Short Baseline Neutrino Program
ICARUS and ICAR-US

Introduction
Motivation(musings on SBL data)
SBN and ICARUS

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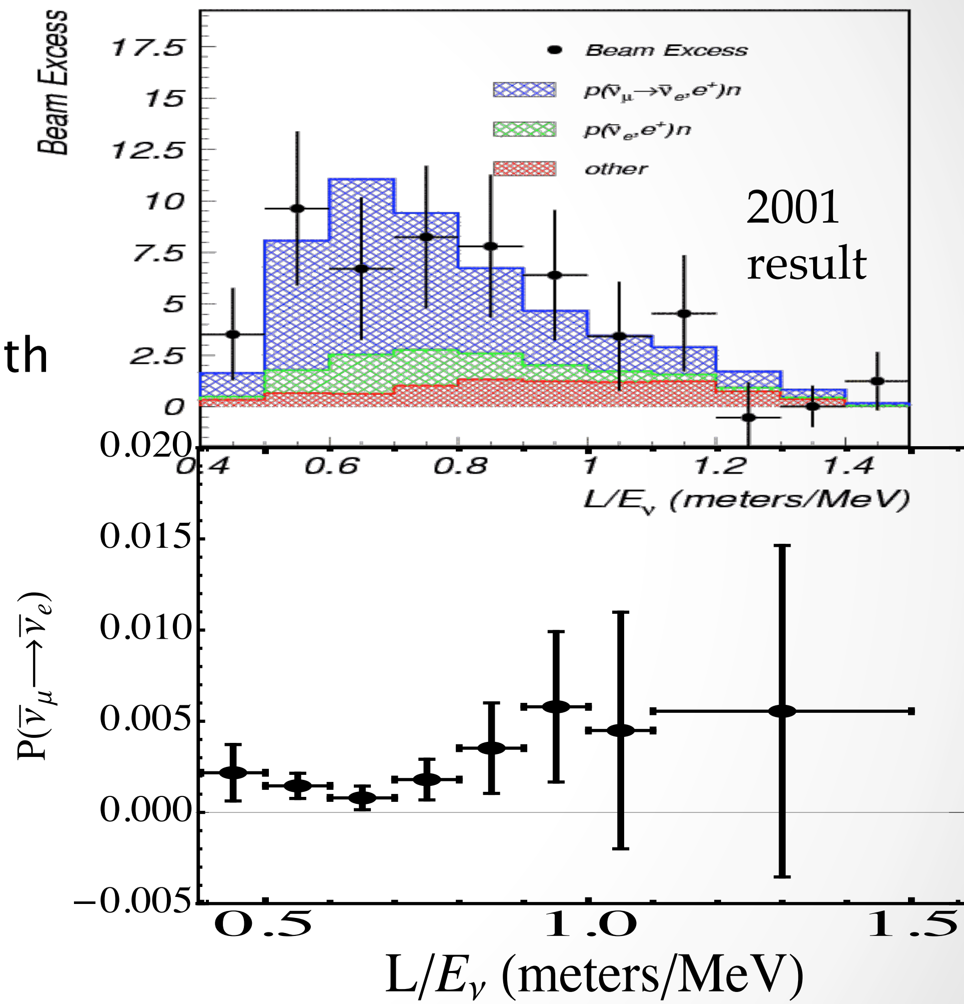
First LSND…

- Data runs 1993-1998
- LSND found an excess of ν_e in ν_μ beam
- Signature: Cerenkov light from e^+ with delayed n-capture (2.2 MeV)
- Excess: 87.9 ± 22.4 ± 6.0 (3.8s)
- *The data was analysed under a two neutrino mixing hypothesis**

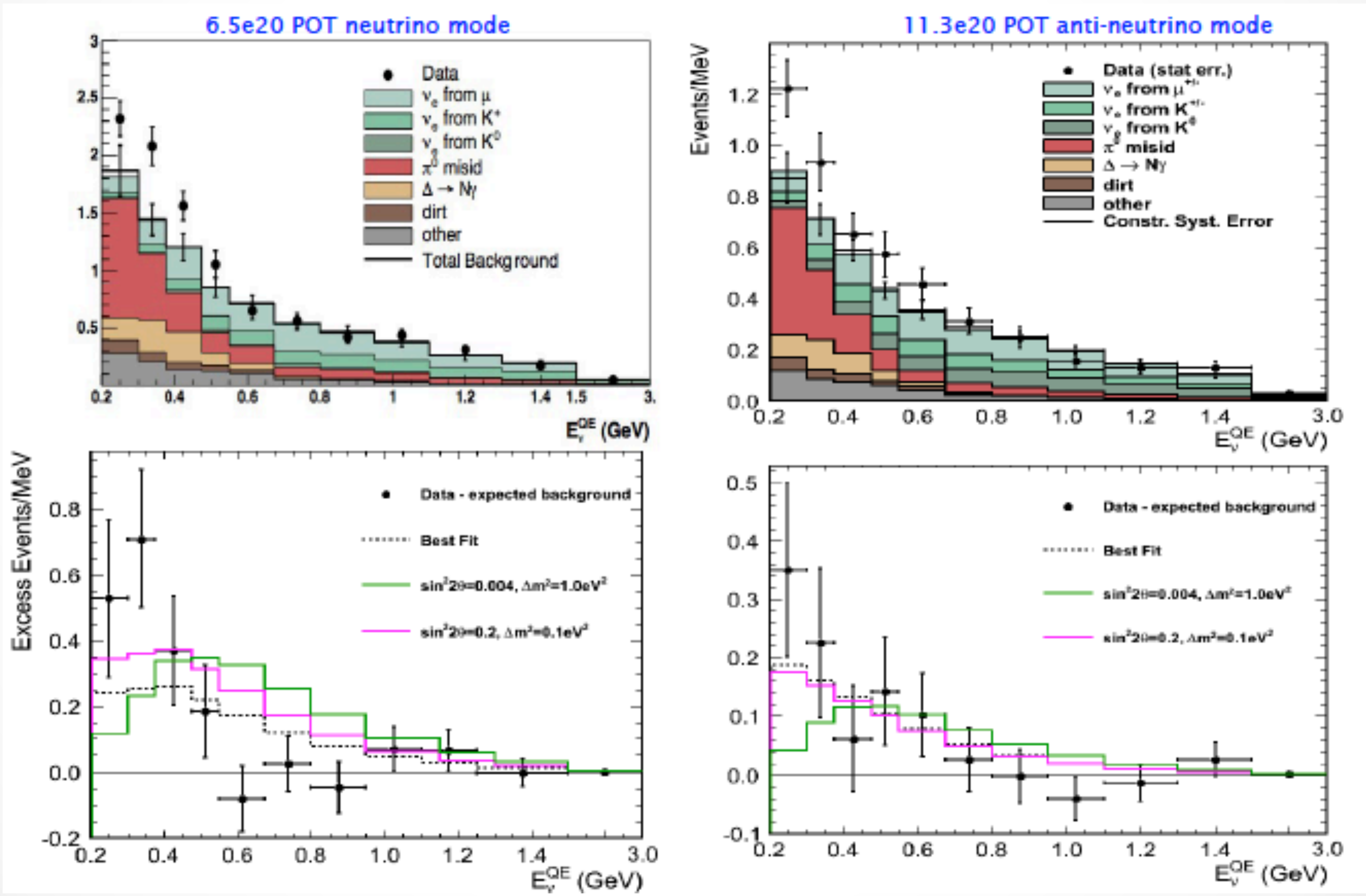
$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\, L\, \Delta m^2}{E}\right)$$

$$= 0.245 \pm 0.067 \pm 0.045\ \%$$



KARMEN at a distance of 17 meters saw no evidence for oscillations → low Δm^2

Then MiniBooNE…



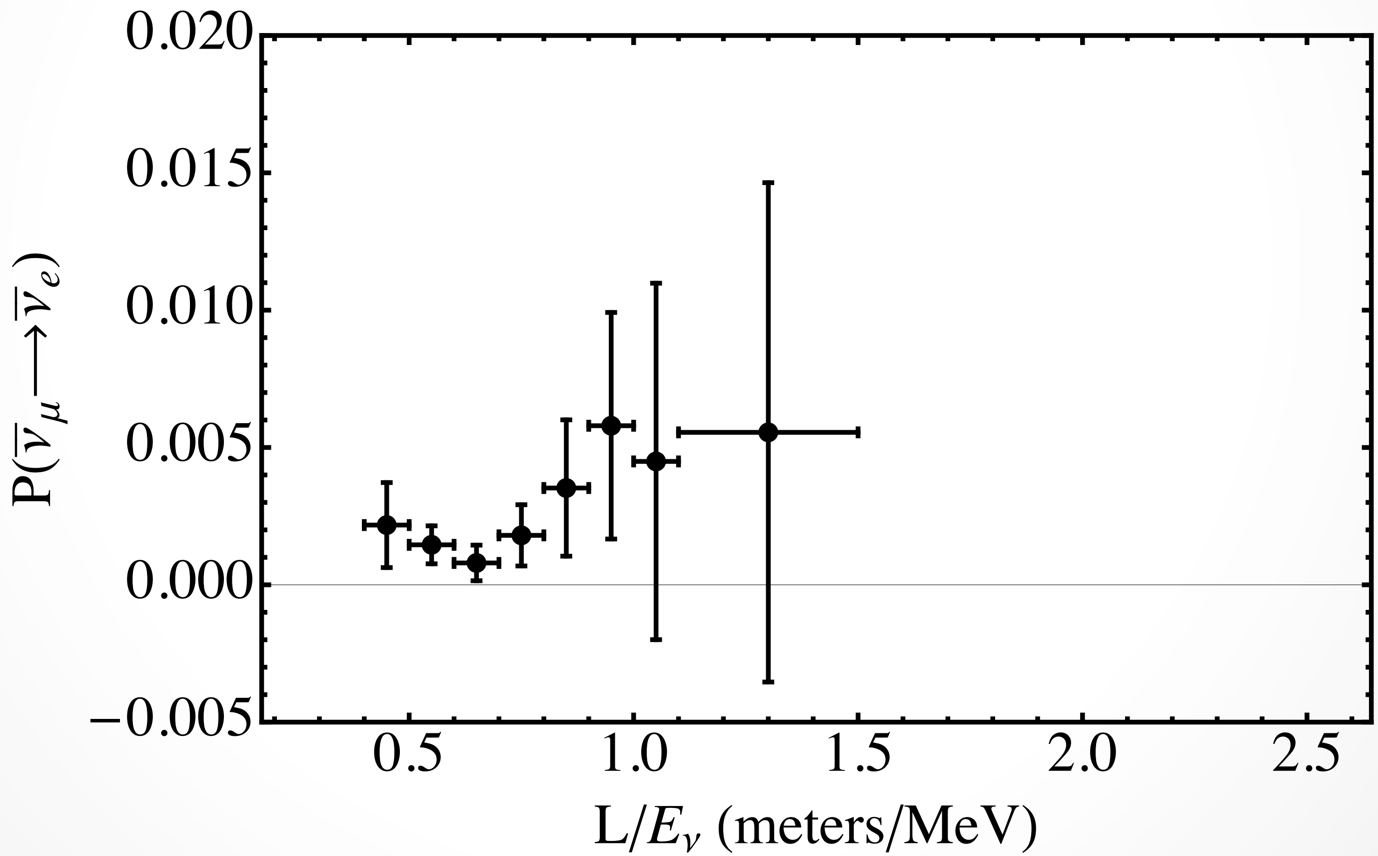
LSND-MiniBooNE Oscillations?

Use L/E representation of data to plot data on same footing

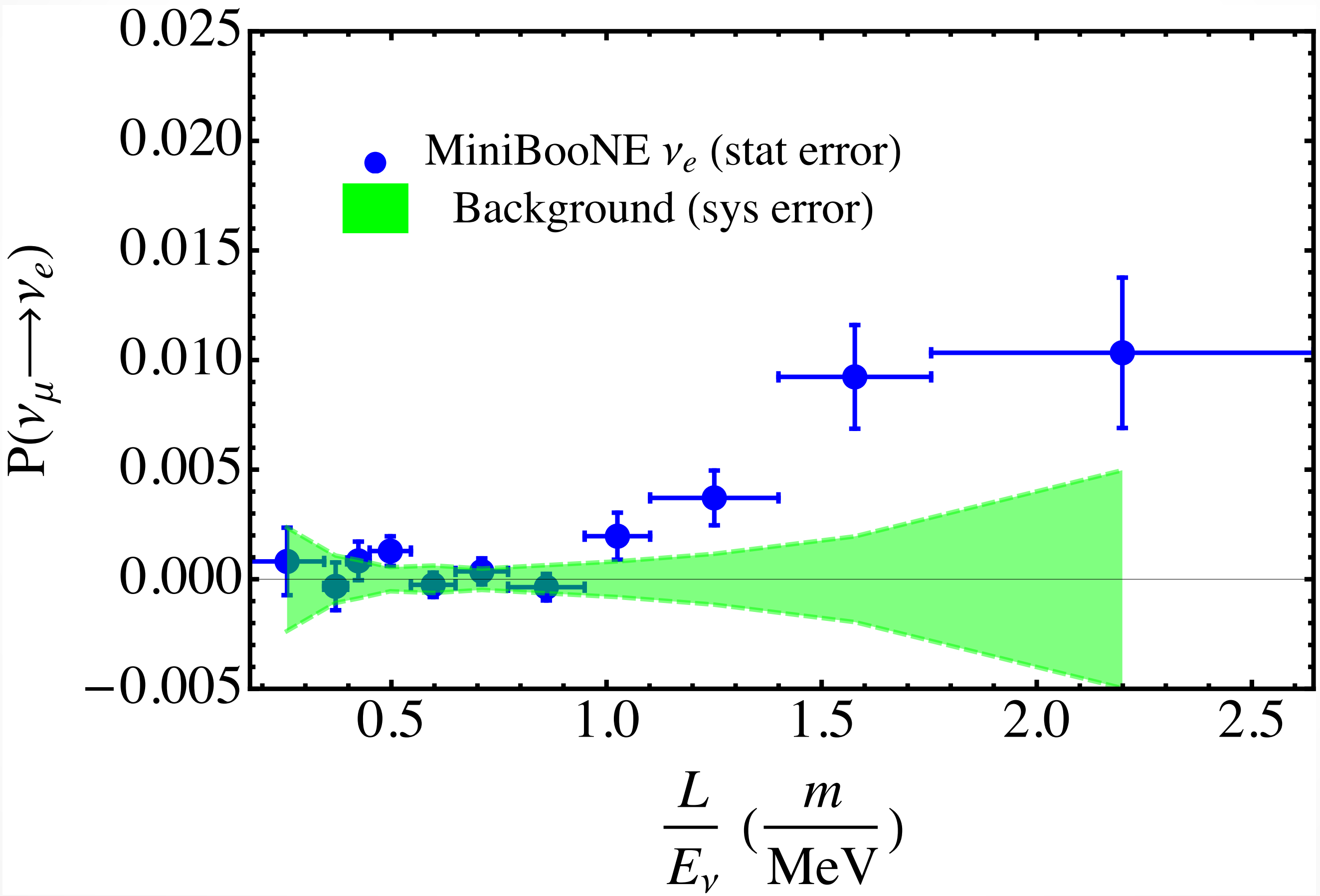
Recast "excess events" to "oscillation probability"

$$P_{osc} = \frac{\text{Excess } \nu_e \text{ events}}{\text{Expected } \nu_e \text{ events for completely oscillated source } (\nu_\mu \; or \; \bar{\nu}_\mu)}$$

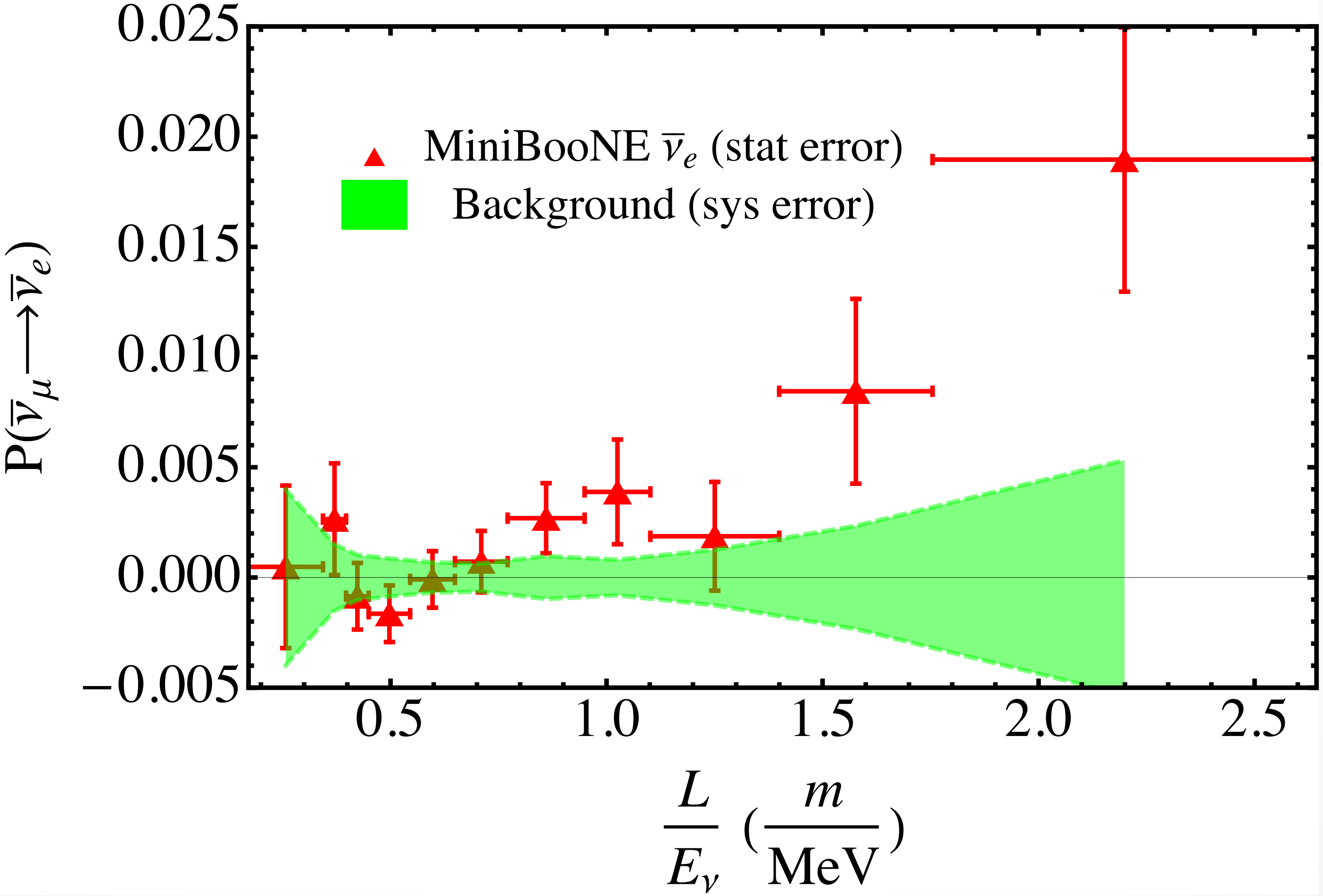
LSND Antineutrino Data



MiniBooNE Nu Mode



MiniBooNE NuBar Mode



3+2 Model

$$P\left(\overset{(-)}{\nu}_{\mu} \rightarrow \overset{(-)}{\nu}_{e}\right) = 4A^2 \sin^2\left(\frac{\Delta m_{41}^2 L}{E_\nu}\right) + 4B^2 \sin^2\left(\frac{\Delta m_{51}^2 L}{E_\nu}\right)$$

$$+ 8AB \sin\left(\frac{\Delta m_{41}^2 L}{E_\nu}\right) \sin\left(\frac{\Delta m_{51}^2 L}{E_\nu}\right) \cos\left(\frac{\left(\Delta m_{51}^2 - \Delta m_{41}^2\right) L}{E_\nu} \pm \varphi_{CP}\right)$$

where

$$A = \left|U_{e4} U_{\mu 4}\right|, \quad B = \left|U_{e5} U_{\mu 5}\right|, \quad and \quad \begin{cases} + & \text{neutrinos} \\ - & \text{antineutrinos} \end{cases}$$

3+2 Model Cont.

Difference of Probabilities:

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16\,A\,B \sin\left(\frac{\Delta m_{41}^2 L}{E_\nu}\right)\sin\left(\frac{\Delta m_{51}^2 L}{E_\nu}\right)\sin\left(\frac{\Delta m_{54}^2 L}{E_\nu}\right)\sin(\varphi_{CP})$$

Average of Probabilities:

$$\frac{\left(P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)\right)}{2} = 4A^2 \sin^2\left(\frac{\Delta m_{41}^2 L}{E_\nu}\right) + 4B^2 \sin^2\left(\frac{\Delta m_{51}^2 L}{E_\nu}\right)$$

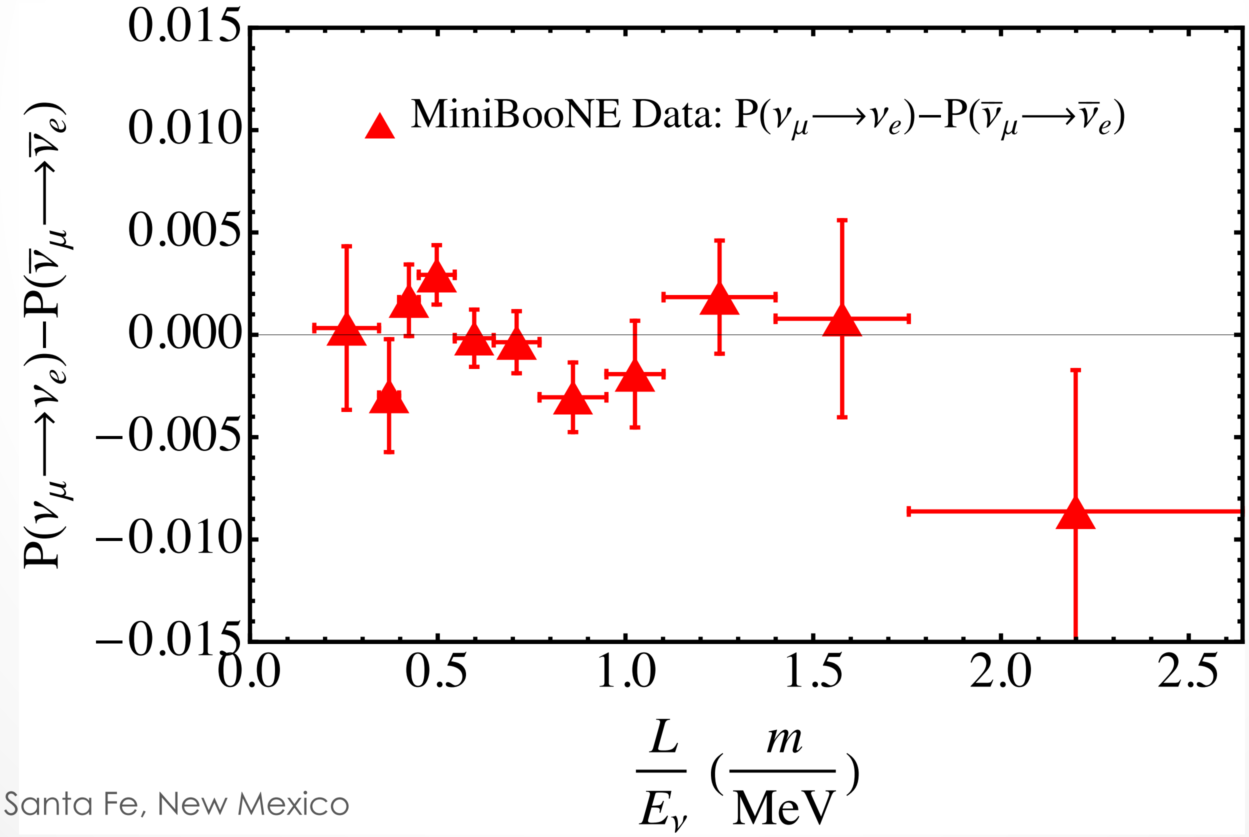
$$-8\,A\,B \sin\left(\frac{\Delta m_{41}^2 L}{E_\nu}\right)\sin\left(\frac{\Delta m_{51}^2 L}{E_\nu}\right)\cos\left(\frac{\Delta m_{54}^2 L}{E_\nu}\right)\cos(\varphi_{CP})$$

where

$$A = \left|U_{e4}U_{\mu 4}\right|, \quad B = \left|U_{e5}U_{\mu 5}\right|$$

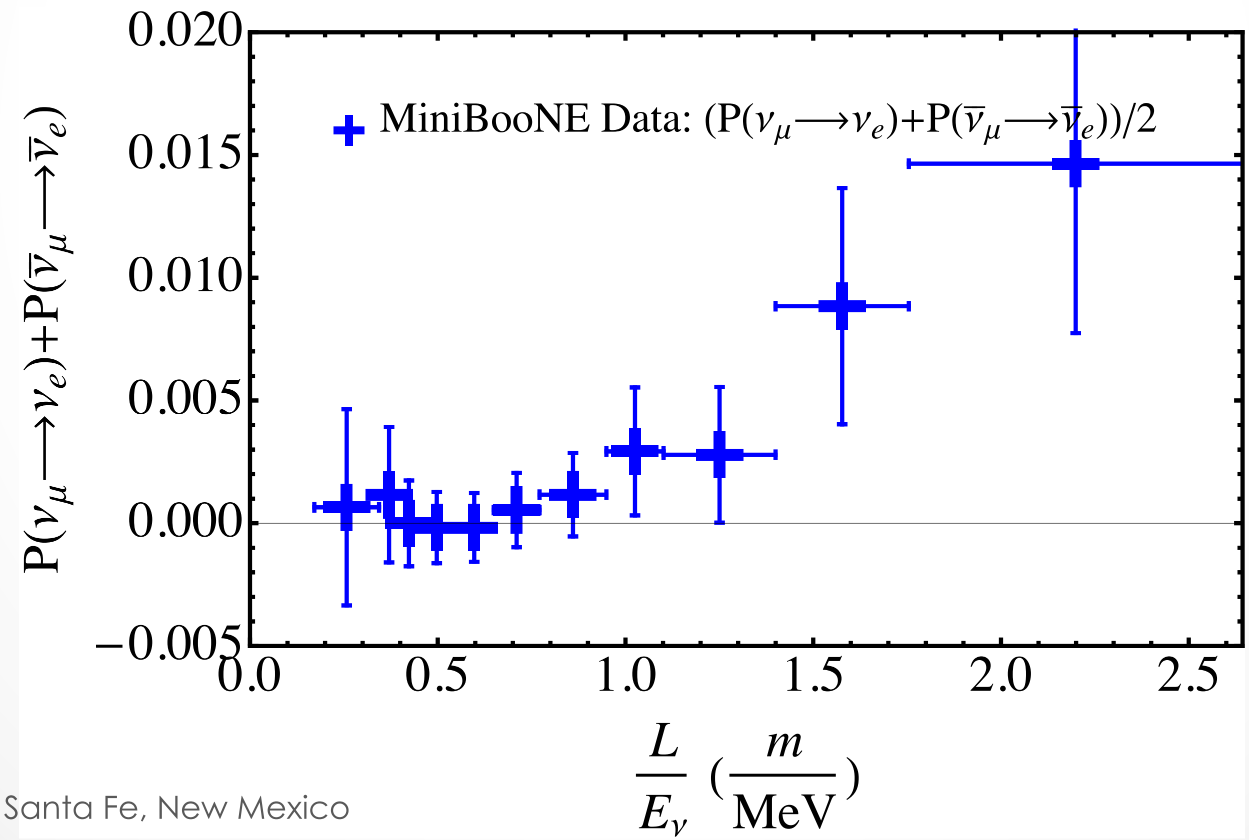
3+2 Difference

$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = -16\, A\, B \sin\left(\frac{\Delta m_{41}^2 L}{E_\nu}\right)\sin\left(\frac{\Delta m_{51}^2 L}{E_\nu}\right)\sin\left(\frac{\Delta m_{54}^2 L}{E_\nu}\right)\sin(\varphi_{CP})$$



3+2 Average

$$\frac{\left(P\left(\nu_\mu \to \nu_e\right) + P\left(\bar{\nu}_\mu \to \bar{\nu}_e\right)\right)}{2} = 4A^2 \sin^2\left(\frac{\Delta m_{41}^2 L}{E_\nu}\right) + 4B^2 \sin^2\left(\frac{\Delta m_{51}^2 L}{E_\nu}\right) - 8AB\sin\left(\frac{\Delta m_{41}^2 L}{E_\nu}\right)\sin\left(\frac{\Delta m_{51}^2 L}{E_\nu}\right)\cos\left(\frac{\Delta m_{54}^2 L}{E_\nu}\right)\cos\left(\varphi_{CP}\right)$$

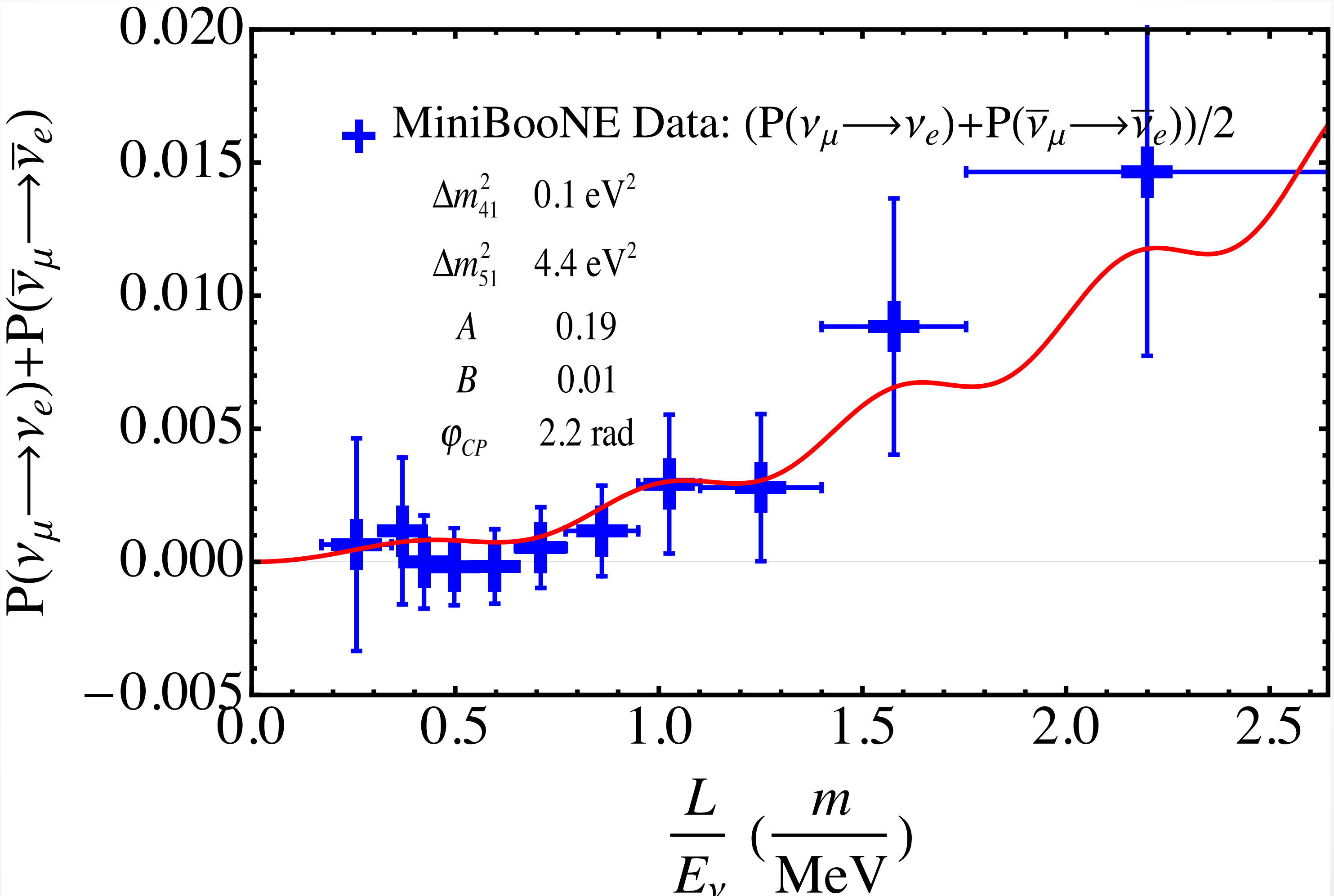


3+2 Fit

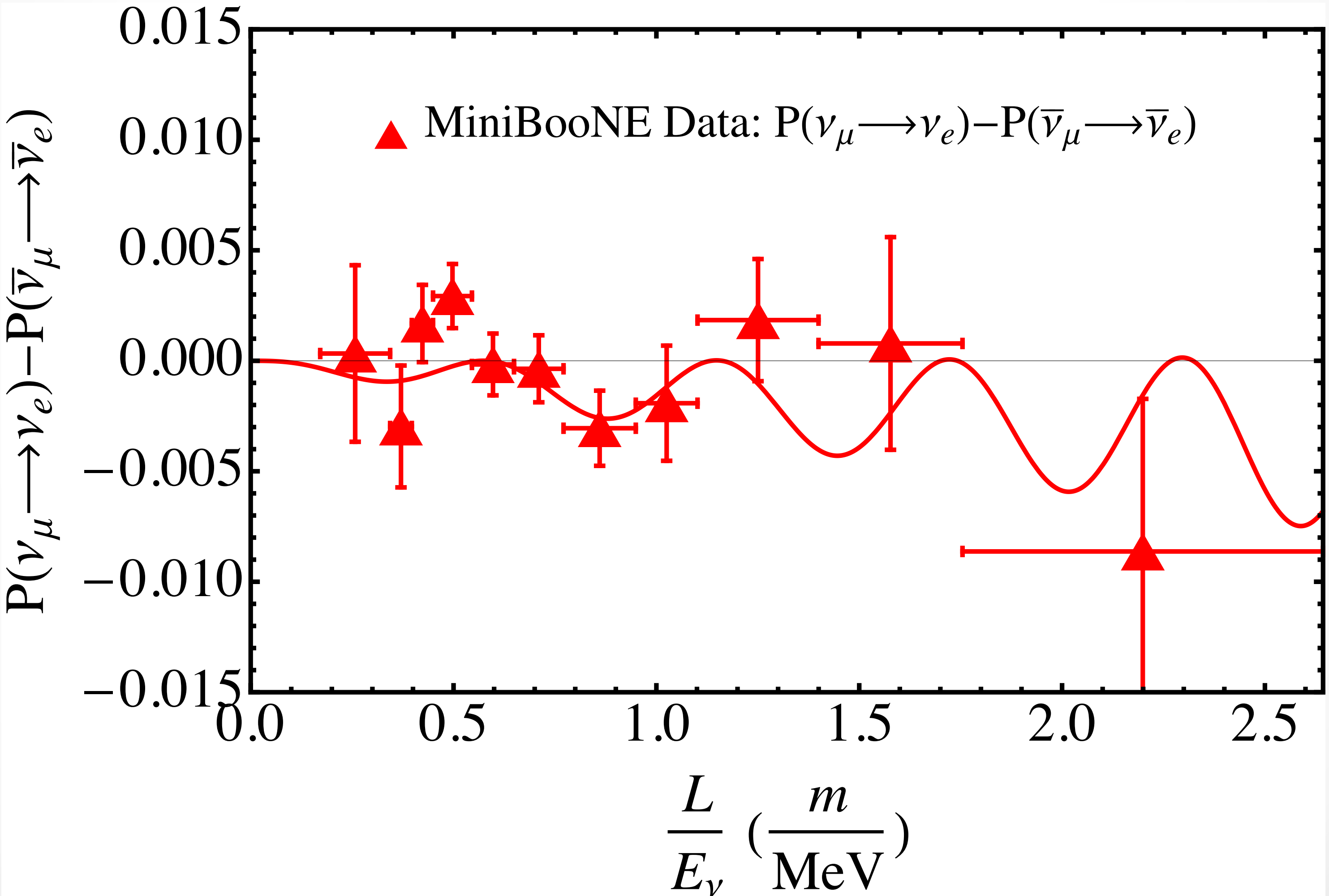
- Fit to MiniBooNE data only
- Average and difference probabilities simultaneously
- Use independent, constrained covariance matrices
- NDOF = 22 bins – 5 parameters = 17

Solution 1: (of several…)		
	Δm_{41}^2	$0.1\ \mathrm{eV}^2$
	Δm_{51}^2	$4.4\ \mathrm{eV}^2$
	A	0.19
	B	0.01
	φ_{CP}	$2.2\ \mathrm{rad}$

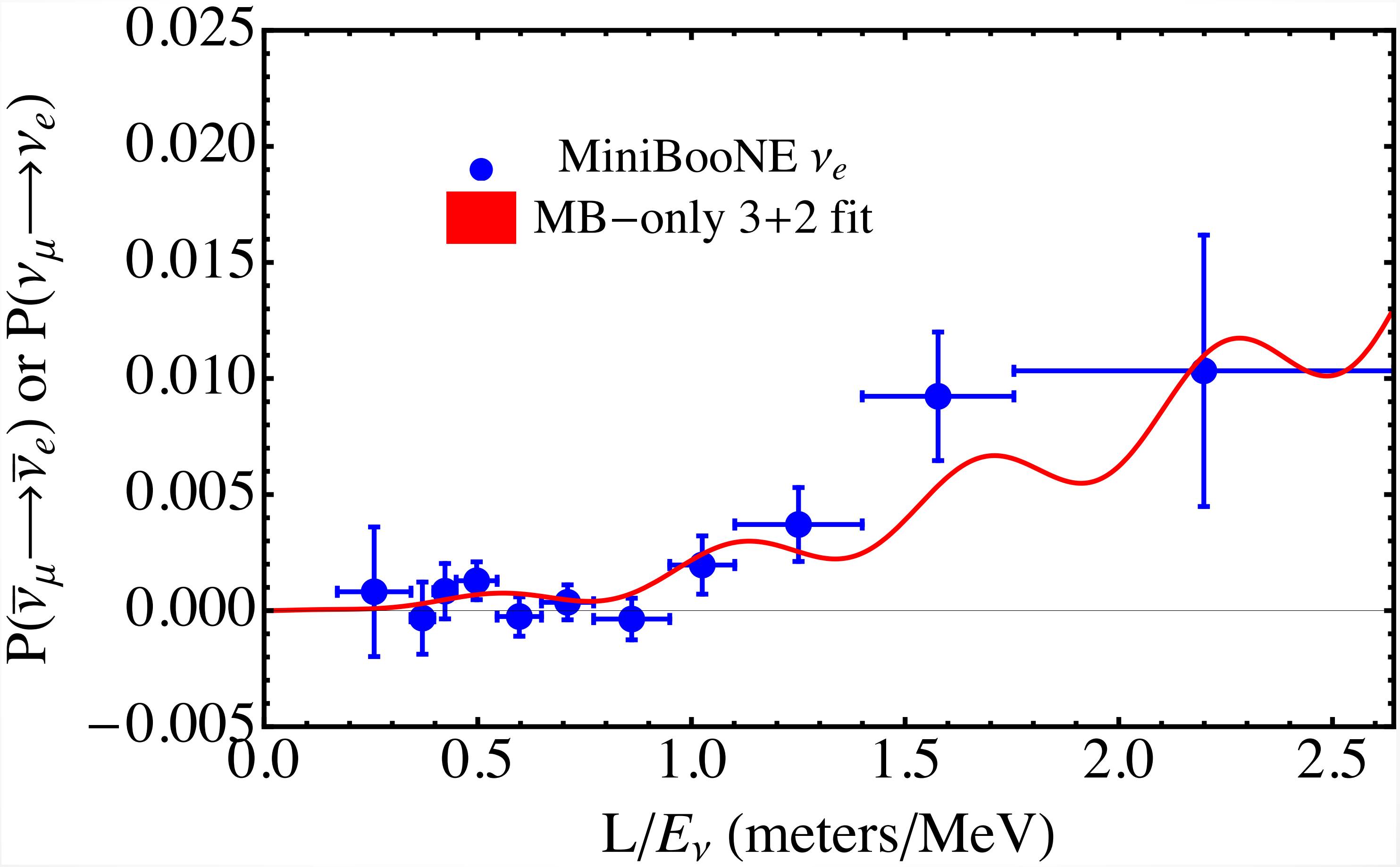
3+2 Fit Results: Average



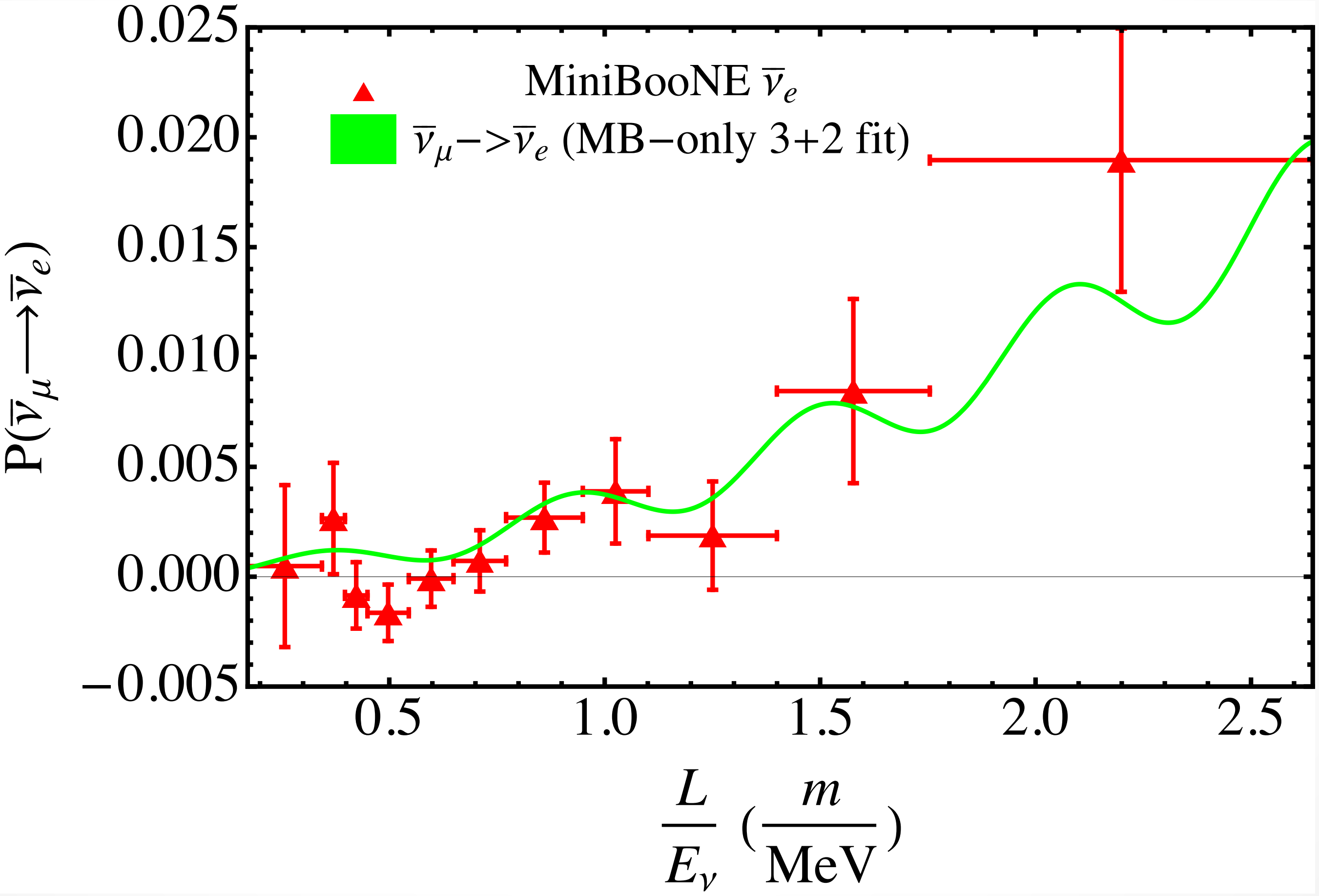
3+2 Fit Results: Difference



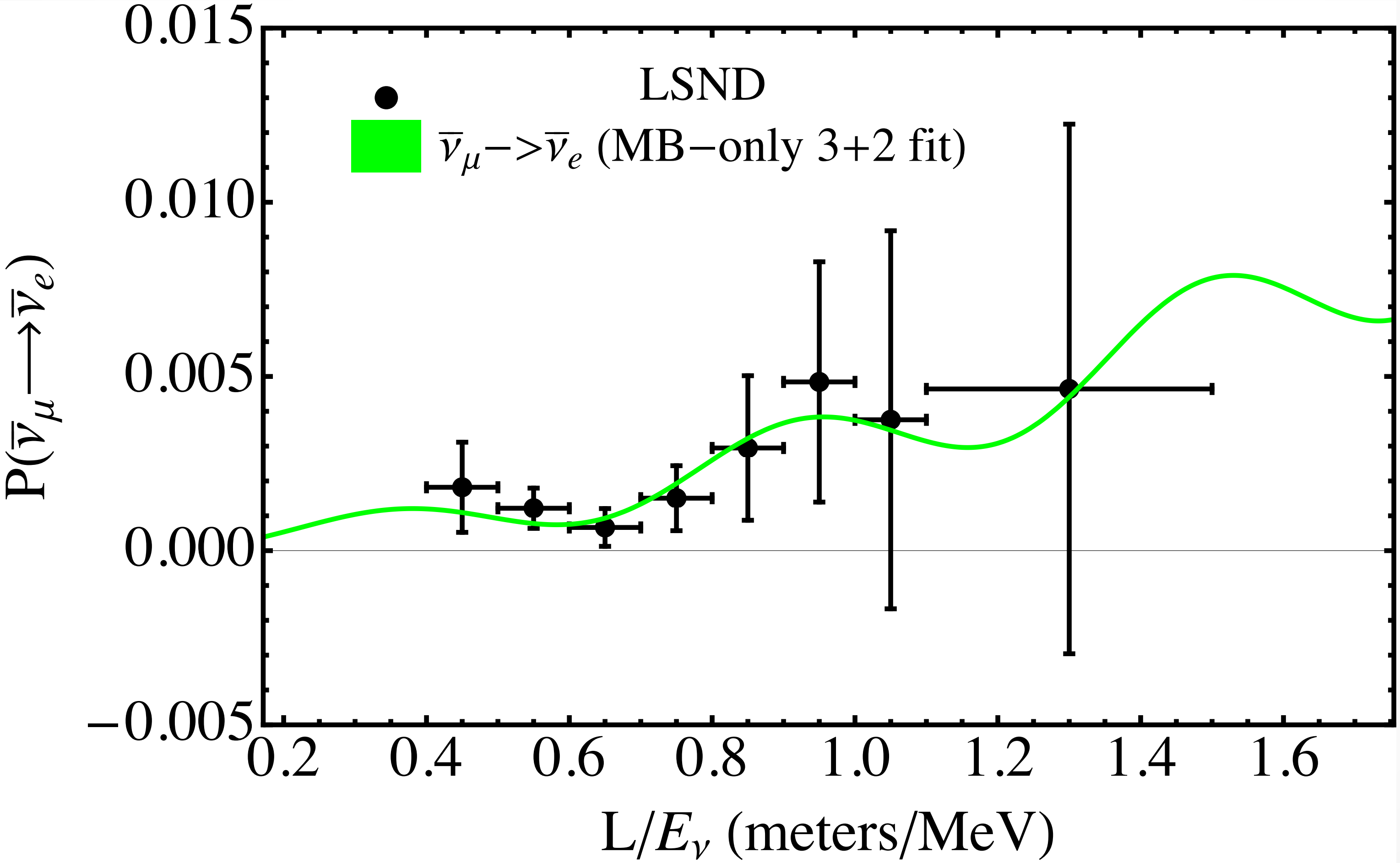
3+2 Fit Results: Nu Mode



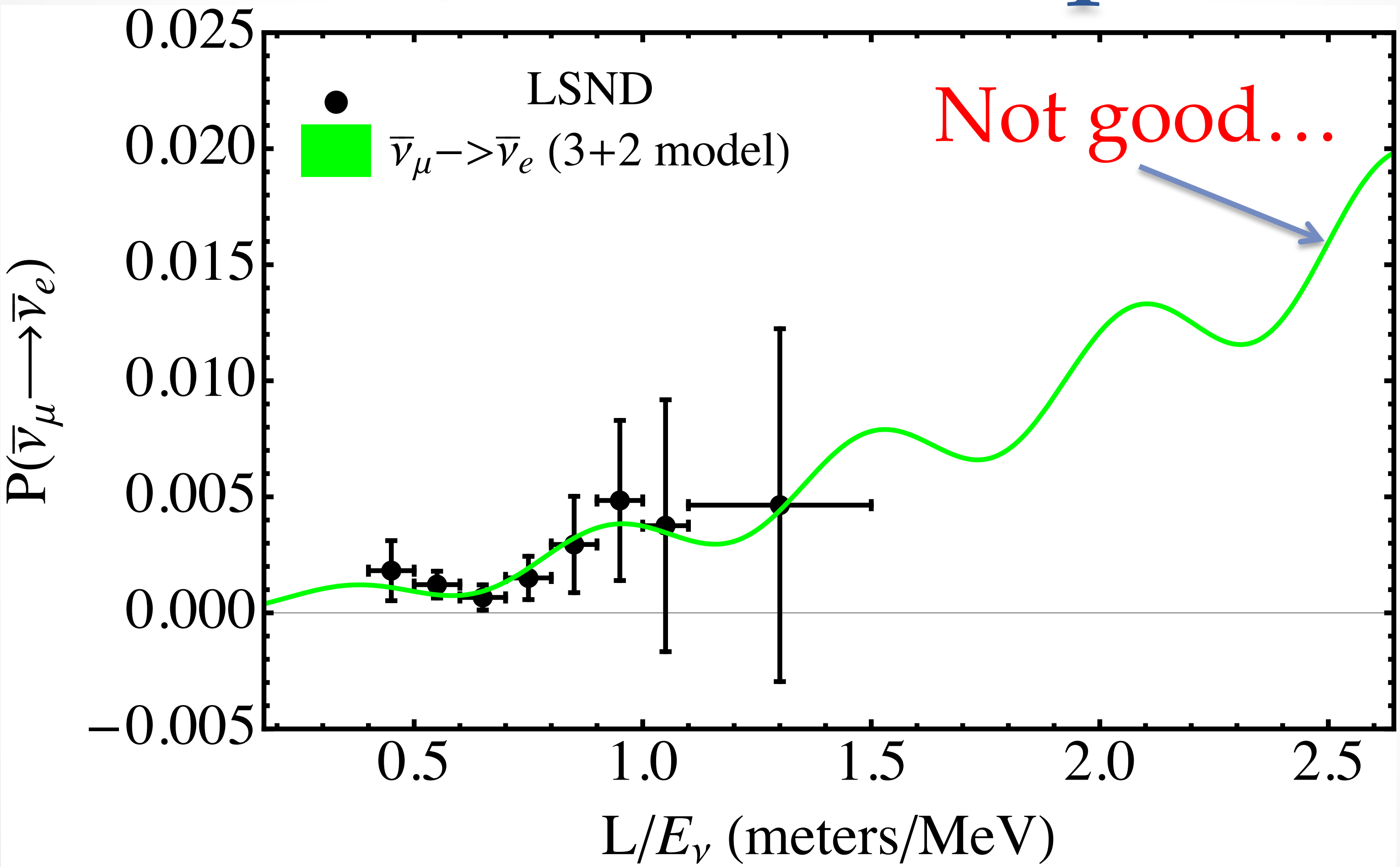
3+2 Fit Results: NuBar Mode



3+2 MiniBooNE-only Fit Results

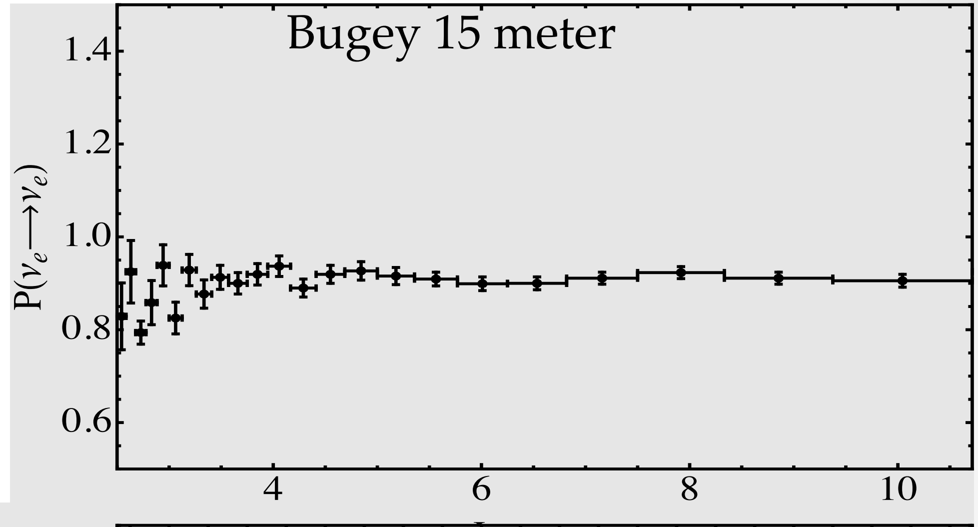


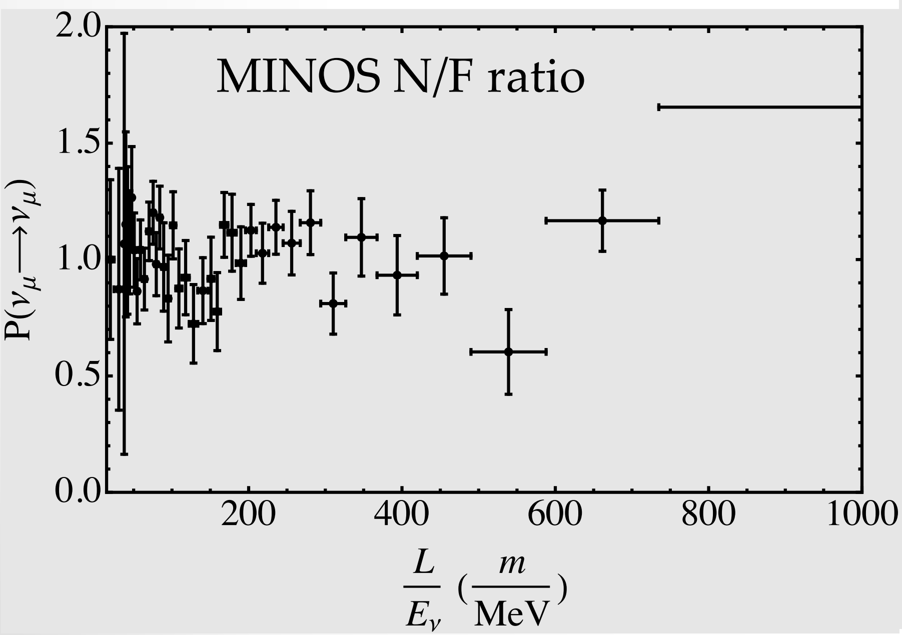
But wait, is there a problem?

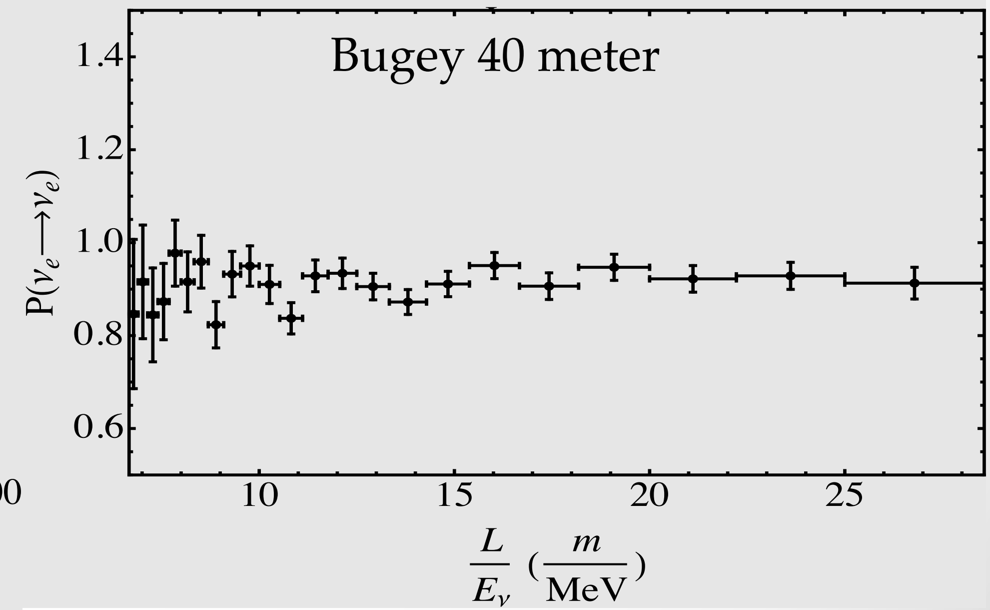


Bugey & MINOS Disappearance

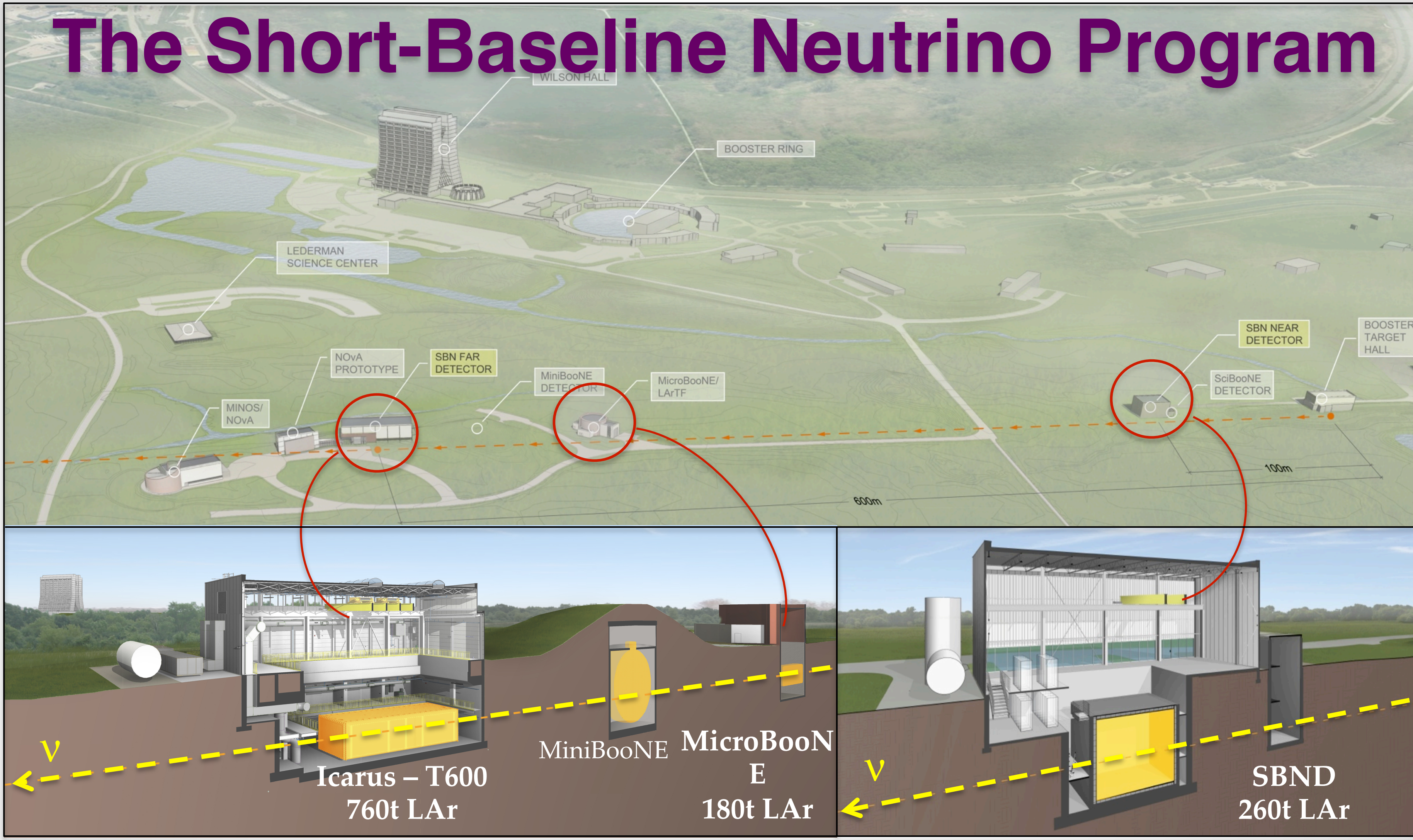
While a deficit exists in the Bugey, the ratio of 15m to 40 m is insensitive to the reactor neutrino flux, and cannot be easily accommodated in a 3+2 model. MINOS+ should yield higher statistics.







The Short-Baseline Neutrino Program

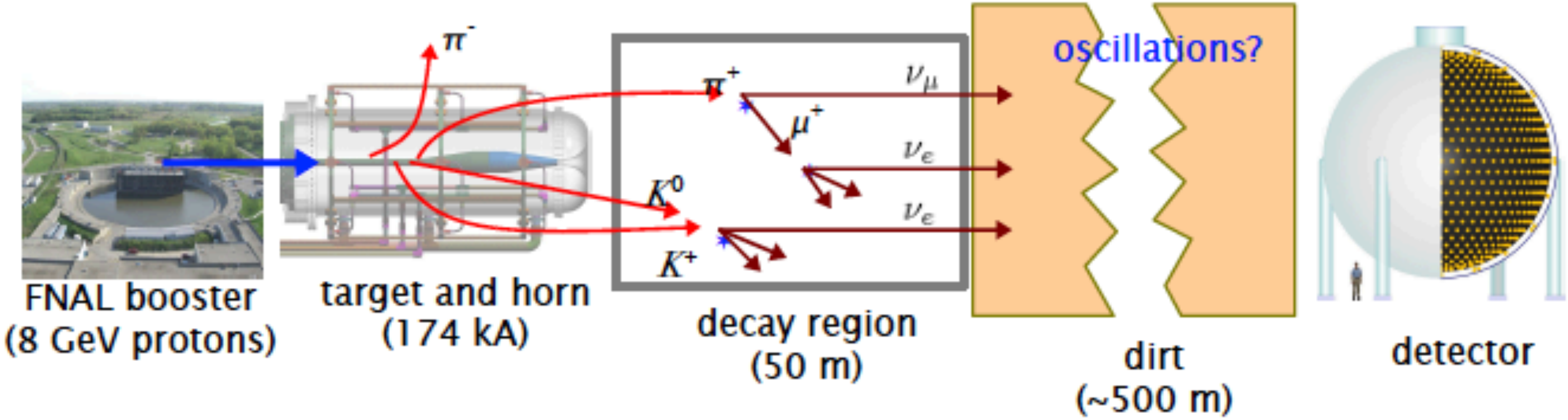


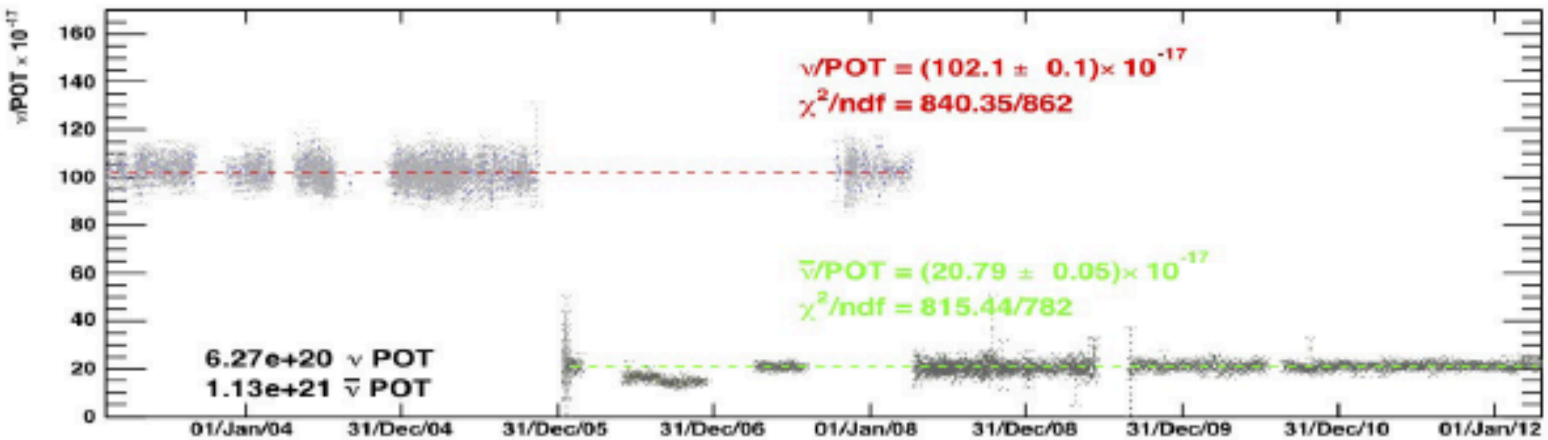
- Three Liquid Argon TPC detectors to search for sterile neutrinos with $\Delta m^2 \sim 1eV^2$ in both ν_μ disappearance and ν_e appearance oscillation channels.
- Joint proposal by ICARUS, MicroBooNE and Short-Baseline Near Detector collaborations to Fermilab PAC in January 2015 (http://arxiv.org/abs/1503.01520). Granted stage 1 approval in February 2015.

SBN Ingredients

- Robust Booster Neutrino Beam (BNB)
  - Efforts are underway to upgrade the BNB
  - A two-horn system promises higher event rates
- MicroBooNE
  - Successful liquid argon fill achieved last week!
  - Will address low energy excess of MiniBooNE
- SBND
  - Will act as near detector for SBN
  - R&D platform for DUNE liquid argon technology
- ICARUS (SBFD?)
  - 600T far detector at 600 meters (directly downstream of MiniBooNE)
  - Installation in 2017, operation in 2018

Fermilab Booster Neutrino Beam



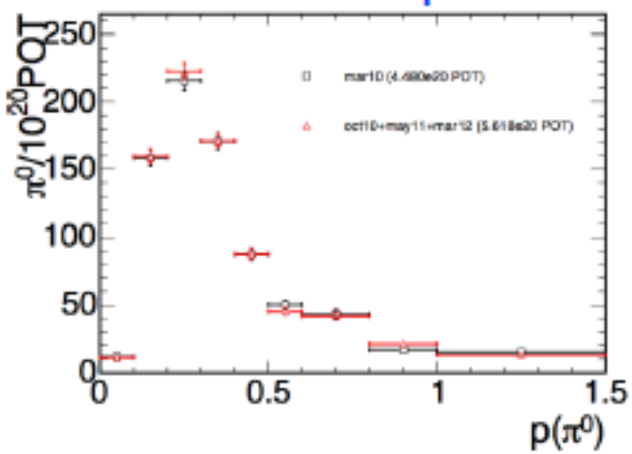


- 8 GeV FNAL Booster protons
  - 6.5e20 POT delivered for ν running
  - anti-ν running total 11.3e20 POT: Collected 5.7E20 POT since May 2010

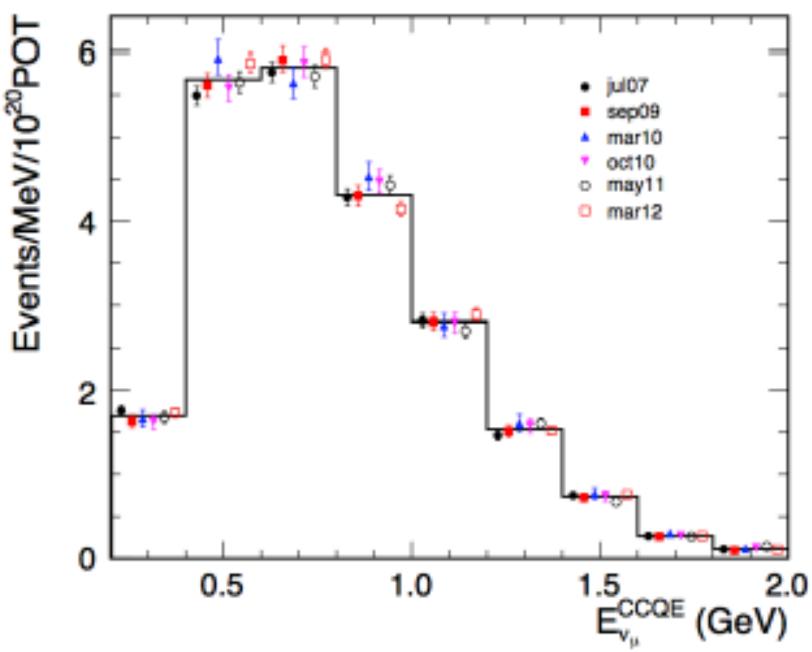
Stable Neutrino Flux Over 10 Years

- Statistics of anti-neutrino running has doubled since Phys.Rev.Lett.105 181801 (2010)
  - 5.66e20 POT --> 11.3e20 POT
  - higher statistics in anti-ν_e appearance
  - ...and samples used for constraints

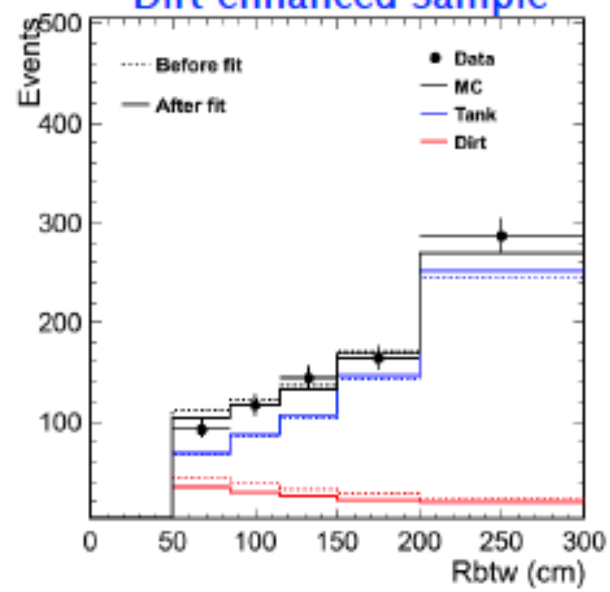
NC π^0 Sample



ν_μ CCQE Sample



Dirt-enhanced Sample

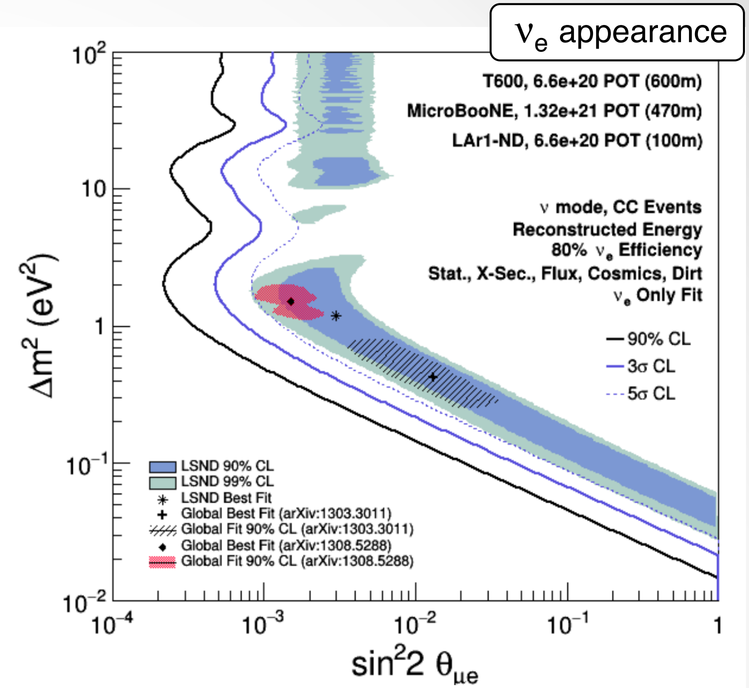


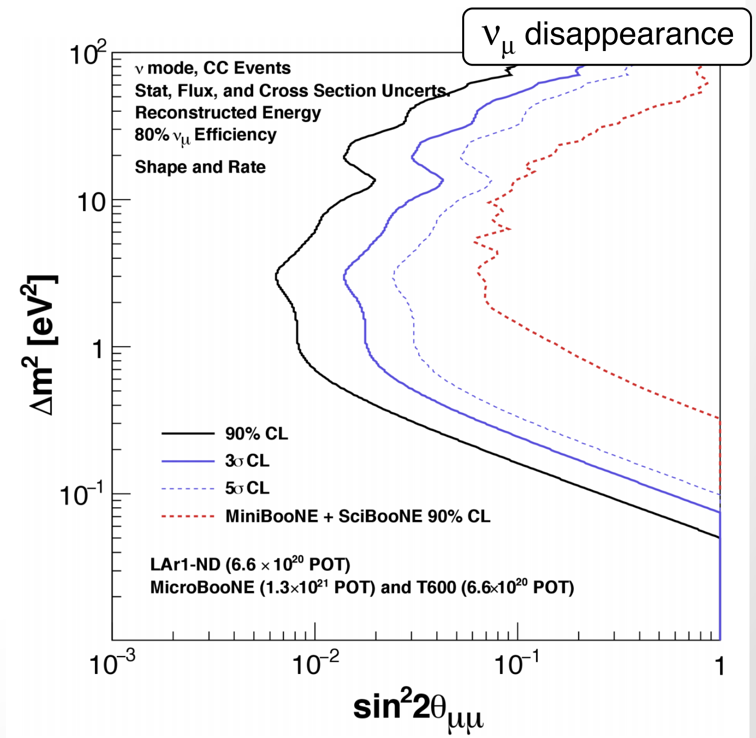
SBN and ICARUS

- The unresolved issues surrounding LSND and MiniBooNE have generated a desire to develop a multi-detector program to explore this region of Δm^2 and extend the existing sensitivities greatly.
- With the shutdown or the CNGS (CERN-Grand Sasso) beam, the 600T ICARUS detector was decommissioned
- Efforts to construct a SBL beam at CERN were deemed to costly, and a solution presented itself
- CERN, INFN, Fermilab, and DOE have agreed to promote both long-term (DUNE) and short-term (SBN) neutrino oscillation experiments at Fermilab

SBN Program Physics

- Build on 10+ years of neutrino oscillation physics with the Booster Neutrino Beam: MiniBooNE and SciBooNE experiments
- Address LSND and MiniBooNE anomalies
- 2015-18: MicroBooNE to address the MiniBooNE low energy excess (e or g)
- 2015-18: refurbish ICARUS, Design and construct SBND; install and commission
- 2018-2021: three detector SBN program operations to address LSND anomaly and search for sterile neutrinos
- SBN program projected sensitivities (6.6x10^{20} P.O.T. three years nominal operation)
  - ν_e appearance: ~5s coverage of LSND 99% CL Region in neutrino mode
  - ν_μ disappearance: factor of 10 better than MiniBooNE+SciBooNE





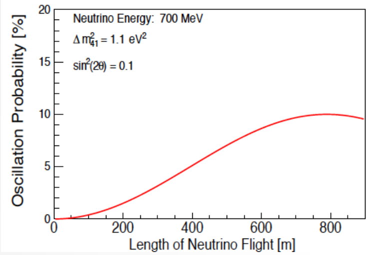
ICARUS-T600
Far Detector @ Fermilab Short-Baseline Neutrino Program

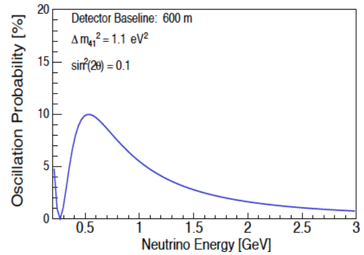
The ICARUS-WA104 Collaboration

M. Antonello[16], B. Baibussinov[31], V. Bellini[5], P. Benetti[32], S. Bertolucci[6], H. Bilokon[15], F. Boffelli[32], M. Bonesini[17], J. Bremer[6], E. Calligarich[32], S. Centro[31], A.G. Cocco[19], A. Dermenev[20], A. Falcone[32], C. Farnese[31], A. Fava[31], A. Ferrari[6], D. Gibin[31], S. Gninenko[20], N. Golubev[20], A. Guglielmi[31], A. Ivashkin[20], M. Kirsanov[20], J. Kisiel[38], U. Kose[6], F. Mammoliti[5], G. Mannocchi[15], A. Menegolli[32], G. Meng[31], D. Mladenov[6], C. Montanari[32], M. Nessi[6], M. Nicoletto[31], F. Noto[6], P. Picchi[15], F. Pietropaolo[31], P.Płoński[42], R. Potenza[5], A. Rappoldi[32], G. L. Raselli[32], M. Rossella[32], C. Rubbia*[6,11,16], P. Sala[18], A. Scaramelli[18], J. Sobczyk[44], M. Spanu[32], D. Stefan[18], R. Suley[43], C.M. Sutera[5], M. Torti[32], F. Tortorici[5], F. Varanini[31], S. Ventura[31], C. Vignoli[16], T. Wachala[12], and A. Zani[32]

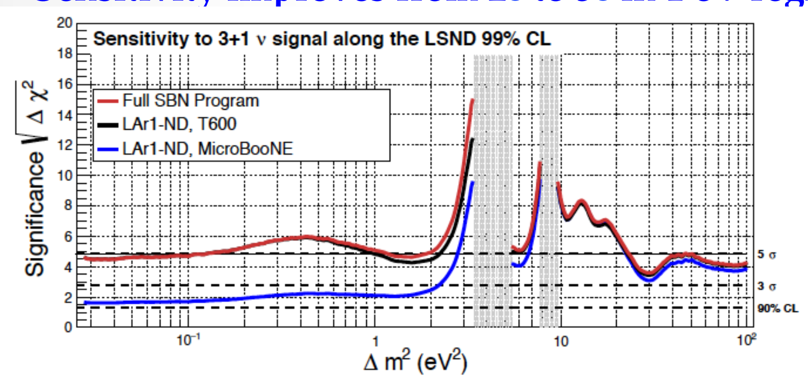
New US members from: Argonne National Lab, Colorado State University, Los Alamos National Lab, Fermilab, Univ. of Pittsburgh and SLAC.

High sensitivity to eV-scale sterile neutrinos at L= 600 m





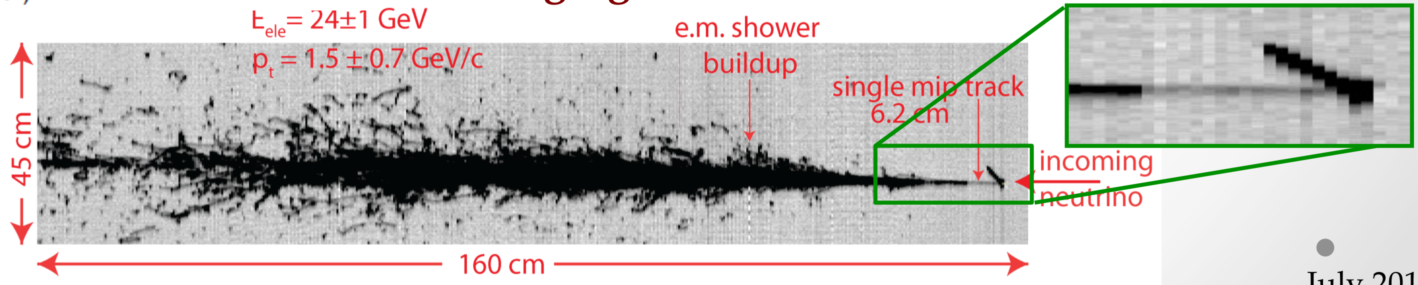
Sensitivity improves from 2s to 5s in 1 eV region



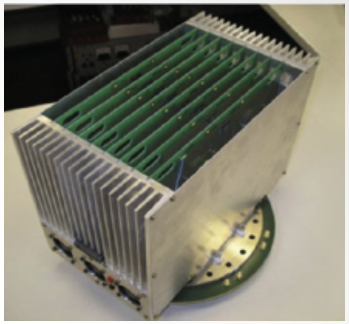
Liquid Argon TPC Pioneered by ICARUS team
World's largest LArTPC (760 t total/476 t active)

Unique detection capabilities: ~1 mm^3 3D imaging and accurate dE/dx measurement

CNGS ν_e event

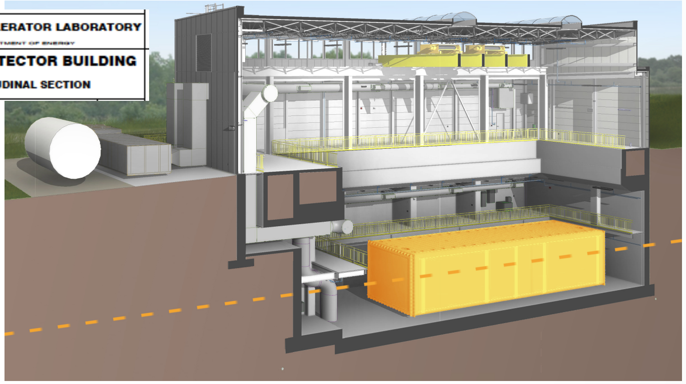


WA104: CERN-INFN for relocation to CERN for refurbishment and upgrades



50x more compact electronics

Then to Fermilab as Short-Baseline Neutrino Program Far Detector



- Refurbishment proceeding well at CERN – on schedule for transport to Fermilab Dec. 2016
- New Aluminum cold vessels and thermal insulation, re-shaping of cryogenics and purification system
- New (expanded coverage) photomultiplier tubes for LAr photon system ordered
- Far detector building design is completed - beneficial occupancy Nov. 2016
- Conceptual designs for cosmic ray tagger (CRT) underway
- US groups incorporated in high need areas: CRT design, TPC+CRT electronics, DAQ, software; assisting integration with other short-baseline detectors; ways to support these efforts being investigated
- Data-taking with beam Apr. 2018; 3-year data run anticipated

First T300 wireframe in the CERN clean room (Feb 2015)

First T300 wireframe in the CERN clean room (Feb 2015)

ICARUS Refurbishment at CERN

- New PMTs are on order from Hamamatsu
  - UV coating will be applied at CERN
- Cathode plane replacement underway
  - Tighter flatness tolerance
- Construction of new cryostats at CERN
  - Engineering nearly complete
- New electronics
  - CAEN involved in readout
  - Warm front-end is likely
- First module scheduled to complete end of 2015
  - Second module to complete end of 2016 or early 2017
- Modules are scheduled to arrive at Fermilab when detector hall is finished

Conclusions

- SBN offers a bright future for near-term neutrino physics at Fermilab
- ICARUS will provide a powerful far detector for SBN on a short time scale
- Program is designed to lay the foundations for European-US collaboration in future long baseline experiments like DUNE