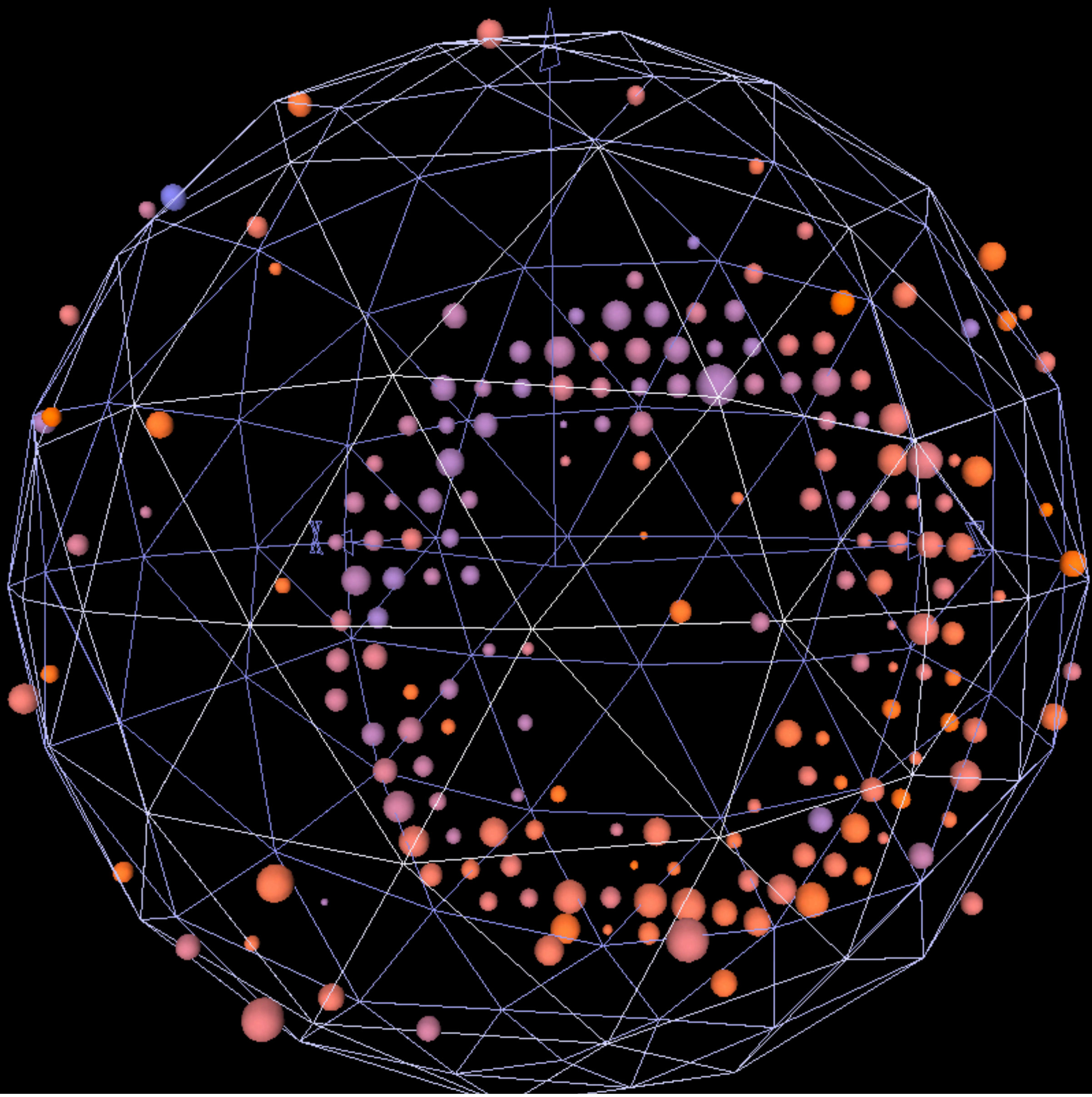
Updated Anti-neutrino Oscillation Results from MiniBooNE



Byron Roe

University of Michigan

For the MiniBooNE Collaboration

The MiniBooNE Collaboration

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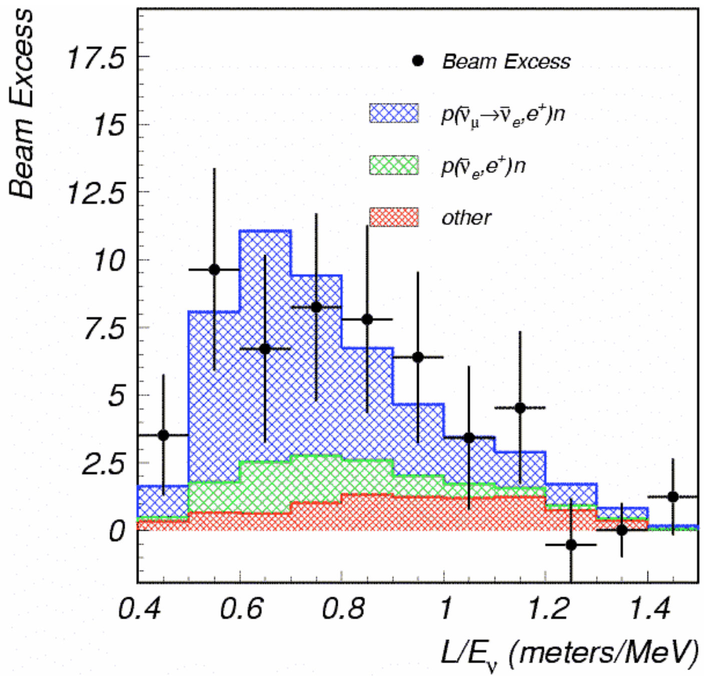
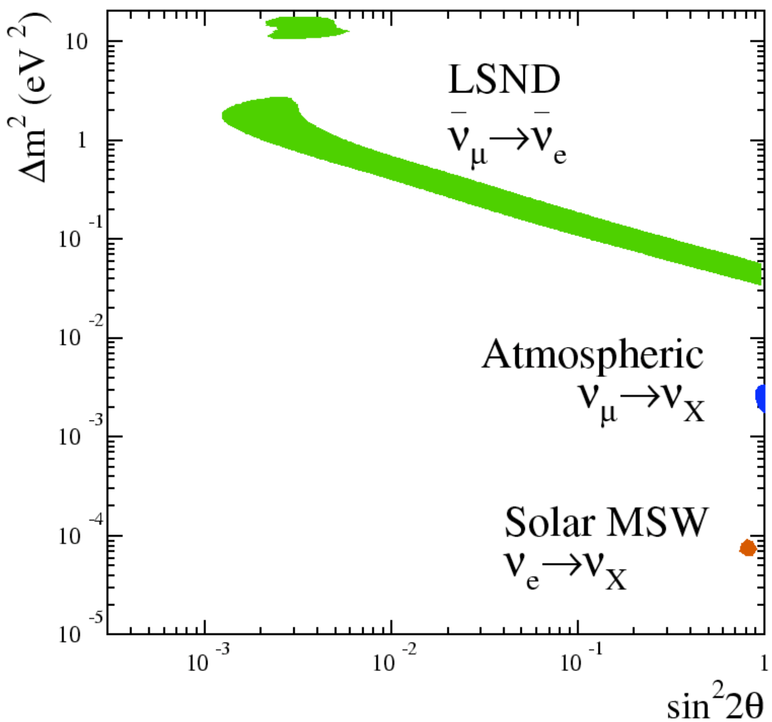
Introduction

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

Motivation for MiniBooNE: The LSND Evidence for Oscillations





LSND Saw an excess of $\bar{\nu}_e$

87.9 ± 22.4 ± 6.0 events.

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

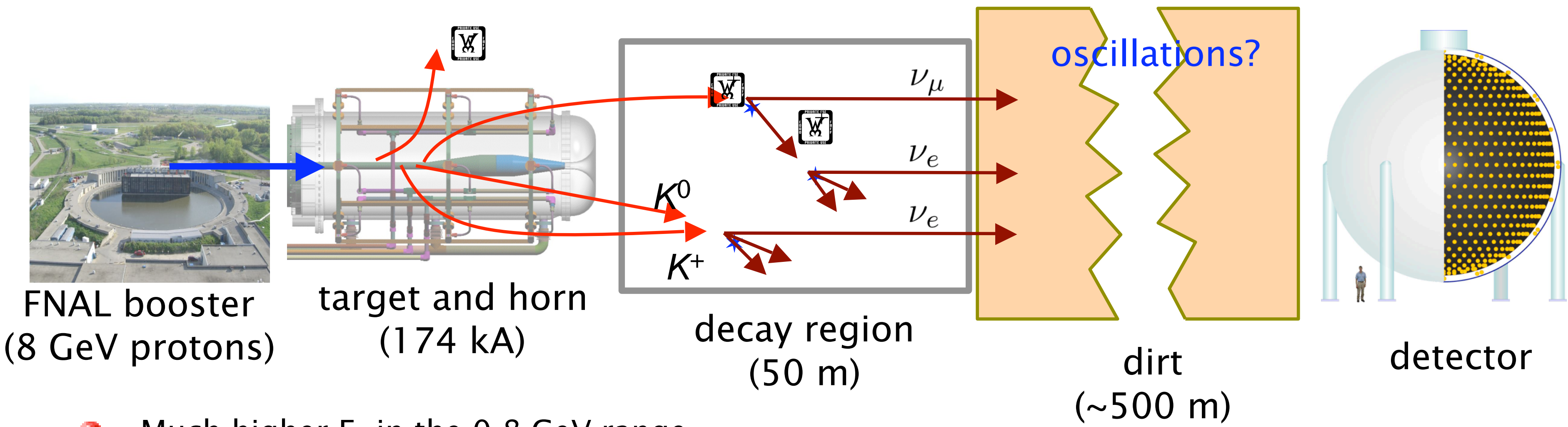
3.8 σ evidence for oscillation.

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

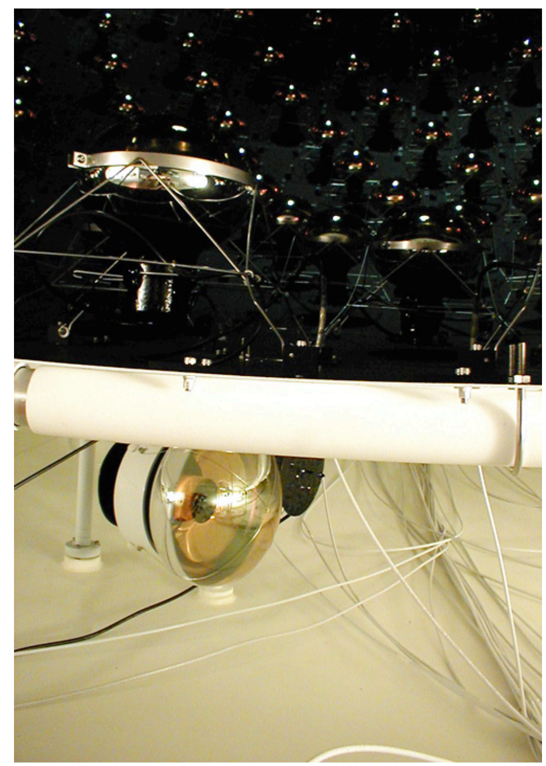
For 3 nu, oscillations depend on delta m^2 and

$$(m_1^2 - m_2^2) + (m_2^2 - m_3^2) = (m_1^2 - m_3^2)$$

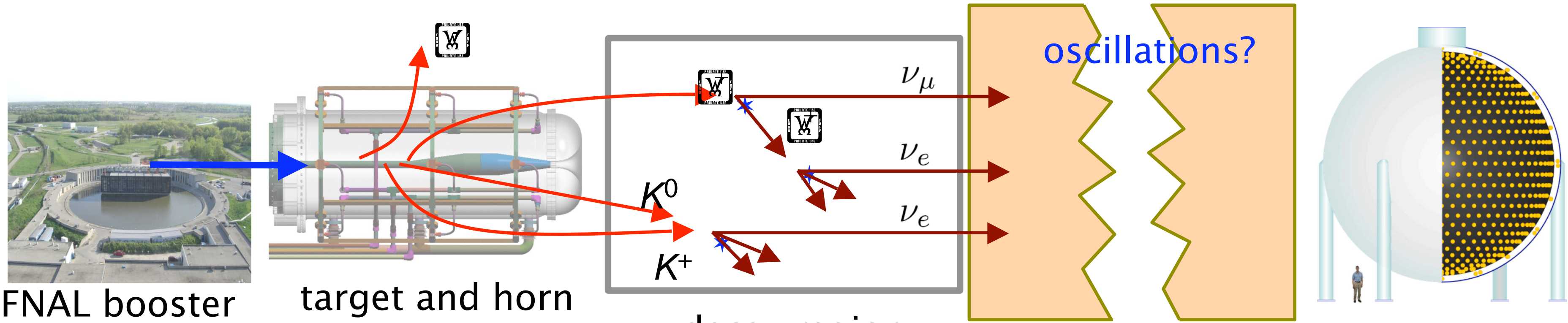
Contrasting MiniBooNE with LSND



- Much higher E_ν in the 0.8 GeV range
- Detector placed to preserve LSND L/E:
  - MiniBooNE: (0.5 km) / (0.8 GeV)
  - LSND: (0.03 km) / (0.05 GeV)
- Signal: nue CCQE <--> inverse beta decay, delayed neutron signal
- Backgrounds--
  - Mis-ID: No numu CCQE or NCpi0 interactions in LSND decay-at-rest source <--> MB has to pull ~300 nue CCQE from a background of 200,000 numu CCQE and deal with pi0s that fake a nue signal
  - Intrinsic nues: No nues from kaons in LSND beam (a few from muons) <--> intrinsic nues from kaons and muons comparable to signal strength in MB
- 800t mineral oil Cherenkov detector



Contrasting MiniBooNE with LSND

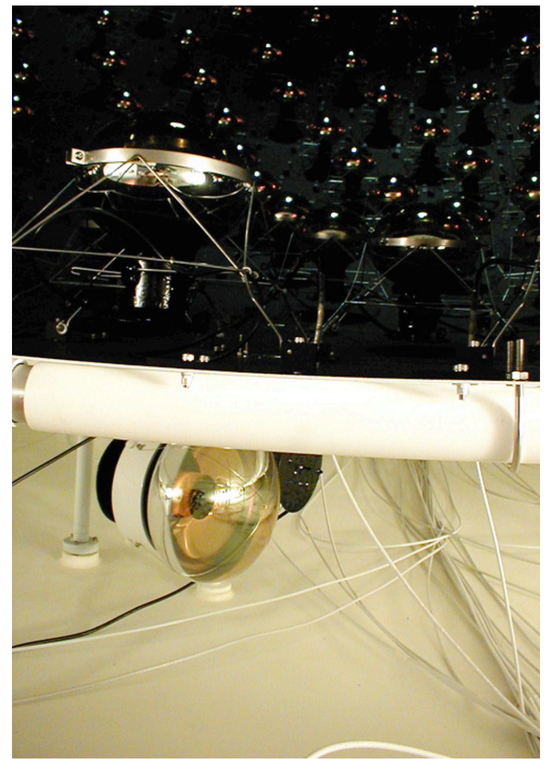


- Much higher E_ν in the 0.8 GeV range
- Detector placed to preserve LSND L/E:

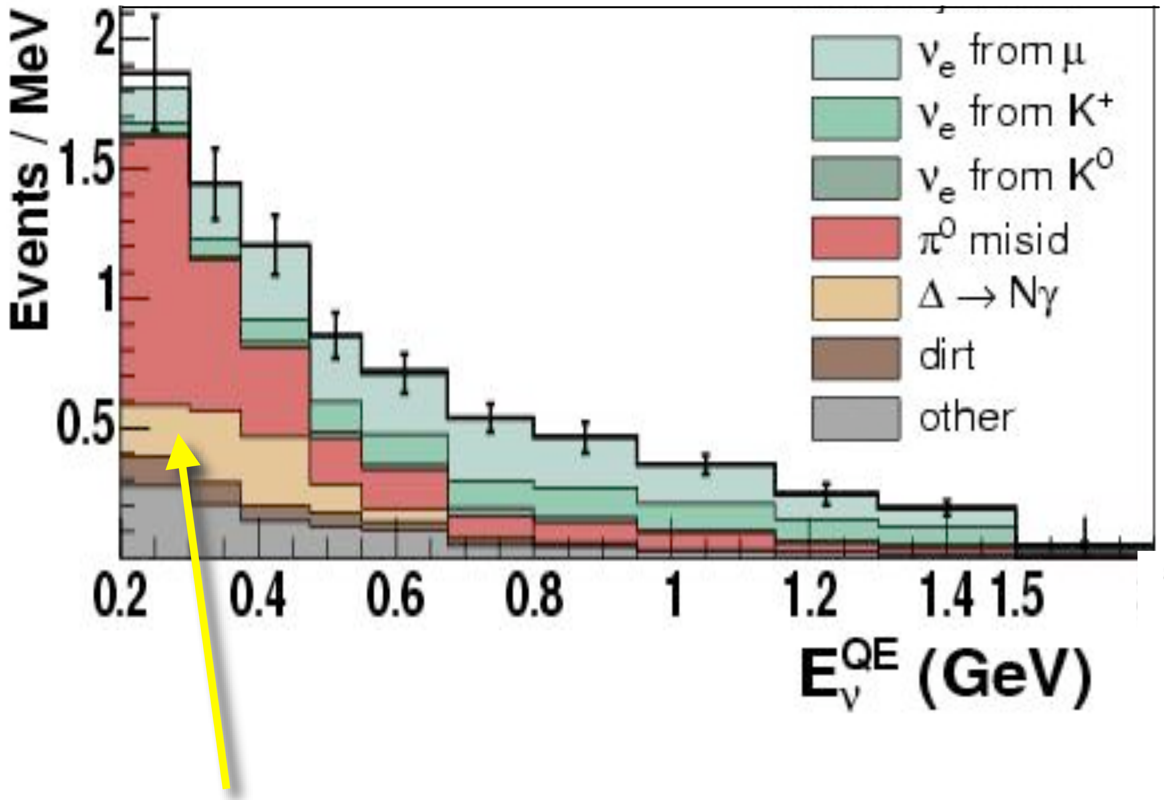
MiniBooNE:	(0.5 km) / (0.8 GeV)
LSND:	(0.03 km) / (0.05 GeV)

- Signal: nue CCQE <--> inverse beta decay
- Backgrounds--

Obviously MB is a difficult experiment without a near detector to measure bkgs, however with years of work we were able to constrain every known bkg source

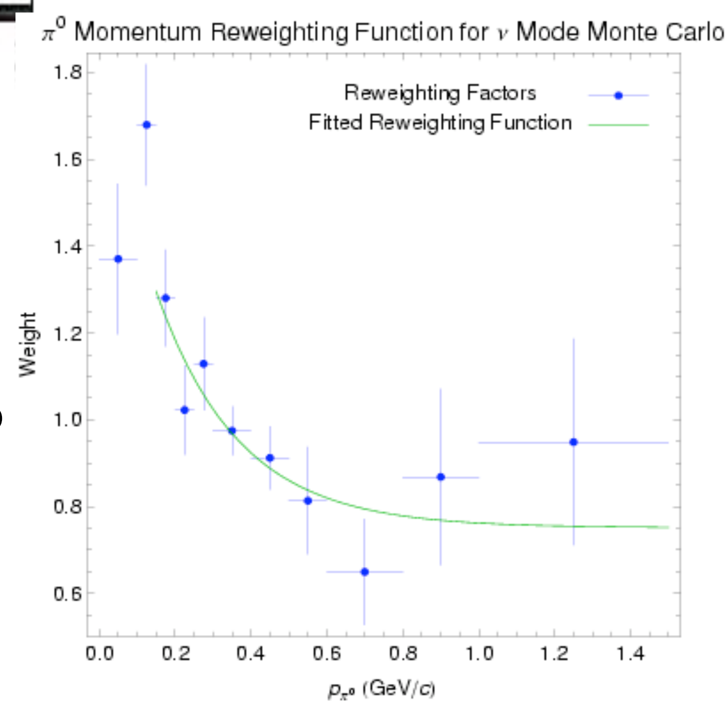


In situ background constraints: NC π^0



475 MeV – 1250 MeV

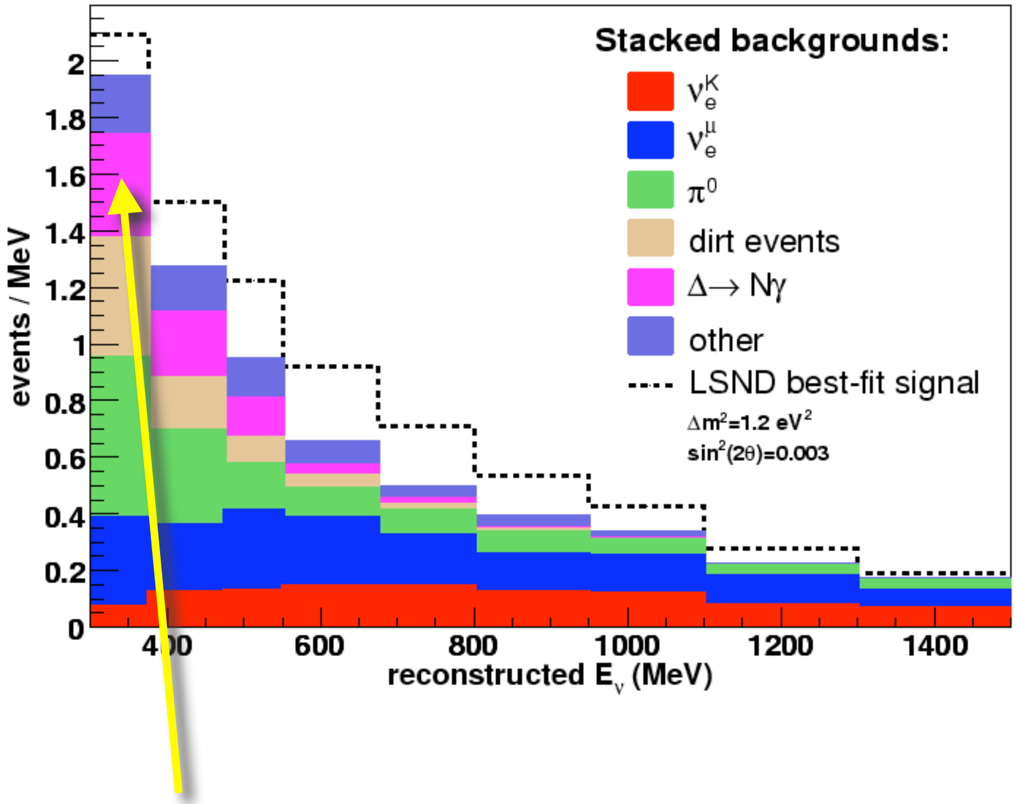
ν_e^K	94
ν_e^μ	132
π^0	62
dirt	17
$\Delta \to N\gamma$	20
other	33
total	358



- Reconstruct majority of π^0 events
- Error due to extrapolation uncertainty into kinematic region where 1 γ is missed due to kinematics or escaping the tank
- Overall < 7% error on NC π^0 bkgs

MB, Phys Lett B. 664, 41 (2008)

In situ background constraints: $\Delta \rightarrow N\gamma$



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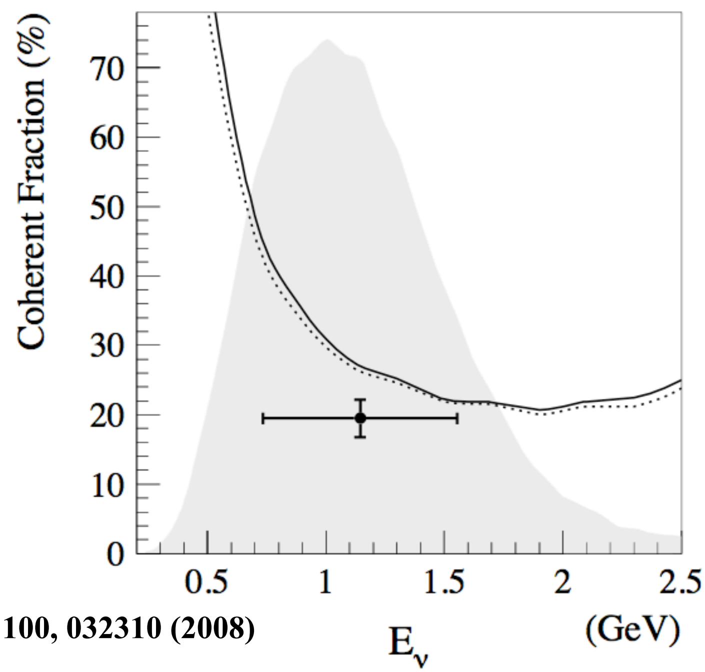
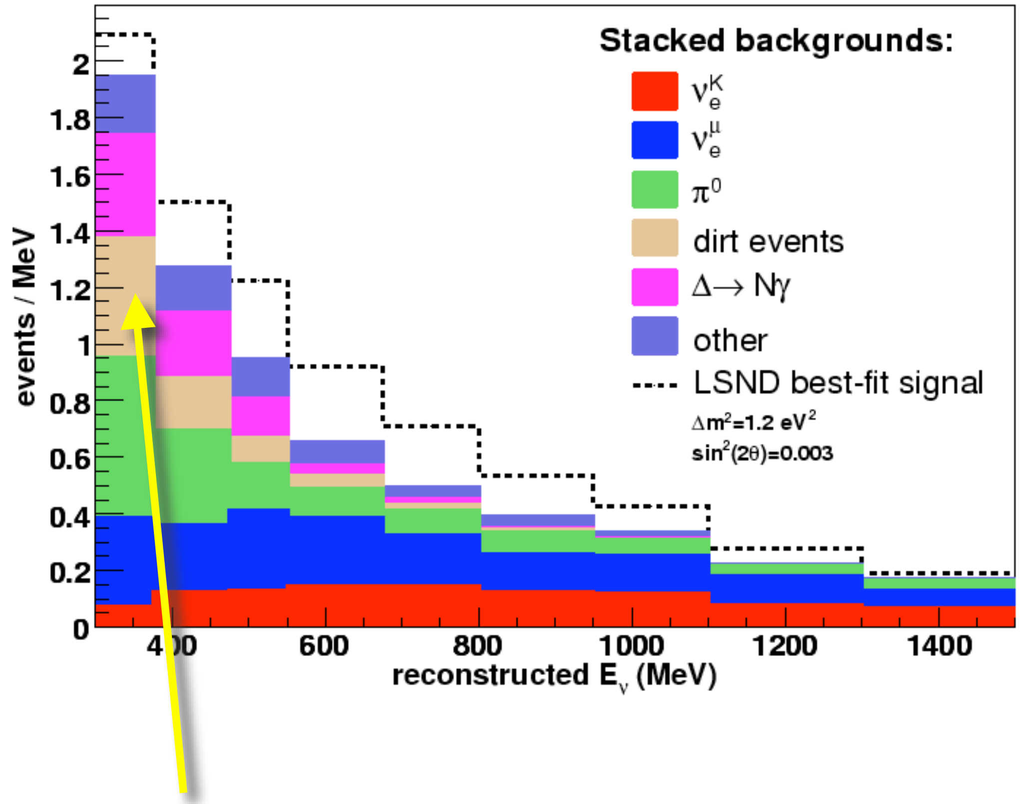
- About 80% of our NC π^0 events come from resonant Δ production
- Constrain $\Delta \rightarrow N\gamma$ by measuring the resonant NC π^0 rate, apply known branching fraction to $N\gamma$, including nuclear corrections



MB, PRL 100, 032310 (2008)

In situ background constraints: Dirt



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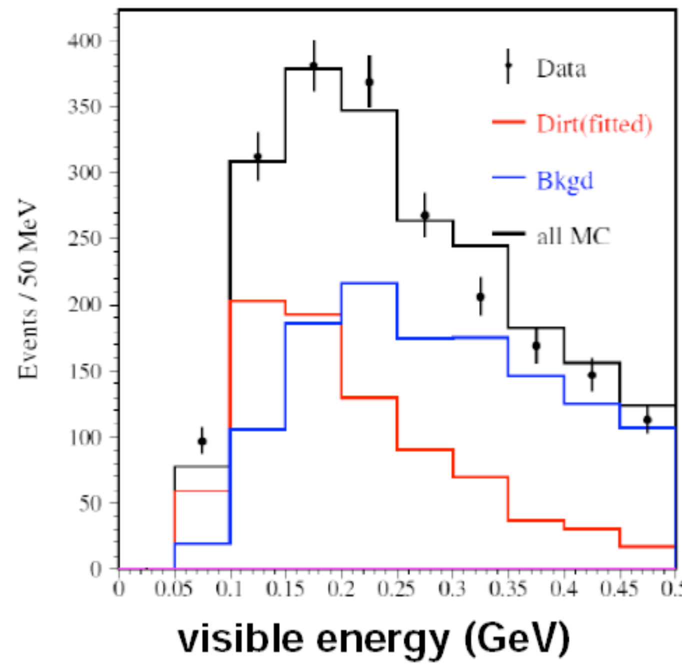
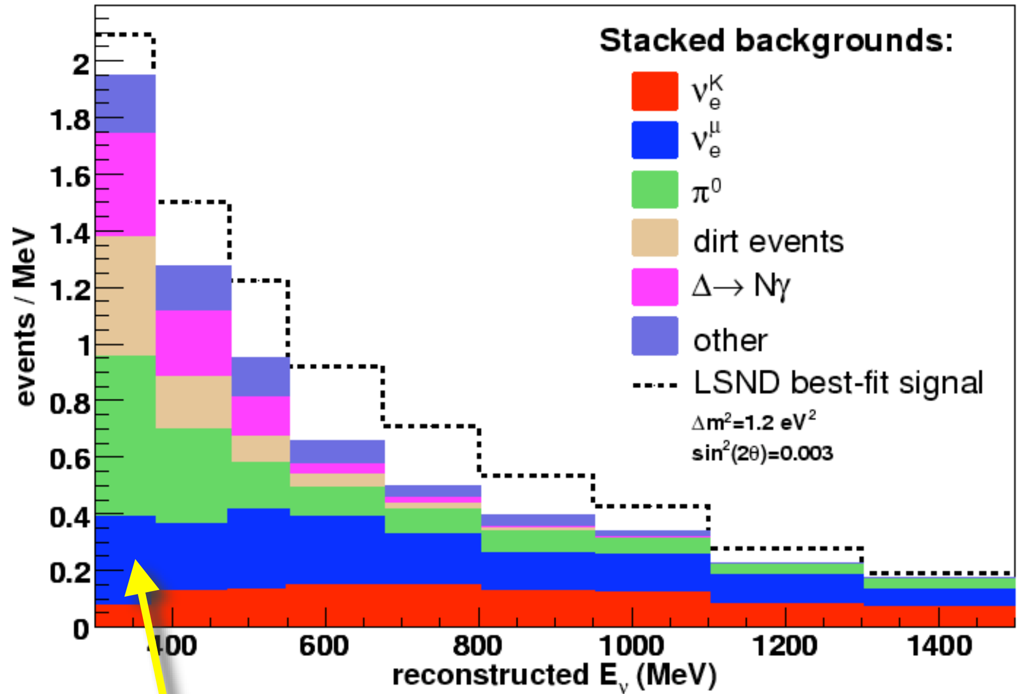
- Come from ν events int. in surrounding dirt
- Pileup at high radius and low E
- Fit dirt-enhanced sample to extract dirt event rate with 10% uncertainty



In situ background constraints: Muon ν_e



475 MeV – 1250 MeV

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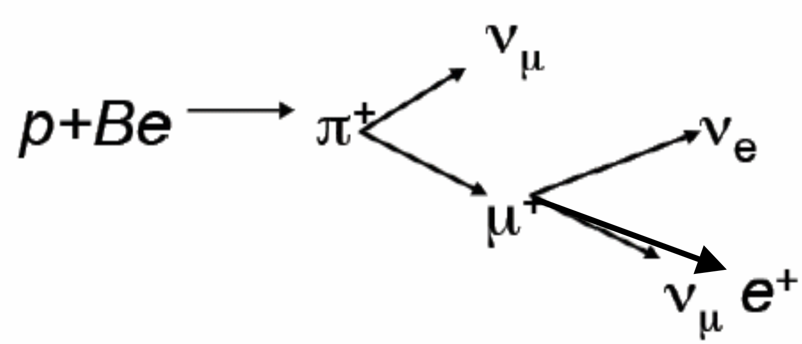
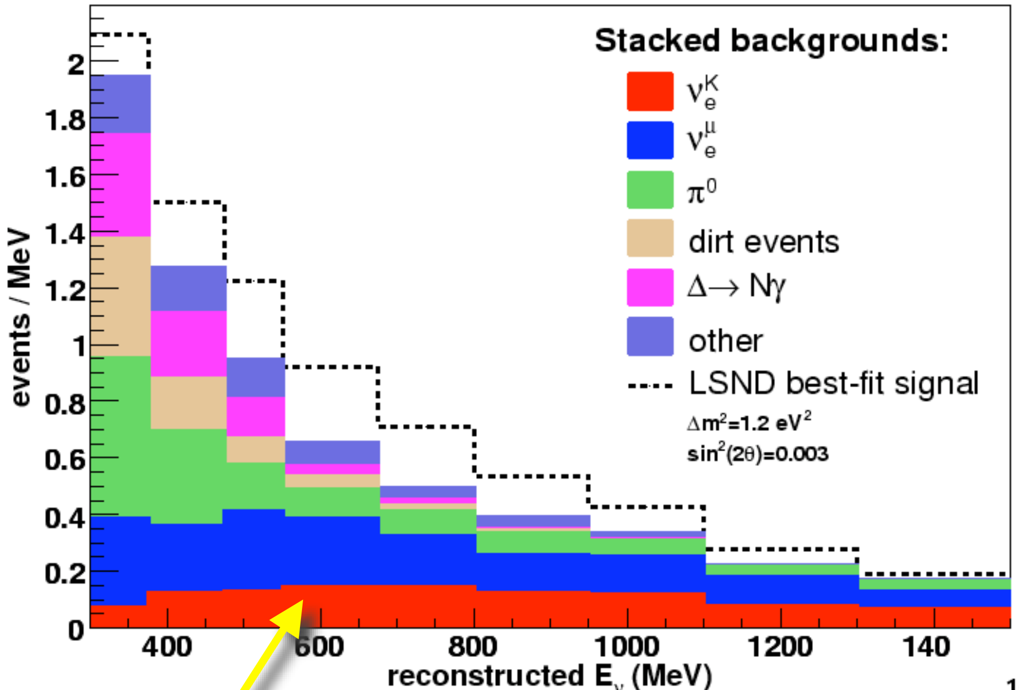
total	358

- Intrinsic ν_e from μ^+ originate from same π^+ as the ν_μ CCQE sample
- Measuring ν_μ CCQE channel constrains intrinsic ν_e from π^+



In situ background constraints: Kaon ν_e



475 MeV – 1250 MeV

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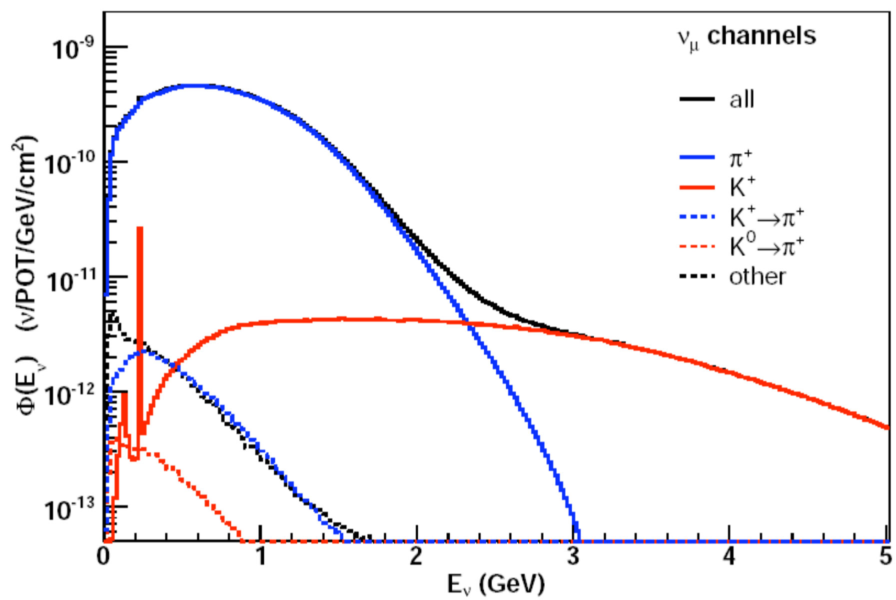
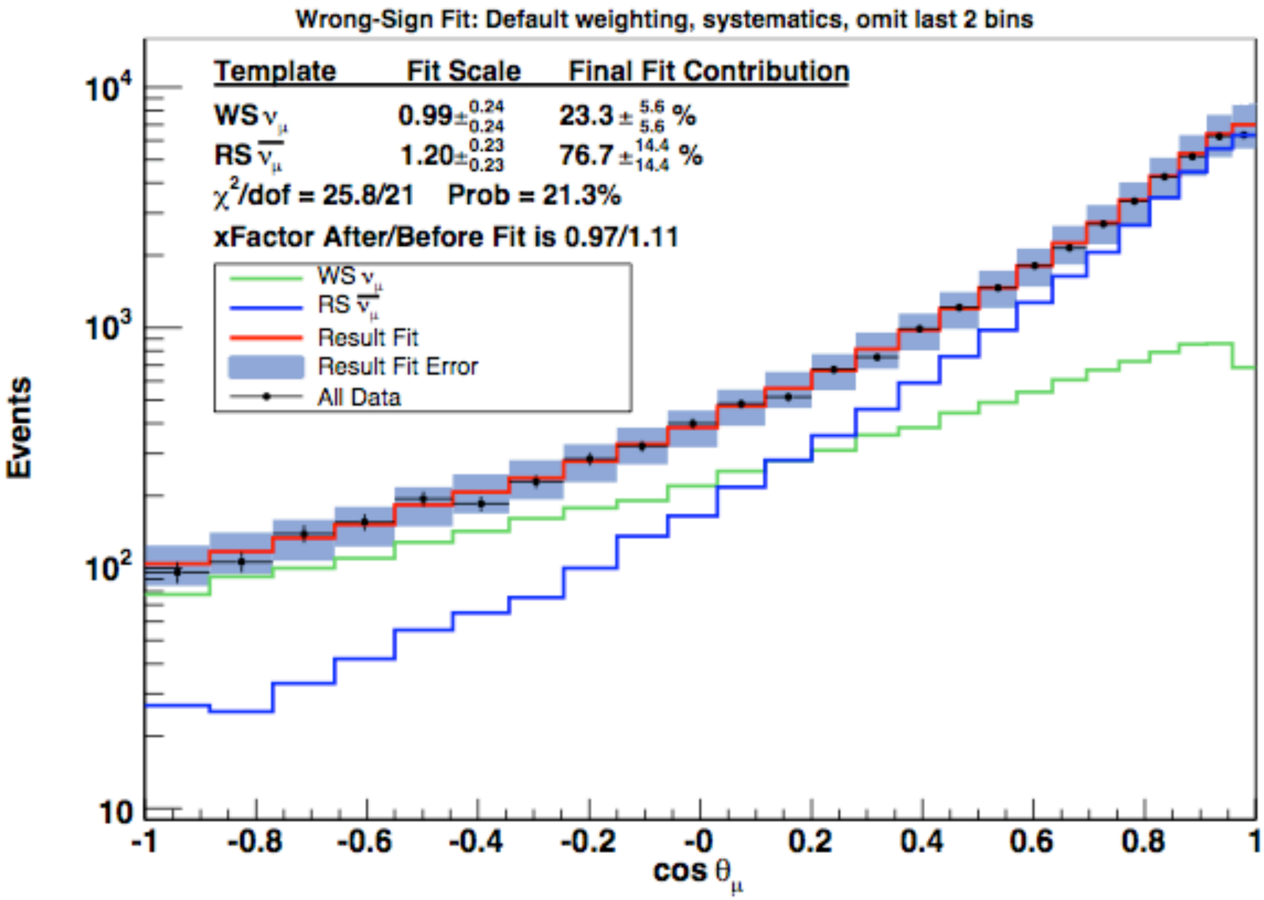
- At high energy, ν_μ flux is dominated by kaon production at the target
- Measuring ν_μ CCQE at high energy constrains kaon production, and thus intrinsic ν_e from K^+

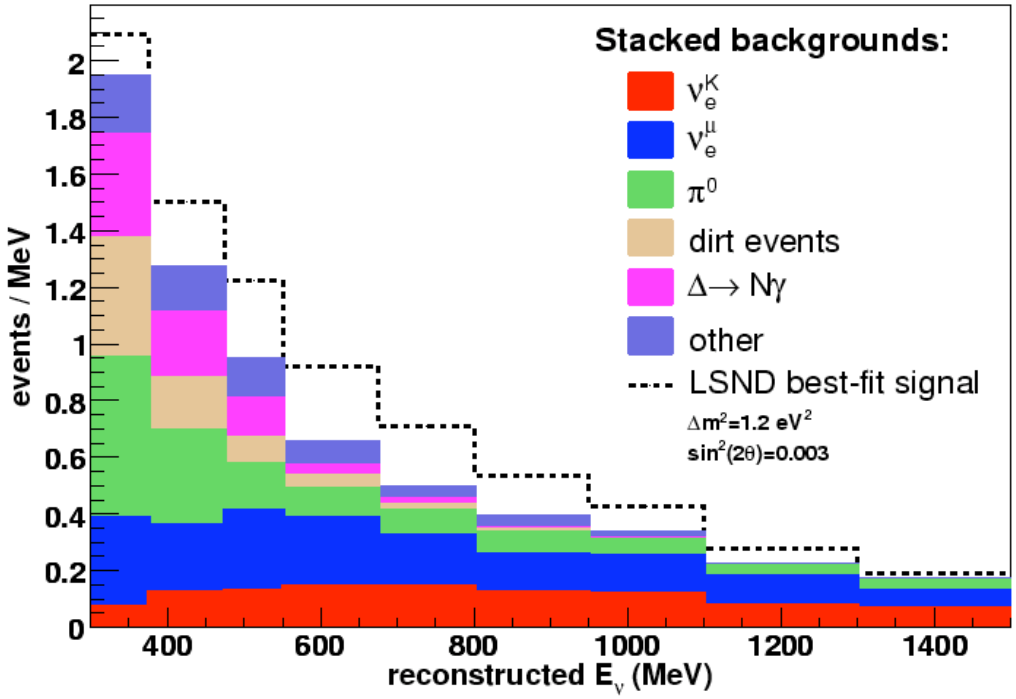


Wrong-sign Contribution Fits



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

In situ background constraints



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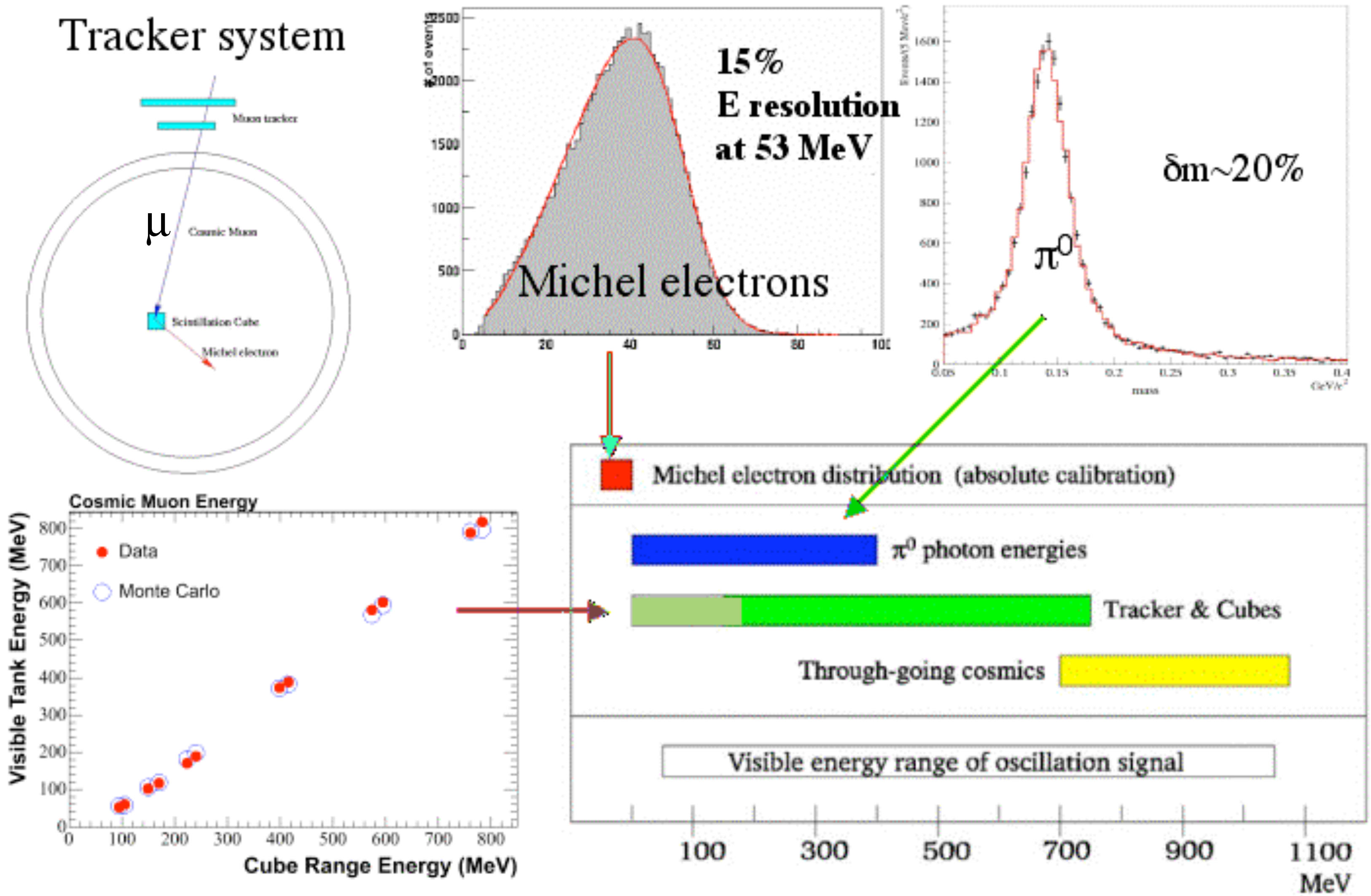
Also, pi and K production flux measurements (HARP) constrain flux

☆ In the end, every major source of background can be internally constrained by MB at various levels.

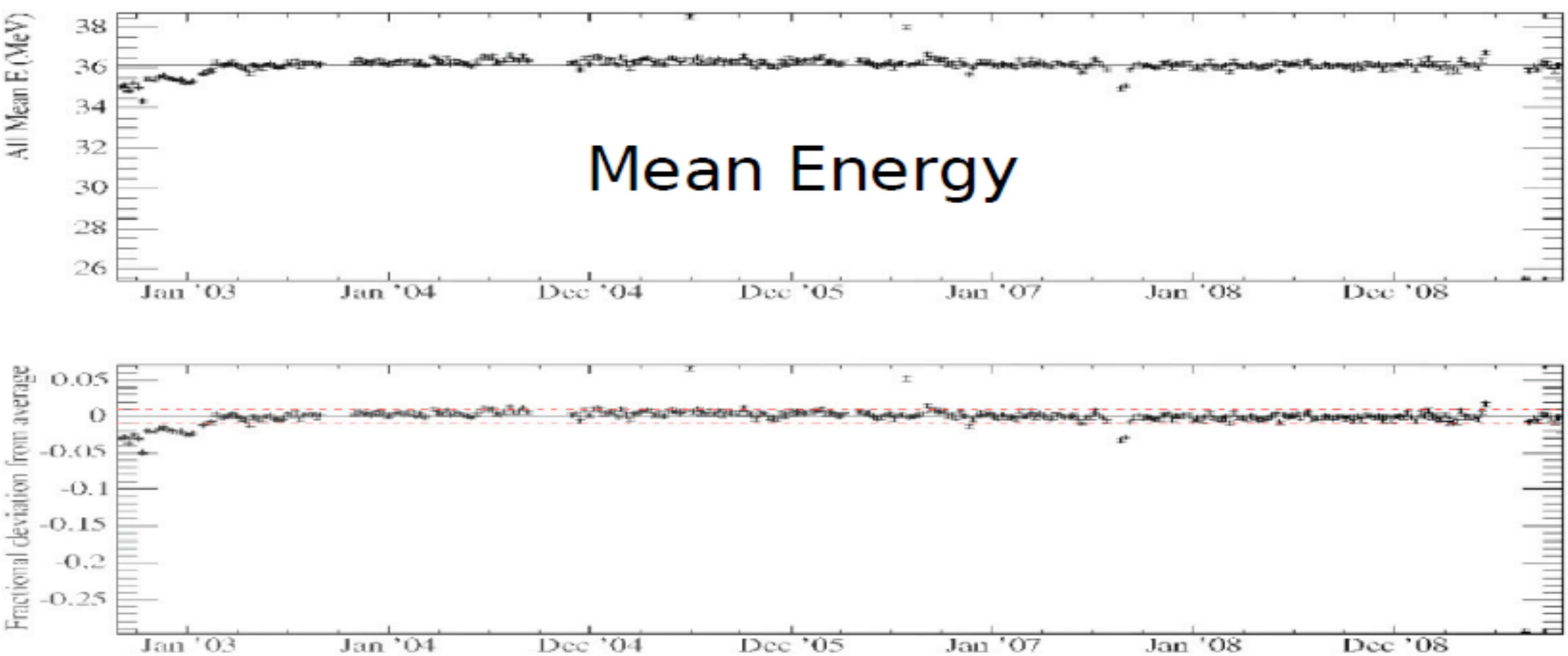
Calibration Sources



Detector calibration

Very stable

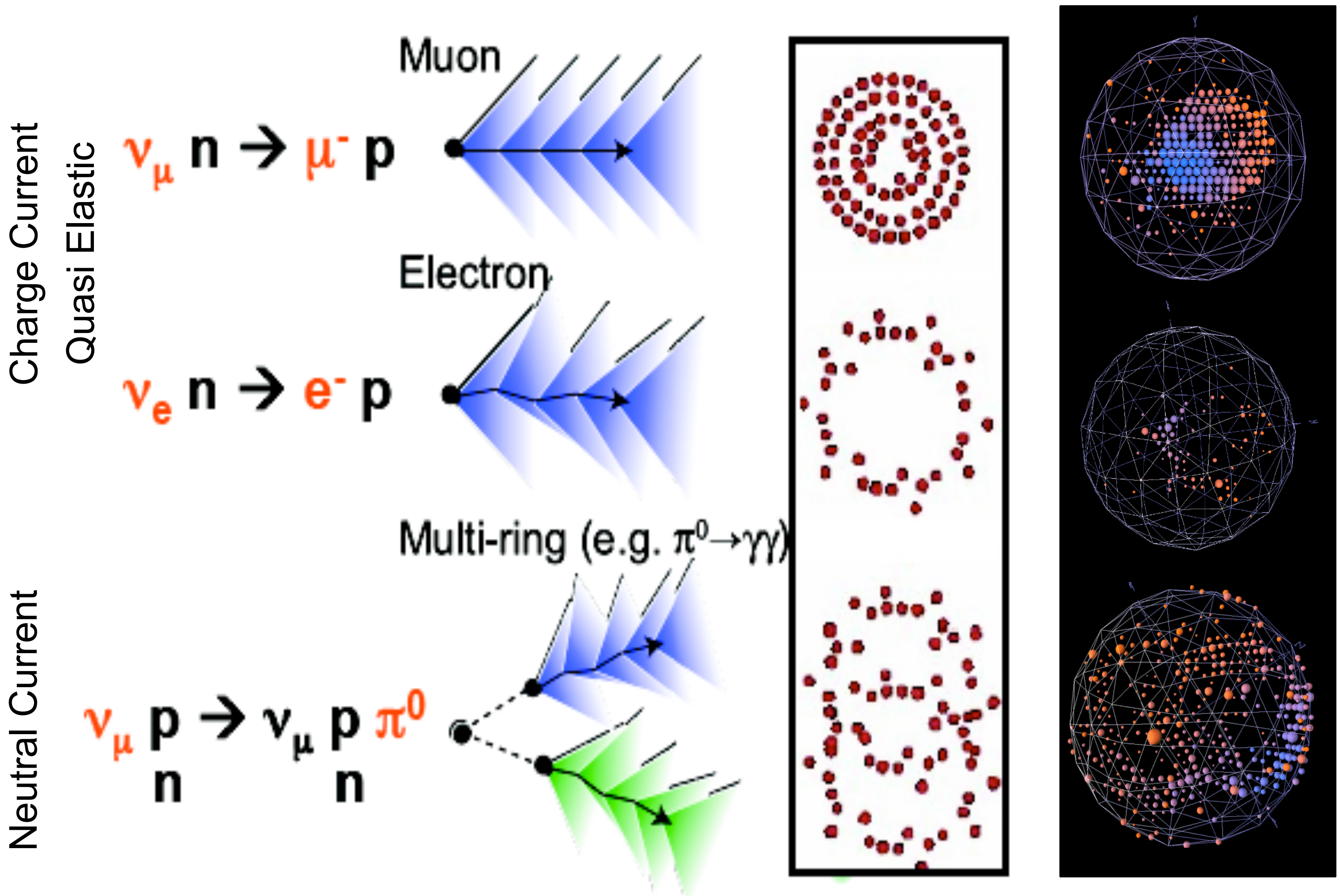
For example: Michel electron mean energy within 1% since beginning of run (2002)



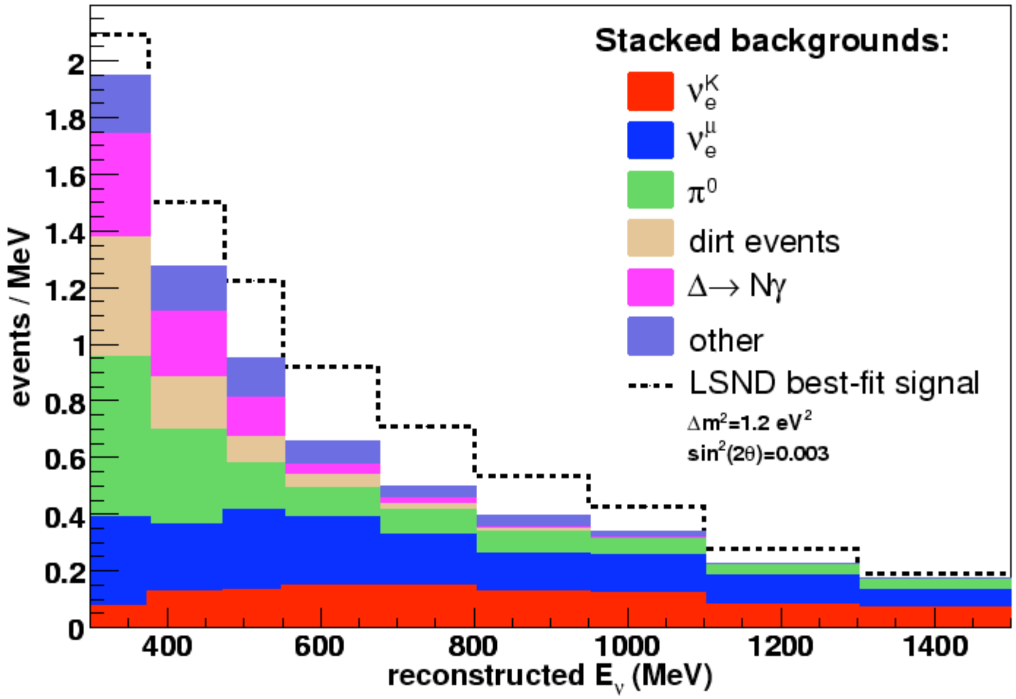
Events in MB

Identify events using timing and hit topology

Use primarily Cherenkov light

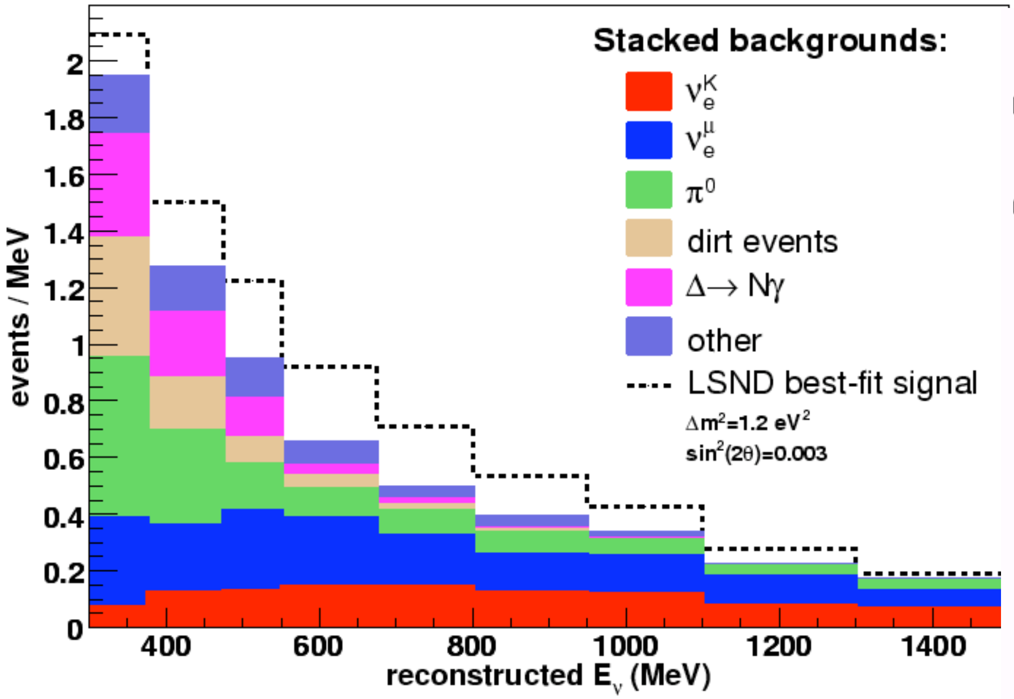


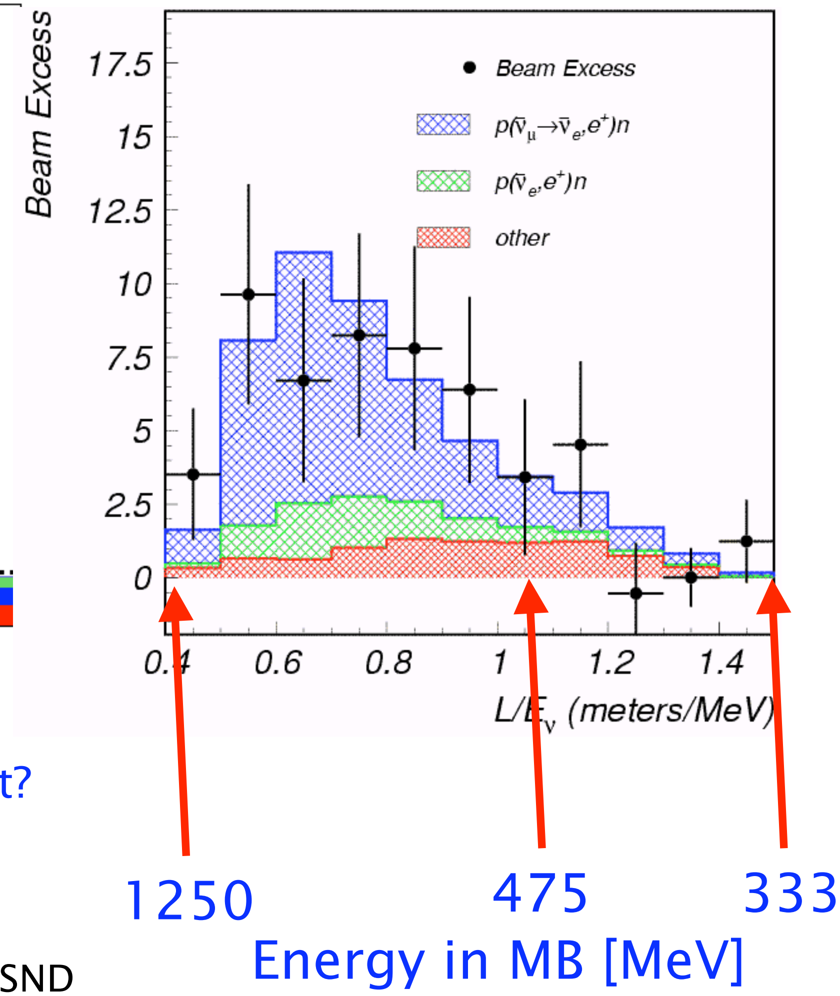
Reminders of some analysis choices



- Data bins chosen to be variable width to minimize N bins without sacrificing shape information
  - Technical limitation on N bins used in building syst error covariance matrices with limited statistics MC
- First step in unblinding revealed a poor chi2 for oscillation fits extending below 475 MeV
  - Region below 475 MeV not important for LSND-like signal -> chose to cut it out and proceed

Reminders of some pre-unblinding choices

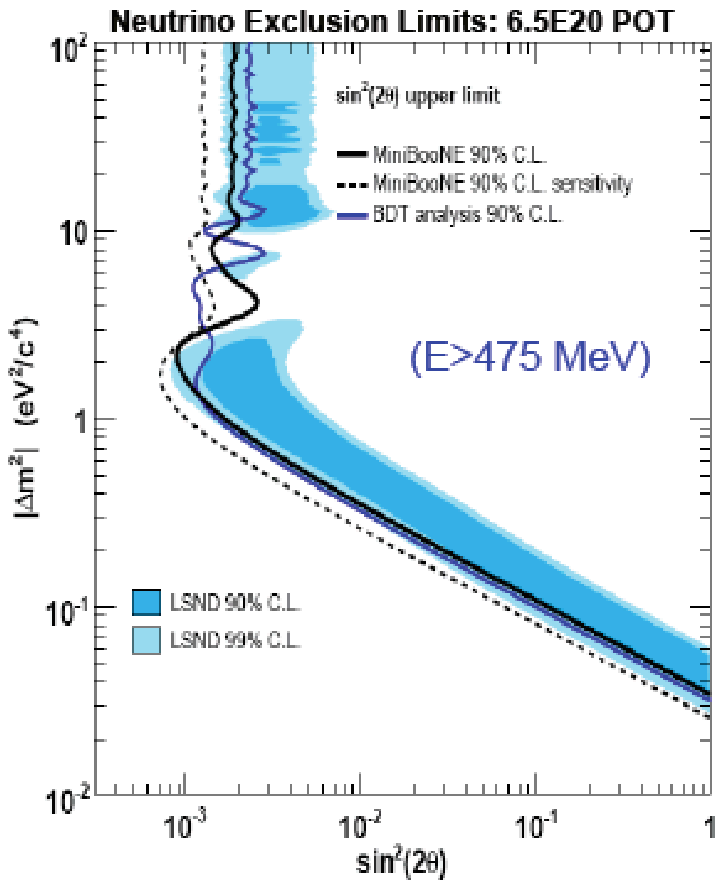




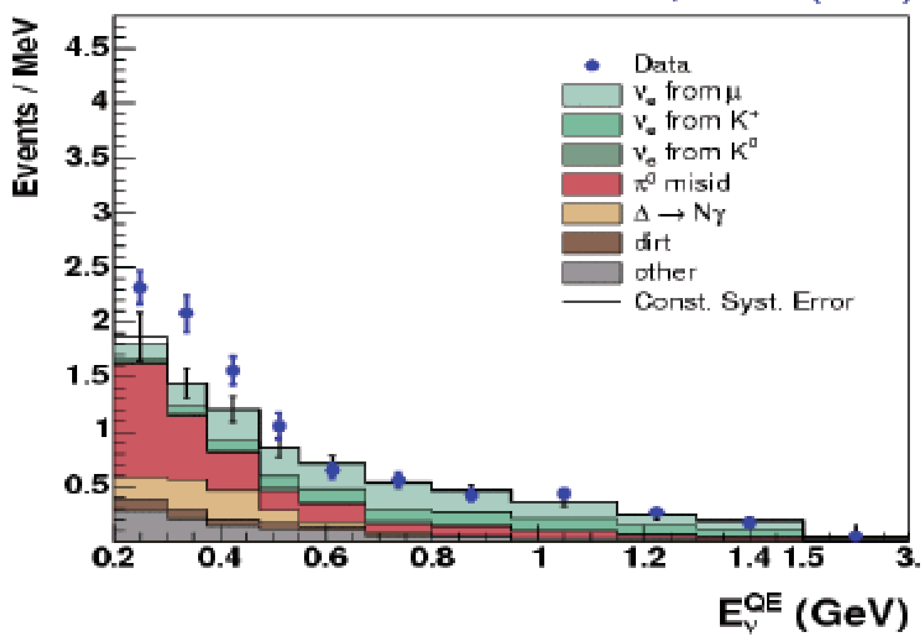
- Why is the 300-475 MeV region unimportant?
  - Large backgrounds from mis-ids reduce S/B
  - Many systematics grow at lower energies
  - Most importantly, not a region of L/E where LSND observed a significant signal!

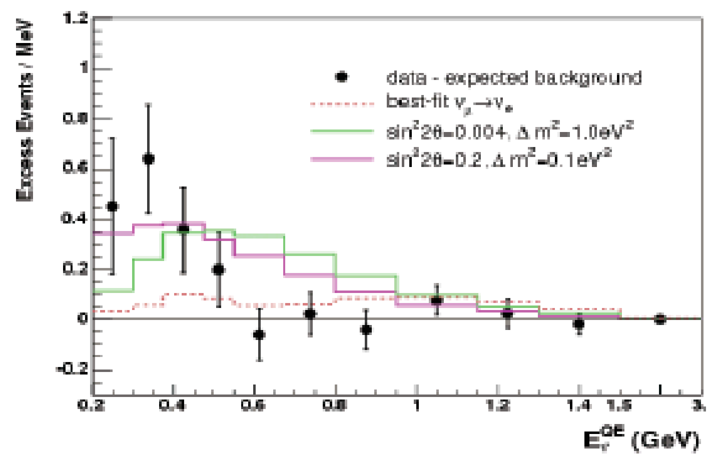
Neutrino mode MB results (2009)

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



Published PRL 102,101802 (2009)

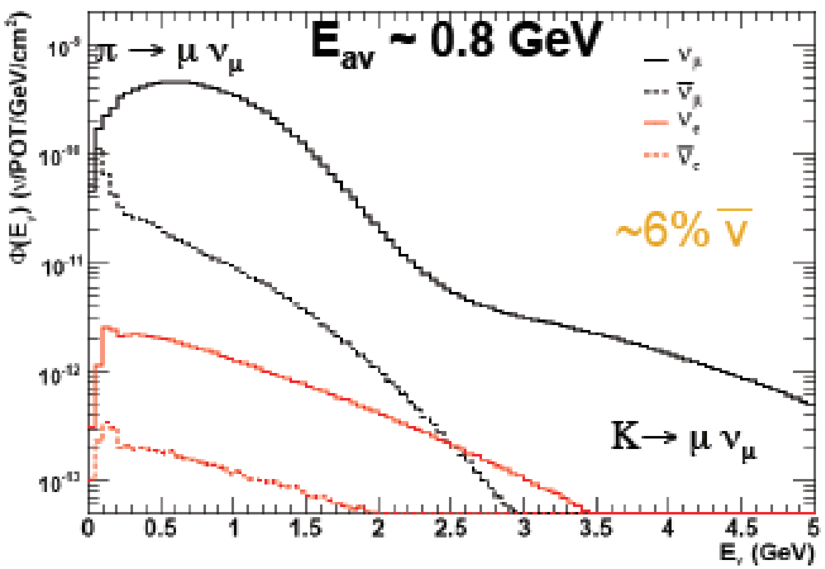




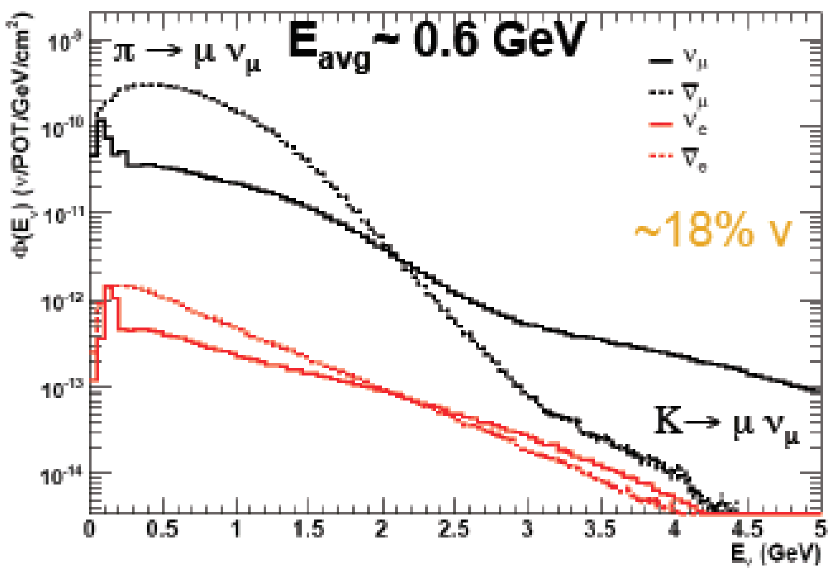
MiniBooNE Flux (Flux paper arXiv: 0806.1449)

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

ν mode flux



$\bar{\nu}$ mode flux



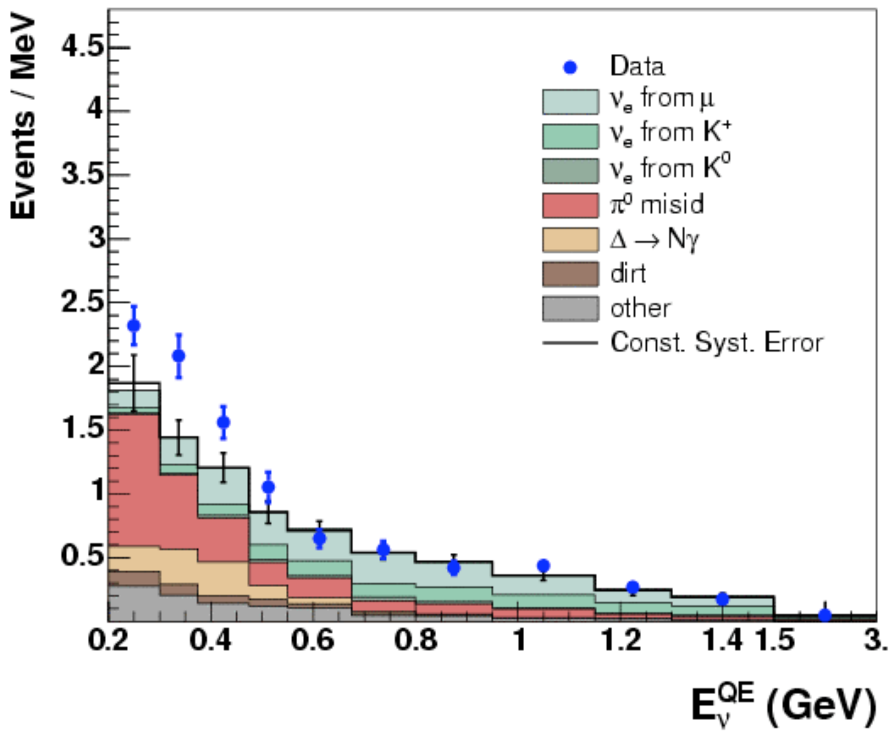
Subsequent decay of the **μ+ (μ-)** produces $\bar{\nu}_e$ (ν_e) intrinsics ~0.5%

neutrino mode: $\nu_\mu \rightarrow \nu_e$ **oscillation search**

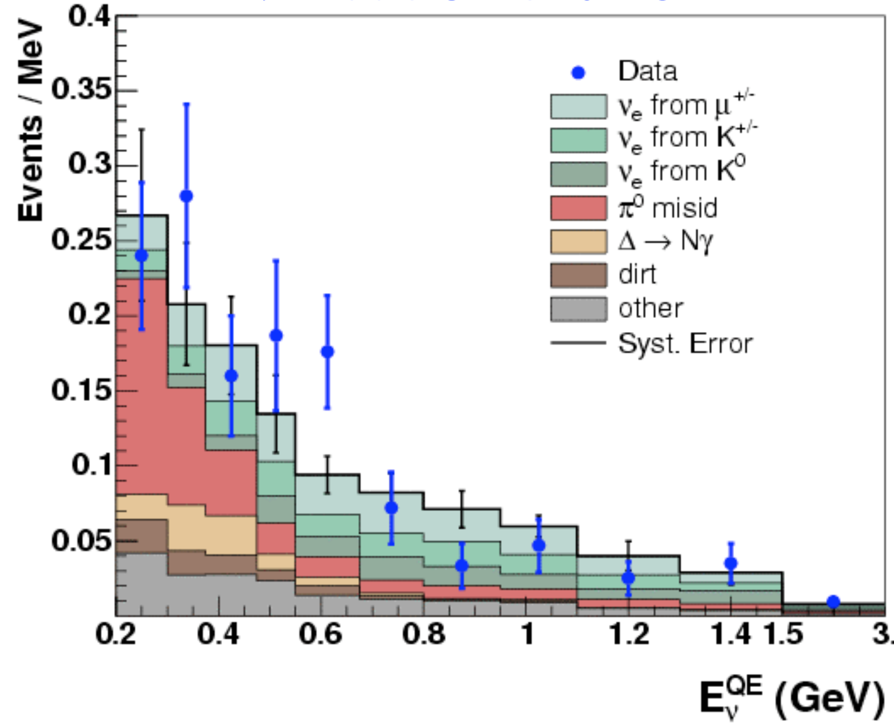
antineutrino mode: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ **oscillation search**

Anti-ν results from 2009 PRL

ν mode 6.6e20 POT



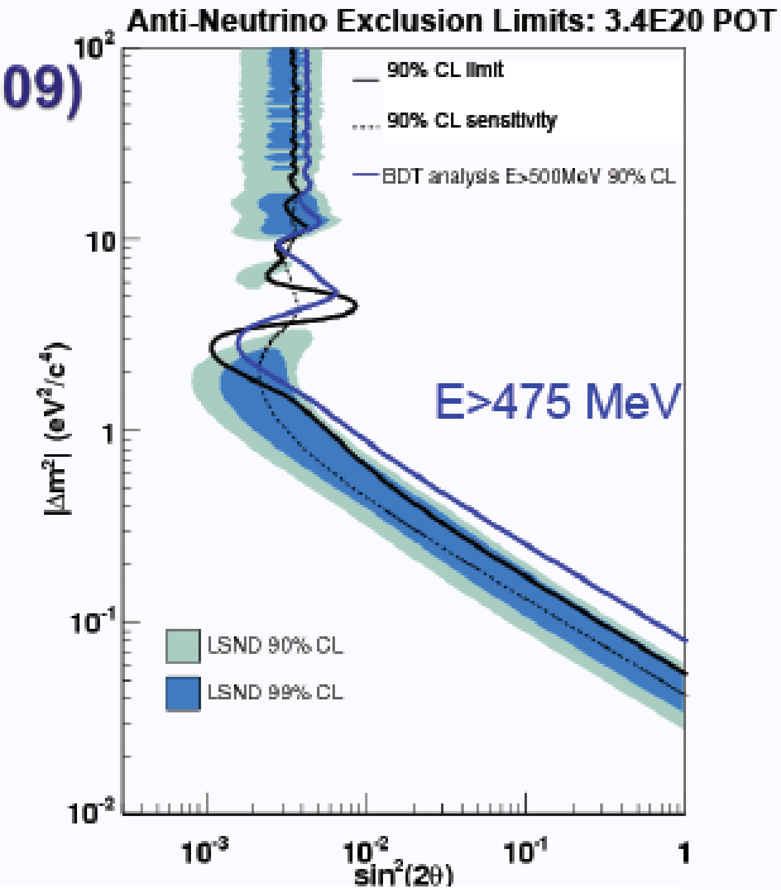
$\bar{\nu}$ mode 3.4e20 POT



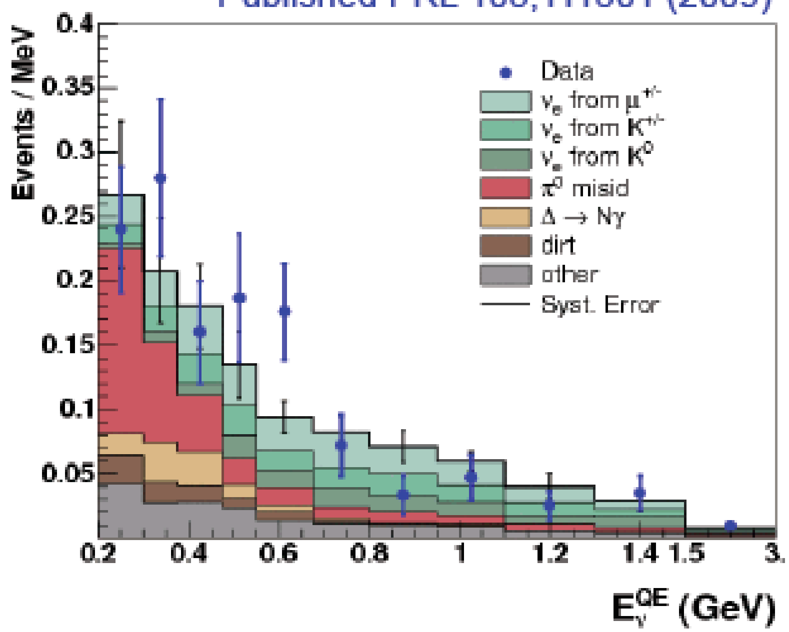
- Contrasting neutrino to anti-neutrino
  - Anti-neutrino beam contains a 30% WS background, fits (above 475 MeV) assume only nubar are allowed to oscillate
  - Background composition fairly similar, bkg constraints re-extracted
  - Rates reduced by ~5 due to flux and cross-section

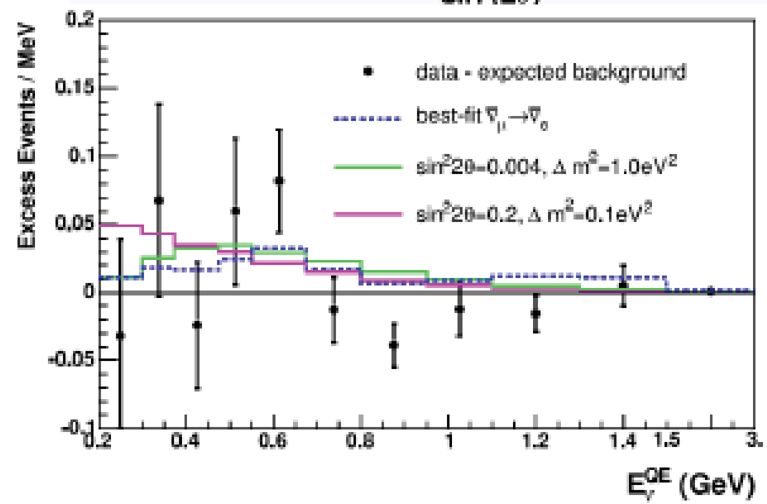
First Antineutrino mode MB results (2009)

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



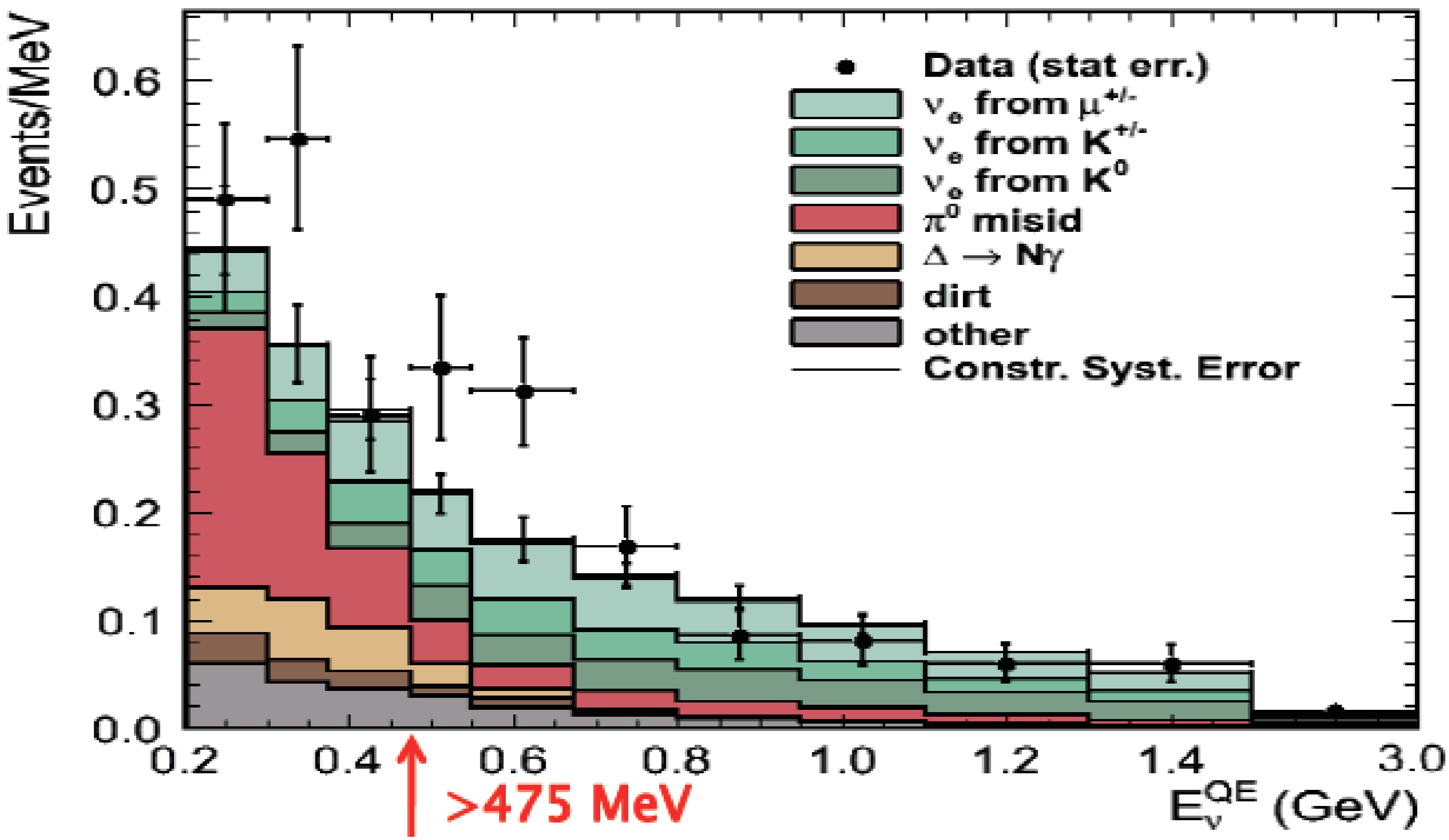
Published PRL 103,111801 (2009)



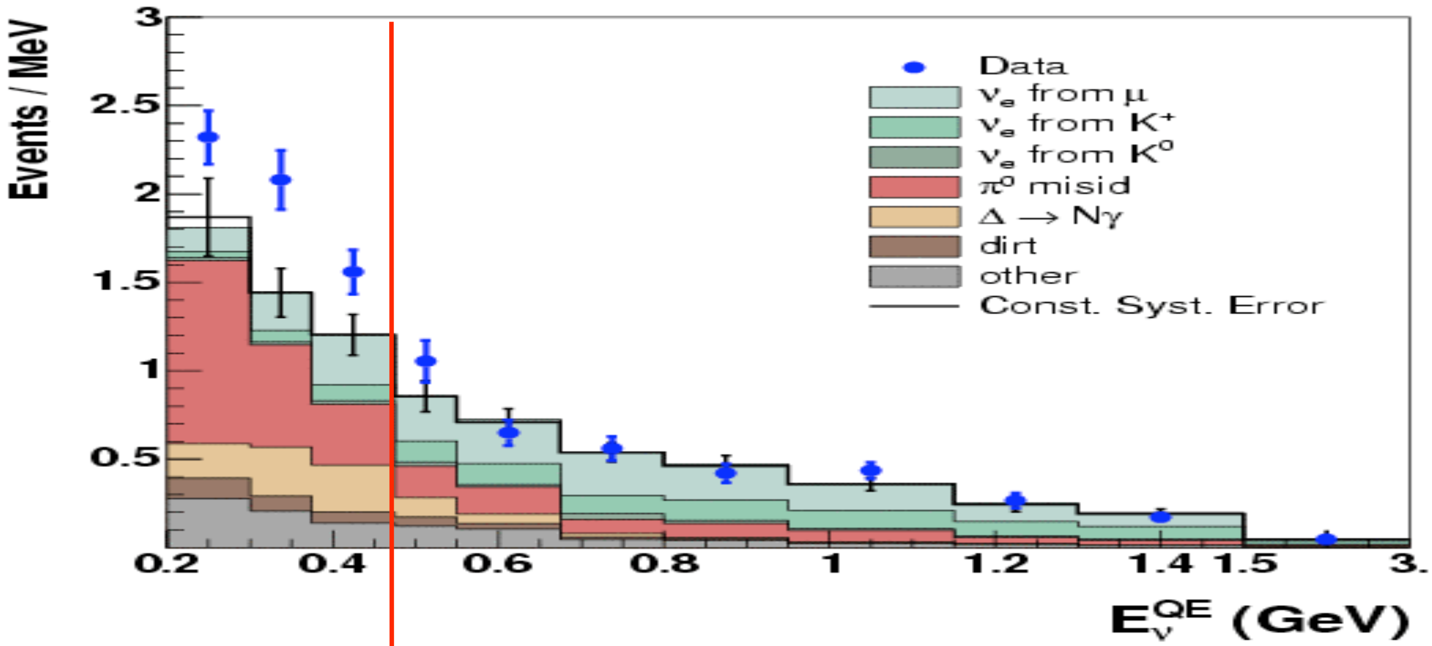


New Antinuetrino Result with 5.66E20 POT

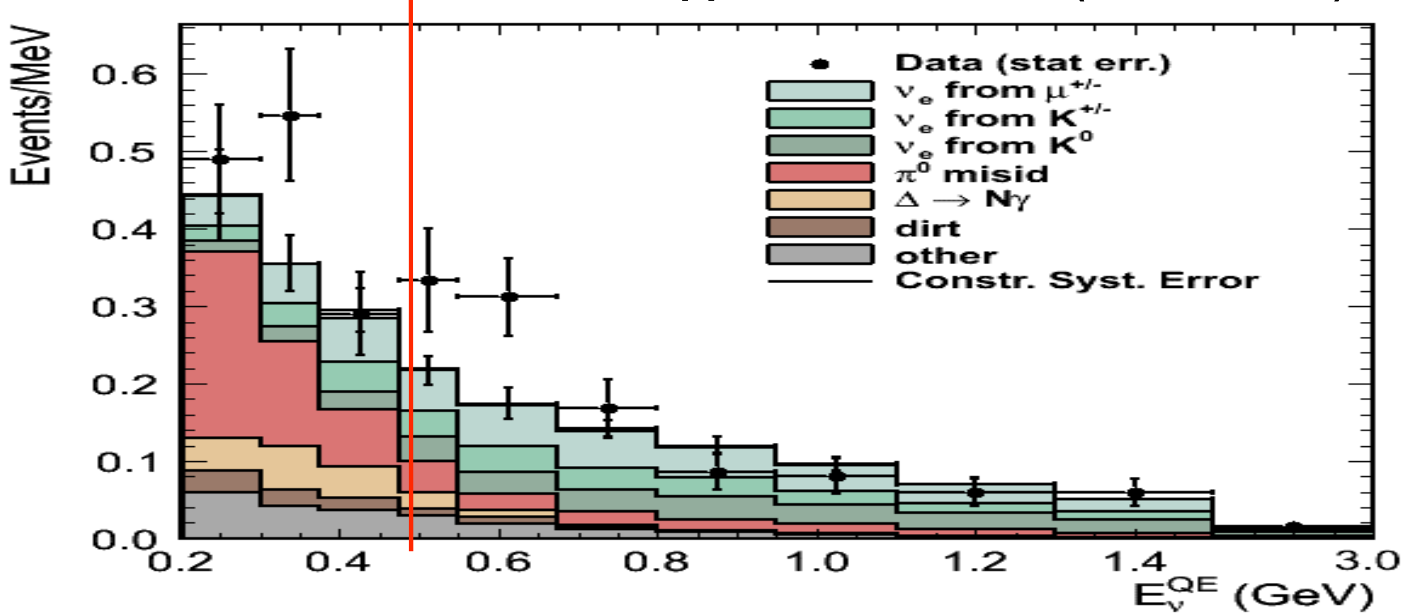
	200-475 MeV	475-1250 MeV	200-3000 MeV
Data	119	120	277
MC (stat+sys)	100.5 ± 14.3	99.1 ± 13.9	233.8 ± 22.5
Excess (stat)	18.5 ± 10.0 (1.9σ)	20.9 ± 10.0 (2.1σ)	43.2 ±15.3 (2.8σ)
Excess (stat+sys)	18.5 ± 14.3 (1.3σ)	20.9 ± 13.9 (1.5σ)	43.2 ± 22.5 (1.9σ)



Neutrino ve Appearance Results (6.5E20POT)



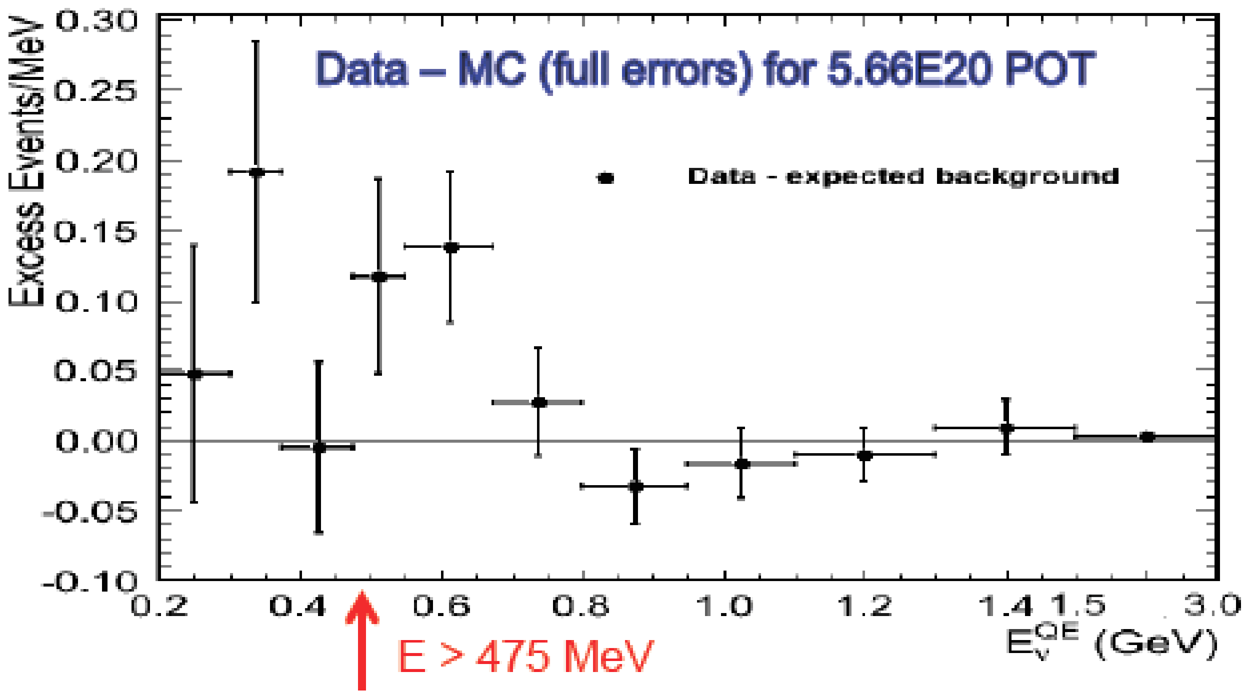
Antineutrino $\overline{\nu}$e Appearance Results (5.66E20POT)



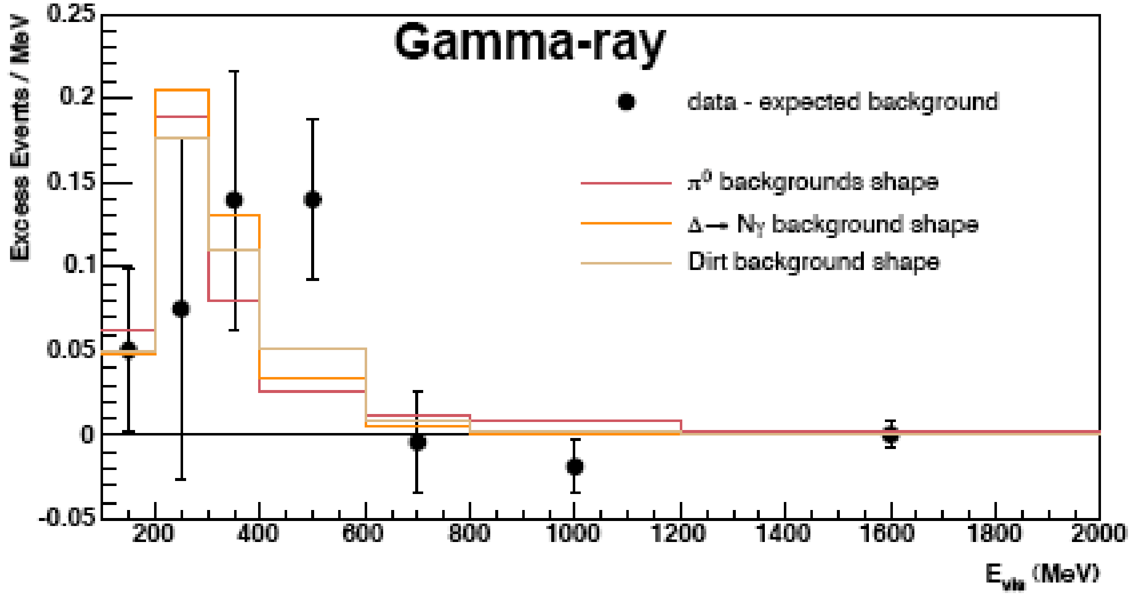
Testing the Null Hypothesis

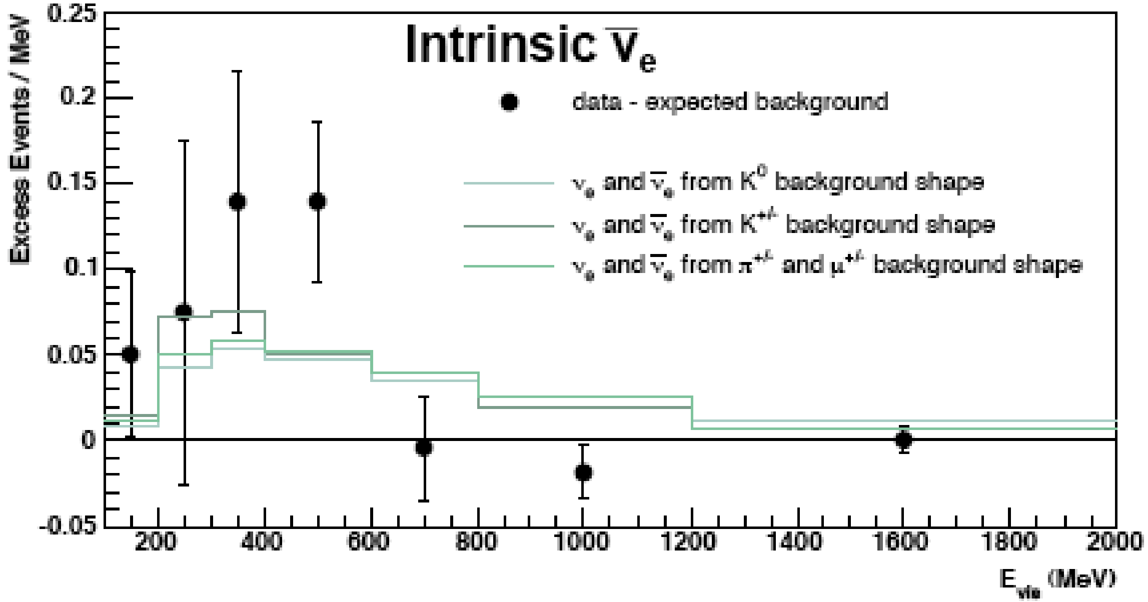
- Model independent.
- At null look at the X^2 distribution of fake experiments (thrown from null error matrix).

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

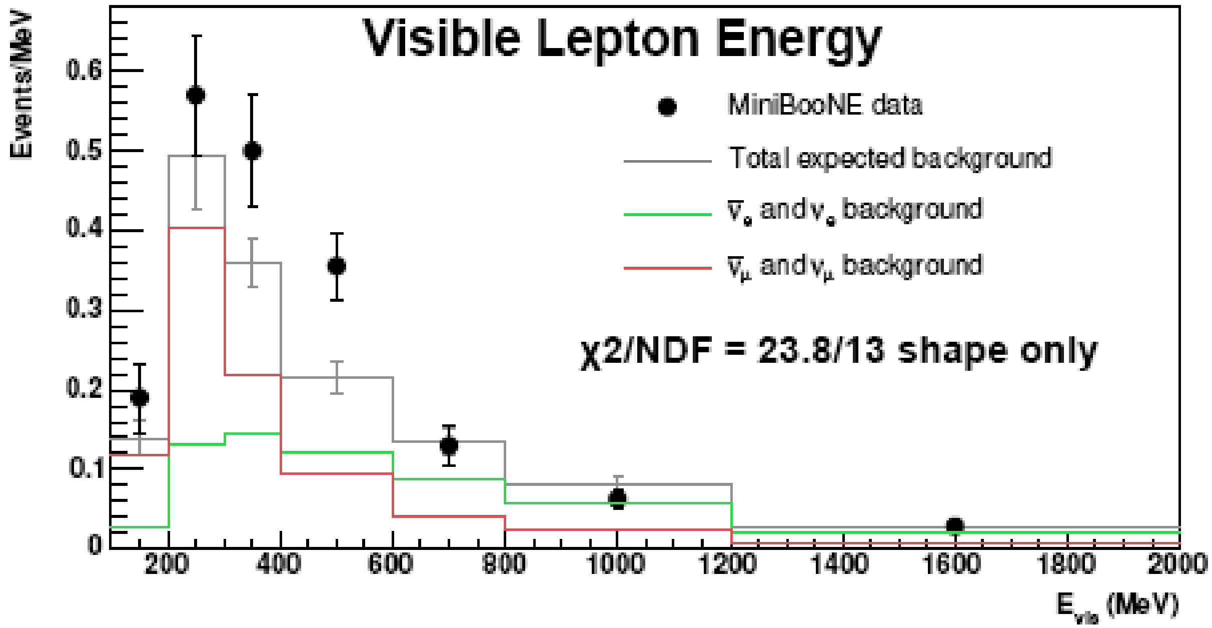


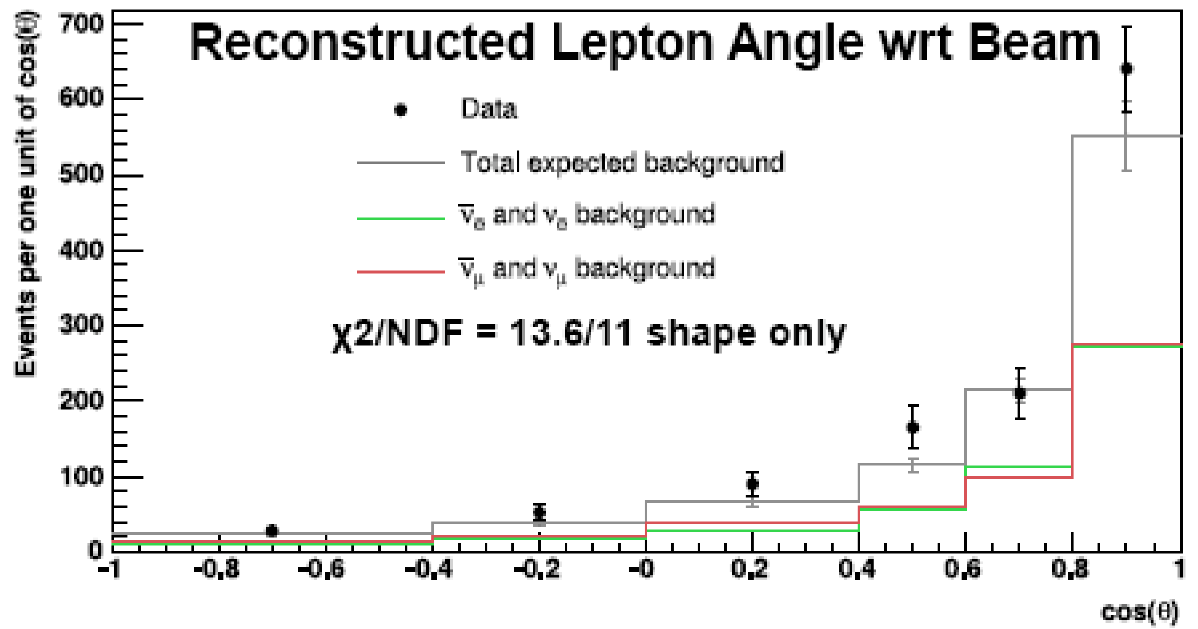
Background $\overline{\nu}_e$ Evis distributions for 5.66E20 POT





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





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

- Beam and Detector low level stability checks; beam stable to 2%, and detector energy response to 1%.
- $\bar{\nu}\mu$ rates and energy stable over entire antineutrino run.
- Latest $\bar{\nu}e$ data rate is 1.9σ higher than 3.4E20POT data set.
- Independent measurement of π0 rate for antineutrino mode.
- Measured dirt rates are similar in neutrino and antineutrino mode.
- Measured wrong sign component stable over time and energy.
- Checked off axis rates from NuMI beam.
- Above 475 MeV, about two thirds of the electron (anti)neutrino intrinsic rate is constrained by simultaneous fit to $\bar{\nu}\mu$ data.
  - New SciBooNE neutrino mode K+ weight = 0.75 ± 0.05(stat) ± 0.30(sys).
- One third of electron neutrino intrinsic rate come from K0, where we use external measurements and apply 30% error.
  - Would require >3σ increase in K0 normalization, but shape does not match well the excess.

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

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

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

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

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

Oscillation Fit Method

Maximum likelihood fit:

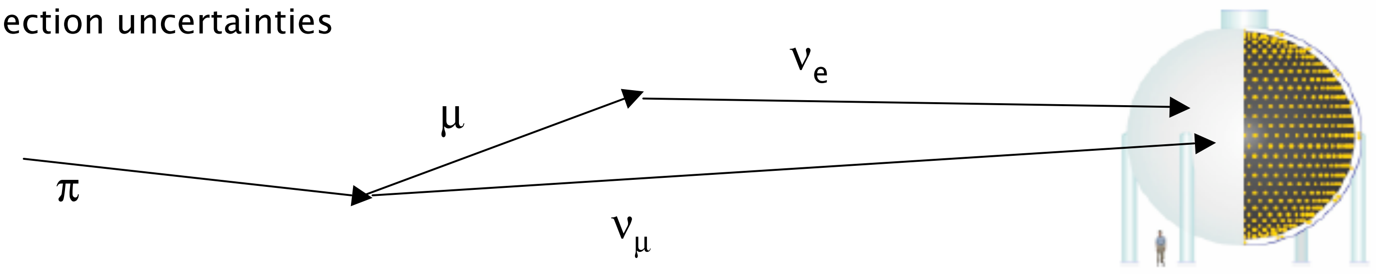
$$-2\ln(L) = (x_1 - \mu_1, ...x_n - \mu_n)M^{-1}(x_1 - \mu_1, ...x_n - \mu_n)^T + \ln(|M|)$$

Simultaneously fit

- Nue CCQE sample
- High statistics numu CCQE sample

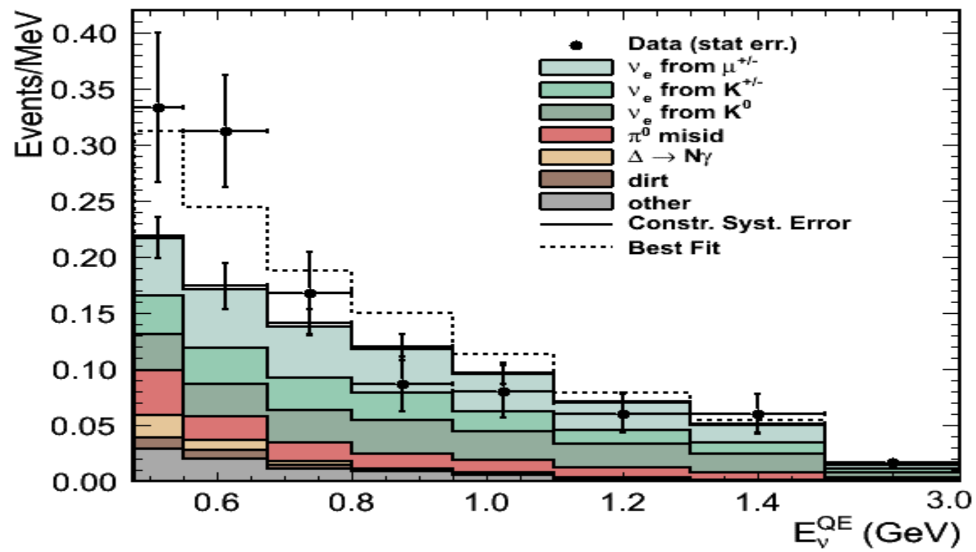
Numu CCQE sample constrains many of the uncertainties:

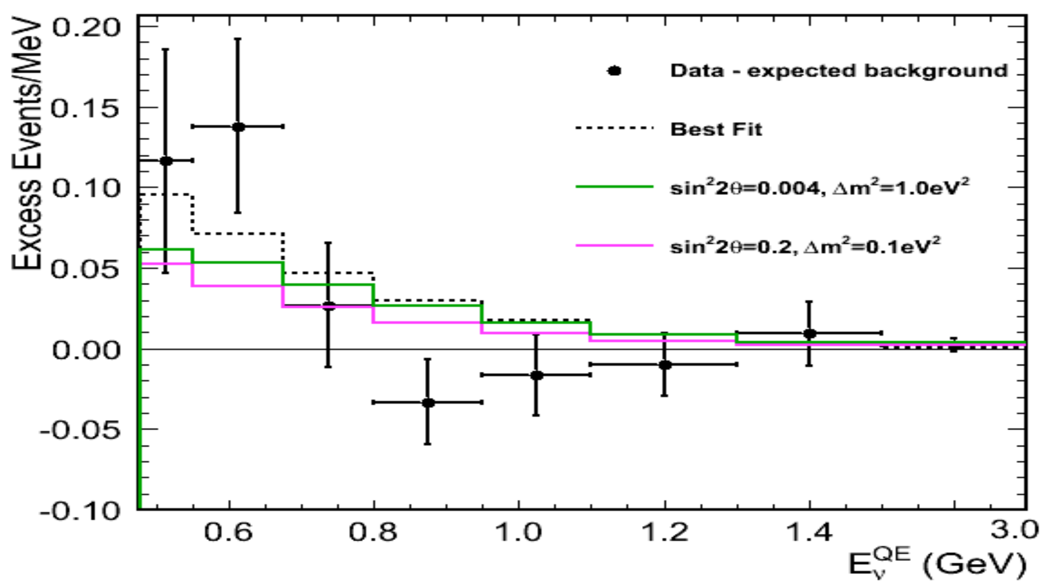
- Flux uncertainties
- Cross section uncertainties



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

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





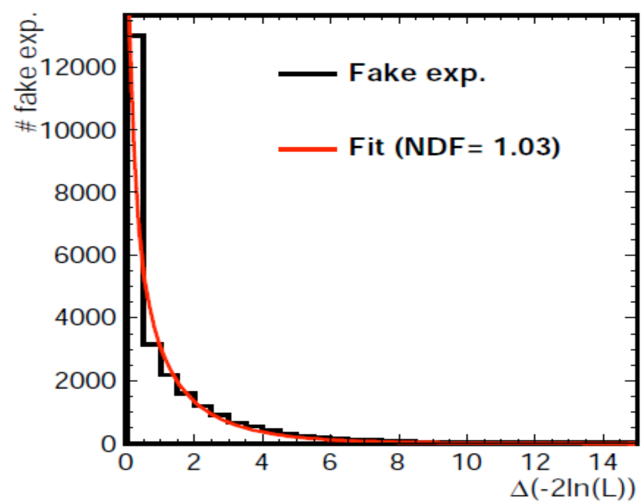
Drawing contours

Frequentist approach

Fake data experiments on grid of ($\sin^2 2\theta$, Δm^2) points

At each point find the cut on likelihood ratio for X% confidence level such that X% of experiments below cut

Fitting two parameters, so naively expect chi2 distribution with 2 degrees of freedom, in reality at null it looks more like 1 degree of free



Updated Antineutrino mode MB results for E>475 MeV

(official oscillation region)

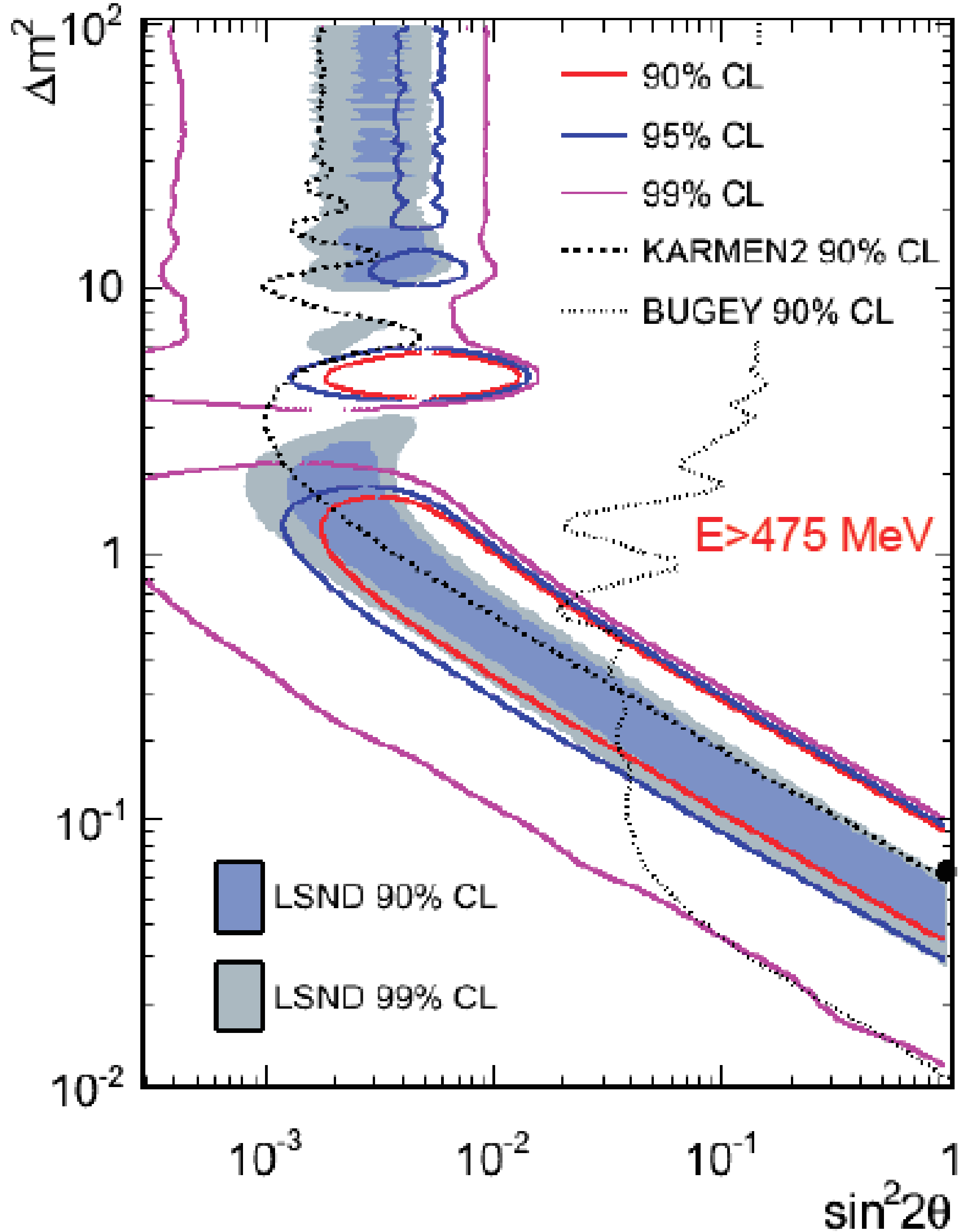
- Results for 5.66E20 POT
- Maximum likelihood fit.
- Null excluded at 99.4% with respect to the two neutrino oscillation fit.
- Best Fit Point

  $(\Delta m^2, \sin^2 2\theta) =$

  $(0.064\ eV^2, 0.96)$

  $\chi^2/NDF = 16.4/12.6$

  $P(\chi^2) = 20.5\%$
- Results to be published.



Antineutrino mode MB results for E>200 MeV:

Curves have also been drawn for E>200 MeV.

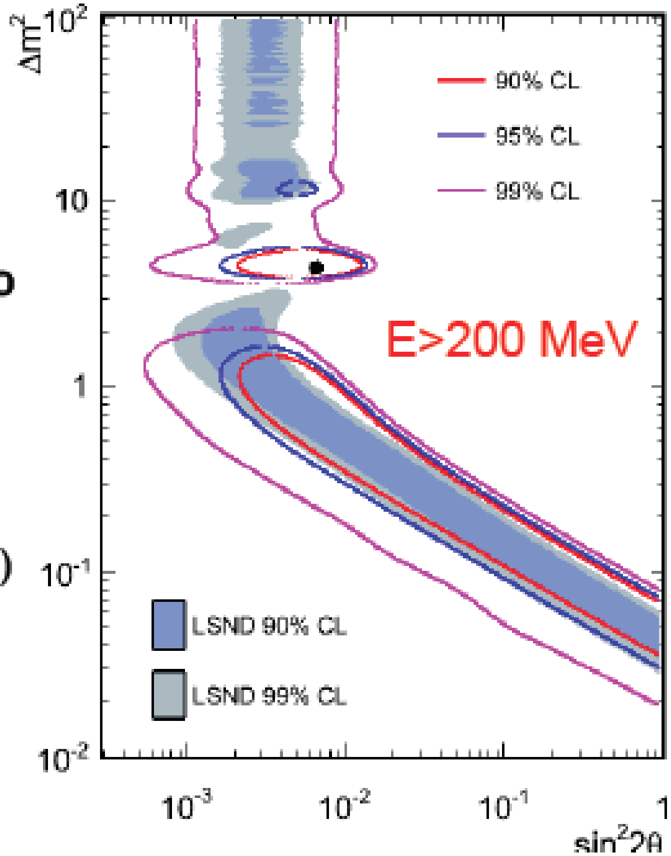
There is an ambiguity for these curves.

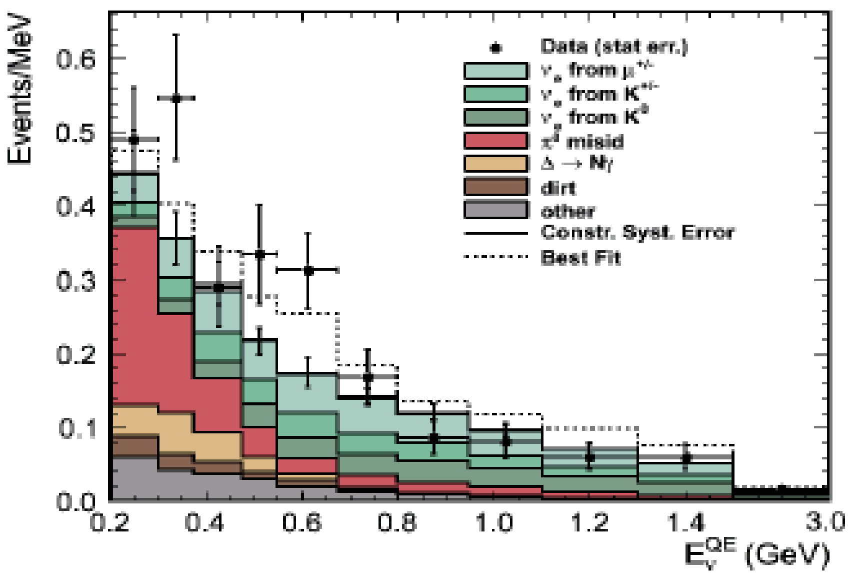
If one subtracts for the neutrino low energy excess, then the results hardly change from the E>475 plots.

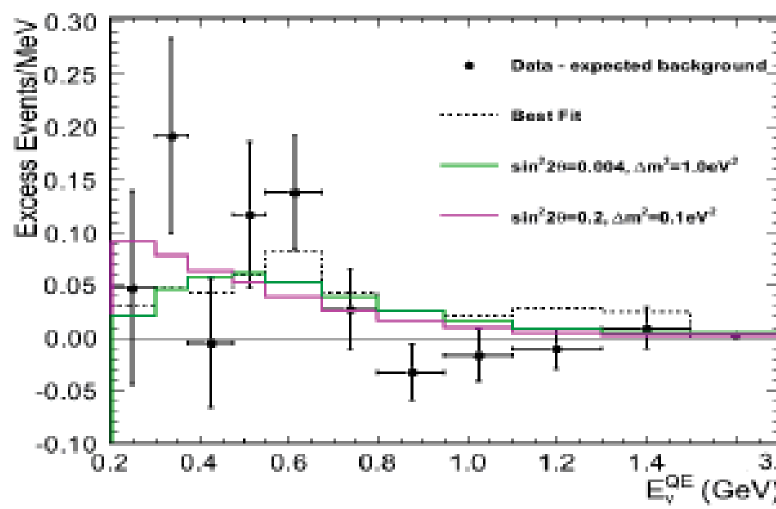
If one does not make this subtraction, then the result is even stronger.

New Antineutrino mode MB results for E>200 MeV:

- Results for 5.66e20 POT.
- **Does not include effects (subtraction) of neutrino low energy excess.**
- Maximum likelihood fit method.
- Null excluded at 99.6% with respect to the two neutrino oscillation fit (model dependent).
- Best Fit Point (Δm^2, $\sin^2 2\theta$) = (4.42 eV², 0.0066)
  χ^2/NDF= 20.4/15.3, P(χ2)= 17.1%.



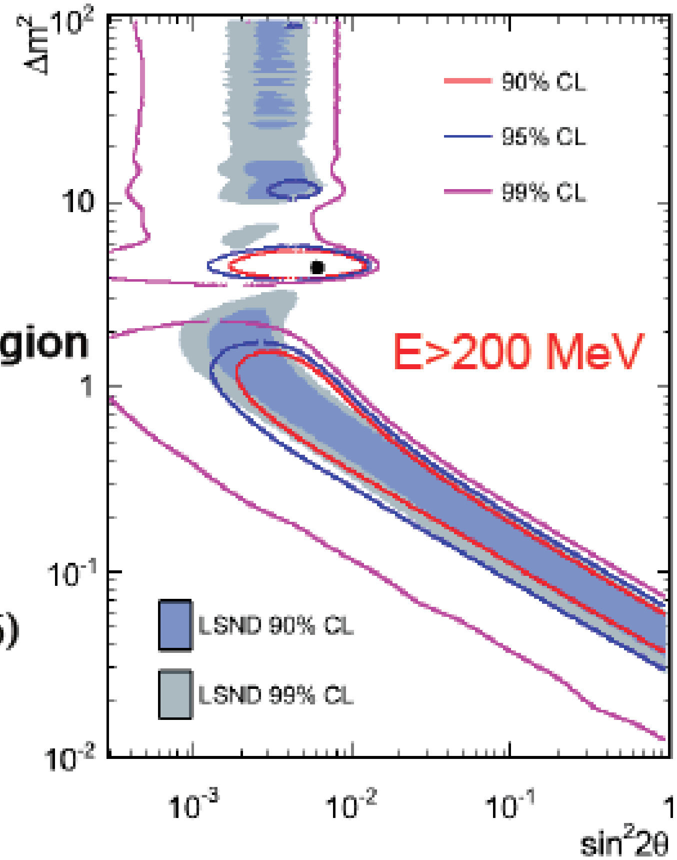


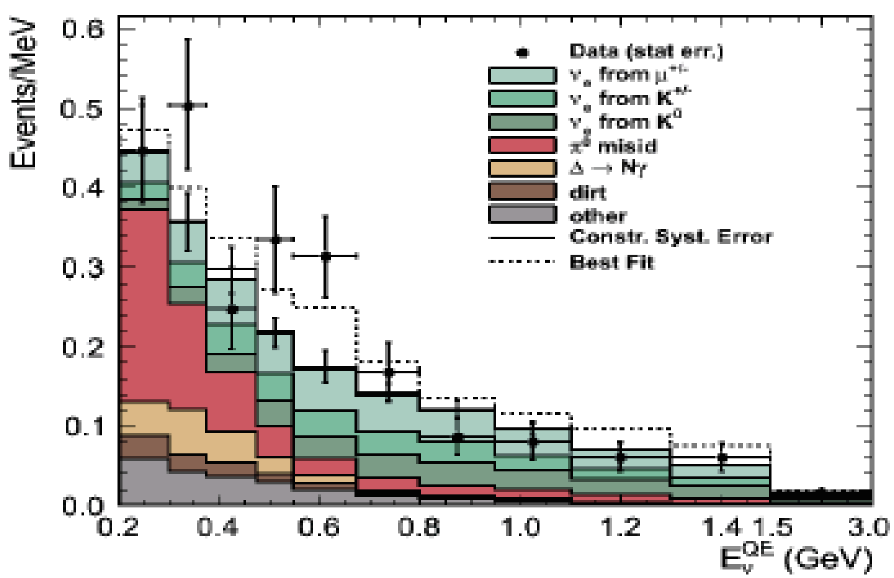


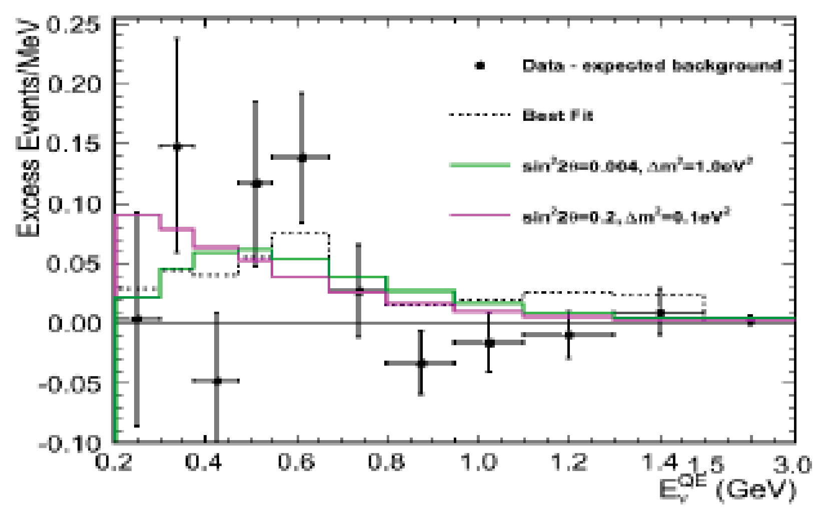
New Antineutrino mode MB results for E>200 MeV: Include low E Effects

- Results for 5.66e20 POT.
- **Assume simple scaling of neutrino low energy excess; subtract 11.6 events from low energy region (200-475 MeV).**
- Maximum likelihood fit method.
- Null excluded at 99.6% with respect to the two neutrino oscillation fit (model dependent).
- Best Fit Point (Δm^2, $\sin^2 2\theta$) = (4.42 eV^2, 0.0066)

  χ^2/NDF= 21.6/15.3, P(χ2)= **13.7%**







Summary

➢ The MiniBooNE nue and nuebar appearance picture starting to emerge is the following:

1) **Neutrino Mode**

a) E<475 MeV: An unexplained 3 sigma electron-like excess.

b) E>475 MeV: A two neutrino fit rules out LSND at the 98% CL.

2) **Anti-neutrino mode**

a) E<475 MeV: A small 1.3 sigma electron-like excess

b) E>475 MeV: An excess that is 3.0% consistent with null. Two neutrino oscillation fits consistent with LSND at 99.4% CL relative to null.

➢ **Basically:**

All of the world neutrino data is in reasonable agreement.

All of the world anti-neutrino data is in reasonable agreement

The neutrino data is not in good agreement with the anti-neutrino data

Comments on Theory

- If neutrinos and antineutrinos oscillate differently, and if one wishes to explain this by means of sterile neutrinos, it is necessary to add two sterile neutrinos to have the possibility of CP violation
- Anti-neutrinos have too few low energy electron-like events to be explained by Standard Model NC gamma-ray mechanisms, e.g. Axial Anomaly. We would have expected 67 events in the 200-475 MeV region and had only about 8 after subtracting excess from neutrino (wrong sign) events.

What is the Outlook for More Data?

- MiniBooNE has about 0.6E20 more events already recorded and is running to double the antineutrino data set for a total of ~$10x10^{20}$ POT. If the signal continues at the current rate, the statistical error will be ~4sigma and the two neutrino best fit will be >3sigma.
- There are other follow on experiments

  1. MicroBooNE as CD-1 approval. It will try to check whether a low energy anomaly in neutrinos is due to electron tracks or gamma tracks. A similar experiment with a larger liquid argon TPC is suggested for CERN.

  2. BooNE (LOI) A MB-like near detector at 200 m. (arXiV:0909.0355v3)

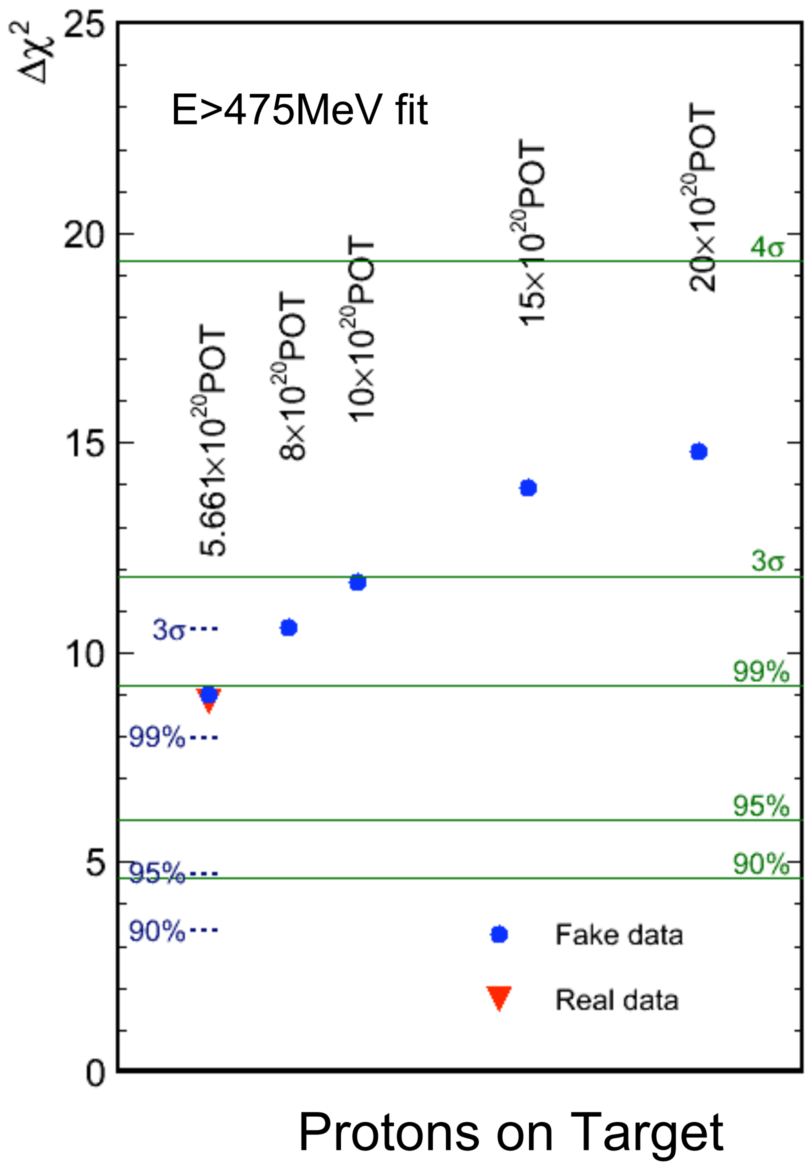
  3. OscSNS(LOI) An experiment at the spallation source at Oak Ridge would have many times the event rate of LSND.

Future sensitivity

MiniBooNE approved for a total of 1e21 POT

Potential exclusion of null point assuming best fit signal

Combined analysis of ν_e and $\overline{\nu_e}$



OscSNS

Spallation neutron source at ORNL

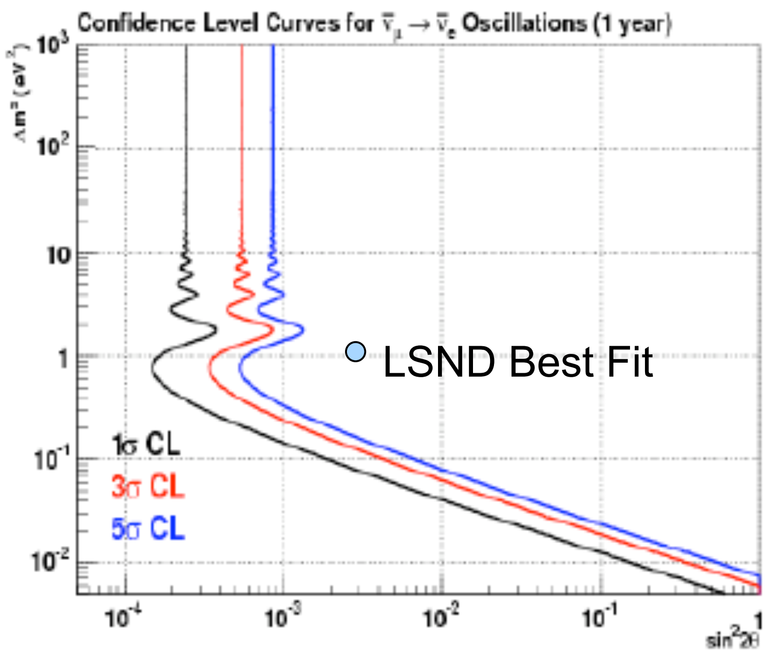
1GeV protons on Hg target (1.4MW)

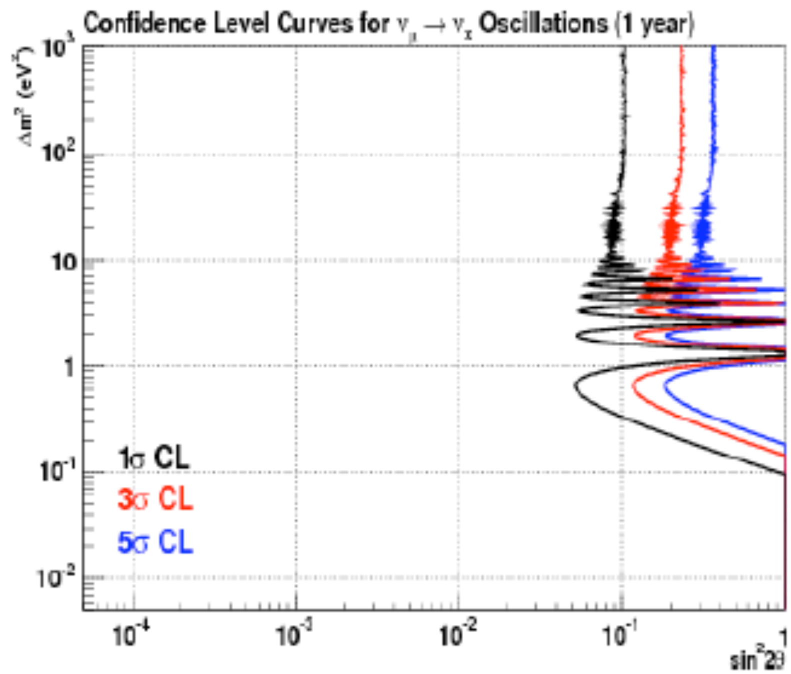
Free source of neutrinos

Well understood flux of neutrinos

OscSNS

Nuebar appearance (left) and numu disappearance sensitivity (right) for 1 year of running





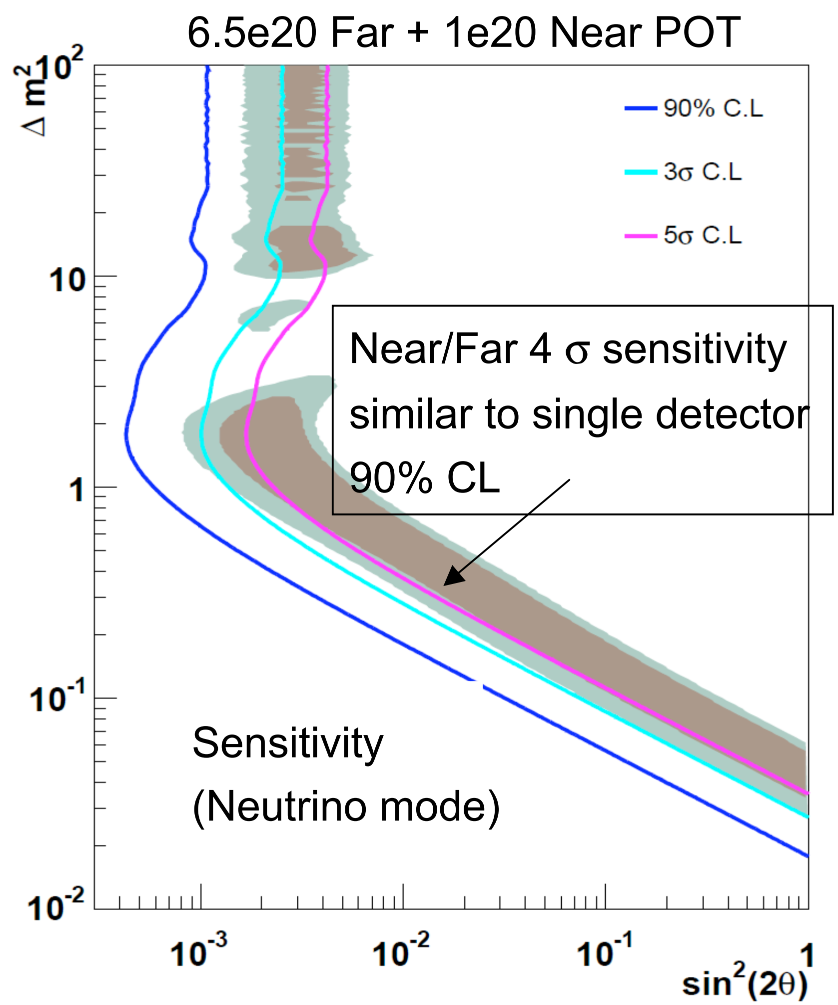
BooNE

MiniBooNE like detector at 200m

Flux, cross section and optical model errors cancel in 200m/500m ratio analysis

Present neutrino low energy excess is 6 sigma statistical; 3 sigma when include systematics

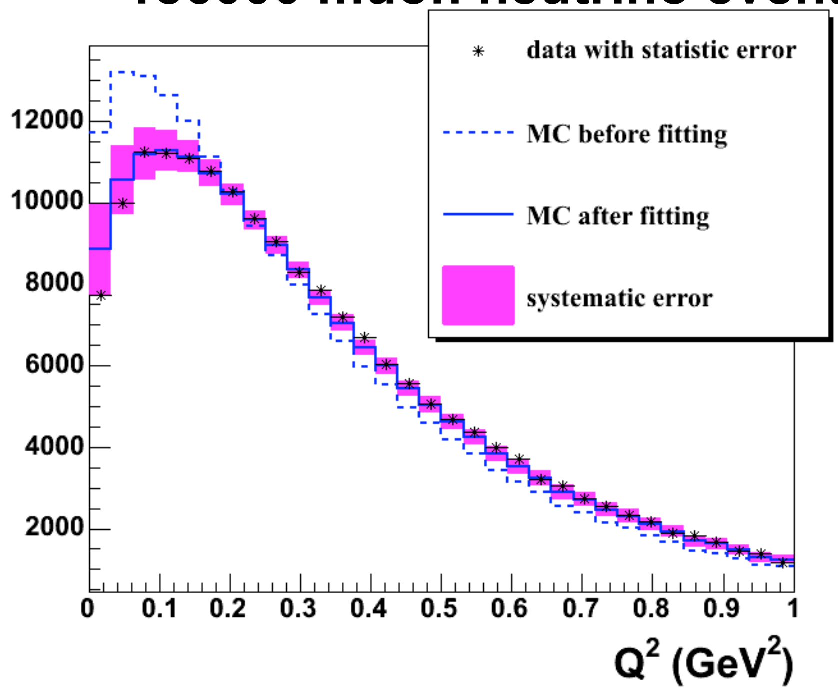
Gain statistics quickly, already have far detector data



Backup Slides

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

186000 muon neutrino events



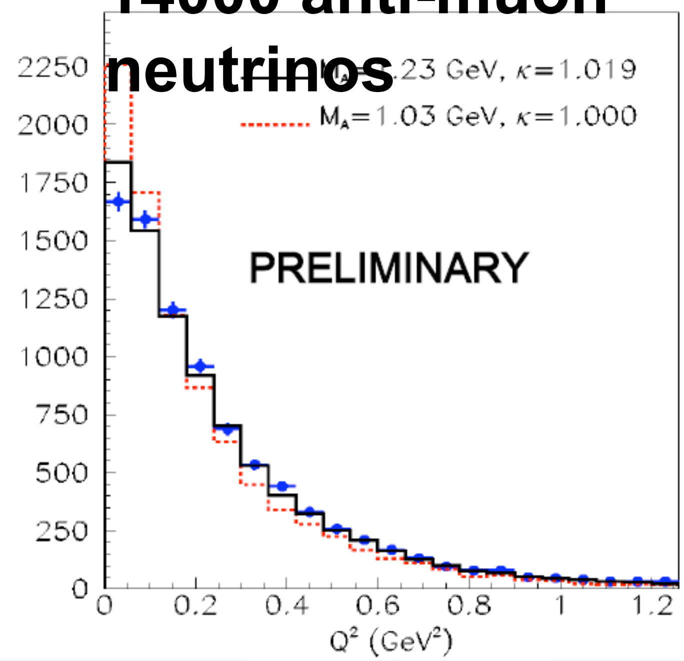
From Q2 fits to MB νμ CCQE data:

- MAeff -- effective axial mass
- κ -- Pauli Blocking parameter

From electron scattering data:

- Eb -- binding energy
- pf -- Fermi momentum

14000 anti-muon neutrinos



Fermi Gas Model describes CCQE νμ data well

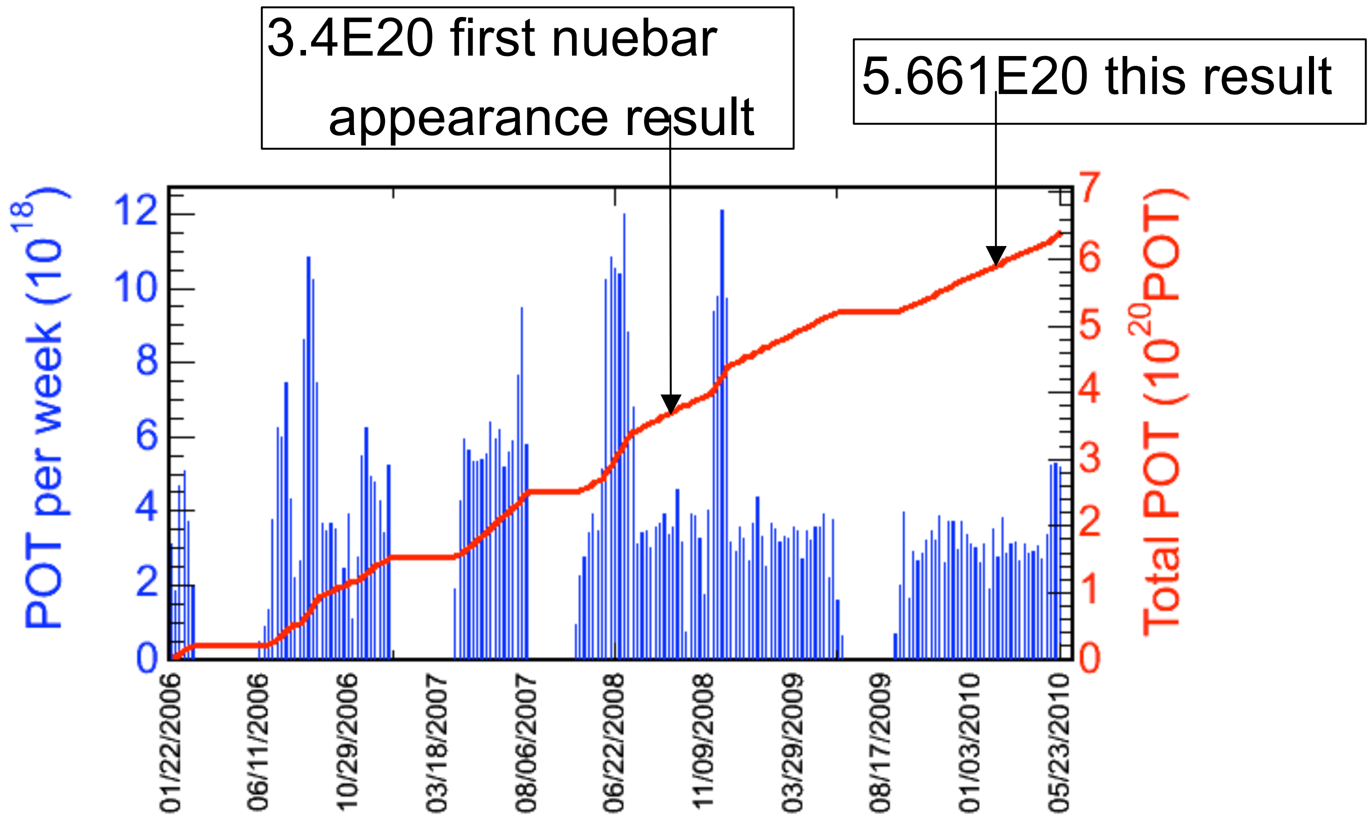
MA = 1.23+-0.20 GeV

κ = 1.019+-0.011

Also used to model νe and $\overline{\nu e}$ interactions

POT collection

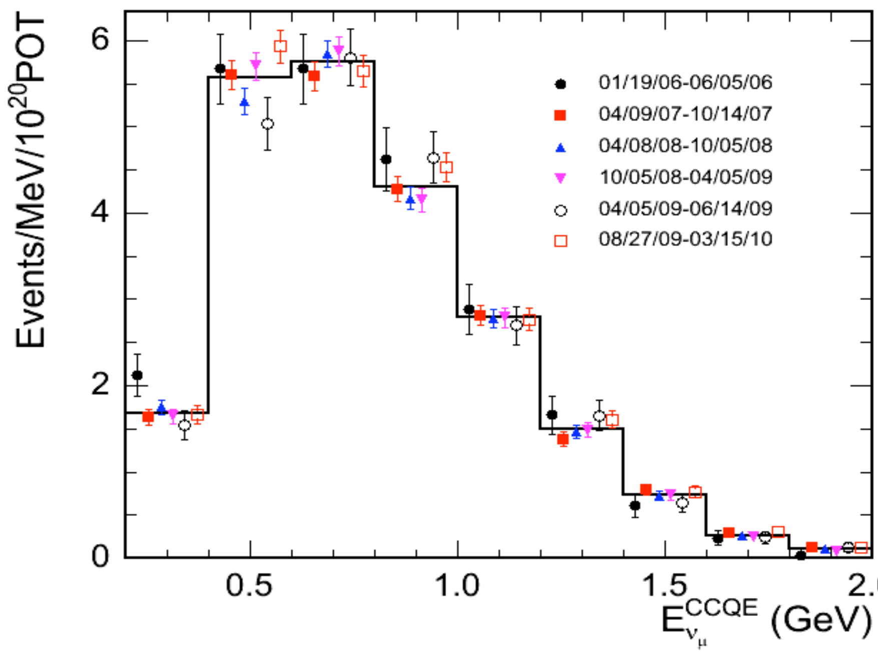
Protons on target in anti-neutrino mode

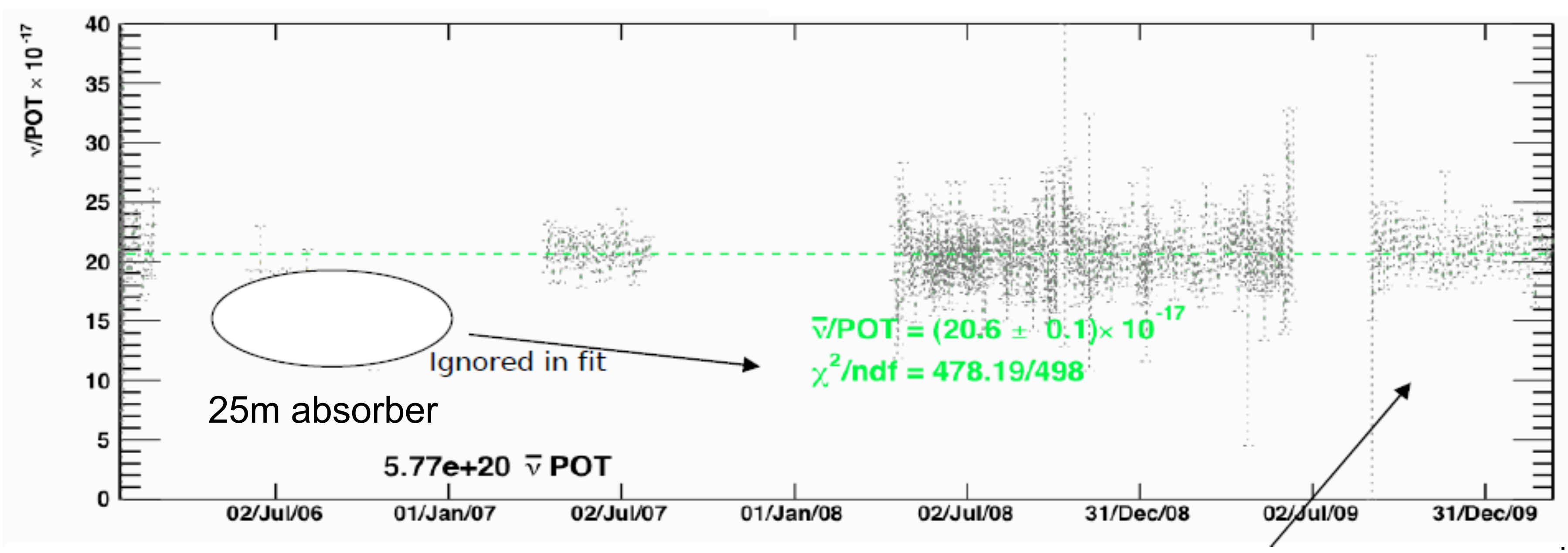


Thanks to Accelerator Division on all the POT!

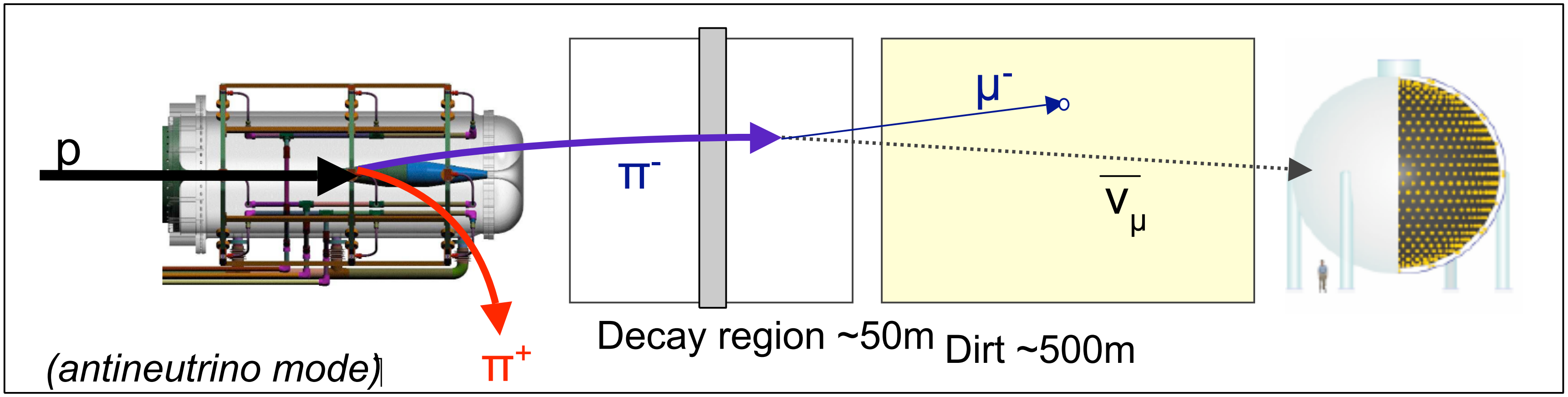
Data stability

Very stable throughout the run





25m Absorber



Two periods of running with 1 & 2 absorber plates

1 absorber plate - 0.569E20 POT

2 absorber plates - 0.612E20 POT

Good data/MC agreement ih high statistics samples (numu CCQE, NC pi0, ...)

Data included in this analysis

Nue Background Uncertainties

Uncertainty (%)	200-475MeV	475-1100MeV
p^+	0.4	0.9
p^-	3	2.3
K^+	2.2	4.7
K^-	0.5	1.2
K^0	1.7	5.4
Target and beam models	1.7	3
Cross sections	6.5	13
NC pi0 yield	1.5	1.3
Hadronic interactions	0.4	0.2
Dirt	1.6	0.7
Electronics & DAQ model	7	2
Optical Model	8	3.7
Total	13.43%	16.02%

Unconstrained nue background uncertainties

Propagate input uncertainties from either MiniBooNE measurement or external data

Nue Background Uncertainties

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Dirt	1.6	0.7
Electronics & DAQ model	7	2
Optical Model	8	3.7
Total	13.43	16.02

Uncertainty determined by varying underlying cross section model parameters (M_A, Pauli blocking, …)

Many of these parameters measured in MiniBooNE

Nue Background Uncertainties

Uncertainty (%)	200-475MeV	475-1100MeV
p^+	0.4	0.9
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Hadronic interactions	0.4	0.2
Dirt	1.6	0.7
Electronics & DAQ model	7	2
Optical Model	8	3.7
Total	13.43	16.02

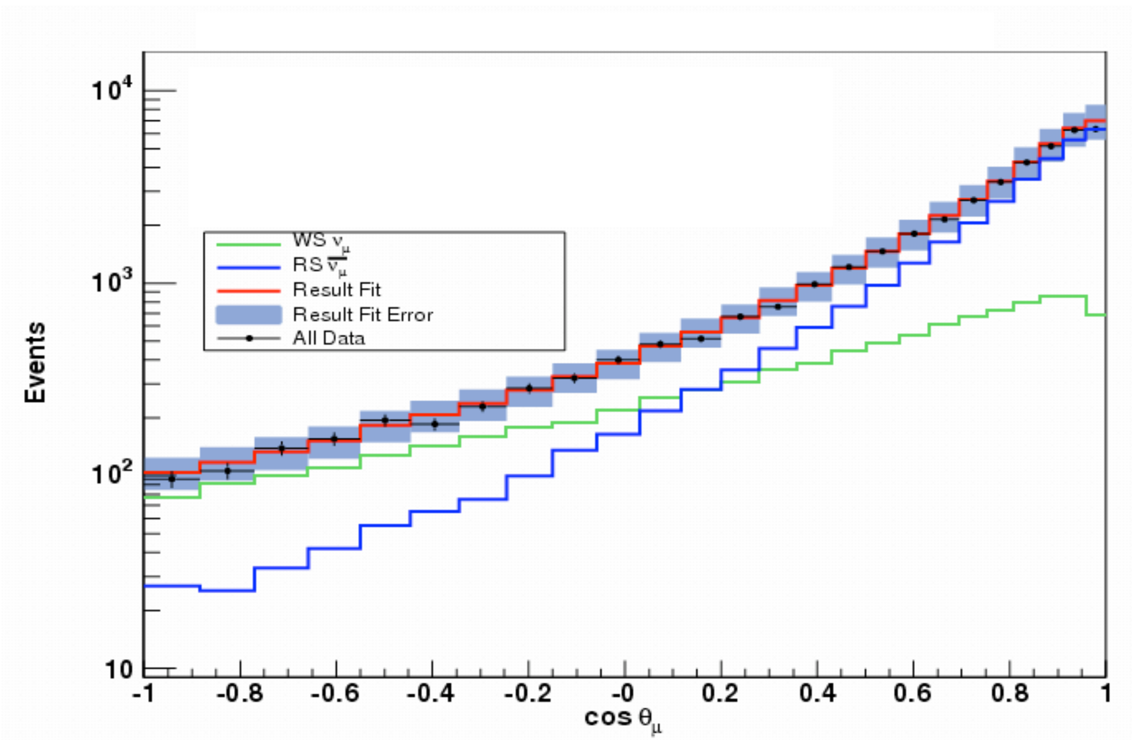
Uncertainty in light creation, propagation and detection in the detector

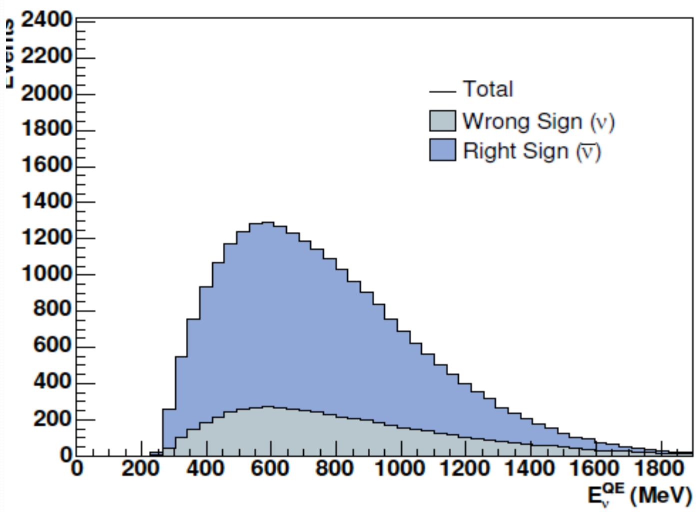
Signal prediction

Assuming only right sign oscillates ($\bar{\nu}_\mu$)

Need to know wrong sign vs right sign

ν_μ CCQE gives more forward peaked muon





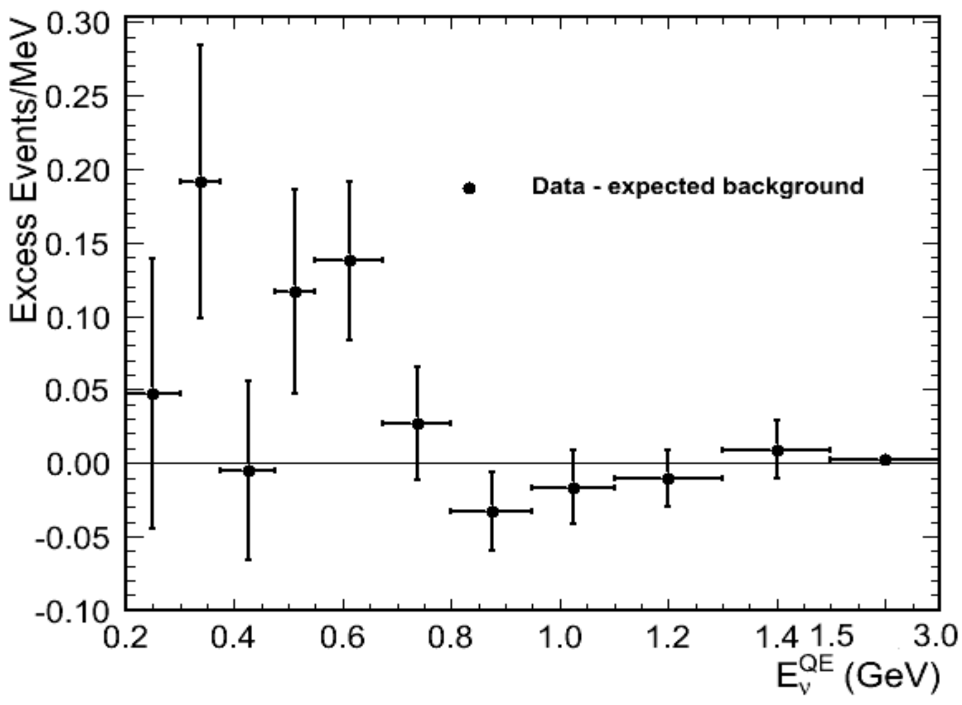
Paper in progress

Null probability

Absolute chi2 probability - model independent

Frequentist approach

	chi2/NDF	probability
E>475MeV	26.75/14.9	3.0%
E>200MeV	33.21/18.0	1.6%

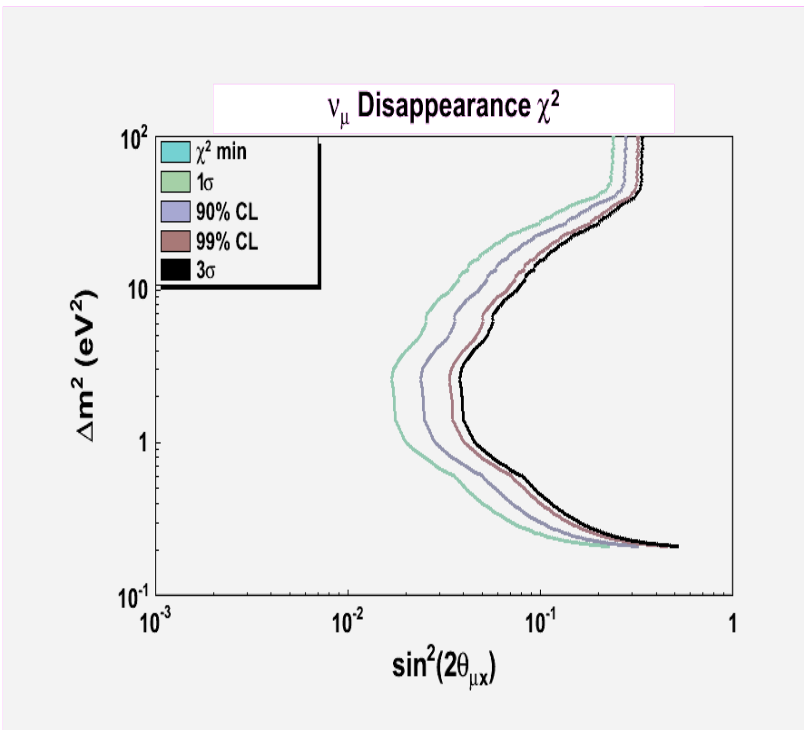


BooNE

Better sensitivity to ν_μ (ν_μ) disappearance

Look for CPT violation ($\nu_\mu \rightarrow \nu_\mu = \nu_\mu \rightarrow \nu_\mu$)

6.5e20 Far/1e20 Near POT



1e21 Far/1e20 Near POT