New MiniBooNE results and non-standard neutrino interactions

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MiniBooNE: a dedicated experiment to test the LSND claim of $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance.

Neutrino mode run: no evidence for ν_e appearance, but an unexplained excess of low-E ($E < 475$ MeV) events

Antineutrino mode run: excess (43.2 ± 22.5) of $\bar{\nu}_e$ events in the full energy range $200 < E_\nu < 3000$ MeV.

In the 'oscillations-sensitive' region $475 < E_\nu < 1250$ MeV, the probability of background-only hypothsis is 0.5%. Results are in agreement with those of LSND.

No significant excess of low-E events observed in $\bar{\nu}$ channel.

The goal of this study: assuming the MiniBooNE results are due to some new physics, try to describe them in the $(3+1)$ NSI framework.

The framework

To reconcile the evidence of $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance with absence of the appearance in the neutrino mode, one needs CP (or even CPT) violation.

To describe transitions in an oscillation scenario, at least one extra (sterile) neutrino is necessary with $\Delta m^2 \sim 1\ \mathrm{eV}^2$.

In the minimal (3+1) scheme – no CPV in short-baseline experiments $\Rightarrow$ we add NSI. (Another option – (3+2) scenario).

For $L \lesssim 1\ \mathrm{km}$ matter effects on neutrino propagtion are negligible $\Rightarrow$ consider CC-like NSI that contribute to neutrino production and detection mechansims:

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2} G_F \sum_{\alpha,\beta} \varepsilon_{\alpha\beta}^{ff'} (\bar{f} P_{L,R} \gamma^\mu f')(\bar{l}_\alpha P_L \gamma_\mu \nu_\beta) + h.c.\,.$$

The neutrino state $|\nu_\alpha^X\rangle$ produced or detected along with a charged lepton l_α:

$$\diamondsuit \qquad |\nu_\alpha^X\rangle = C_\alpha^X \Big(|\nu_\alpha\rangle + \sum_\beta \varepsilon_{\alpha\beta}^X |\nu_\beta\rangle\Big) \qquad (\alpha, \beta = e, \mu, \tau, s).$$

The formalism

Normalisation condition:

$$|C^X_\alpha|^2\Big(1+2\mathrm{Re}\,\varepsilon^X_{\alpha\alpha}+\sum_\rho|\varepsilon^X_{\alpha\rho}|^2\Big)=1\,.$$

In terms of mass eigenstates $\nu_i \;\; (i=1,...,4)$:

$$|\nu^X_\alpha\rangle \;=\; C^X_\alpha\sum_i\Big(U^*_{\alpha i}+\sum_\beta\varepsilon^X_{\alpha\beta}U^*_{\beta i}\Big)|\nu_i\rangle \;=\; C^X_\alpha\sum_{\beta,i}\left(\delta_{\alpha\beta}+\varepsilon^X_{\alpha\beta}\right)U^*_{\beta i}|\nu_i\rangle\,.$$

Transition amplitude:

$$\mathcal{A}_{\alpha\beta}(L)=\langle\nu^D_\beta|\nu^S_\alpha(L)\rangle=\sum_i F^S_{\alpha i}F^{D\,*}_{\beta i}e^{-iE_iL}\,,\qquad \text{where}$$

$$\boxed{F^X_{\alpha i}\equiv C^X_\alpha\sum_\rho\left(\delta_{\alpha\rho}+\varepsilon^X_{\alpha\rho}\right)U^*_{\rho i}\,.}$$

$L\lesssim 1\ \mathrm{km} \quad \Rightarrow \quad$ neglect all Δm^2 except those involving ν_4 ;

$$\Delta\equiv\frac{\Delta m^2_{41}}{2E}L$$

The formalism – contd.

The transition amplitude takes the form

$$\mathcal{A}_{\alpha\beta}(L) = \alpha_{\alpha\beta}(e^{-i\Delta} - 1) + \beta_{\alpha\beta}\,,$$

where

$$\alpha_{\alpha\beta} = F^S_{\alpha 4} F^{D*}_{\beta 4}\,, \qquad\qquad \beta_{\alpha\beta} = \sum_i F^S_{\alpha i} F^{D*}_{\beta i}\,.$$

The transition probability $P_{\alpha\beta}(L) = |\mathcal{A}_{\alpha\beta}(L)|^2$:

$$\boxed{P_{\alpha\beta}(L) = 2\left[|\alpha_{\alpha\beta}|^2 - \mathrm{Re}(\beta^*_{\alpha\beta}\alpha_{\alpha\beta})\right](1-\cos\Delta) + |\beta_{\alpha\beta}|^2 + 2\mathrm{Im}(\beta^*_{\alpha\beta}\alpha_{\alpha\beta})\sin\Delta}$$

Last term is CP-odd. Note:

$$P_{\alpha\beta}(L=0) = |\beta_{\alpha\beta}|^2$$

$\Rightarrow$ Non-trivial zero-distance effects possible (e.g., nonzero appearance probability at $L=0$).

The formalism – contd.

1. Disappearance experiments (P_{ee} and $P_{\mu\mu}$)

P_{ee} (reactor experiments): same NSI types at production and detection (β decay and inv. β decay) $\Rightarrow$ $\varepsilon^S_{e\alpha} = \varepsilon^D_{e\alpha}$

For ν_μ disappearance (CDHS and atm): prod. and det. typically both involve ud quarks (semi-leptonic). Prod. – pion decay (but: atm.), pure axial-vector (A) NSI; detection – $\nu_\mu N$ capture, can be both V and A. Still, for simplicity assume also for now

$$\varepsilon^S_{\mu\alpha} = \varepsilon^D_{\mu\alpha}$$

(relaxing this does not lead to a significant numerical effect).

$$\Rightarrow \qquad \alpha_{ee} \equiv \alpha_e = |F^{ud}_{e4}|^2\,, \qquad \alpha_{\mu\mu} \equiv \alpha_\mu = |F^{ud}_{\mu 4}|^2\,, \qquad \beta_{ee} = \beta_{\mu\mu} = 1.$$

Survival probabilities:

$$\boxed{P_{\beta\beta} = 1 - 2\alpha_\beta(1-\alpha_\beta)(1-\cos\Delta)}$$

No CPV, $P_{\beta\beta}(L=0) = 1$ – consequences of $\varepsilon^S = \varepsilon^D$; $\alpha_\beta \Rightarrow |U_{\beta 4}|$ of (3+1).

The formalism – contd.

2. Appearance experiments ($\mu \to e$):

$$\alpha_{\mu e} = F^S_{\mu 4} F^{D*}_{e4}\,,$$

$$F^S_{\mu 4} = C^S_\mu \left(U^*_{\mu 4} + \varepsilon^S_{\mu e} U^*_{e4} + \varepsilon^S_{\mu\mu} U^*_{\mu 4} + \varepsilon^S_{\mu\tau} U^*_{\tau 4} + \varepsilon^S_{\mu s} U^*_{s4}\right),$$

$$F^D_{e4} = C^D_e \left(U^*_{e4} + \varepsilon^D_{ee} U^*_{e4} + \varepsilon^D_{e\mu} U^*_{\mu 4} + \varepsilon^D_{e\tau} U^*_{\tau 4} + \varepsilon^D_{es} U^*_{s4}\right).$$

The parameter $\beta_{\mu e}$:

$$\beta_{\mu e} = \sum_i F^S_{\mu i} F^{D*}_{ei} = C^S_\mu C^{D*}_e \Big(\varepsilon^S_{\mu e} + \varepsilon^{D*}_{e\mu} + \sum_\rho \varepsilon^S_{\mu\rho} \varepsilon^{D*}_{e\rho}\Big).$$

Under the assumption $\varepsilon^S_{\alpha\beta} = \varepsilon^D_{\alpha\beta}$: factorization $|\alpha_{\mu e}| = \sqrt{\alpha_e \alpha_\mu}$.

Groups of expts. and parameter choices

1. All expts. except LSND and KARMEN: depend on semi-leptonic NSI.
Assuming $\varepsilon^S_{\alpha\beta} = \varepsilon^D_{\alpha\beta}$ ($\Rightarrow$ $|\alpha_{\mu e}| = \sqrt{\alpha_e \alpha_\mu}$) – depend on 5 parameters:

$$\alpha_e, \;\; \alpha_\mu, \; |\beta_{\mu e}|, \;\; \delta \equiv \mathrm{Arg}\left(\alpha_{\mu e}\beta^*_{\mu e}\right), \; \Delta m^2_{41} \, .$$

2. LSND and KARMEN: purely leptonic NSI also contribute, while semi-leptonic NSI involving the charged muon, $\varepsilon^{ud}_{\mu\alpha}$, contribute to the other experiments but not to LSND and KARMEN $\Rightarrow$
Effectively leads to a decoupling from the other experiments. LSND and KARMEN can be described by the three independent parameters

$$|\alpha^{\rm LK}_{\mu e}|, \;\; |\beta^{\rm LK}_{\mu e}|, \;\; \delta^{LK} \equiv \mathrm{Arg}(\alpha^{\rm LK}_{\mu e}\beta^{\rm LK *}_{\mu e})$$

in addition to the common Δm^2_{41}.

N.B.: In this framework MiniBooNE cannot be considered as a direct test of LSND, due to the different production mechanisms.

Parameter choices – contd.

Two cases considered: NSI^g ('general') and NSI^c ('constrained').

1. General (3+1) NSI scheme – different ε-parameters for (KARMEN+LSND) and the rest (for which $\varepsilon^S_{\mu\alpha} = \varepsilon^D_{\mu\alpha}$ still assumed, leading to $F^S_{\alpha i} = F^D_{\alpha i} \equiv F^{ud}_{\alpha i}$ and the factorization $|\alpha_{\mu e}| = \sqrt{\alpha_e \alpha_\mu}$ – can be relaxed). Depends on 8 parameters.

2. Constrained case (NSI^c): Assuming $F^S_{\alpha i} = F^D_{\alpha i} \equiv F^{ud}_{\alpha i}$ holds for the global data, also including LSND and KARMEN. Can be realized if all NSI parameters involving the charged muon (leptonic as well as semi-leptonic) vanish:

$$\varepsilon^X_{\mu\beta} = 0\,.$$

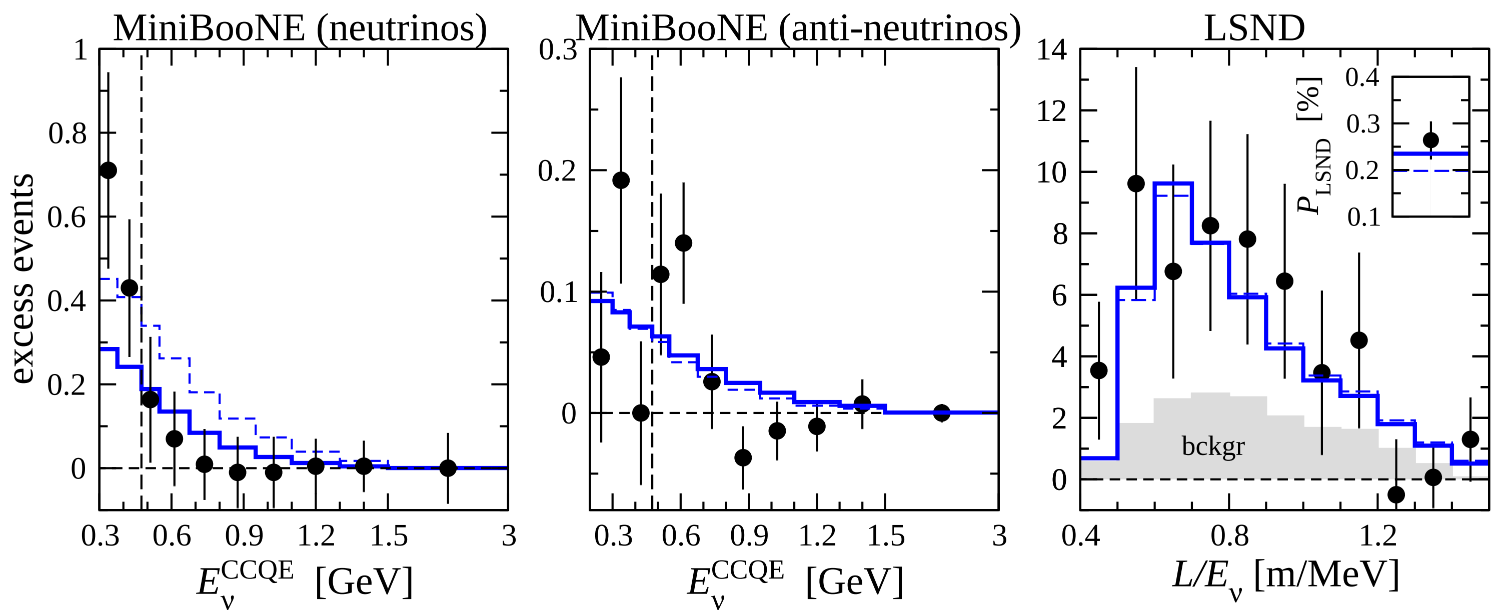
In this case $F^S_{\mu i} = F^D_{\mu i} = U^*_{\mu i}$. Since also $F^S_{ei} = F^D_{ei}$ for processes we consider, the global data depends only on the 5 parameters and the factorisation $|\alpha_{\mu e}| = \sqrt{\alpha_e \alpha_\mu}$ applies in general.

Numerical data

Used data (115 data points):

Disappearance				Appearance			
Experiment	Ref.	Channel	Data	Experiment	Ref.	Channel	Data
Bugey	[4]	$\bar{\nu}_e \to \bar{\nu}_e$	60	LSND	[2]	$\bar{\nu}_\mu \to \bar{\nu}_e$	11
Chooz	[5]	$\bar{\nu}_e \to \bar{\nu}_e$	1	KARMEN	[49]	$\bar{\nu}_\mu \to \bar{\nu}_e$	9
Palo Verde	[50]	$\bar{\nu}_e \to \bar{\nu}_e$	1	NOMAD	[51]	$\nu_\mu \to \nu_e$	1
CDHS	[6]	$\nu_\mu \to \nu_\mu$	15	MiniB (ν)	[3]	$\nu_\mu \to \nu_e$	8
atmospheric	[18]	$\nu_\mu \to \nu_\mu$	1	MiniB ($\bar{\nu}$)	[1]	$\bar{\nu}_\mu \to \bar{\nu}_e$	8

Spectra at bfp to appearance data

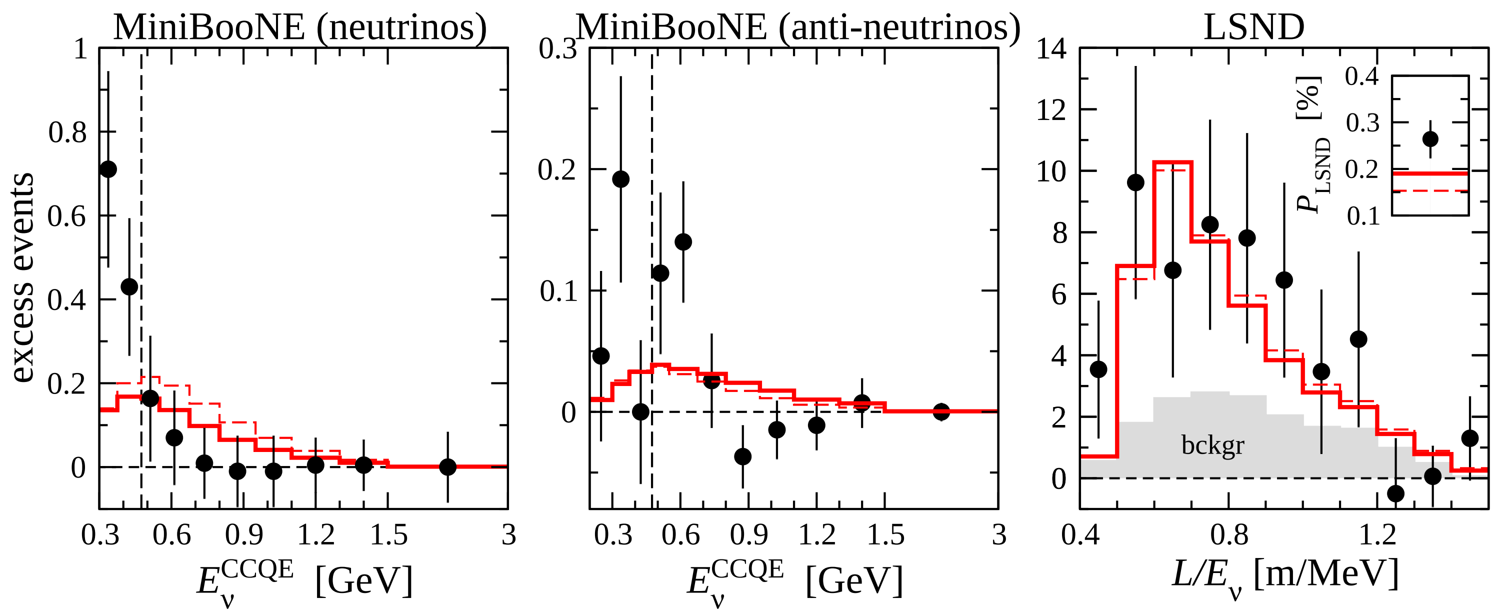


Dashed: (3+1) oscillations, solid: (3+1) NSI^c.

Data set	$\lvert\alpha_{\mu e}\rvert$	$\lvert\beta_{\mu e}\rvert$	δ	Δm^2_{41}	χ^2/dof
Appearance	0.2075	0.0091	1.5π	0.1 eV^2	$33.5/(37-4)$
Global	0.019	0.017	1.3π	0.89 eV^2	$107/(115-5)$

(3+1) NSI^c best fit parameter and χ^2 values for appearance data and global data. For global data: $\alpha_e = 0.014,\ \alpha_\mu = 0.026$ with $|\alpha_{\mu e}|^2 = \alpha_e \alpha_\mu$.

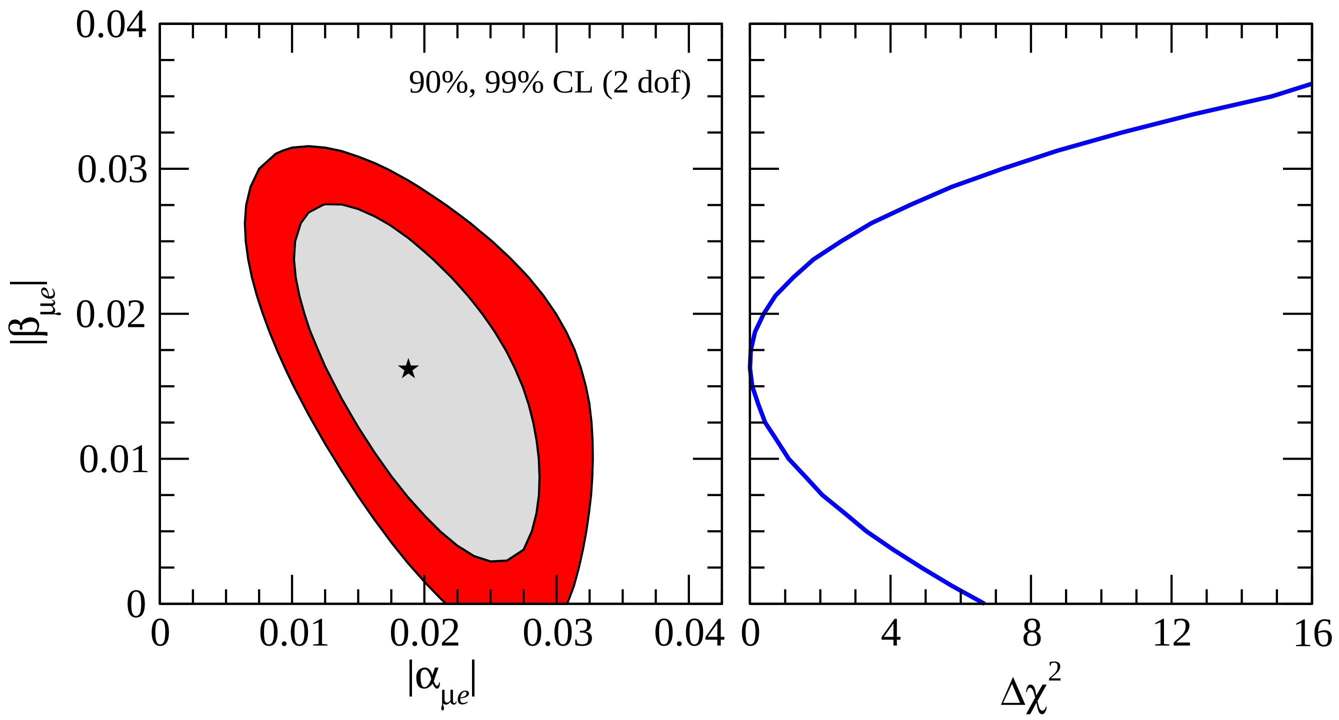
Spectra at bfp to global data



Dashed: (3+1) oscillations, solid: (3+1) NSI^c.

Constraint from disappearance data push the LSND transition probability to low values: at BFP $P_{\rm LSND} = 0.19\%$ (1.8σ away from the measured value $P_{\rm LSND}^{\rm exp} = (0.264 \pm 0.04)\%$)

Global fit in NSI^c framework

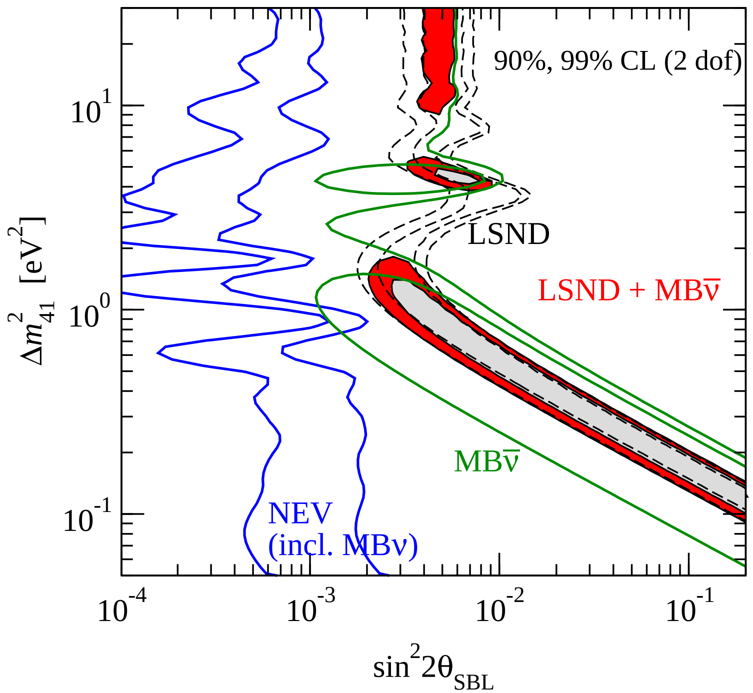


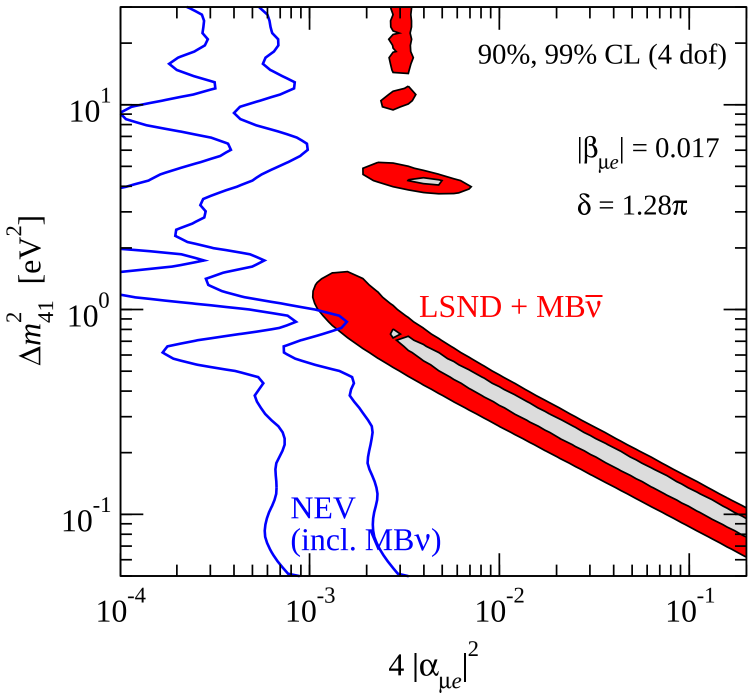
Left: allowed regions projected onto the plane of $|\alpha_{\mu e}|$ and $\beta_{\mu e}$ at 90% and 99% CL (2 dof). Right: $\Delta\chi^2$ as a function of $\beta_{\mu e}$. Minimisation done over all undisplayed parameters.

$$\chi^2_{\text{min,(3+1)osc}} - \chi^2_{\text{min,(3+1)NSI}^c} = 6.9 \qquad (2\text{dof})$$

NSI^c case favoured at 97% CL (slightly more than 2σ) compared to the pure oscillation case. Allowed interval for $|\beta_{\mu e}|$ (1 dof) does not include 0 at 2.6σ.

Comparing (3+1) and (3+1) NSI^c cases



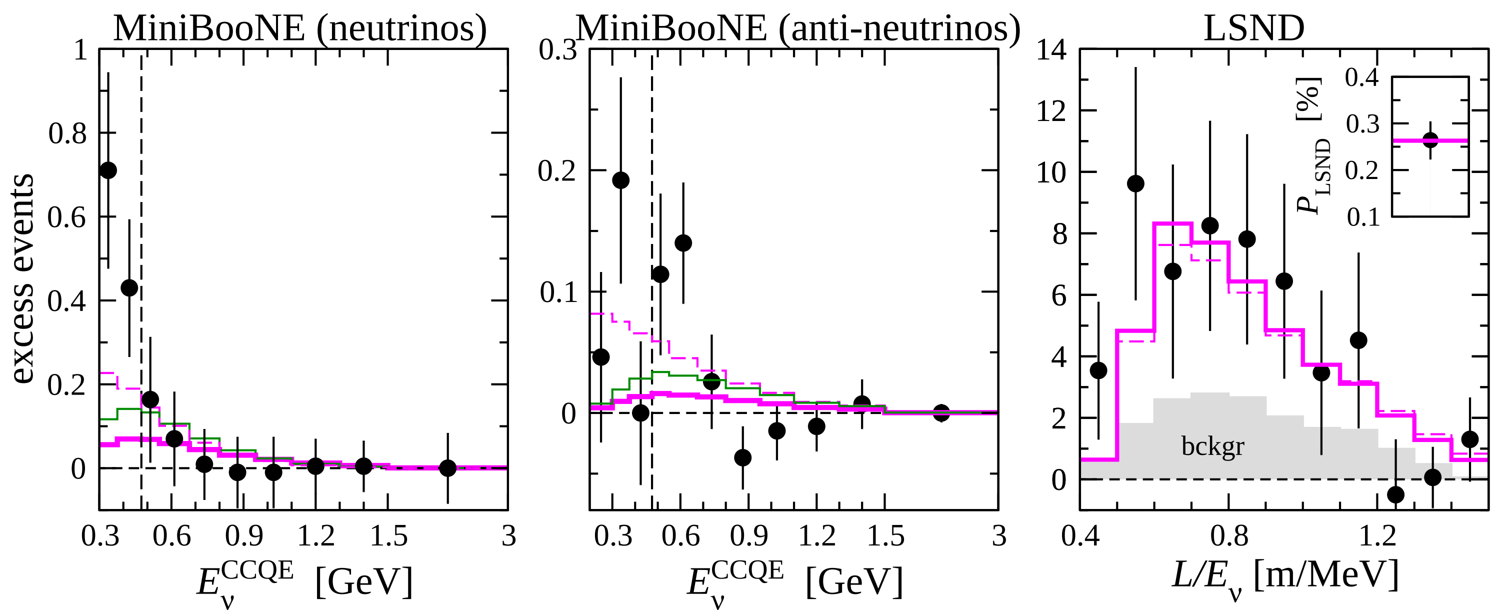


Left: Data compared to allowed regions of (3+1) oscillations. Right: Data compared to allowed regions in (3+1) NSI^c case. The values of $|\beta_{\mu e}|$ and δ are those for which the NEV and allowed regions touch each other (at $\Delta\chi^2 = 11.7$ corresponding to 98% CL for 4 dof).

Possible realization in terms of the NSI parameters: enough to assume only $\varepsilon^{ud}_{e\mu} \neq 0$. Neglecting quadratic term in norm. factor C^X_e and the term $\sim \varepsilon^{ud}_{e\mu} U^*_{\mu 4}$ (product of two small quantities) in F^{ud}_{e4}:

$$\alpha_{\mu e} = U_{e4} U^*_{\mu 4}\,, \qquad \beta_{\mu e} = \varepsilon^{ud*}_{e\mu}\,, \qquad \alpha_e = |U_{e4}|^2\,, \qquad \alpha_\mu = |U_{\mu 4}|^2\,.$$

Spectra at bfp for NSI^g



Dashed: appearance data, solid red: global data, green: global fit results for MiniBooNE without assumption $\varepsilon^S = \varepsilon^D$ for ν_μ disappearance data.

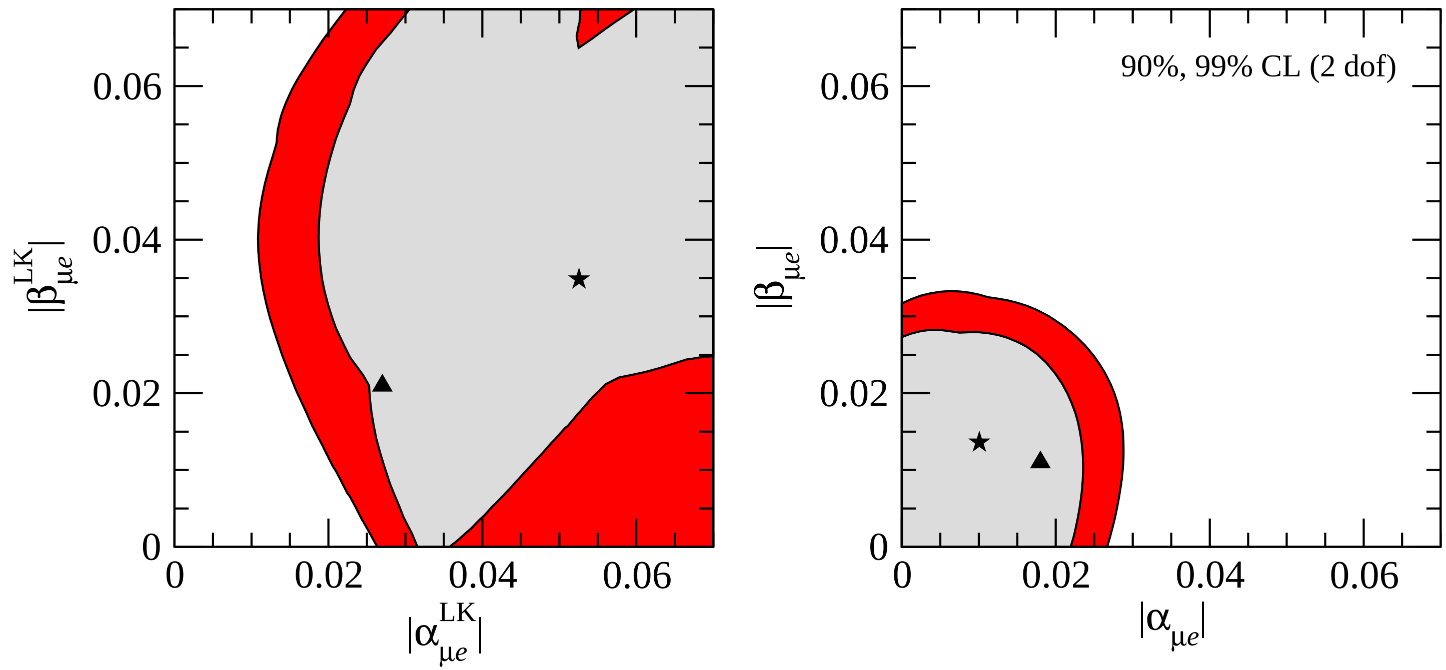
Data set	$\lvert\alpha_{\mu e}^{\rm LK}\rvert$	$\lvert\beta_{\mu e}^{\rm LK}\rvert$	$\delta^{\rm LK}$	$\lvert\alpha_{\mu e}\rvert$	$\lvert\beta_{\mu e}\rvert$	δ	Δm^2_{41}	χ^2/dof
Appearance	0.31	0.029	0.49π	0.15	0.011	1.5π	0.13 eV^2	$29.4/(37-7)$
Global	0.053	0.036	0.39π	0.010	0.013	1.2π	0.89 eV^2	$95.4/(115-8)$

An excellent fit of all the data. But: MB $\bar\nu$ signal is not well described (due to its small statistical weight in global data). Can be different in future if MB $\bar\nu$ signal is confirmed with higher statistics!

$\mathbf{NSI}^g$ – contd.

$$\chi^2_{\text{min,(3+1)osc}} - \chi^2_{\text{min,(3+1)NSI}^g} = 18.5 \qquad (5\text{dof}) \,.$$

$\Delta\chi^2$ value corresponds to 99.76% CL $\Rightarrow$ (3+1) oscillation can be excluded at 3σ level compared to the NSI^g case. Unlike in the NSI^c case, the tension between appearance and disappearance experiments is significantly relaxed because of decoupling of LSND.



Minimisation done over all undisplayed parameters. Stars indicate the global best fit point, triangles correspond to the example below.

NSI^g – contd.

Global NSI^g bfp requires rather large values of $|\alpha_{\mu e}^{\rm LK}|$ and $|\beta_{\mu e}^{\rm LK}|$. But: allowed regions extend to rather small values even at 90% CL. One possible realization in terms of fundamental mixing and NSI parameters – take the following ε to be non-zero:

$$|\varepsilon_{\mu s}^{ud}| \approx 0.05\,, \qquad |\varepsilon_{e\mu}^{ud}| \approx 0.011\,, \qquad |\varepsilon_{\mu s}^{e\nu}| \approx 0.03\,, \qquad |\varepsilon_{\mu e}^{e\nu}| \approx 0.01 \qquad \Rightarrow$$

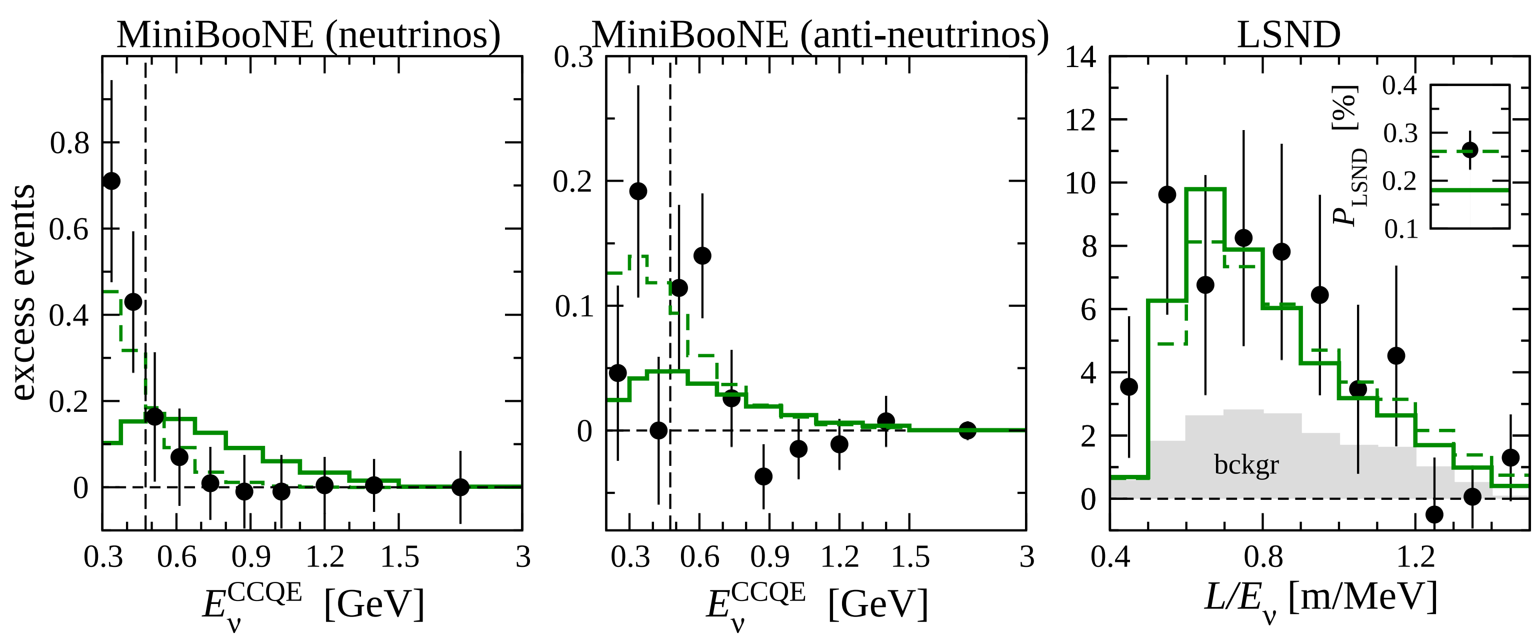
$$\begin{aligned}
|\alpha_{\mu e}| &\approx (|U_{\mu 4}| - |\varepsilon_{\mu s}^{ud}|)|U_{e4}| \approx 0.018\,,\\
|U_{e4}| &\approx 0.116\,, \qquad |U_{\mu 4}| \approx 0.205\,,\\
|\beta_{\mu e}| &\approx |\varepsilon_{e\mu}^{ud}| \approx 0.011\,,\\
|\alpha_{\mu e}^{\rm LK}| &\approx (|U_{\mu 4}| + |\varepsilon_{\mu s}^{e\nu}|)|U_{e4}| \approx 0.027\,,\\
|\beta_{\mu e}^{\rm LK}| &\approx |\varepsilon_{e\mu}^{ud}| + |\varepsilon_{\mu e}^{\nu e}| \approx 0.021\,.
\end{aligned}$$

Here: $|U_{s4}| \approx 1$ assumed and terms quadratic in small quantities neglected. At this point (with $\Delta m_{41}^2 = 0.98\ {\rm eV}^2$) $\chi^2 = 101.0$ – 5.6 units larger than at bfp. For 8 parameters this corresponds to 69% CL $\Rightarrow$ this point is located close to the 1σ volume in the 8-dimensional parameter space.

(3+2) oscillations case

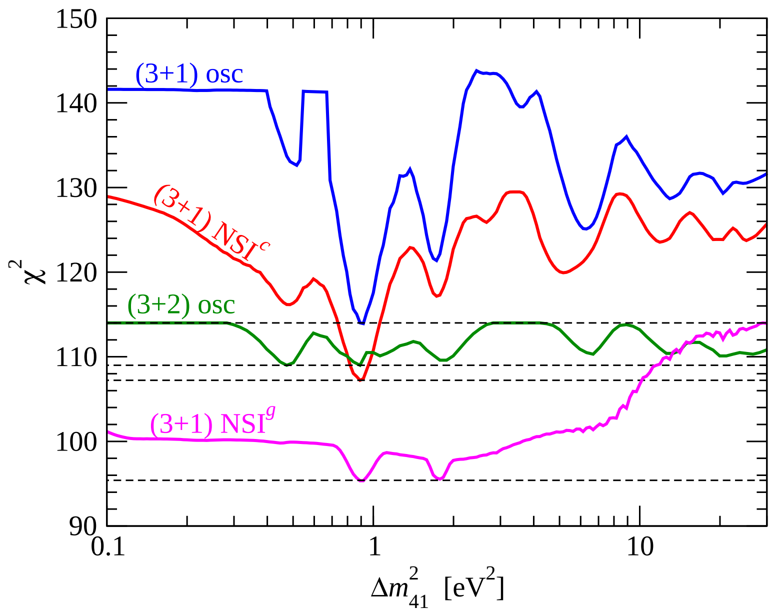
	$\lvert U_{e4}U_{\mu4}\rvert$		Δm^2_{41}	$\lvert U_{e5}U_{\mu5}\rvert$		Δm^2_{51}	δ	χ^2/dof
Appearance	0.397		0.94 eV^2	0.375		1.0 eV^2	1.01π	$26.3/(37-5)$
	$\lvert U_{e4}\rvert$	$\lvert U_{\mu4}\rvert$		$\lvert U_{e5}\rvert$	$\lvert U_{\mu5}\rvert$			
Global	0.10	0.15	0.47 eV^2	0.13	0.17	0.89 eV^2	1.69π	$109/(115-7)$

Parameter and χ^2 values of the best fit points in the (3+2) oscillation scheme for appearance data from LSND, MiniBooNE ν and $\bar{\nu}$, KARMEN, NOMAD (upper part), and global data (lower part).



Predicted spectra. Dashed: appearance data, solid: global data

Comparing (3+1) NSI with (3+2) osc.



	(3+1) NSI^c		(3+1) NSI^g		(3+2) oscillations	
	$\chi^2_{\rm PG}$/dof	PG prob.	$\chi^2_{\rm PG}$/dof	PG prob.	$\chi^2_{\rm PG}$/dof	PG prob.
Evid. vs no-evid.	23.3/4	1.1×10^{-4}			26.9/5	6×10^{-5}
App. vs disapp.	11.5/2	3×10^{-3}	3.8/2	15%	21.7/4	2.3×10^{-4}
	$\Delta\chi^2$/dof	CL	$\Delta\chi^2$/dof	CL	$\Delta\chi^2$/dof	CL
Fit wrt (3+1) osc.	6.9/2	97%	18.5/5	99.76%	5.0/4	71%

Can we explain MINOS $\nu/\bar{\nu}$ discrepancy?

NSI in the standard 3f scheme (no sterile neutrinos necessary).

I. NSI at neutrino production/detection. Survival probabilities can be different for ν_μ and $\bar{\nu}_\mu$ even in the absence of CPT violation provided NSI at neutrino production and detection are different.

Production: pion decay (only axial-vector NSI contribute).
Detection: $\nu_\mu N$ reaction – both V- and A- NSI can contribute.

The same formalism as for MB applies, with $\Delta m^2_{41} \to \Delta m^2_{31}$.
The result: $\varepsilon \simeq 0.1$ are necessary, the gain $\Delta\chi^2 \simeq 2.5$ – insignificant.

II. NSI effects on neutrino propagation (NC-type NSI). Contribute to matter effects on neutrino propgation. We find:

(i) Diagonal NSI: If $\varepsilon^{\rm NC}_{\mu\mu}, \varepsilon^{\rm NC}_{\tau\tau} \lesssim 0.5$ – negligible effect.
(ii) Off-diagonal NSI: For $\varepsilon^{\rm NC}_{\mu\tau} \simeq 0.2$ the gain $\Delta\chi^2 \simeq 2.5$ – very small improvement of the fit.

But: These values of the NSI parameters are about one order of magnitude larger than the upper bounds from atm. neutrino data

Conclusions

- (3+1) scenarios with NSI at neutrino production give good (NSI^c) or very good (NSI^g) fits to SBL data, including LSND and MiniBooNE $\bar{\nu}$ and ν, while satisfying all the constraints from disappearance data.
- Analysis performed in terms of the effective parameters $\alpha_{\alpha\beta}$ and $\beta_{\alpha\beta}$. In each case expressions are given for these parameters in terms of the NSI parameters $\varepsilon^X_{\alpha\beta}$ and elements of the mixing matrix $U_{\alpha i}$ which satisfy all the current phenomenological constraints.
- CPV due to the inteference of the osc. and NSI effects is present even in the one mass scale dominance limit and with only one non-zero NSI parameter. Allows one to reconcile (LSND + MB $\bar{\nu}$) with MB ν.
- The (3+1) NSI scenarios give significntly better description of the data than pure (3+1) and (3+2) oscillation scenarios.
- Non-trivial zero-distance effect is predicted for appearance experiments: $P_{\mu e}(L=0) = |\beta_{\mu e}|^2$. Also: ν_s at the eV scale; NSI mediators at LHC ?

Backup slides

Fundamental and effective parameters

Abbreviations for various production and detection processes:

μ : muon decay

π : pion decay

Ne : neutrino–nucleus CC interaction involving an electron

$N\mu$: neutrino–nucleus CC interaction involving a muon

The relevant effective parameters:

LSND/KARMEN:	$\alpha_{\mu e} = F^{\mu}_{\mu 4} F^{Ne*}_{e4}\,,$	$\beta_{\mu e} = \sum_i F^{\mu}_{\mu i} F^{Ne*}_{ei}$
MiniBooNE/NOMAD:	$\alpha_{\mu e} = F^{\pi}_{\mu 4} F^{Ne*}_{e4}\,,$	$\beta_{\mu e} = \sum_i F^{\pi}_{\mu i} F^{Ne*}_{ei}$
reactor:	$\alpha_{ee} = \lvert F^{Ne}_{e4}\rvert^2\,,$	$\beta_{ee} = 1$
CDHS/atmospheric:	$\alpha_{\mu\mu} = F^{\pi}_{\mu 4} F^{N\mu*}_{\mu 4}\,,$	$\beta_{\mu\mu} = \sum_i F^{\pi}_{\mu i} F^{N\mu*}_{\mu i}$

1. NSI^c case. Choose $\varepsilon^X_{\mu\alpha} = 0 \quad \Rightarrow \quad F^X_{\mu i} = U^*_{\mu i}$: $\alpha^{\mathrm{LK}}_{\mu e}$ and $\beta^{\mathrm{LK}}_{\mu e}$ are the same as for the rest of experiments, $\beta_{\mu\mu} = 1$, $|\alpha_{\mu e}|^2 = \alpha_{ee}\alpha_{\mu\mu}$.

2. Relaxing the constraint $\varepsilon^S_{\mu\alpha} = \varepsilon^D_{\mu\alpha}$.

It is possible to have $P_{\mu\mu} = 1$ while allowing for a non-zero transition probability in MiniBooNE, which requires some cancellation between NSI parameters and elements of the mixing matrix. E.g.

$$F^{N\mu}_{\mu 4} \approx U^*_{\mu 4} + \varepsilon^{N\mu}_{\mu s} U^*_{\mu s} \approx 0\,, \qquad \varepsilon^{\pi}_{\mu s} \approx 0\,.$$

This implies $\alpha_{\mu\mu} \approx 0$ and $\beta_{\mu\mu} \approx 1$, therefore $P_{\mu\mu} \approx 1$, as required by the data from CDHS and atm. neutrinos. On the other hand, $F^{\pi}_{\mu 4} \approx U^*_{\mu 4}$ and we can have $P_{\mu e} \neq 0$ for MiniBooNE, including the possibility of CP violation.

Reactor expts. still constrain $|F^{Ne}_{e4}|$ to be small $\Rightarrow$ exclude small Δm^2_{41} (due to the factoris. relation $\alpha_{\mu e}$ has to be small) where a better fit to the MB spectrum would be possible (such as e.g. for the app. data only fit), and we find $\Delta m^2_{41} \simeq 0.9$ eV^2 at the bfp. The spectral shape of the signal for such values of Δm^2_{41} does not allow for a better fit of MB data even without the constraint from ν_μ disapp.

Decouple the ν_μ disappearance data by setting $P_{\mu\mu} = 1$: bfp with $\chi^2 = 92.7$, to be compared with 95.4 for the standard NSI^g including the assumption $\varepsilon^S_{\mu\alpha} = \varepsilon^D_{\mu\alpha}$. $\Rightarrow$ Improvement of the fit by relaxing this assumption is not significant. The reason: there is already very good agreement between appearance and disappearance data in NSI^g.

Also: decoupling ν_μ disappearance data requires an unpleasant cancellation. At the bfp: $U_{\mu 4} \approx 0.26$ $\Rightarrow$ To cancel this in $F^{N\mu}_{\mu 4}$ one needs $\varepsilon^{N\mu}_{\mu s}$ of the same order. Together with the observation that the improvement of the fit is not significant, this motivates us to stick to the assumption $\varepsilon^S_{\mu\alpha} = \varepsilon^D_{\mu\alpha}$ in order to simplify the analysis.