Short Baseline Neutrino Oscillations

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Standard Model & Neutrino Oscillations

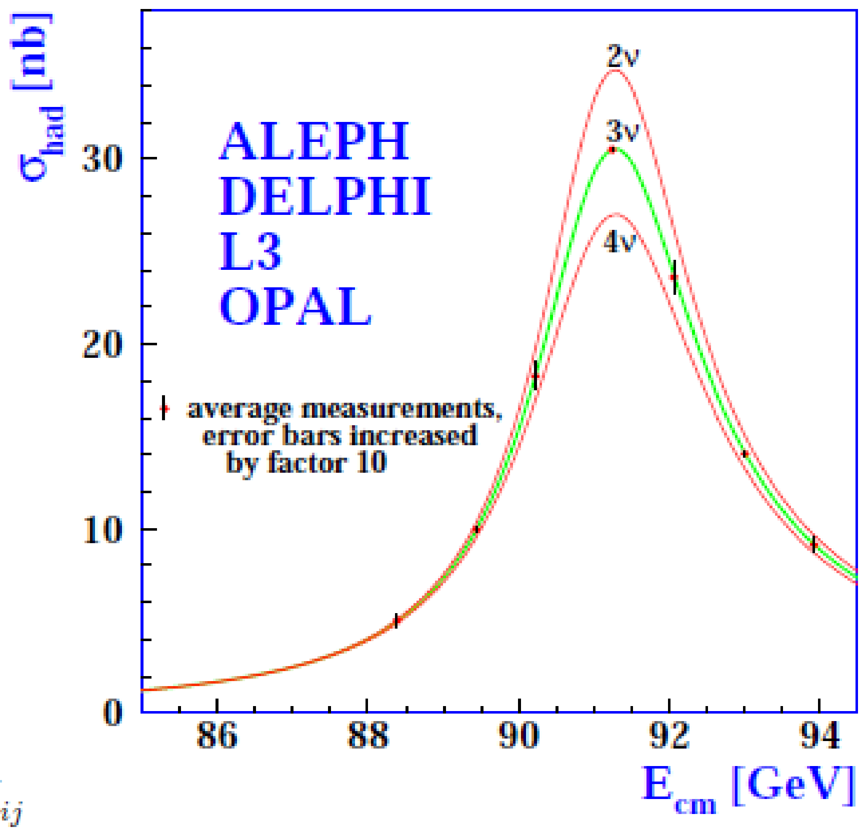
- 3 neutrinos
  - Initially assumed massless
- Mixing matrix:

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

- Oscillation Probability:

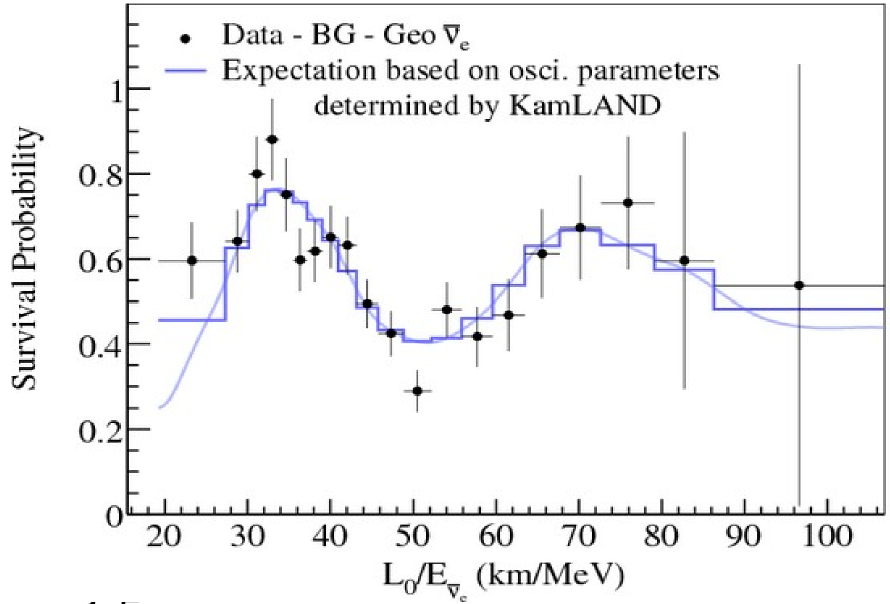
$$P_{\alpha\beta} = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 = \delta_{\alpha\beta} - 4 \sum_{i<j}^{n} \mathrm{Re}[U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}] \sin^2 X_{ij} + 2 \sum_{i<j}^{n} \mathrm{Im}[U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}] \sin 2X_{ij}$$

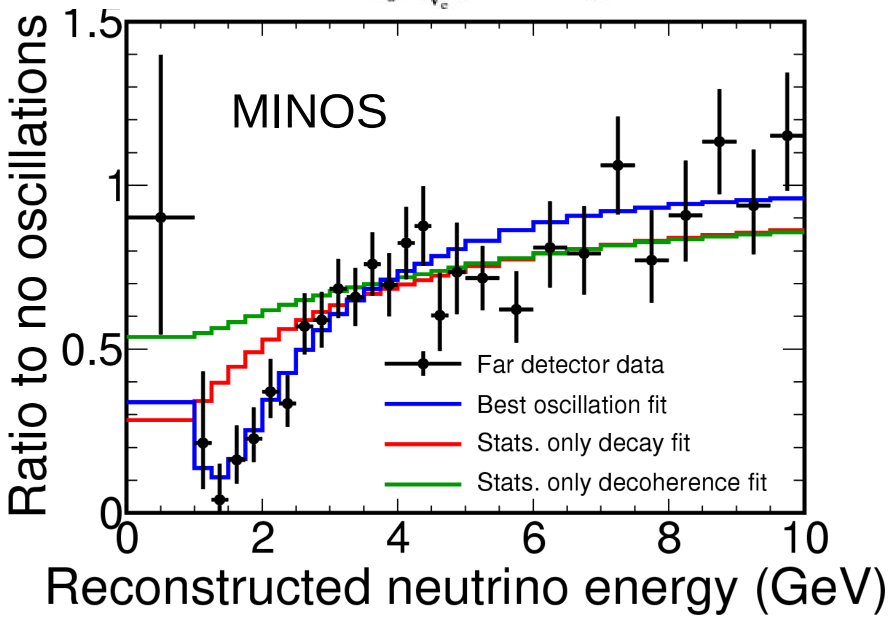
$$X_{ij} = \frac{(m_i^2 - m_j^2)L}{4E} = 1.27 \frac{\Delta m_{ij}^2}{\mathrm{eV}^2} \frac{L/E}{\mathrm{m/MeV}}$$

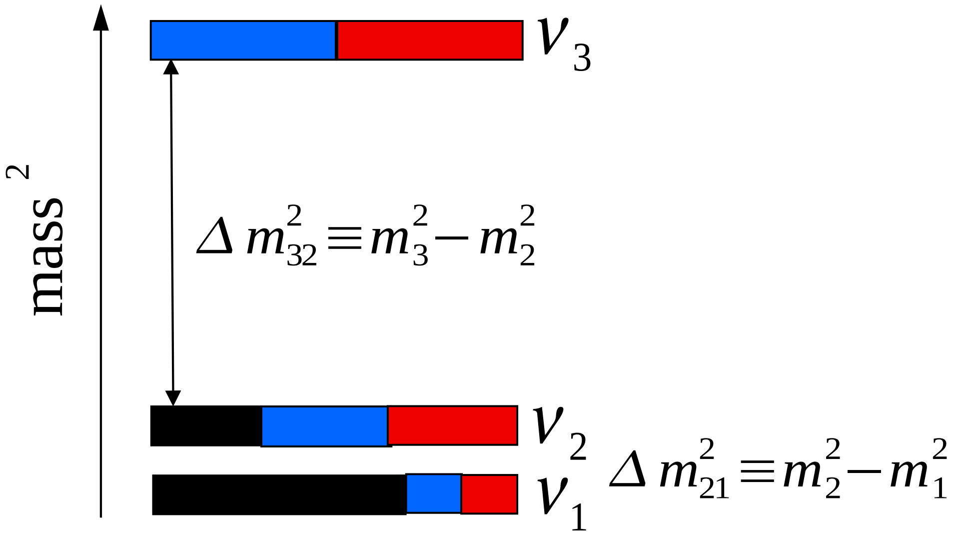


Neutrino Oscillations

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

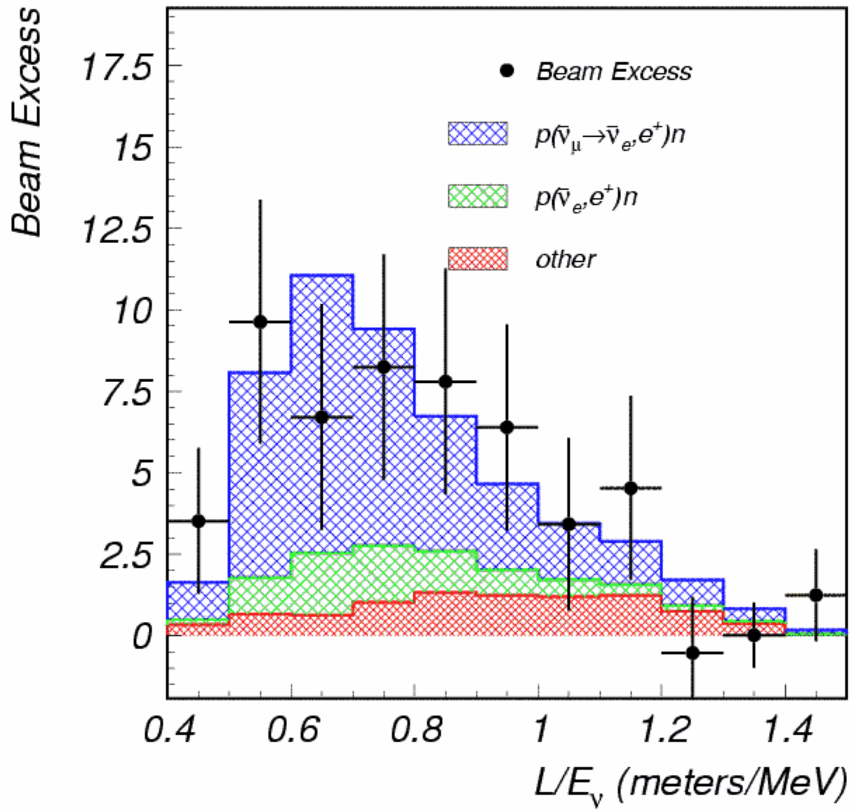






LSND

- Evidence for oscillations at higher Δm^2 than atmospheric and solar
- Stopped pion beam
  $\pi^+ \to \mu^+ + \nu_\mu$
  $\hookrightarrow e^+ + \bar{\nu}_\mu + \nu_e$
- 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)

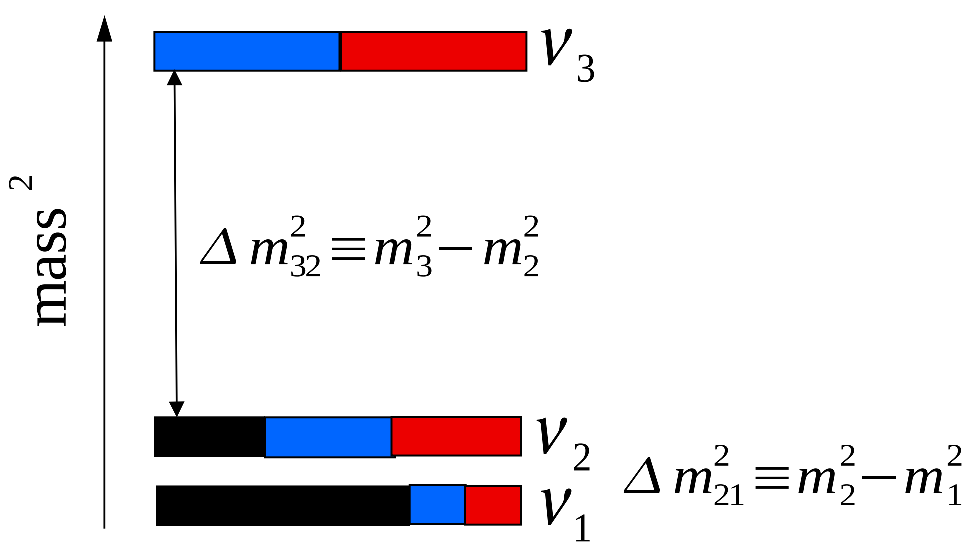


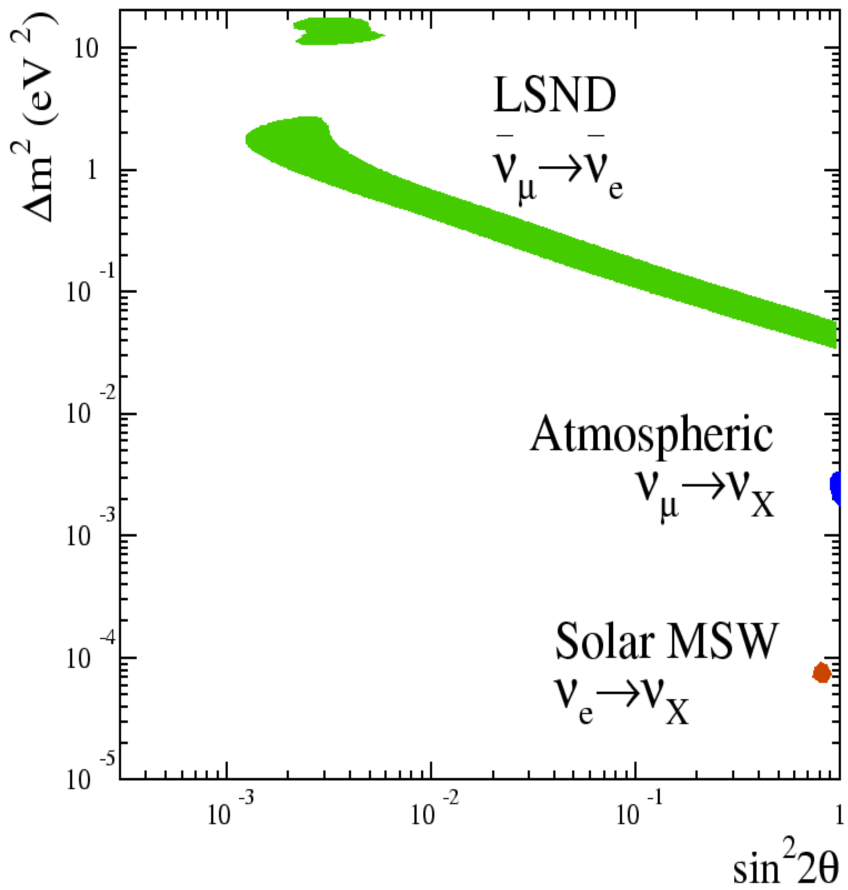
LSND signal

- Assuming two neutrino oscillations

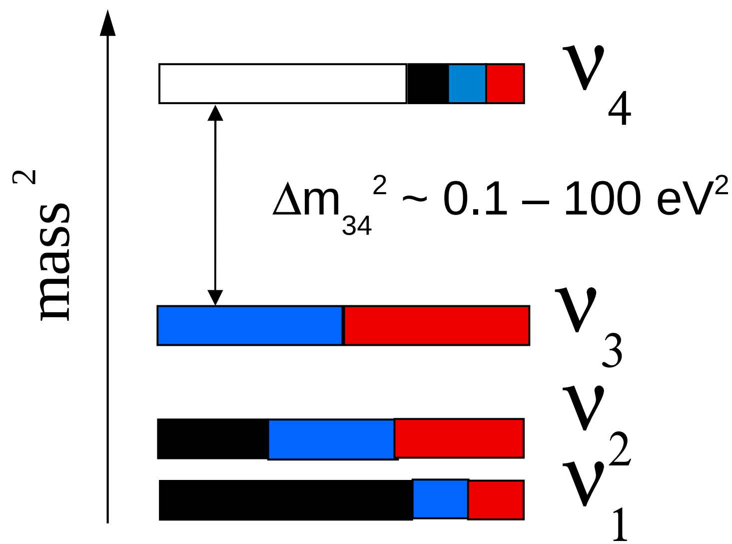
$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\ L\,\Delta m^2}{E}\right)$$
$$= 0.245 \pm 0.067 \pm 0.045\ \%$$

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





Sterile neutrinos



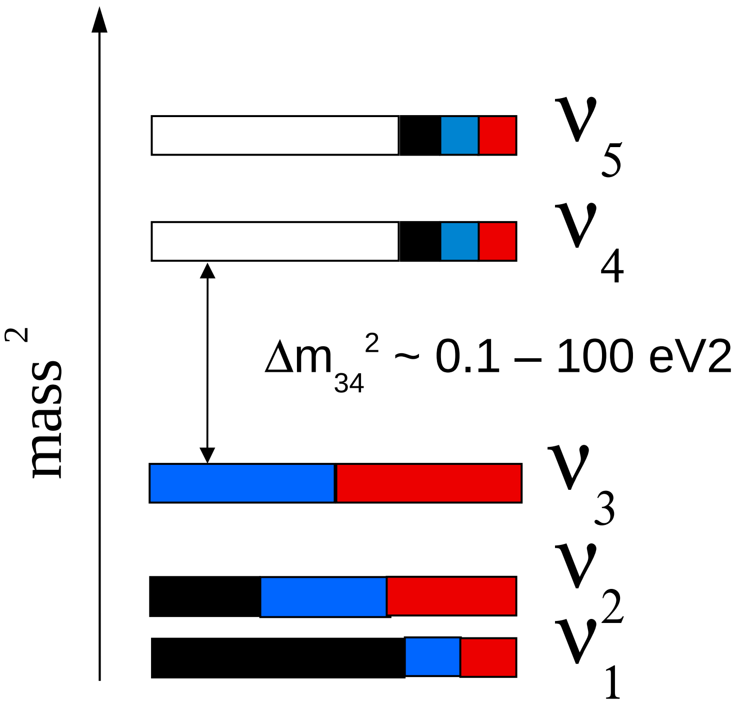
- 3 active neutrinos + 1 sterile neutrino
- Sterile neutrino has no Standard Model interactions
- Active neutrinos can oscillate into sterile
- 3 parameters relevant for short baseline exp.: Δm_{41}^2, $|U_{e4}|$ and $|U_{\mu 4}|$

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

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

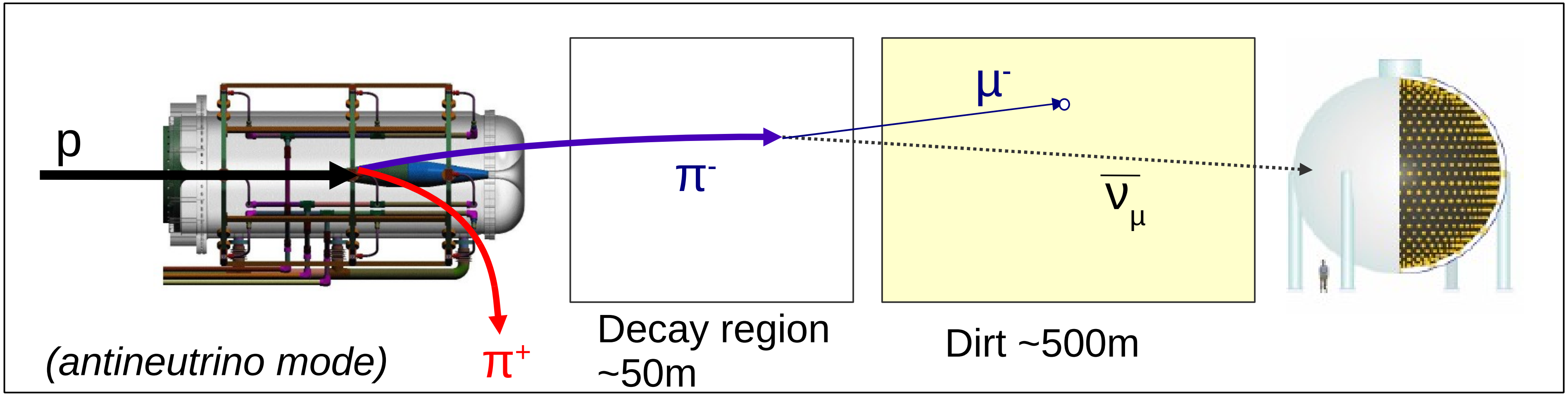
$$P(\nu_\mu \to \nu_\mu) = 1 - 4|U_{\mu 4}|^2 \left(1 - |U_{\mu 4}|^2\right) \sin^2(1.27\,\Delta m_{41}^2\, L/E)$$

More sterile neutrinos



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

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

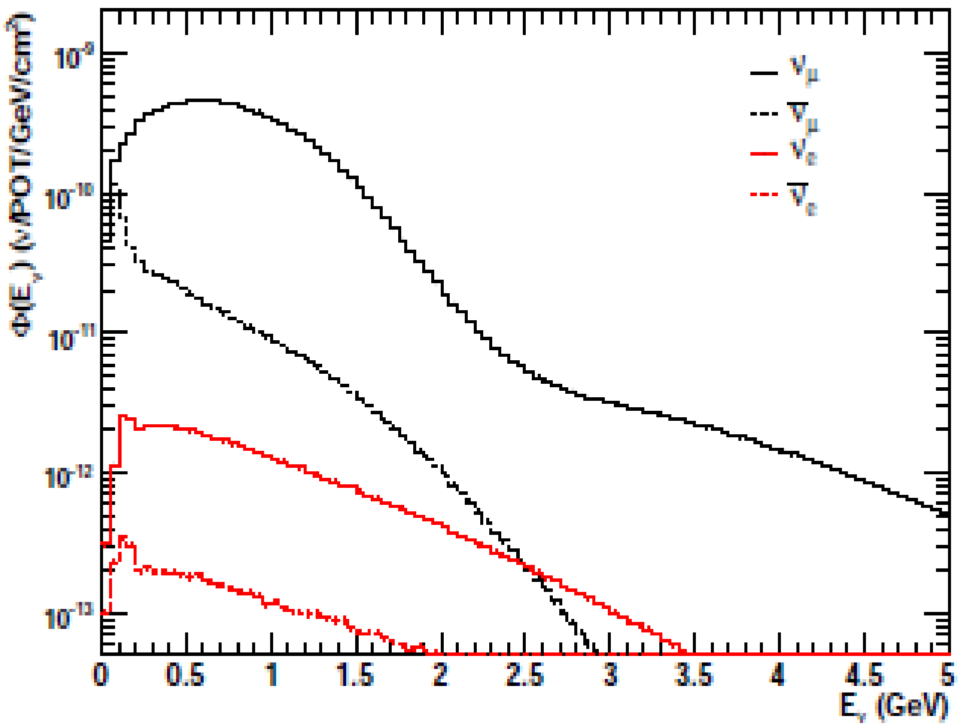
Predicted neutrino flux

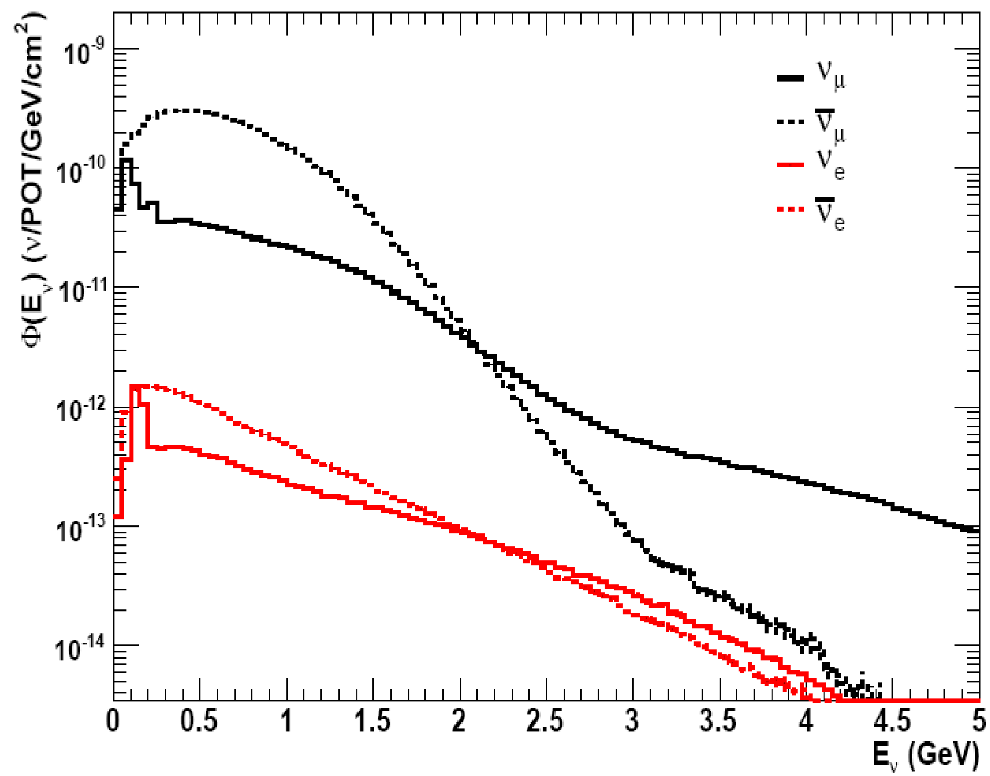
- Neutrino mode

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%

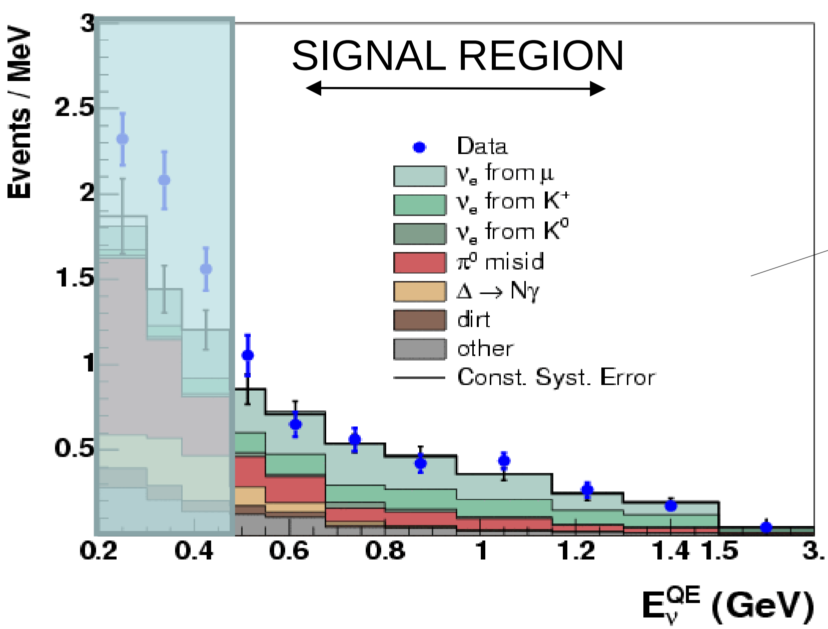


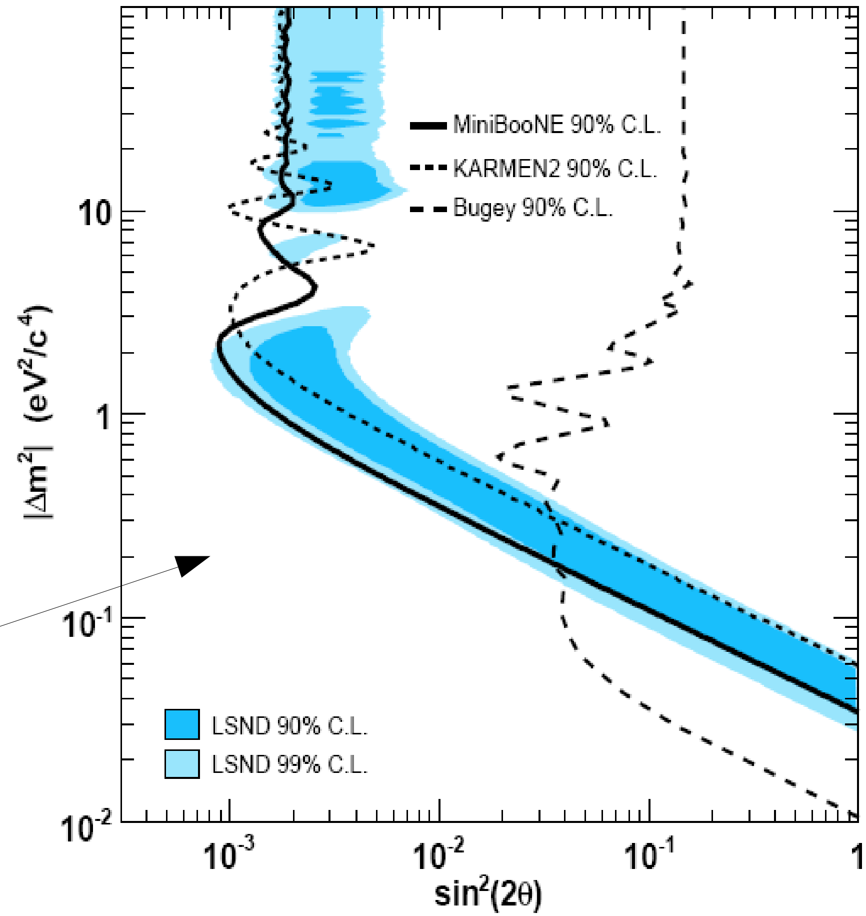


Phys. Rev. D79, 072002 (2009)

MiniBooNE neutrino result

- 6.5e20 Protons On Target (POT)
- No excess of events in fit region (E>475 MeV)
- Disfavors LSND 2 ν oscillation explanation for neutrinos (assuming no CP or CPT violation)





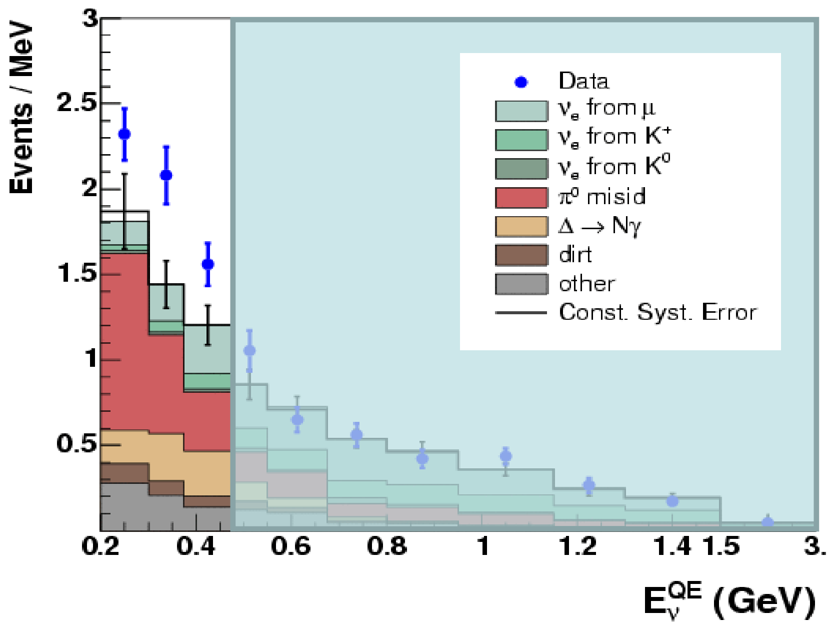
Phys. Rev. Lett. 98, 231801 (2007)

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.

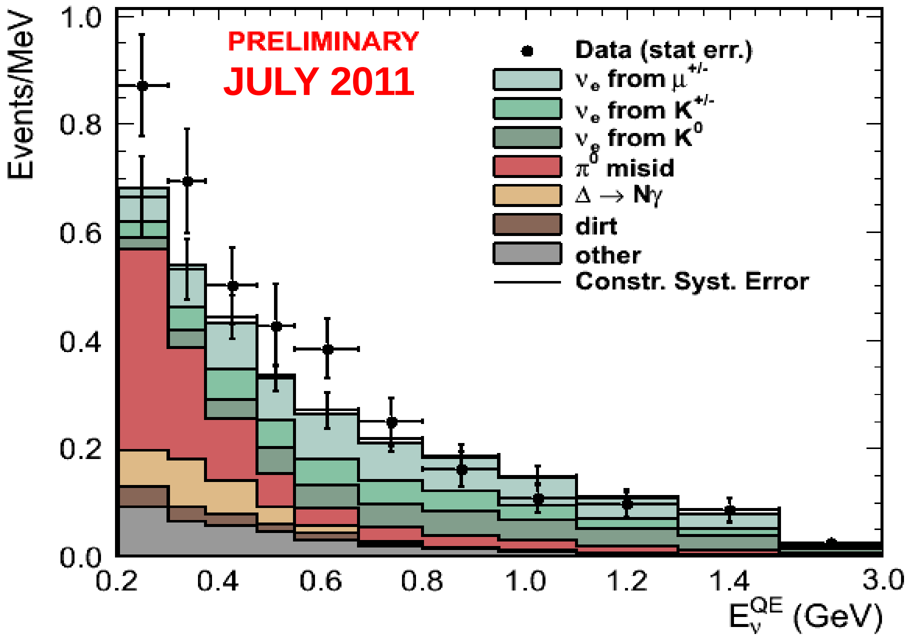
Extra Dimensions 3+1 Model: Pas, Pakvasa, & Weiler, Phys. Rev. D72 (2005) 095017

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

New $\bar{\nu}_e$ appearance results



	200-475MeV	475-1250MeV
Data	189	168
MC	150.4±18.5	151.7±19.4
Excess	38.6±18.5	16.3±19.4
LSND Best Fit	11.4	33.3
Expectation from ν low E excess	17	0
LSND+Low E	28.4	33.3

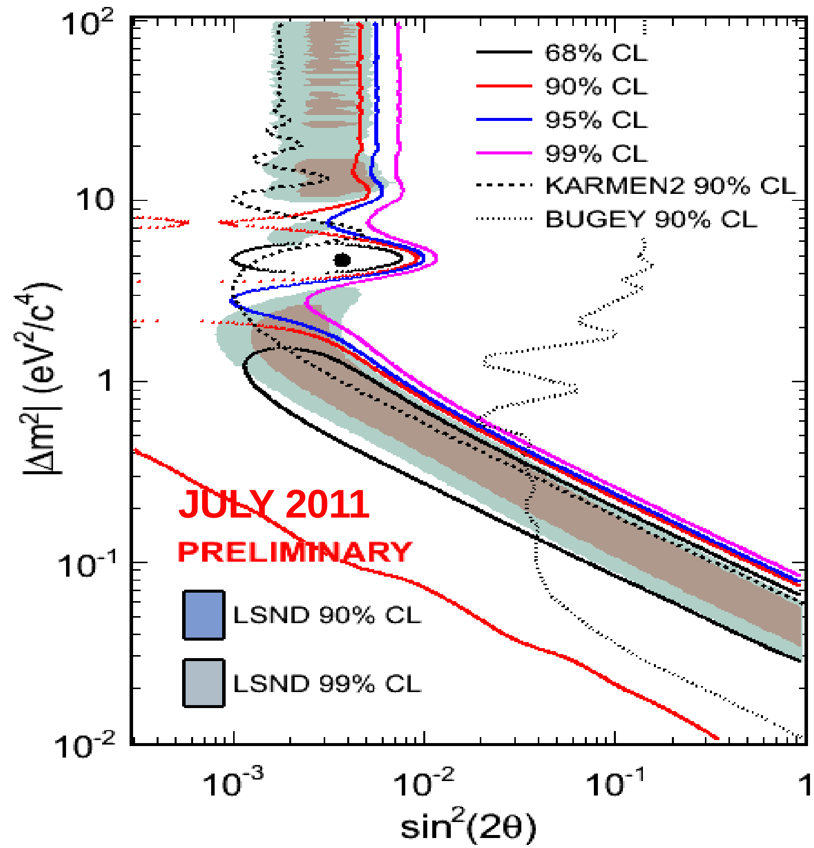
- Updated analysis with 8.58E20 POT - ~50% more data
- Nearly same analysis as before
  - New constraint on nue flux from K+ decays using SciBooNE + fit to K+ production global data (1105.2871, accepted by Phys. Rev. D)
- Compared to last analysis:
  - excess of events in 200-475 MeV is more significant
  - excess somewhat reduced in 475-1250MeV region, but still consistent with LSND

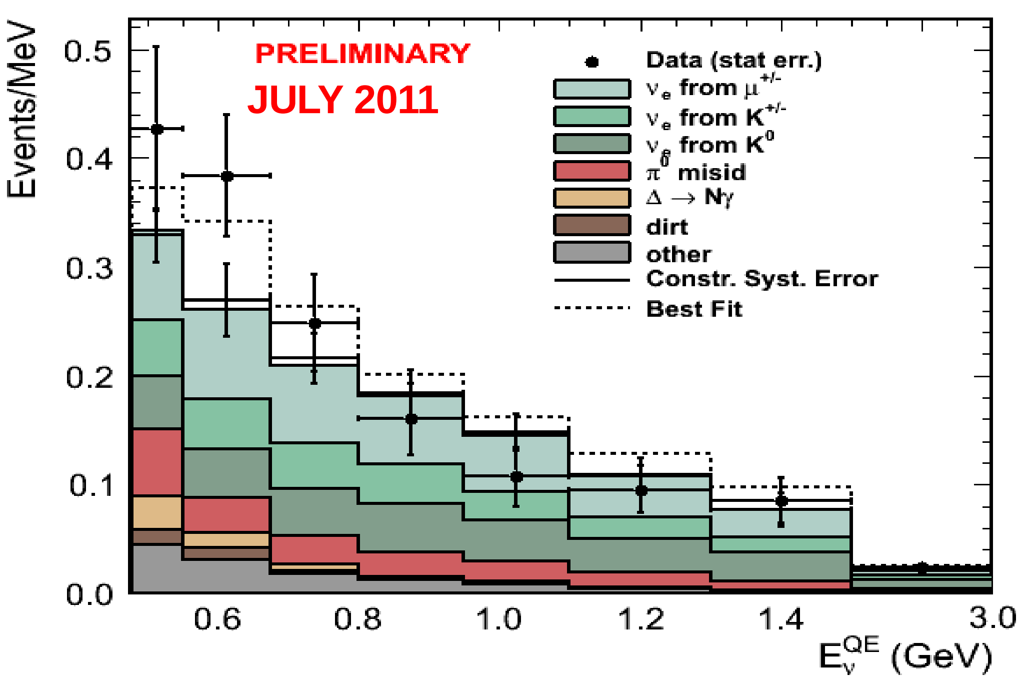
Fit E>475MeV

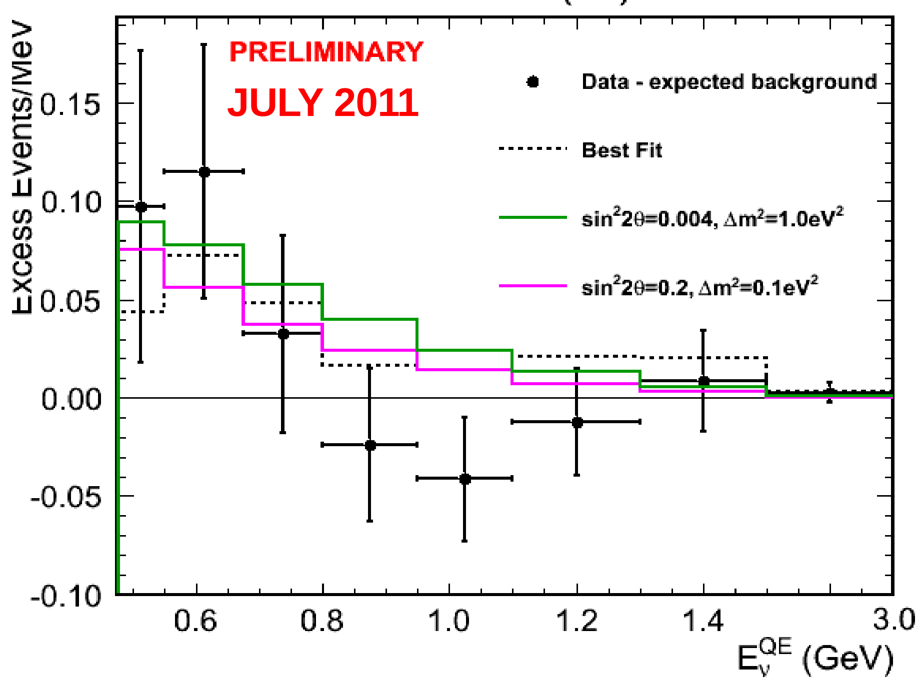
- 8.58E20 POT
- E>475 is neutrino mode fit region
- Oscillations favored over background only hypotheses at 91.4% CL
- Probability:

  P(null)=14.9%

  P(Best Fit)=35.5%

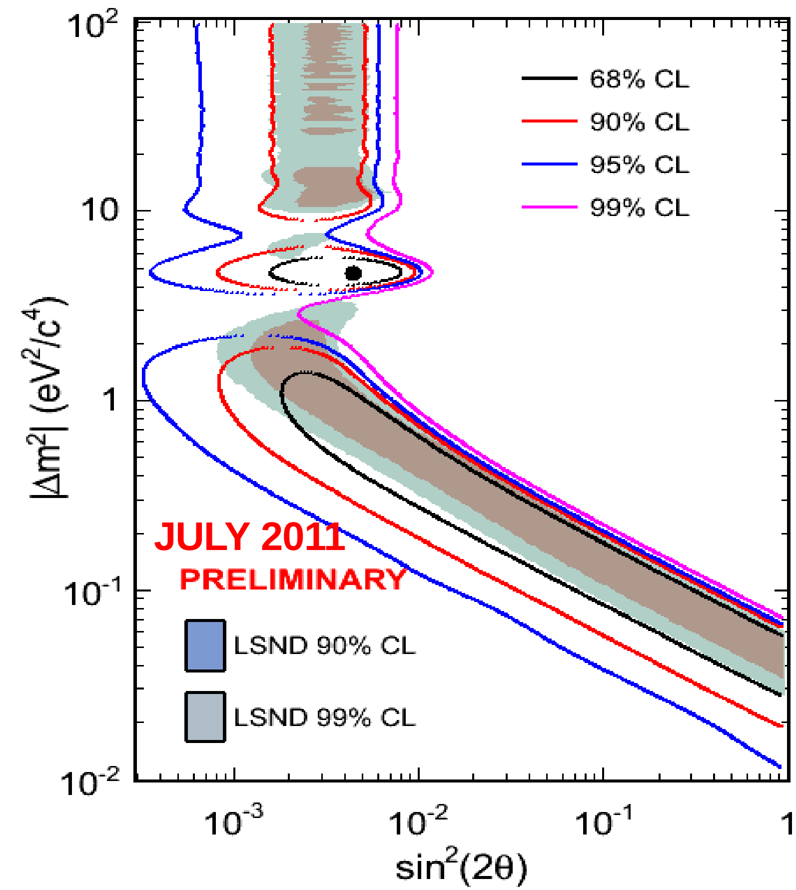


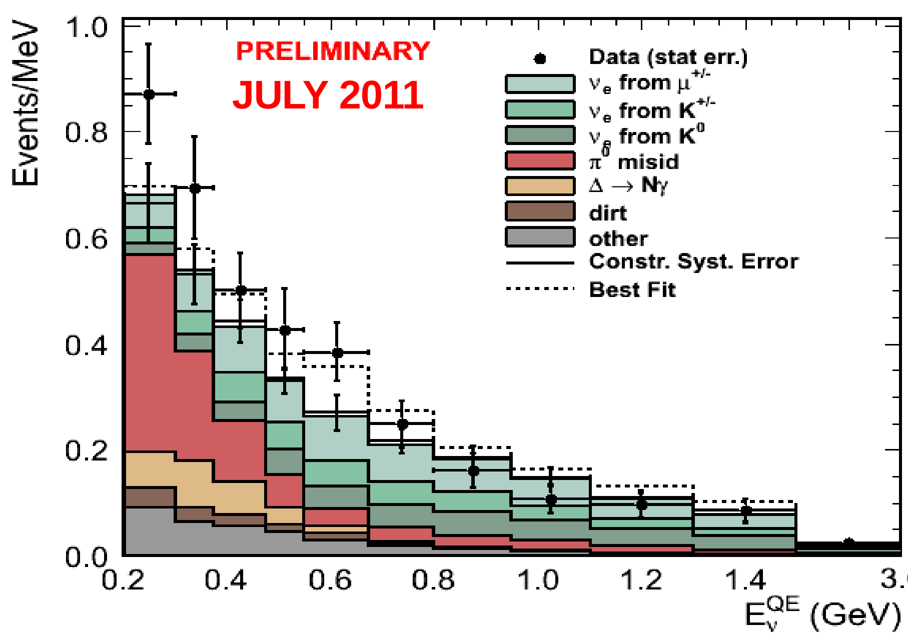


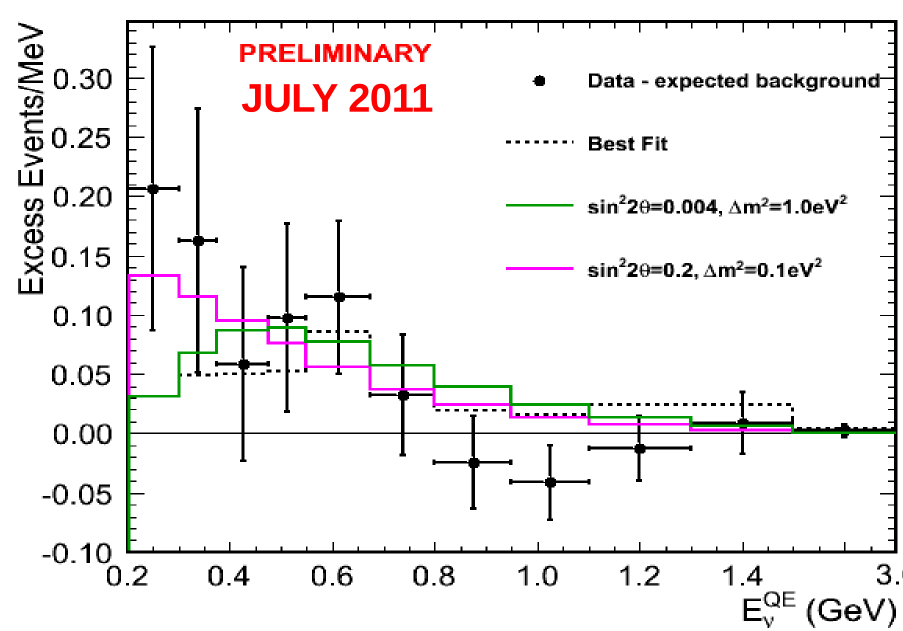


E>200MeV

- E<475MeV:
  - Larger background & systematics
- Oscillations favored over background only hypotheses at 97.6% CL (model dependent)
- No assumption made about low energy excess
- p(null)=10.1%
  p(BF) =50.7%

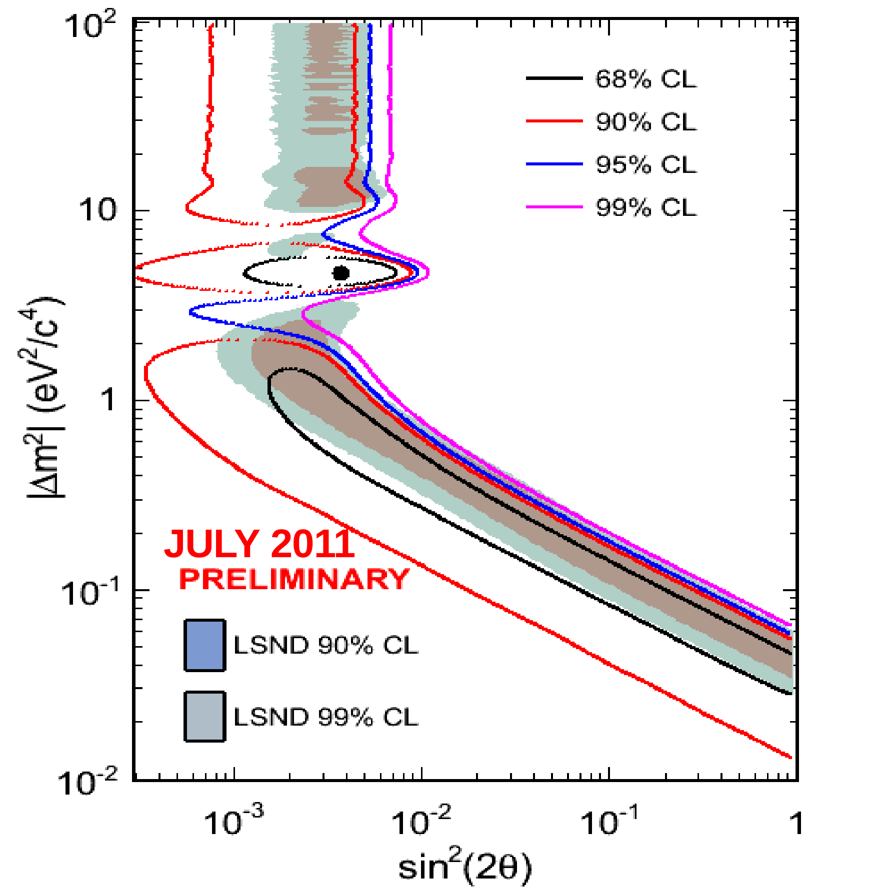


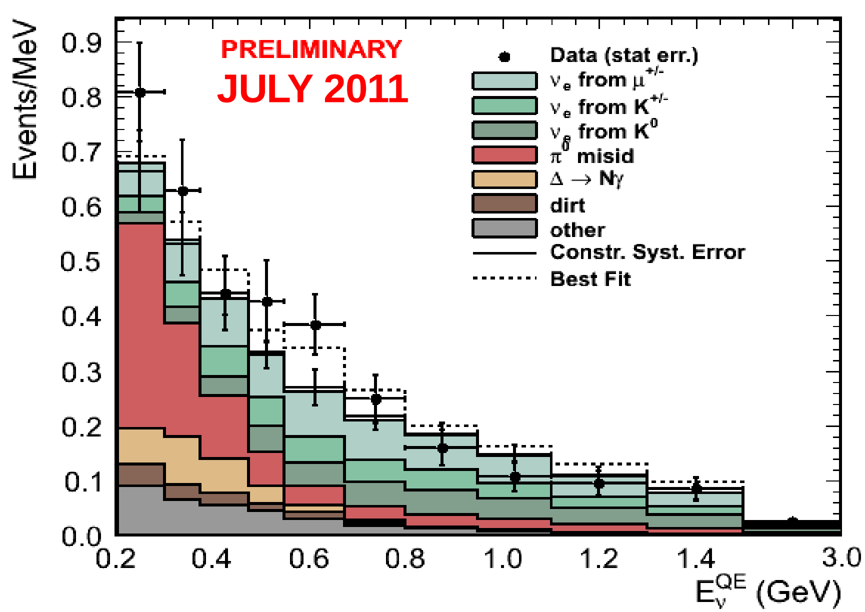


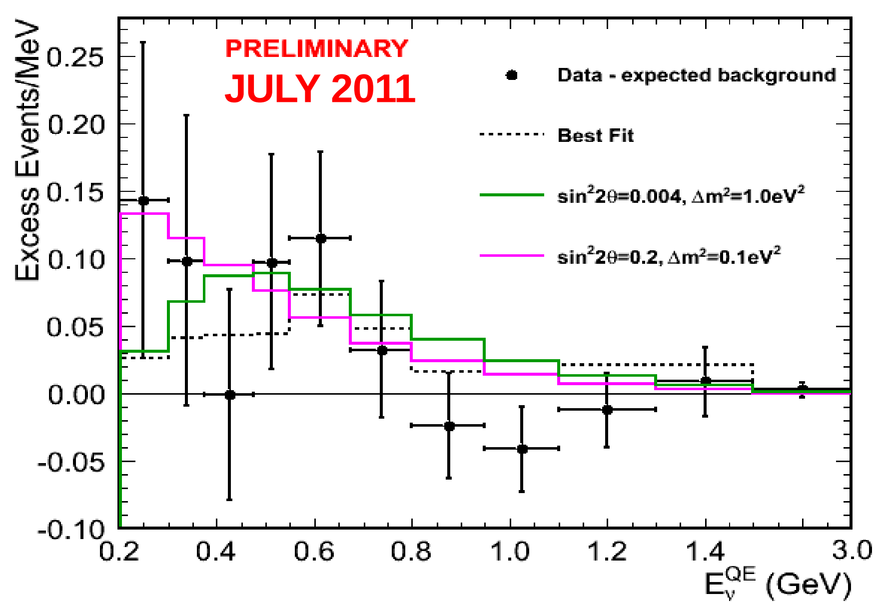


E>200MeV

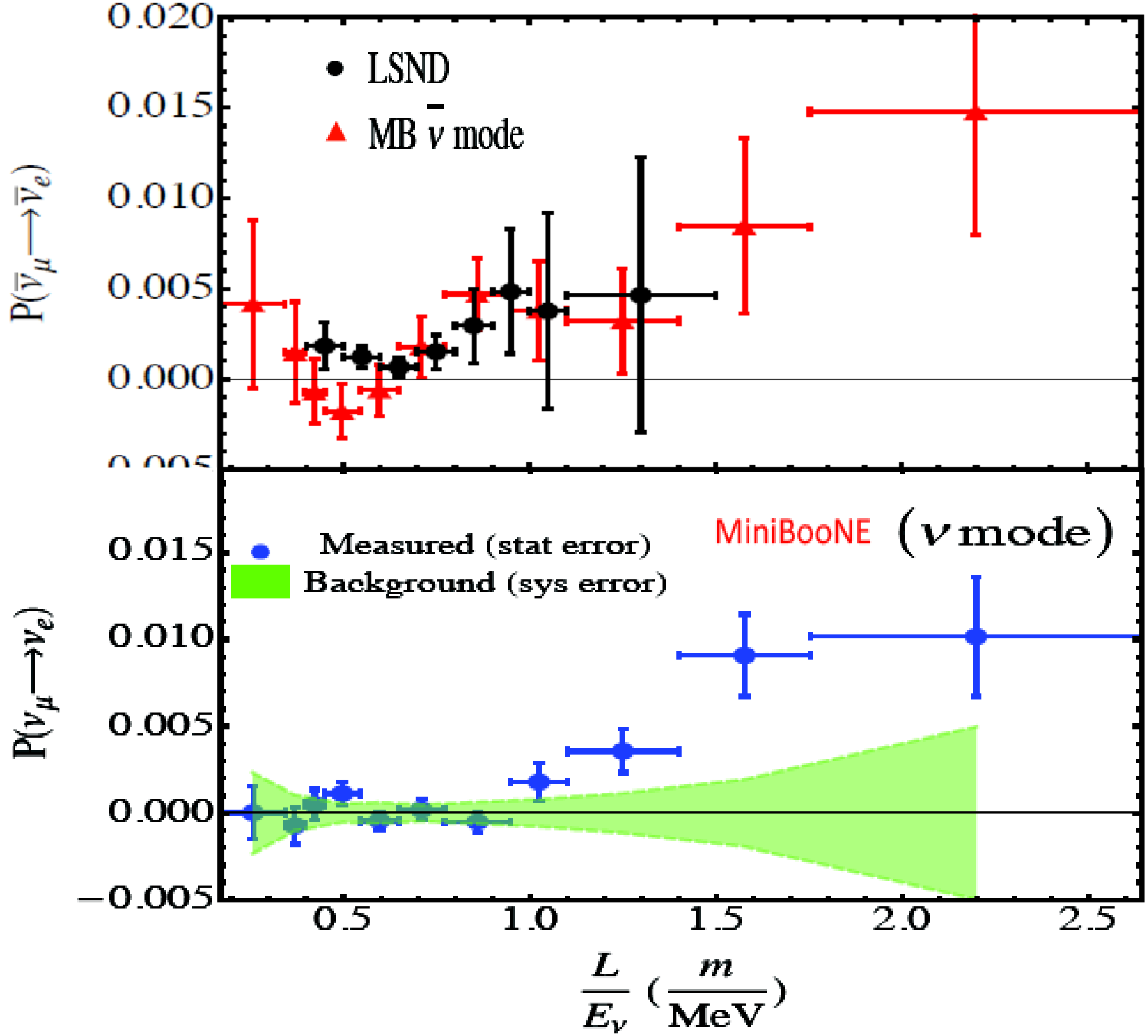
- E<475MeV:
  - Larger background & systematics
- Oscillations favored over background only hypotheses at 94.2% CL (model dependent)
- Subtract low energy excess assuming neutrinos anti-neutrino mode contribute to the excess (17 events)
- p(null)=28.3%
  p(BF) =76.5%





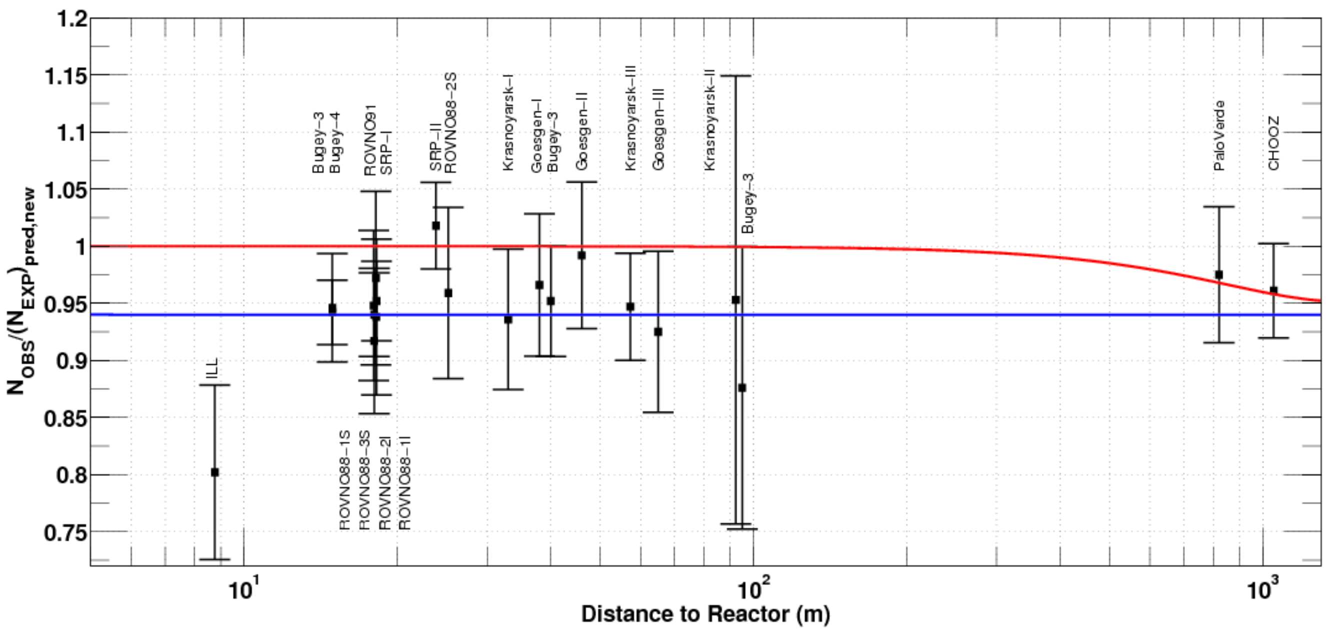


LSND vs MB direct comparison



Reactor antineutrino anomaly

- Recent re-evaluation 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: $^{71}Ga+\nu_e \text{->} ^{71}Ge+e^-$
  - 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)

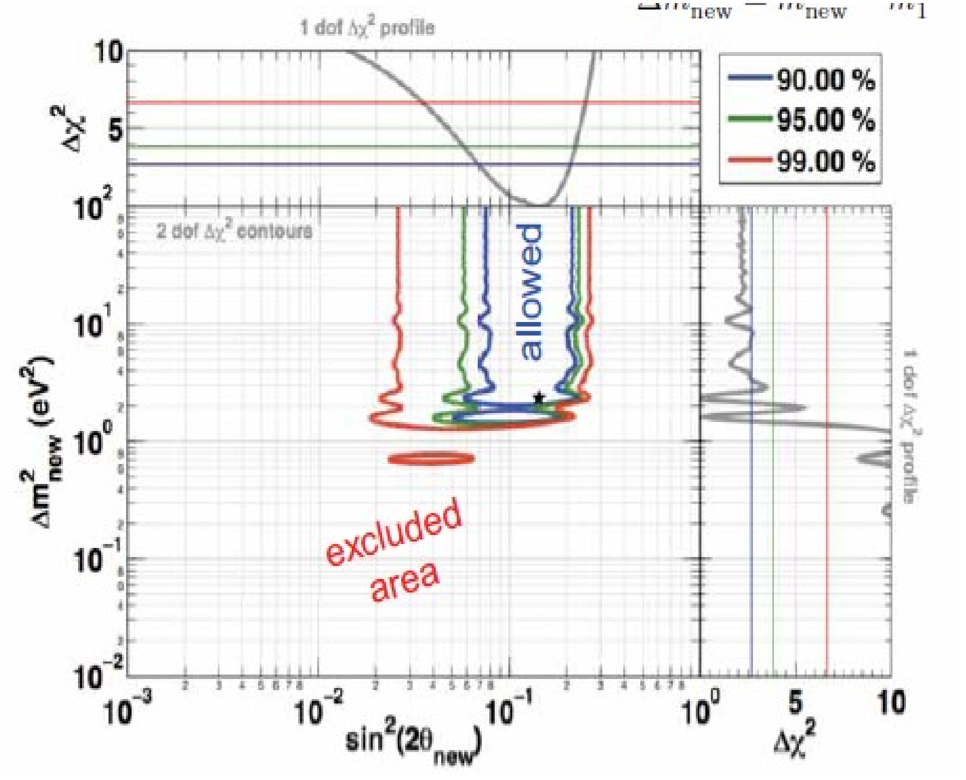
Sterile neutrinos?

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

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

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

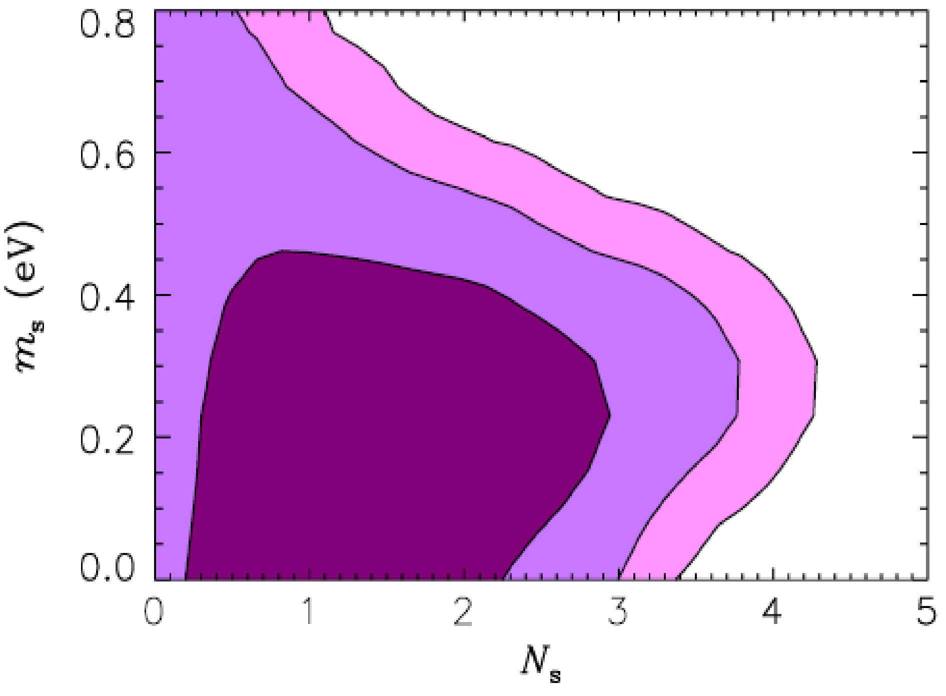
- High Δm^2 excluded
by limits on nue disappearance
using KARMEN and LSND
(*arxiv:1106.5552*)



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:

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

- From reactor experiments:

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

- From LSND/MiniBooNE:

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

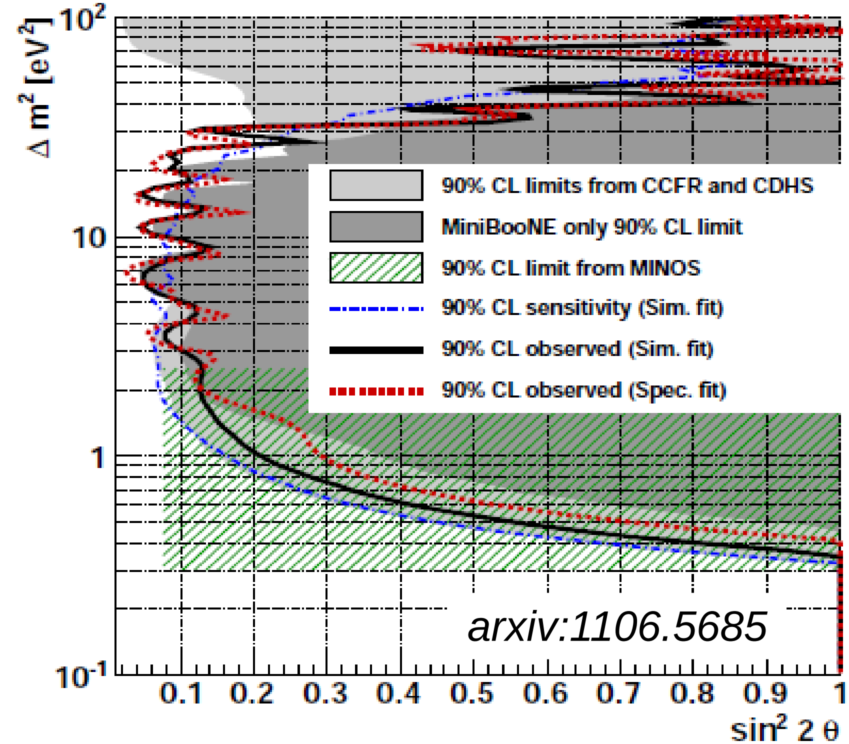
- Therefore:

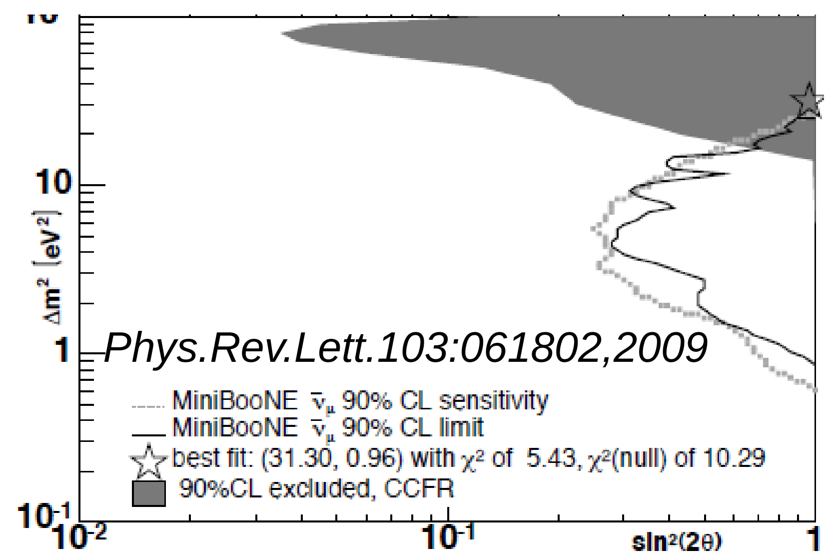
$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_x) > 10\%$$

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

ν_μ disappearance

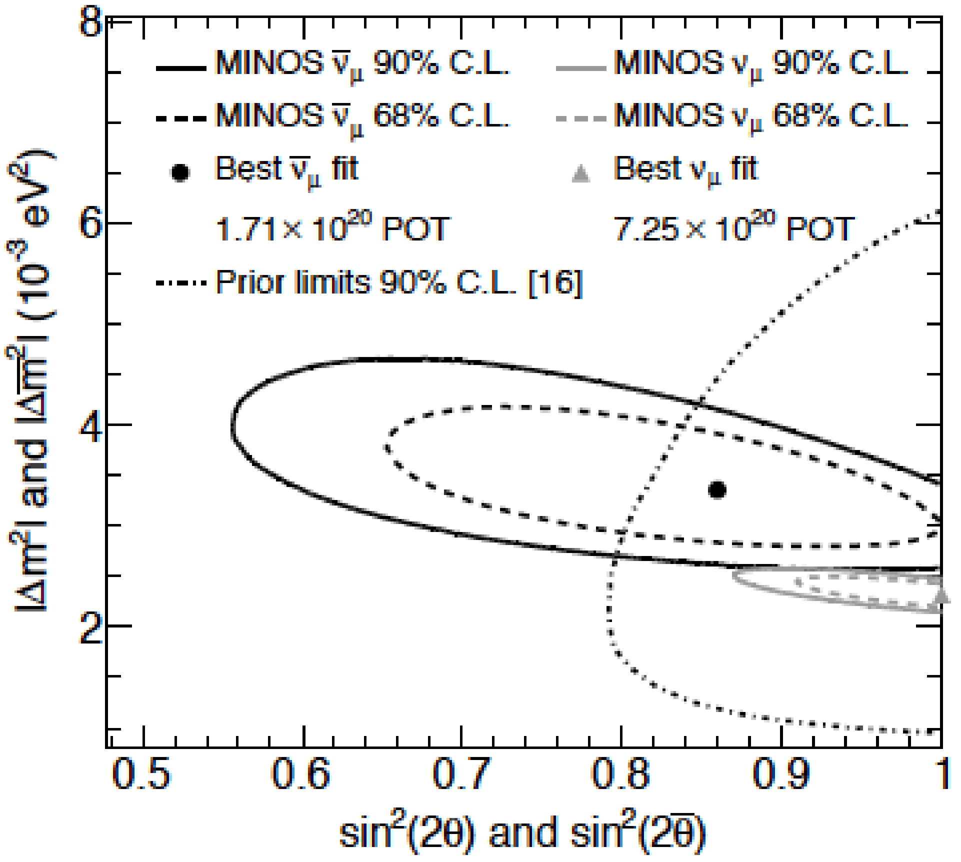
- Provides a constraint on ν_e appearance
- Combined SciBooNE-MiniBooNE analysis in neutrino mode
- MiniBooNE only in anti-neutrino mode





MINOS ν_μ vs $\bar{\nu}_\mu$

- Hint of NSI or CPT violation?



Phys.Rev.Lett.107:021801,2011

Future outlook

- MiniBooNE – more antineutrino data, approved to run through spring 2012
- Joint MiniBooNE/SciBooNE $\bar{\nu}_\mu$ disappearance
- MicroBooNE - resolve the low energy excess
- MINOS+ - sterile neutrinos, NSI, …

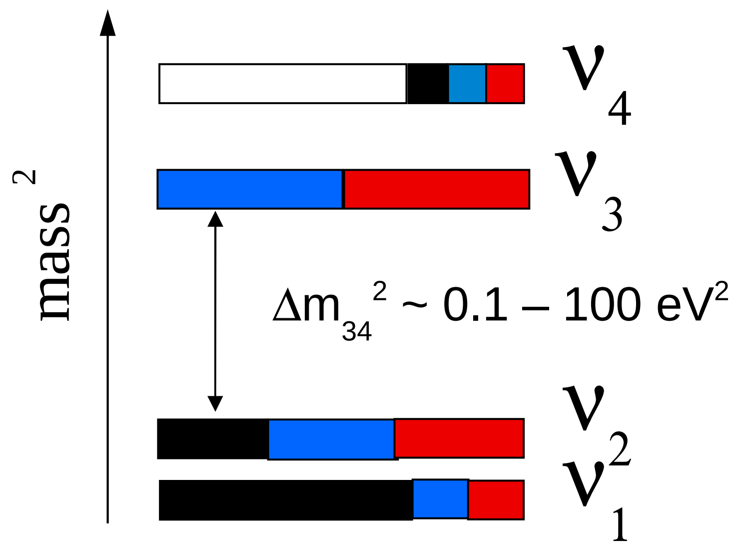
- BooNE
- Stopped pion source exp. (OscSNS,...)
- Icarus at CERN-PS

Conclusion

- MiniBooNE anti neutrino data consistent with LSND and $\bar{\nu}_\mu$->$\bar{\nu}_e$ oscillations at Δm^2~1eV^2
- Few other hints of sterile neutrinos – reactor anomaly, gallium anomaly, cosmology
- 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



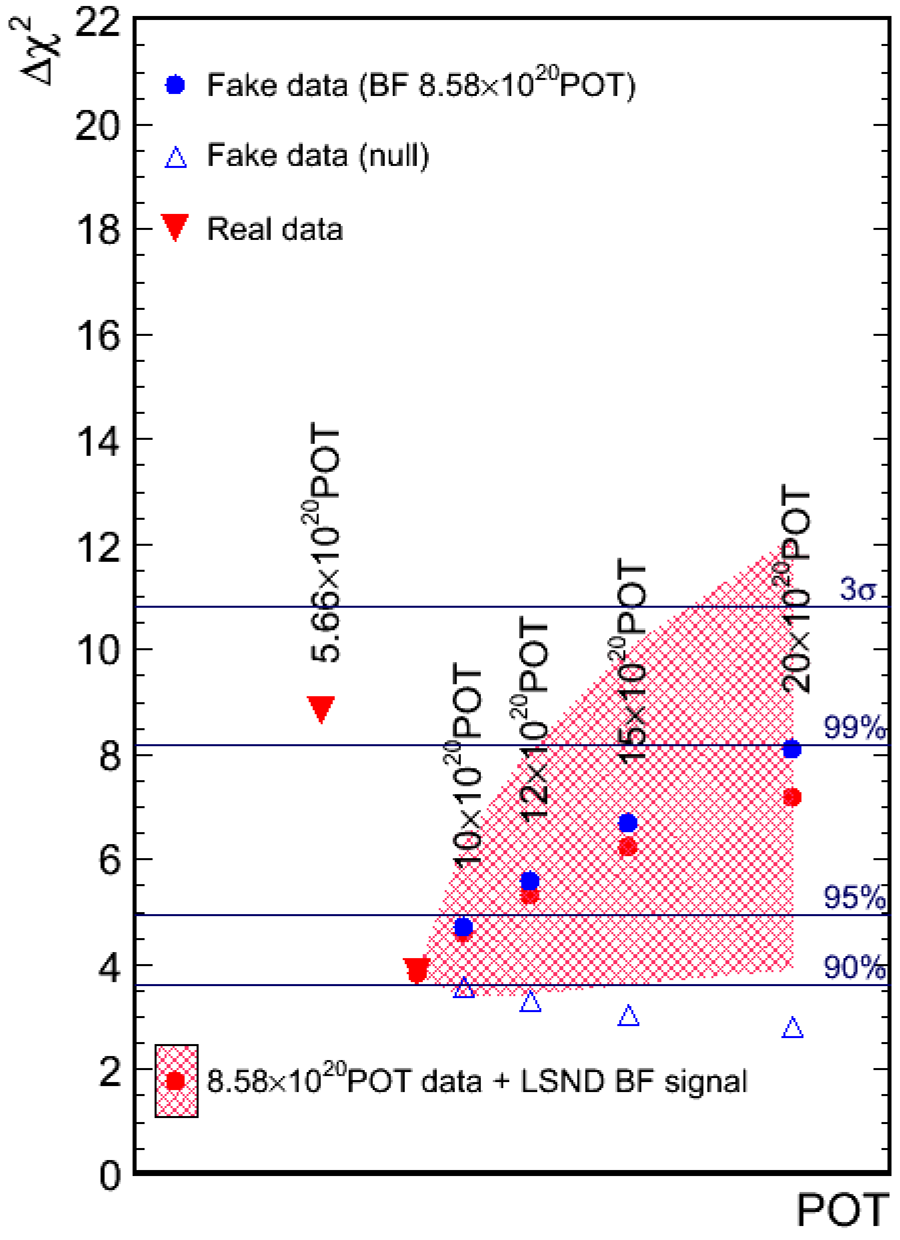
- Within 2+2 model Sterile neutrino participates in either solar or atmospheric neutrino oscillations (or both)
- Experiments measuring solar and atmospheric dm2 disfavor oscillations to pure sterile neutrinos

=> 2+2 is strongly disfavored

Future sensitivity

- Potential exclusion of null point assuming best fit signal

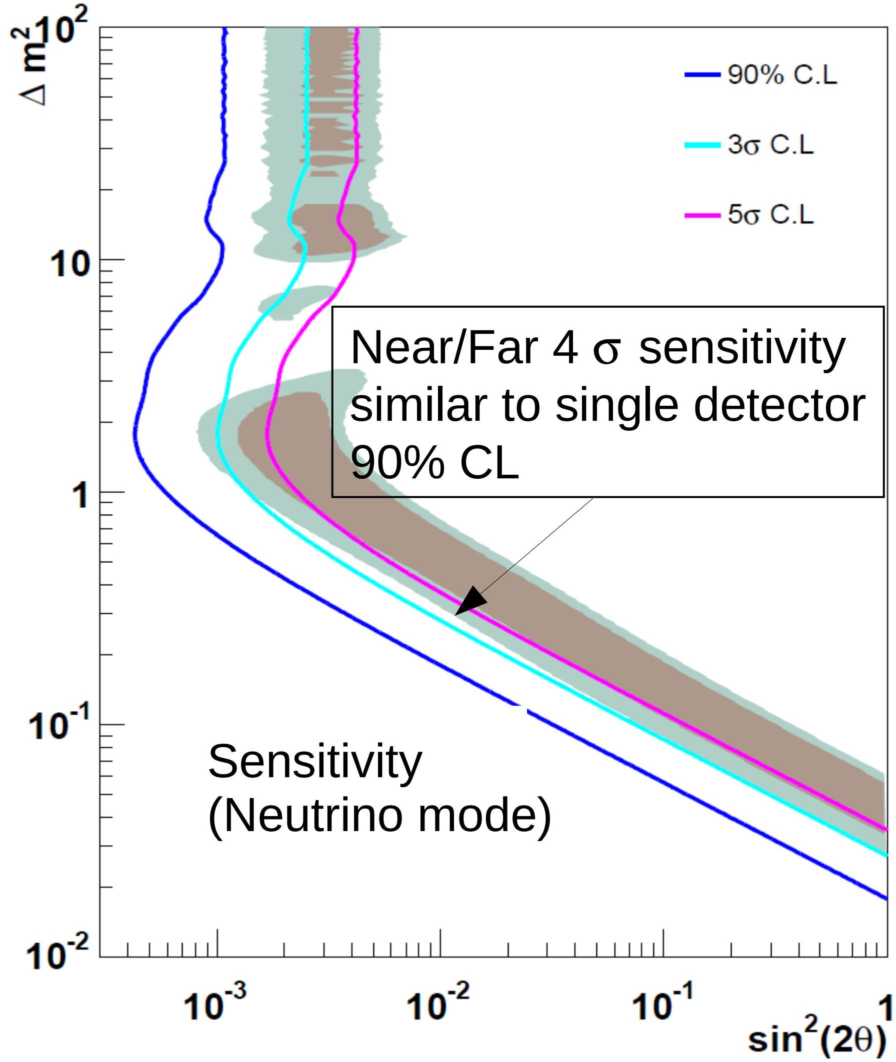
- Combined analysis of ν_e and $\bar{\nu}_e$



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

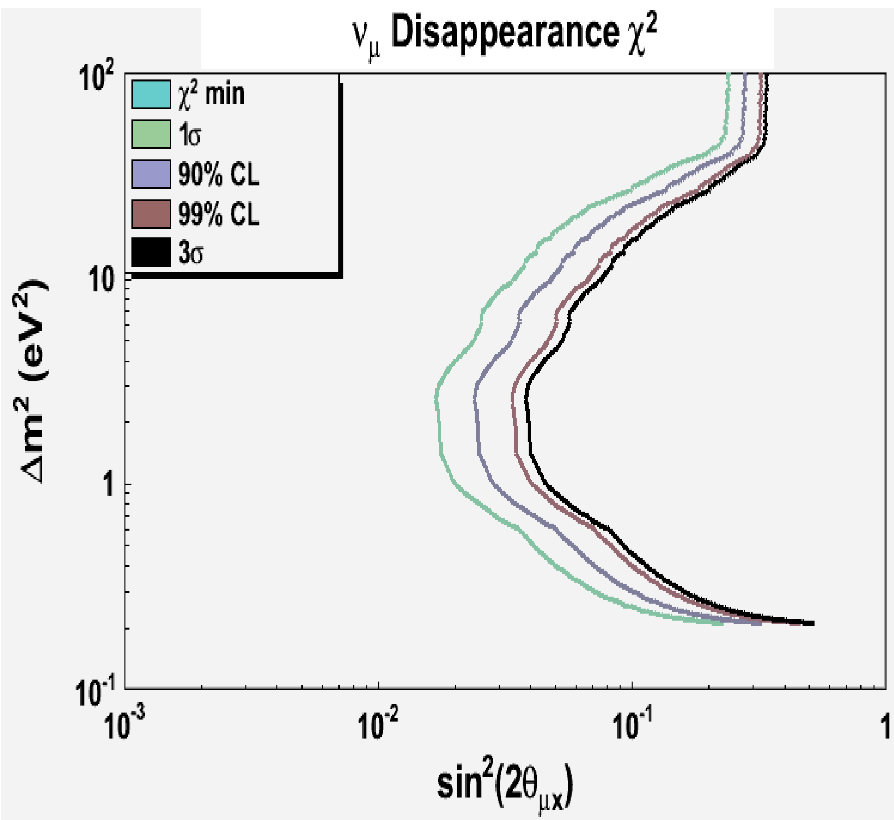
6.5e20 Far + 1e20 Near POT



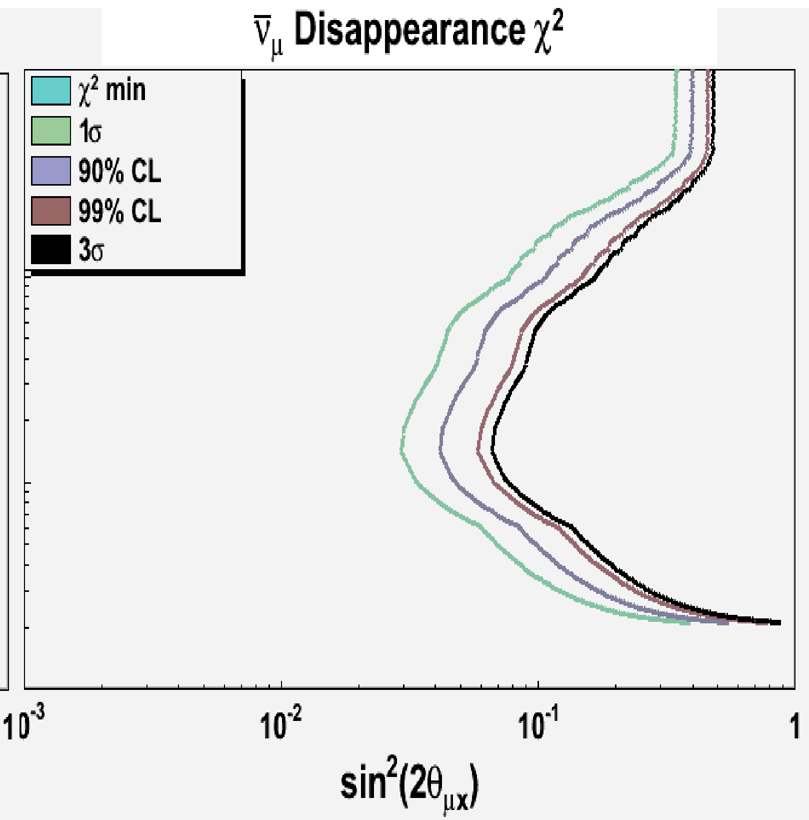
BooNE

- 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

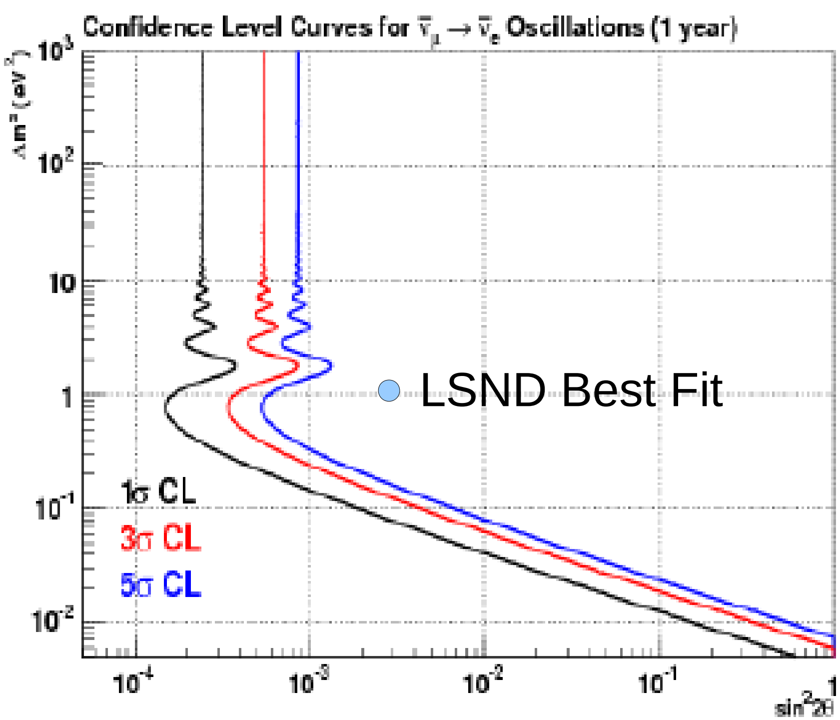


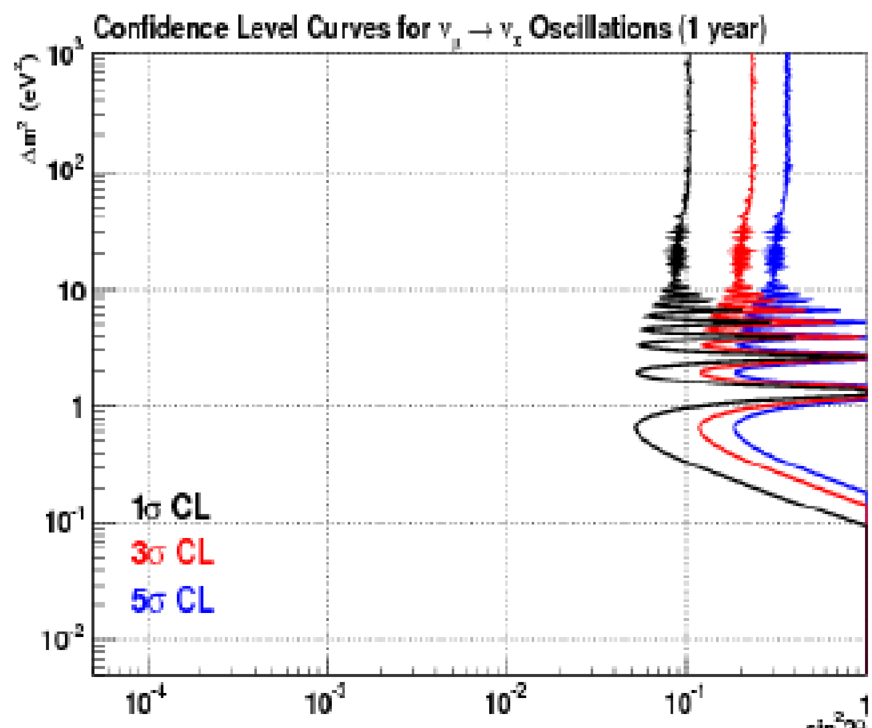
OscSNS

- 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**)

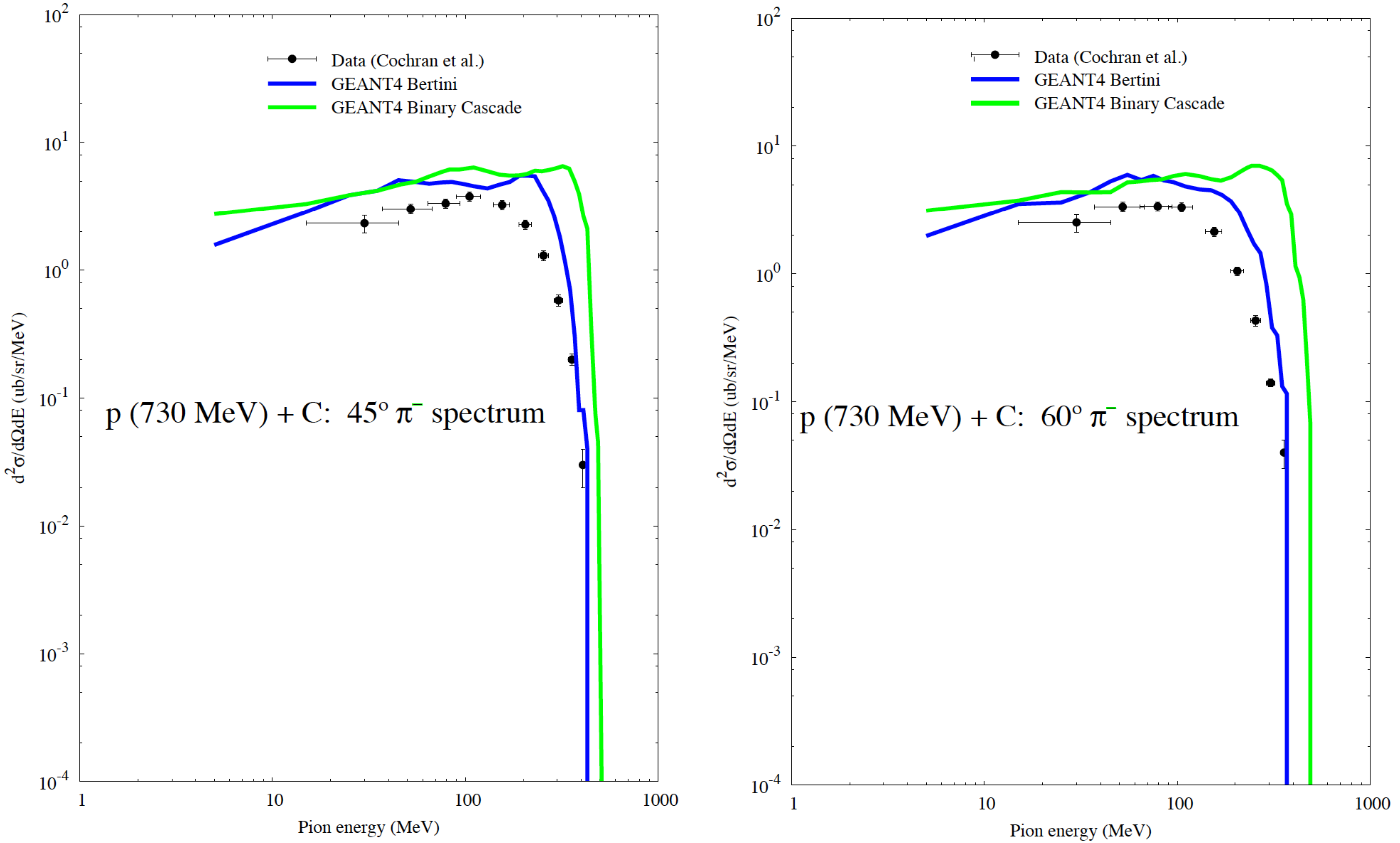
Zhemchugov Poster: **FLUKA** $\bar{\nu}_e/\bar{\nu}_\mu$ ratio presented at the ICHEP 2010 Conference, Paris

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 -> e^- N_{gs} Events Do Not Simulate $\bar{\nu}_e$ p -> 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.