Sterile Neutrino Oscillations and CP-Violation Implications for MiniBooNE

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Outline

- Sterile neutrino oscillation formalism
- Oscillation analysis
- Constraints from MiniBooNE result
- Preliminary oscillation analysis results
- CPV Implications and Future Studies at MiniBooNE

Sterile Neutrino Oscillation Formalism

3 active + n sterile neutrinos:

•***light*** sterile neutrinos

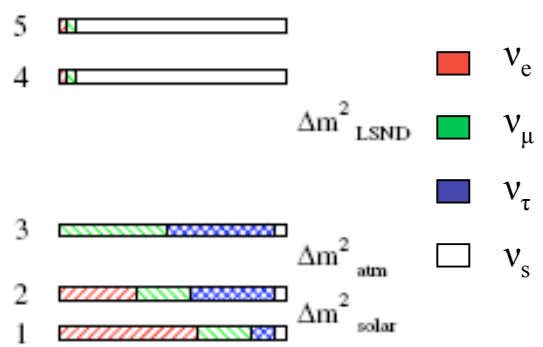
• they don't interact thru standard weak couplings

• they have very small active flavor content (U_{e4}, $U_{\mu 4}$, …, U_{en}, $U_{\mu n}$)

→ can participate in neutrino oscillations

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum \mathrm{Re}\{U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\} \sin^2 x_{ij}$$
$$+2\sum \mathrm{Im}\{U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta i}\} \sin 2x_{ij} \qquad x_{ij} = 1.27\Delta m^2_{ij} L/E$$

• ***For example, for 2 sterile neutrinos (3+2):***



Oscillation: $\nu_\alpha \to \nu_s \to \nu_\beta$

$$P(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2 \sin^2 x_{41} + 4|U_{\alpha 5}|^2|U_{\beta 5}|^2 \sin^2 x_{51} +$$
$$8|U_{\alpha 5}||U_{\beta 5}||U_{\alpha 4}||U_{\beta 4}| \sin x_{41} \sin x_{51} \cos(x_{54} \mp \varphi_{54})$$

Disappearance: $\nu_\alpha \to \nu_s$

$$P(\nu_\alpha \to \nu_\alpha) = 1 - 4[(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2)(|U_{\alpha 4}|^2 \sin^2 x_{41} + |U_{\alpha 5}|^2 \sin^2 x_{51}) +$$
$$+ |U_{\alpha 4}|^2|U_{\alpha 5}|^2 \sin^2 x_{54}]$$

Oscillation Analysis

Neutrino **oscillations and disappearance** due to sterile neutrinos can be constrained by **short-baseline experiments** (sensitive to *high* Δm^2)

We are interested in:

- **constraining the oscillation parameters** by a combined analysis of SBL data
- studying the **compatibility** of null SBL results with LSND and MiniBooNE results in a 3 active + n sterile neutrino hypothesis

Channel	Experiment	Lowest Δm^2 Reach (90%CL)	$\sin^2\theta$ constraint (90%CL)	
			High Δm^2	Optimal Δm^2
$\nu_\mu \to \nu_e$	LSND KARMEN NOMAD MiniBooNE	3×10^{-2} 6×10^{-2} 4×10^{-1} 2.5×10^{-2}	$> 2.5\times10^{-3}$ $< 1.7\times10^{-3}$ $< 1.4\times10^{-3}$	$> 1.2\times10^{-3}$ $< 1.0\times10^{-3}$ $< 1.0\times10^{-3}$
$\nu_e \to \nu_\ell$	Bugey Chooz	1×10^{-2} 7×10^{-4}	$< 1.4\times10^{-1}$ $< 1.0\times10^{-1}$	$< 1.3\times10^{-2}$ $< 5\times10^{-2}$
$\nu_\mu \to \nu_\mu$	CCFR84 CDHS	6×10^{0} 3×10^{-1}	none none	$< 2\times10^{-1}$ $< 5.3\times10^{-1}$

Oscillation Analysis

Using data from short baseline experiments:

- Start with ν_μ, ν_e *unoscillated* signal predictions from:

Dataset:	LSND	KARMEN	NOMAD	MB	CCFR	CDHS	CHOOZ	BUGEY	(+ atm constraint)
# of bins:	5	9	30	8	18	15	14	60	(1)

appearance experiments $\nu_\mu \to \nu_e$

disappearance experiments $\nu_\mu \to \nu_\mu, \nu_e \to \nu_e$

- Generate model parameters (importance sampling via *Markov chain*)

$(\Delta m^2, U_{ei}, U_{\mu i}, \varphi_{CP})$

Model acceptance probability:

$$P(x_i \to x_{i+1}) = \min\{1, \exp[-(\chi^2_{i+1} - \chi^2_i)/T]\}$$

$$x_{i+1} = x_i + e$$

- For each set of parameters,
  - get signal prediction after oscillation/disappearance for all experiments considered
  - compare signal prediction to experimental data and calculate χ^2, goodness-of-fit for each experiment considered, and combined χ^2, goodness-of-fit
  - determine allowed regions by Gaussian approx.

Oscillation Analysis

3+n model parameter assumptions:

Approximation: $m_1 \approx m_2 \approx m_3 \approx 0$

→ n independent mass splittings: $\Delta m_{41}^2 = m_4^2, \Delta m_{51}^2 = m_5^2, \ldots$

$2n$ moduli of mixing parameters: U_{e4}, $U_{\mu 4}$, ...

n-1 Dirac CPV phases

$0.1eV^2 \leq \Delta m_{ij}^2 \leq 100eV^2$ (motivated by LSND signal)

$U_{ei}^2 + U_{\mu i}^2 \leq 0.5, U_{\alpha 4}^2 + U_{\alpha 5}^2 \leq 0.5$ (imposed by atm and solar data)

Atmospheric constraint:

upper limit: $d_\mu \square U_{\mu 4}^2 + U_{\mu 5}^2$

$\chi_{atm}^2(d_\mu)/1dof$

[M. Maltoni, et al., hep-ph/0405172]

CP violation option:

Fix $\varphi = 0, \pi$, *or allow to vary within* $(0, 2\pi)$

For example, for 3+2 oscillations:

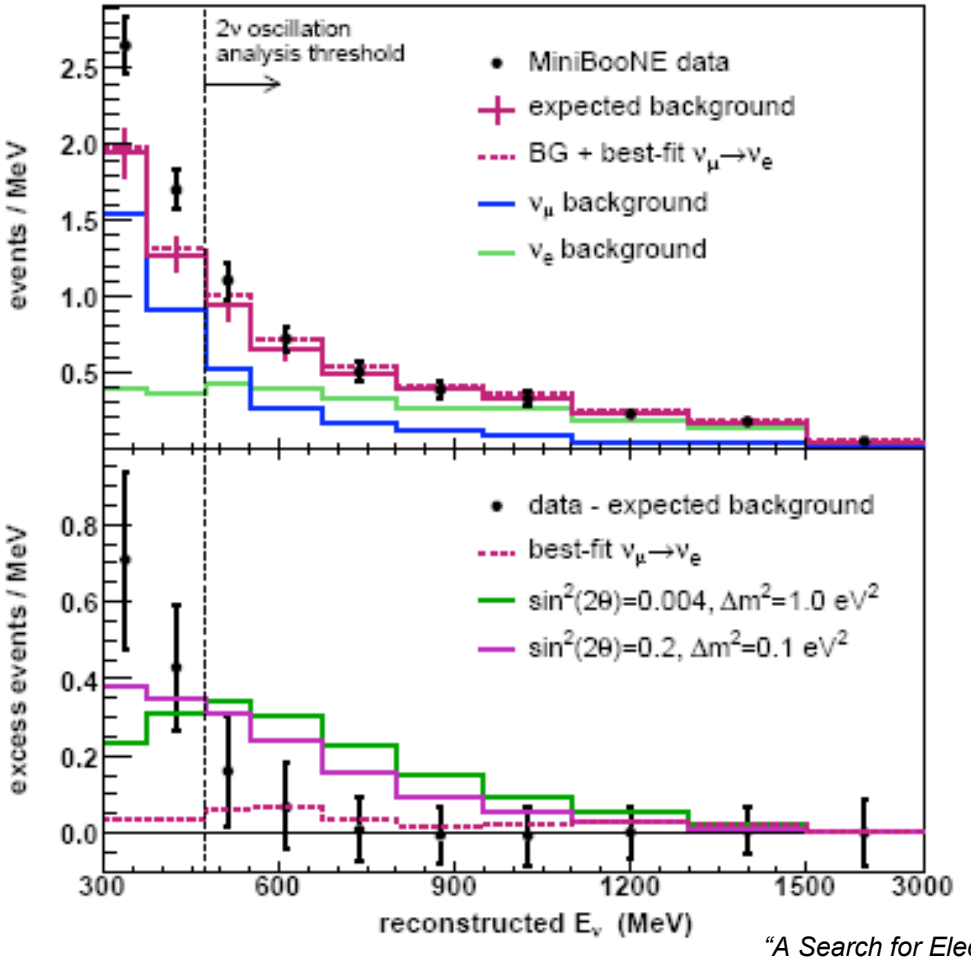
2 indep. mass splittings: $\Delta m_{41}^2, \Delta m_{51}^2$

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

1 CPV phase: $\varphi_{45} = \arg(U_{\mu 5}^* U_{e5} U_{\mu 4} U_{e4}^*)$

No CPV allowed for 3+1 models!

Constraints from MiniBooNE



Recent MiniBooNE result implies that MiniBooNE is **incompatible** with LSND within **2-neutrino oscillation hypothesis**.

[see talk by C. Polly]

Calls for more complicated oscillation scenario (e.g., 3+2, CPV, …) in order to reconcile the two results.

Interested in "low-E excess" and implications for 3+n → We consider the full energy range data (300 MeV < E < 3000 MeV) in our analysis.

"A Search for Electron Neutrino Appearance at the $\Delta m^2 \sim 1eV^2$ Scale," The MiniBooNE Collaboration [hep-ex/0704.1500].

MiniBooNE Dataset

Allow both:	$\nu_\mu \to \nu_s \to \nu_e$	($\nu_\mu \to \nu_e$ **oscillations**)	
and:	$\nu_\mu \to \nu_s$ $\nu_e \to \nu_s$	(ν_μ ***disappearance***) (ν_e ***background disappearance***)	**NEW!!!**

Use a **ratio** method:

Compare: ν_e/ν_μ **ratio** from **MC prediction** (first principles) after applying $\nu_\mu \to \nu_e$ oscillation, ν_μ disappearance, ν_e disappearance

to: ν_e/ν_μ **ratio** from **data**

MC prediction =

$$\frac{(\nu_\mu^{misID})P(\nu_\mu \to \nu_\mu) + (\nu_e^{full-osc.})P(\nu_\mu \to \nu_e) + (\bar{\nu}_e^{full-osc.})P(\bar{\nu}_\mu \to \bar{\nu}_e) + (\nu_e^{intrins.})P(\nu_e \to \nu_e)}{(\nu_\mu)P(\nu_\mu \to \nu_\mu)}$$

ν_e's with ν_μ energy spectrum
(full $\nu_\mu \to \nu_e$ conversion;
takes into account different cross sections)

intrinsic ν_e's ~0.5% of beam

full MiniBooNE error matrix (scaled to MC prediction)
[see talk by K. Mahn]

$$\chi^2_{\mathrm{BooNE}} = \sum [(\nu_e/\nu_\mu)_{Data} - (\nu_e/\nu_\mu)_{MC,osc}]_i M^{-1}_{ij} \sum [(\nu_e/\nu_\mu)_{Data} - (\nu_e/\nu_\mu)_{MC,osc}]_j$$

$$n^{bins}{}_{BooNE} = 8, \qquad ndf_{BooNE} = n^{bins}{}_{BooNE} - 2n^{sterile} - 2n^{sterile} - (n^{sterile}-1)$$

CPV case

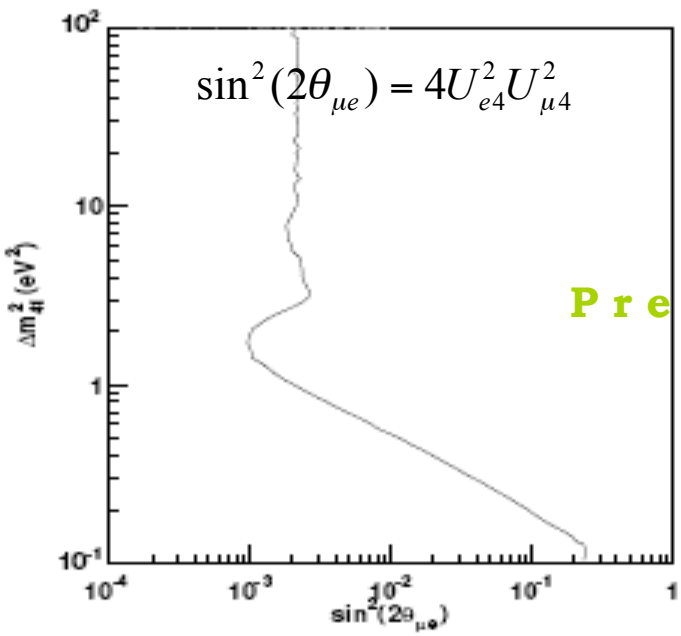
Preliminary Oscillation Results: 3+1

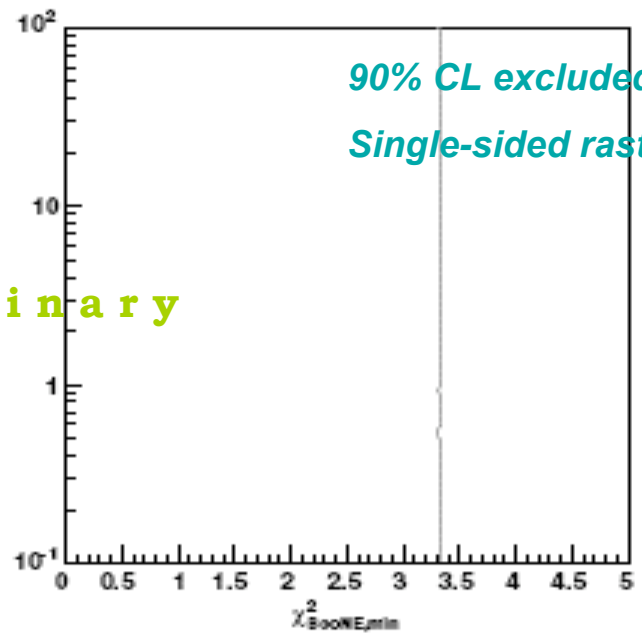
3+1 already excluded from previous studies (independent of MiniBooNE result)

[See, e.g.: M. Sorel, et al., hep-ph/0305255 and talk by T. Schwetz]

MiniBooNE $\nu_\mu \to \nu_e$ **oscillation** upper limits in 3+1 scenario:

$$\frac{(\nu_\mu^{misID})\cancelto{1}{P(\nu_\mu \to \nu_\mu)} + (\nu_e^{full-osc.})P(\nu_\mu \to \nu_e) + (\bar{\nu}_e^{full-osc.})P(\bar{\nu}_\mu \to \bar{\nu}_e) + (\nu_e^{intrins.})\cancelto{1}{P(\nu_e \to \nu_e)}}{(\nu_\mu)\cancelto{1}{P(\nu_\mu \to \nu_\mu)}}$$





Preliminary Oscillation Results: 3+1

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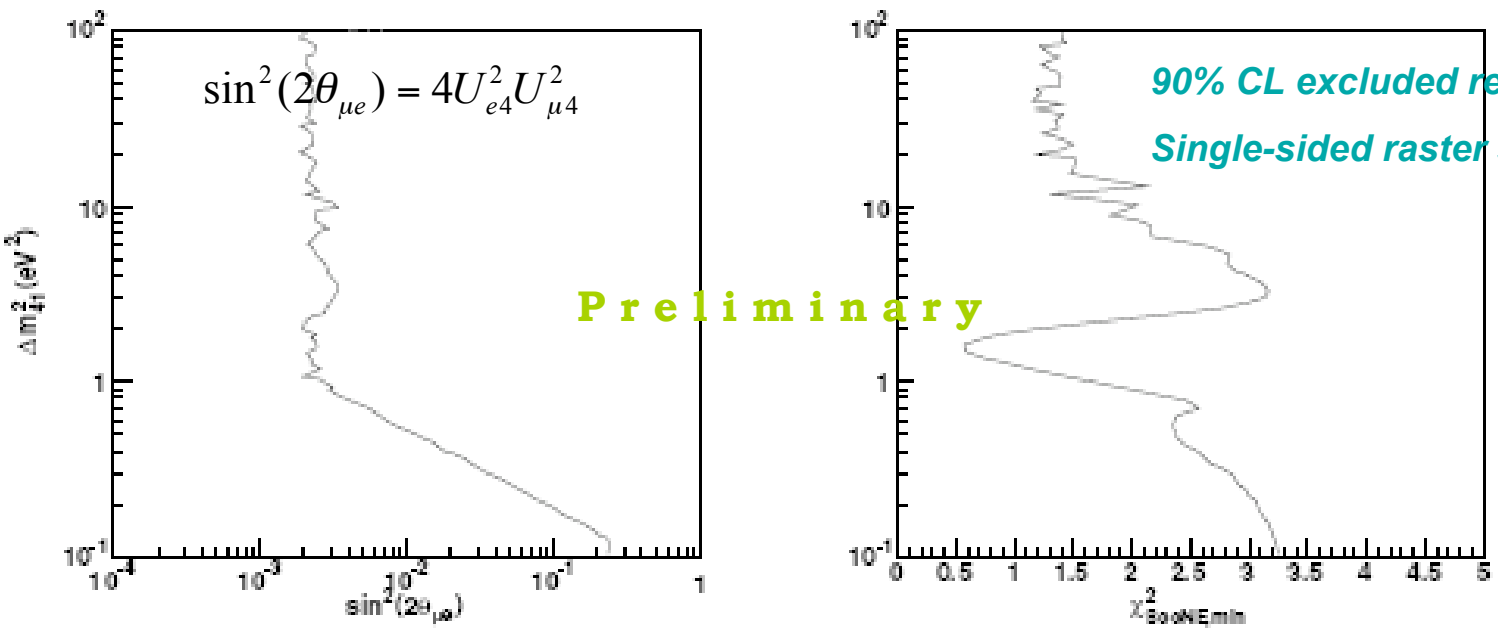
[See, e.g.: M. Sorel, et al., hep-ph/0305255 and talk by T. Schwetz]

MiniBooNE $\nu_\mu \rightarrow \nu_e$ **oscillation** upper limits in 3+1 scenario:

$$\frac{(\nu_\mu^{misID})P(\nu_\mu \rightarrow \nu_\mu) + (\nu_e^{full-osc.})P(\nu_\mu \rightarrow \nu_e) + (\bar{\nu}_e^{full-osc.})P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) + (\nu_e^{intrins.})P(\nu_e \rightarrow \nu_e)}{(\nu_\mu)P(\nu_\mu \rightarrow \nu_\mu)}$$



90% CL excluded regions

Single-sided raster scan, 2 dof

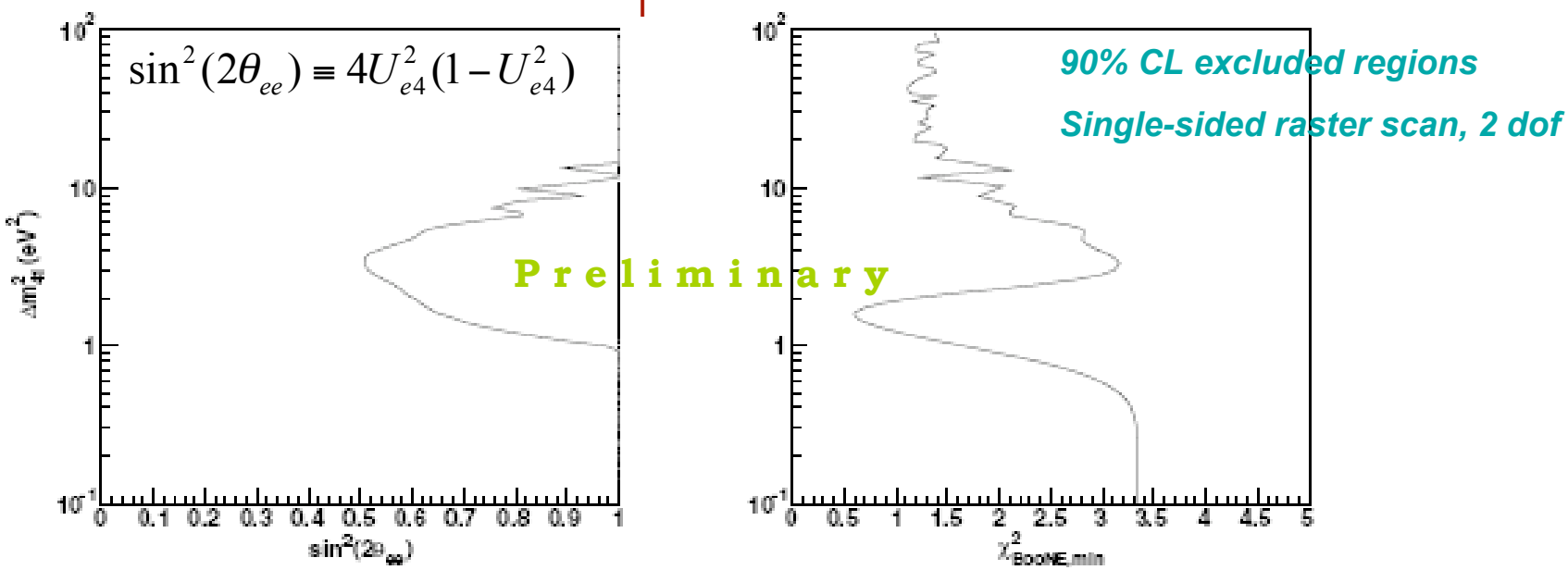
Preliminary Oscillation Results: 3+1

3+1 already excluded from previous studies (independent of MiniBooNE result)

[See, e.g.: M. Sorel, et al., hep-ph/0305255]

MiniBooNE ν_e **disappearance** upper limits in 3+1 scenario:

$$\frac{(\nu_\mu^{misID})\overset{1}{P(\nu_\mu \to \nu_\mu)} + (\nu_e^{full-osc.})\overset{0}{P(\nu_\mu \to \nu_e)} + (\bar{\nu}_e^{full-osc.})\overset{0}{P(\bar{\nu}_\mu \to \bar{\nu}_e)} + (\nu_e^{intrins.})P(\nu_e \to \nu_e)}{(\nu_\mu)\underset{1}{P(\nu_\mu \to \nu_\mu)}}$$



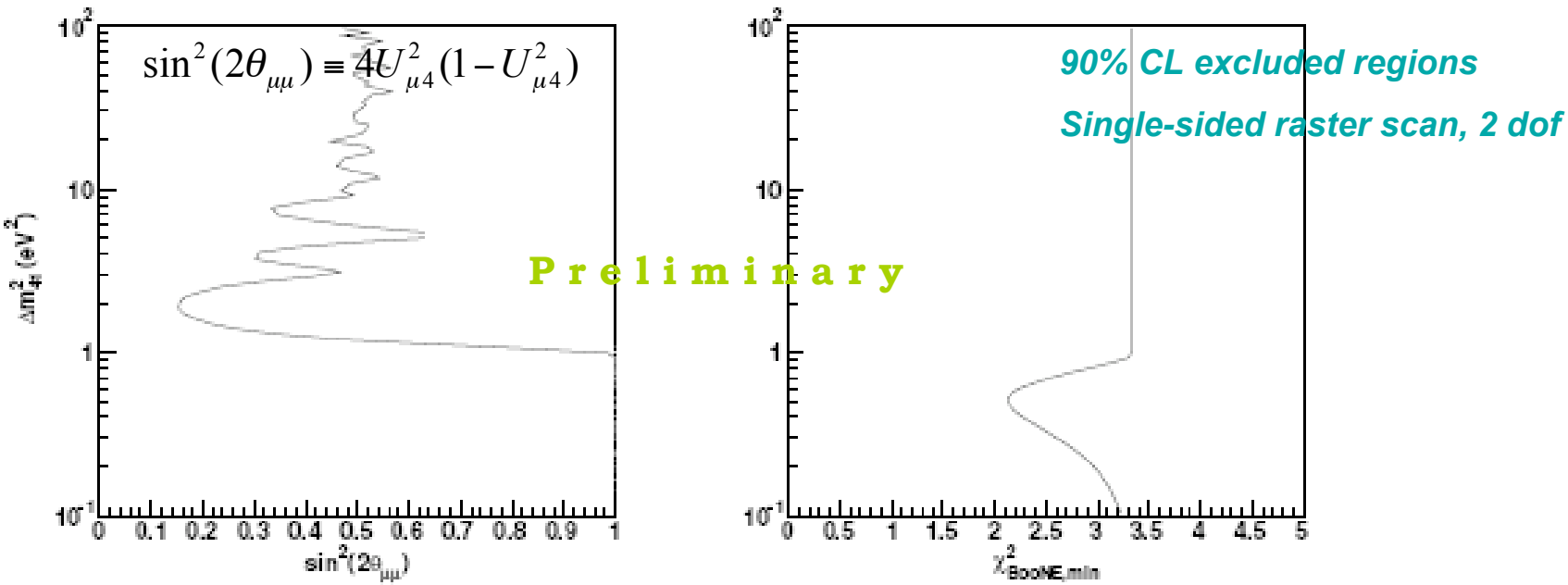
Preliminary Oscillation Results: 3+1

3+1 already excluded from previous studies (independent of MiniBooNE result)

[See, e.g.: M. Sorel, et al., hep-ph/0305255]

MiniBooNE ν_μ **disappearance** upper limits in 3+1 scenario:

$$\frac{(\nu_\mu^{misID})P(\nu_\mu \to \nu_\mu) + (\nu_e^{full-osc.})\overset{0}{P(\nu_\mu \to \nu_e)} + (\bar{\nu}_e^{full-osc.})\overset{0}{P(\bar{\nu}_\mu \to \bar{\nu}_e)} + (\nu_e^{intrins.})\overset{1}{P(\nu_e \to \nu_e)}}{(\nu_\mu)P(\nu_\mu \to \nu_\mu)}$$



Preliminary Oscillation Results: 3+2

For comparison, we show 2 analyses:

- MiniBooNE data with $\nu_\mu \rightarrow \nu_e$ **oscillations only**

- MiniBooNE data with $\nu_\mu \rightarrow \nu_e$ oscillations **and** ν_e **and** ν_μ **disappearance**

In both cases we show results from fits with:

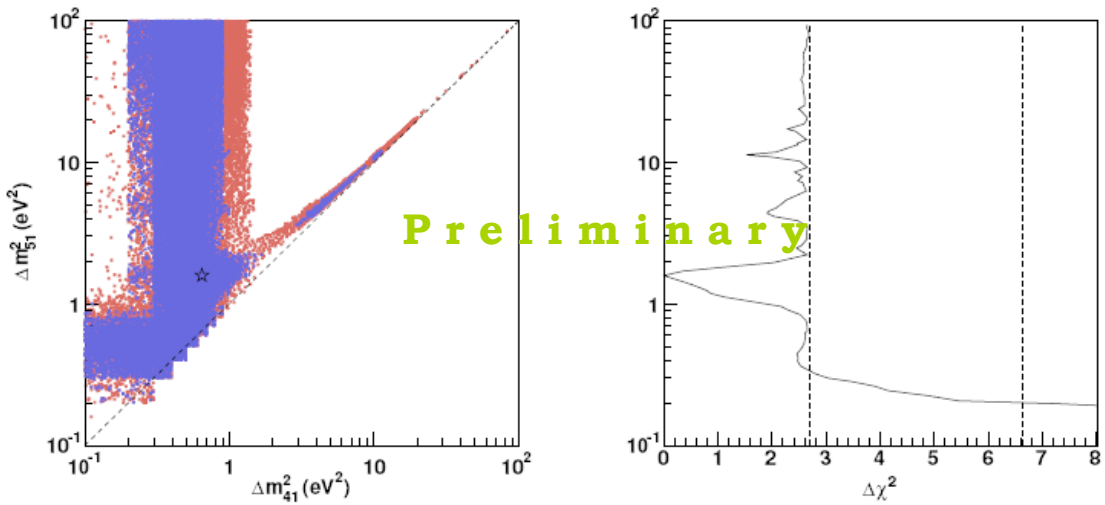
- Appearance only experiments
- All experiments combined

Preliminary Oscillation Results: 3+2

Allowing Only $\nu_\mu \rightarrow \nu_e$ **Oscillations** in MiniBooNE Data

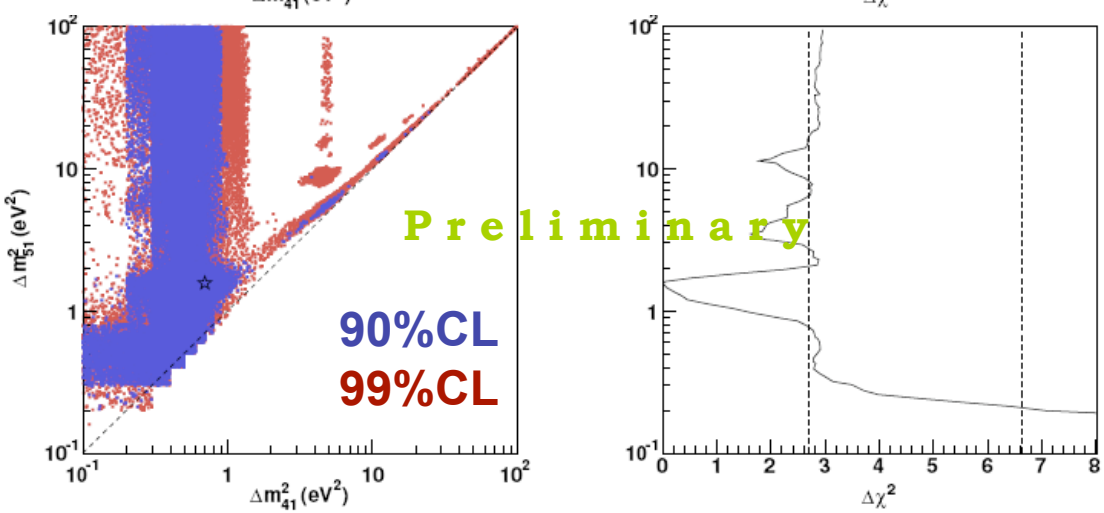
Appearance-only experiments: KARMEN, MB, LSND, NOMAD

CPC



$$\chi^2 / ndf = 52.6/52$$
$$gof = prob(\chi^2, ndf) = 45\%$$

CPV

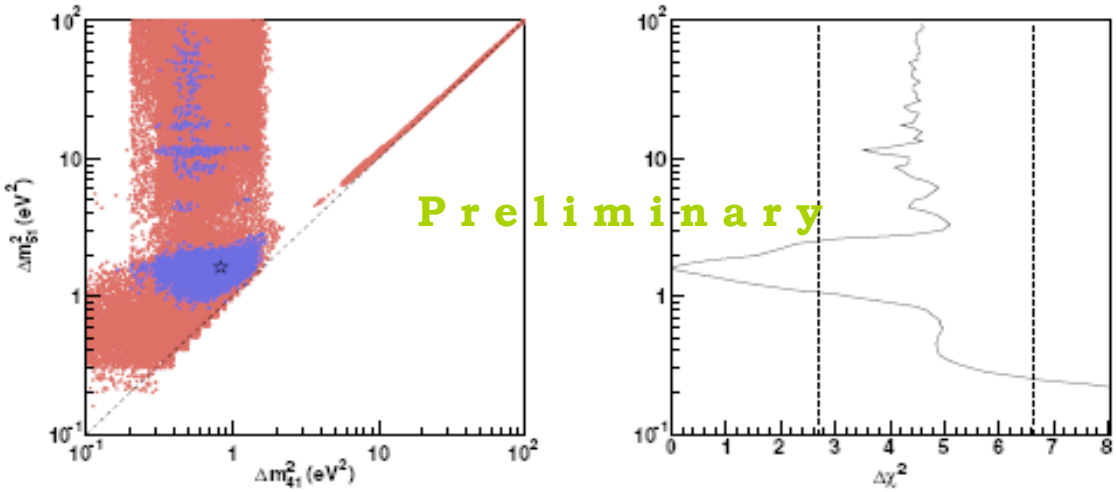


$$\chi^2 / ndf = 52.3/51$$
$$gof = prob(\chi^2, ndf) = 42\%$$
$$\varphi_{45}^{best} = 1.07\pi$$

Preliminary Oscillation Results: 3+2
Allowing ν_e and ν_μ Disappearance Also

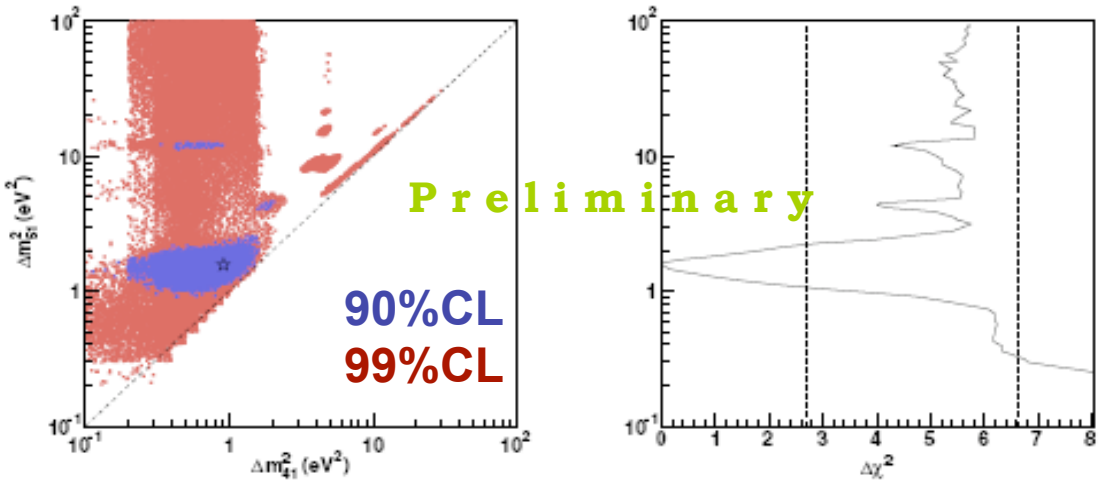
Appearance-only experiments: KARMEN, MB, LSND, NOMAD

CPC



$$\chi^2 / ndf = 50.1/48$$
$$gof = prob(\chi^2, ndf) = 39\%$$

CPV



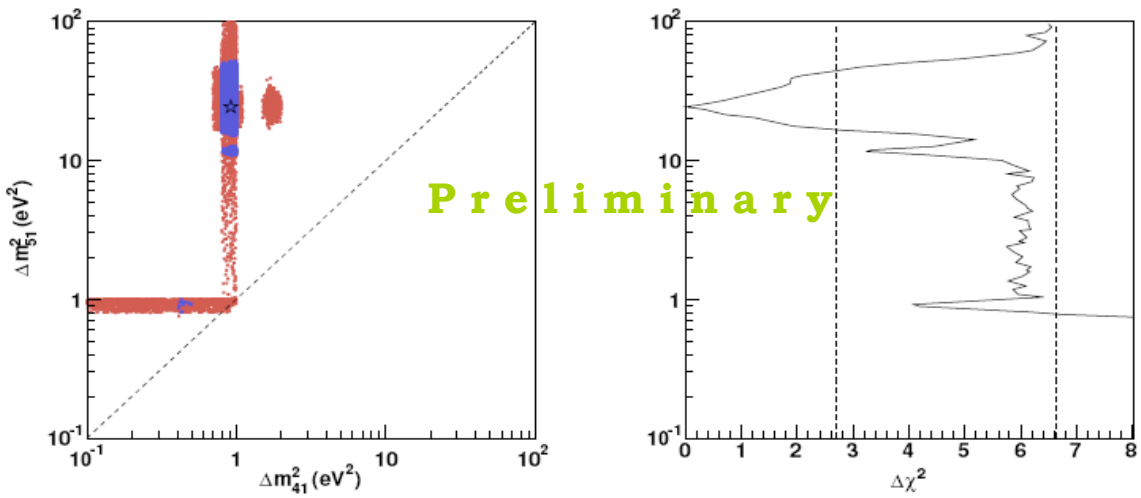
$$\chi^2 / ndf = 48.8/47$$
$$gof = prob(\chi^2, ndf) = 40\%$$
$$\varphi_{45}^{best} = 1.12\pi$$

Preliminary Oscillation Results: 3+2

Allowing Only $\nu_\mu \rightarrow \nu_e$ **Oscillations** in MiniBooNE Data

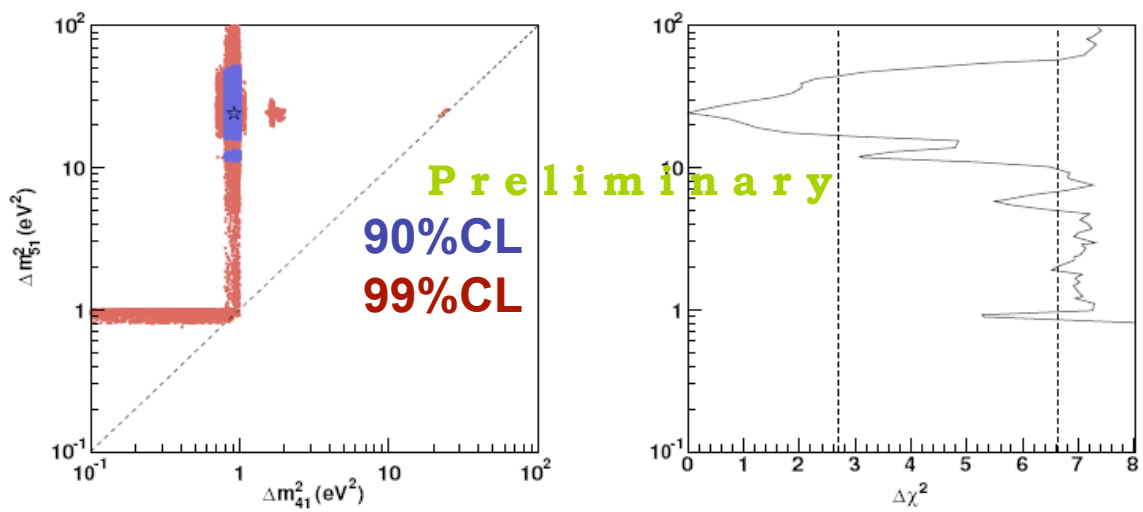
Combined analysis: all experiments

CPC



$$\chi^2 / ndf = 147.9/157$$
$$gof = prob(\chi^2, ndf) = 69\%$$

CPV

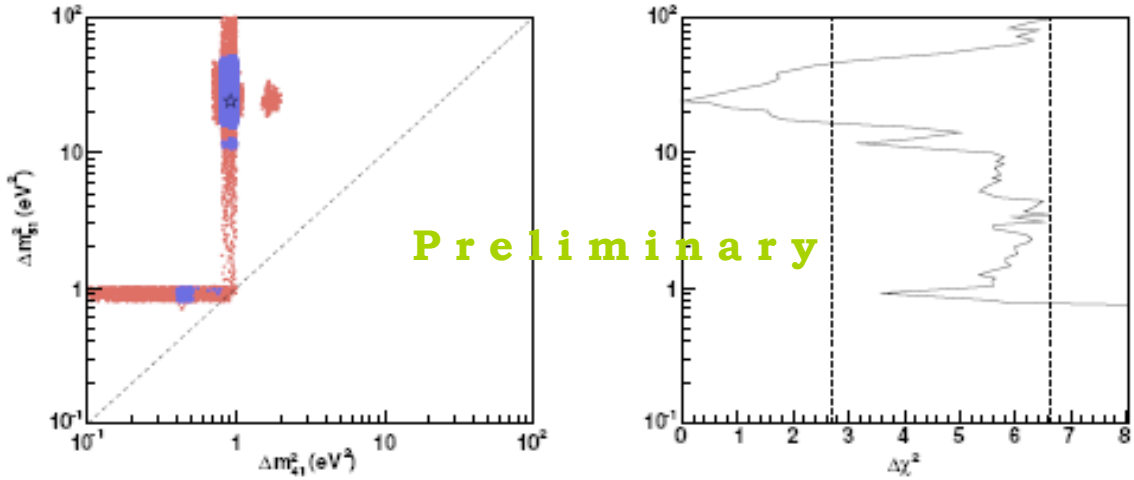


$$\chi^2 / ndf = 146.7/156$$
$$gof = prob(\chi^2, ndf) = 69\%$$
$$\varphi_{45}^{best} = 1.74\pi$$

Preliminary Oscillation Results: 3+2
Allowing ν_e and ν_μ Disappearance Also

Combined analysis: all experiments

CPC



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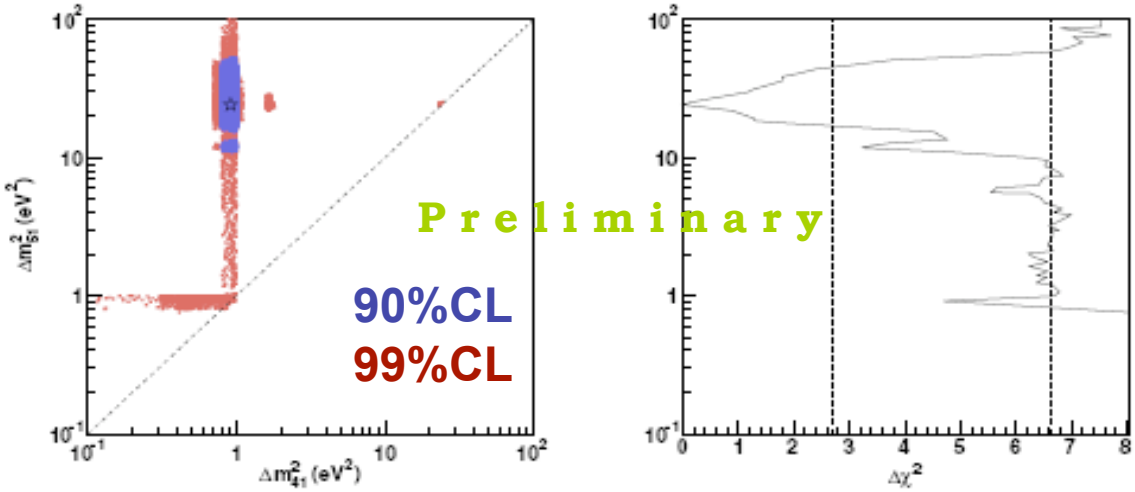
CPV

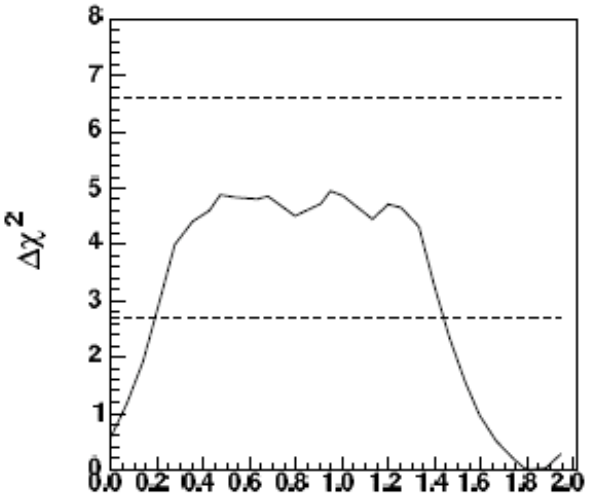


$$\chi^2 / ndf = 146.8/156$$
$$gof = prob(\chi^2, ndf) = 69\%$$
$$\varphi_{45}^{best} = 1.72\pi$$

General Remarks for 3+2

- There are allowed 3+2 regions
- Allowing ν_e and ν_μ disappearance along with $\nu_\mu \rightarrow \nu_e$ oscillations to describe MiniBooNE data does not seem to either favor or disfavor combined fits, compared to only allowing $\nu_\mu \rightarrow \nu_e$
- There is no preference for CPC vs. CPV scheme
  - Best fit models:
    - CPC combined analysis: $\Delta m_{41}^2 = 0.91 eV^2, \Delta m_{41}^2 = 24 eV^2$
      $U_{e4} = 0.13, U_{\mu 4} = 0.15$
      $U_{e5} = 0.07, U_{\mu 5} = 0.16$
    - CPV combined analysis: $\Delta m_{41}^2 = 0.91 eV^2, \Delta m_{41}^2 = 24 eV^2$
      $U_{e4} = 0.12, U_{\mu 4} = 0.14$
      $U_{e5} = 0.07, U_{\mu 5} = 0.17$
      $\varphi_{45} = 1.72\pi$

CP-Violation: Implications for MiniBooNE

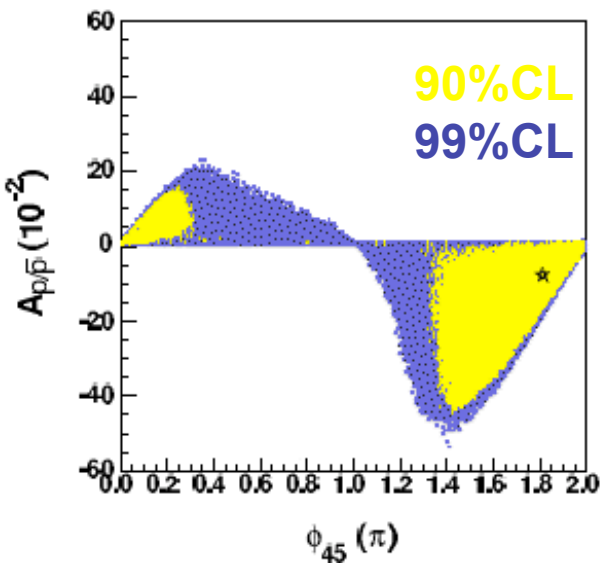


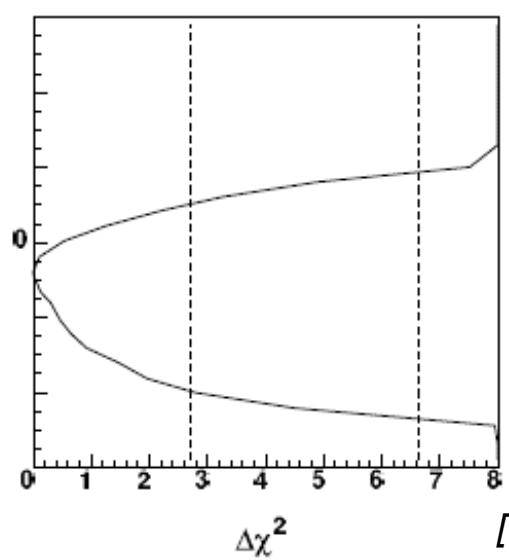
Allowed MiniBooNE **oscillation probability asymmetry** within 3+2 oscillation scenario:

$$A_{p/\bar{p}} = \frac{p_{BooNE} - \bar{p}_{BooNE}}{p_{BooNE} + \bar{p}_{BooNE}}$$

$$\overset{(-)}{p}_{BooNE} = \frac{\int dE[P(\nu_\mu \to \nu_e)\overset{(-)}{N}_0(\nu) + P(\bar{\nu}_\mu \to \bar{\nu}_e)\overset{(-)}{N}_0(\bar{\nu})]}{\int dE[\overset{(-)}{N}_0(\nu) + \overset{(-)}{N}_0(\bar{\nu})]}$$

MC predicted MiniBooNE $\nu_\mu \to \nu_e$ full-osc rates

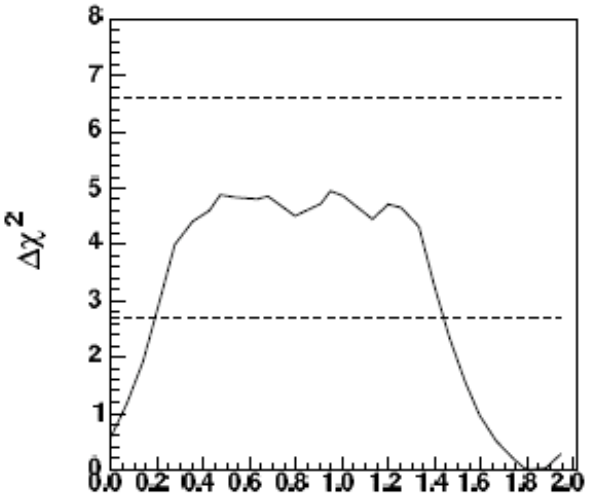




Allowed region obtained using constraints from null SBL + LSND experiments only

[G. K. et al., hep-ph/0609177].

CP-Violation: Implications for MiniBooNE



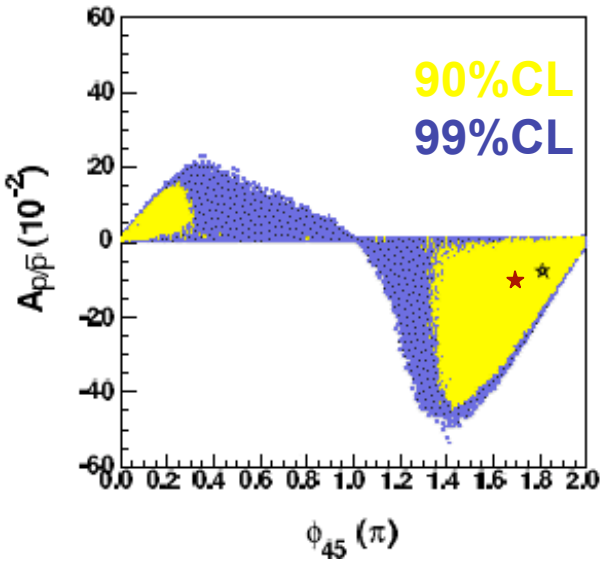
- MiniBooNE asymmetry predicted based on 3+2 best fit model for CPV combined analysis:

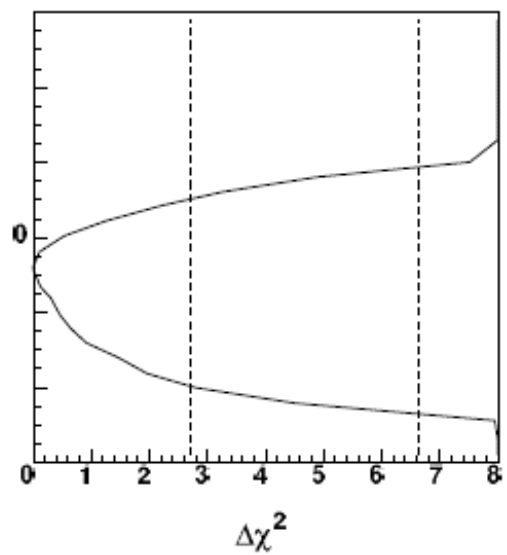
$$A_{p/\bar{p}} = \frac{p_{BooNE} - \bar{p}_{BooNE}}{p_{BooNE} + \bar{p}_{BooNE}} = -12\%$$

$$p_{BooNE} = 0.08\%$$

$$\bar{p}_{BooNE} = 0.10\%$$

$$\varphi_{45} = 1.72\pi$$





Asymmetry significance ~ 1σ
assuming 6x10^{20} POT in both neutrino and antineutrino running mode

(data collected as of now:
neutrino mode: 7.0x10^{20} POT
antineutrino mode: 2.4x10^{20} POT)

Conclusions

- Both CPC and CPV 3+2 oscillation scenarios are allowed by a combined analysis of SBL data, including LSND and MiniBooNE
- MiniBooNE provides strong limits on $\nu_\mu \rightarrow \nu_e$ oscillations and limits on ν_e and ν_μ disappearance within a 3+1 hypothesis

- MiniBooNE data: important in addressing the viability of sterile neutrino models
- Leptonic CP-violation possibility opened up in the 3+2 sterile neutrino hypothesis could have measurable effects at MiniBooNE
  - A longer running in anti-neutrino mode would allow more detailed studies of CPV scenario and more confident determination of a possible CPV phase