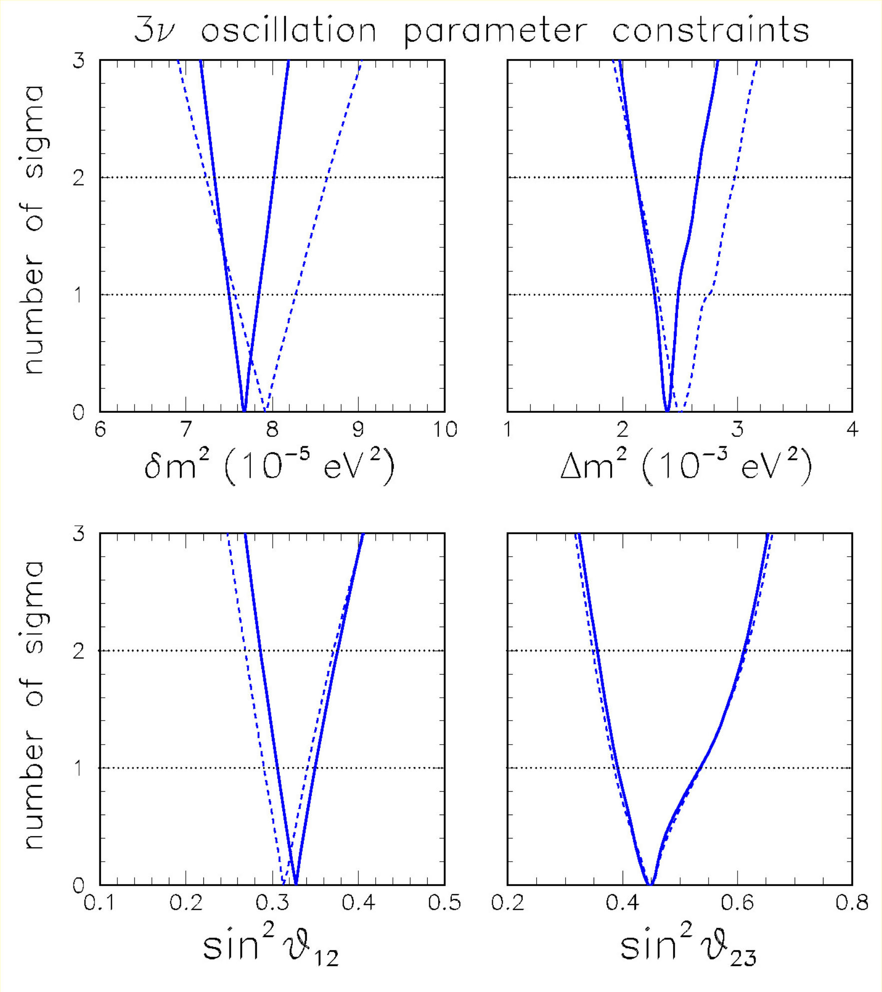
Visible progress from 2006 (dashed) to 2008 (solid)

"Solar" neutrinos



"Atmospheric" neutrinos

2008 parameter summary at 2σ level (95 % CL)

$$\begin{aligned}
\delta m^2/\mathrm{eV}^2 &= 2.38 \pm 0.27 \\
|\Delta m^2|/\mathrm{eV}^2 &= 7.66 \pm 0.35 \\
\sin^2\theta_{12} &= 0.326\ ^{+0.05}_{-0.04} \\
\sin^2\theta_{23} &= 0.45\ ^{+0.16}_{-0.09} \\
\sin^2\theta_{13} &< 3.2 \times 10^{-2}
\end{aligned}$$

(Addendum to hep-ph/0608060, in preparation)

This is what we know.

Concerning

What we would like to know
- Hierarchy (normal or inverted)
- CP in the ν sector
- θ_{13} mixing

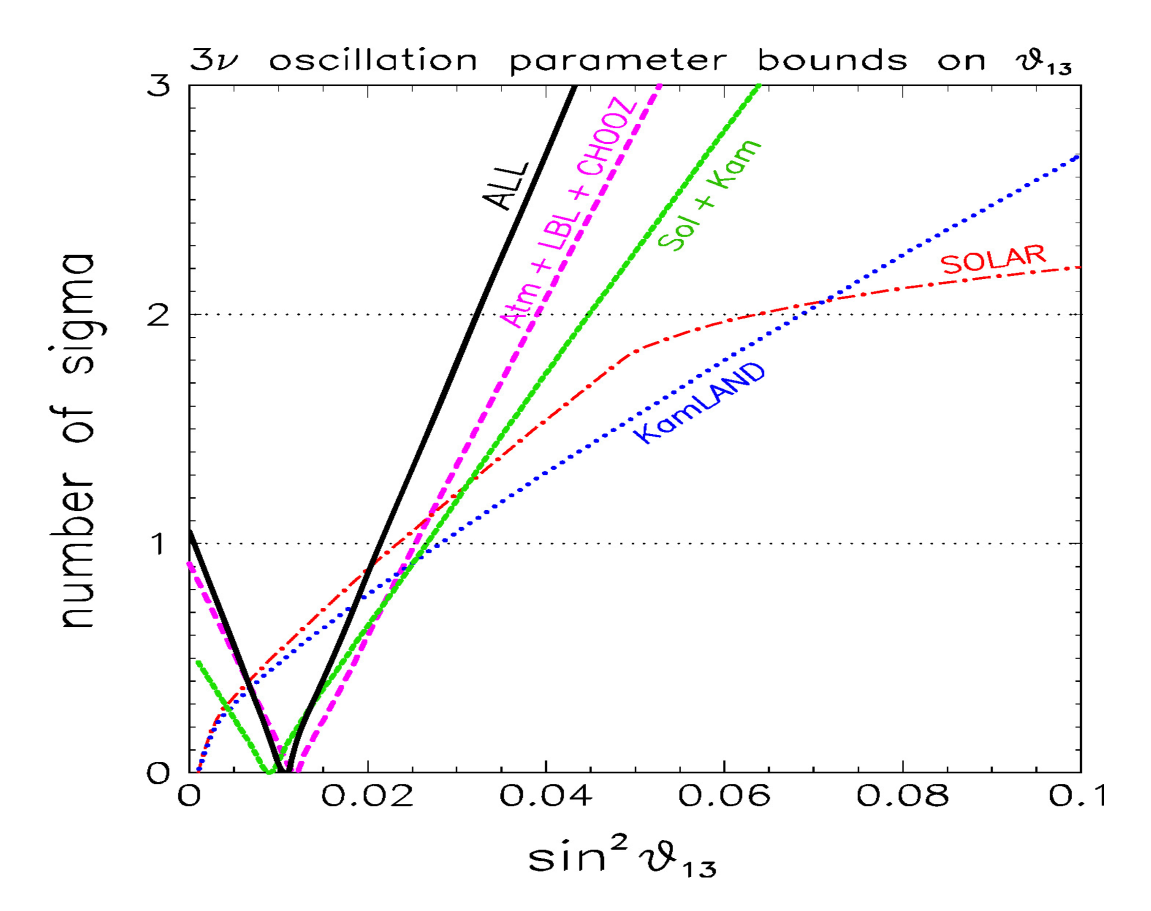
Some aspect is currently "hidden" below **1σ** C.L.

A recent example:

slight preference for

$\sin^2\theta_{13} \sim 0.01$

from the combination of solar +reactor 2008 data
(green curve in the figure)

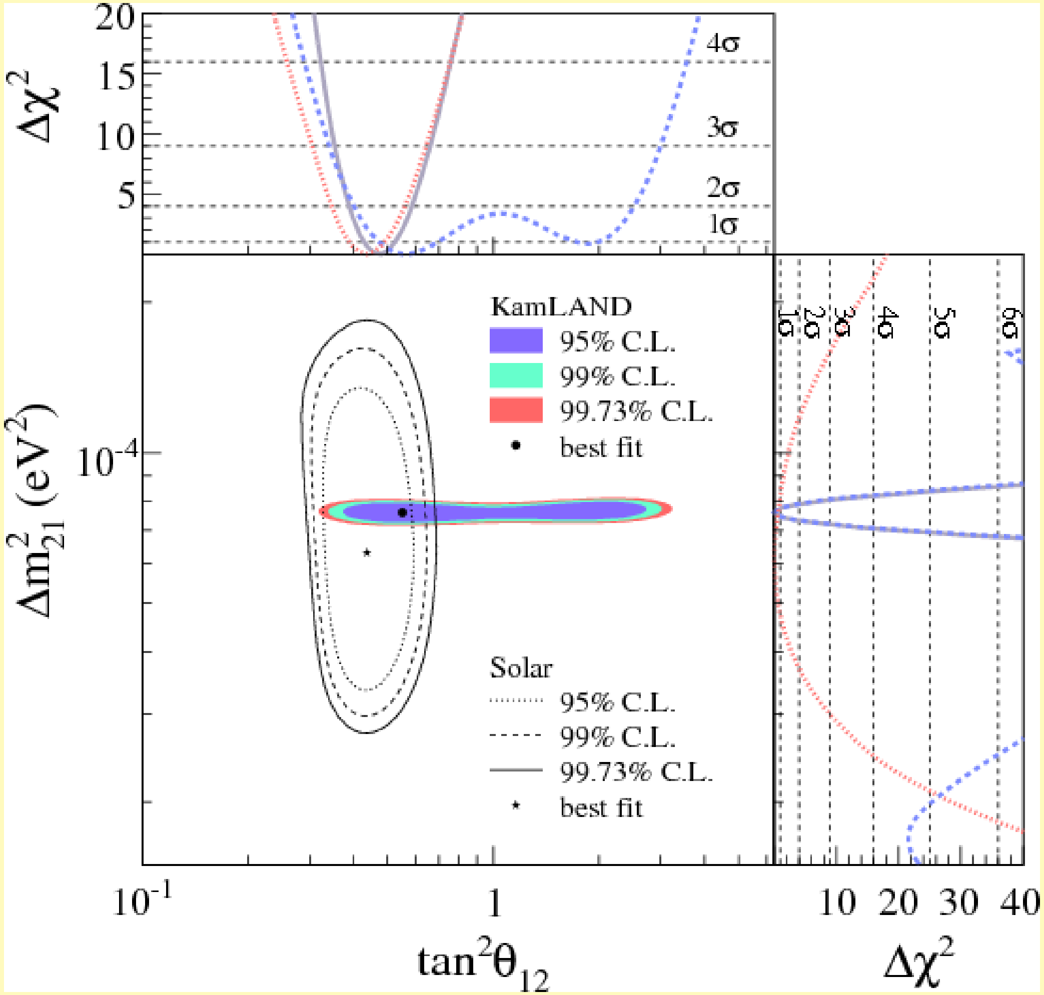


Reason:

Slight disagreement between

- Solar data (SNO dominated)
- KamLAND data (at $\theta_{13} = 0$)

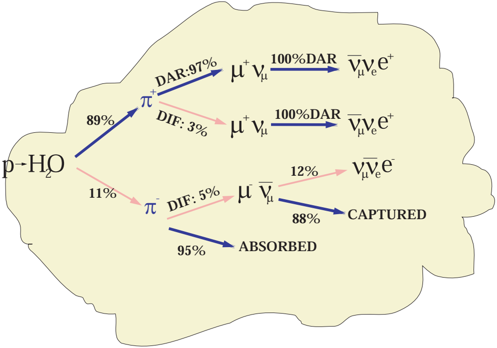
when the two best-fits are compared in the usual plane (m^2_{12}, $\tan^2\theta_{12}$)



[figure taken from the official Kamland site (2008)]

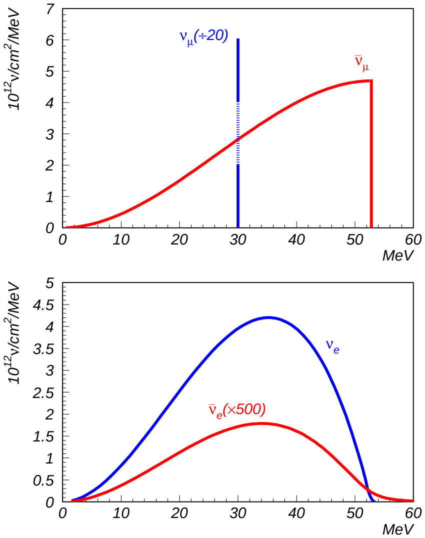
Neutrino Source High intensity (1mA) low energy (800 MeV) p beam into stop target

Look for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation from decay at rest (DAR) neutrino flux and for $\nu_\mu \rightarrow \nu_e$ oscillation from decay in flight (DIF) neutrino flux.

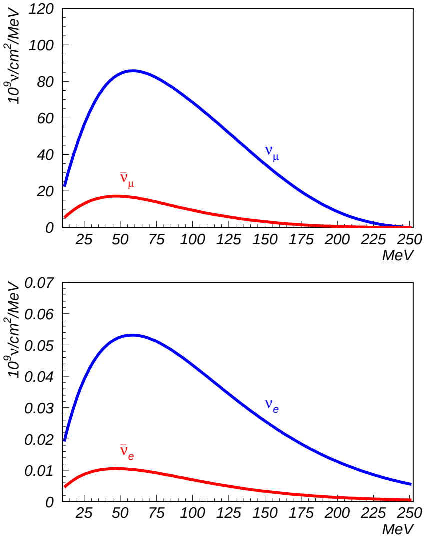


- $\bar{\nu}_e$ flux is $\bar{\nu}_e / \bar{\nu}_\mu$ (DAR) $= 7.8 \cdot 10^{-4}$
- Oscillated $\bar{\nu}_e$ events have a maximum energy of 52.8 MeV.
- No electron from ν_e above 36 MeV ($\nu_e^{12}C \rightarrow e^- \ {}^{12}N$)
- No electron with a correlated γ above 20 MeV ($\nu_e^{12}C \rightarrow e^- n^{11}N$)

DAR FLUXES



DIF FLUXES



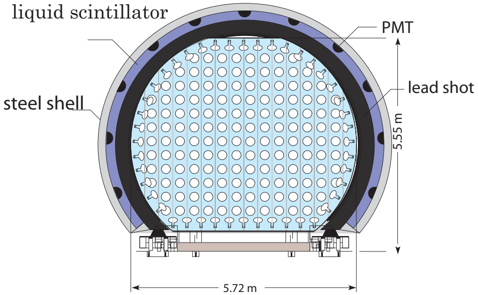
Liquid Scintillator Neutrino Detector

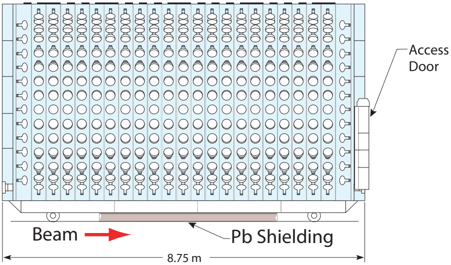
167t of Dilute Mineral Oil

Cerenkov light (n=1.47): threshold+direction
Scintillation : energy
Cerenkov/scintillation: particle identification

central detector: 1220x8" PMT
(25% surface coverage)
mineral oil (CH2) doped with
0.031 g/l of b-PBD .

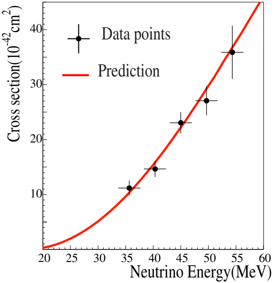
veto detector: 292x8" PMT,
passive shield: ~2 Kg/cm2





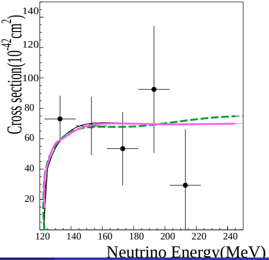
YEAR	COULOMBS	
1993	1787	
1994	5904	First DAR paper: "Candidate events .." (PRL 75(1995)2650)
1995	7081	Second DAR paper: “Evidence for ...", (Ph.Rev.C 54(1996)2685
		DIF paper: " Results on ...", (PRL 81(1998)1774 and Ph.Rev.C
1996	3790	Water tank substituted with high Z target.
1997	7181	Preliminary results at Neutrino 1998
1998	3154	End of data taking 21 dec 1998

ν_e detected and flux measured by $\nu_e\ ^{12}C \rightarrow ^{12} N_{gs} e^-$ and $\nu_e\ e^- \rightarrow \nu_e\ e^-$



$\overline{\nu}_\mu$ flux known at 7% through the results of a subsidiary experiment.

ν_μ detected and flux measured by $\nu_\mu^{12} C \rightarrow ^{12} N_{gs} \mu^-$



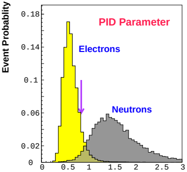
DAR OSCILLATION SEARCH

prompt positron signal, energy range.

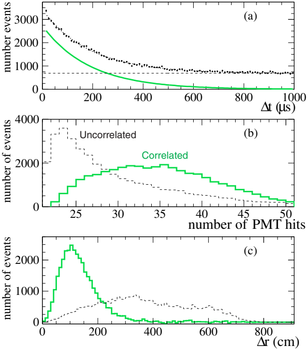
$$\overline{\nu_e}\, p \longrightarrow e^+ n$$

$$n + p \underset{\tau \simeq 186\ \mu s}{\longrightarrow} d + \gamma(2.2\ MeV)$$

delayed correlated photon.

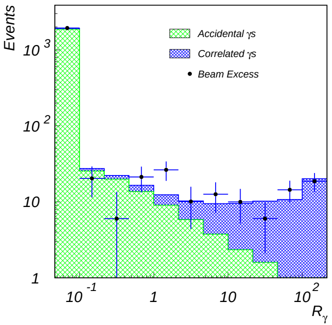


1. Particle identification through position, direction, #PMT (e^- calibration through Michel e^- from CR μ decays)
2. CR veto through veto on detector activity before and after the trigger.
3. Correlated γ through likelihood function $\mathcal{R}$ (built with CR muons and/or MC)
4. Energy range: $20 \leq E_e \leq 60$ or $36 \leq E_e \leq 60\ MeV$ (golden sample).



Overall $\overline{\nu}_e$ detection efficiency: 22%

EXCESS OF $\overline{\nu}_e$ EVENTS



BACKGROUNDS

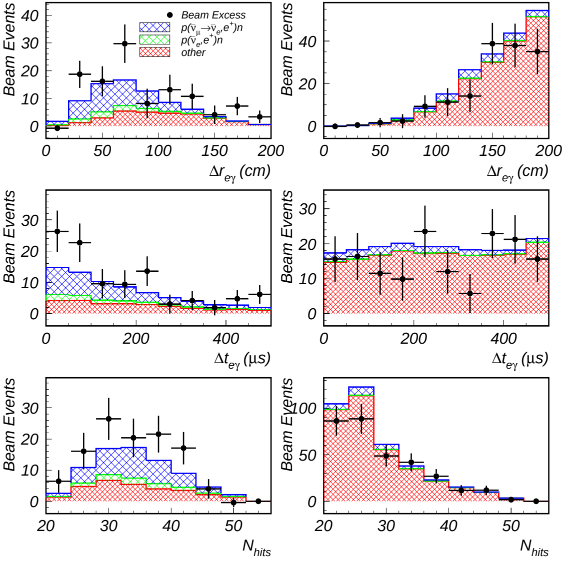
1. Cosmic Rays. Measured in beam off data (beam-off/beam-on$\simeq$ 13, $\rightarrow$ good statistical accuracy for background subtraction).
2. Beam interactions with a random γ (measured)
3. Genuine $\overline{\nu}_e$ and $\overline{\nu}_\mu$ with a correlated γ. Studied via MC simulations.

Selection	Beam-On Events	Beam-Off Background	ν Background	Event Excess	Probability
$R_\gamma > 1$	205	106.8 ± 2.5	39.2 ± 3.1	$59.0 \pm 14.5 \pm 3.1$	7.8×10^{-6}
$R_\gamma > 10$	86	36.9 ± 1.5	16.9 ± 2.3	$32.2 \pm 9.4 \pm 2.3$	1.1×10^{-4}
$R_\gamma > 100$	27	8.3 ± 0.7	5.4 ± 1.0	$13.3 \pm 5.2 \pm 1.0$	1.8×10^{-3}

Events with $20 \leq E_e \leq 60\ MeV$, $R_\gamma > 10$:

Analysis	Excess Events	Oscillation Probability
Present Analysis (1993-1998)	$87.9 \pm 22.4 \pm 6.0$	$(0.264 \pm 0.067 \pm 0.045)\%$
Previous Analysis (1993-1995)	$51.0^{+20.2}_{-19.5} \pm 8.0$	$(0.31 \pm 0.12 \pm 0.05)\%$

Excess events fit oscillated event characteristics:

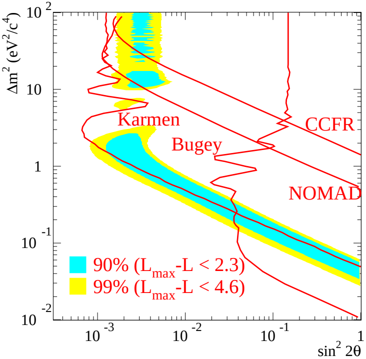


While don't fit backgrounds:

- Fit the excess with the μ^- background: it must be multiplied by 8.6 and χ^2 is 2.2 units worse than oscillation fit
- π^- DIF backgrounds studied with a special trigger during 1995, in order to increase sensitivity to muons associated to small activity: it resulted compatible with the MC predictions.

SIGNAL PLOT

- Global $\overline{\nu}_\mu - \overline{\nu}_e$ and $\nu_\mu - \nu_e$ analysis (DAR + DIF).
  5697 candidate events with
  $20 < E_\nu < 200$ MeV.
- 3600 bins in 4 variables: the energy, the likelihood R_γ, the angle respect the beam direction ($\cos\theta_b$) and the path length L
- Systematics included: neutrino flux $\times$ detection efficiency = 10%.
- Bidimensional $(sin^2(2\theta), \Delta m^2)$ grid, selecting $\Delta\chi^2 = 2.6(90\%)$ and 4.5(99%) above the minimum.
- The other exclusion curves in the plot are built with several different statistical methods!.



KARMEN EXPERIMENT

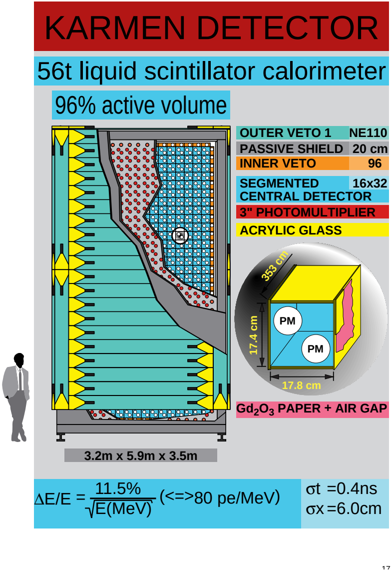
Performed at ISIS neutron spallation facility at RAL.

The detector (56 t), is at 17 m, 90^0, from the beam stop. Beam current is 0.2 mA. The time structure of the beam permits a separation between neutrinos from μ^+ DAR and those from π decay (both DAR and DIF).

KARMEN 1: 1990-1995, 9120 Coulombs. Seen 171 events, expected 140 from cosmic rays and beam backgrounds.
Beam excess $= 31 \pm 17$ (2.4σ), delayed event seen but prompt positron do not exhibit time and energy distribution from oscillations. A lower limit on oscillation probability: $P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e) < 4.25 \cdot 10^{-3}$ ($90\% CL$) was set.
Also performed a search for $\nu_\mu \rightarrow \nu_e$ oscillation, with a 90% CL limit of $2 \cdot 10^{-2}$ on the probability.

UPGRADE (KARMEN 2): new 300 m^2 active veto layer surrounding the iron blockhouse (4λ)

- throughgoing or stopping muons can be off-line vetoed
- Cosmic background suppression reduced by a factor 43.


KARMEN DETECTOR
56t liquid scintillator calorimeter
96% active volume
OUTER VETO 1 NE110
PASSIVE SHIELD 20 cm
INNER VETO 96
SEGMENTED 16x32
CENTRAL DETECTOR
3" PHOTOMULTIPLIER
ACRYLIC GLASS
353 cm
17.4 cm
PM
PM
17.8 cm
Gd_2O_3 PAPER + AIR GAP
3.2m x 5.9m x 3.5m
$\Delta E/E = \frac{11.5\%}{\sqrt{E(MeV)}}$ (<=>80 pe/MeV)
σt =0.4ns
σx =6.0cm
17.05.98

KARMEN EXPERIMENT

Performed at ISIS neutron spallation facility at RAL.

The detector (56 t), is at 17 m, 90^0, from the beam stop. Beam current is 0.2 mA.

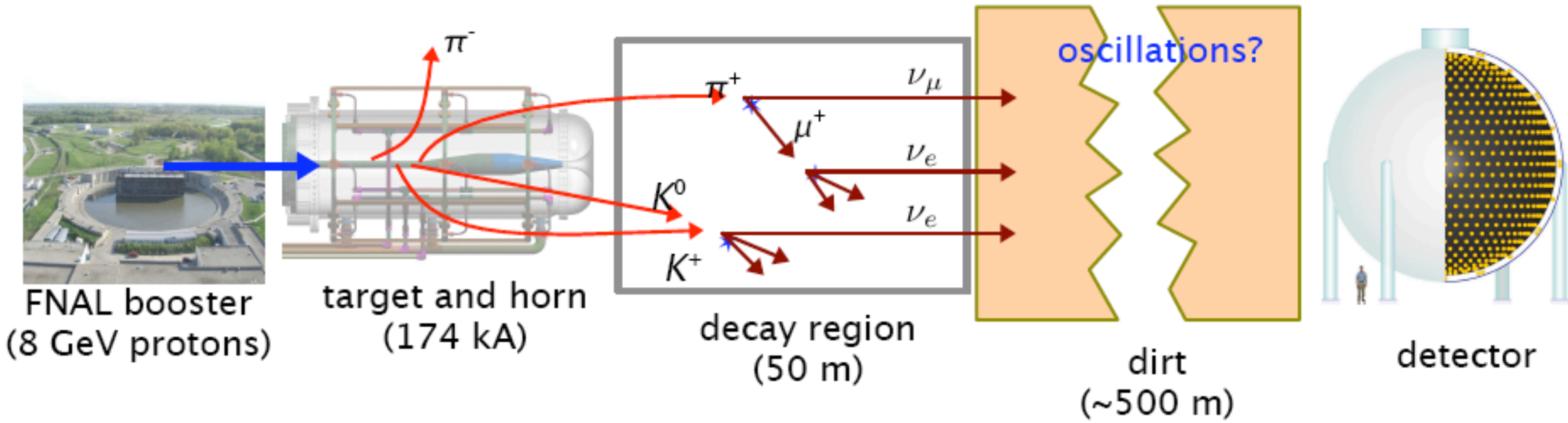
The time structure of the beam permits a separation between neutrinos from μ^+ DAR and those from π decay (both DAR and DIF).

KARMEN 1: 1990-1995, 9120 Coulombs. Seen 171 events, expected 140 from cosmic rays and beam backgrounds. Beam excess $= 31 \pm 17$ (2.4σ), delayed event seen but prompt positron do not exhibit time and energy distribution from oscillations. A lower limit on oscillation probability: $P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e) < 4.25 \cdot 10^{-3}$ $(90\%CL)$ was set.
Also performed a search for $\nu_\mu \rightarrow \nu_e$ oscillation, with a 90% CL limit of $2 \cdot 10^{-2}$ on the probability.

UPGRADE (KARMEN 2): new 300 m^2 active veto layer surrounding the iron blockhouse (4λ)

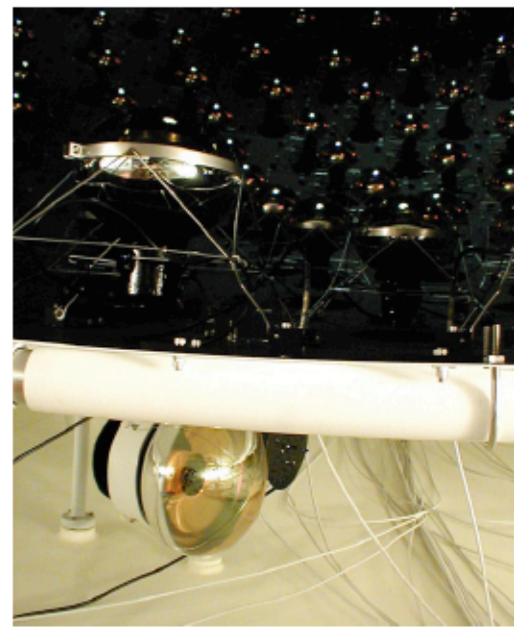
- throughgoing or stopping muons can be off-line vetoed
- Cosmic background suppression reduced by a factor 43.

The MiniBooNE design strategy...must make ν_μ

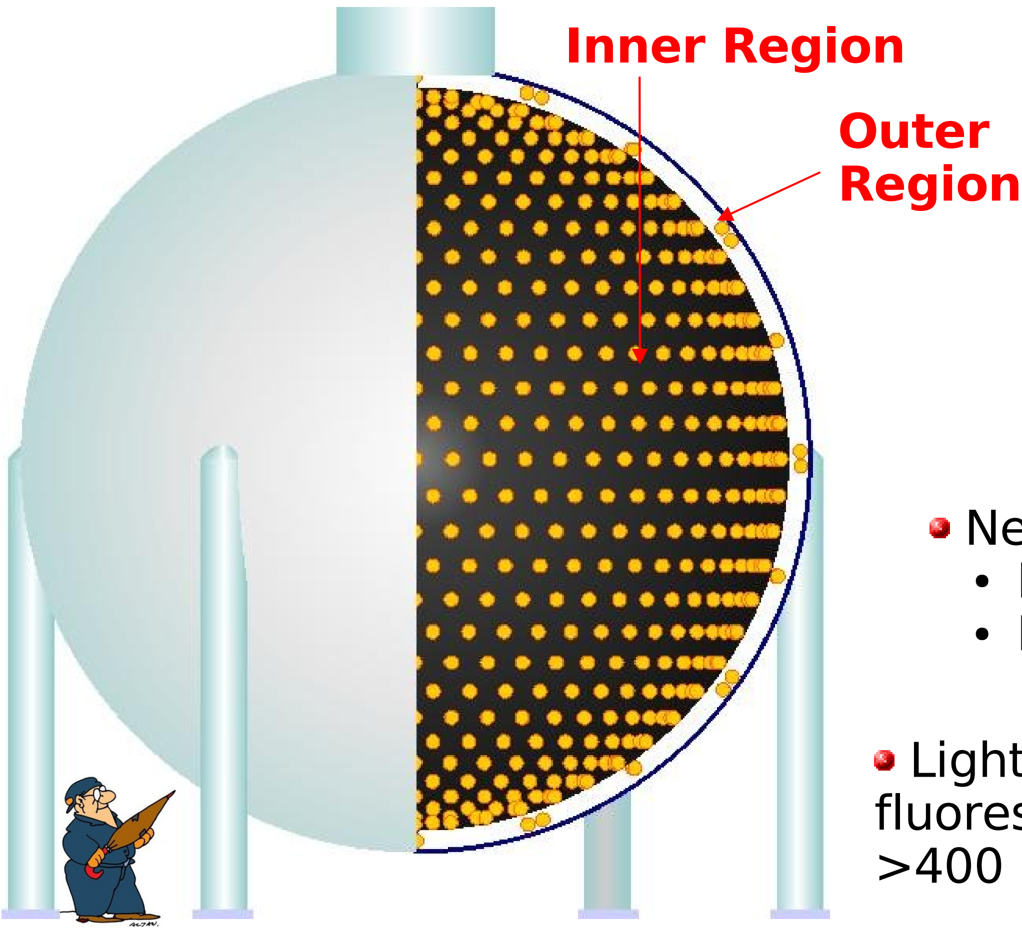


- Start with 8 GeV proton beam from FNAL Booster
- Add a 174 kA pulsed horn to gain a needed x 6
- Requires running ν (not anti-ν) to get flux
- Pions decay to ν with E_ν in the 0.8 GeV range
- Place detector to preserve LSND L/E:
  - MiniBooNE: (0.5 km) / (0.8 GeV)
  - LSND: (0.03 km) / (0.05 GeV)
- 5.58×10^{20} P.O.T. total; up to 5×10^{12} p/pulse at up to 4 Hz

$$\nu_\mu = 93.5\%,\ \nu_e = 0.5\%,\ \bar{\nu}_\mu = 6\%$$

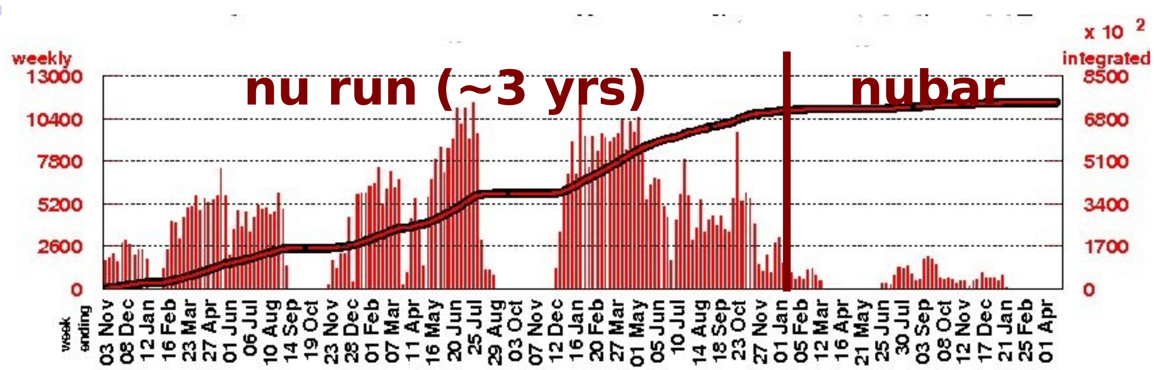


Neutrino Detector



- 12 m in diameter sphere filled with 800 t of undoped mineral oil
- Light tight inner region with 1280, 20 cm diam., PMTs (10% coverage)
- 240 PMTs in veto region (>99.9% veto efficiency)
- Neutrino interactions in oil produce:
  - Prompt, ring-distributed, Cerenkov light
  - Delayed, isotropic, scintillation light
- Light transmission affected by: fluorescence, scattering, absorption (>20m for >400 nm light)

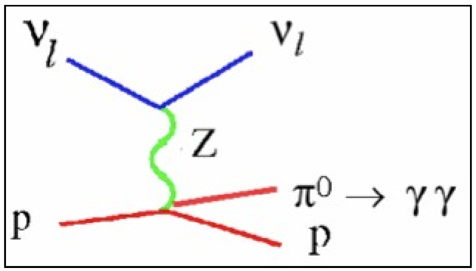
Number of accumulated neutrino interactions: $7.4 \cdot 10^5$

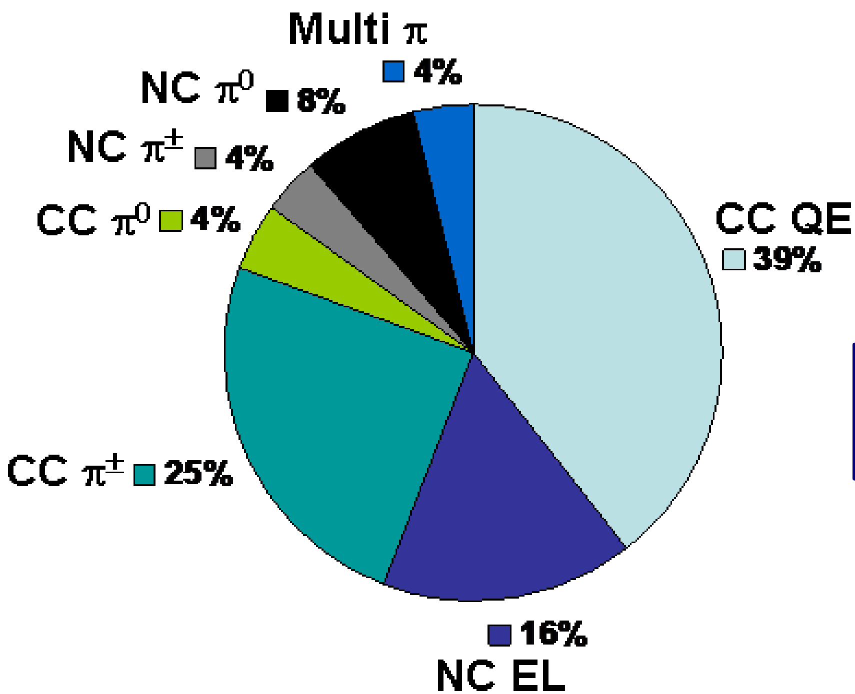


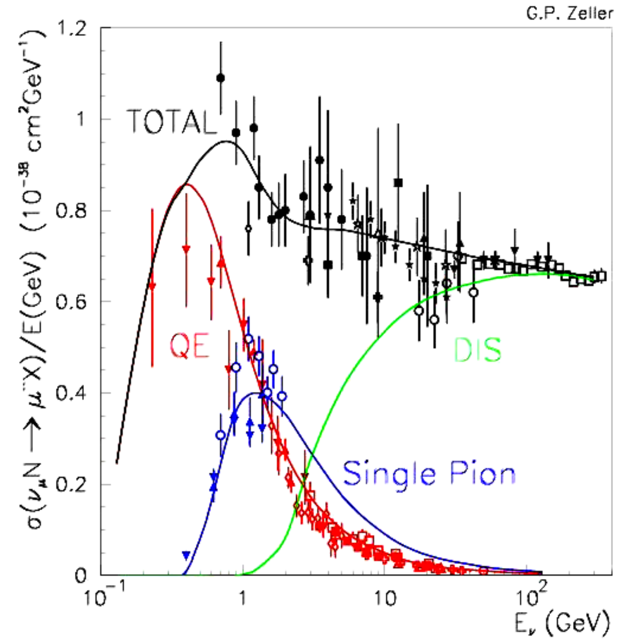
Neutrino Interactions at MiniBooNE

• Several interaction channels contribute in ~1 GeV neutrino energy regime

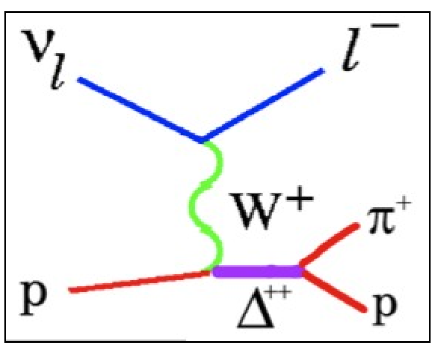
Neutral current
π^0 production



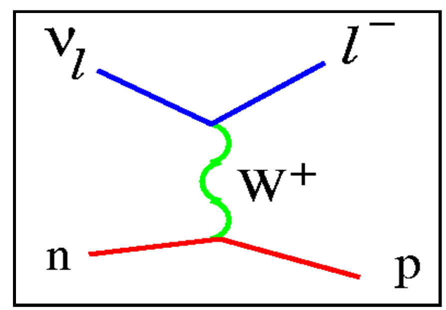




Charged current
π^+ production



Charged current
quasi-elastic scattering

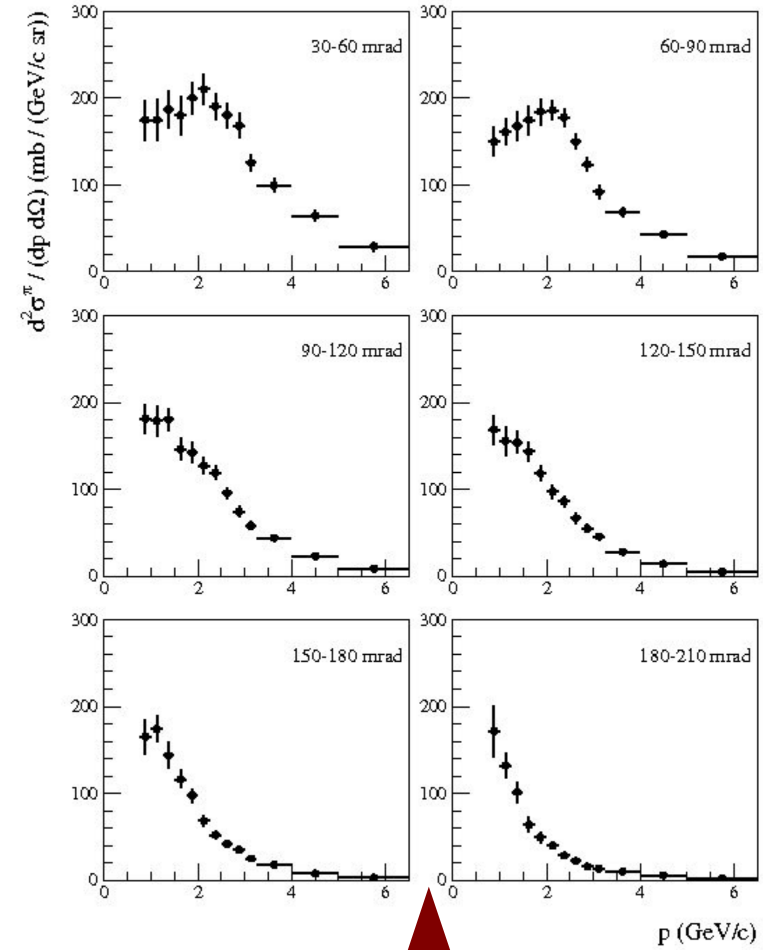


Modeling Neutrino Fluxes

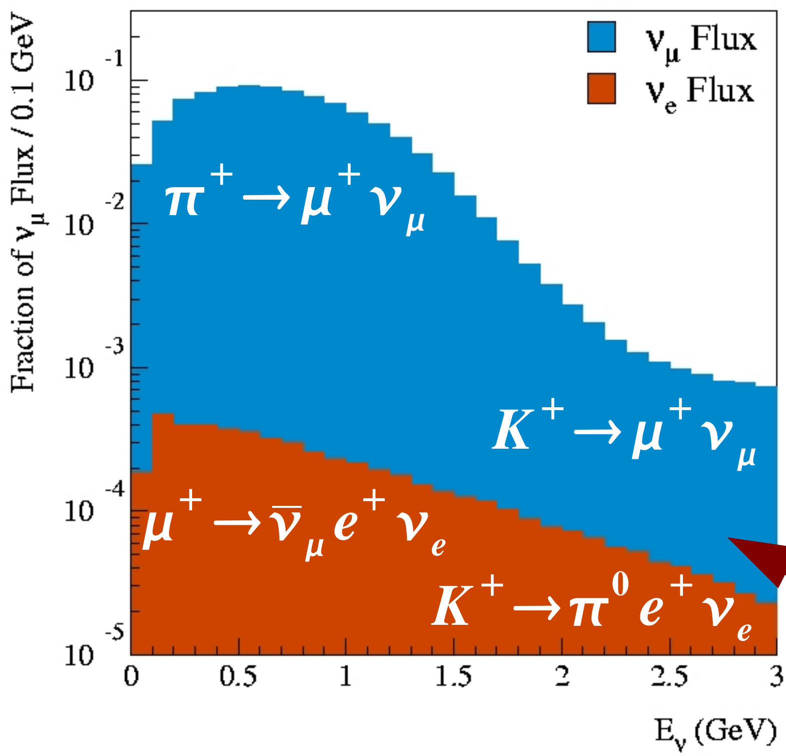
GEANT4 beamline description, simulating:

- Primary protons, geometry, materials and horn field
- Interactions, focusing, meson and muon decays

- Pion/kaon production data on beryllium is the most important external physics input to the simulation *-> parametrized according to relevant hadron production data sets*



HARP data on:
p(8.9 GeV/c) + Be $\rightarrow \pi^+$ + X
(hep-ex/0702024)



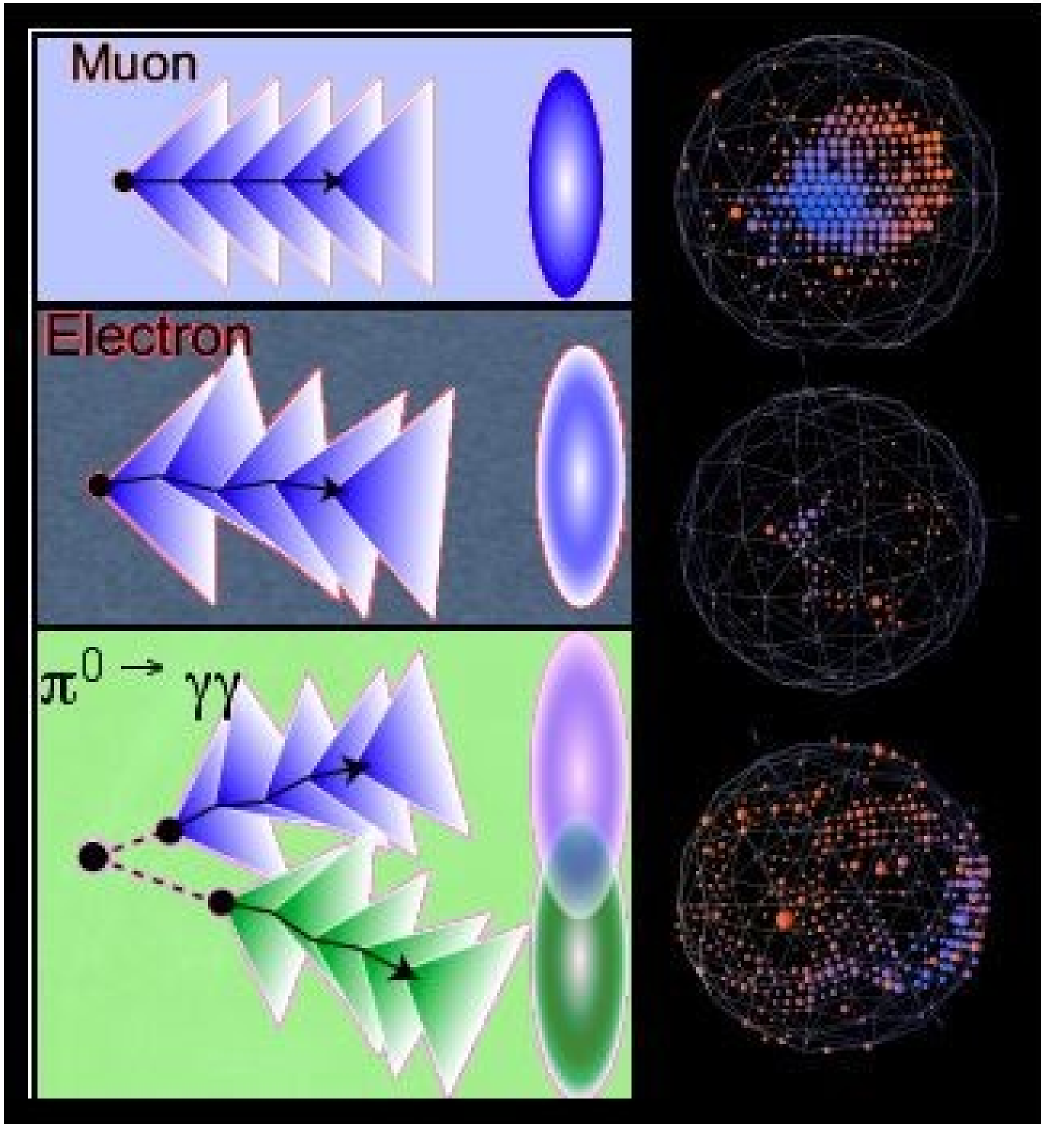
ν_μ and ν_e flux predictions. $\nu_e/\nu_\mu \sim 0.5$ %

Particles to Identify in Appearance Search

Muons (background):
- long tracks
- sharp Cherenkov ring
- ~80% with decay electron tag

Electrons (signal and intrinsic background):
- short tracks
- fuzzy Cherenkov ring
- single subevent

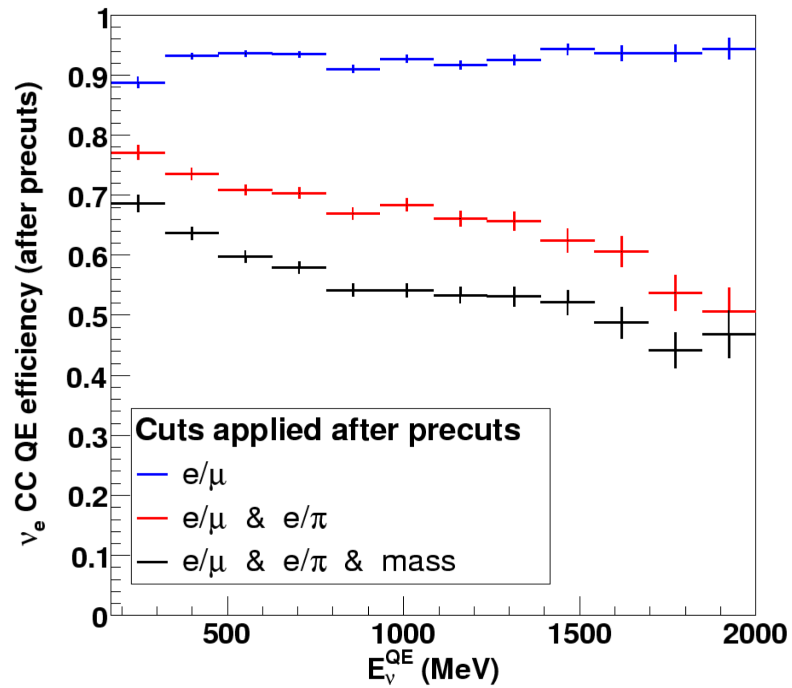
π^0 -> $\gamma\gamma$ decays (background):
- disconnected short tracks
- typically two fuzzy Cherenkov rings
- single subevent

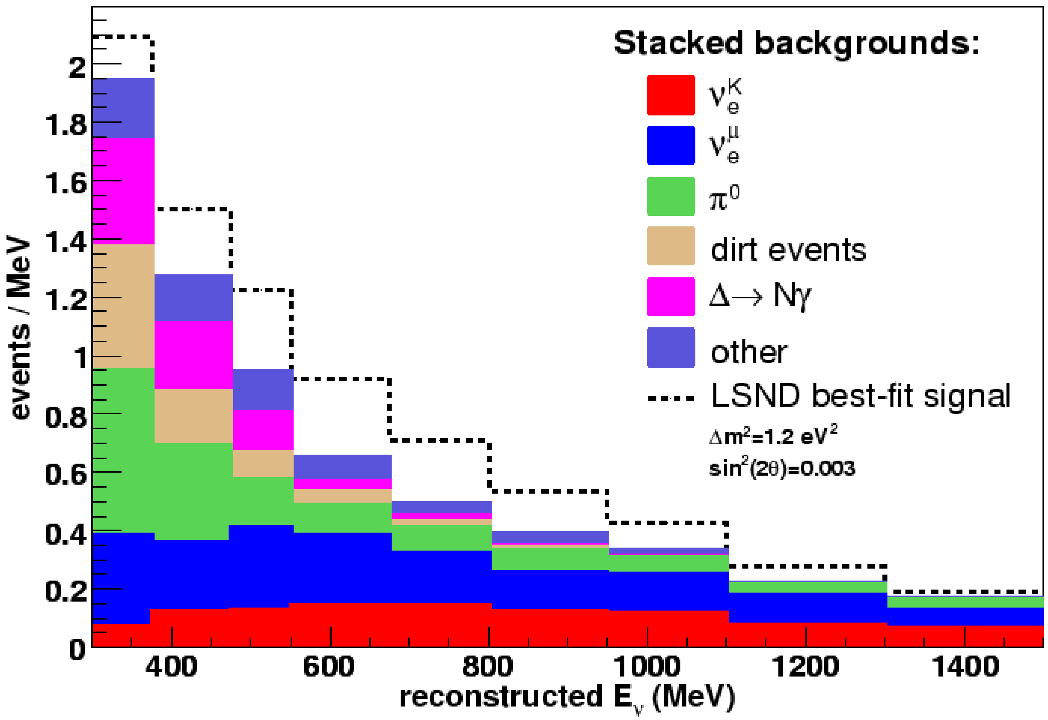


Signal Efficiency and Background Composition

- Signal efficiency:

Single subevent,hit-level,
fiducial volume, energy threshold cuts
+ $\text{Log}(L_e/L_\mu)$
+ $\text{Log}(L_e/L_\pi)$
+ invariant mass cuts





- Background events in signal region can be constrained or checked with other samples:

high energy events
ν_μ CC QE
π^0
high radius events
π^0
ν_μ CC QE
ν_μ CC QE

Electron Neutrino Box Opening Procedure

Step 1: perform fit of E_ν distribution of electron candidate events in the $300 < E_\nu < 3000$ MeV energy range to oscillation hypothesis, where best-fit oscillation signal added to background prediction is unknown. Disclose X^2 values from data/MC comparisons of several diagnostic variables

Step 2: disclose histograms for data/MC comparisons of same diagnostic variables

Step 3: disclose X^2 value for E_ν data/MC comparison over oscillation fit range, still retaining blindness to oscillation signal component

Step 4: disclose full information on electron candidate events and oscillation fit results

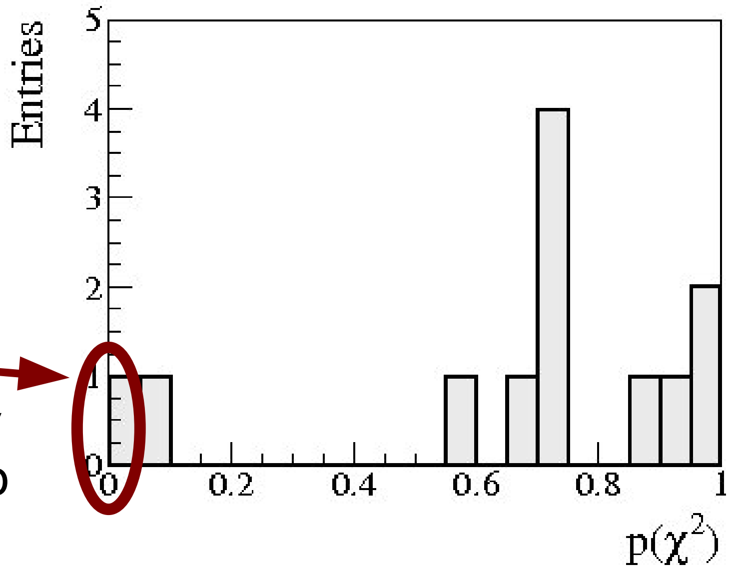
- Progress in a step-wise fashion, with ability to iterate if necessary
- All event selection and oscillation fit procedures were determined before full information on electron candidate events and oscillation fit results was disclosed

Box Opening Step 1: First Try

• χ^2 probability for data/MC comparisons on 12 diagnostic variables:

event/track position, direction, visible energy, and PID quantities

• Comparisons looked good except event visible energy: p($\chi^2 > \chi^2$(obs)) = 1%



• Indicates poor data/MC agreement beyond ability of 2-neutrino, appearance-only oscillation model to handle

• Triggered further investigations of background estimates and associated uncertainties, using "sideband" samples
-> we found no evidence of a problem

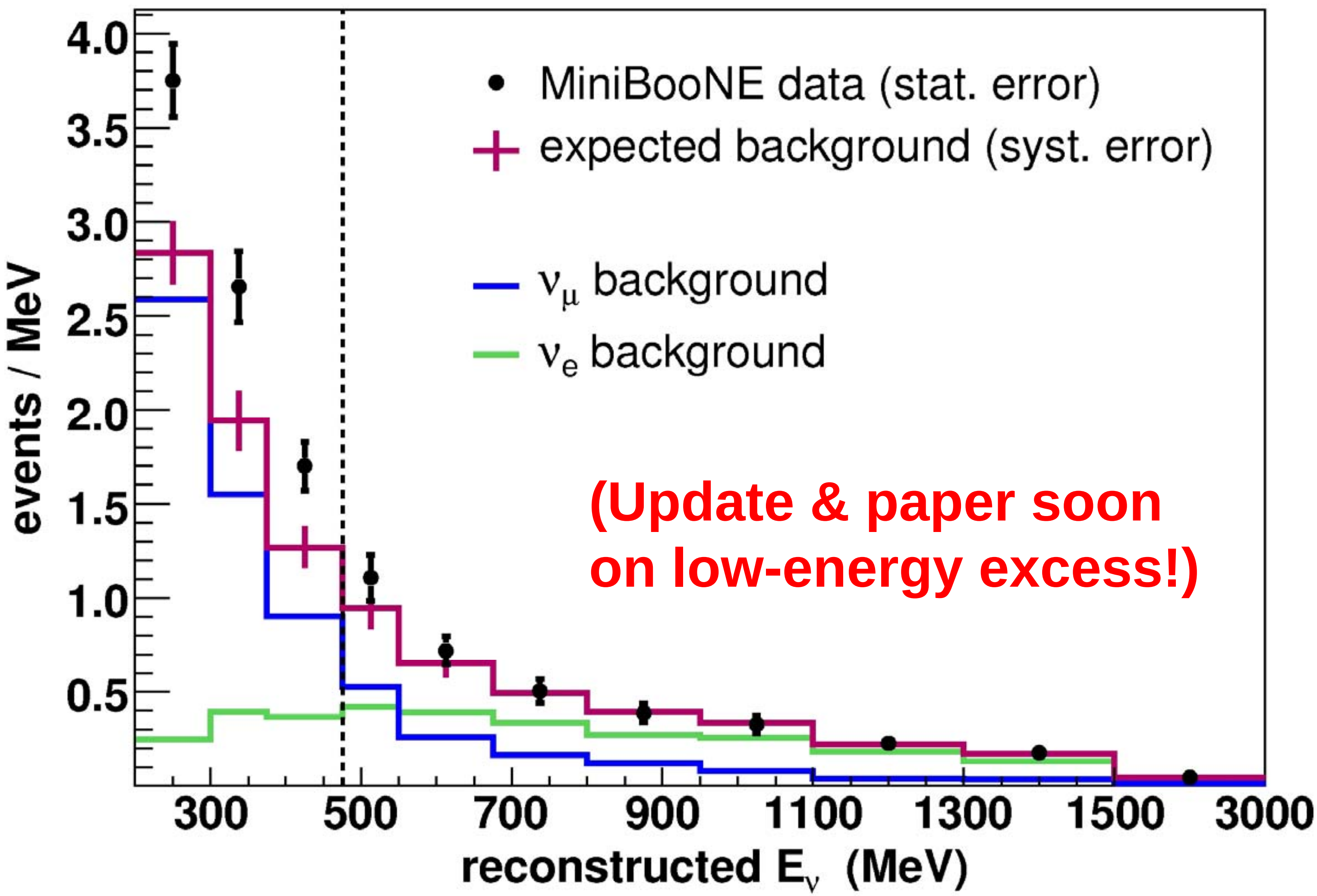
• However, knowing that:

- backgrounds predicted to rise at low energy
- studies focused suspicions in low-energy region
- choice has negligible impact on oscillation sensitivity

-> we decided to look for oscillations (and diagnostic χ^2) in the reduced (475 < E_ν < 3000 MeV) range, and report events over full (300 < E_ν < 3000 MeV) one

MiniBooNE observes a low-energy excess!

A. A. Aguilar-Arevalo et al., PRL98, 231801 (2007);



Oscillation Search Results

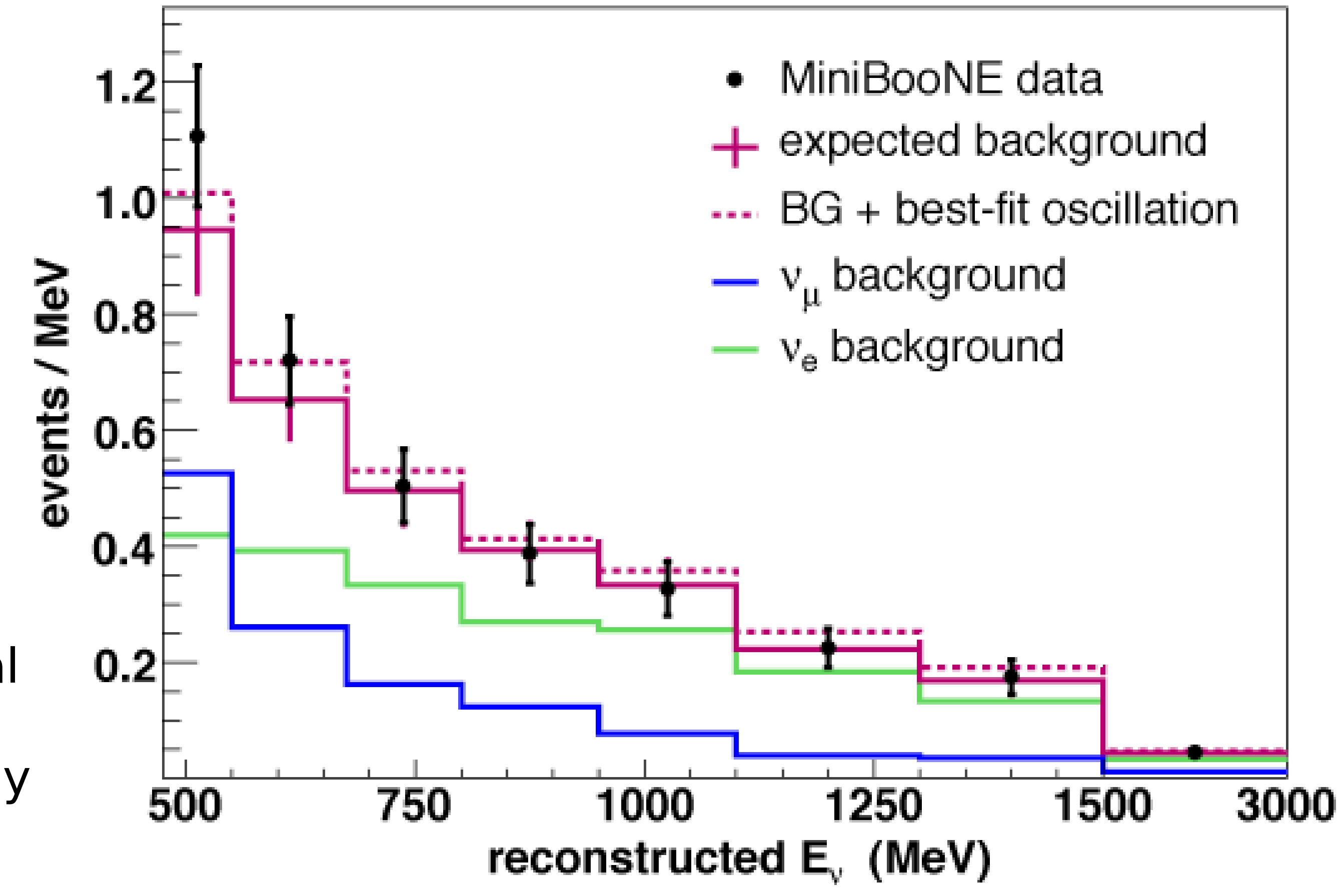
Counting experiment (475-1250 MeV):

- Observe **380 events,** predict **358±19±35 events**
- **0.55 σ** excess over no-oscillations background

No evidence for oscillations

Energy-dependent Oscillation Best-Fit (475-3000 MeV):

- $\sin^2 2\theta = 1.1 \times 10^{-3}$
- $\Delta m^2 = 4.1\ eV^2/c^4$
- $\chi^2_{null} - \chi^2_{best} = 0.94$



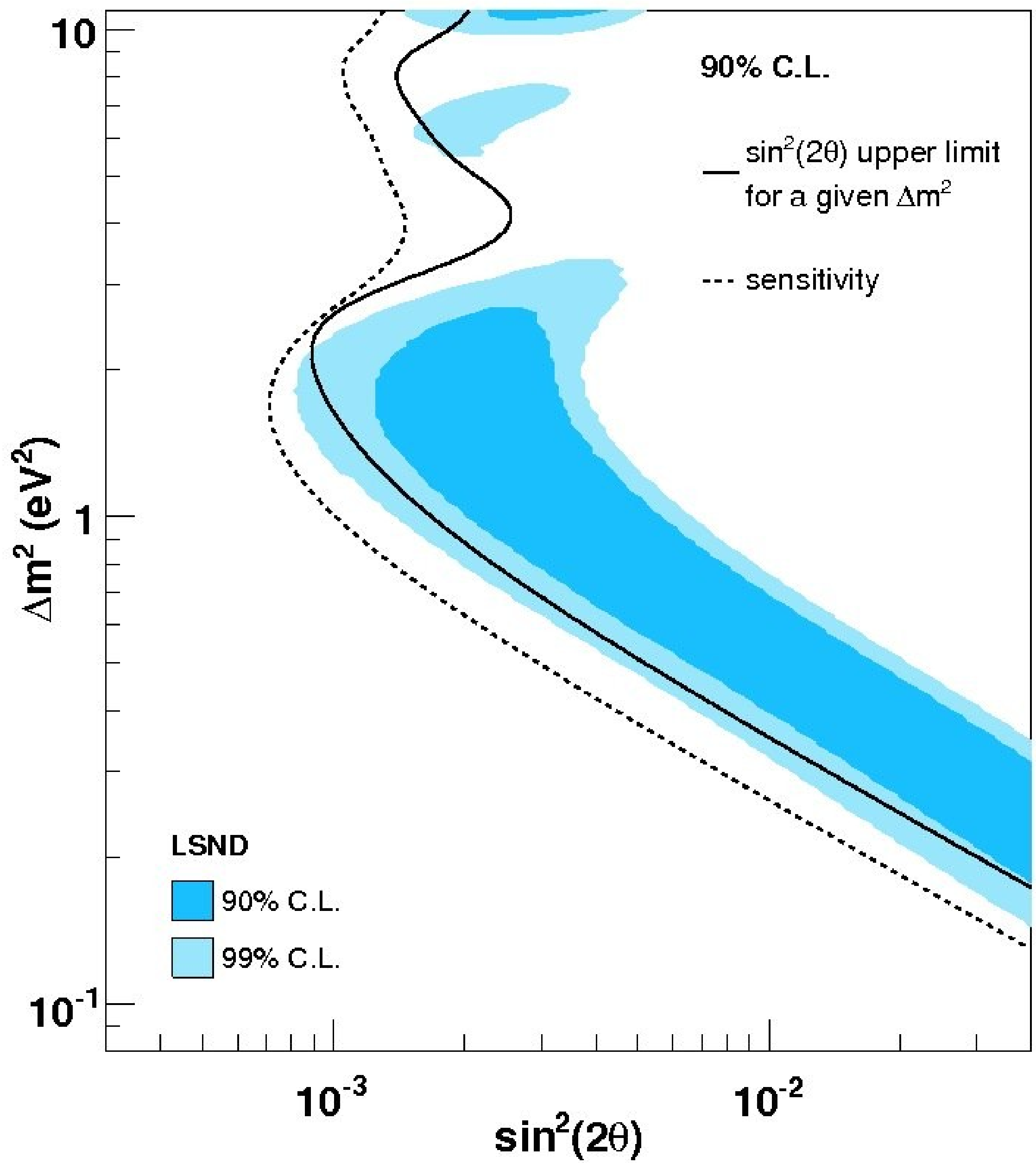
- Data error bars are statistical
- Predictions error bars from diagonal elements of syst.-only covariance matrix

Oscillation Parameters Exclusion

• No overlap in 90% CL allowed LSND and MiniBooNE regions

• MiniBooNE **excludes** two neutrino appearance-only oscillations as the explanation of the LSND anomaly at **~98% CL**

• Any interpetation of the LSND anomaly that would produce a significant excess for E_ν>475 MeV at MiniBooNE is also ruled out

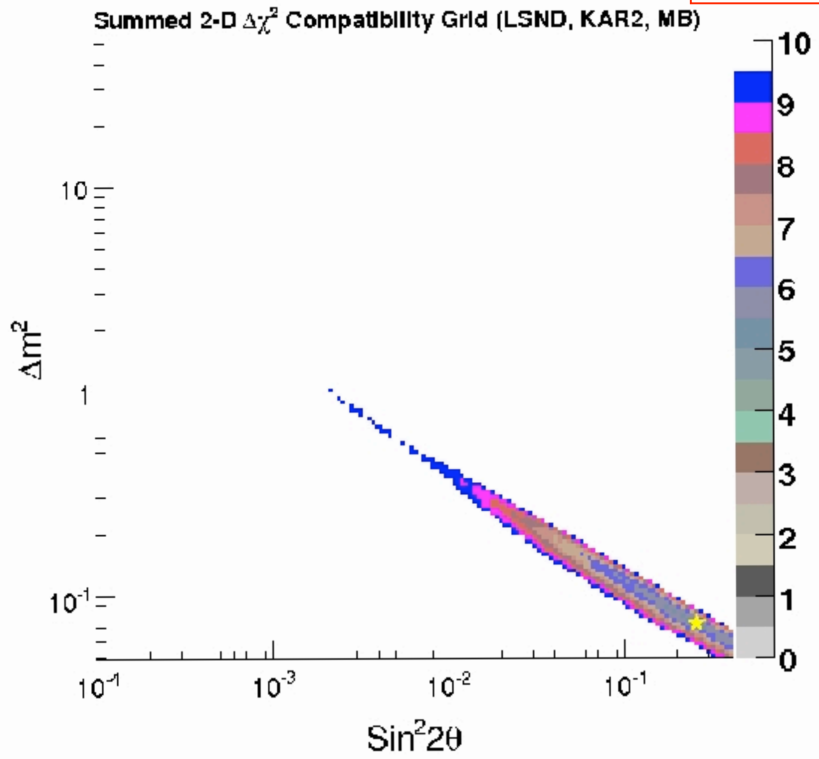


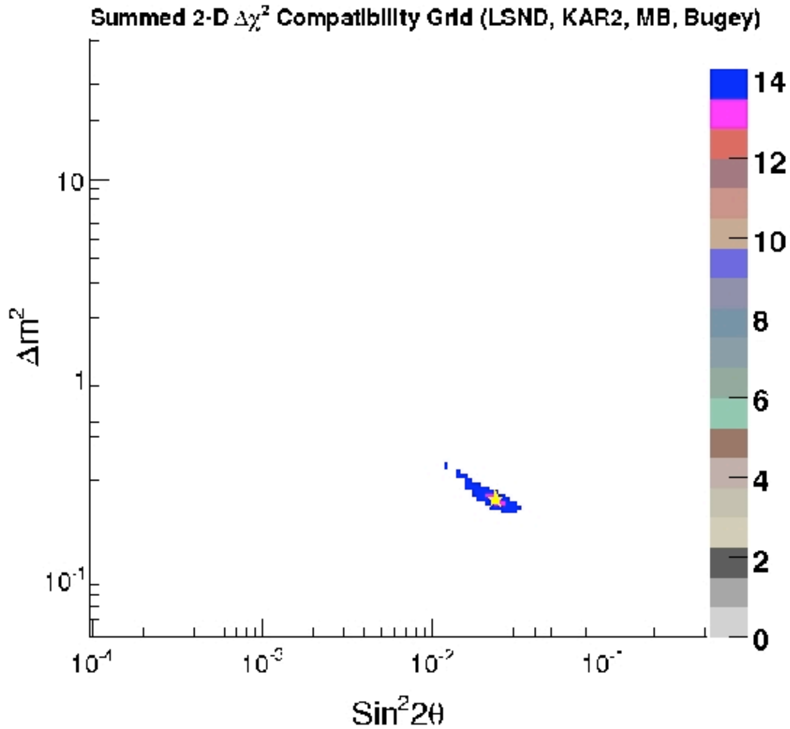
Global Fit Results (H. Ray)

- Combine results from several experiments--LSND, MiniBooNE, Karmen and Bugey
- Convert each to a chisq. However, only Delta chisq is available.
- Do fits with this. Omits effect of goodness-of-fit of individual experiments
- 2-D fits--both oscillation parameters fitted
- 1-D fits-- only sinsq theta fit. For each delta-msq asks: “ If this is the true deltamsq, what is the compatibility?”

Global Fit Results-2D Fits

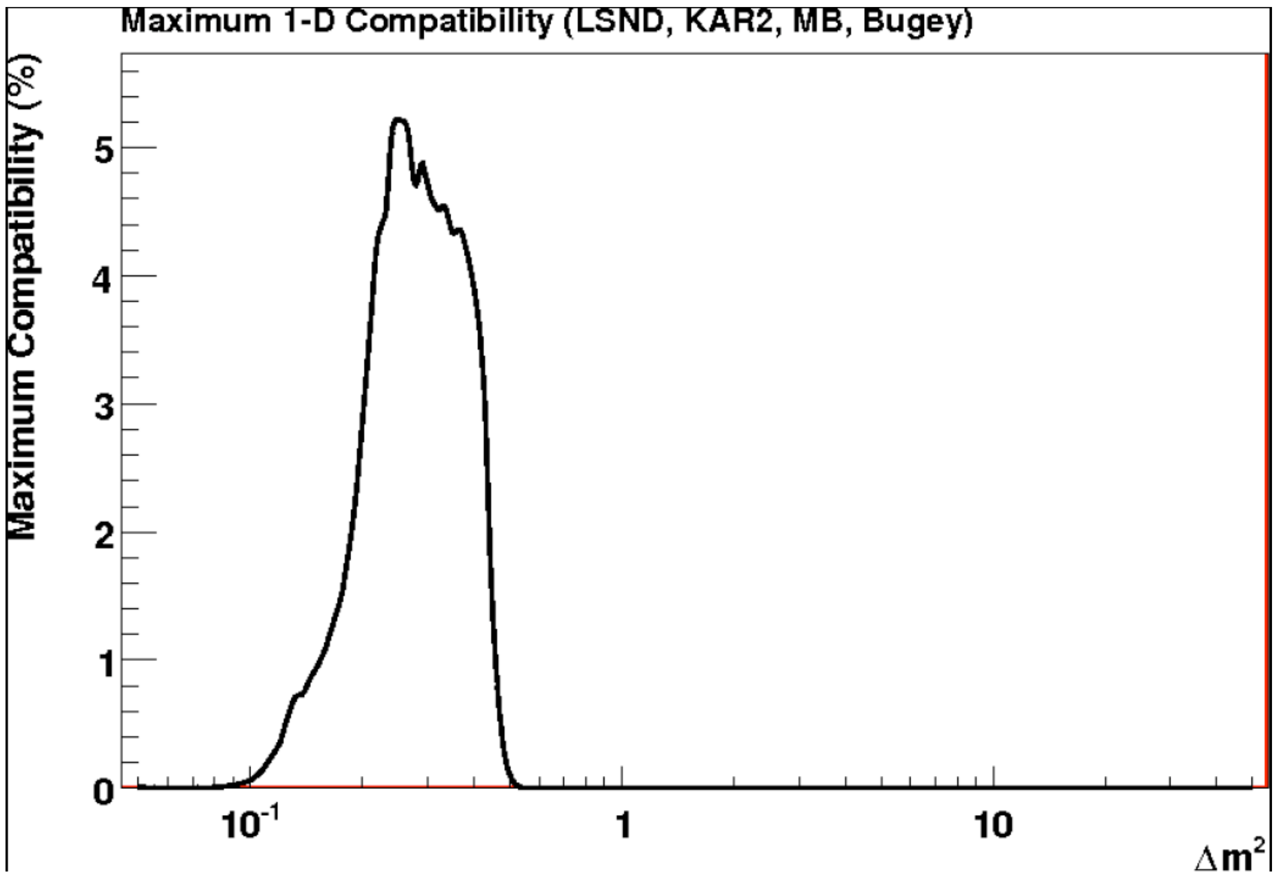
Colors represent $\Delta\chi^2$





- The star is the point of maximum compatibility
- LSND, KARMEN2, MB + BUGEY

Global Fits Results--1D



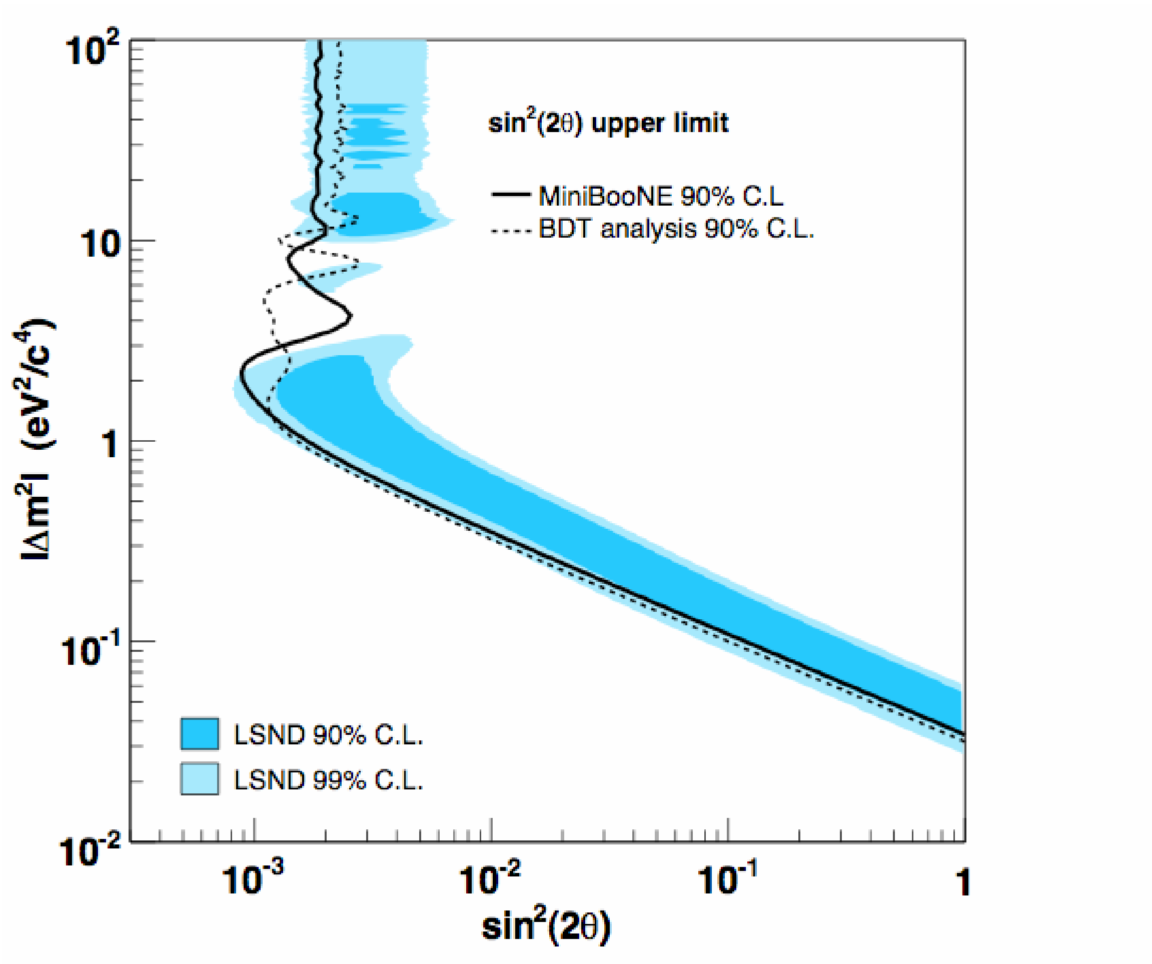
Maximum compatibility as a function of Δm^2 for the 1-D LSND, KARMEN2, MB, BUGEY analysis.

Global Fits to Experiments

LSND	KARMEN2	MB	Bugey	Max Compat (%)	Δm^2	$\sin^2 2\theta$
X	X	X		25.36	0.072	0.256
X	X	X	X	3.94	0.242	0.023
	X	X		73.44	0.052	0.147
	X	X	X	27.37	0.221	0.012
X		X		16.00	0.072	0.256
X		X	X	2.14	0.253	0.023
X	X			32.21	0.066	0.4

Oscillation Limit

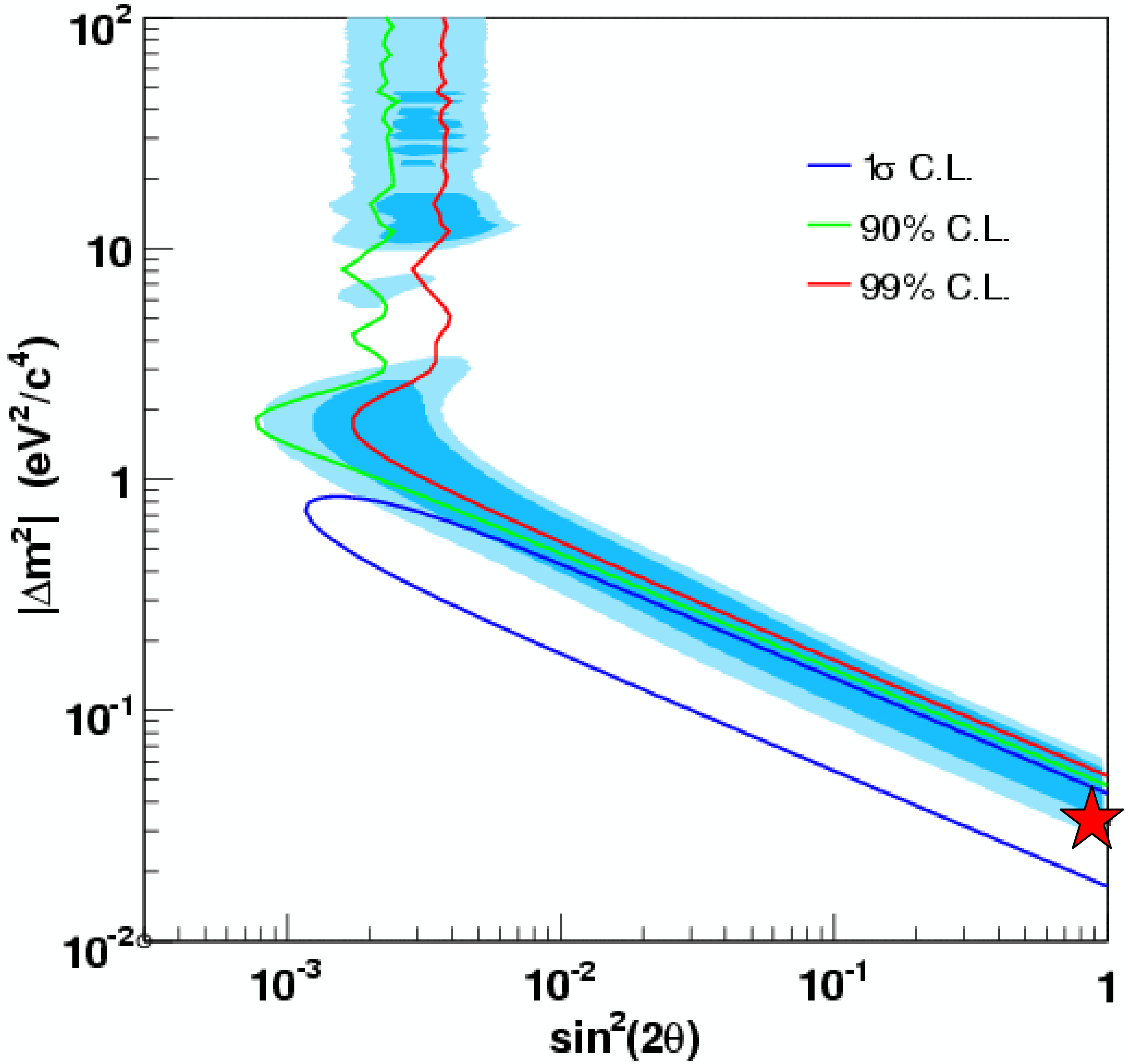
Energy fit: $475<E_\nu^{QE}<3000$ MeV



Simple 2-neutrino oscillations excluded at 98% C.L.

Allowed Region

Energy Fit : 300< E_ν^{QE}< 3000 MeV



Possible Explanations for the Low-Energy Excess

- 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
- 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

Other data sets (NuMI, antineutrino, SciBooNE) may provide an explanation!

arXiv:0904.1958, based on 3.39×10^{20} *pot*