SBN @ BNB

Short-Baseline Neutrinos @ the Booster Neutrino Beam

Physics Opportunities

PIP-II Collaboration Meeting:

4 June 2014

David Schmitz, University of Chicago

The Short-Baseline Neutrino Program

- The SBN Program takes advantage of the existing Booster Neutrino Beam to build a world-leading short-baseline (high-Δm^2) oscillation experiment at Fermilab that can:
    - Address existing anomalies in experimental neutrino physics
    - Search for evidence of light sterile neutrinos (~1 eV^2) through both appearance and disappearance oscillation channels
    - Advance neutrino detector technology (e.g. LAr TPCs) leading to long-baseline needs in the future using relatively modest size (i.e. cost) detectors while expanding the science reach of the FNAL neutrino program
- As in all sensitive oscillation searches using accelerator beams, high event rates and the utilization of multiple detectors at different baselines is key to enabling a sensitive measurement

Maintaining intense beam to the BNB throughout the PIP-I era and into PIP-II is critical to the success of this program

Experimental Anomalies and Sterile Neutrinos

Three Neutrino Mixing

- Three neutrino mixing firmly established

$$\theta_{12} \approx 34^\circ$$

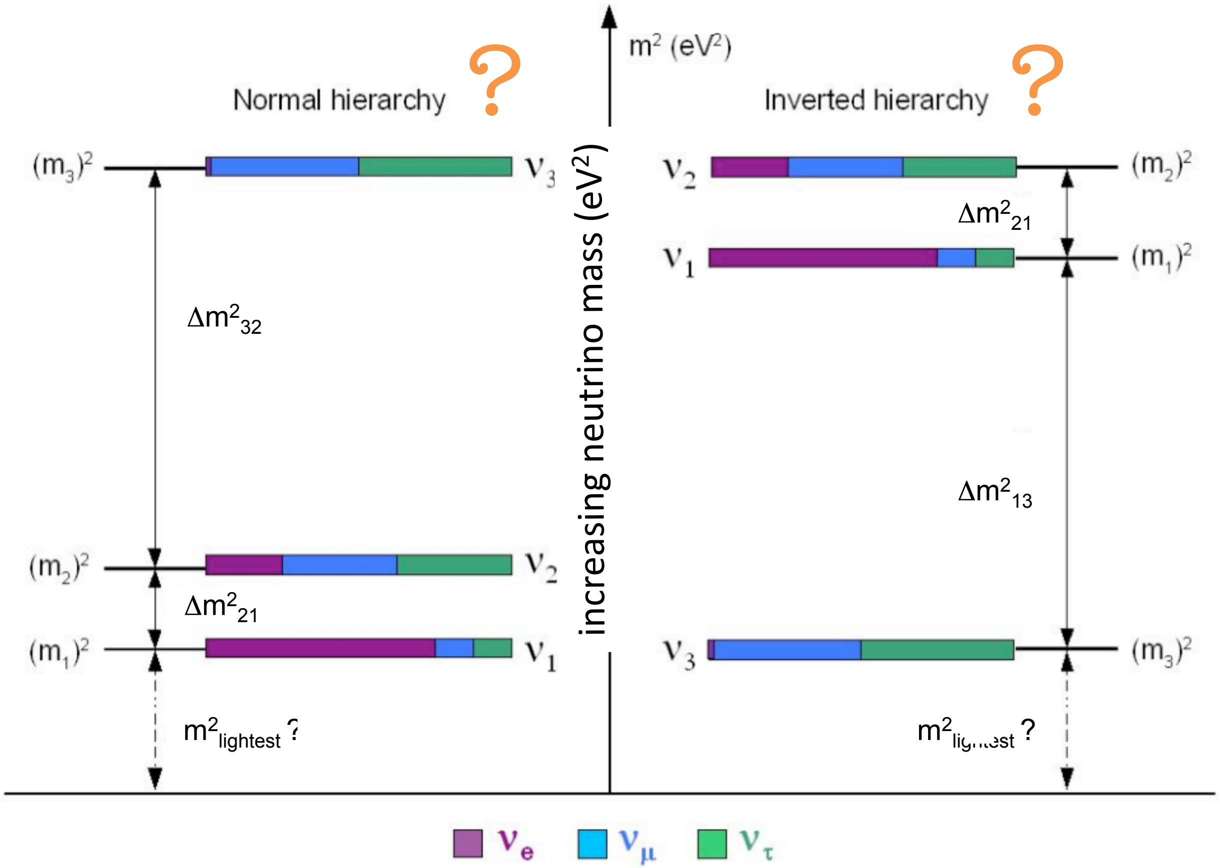
$$\theta_{23} \approx 45^\circ$$?

$$\theta_{13} \approx 9^\circ$$

$$\Delta m^2_{21} \approx 7.5 \times 10^{-5} eV^2$$

$$|\Delta m^2_{31}| \approx 2.4 \times 10^{-3} eV^2$$

$$\delta_{CP} = \ ?$$?



Long-Baseline Goals

Existing Anomalies in Neutrino Physics @ SBL

- Experimental anomalies ranging in significance (2.8–3.8σ) have been reported from a variety of experiments studying neutrinos over baselines less than 1 km.

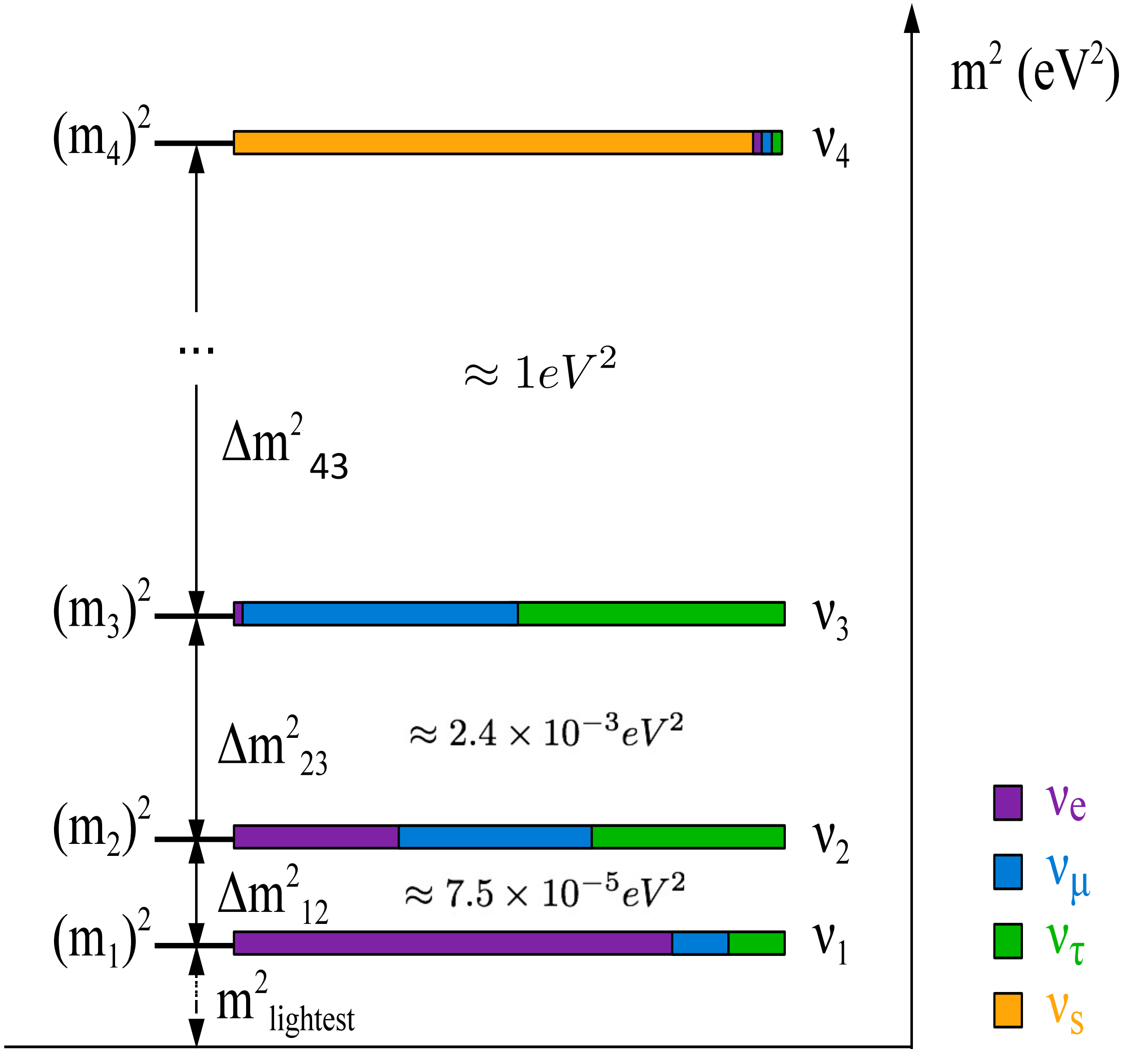
Current anomalies from:
accelerator beams
radioactive sources
reactor neutrinos

Experiment	Type	Channel	Significance
LSND	DAR	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	3.8σ
MiniBooNE	SBL accelerator	$\nu_\mu \to \nu_e$ CC	3.4σ
MiniBooNE	SBL accelerator	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	2.8σ
GALLEX/SAGE	Source - e capture	ν_e disappearance	2.8σ
Reactors	Beta-decay	$\bar{\nu}_e$ disappearance	3.0σ

K. N. Abazajian et al. "Light Sterile Neutrinos: A Whitepaper", arXiv:1204.5379 [hep-ph], (2012)

- Most common interpretation is as evidence for high mass-squared neutrino oscillations and the existence of one or more additional, mostly “sterile” neutrino states with masses at or below a few electron volts
  - Many global fits to data (both with signal and null results) available in the literature that fit the data to 3+1, 3+2 and 3+3 models for sterile neutrinos (Kopp et al. Conrad et al., Giunti et al. etc)
- While each of these measurements taken separately lack the significance to claim a discovery, together these signals could be hinting at important new physics that requires further exploration

Sterile Neutrinos



Sterile neutrino

Additional neutrino flavor and mass state(s) that do not participate in SM weak interactions through the W/Z bosons

Mass state(s) accessed only through mixing with standard model neutrinos

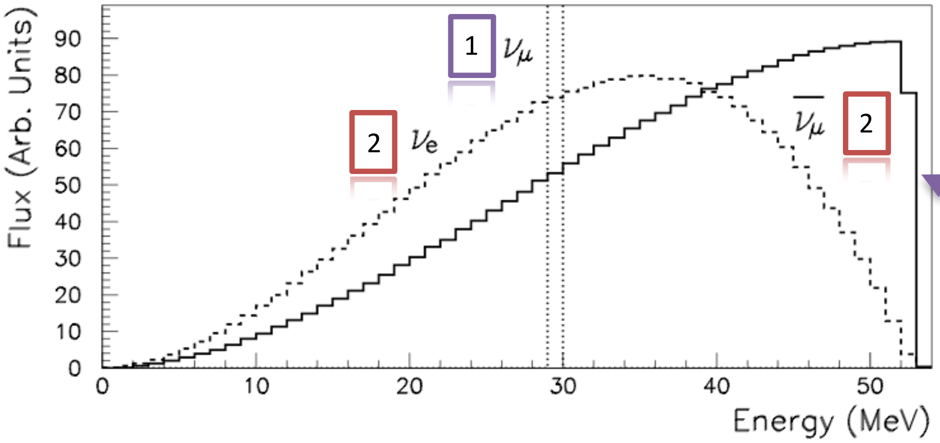
Liquid Scintillator Neutrino Detector (LSND)

1 $\pi^+ \rightarrow \mu^+ \nu_\mu$

2 $\quad \hookrightarrow e^+ \nu_e \bar{\nu}_\mu$

$\quad\quad \xrightarrow{?} \bar{\nu}_e$

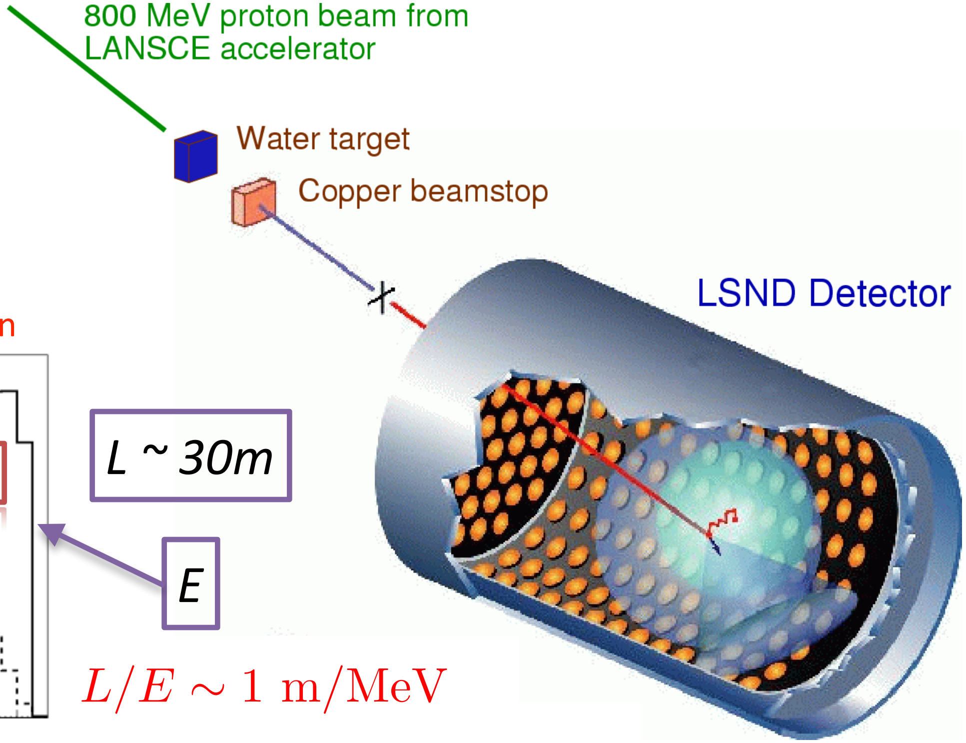
Beam produced by decays *at rest* is precisely known



L ~ 30m

E

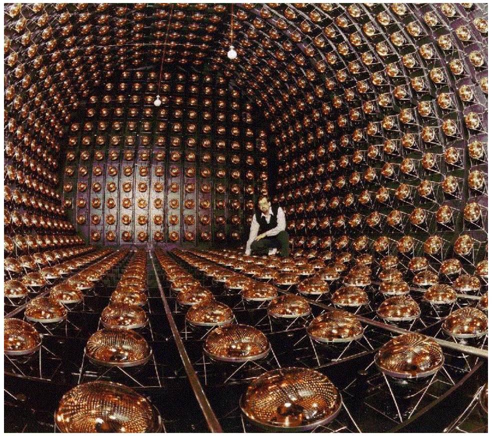
$L/E \sim 1\ \mathrm{m/MeV}$



Look for electron anti-neutrinos in a beam with well-predicted fluxes and small electron anti-neutrino background

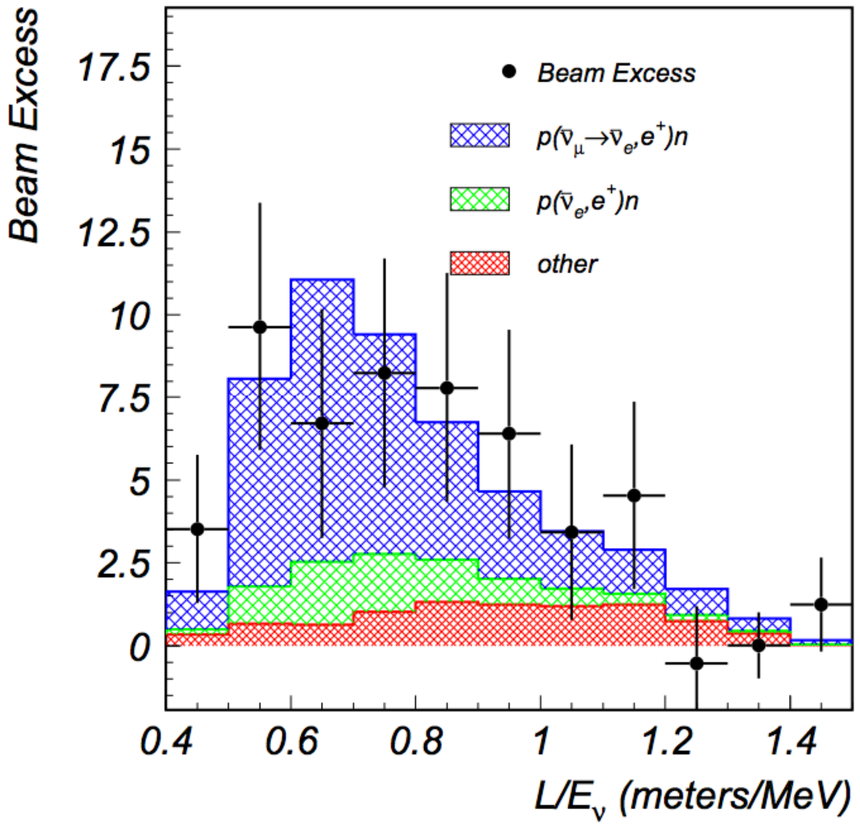
neutron captures to produce a 2.2 MeV gamma

$\bar{\nu}_e$ detection via inverse-beta-decay: $\bar{\nu}_e + p \rightarrow e^+ + n$
(coincidence signal)



Phys. Rev. D64 (2001) 112007

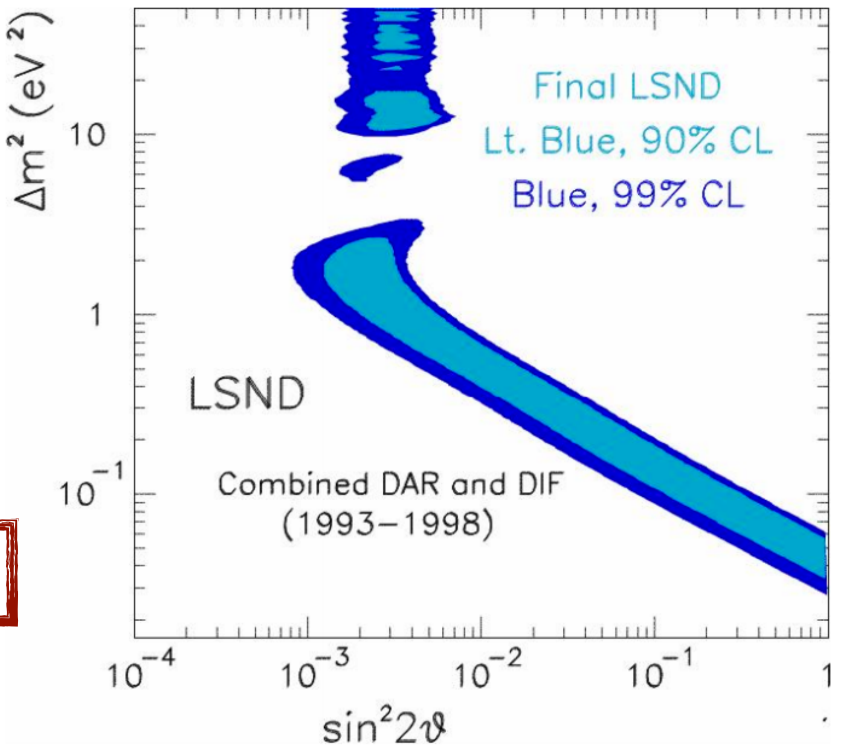
Liquid Scintillator Neutrino Detector (LSND)



L/E distribution of the most signal-like events

Observed excess described by best fit oscillation probability:

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = (0.264 \pm 0.067 \pm 0.045)\%$$



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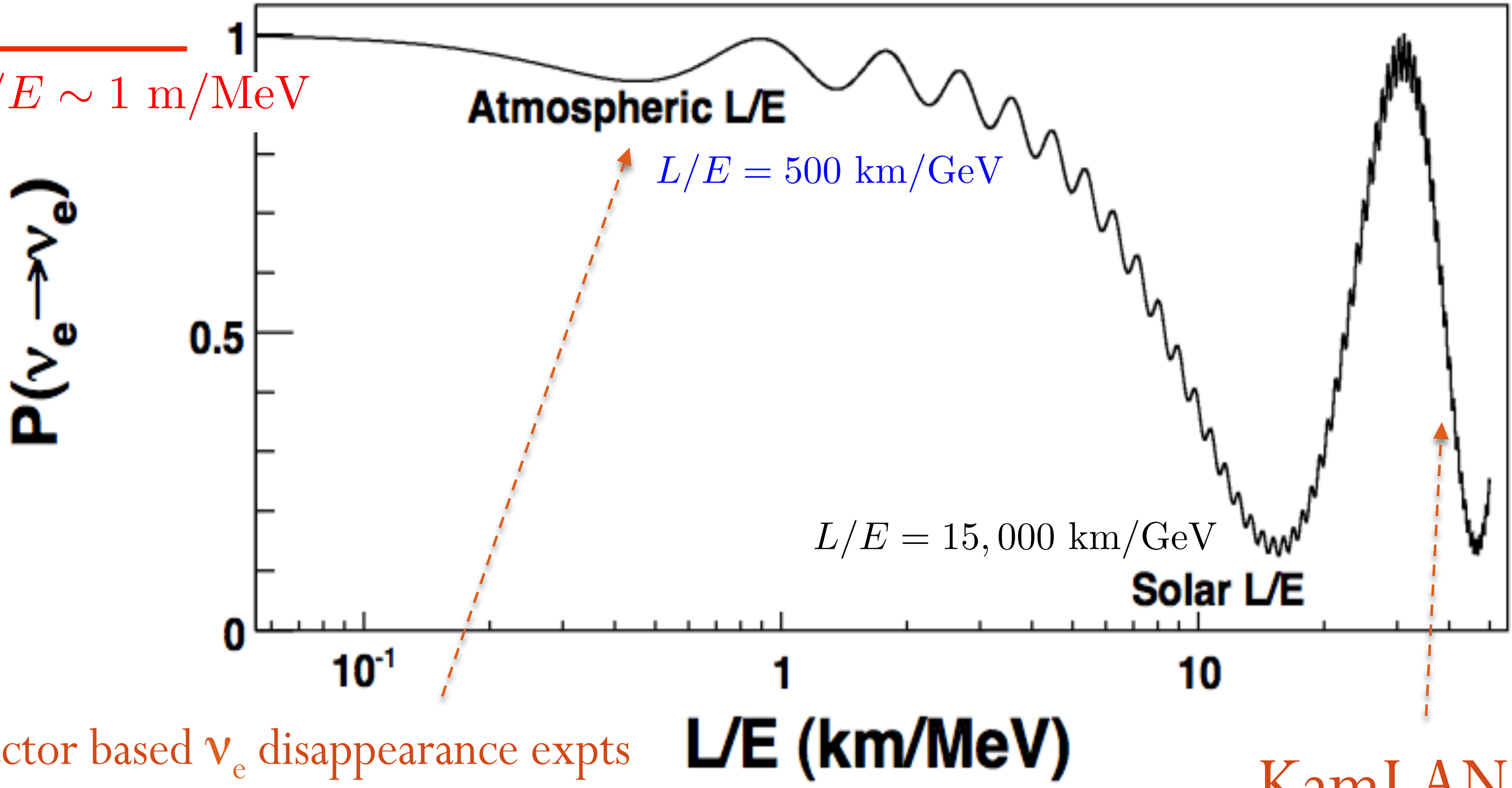
Oscillations with Reactor Neutrinos



$L/E \sim 1\ \mathrm{m/MeV}$

$L/E = 500\ \mathrm{km/GeV}$

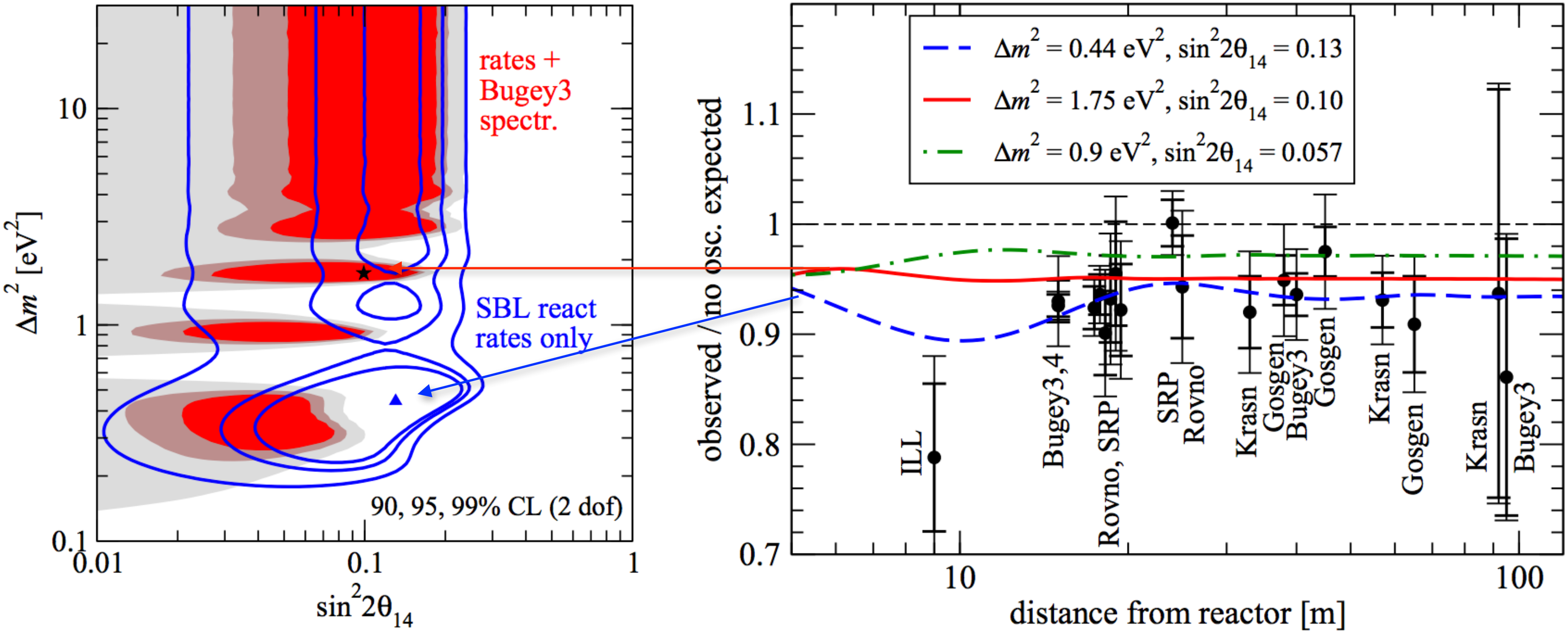
$L/E = 15,000\ \mathrm{km/GeV}$

Reactor based ν_e disappearance expts such as Double Chooz and Daya Bay

KamLAND

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \cdot \sin^2(1.27 \cdot \Delta m^2_{23} \cdot L/E)$$

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{12} \cdot \sin^2(1.27 \cdot \Delta m^2_{12} \cdot L/E)$$

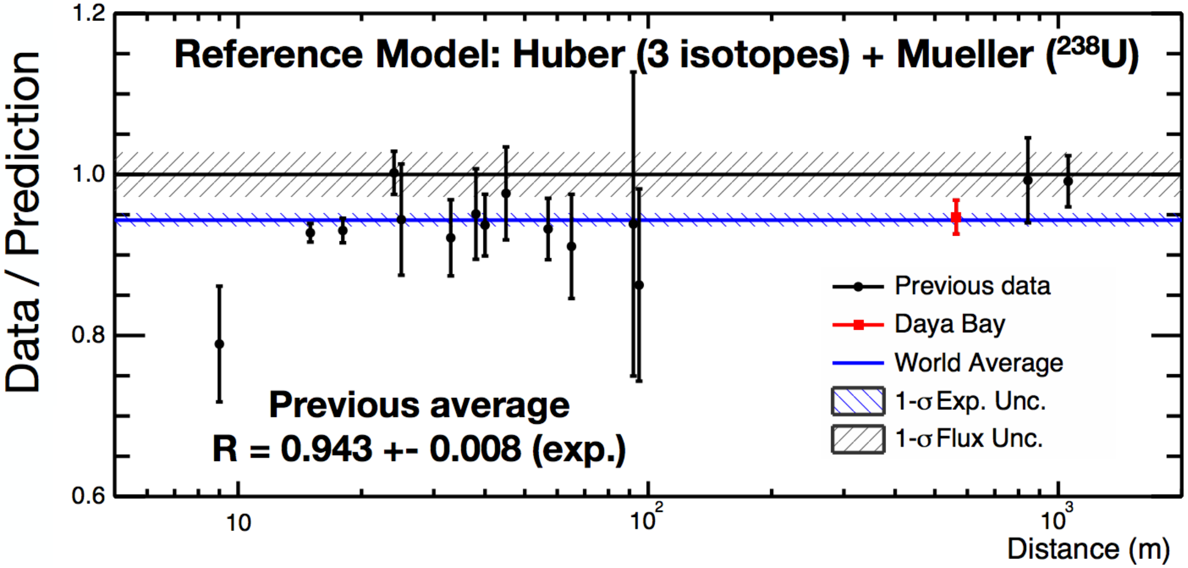


Global fit to reactor data from J. Kopp et al. “Sterile Neutrino Oscillations: the global picture”, arXiv:1303.3011.

New results presented by Daya Bay yesterday at NEUTRINO 2014 in Boston.

Total rate consistent with previous experiments

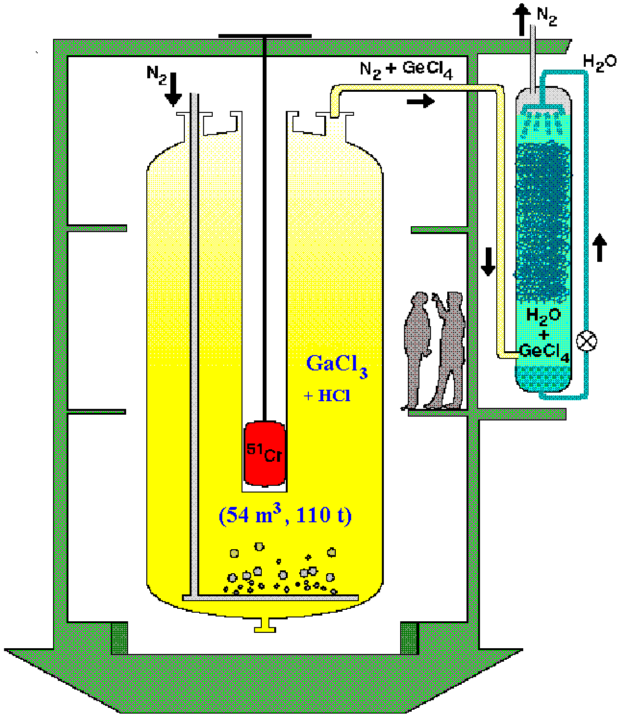
Stringent limit on sterile neutrinos below 0.1 eV^2



GALLEX and SAGE Source Calibration

- G & S measured solar neutrino rates well below the prediction, which of course we now know to be oscillations
- To understand their absolute efficiencies, they calibrated their detectors with low energy neutrino sources - running with Cr-51 or Ar-37 sources
  - Cr-51, for example, produces 750 keV (90%) and 430 keV (10%) neutrinos
  - Ar-37 produces an 811 keV neutrino
- This amounts to an experiment with very low energy neutrinos (100s keV) over a very short baseline (~1-few meters)

$$\nu_e \rightarrow \nu_x$$



GALLEX

GALLEX

$$R_1(Cr) = 0.94 \pm 0.11$$

$$R_2(Cr) = 0.80 \pm 0.10$$

SAGE

$$R_3(Cr) = 0.93 \pm 0.12$$

$$R_4(Ar) = 0.77 \pm 0.08$$

$$\boxed{R = 0.86 \pm 0.05}$$

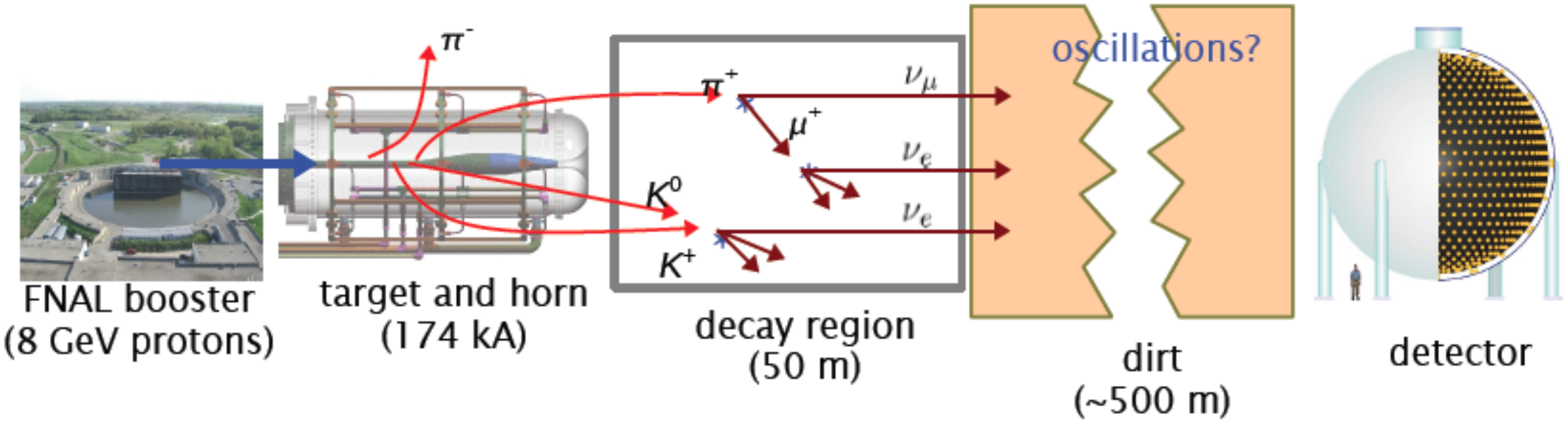
GALLEX: F. Kaether, W. Hampel, G. Heusser, J. Kiko, and T. Kirsten, Phys.Lett. B685 (2010) 47-54. [arXiv:1001.2731].

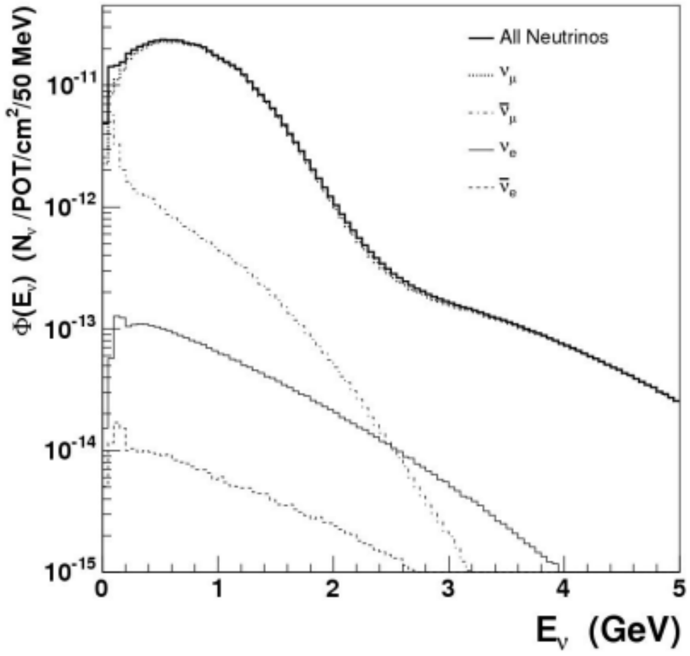
SAGE Cr: J. Abdurashitov et al., Phys. Rev. C59 (1999) 2246-2263. [hep-ph/9803418].

SAGE Ar: J. Abdurashitov, V. Gavrin, S. Girin, V. Gorbachev, P. Gurkina, et al., Phys. Rev. C73 (2006) 045805, [nucl-ex/0512041].

MiniBooNE - The First BNB Experiment

- Designed to follow up on the LSND result as oscillations but with different source, different detector, thus different systematics





$$L/E \sim 1 \ \ \mathrm{m/MeV}$$

same as LSND

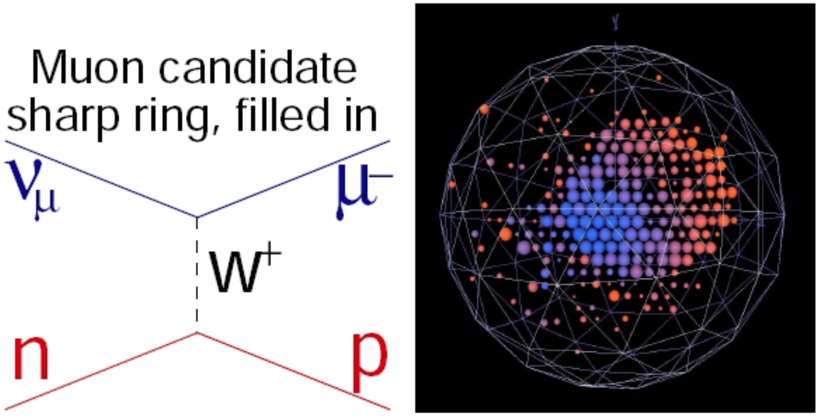
MiniBooNE

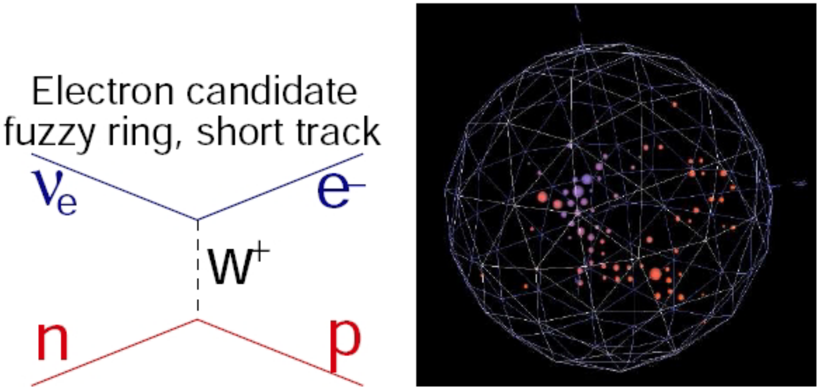
- Cherenkov detector - see Cherenkov light rings generated by charged particles
- Looking for:

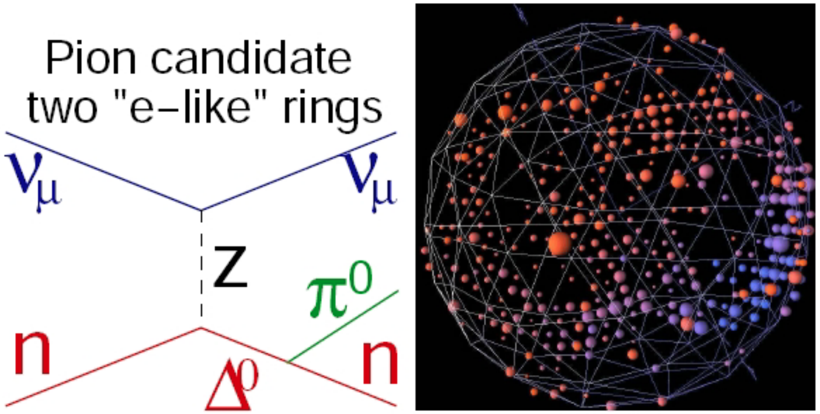
$$\nu_\mu \rightarrow \nu_e$$

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

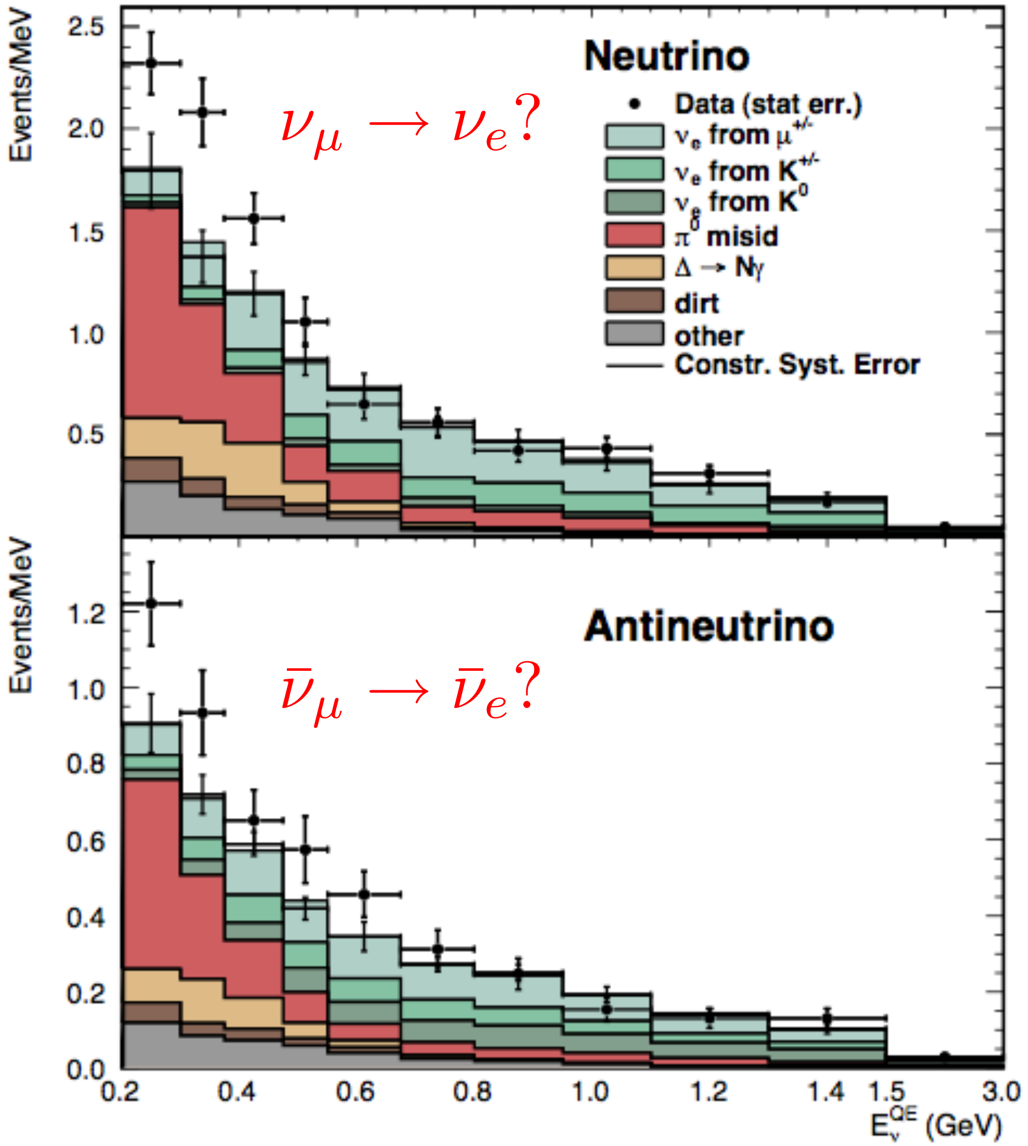
- Backgrounds come from small intrinsic electron neutrino rate in the beam and any ν_μ interactions that leave a single reconstructed photon in the final state
- Cherenkov detector can <u>not</u> distinguish electron from single gamma


Muon candidate
sharp ring, filled in

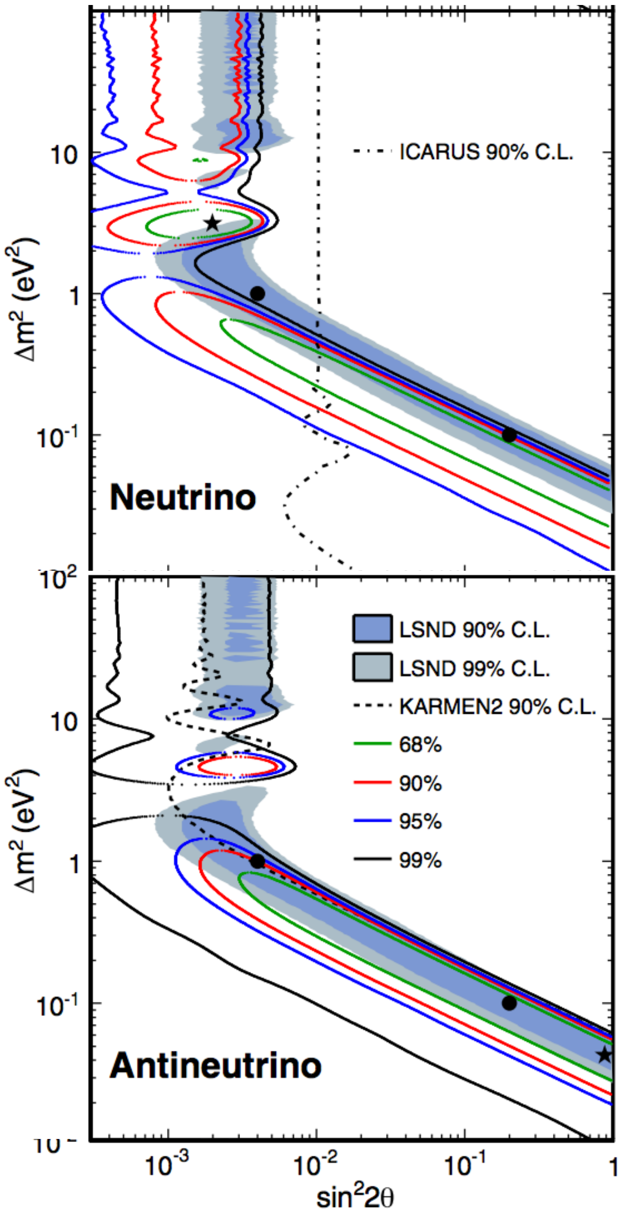

Electron candidate
fuzzy ring, short track


Pion candidate
two "e–like" rings

MiniBooNE Results


$\nu_\mu \rightarrow \nu_e?$

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e?$



Sterile Neutrinos in Cosmology

PRL 112, 051302 (2014)

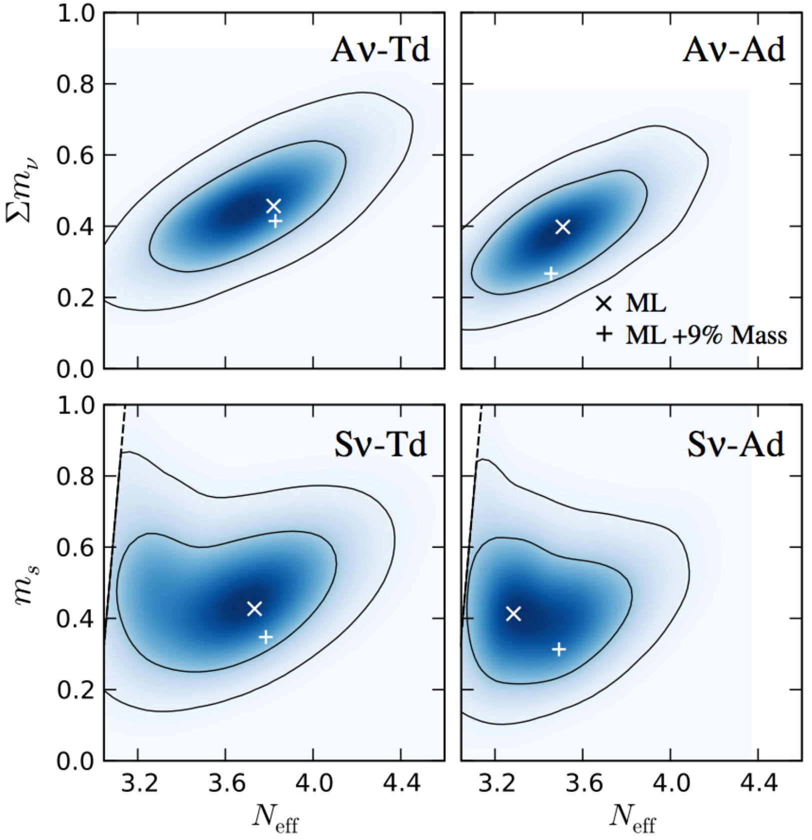
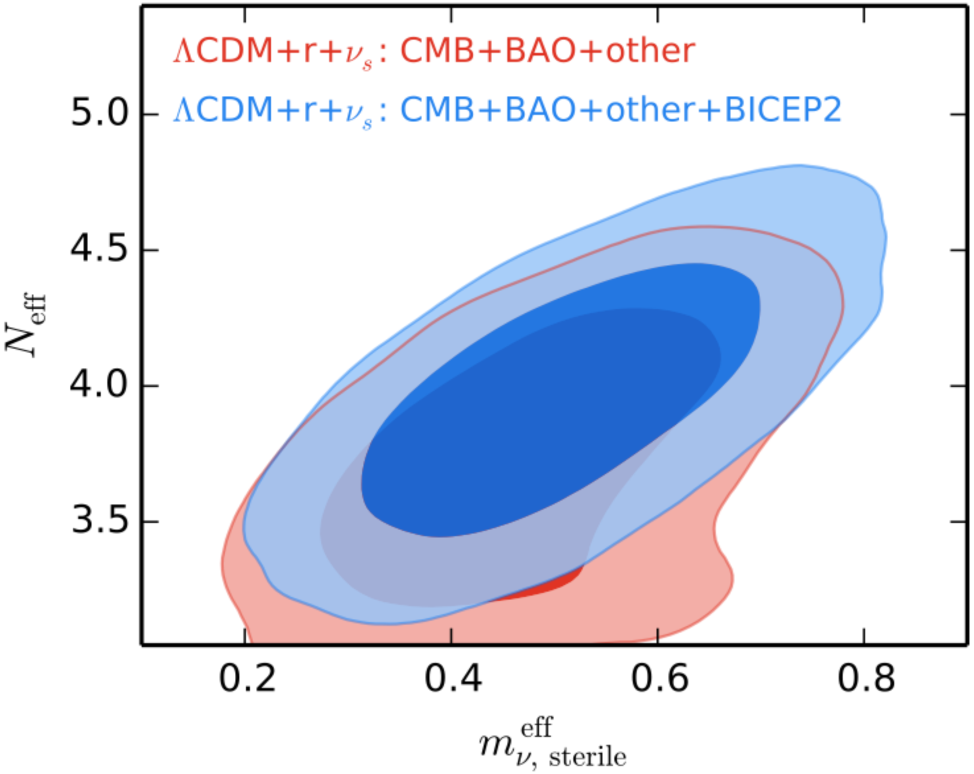
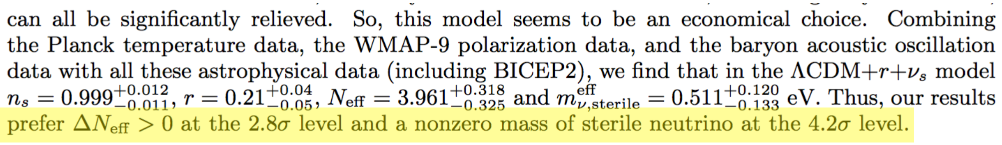


FIG. 2 (color online). Neutrino mass and effective number constraints, labeled as in Fig. 1 (× indicates the ML model, + its shift from a 9% cluster mass increase). Bottom: Sν sterile case for Td (left) and Ad (right). The region excluded by the $m_s^{\rm DW} < 7$ eV prior is left of the dashed line. Top: Aν active case for Td (left) and Ad (right). In all cases the minimal $\sum m_\nu = 0.06$ eV, $N_{\rm eff} = 3.046$, and $m_s = 0$ is highly excluded.

arXiv:1403.7028v2





can all be significantly relieved. So, this model seems to be an economical choice. Combining the Planck temperature data, the WMAP-9 polarization data, and the baryon acoustic oscillation data with all these astrophysical data (including BICEP2), we find that in the ΛCDM+r+ν_s model $n_s = 0.999^{+0.012}_{-0.011}$, $r = 0.21^{+0.04}_{-0.05}$, $N_{\rm eff} = 3.961^{+0.318}_{-0.325}$ and $m_{\nu,\rm sterile}^{\rm eff} = 0.511^{+0.120}_{-0.133}$ eV. Thus, our results prefer $\Delta N_{\rm eff} > 0$ at the 2.8σ level and a nonzero mass of sterile neutrino at the 4.2σ level.

$$m_{\nu,sterile} \sim 0.5\ eV$$

The Fermilab Short-Baseline Neutrino Program

Why π Decay-In-Flight Experiments?

DIF beam provides a rich oscillations program with a single facility:

- $\nu_\mu \rightarrow \nu_e$ appearance
- ν_μ and ν_e disappearance
- both neutrinos and antineutrinos
- CC and NC interactions

Anomalies exist here (MiniBooNE neutrino and antineutrino) and these need to be addressed

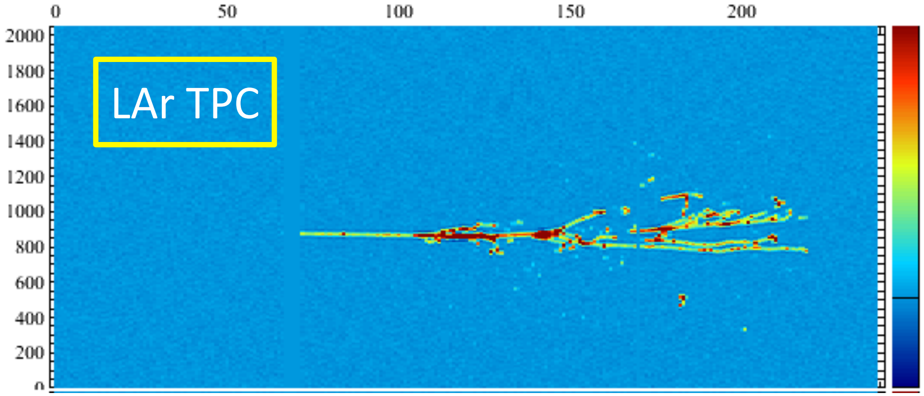
Need detectors that can distinguish electrons from photons

Multiple detectors very valuable for reducing systematic uncertainties

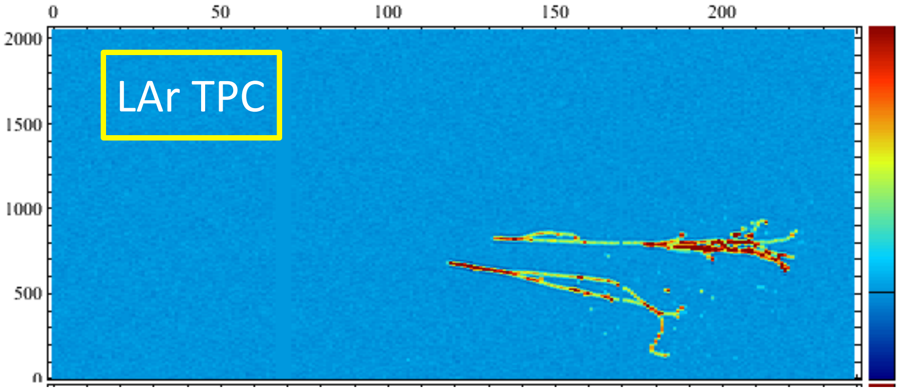
Fermilab is taking the next step on this front with the MicroBooNE experiment

Electron/photon Separation with LAr TPCs

1 GeV electron shower

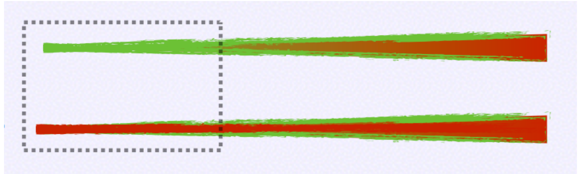


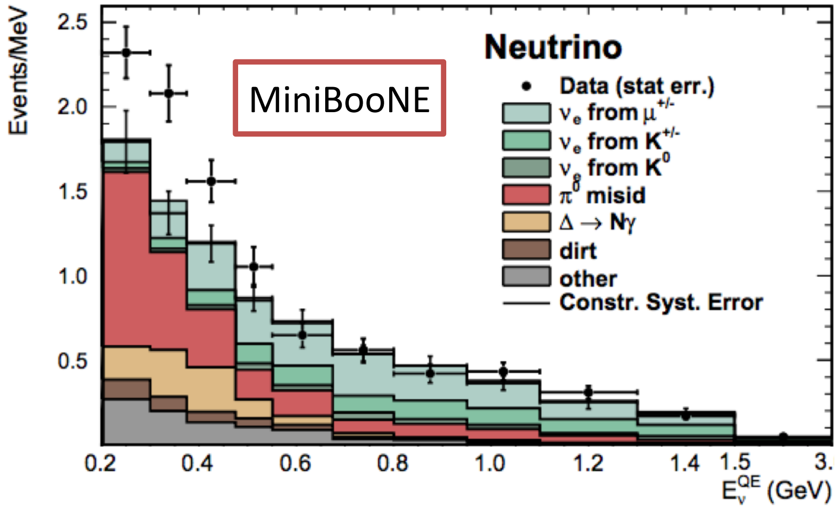
Decay of a 1 GeV π^0 to two photons.

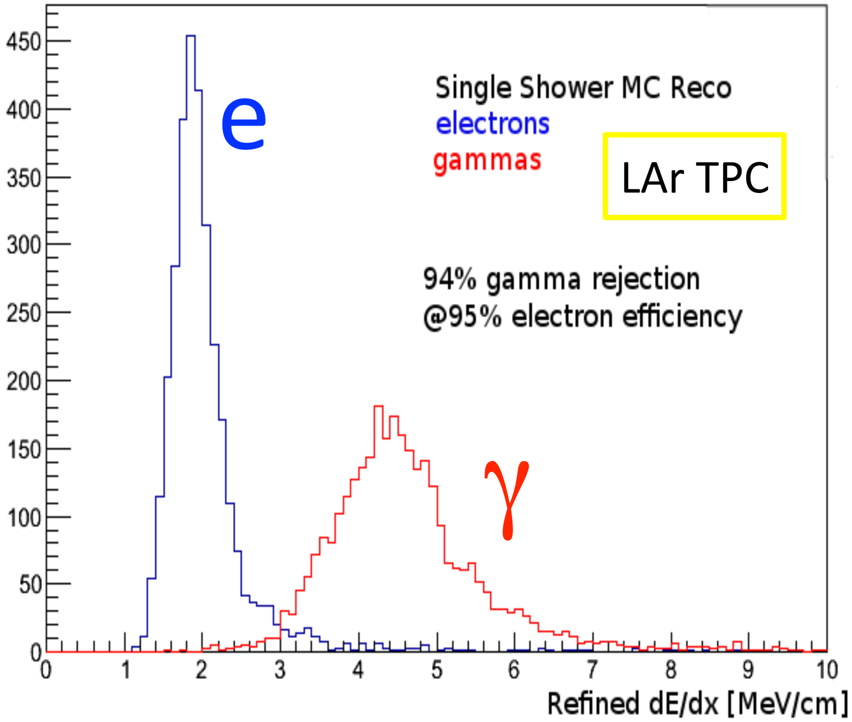


Electron

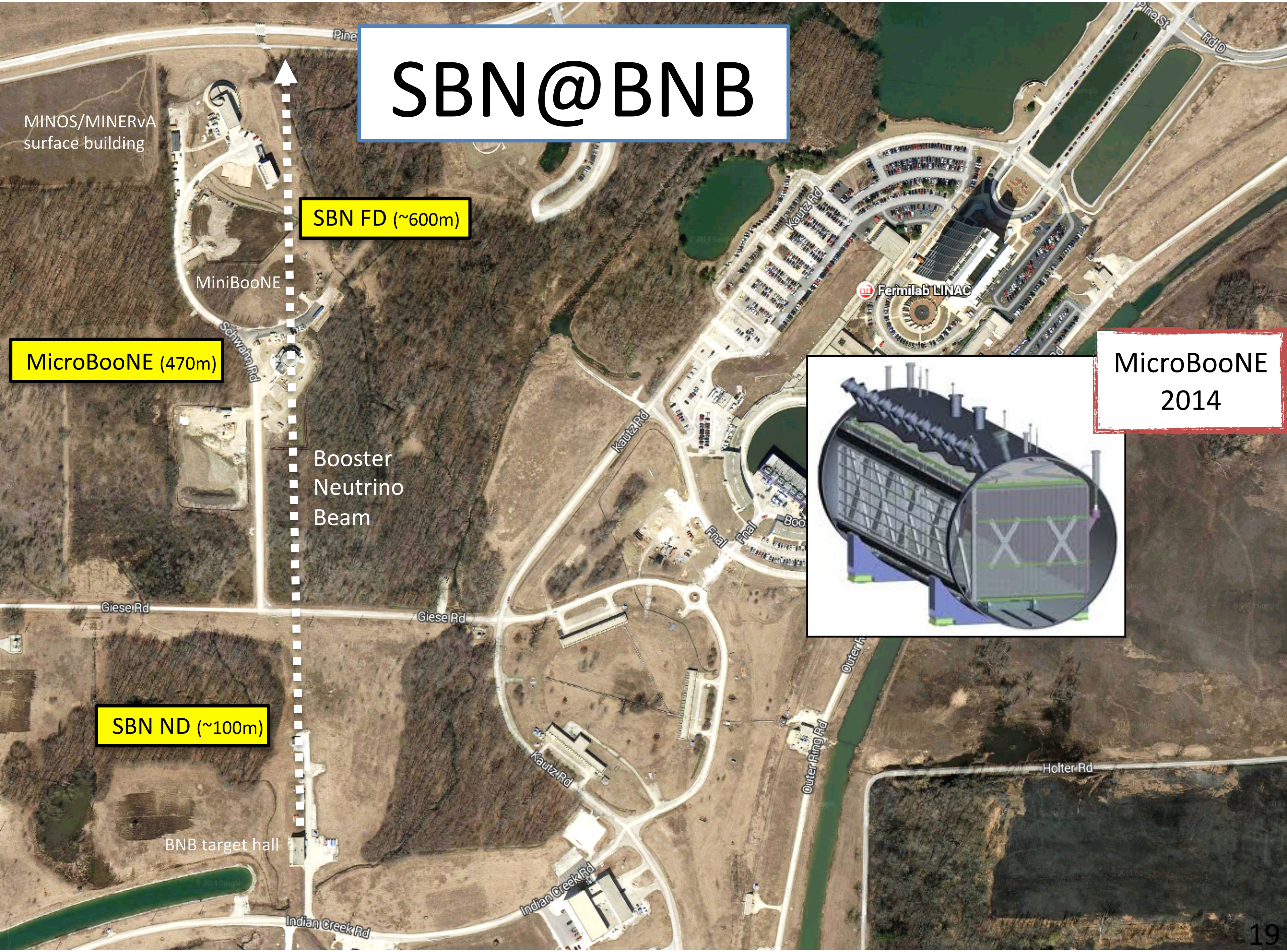
$$\gamma \rightarrow e^+ + e^-$$



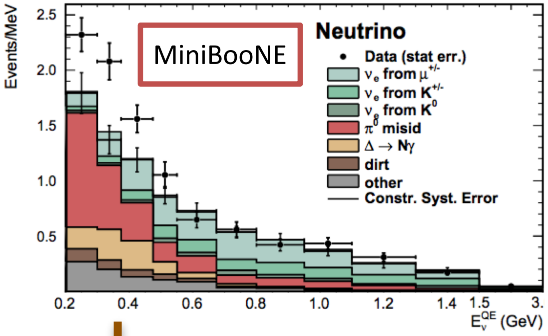


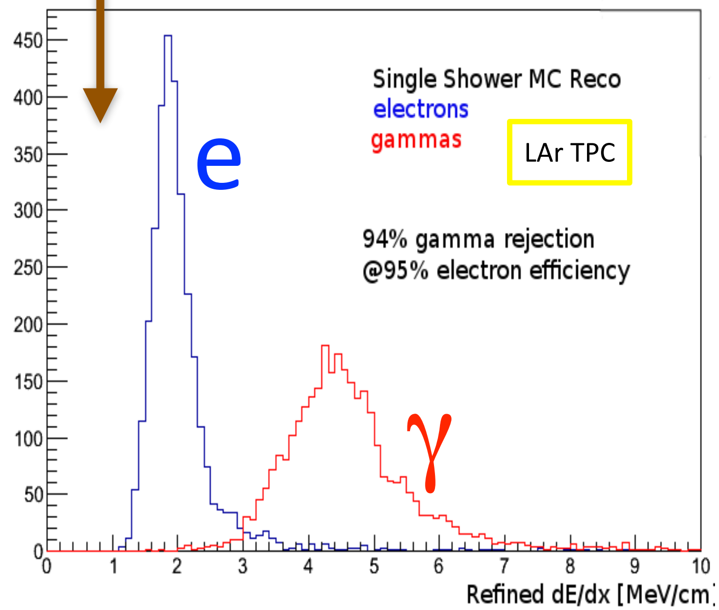


SBN@BNB


MINOS/MINERvA surface building
SBN FD (~600m)
MiniBooNE
MicroBooNE (470m)
Booster Neutrino Beam
SBN ND (~100m)
BNB target hall
MicroBooNE 2014
Pine
Pine St
Rd D
Kautz Rd
Fermilab LINAC
Schwahn Rd
Giese Rd
Giese Rd
Fnal
Fnal
Outer Ring Rd
Holter Rd
Indian Creek Rd
Indian Creek Rd

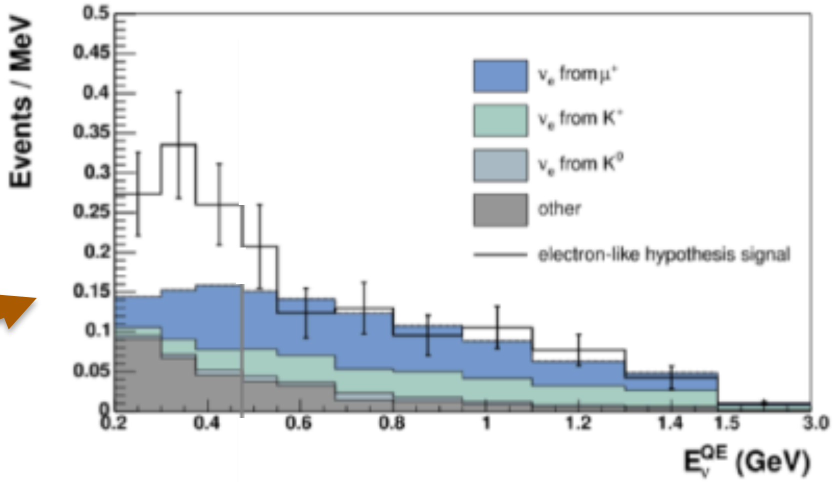
MicroBooNE and the MiniBooNE Excess





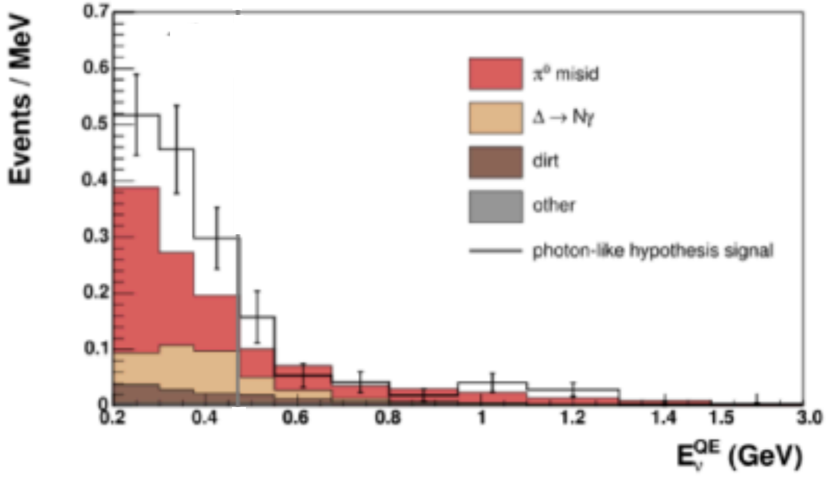
electrons

>5σ stat. significance if all electrons



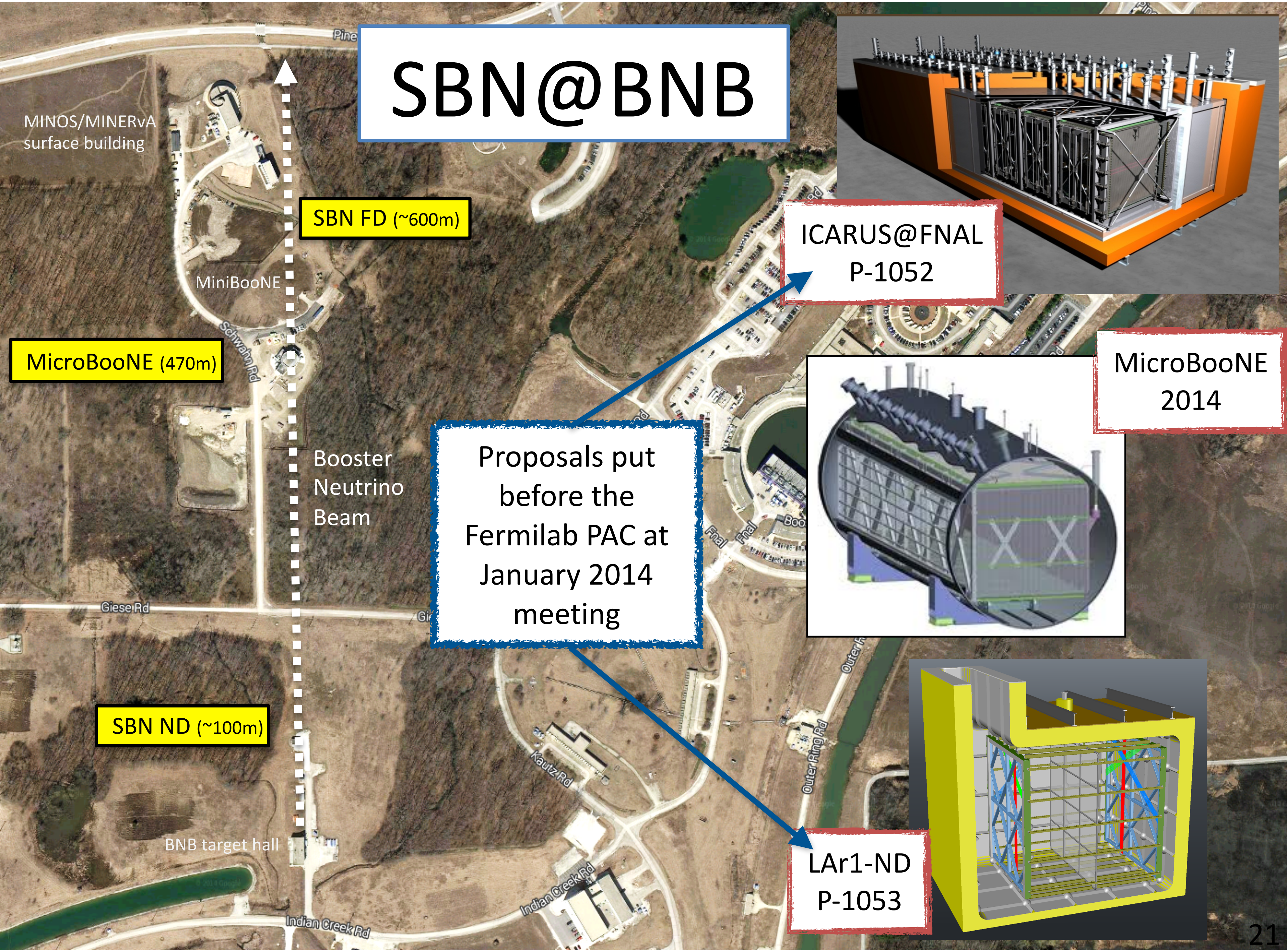
photons

>4σ stat. significance if all photons



MicroBooNE can investigate a critical piece of the puzzle: **are the excess events seen by MiniBooNE electrons or photons?**

SBN@BNB



MINOS/MINERvA surface building

SBN FD (~600m)

MiniBooNE

MicroBooNE (470m)

Booster Neutrino Beam

SBN ND (~100m)

BNB target hall

ICARUS@FNAL
P-1052

MicroBooNE
2014

Proposals put before the Fermilab PAC at January 2014 meeting

LAr1-ND
P-1053

SBN Program Development

- Since the January PAC, proponents of the LAr1-ND and ICARUS proposals, members of the MicroBooNE collaboration, and the laboratory, have been working together to further develop plans for the SBN program

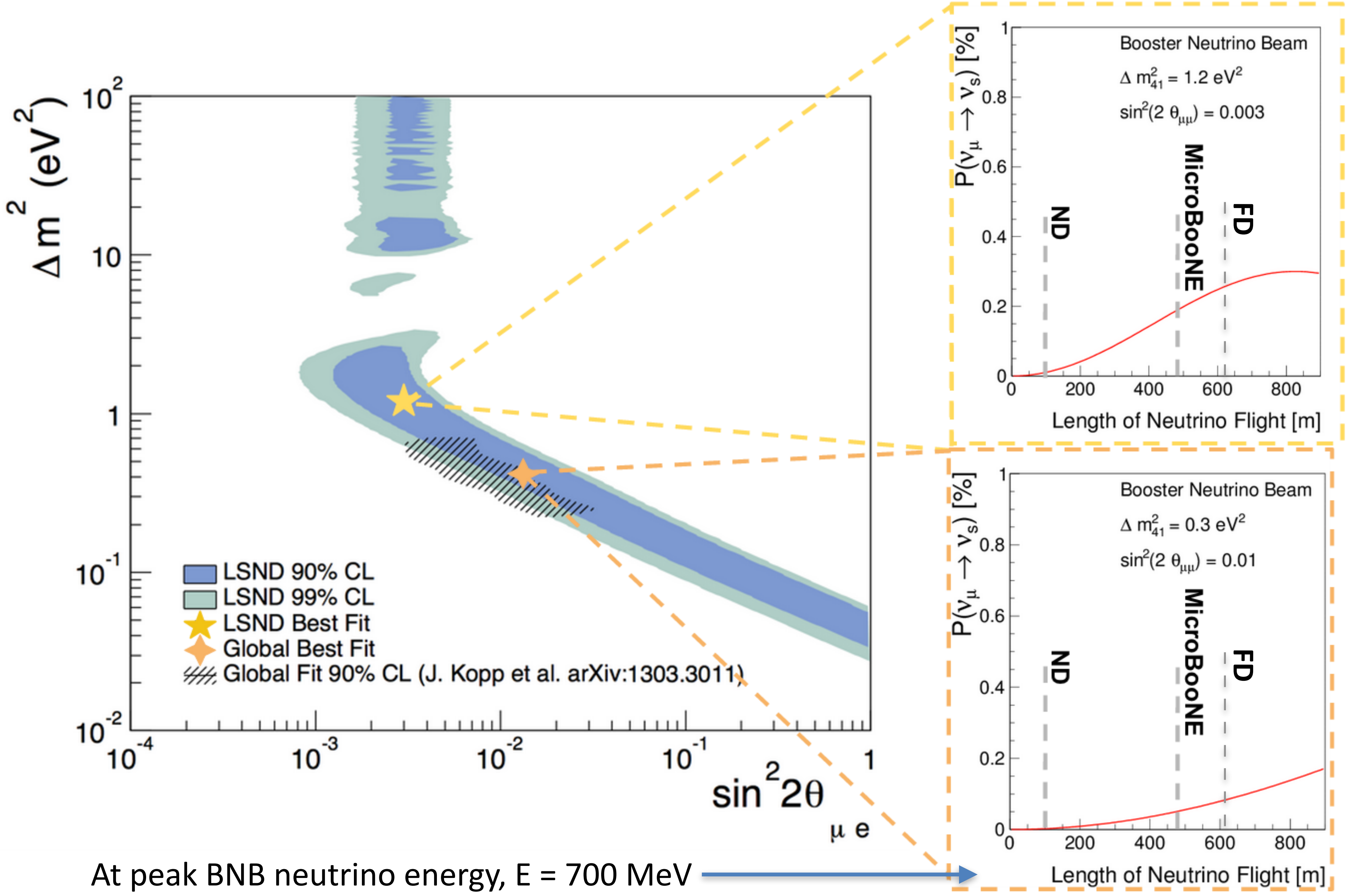
- An international team now drafting a CDR to submit to the PAC for their next meeting in July

- On-going work to study systematics and backgrounds in detail in order to optimize configuration of the program

- Possible Booster Neutrino Beamline modifications being studied as a way to increase fluxes, optimize S/B, or reduce systematics

- Anticipate start of data-taking (for phase beyond MicroBooNE) by <u>2018</u>

Sterile Neutrino Oscillations

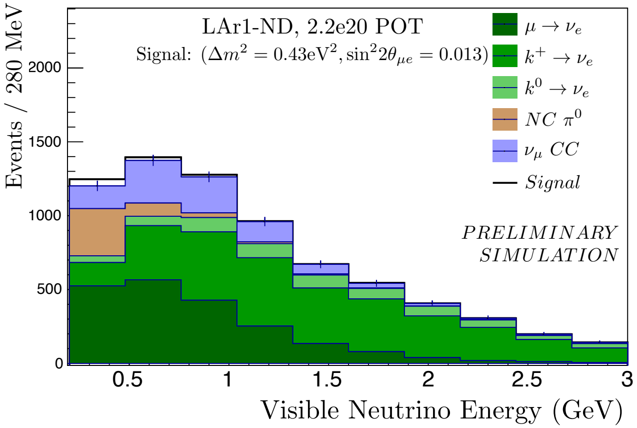


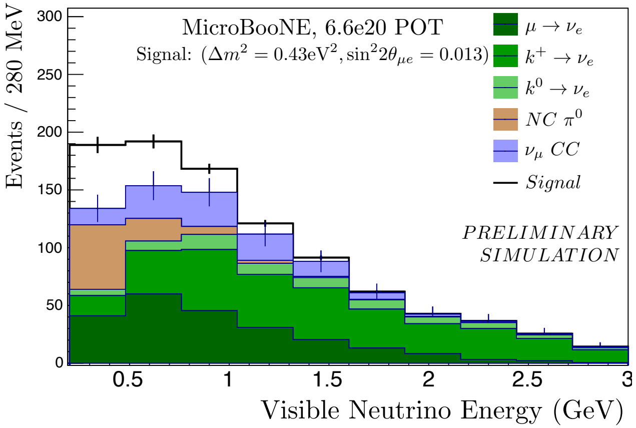
At peak BNB neutrino energy, E = 700 MeV

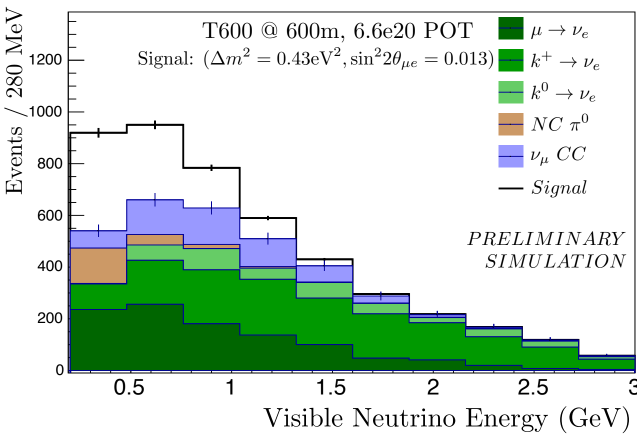
ND @ 100 m

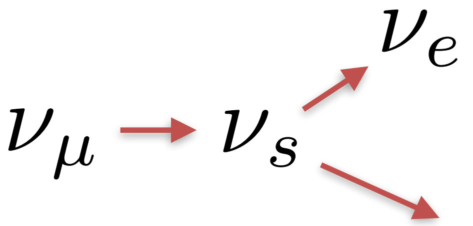
MicroBooNE @ 470 m

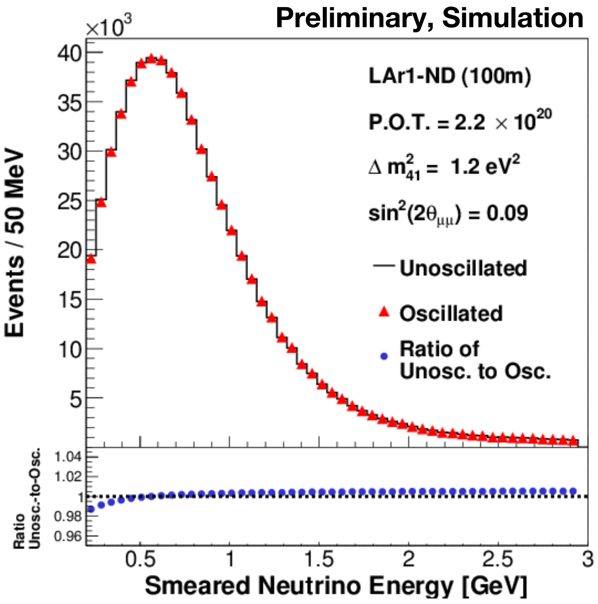
ICARUS T600 @ 600 m

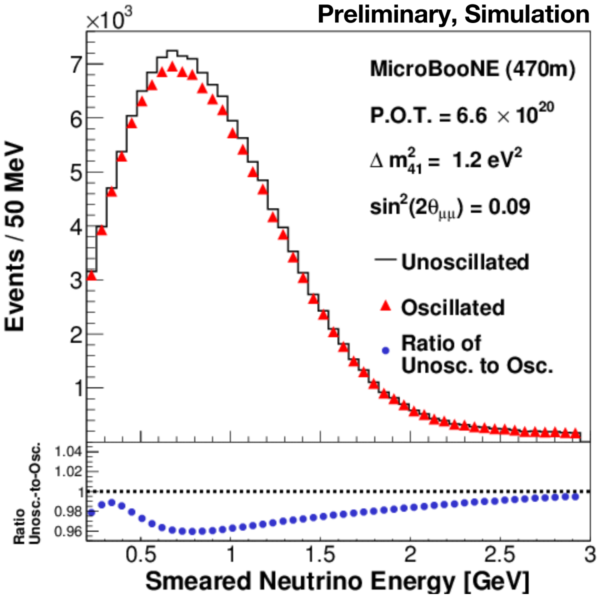


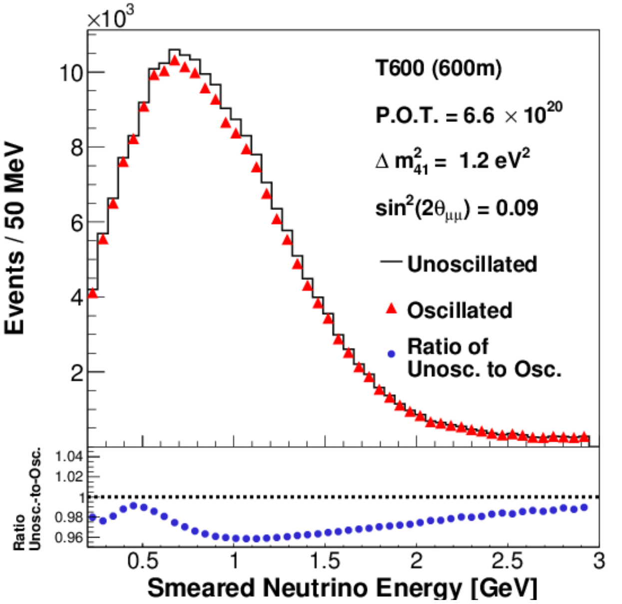




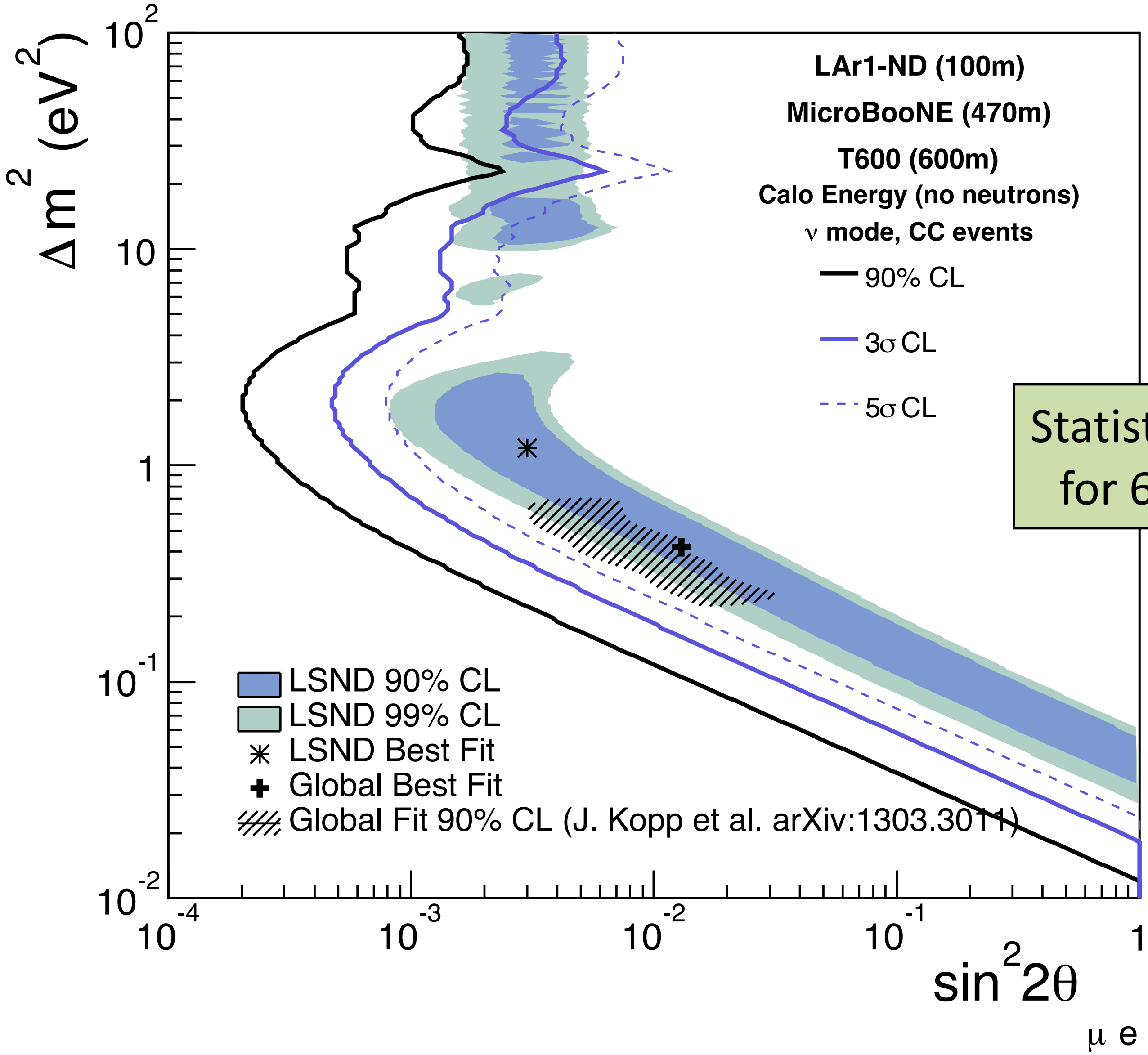








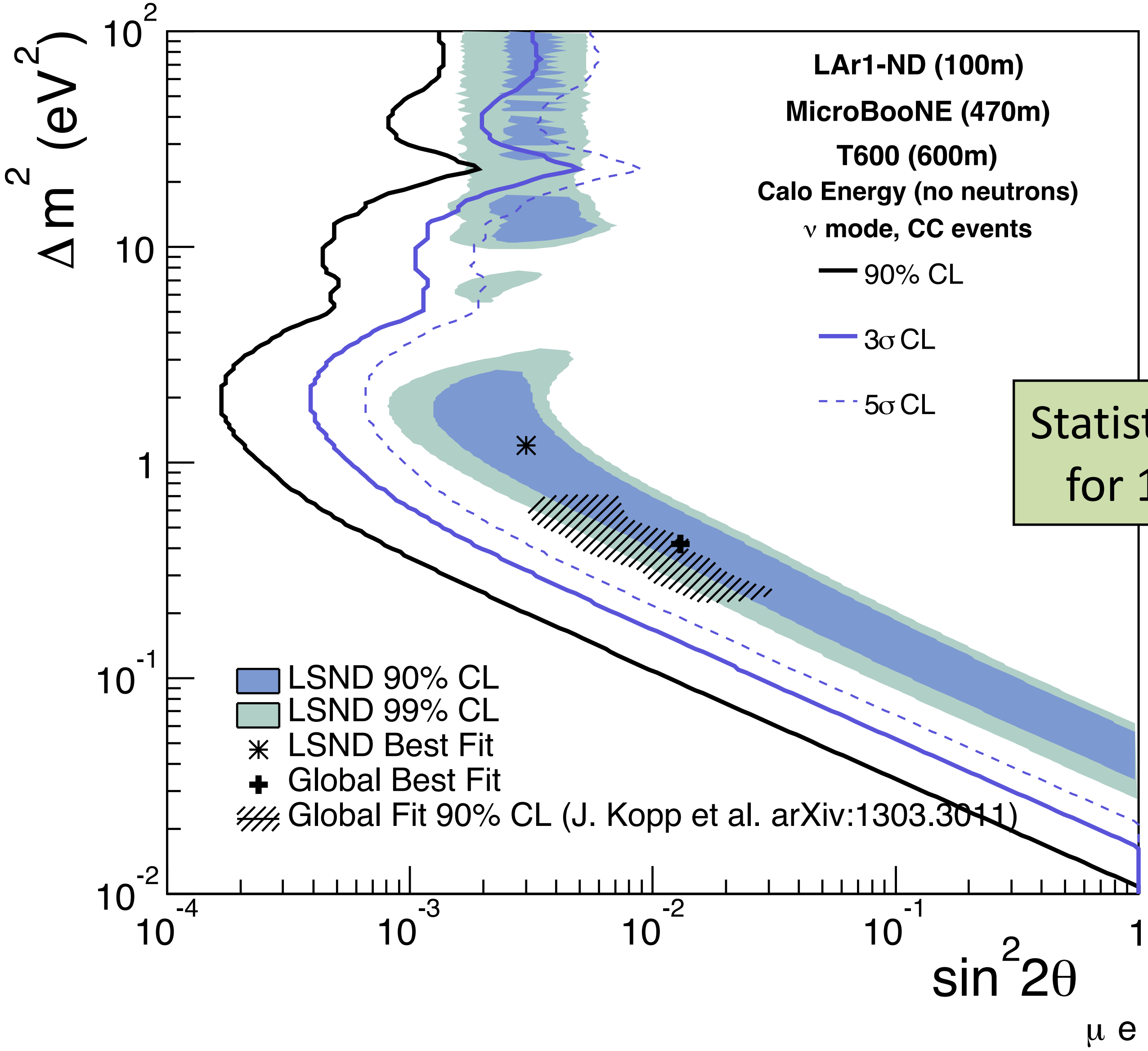
$\nu_\mu \rightarrow \nu_e$ Appearance



Statistical Uncertainty Limit for 6.6e20 POT exposure

Projecting this exposure onto a time axis is clearly important and depends on proton economics after ~2018.

$\nu_\mu \rightarrow \nu_e$ Appearance

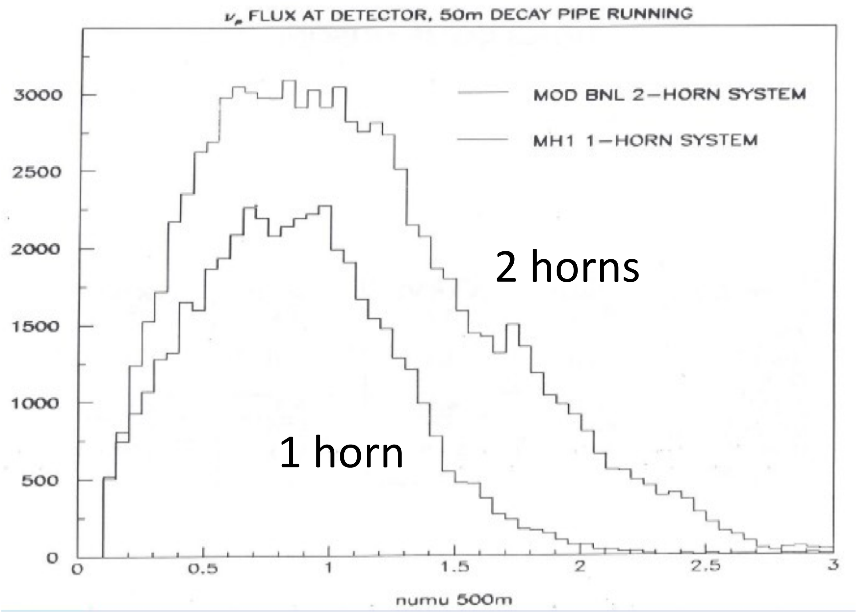


Impact of increased exposure by 50%

Statistical Uncertainty Limit for 10e20 POT exposure

Make Every Proton Count

- Possible BNB upgrades:
  - 2nd horn?
  - New target?
  - New horn inner conductor design?
  - Deploy 25m absorber?



- Beamline was optimized for MiniBooNE in 1990s
  - Neutrino detector technology matters (S/B is the metric)
  - Available hadron production data (from HARP expt.) means pion production off the target now better understood. Re-optimize focusing?

Summary

- The search for sterile neutrinos is a place where neutrino physics is confronting potentially new physics.
  A discovery would be revolutionary.

- We are pursuing to build a world-leading program here at Fermilab, utilizing the existing BNB. An optimized program is under development for the summer PAC.

- Possible optimizations of BNB components being studied.

- Reaching the SBN goals will require intense beam delivery to the BNB for several years to come, well into the 2020s.

Overflow

Three Neutrino Mixing

- Three neutrino mixing firmly established…

Leptonic Mixing Matrix

flavor states
participating in
standard weak
interactions

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

neutrino
mass states

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospheric &
Long-baseline accelerator
neutrinos

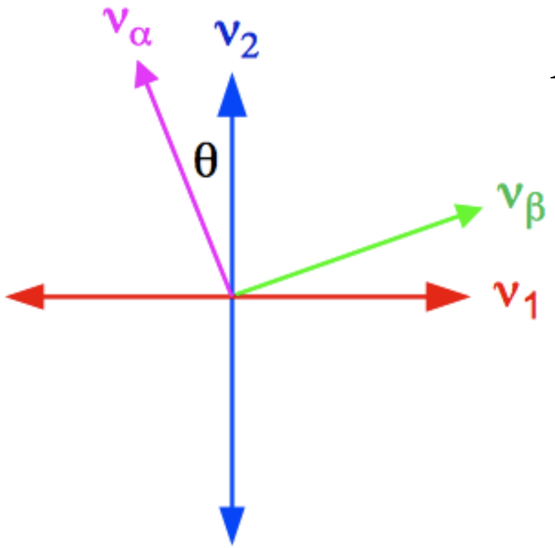
Quasi
2-neutrino
mixing

Solar &
Long-baseline reactor
neutrinos

$L/E = 500\ \mathrm{km/GeV}$

$L/E = 15,000\ \mathrm{km/GeV}$

Simplified Neutrino Oscillations



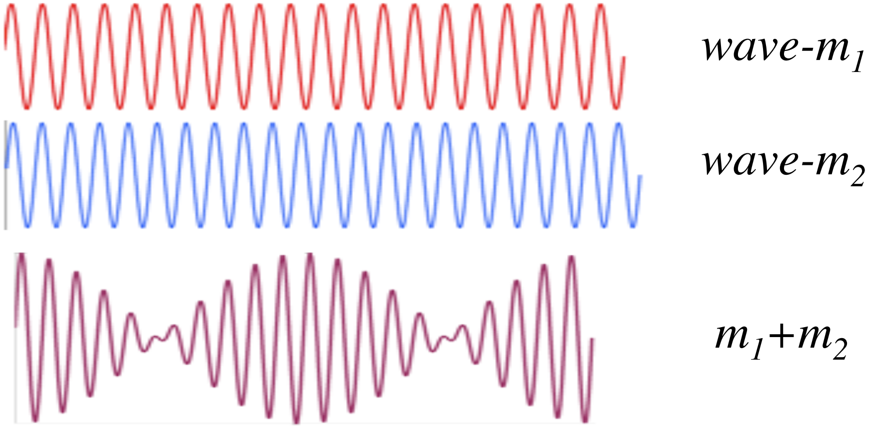
$$P\left(\nu_\alpha \rightarrow \nu_\beta\right) = \sin^2 2\theta_{ij} * \sin^2\left(1.27\,\Delta m_{ij}^2 \frac{L}{E}\right)$$

The mixing angle, θ, determines the amplitude of the oscillation

Δm^2 determines the shape of the oscillation as a function of L (or E)

$$\Delta m_{ij}^2 \equiv m_j^2 - m_i^2$$

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta_{ij} & \sin\theta_{ij} \\ -\sin\theta_{ij} & \cos\theta_{ij} \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix}$$



Reactor Neutrino Anomaly

- In preparation for Double Chooz analysis with a single far detector, Mueller et al. applied an improved procedure to go from measured ^{235}U, ^{239}Pu, and ^{241}Pu β^- spectra (at ILL) to neutrino spectra.
  - Th. A. Mueller et al. "Improved Predictions of Reactor Antineutrino Spectra" Phys. Rev. C83 (2011) 054615; arXiv:1101.2663.
- Result was a net 3% increase in the estimated fluxes relative to previous predictions, leading to reanalysis of 19 past reactor neutrino experiments at baselines less that 100 m. Mean average data/theory ratio including correlations is 0.927 ± 0.023, indicating a 7.3% deficit in electron antineutrinos at short-baseline.
  - G. Mention et al. "The Reactor Antineutrino Anomaly", Phys. Rev. D83 (2011) 083006; arXiv: 1101.2755.
- P. Huber, using a different method to go from β- to neutrino spectra, finds a similar shift
  - P. Huber, "On the determination of anti-neutrino spectra from nuclear reactors"; arXiv:1106.0687.
- Uncertainties are challenging to understand and could be underestimated as pointed out by Hayes et. al.
  - A.C Hayes et al. "Systematic Uncertainties in the Analysis of the Reactor Neutrino Anomaly"; arXiv: 1309.4146

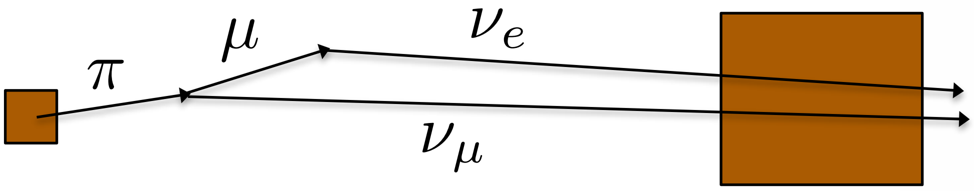
Different Approaches Being Pursued

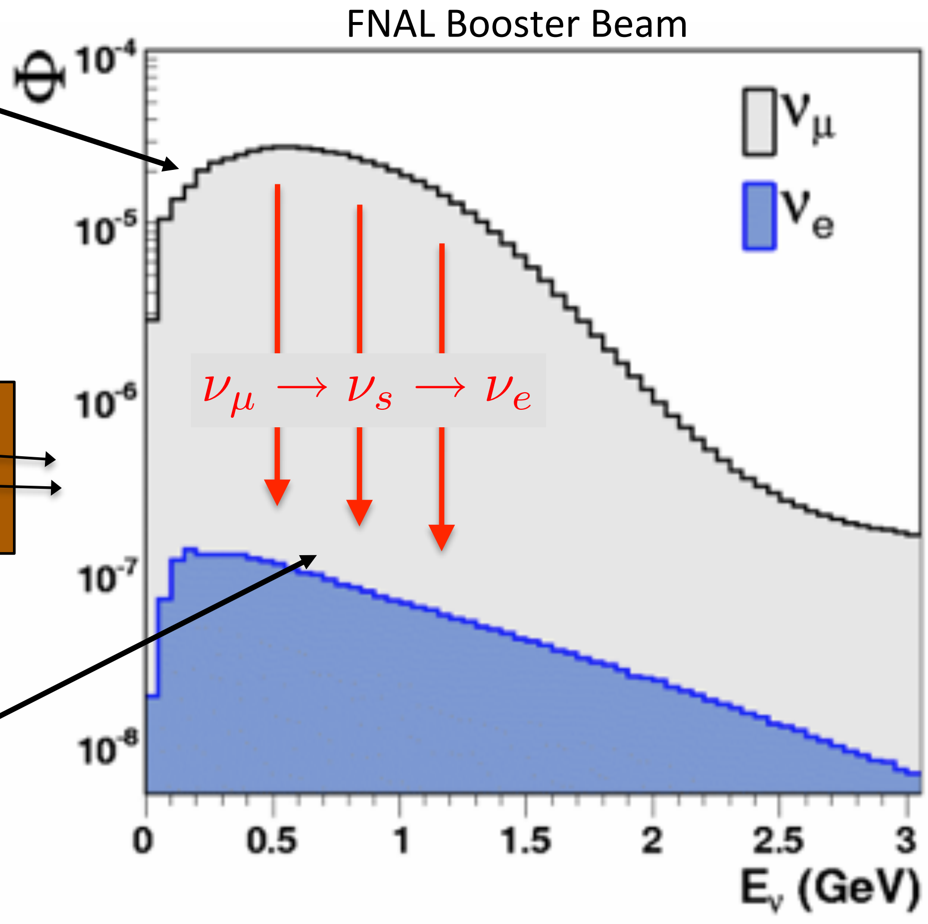
"Given the potential implications [and challenges] of sterile neutrinos, it is important to confirm their existence in multiple (preferably orthogonal) approaches." Light Sterile Neutrinos: A White Paper (arXiv:1204.5379)

Radioactive neutrino sources	$\nu_e/\bar{\nu}_e$ dis.	$100s$ of keV, $10s$ of cm
Nuclear reactor antineutrinos	$\bar{\nu}_e$ dis.	< 10 MeV, < 20 m
Stopped π beams	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	~ 30 MeV, 30 m
Stopped K beams	$\nu_\mu \rightarrow \nu_e$	235.5 MeV, 160 m
Decay in flight π/K beams	$\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_\mu/\bar{\nu}_\mu$ dis. , $\nu_e/\bar{\nu}_e$ dis.	500 MeV – 2 GeV 100 m – 2000 m
Atmospheric neutrinos	$\nu_\mu/\bar{\nu}_\mu$ dis.	< 20 GeV, 15 – 130 km 100 GeV – 400 TeV, $< 1.3 \times 10^4$ km
Cosmology	indirect N_s, m_ν	

MiniBooNE - A One Detector Experiment

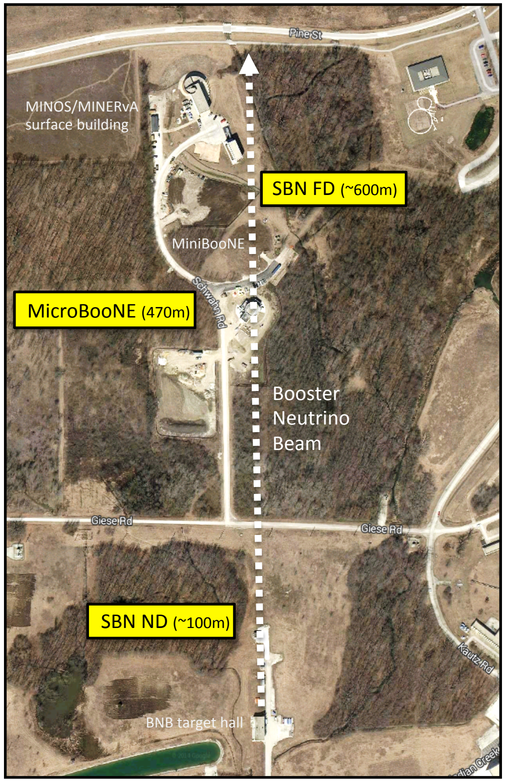
effectively unoscillated large-statistics muon neutrino CC sample provides a <u>constraint</u> on (*flux* × *xsec*) of electron neutrino CC rate



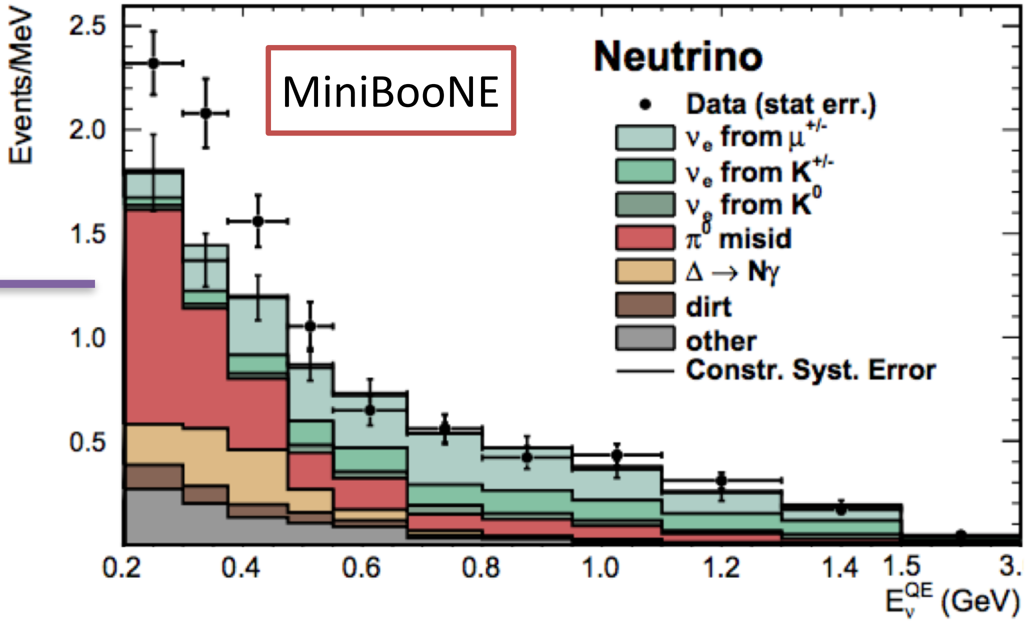


look for an **excess** on top of the expected intrinsic electron neutrino CC rate

Length Dependence of MiniBooNE Excess



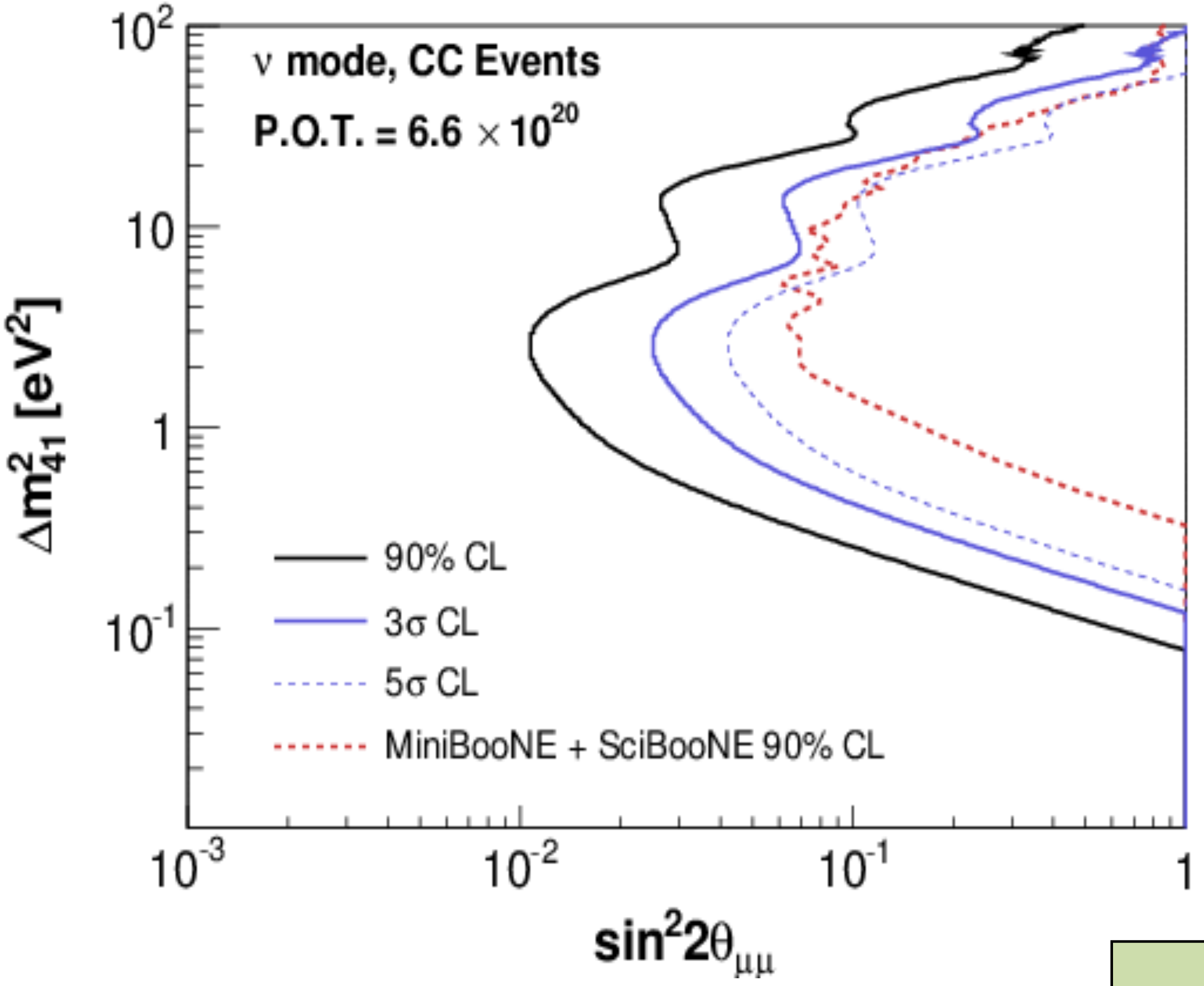
A. A. Aguilar-Arevalo *et al.*, Phys. Rev. Lett. 110 161801 (2013)



By scaling directly from observed rates in MiniBooNE, MicroBooNE expects to see ~50 background and 50 excess events in 6.6x10^{20} POT run

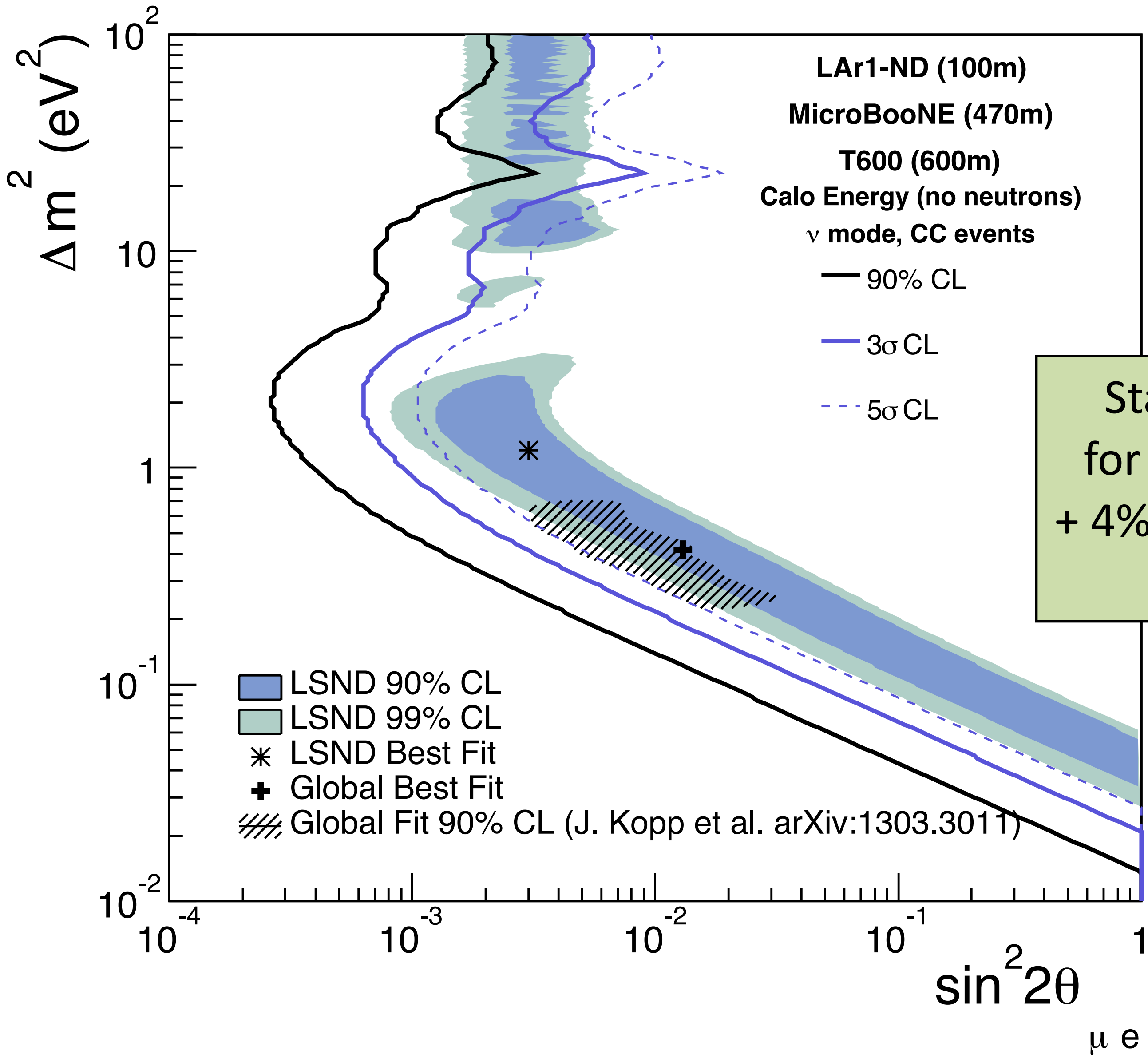
Assuming NO L/E dependence, ND would expect to see ~320 background and 300 excess events in 2.2x10^{20} POT run

ν_μ Disappearance



4% systematics on near to far extrapolation

$\nu_\mu \rightarrow \nu_e$ Appearance



Statistical Uncertainty
for 10e20 POT exposure
+ 4% systematic on near to
far extrapolation