A search for muon neutrino and antineutrino disappearance with MiniBooNE

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Sterile Neutrinos and Disappearance Experiments

The MiniBooNE Experiment

Neutrino (and Antineutrino) Disappearance Fits

Summary

The MiniBooNE Collaboration

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Neutrino Oscillation Observations

Plot of all oscillation experiments:

"Solar": $\Delta m^2_{12} \sim 10^{-5} eV^2$, $\theta_{12} \sim 32°$

Confirmed! via reactor neutrinos

"Atmospheric": $\Delta m^2_{23} \sim 10^{-3} eV^2$, $\theta_{23} \sim 45°$

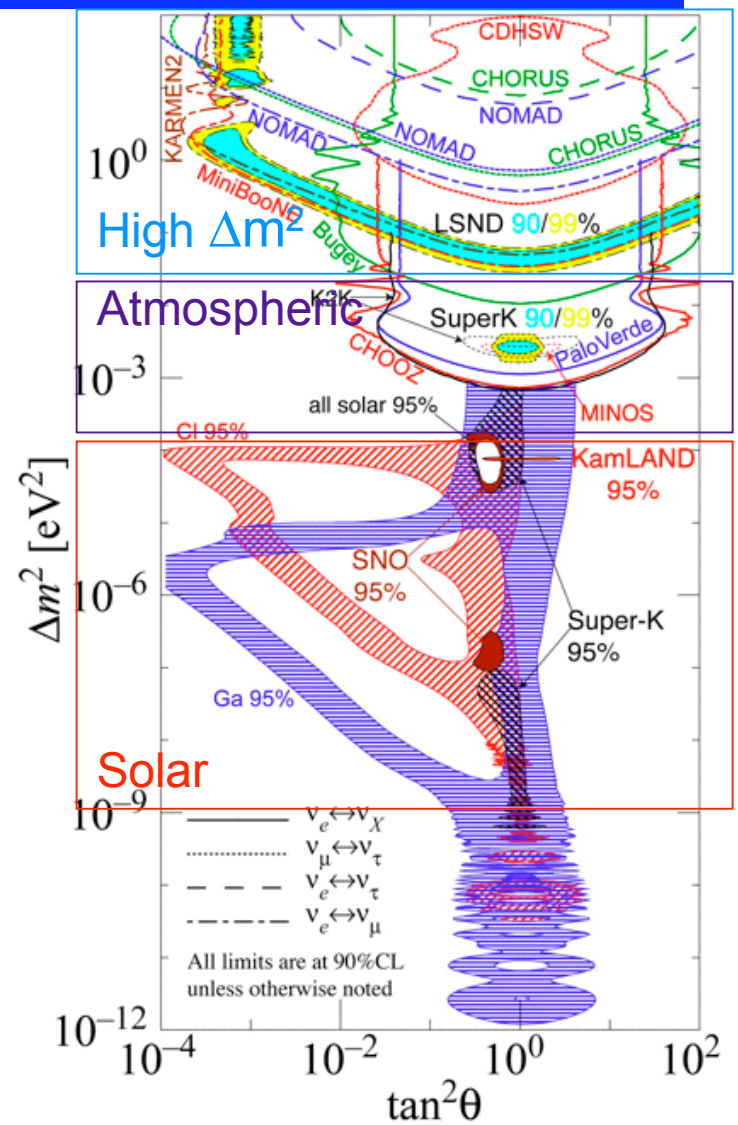
Confirmed! via accelerator neutrinos

"High Δm^2": $\Delta m^2 \sim 1\text{-}10 eV^2$

LSND observed of 3.8 σ excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam

Karmen, Bugey and MiniBooNE exclude the parameter space

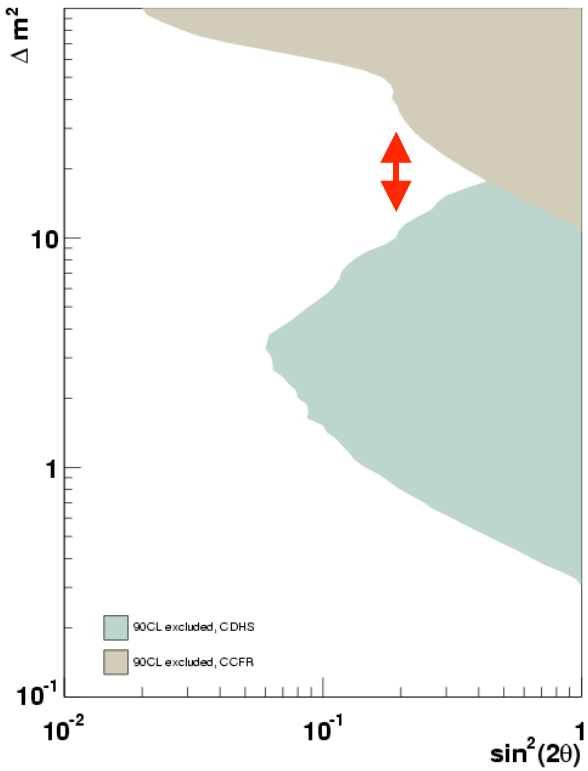
If $\bar{\nu}_e$ oscillate but the ν_e do not, then exotic physics is needed



Sterile Neutrinos

One explanation for the LSND oscillation signal is to add another "sterile" flavor of neutrino (or 2 or N) to the neutrino mixing matrix: Adding 1 sterile neutrino is 3+1, adding N is 3+N

$$U_{\alpha i} = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \vdots \\ \nu_s \end{pmatrix} \begin{pmatrix} U_{e1} & U_{e2} & \cdots & U_{eN} \\ U_{\mu 1} & U_{\mu 2} & \cdots & U_{\mu N} \\ U_{\tau 1} & U_{\tau 1} & \cdots & U_{\mu N} \\ \vdots & \vdots & \ddots & \vdots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \vdots \\ \nu_N \end{pmatrix}$$



Disappearance expts (CDHS/CCFR/atmospheric) disfavor 3+1 already

Maltoni, Schwetz, Valle, Phys.Lett.B518:252-260,2001. hep-ph/0107150

3+2 models have large mixing and prefer the region where experimental limits are weakest

G. Karagiorgi et al, Phys.Rev.D75:013011,2007. hep-ph/0609177

Motivation for Neutrino Disappearance

The observation of ν_μ disappearance could imply exotic physics, such as sterile neutrinos

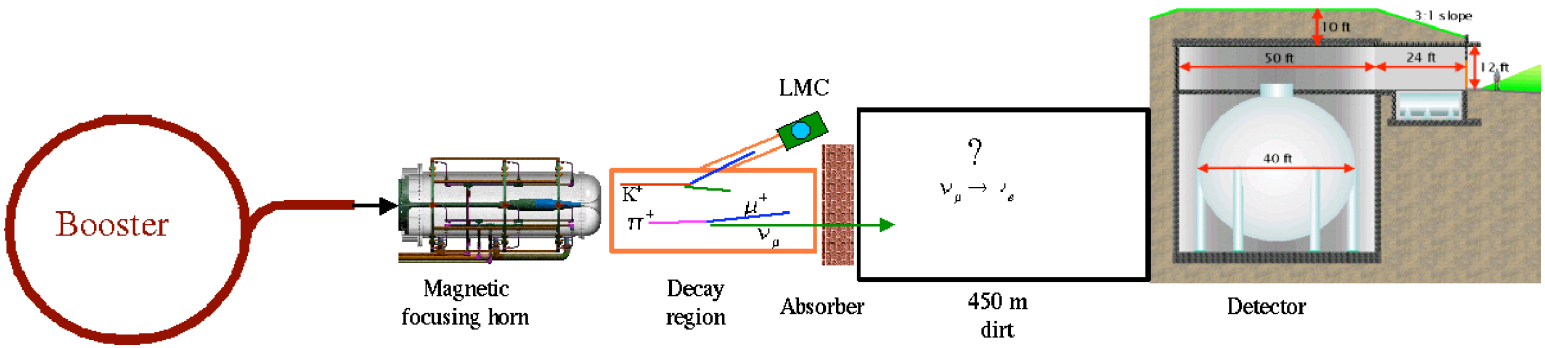
The lack of ν_μ disappearance constrains sterile neutrino models

The combination of ν_μ and $\bar{\nu}_\mu$ disappearance tests unitarity of the mixing matrix

MiniBooNE can further our understanding of disappearance at high Δm^2 with both neutrinos and antineutrinos

MiniBooNE Experiment

Short baseline (L=~500m) designed to test LSND-like ν_e appearance

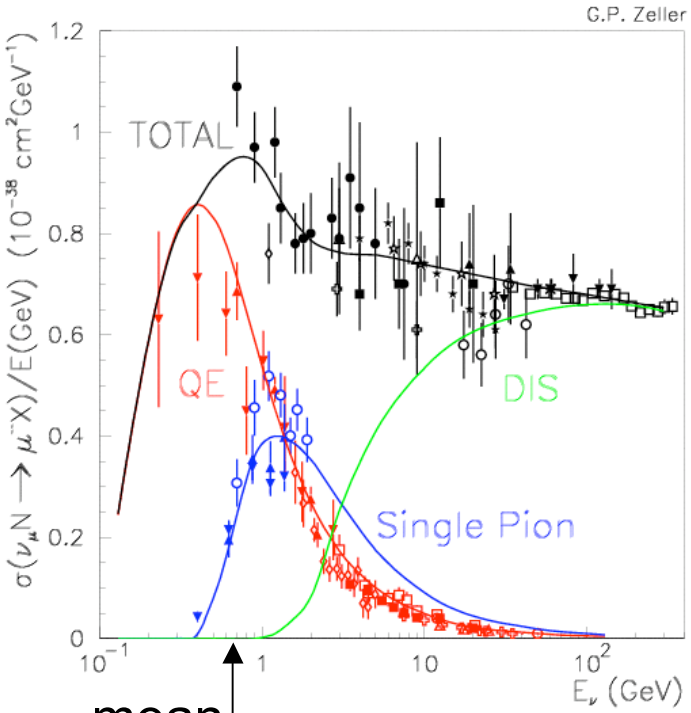


8.9 GeV/c protons on Be produce mesons which decay to neutrinos (or antineutrinos) detected in a ~1kton mineral oil Cherenkov detector

Changing the polarity of the magnetic horn focuses positive (negative) mesons and produces a neutrino (antineutrino) beam

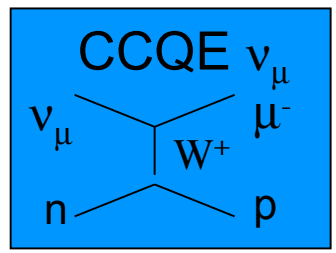
Neutrino Interactions at ~1 GeV

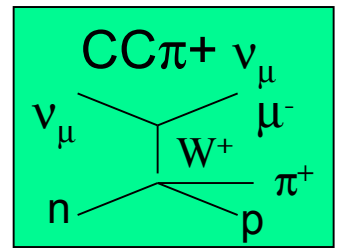
World's data on
GeV neutrino cross sections



mean
flux Eν (0.8 GeV)

At 1 GeV, neutrinos interact via
- CCQE (quasi-elastic scattering)
- CCπ^+ (single pion production)





In CCQE interactions, the muon's energy (E_μ), and angle (θ_μ) are sufficient to reconstruct the neutrino energy:

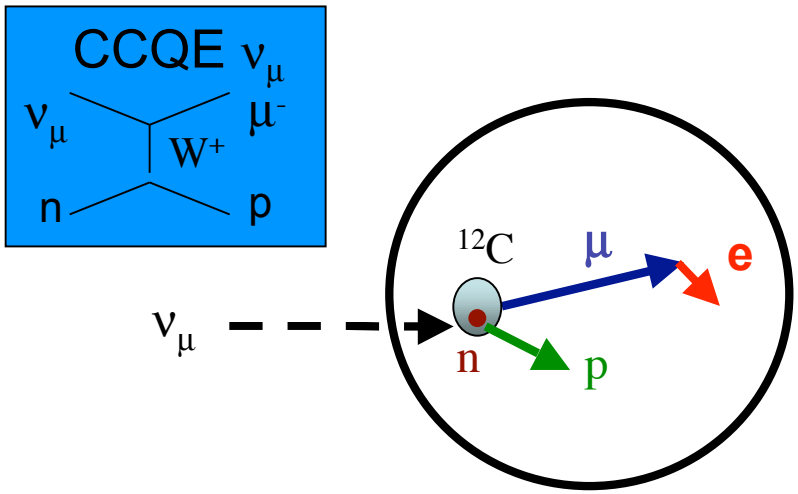
$$E_\nu(QE) = \frac{m_N E_\mu - \frac{1}{2} m_N^2}{p_\mu \cos\theta_\mu + m_N - E_\mu}$$

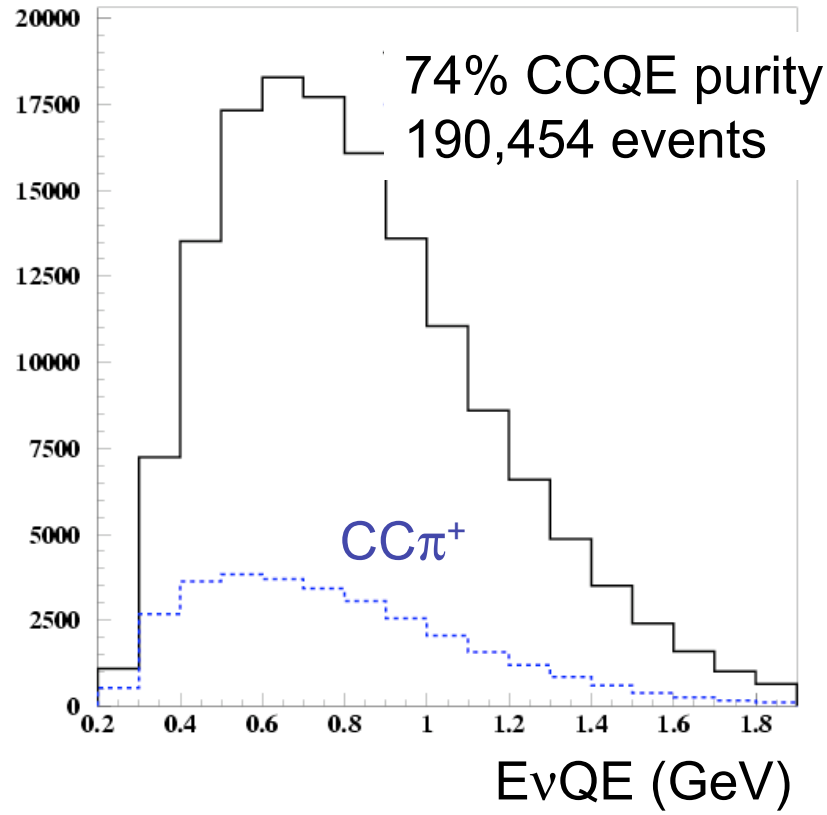
where m_N is the mass of the nucleon

MiniBooNE CCQE Selection

Tag single muon events and their decay electron

- Two sets of hits separated in time (μ, e)
- Minimal hits in the veto
- Muon-like track, 2nd event below decay electron energy endpoint
- Also require events within fiducial volume, beam timing and data quality selections



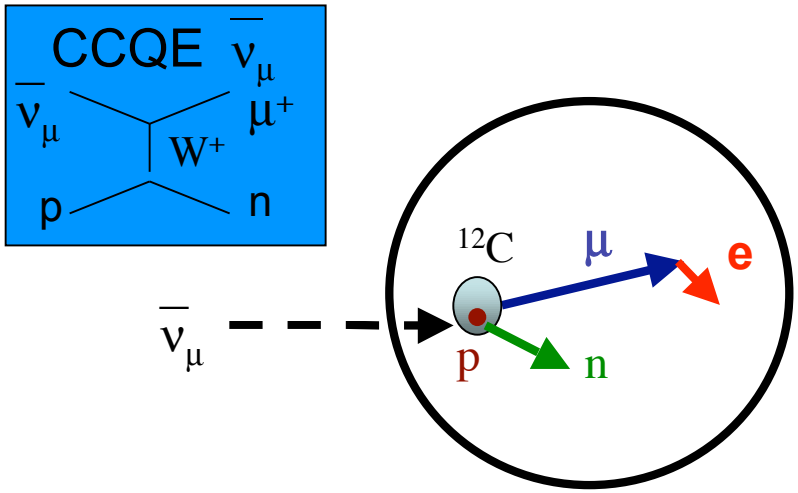


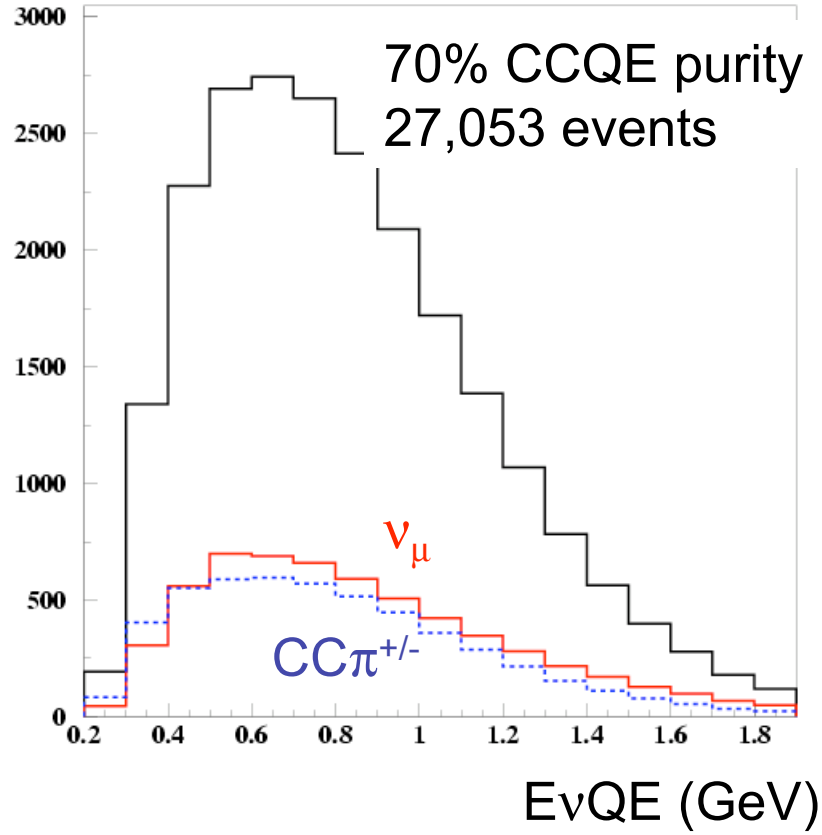
Background is $CC\pi^+$ where the pion is absorbed in the nucleus or detector

Antineutrino-Mode CCQE Sample

Apply same CCQE selection to antineutrino dataset

- No selection on final state nucleon (n,p)
- No magnetic field, cannot identify muon charge
- Decay positron looks like electron event as well





Similar $CC\pi^{+/-}$ background, and CCQE purity as in neutrino mode

Substantial neutrino events in the antineutrino sample (~25%)

Fitting for Disappearance

Compare the difference between data and prediction to the error as a function of reconstructed neutrino energy:

$$\chi^2 = \sum (d_i - p_i) M_{ij}^{-1} (d_j - p_j)$$

where d_i, is the data, and $p_i(\Delta m^2, \sin^2 2\theta)$, is the prediction in energy bin i, assuming disappearance, normalized to total data

M_{ij}^{-1} is the inverse of the shape-only error matrix

Error matrix includes systematic and statistical uncertainties

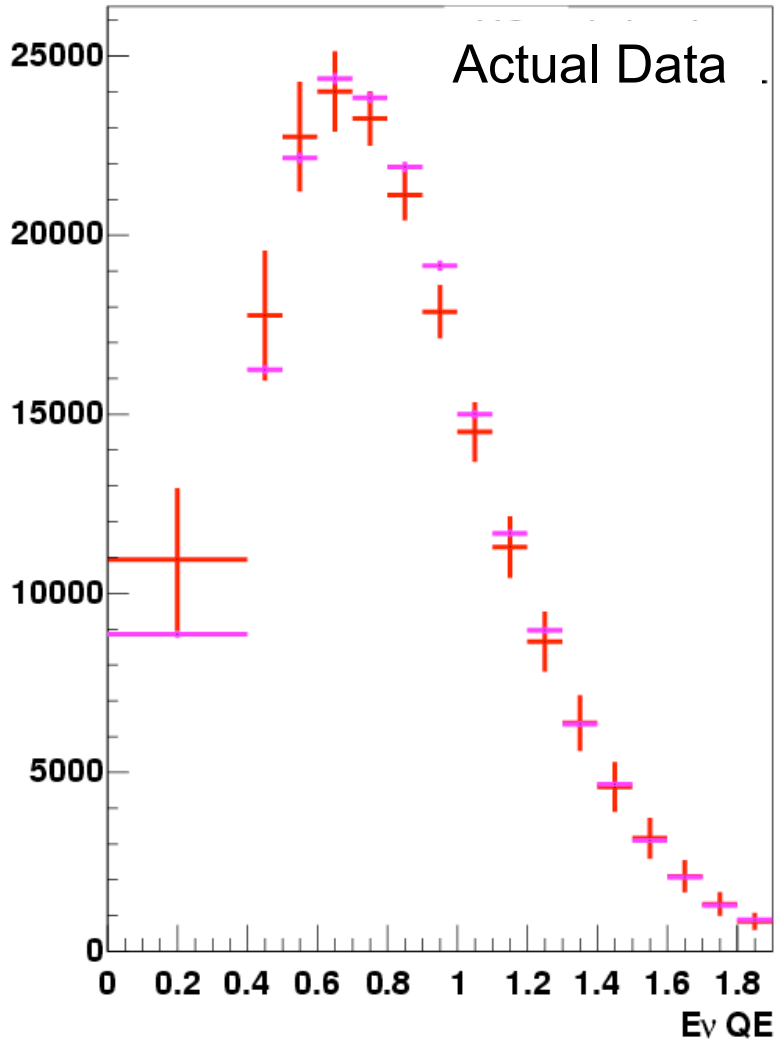
flux, cross section errors based on external data

detector uncertainties based on calibration sample

Where $\chi^2(\Delta m^2, \sin^2 2\theta)$ is larger than χ^2(90% CL) then that oscillation prediction is excluded at 90% CL

For 16 bins, χ^2(90% CL) = 23.5

Data and No-Oscillation Prediction

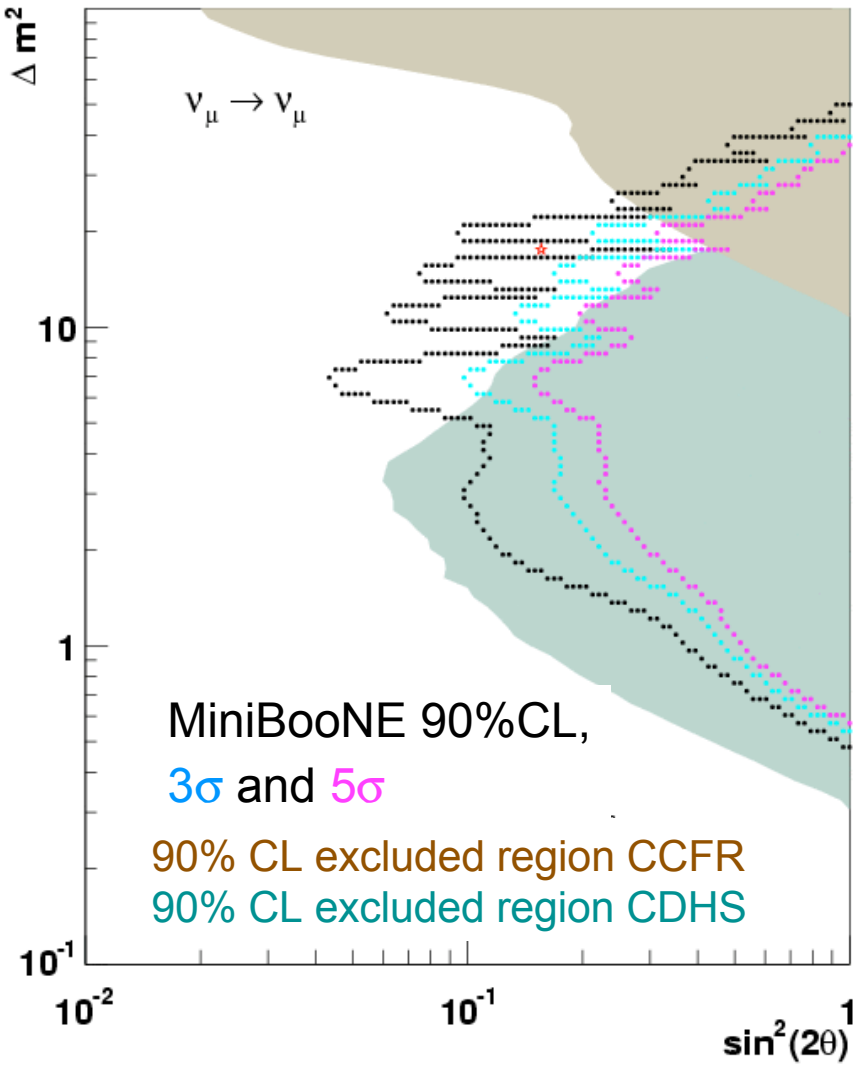


Neutrino dataset (statistical errors shown) with prediction (no oscillation) (normalized to total data) vs EνQE

Errors shown are diagonal elements of the shape-only error matrix

χ^2(null) =17.78 (34% for 16 bins)

Neutrino Disappearance Results

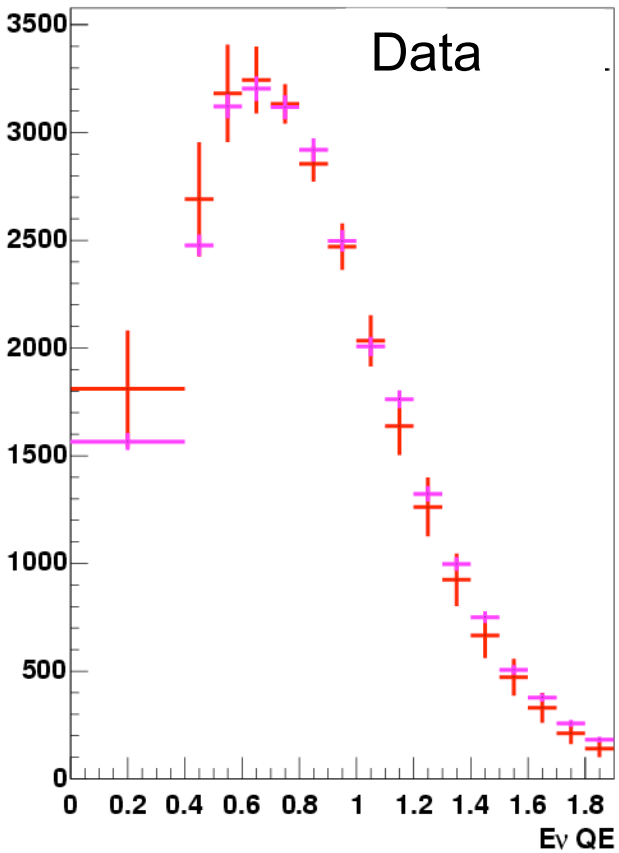


MiniBooNE limit
for 90%CL, 3σ and 5σ
χ^2 (null) =17.78 (34%,16 bins)
χ^2 (min) =12.72 (69%, 16bins)
at Δm^2=17.5eV^2, $\sin^2\theta$ =0.16

MiniBooNE observes
no neutrino disappearance

This data excludes some
3+2 models

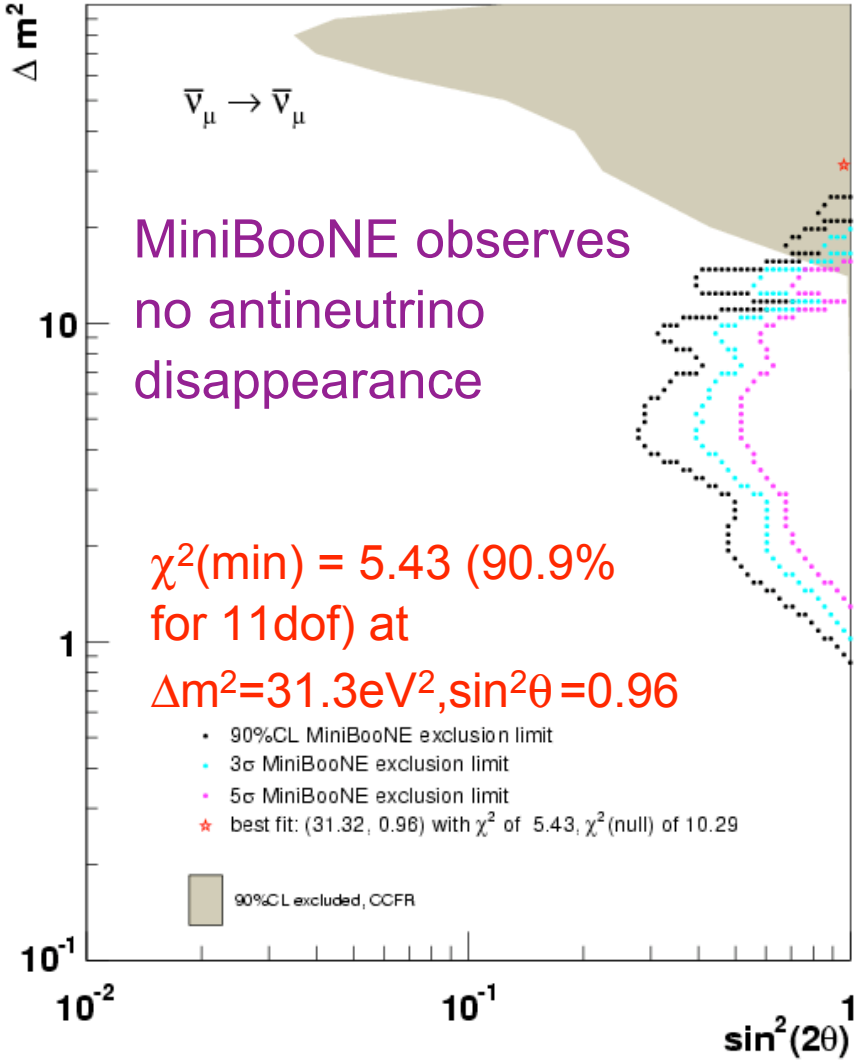
Antineutrino Disappearance Results



Antineutrino dataset w/ statistical errors

no-oscillation prediction w/ diagonal shape errors

χ^2(null) = 10.29 (85% for 16dof)



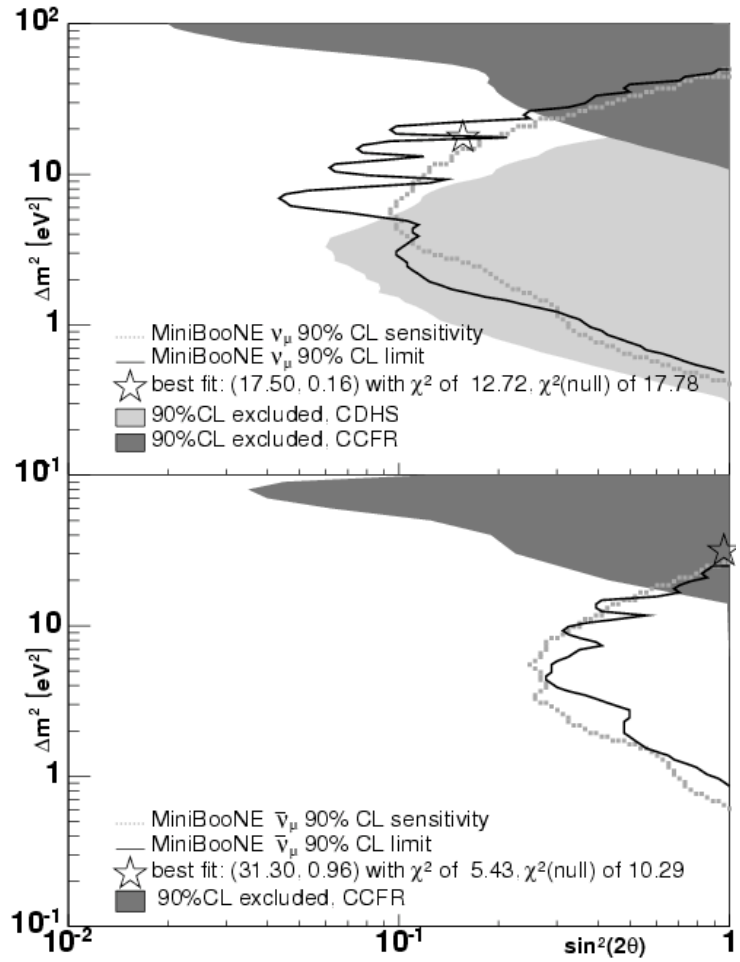
Conclusion

MiniBooNE observes no neutrino or antineutrino disappearance at 90%CL

- Neutrino data excludes some 3+2 models
- First antineutrino disappearance measurement between 0.1-10 eV^2
- No indications of CPT violation or non unitarity of the mixing matrix

Future work will incorporate data from a second detector, SciBooNE

- SciBooNE shares the same flux, cross section and can provide an additional constraint



Normalization Information

To search for disappearance, can use normalization or shape information

1) Normalization information:

Compare total number of events to expectation ("counting experiment")

Source of error	**Total fractional error (%) (counting experiment)**
flux	**6.2**
cross sections	**19.1**
detector model	**3.4**
total	**20.4**

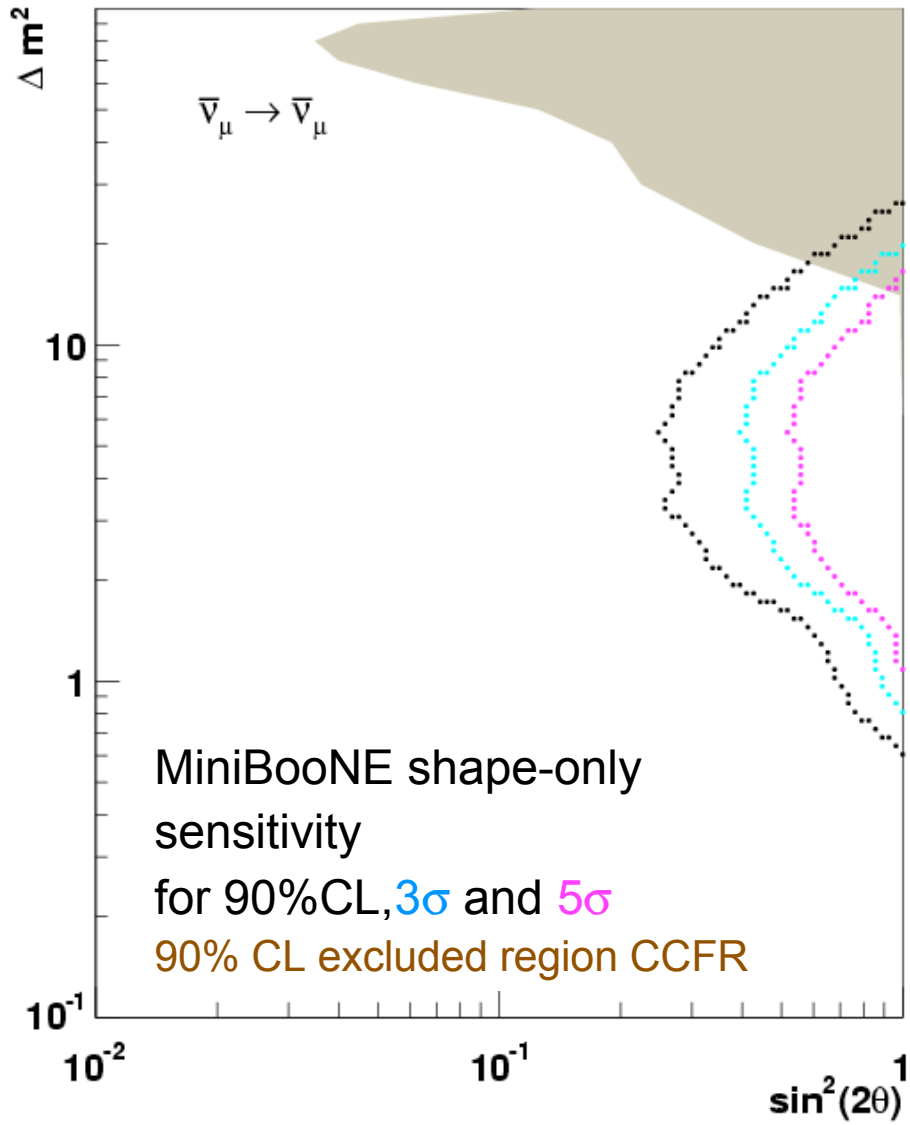
MiniBooNE's substantial normalization uncertainties make it insensitive to overall normalization changes

MiniBooNE Antineutrino Disappearance Sensitivity

Apply same analysis to the antineutrino data set

- Detector does not distinguish $\bar{\nu}_\mu$ from ν_μ
- Include uncertainties on:
  - Antineutrino (and neutrino background) fluxes
  - Antineutrino cross sections
  - Detector uncertainties
- Fit machinery identical
  - Assume no ν_μ disappearance based on previous MiniBooNE result

Substantial new parameter space covered!

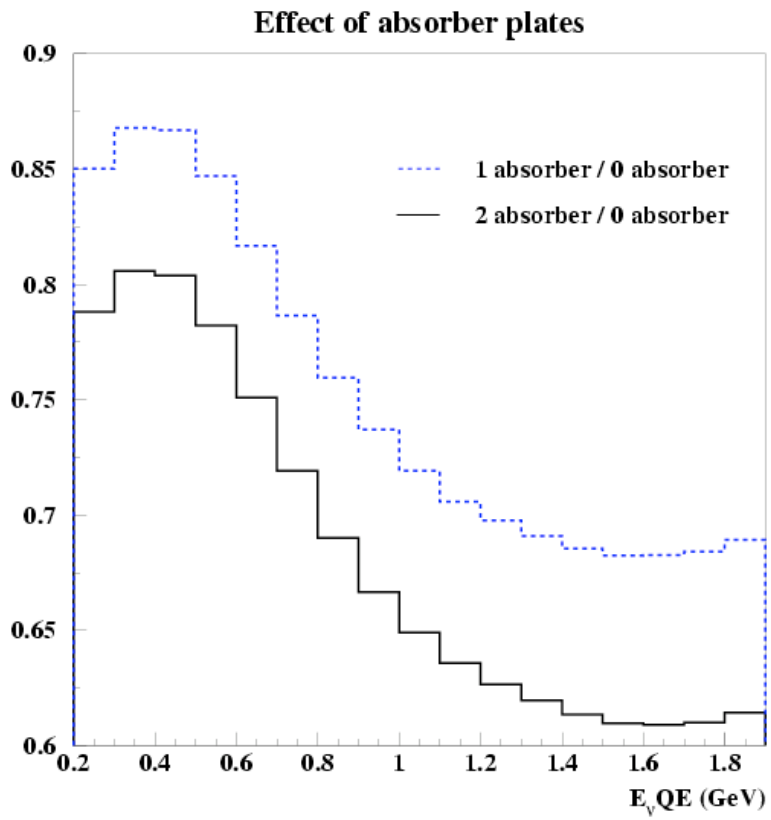


Absorber plates and disappearance fits

In 2006, two absorber plates fell into the beamline, and were later removed

Antineutrino running therefore has three “configurations” defined by the number of plates in the beamline

The addition of an absorber plates removes higher energy mesons which travel farther before they decay

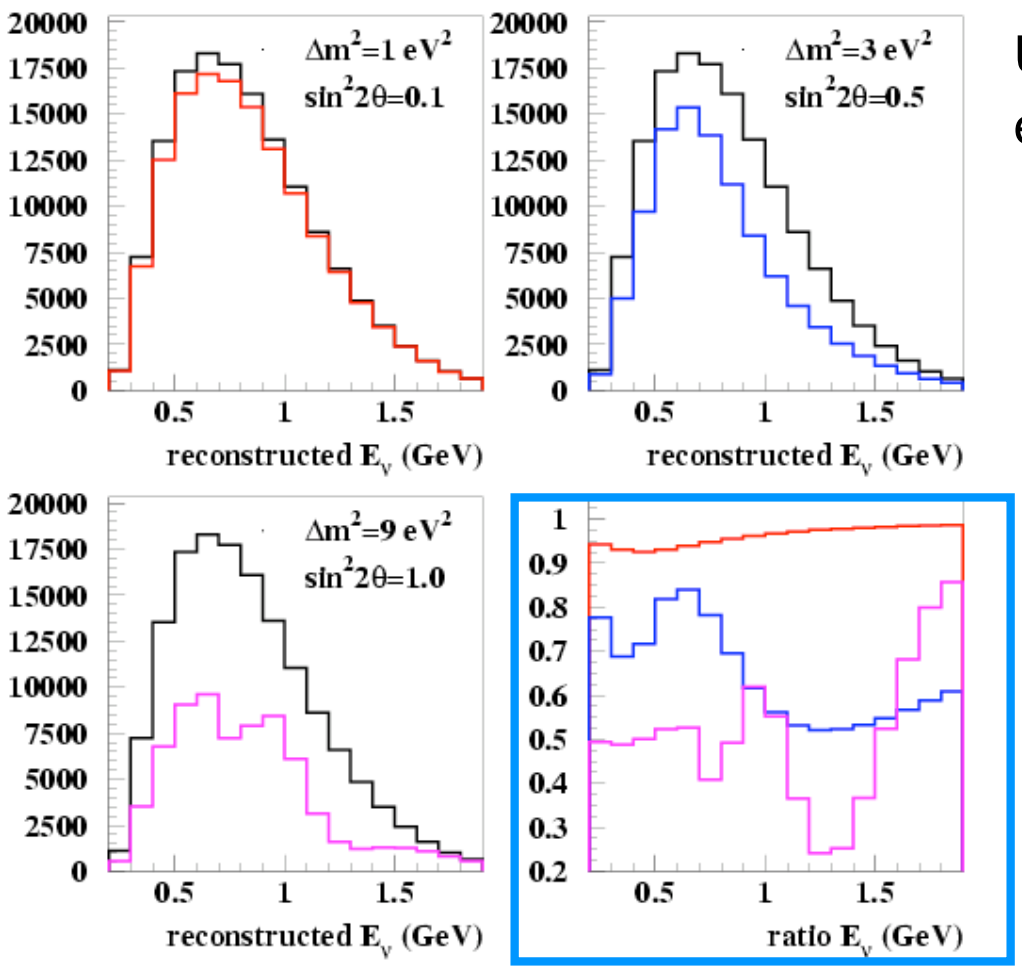


We run the beam simulation with an absorber plate (or zero or two) in the beamline at the appropriate position to account for this change

Shape Information

To search for disappearance, can use normalization or shape information

2) Shape information in neutrino energy spectrum distortion



Unoscillated MiniBooNE energy spectrum

Δm^2=1 eV^2, $\sin^2 2\theta$=0.1

Δm^2=3 eV^2, $\sin^2 2\theta$=0.5

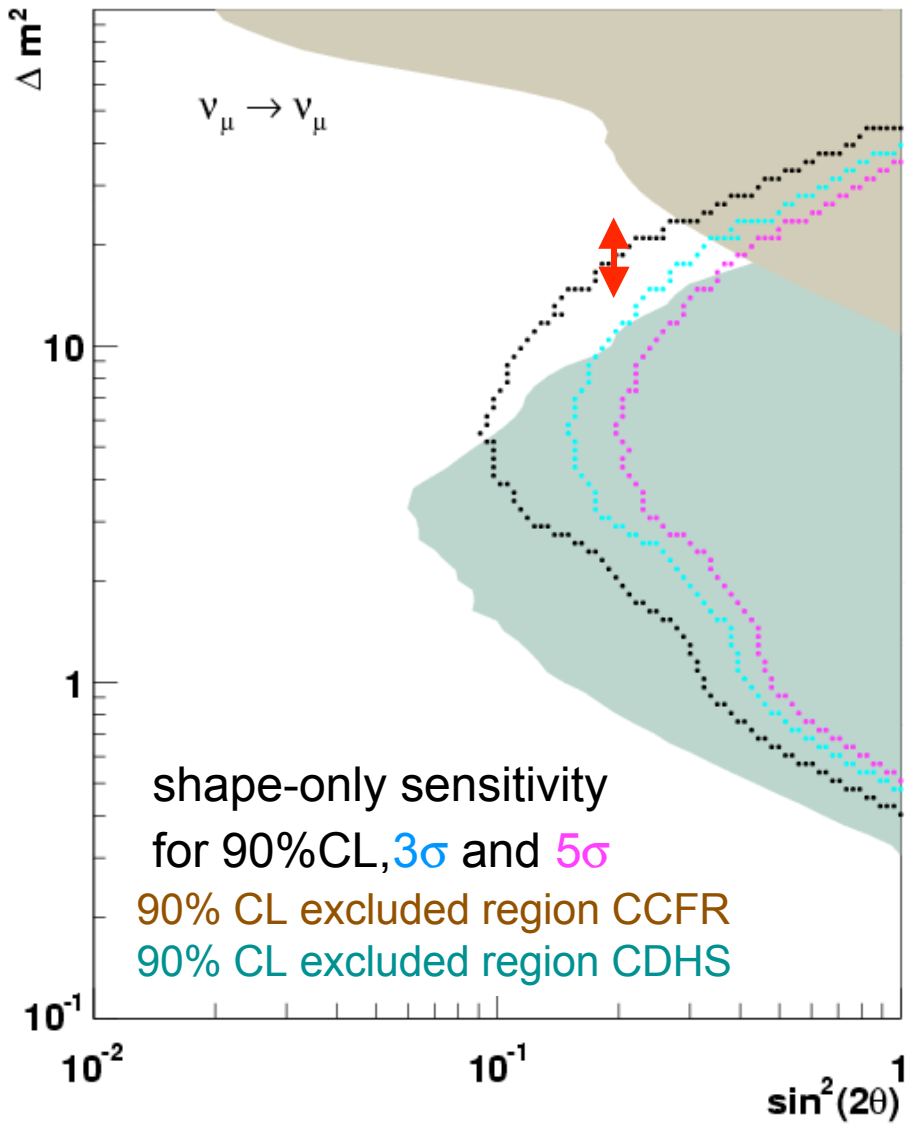
Δm^2=9 eV^2, $\sin^2 2\theta$=1.0

Ratio of oscillated to unoscillated spectrum

Δm^2 changes the periodicity of the oscillation

$\sin^2 2\theta$ changes the size of the oscillation

MiniBooNE Sensitivity



The sensitivity provides an estimate of how well an experiment will perform

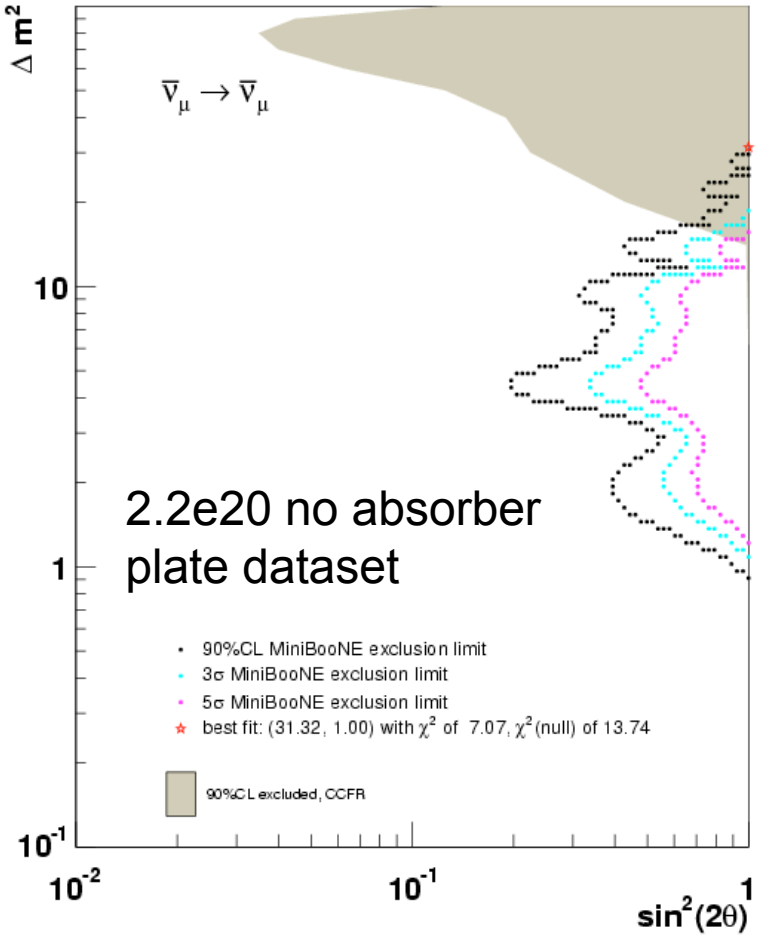
Fit to fake data identical to the null prediction, including all statistical and systematic uncertainties

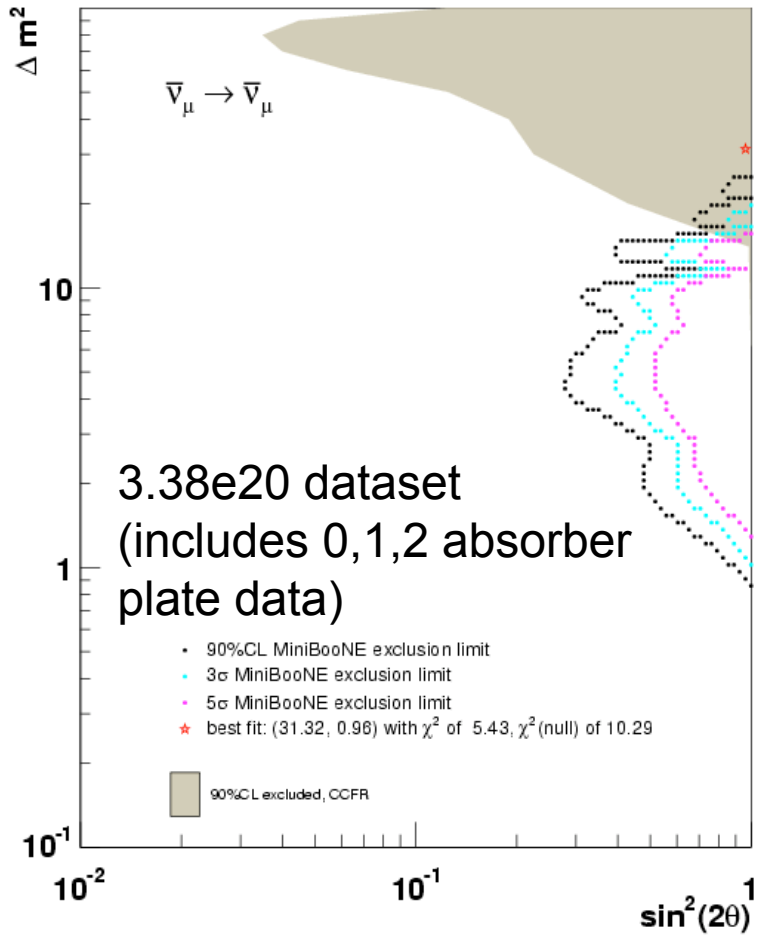
Actual fluctuations of the experiment may be exclude more or less of the parameter space

Sensitive to ν_μ disappearance in the particular region favored by 3+2 models

Absorber plates and disappearance fits

Fit to data with no absorber plates present is consistent with full data set



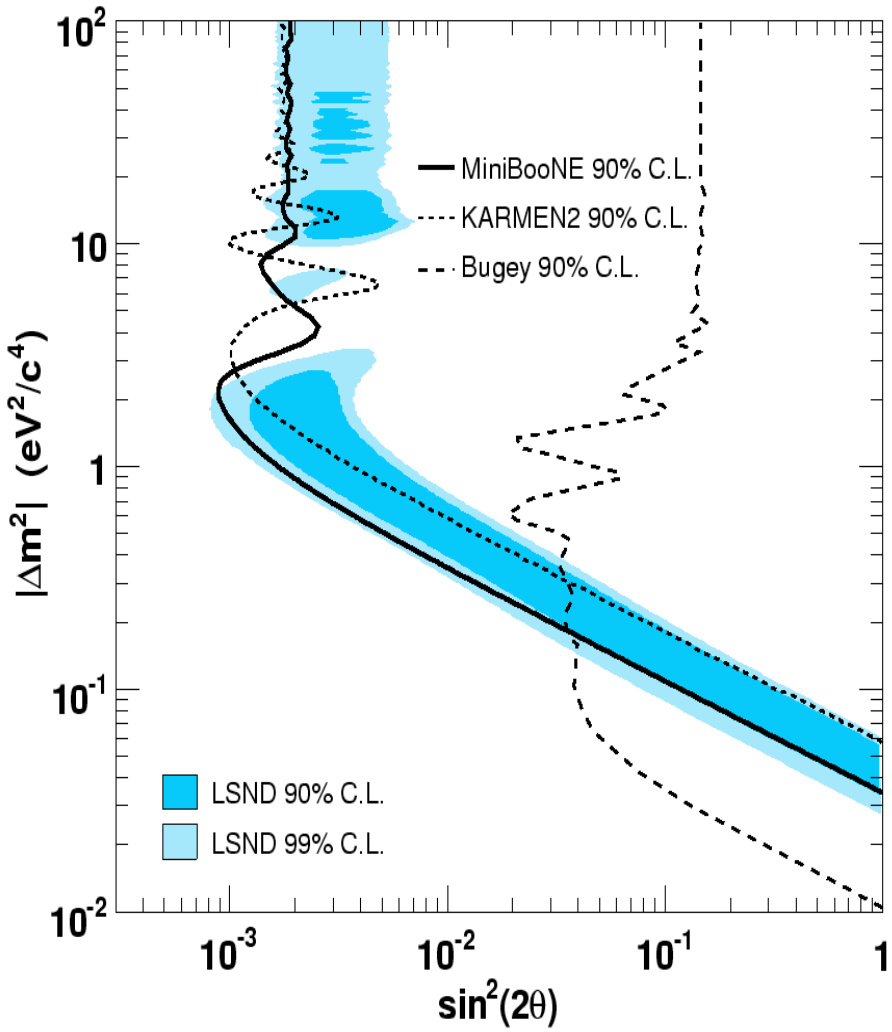


LSND ν_e appearance

LSND experiment

Observation of 3.8 σ excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam

Third observed Δm^2

Karmen, Bugey and MiniBooNE exclude the LSND parameter space

If $\bar{\nu}_e$ oscillate but ν_e do not, then exotic physics is needed to explain this signal