Toward Solution

of the

MiniBooNE and LSND Anomalies

Georgia Karagiorgi, MIT

Neutrino 2010

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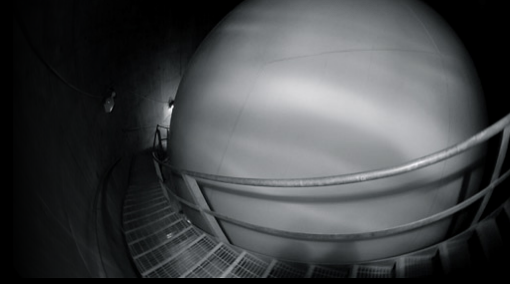


Outline

- Summary of LSND and MiniBooNE excesses
- Light sterile neutrino oscillations: The standard interpretation of LSND
- *Are they still viable?*
  - Exploring sterile neutrino fits using available data, including
    - LSND
    - MiniBooNE neutrino (6.46e20 POT)
    - MiniBooNE antineutrino (**old results**, 3.39e20 POT)
  - in various combinations with other experimental constraints
- Impact of new (5.66e20 POT) antineutrino results from MiniBooNE
- Summary of other potential interpretations and future experimental tests

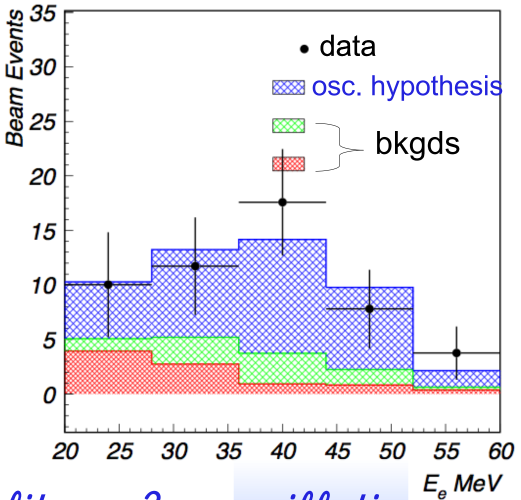
Excess signatures from LSND and MiniBooNE

LSND

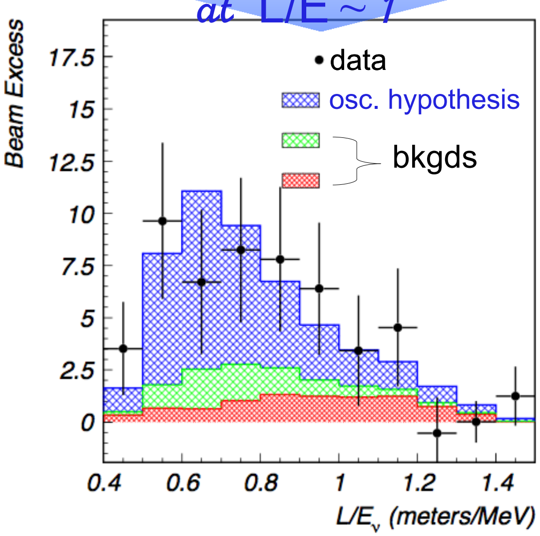
3.8 σ excess of $\bar{\nu}_e$

in a $\bar{\nu}_\mu$-dominated beam

from μ^+ decay at rest



fits a 2-ν oscillation interpretation at L/E ~ 1



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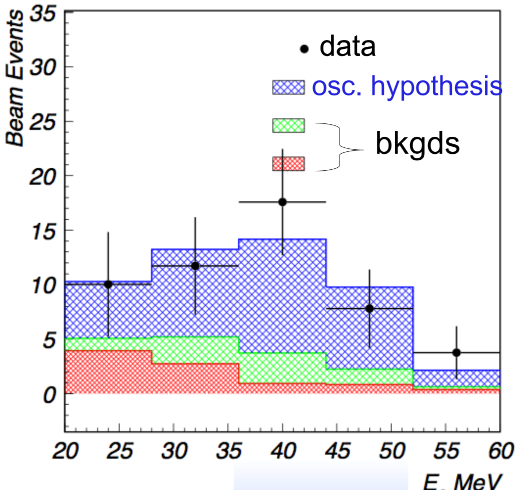

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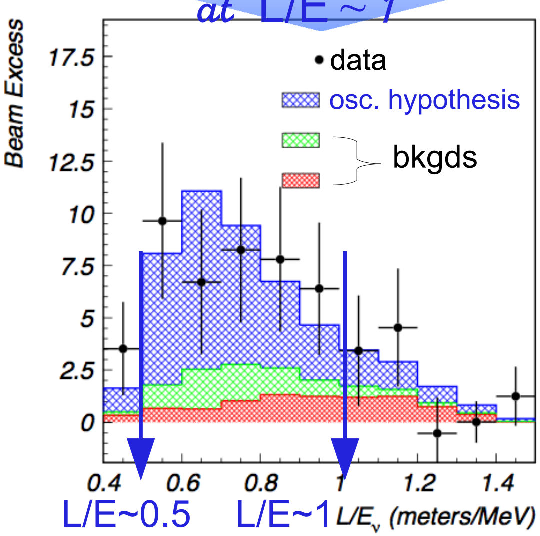


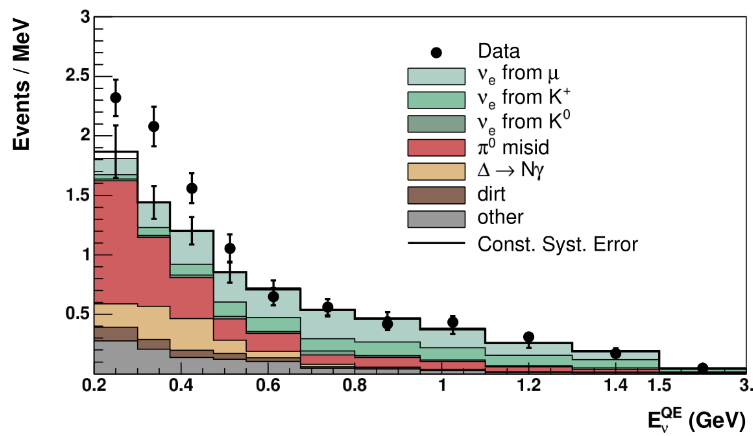
L/E~0.5 L/E~1

MiniBooNE neutrino mode

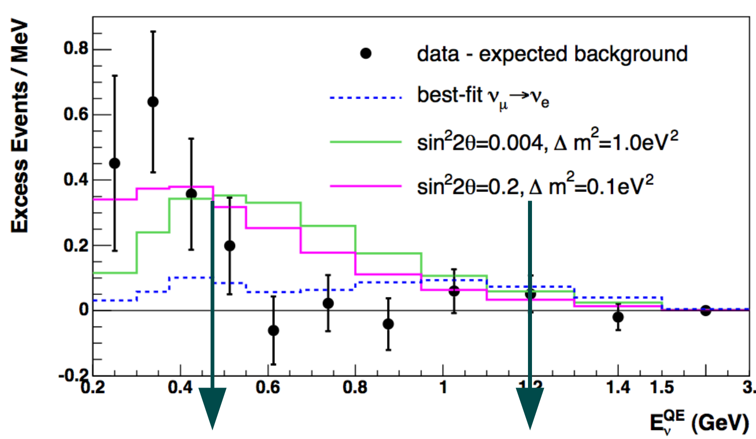
3.0 σ excess of ν_e

in a ν_μ-dominated beam

from π^+ decay in flight



shows up at a slightly different L/E compared to LSND



L/E~1 L/E~0.5

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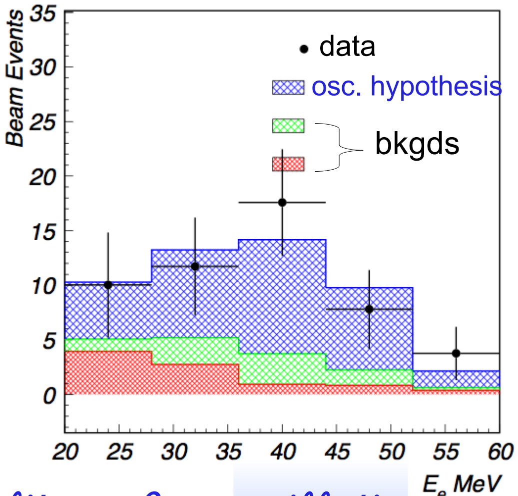

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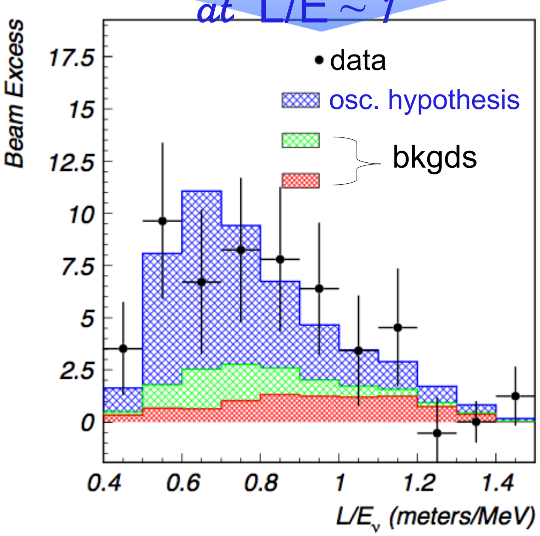

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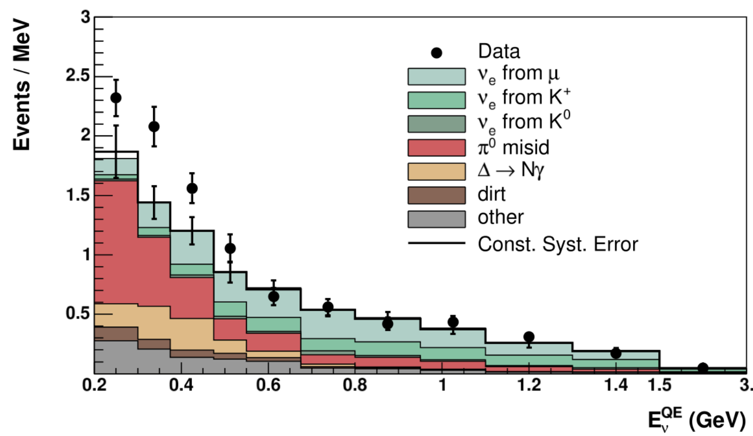
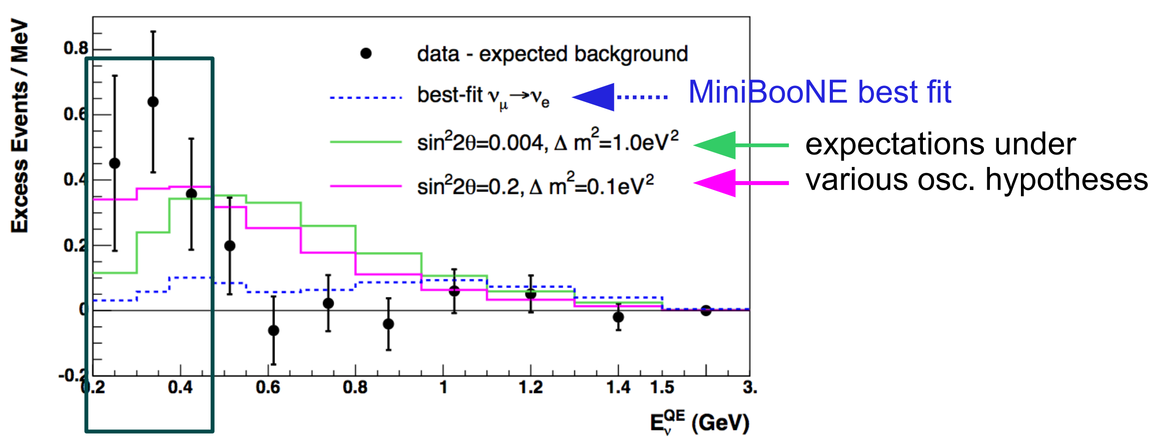


and is too sharply peaked at low energy to accommodate 2-ν oscillation interpretation



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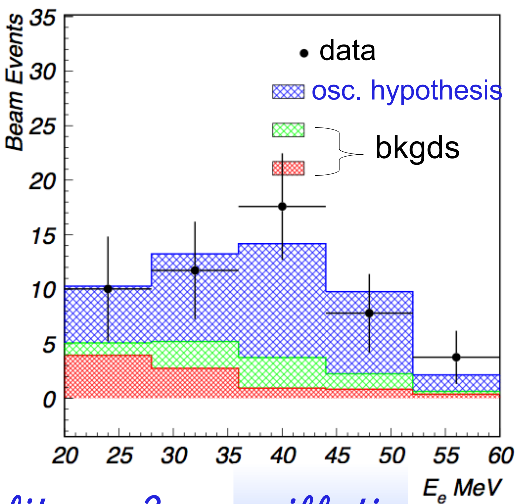

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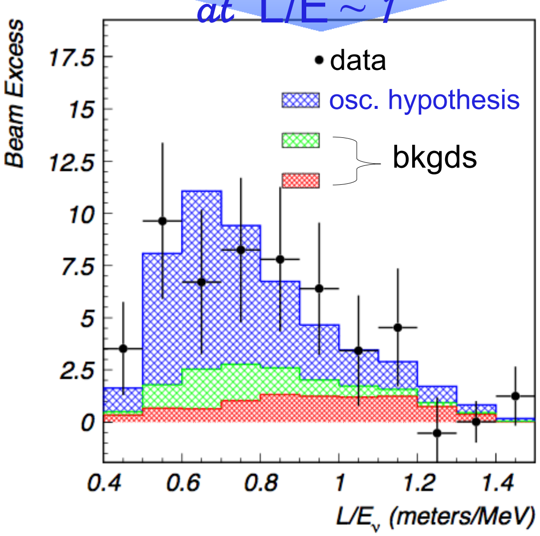

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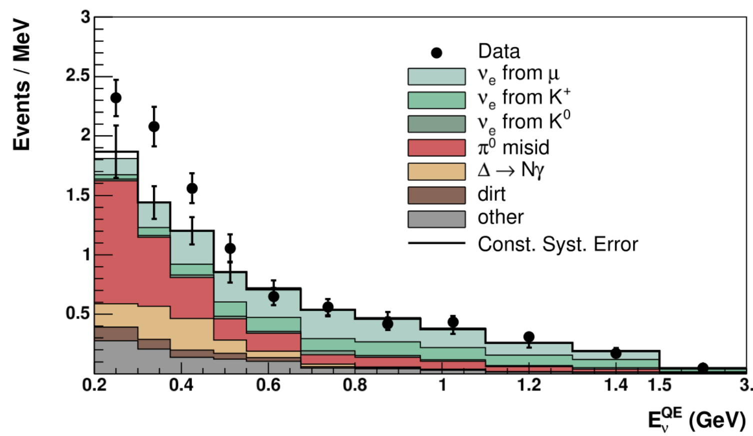

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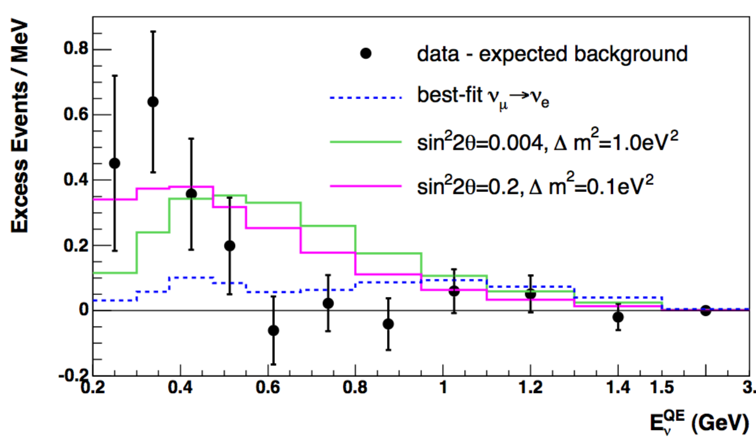
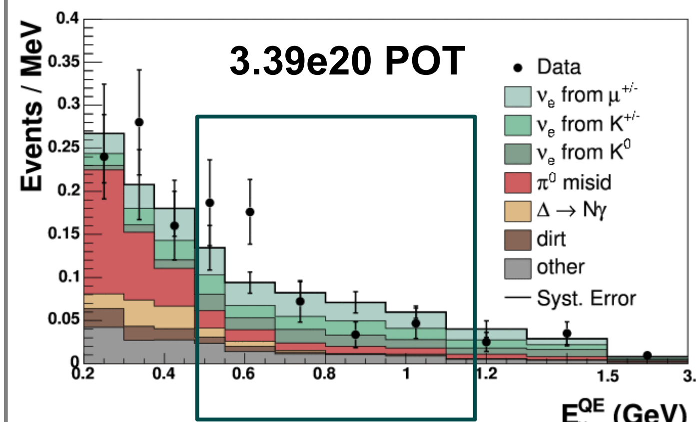


MiniBooNE antineutrino mode

no significant* excess of $\bar{\nu}_e$

in a $\bar{\nu}_\mu$-dominated beam

from π^- decay in flight (*low stats)



Inconclusive with respect to LSND-like oscillations at L/E ~ 1

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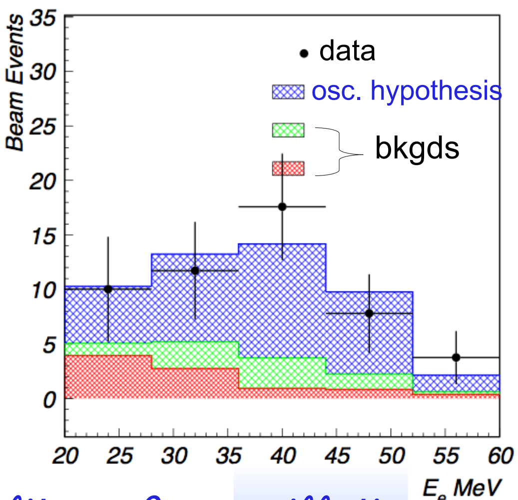

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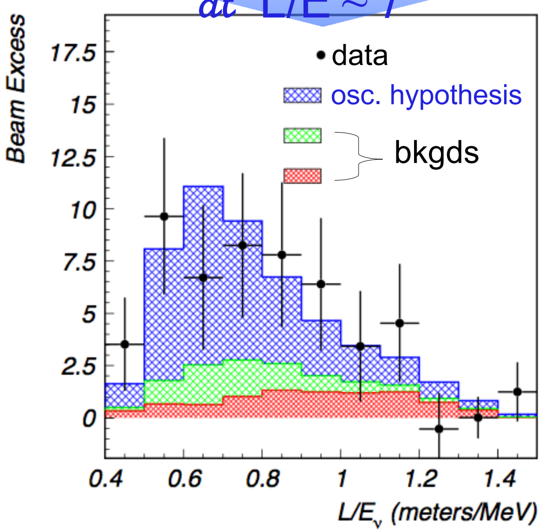
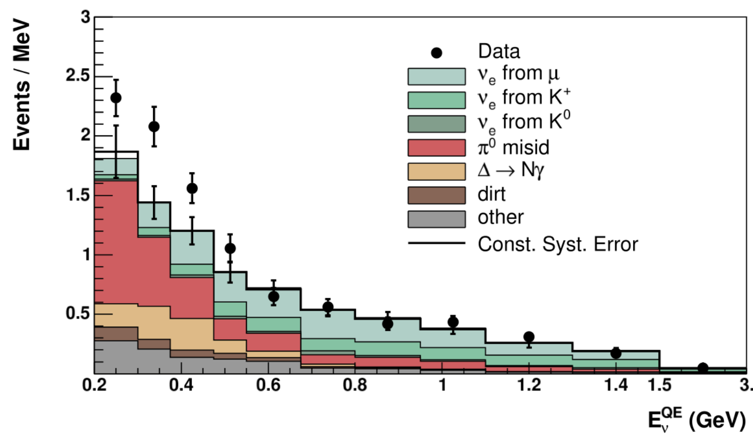


MiniBooNE neutrino mode

3.0 σ excess of ν_e

in a ν_μ-dominated beam

from π^+ decay in flight



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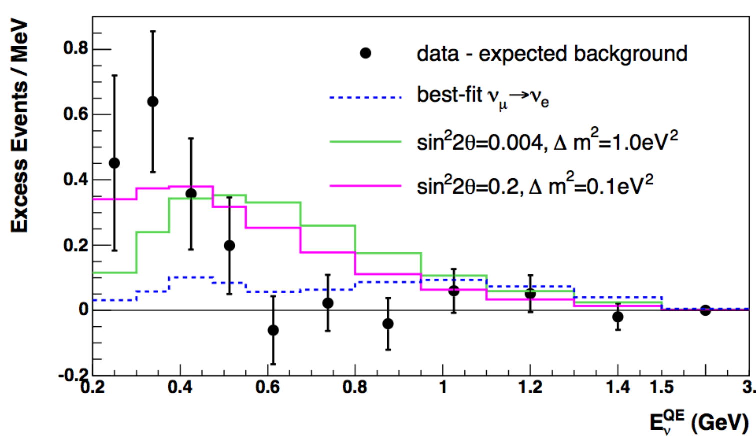

MiniBooNE antineutrino mode

no significant* excess of $\bar{\nu}_e$

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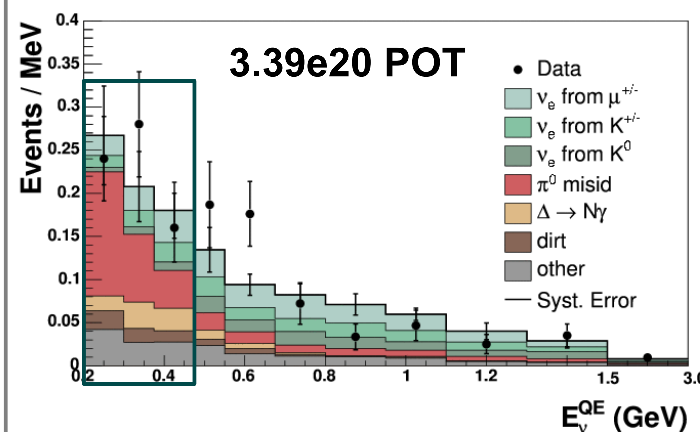
from π^- decay in flight (*low stats)



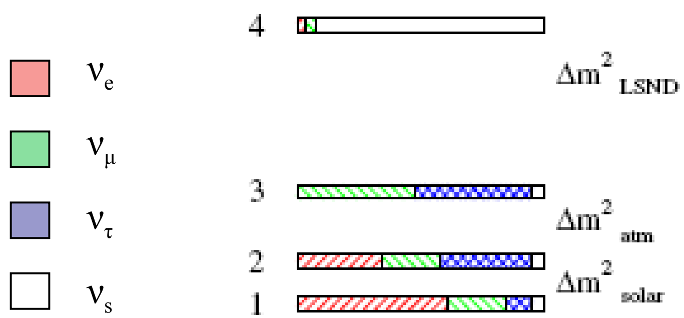
Inconclusive with respect to LSND-like oscillations at L/E ~ 1

and no significant excess at low energy

Light sterile neutrino oscillations: Are they still viable?

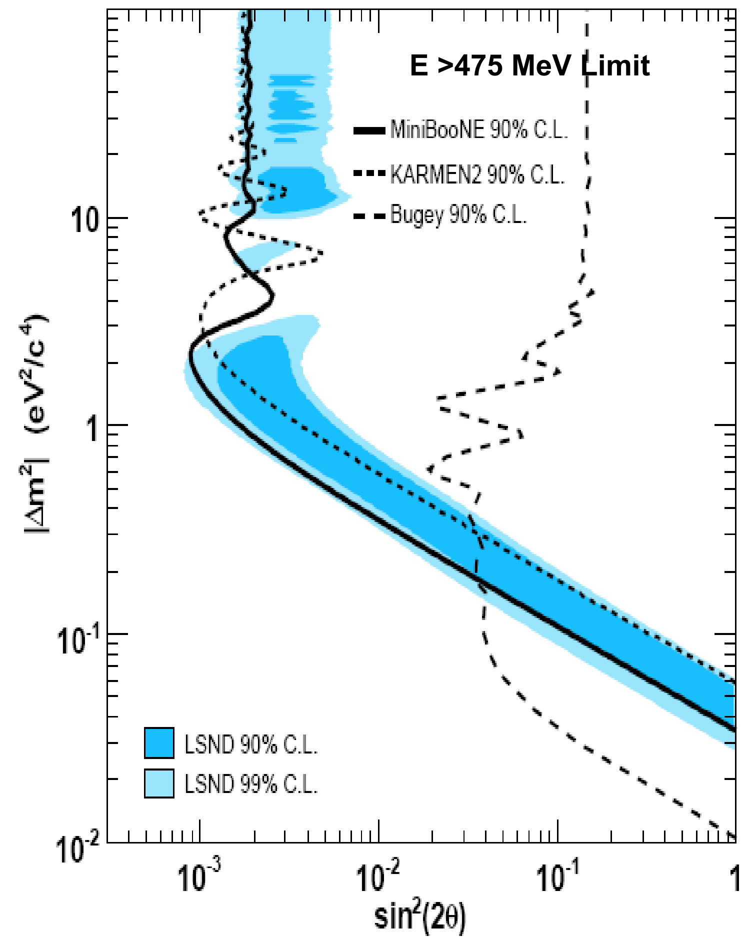
MiniBooNE's lack of excess above 475 MeV in **neutrino mode** rules out:

3 active + 1 sterile neutrinos (3+1)



approximated as two-neutrino oscillations →

$$P(\nu_\mu \rightarrow \nu_e) = \underbrace{\sin^2 2\theta}_{4\,|U_{e4}|^2\,|U_{\mu 4}|^2} \sin^2(1.27\,\underbrace{\Delta m^2}_{\Delta m^2_{41} \sim \Delta m^2_{LSND}}\,L[m]/\,E[MeV])$$

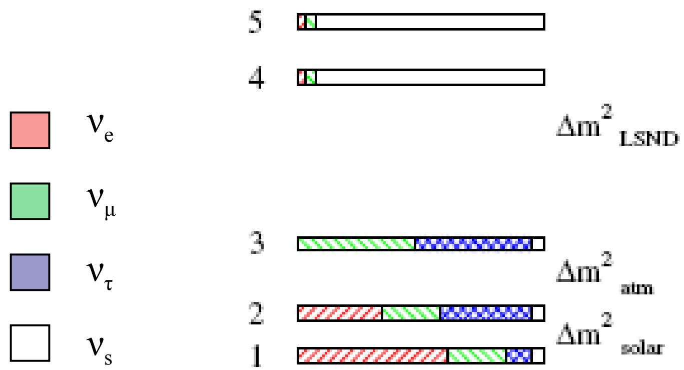


(implying neutrino and antineutrino oscillation probabilities must be identical)

Light sterile neutrino oscillations: Are they still viable?

However, it provides no direct constraints to oscillations due to:

3 active + 2 sterile neutrinos (3+2)



Dirac CPV phase: free parameter of the model

→ room for observable differences in neutrino vs. antineutrino <u>appearance</u> probabilities

approximated as three-neutrino oscillations →

$$P(\nu_\mu \to \nu_e) = 4\,|U_{e4}|^2\,|U_{\mu 4}|^2 \sin^2(1.27\,\Delta m^2_{41}\,L/E)$$
$$+ 4\,|U_{e5}|^2\,|U_{\mu 5}|^2 \sin^2(1.27\,\Delta m^2_{51}\,L/E)$$
$$+ 4\,|U_{e4}|\,|U_{\mu 4}|\,|U_{e5}|\,|U_{\mu 5}| \sin(1.27\,\Delta m^2_{41}\,L/E)\sin(1.27\,\Delta m^2_{51}\,L/E)$$
$$\times \cos(1.27\,\Delta m^2_{54}\,L/E - \varphi_{45})$$

Available constraints to light sterile neutrino oscillations:

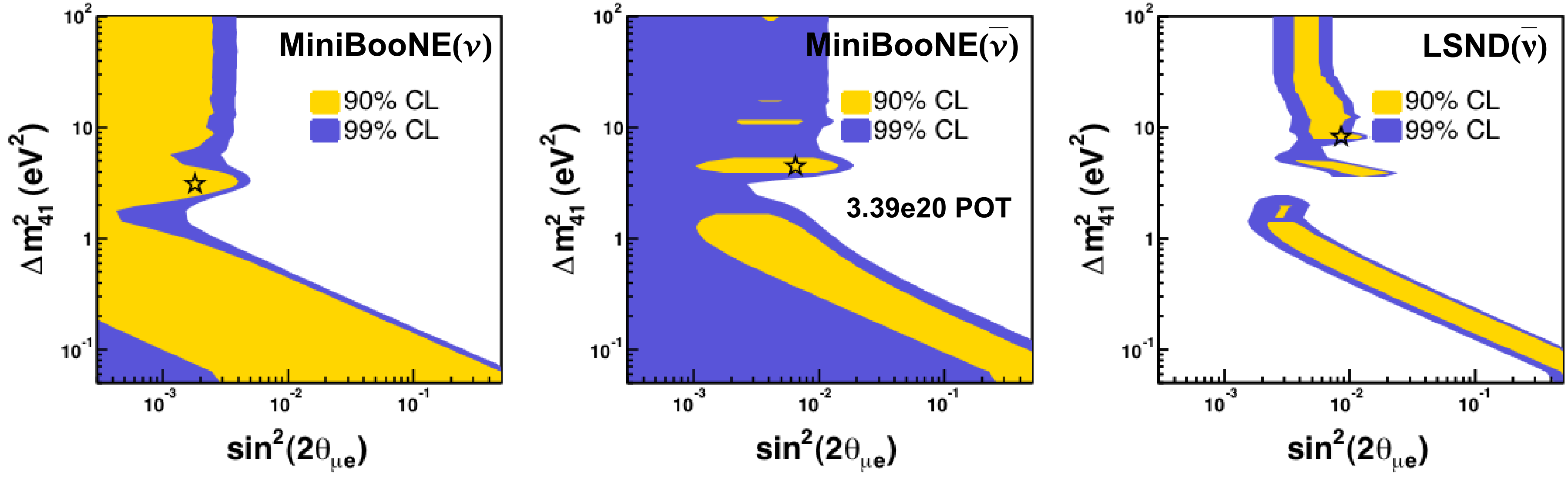
Experiments with $\Delta m^2 \sim 1$ eV^2 sensitivity, or sensitivity to overall mixing to sterile neutrinos:

	Dataset	Channel	Result	Constrained Mixing Elements
appearance	MiniBooNE ($\bar{\nu}$) 3.39e20 POT	$\bar{\nu}_\mu \to \bar{\nu}_e$	signal?	$\|U_{e4}\|\|U_{\mu4}\|, \|U_{e5}\|\|U_{\mu5}\|$
	LSND (DAR → $\bar{\nu}$-only)	$\bar{\nu}_\mu \to \bar{\nu}_e$	signal	$\|U_{e4}\|\|U_{\mu4}\|, \|U_{e5}\|\|U_{\mu5}\|$
	KARMEN	$\bar{\nu}_\mu \to \bar{\nu}_e$	null	$\|U_{e4}\|\|U_{\mu4}\|, \|U_{e5}\|\|U_{\mu5}\|$
	NOMAD	$\nu_\mu \to \nu_e$	null	$\|U_{e4}\|\|U_{\mu4}\|, \|U_{e5}\|\|U_{\mu5}\|$
	MiniBooNE (ν)	$\nu_\mu \to \nu_e$	signal?	$\|U_{e4}\|\|U_{\mu4}\|, \|U_{e5}\|\|U_{\mu5}\|$
	MiniBooNE-NuMI (ν)	$\nu_\mu \to \nu_e$	null	$\|U_{e4}\|\|U_{\mu4}\|, \|U_{e5}\|\|U_{\mu5}\|$
disappearance	Bugey	$\bar{\nu}_e \to \bar{\nu}_e$	null	$\|U_{e4}\|, \|U_{e5}\|$
	CHOOZ	$\bar{\nu}_e \to \bar{\nu}_e$	null	$\|U_{e4}\|, \|U_{e5}\|$
	CCFR84	$\nu_\mu \to \nu_\mu$	null	$\|U_{\mu4}\|, \|U_{\mu5}\|$
	CDHS	$\nu_\mu \to \nu_\mu$	null	$\|U_{\mu4}\|, \|U_{\mu5}\|$
	ATM	$\nu_\mu \to \nu_\mu$	null	$\|U_{\mu4}\|, \|U_{\mu5}\|$

Results based on analysis of PRD 80,073001 (2009) [arXiv:0906.1997]

MiniBooNE and LSND fits to sterile neutrino oscillations: (3+1)

Each of the three datasets fit separately to a (3+1) model yields the following allowed regions:



All three results have low compatibility, at 1.8%,
but two of them (antineutrino) are compatible at 49%.

Results based on analysis of PRD 80,073001 (2009) [arXiv:0906.1997]

Global fits to sterile neutrino oscillations: (3+1)

Status of (3+1) sterile neutrino oscillation hypothesis:

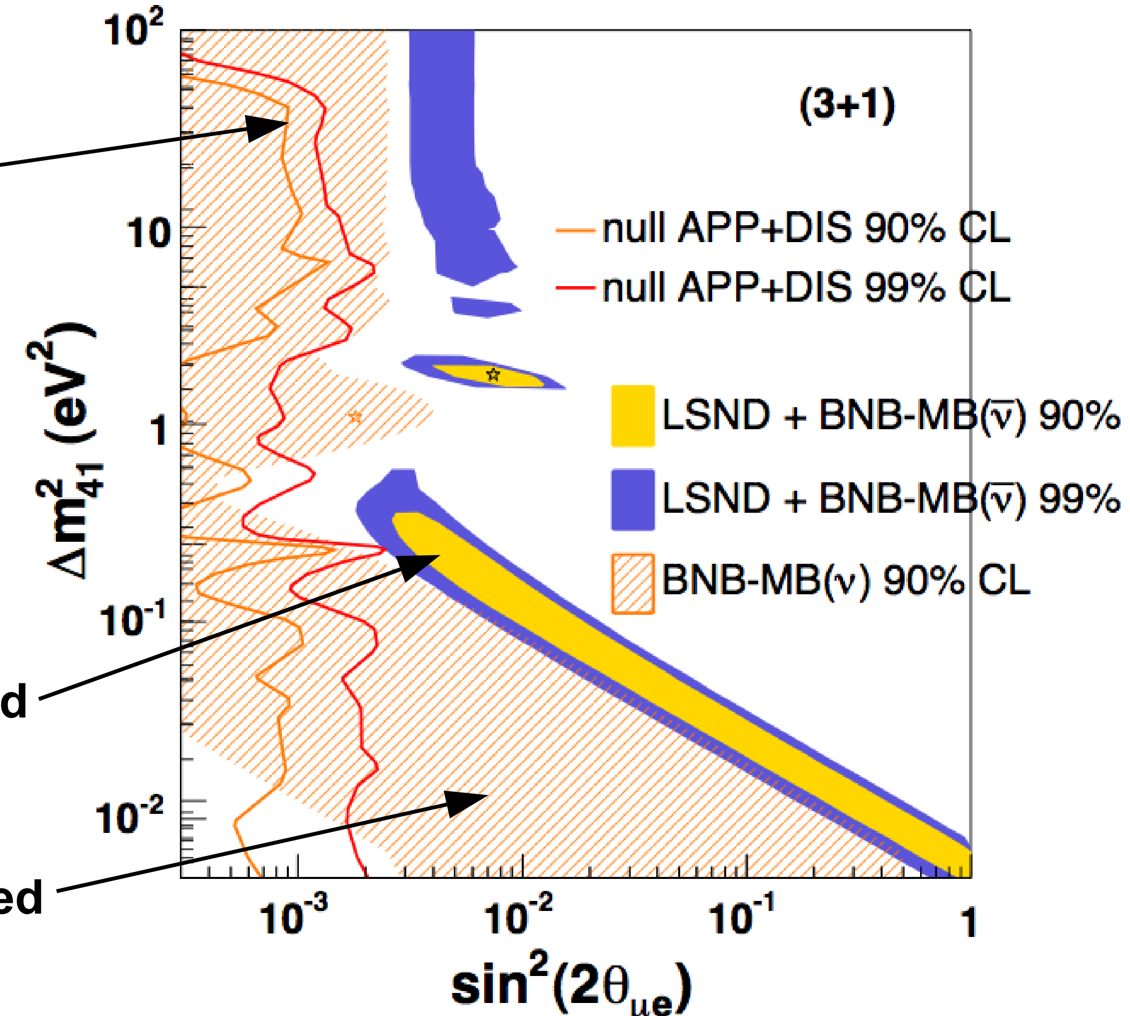
All short-baseline and atmospheric experimental results are highly incompatible: 0.11%

Combined **exclusion limits from null** atmospheric ν_μ disappearance and null short-baseline experiments:

- Bugey and Chooz: $\bar{\nu}_e$ disappearance
- CCFR, CDHS: ν_μ disappearance
- NOMAD, NuMI-MiniBooNE $\nu_\mu \rightarrow \nu_e$ appearance
- KARMEN: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance

Joint **LSND+MiniBooNE($\bar{\nu}$) allowed**

MiniBooNE(ν) allowed



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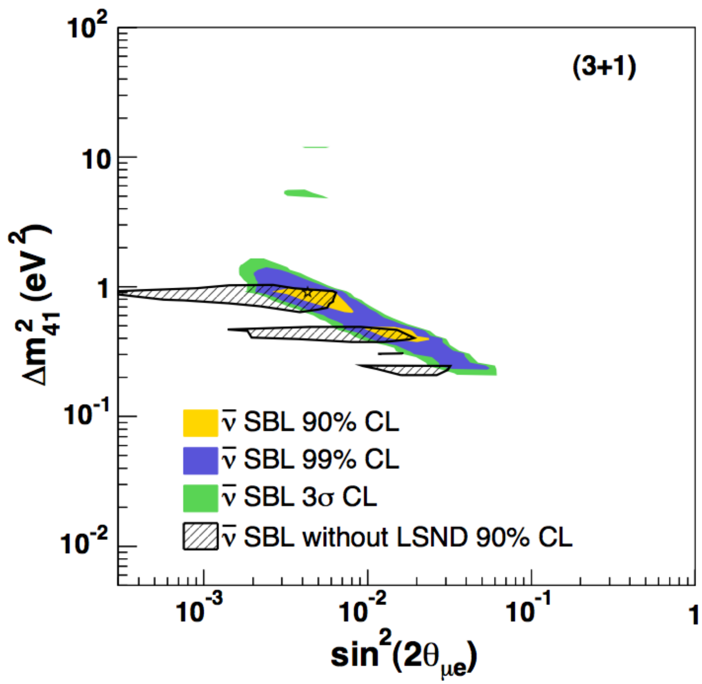
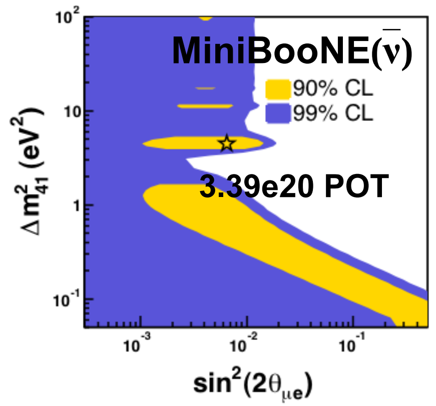
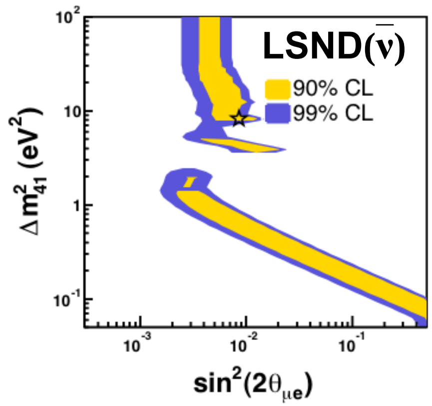
(3+1): Are neutrino or antineutrino experimental results compatible when fit separately?







All **antineutrino** experimental results, including appearance and disappearance constraints, are compatible at 30%.

The fit excludes no oscillations at >3σ,
and at >90% CL when LSND is not included in the fit

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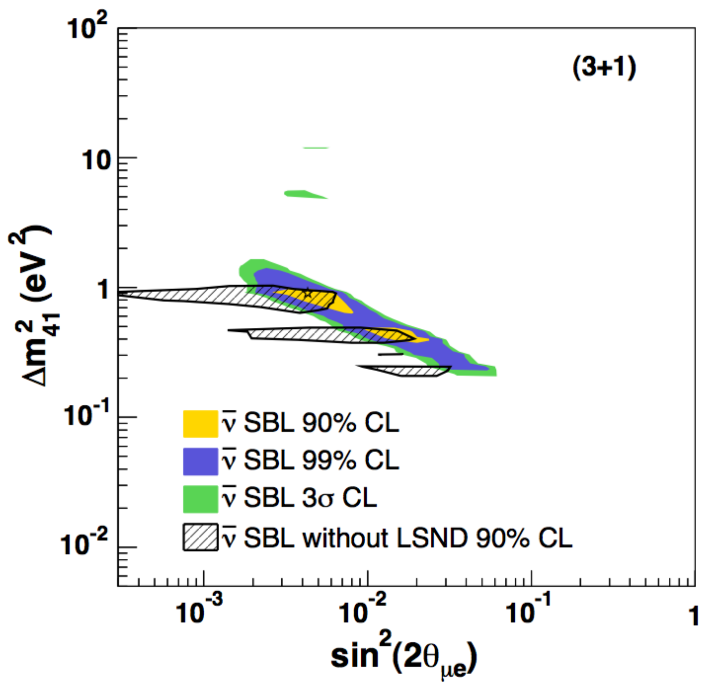

ν_μ disappearance constraints (on $|U_{\mu4}|$) are not applicable in this case

→ large $\bar{\nu}_\mu$ disappearance ($\sin^2 2\theta_{\mu\mu}=0.35$) can account for the observed LSND and MiniBooNE antineutrino excesses ($|U_{e4}||U_{\mu4}|$)

given $\bar{\nu}_e$ disappearance constraints from Bugey and CHOOZ ($|U_{e4}|$)

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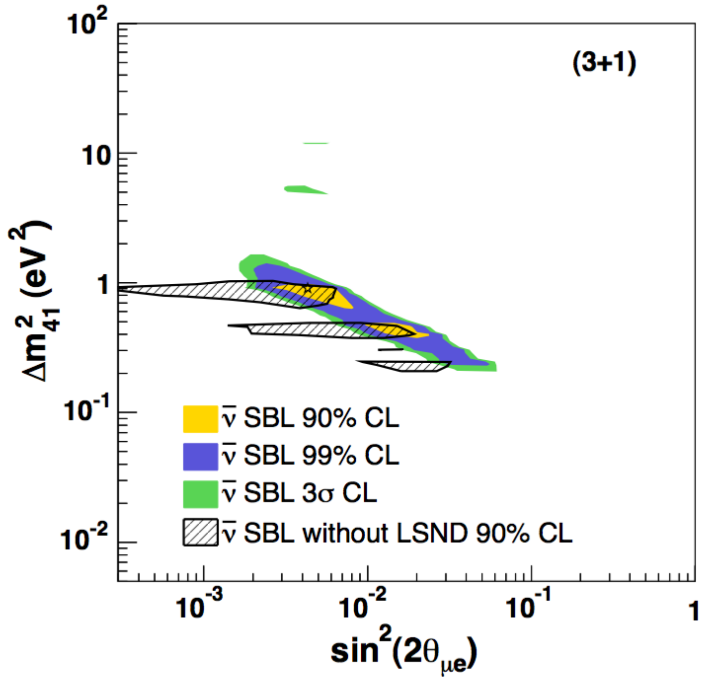

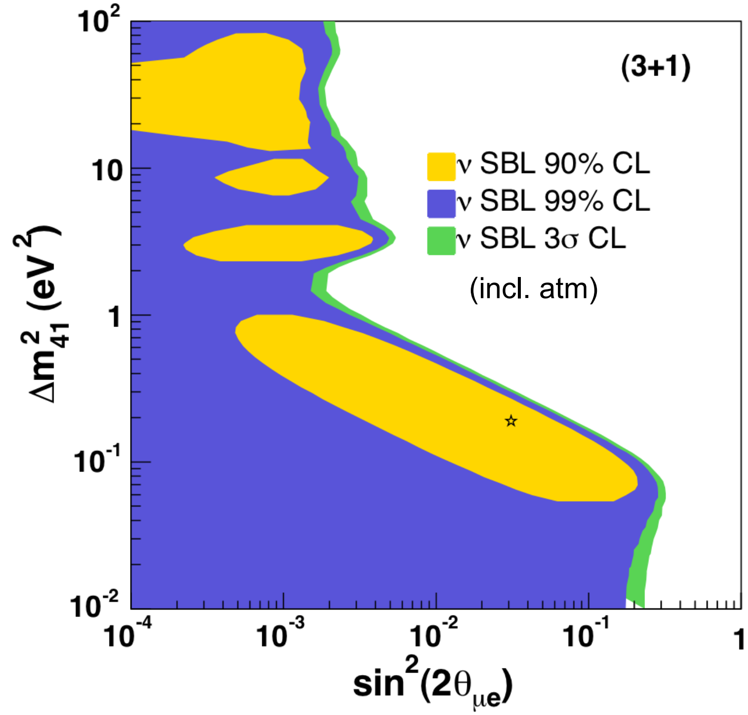

All **antineutrino** experimental results, including appearance and disappearance constraints, are compatible at 30%.

Reasonable compatibility (6.5%) is also obtained when **neutrino** experimental results, including appearance and disappearance constraints, are fit separately.

Results based on analysis of PRD 80,073001 (2009) [arXiv:0906.1997]

Can (3+2) and CP violation account for the observed differences?

If we extend to **two sterile neutrinos, with CP violation**:

"troublemakers" reconciled with CP violation, but...

Datasets	**CPV χ^2-prob**	**CPC χ^2-prob**	**CPV compat.**
MiniBooNE(ν)+ MiniBooNE($\bar{\nu}$)+LSND (90% closed contours)	53%	13%	86%
MiniBooNE(ν)+MiniBooNE($\bar{\nu}$)+LSND+ NUMI+KARMEN+NOMAD (appearance)	**56%**	**22%**	**74%**
all SBL+atm	54%	52%	7%
appearance vs disappearance			0.004%
neutrino vs antineutrino			0.06%
ν	62%		43%
$\bar{\nu}$	88%		80%

There are still large incompatibilities between appearance vs. disappearance experiments, and neutrino vs. antineutrino experiments.

Results based on analysis of PRD 80,073001 (2009) [arXiv:0906.1997]

Can (3+2) and CP violation account for the observed differences?

Which experiments are causing the large incompatibility among neutrino and antineutrino experiments, or appearance and disappearance experiments?

Aside from MiniBooNE($\bar{\nu}$) and LSND,

MiniBooNE(ν), CDHS and atmospheric constraints on ν_μ disappearance.
The compatibility is low (<5% as long as at least one of the experiments is included in the fit).

Excluding the above three datasets from the fit yields:

- 56.5% compatibility between neutrino and antineutrino datasets
- 23.7% compatibility between appearance and disappearance experiments

Results based on analysis of PRD 80,073001 (2009) [arXiv:0906.1997]

Viability of light sterile neutrino oscillation models: Summary

• It is **possible to accommodate MiniBooNE and LSND results** within CP-violating sterile neutrino oscillations. However, this possibility is highly **disfavored by disappearance experiments**.

• Still, there is **compatibility among all neutrino datasets** (which may increase further by excluding the MiniBooNE neutrino mode low E excess from the fit), as well as **compatibility among all antineutrino datasets**, excluding the no oscillations hypothesis at $>3\sigma$.

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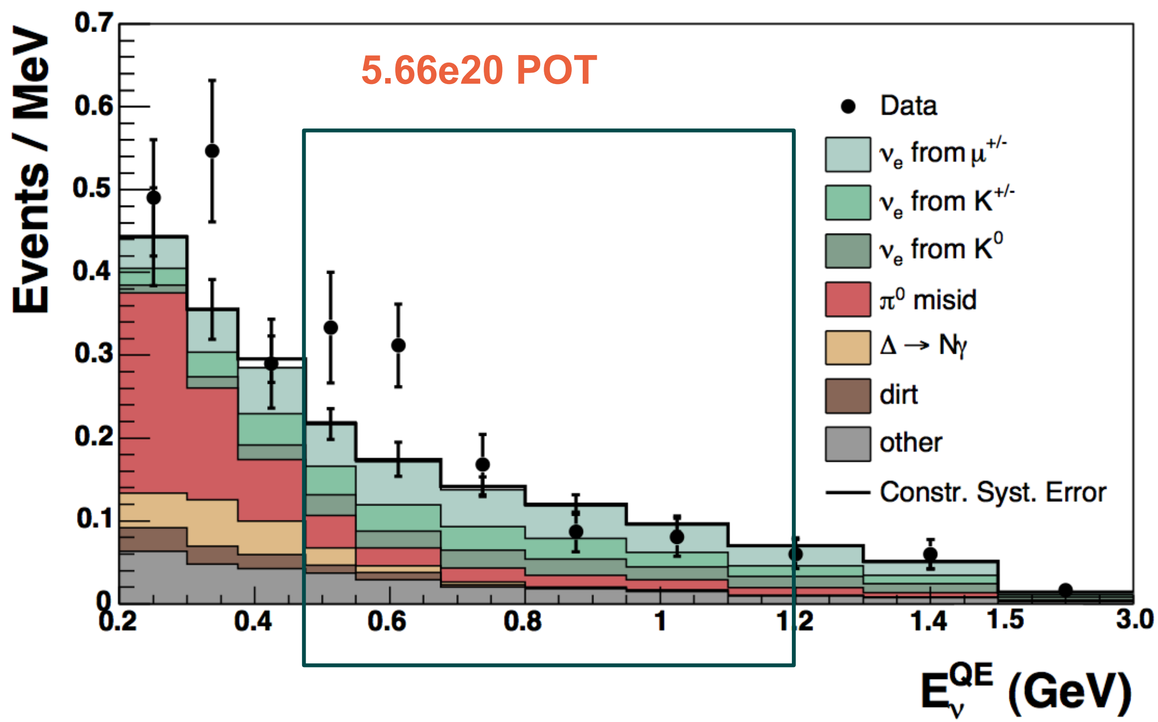
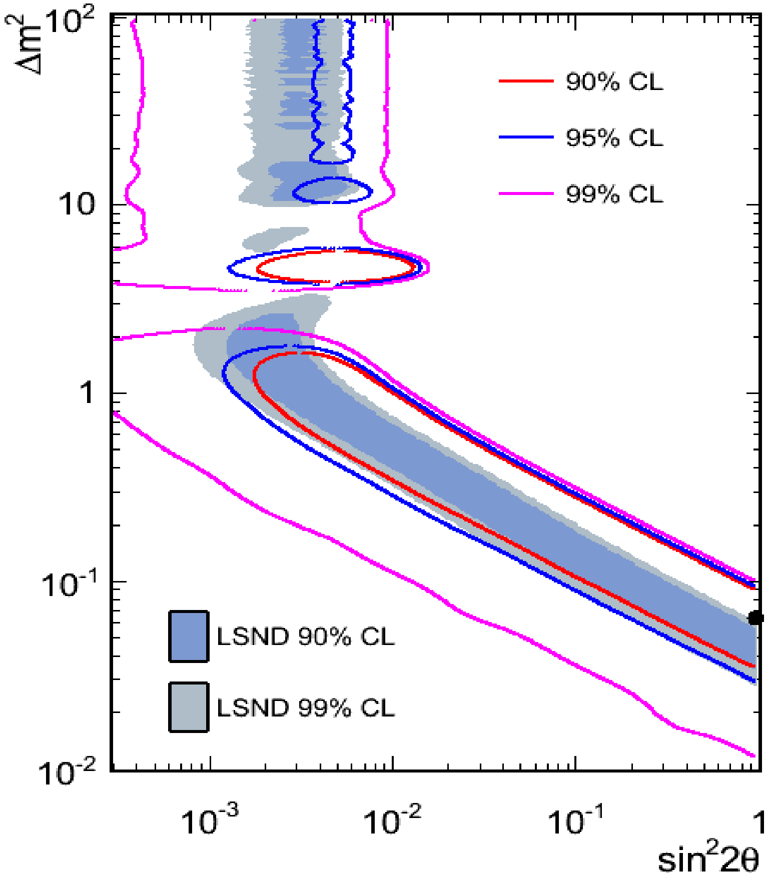
How do these conclusions change given the new MiniBooNE antineutrino results?

Results based on analysis of PRD 80,073001 (2009) [arXiv:0906.1997]

Implications of new antineutrino results from MiniBooNE

New results have become more conclusive with respect to LSND-like oscillations:





And confirm a 2-ν oscillation interpretation at 99% CL

Implications of new antineutrino results from MiniBooNE

Preliminary

New antineutrino results from MiniBooNE support conclusions in previous sterile neutrino fits:

In a (3+1) fit, antineutrino experiments are still compatible at 20% (from 30%), and still strongly exclude the no oscillations hypothesis.

Compatibility among **all datasets (SBL+atm)** decreases further:

0.11% → **0.04%**	in a (3+1) hypothesis
7% → **3%**	in a (3+2) CPV hypothesis

What could the evident neutrino-alone vs antineutrino-alone compatibilities mean?

More exotic oscillation models have been explored, with effective differences between neutrinos and antineutrinos:

[A modest list:]

Decaying Sterile Neutrinos: Palomares-Ruiz, Pascoli, & Schwetz, J HEP 0509, 048 (2005)

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]

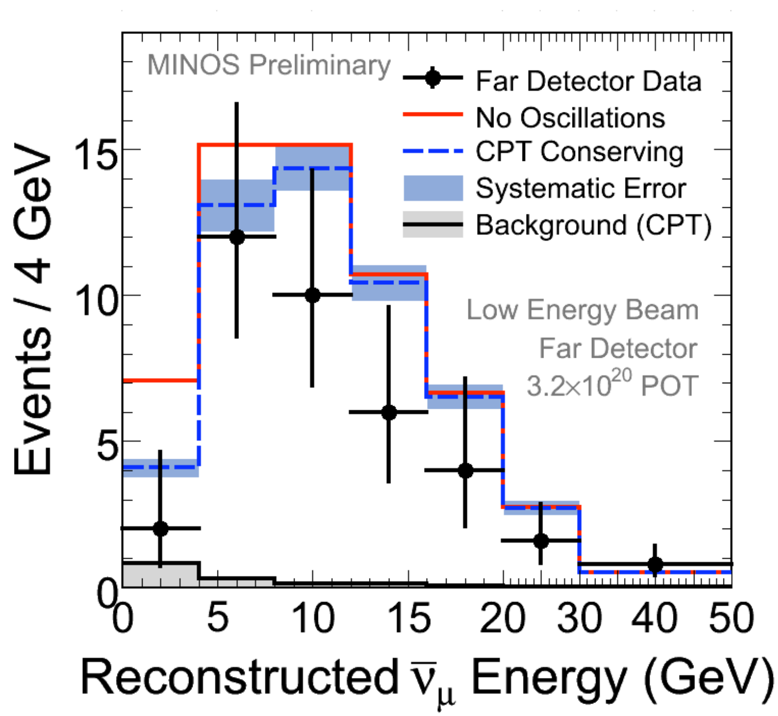
CPT Violating Decoherence: Barenboim, & Mavromatos, JHEP0501:034,2005

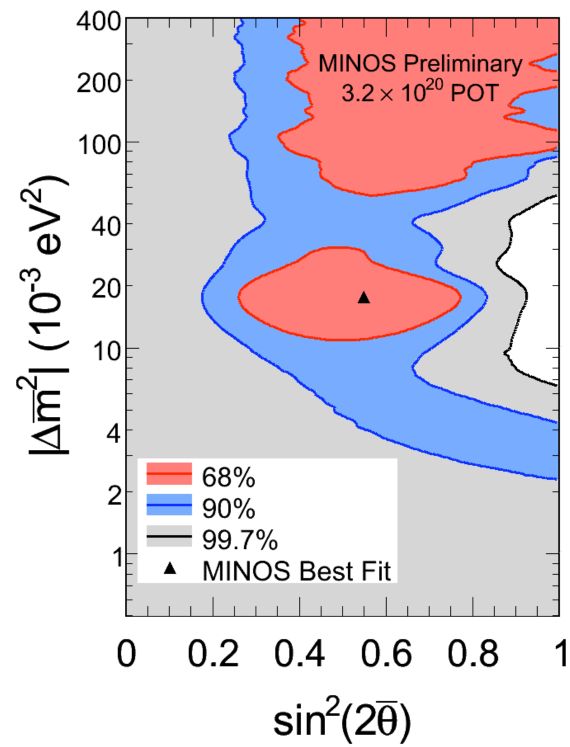
[and others...]

What could the evident neutrino-alone vs antineutrino-alone compatibilities mean?

It will be interesting to also confront these phenomenological models with MINOS:

Old results from MINOS:





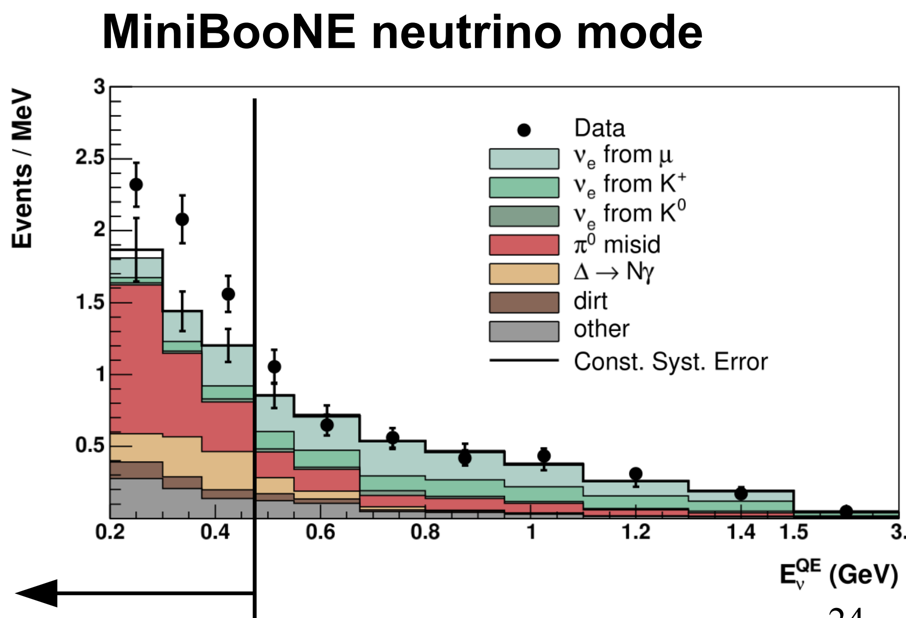
Also updated results this morning by P. Vahle, consistent with this picture.

Within standard neutrino mixing, disappearance probabilities for neutrinos and antineutrinos are identical, by CPT conservation!

A note on the low energy excess in MiniBooNE neutrino running

Global fits to sterile neutrino oscillations: We have seen that "incompatibilities also arise due to MiniBooNE neutrino mode dataset included in global fits."

Must acknowledge the possibility that the MiniBooNE low energy excess could be an unrelated effect to that inducing the apparent LSND and MiniBooNE antineutrino signals.



A note on the low energy excess in MiniBooNE neutrino running

A misestimated background?

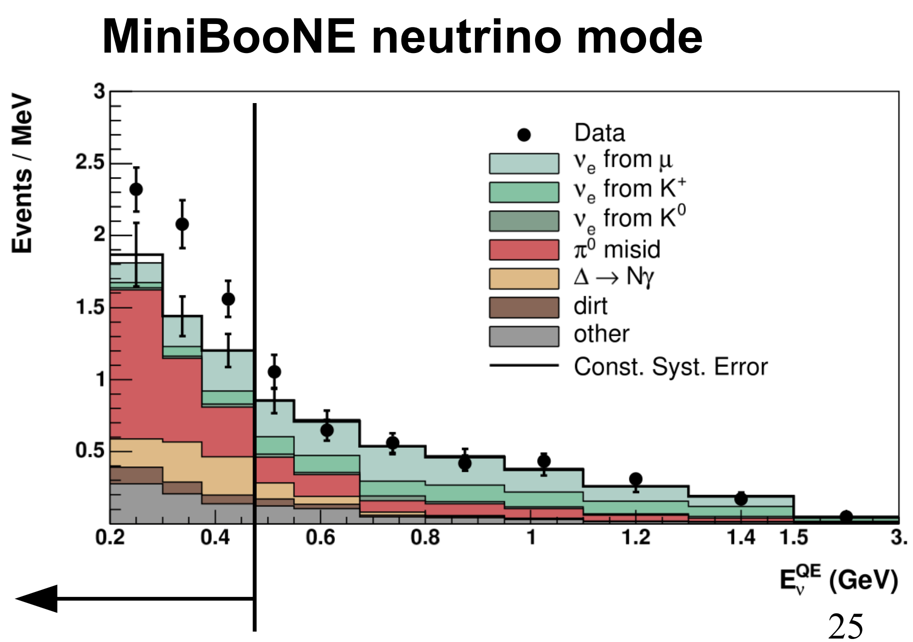
Excess **shape at low energy is consistent with single-photon backgrounds** in that range:

e.g. NC π^0, $\Delta \rightarrow N\gamma$

However,

the **required normalization increase** to account for the excess under each Background hypothesis is **excluded by** MiniBooNE's in-situ measurement of the NC π^0 rate at > 5σ.

Phys. Lett. B 664, 41-46 (2008) [arXiv:0803.3423]



A note on the low energy excess in MiniBooNE neutrino running

In summary, two equally viable hypotheses:

The MiniBooNE neutrino-mode low energy excess is due to events inducing

a single $e^{\pm}$ in the detector, or

a single γ in the detector

e.g.

Anomaly-mediated single photon production, Hill, Hill, & Harvey, Phys. Rev. Lett. 99, 261601 (2007) [arXiv:0708.1281]; also [arXiv:1002.4215] (γ)

Radiative heavy sterile neutrino decay, Gninenko & Gorbunov, Phys. Rev. D81, 075013 (2010) [arXiv:0907.4666] (γ)

ν_e disappearance, Giunti & Laveder, Phys. Rev. D80, 013005 (2009) [arXiv:0902.1992] (**$e^{\pm}$**)

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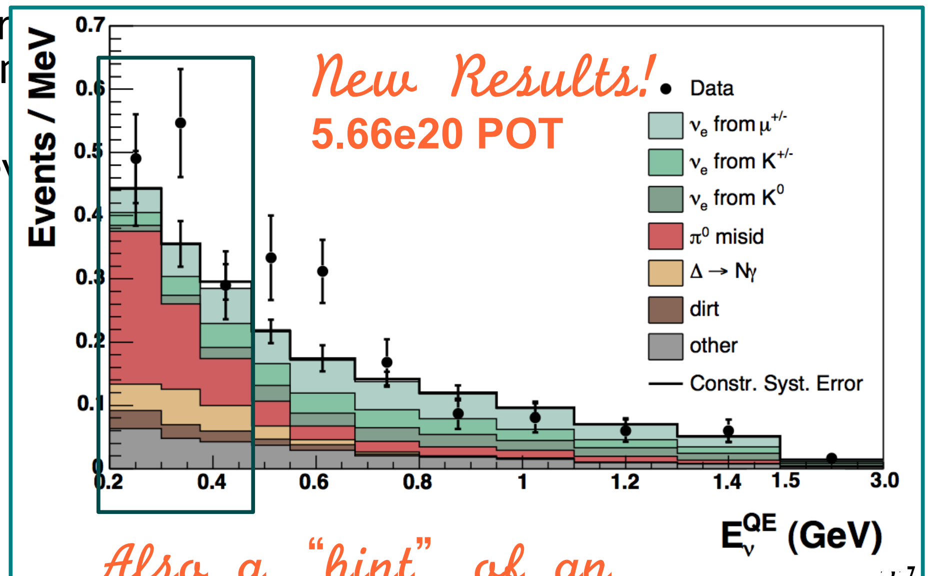


...Also a "hint" of an excess at low energy?

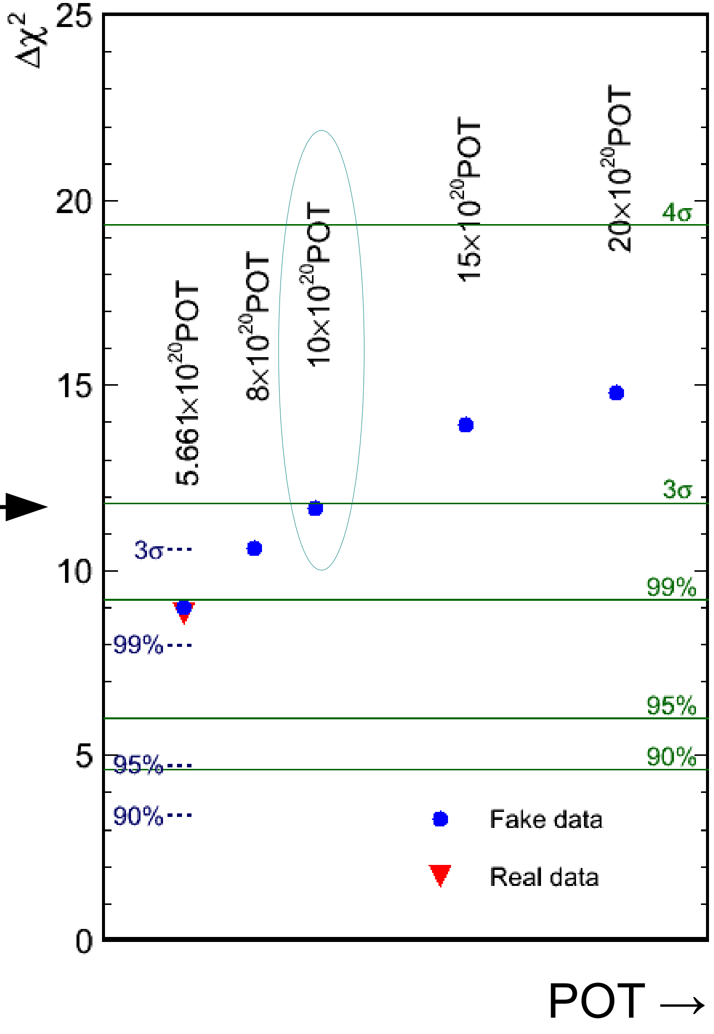
We might also ask,

Can the updated MiniBooNE antineutrino dataset provide further constraints?

Future experimental tests

Increased MiniBooNE antineutrino appearance search statistics (10e20 POT):

Potential exclusion of null point assuming current MiniBooNE antineutrino best fit hypothesis (E>475 MeV fit).
[MiniBooNE Collab. projections]



Future experimental tests

Several other experiments may be able to address these signatures, *e.g.*:

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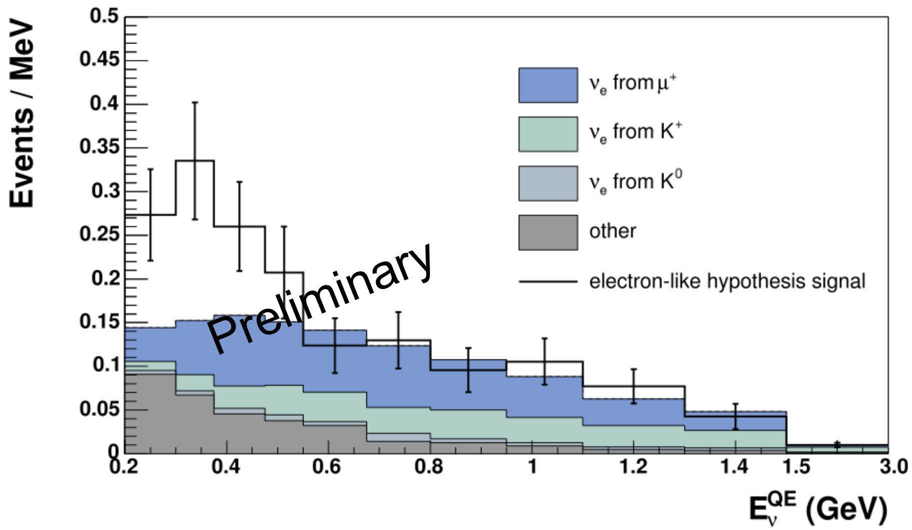
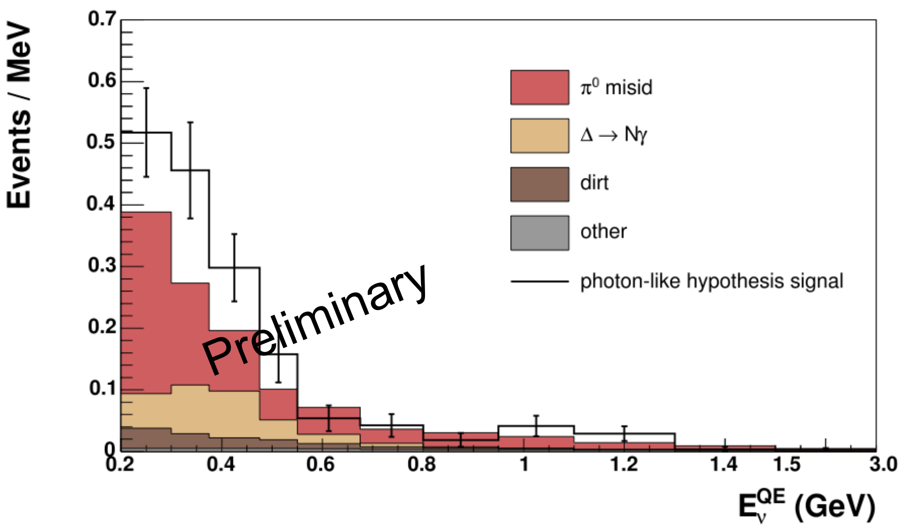
MicroBooNE:
Specifically designed to test electron-like versus photon-like interpretations of the **MiniBooNE neutrino low energy excess**, approved, and in construction phase. → *see talk by M. Soderberg*

Liquid-Argon TPC with exceptional e/photon dE/dx-based differentiation capability

MicroBooNE expectations under each hypothesis:





MicroBooNE's sensitivity to e/γ hypothesis: 5.7σ / 4.1σ

Future experimental tests

Several other experiments may be able to address these signatures, *e.g.*:

MicroBooNE:
Specifically designed to test electron-like versus photon-like interpretations of the **MiniBooNE neutrino low energy excess**, approved, and in construction phase. → *see talk by M. Soderberg*

BooNE:
LOI [0910.2698] submitted for construction of a Near (200 m) MiniBooNE detector to search for **sterile (anti)neutrino oscillations** with high-sensitivity
→ *see poster by G. Mills*

LArTPC detector at CERN-PS:
Near/Far identical LArTPC detectors to search for **non-standard sterile neutrino oscillations** [0909.0355]

Spallation Source Neutrino experiments (OscSNS, ESS), and others...

Closing remarks

Observation of two 3σ excess signatures, one in neutrinos and one in antineutrinos:

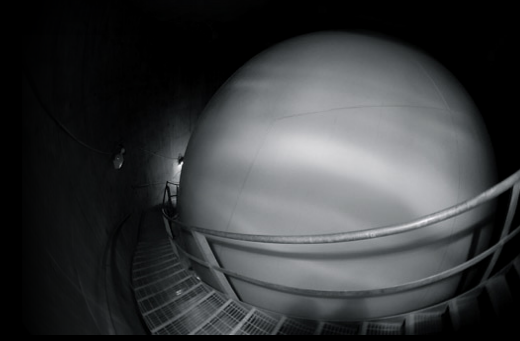
- at a similar L[m]/E[MeV]
- seem compatible in a model with two light sterile neutrinos and CP violation, but
- in conflict with current muon neutrino disappearance constraints.

Clear neutrino versus antineutrino differences are evident, which cannot be accommodated by CP violation.

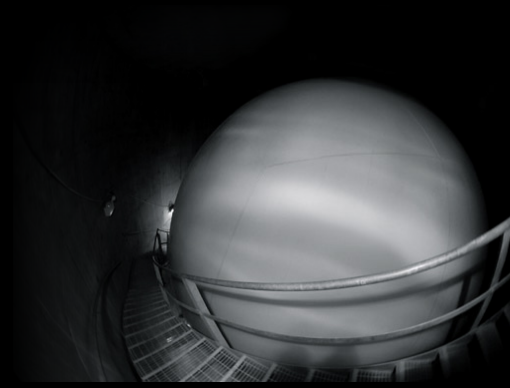
- Antineutrino results alone are compatible under a two neutrino oscillation scenario, and so are neutrino results.

Alternative explanations have been suggested, most of them based on exotic oscillation scenarios, and should be explored further in global fits to current experimental results.

More to come: New experiments are currently planned with high sensitivity to several interpretations.



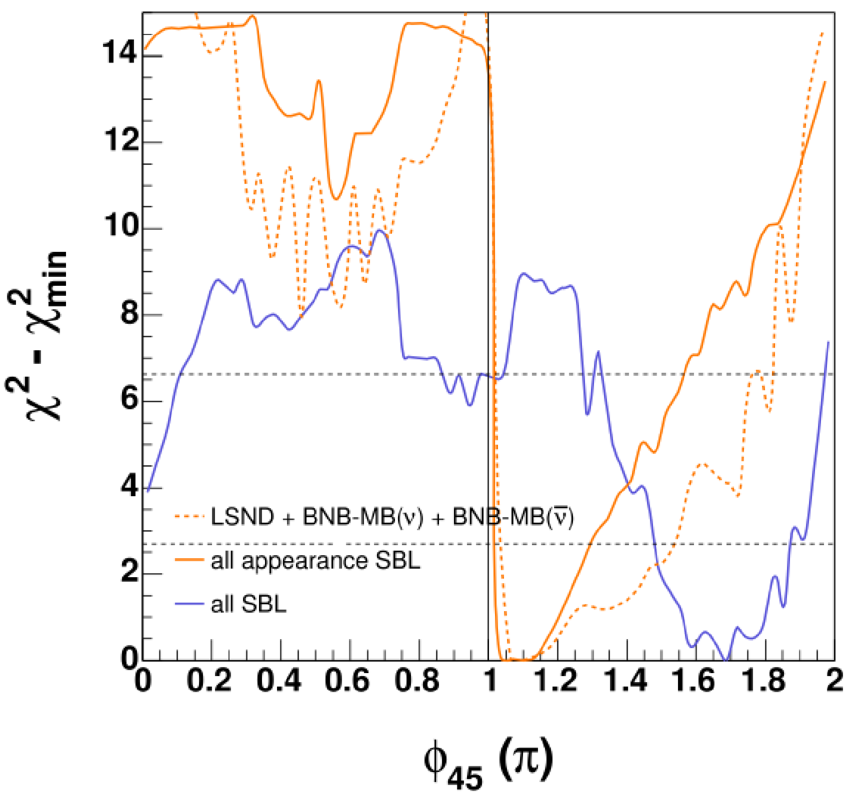
Thank you!

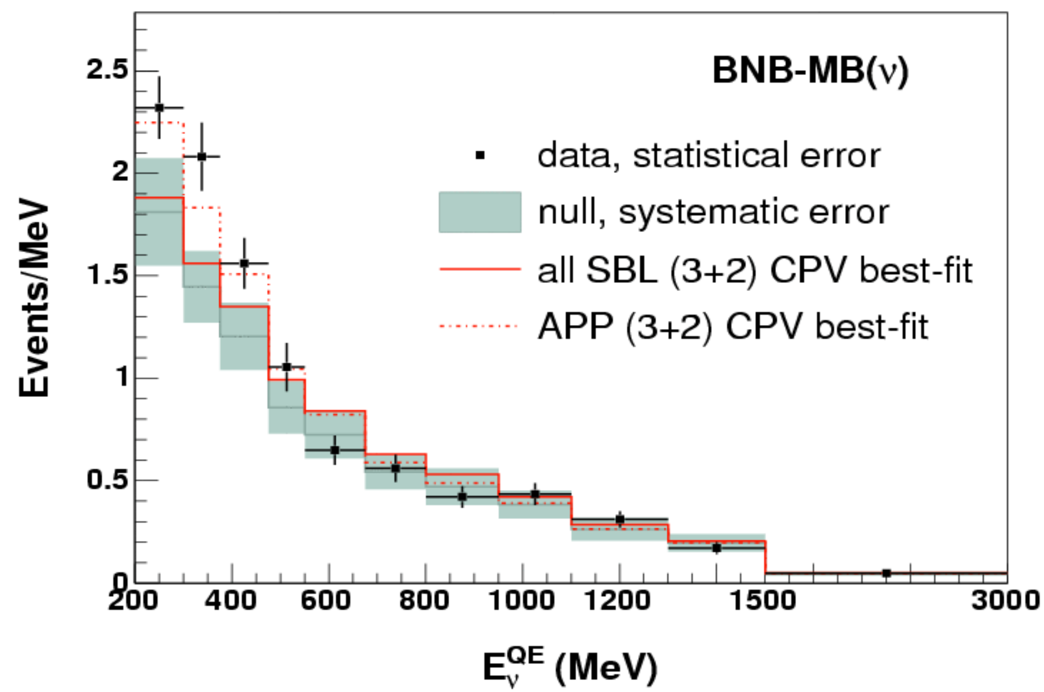


Back-up slides

(3+2) CPV fits

Data Set	Fit	χ^2 (dof)	χ^2-probability	Δm^2_{41}	Δm^2_{51}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 5}\rvert$	ϕ_{45}
signal APP	CPV	34.7(36)	53%	0.59	1.21	0.19	0.33	0.20	0.16	1.1π
signal APP	CPC	46.9(37)	13%	2.01	2.22	0.42	0.24	0.33	0.33	0
APP	CPV	82.5(85)	56%	0.39	1.10	0.40	0.20	0.21	0.14	1.1π
APP	CPC	95.8(86)	22%	0.18	2.31	0.32	0.38	0.086	0.071	0
all SBL	CPV	189.3(192)	54%	0.92	26.5	0.13	0.13	0.078	0.15	1.7π
all SBL	CPC	191.5(193)	52%	0.92	24.0	0.12	0.14	0.070	0.14	0





Quantifying compatibility

"Testing the statistical compatibility of independent data sets",
Maltoni & Schwetz, Phys.Rev. D68 (2003) 033020

$$\chi^2_{PG} = \chi^2_{min,all} - \sum_i \chi^2_{min,i}, \qquad PG = prob(\chi^2_{PG}, ndf_{PG}).$$

A measure of how well preferred parameter regions by different subsets of data overlap

Gives sensible results even in cases where

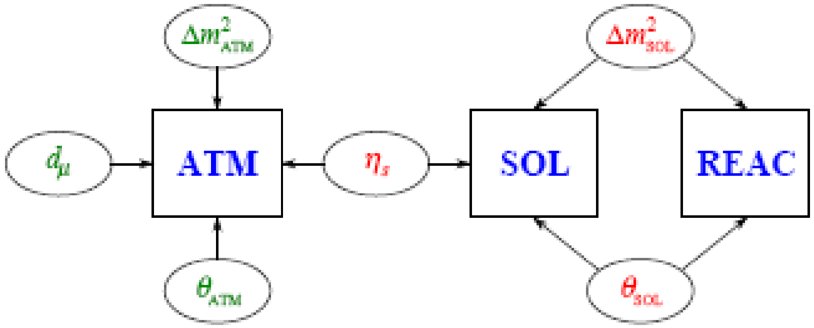
- the **errors** are estimated very **conservatively**
- the total **number of data points is very large**

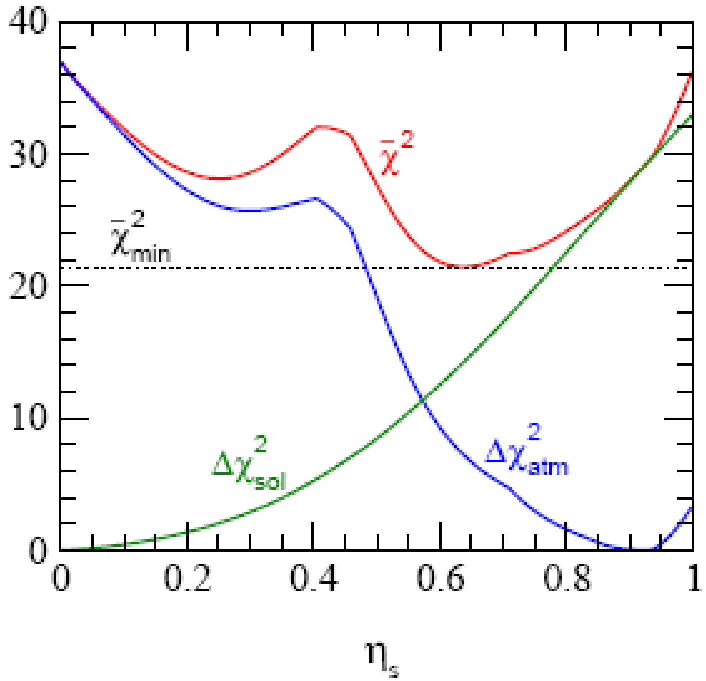
Avoids the problem that a possible disagreement between data sets becomes diluted by **data points which are insensitive** to the prxoblem in the fit

Can also be very useful when a set consisting of a rather small number of data points is combined with a very **large data sample**

Quantifying compatibility

Example from hep-ph/0304176:





data sets	N_{tot}	$\chi^2_{tot,min}$/d.o.f.	SG	$\sum_r P_r$	P	$\bar{\chi}^2_{min}/P_c$	PG
sol + atm	146	126.7/140	78.3%	3+4	6	21.5/1	3.54×10^{-6}
react + sol	108	77.4/105	98.0%	2+3	3	0.13/2	93.5%
react + atm	92	49.9/86	99.9%	2+4	6	0.0/0	–
KamL + sol + atm	159	132.7/153	88.1%	2+3+4	6	21.7/3	7.53×10^{-5}
react + sol + atm	173	138.2/167	95.0%	2+3+4	6	21.7/3	7.53×10^{-5}

Table II: Comparison of SG and PG for various combinations of the data sets from solar, atmospheric and reactor neutrino experiments.

Fit method

Model parameters:

approximate $m_1 = m_2 = m_3 = 0$ *

two independent mass splittings: Δm^2_{41}, Δm^2_{51}

four moduli: $|U_{e4}|$, $|U_{\mu 4}|$, $|U_{e5}|$, $|U_{\mu 5}|$

one CPV phase: $\varphi_{54} = \arg(U^*_{\mu 5} U_{e5} U_{\mu 4} U^*_{e4})$

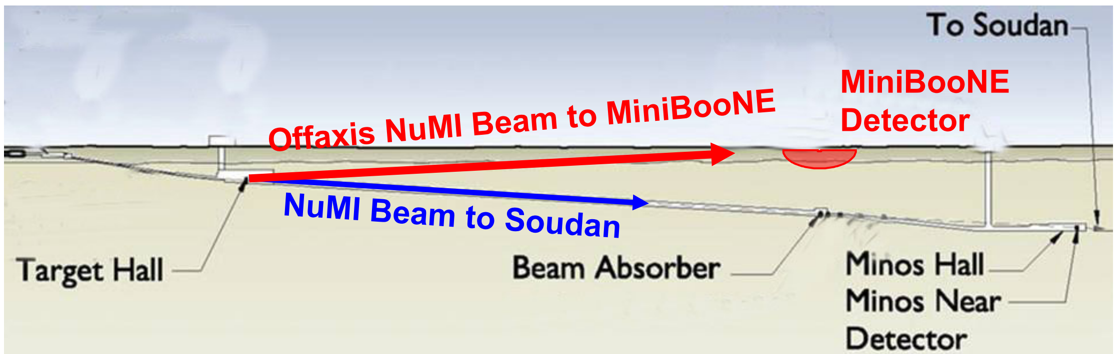
Fit method:

- Generate masses and mixing parameters by importance sampling:
  - $0.01eV^2 \leq \Delta m^2_{41}, \quad \Delta m^2_{51} \leq 100eV^2$

    $\Delta m^2_{51} \geq \Delta m^2_{41}$
  - $|U_{e4}|$, $|U_{\mu 4}|$, $|U_{e5}|$, $|U_{\mu 5}|$
  - *CP violation option: Fix* $\varphi_{54} = 0, \pi$, *or allow to vary within* $(0,2\pi)$
- Minimize $\chi^2 = \Sigma_i \chi^2_i$, i = dataset (LSND, KARMEN, etc…)
- Determine allowed regions by Gaussian approximation, and marginalize (2 dof) over 2 parameters at a time

Markov chain/
Model acceptance probability:
$P(x_i \rightarrow x_{i+1}) = \min\{1, \exp[-(\chi^2_{i+1} - \chi^2_i)/T]\}$
$x_{i+1} = x_i + e$

The NuMI off-axis beam at MiniBooNE



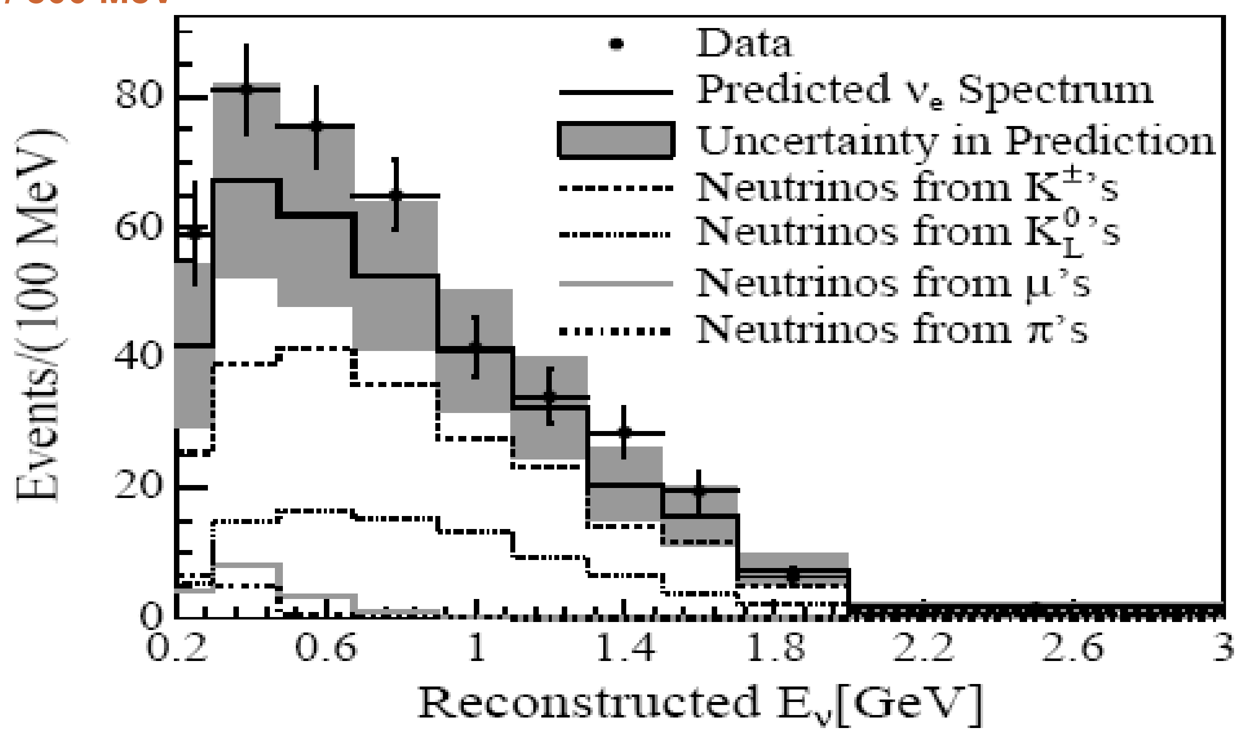
MiniBooNE sees a 1.2 sigma excess from the NuMI beam at 200-900 MeV

Booster Neutrino Beam L/E : ~ 500m / 700MeV
NuMI Off-axis Beam L/E : ~ 700m / 800 MeV

Different background composition and systematics than BNB

Distribution of ν_e events

$(1.42 \times 10^{20}$ POT)



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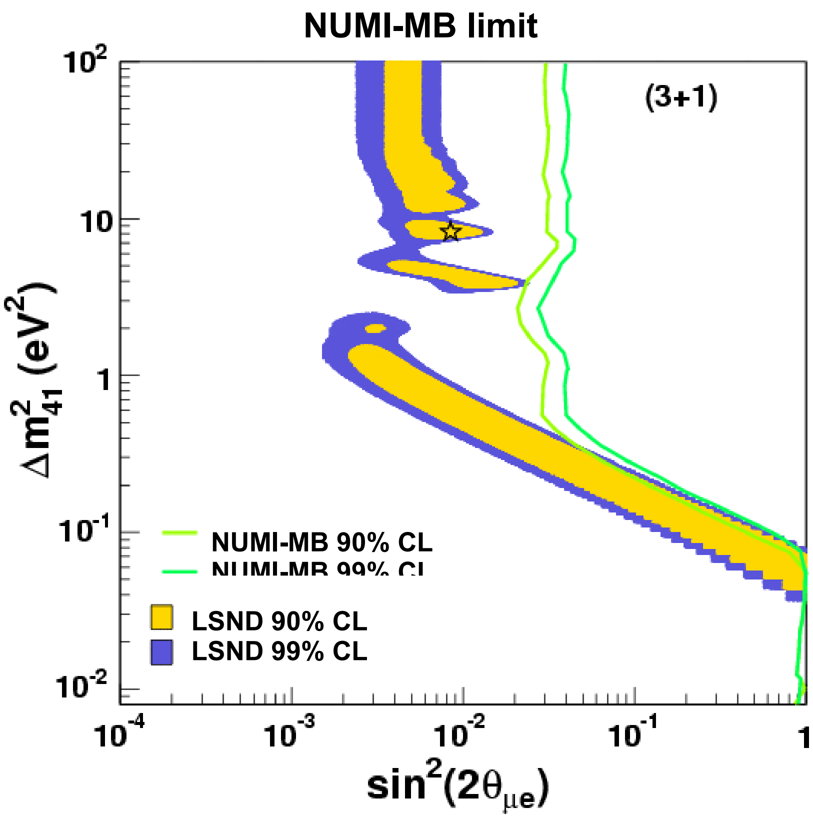

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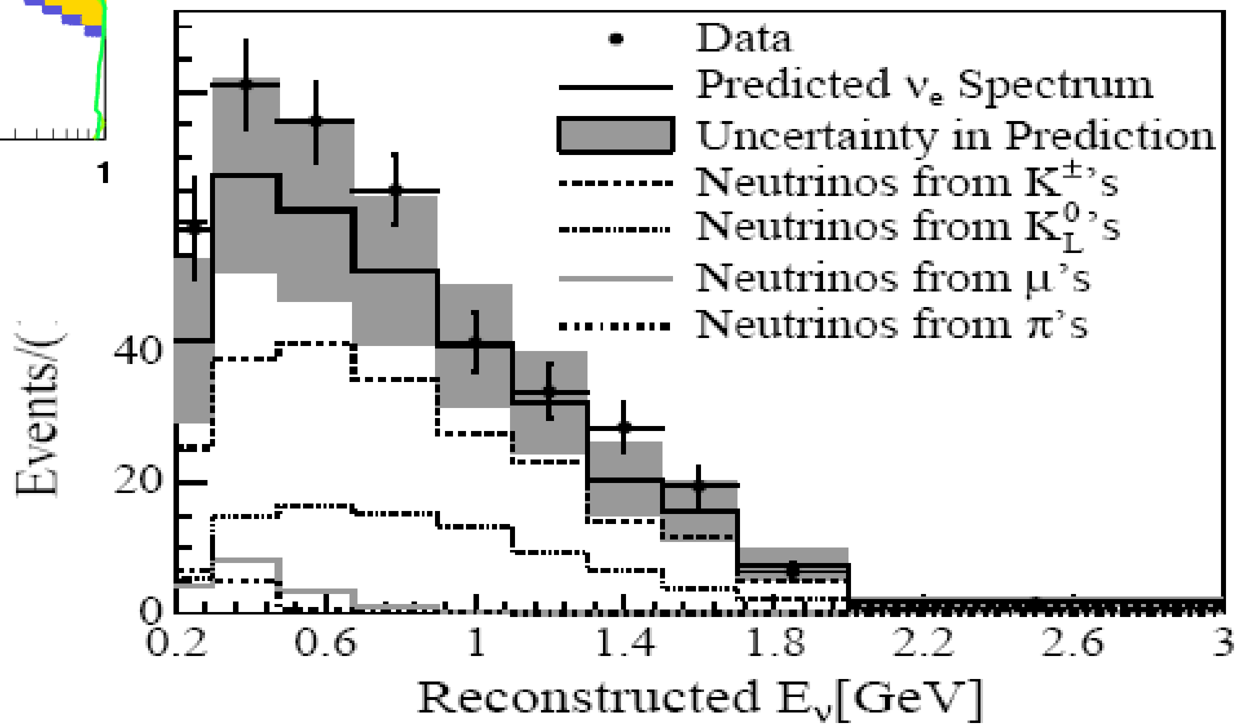


Atmospheric constraints

Super-K and K2K re-analyses by:

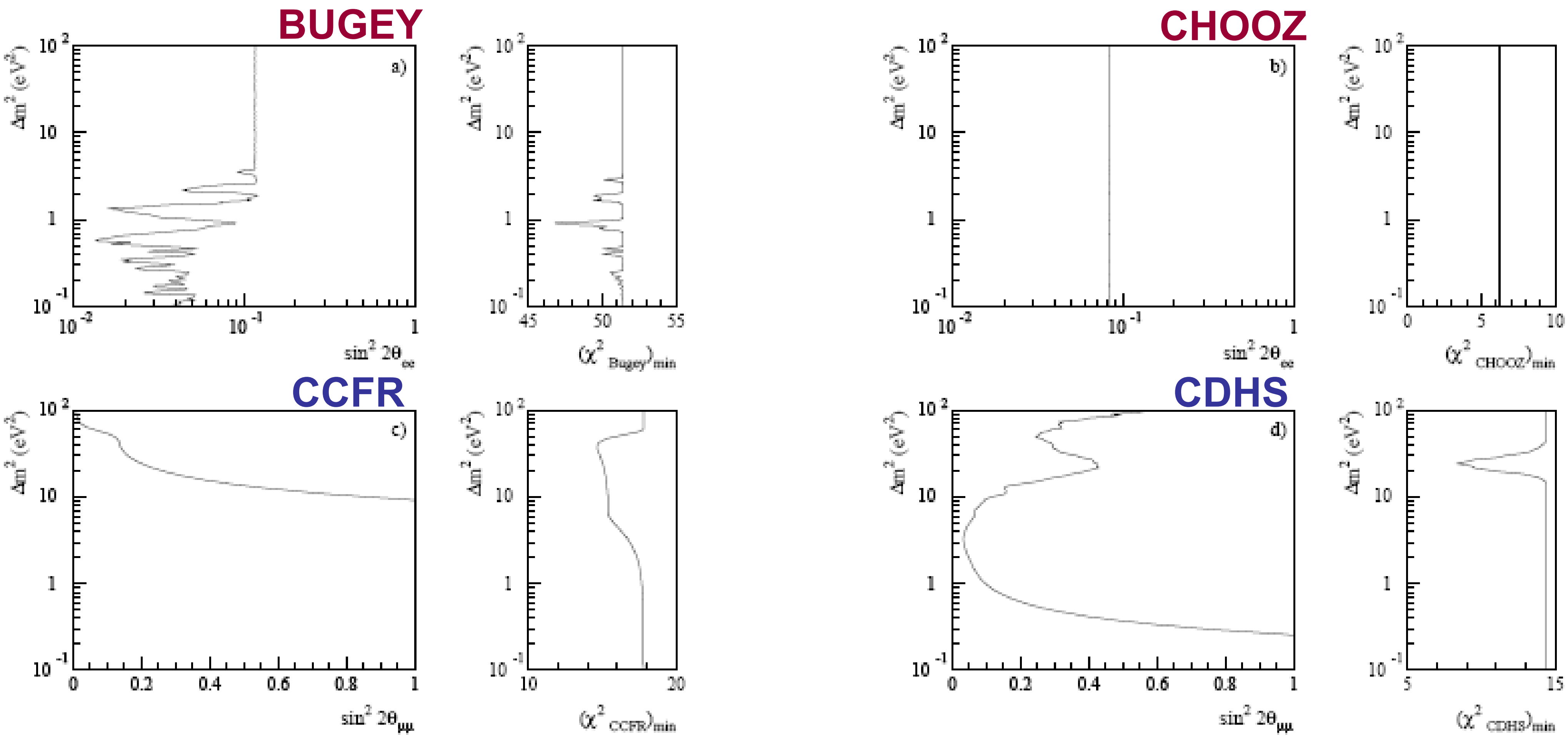
M. Maltoni, T. Schwetz, M. Tortola and J. W. F. Valle, New J. Phys. 6, 122 (2004) [arXiv:hep-ph/0405172]

constrain muon neutrino mixing to additional (beyond three) neutrino mass states

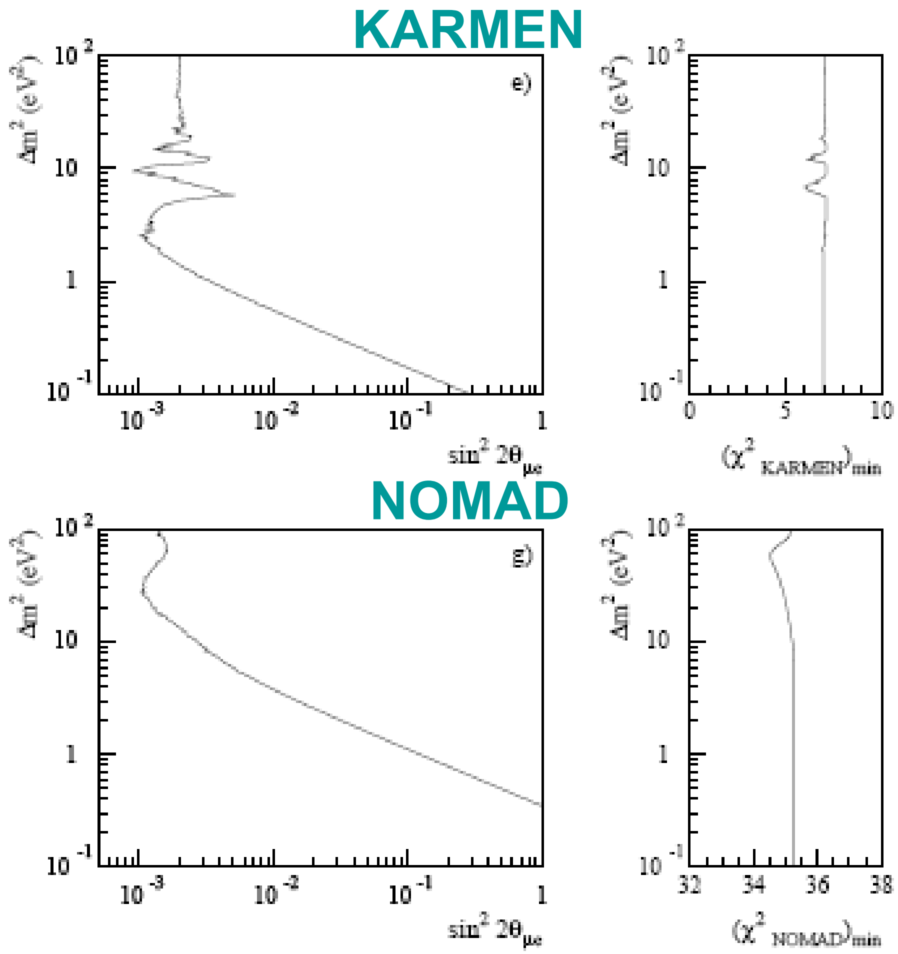
Additional fit parameter: $d_\mu = \frac{1 - \sqrt{1 - 4A}}{2}$

$$A \equiv (1 - |U_{\mu 4}|^2 - |U_{\mu 5}|^2)(|U_{\mu 4}|^2 + |U_{\mu 5}|^2) + |U_{\mu 4}|^2 |U_{\mu 5}|^2$$

+1 degree of freedom to the fit

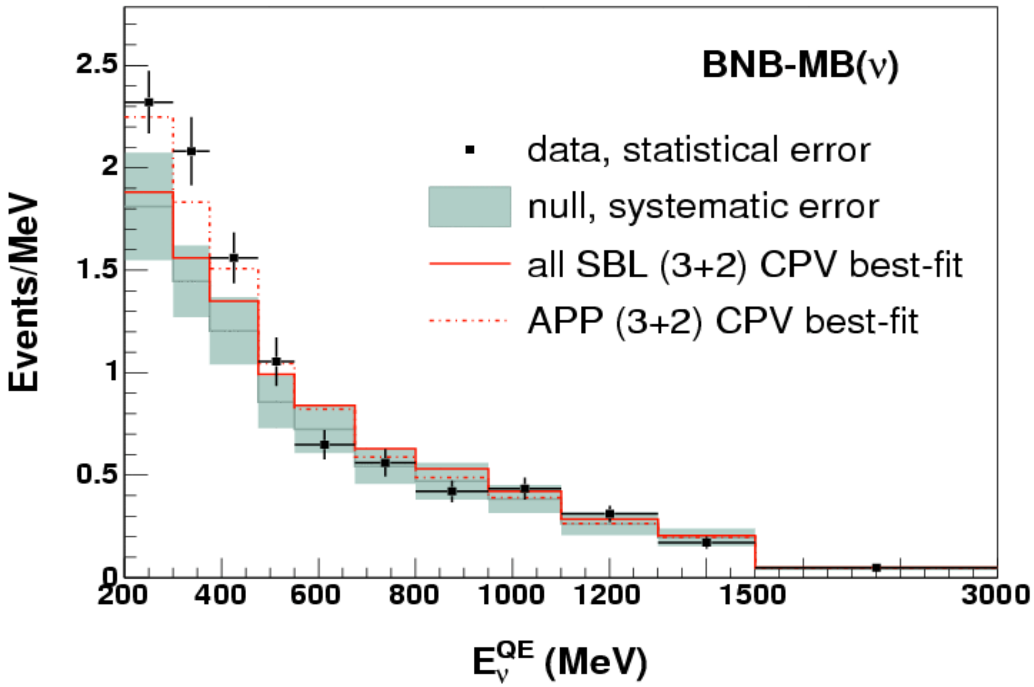


[limits summarized in PRD 70 073004 (2004)]



[limits summarized in PRD 70 073004 (2004)]

(3+2) CPV and MiniBooNE low Energy excess



APP-only (3+2) CPV best-fit is strongly preferred. However...

^{2}	Δm_{51}^2	$\vert U_{e4}\vert$	$\vert U_{\mu 4}\vert$	$\vert U_{e5}\vert$	$\vert U_{\mu 5}\vert$	φ_{45}

Testing APP vs. DIS and neutrino vs. antineutrino compatibility in (3+2) CPV fits

Source of constraints: CDHS, MiniBooNE (ν) and ATM

Data Sets	
ν vs. $\bar{\nu}$	0.06
ν (no BNB-MB(ν) + CDHS + ATM) vs. $\bar{\nu}$	56.5
ν (no BNB-MB(ν) + CDHS) vs. $\bar{\nu}$	3.7
ν (no BNB-MB(ν) + ATM) vs. $\bar{\nu}$	4.4
ν (no BNB-MB(ν)) vs. $\bar{\nu}$	1.1
ν (no CDHS + ATM) vs. $\bar{\nu}$	2.3
ν (no CDHS) vs. $\bar{\nu}$	0.07
ν (no ATM) vs. $\bar{\nu}$	0.21

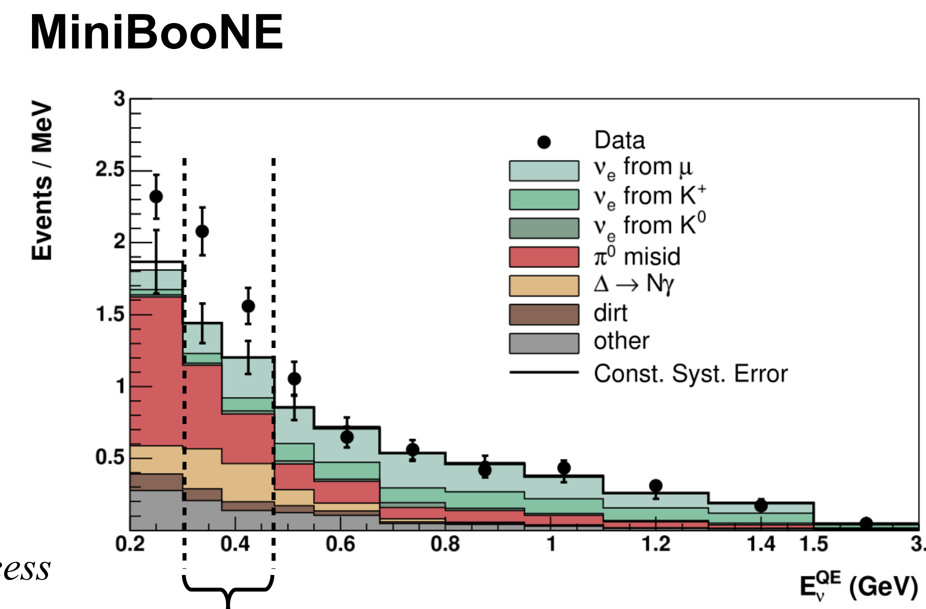
Data Sets	
APP vs. DIS	0.004
APP (no BNB-MB(ν)) vs. DIS (no CDHS + ATM)	23.7
APP (no BNB-MB(ν)) vs. DIS (no CDHS)	0.36
APP (no BNB-MB(ν)) vs. DIS (no ATM)	0.52
APP (no BNB-MB(ν)) vs. DIS	0.067
APP vs. DIS (no CDHS + ATM)	2.9
APP vs. DIS (no CDHS)	0.027
APP vs. DIS (no ATM)	0.019

MiniBooNE low Energy:

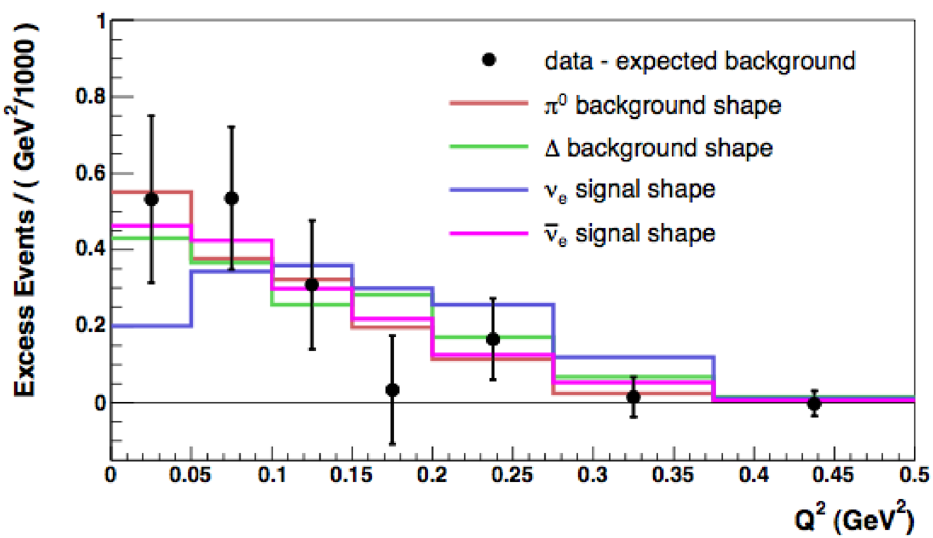
A mis-estimated background?

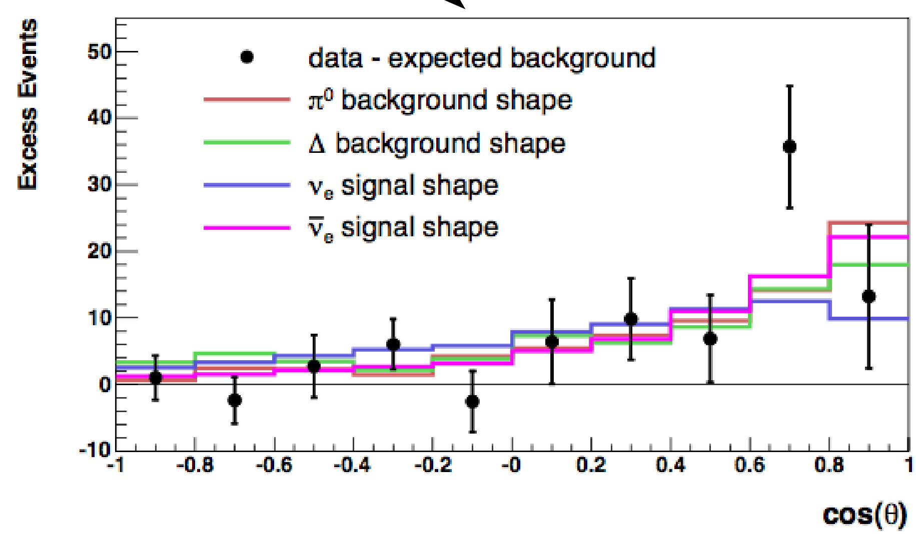
Excess **shape agrees with single-photon Backgrounds** at low energy:

e.g. NC pi0, Delta-->Ngamma



zoom-in at low E excess





Excess vs. background shape comparisons, for events with 300<E<475 MeV

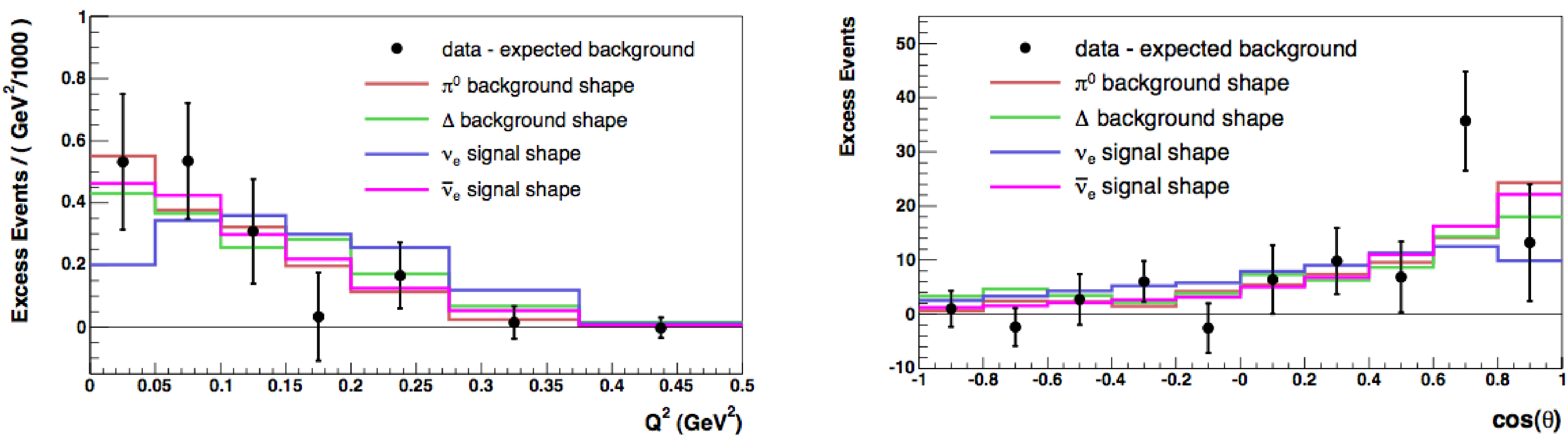
MiniBooNE low Energy:

A mis-estimated background?

Required factor increase >5 sigma larger than allowed by individual background uncertainties!

Perform a shape-only fit for various hypotheses:
[Is the excess kinematically consistent with any known process?]

Process	$\chi^2(cos\theta)/9$ DF	$\chi^2(Q^2)/6$ DF	Factor Increase
NC π^0	13.46	2.18	2.0
$\Delta \rightarrow N\gamma$	16.85	4.46	2.7
$\nu_e C \rightarrow e^- X$	14.58	8.72	2.4
$\bar{\nu}_e C \rightarrow e^+ X$	10.11	2.44	65.4



Excess vs. background shape comparisons, for events with 300<E<475 MeV

MiniBooNE low Energy:

Excess shape also in agrees with **wrong-sign flux interacting as nuebar CCQE**... except with an extremely large probability of interaction (~20%) ?!

Perform a shape-only fit for various hypotheses:

Process	$\chi^2(cos\theta)/9$ DF	$\chi^2(Q^2)/6$ DF	Factor Increase
NC π^0	13.46	2.18	2.0
$\Delta \rightarrow N\gamma$	16.85	4.46	2.7
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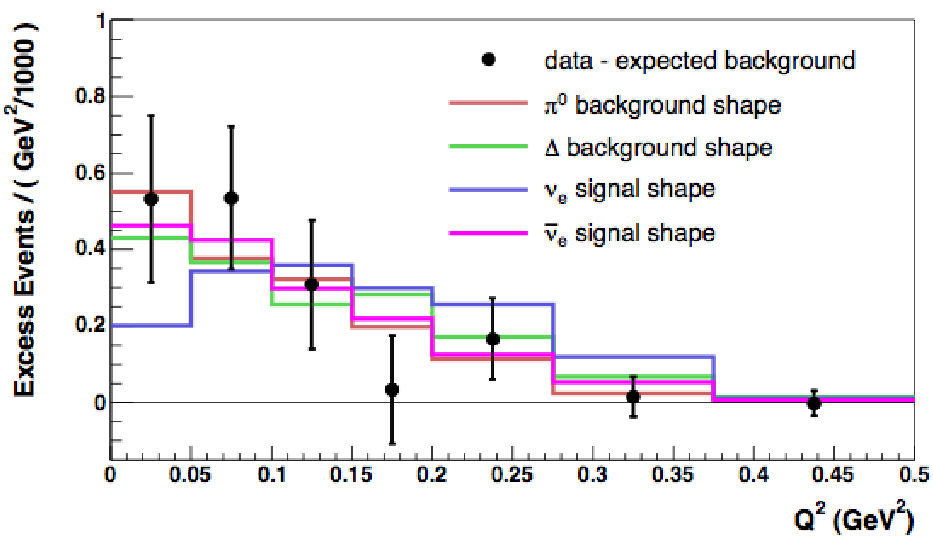
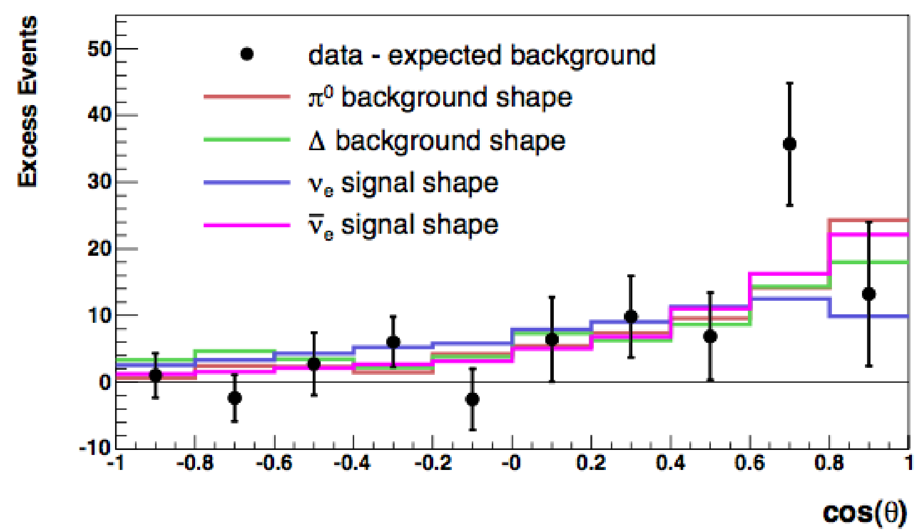
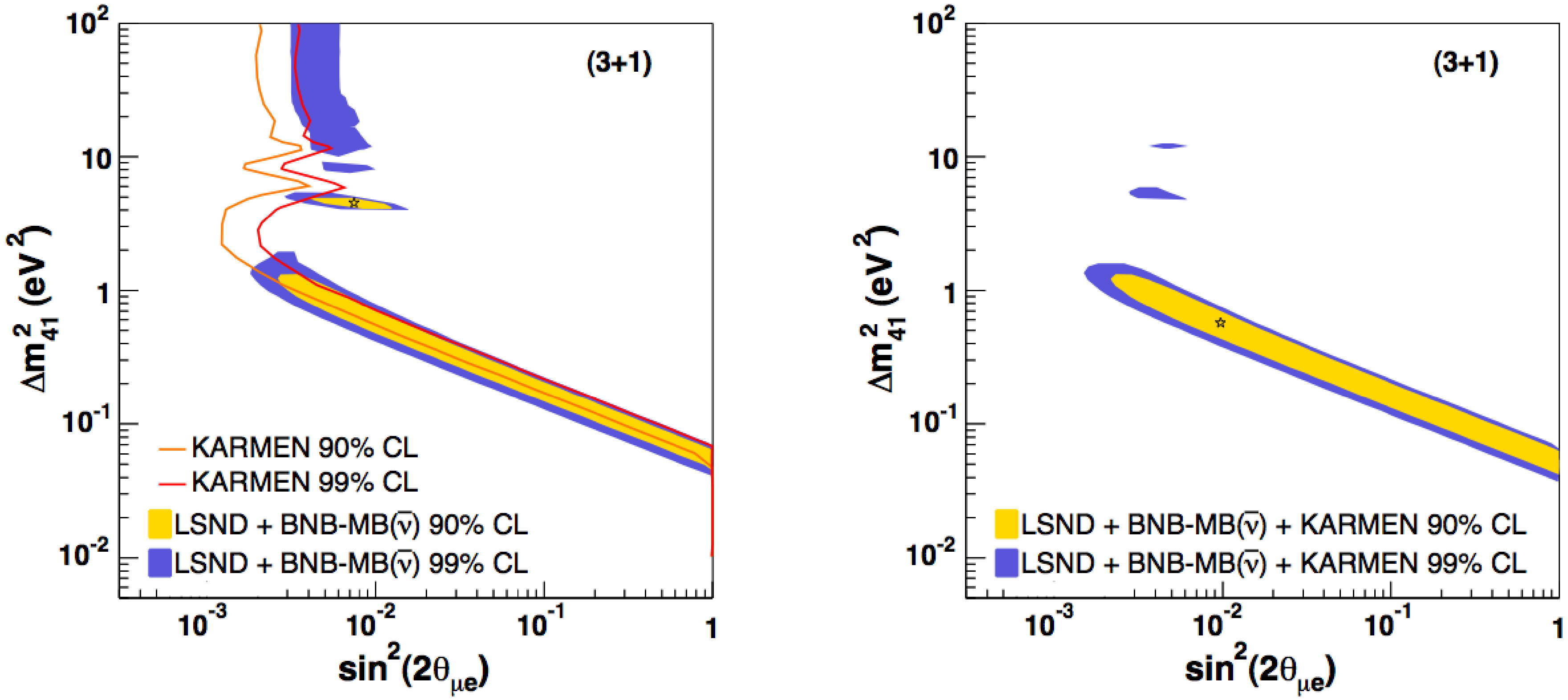


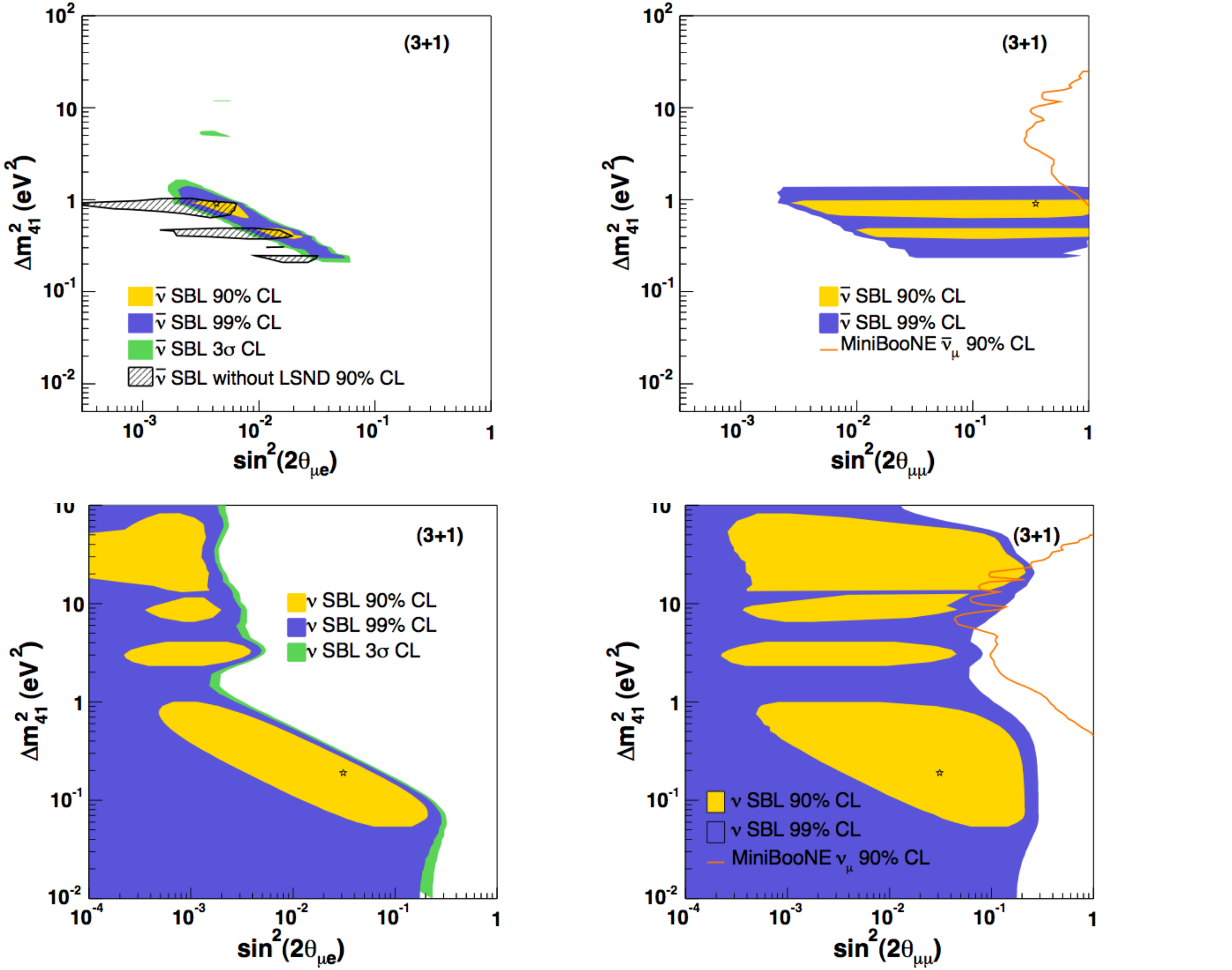


Excess vs. background shape comparisons, for events with 300<E<475 MeV

Constraints from KARMEN

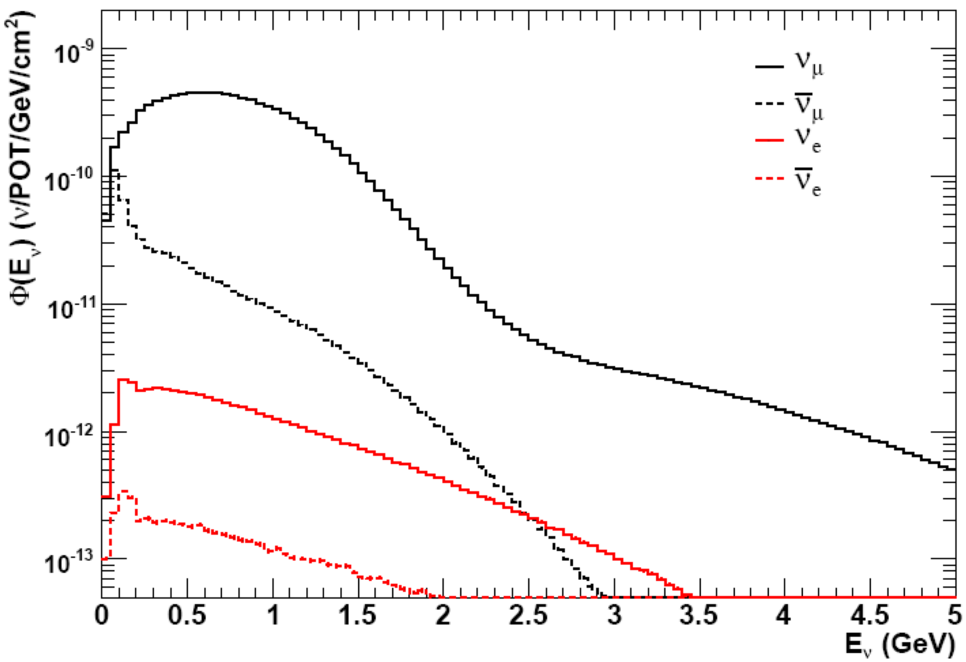


MiniBooNE muon neutrino disappearance constraints



MiniBooNE neutrino vs. antineutrino flux

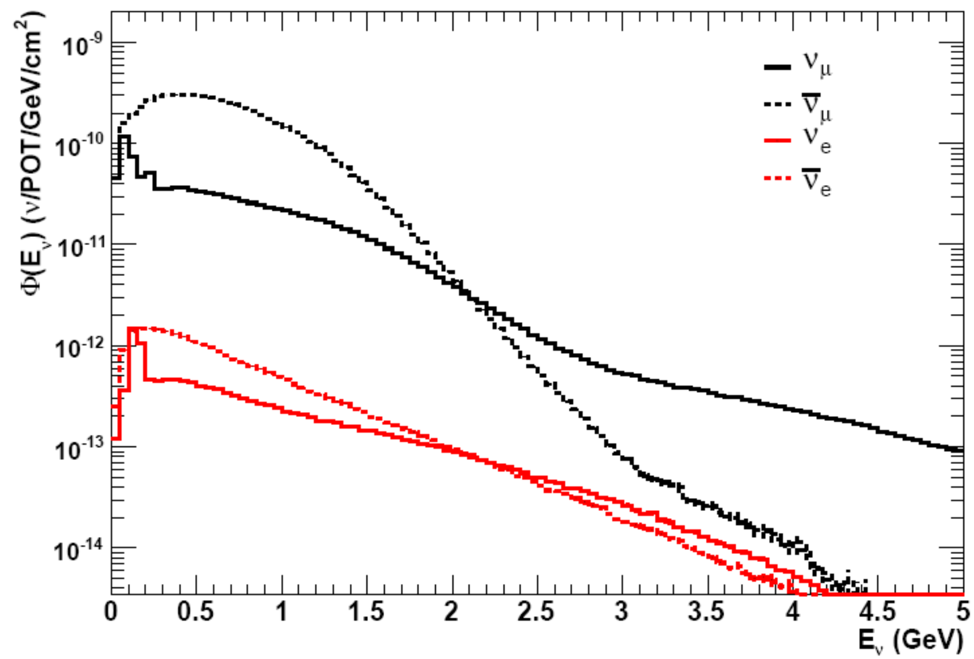
Neutrino mode



>99% pure in muon flavor
~6% wrong-sign (antineutrino) contamination

peaks at ~ 600 MeV

Antineutrino mode



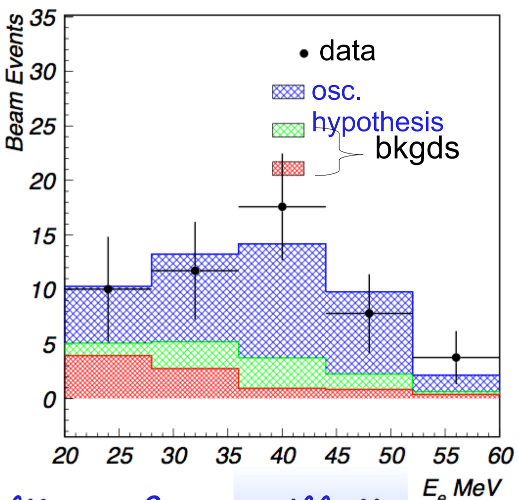
>99% pure in muon flavor
~18% wrong-sign (neutrino) contamination

peaks at ~ 400 MeV

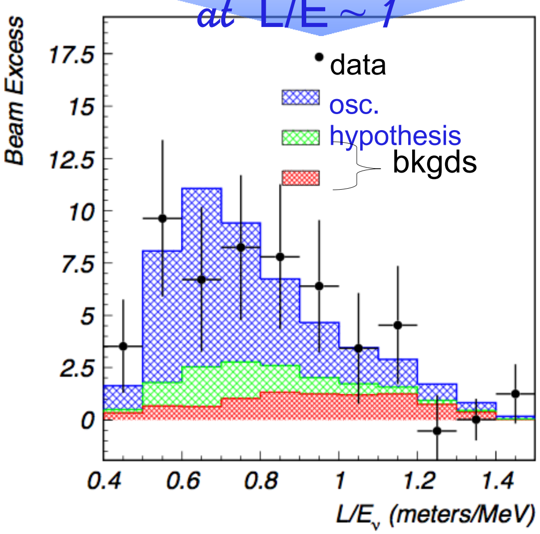
Excess signatures from LSND and MiniBooNE

LSND

3.8 σ excess of $\bar{\nu}_e$
in a $\bar{\nu}_\mu$-dominated beam
from μ^+ decay at rest



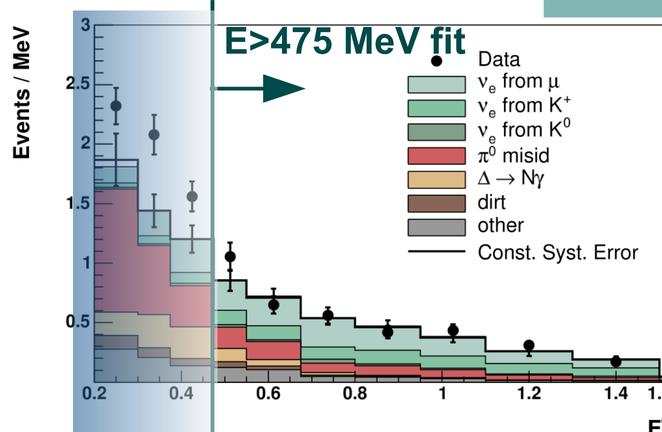
fits a 2-ν oscillation interpretation at L/E ~ 1

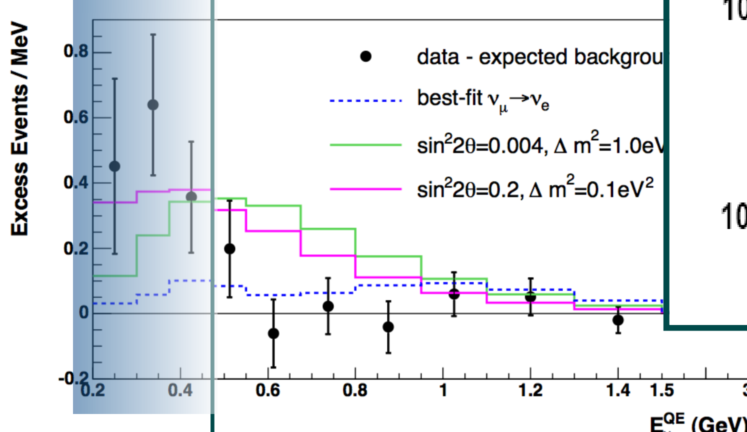


MiniBooNE neutrino mode

3.0 σ excess of ν_e
in a ν_μ-dominated beam
from π^+ decay in flight

In neutrino running, MiniBooNE excludes the LSND 2-ν oscillation interpretation at 98% confidence level.





E>475 MeV fit

and is too sharply peaked at energy to accommodate 2-ν oscillation interpretation