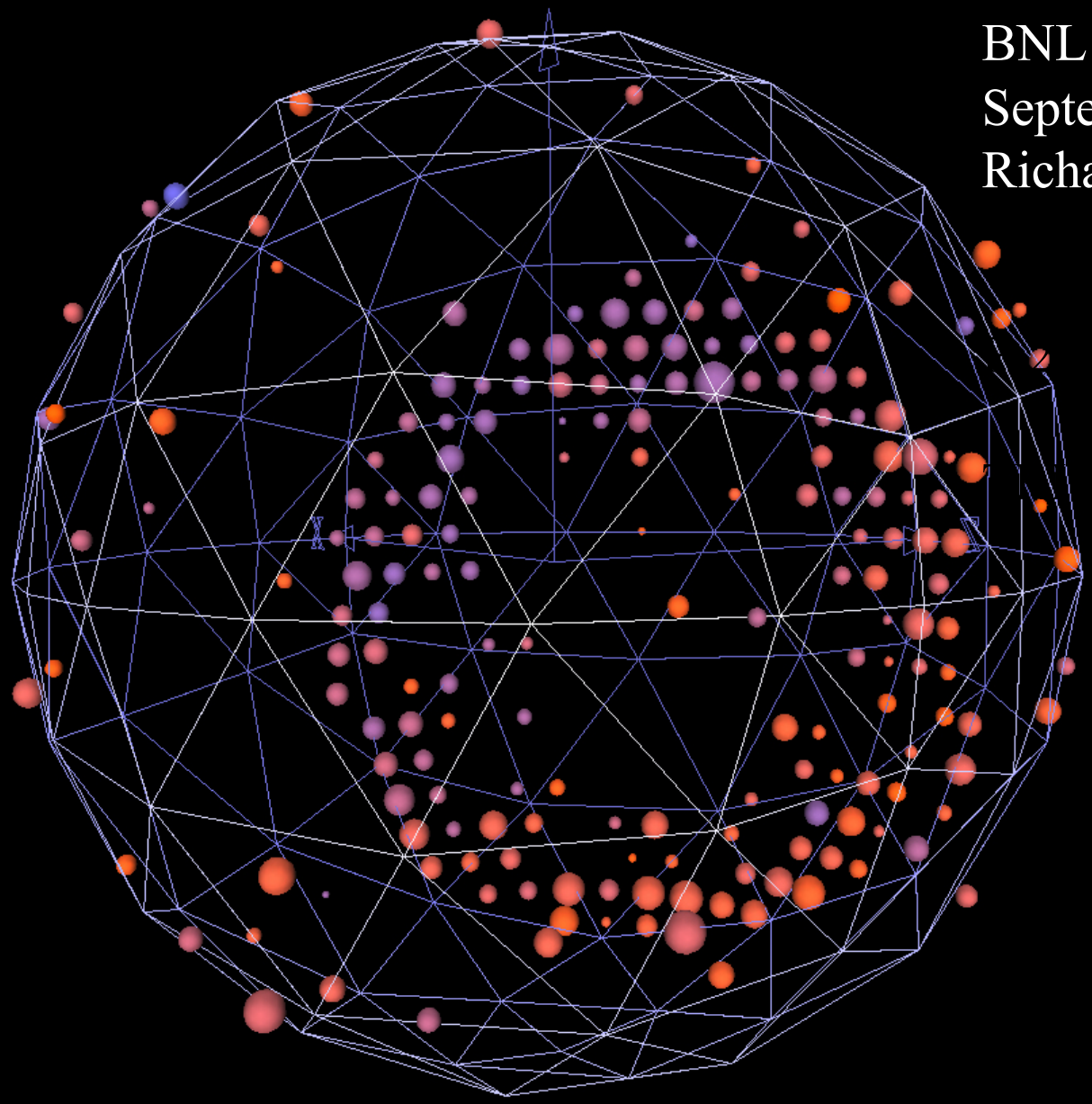
A Decade Later: Are We Any Closer to Resolving the LSND Puzzle?



BNL Seminar
September 23, 2010
Richard Van de Water, LANL, P-25

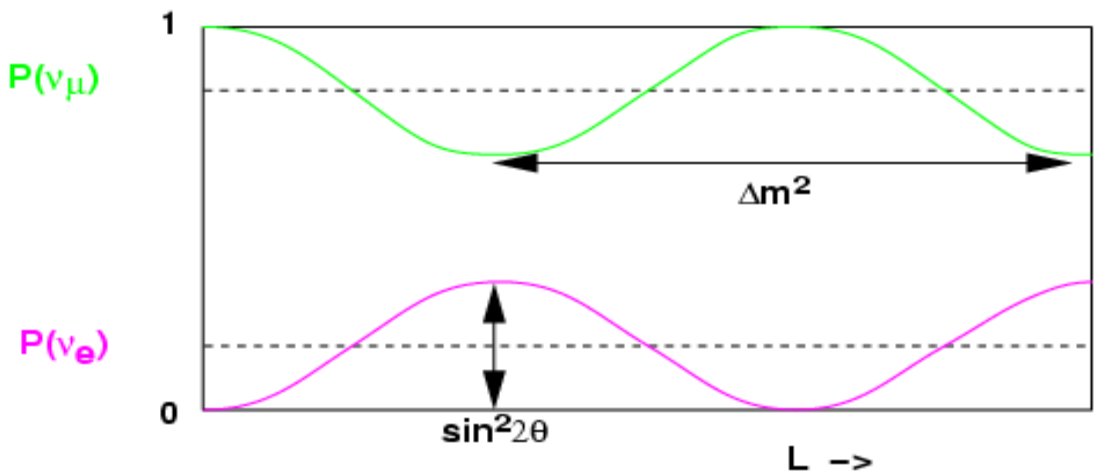
Outline

- Motivation for MiniBooNE: Testing the LSND anomaly.
- MiniBooNE design strategy and background estimates
- Neutrino oscillation results; PRL 102,101802 (2009)
- Antineutrino oscillation results; PRL 103,111801 (2009)
- Updated Antineutrino oscillation results; ~70% more data
- Interpretation; fits to world oscillation data, cosmology, etc
- Summary and Future Experiments

Motivation for MiniBooNE

Neutrino Oscillations

Weak Eigenstates		Eigenstates of Propagation
ν_μ	=	$\cos\Theta\ \nu_1 + \sin\Theta\ \nu_2$
ν_e	=	$-\sin\Theta\ \nu_1 + \cos\Theta\ \nu_2$

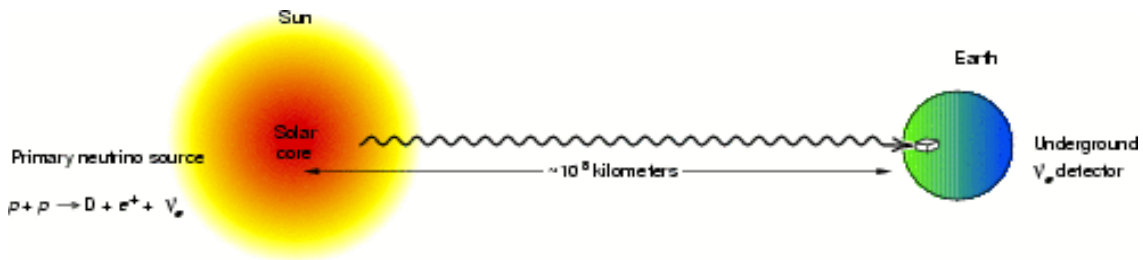


$$P_{\nu_\mu \to \nu_e} = \sin^2(2\Theta)\ \sin^2(1.27\ \Delta m^2\ L/E_\nu)$$

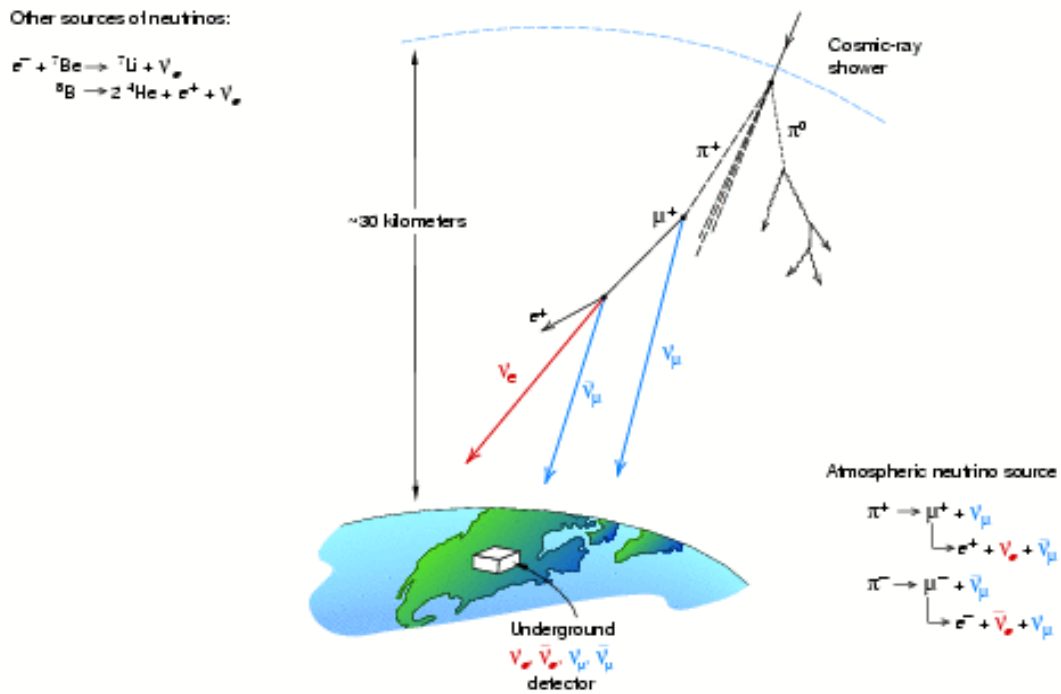
$\Delta m^2 = m_2^2 - m_1^2$ in eV^2, L in meters, E_ν in MeV

For oscillations to occur, neutrinos must have mass!

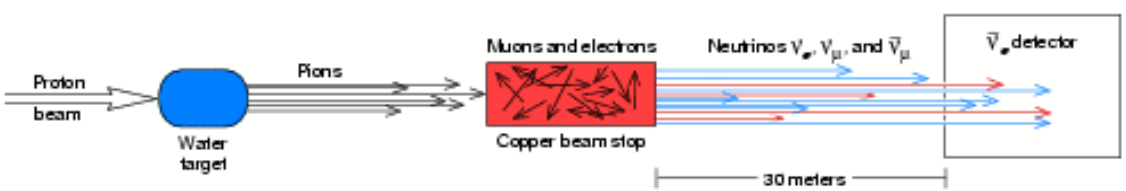
Neutrino Oscillations Have Been Observed!



SuperK, SNO, KamLAND (Very long baseline)

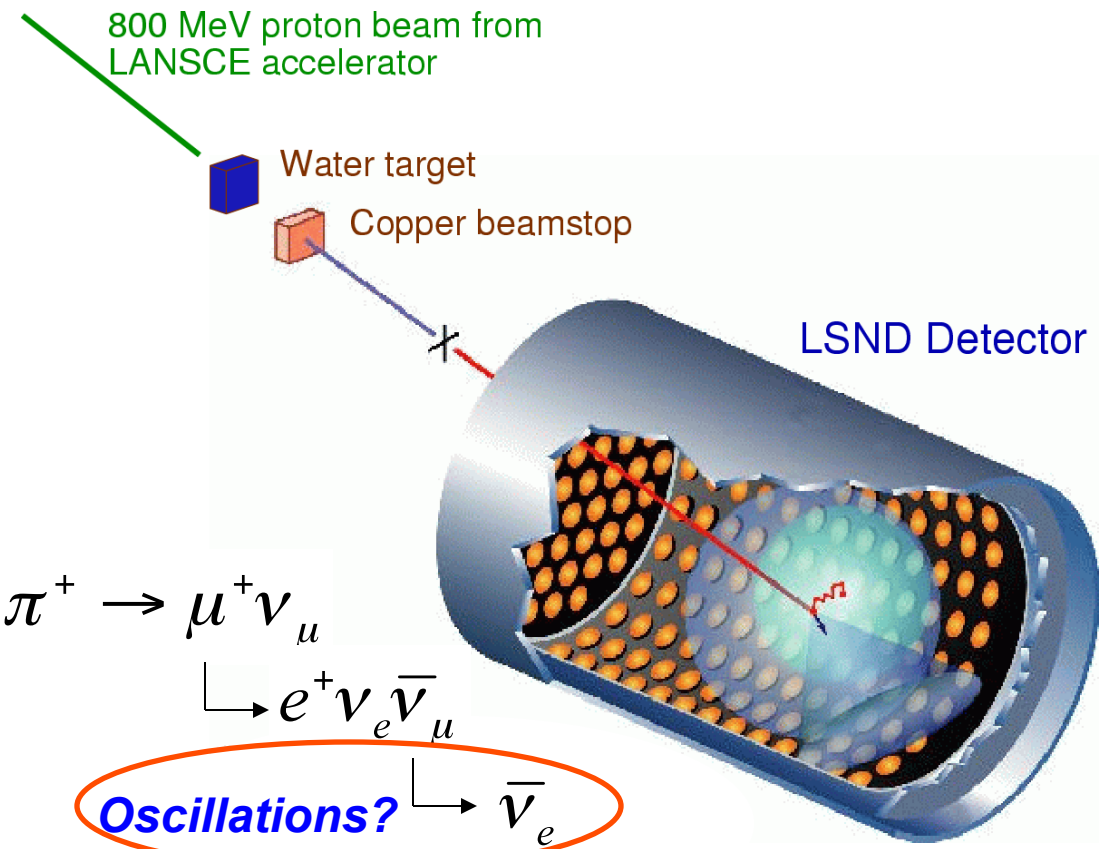


SuperK, K2K, MINOS (intermediate baseline)



LSND? (short baseline)

The LSND Experiment: Evidence for Oscillations



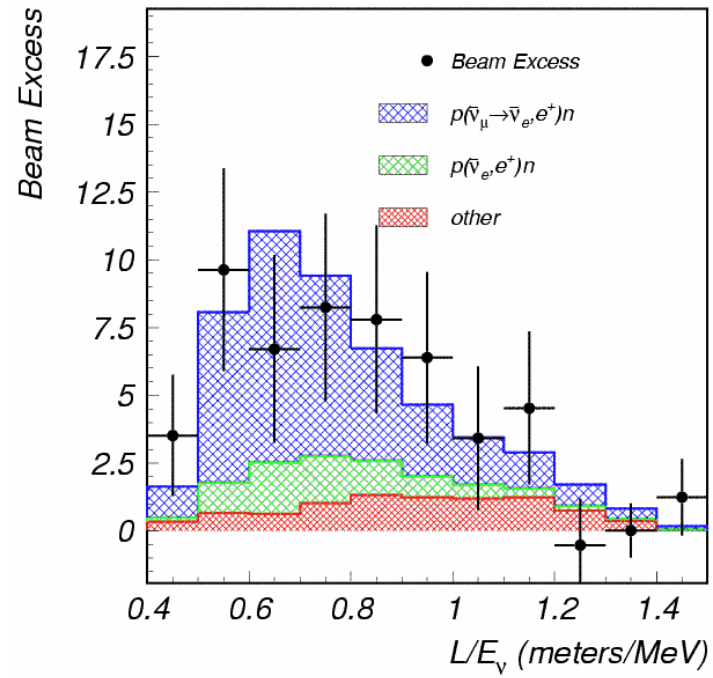
$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$

Oscillations? $\hookrightarrow \bar{\nu}_e$

Signal: $\bar{\nu}_e$ p → e$^+$ n

$\hookrightarrow$ n p → d γ(2.2MeV)



LSND took data from 1993-98

- 49,000 Coulombs of protons
- L = 30m and 20 < E_ν < 53 MeV

Saw an excess of $\bar{\nu}_e$:
87.9 ± 22.4 ± 6.0 events.

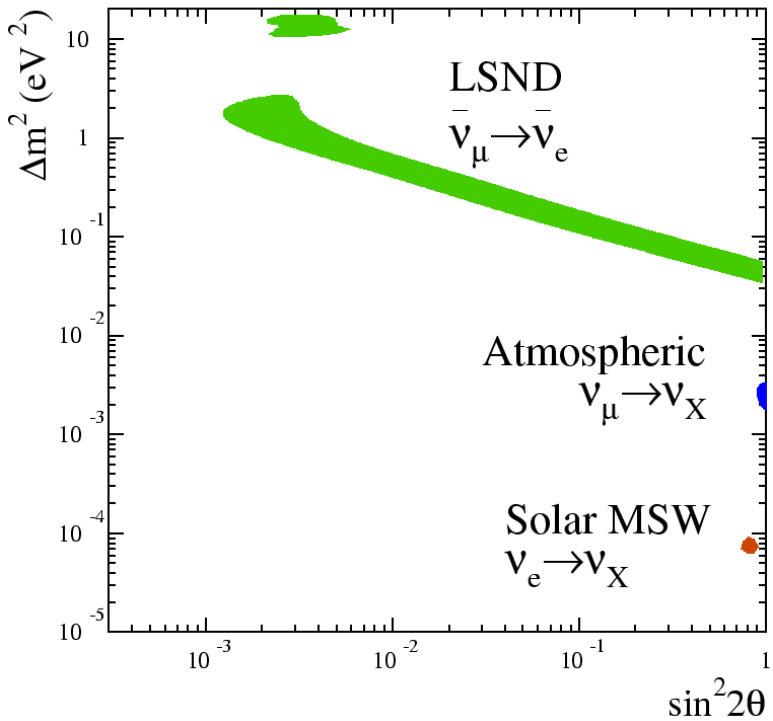
With an oscillation probability of (0.264 ± 0.067 ± 0.045)%.

3.8 σ evidence for oscillation.

HARP recently announced measurements that confirm LSND $\bar{\nu}_e$ background estimate

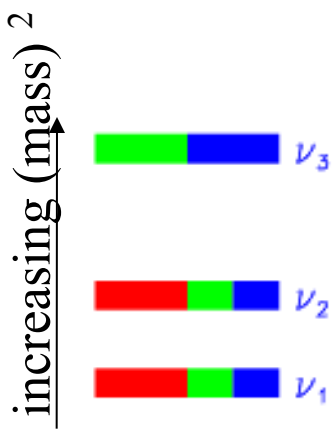
MiniBooNE was designed to test the LSND signal

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



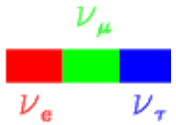
A three neutrino picture requires

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



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

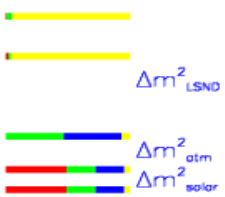
$$\Delta m_{12}^2 = m_1^2 - m_2^2$$



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

If LSND Excess Confirmed: Physics Beyond the Standard Model!

3+n Sterile Neutrinos — Sorel, Conrad, & Shaevitz (PRD70(2004)073004)



Possible CP violation - Explain Baryon Asymmetry in the Universe?
Explain Pulsar Kicks?
Explain R-Process in Supernovae?
Explain Dark Matter?

Mass Varying Neutrino — Kaplan, Nelson, & Weiner (PRL93(2004)091801)
Explain Dark Energy?

Sterile Neutrino Decay — Palomares-Ruiz, Pascoli, Schwetz (hep-ph/0505216v2)

New Scalar Bosons — Nelson, Walsh (arXiv:0711-1363)

CPT Violation — Barger, Marfatia, & Whisnant (PLB576(2003)303)
Explain Baryon Asymmetry in the Universe?

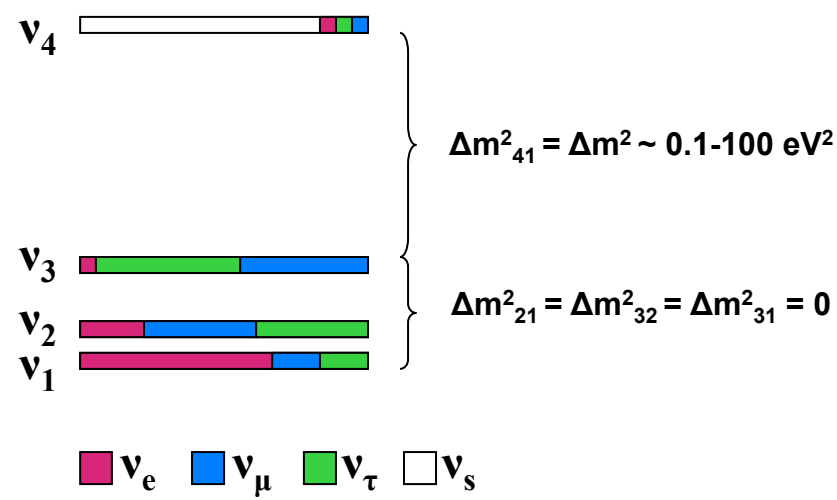
Lorentz Violation — Kostelecky & Mewes (PRD70(2004)076002)
Katori, Kostelecky, Tayloe (hep-ph/0606154)

Extra Dimensions — Pas, Pakvasa, & Weiler (PRD72(2005)095017)

LSND interpretation: simple two neutrino oscillations

- **Sterile neutrino models**
  - **3+1**

2-ν approximation:



Oscillation probability:

$$P(\nu_\mu \rightarrow \nu_e) = 4|U_{\mu 4}|^2|U_{e4}|^2 \sin^2(1.27\Delta m^2_{41}\, L/E)$$

$$= \sin^2 2\theta \sin^2(1.27\Delta m^2\, L/E)$$

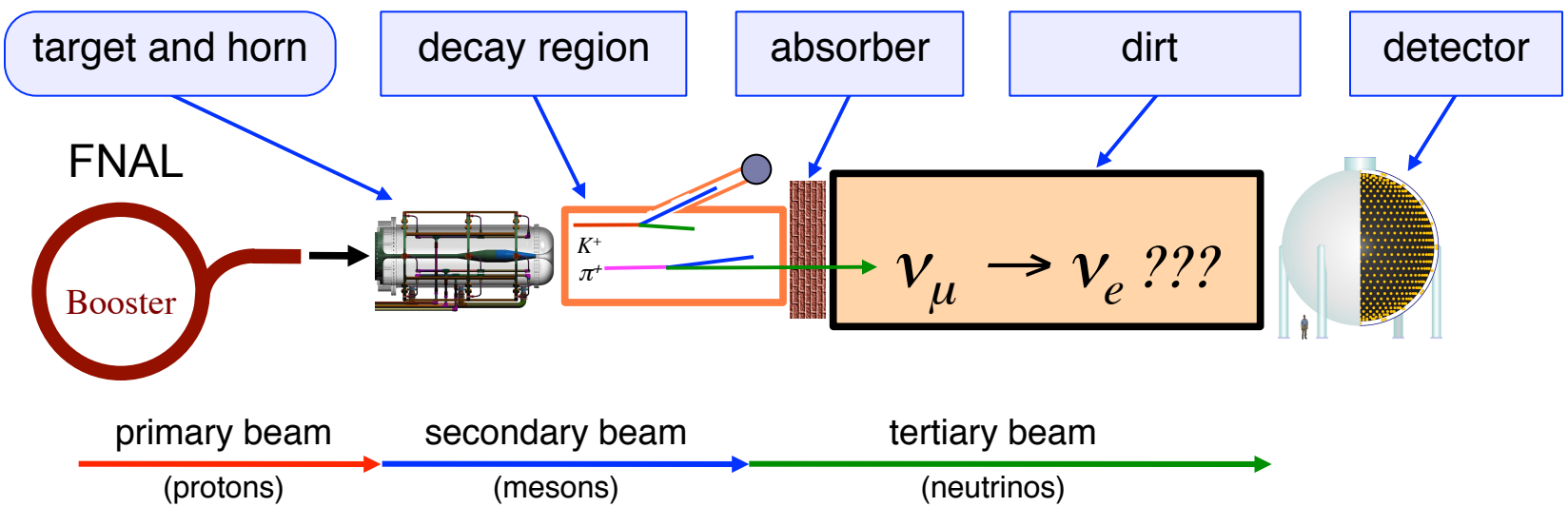
The MiniBooNE Experiment: How to measure neutrino oscillations at the ~1% level….very difficult!

MiniBooNE was designed to test the LSND signal

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

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

LSND:	E ~30 MeV	L ~30 m	L/E ~1
MiniBooNE:	E ~500 MeV	L ~500 m	L/E ~1

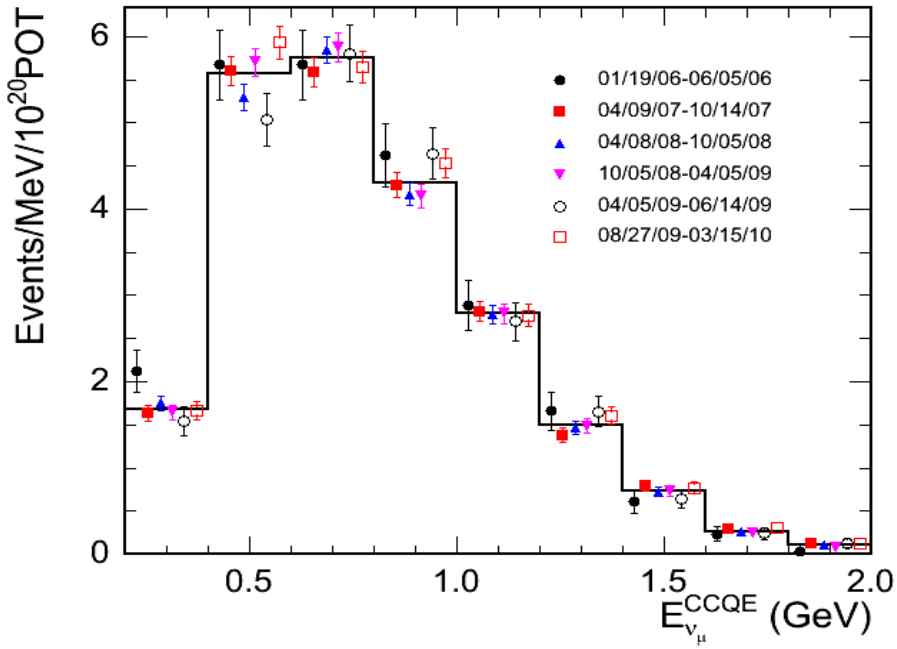


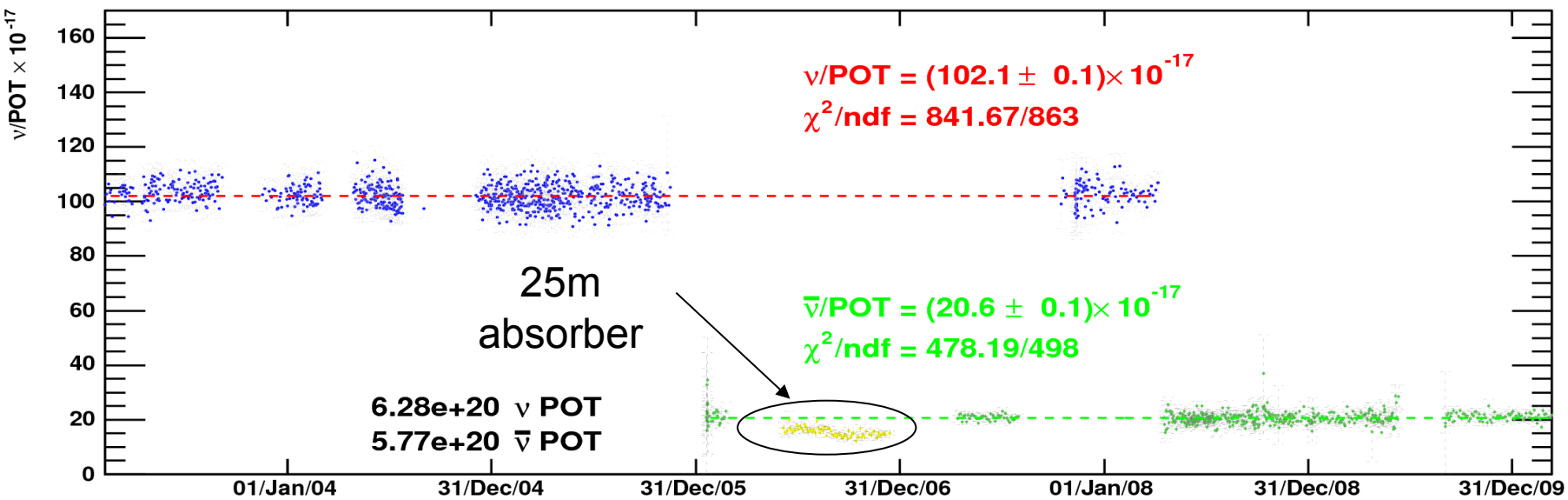
Neutrino mode: search for ν_μ -> ν_e appearance with 6.5E20 POT ➔ assumes CP/CPT conservation
Antineutrino mode: search for $\bar{\nu}_\mu$ -> $\bar{\nu}_e$ appearance with 5.66E20 POT ➔ direct test of LSND

FNAL has done a great job delivering beam!

Data stability

- Very stable throughout the run

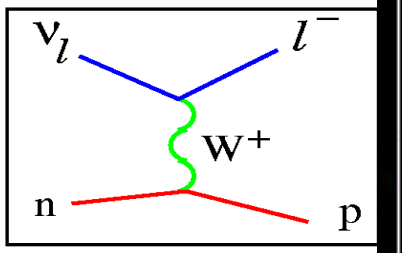




MiniBooNE is a Cerenkov Light Detector:

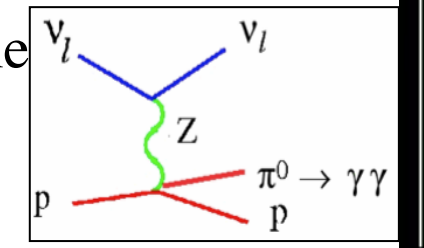
The main types of particles neutrino events produce:
MB does not discriminate between electron and photons.

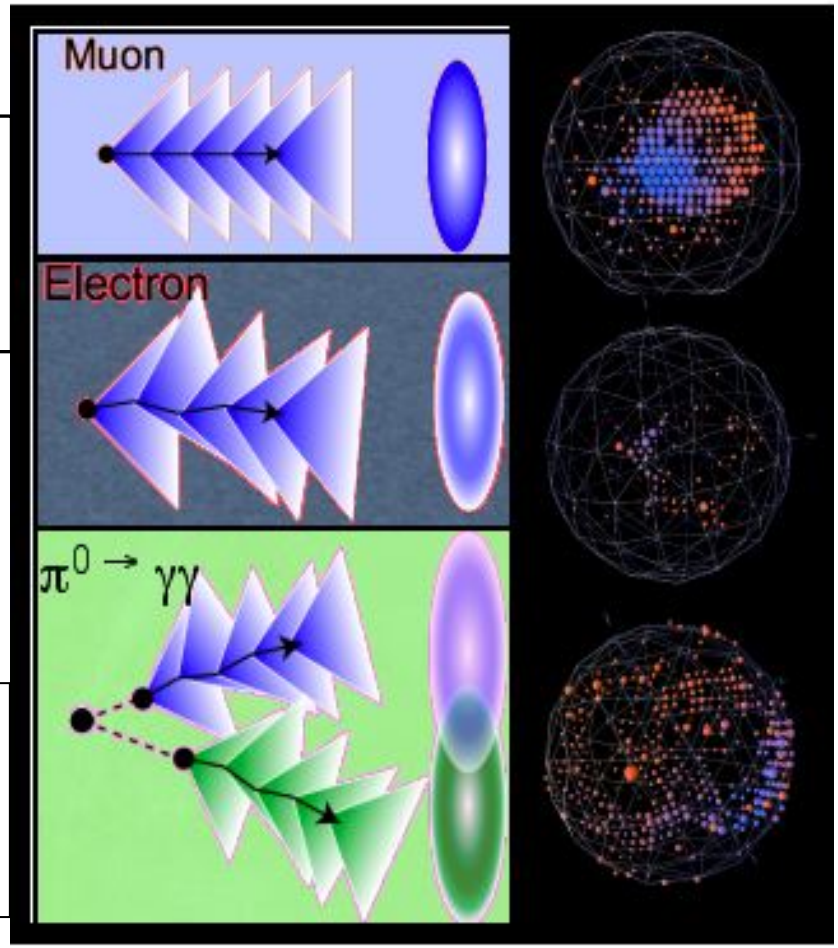
Muons (or charged pions):
Produced in most CC events.
Usually 2 or more subevents
or exiting through veto.



Electrons (or single photon):
Tag for $\nu_\mu \rightarrow \nu_e$ CCQE signal.
1 subevent

π^0s:
Can form a background if one
photon is weak or exits tank.
In NC case, 1 subevent.





$\overset{(-)}{\nu}_e$ *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, $\Delta \longrightarrow N\gamma$, dirt, and intrinsic ν_e constrained from data.

Detailed detector simulation and PID Checked with neutrino data and calibration sources.

- A. A. Aguilar-Arevalo et al., *"Neutrino flux prediction at MiniBooNE"*, Phys. Rev. D79, 072002 (2009).

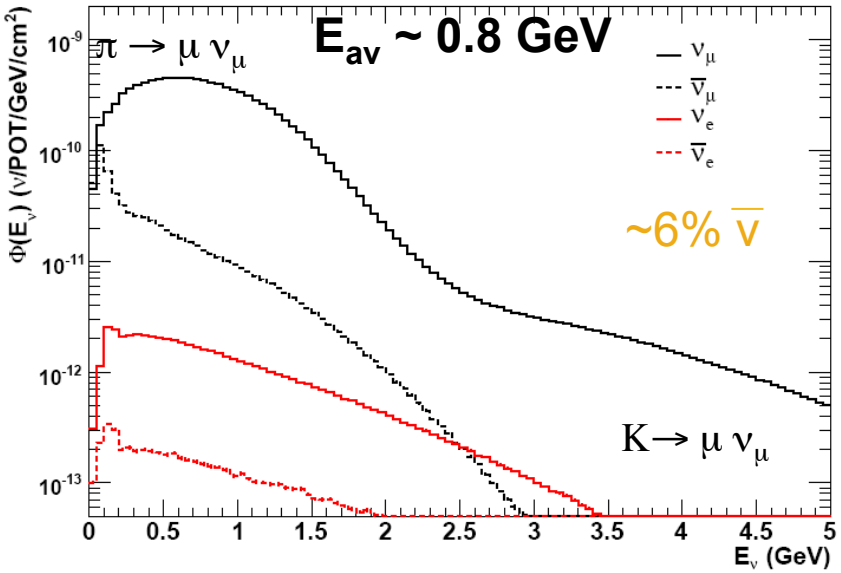
- A. A. Aguilar-Arevalo et al., *"Measurement of Muon Neutrino Quasi-Elastic Scattering on Carbon"*, Phys. Rev. Lett. 100, 032301 (2008).
- A. Aguilar-Arevalo et al., *"First Observation of Coherent π^0 Production in Neutrino Nucleus Interactions with Neutrino Energy <2 GeV"*, Phys. Lett. 664B, 41 (2008).
- A. A. Aguilar-Arevalo et al., *"Measurement of the Ratio of the ν_μ Charged-Current Single-Pion Production to Quasielastic Scattering with a 0.8 GeV Neutrino Beam on Mineral Oil"*, Phys. Rev. Lett. 103, 081801 (2009).
- A. A. Aguilar-Arevalo et al., *"Measurement of ν_μ and $\bar{\nu}_\mu$ induced neutral current single π^0 production cross sections on mineral oil at E_n ~ 1 GeV"*, Phys. Rev. D81, 013005 (2010).
- A. A. Aguilar-Arevalo et al, "*Measurement of the ν_μ charged current π+ to quasi-elastic cross section ratio on mineral oil in a 0.8 GeV neutrino beam*". Phys.Rev. Lett. 103:081801 (2010).
- A. A. Aguilar-Arevalo et al, "*First Measurement of the Muon Neutrino Charged Current Quasielastic Double Differential Cross Section*", Phys. Rev, D81, 092005 (2010), arXiv: 1002.2680 [hep-ex].

- A. A. Aguilar-Arevalo et al., *"The MiniBooNE Detector"*, Nucl. Instr. Meth. A599, 28 (2009).
- P. Adamson et al., *"Measurement of ν_μ and ν_e Events in an Off-Axis Horn-Focused Neutrino Beam"*, Phys. Rev. Lett. 102, 211801 (2009).
- R.B. Patterson et al, "The Extended-Track Event Reconstruction for MiniBooNE", Nucl. Instrum. Meth. A608, 206 (2009).

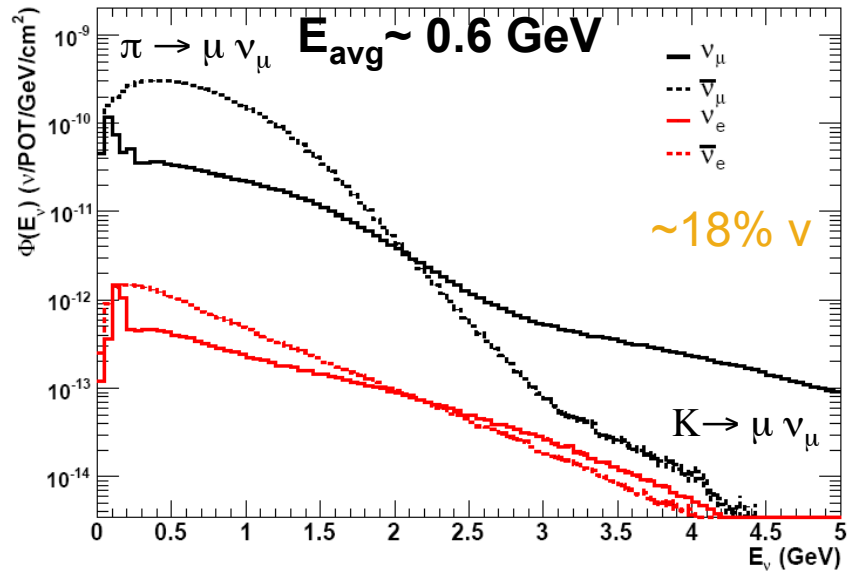
MiniBooNE Flux (Flux paper arXiv: 0806.1449)

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

ν mode flux



$\bar{\nu}$ mode flux

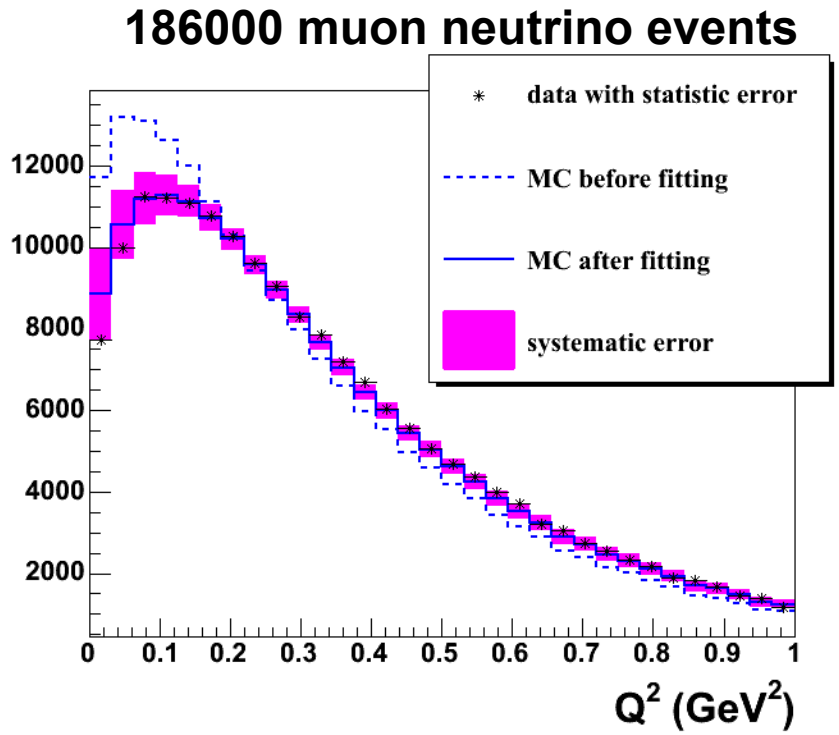


Subsequent decay of the **μ+ (μ-)** produces $\bar{\nu}_e$ **(ν_e)** intrinsics ~0.5%

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

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

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

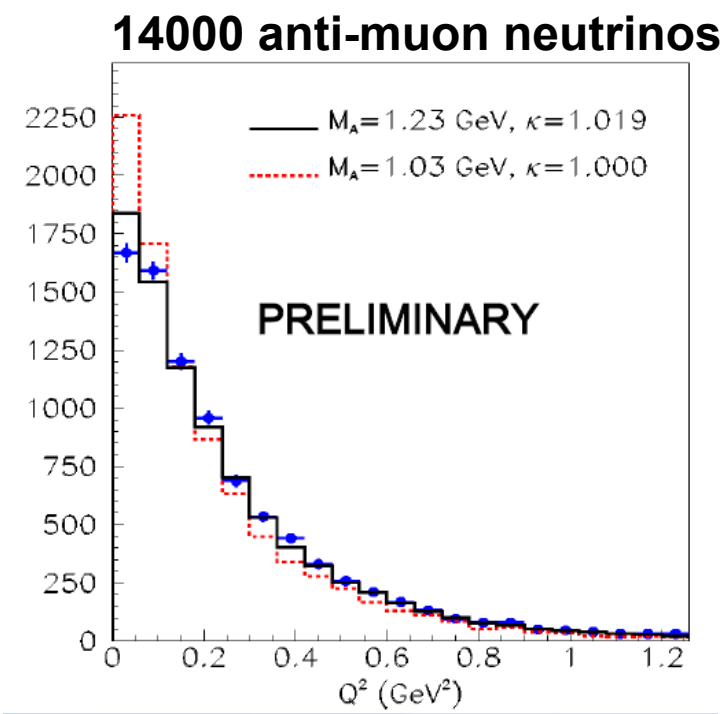


From Q^2 fits to MB ν_μ CCQE data:

- M_A^{eff} -- effective axial mass
- $\varkappa$ -- Pauli Blocking parameter

From electron scattering data:

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



Fermi Gas Model describes CCQE ν_μ data well

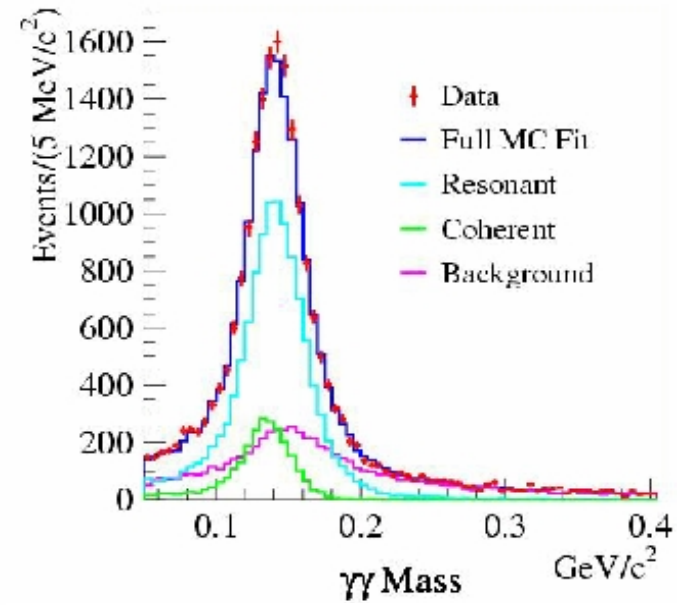
$M_A = 1.23 \pm 0.20$ GeV

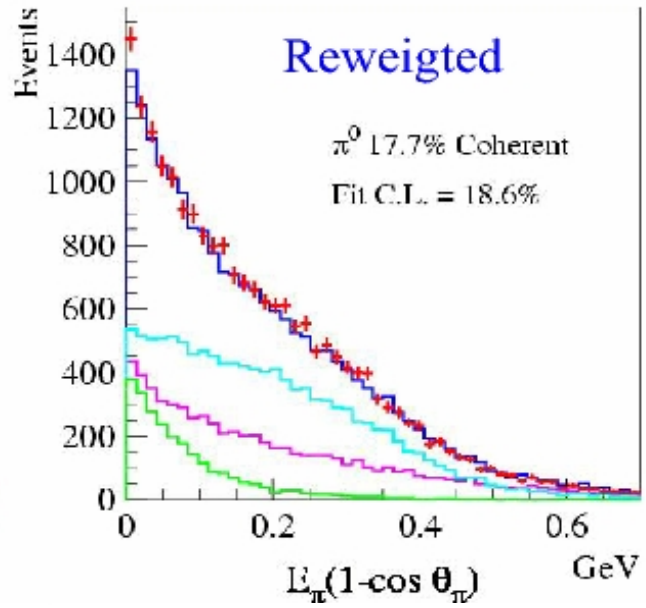
$\varkappa = 1.019 \pm 0.011$

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

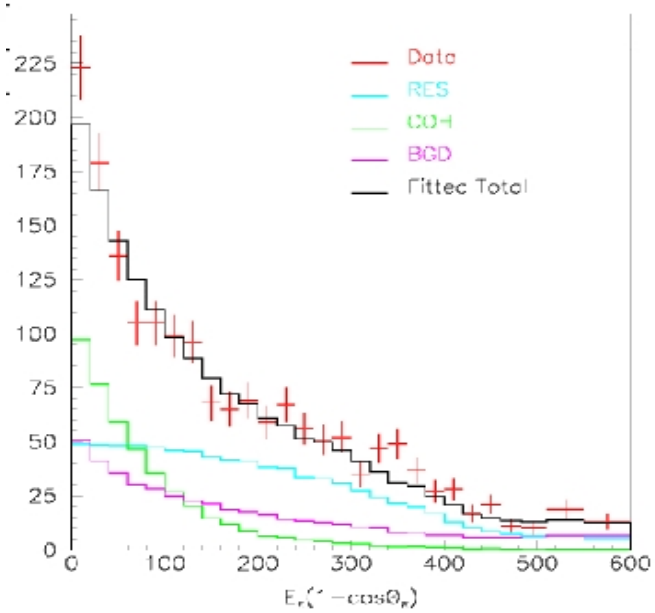
Neutral Current π^0: Good Data/MC agreement

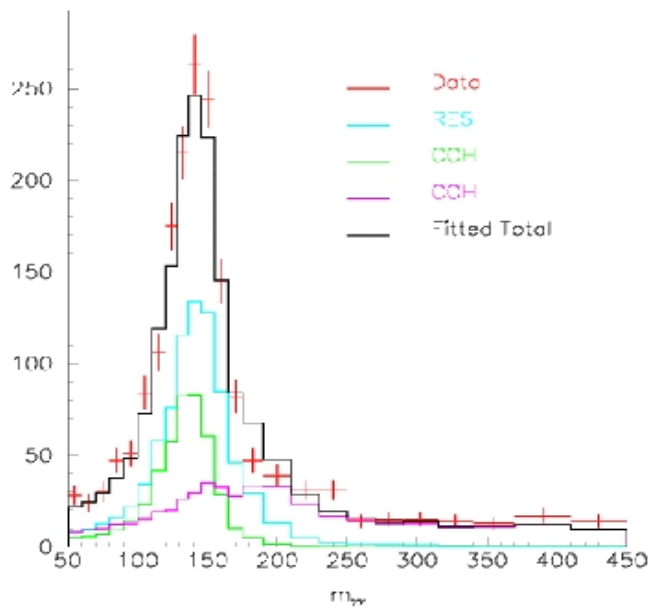
Neutrino





Antineutrino



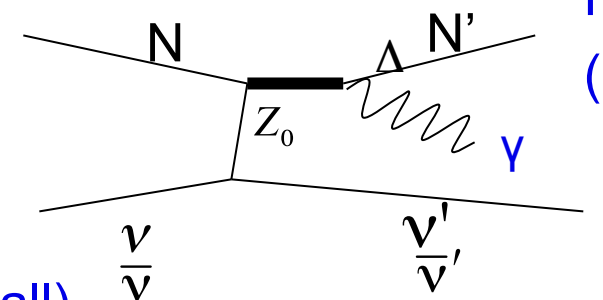


Backgrounds: Order(α_{QED} x NC) , single photon FS

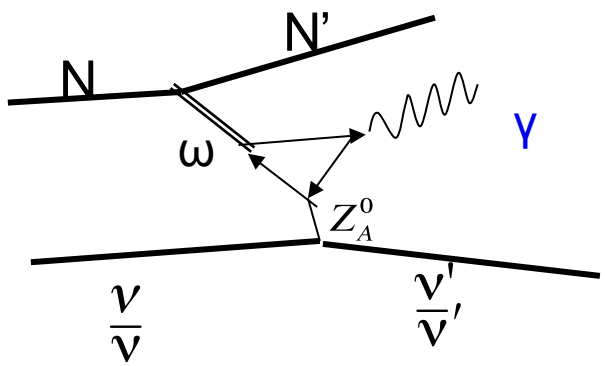
Radiative Delta Decay

(constrained by NCπ^0)

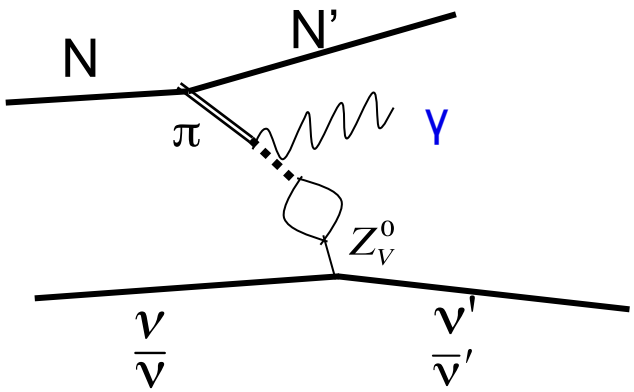
($G^2\alpha/\alpha_S$)

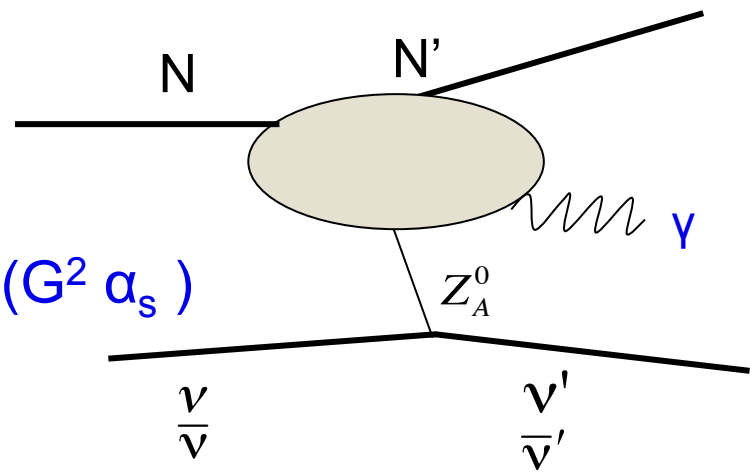


Axial Anomaly (small)



Other PCAC (small)

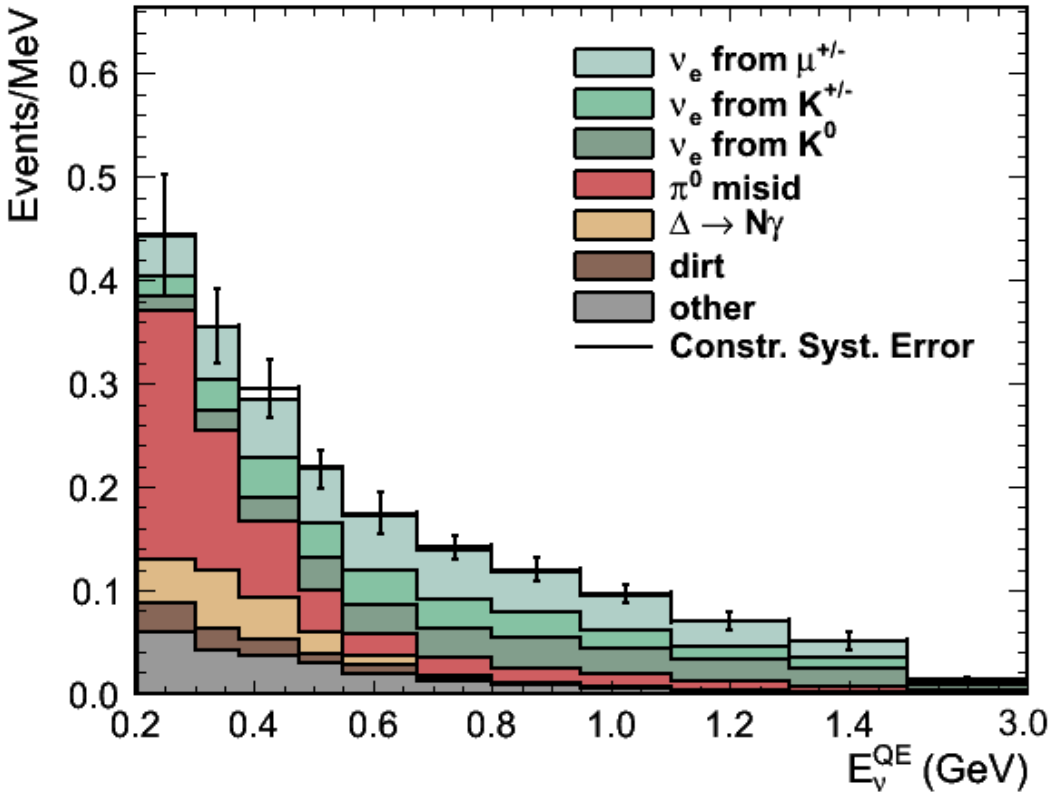




All order (G^2 α_s)

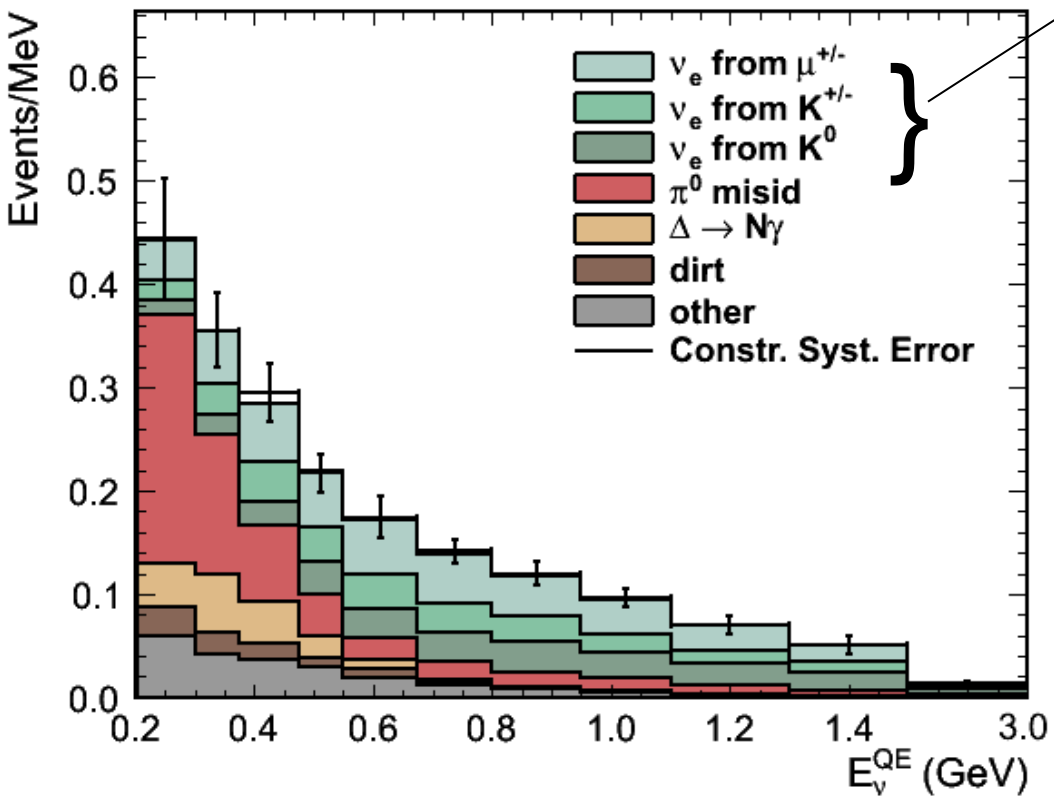
$\nu - \bar{\nu}$ comparison to test neutral current hypothesis

Background prediction $\bar{\nu}$ mode



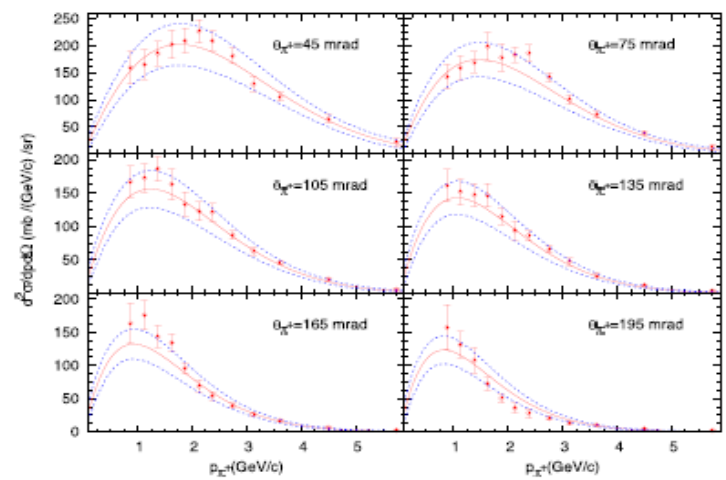
5.66e20 Protons on Target			
	200-475	475-125	
$\mu^\pm$	13.45	31.39	Intrinsic ν_e
$K^\pm$	8.15	18.61	
K^0	5.13	21.2	
Other ν_e	1.26	2.05	
NC π^0	41.58	12.57	
$\Delta \rightarrow N\gamma$	12.39	3.37	Mis-ID
dirt	6.16	2.63	
ν_μ	4.3	2.04	
Other ν_μ	7.03	4.22	
Total	99.45	98.08	

High Energy Backgrounds



Phys. Rev. D79, 072002 (2009)

- Intrinsic $\bar{\nu}_e$ & ν_e
  - External measurements – HARP p+Be for $\pi^{\pm}$



  - – Sanford-Wang fits to world K^+/K^0 data

- $\bar{\nu}_u$ & ν_u constraint

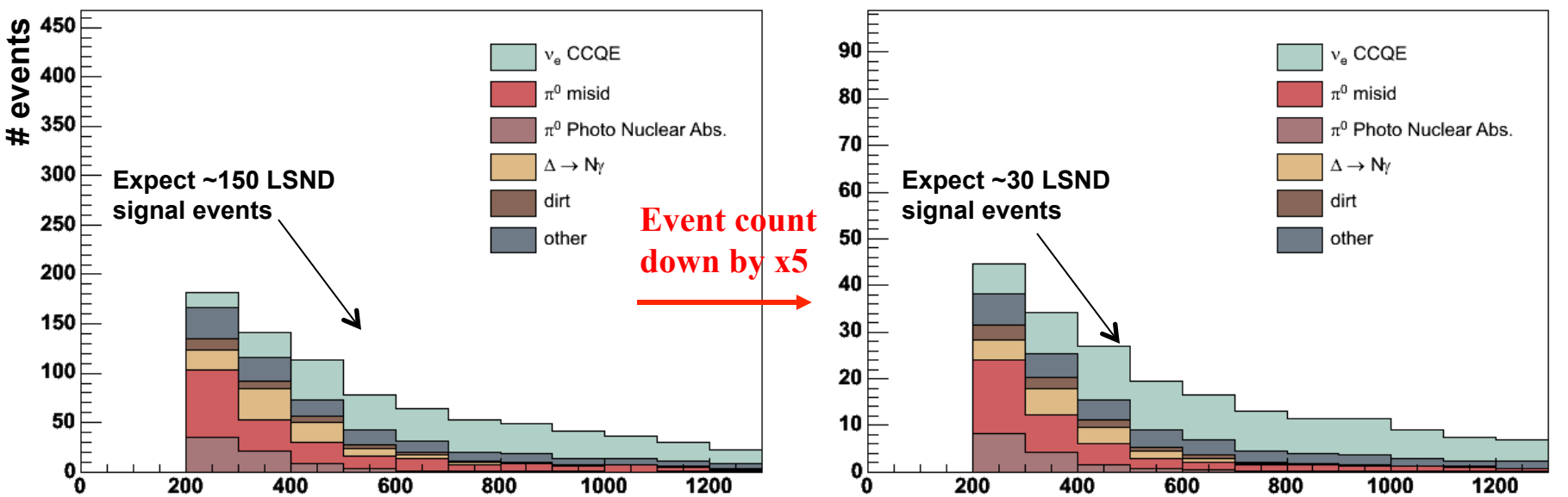
- SciBooNE neutrino mode K^+ weight = 0.75 ± 0.05(stat) ± 0.30(sys).

$\overset{(-)}{\nu}_e$ *Event Rate Predictions for Appearance Analysis*

- Antineutrino rate down by a factor of 5 (reduced flux and cross section)
- Background types and relative rates are similar for neutrino and antineutrino mode.
  - except inclusion of 15.9% wrong-sign neutrino flux component in antineutrino mode
- Fit analysis and errors are similar.

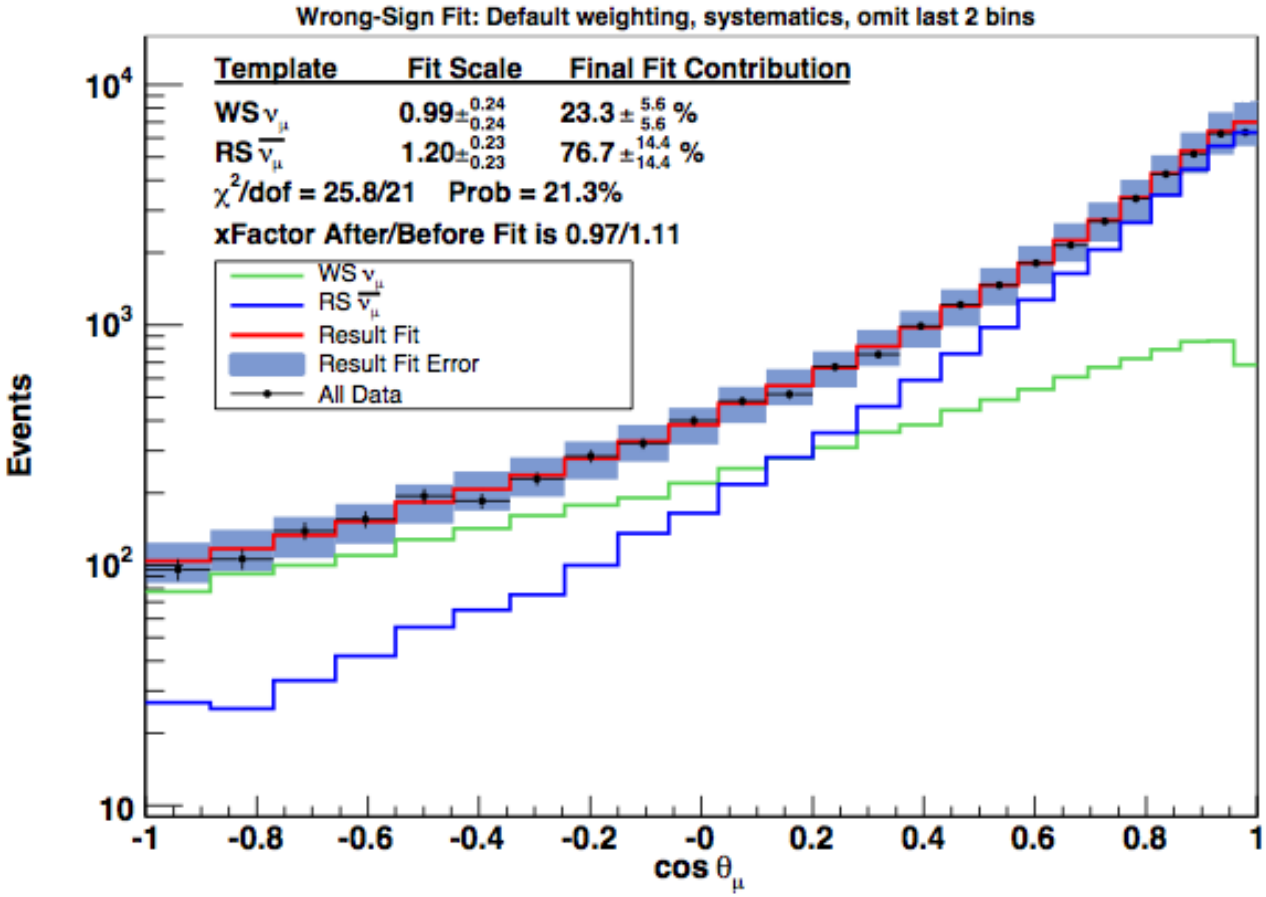
$\overset{(-)}{\nu}_e$ Backgrounds after PID cuts (Monte Carlo)

Neutrino 6.5x10^{20} POT **AntiNeutrino 5.66x10^{20} POT**



E_ν^{QE} = Reconstructed neutrino energy

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

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*

Previous Oscillation Results

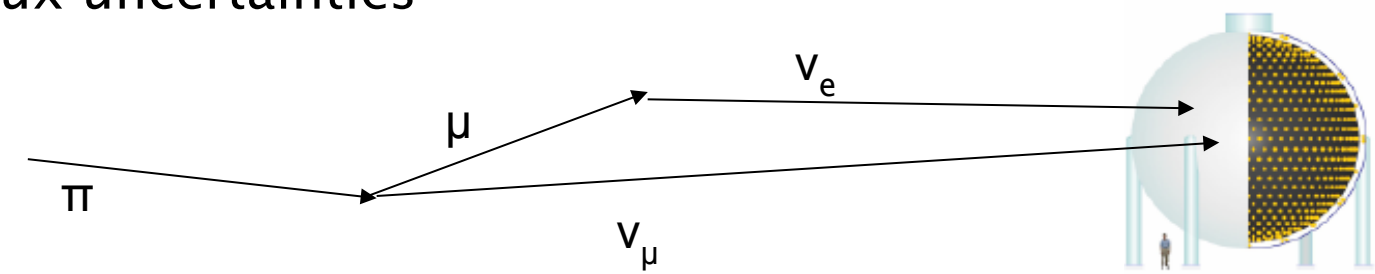
Oscillation Fit Method

- Binned Maximum likelihood fit:

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

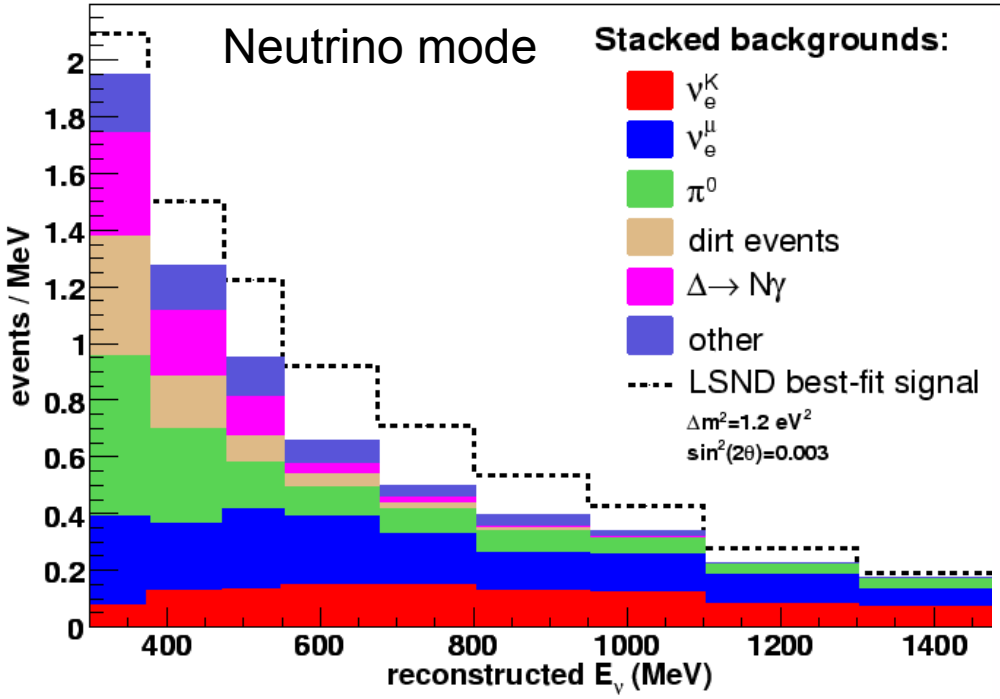
- Simultaneously fit
  - ν_e CCQE sample
  - High statistics ν_μ CCQE sample

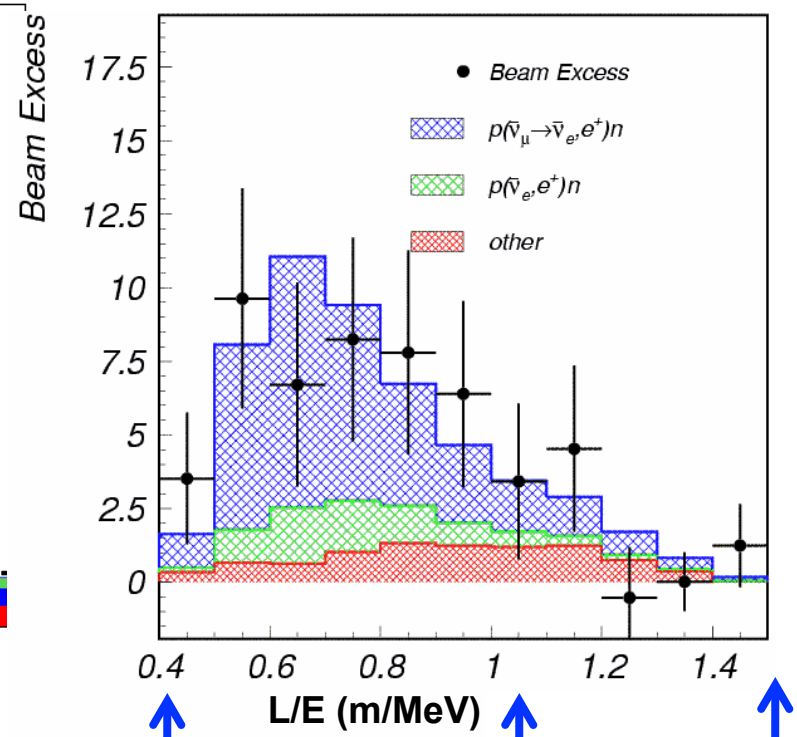
- ν_μ CCQE sample constrains many of the uncertainties:
  - Flux uncertainties



  - Cross section uncertainties

Reminders of some pre-unblinding choices





1250 475 333

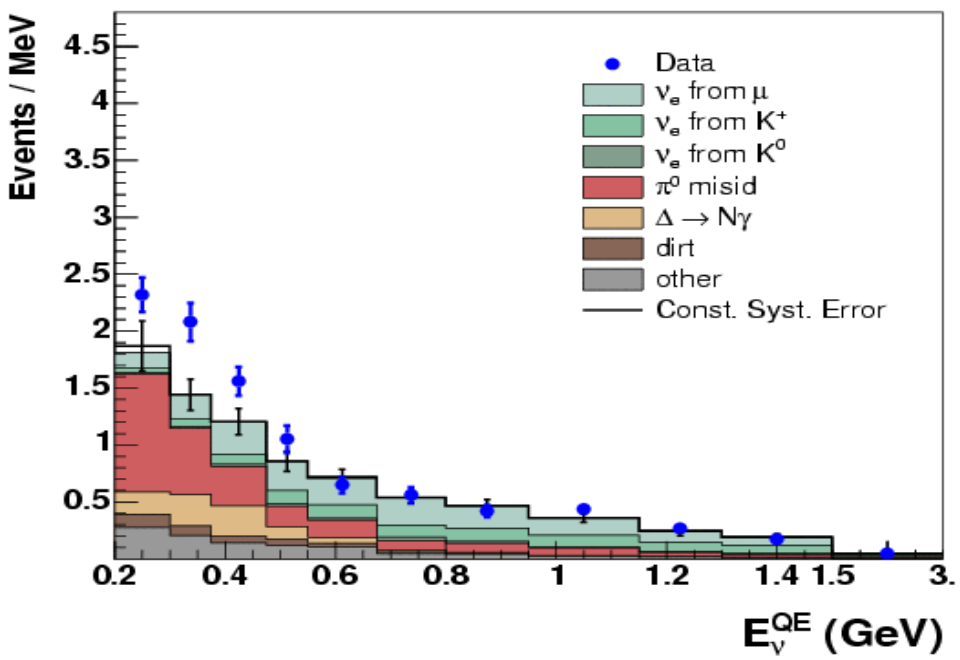
Energy in MB [MeV]

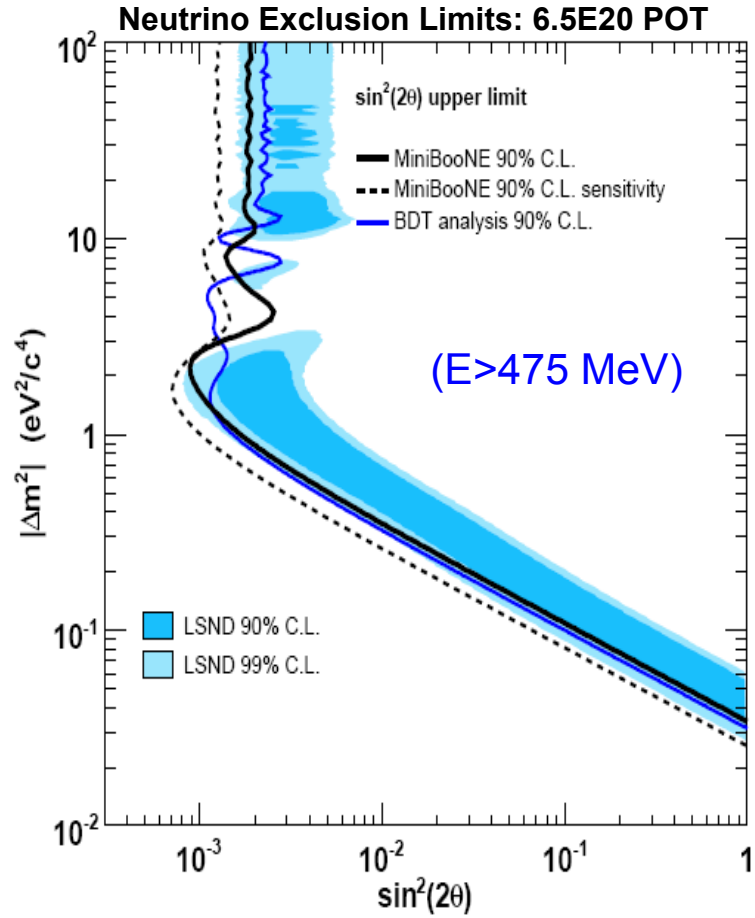
- Why is the 200-475 MeV region unimportant?
  - Large backgrounds from mis-ids reduce S/B.
  - Many systematics grow at lower energies, especially on signal.
  - Most importantly, not a region of L/E where LSND observed a significant signal!

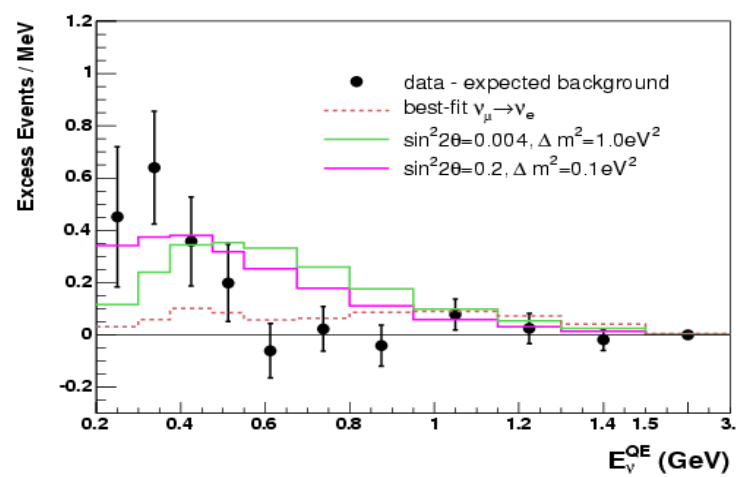
Neutrino mode MB results (2009)

- 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)



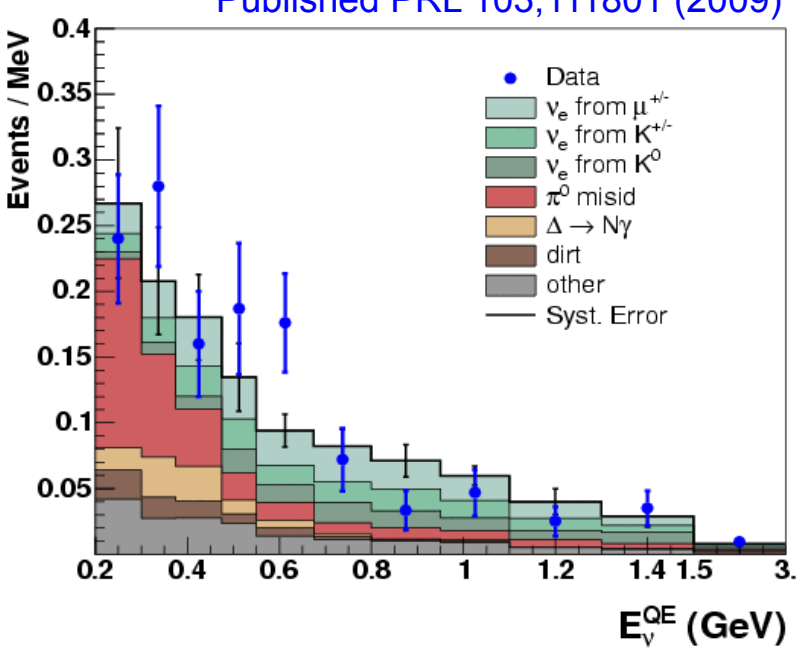




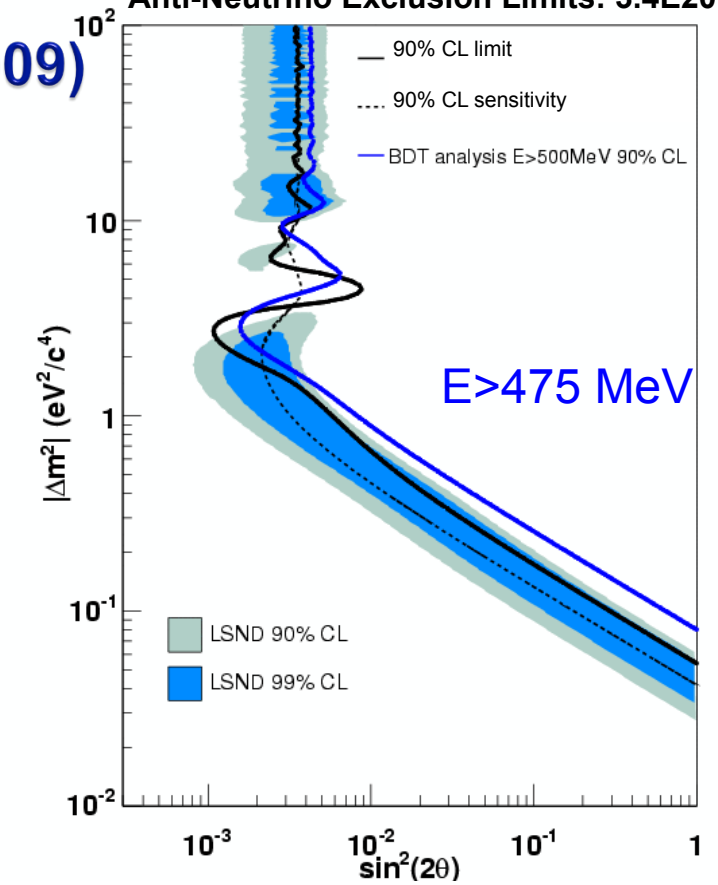
First Antineutrino mode MB results (2009)

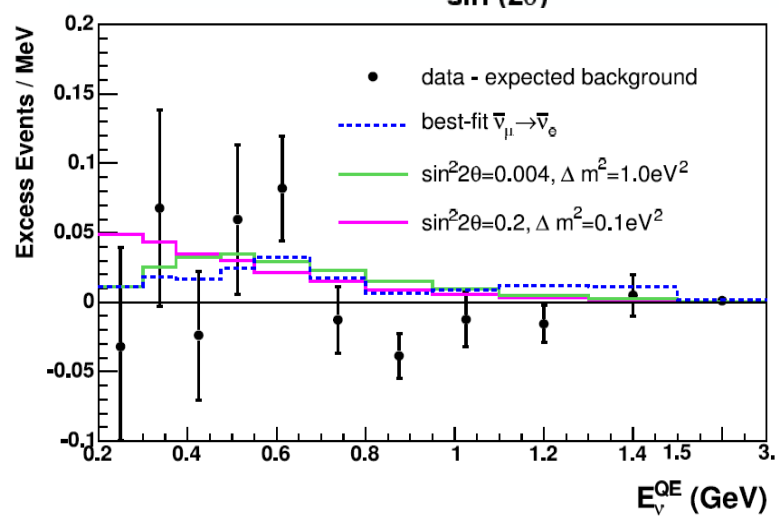
- 3.4E20 POT collected in anti-neutrino mode
- From 200-3000 MeV excess is 4.8 +/- 17.6 (stat +sys) events.
- Statistically small excess (more of a wiggle) in 475-1250 MeV region
  - Only antineutrino's allowed to oscillate in fit
  - Limit from two neutrino fit excludes less area than sensitivity due 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)



Anti-Neutrino Exclusion Limits: 3.4E20 POT

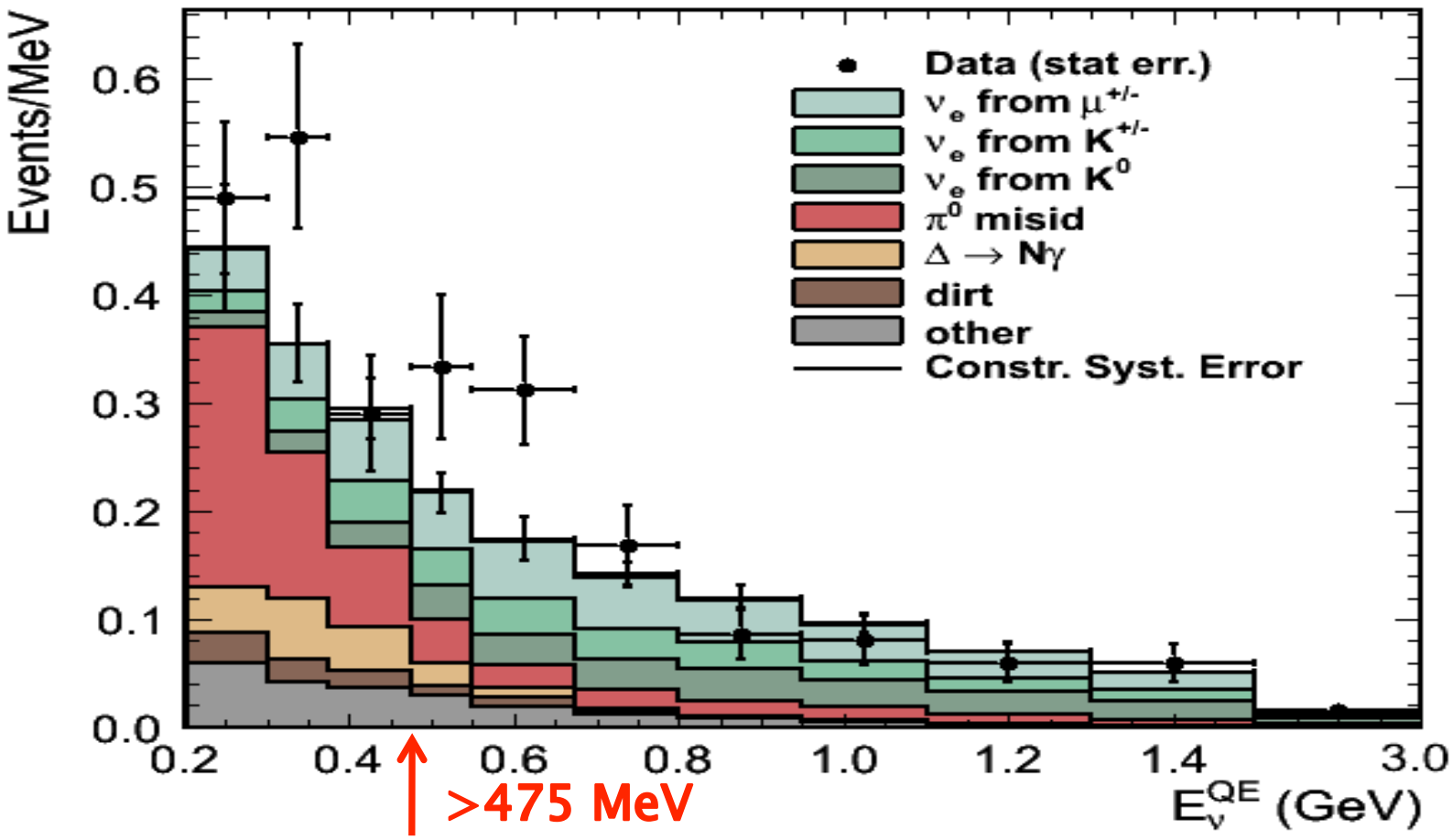




New Antineutrino Oscillation Results

New Antinuetrino Result with 5.66E20 POT

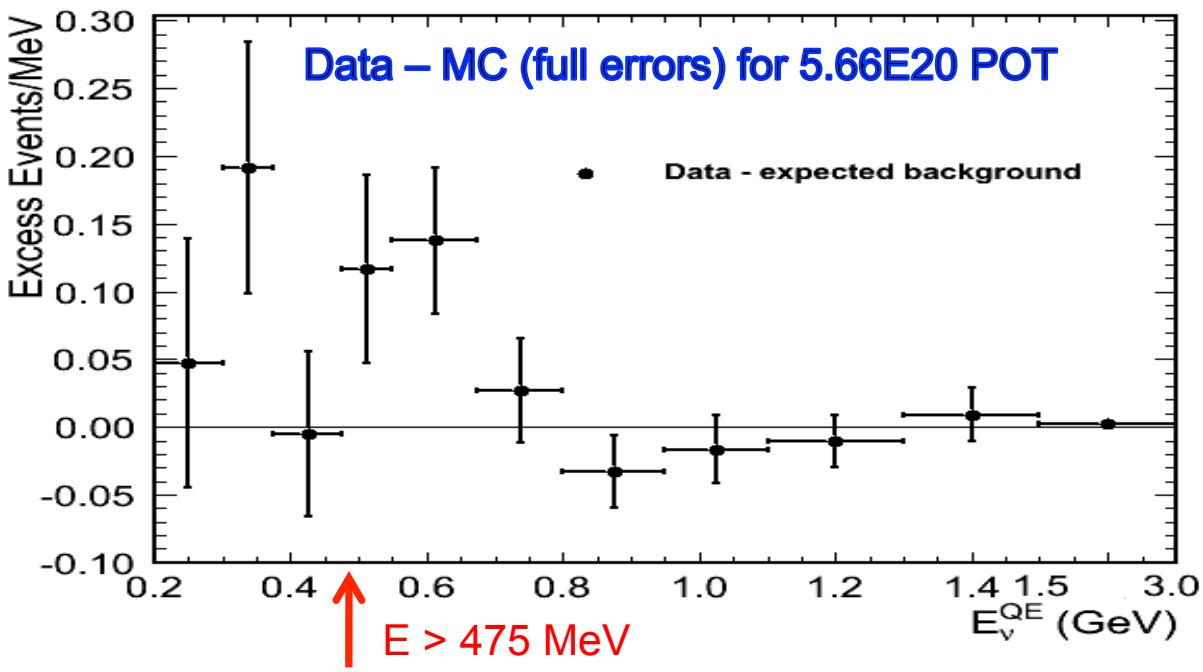
	200-475 MeV	475-1250 MeV	200-3000 MeV
Data	119	120	277
MC (stat+sys)	100.5 ± 14.3	99.1 ± 13.9	233.8 ± 22.5
Excess (stat)	18.5 ± 10.0 (1.9σ)	20.9 ± 10.0 (2.1σ)	43.2 ±15.3 (2.8σ)
Excess (stat+sys)	18.5 ± 14.3 (1.3σ)	20.9 ± 13.9 (1.5σ)	43.2 ± 22.5 (1.9σ)



Testing the Null Hypothesis

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

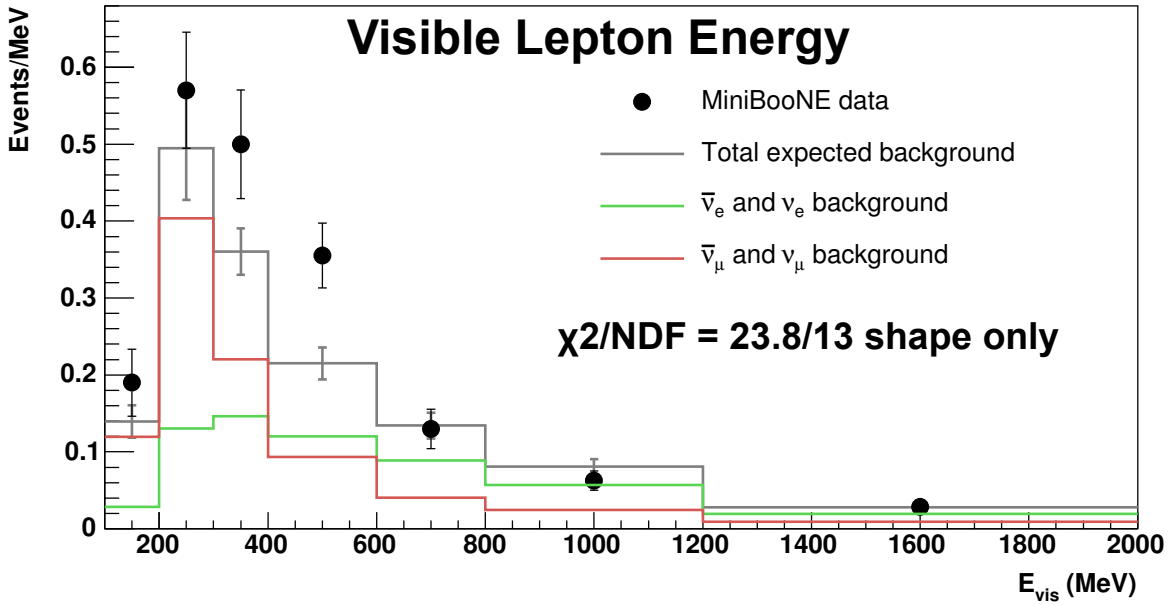
Fitting only $\bar{\nu}_e$ in the range 475 – 1250 MeV, null probability = 0.5%

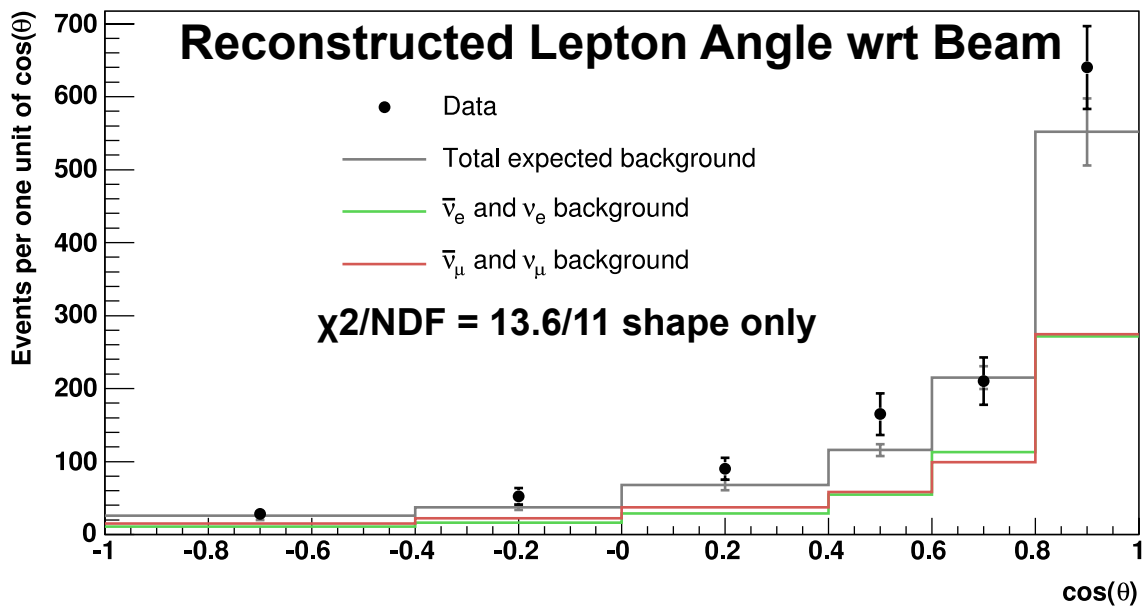


Data Checks for 5.66E20 POT (~70% more data)

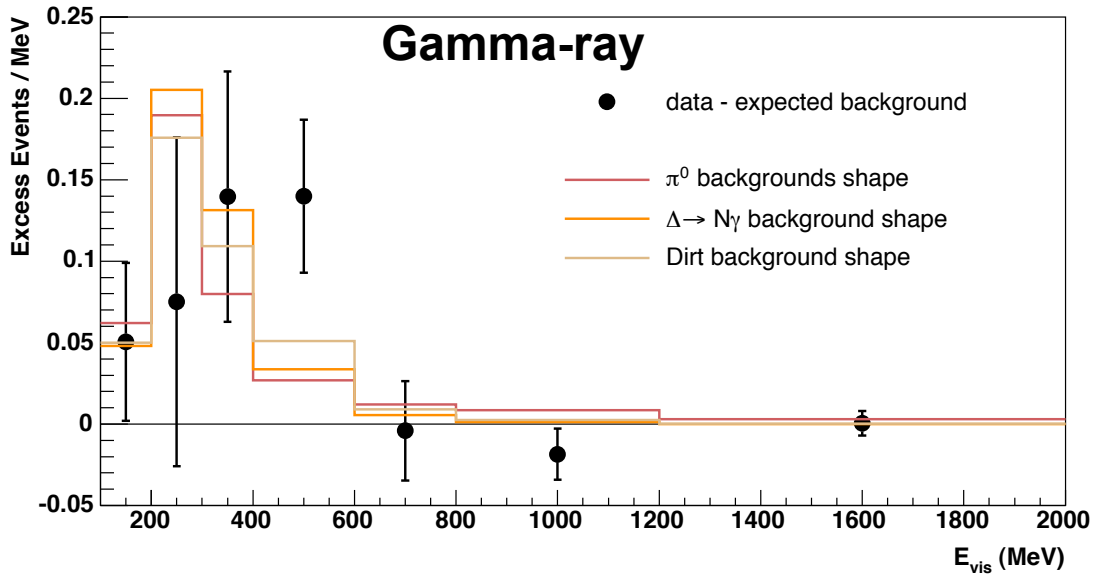
- Beam and Detector low level stability checks; beam stable to 2%, and detector energy response to 1%.
- $\bar{\nu}_\mu$ rates and energy stable over entire antineutrino run.
- Latest $\bar{\nu}_e$ data rate is 1.9σ higher than 3.4E20POT data set.
- Independent measurement of π^0 rate for antineutrino 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 **(see poster by Zelimir Djurcic)**.
- 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 K^0, where we use external measurements and apply 30% error.
  - Would require >3σ increase in K^0 normalization, but shape does not match well the excess.

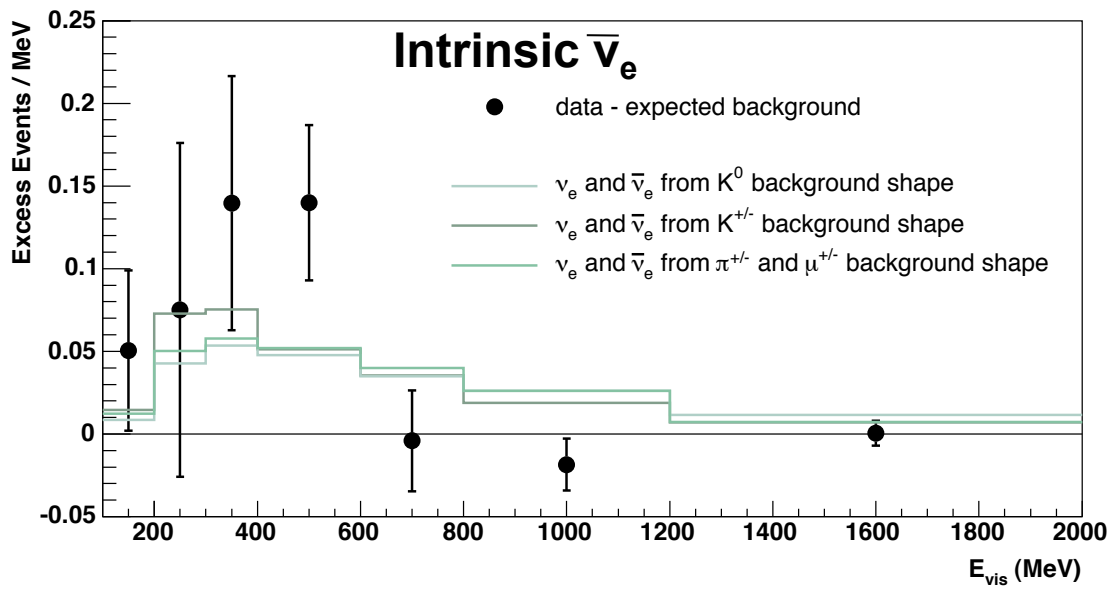
Other $\bar{\nu}_e$ kinematic distributions for 5.66E20 POT





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





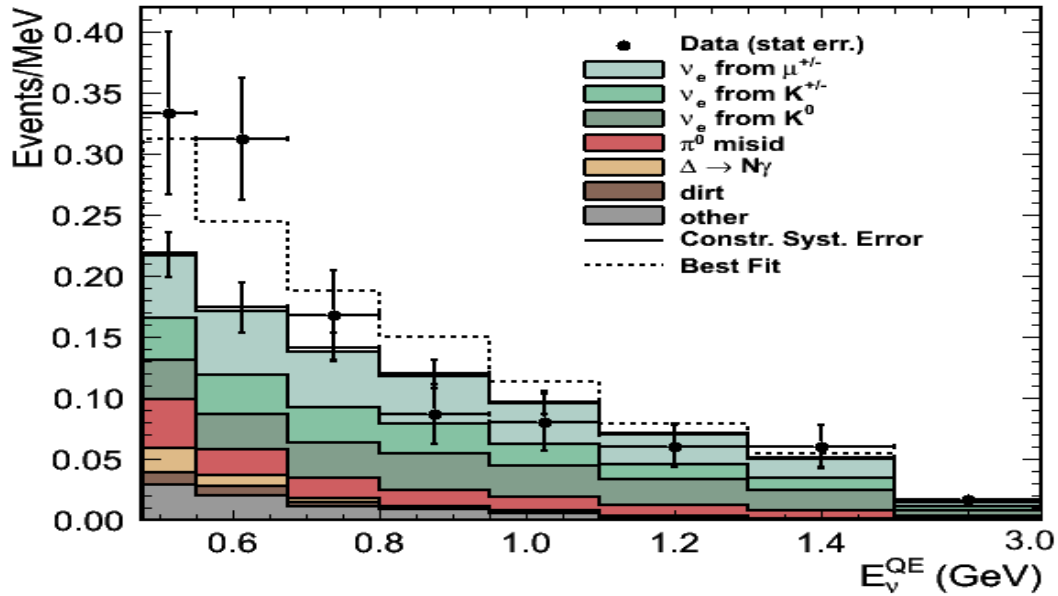
Comparison to LSND's best fit prediction and neutrino low energy expectation

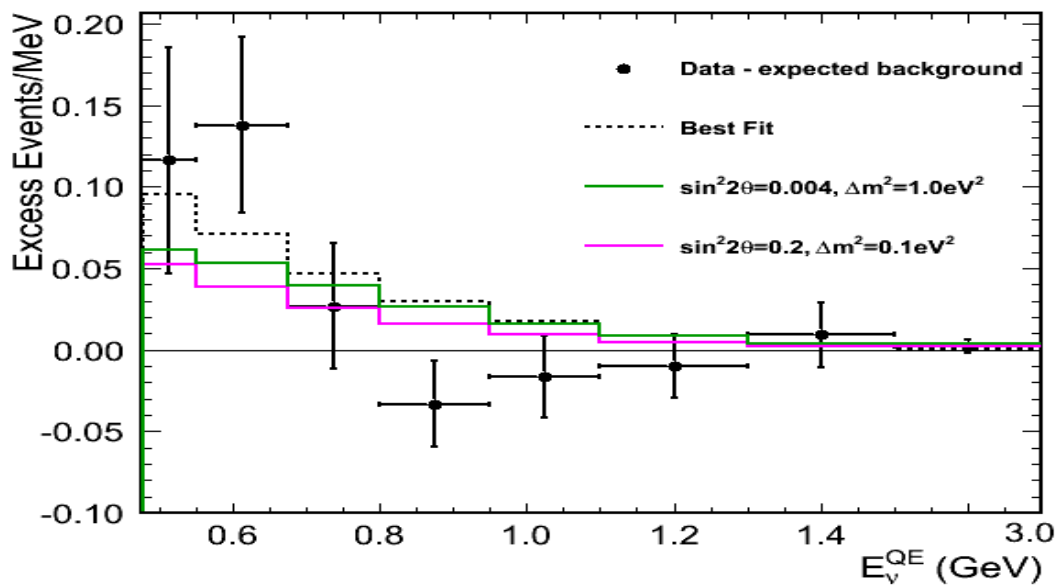
	E_ν(QE) [MeV]		
	200-475	475-1250	1250-3000
MC Background	100.5	99.1	34.2
Data	119	120	38
Excess	18.5 ± 14.3	20.9 ± 13.9	3.8 ± 5.8
LSND Best Fit	7.6	22.0	3.5
Expectation from ν low-E excess	11.6	0	0
LSND + Low-E	19.2	22.0	3.5

- 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.

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

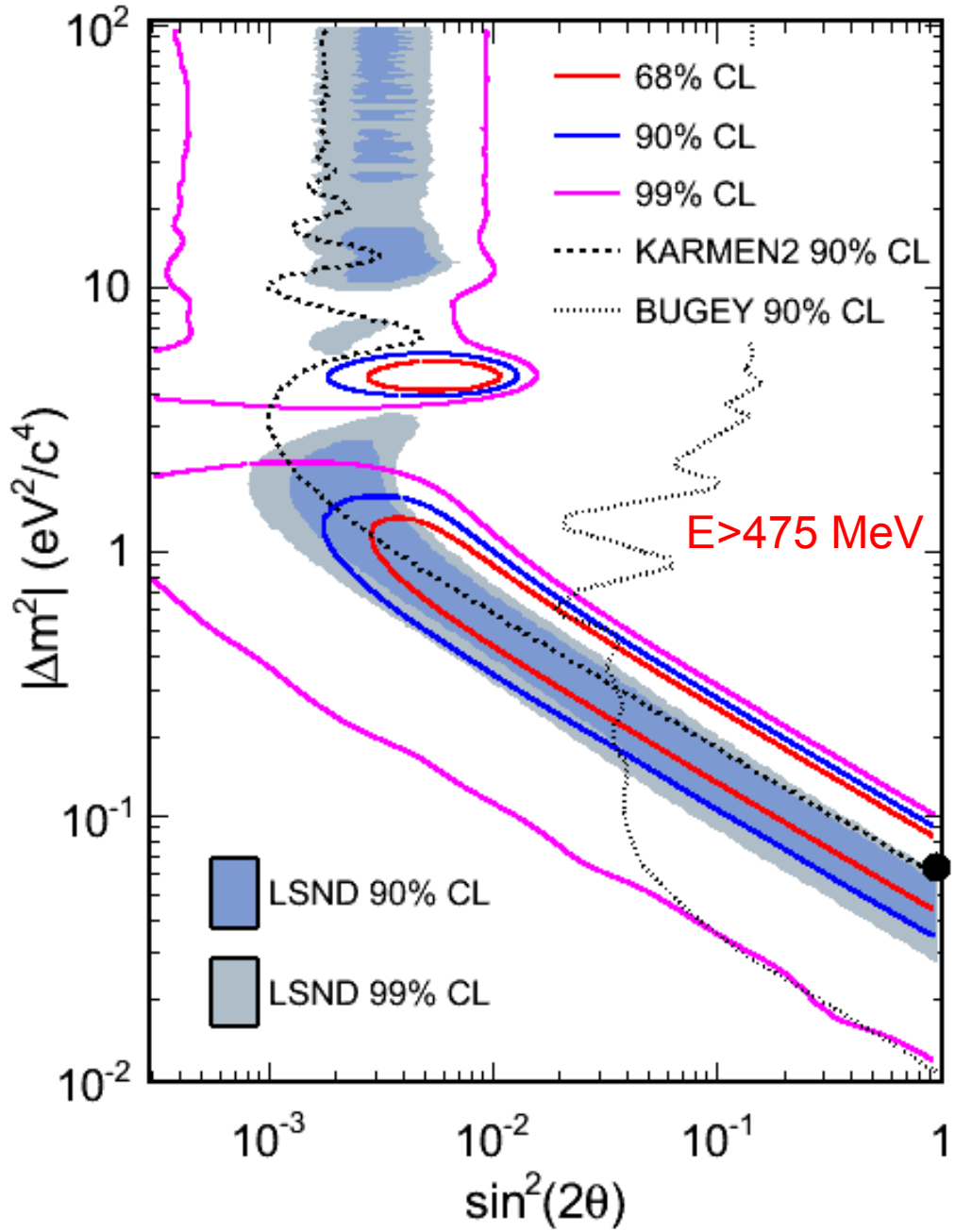
- Results for 5.66E20 POT.
- Maximum likelihood fit.
- Only antineutrinos allowed to oscillate.
- E > 475 MeV region is free of effects of low energy neutrino excess. This is the same official oscillation region as in neutrino mode.
- Accepted by PRL (arXiv: 1007.5510)





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

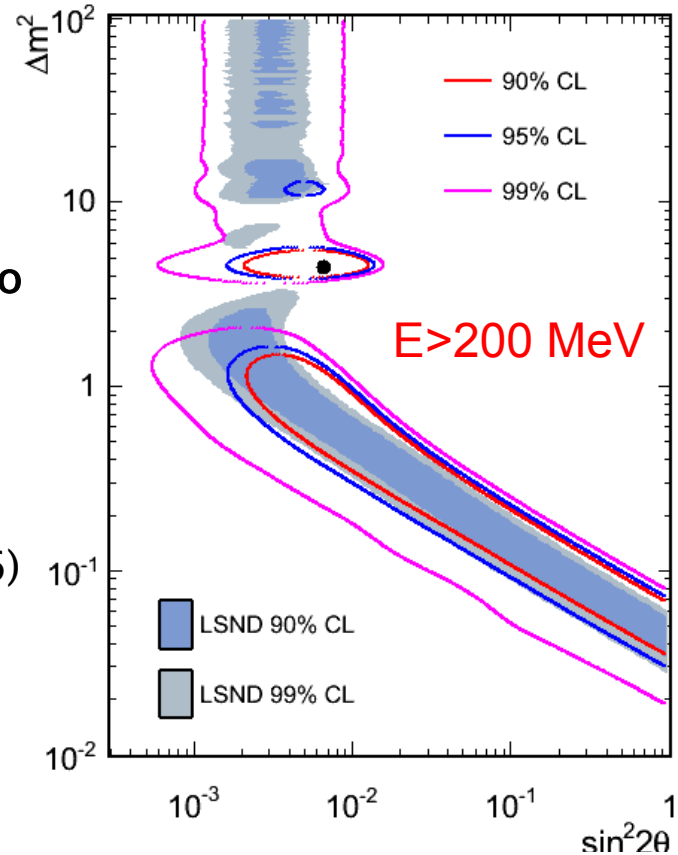
- Results for 5.66E20 POT
- Maximum likelihood fit.
- Null excluded at 99.4% with respect to the two neutrino oscillation fit (2.7σ).
- Best Fit Point
  (Δm^2, $\sin^2 2\theta$) =
  (0.064 eV^2, 0.96)
  $P(\chi^2)$= 8.7%
- Accepted by PRL (arXiv: 1007.5510)

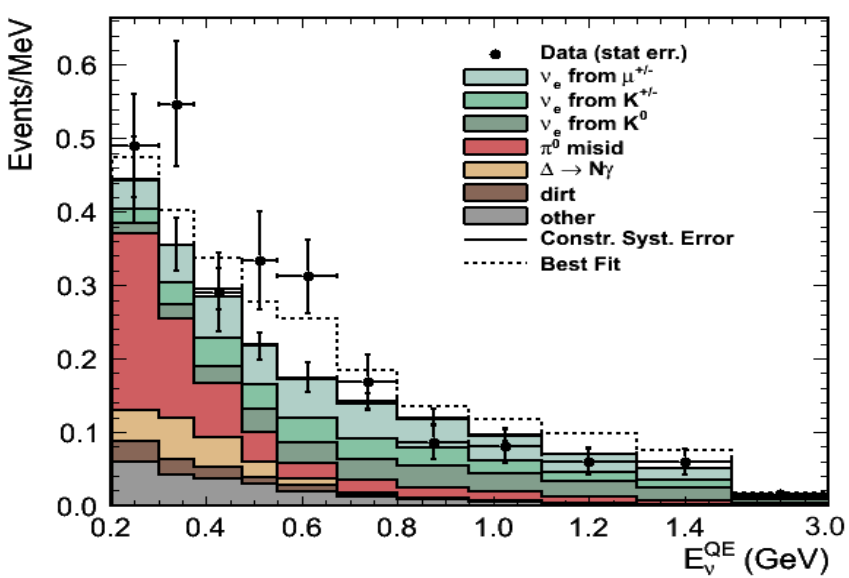


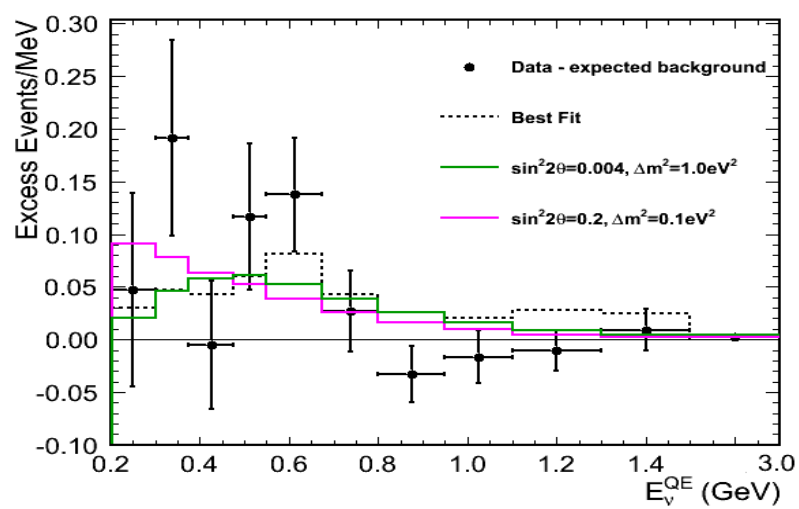
Is Best fit point really excluded by BUGEY?

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 eV^2, 0.0066) $P(\chi 2)$= 10.9%.

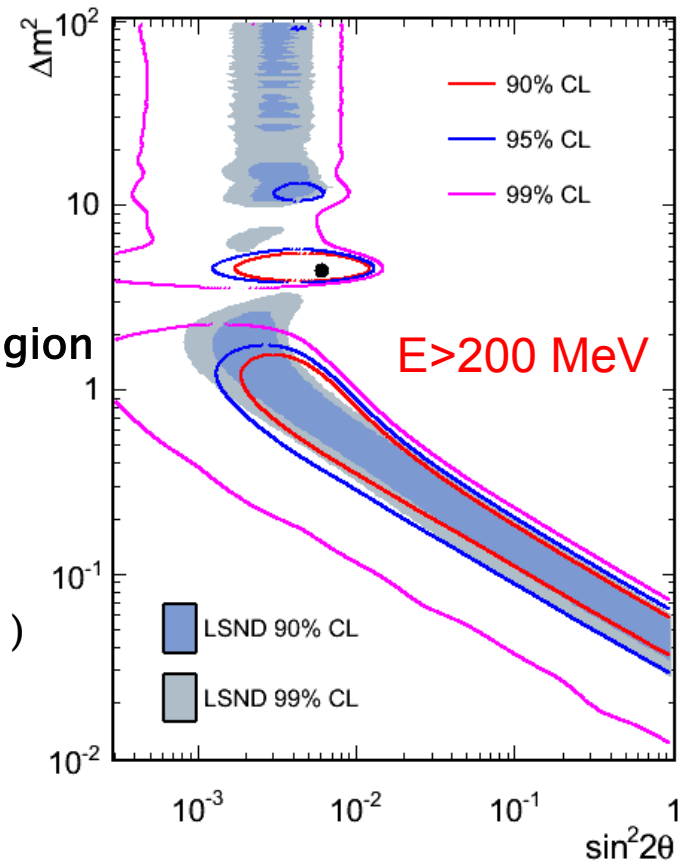


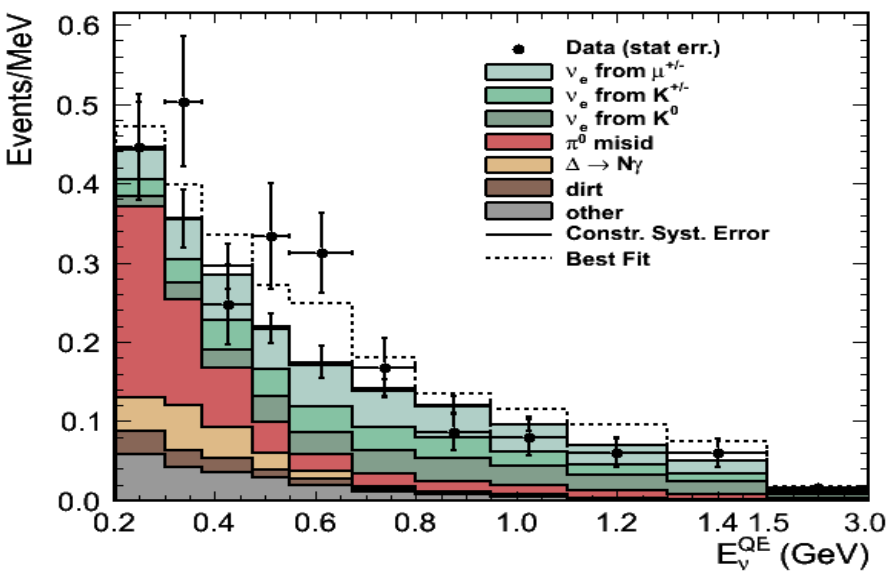


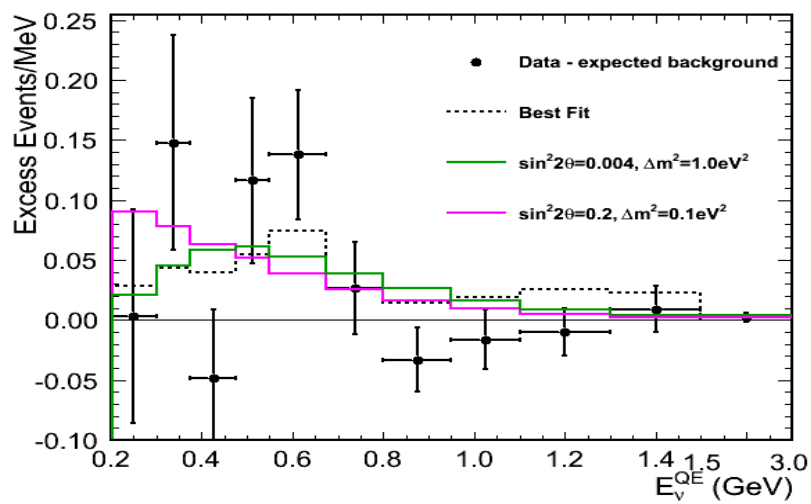


New Antineutrino mode MB results for E>200 MeV: Subtract low E Effects

- 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, 0.0061) $P(\chi 2)$= 7.5%.







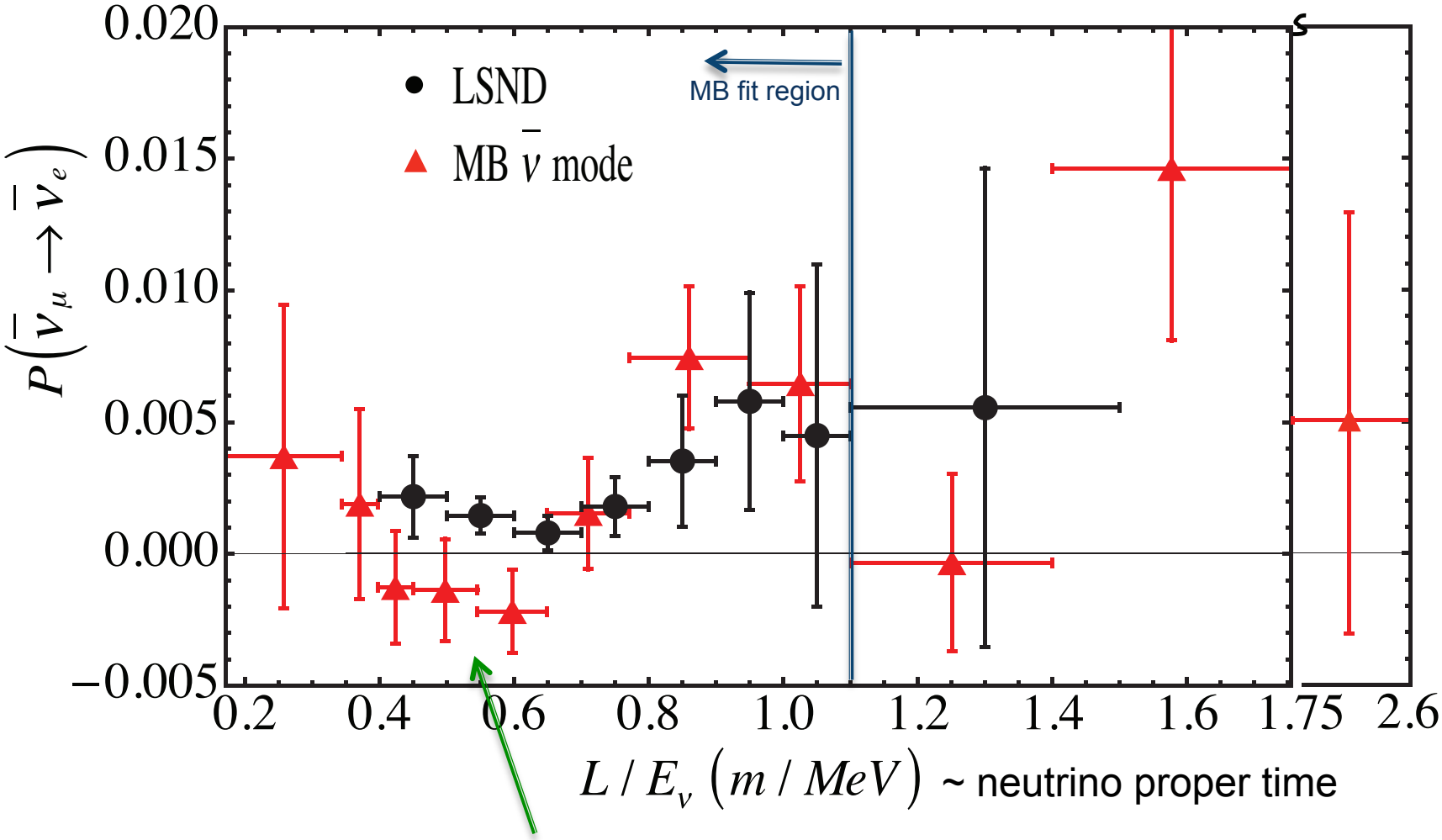
Other Interpretations

Model Independent Views of Oscillations

- *The next graph show P(osc) vs L/E:*

$$P(\alpha \rightarrow \beta) \equiv \frac{\text{observed event excess}}{\text{number expected for full transmutation of } \nu_\mu \text{ or } \bar{\nu}_\mu}$$

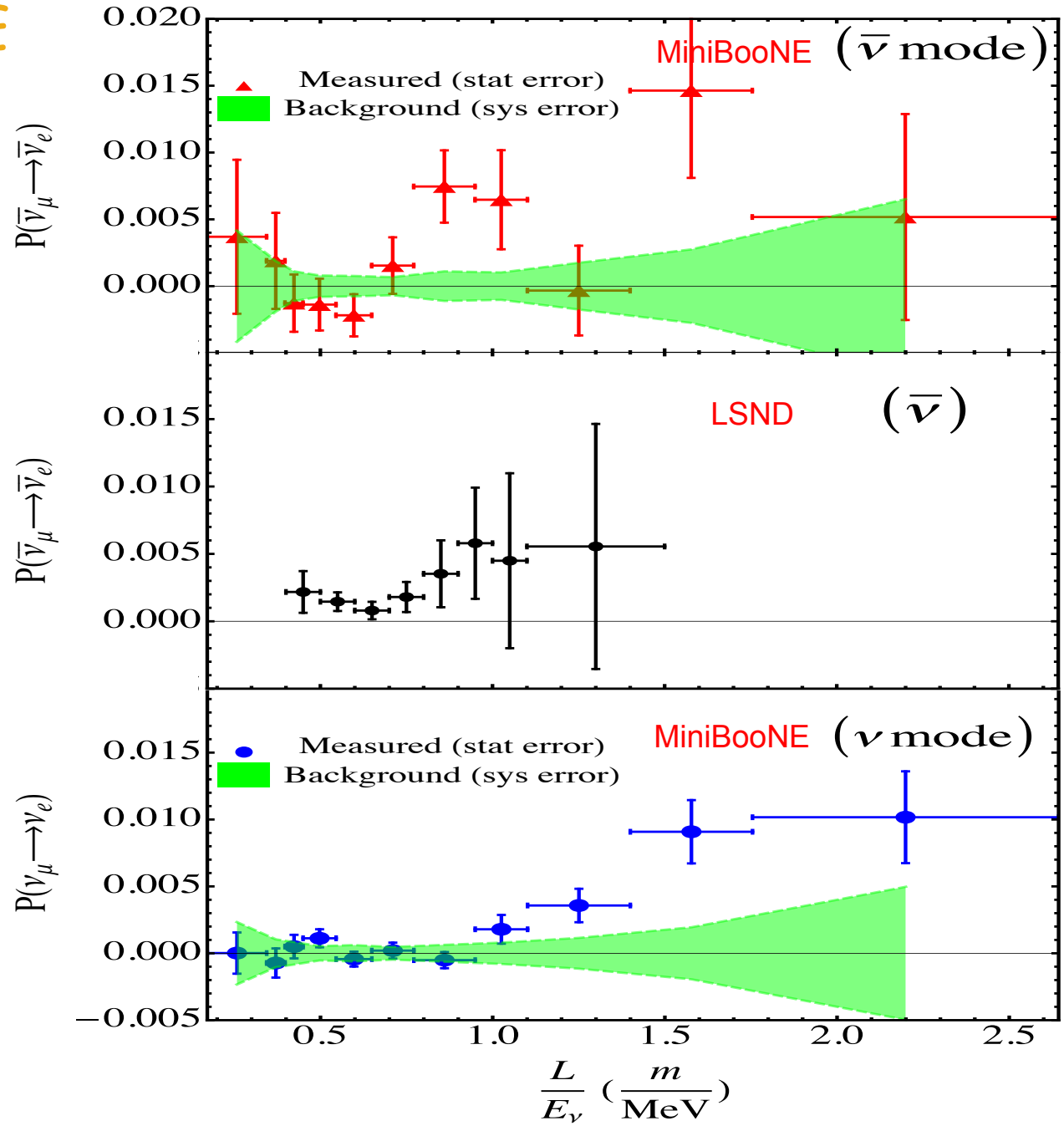
LSND and MiniBooNE Oscillation Probability Direct Data Comparison



KARMEN reported no signal around L/E ~ 0.5

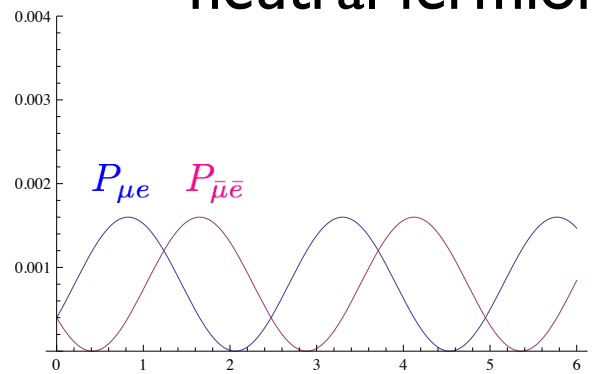
Data plotted vs L/E

New!
5.66E20 POT



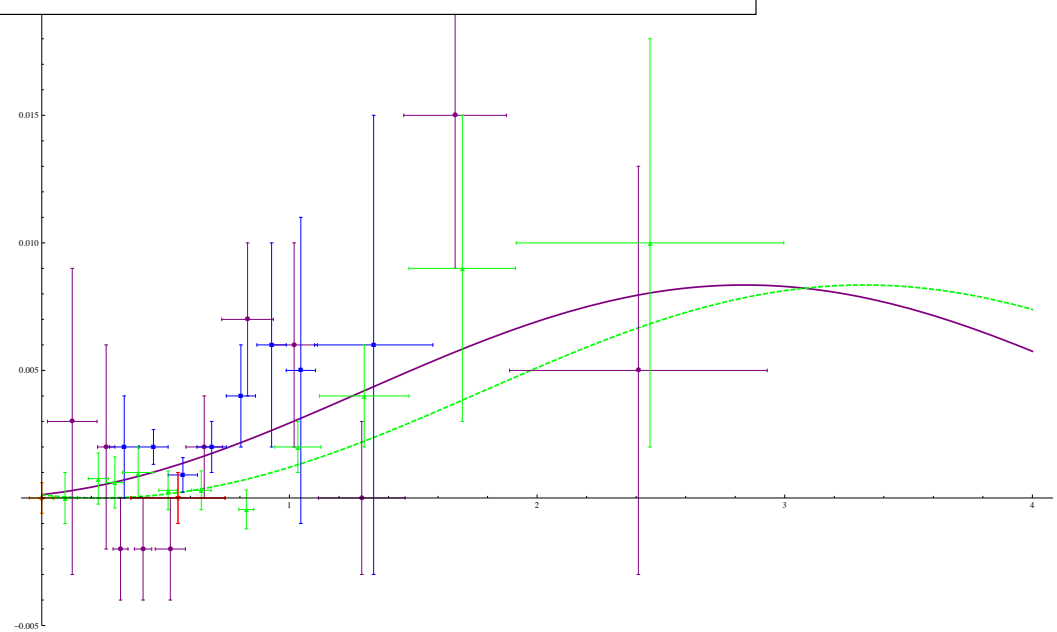
Theorist Busy Playing with the Data!

3+1 neutrinos + 1 heavy neutral fermion



note oscillation prob can reach 0, but not at L/E=0 with CPV

$m_4^2 - m_1^2 = 1\ eV^2 \quad m_5^2 \gg 10^{10} eV^2 \quad \delta_{CPV} = -2.1 \quad |U_{e4}U_{\mu 4}| = |U_{e5}U_{\mu 5}| = .02$



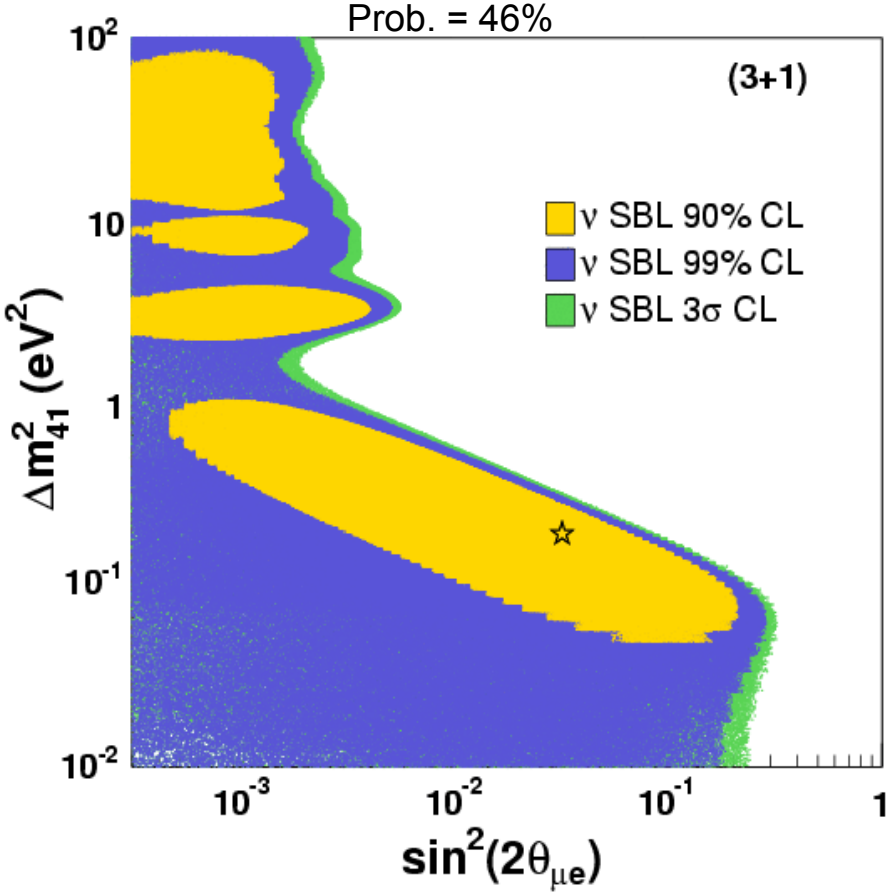
Ann Nelson, University of Washington, INT 2010 Talk

Separate 3+1 Global Fit to World Antineutrino Data (G. Karagiorgi et al., arXiv:0906.1997)

Do not assume CP/CPT conservation, i.e. perform separate neutrino and antineutrino fits

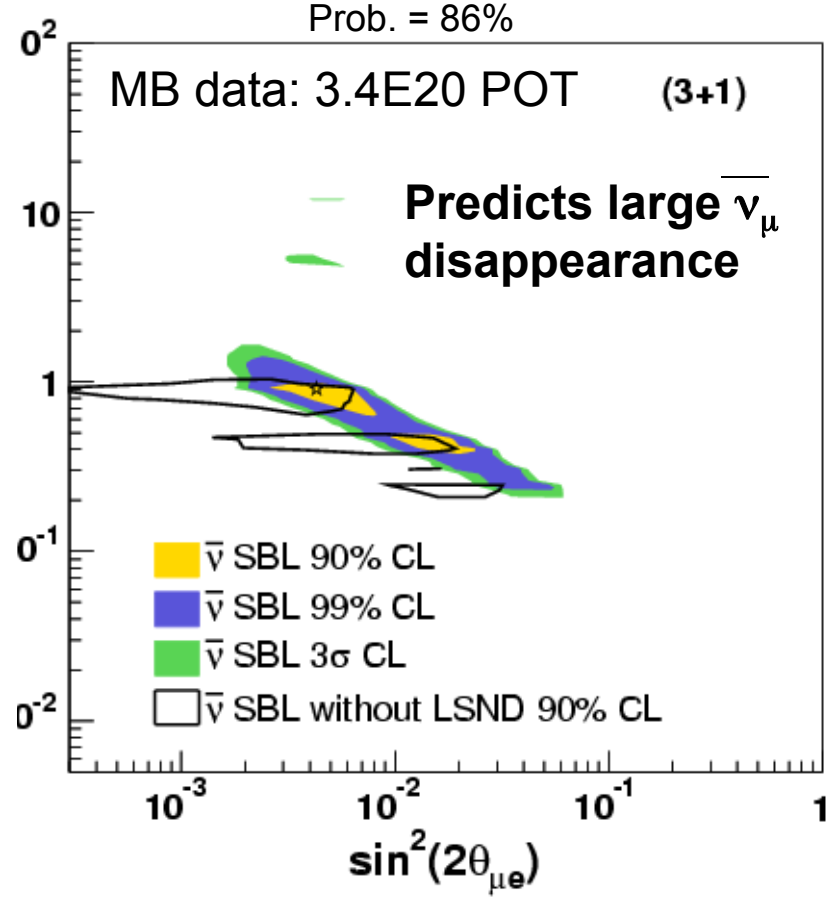
Neutrino

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%



Antineutrino

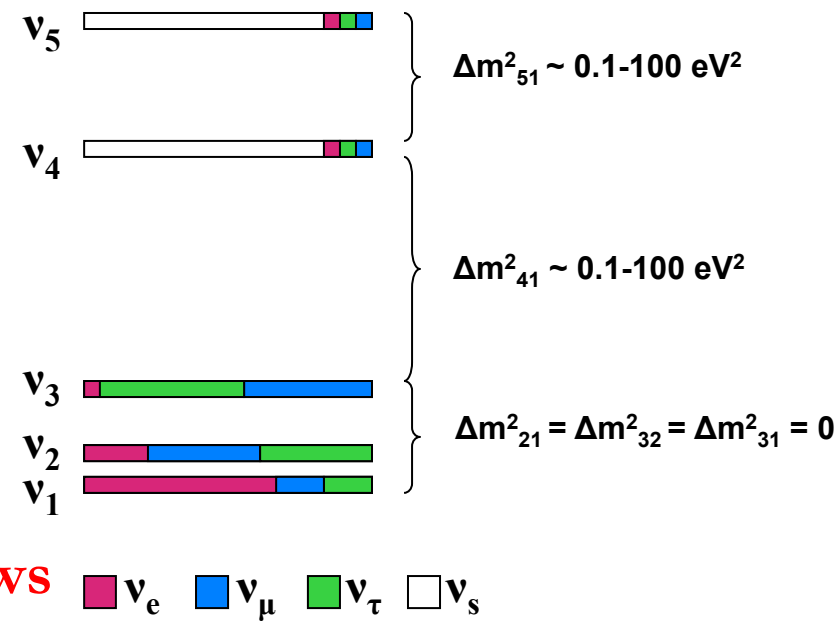
Best 3+1 Fit:
$\Delta m_{41}^2 = 0.915\ eV^2$
$\sin^2 2\theta_{\mu e} = 0.0043$
$\chi^2 = 87.9/103$ DOF
Prob. = 86%



With new MB data, fit to world antineutrino data will be over 5σ !
Will test $\bar{\nu}_\mu$ disappearance with SB/MB data (results soon).

LSND interpretation: More complicated Oscillations (3+2)

- **Sterile neutrino models**
  - 3+2 → next minimal extension to 3+1 models



2 independent Δm^2

4 mixing parameters

1 Dirac CP phase which allows difference between neutrinos and antineutrinos

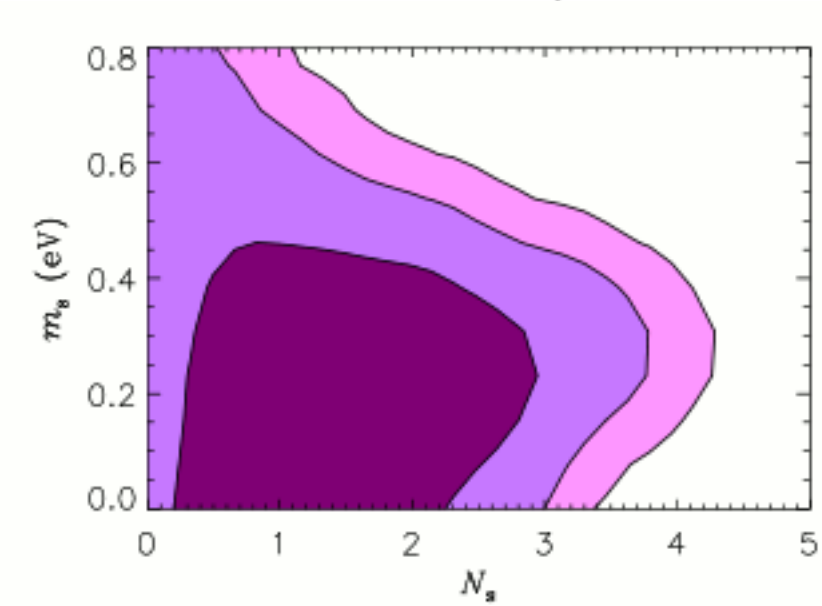
Oscillation probability:

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) = 4|U_{\mu 4}|^2|U_{e4}|^2 \sin^2 x_{41} + 4|U_{\mu 5}|^2|U_{e5}|^2 \sin^2 x_{51} +$$

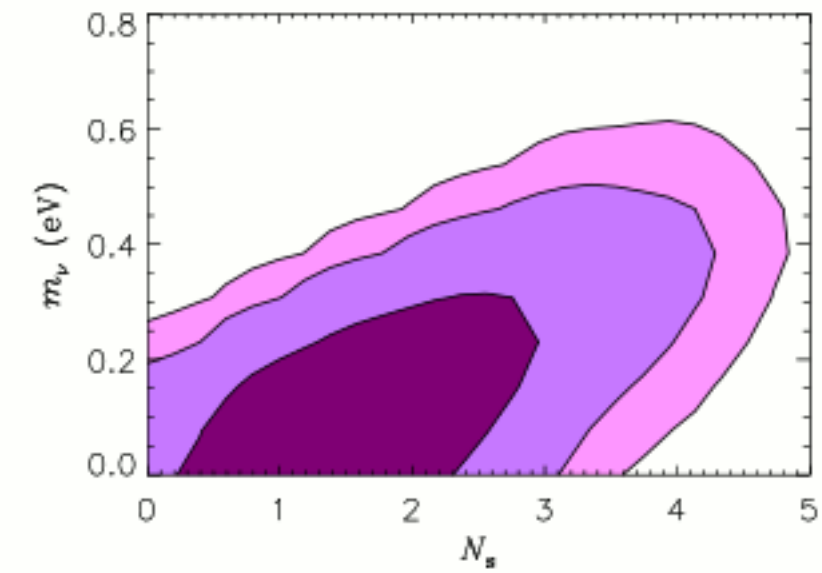
$$+ 8\,|U_{\mu 5}||U_{e5}||U_{\mu 4}||U_{e4}| \sin x_{41} \sin x_{51} \cos(x_{54} \pm \varphi_{45})$$

Recent Cosmology Fits for Sterile Neutrinos

(J. Hamann, et. al. arXiv:1006.5276)



$3 + N_s$
$m_\nu = 0$



$N_s + 3$
$m_s = 0$

Summary and Future Experiments

MiniBooNE Oscillation Summary:

- The MiniBooNE ν_e and $\bar{\nu}_e$ appearance picture starting to emerge is the following:

  1) **Neutrino Mode**:

     a) $E < 475$ MeV: An unexplained 3σ (~6σ statistical) electron-like excess.

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

  Need near detector to reduce systematic errors.

  2) **Anti-neutrino Mode**:

     a) $E < 475$ MeV: A small 1.3σ electron-like excess.

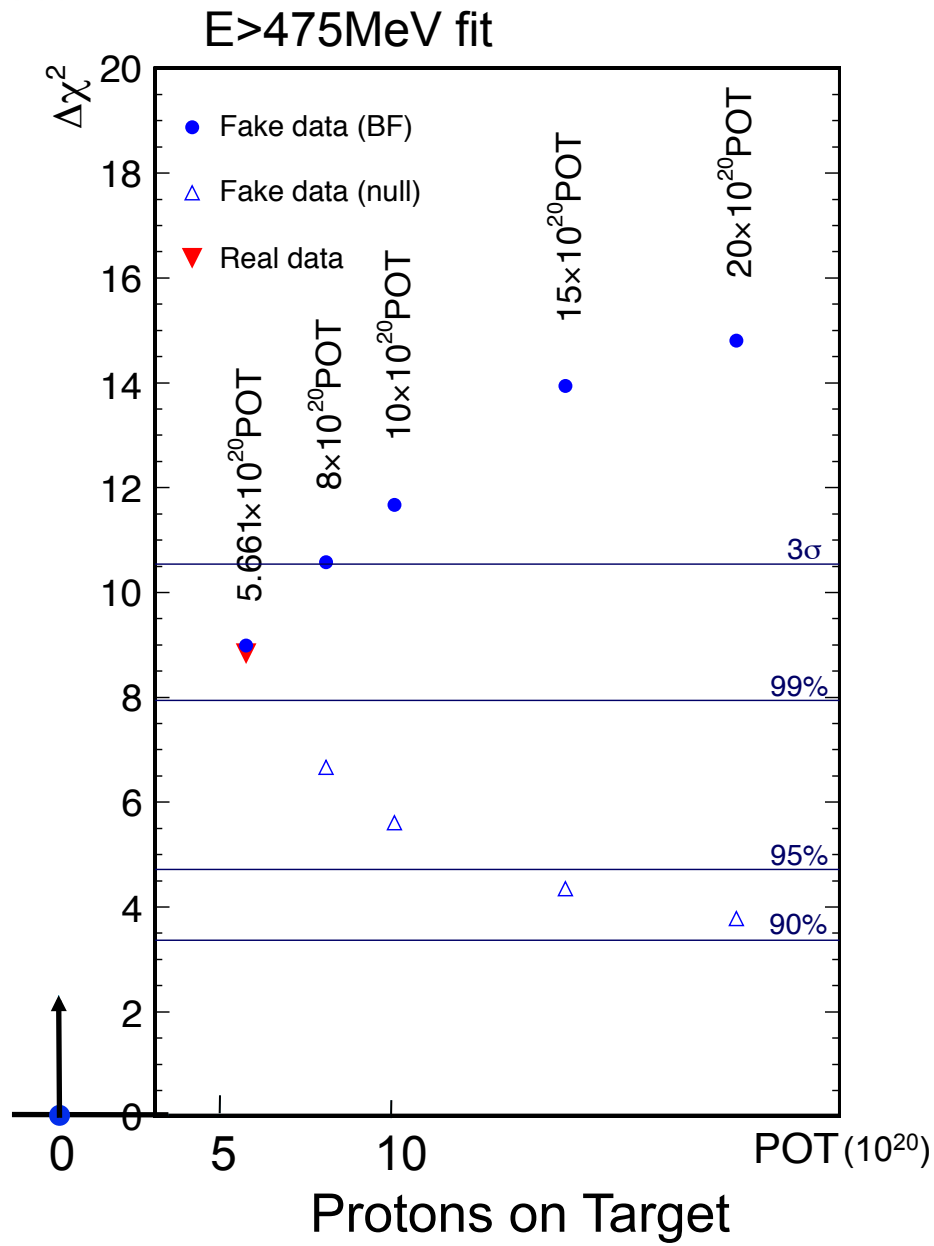
     b) $E > 475$ MeV: Two neutrino oscillation fits consistent with LSND at 99.4% (2.7σ) C.L. relative to null.

  Need more statistics!

Future sensitivity in $\bar{\nu}$ Data

- MiniBooNE approved for a total of 1×10^{21} POT
- Potential 3σ exclusion of null point assuming best fit signal
- Writing request for 1.5×10^{21} POT.

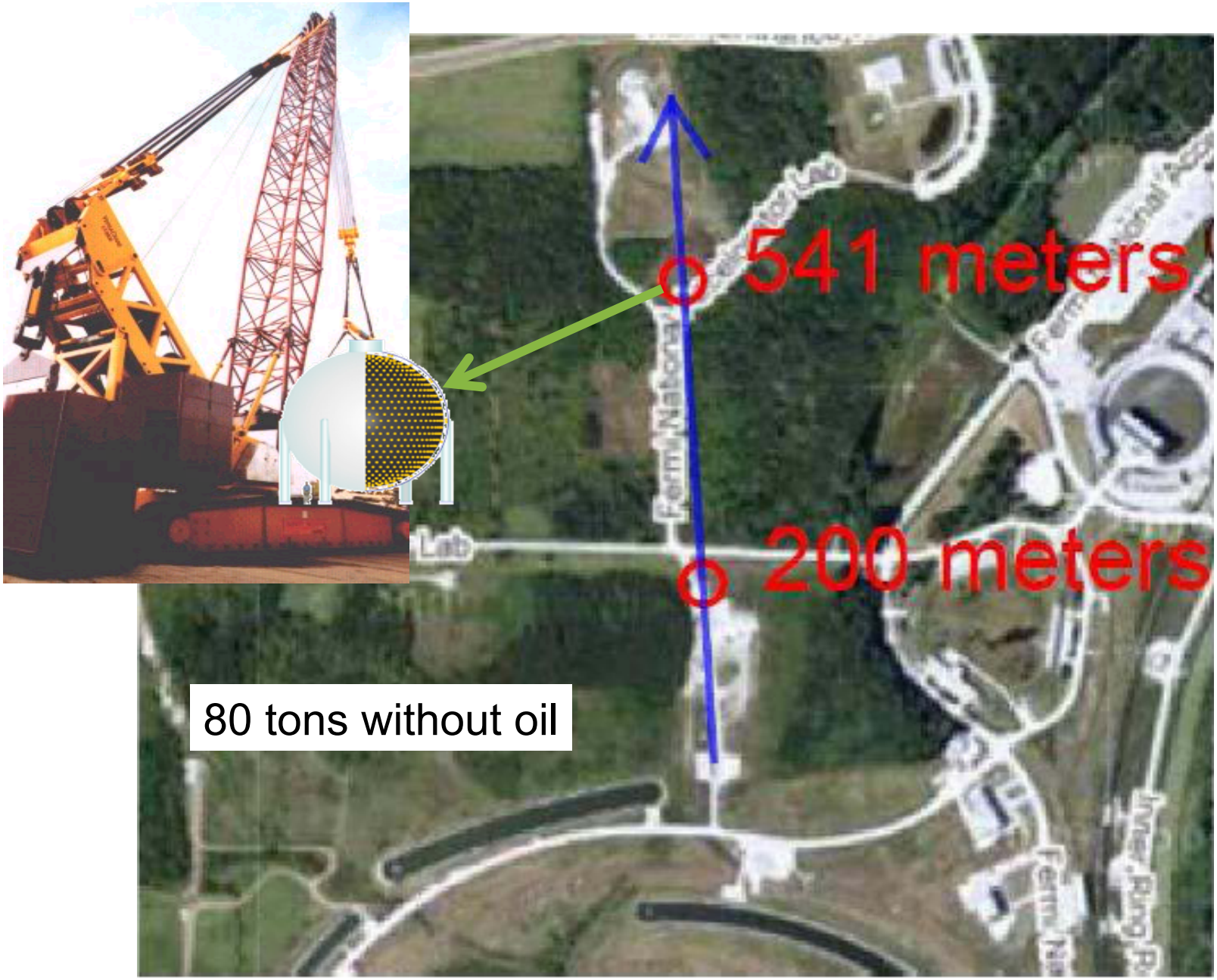
Limited by Statistics!!



Resolving MiniBooNE & LSND

- More Anti-neutrino running! (1.5×10^{21} pot?)
- Moving (or building) the MiniBooNE detector to (at) 200m
  - Letter of Intent: arXiv:0910.2698
  - Accumulate a sufficient data sample in < 1 year
  - will dramatically reduce systematic errors (low energy excess is ~ 6 sigma significance with statistical errors only.
- MicroBooNE:
  - is a 70 ton liquid argon time projection chamber in the Fermilab BNB
  - can differentiate single gamma-rays from electrons.
- CERN: ICARUS @PS
  - Liquid argon TPC detectors discussed in arXiv:0909.0355v3
  - **600T** Far detector exists @ Grand Sasso, ~ 100 T near detector needed
  - Use old PS neutrino beam line and CDHS Hall
- Direct Test of LSND:
  - A "LSND"-like detector at the SNS (OscSNS)

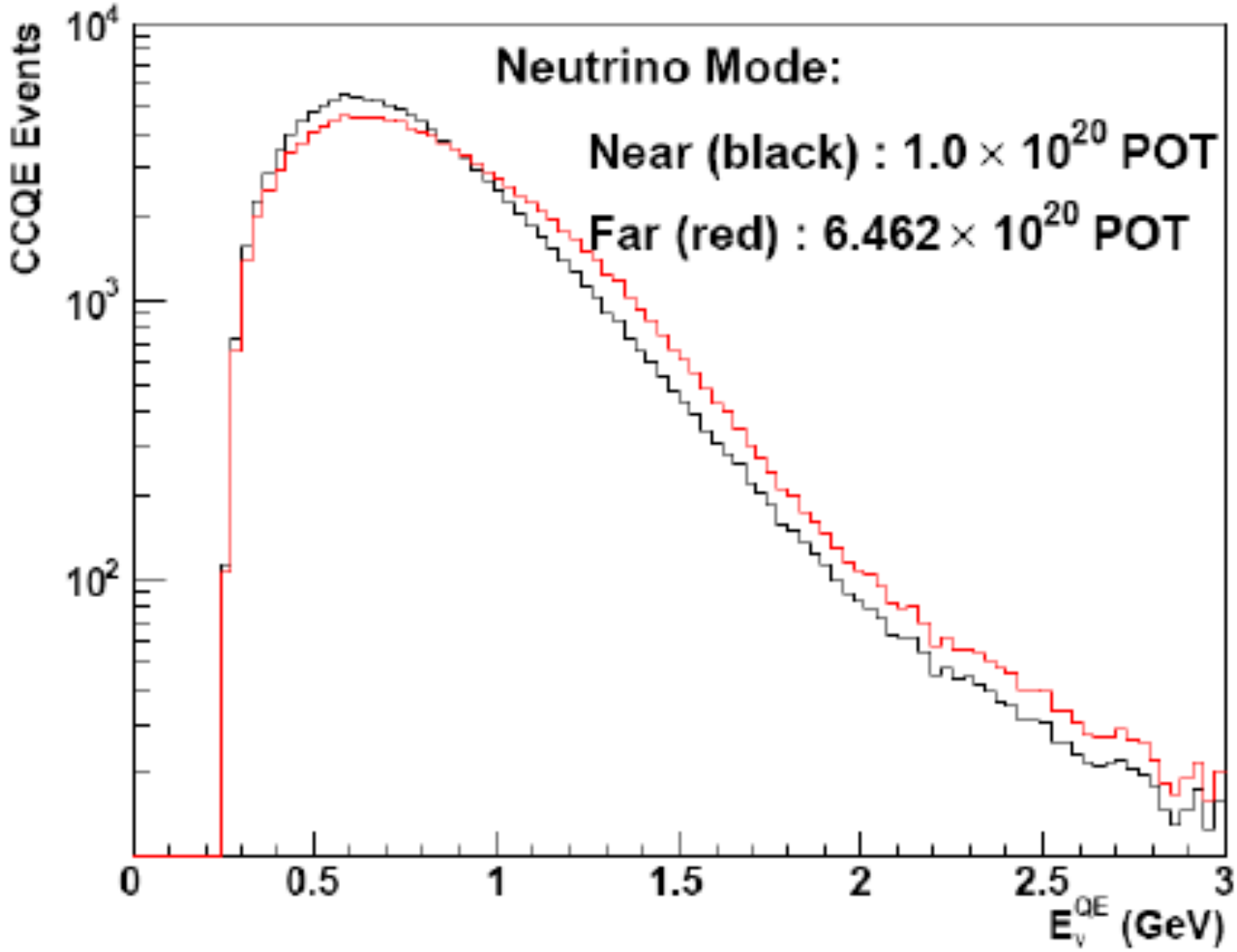
New Location at 200 meters from BNB Target



New Location at 200 meters from BNB Target

New Location at 200 meters from BNB Target

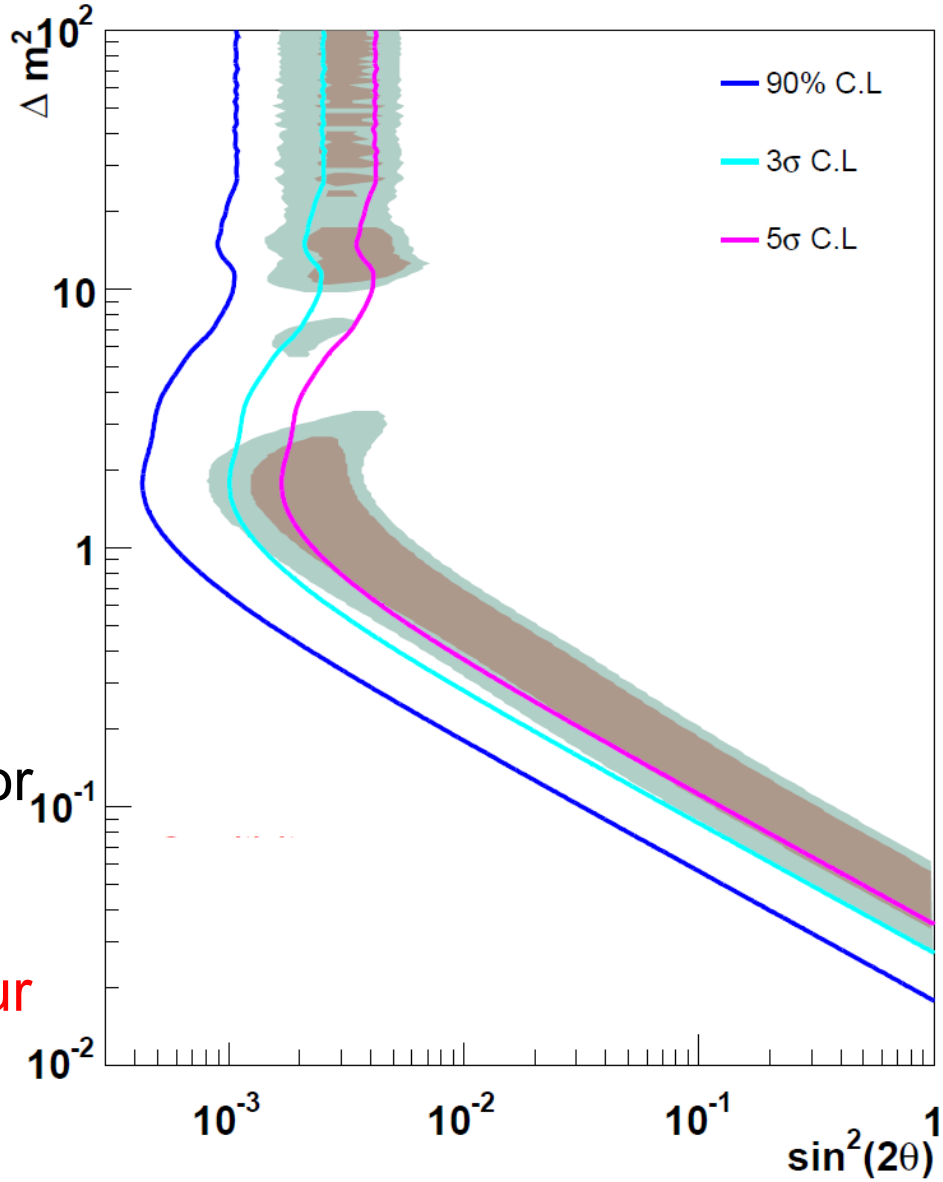
ν_μ Charged Current Event Rates Near and Far



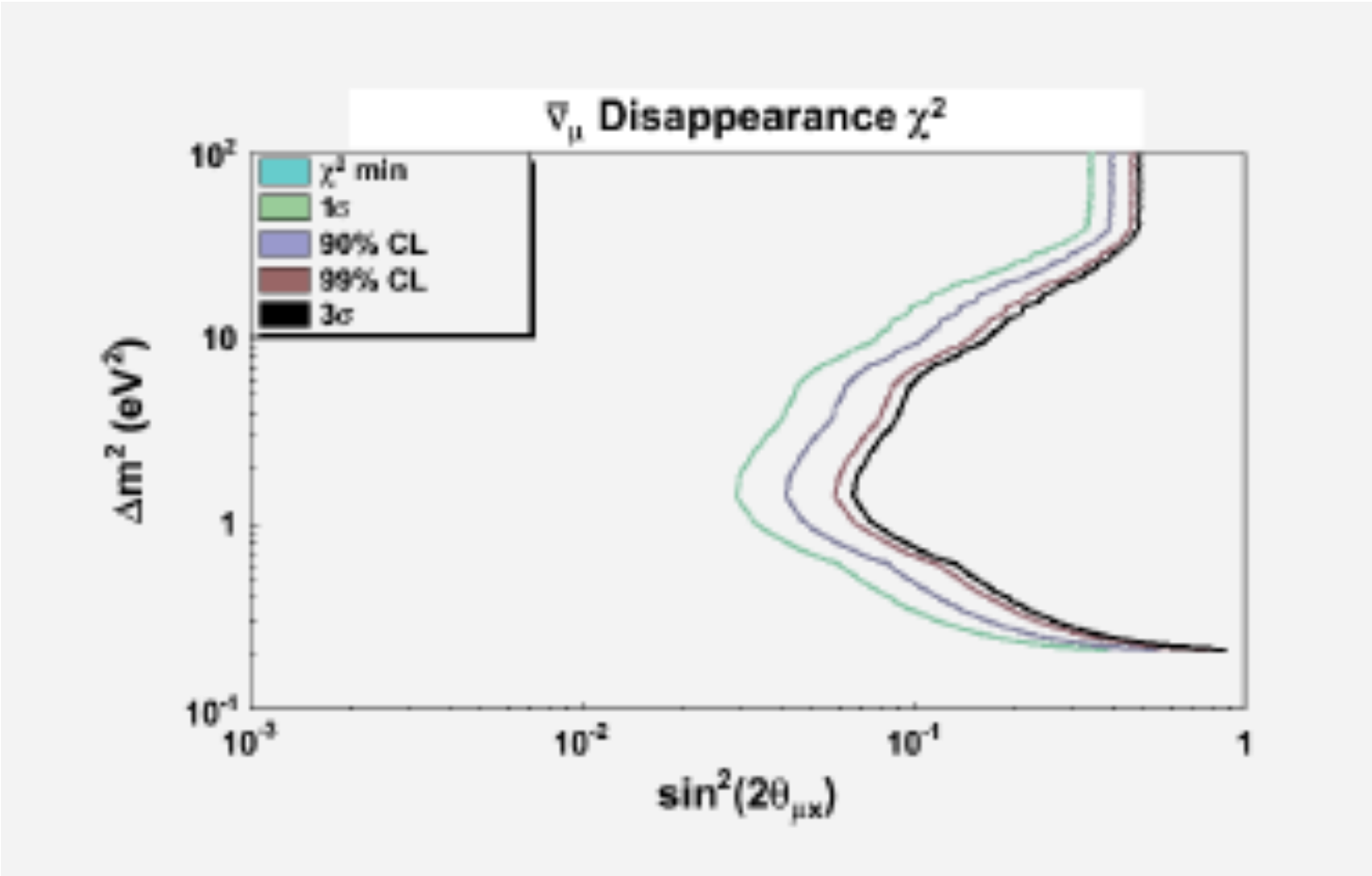
Quasi elastic event rates

Sensitivity with Near/Far Comparison (neutrino mode)

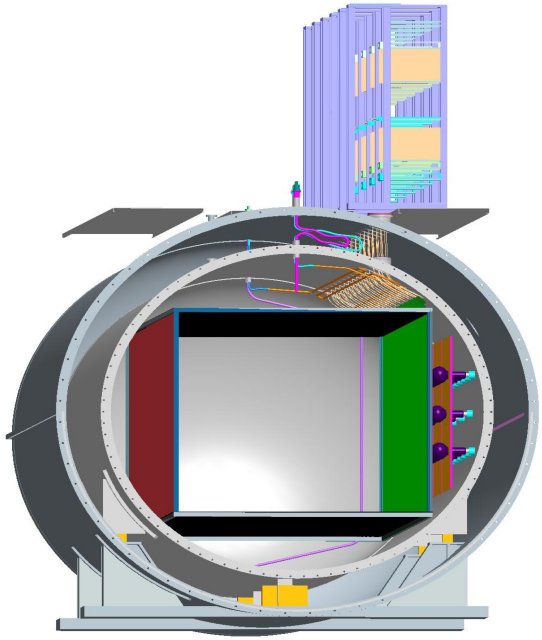
- Near/Far comparison sensitivity
  - ➢Near location at 200 meter
    - ✓ 1×10^{20} pot ~1 yr of running
  - ➢Full systematic error analysis
    - ✓Flux, cross section, detector response
  - ➢ 90%CL becomes ~ 4 σ contour



Antineutrino Disappearance Sensitivity with Detector at 200 Meters



MicroBooNE

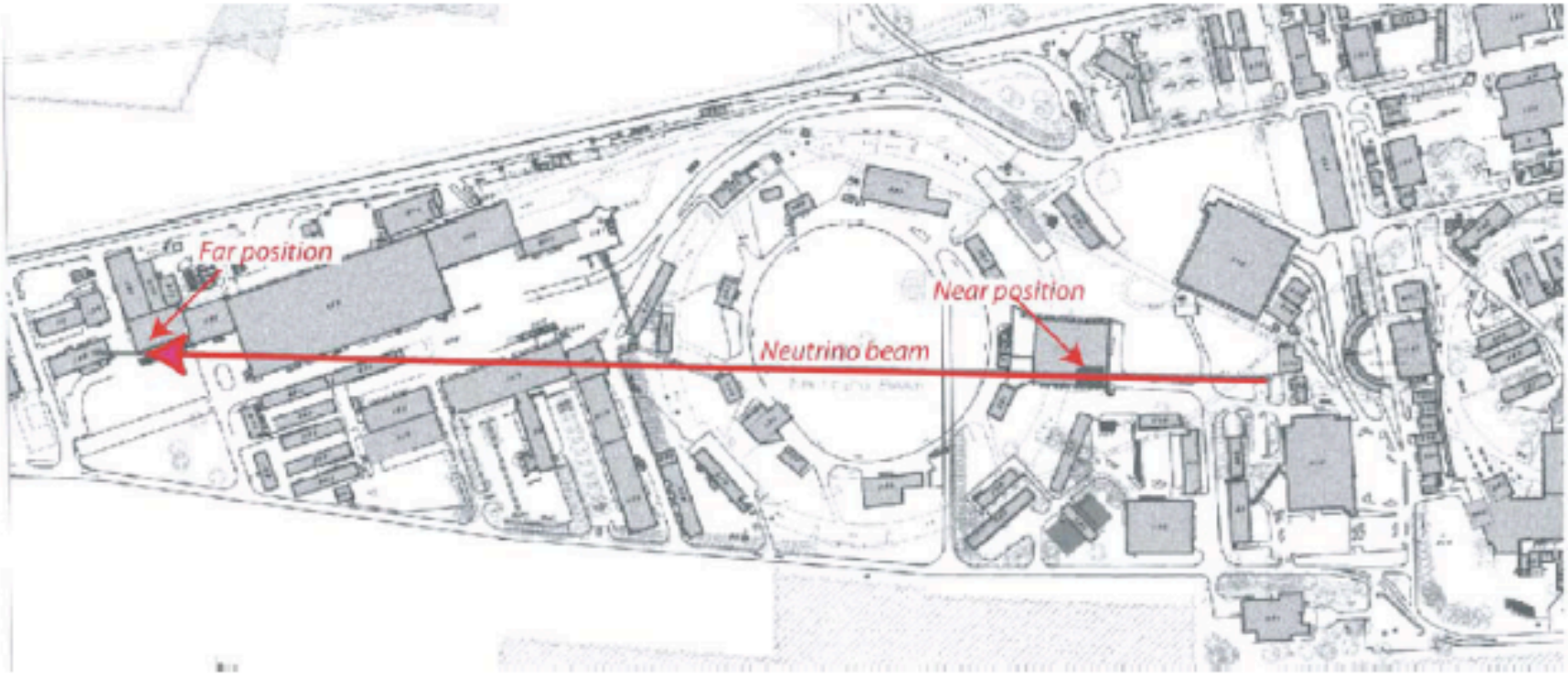


- 70 tons Liquid Argon TPC
- Good photon-electron separation
- Similar sensitivity to MiniBooNE in neutrino mode.
- Would require ~ >3 years of running, too small to address signal in antineutrino mode.

ICARUS @PS

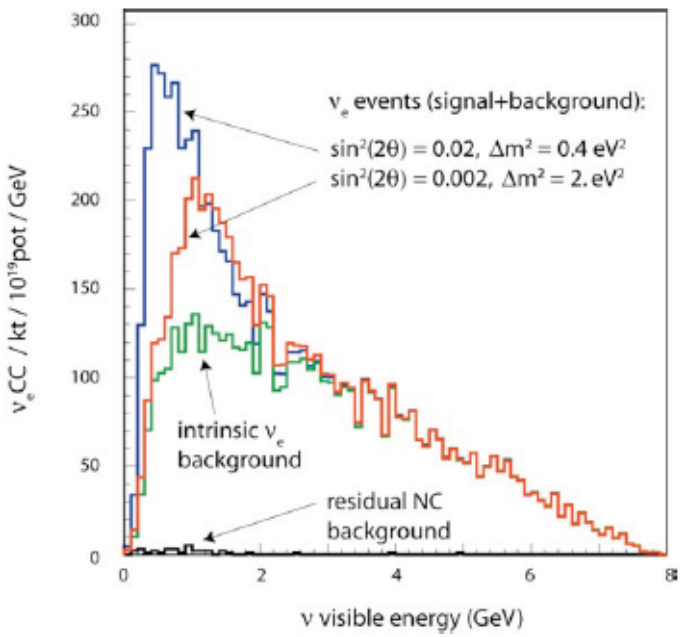
A new search for anomalous neutrino oscillations at the CERN-PS

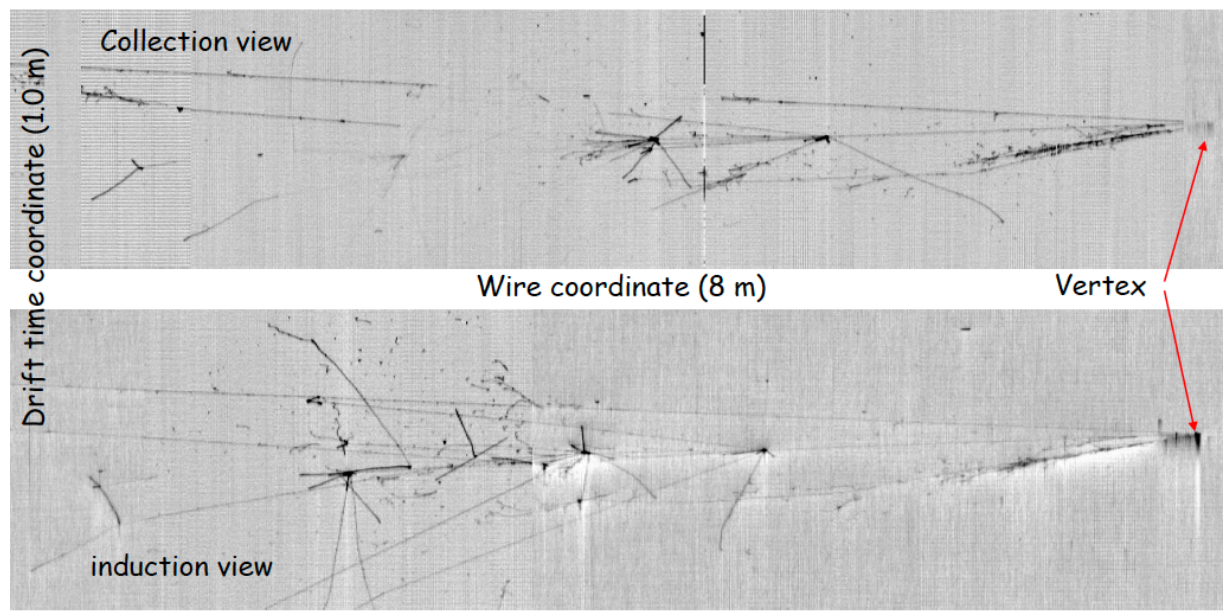
B. Baibussinov[a], E. Calligarich[b] S. Centro[a], D. Gibin[a], A. Guglielmi[a], F. Pietropaolo[a], C. Rubbia[c,*] and P. Sala[d]



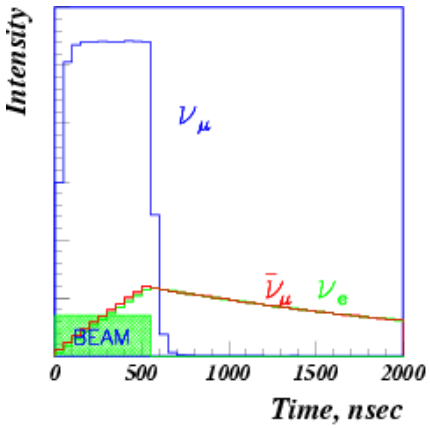
ICARUS @PS

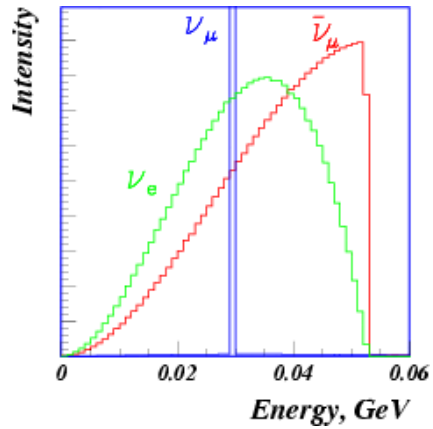
- Powerful event identification (only intrinsic ν_e background)
- 600 ton far detector @ 850 m (exists already!)
- ~ 127 ton near detector (needs to be constructed)





OscSNS at ORNL: A Smoking Gun Measurement of Active-Sterile Neutrino Oscillations





SNS: ~1 GeV, ~1.4 MW

ν_μ -> ν_e ; ν_e p -> e^+ n => re-measure LSND an order of magnitude better.

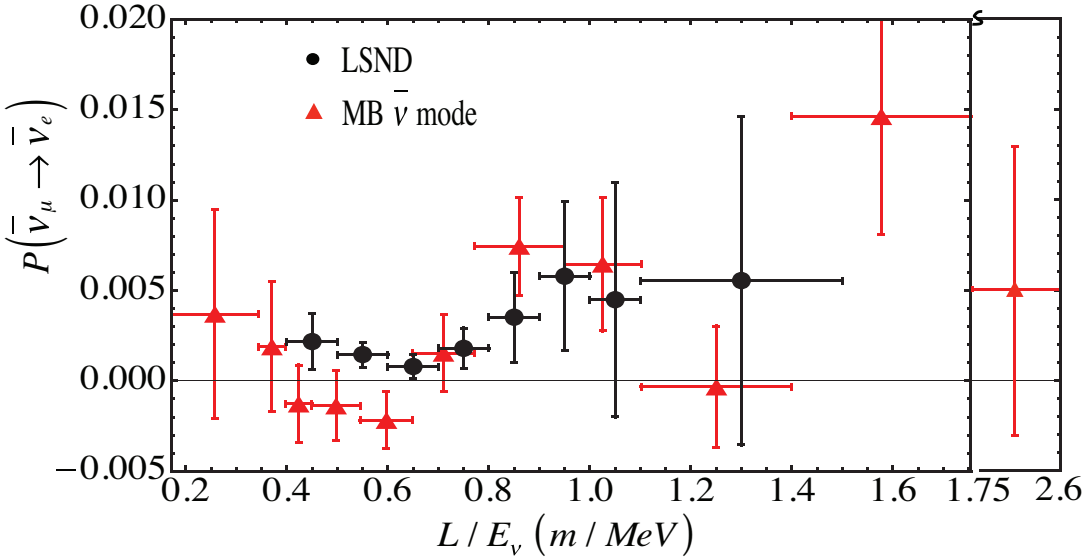
ν_μ -> ν_s ; **Monoenergetic ν_μ** ; ν_μ C -> ν_μ C*(15.11) => search for sterile ν

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.

Final Conclusions

Has MiniBooNE answered the question about the LSND Puzzle?

MAYBE: we are beginning to confirm the effect, i.e. two different experiments running at the same L/E see a similar oscillation probability pattern.



NO: we do not understand the underlying physics, i.e. does not appear to be simple two neutrino oscillations.
YES: We will need a new series of experiments to fully understand what is going on!

The LSND saga continues to evolve in ways we never anticipated.

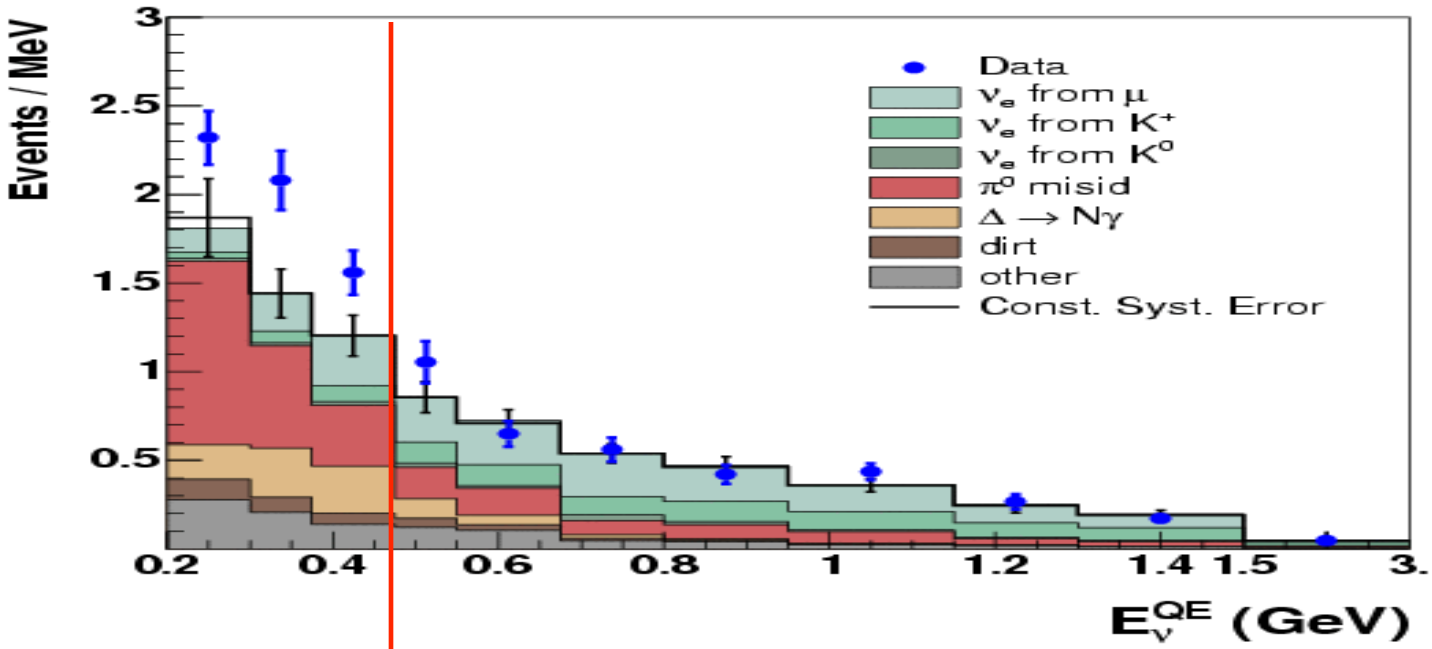
Long-Baseline News, May 2010:

" *** LSND effect rises from the dead… ?"

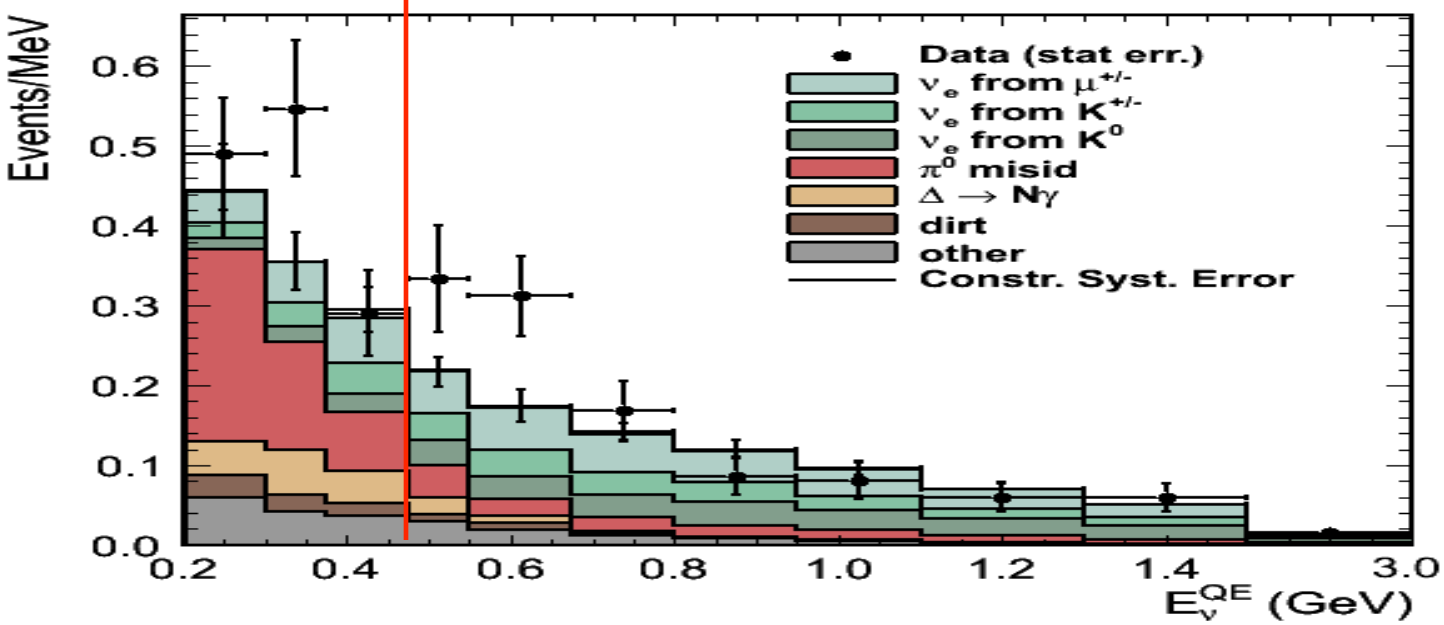
Slide by Geoff Mills, LANL

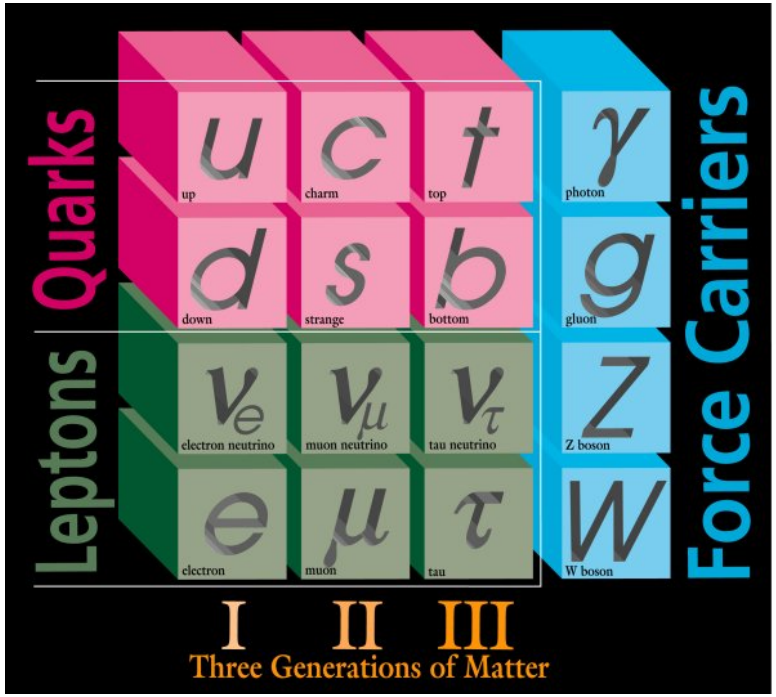
Backup Slides

Neutrino ν_e Appearance Results (6.5E20POT)



Antineutrino $\bar{\nu}_e$ Appearance Results (5.66E20POT)





ν's are special !

- Weakly interacting, hard to measure its properties
- Can mix with exotic neutral fermions
  - sterile neutrinos in oscillations
  - nonunitarity in mixing
  - exotic interactions in oscillations
- Can experience dark forces much more strongly than other particles
- neutrino oscillations phenomenally sensitive to wide variety of exotic, very weakly coupled physics

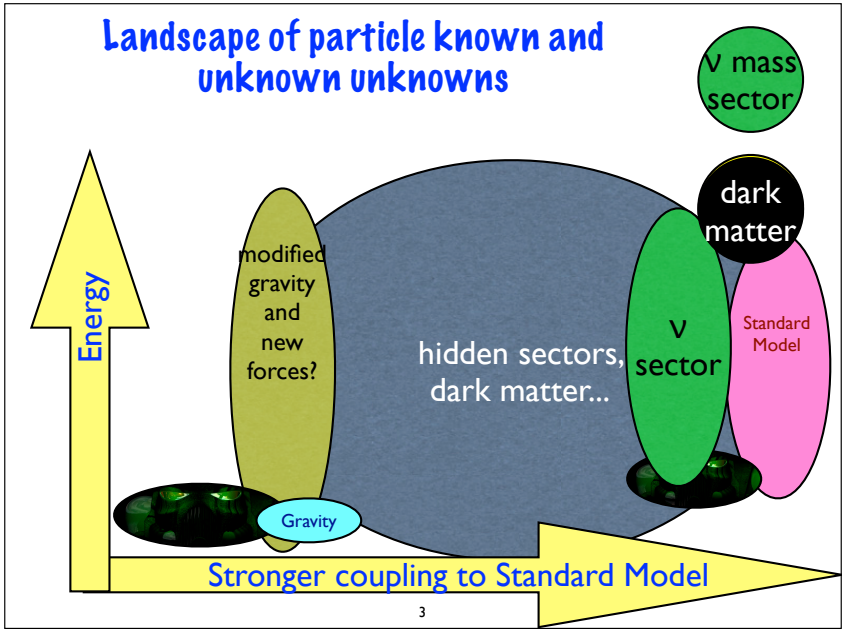


Figure from Ann Nelson, University of Washington, INT 2010 Talk