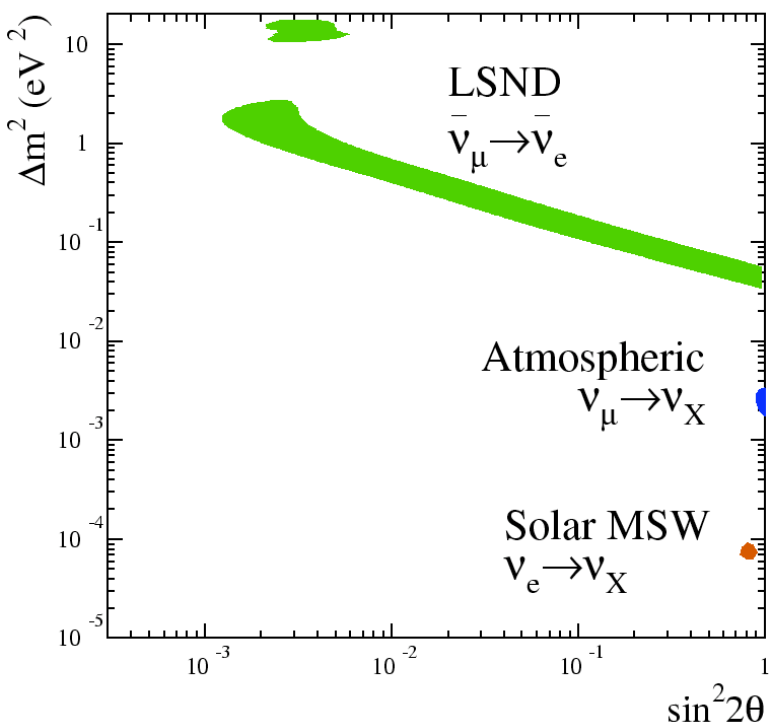
MiniBooNE Results & Future Experiments

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

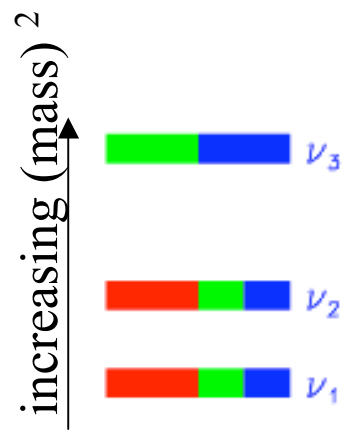
MiniBooNE was designed to test the LSND signal

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



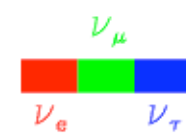
A 3 neutrino picture requires

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



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

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

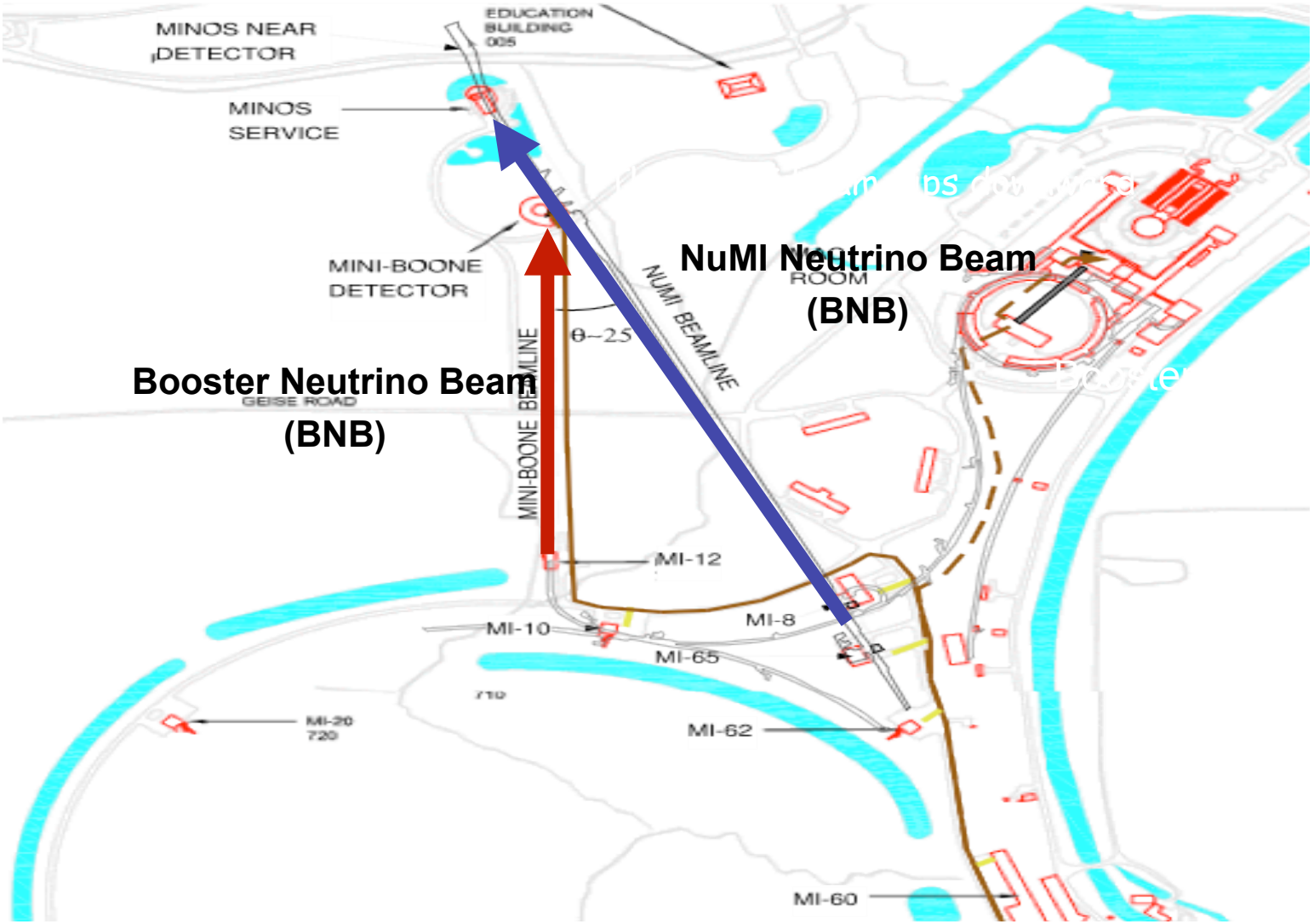


The three oscillation signals cannot be reconciled without introducing Beyond Standard Model Physics

MiniBooNE

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

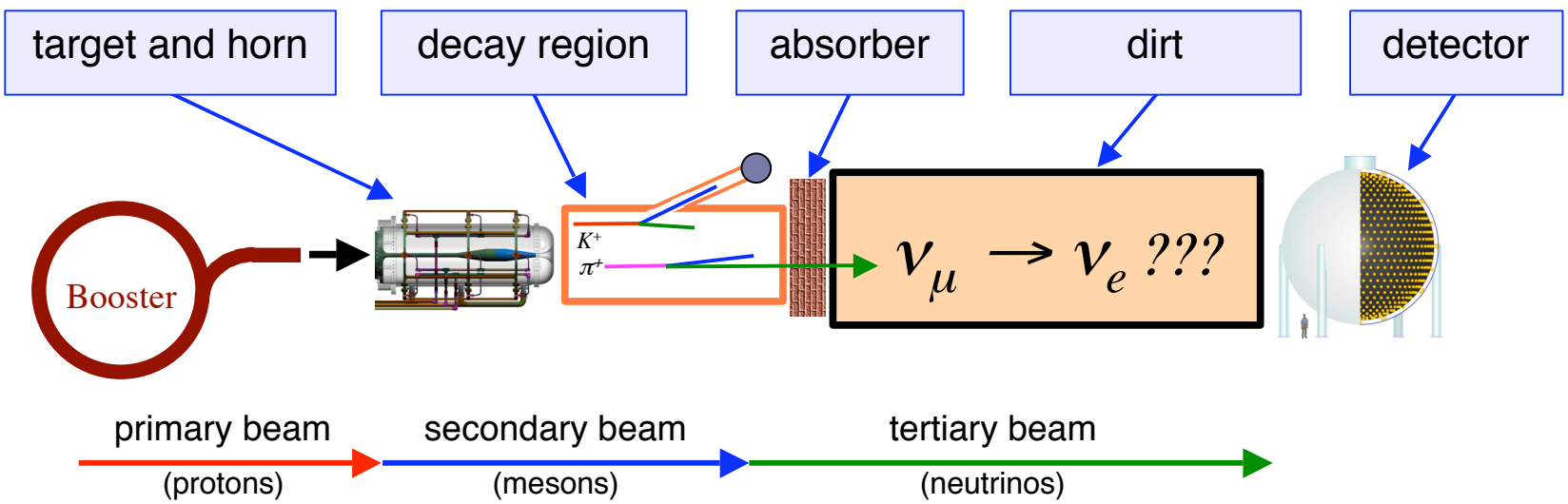
Neutrino beams at Fermilab



MiniBooNE's Design Strategy

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

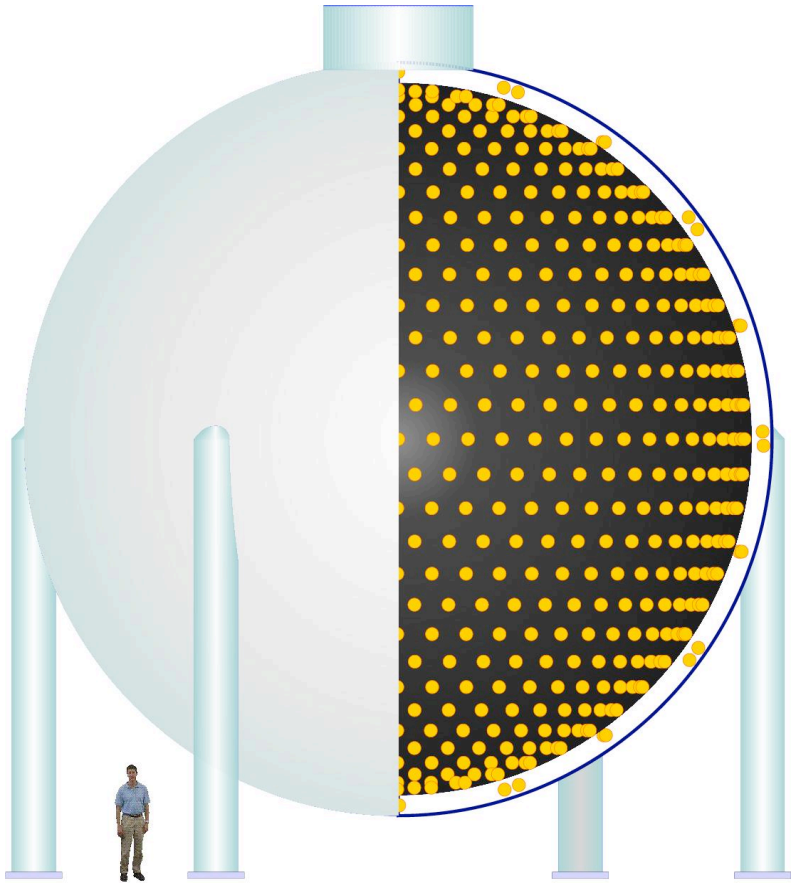
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2(1.27\Delta m^2 L/E)$$



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

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

The MiniBooNE Detector



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

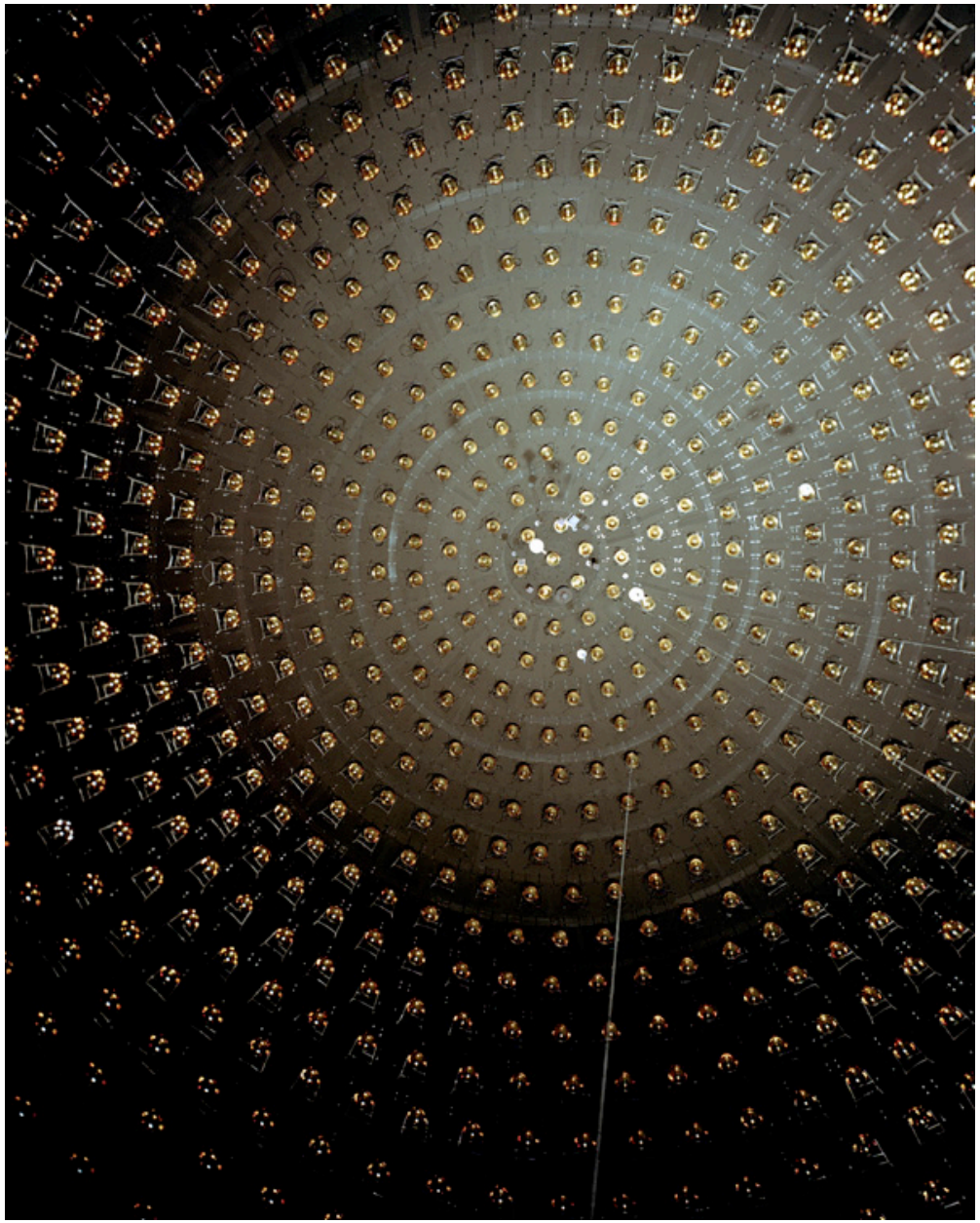
  (10 meter "fiducial" volume)

  - 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

ν_e *Event Rate Predictions*

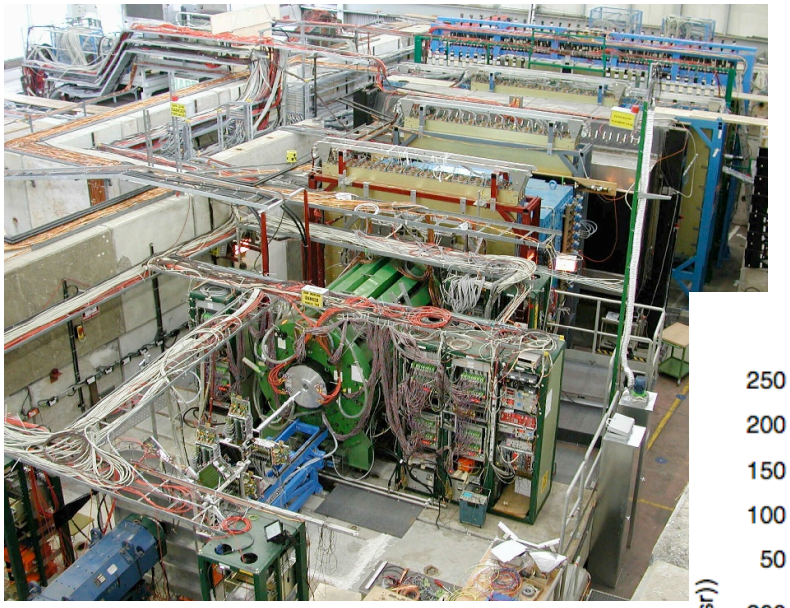
#Events = Flux x Cross-sections x Detector response

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

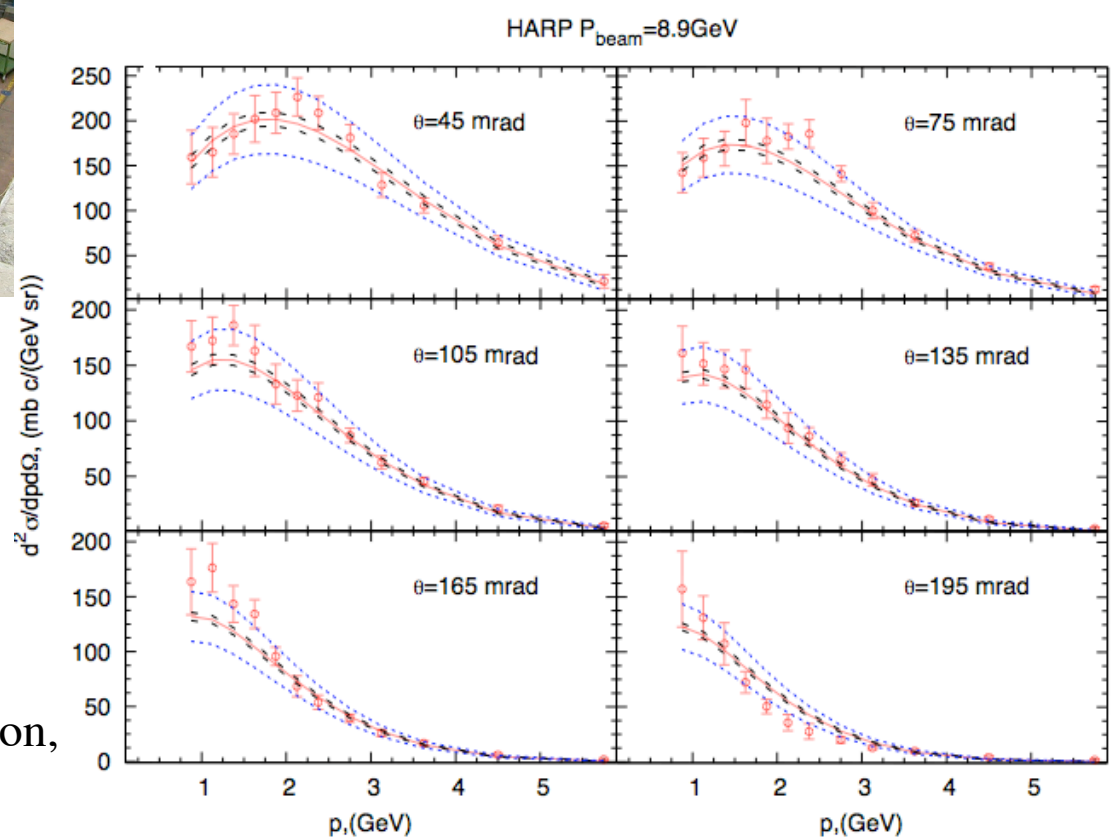
External and MiniBooNE measurements
-π^0, delta and dirt backgrounds constrained from data.

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^-

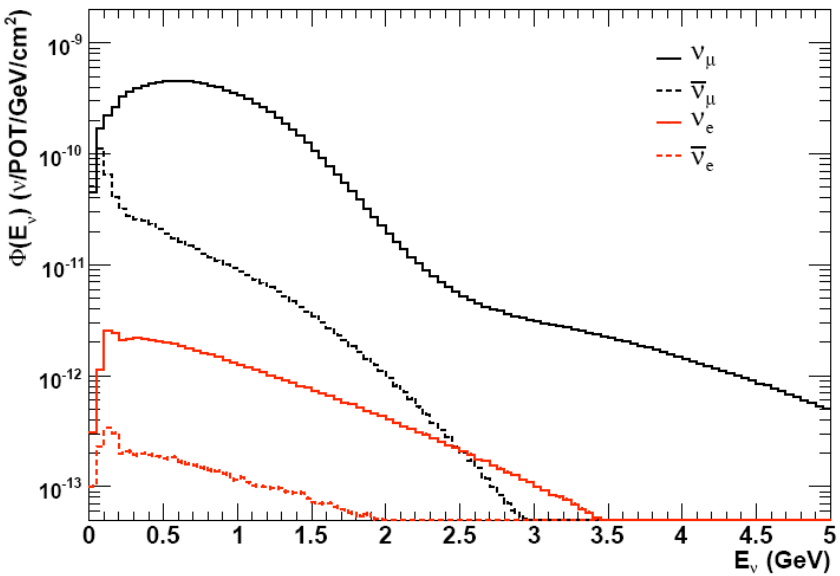


Data are fit to a Sanford-Wang parameterization.

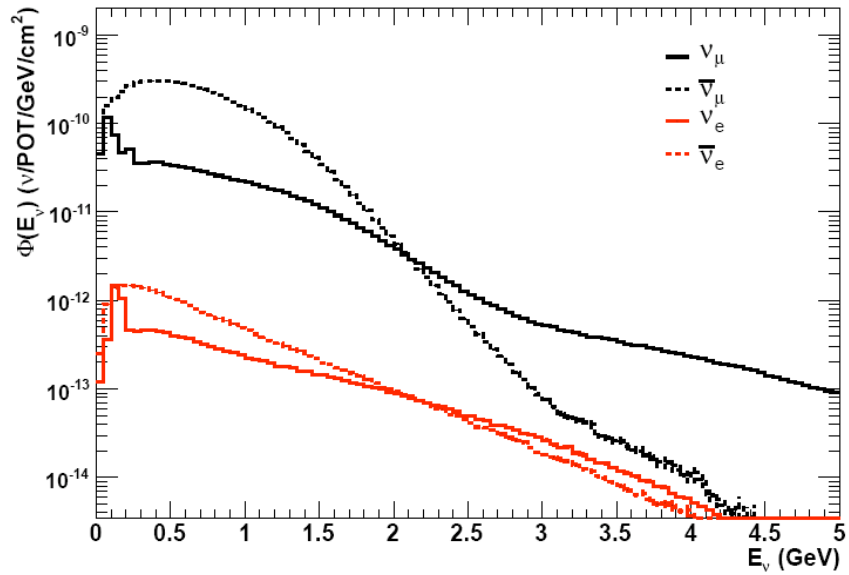
HARP collaboration, hep-ex/0702024

Neutrino Flux from GEANT4 Simulation

Neutrino-Mode Flux

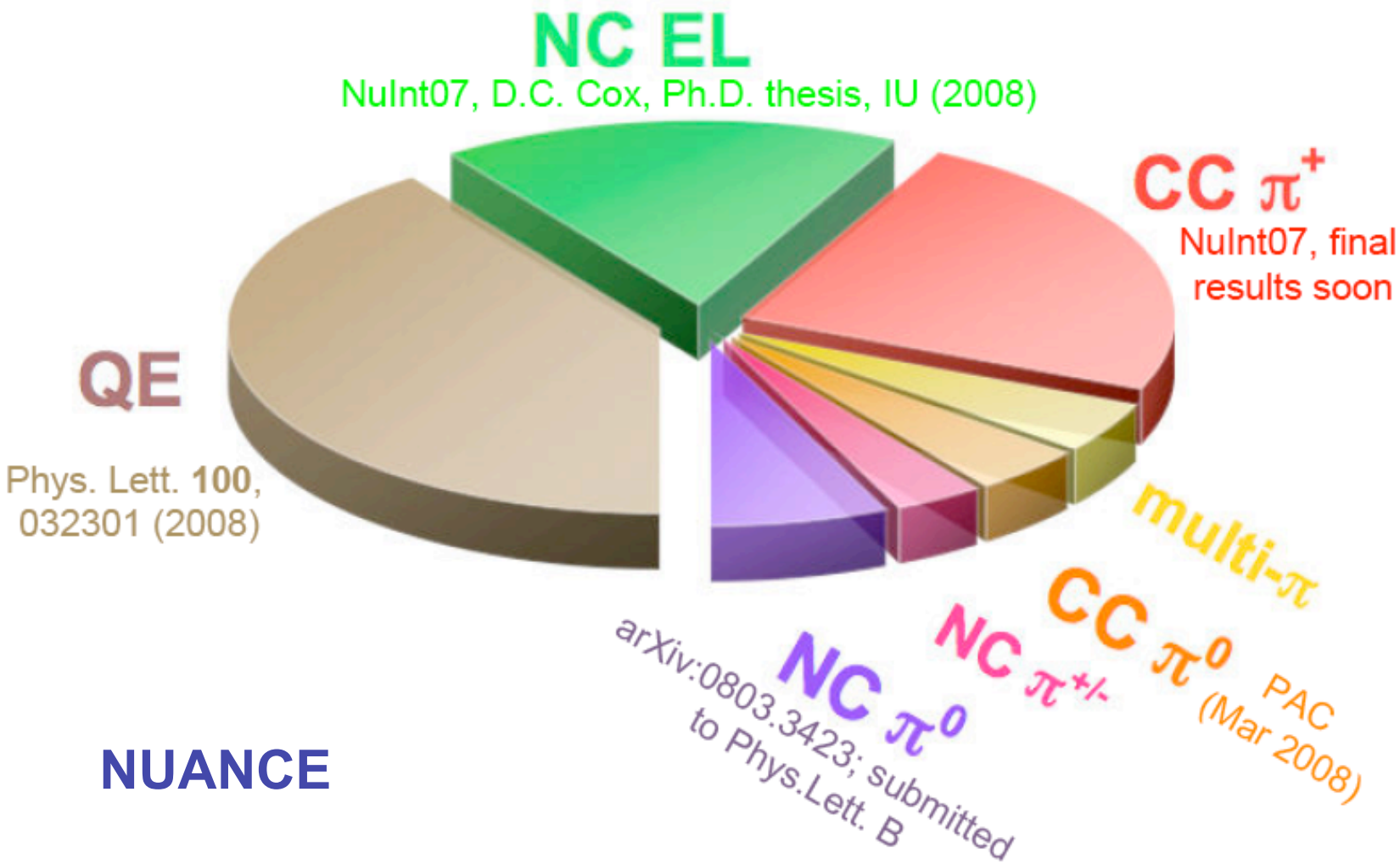


Antineutrino-Mode Flux



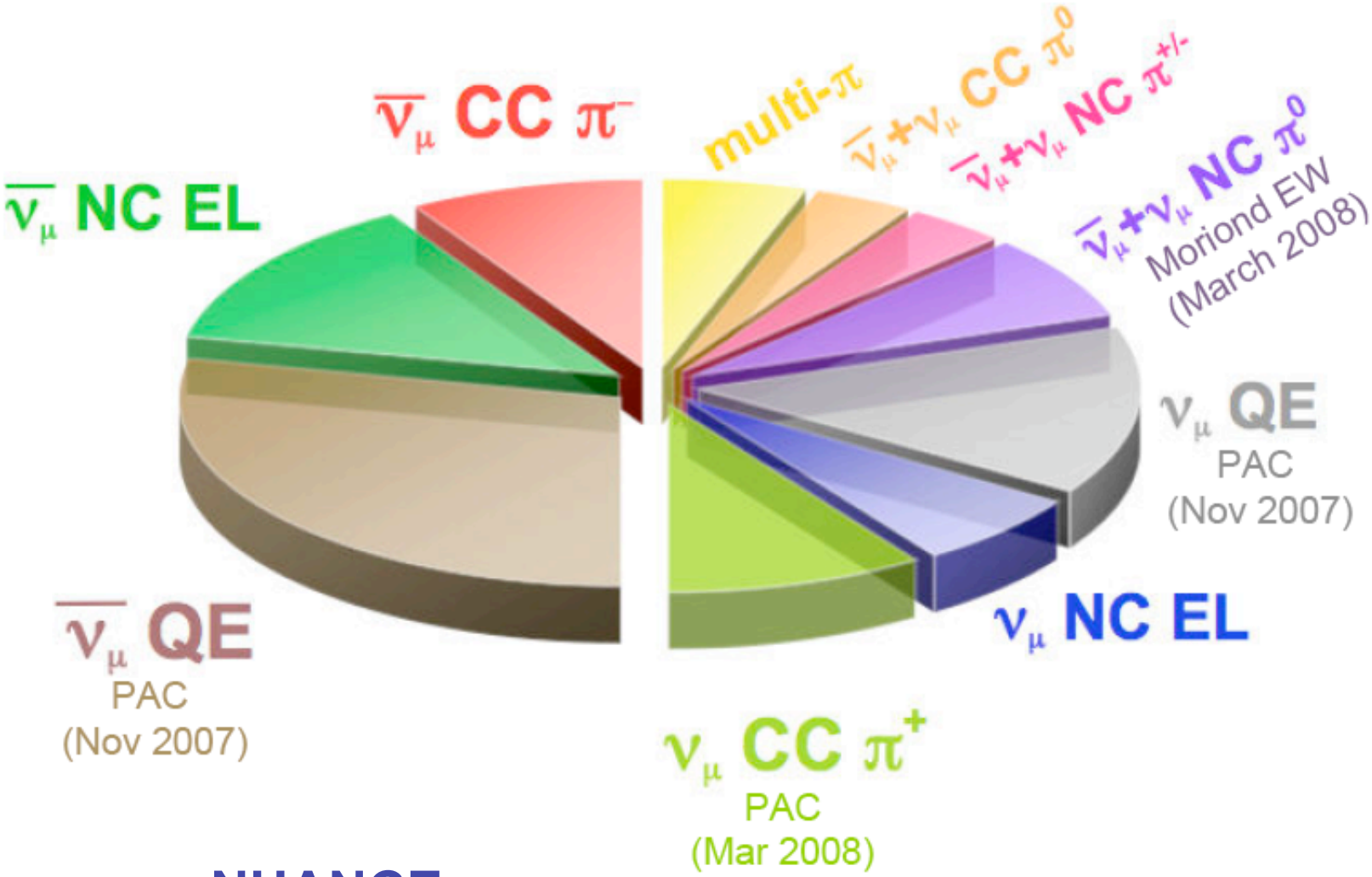
Wrong-sign background is ~6% for Nu-Mode & ~18% for Antinu-Mode
Instrinsic ν_e background is ~0.5% for both Nu-Mode & Antinu-Mode

Neutrino Cross Sections



NUANCE

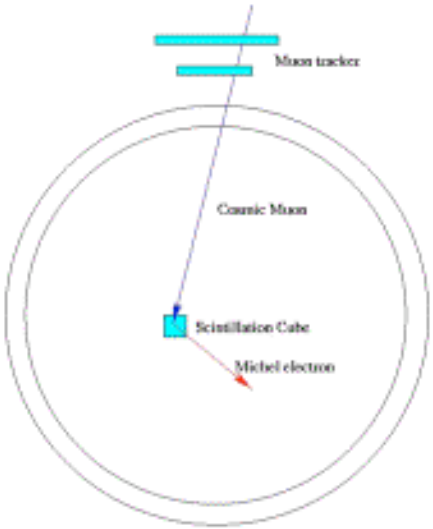
Antineutrino Cross Sections

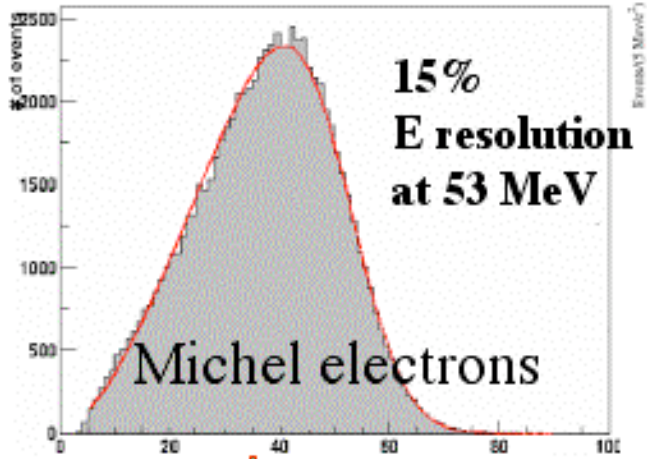


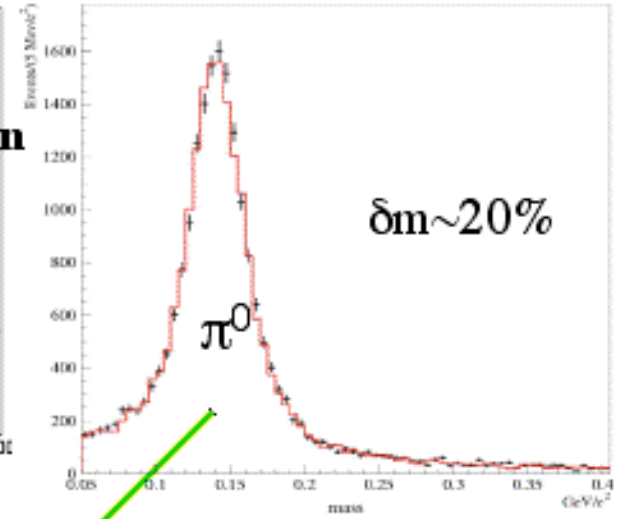
NUANCE

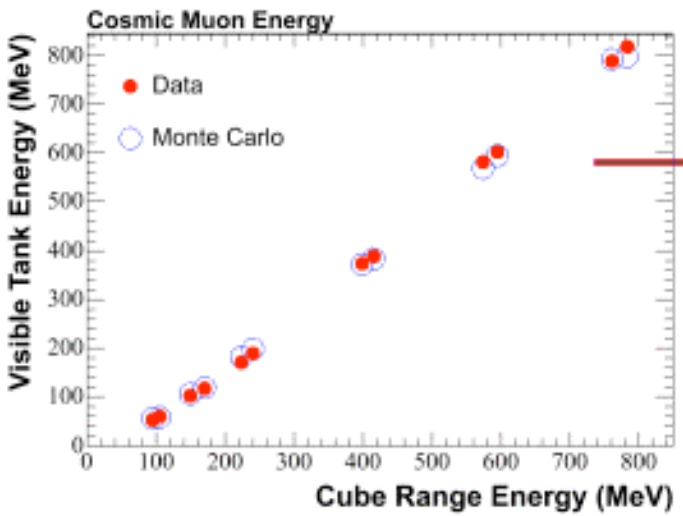
Calibration Sources

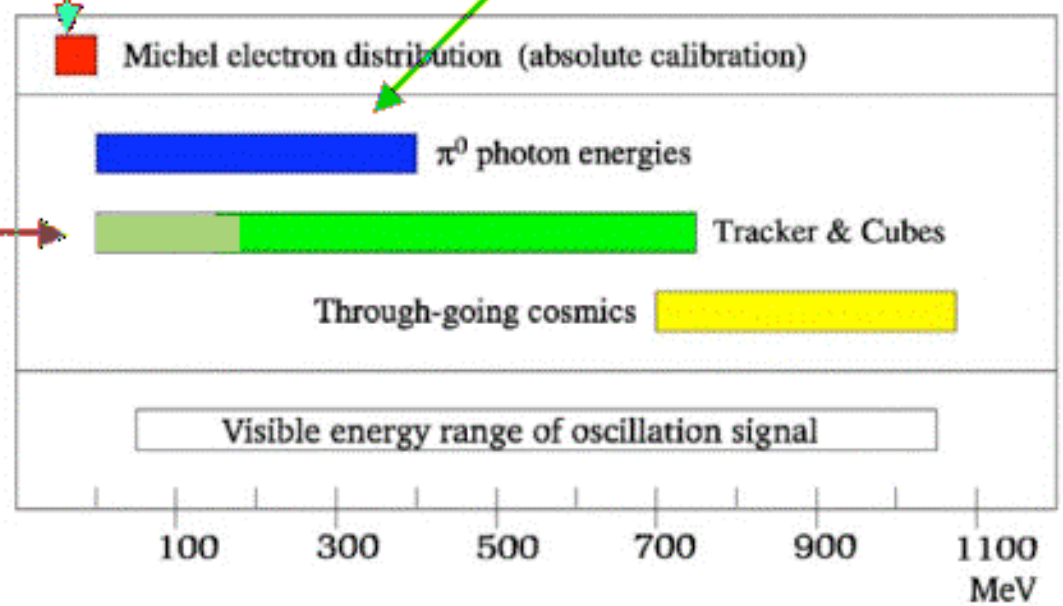
Tracker system





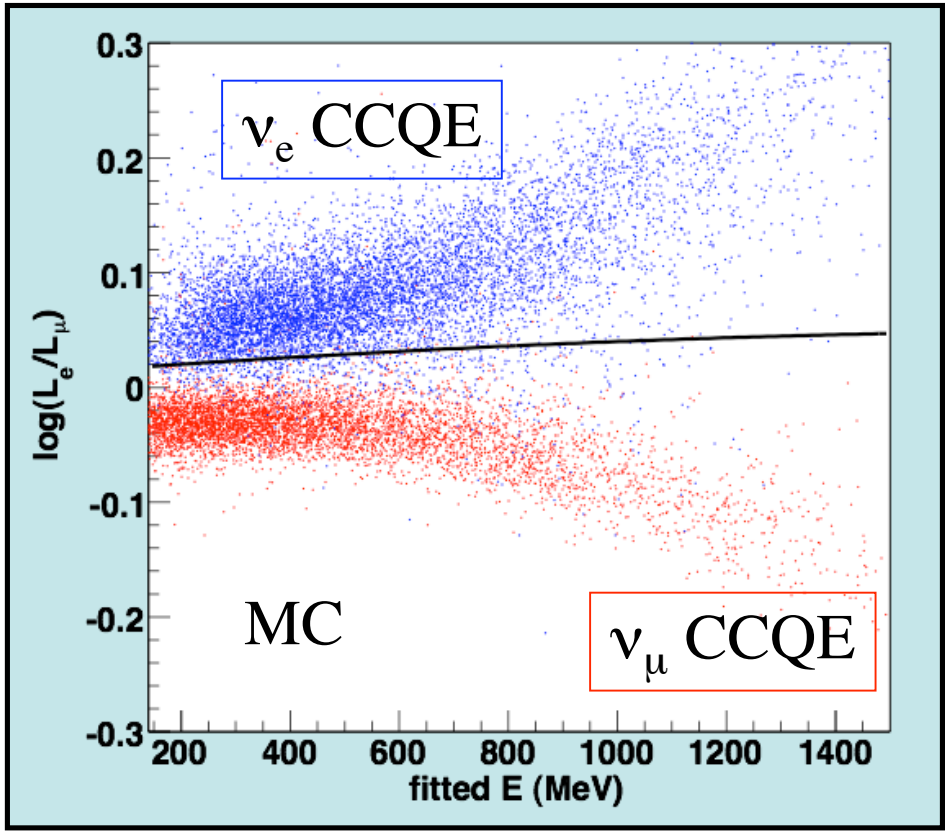






Rejecting "muon-like" events Using log(L_e/L_μ)

$\log(L_e/L_\mu)>0$ 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

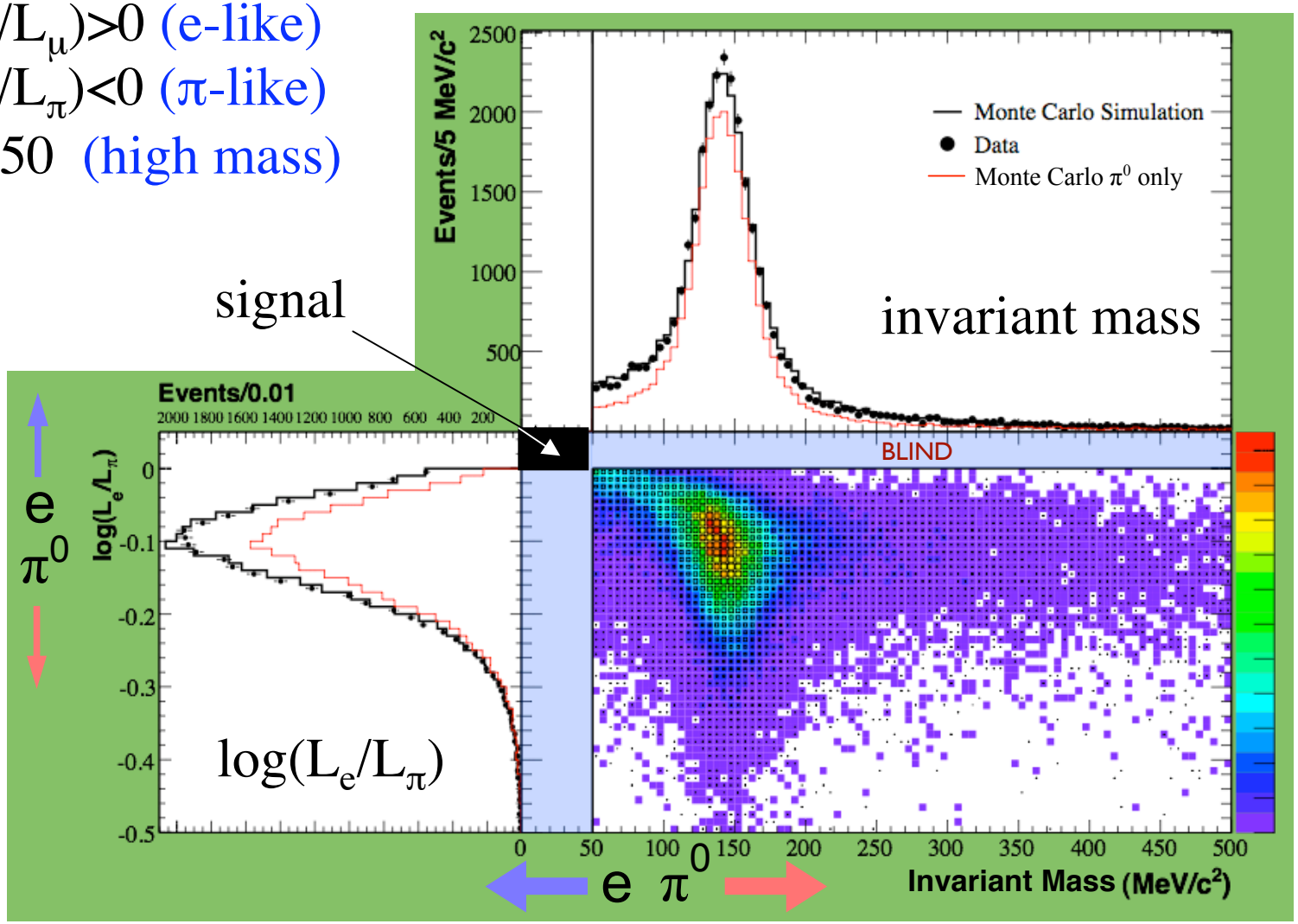
Testing e-π^0 separation using ***data***

1 subevent

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

$\log(L_e/L_\pi)<0$ (π-like)

mass>50 (high mass)



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

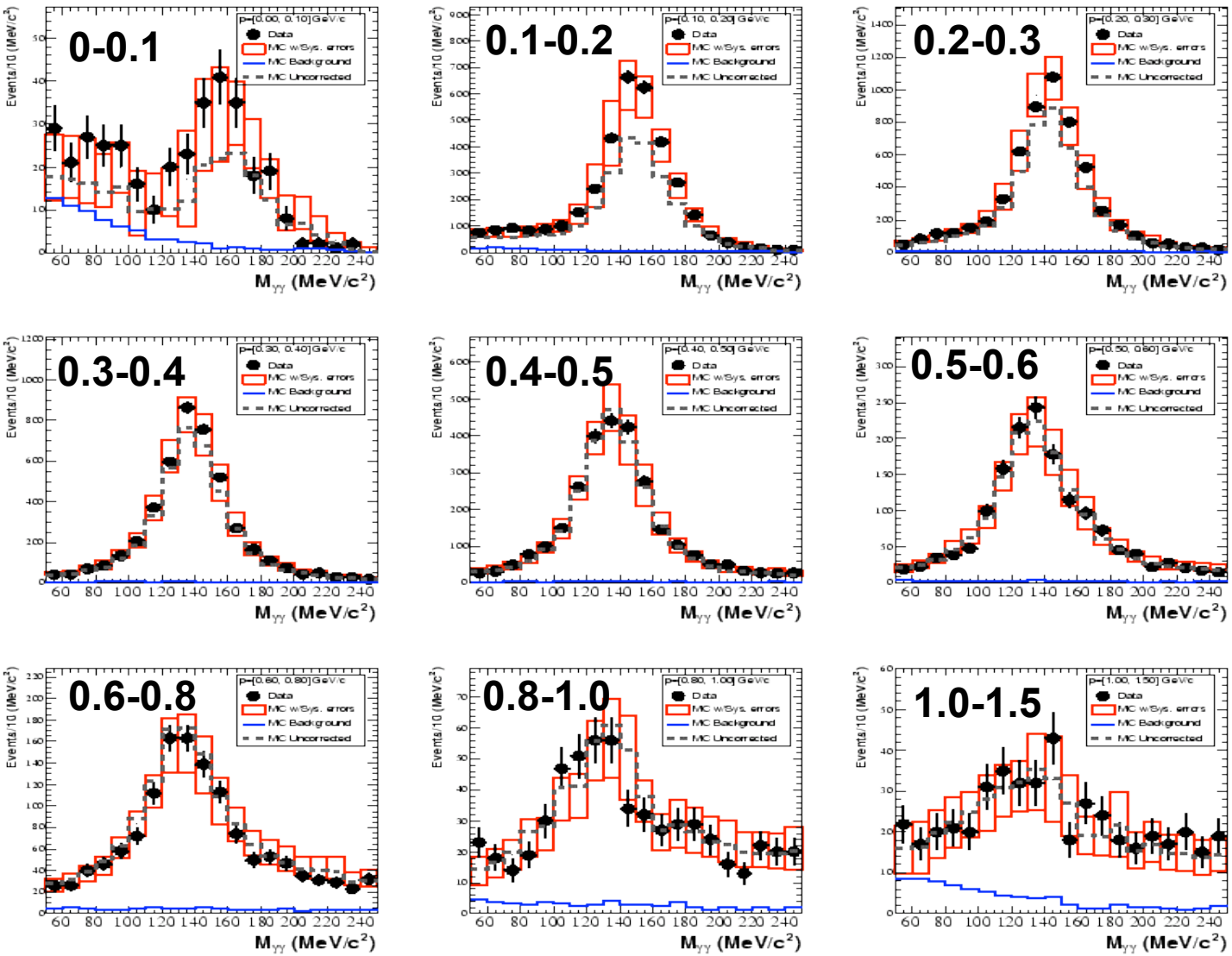
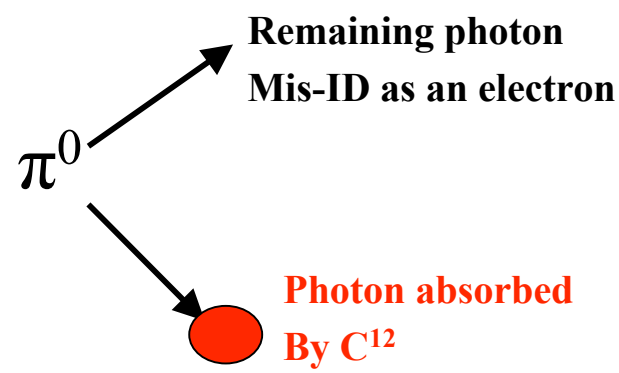


Photo-nuclear absorption of π^0 photon

A single γ is indistinguishable from an electron in MiniBooNE

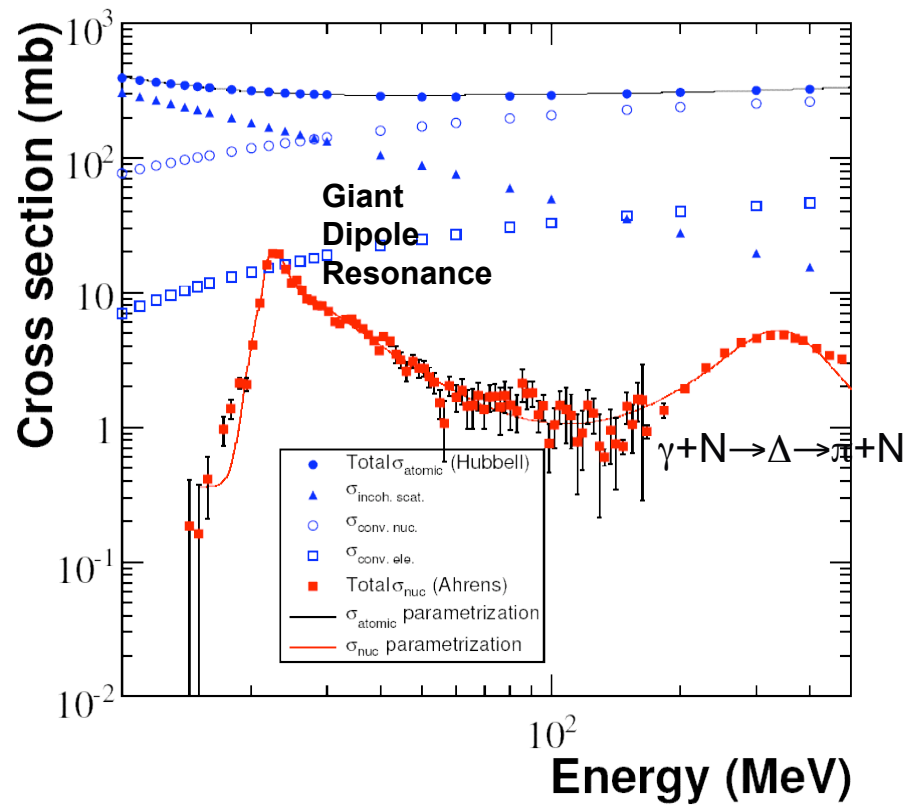


Photonuclear processes can remove ("absorb") one of the gammas from NC $\pi^0 \rightarrow \gamma\gamma$ event

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

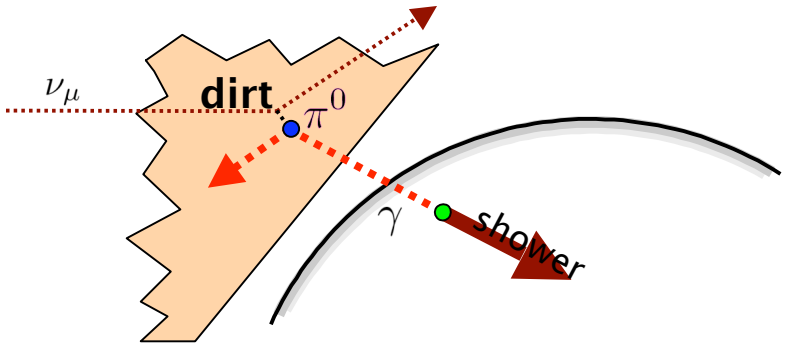
Photonuclear absorption recently added to our GEANT3 detector Monte Carlo.

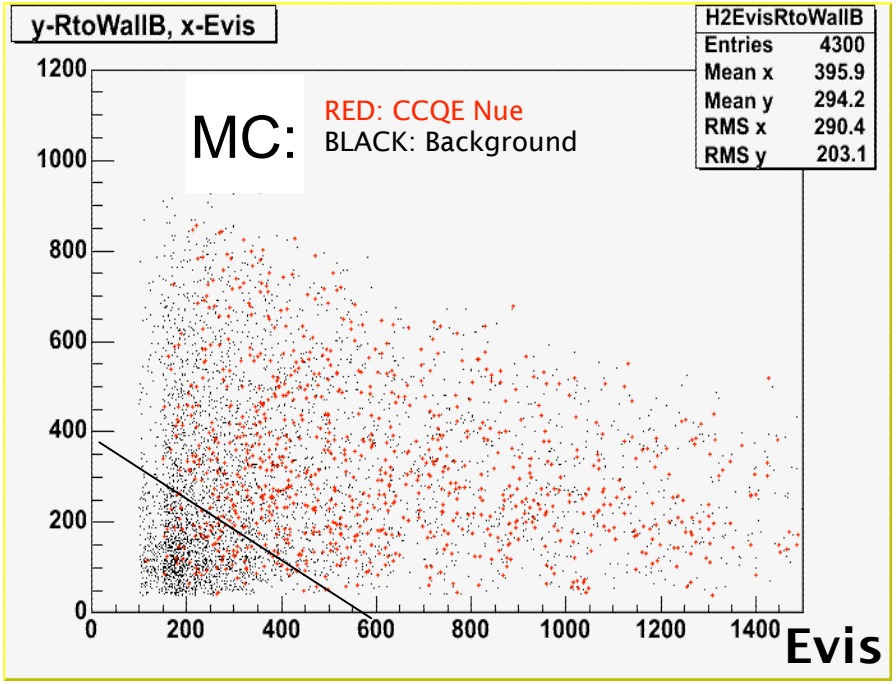
- *Extra final state particles carefully modelled*
- *Reduces size of excess*
- *Systematic errors are small.*
- *No effect above 475 MeV*



External Events ("dirt")

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



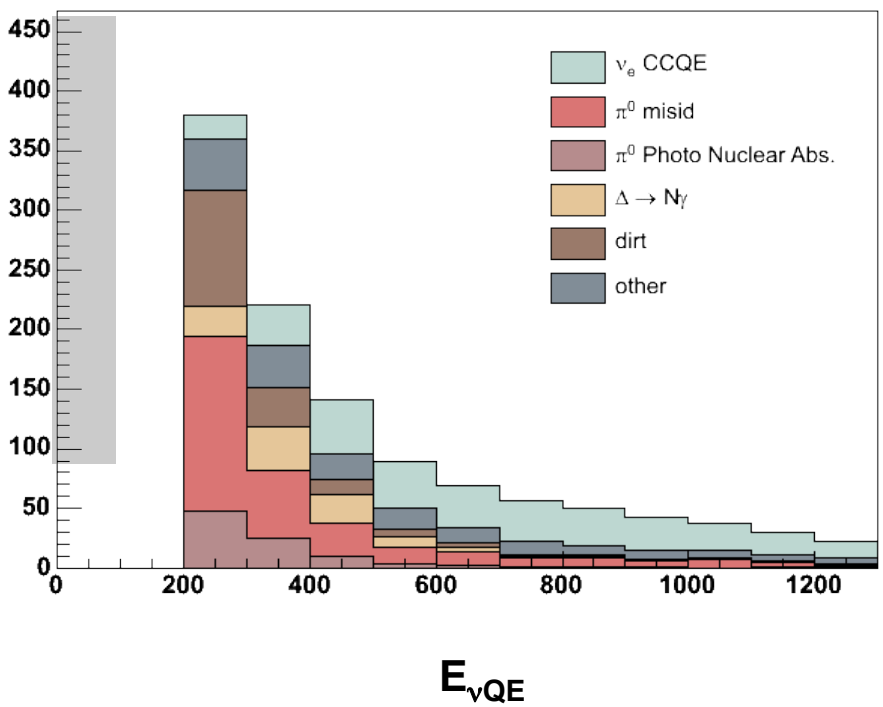


- occur at large radius
- inwardly directed
- low energy

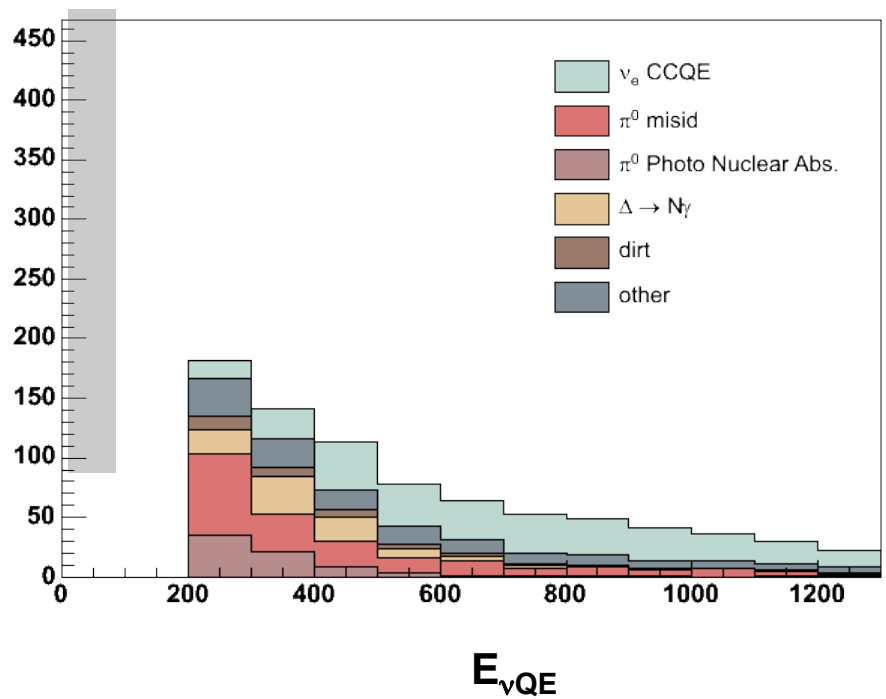
The background can be largely eliminated with an energy dependent fiducial cut (rtowallb)

Comparing Neutrino Low Energy ν_e Candidates with & without dirt cut

Without Dirt Cut



With Dirt Cut



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

Sources of Systematic Errors

Source of Uncertainty On ν_e background	Track Based error in % 200-475 MeV	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	

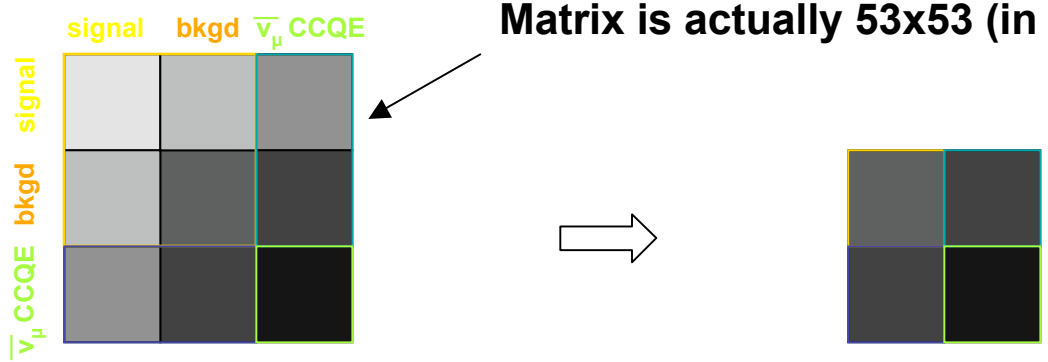
ν_μ CCQE events constrain (ϕ x σ) !

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

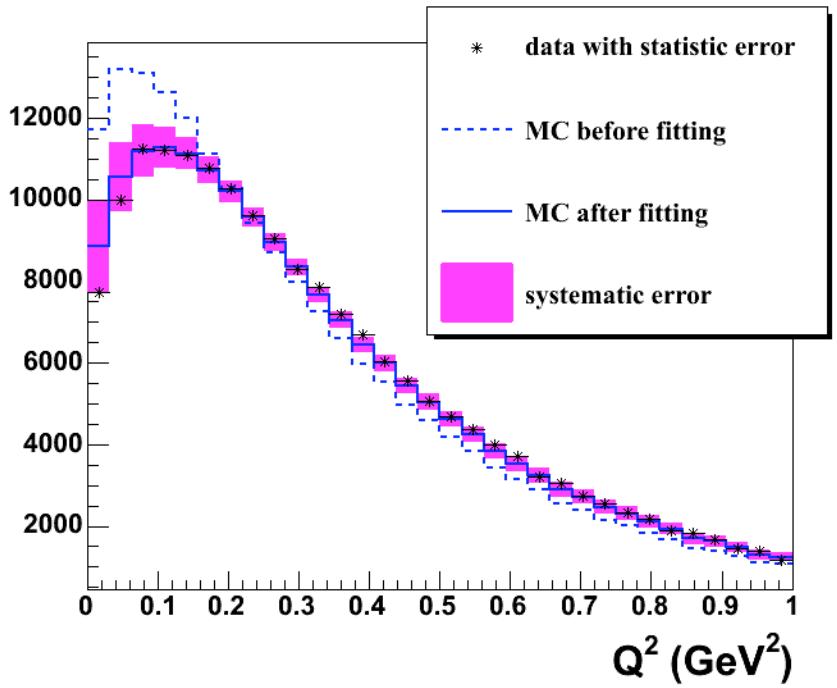
collapsed to block-2x2 matrix ($\bar{\nu}_e$ and $\bar{\nu}_\mu$ CCQE) for χ^2 calculation

MiniBooNE Neutrino Results

- Results based on 6.46×10^{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)

ν_μ *CCQE Scattering*

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



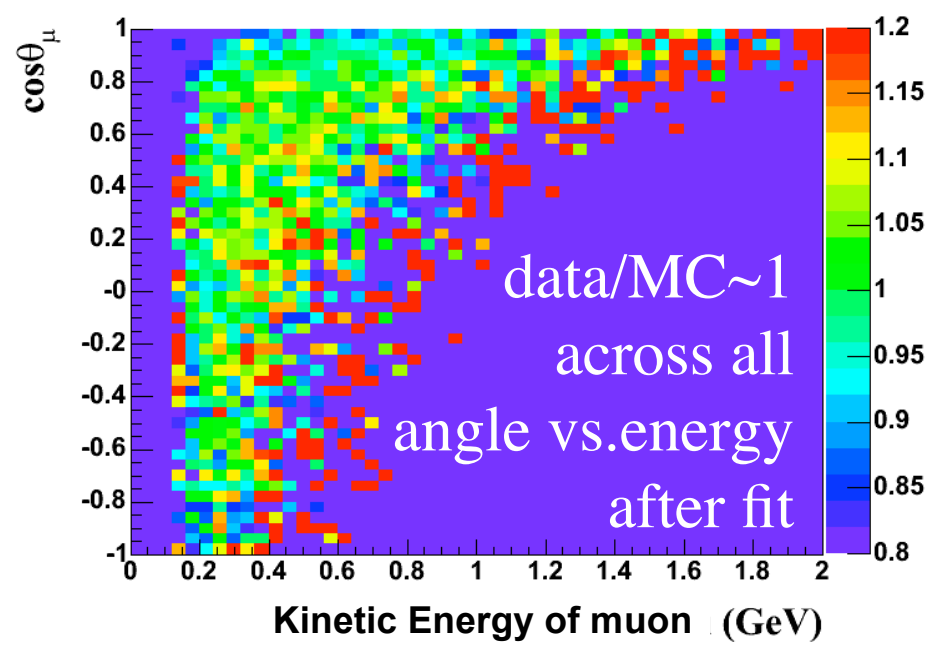
We adjust parameters of a Fermi Gas Model to match observed Q^2 distribution

From Q^2 fits to MB ν_μ CCQE data:

- M_A^{eff} -- effective axial mass
- E_{lo}^{SF} -- Pauli Blocking parameter

From electron scattering data:

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



Model describes CCQE ν_μ data well

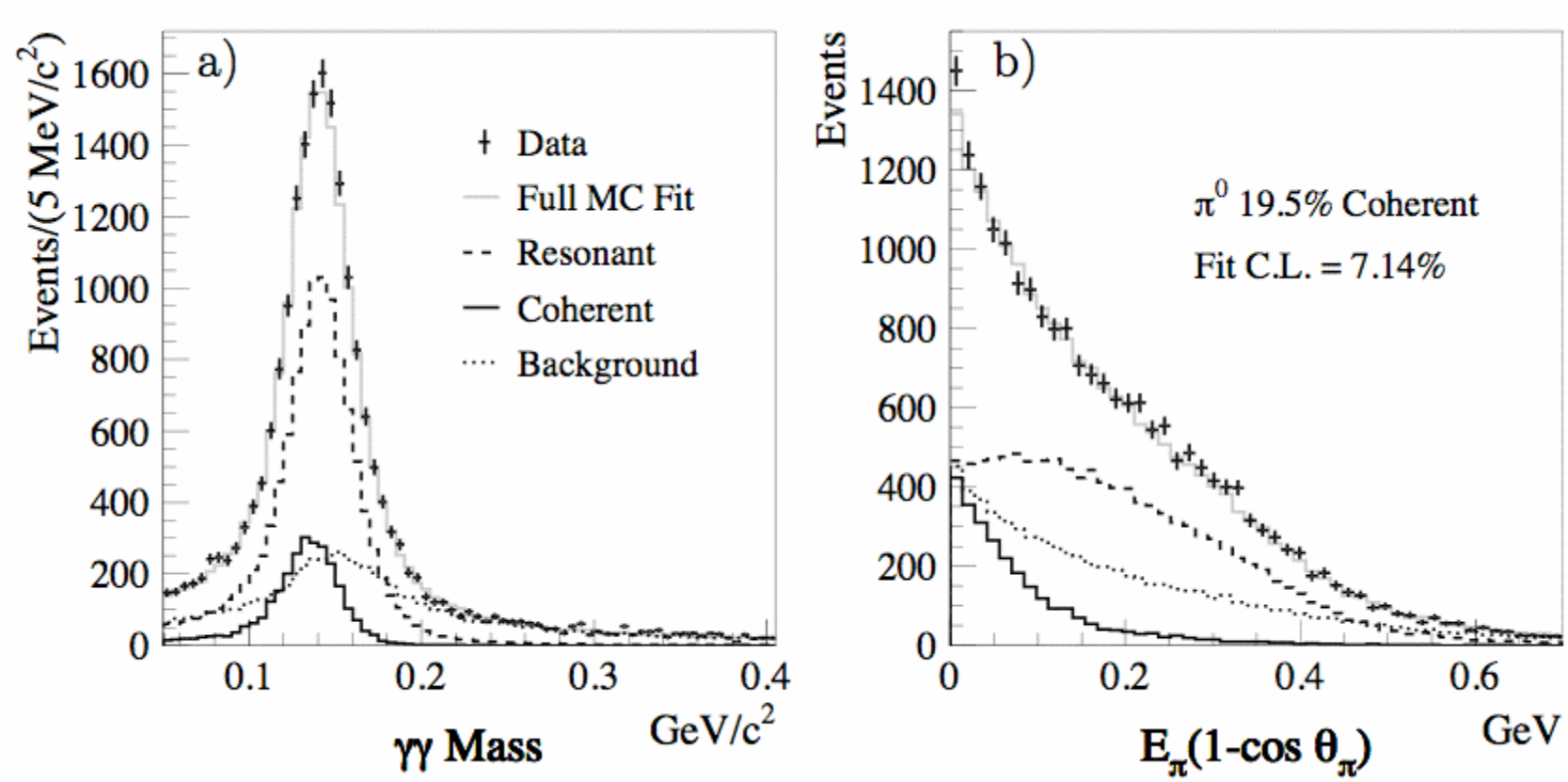
M_A = 1.23+-0.20 GeV

E_{lo} = 1.019+-0.011

NCpi0 Scattering

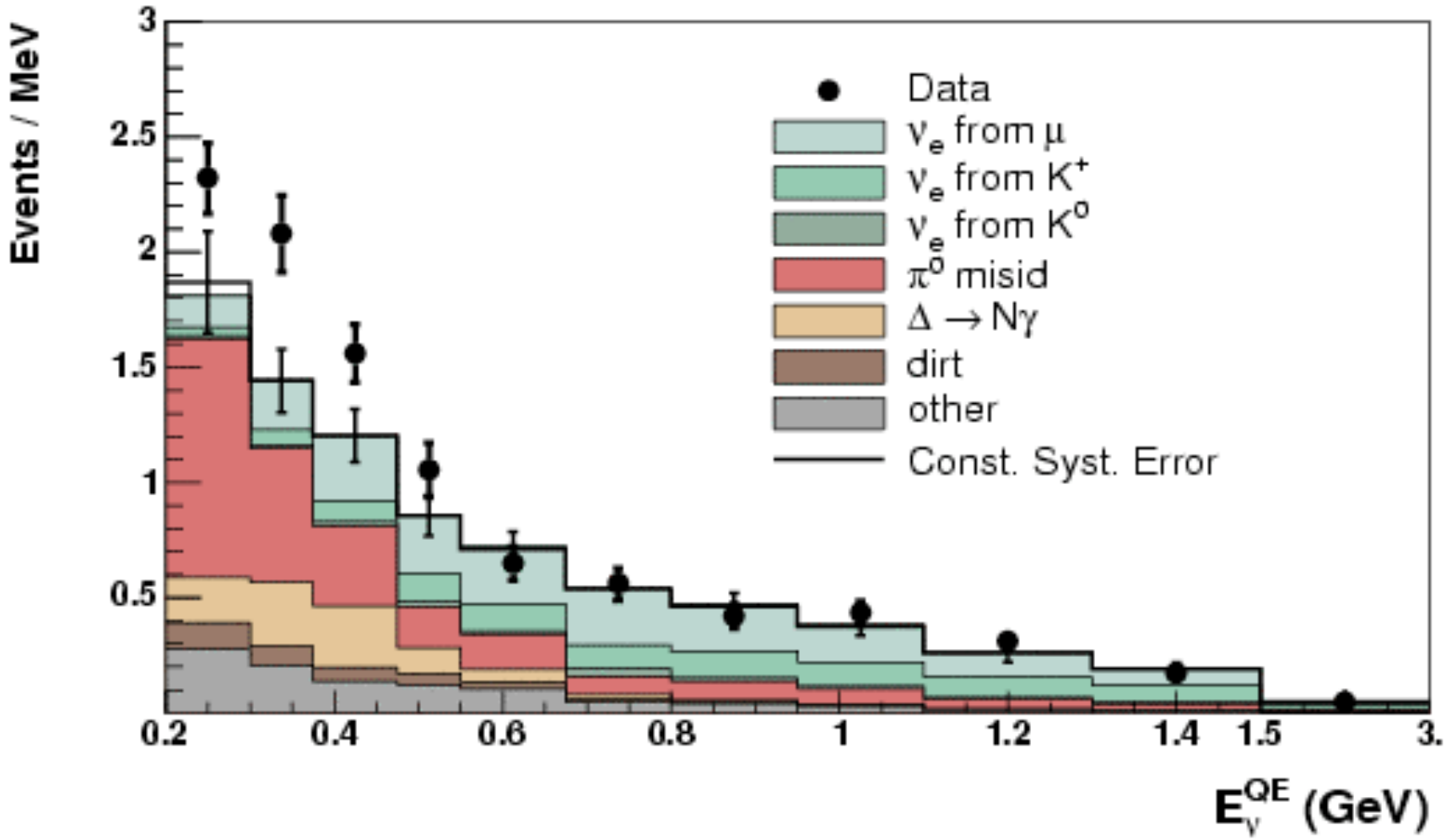
A. A. Aguilar-Arevalo et al., Phys. Lett. B 664, 41 (2008)

coherent fraction=19.5+-1.1+-2.5%

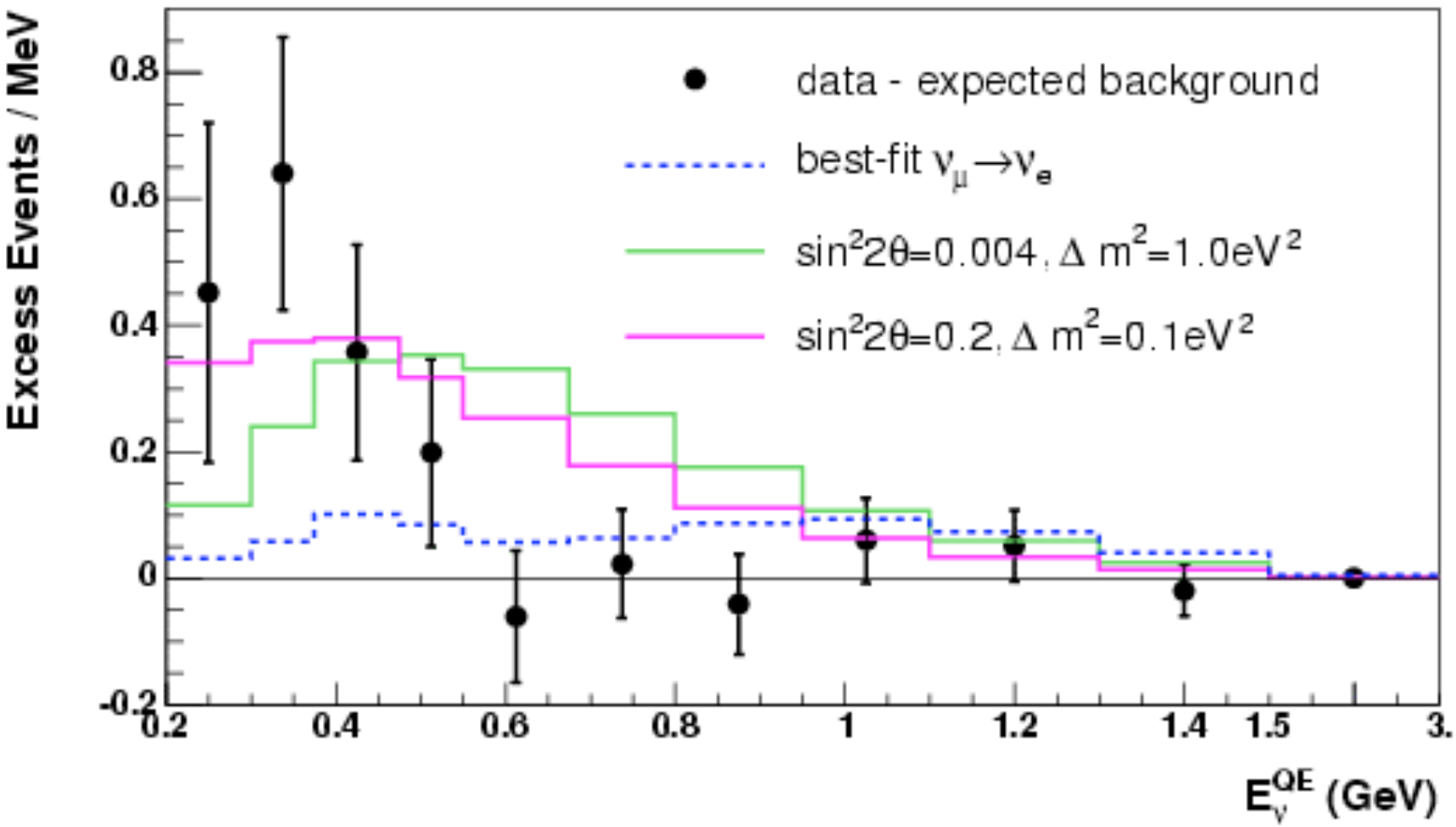


MiniBooNE observes a low-energy excess!

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_ν^{QE}

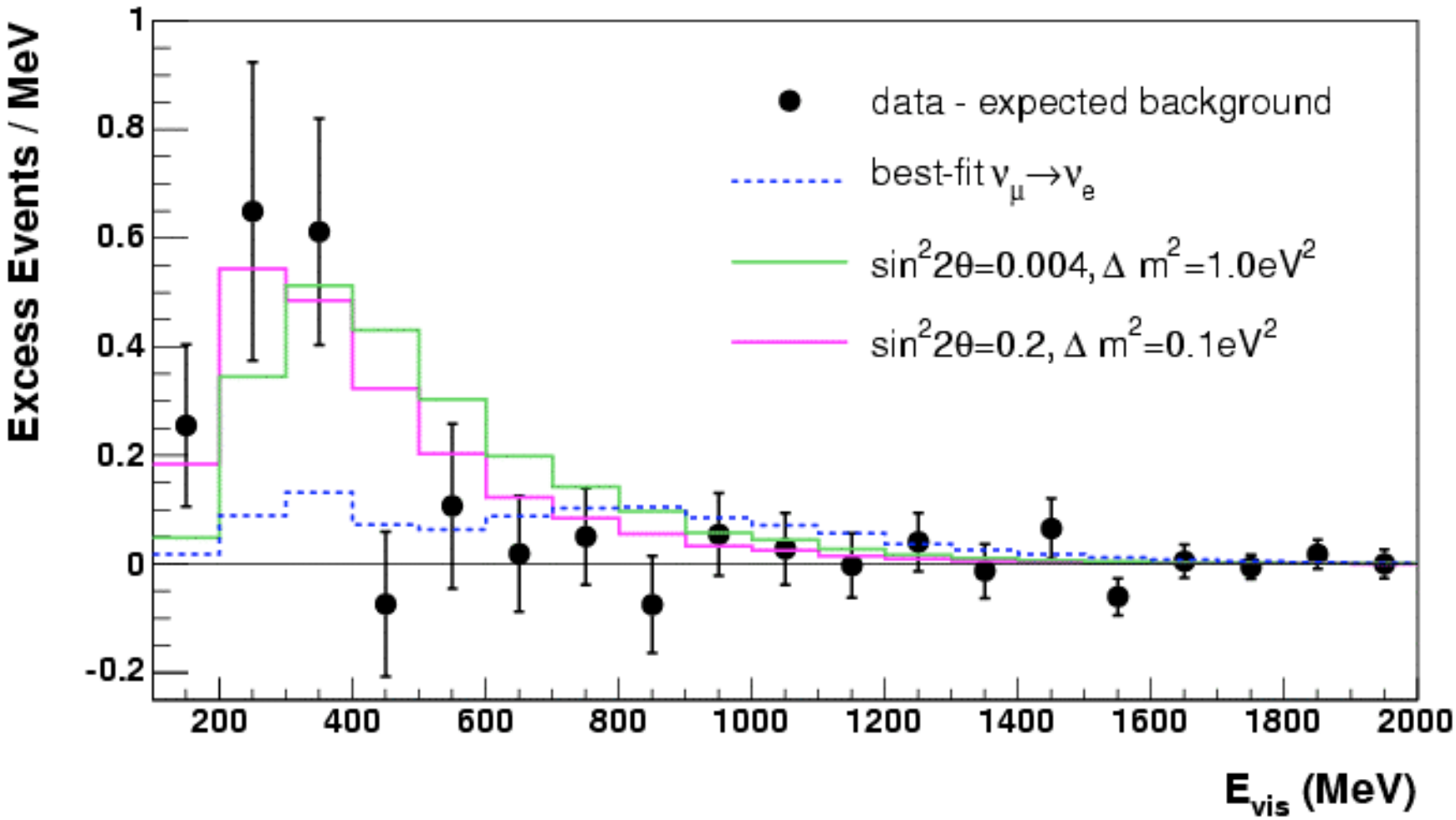


Number of Excess Events

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)

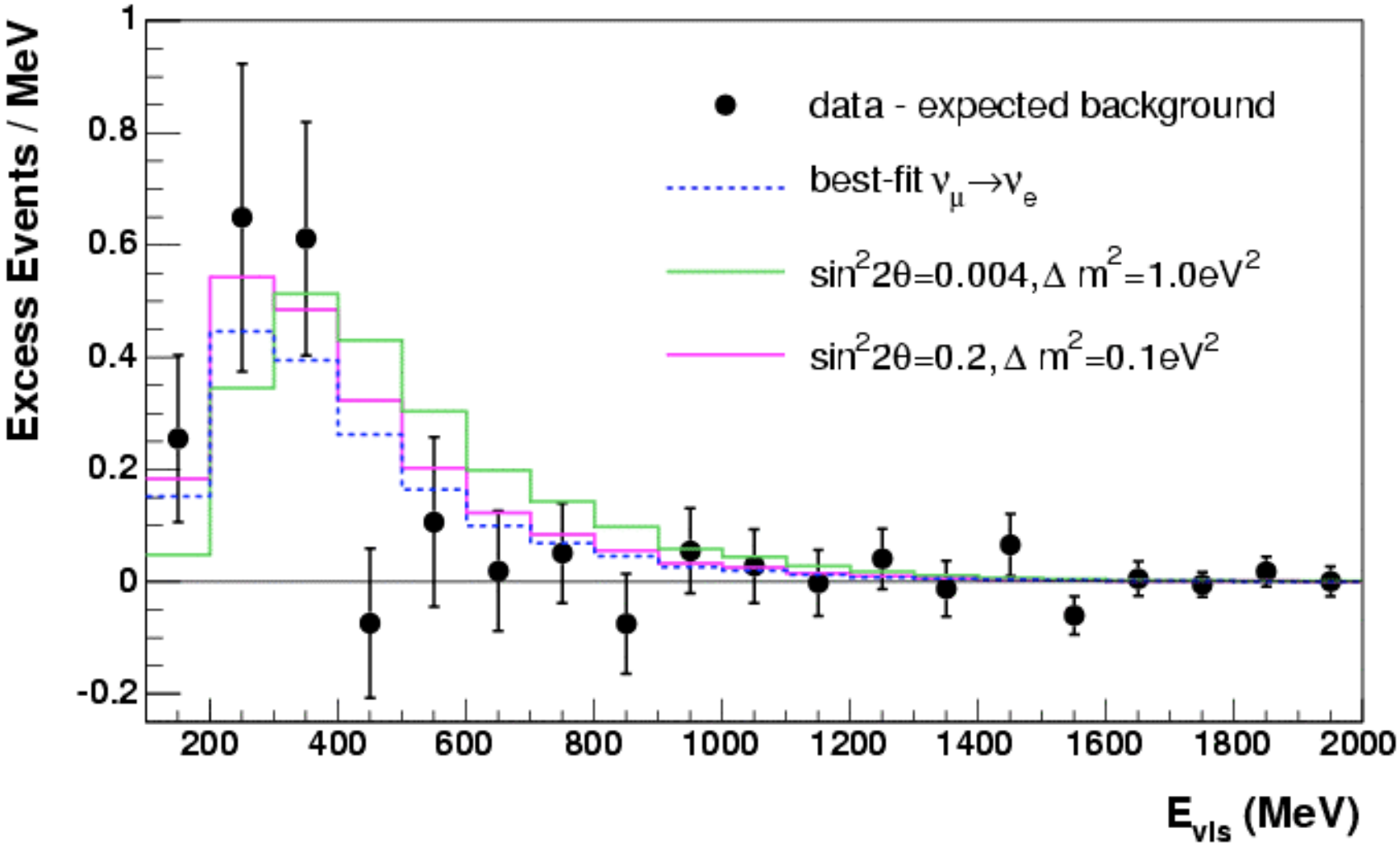
Low-energy excess vs E_{vis}

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

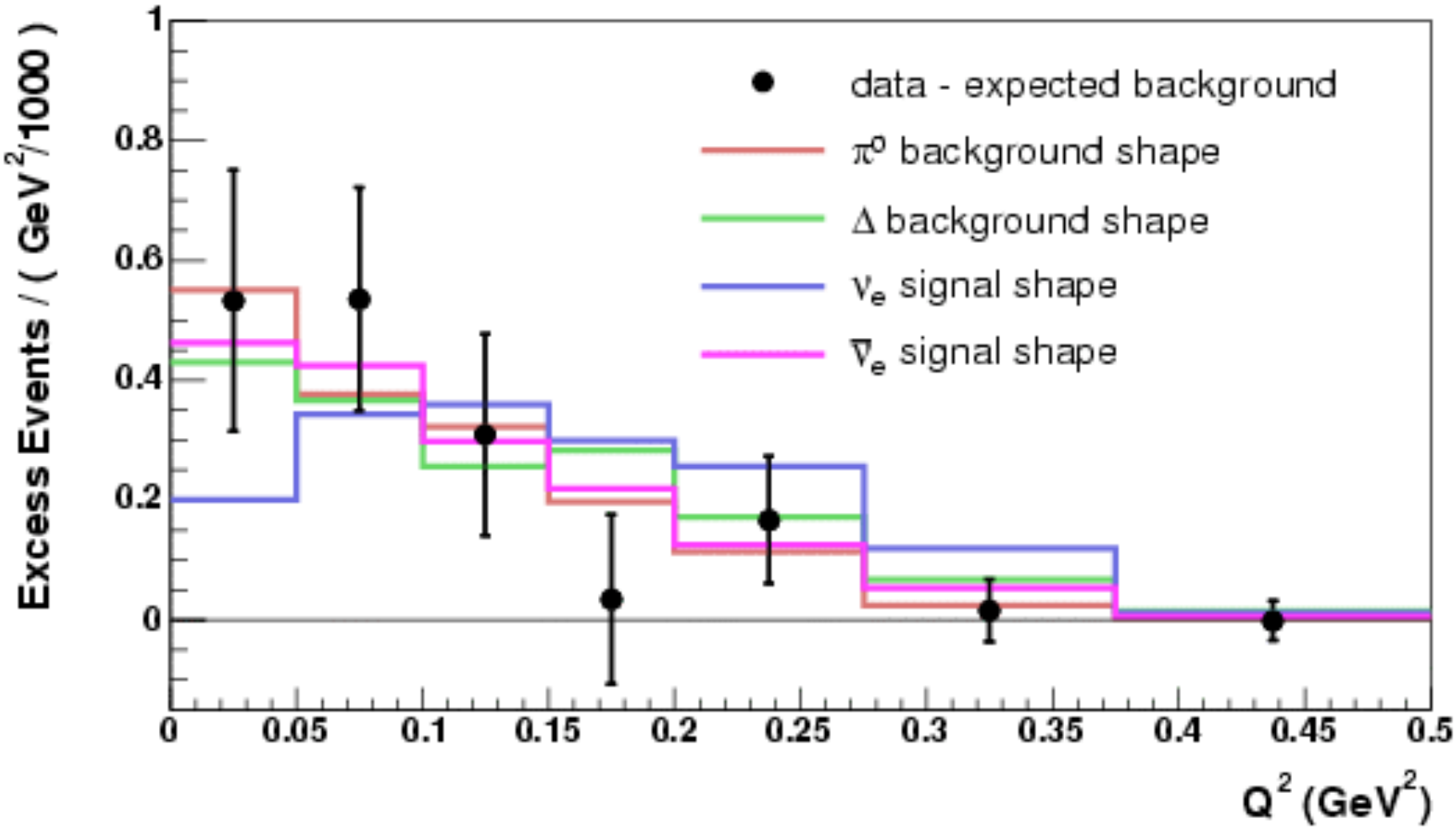


Low-energy excess vs E_{vis}

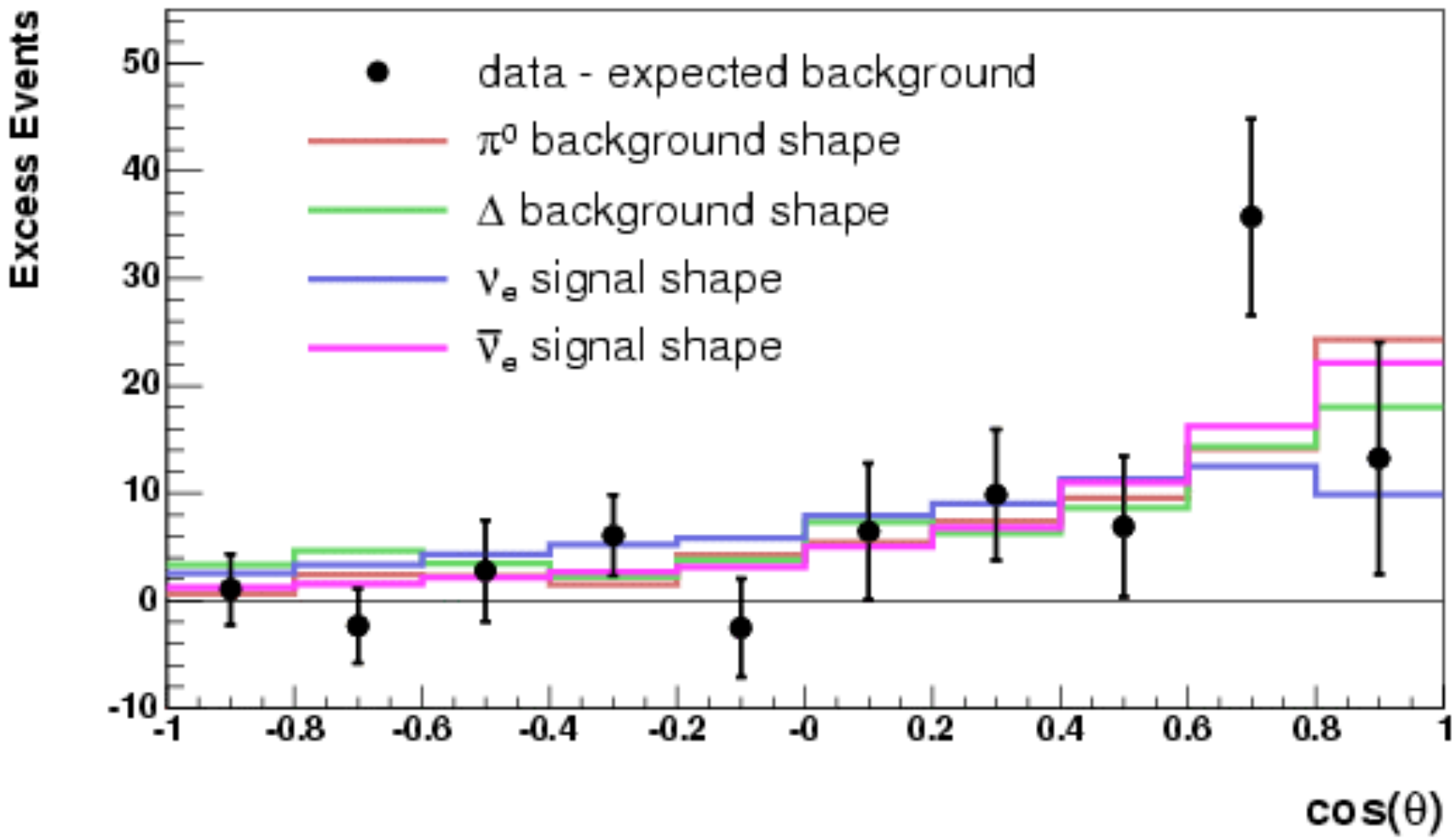
With E_{vis} Best Fit (0.04 eV^2, 0.96)



Low-energy excess vs Q^2



Low-energy excess vs cosθ

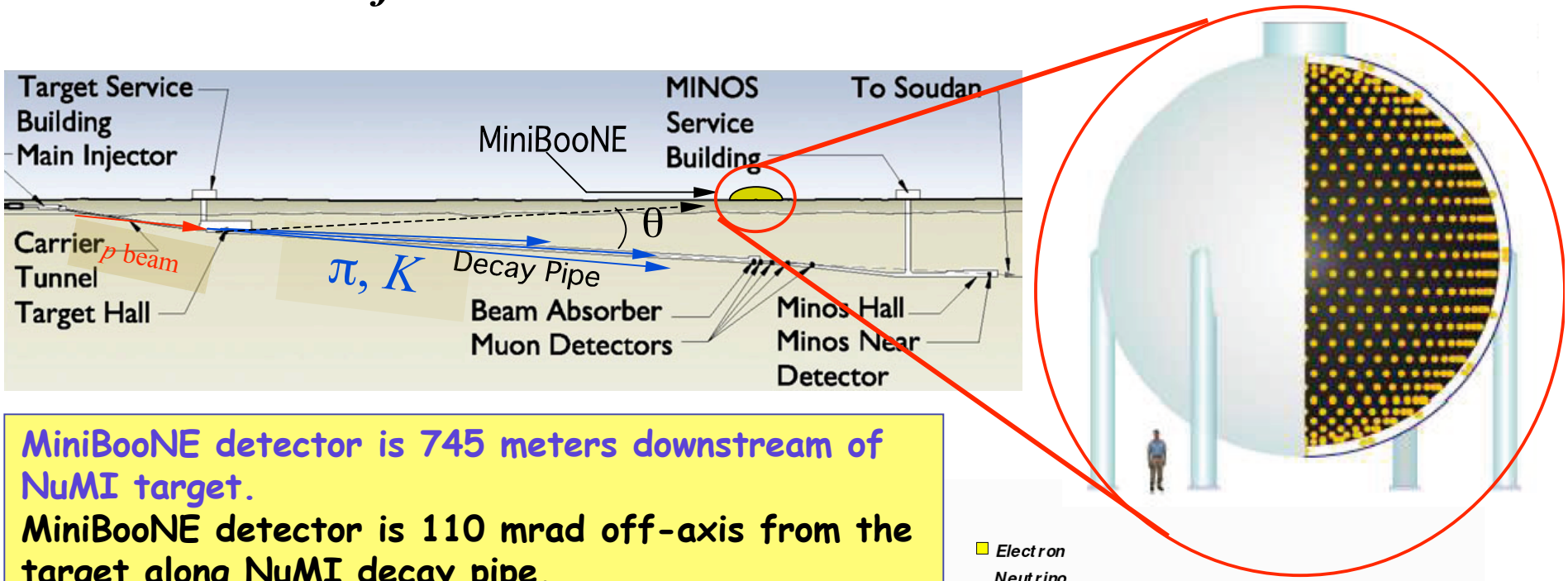


χ^2 Values from Data/MC Comparisons

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

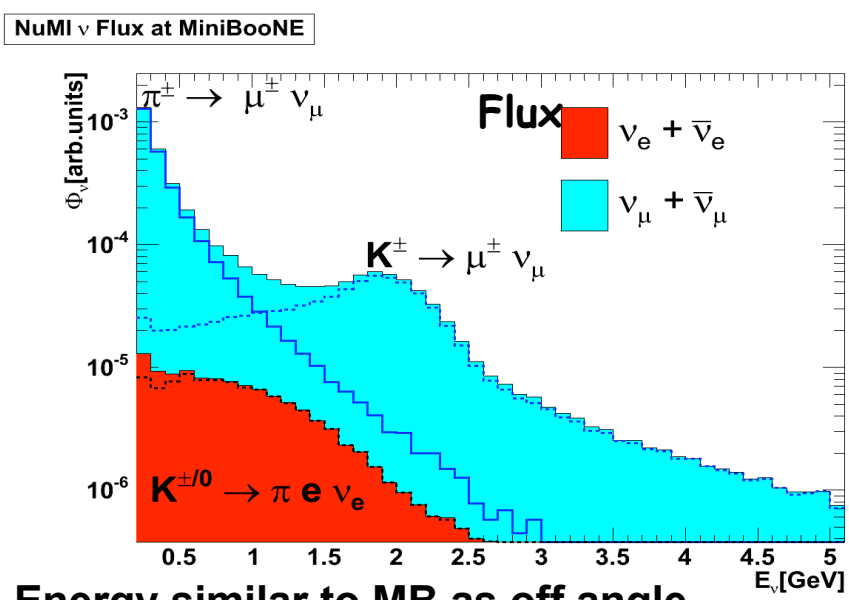
* Any background would have to increase by >5σ!

Events from NuMI Directed at MiniBooNE

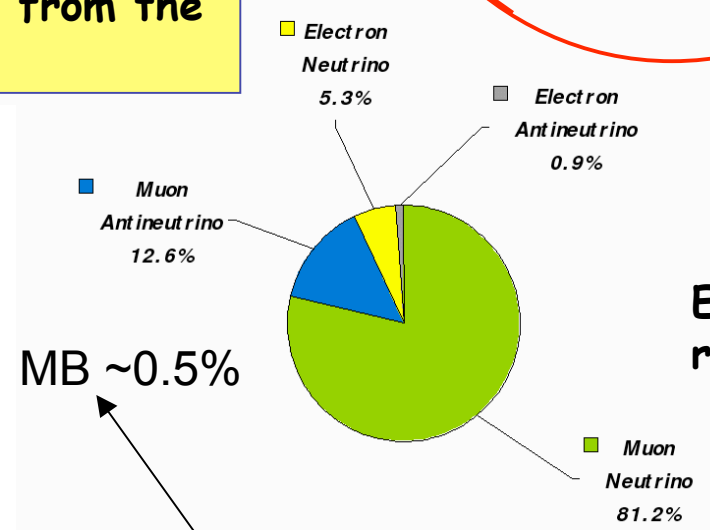


MiniBooNE detector is 745 meters downstream of NuMI target.

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



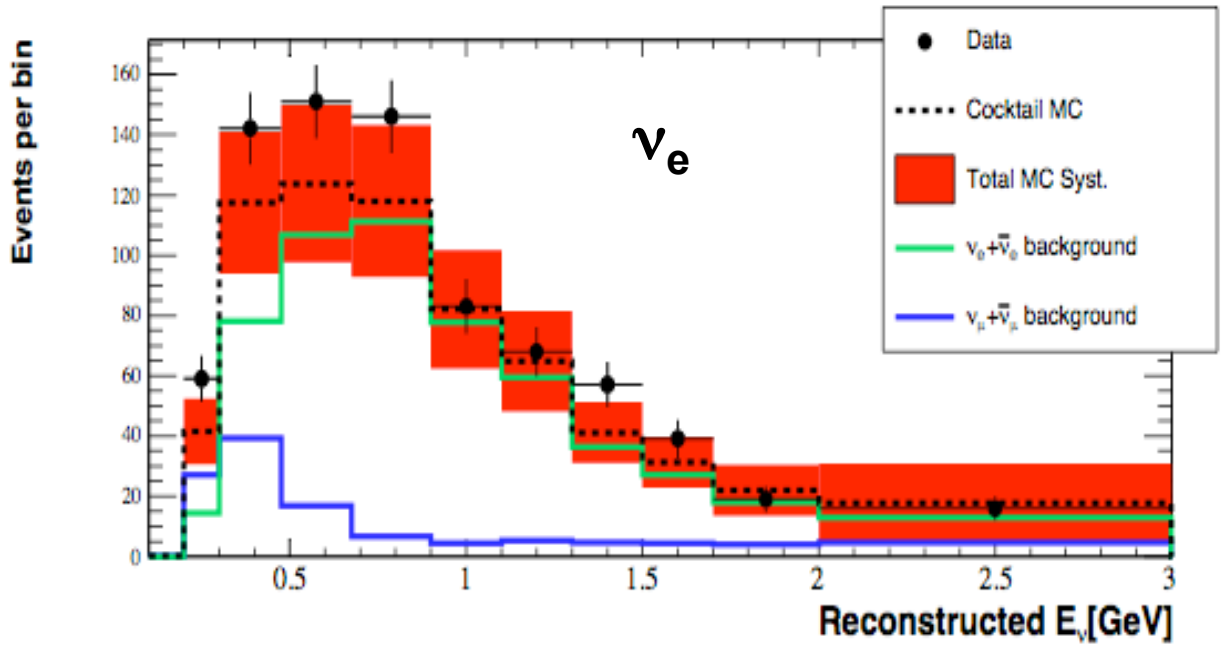
Energy similar to MB as off angle

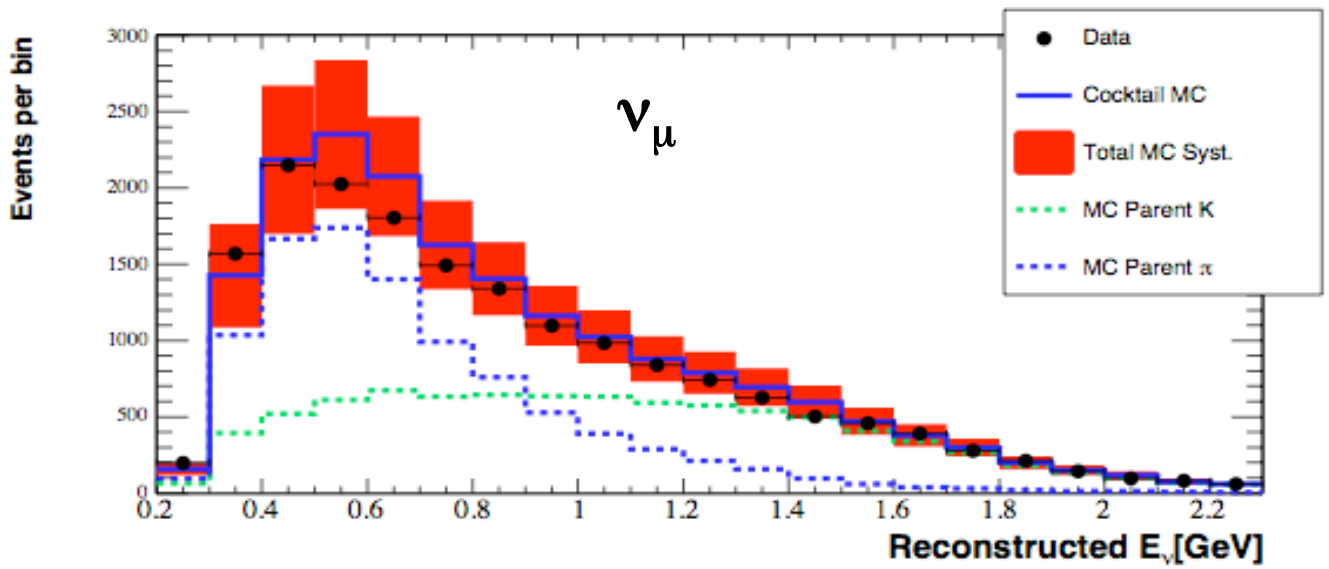


Event rates

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

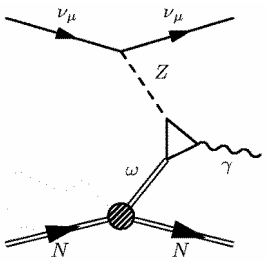
Excess Also Observed in NuMI Data!





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
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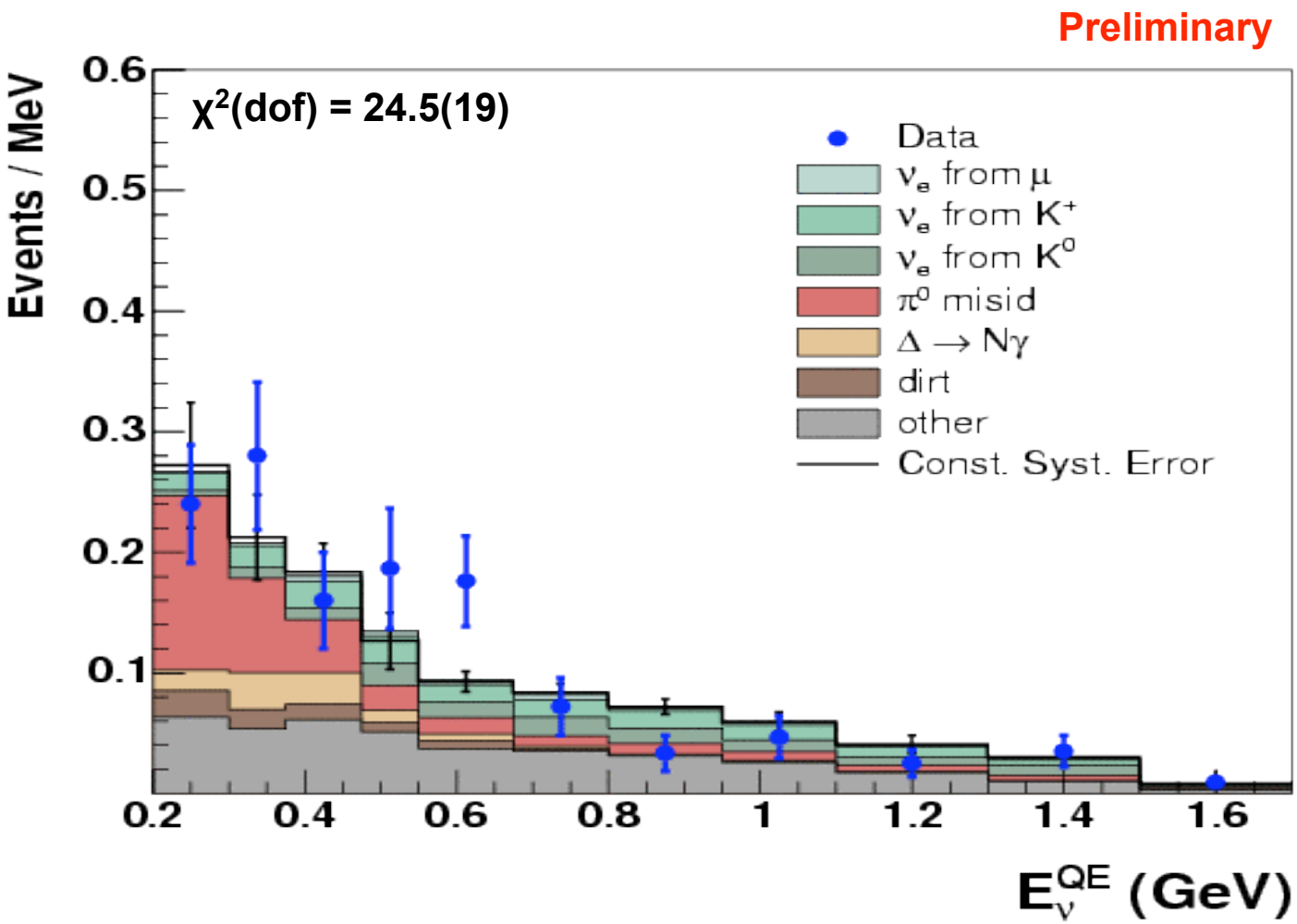
- New Gauge Boson with Sterile Neutrinos: Ann E. Nelson & Jonathan Walsh, arXiv:0711.1363

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

MiniBooNE Antineutrino 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 = 4.5E20 POT.)
- Approximately 0.1×10^6 antineutrino events recorded.
- Antineutrino analysis is the same as the neutrino analysis.

Antineutrino Results (3.39e20POT)



Data - MC → 200-475 MeV: -0.5 +/- 11.7 events

→ 475-1250 MeV: 3.2 +/- 10.0 events

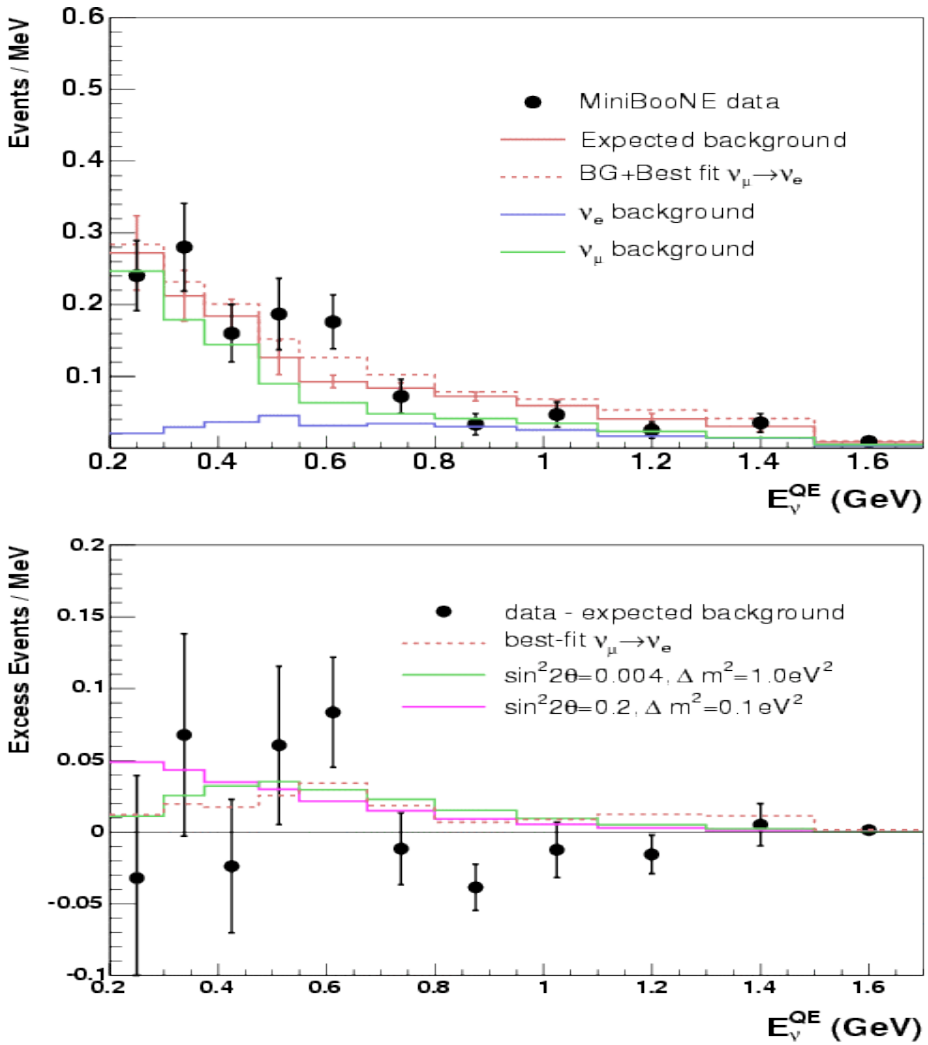
Implications for Low-E Excess

	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 with neutrino flux!**

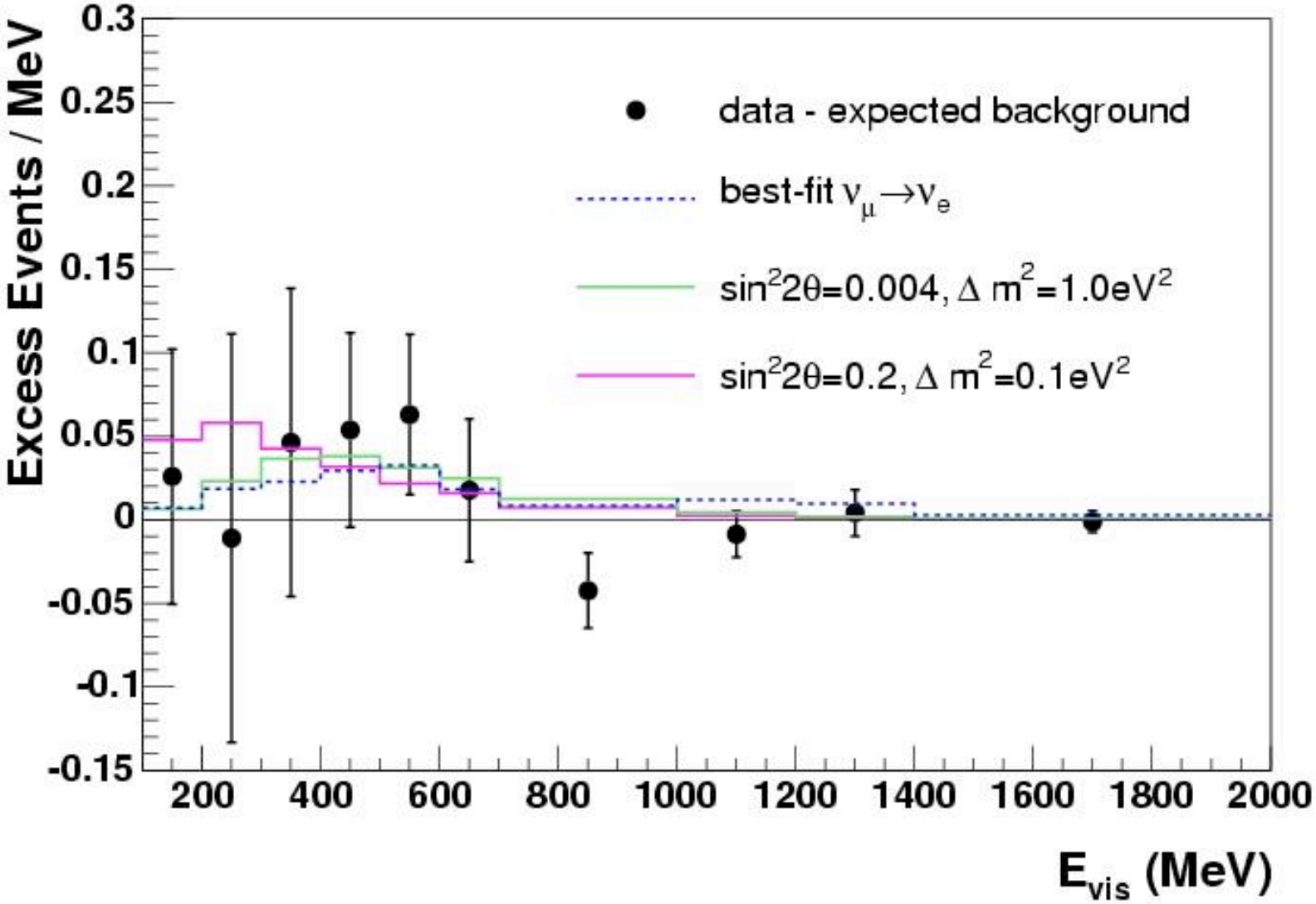
Oscillation fit (>475 MeV) consistent with LSND and Null



Preliminary

Fit yields 18.6+/-13.2 events, consistent with expectation from LSND.
However, not conclusive due to large errors.

Antineutrino Excess Events



Antineutrino Statistics

Energy (MeV)	Data	MC	Excess	
200-475	61	61.5+-11.7	-0.5+-11.7	(-0.04 σ)
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	

Fit Summary

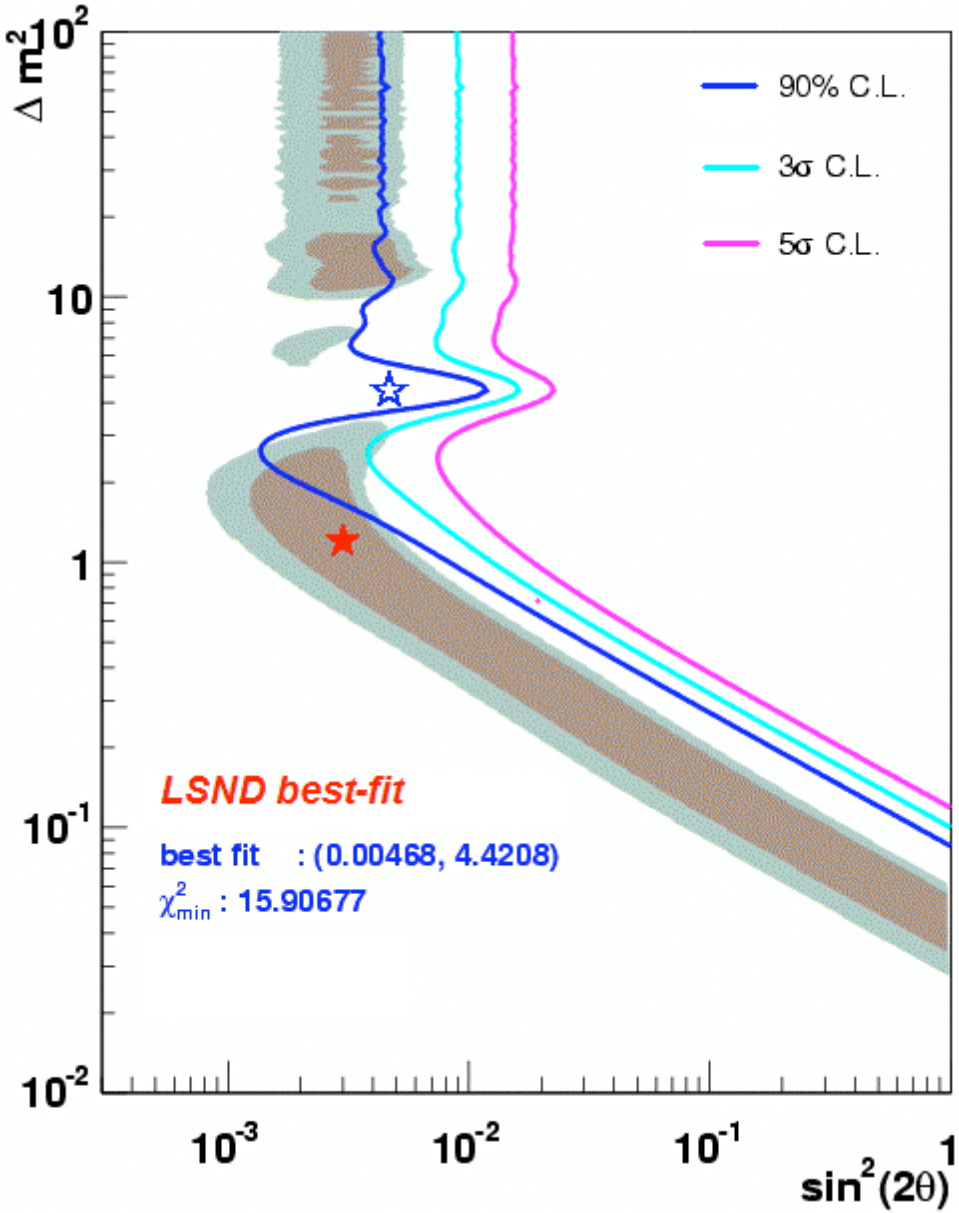
Energy	χ^2 Null	χ^2 LSND	χ^2 Null*	χ^2 Best
>475 MeV	22.19/16 (13.7%)	17.63/16 (34.6%)	17.88/14 (21.2%)	15.91/14 (31.9%)

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

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

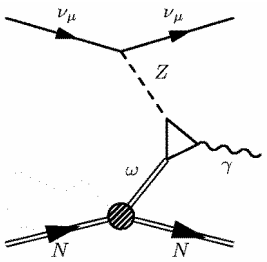
(* Using error matrix at best fit)

Antineutrino Allowed Region



E_ν^{QE} > 475 MeV

Possible Explanations for the Low-Energy Excess



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- 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**

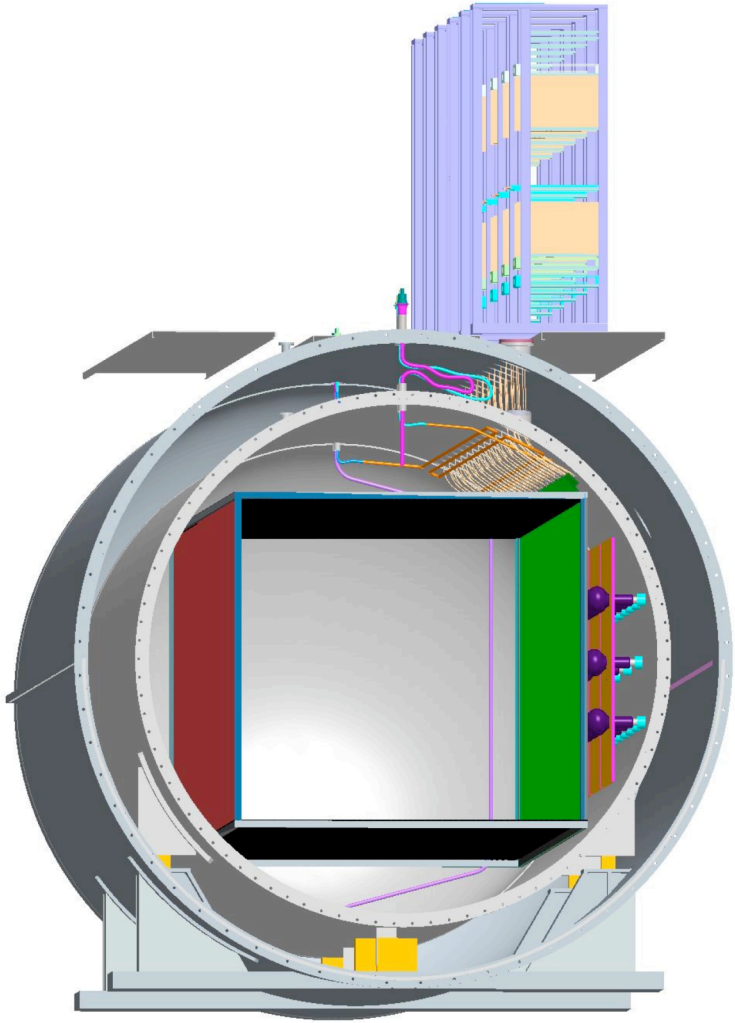
Other data sets (NuMI, antineutrino, SciBooNE) may provide an explanation!

Future

- Collect more antineutrino data! (~5E20 POT by summer) to study low-energy excess and LSND signal directly.
- Complete analysis of NuMI data with reduced systematic and statistical errors.
- Understand difference between neutrinos & antineutrinos!
- Future experiments at FNAL (MicroBooNE & BooNE) and ORNL (OscSNS) should be able to determine whether the low-energy excess is due to a Standard Model process (e.g. interference of NC γ processes) or to Physics Beyond the Standard Model (e.g. sterile neutrinos with CP violation)

MicroBooNE

- LArTPC detector designed to advance LAr R&D and determine whether the MiniBooNE low-energy excess is due to electrons or photons.
- Approximately 70-ton fiducial volume detector, located near MiniBooNE (cost <$20M).
- Received Stage-1 approval at Fermilab and initial funding from DOE and NSF.
- May begin data taking as early as 2011.



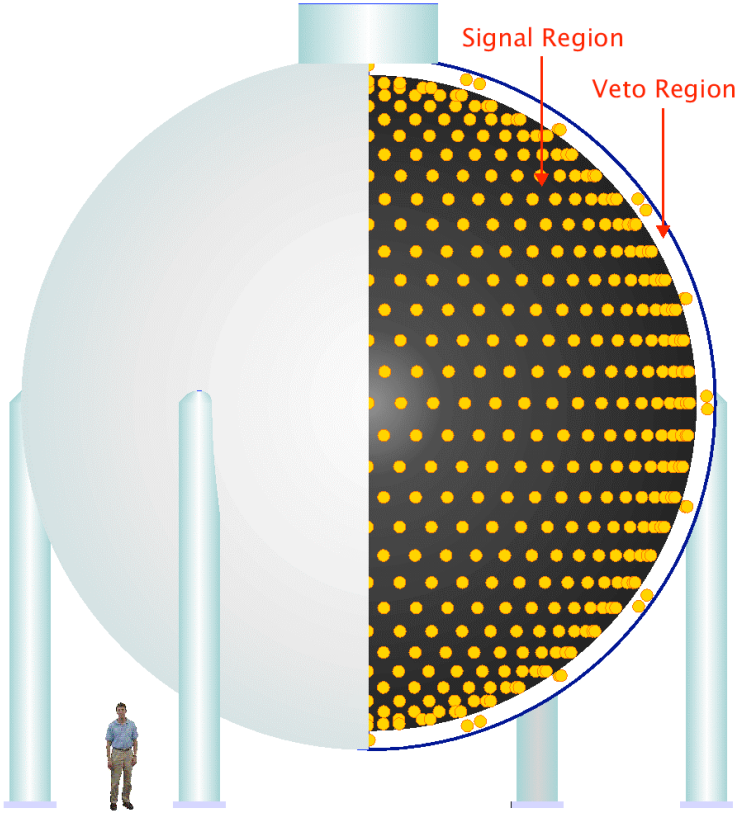
Future Experiments: BooNE & OscSNS

Search/Explore physics beyond the Standard Model!

BooNE would involve a second "MiniBooNE-like" detector (~$8M) at FNAL at a different distance; with 2 detectors, many of the systematics would cancel

OscSNS would involve building a "MiniBooNE-like" detector (~$12M) with higher PMT coverage at a distance of ~60 m from the SNS beam stop at ORNL

MiniBooNE Detector



BooNE at FNAL

Two identical detectors at different distances

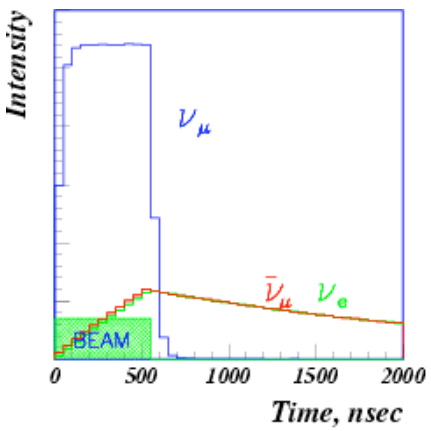
Search for ν_e appearance & ν_μ disappearance

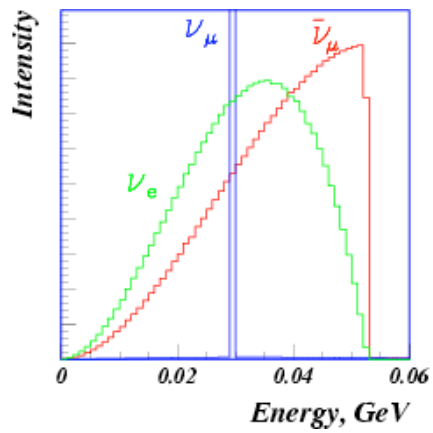
Search for sterile neutrinos via **NCPI0** scattering & **NCEL** scattering

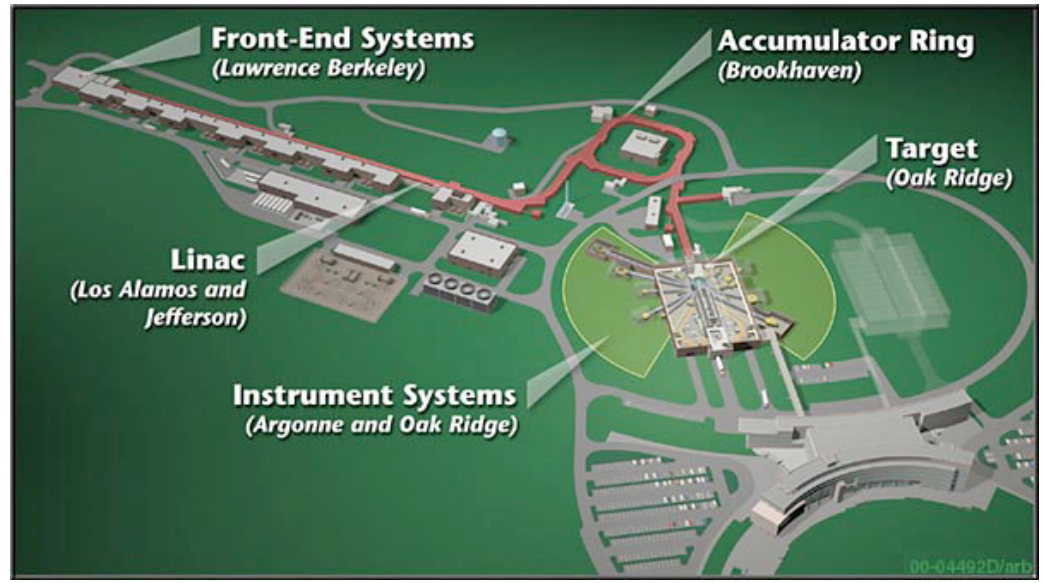
Problem: imprecise ν energy determination smears oscillations!

OscSNS at ORNL

Very high neutrino flux! Very low background! Beam is free!







SNS: ~1 GeV, ~1.4 MW

$\bar{\nu}_\mu \to \bar{\nu}_e$ $\Delta(L/E) \sim 3\%$; $\bar{\nu}_e\, p \to e^+ n$

$\nu_\mu \to \nu_s$ $\Delta(L/E) < 1\%$; **Monoenergetic ν_μ** !; $\nu_\mu\, C \to \nu_\mu\, C^*(15.11)$

OscSNS would be capable of making precision measurements of ν_e appearance & ν_μ disappearance and proving, for example, the existence of sterile neutrinos! (see Phys. Rev. D72, 092001 (2005)). Flux shapes are known perfectly and cross sections are known very well

OscSNS Physics Goals

ν_e appearance (ν_e ^{12}C -> e^- $^{12}N_{gs}$ + β)

$\bar{\nu}_e$ appearance ($\bar{\nu}_e$ p -> e^+ n + γ)

ν_μ disappearance & search for sterile ν

(ν_μ ^{12}C -> ν_μ C* + γ) **(~1300 events per year)**

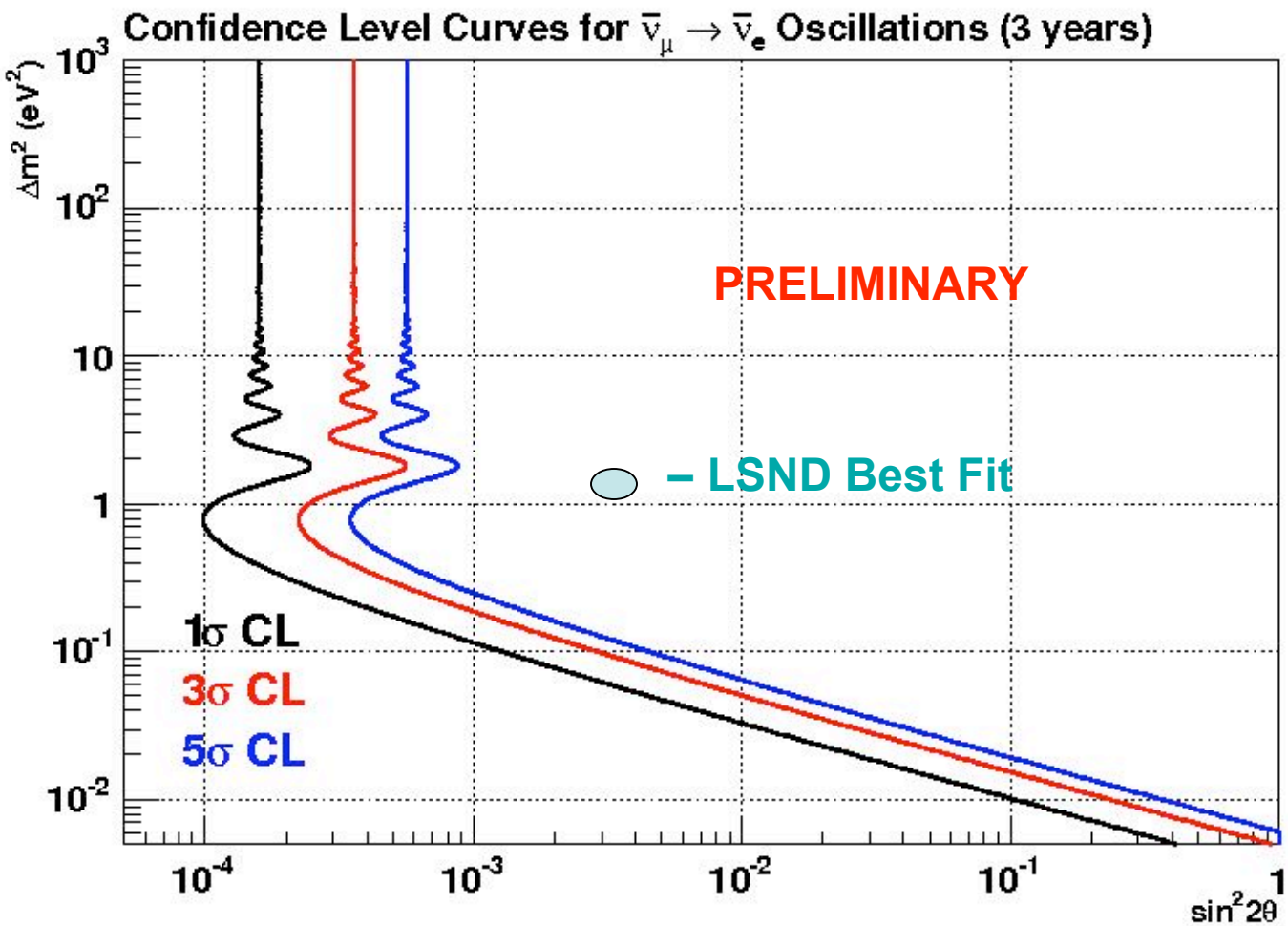
νe–>νe elastic scattering (μ_ν?) **(~1700 ev. per year)**

νC cross sections **(~4600 events per year)**

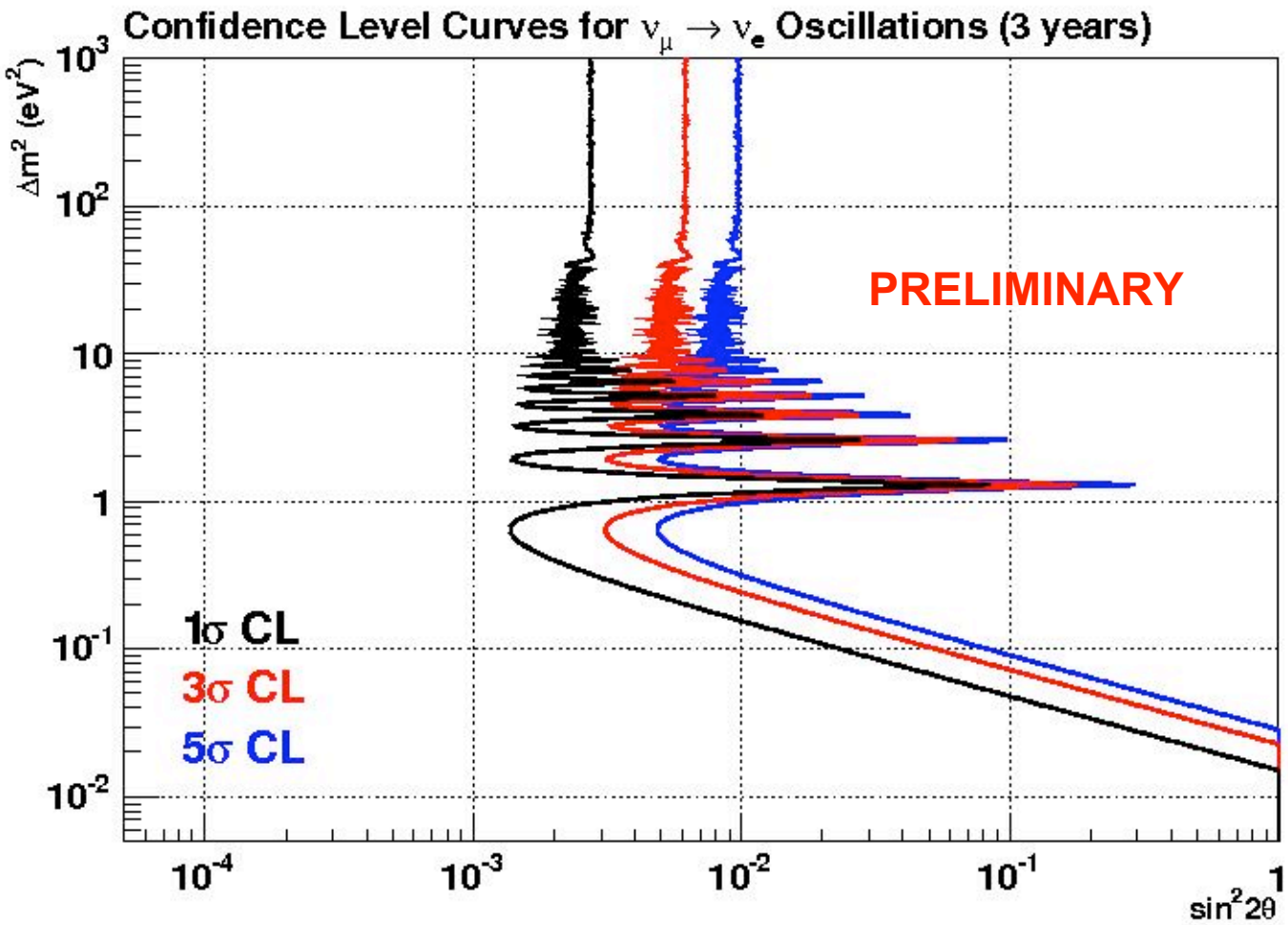
OscSNS vs LSND

- **x5** more detector mass
- **x1000** lower duty factor
- **x2** higher neutrino flux
- **x10** lower DIF background
- **x10** better neutrino oscillation sensitivity
- **x10** higher statistics

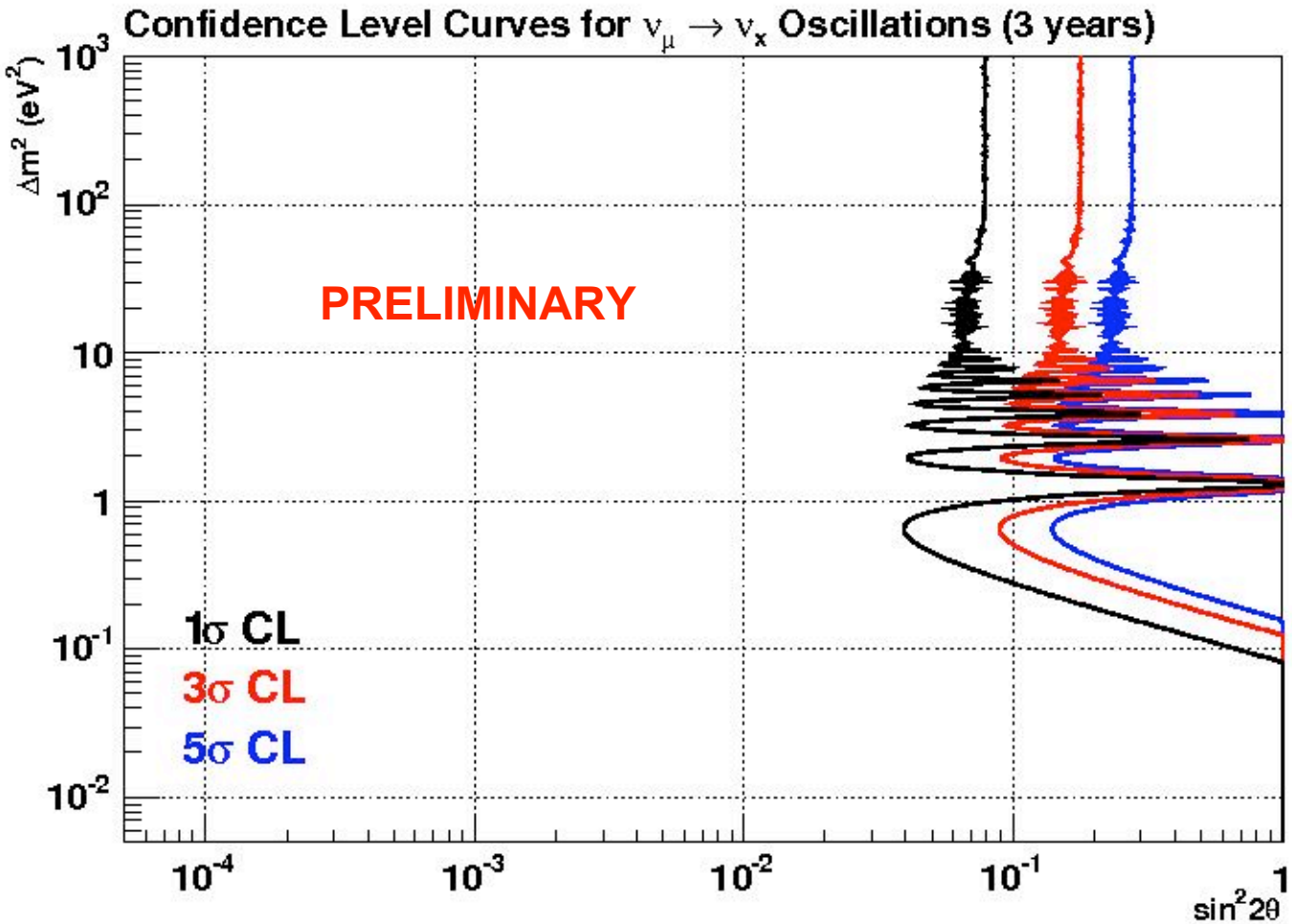
OscSNS ν Oscillation Sensitivities



OscSNS ν Oscillation Sensitivities



OscSNS ν Oscillation Sensitivities



Conclusions 1

- **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-ν 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 (χ^2=17.6/16, P=34.6%) & the null point (χ^2=22.2/16, P=13.7%). (LSND is alive & well!)**
- **The low-energy excess (~1%) is interesting in its own right and important for future long-baseline experiments (T2K, NOvA, DUSEL). Monte Carlos need improvement!**
- **More antineutrino data & other data sets (NuMI & SciBooNE) will help improve our understanding of the low-energy excess.**

Conclusions 2

- **Follow-on experiments at FNAL (BooNE & MicroBooNE) and/or ORNL (OscSNS) will provide an explanation for the excess and for the LSND signal.**
- **MicroBooNE is a LAr TPC that will have the capability of determining whether the excess is due to photons or electrons.**
- **BooNE involves moving MiniBooNE or building a 2nd detector at a distance of ~200 m from the BNB target. With two detectors the systematic errors will be greatly reduced and will allow precision appearance and disappearance searches for neutrinos & antineutrinos.**
- **OscSNS involves building a MiniBooNE-like detector at a distance of ~60 m from the SNS beam dump. OscSNS can search for appearance with high precision & disappearance with a NC reaction (sterile neutrinos!).**