Low Energy Neutrino Oscillations

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Standard Model & Neutrino Oscillations

- 3 neutrinos
  - Initially assumed massless
- Mixing matrix:

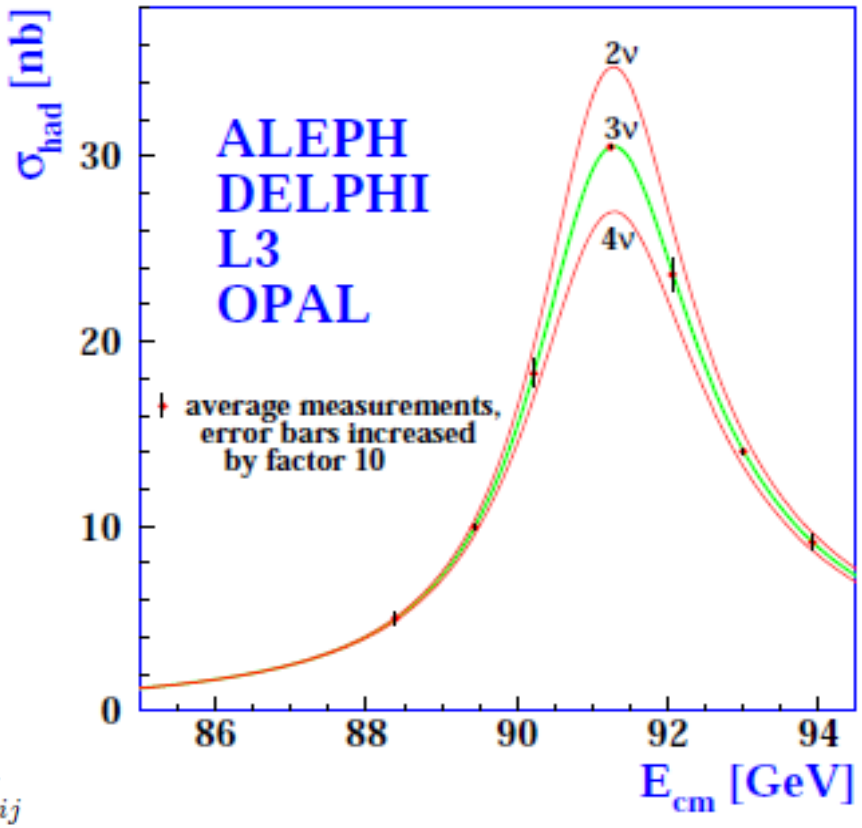
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} U_{e2} U_{e3} \\ U_{\mu 1} U_{\mu 2} U_{\mu 3} \\ U_{\tau 1} U_{\tau 2} U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Oscillation Probability:

$$P_{\alpha\beta} = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 = \delta_{\alpha\beta} - 4 \sum_{i<j}^{n} \mathrm{Re}[U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}] \sin^2 X_{ij}$$

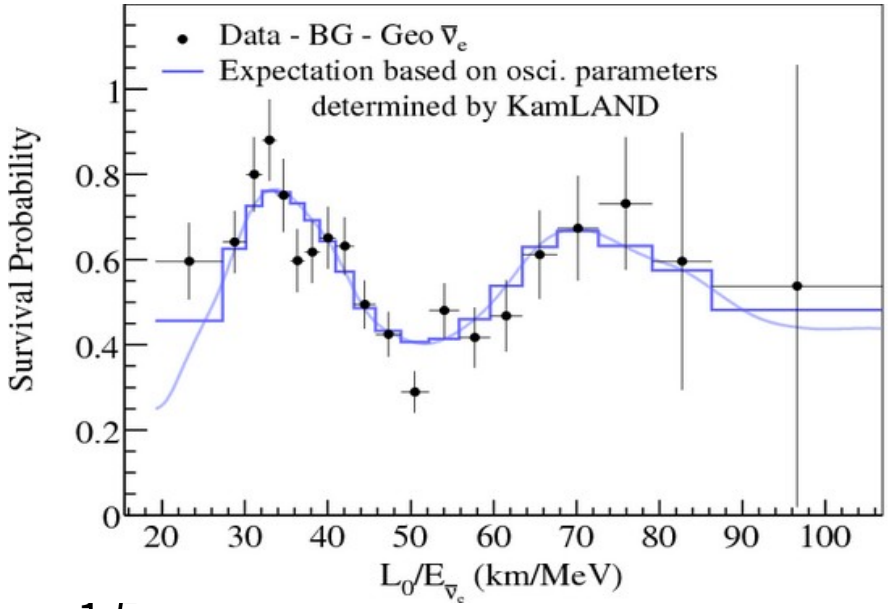
$$+ 2 \sum_{i<j}^{n} \mathrm{Im}[U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}] \sin 2X_{ij}$$

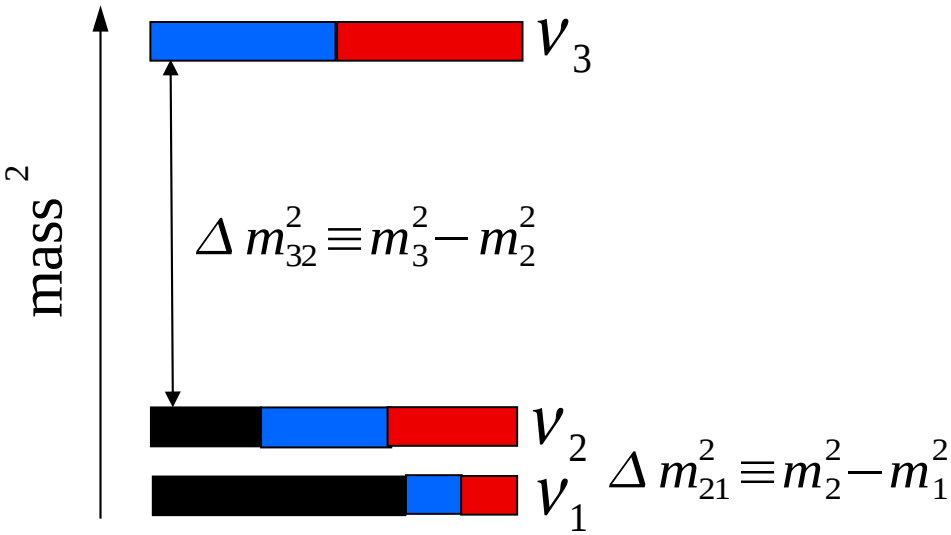
$$X_{ij} = \frac{(m_i^2 - m_j^2)L}{4E} = 1.27 \frac{\Delta m_{ij}^2}{\mathrm{eV}^2} \frac{L/E}{\mathrm{m/MeV}}$$

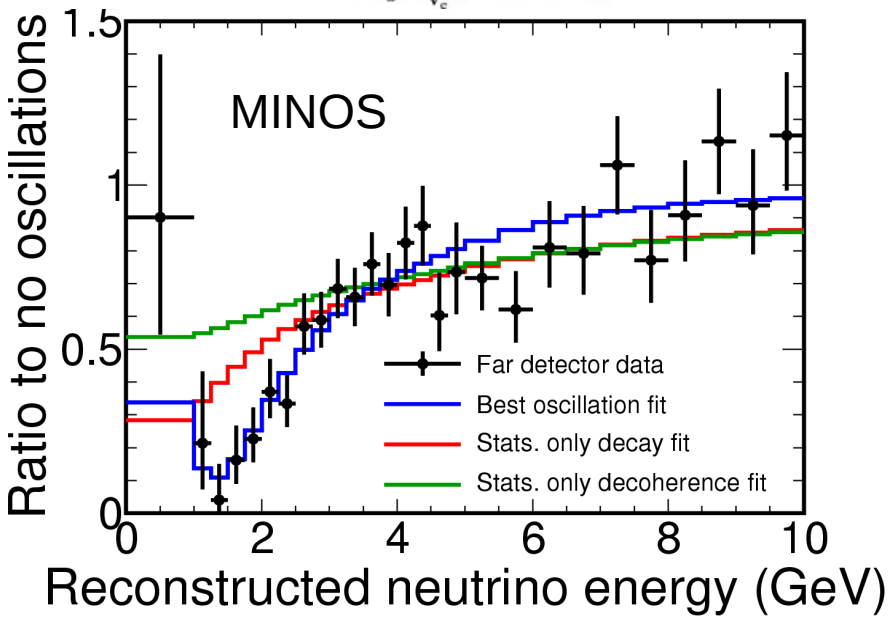


Neutrino Oscillations

- Lot of experimental evidence
- L/E dependence
- Precise measurement of atmospheric and solar Δm^2





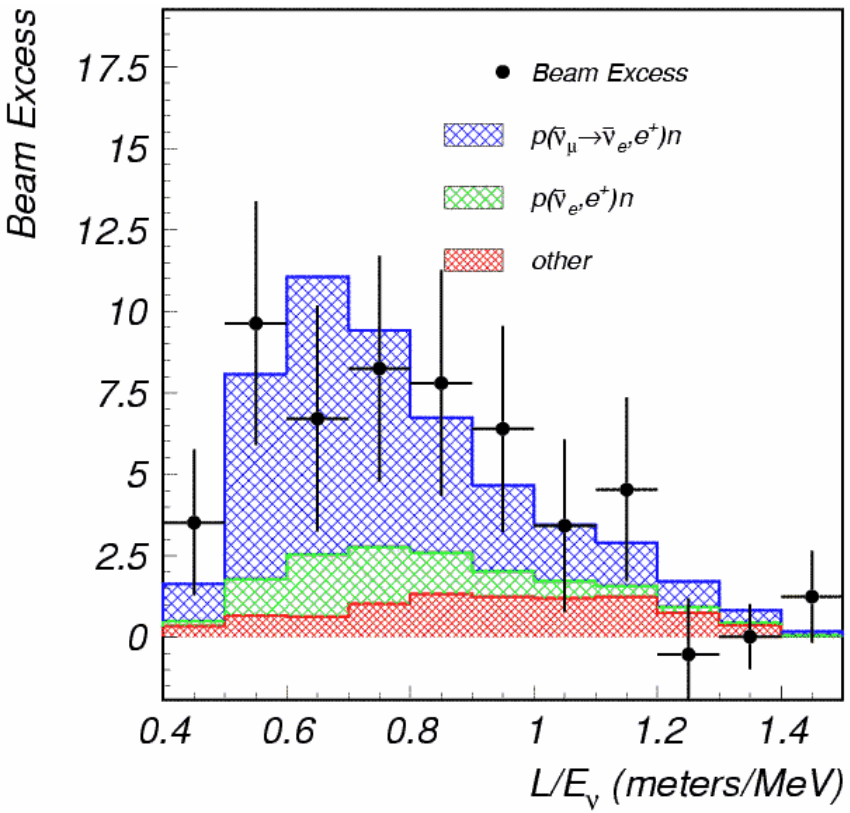


LSND

- Evidence for oscillations at higher Δm^2 than atmospheric and solar
- Stopped pion beam

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

- Excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam
- $\bar{\nu}_e$ signature: Cherenkov light from e^+ with delayed n-capture
- Excess=87.9 ± 22.4 ± 6 (3.8σ)

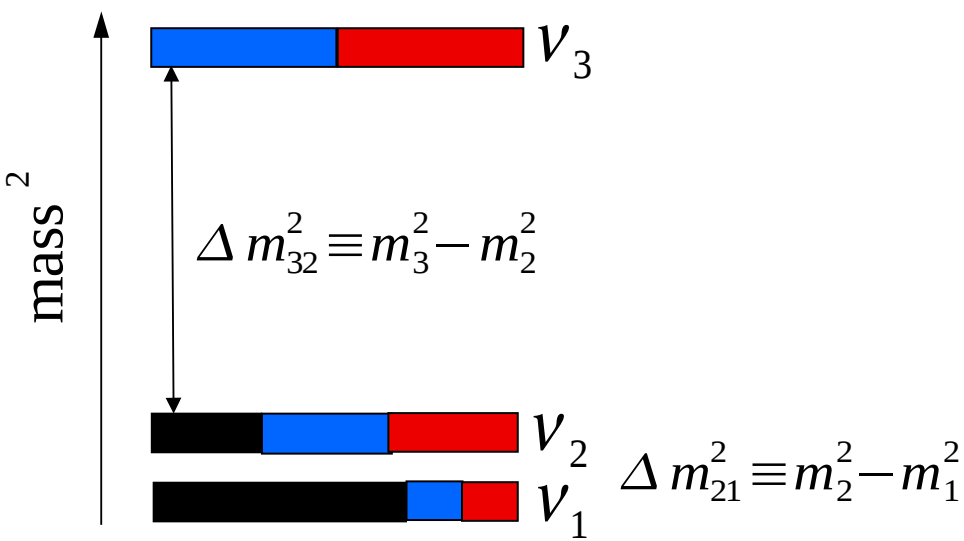


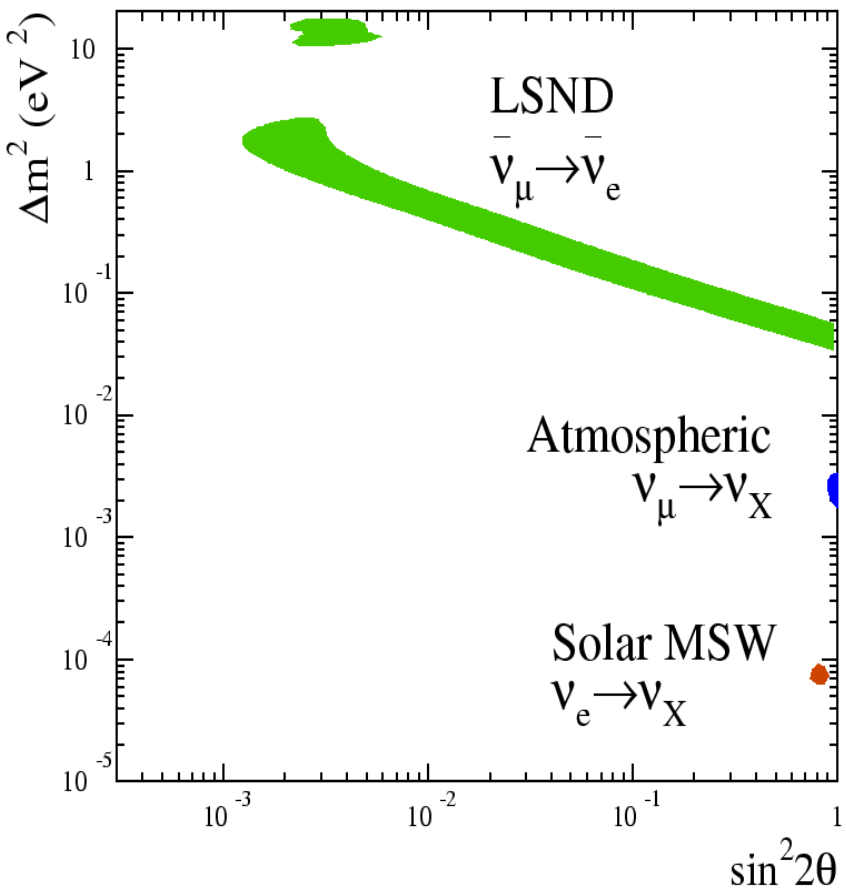
LSND signal

- Assuming two neutrino oscillations

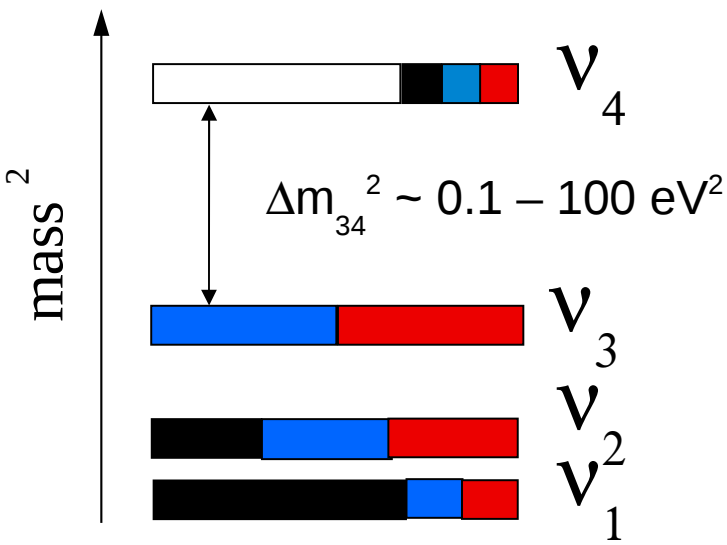
$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\ L\,\Delta m^2}{E}\right)$$
$$= 0.245 \pm 0.067 \pm 0.045\ \%$$

- Can't reconcile LSND result with atmospheric and solar neutrino using only 3 Standard Model neutrinos – only two independent mass splitings





Sterile neutrinos



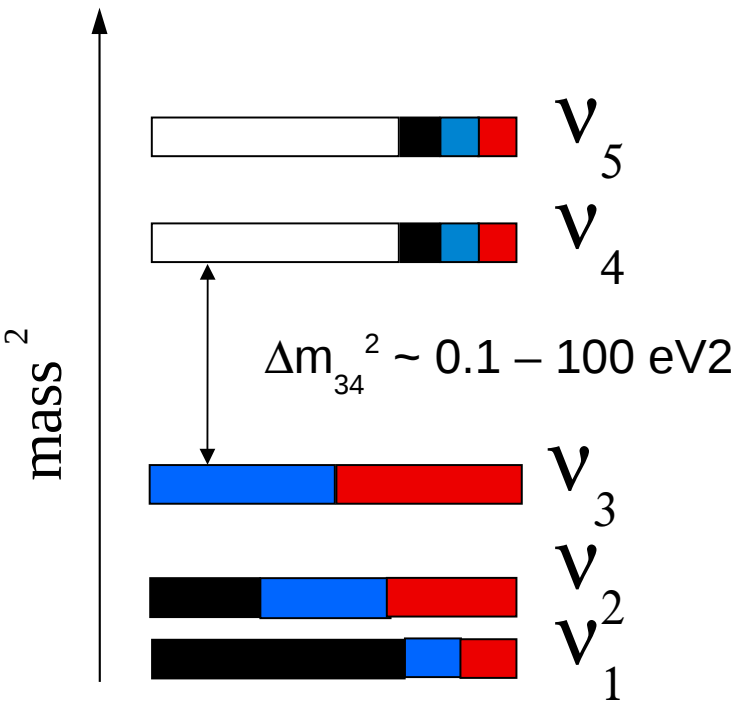
- 3 active neutrinos + 1 sterile neutrino
- Sterile neutrino has no Standard Model interactions
- Active neutrinos can oscillate into sterile
- 3 parameters relevant for short baseline exp.: Δm_{41}^2, $|U_{e4}|$ and $|U_{\mu 4}|$

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

$$P(\nu_e \to \nu_e) = 1 - 4|U_{e4}|^2\left(1 - |U_{e4}|^2\right)\sin^2(1.27\,\Delta m_{41}^2 L/E)$$

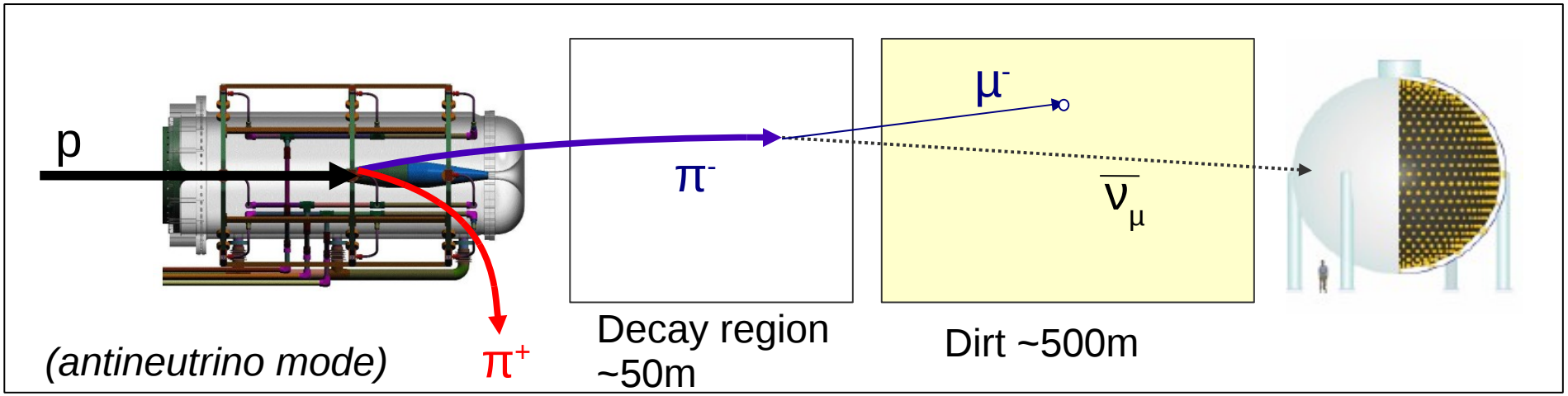
$$P(\nu_\mu \to \nu_\mu) = 1 - 4|U_{\mu 4}|^2\left(1 - |U_{\mu 4}|^2\right)\sin^2(1.27\,\Delta m_{41}^2 L/E)$$

More sterile neutrinos



- Next minimal extension 3+2 models
- Favored by fits to world data
- Model allows CP violation
  - $\nu_\mu \rightarrow \nu_e \neq \bar{\nu}_\mu \rightarrow \bar{\nu}_e$

MiniBooNE experiment



- Similar L/E as LSND
  - MiniBooNE ~500m/~500MeV
  - LSND ~30m/~30MeV
- Horn focused neutrino beam (p+Be)
  - Horn polarity → neutrino or anti-neutrino mode
- 800t mineral oil Cherenkov detector

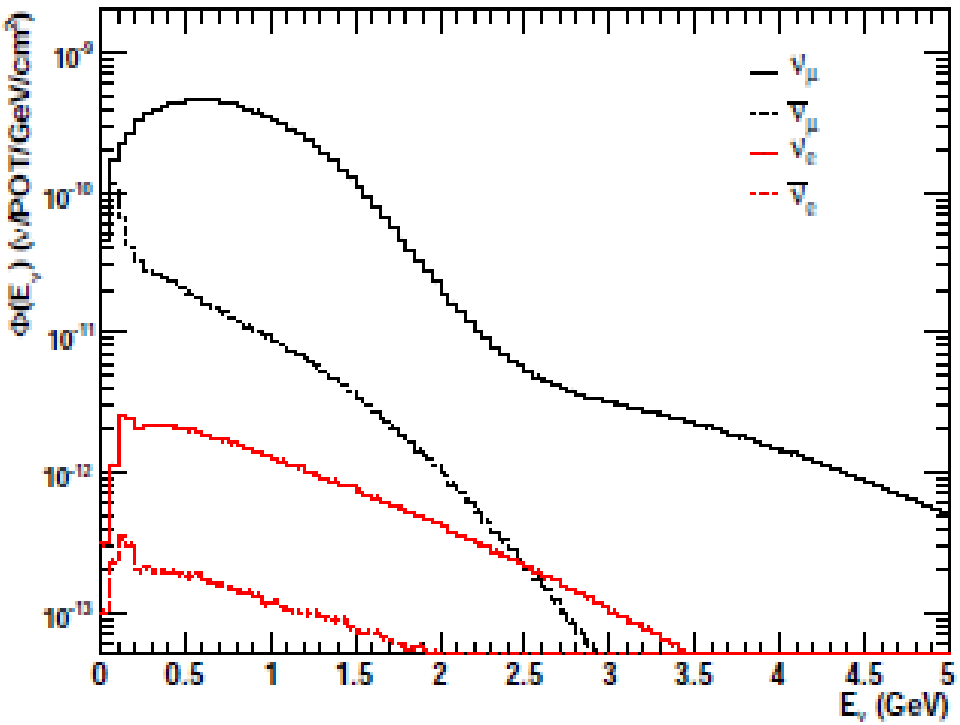
Neutrino flux

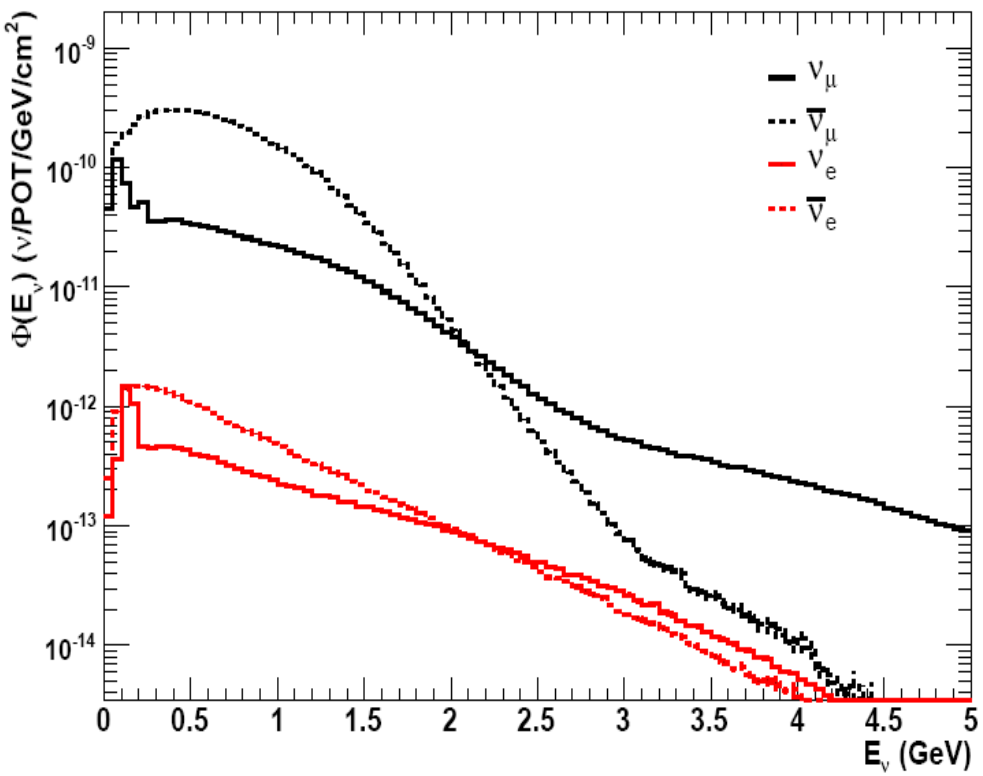
- Neutrino mode

ν_μ	93.6%
$\bar{\nu}_\mu$	5.8%
$\nu_e + \bar{\nu}_e$	0.6%

- Anti-neutrino mode

ν_μ	15.7%
$\bar{\nu}_\mu$	83.7%
$\nu_e + \bar{\nu}_e$	0.6%

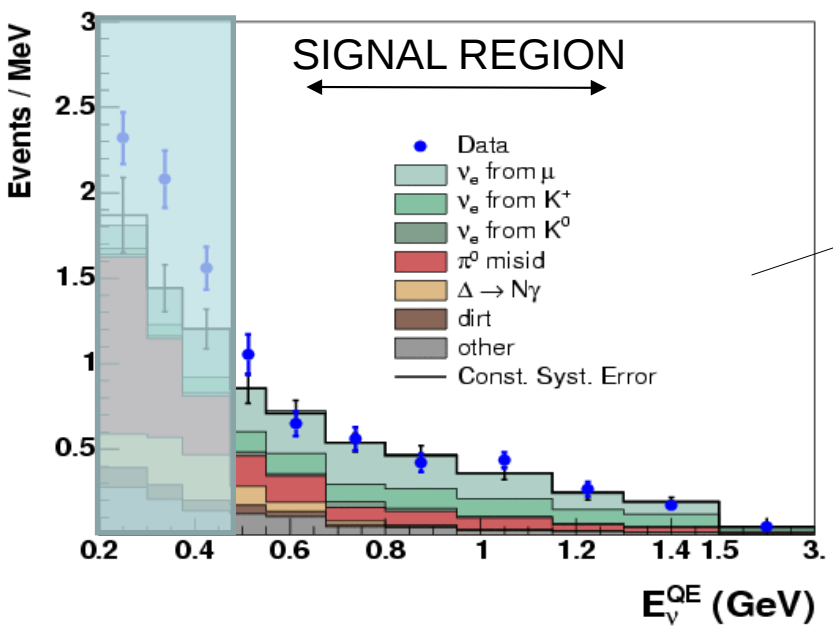


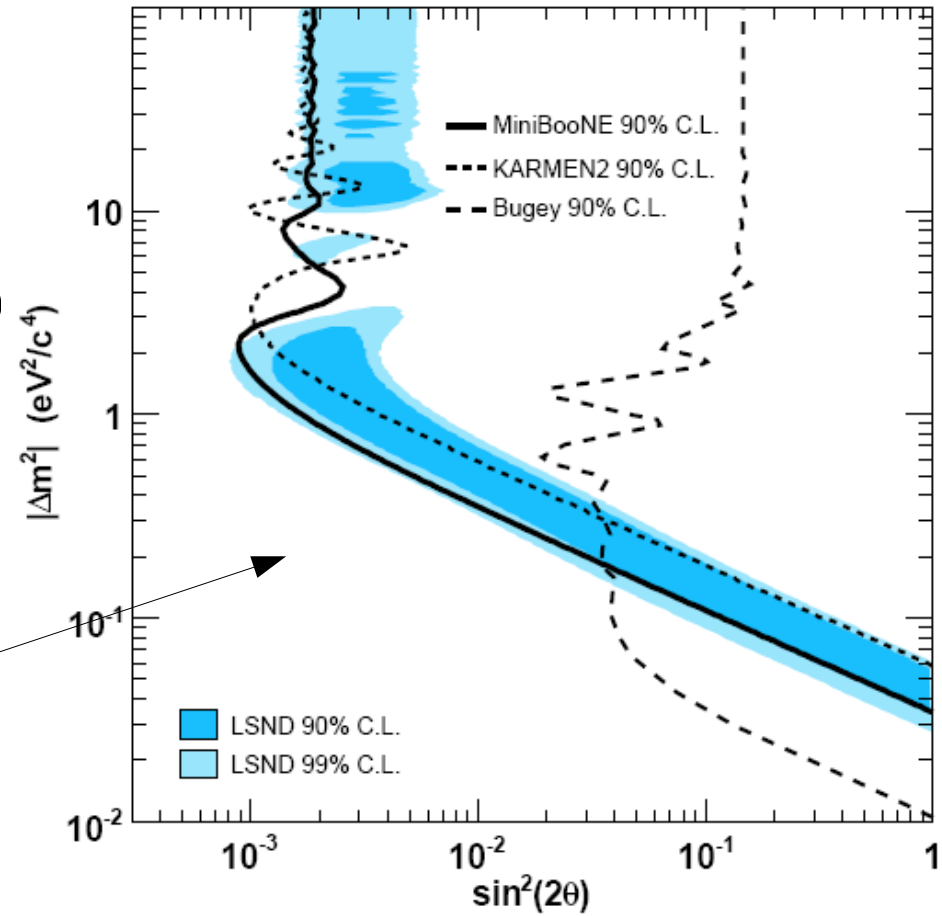


Phys. Rev. D79, 072002 (2009)

MiniBooNE neutrino result

- 6.5e20 Protons On Target (POT)
- No excess of events in signal region (E>475 MeV)
- Ruled out 2 ν oscillation as LSND explanation (assuming no CP or CPT violation)





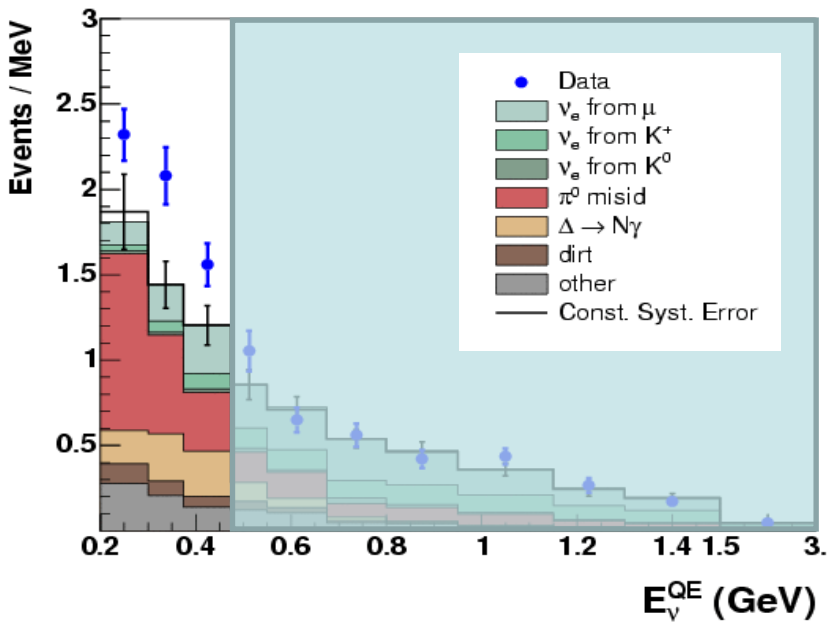
Phys. Rev. Lett. 98, 231801 (2007)

MiniBooNE neutrino result

Excess of events observed at low energy:
128.8 ± 20.4 ± 38.3 (3.0σ)

Shape not consistent with 2 ν oscillations

Magnitude consistent with LSND



Anomaly Mediated Neutrino-Photon Interactions at Finite Baryon Density: Jeffrey A. Harvey, Christopher T. Hill, & Richard J. Hill, arXiv:0708.1281

CP-Violation 3+2 Model: Maltoni & Schwetz, arXiv:0705.0107; T. Goldman, G. J. Stephenson Jr., B. H. J. McKellar, Phys. Rev. D75 (2007) 091301.

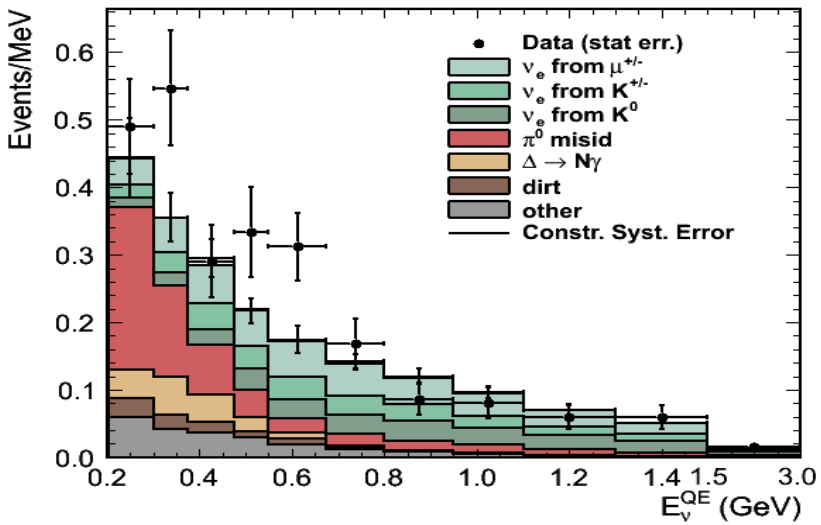
Extra Dimensions 3+1 Model: Pas, Pakvasa, & Weiler, Phys. Rev. D72 (2005) 095017

Lorentz Violation: Katori, Kostelecky, & Tayloe, Phys. Rev. D74 (2006) 105009

CPT Violation 3+1 Model: Barger, Marfatia, & Whisnant, Phys. Lett. B576 (2003) 303

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

$\bar{\nu}_e$ appearance results



- 5.66E20 POT
- Excess of events in 200-475MeV and 475-1250MeV region

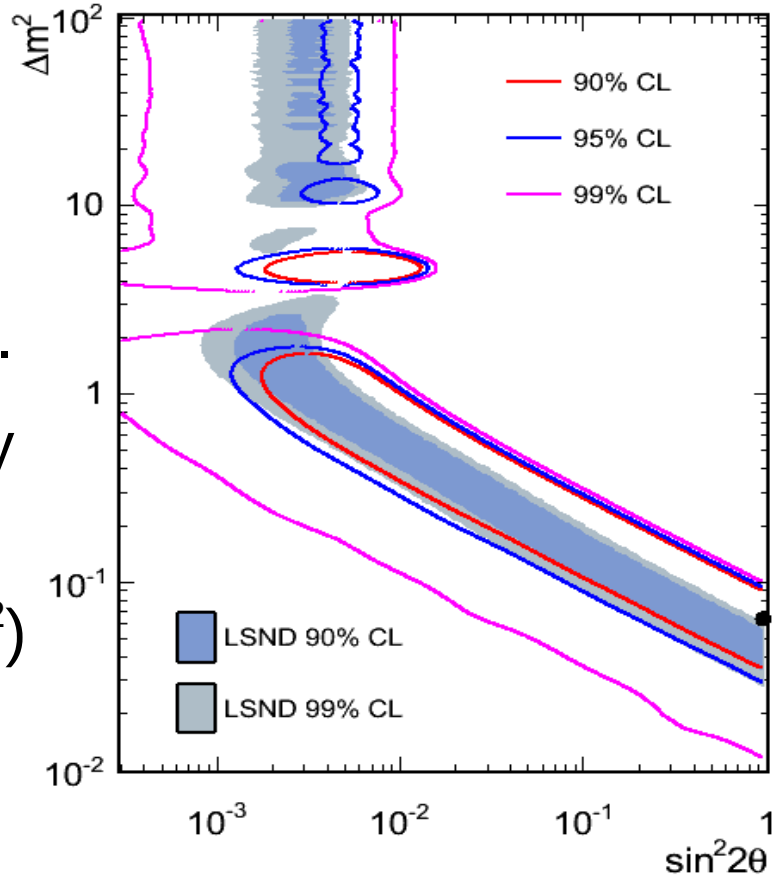
	200-475MeV	475-1250MeV
Data	119	120
MC	100.5±14.3	99.1±14.0
Excess	18.5±14.3	20.9±14.0
LSND Best Fit	7.6	22
Expectation from ν low E excess	11.6	0
LSND+Low E	19.2	22

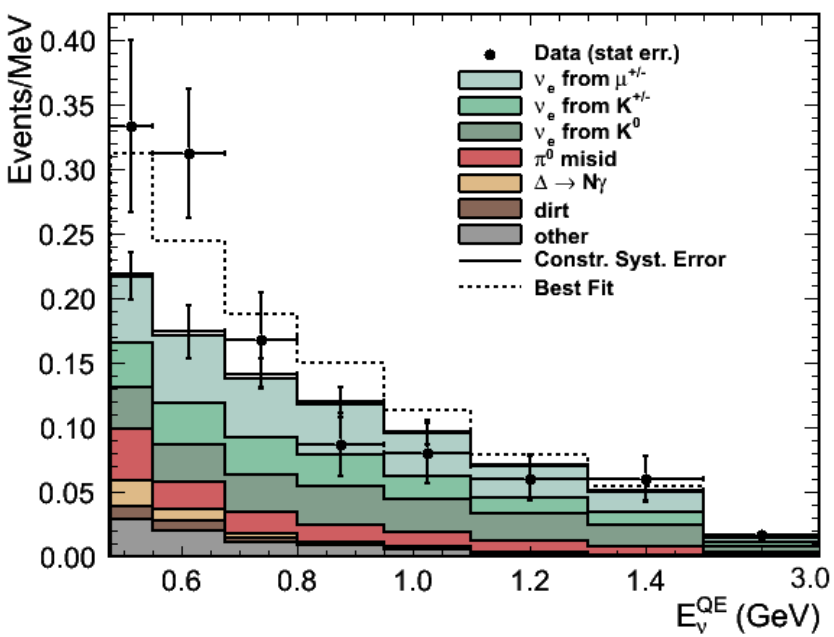
Phys. Rev. Lett. 105, 181801 (2010)

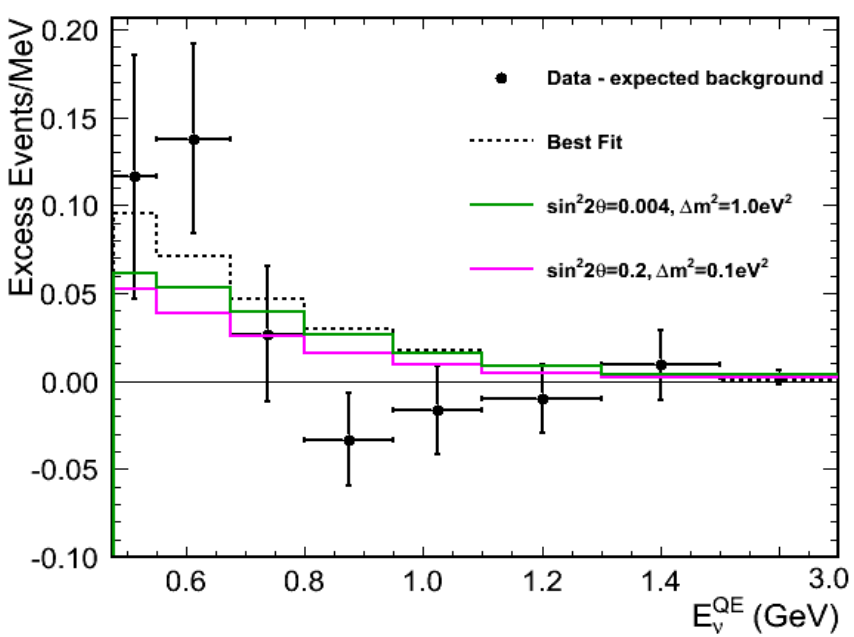
Fit E>475MeV

- 5.66E20 POT
- E>475 is signal region for LSND type osc.
- Oscillations favored over background only hypotheses at 99.4% CL
- Best fit ($\sin^2 2\theta$, Δm^2) = (0.9584, 0.064 eV^2)

  χ^2/NDF = 8.0/4; Prob. = 8.7% (475-1250 MeV)

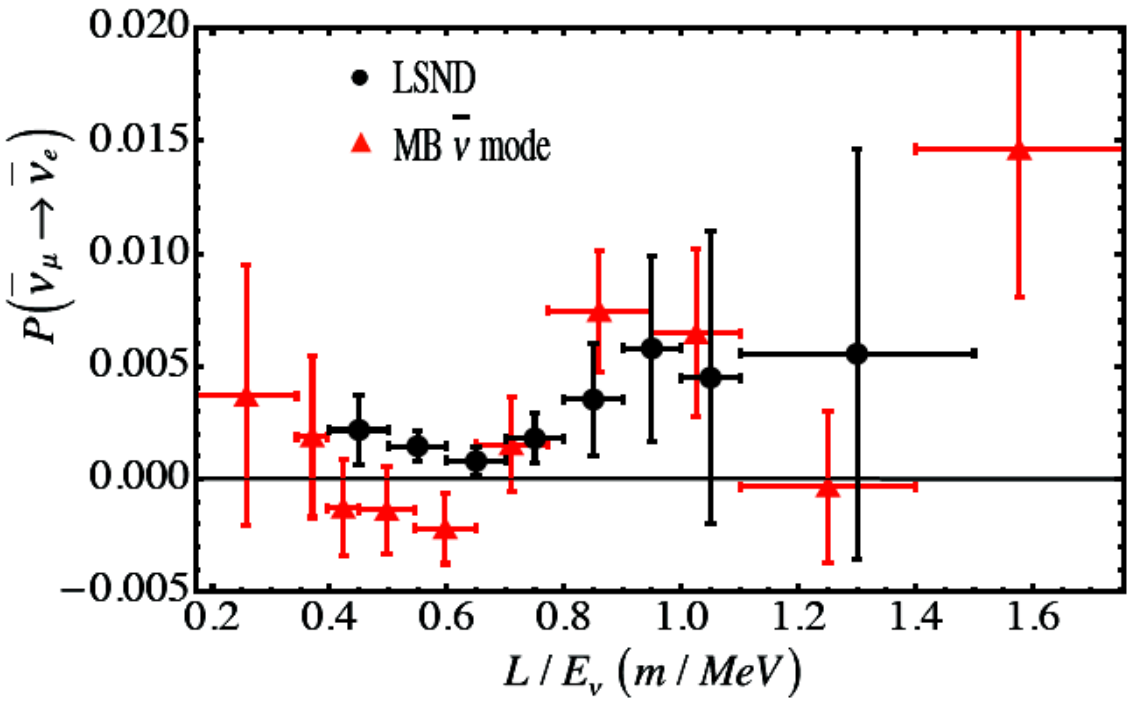






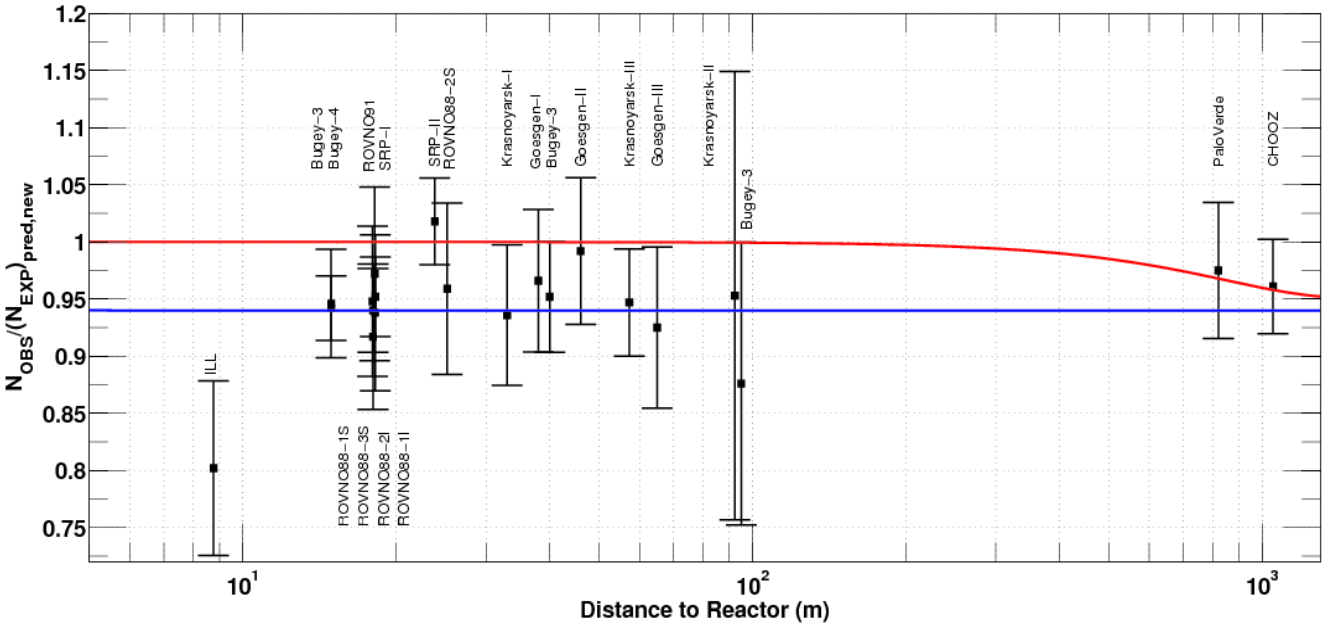
LSND vs MB direct comparison

- Anti-neutrino data
- Data plotted as a function of L/E



Reactor antineutrino anomaly

- Recent revaluation of reactor fluxes → +3%
- Observed/predicted event rate=0.943+-0.023
- Deviation from unity at 98.6% CL



Phys.Rev.D 83, 073006 (2011)

Gallium Anomaly

- GALLEX and SAGE calibration runs with intense MCi sources (ν_e)
- Neutrinos detected through radiochemical counting of Ge nuclei: $^{71}Ga+\nu_e \rightarrow {}^{71}Ge+e^-$
  - 2 runs at GALLEX with ^{51}Cr source (~750keV)
  - 1 run at SAGE with ^{51}Cr source
  - 1 run at SAGE with ^{37}Ar source (~810 keV)
- All runs observed deficit of neutrino interactions compared to the expected activity
  - R=meas/pred = 0.86+-0.06

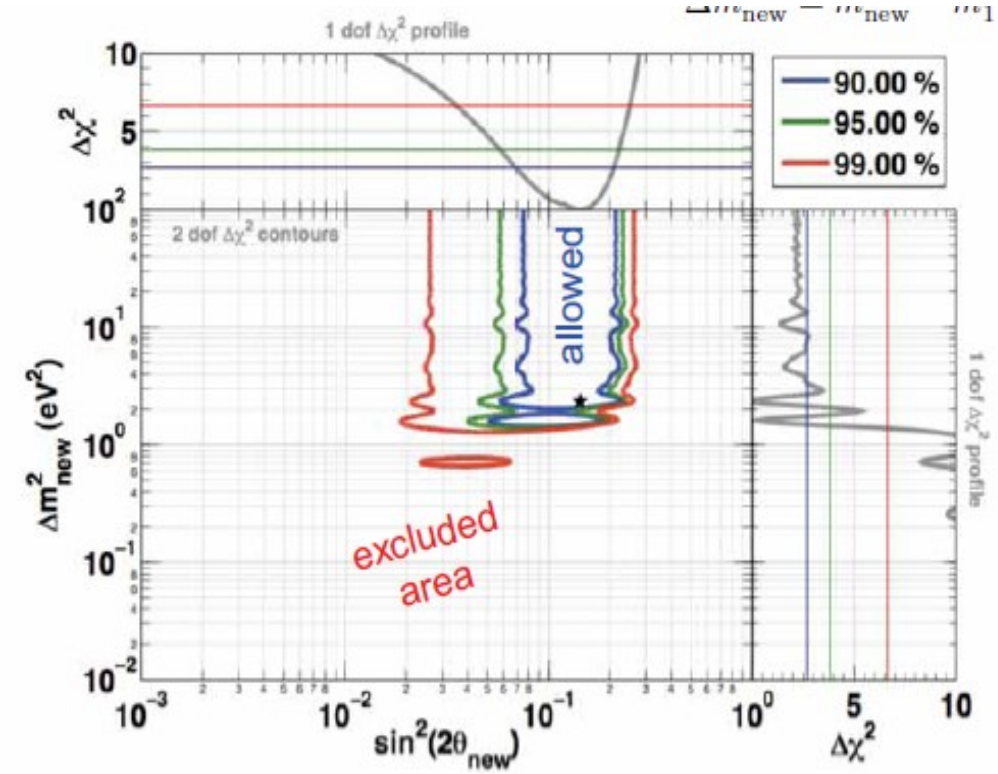
Phys.Rev.D 83, 073006 (2011)

Sterile neutrinos?

- Reactor data and GALLEX/SAGE
- Data consistent with sterile neutrino oscillations
- Null disfavored at 99.8%

$$\sin^2(2\theta) = 0.14 \pm 0.07$$

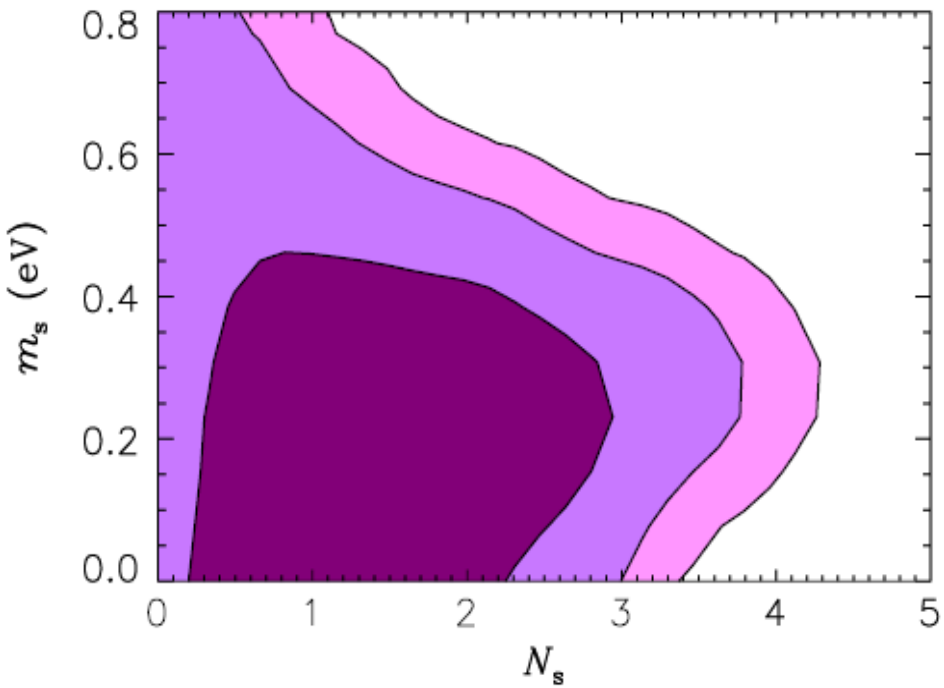
$$\Delta m^2 > 1.5\,\mathrm{eV}^2 @ 99\%\, CL$$



Phys.Rev.D 83, 073006 (2011)

Cosmology

- Data consistent with extra sterile neutrinos
- N_s = number of thermalized sterile neutrinos



Phys.Rev.Lett. 105, 181301 (2010)

3+N models require large $\bar{\nu}_\mu$ disappearance

- In general:

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) < \frac{1}{4} P(\bar{\nu}_\mu \to \bar{\nu}_x) P(\bar{\nu}_e \to \bar{\nu}_x)$$

- From reactor experiments:

$$P(\bar{\nu}_e \to \bar{\nu}_x) < 8\%$$

- From LSND/MiniBooNE:

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) \sim 0.25\%$$

- Therefore:

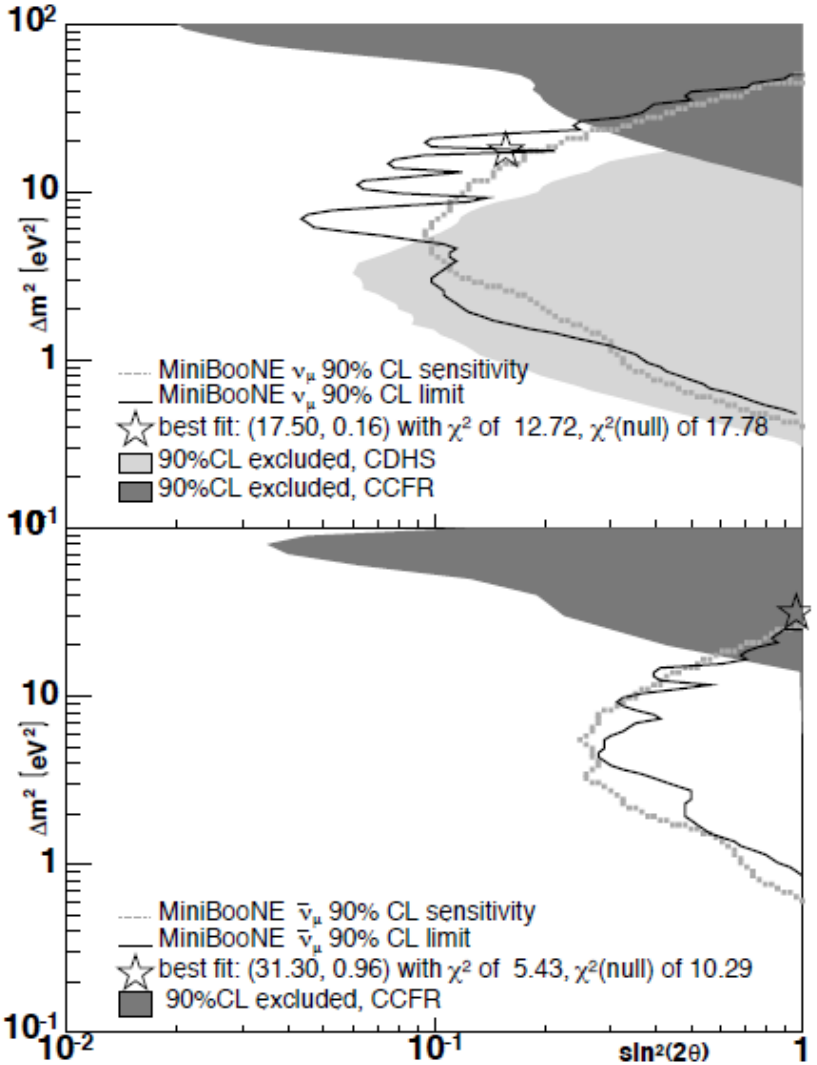
$$P(\bar{\nu}_\mu \to \bar{\nu}_x) > 10\%$$

*Assuming light neutrinos are mostly active and sterile neutrinos are heavy

ν_μ disappearance

- Provides a constraint on ν_e appearance

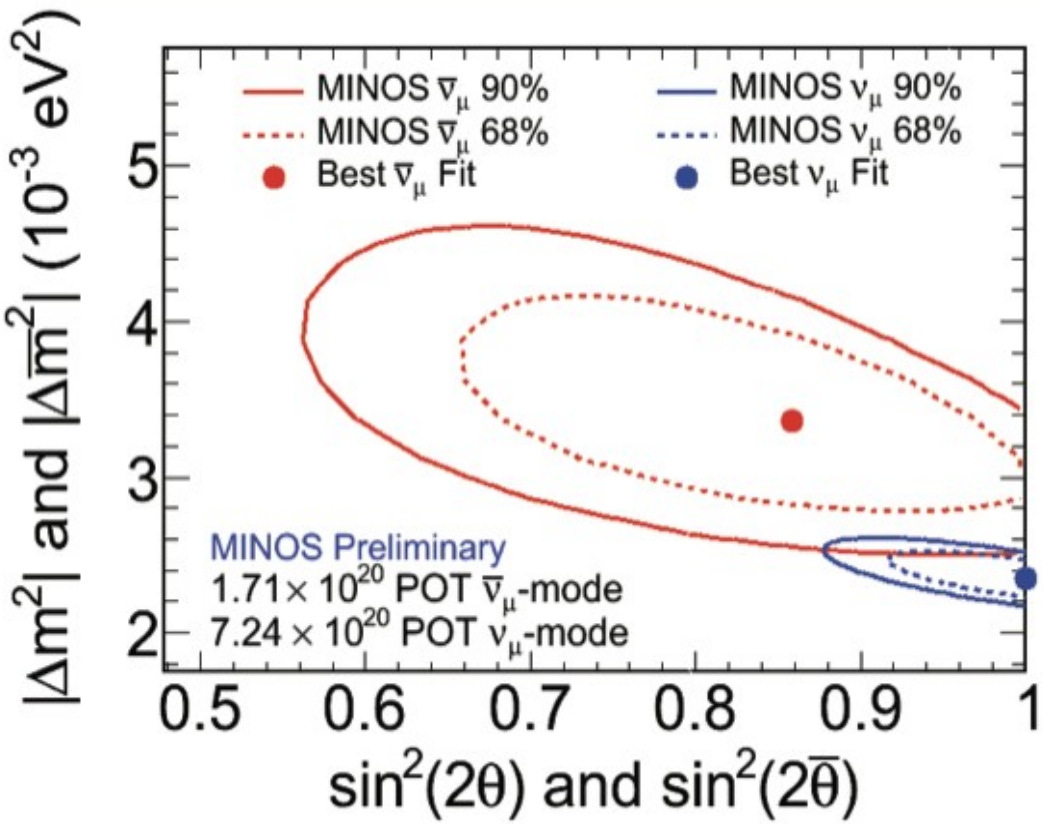
- New results from combined SciBooNE-MiniBooNE analysis
(see talk by Kendall Mahn session J8)



Phys.Rev.Lett.103:061802,2009

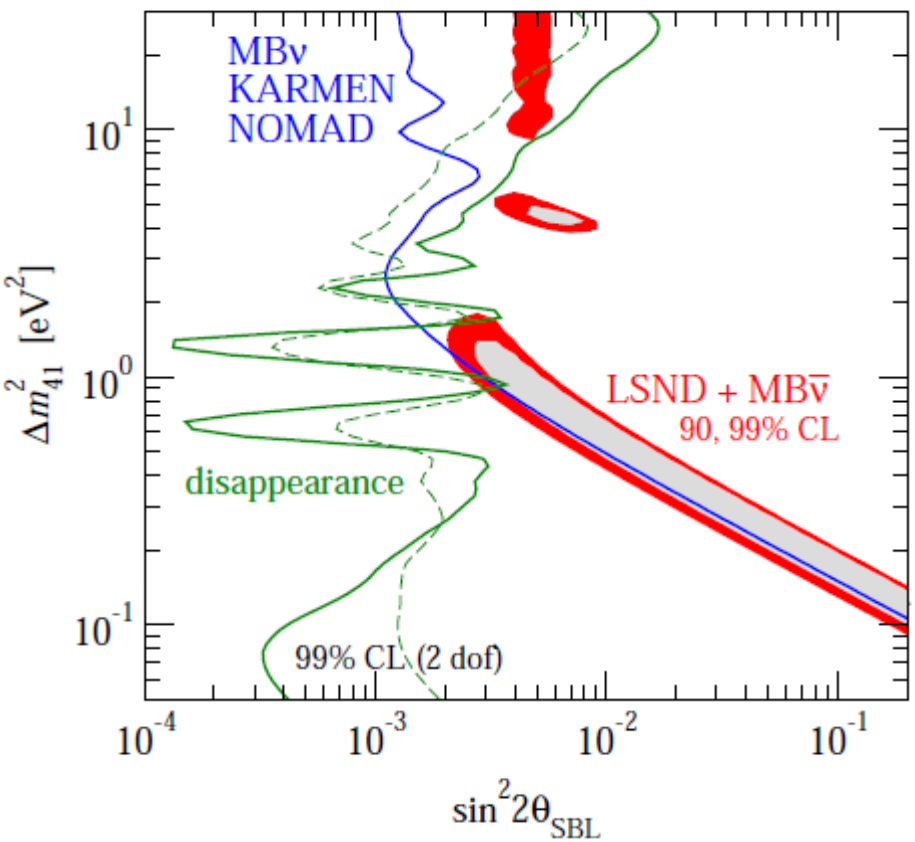
MINOS ν_μ vs $\bar{\nu}_\mu$

- Hint of CPT violation?



arxiv:1103.0340

Global fits with 3+1 model

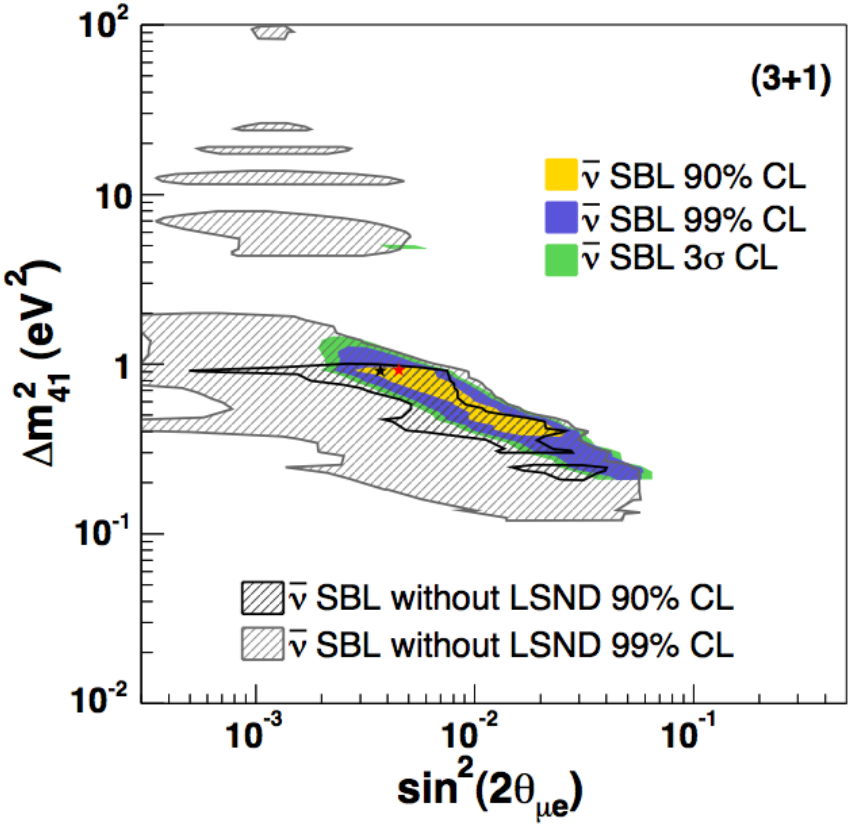


Kopp, Maltoni & Schwetz, arxiv:1103.4570

- Tension between neutrino mode and anti-neutrino mode appearance experiments
- Tension between disappearance and appearance experiments
- 3+1 does not fit data well

3+1 fits to world anti-neutrino data

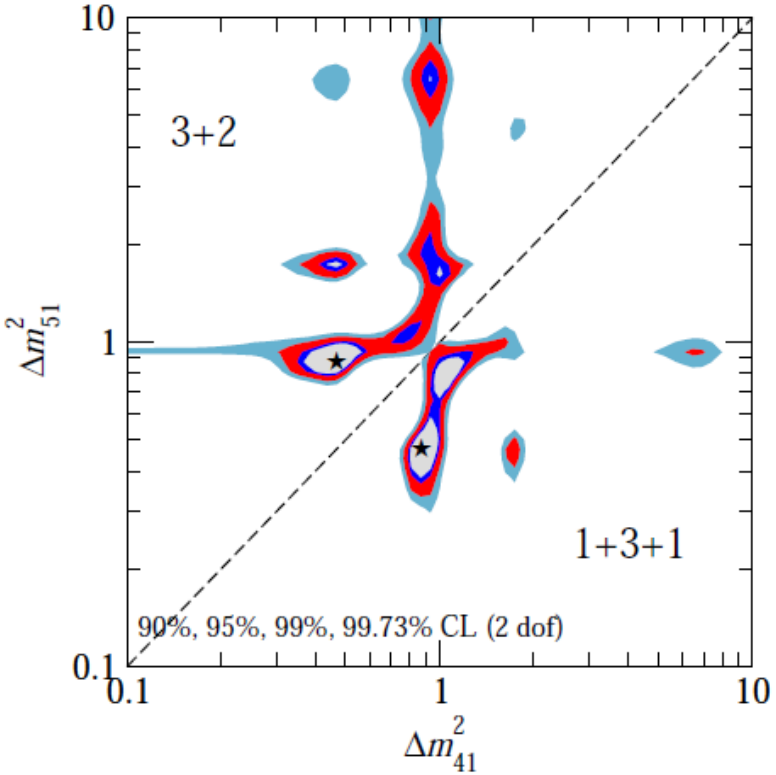
- World anti-neutrino data
  - MiniBooNE + LSND + KARMEN + Bugey + CHOOZ
- Tension between short baseline disappearance and appearance experiments is relaxed
- Good fit to data



Phys.Rev.D80,073001 (2009) updated with latest MiniBooNE results

3+2 model

- Much better fit to global data
- Some tension remains in the fit
  - appearance vs disappearance



Kopp, Maltoni & Schwetz, arxiv:1103.4570

Future outlook

- MiniBooNE – more antineutrino data
- Joint MiniBooNE/SciBooNE numubar disappearance
- MicroBooNE resolve the low energy excess

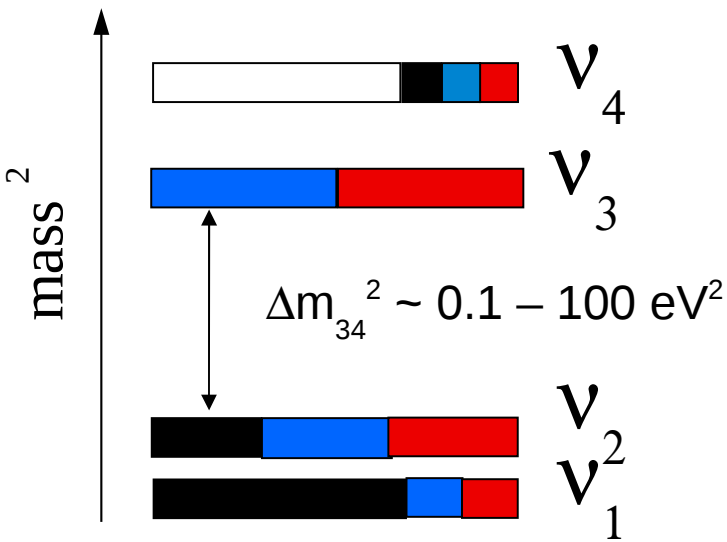
- MINOS+
- BooNE
- Stopped pion source exp. (OscSNS,...)
- Icarus at CERN-PS

Conclusion

- MiniBooNE data consistent with $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations at $\Delta m^2 \sim 1 eV^2$
- The world antineutrino data fit well to a 3+1 oscillation model with $\Delta m^2 \sim 1 eV^2$
  - Tension between neutrino and anti-neutrino data;
    CP, CPT violation?
- Reactor and Gallium anomaly consistent with sterile neutrino oscillation
- Very active topic:
  - Workshop on Sterile Neutrinos and on the Reactor (anti)-Neutrino Anomaly, TUM, Garching, Feb 8 2011
  - Beyond3nu, Gran Saso, May 3-4 2011
  - Short Baseline Neutrino Workshop, Fermilab, May 12-14 2011
  - Sterile Neutrinos At The Crossroads, Virginia Tech, Sep 26-28 2011

Backup slides

2+2

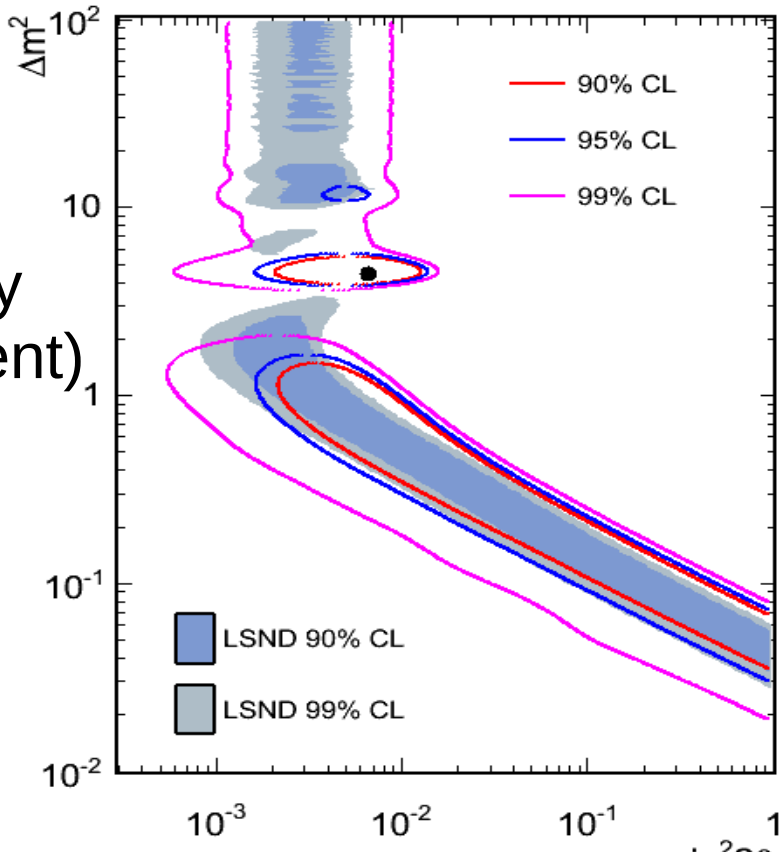


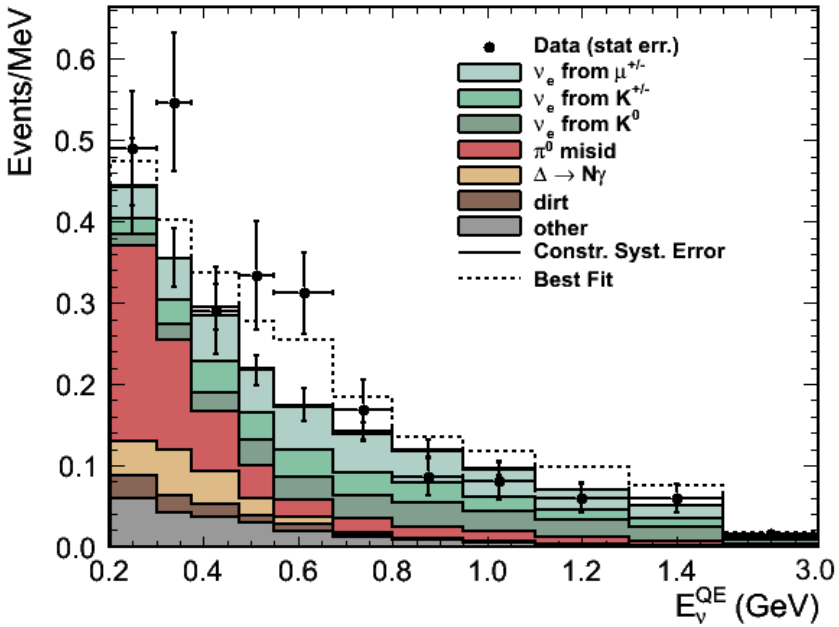
- Within 2+2 model Sterile neutrino participates in either solar or atmospheric neutrino oscillations (or both)
- Experiments measuring solar and atmospheric dm2 disfavor oscillations to pure sterile neutrinos

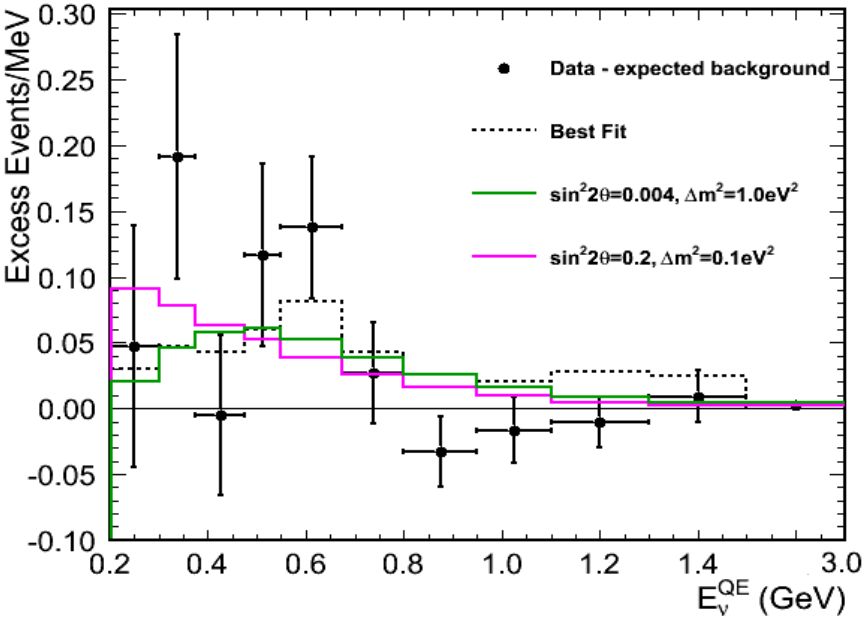
=> 2+2 is strongly disfavored

E>200MeV

- 5.66E20 POT
- Oscillations favored over background only hypotheses at 99.6% CL (model dependent)
- No assumption made about low energy excess
- Best fit ($\sin^2 2\theta$, Δm^2) = (0.0066, 4.42 eV^2)
  χ^2/NDF = 20.4/15.3
  p=17.1%



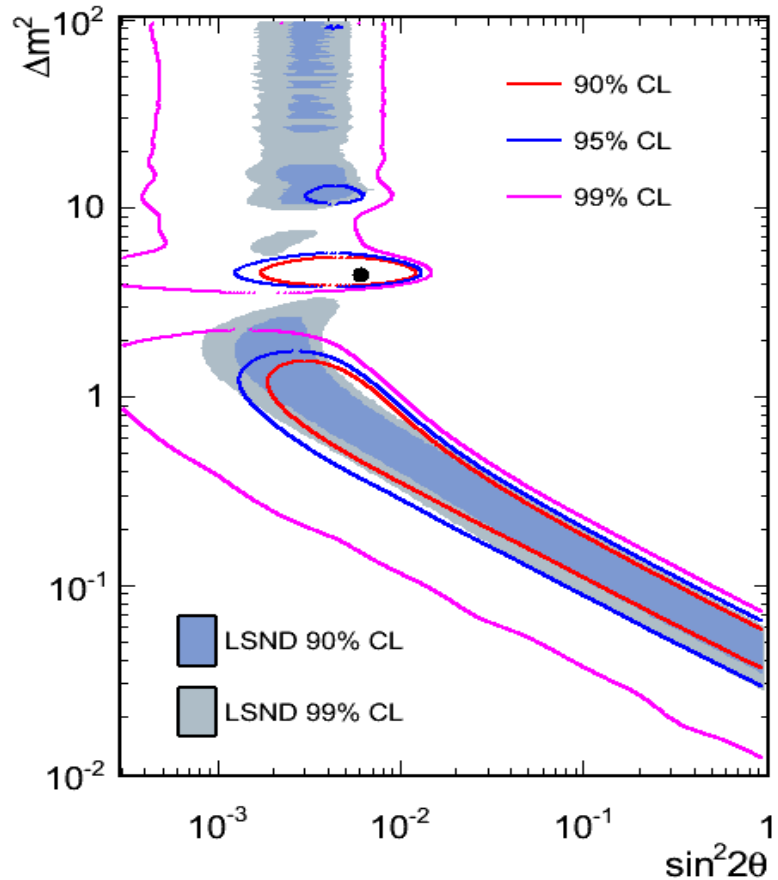


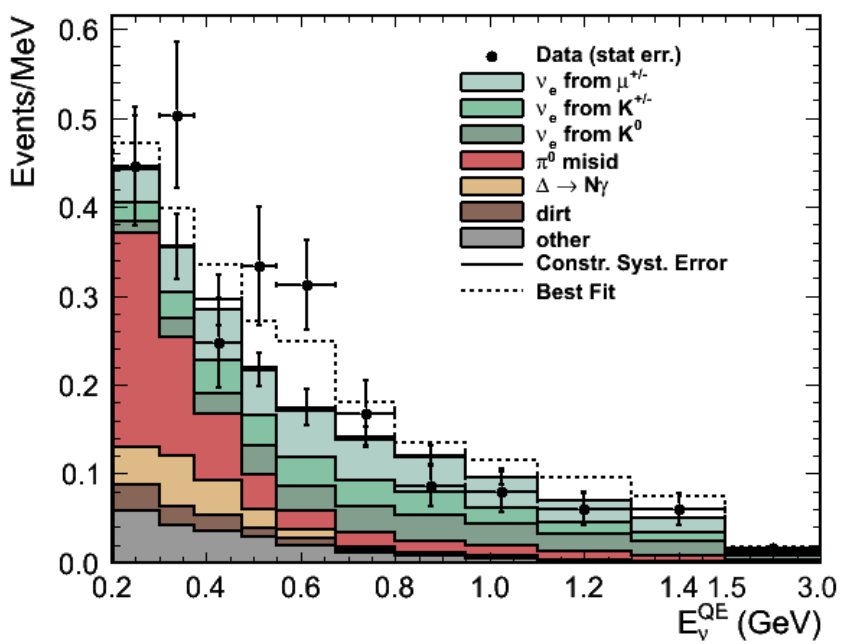


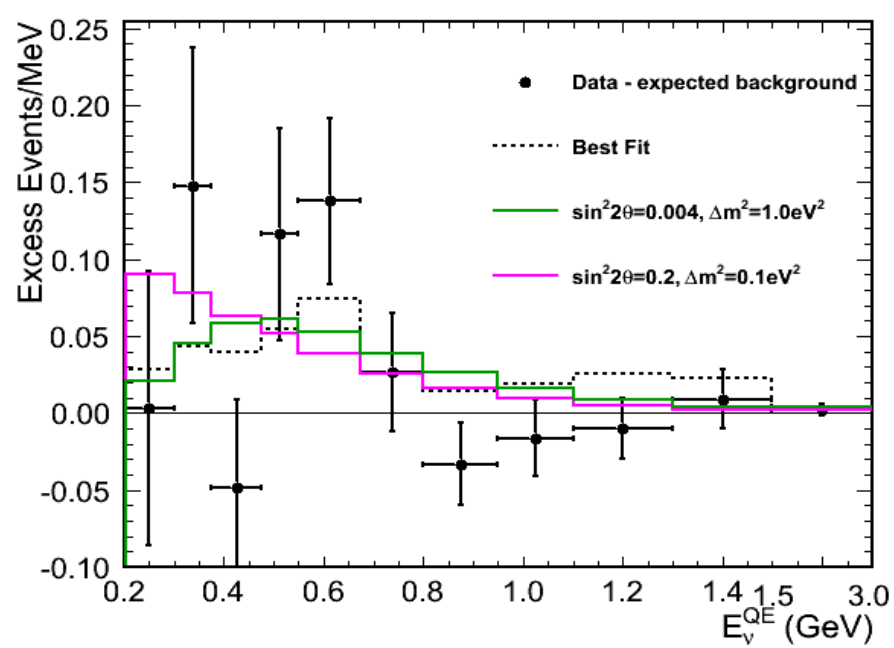
E>200MeV

- Subtract excess produced by neutrinos in $\bar{\nu}$ mode (11.6 events)
- E<475MeV:
  - Large background
  - Not relevant for LSND type osc.
  - Big systematics
- Null χ^2=32.8; p=1.7%

Best fit ($\sin^2 2\theta$, Δm^2) = (0.0061, 4.42 eV^2)
χ^2/NDF = 21.6/15.3; p=13.7%

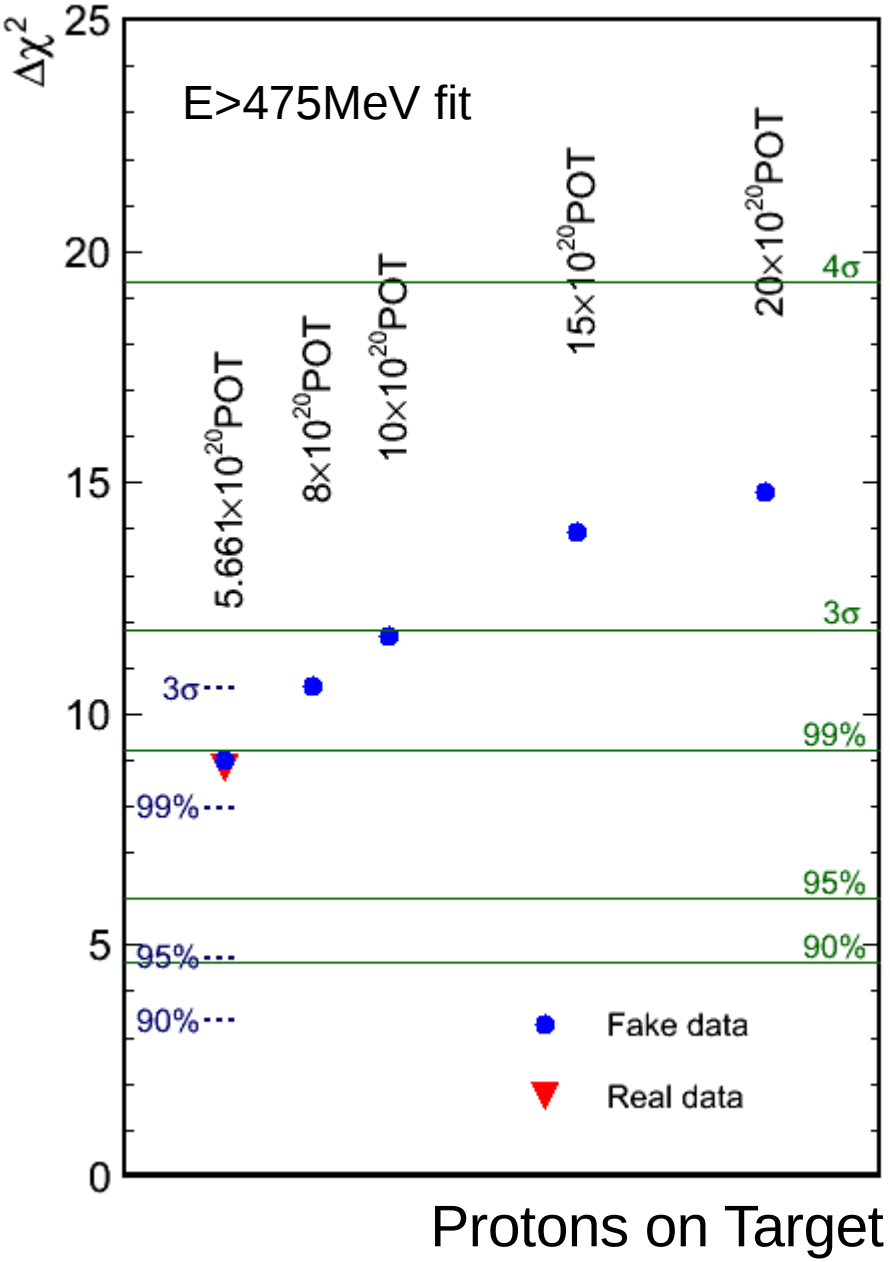






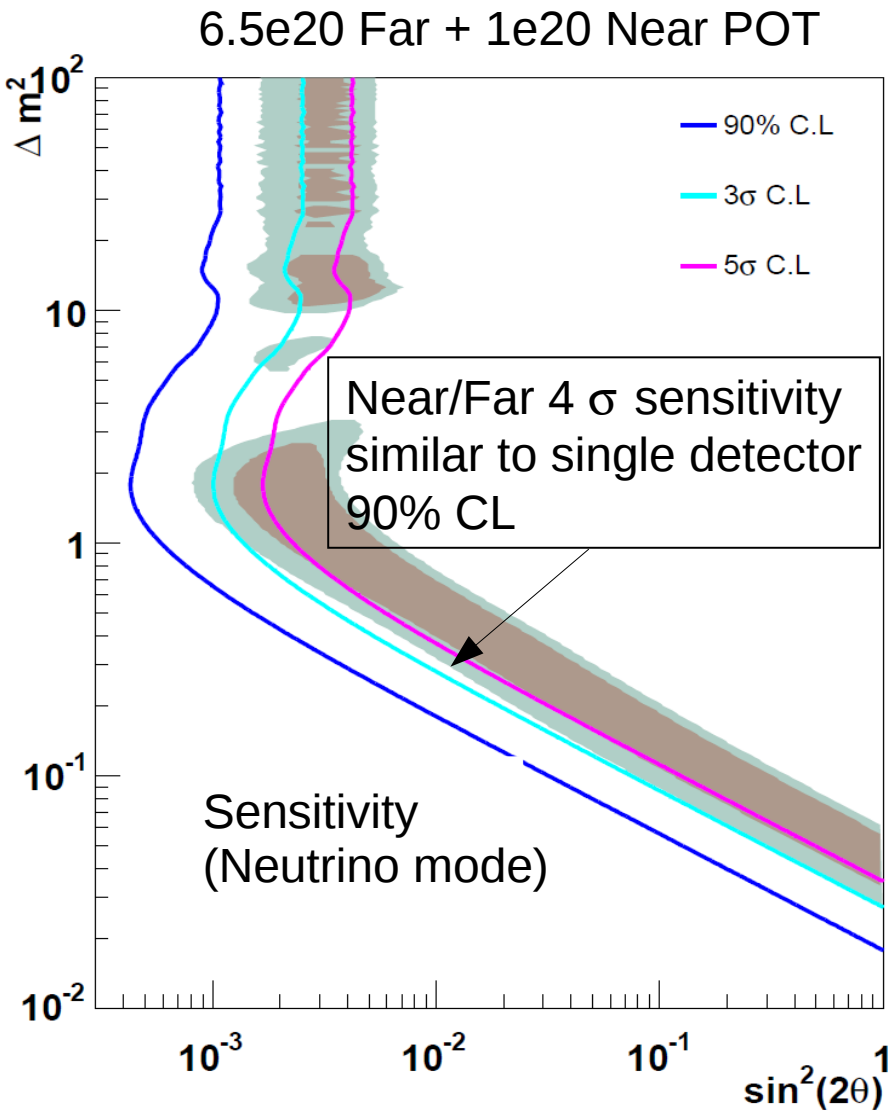
Future sensitivity

- MiniBooNE approved for a total of 1e21 POT
- Potential exclusion of null point assuming best fit signal
- Combined analysis of ν_e and $\bar{\nu}_e$



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
- Study L/E dependence
- Gain statistics quickly, already have far detector data

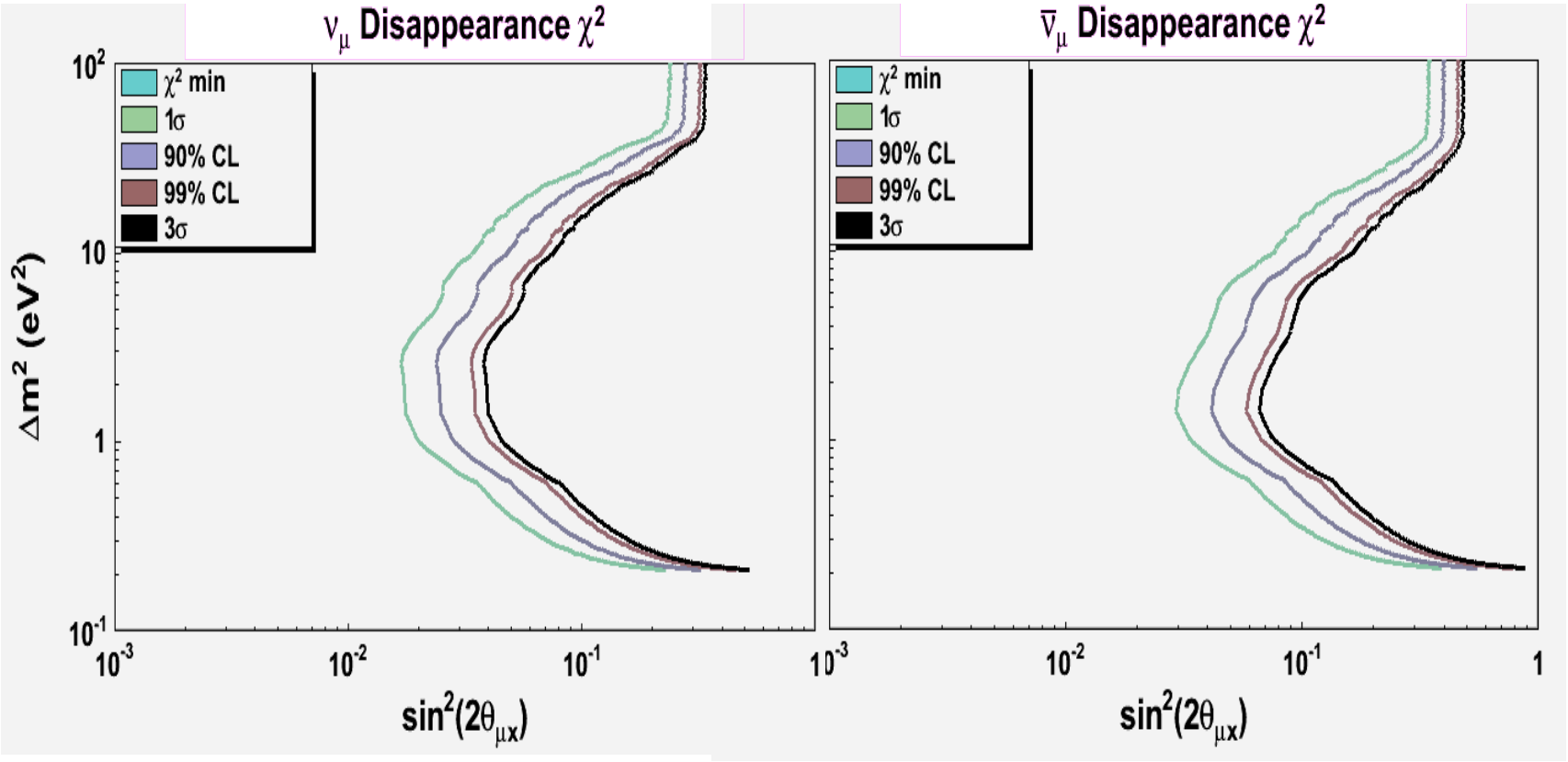


BooNE

- Better sensitivity to ν_μ ($\bar{\nu}_\mu$) disappearance
- Look for CPT violation ($\nu_\mu \rightarrow \nu_\mu \neq \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$)

6.5e20 Far/1e20 Near POT

1e21 Far/1e20 Near POT

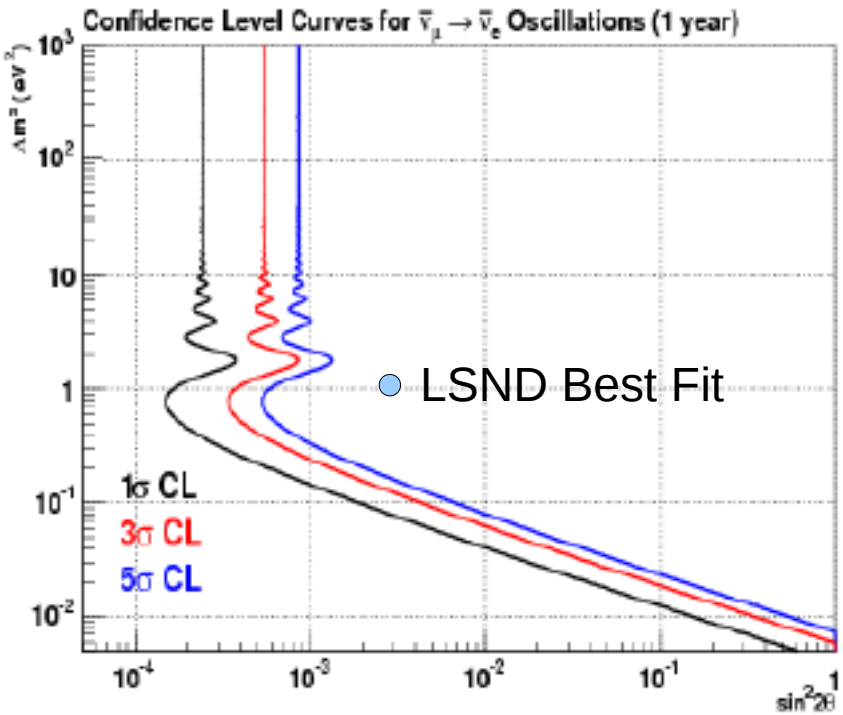


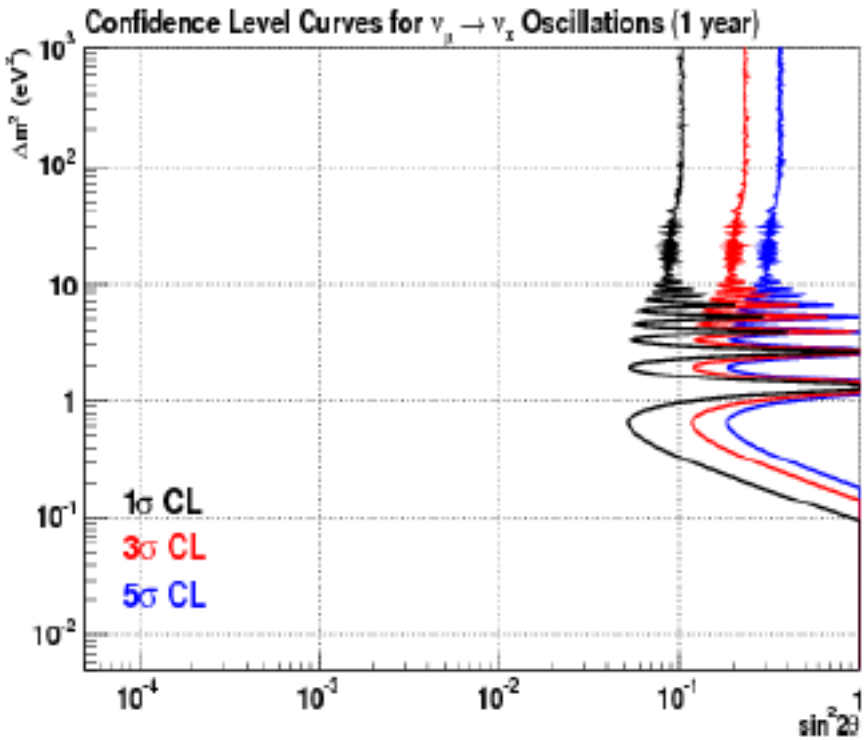
OscSNS

- Spallation neutron source at ORNL
- 1GeV protons on Hg target (1.4MW)
- Free source of neutrinos
- Well understood flux of neutrinos

OscSNS

- $\bar{\nu}_e$ appearance (left) and ν_μ disappearance sensitivity (right) for 1 year of running





LSND $\bar{\nu}_e$ Background Estimates

Estimate	$\bar{\nu}_e/\bar{\nu}_\mu$	$\bar{\nu}_e$ Bkgd	LSND Excess
LSND Paper	0.086%	19.5+-3.9	87.9+-22.4+-6.0
Zhemchugov Poster	0.071%	16.1+-3.2	91.3+-22.4+-5.6
Dydak Seminar	0.116%	26.3+-5.3	81.1+-22.4+-7.0

All $\bar{\nu}_e$ background estimates assume a 20% error. Note that the $\bar{\nu}_e/\bar{\nu}_\mu$ ratio determines the background!

LSND Paper: A. Aguilar et al., Phys. Rev. D 64, 112007 (2001); (uses **MCNP**)

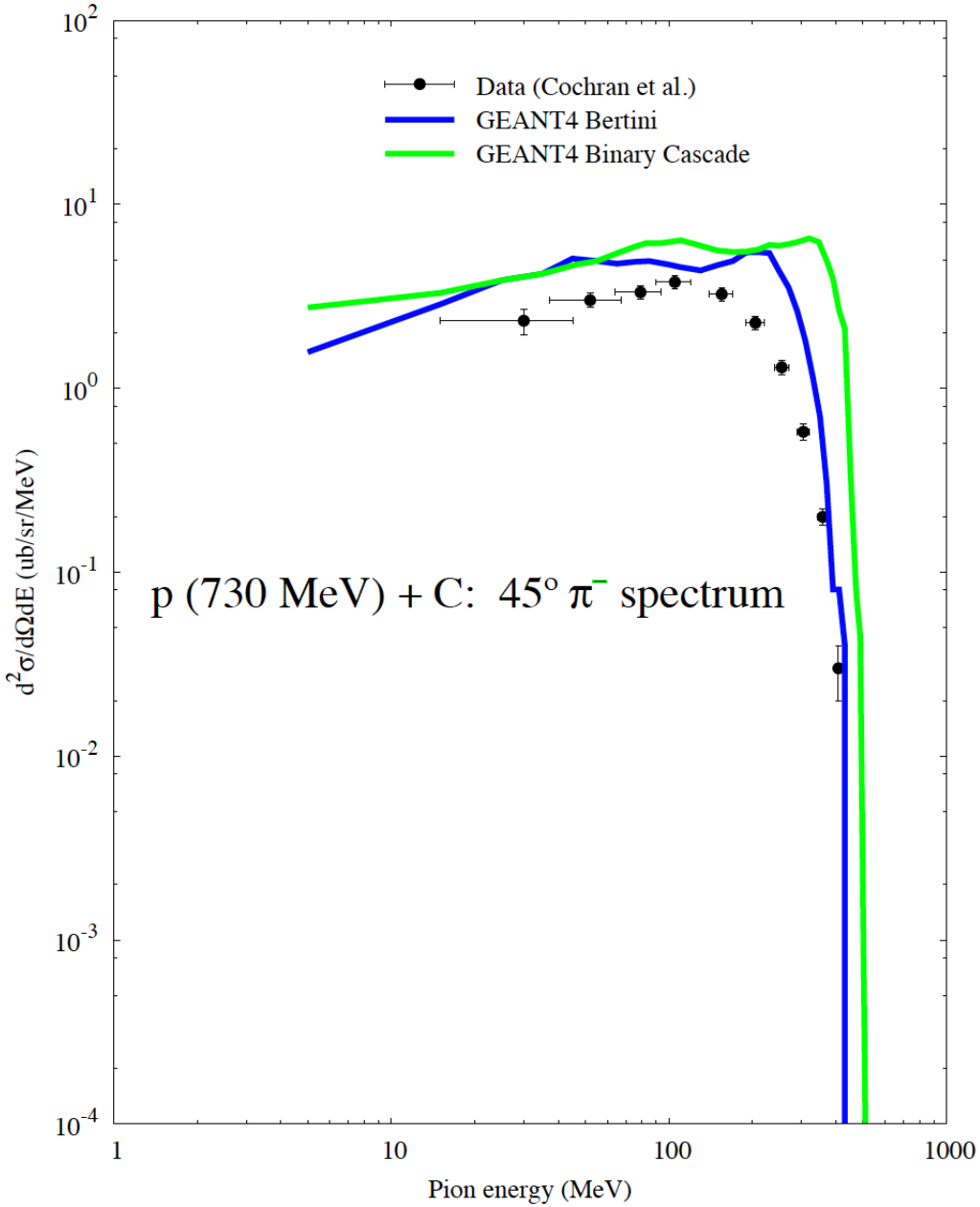
Zhemchugov Poster: **FLUKA** $\bar{\nu}_e/\bar{\nu}_\mu$ ratio presented at the ICHEP 2010 Conference, Paris

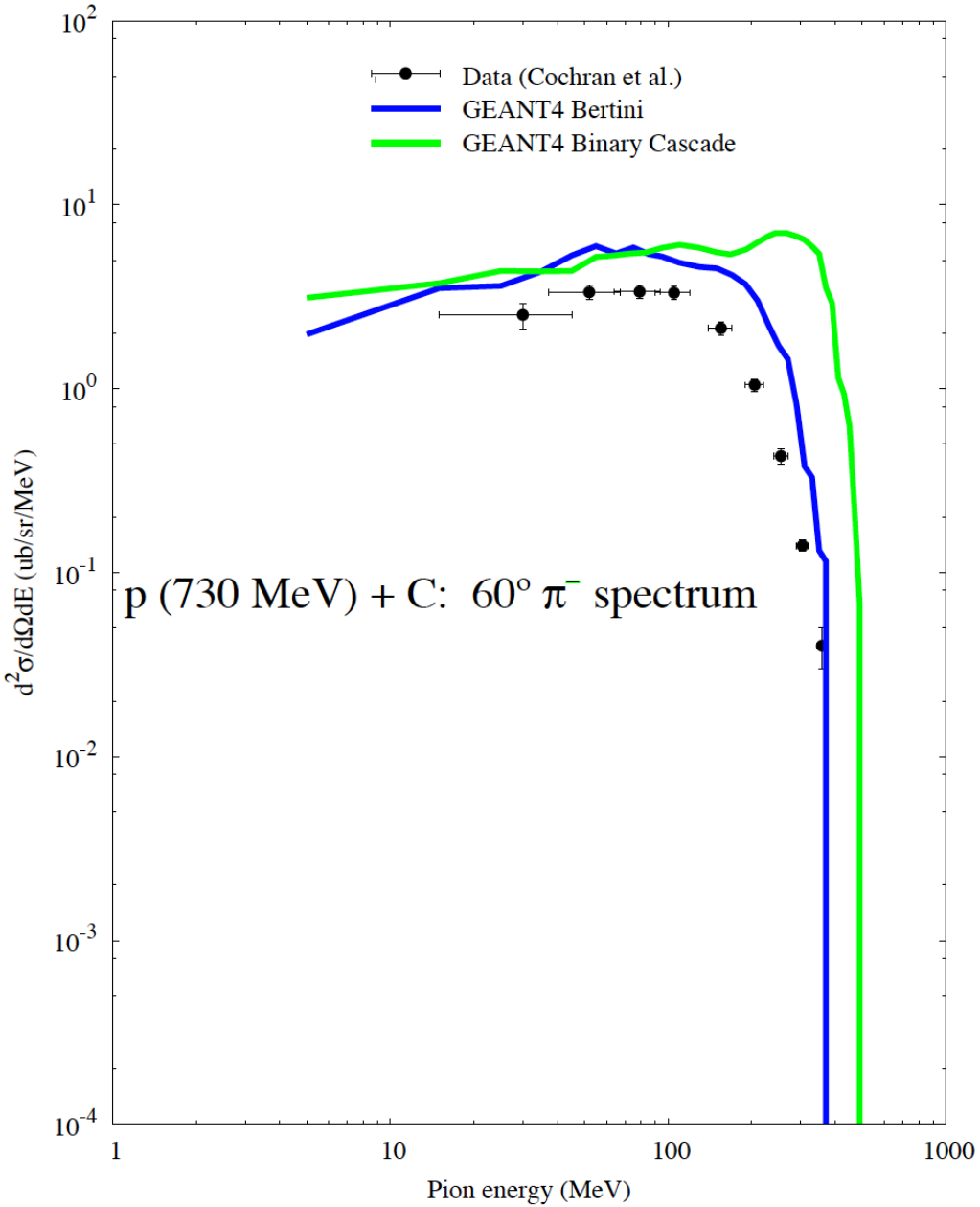
Dydak Seminar: **FLUKA** $\bar{\nu}_e/\bar{\nu}_\mu$ ratio presented at FNAL on January 14, 2011

Although the analysis of Zhemchugov, Dydak et al. is not fully understood or endorsed, their $\bar{\nu}_e/\bar{\nu}_\mu$ ratios agree reasonably well with the published LSND results.

Note that LSND measures the correct rate of $\bar{\nu}_\mu$ p -> μ^+ n interactions, which confirms the π^- production and background estimates. Note also, that FLUKA & GEANT4 overestimate π^- production at ~800 MeV. Note that N_{gs} events are included in the LSND background estimate.

GEANT4 Overestimates π^- Production!





ν_e C $\rightarrow$ e^- N_{gs} Events Do Not Simulate $\bar{\nu}_e$ p $\rightarrow$ e^+ n Events!

For N_{gs} β decay to be considered a 2.2 MeV γ:
$\Delta r<2m$, $\Delta t<500\mu s$, $19<N_{hits}<51$

The number of N_{gs} events with a β that satisfies this initial requirement is approximately: (600)(1)(1/31.8)(0.05) ~ 1 event.

The number of N_{gs} events with $R_\gamma>10$ ~ 0.1 events.

This background is included in the LSND background estimate.