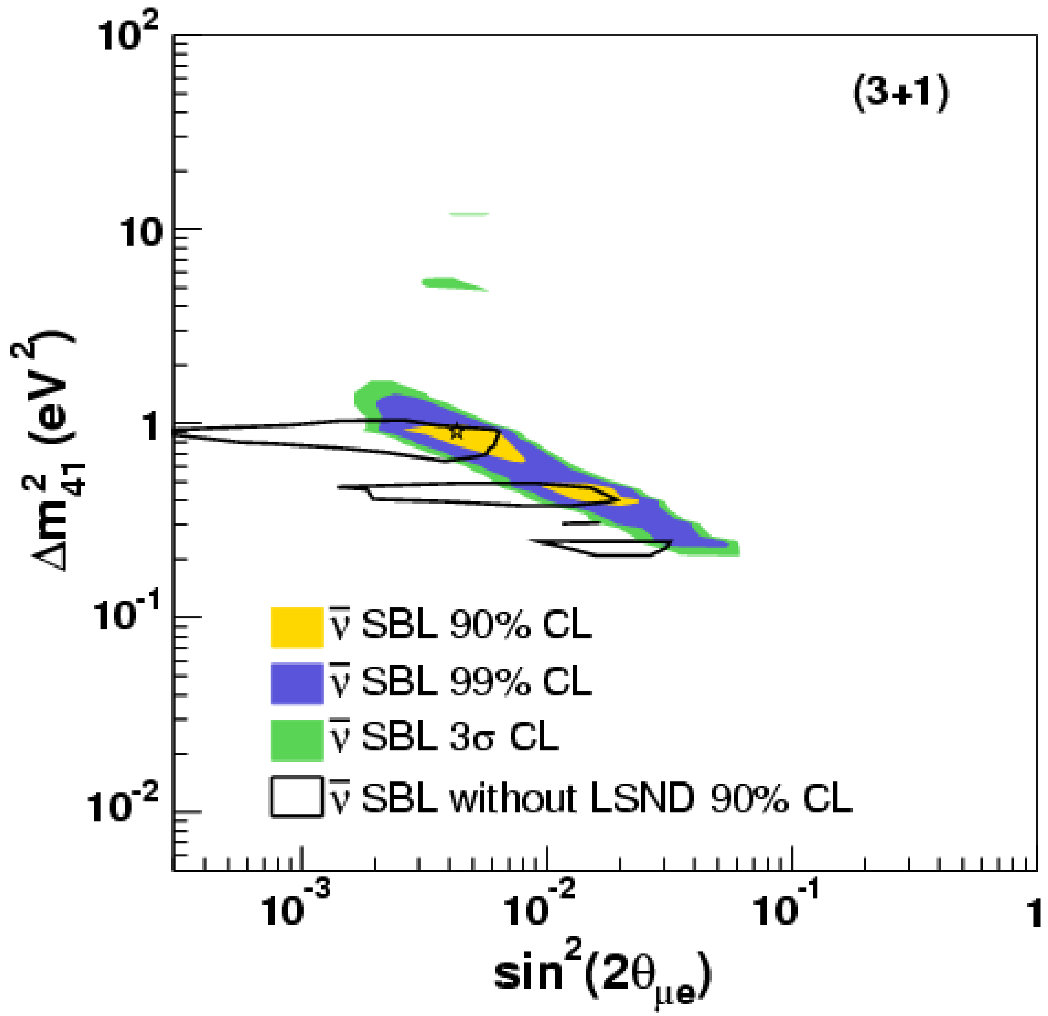
Energy (MeV)	Data	MC	Excess	
475-3000	83	77.4+-13.0	5.6+-13.0	(0.4 σ)
Best Fit			18.6+-13.2	(1.4 σ)
LSND Expect.			14.7	

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

Best fit: Δm2 = 4.4 eV^2, sin$^2 2\theta$ = 0.004

LSND Best Fit: Δm^2 = 1.2 eV^2, sin$^2 2\theta$ = 0.003

3+1 Global Fit to World Antineutrino Data

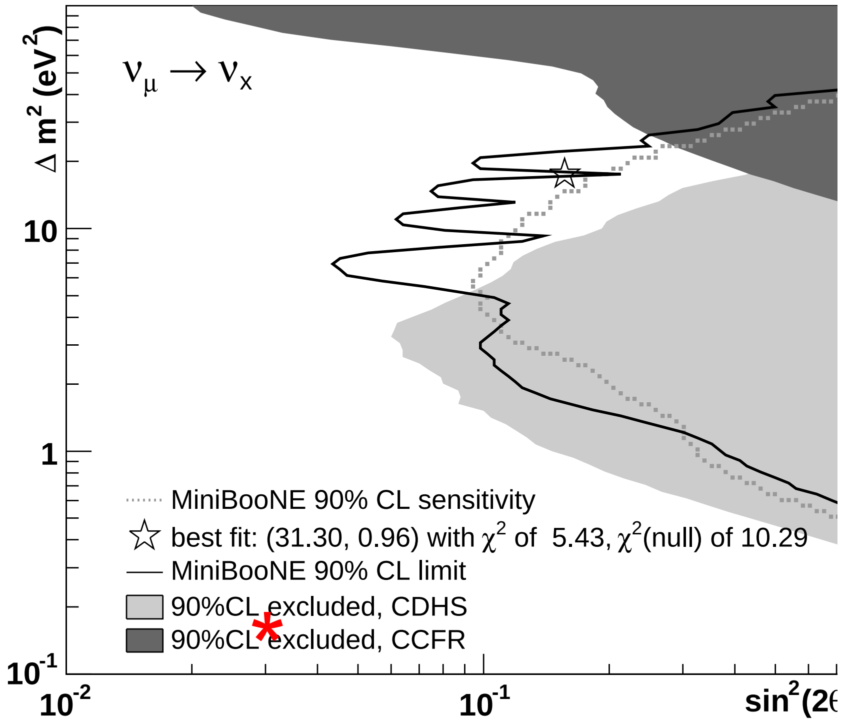


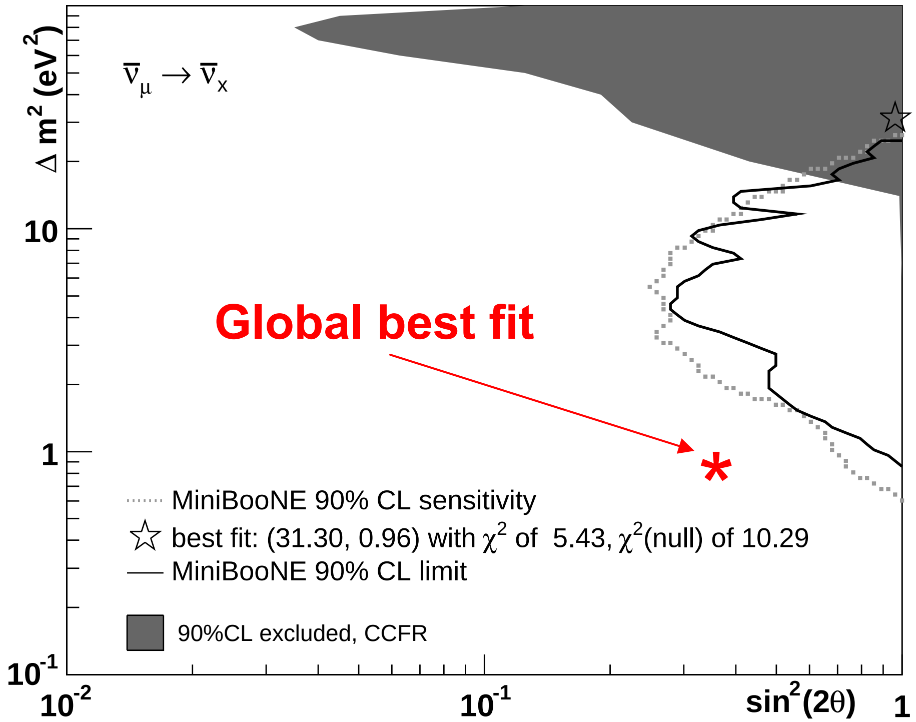
G. Karagiorgi et al., arXiv:0906.1997

Best 3+1 Fit:
Δm_{41}^2 = 0.915 eV^2
$\sin^2 2\theta_{\mu e}$ = 0.0043
χ^2 = 87.9/103 DOF
Prob. = 86%

Predicts $\overline{\nu_\mu}$ & $\overline{\nu_e}$ disappearance of $\sin^2 2\theta_{\mu\mu}$ ~ 35% and $\sin^2 2\theta_{ee}$ ~ 4.3%

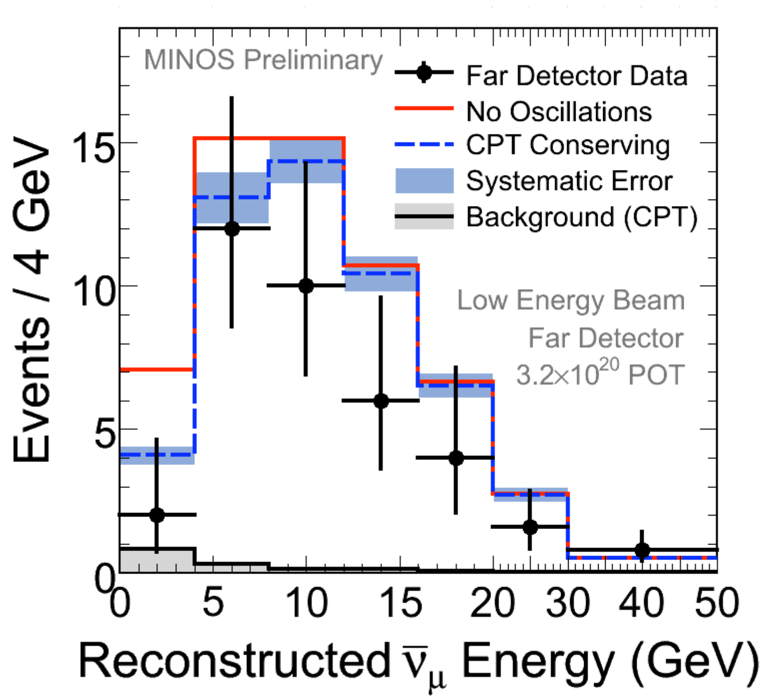
A.A. Aguilar-Arevalo et al., PRL 103, 061802 (2009)

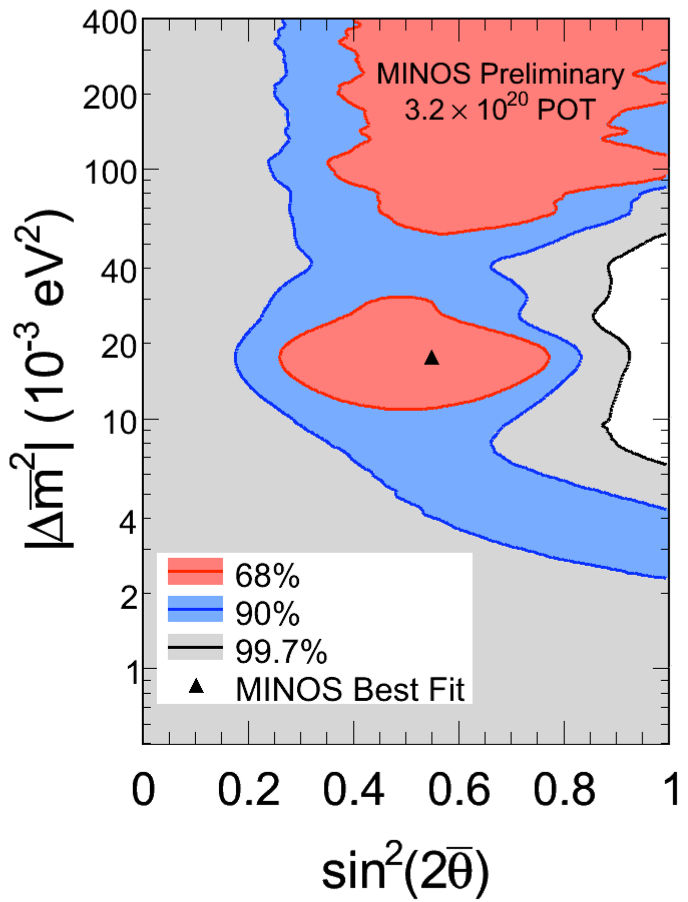




Improved results soon from MiniBooNE/SciBooNE Joint Analysis!

Initial MINOS $\overline{\nu}_\mu$ Disappearance Results





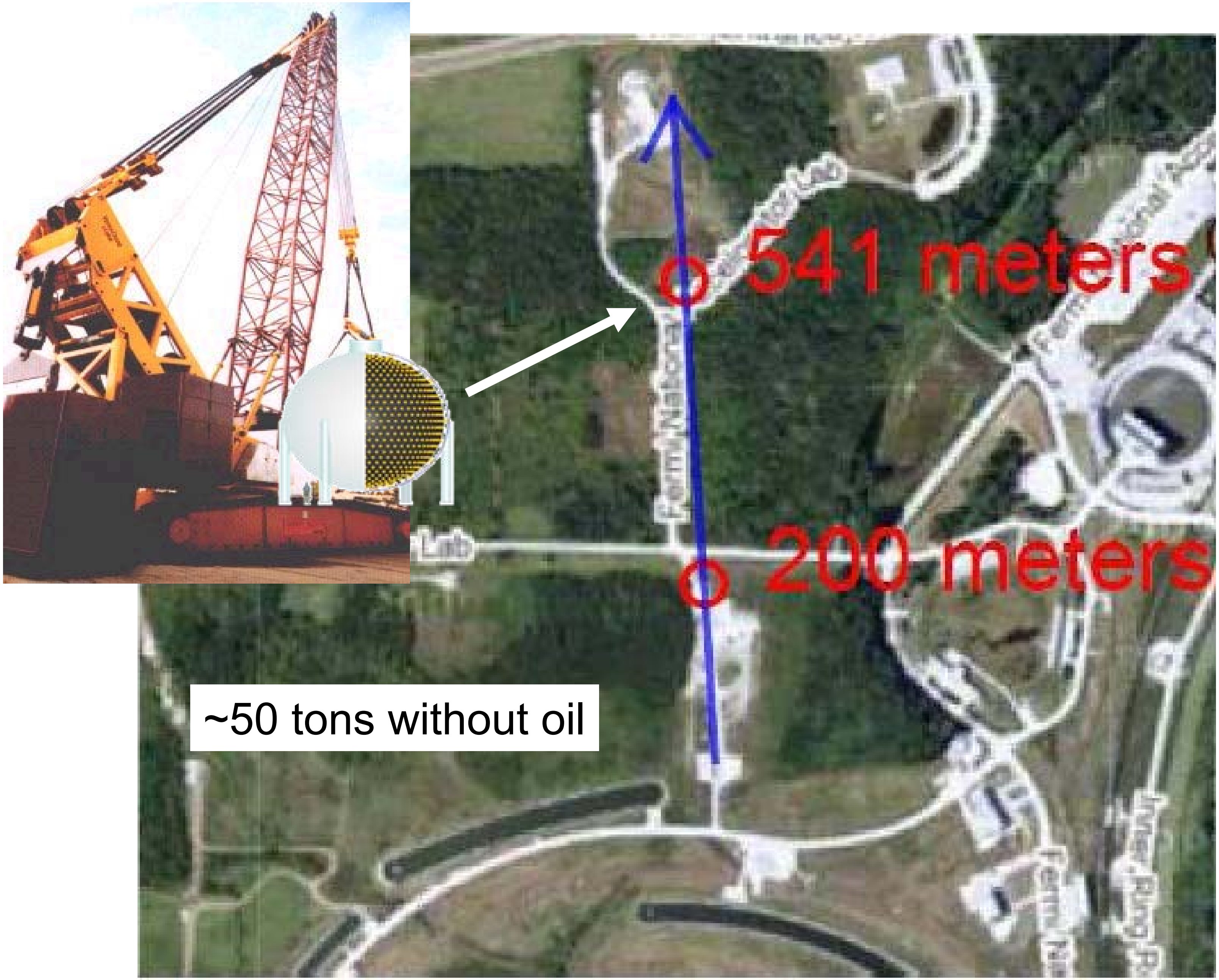
Expect $\overline{\nu}_\mu$ disappearance above 10 GeV for LSND neutrino oscillations.

Future

- Collect more antineutrino data! (~5.5E20 POT at present, ~6E20 POT for Neutrino 2010, & ~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.
- 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. a NC γ process) or to Physics Beyond the Standard Model (e.g. sterile neutrinos with CP or CPT violation or sterile neutrino decay)

Move MiniBooNE: BooNE

Move MiniBooNE: BooNE



Move MiniBooNE: BooNE

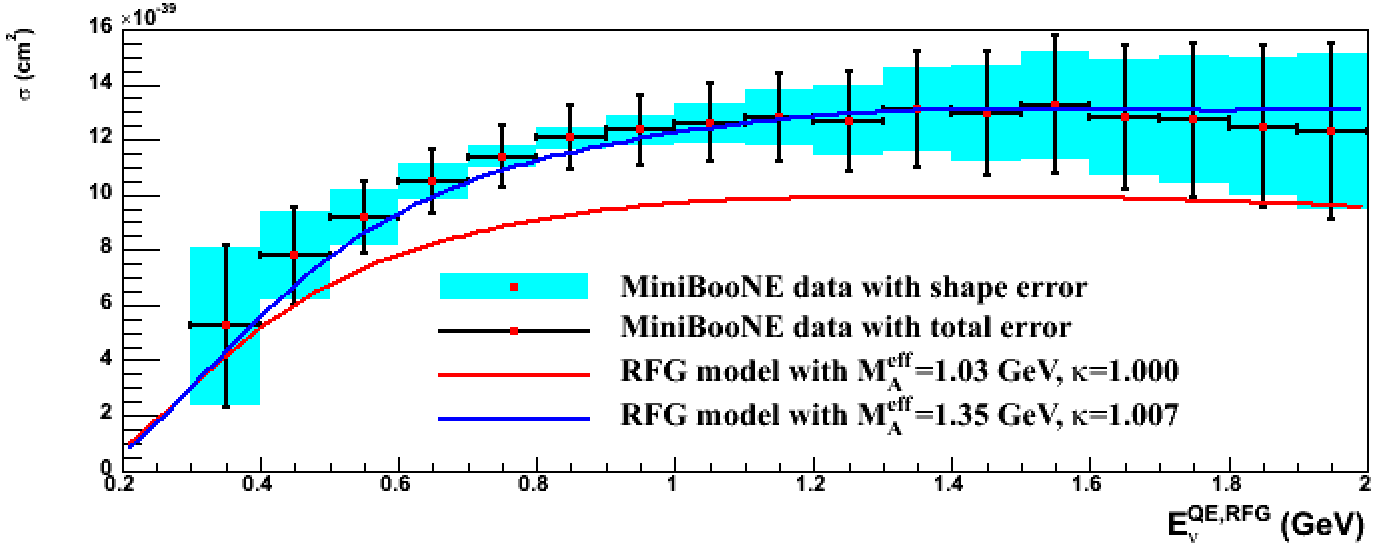
Move MiniBooNE: BooNE

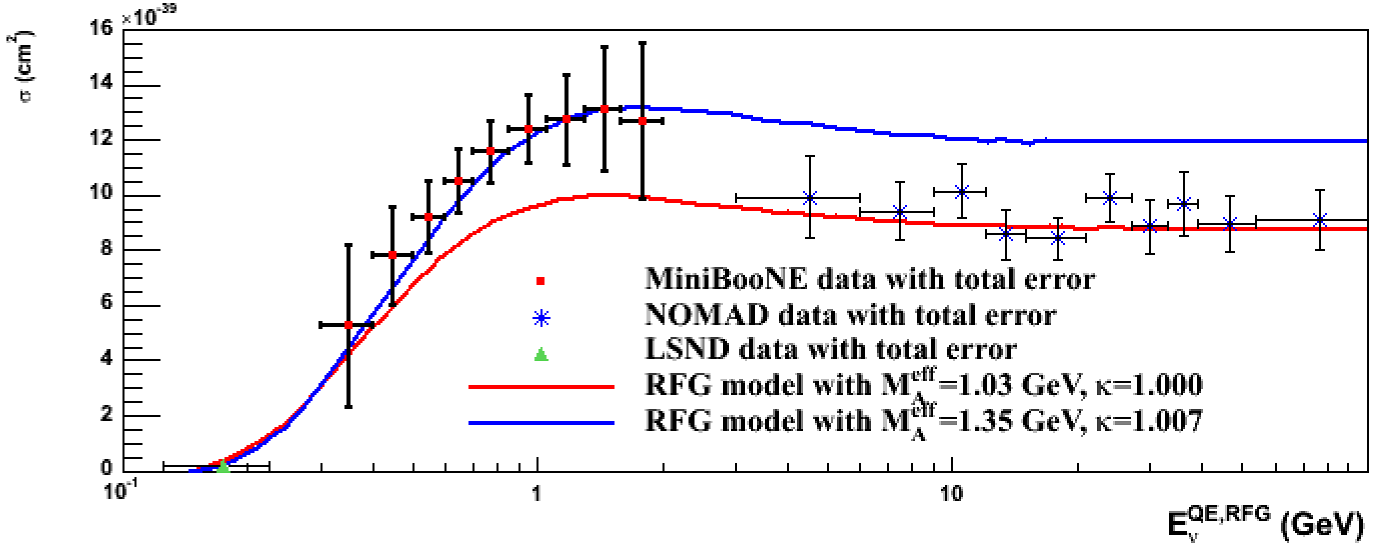
Conclusion

- **MiniBooNE observes an unexplained excess at low energies, which could be due to ν oscillations, sterile ν decay, or to NCγ scattering. No large low-energy excess is observed so far in antineutrino mode.**
- **All antineutrino data fit well to a simple 3+1 model. (LSND is alive & well!) However, there is tension between neutrino & antineutrino data. (CPT Violation?)**
- **The global fit to the world antineutrino data predicts large $\bar{\nu}_\mu$ disappearance, which will be tested soon by MINOS and SciBooNE/MiniBooNE.**
- **BooNE, which involves building a near MiniBooNE detector, will be able to exploit the data taken in the far detector (the hard part!) and determine whether there is large $\bar{\nu}_\mu$ disappearance and whether the MiniBooNE low-energy excess is due to ν oscillations.**
- **Thorough understanding of this short-baseline physics is of great importance to long-baseline ν oscillation experiments. BooNE would be a small investment to ensure their success!**

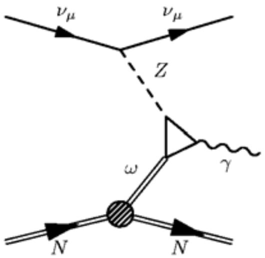
Backup Slides

ν_μ CCQE Scattering





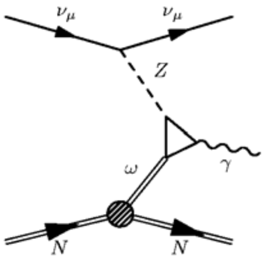
Possible Explanations for the Low-Energy Excess



- **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!

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**
- **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!

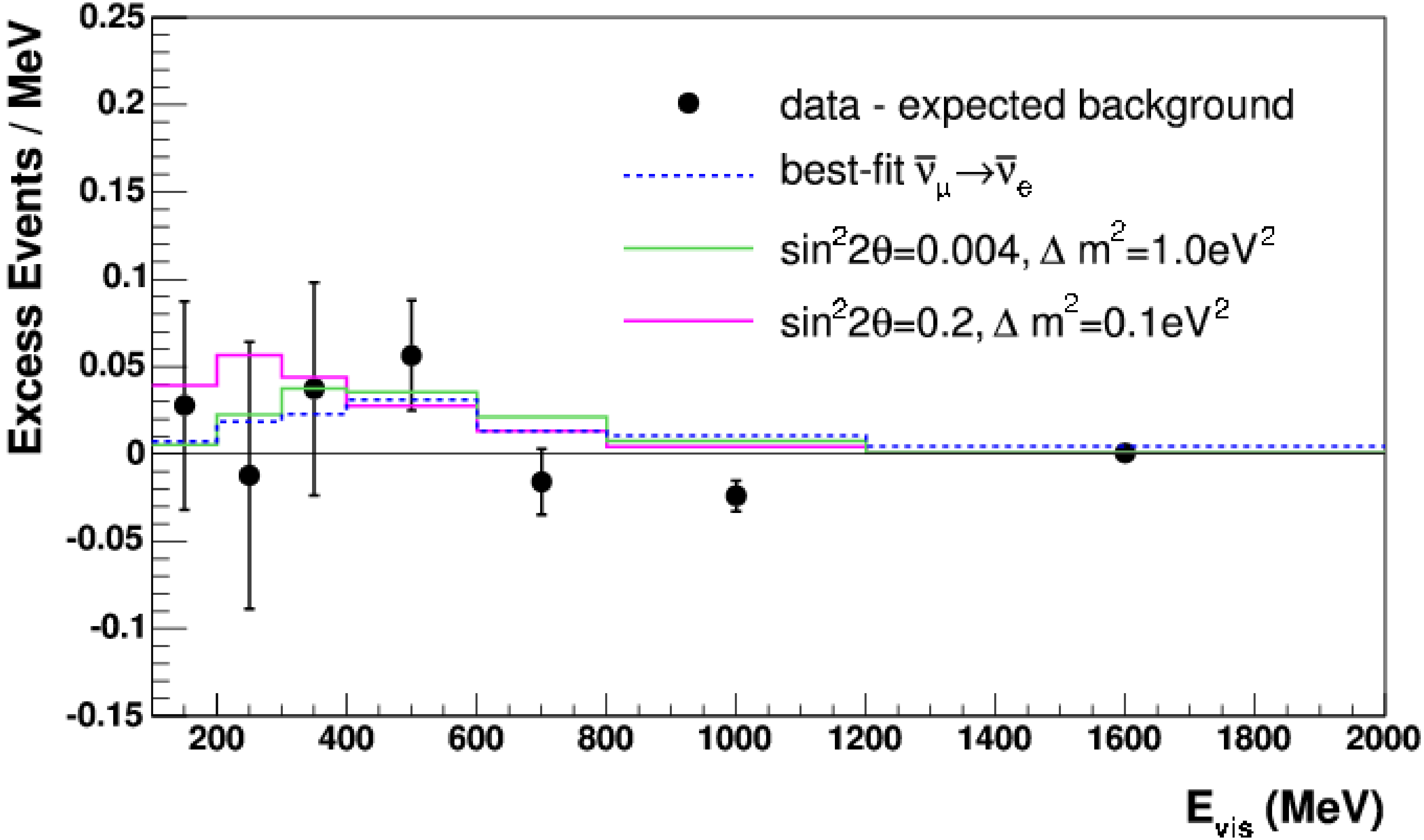
Implications for Low-E Excess (E<475 MeV)

	Antineutrino	*Neutrino*
Data	*61*	*544*
MC ± sys+stat (constr.)	*61.5 ± 7.8 ± 8.7*	*415.2 ± 20.4 ± 38.3*
Excess (σ)	*-0.5 ± 7.8 ± 8.7 (-0.04σ)*	*128.8 ± 20.4 ± 38.3 (3.0σ)*

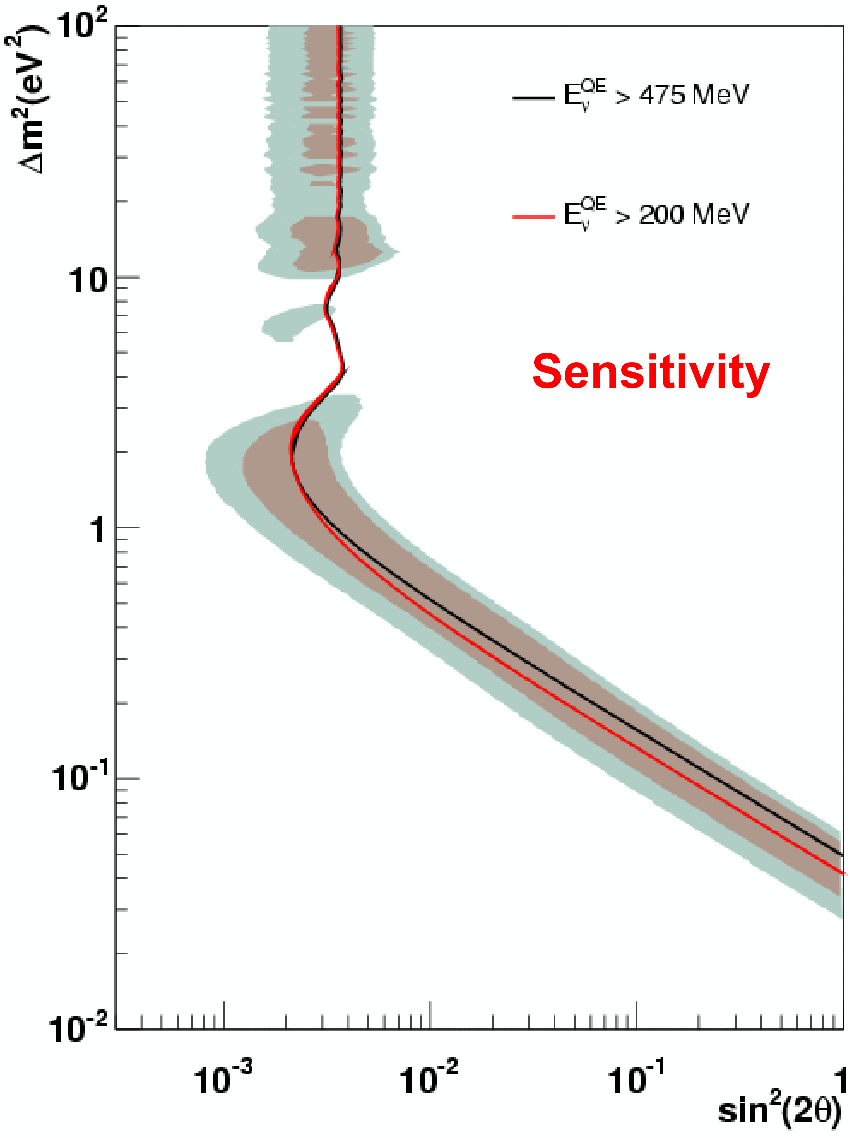
Hypothesis	Stat Only	Cor. Syst	Uncor. Syst	# $\bar{\nu}$ Expec.
Same $\nu,\bar{\nu}$ NC	0.1%	0.1%	6.7%	37.2
NC π^0 scaled	3.6%	6.4%	21.5%	19.4
POT scaled	0.0%	0.0%	1.8%	67.5
Bkgd scaled	2.7%	4.7%	19.2%	20.9
CC scaled	2.9%	5.2%	19.9%	20.4
Low-E Kaons	0.1%	0.1%	5.9%	39.7
* ν scaled	38.4%	51.4%	58.0%	6.7

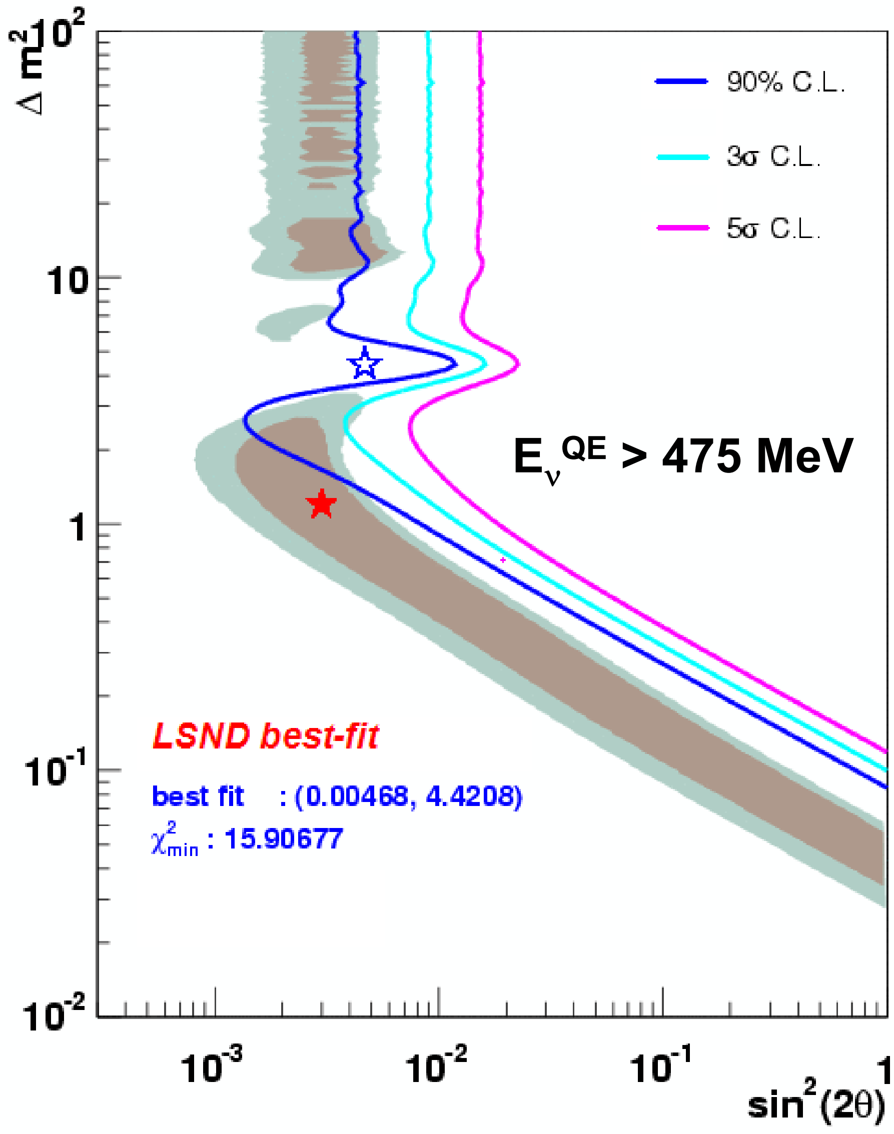
*** Best fit is where excess scales only with neutrino flux!**

Antineutrino Excess Events



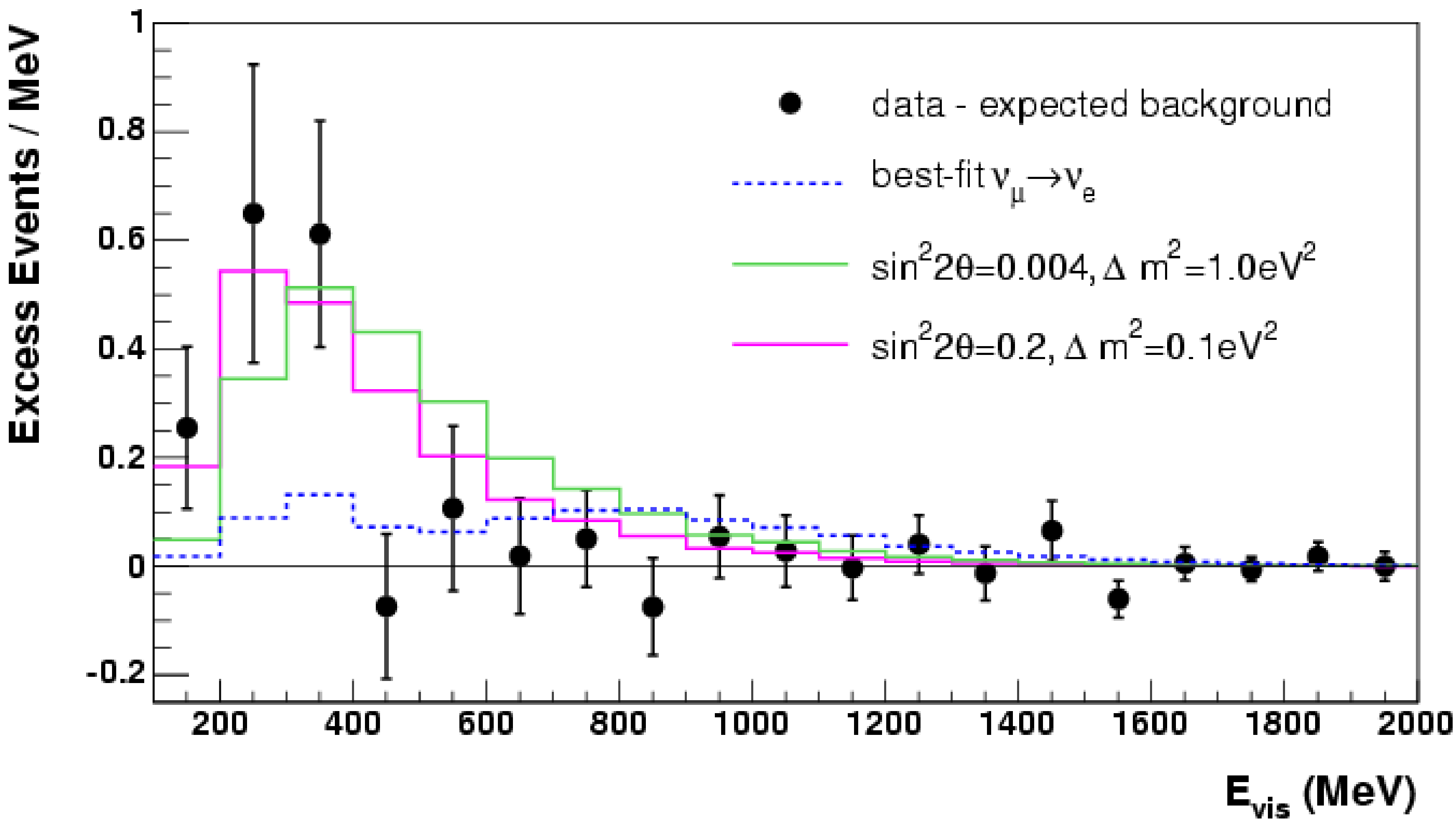
Antineutrino Allowed Region



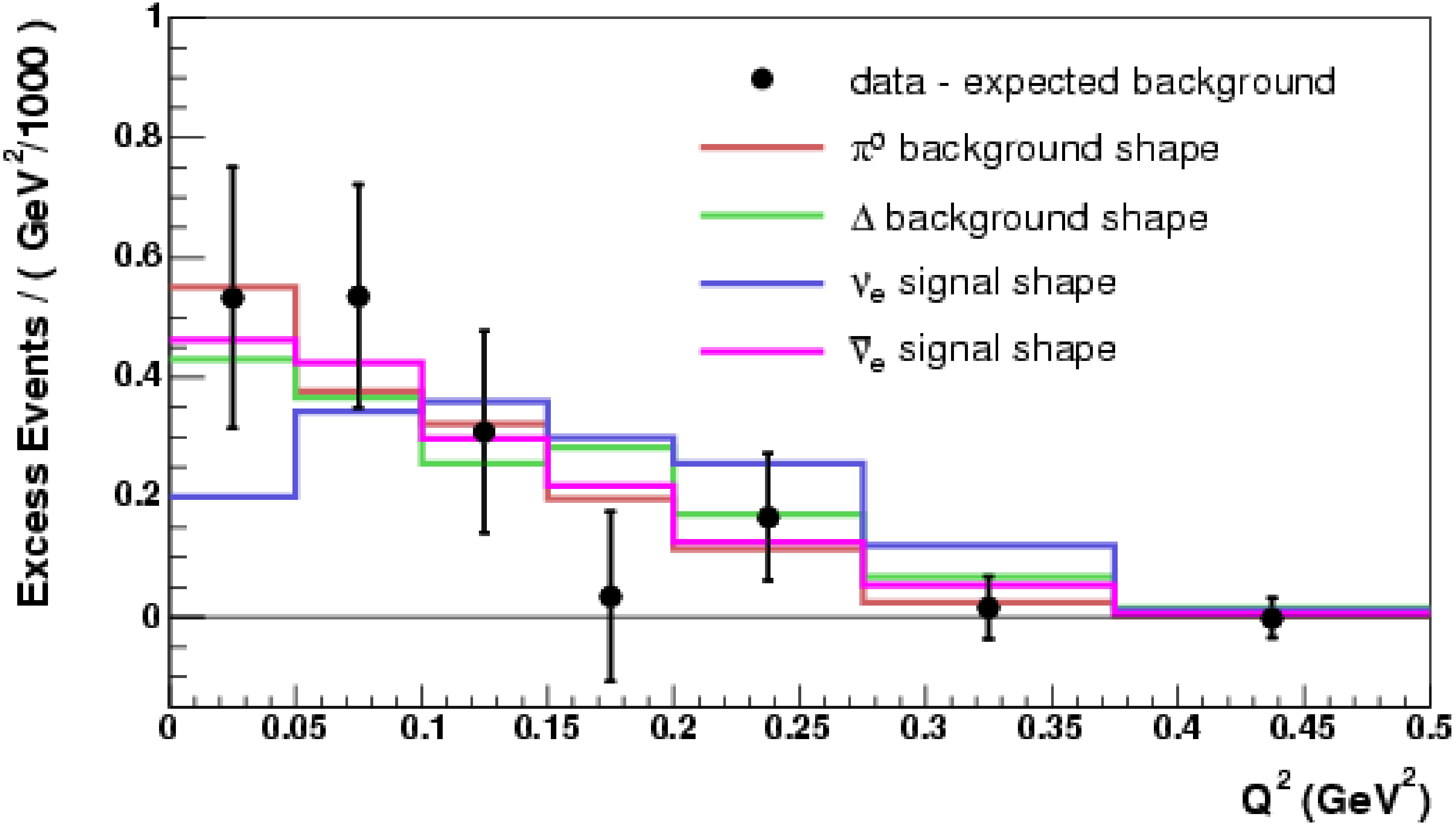


Low-energy excess vs E_{vis}

With E_ν^{QE} Best Fit (3.14 eV^2, 0.0017)



Low-energy excess vs Q^2



χ^2 Values from Data/MC Comparisons

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

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

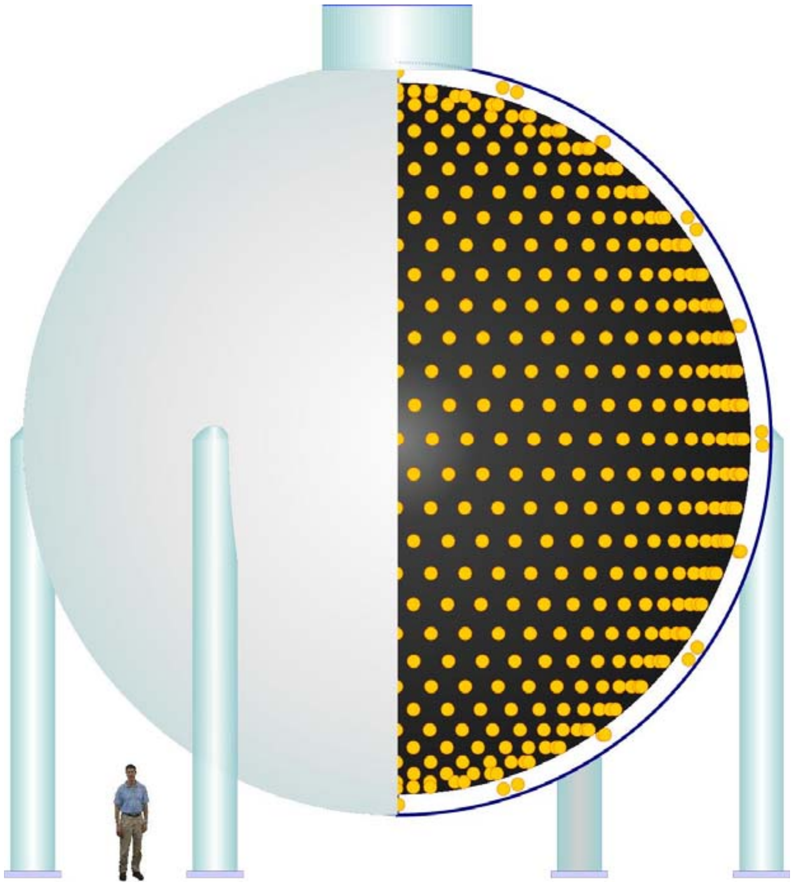
MiniBooNE

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

Neutrino Backgrounds

Background	200-300 MeV	300-475 MeV	475-1250 MeV
ν_μ CCQE	9.0	17.4	11.7
ν_μ e –> ν_μ e	6.1	4.3	6.4
NC π^0	103.5	77.8	71.2
Δ–>Nγ	19.5	47.5	19.4
External	11.5	12.3	11.5
Other	18.4	7.3	16.8
ν_e from μ	13.6	44.5	153.5
ν_e from K^+	3.6	13.8	81.9
ν_e from K_L	1.6	3.4	13.5
Total Bkgd	186.8+-26.0	228.3+-24.5	385.9+-35.7

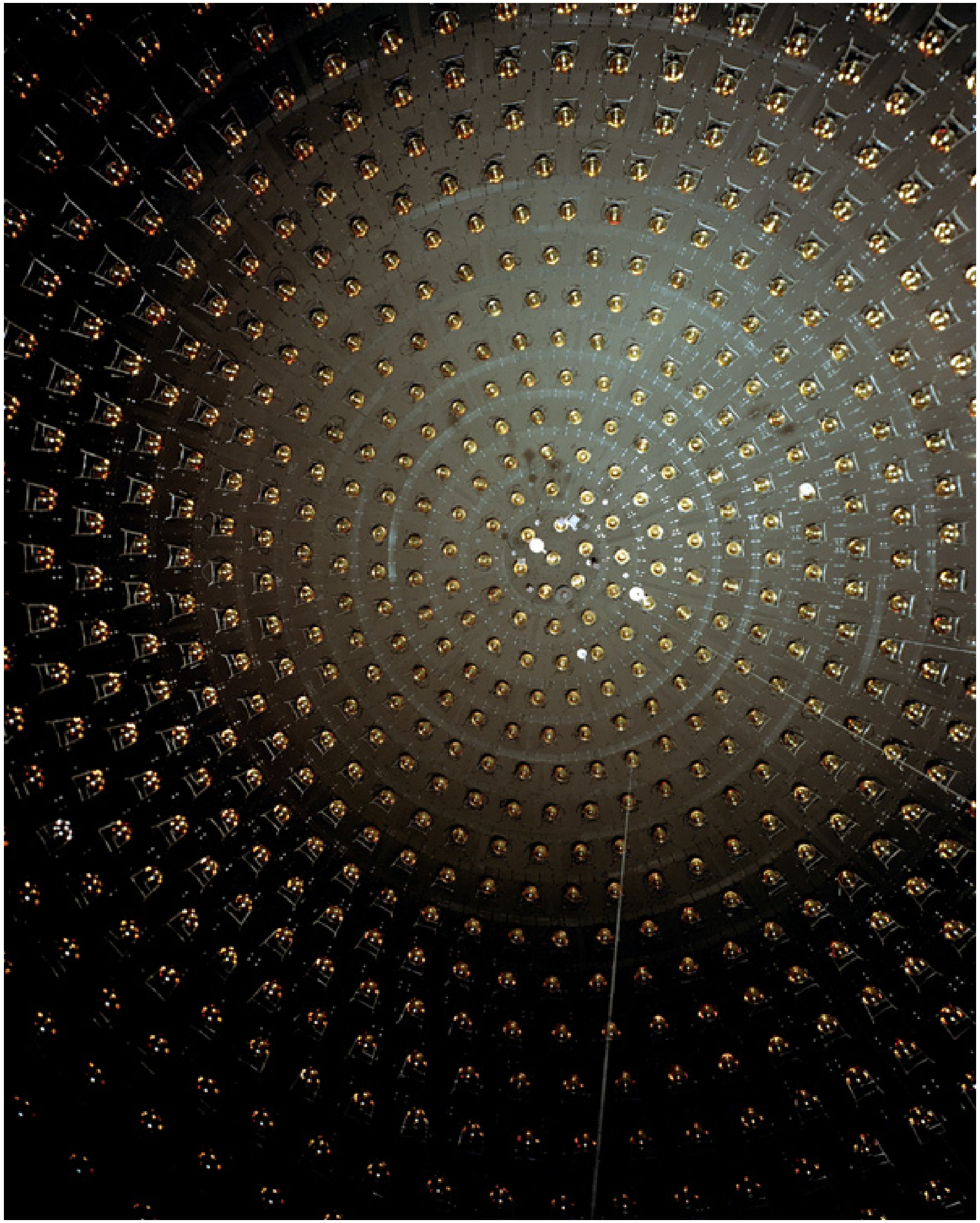
The MiniBooNE Detector



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

    (10 meter "fiducial" volume)

    - Filled with 800 t of pure mineral oil (CH_2) (Fiducial volume: 450 t)
    - 1280 inner phototubes, 240 veto phototubes
    - Simulated with a GEANT3 Monte Carlo



10% Photocathode coverage

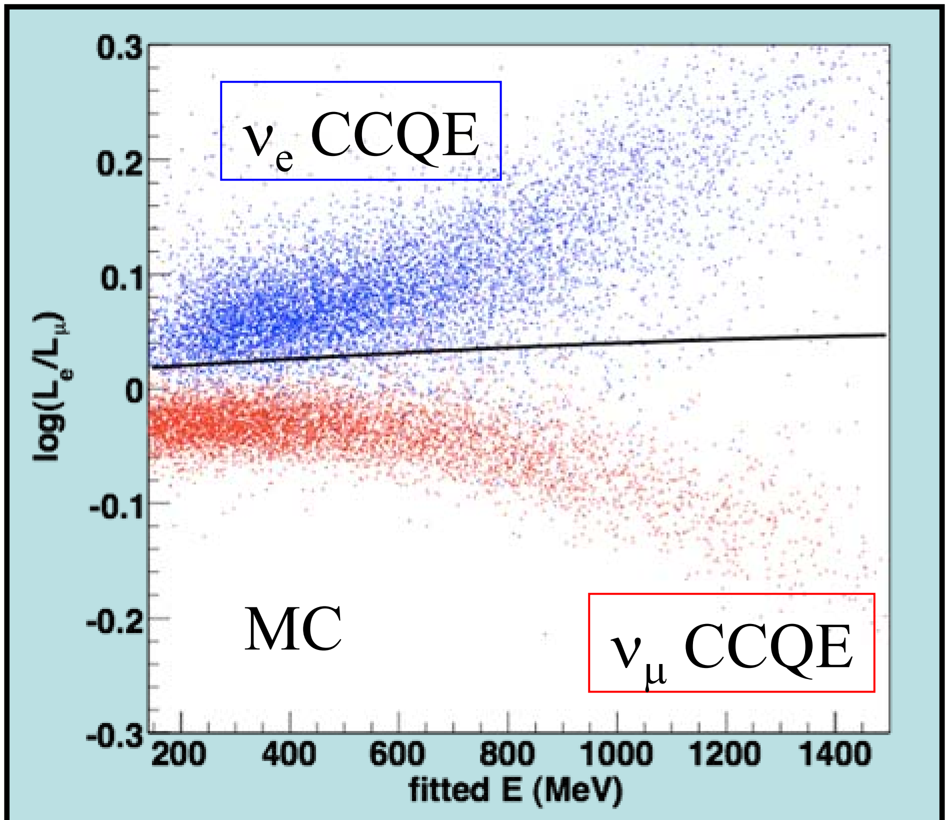
Two types of Hamamatsu Tubes: R1408, R5912

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/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

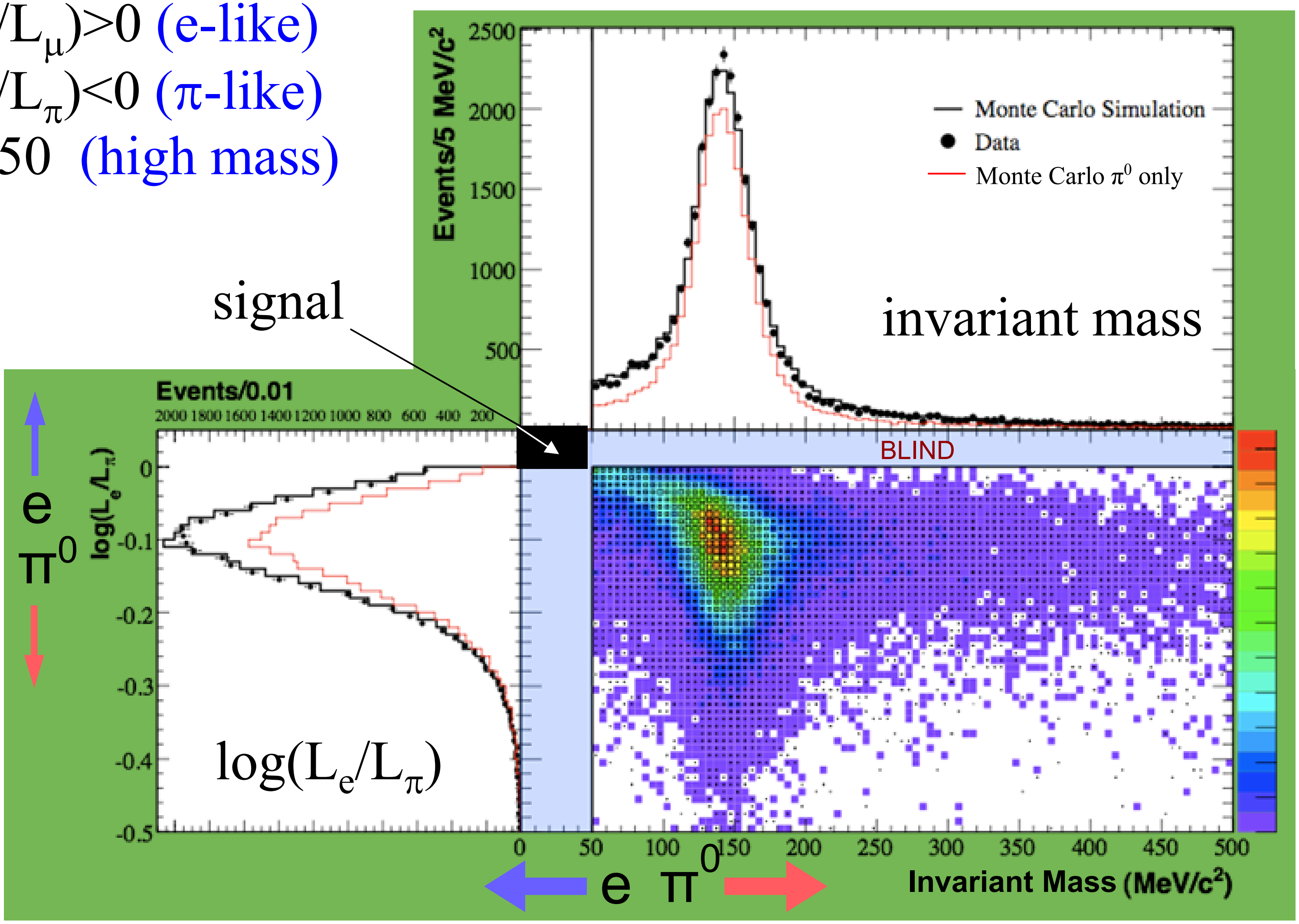
Testing e-π^0 separation using <u>data</u>

1 subevent

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

$\log(L_e/L_\pi)<0$ (π-like)

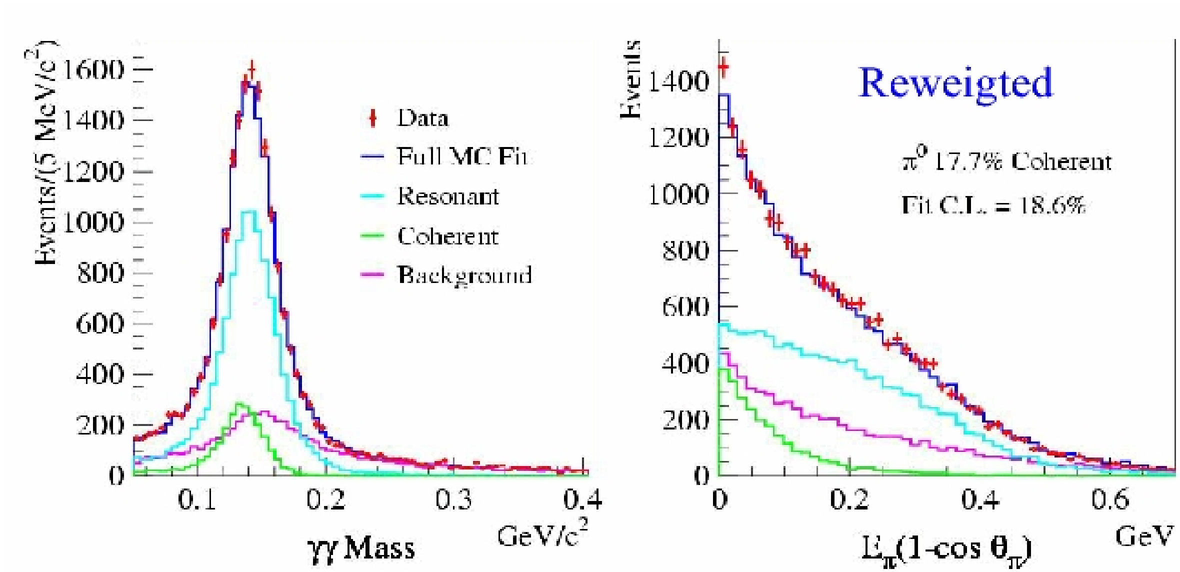
mass>50 (high mass)



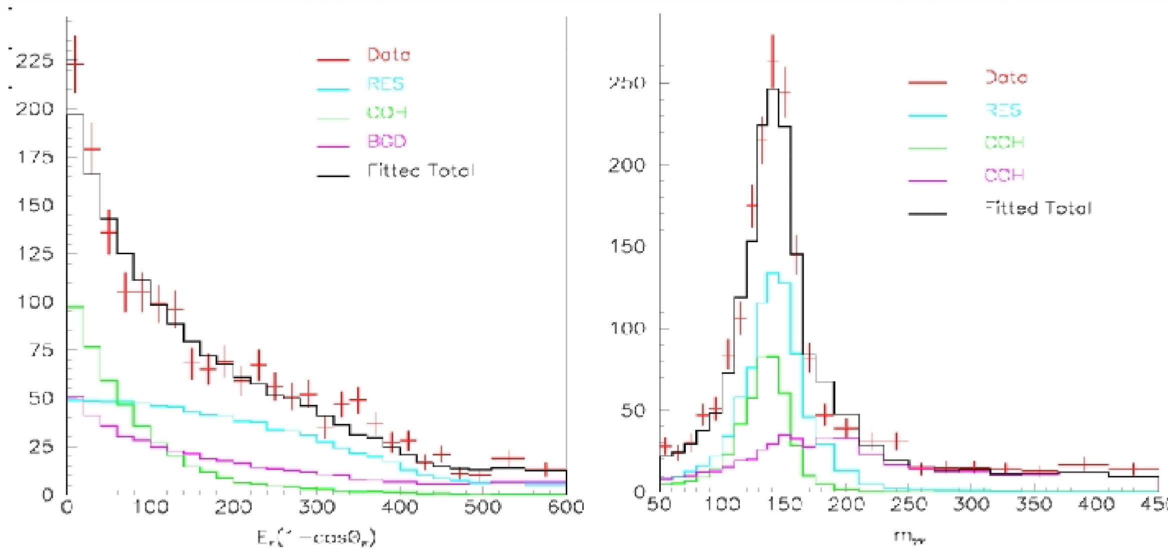
Neutral Current π^0 Scattering

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 (π^0, $\Delta \rightarrow N\gamma$, 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, $\Delta \rightarrow N\gamma$, 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.

(Re)Measuring the π^0 rate versus π^0 momentum

- Fit invariant mass peak in each momentum range
- $\Delta \rightarrow N\gamma$ also constrained

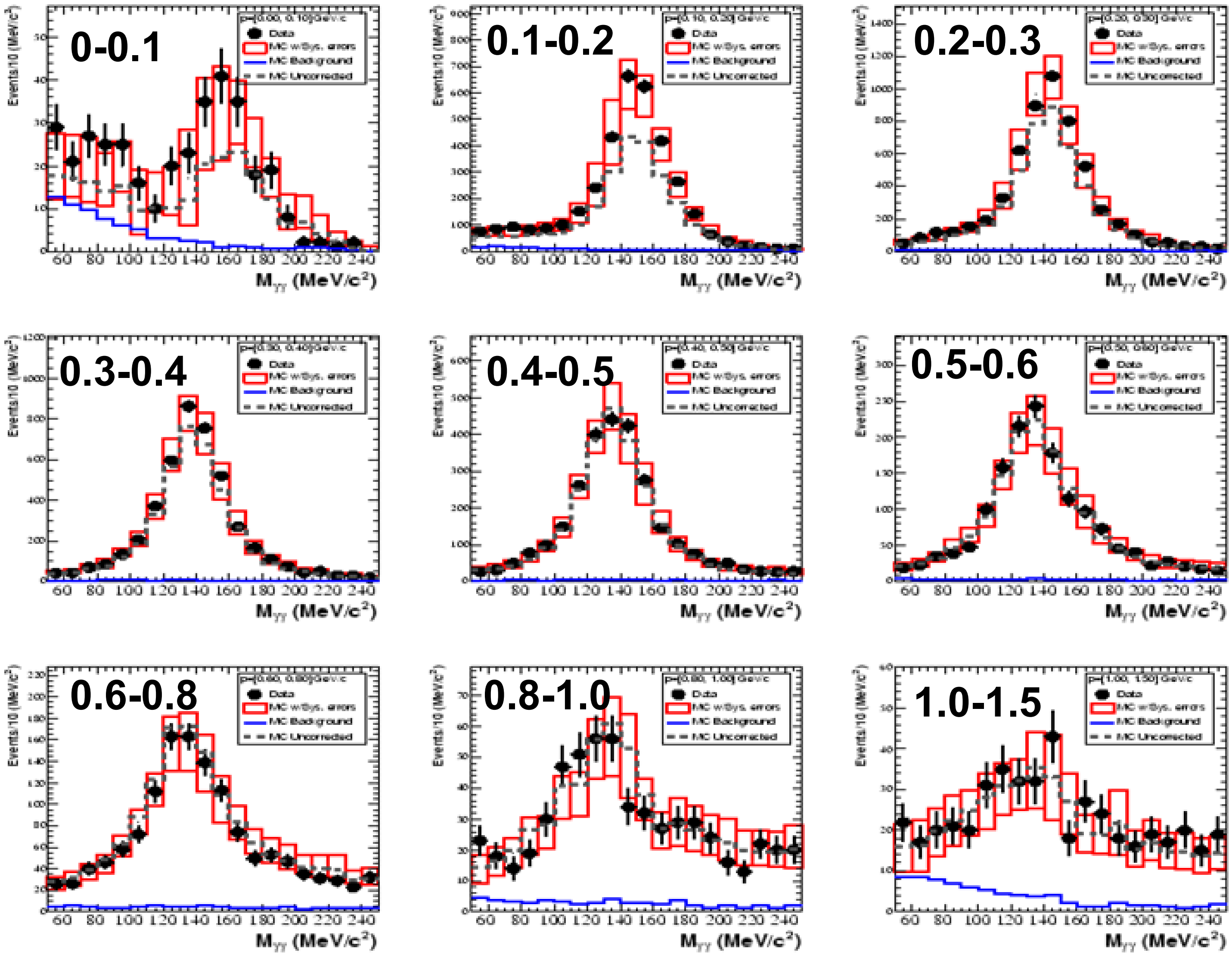
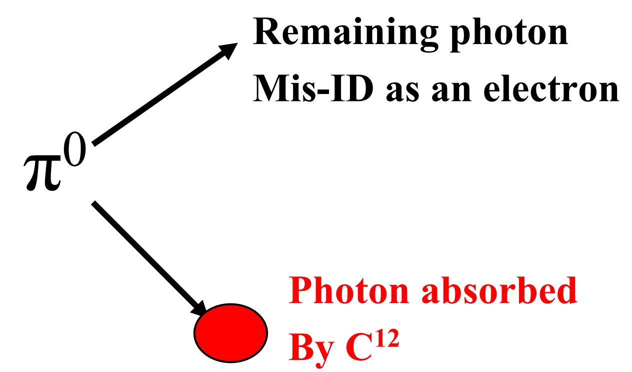


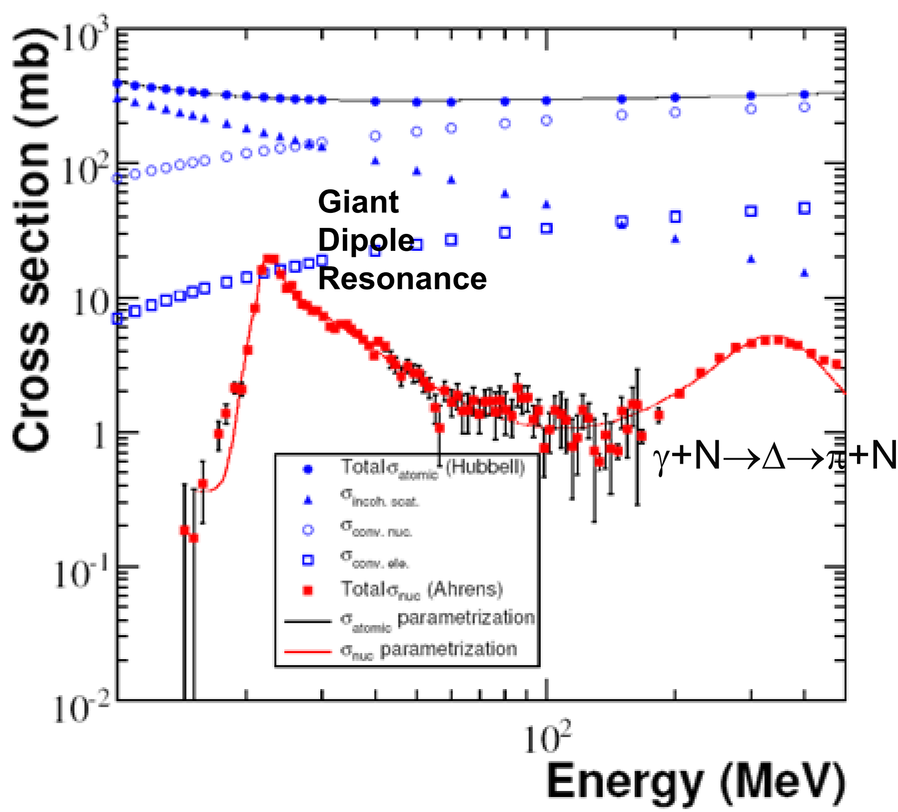
Photo-nuclear absorption of π^0 photon

A single γ 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.*

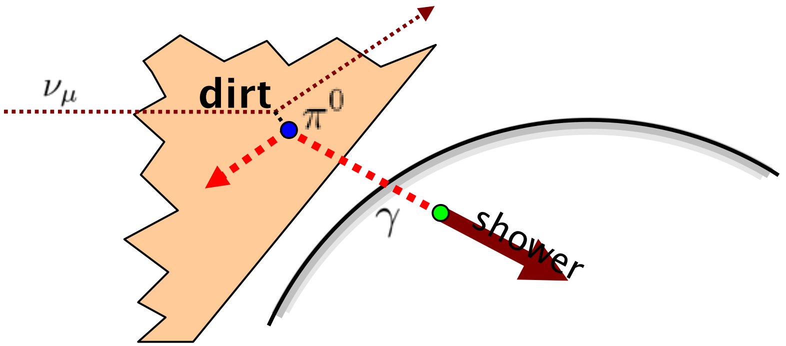


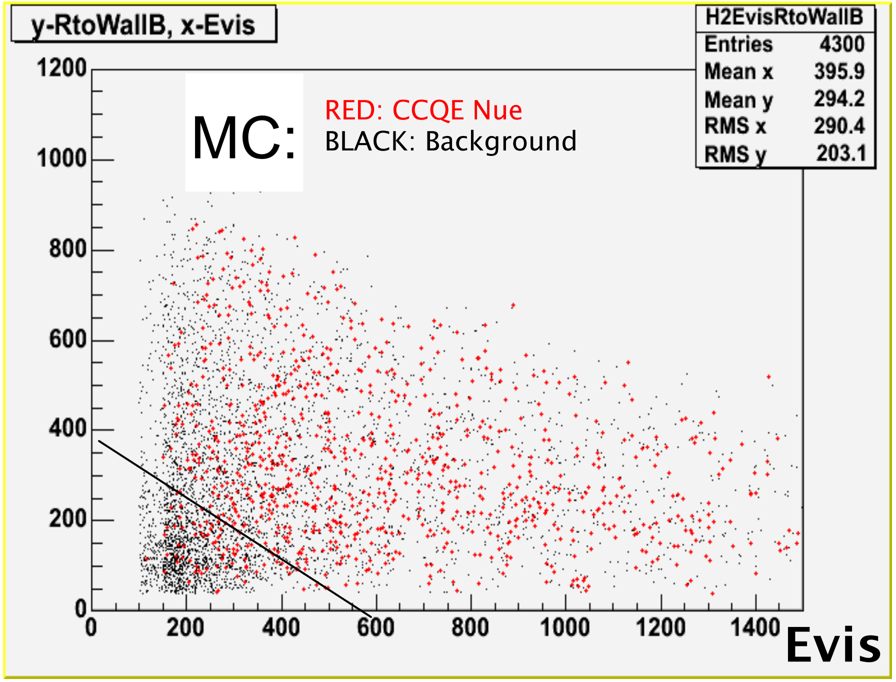
Photonuclear absorption recently added to our GEANT3 detector Monte Carlo.

- *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)



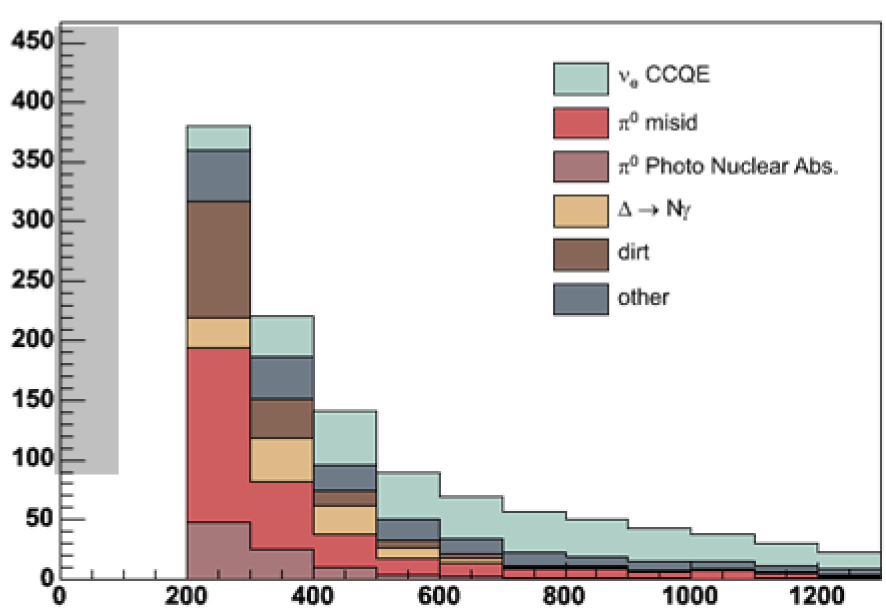


- occur at large radius
- inwardly directed
- low energy

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

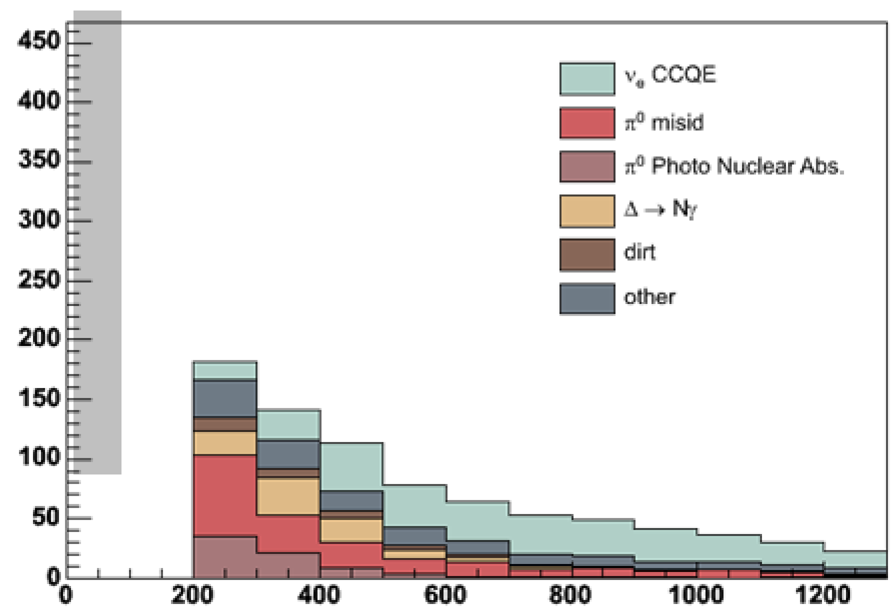
Comparing Neutrino Low Energy ν_e Candidates with & without dirt cut

Without Dirt Cut



$E_{\nu QE}$

With Dirt Cut



$E_{\nu QE}$

Sources of Systematic Errors

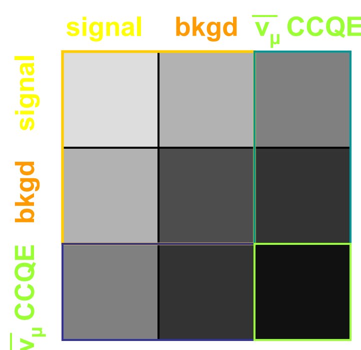
Source of Uncertainty On ν_e background	Track Based error in % 200-475 MeV	Track Based error in % 475-1250 MeV	Checked or Constrained by MB data
Flux from π^+/μ^+ decay	1.8	2.2	√
Flux from K^+ decay	1.4	5.7	√
Flux from K^0 decay	0.5	1.5	√
Target and beam models	1.3	2.5	√
ν-cross section	5.9	11.8	√
NC π^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	

ν_μ CCQE events constrain (ϕ x σ) !

Fit method

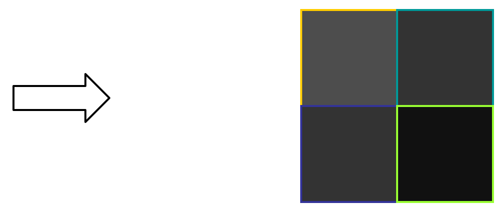
The following three distinct samples are used in the oscillation fits (fitting ν_e & ν_μ energy spectra)

1. **Background** to ν_e oscillations
2. **ν_e Signal** prediction (dependent on Δm^2, $\sin^2 2\theta$)
3. **ν_μ CCQE** sample, used to constrain ν_e prediction (signal+background)



Matrix is actually 53x53 (in E_ν^{QE} bins) !

Syst+stat block-3x3 covariance matrix in E_ν^{QE} bins
(in units of events^2) for all 3 samples



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

Low-energy excess vs E_{vis}

With E_{vis} Best Fit (0.04 eV^2, 0.96)