MiniBooNE Oscillation Results

and the

Sterile Neutrino Mystery

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Weak Interactions and Neutrinos 2009 – Perugia, Italy

1. Introduction

- MiniBooNE Experiment
- Sterile Neutrinos

2. MiniBooNE Results

- $\nu_\mu \to \not\nu_\mu$ and $\bar{\nu}_\mu \to \not{\bar{\nu}}_\mu$ Disappearance Results
  [PRL 103, 061802 (2009)]
- $\nu_\mu \to \nu_e$ Appearance Results
  [PRL 102, 101802 (2009); PRL 98, 231801 (2007)]
- $\bar{\nu}_\mu \to \bar{\nu}_e$ Appearance Results
  [PRL 103, 111801 (2009)]
- NuMI Off-Axis ν_e CCQE Results
  [PRL 102, 211801 (2009)]

3. Global fits to Sterile Neutrino Models

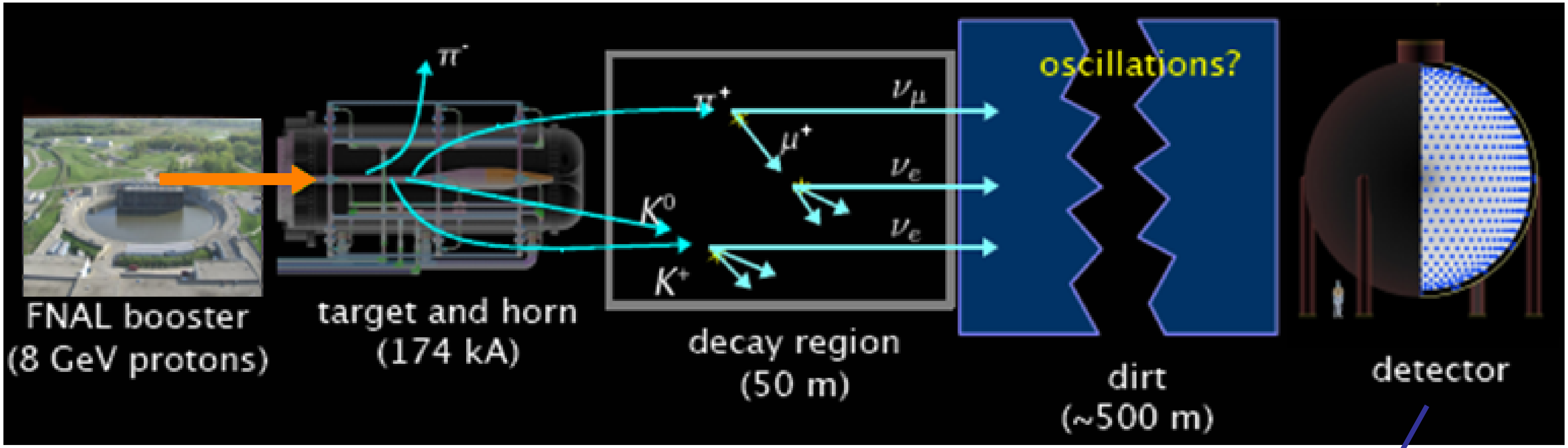
[G.K. *et al*, arXiv:0906.1997, submitted to PRD]

4. Conclusions

1. Introduction: MiniBooNE Experiment

MiniBooNE was designed to study $\nu_\mu \rightarrow \nu_e$ oscillations at $\Delta m^2 \sim 1 eV^2$

Oscillation probability $P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) = \sin^2 2\theta \sin^2(1.27 \Delta m^2[eV^2] L[m]/E[MeV])$

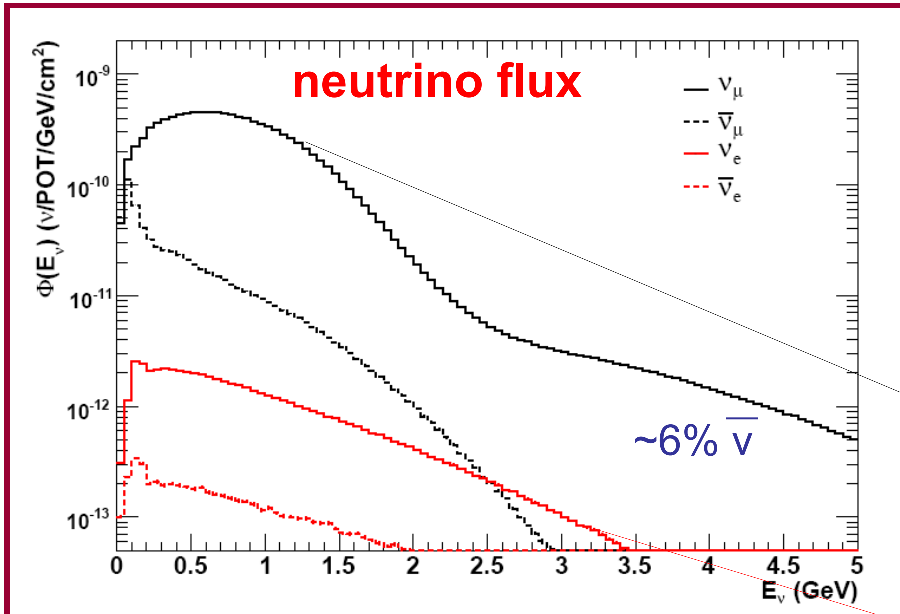


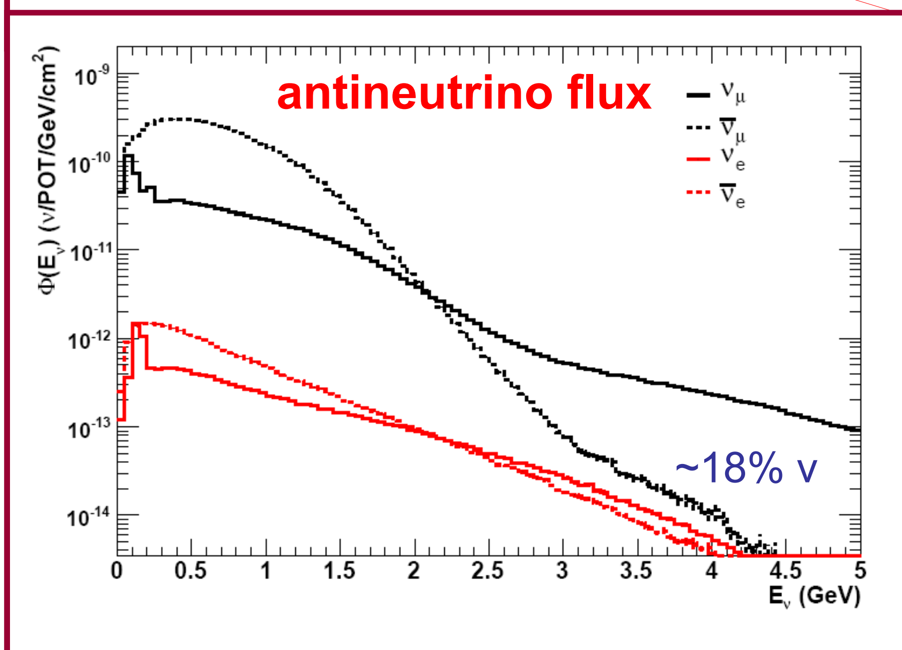
by switching horn polarity, we focus negatively charged mesons, yielding an anti-ν_μ beam

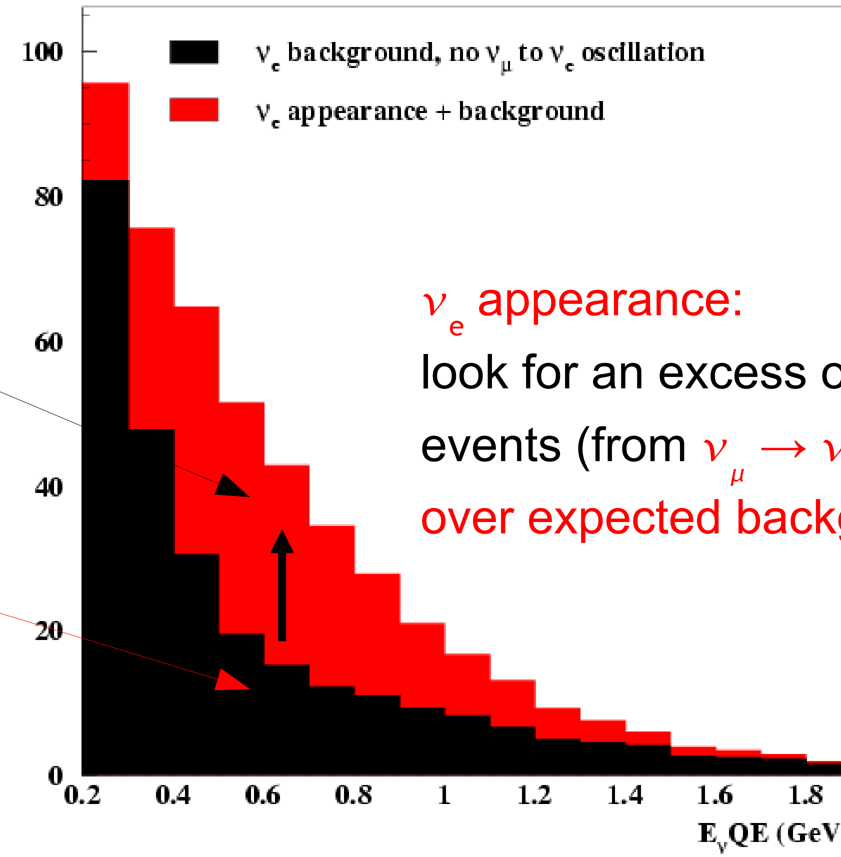
800 ton mineral oil Cherenkov detector
12 m in diameter (450 ton fiducial volume)
lined with 1280 inner PMT's, and 240 outer veto PMT's

NIM A599, 28 (2009)

1. Introduction: MiniBooNE Experiment







ν_e appearance:

look for an excess of ν_e events (from $\nu_\mu \rightarrow \nu_e$) over expected background

Phys. Rev. D. 79, 072002 (2009)

MiniBooNE can look for both $\overset{(-)}{\nu}_e$ **appearance** ($\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ oscillations)

and $\overset{(-)}{\nu}_\mu$ **disappearance** ($\overset{(-)}{\nu}_\mu \rightarrow \not\overset{(-)}{\nu}_\mu$ oscillations)

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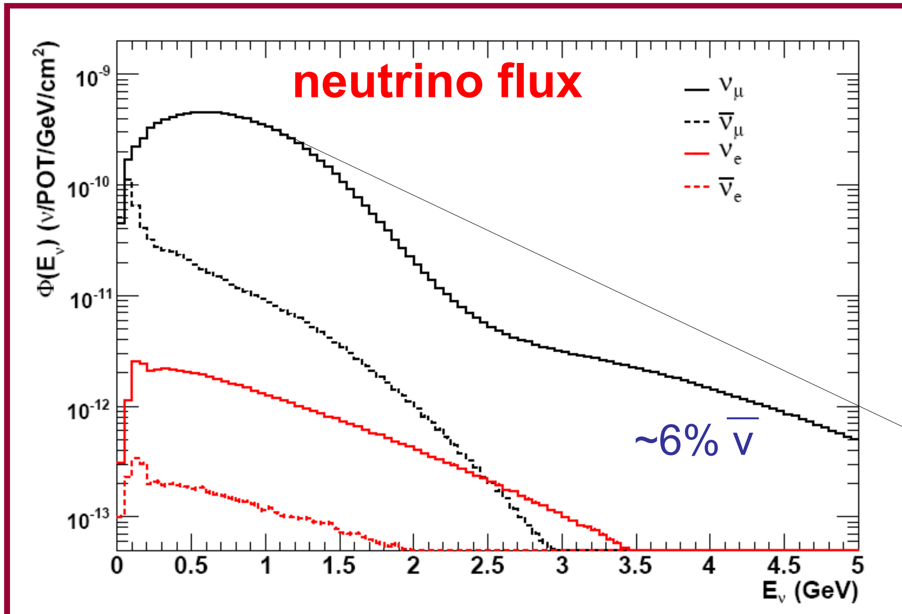
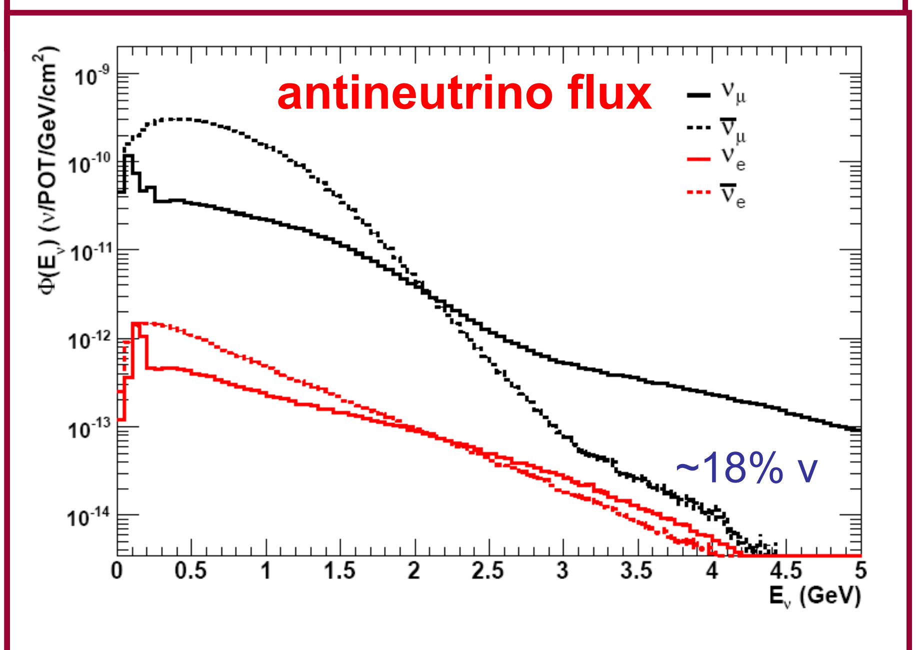
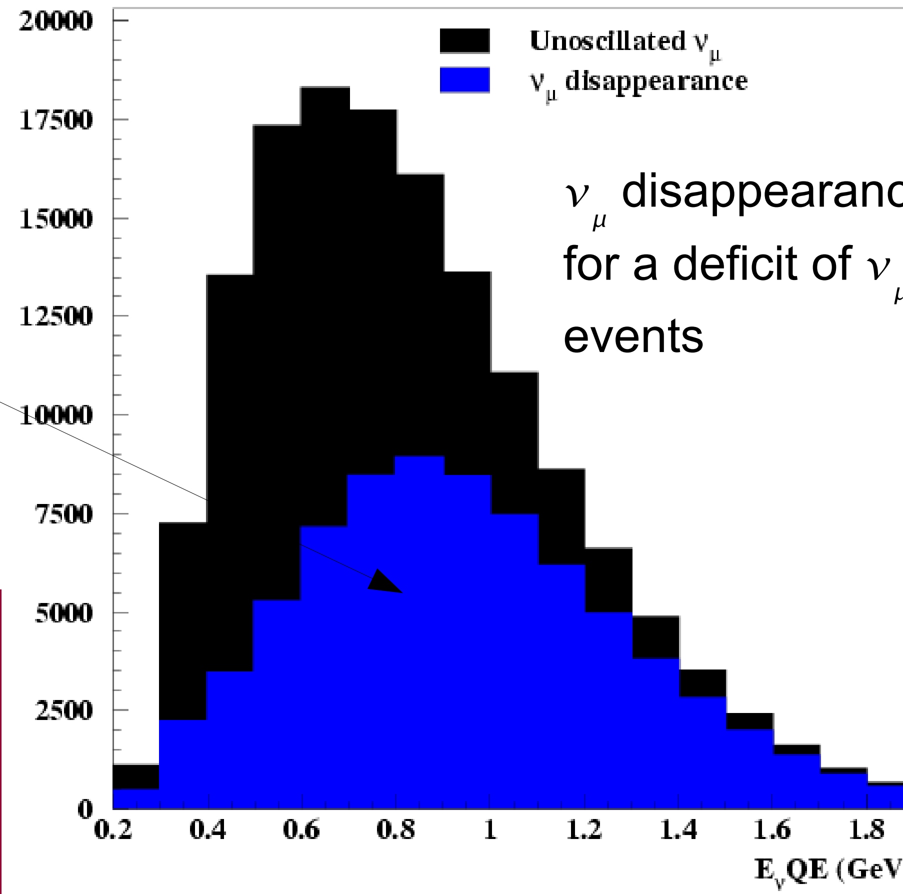






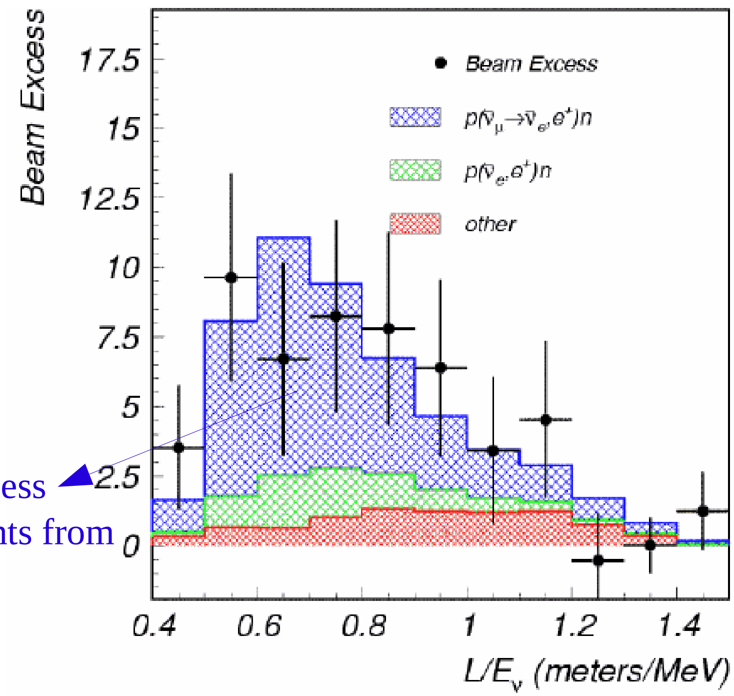
ν_μ disappearance: look for a deficit of ν_μ events

Phys. Rev. D. 79, 072002 (2009)

MiniBooNE can look for both $\overset{(-)}{\nu}_e$ **appearance** ($\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ oscillations) and $\overset{(-)}{\nu}_\mu$ **disappearance** ($\overset{(-)}{\nu}_\mu \not\rightarrow \overset{(-)}{\nu}_\mu$ oscillations)

1. Introduction: Sterile Neutrinos

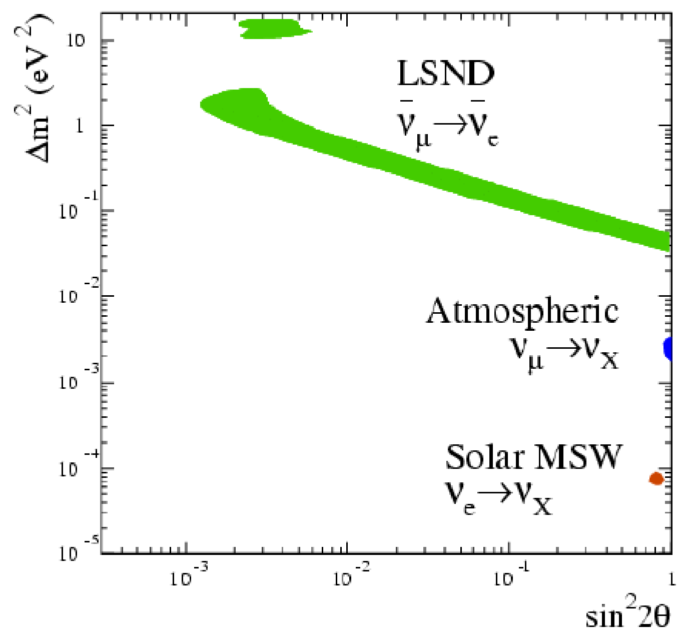
LSND and the [In]Famous Sterile Neutrino...



3.8σ excess of $\bar{\nu}_e$ events from $\bar{\nu}$ beam

interpretation as two-neutrino oscillations

$P(\bar{\nu}_\mu \to \bar{\nu}_e) = \sin^2 2\theta \, \sin^2(\Delta m^2 L/E)$



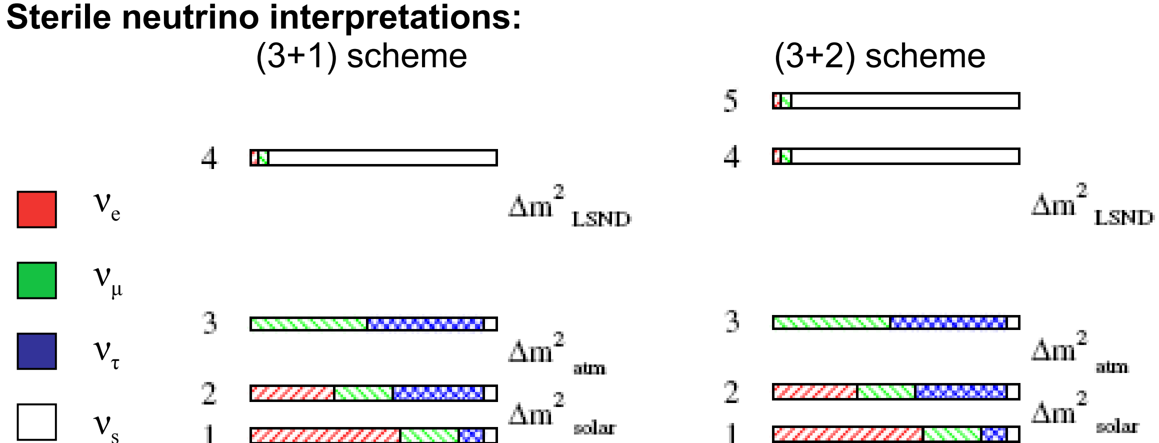
(3+1) possible explanation:

$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \, \sin^2(1.27 \, \Delta m^2 \, L[m]/E[MeV])$

$\sin^2 2\theta = 4 |U_{e4}|^2 |U_{\mu 4}|^2$, **$\Delta m^2 = \Delta m^2_{41}$**

(equivalent to two-neutrino approximation)

Sterile neutrino interpretations:



1. Introduction: Sterile Neutrinos

Other experimental constraints to these models:

experiment	result	search (channel)	constrains	
LSND	signal	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$U_{e4}U_{\mu4}$	APPEARANCE
KARMEN	null	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$U_{e4}U_{\mu4}$	
NOMAD	null	$\nu_\mu \rightarrow \nu_e$	$U_{e4}U_{\mu4}$	
Bugey	null	$\bar{\nu}_e$ disappearance	U_{e4}	ν_e DISAPPEARANCE
CHOOZ	null	$\bar{\nu}_e$ disappearance	U_{e4}	
CCFR	null	ν_μ disappearance	$U_{\mu4}$	ν_μ DISAPPEARANCE
CDHS	null	ν_μ disappearance	$U_{\mu4}$	
atm constraints	null	ν_μ disappearance	$U_{\mu4}$	

Null short-baseline (SBL) experiments and LSND are **incompatible under two-neutrino oscillations** (3+1).

However, models with **more than one sterile neutrino** are more promising:
"*All experiments are compatible at 2.1%*" [Sorel, *et al*. PRD 70 073004 (2004)]

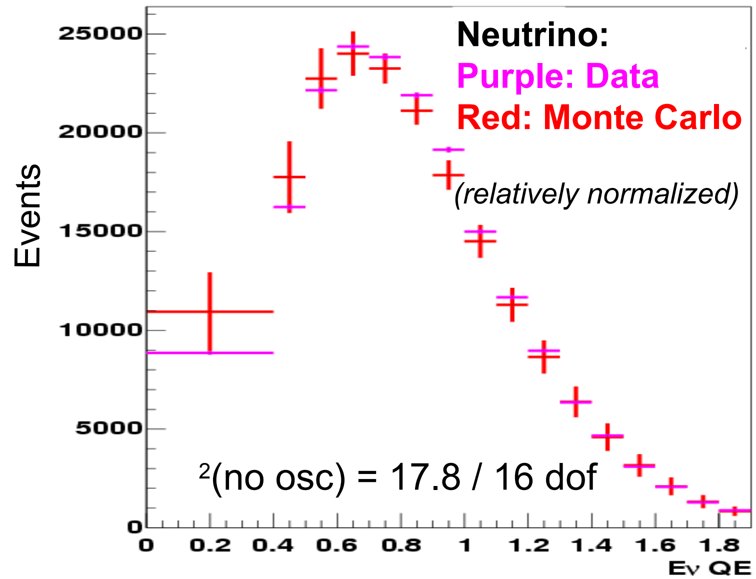
(3+2) model: effectively a three-neutrino oscillation analysis
→ room for observable (Dirac) CP violation

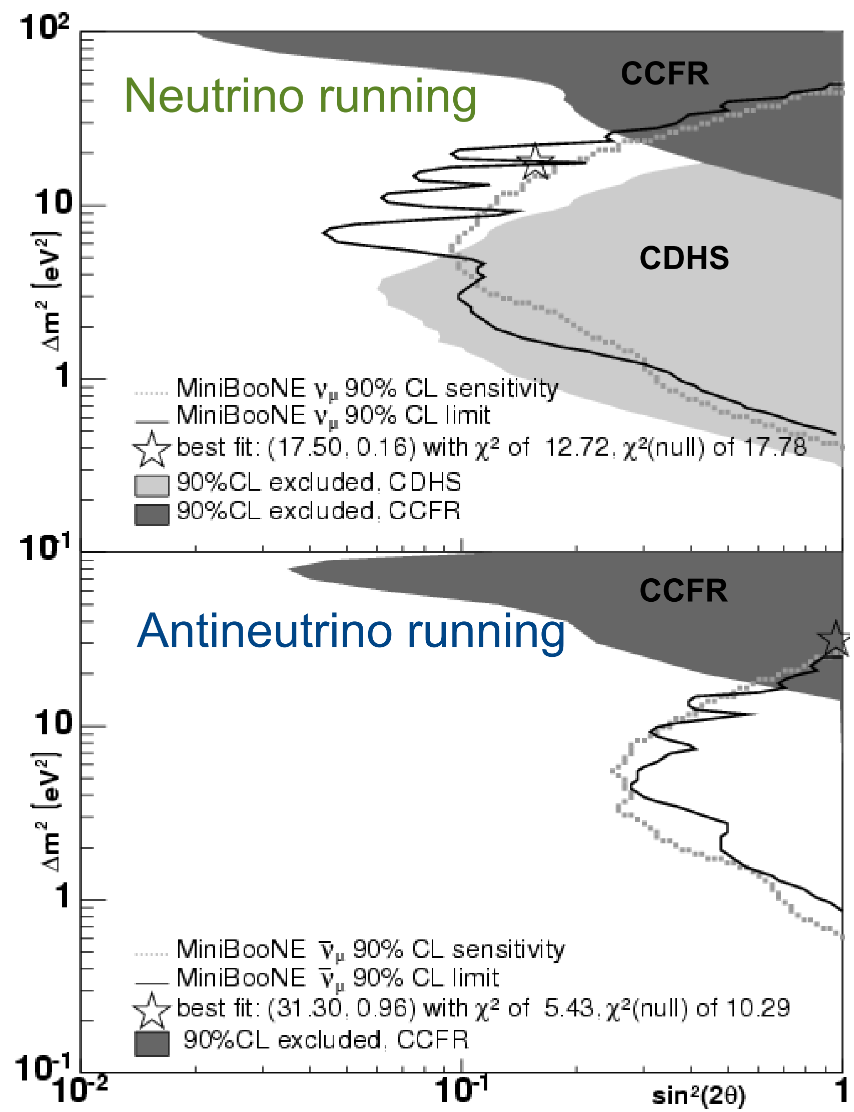
What Did MiniBooNE See?

2. MiniBooNE Results: $\nu_\mu \rightarrow \not\nu_\mu$ and $\bar{\nu}_\mu \rightarrow \not\bar{\nu}_\mu$ Disappearance Results

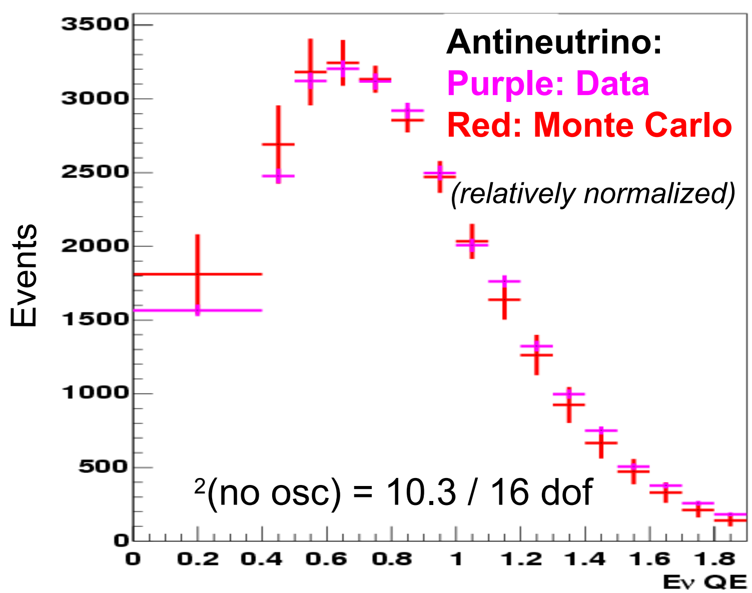
Neutrino running provides a high-statistics, pure ν_μ beam.

The analysis is dominated by systematic flux and cross-section uncertainties → perform a shape-only fit.





The antineutrino disappearance search uses a **smaller data sample** (POT, flux, cross section differences).

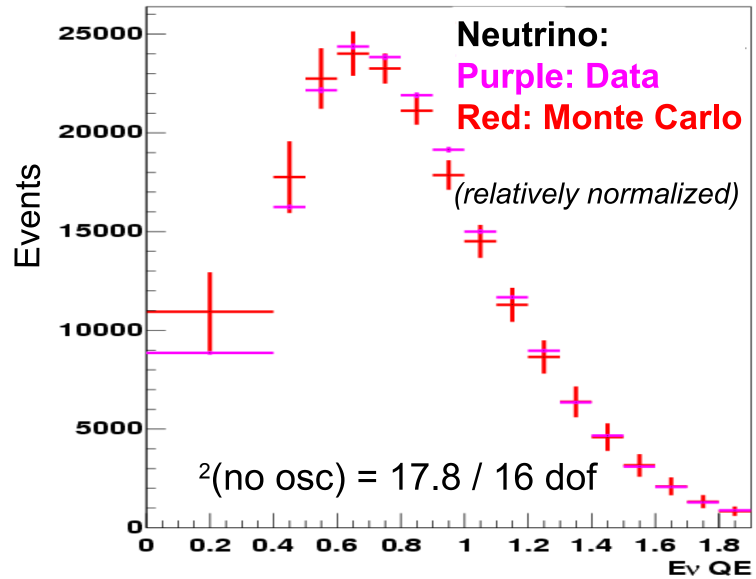


2. MiniBooNE Results: $\nu_\mu \rightarrow \not\nu_\mu$ and $\bar{\nu}_\mu \rightarrow \not\bar{\nu}_\mu$ Disappearance Results

Neutrino running provides a high-statistics, pure ν_μ beam.

MiniBooNE sees no ν_μ or $\bar{\nu}_\mu$ disappearance at 90% CL

The analysis is dominated by systematic flux and cross-section uncertainties → perform a shape-only fit.



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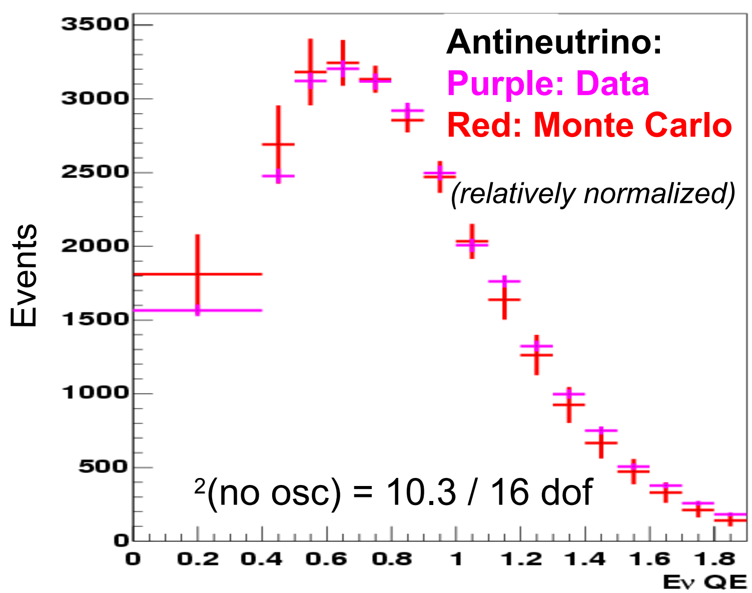
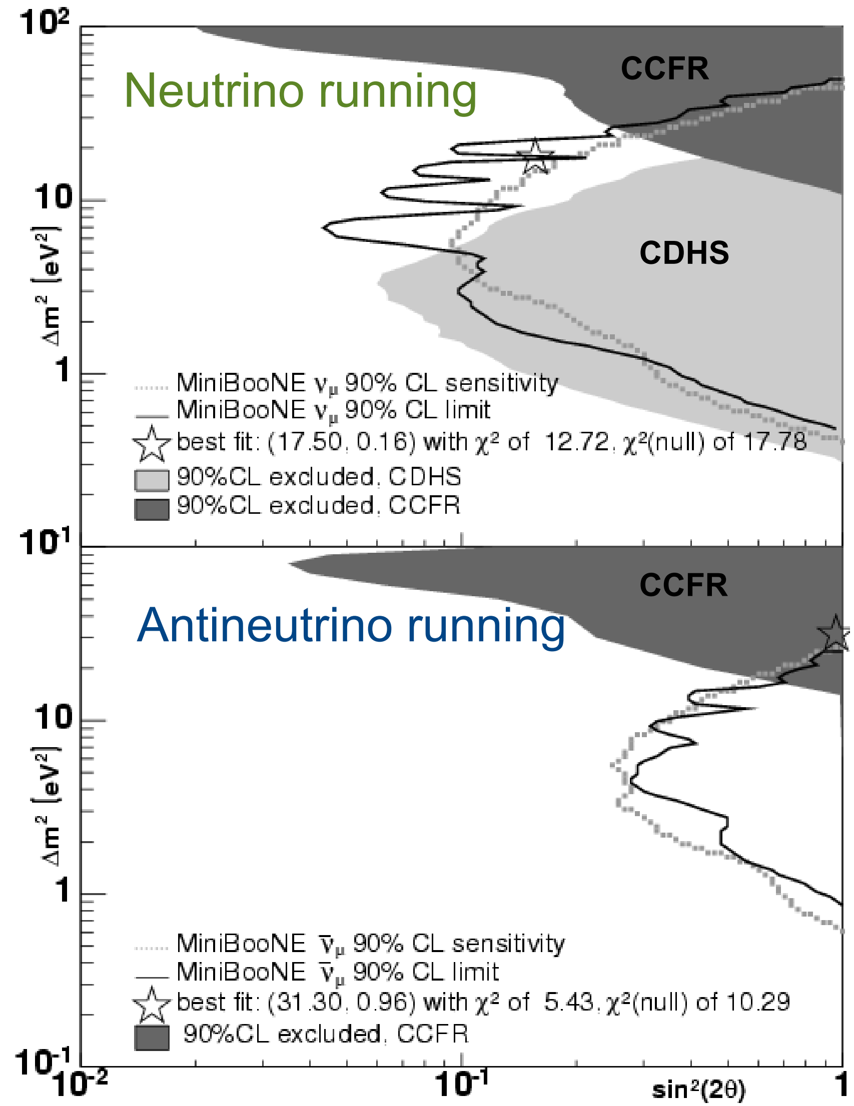
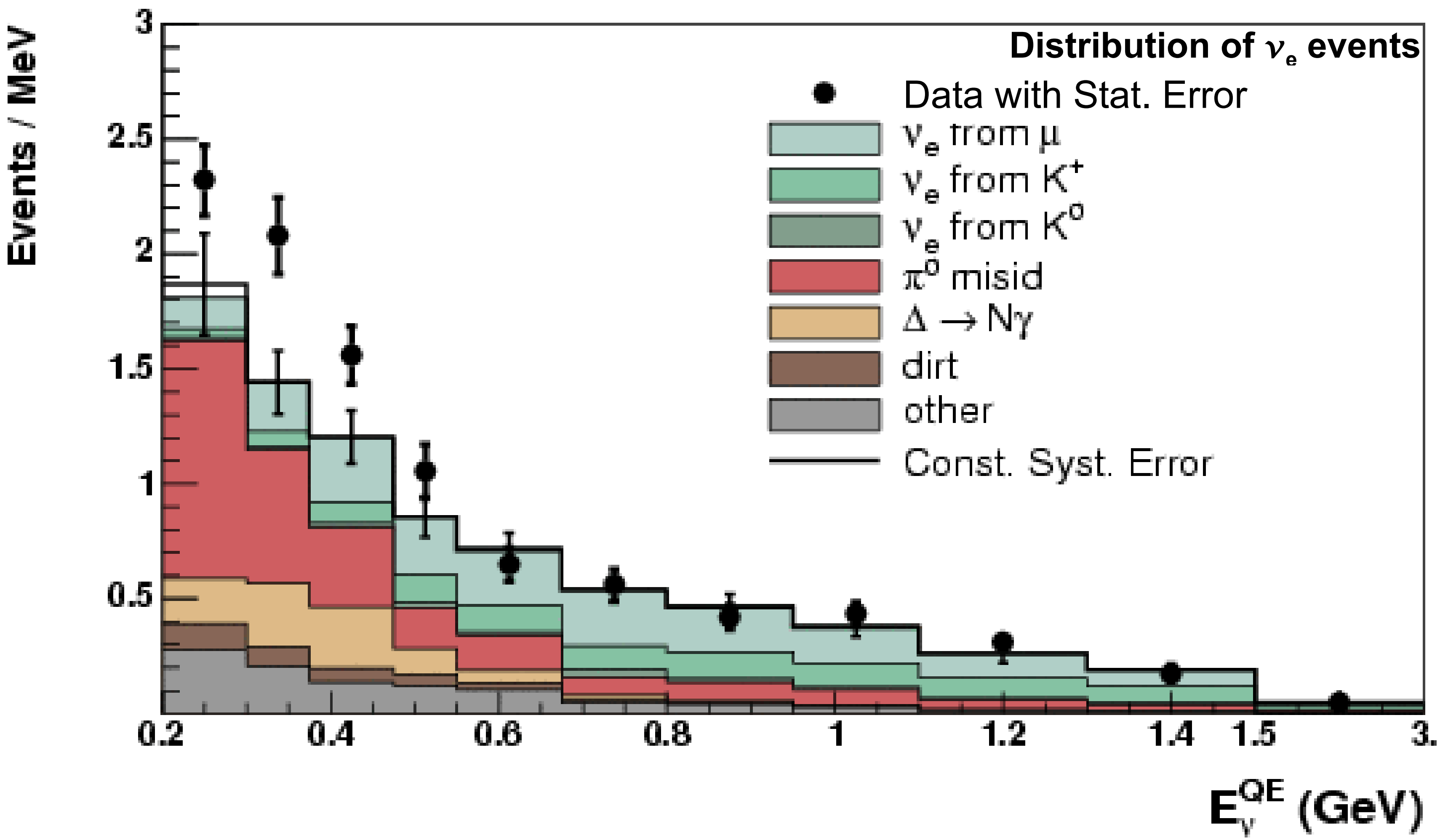




See talk by Y. Nakajima

2. MiniBooNE Results: $\nu_\mu \to \nu_e$ Appearance Results

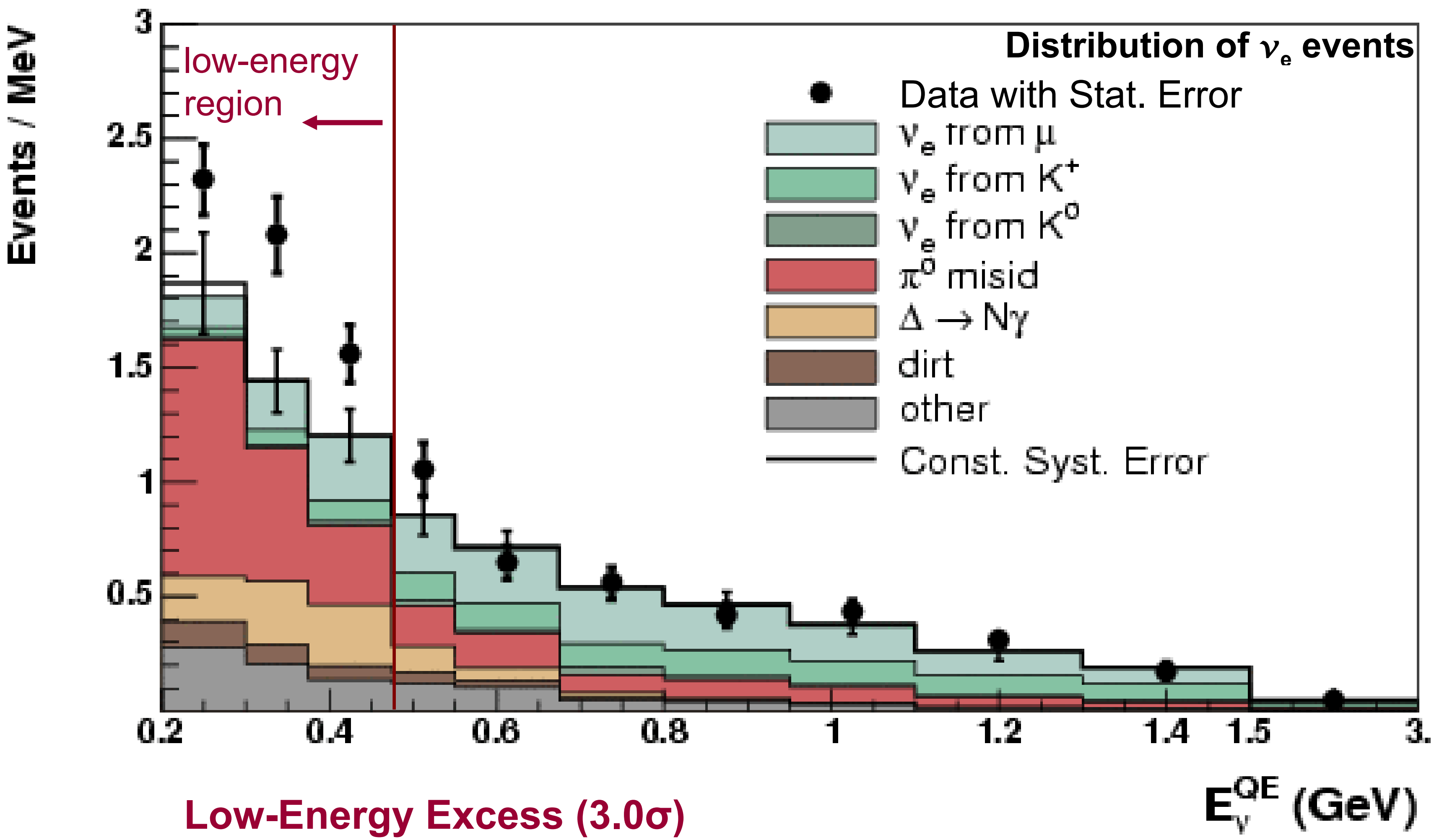


Dataset corresponds to 6.46×10^{20} protons on target

Phys. Rev. Lett. 98, 231801 (2007);
Phys. Rev. Lett. 102, 101802 (2009)

2. MiniBooNE Results: $\nu_\mu \rightarrow \nu_e$ Appearance Results

MiniBooNE sees an excess of ν_e events at low energy



Low-Energy Excess (3.0σ)

Dataset corresponds to 6.46×10^{20} protons on target

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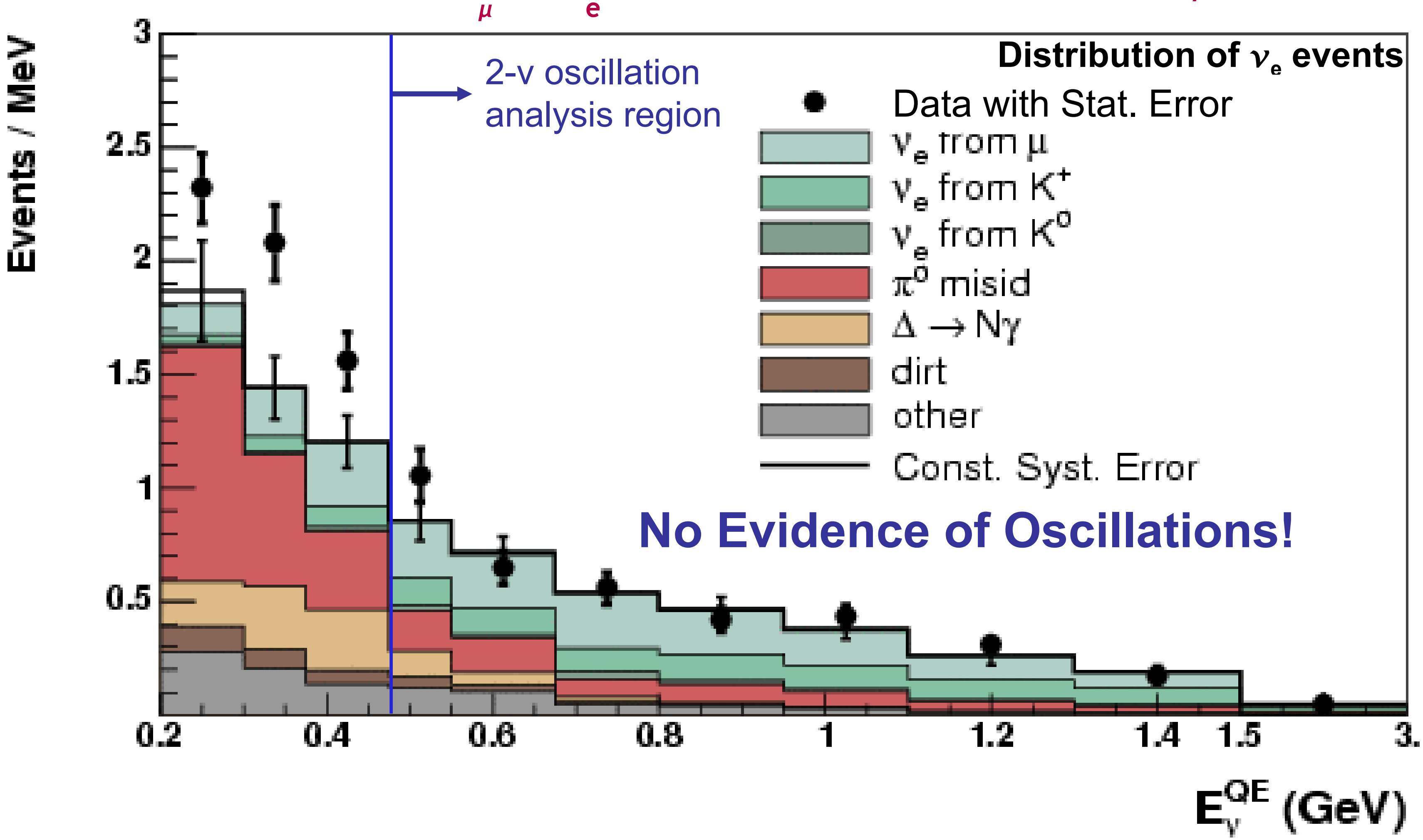
MiniBooNE sees an excess of ν_e events at low energy

But no $\nu_\mu \rightarrow \nu_e$ oscillations at the LSND L/E



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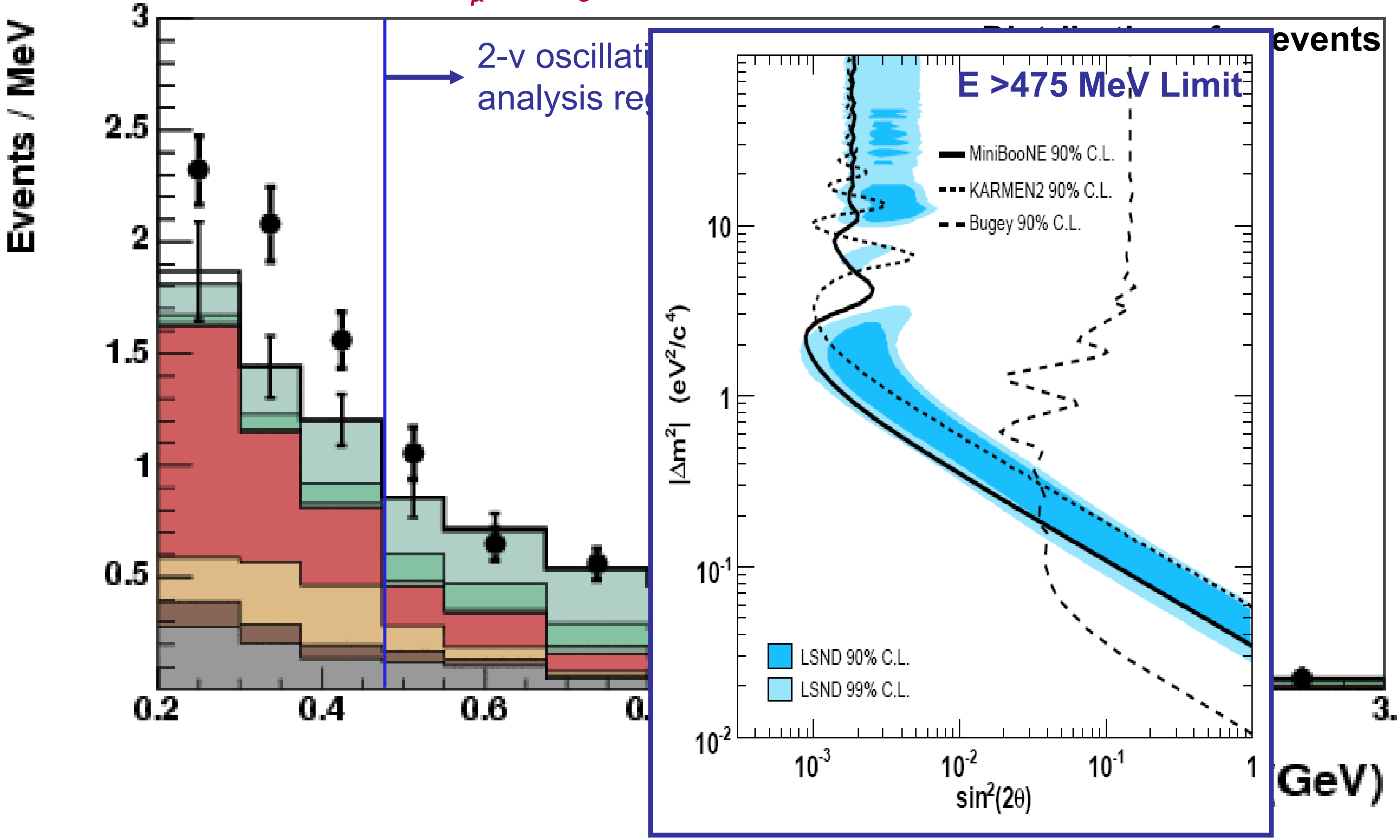

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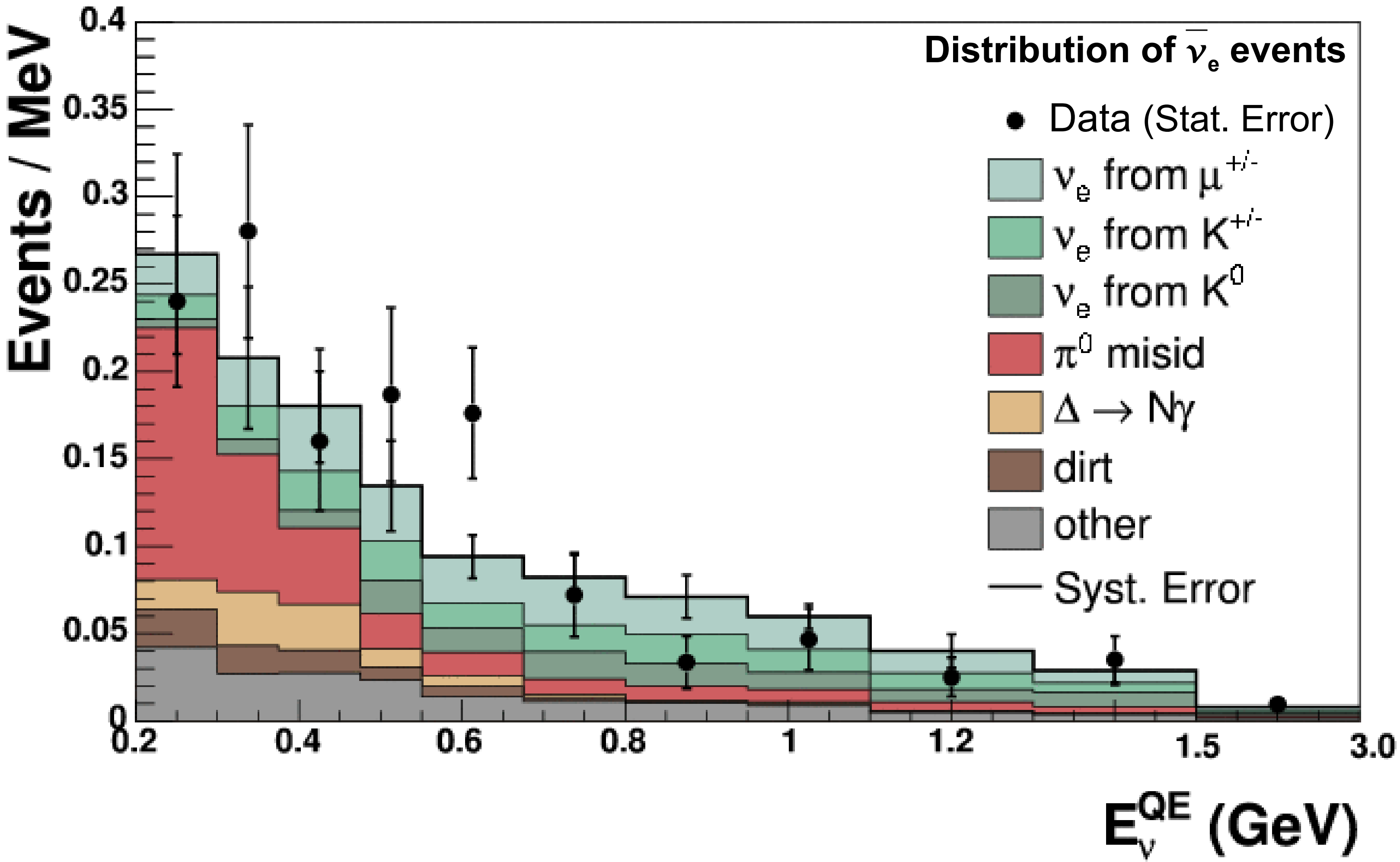
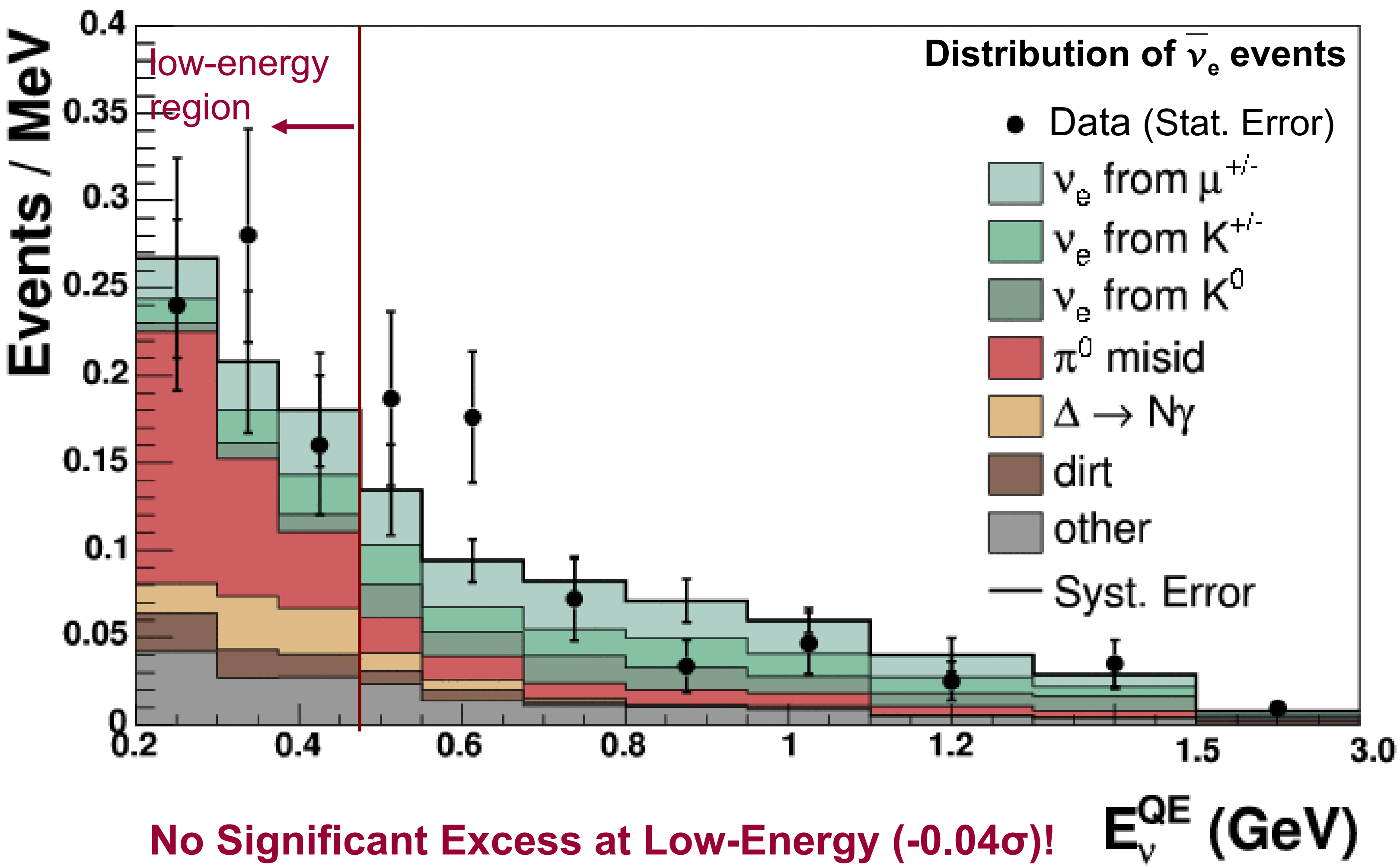


Dataset corresponds to 3.39×10^{20} protons on target

2. MiniBooNE Results: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Appearance Results

MiniBooNE sees no significant excess at low energy



No Significant Excess at Low-Energy (-0.04σ)!

Dataset corresponds to 3.39×10^{20} protons on target

PRL 103, 111801 (2009)

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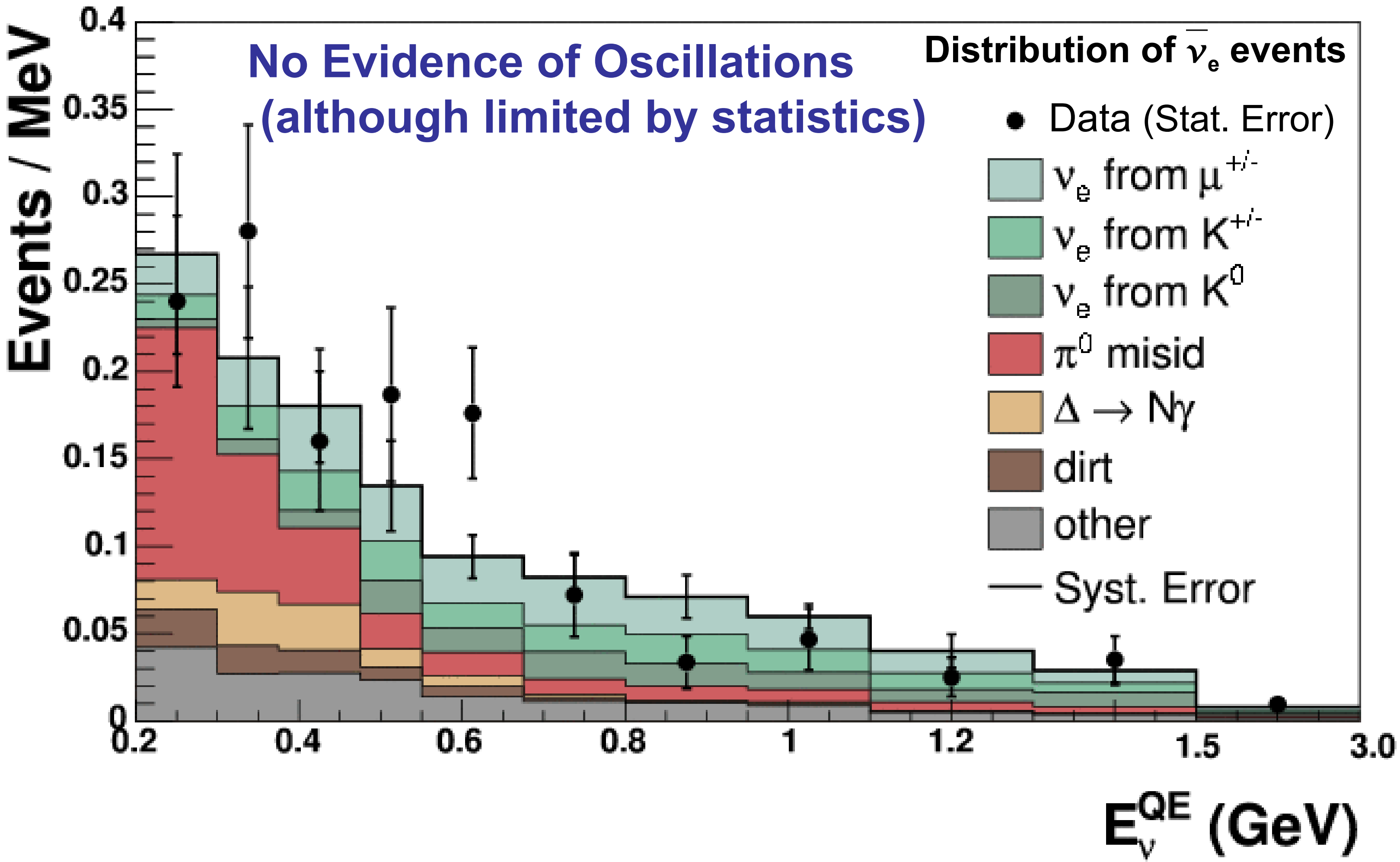

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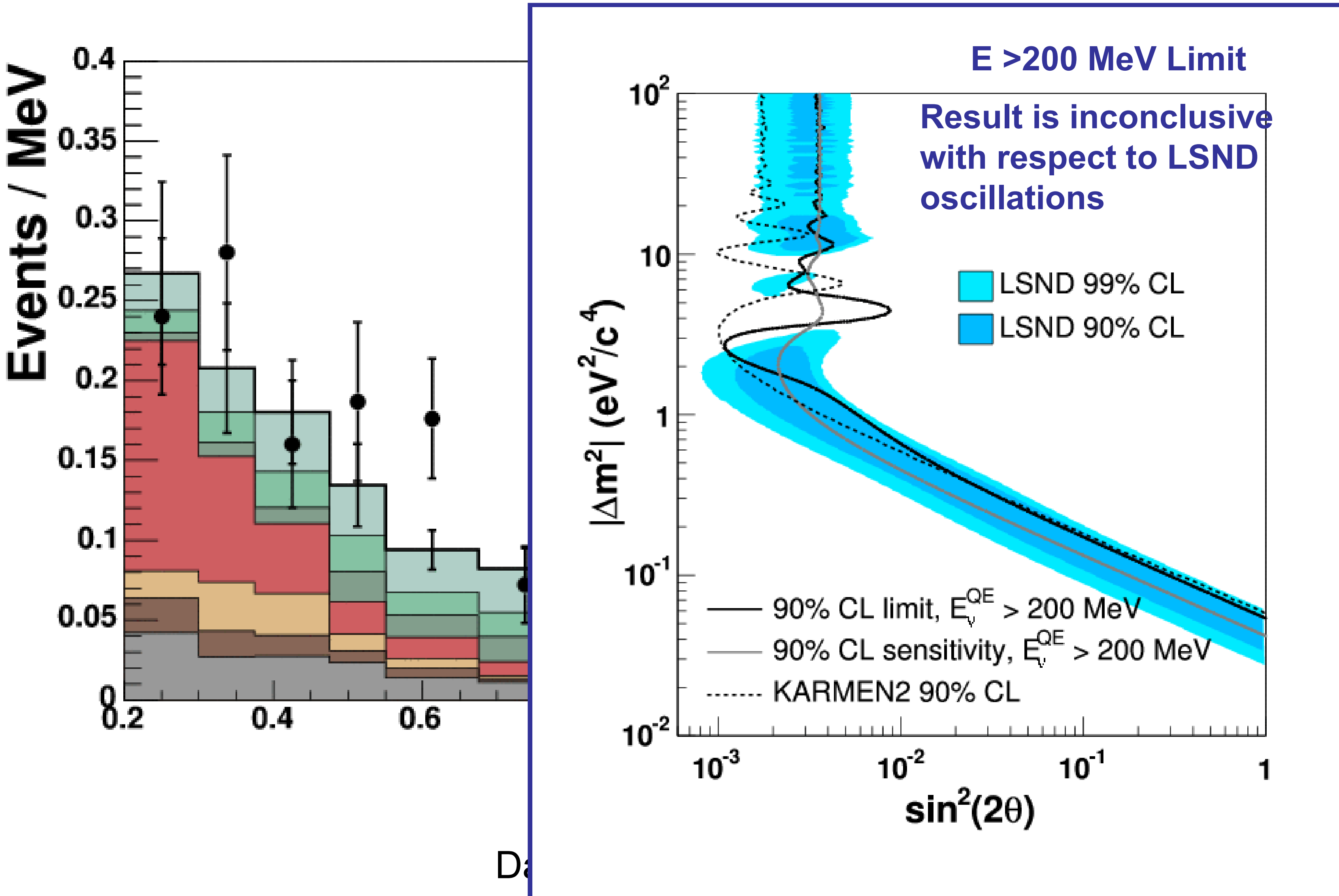
PRL 103, 111801 (2009)

2. MiniBooNE Results: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Appearance Results

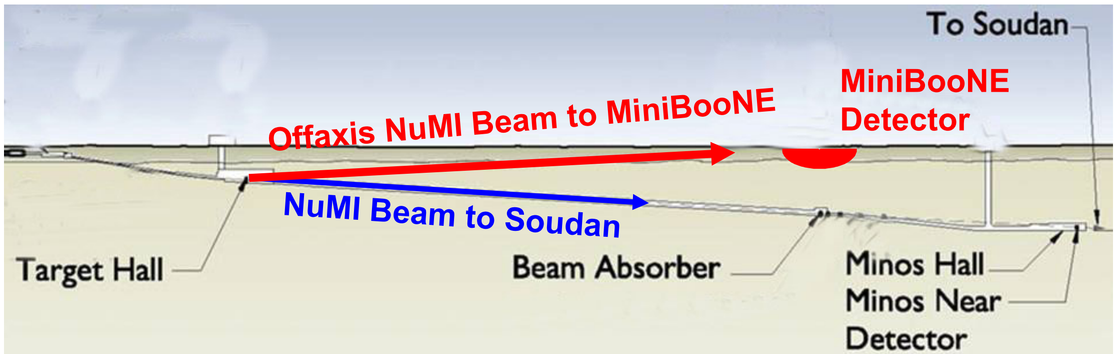
MiniBooNE sees no significant excess at low energy

At this point, inconclusive with respect to $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations at the LSND L/E



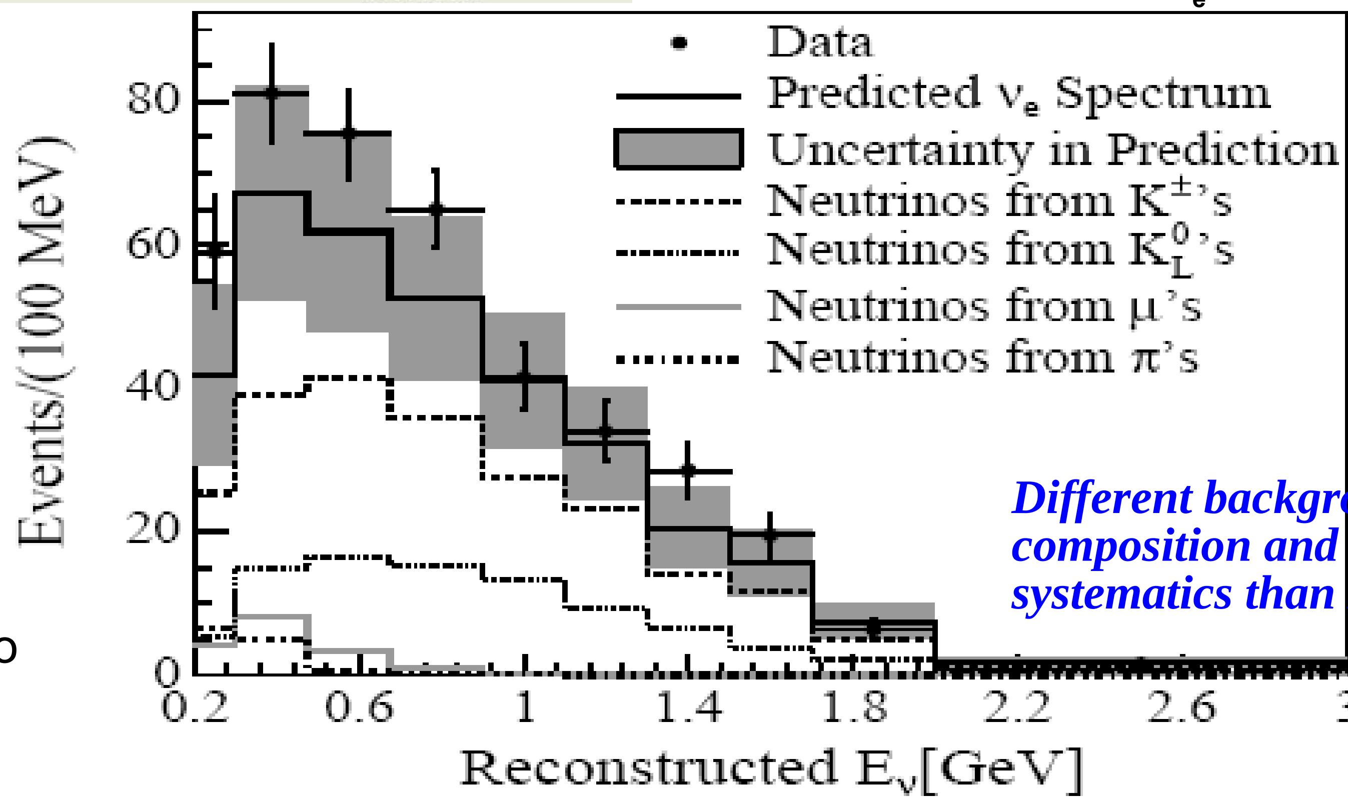
PRL 103, 111801 (2009)

2. MiniBooNE Results: NuMI Off-Axis ν_e CCQE Results



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

Distribution of ν_e events



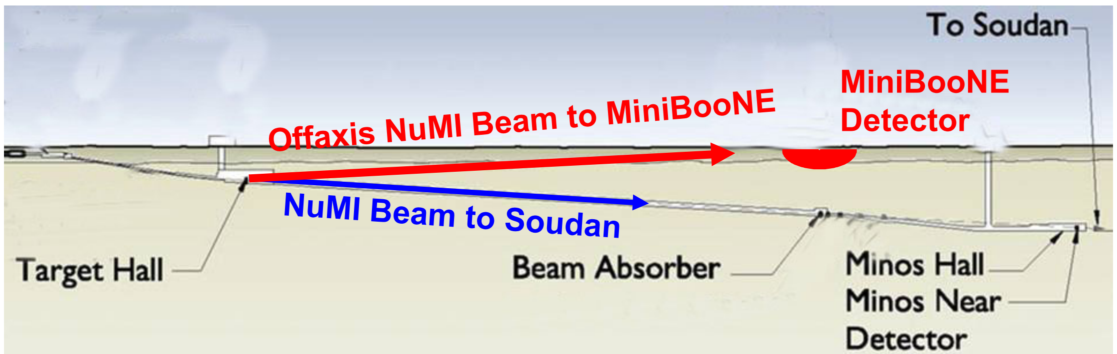
Different background composition and systematics than BNB

Dataset corresponds to 1.42×10^{20} protons on target

Phys. Rev. Lett. 102, 211801 (2009).

2. MiniBooNE Results: NuMI Off-Axis ν_e CCQE Results

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



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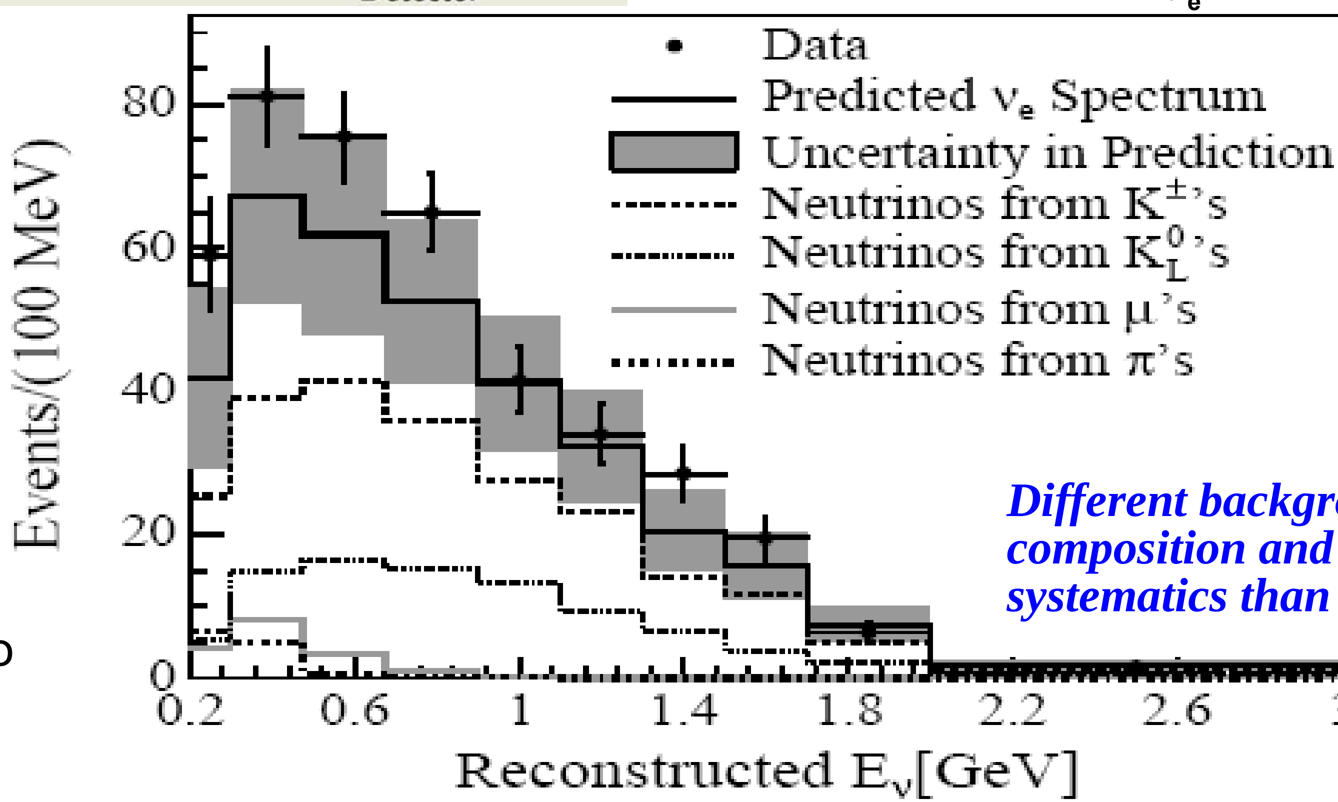

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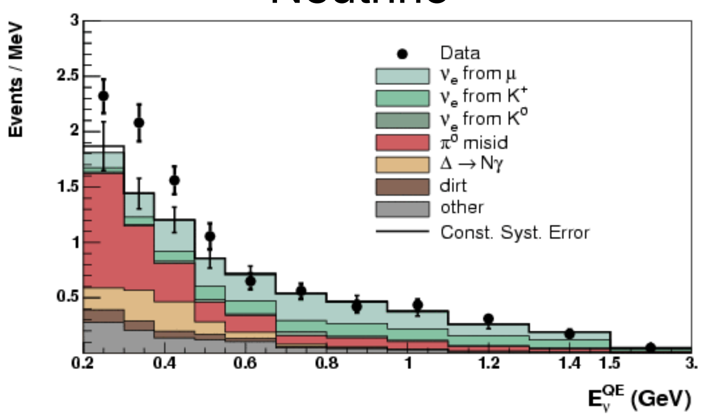
What Could This All Mean*?

(*from an oscillations perspective)

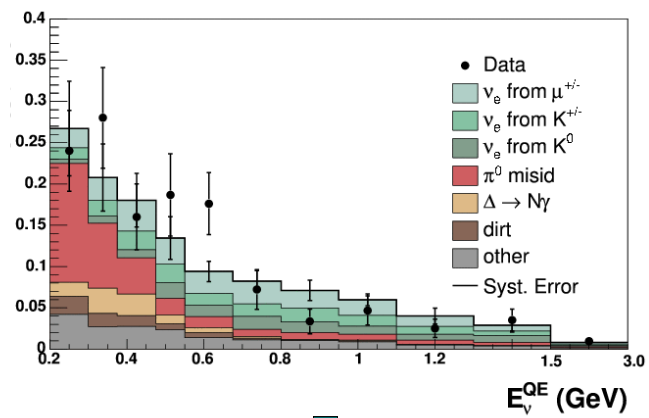
3. Global fits to Sterile Neutrino Models: (3+1)

Appearance results from MiniBooNE were included in global sterile neutrino fits to short-baseline data [arXiv:0609.1997]

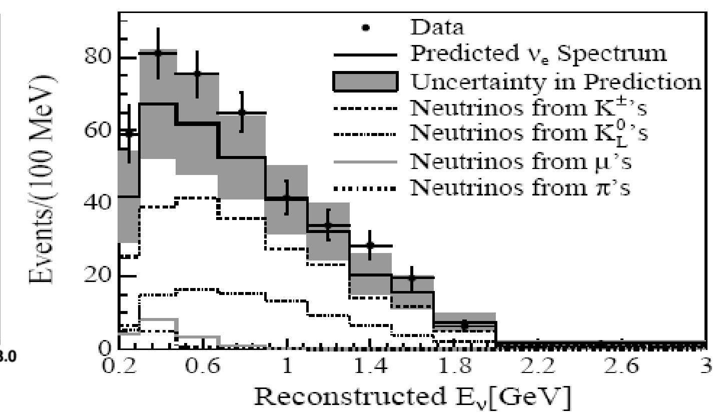
Neutrino



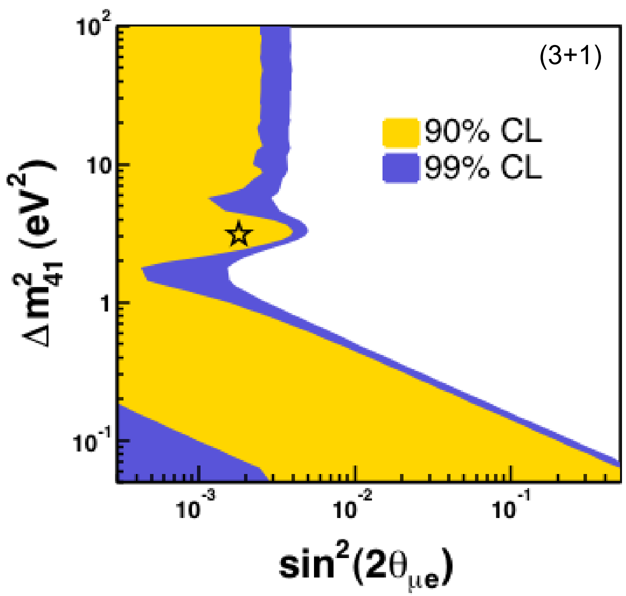
Antineutrino



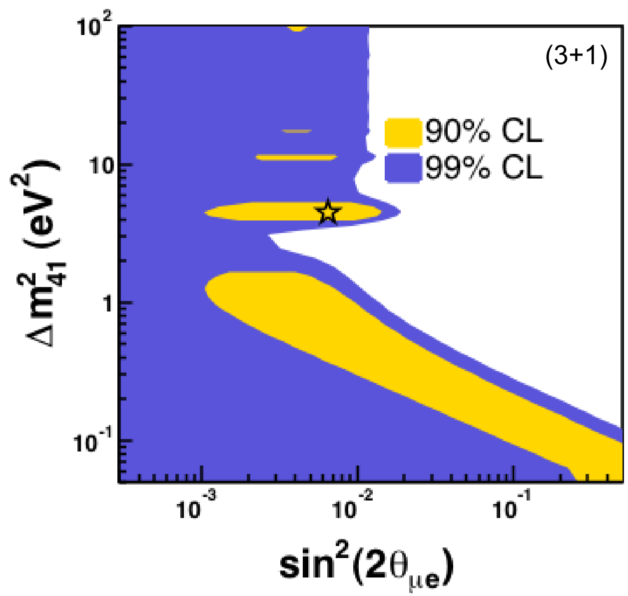
NuMI



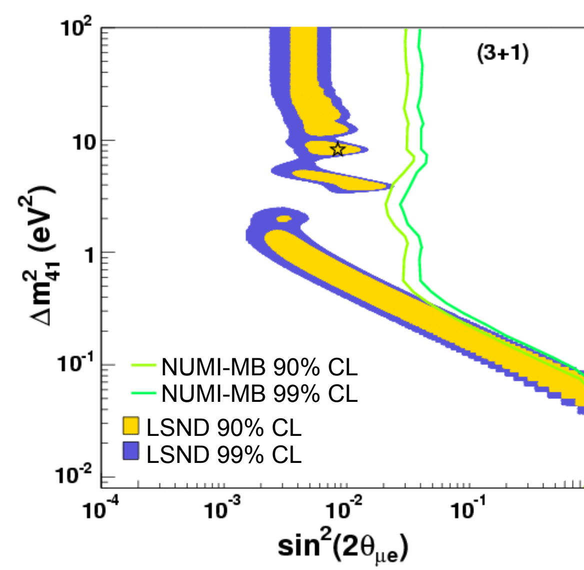
BNB-MB(ν)



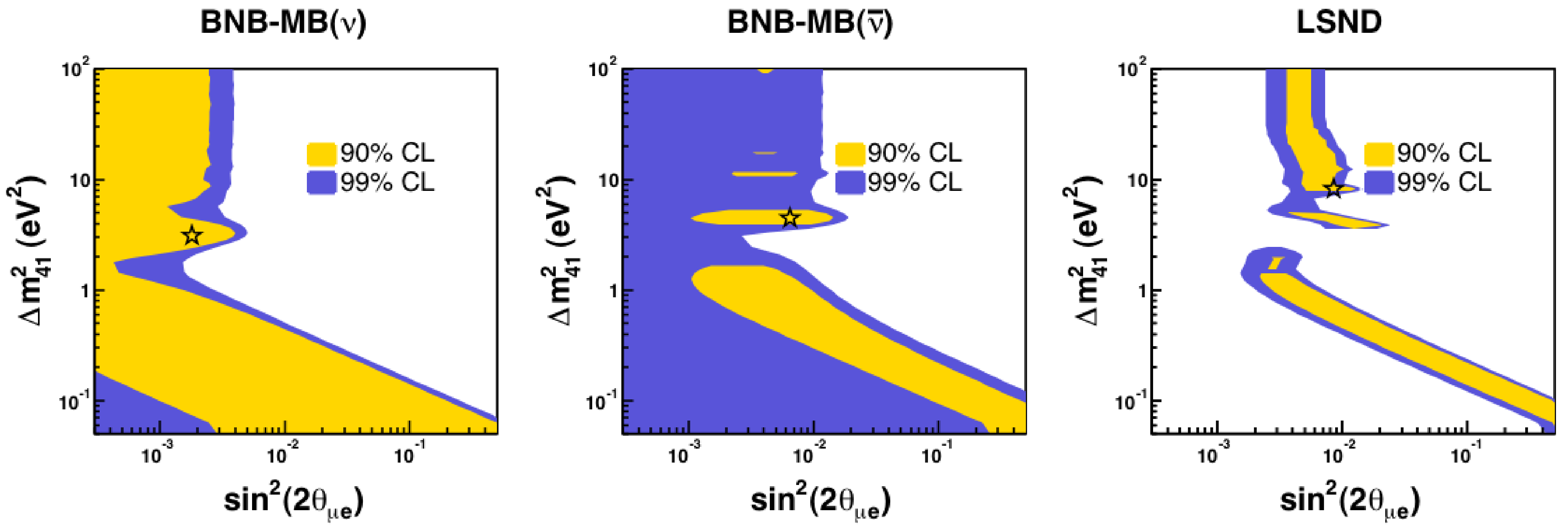
BNB-MB($\bar{\nu}$)



NUMI-MB



3. Global fits to Sterile Neutrino Models: (3+1)



Datasets	χ^2-prob	PG
BNB-MB(ν)+ BNB-MB($\bar{\nu}$)+LSND (90% closed contours)	11%	0.26%
BNB-MB($\bar{\nu}$)+LSND (antineutrino appearance, 90% closed contours)	**38%**	**49%**
BNB-MB($\bar{\nu}$)+LSND+KARMEN (antineutrino appearance)	29%	3.4%
BNB-MB(ν)+NUMI-MB+NOMAD (neutrino appearance)	40%	8.8%
appearance SBL	24%	2e-2%
all SBL	46%	8e-8%
ν SBL	47%	6e-2%
$\bar{\nu}$ SBL	**86%**	**1.5%**

Dataset	Channel
Appearance experiments:	
LSND	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
BNB-MB(ν)	$\nu_\mu \rightarrow \nu_e$
BNB-MB($\bar{\nu}$)	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
NUMI-MB	$\nu_\mu \rightarrow \nu_e$
KARMEN	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
NOMAD	$\nu_\mu \rightarrow \nu_e$
Disappearance experiments:	
Bugey	$\bar{\nu}_e \rightarrow \bar{\nu}_e$
CHOOZ	$\bar{\nu}_e \rightarrow \bar{\nu}_e$
CCFR84	$\nu_\mu \rightarrow \nu_\mu$
CDHS	$\nu_\mu \rightarrow \nu_\mu$

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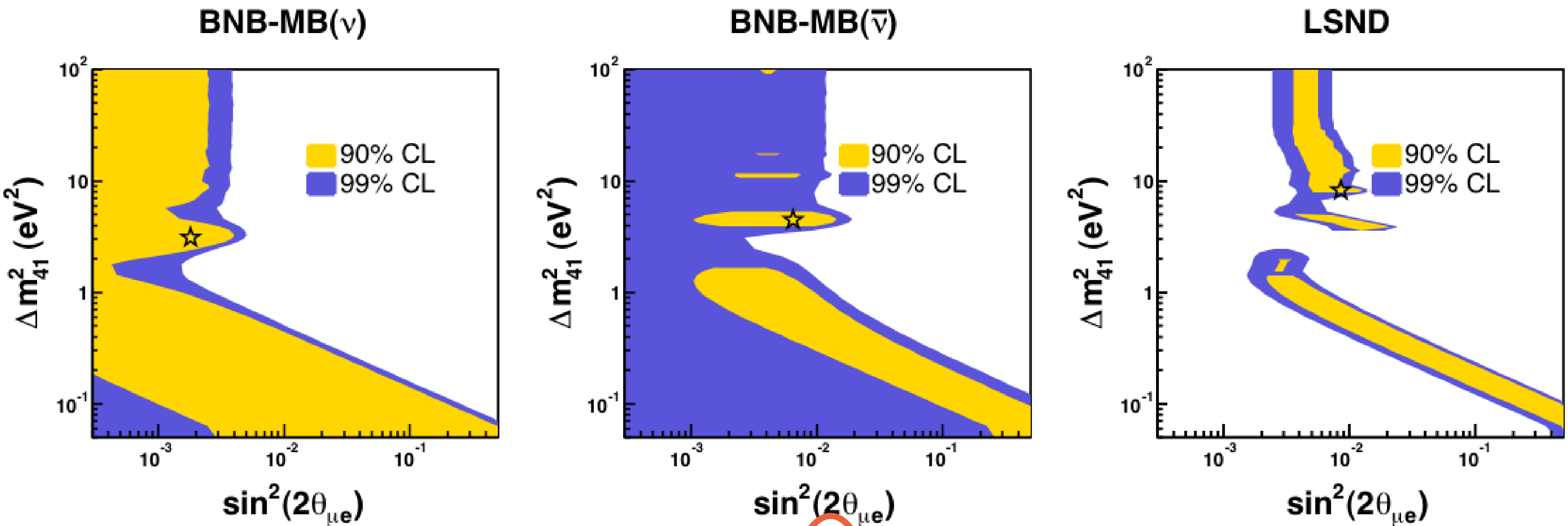

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[illegible]	$\bar{\nu}_e \to \bar{\nu}_e$
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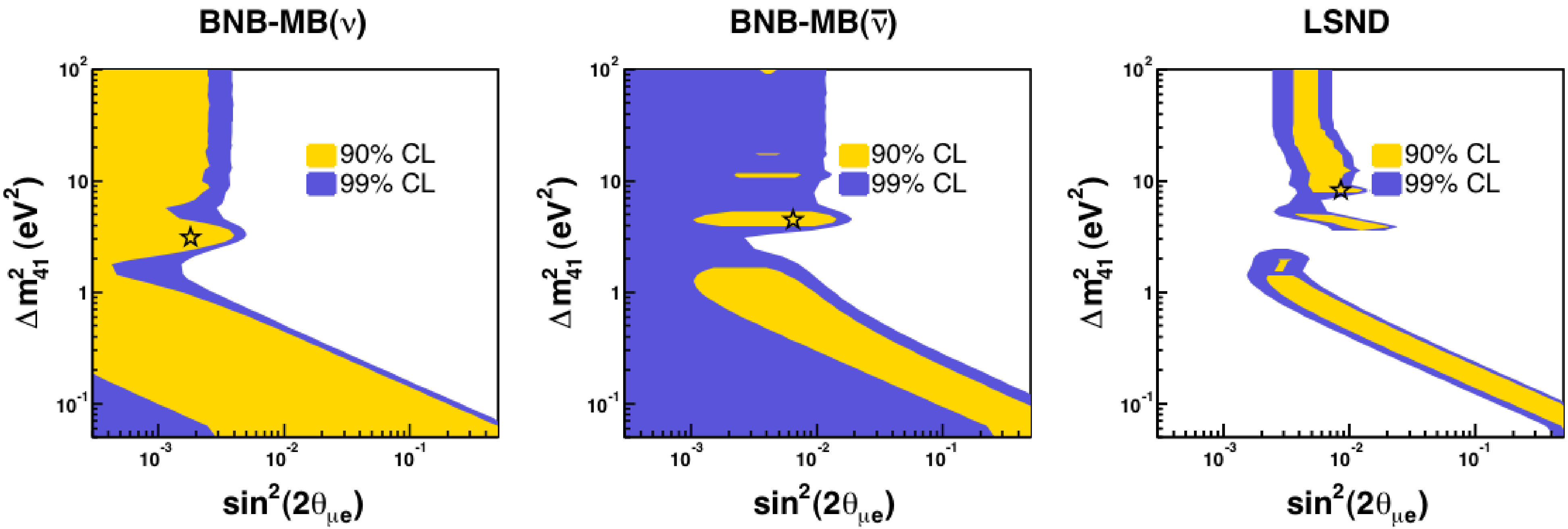
Compatibility
(“Parameter Goodness-of-f t”)

3. Global fits to Sterile Neutrino Models: (3+1)



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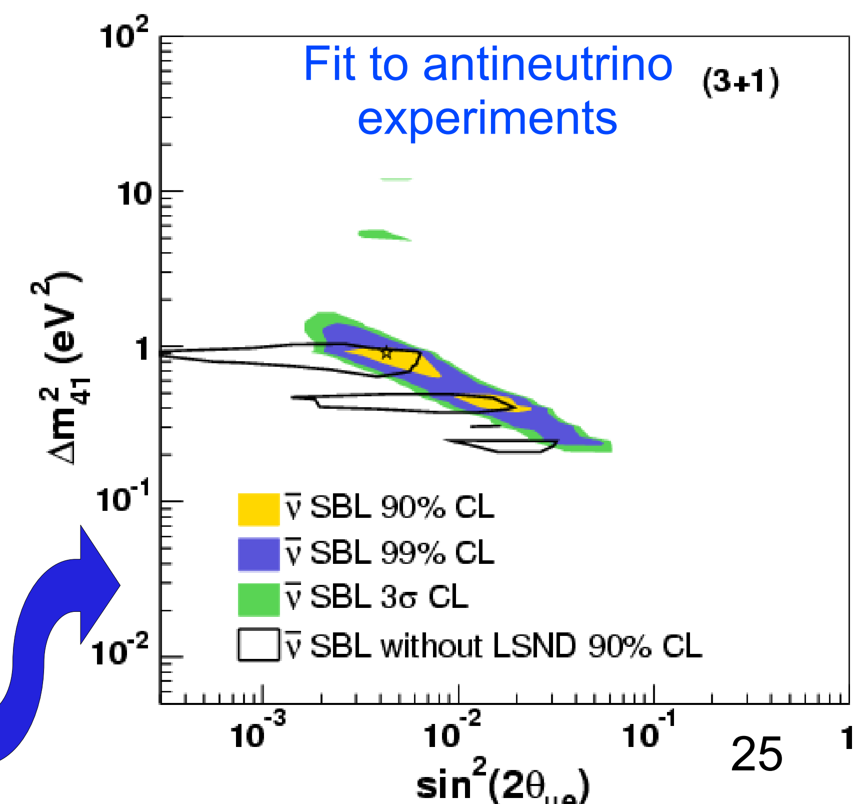

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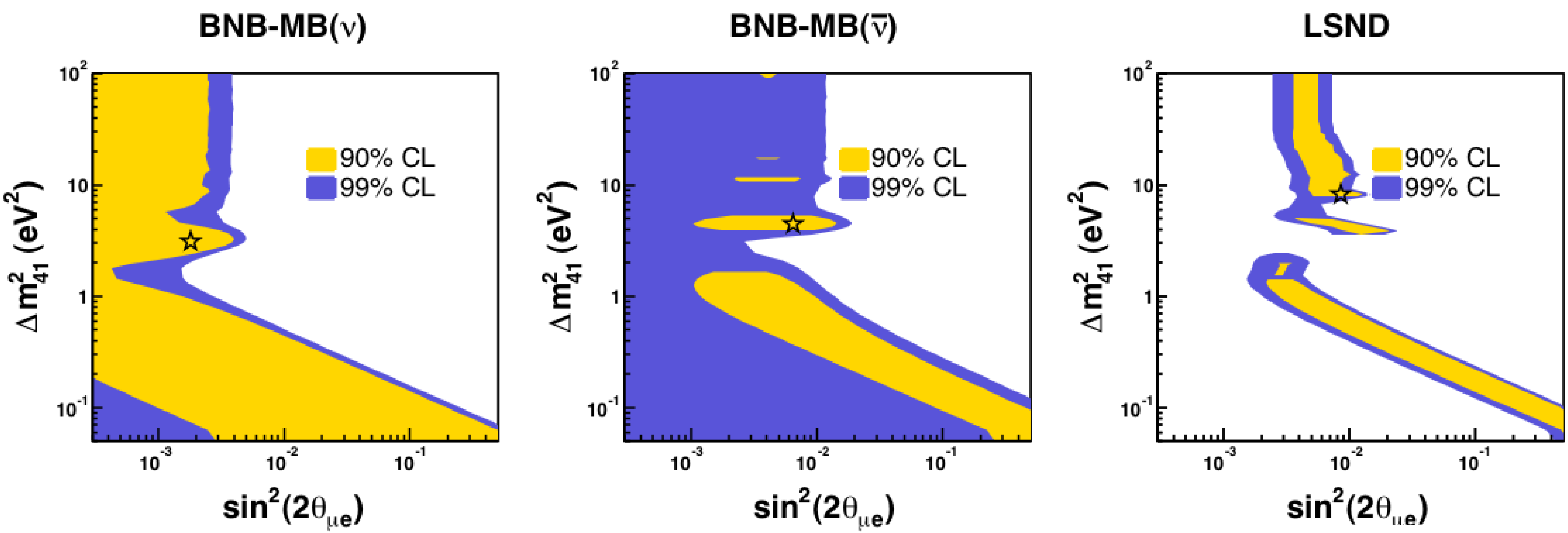

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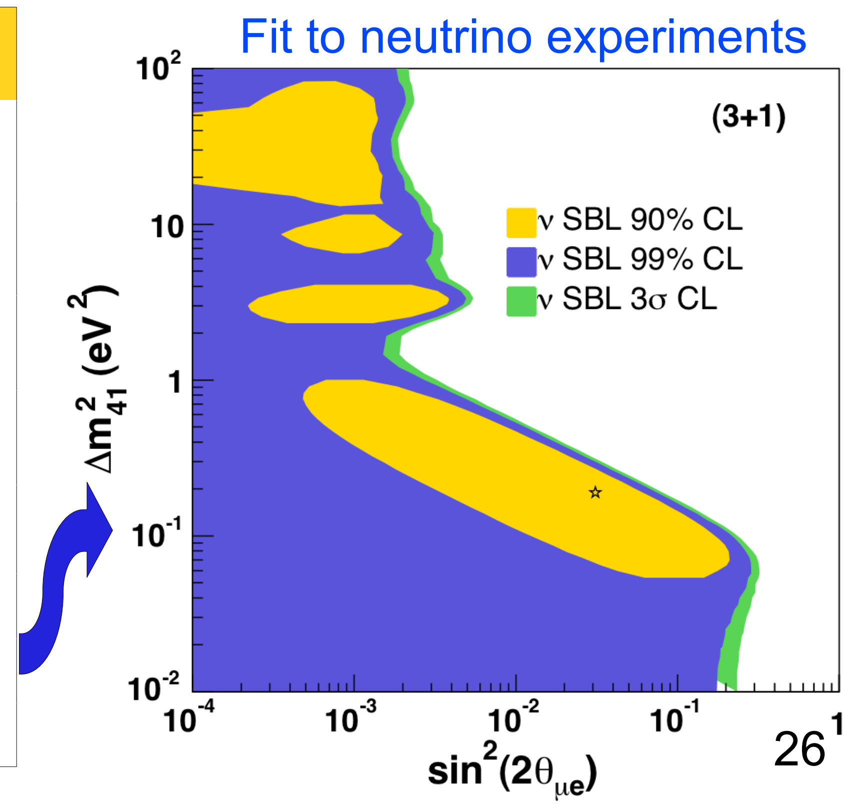
ν SBL	47%	6e-2%
$\bar{\nu}$ SBL	**86%**	**1.5%**



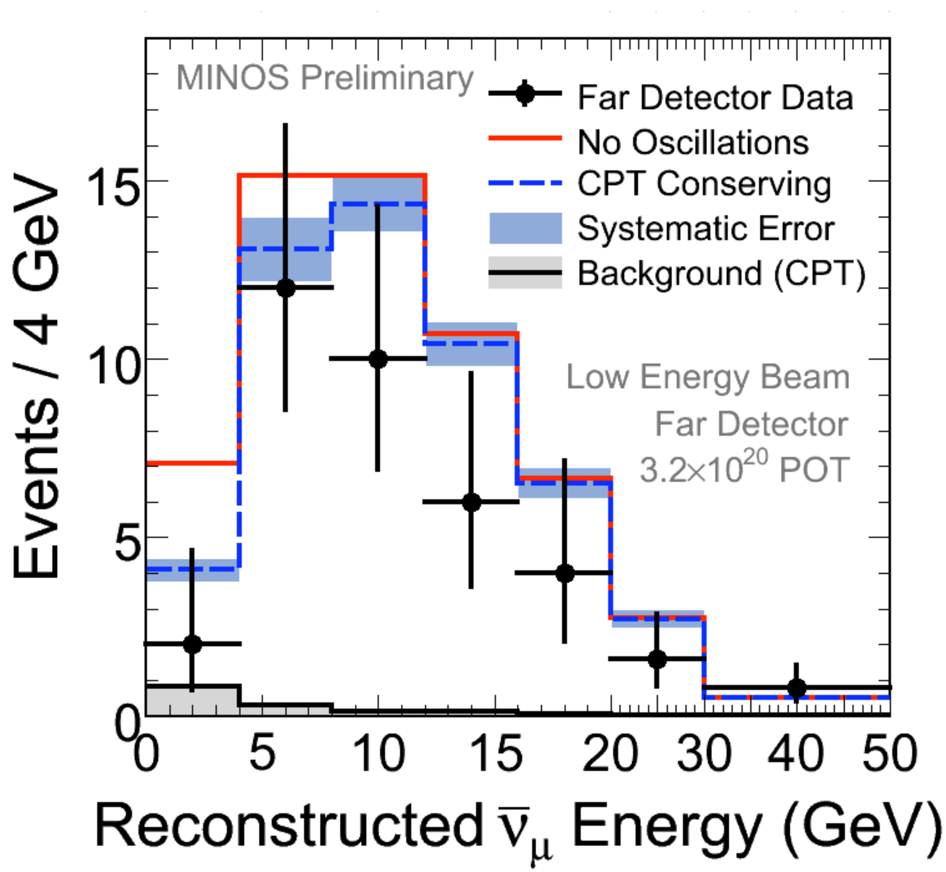
3. Global fits to Sterile Neutrino Models: (3+1)

CPT conservation in a (3+1) model implies that ν and ν oscillations cannot be different.

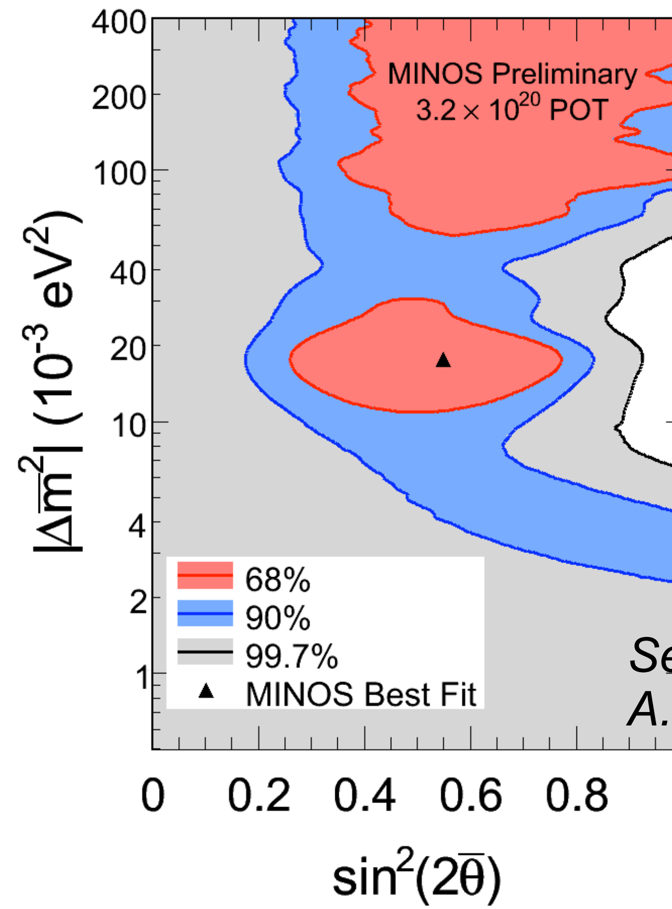
Does the data suggest otherwise?...

MINOS $\bar{\nu}_\mu$ Disappearance Results

FNAL W&C, May 15, 2009
http://theory.fnal.gov/jetp/Hartnell.pdf



Best Fit:
m² = 0.02 eV² sin²2 = 0.55



See talk by A. Sousa

3. Global fits to Sterile Neutrino Models: (3+2)

Before we get carried away,
could this be our good old friend, CP violation?

Examine SBL results under (3+2) scenario: naturally allows for CP violation
→ different appearance probabilities for neutrinos vs antineutrinos

"troublemakers" →

Datasets	CPV χ^2-prob	PG	CPC χ^2-prob
BNB-MB(ν)+ BNB-MB($\bar{\nu}$)+LSND (90% closed contours)	21%		13%
BNB-MB(ν)+BNB-MB($\bar{\nu}$)+LSND+ NUMI-MB+KARMEN+NOMAD (appearance)	**27%**	**2e-2%**	**22%**
all SBL appearance vs disappearance neutrino vs antineutrino	52%	2e-7% 0.26% 8e-2%	52%
ν SBL	48%		
$\bar{\nu}$ SBL	87%		
ν appearance	57%		
$\bar{\nu}$ appearance	37%		

(3+2) CPV fit to appearance-only datasets provides a good description to BNB-MB(nu) and NUMI-MB, (comparable to (3+1) neutrino-only fit), but not for BNB-MB(nubar).

3. Global fits to Sterile Neutrino Models: (3+2)

Before we get carried away,
could this be our good old friend, CP violation?

Examine SBL results under (3+2) scenario: naturally allows for CP violation
→ different appearance probabilities for neutrinos vs antineutrinos

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ν SBL	**48%**		
$\bar{\nu}$ SBL	**87%**		
ν appearance	**57%**		
$\bar{\nu}$ appearance	**37%**		

Again, grouping datasets in neutrino-only and antineutrino-only sets yields higher compatibilities!

4. Conclusions (I)

MiniBooNE Oscillation Results:

• MiniBooNE has reported two-neutrino oscillation search results at $\Delta m^2 \sim 1\ eV^2$, and has seen no evidence of CP/CPT-conserving oscillations at the LSND L/E

• It sees an unexpected excess of events at low energy in neutrino mode

• The antineutrino appearance search, a direct test of LSND independent of CP or CPT assumptions, is, at this point, inconclusive with respect to two-neutrino oscillations at the LSND L/E

New results expected in the near future:

- Updated **antineutrino appearance** analysis (~5E20 POT)
- Joint neutrino + antineutrino (~5E20 POT) appearance analysis and investigation of **low energy excess**
- Joint MiniBooNE and SciBooNE (BNB near detector) **disappearance** analysis
- **NuMI appearance** analysis with higher statistics and reduced systematics

MiniBooNE has already been granted further antineutrino running, for an additional 5E20 POT (data to be collected in 2-3 years)!

4. Conclusions (II)

MiniBooNE's Impact on Sterile Neutrino Models

(3+1) models are still disfavored, but

Antineutrino experiments provide good f ts and higher compatibilities. A (3+1) f t to all antineutrino SBL data yields 86% χ^2-probability, and allowed regions which **exclude the no-oscillations point at** > **5σ.** However, there is large **tension** between neutrino and antineutrino data.

(3+2) provides only a **marginally better** description of all short-baseline (SBL) data over (3+1); CP violation in (3+2) offers **small improvement** in f ts to appearance-only experiments.

New results from MINOS and a joint MiniBooNE/SciBooNE ν_μ and $\bar{\nu}_\mu$ disappearance analysis, expected soon, will provide additional information.

Thank you!

Backup slides

Model parameters:

(arXiv:hep-ph/0906.1997)

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 (models) by importance sampling:
  - $0.01 eV^2 \leq \Delta m^2_{41}, \quad \Delta m^2_{51} \leq 100 eV^2$

    $\Delta m^2_{51} \geq \Delta m^2_{41}$
  - $|U_{e4}|$, $|U_{\mu 4}|$, $|U_{e5}|$, $|U_{\mu 5}|$
  - *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

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

Goodness-of-fit and *compatibility* tests:

•Parameter Goodness-of-fit (PG)

[hep-ph/0304176]

$$\chi^2_{PG} = \chi^2_{min,all} - \sum_i \chi^2_{min,i}$$

$$PG = prob(\chi^2_{PG}, ndf_{PG})$$

Appearance Fit method

$$\chi^2 = \sum_{i,j=1}^{N_e+N_\mu} (D_i - P_i) M_{ij}^{-1} (D_j - P_j)$$

- $N_e = 8(11)$ is the number of E_ν^{QE} bins for observed electron antineutrino events for $E > 200$ MeV ($E > 475$ MeV) fits
- $N_\mu = 8$ is the number of E_ν^{QE} bins for observed muon antineutrino events
- $D_i = (D_j^{\bar{\nu}_e}(j = 1, ..., N_e), D_j^{\bar{\nu}_\mu}(j = 1, ..., N_\mu))$ is a 1D side-by-side array of observed electron antineutrino events and observed muon antineutrino events as functions of E_ν^{QE}
- $P_i = ((B_j^{\bar{\nu}_e} + S_j)(j = 1, ..., N_e), P_j^{\bar{\nu}_\mu}(j = 1, ..., N_\mu))$ is a 1D side-by-side array of predicted electron antineutrino events from background, $B^{\bar{\nu}_e}$ plus any possible signal, S_i, from $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations, and predicted muon antineutrino events, $B^{\bar{\nu}_\mu}$.

Sterile Neutrinos in 2007

Maltoni & Schwetz, PRD 76 093005 (2007):

Global fits to sterile neutrino oscillations, (3+1) and (3+2) with MiniBooNE neutrino appearance data included

They found that:

- all experiments still incompatible under (3+1)
- all appearance experiments are compatible under (3+2) with large CP-violation
- appearance and disappearance experiments are incompatible at more than 3σ

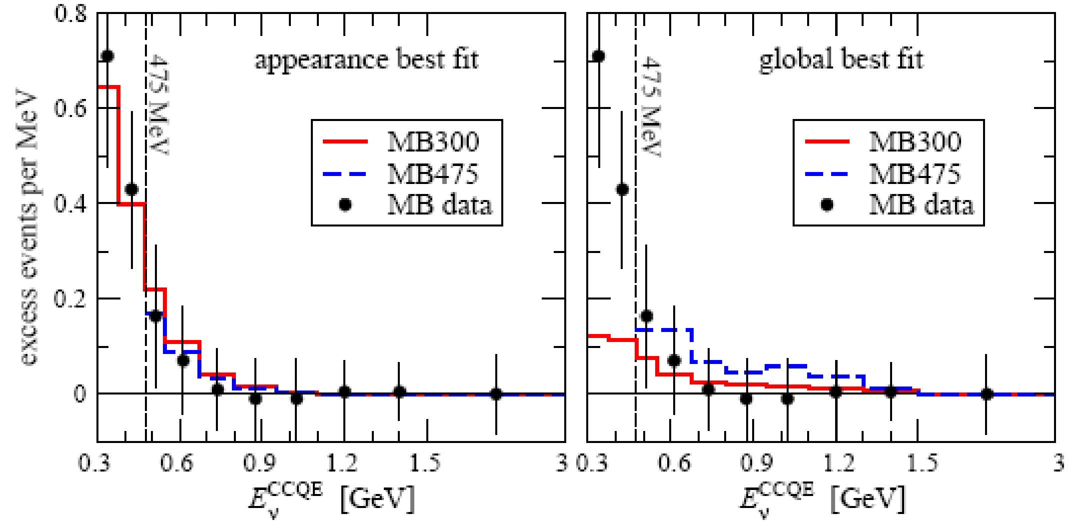


FIG. 3: MB spectral data in bins of reconstructed CCQE neutrino energy. The histograms show the prediction at the best fit points in (3+2) mass schemes for SBL appearance data LSND, KARMEN, NOMAD, MB (left), and for the global data (right). For the solid histograms the full MB energy range has been used in the fit (MB300), whereas for the dashed histogram the two lowest energy data points have been omitted (MB475). The corresponding parameter values are given in Tab. I.

PG test

Dataset	χ^2 (*dof*)	χ^2-probability (%)	PG (%)		
all SBL	190.2 (192)	52.3	PG(BNB-MB(ν),BNB-MB($\bar{\nu}$),NUMI-MB,LSND,KARMEN, NOMAD,Bugey,CHOOZ,CCFR84,CDHS,ATM)	= Prob(49.1,5) =	2.2×10^{-7}
			PG(APP,DIS)	= Prob(16.3,4) =	0.26
			PG(ν,$\bar{\nu}$)	= Prob(21.0,5) =	8.2×10^{-2}
all APP	92.6 (85)	26.9	PG(BNB-MB(ν),BNB-MB($\bar{\nu}$),NUMI-MB,LSND,KARMEN, NOMAD)	= Prob(24.6,5) =	1.7×10^{-2}
all DIS	81.3 (103)	94.4	PG(Bugey,CHOOZ,CCFR84,CDHS,ATM)	= Prob(8.14,4) =	8.6
all ν	86.1 (86)	47.8	PG(BNB-MB(ν),NUMI-MB,NOMAD,CCFR84,CDHS,ATM)	= Prob(17.4,5) =	0.37
all $\bar{\nu}$	83.2 (99)	87.3	PG(BNB-MB($\bar{\nu}$),KARMEN,LSND,Bugey,CHOOZ)	= Prob(10.7,5) =	5.8
ν APP	50.6 (53)	56.8	PG(BNB-MB(ν),NUMI-MB,NOMAD)	= Prob(3.91,5) =	56
$\bar{\nu}$ APP	28.9 (27)	36.7	PG(BNB-MB($\bar{\nu}$),KARMEN,LSND)	= Prob(7.55,5) =	18
			PG(ν APP,$\bar{\nu}$ APP)	= Prob(13.1,5) =	2.2
all - BNB-MB(ν)	167.2 (174)	63.2	PG(all SBL - BNB-MB(ν) , BNB-MB(ν))	= Prob(12.1,5) =	3.4
all - BNB-MB($\bar{\nu}$)	168.5 (174)	60.3	PG(all SBL - BNB-MB($\bar{\nu}$) , BNB-MB($\bar{\nu}$))	= Prob(7.34,5) =	20
all - NUMI-MB	184.2 (182)	43.9	PG(all SBL - NUMI-MB , NUMI-MB)	= Prob(4.34,5) =	50
all - LSND	176.1 (187)	70.6	PG(all SBL - LSND , LSND)	= Prob(12.5,5) =	2.9
all - KARMEN	180.2 (183)	54.6	PG(all SBL - KARMEN , KARMEN)	= Prob(4.72,5) =	45
all - NOMAD	154.2 (162)	65.6	PG(all SBL - NOMAD , NOMAD)	= Prob(1.89,5) =	86
all - Bugey	142.2 (132)	25.7	PG(all SBL - Bugey , Bugey)	= Prob(3.07,4) =	55
all - CHOOZ	180.9 (178)	42.6	PG(all SBL - CHOOZ , CHOOZ)	= Prob(3.06,4) =	55
all - CCFR84	174.7 (174)	47.0	PG(all SBL - CCFR84 , CCFR84)	= Prob(0.82,4) =	94
all - CDHS	175.4 (177)	51.9	PG(all SBL- CDHS , CDHS)	= Prob(7.48,4) =	11
all - ATM	184.4 (190)	60.0	PG(all SBL - ATM , ATM)	= Prob(5.78,2) =	5.6

TABLE V: Comparison of χ^2-probabilities for (3+2) CP-violating fits with different combinations of SBL datasets. Also shown are PG results testing compatibility among different datasets. The last eleven rows of the table provide the compatibility (PG) between the experiment being removed from each fit and all remaining experiments. See text for more details.

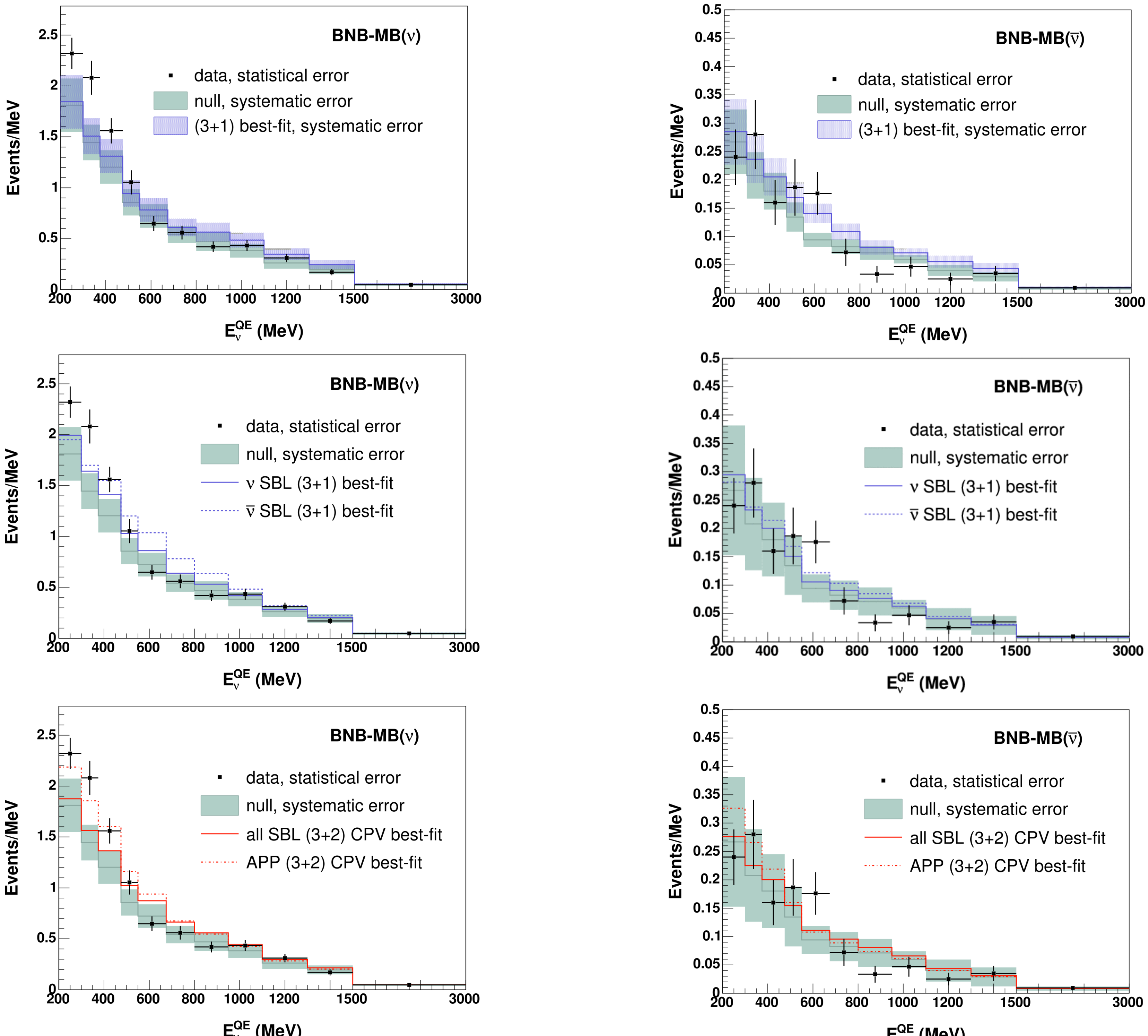
PG test

[hep-ph/0304176]

Gives sensible results even in cases where
- the **errors** are estimated very **conservatively**
- the total **number of data points is very large**

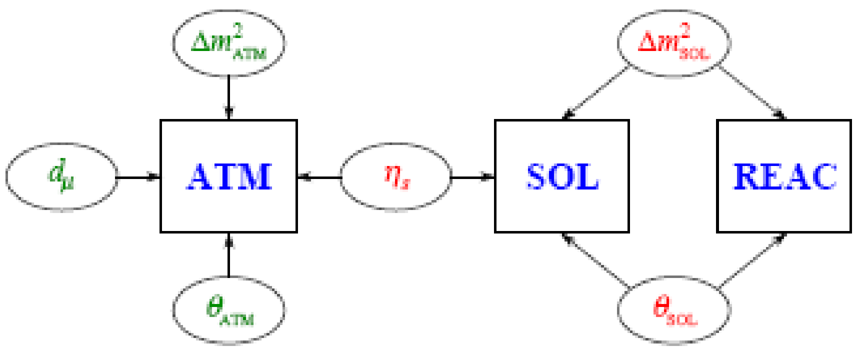
Avoids the problem that a possible disagreement between data sets becomes diluted by **data points which are insensitive** to the problem in the fit

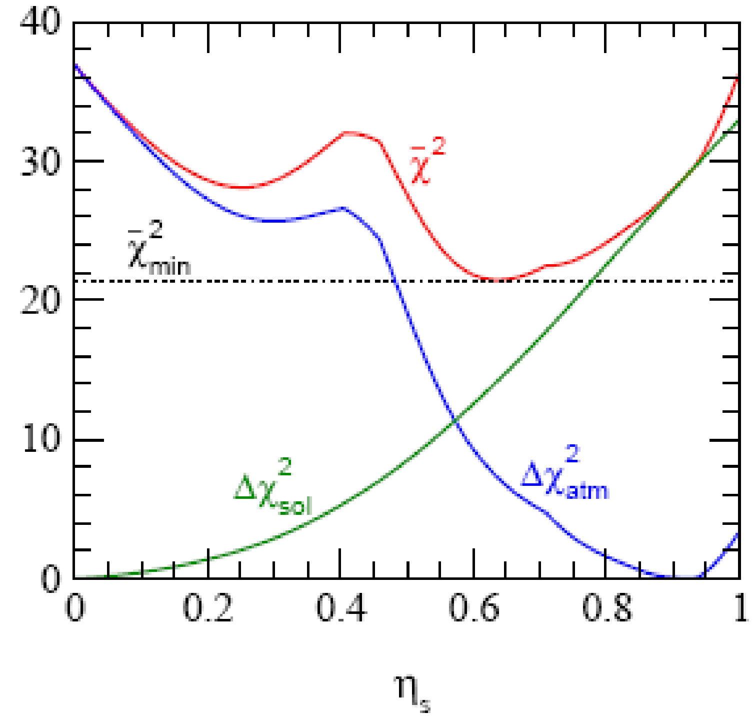
Can also be very useful when a set consisting of a rather small number of data points is combined with a very **large data sample**


BNB-MB(ν)
data, statistical error
null, systematic error
(3+1) best-fit, systematic error
Events/MeV
E_ν^QE (MeV)
BNB-MB(ν̄)
data, statistical error
null, systematic error
(3+1) best-fit, systematic error
Events/MeV
E_ν^QE (MeV)
BNB-MB(ν)
data, statistical error
null, systematic error
ν SBL (3+1) best-fit
ν̄ SBL (3+1) best-fit
Events/MeV
E_ν^QE (MeV)
BNB-MB(ν̄)
data, statistical error
null, systematic error
ν SBL (3+1) best-fit
ν̄ SBL (3+1) best-fit
Events/MeV
E_ν^QE (MeV)
BNB-MB(ν)
data, statistical error
null, systematic error
all SBL (3+2) CPV best-fit
APP (3+2) CPV best-fit
Events/MeV
E_ν^QE (MeV)
BNB-MB(ν̄)
data, statistical error
null, systematic error
all SBL (3+2) CPV best-fit
APP (3+2) CPV best-fit
Events/MeV
E_ν^QE (MeV)

PG test

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.

Atmospheric constraints

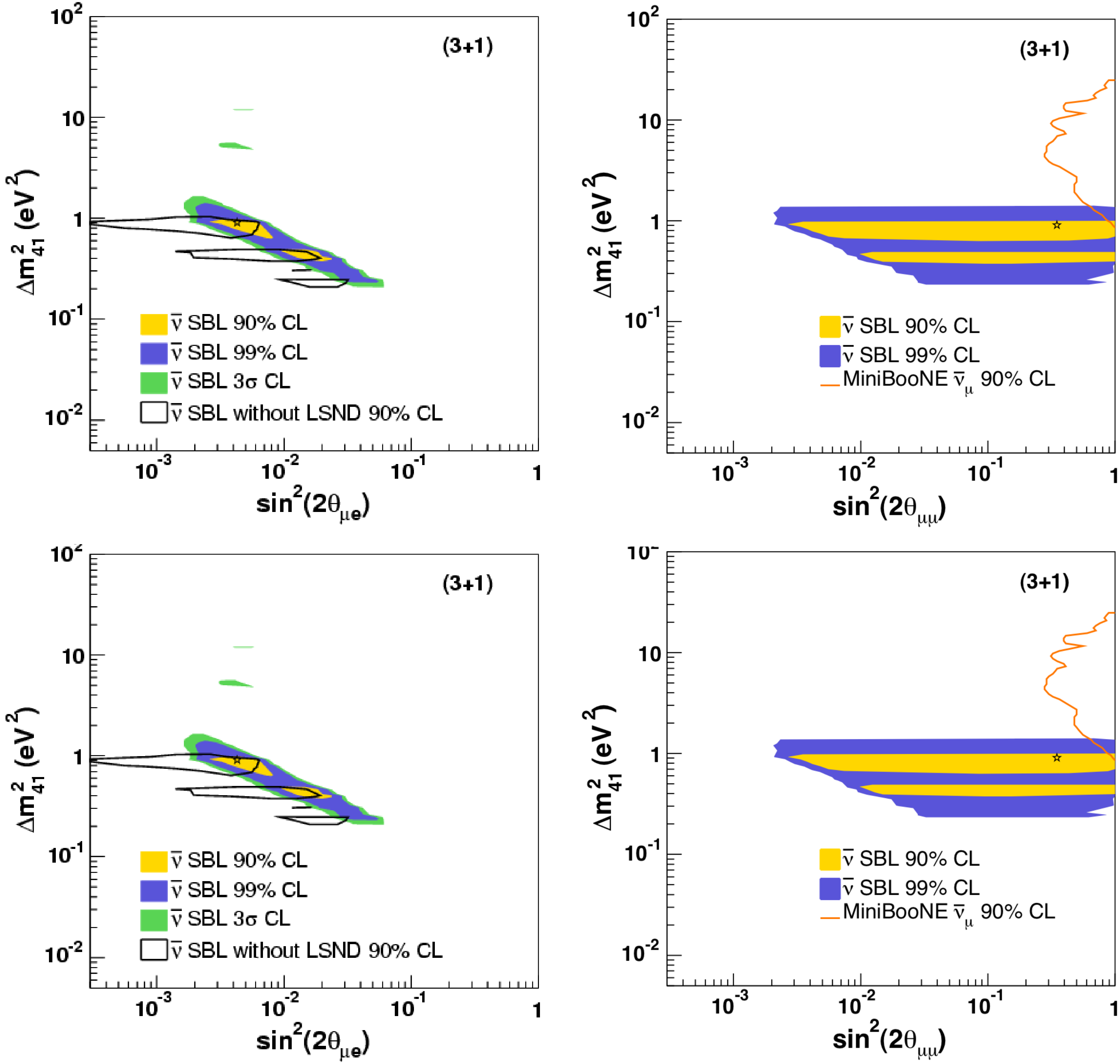
Super-K and K2K re-analyses:

Fitted parameter:

$$d_\mu = \frac{1 - \sqrt{1 - 4A}}{2}$$

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

Adds 1 degree of freedom

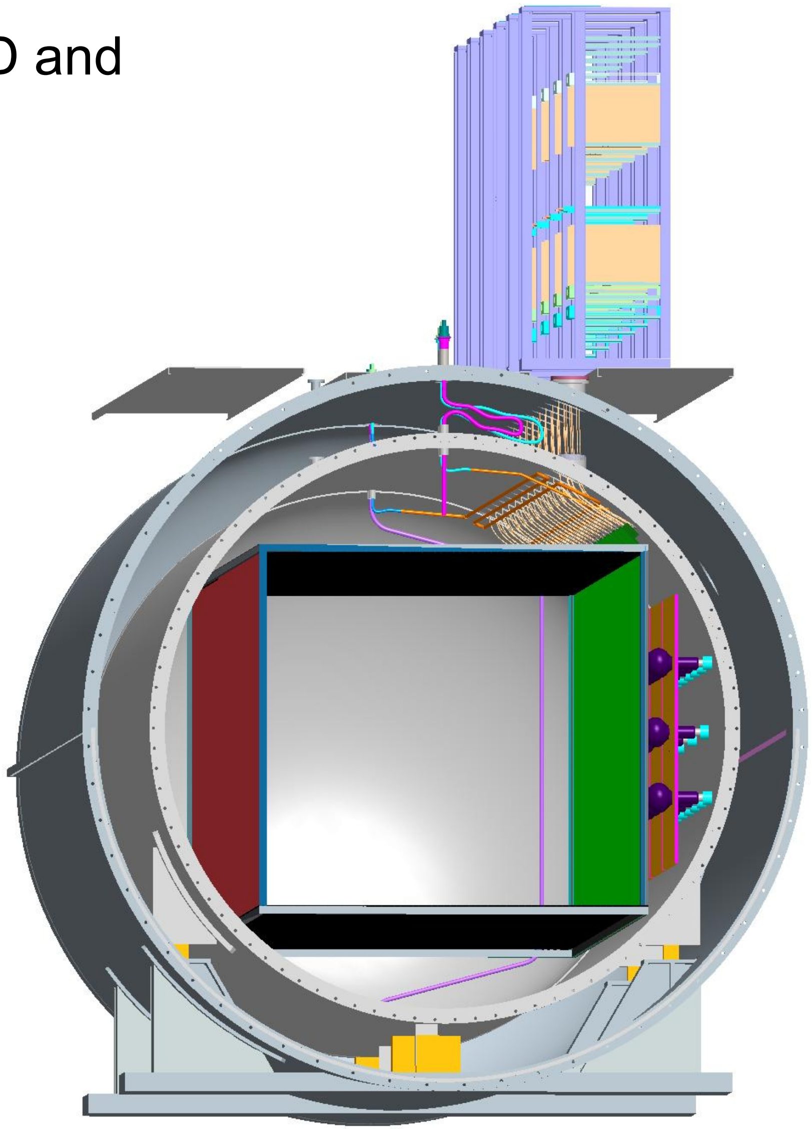

(3+1)
Δm^2_{41} (eV^2)
$\sin^2(2\theta_{\mu e})$
$\bar{\nu}$ SBL 90% CL
$\bar{\nu}$ SBL 99% CL
$\bar{\nu}$ SBL 3σ CL
$\bar{\nu}$ SBL without LSND 90% CL
(3+1)
Δm^2_{41} (eV^2)
$\sin^2(2\theta_{\mu\mu})$
$\bar{\nu}$ SBL 90% CL
$\bar{\nu}$ SBL 99% CL
MiniBooNE $\bar{\nu}_\mu$ 90% CL

MicroBooNE

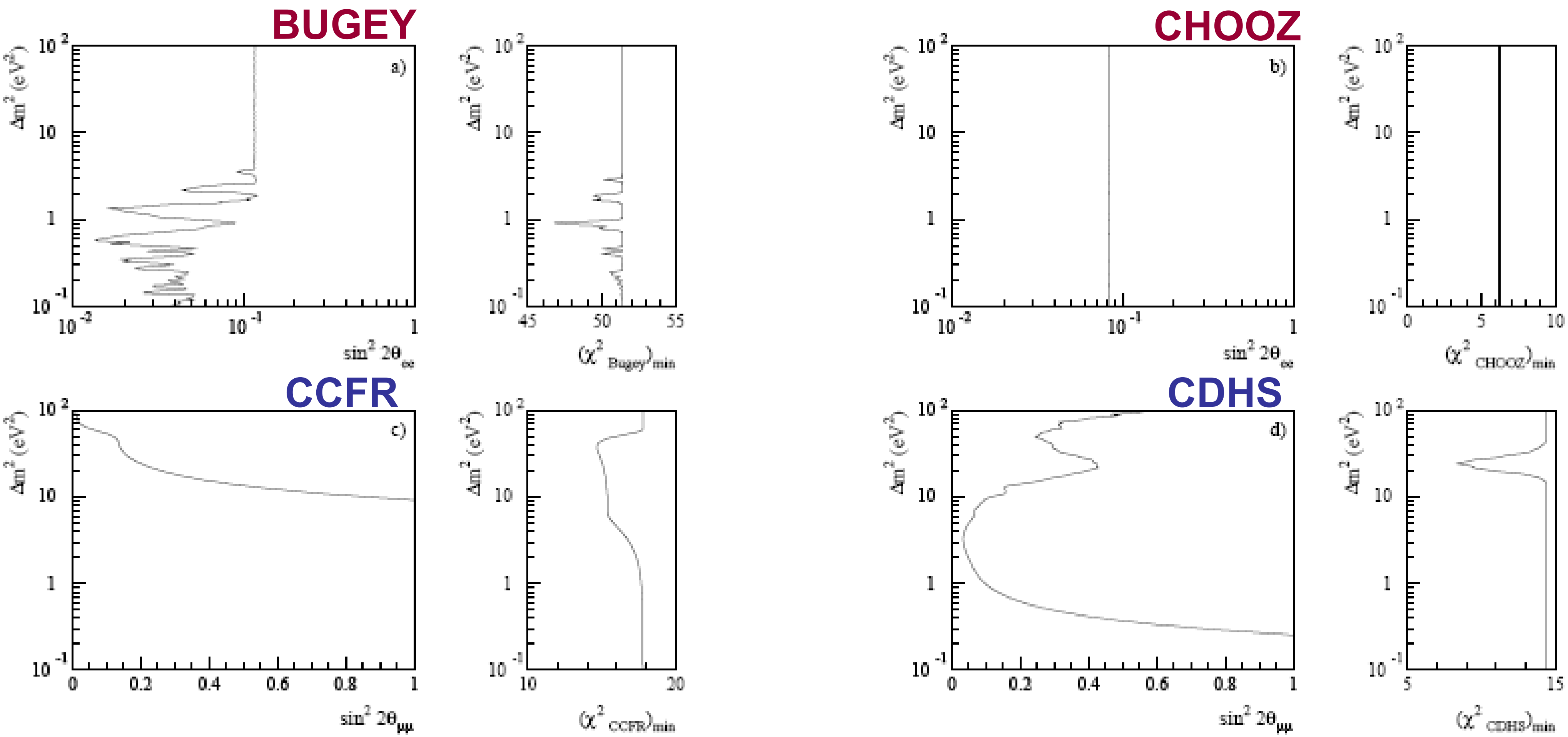
- LArTPC detector designed to advance LAr R&D and determine whether the MiniBooNE **low-energy excess** is due to **electrons or photons**.

- Approximately 70-ton fiducial volume detector, located near MiniBooNE (cost <$20M).

- Received Stage-1 approval at Fermilab and initial funding from DOE and NSF.
- May begin data taking as early as 2012.



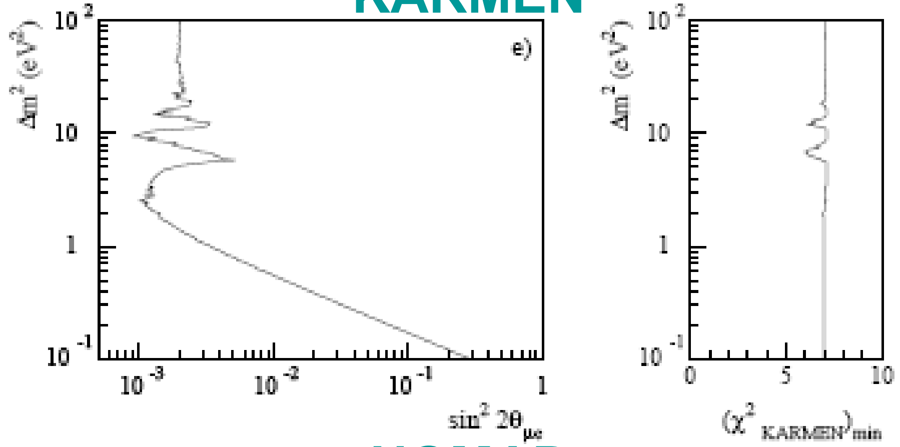
Constraints from Each SBL Experiment



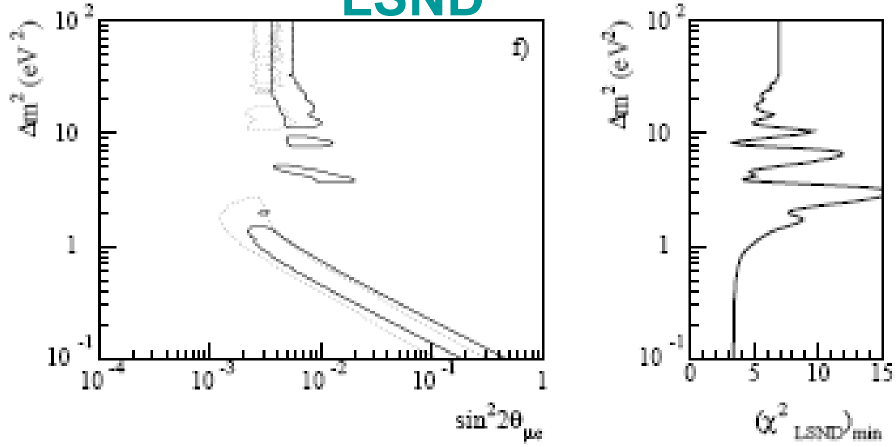
[from Sorel, *et al*. PRD 70 073004 (2004)]

Constraints from Each SBL Experiment

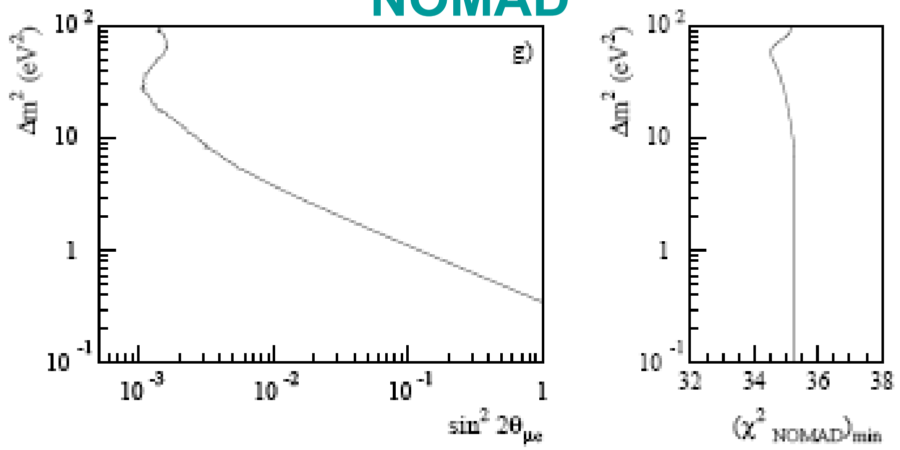
KARMEN



LSND



NOMAD



[from Sorel, *et al*. PRD 70 073004 (2004)]