VSBL Electron Neutrino Disappearance

MARCO LAVEDER

Padova University and INFN

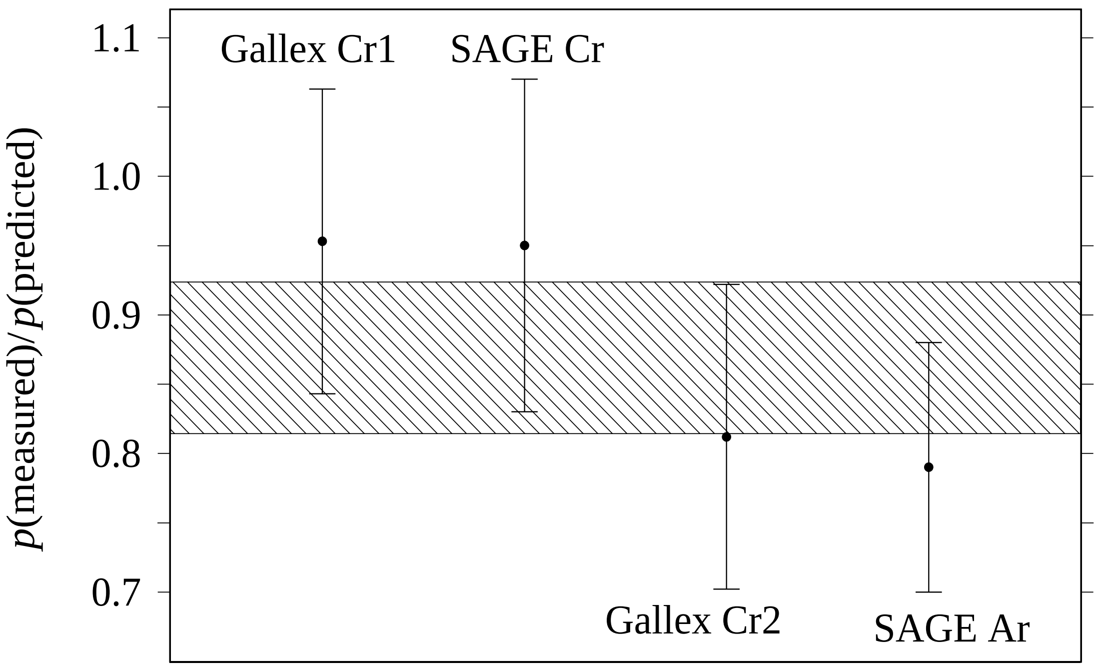
Torino - 31 March 2009

work in collaboration with Carlo Giunti [arXiv:0902.1992v1]

Active-Sterile ν mixing ?

- Charged massive spin 1/2 particles can have only a Dirac mass term
- According to Majorana neutral massive spin 1/2 particles can coincide with their antiparticles having a Majorana mass term.
- Non-SM right-handed neutral particles can have both Dirac and Majorana mass terms.
- If these non-SM right-handed neutral particles are light (sterile neutrinos ν_s) can mix with ordinary active neutrinos.
- The observable effect is a disappearance of active neutrinos.
- We focus on SBL Gallium, Miniboone and Reactors experiments.

ν_e Disappearance in Gallium radioactive source experiments



$R \equiv$ wheighted average value of the ratio of measured and predicted ^{71}Ge production rates (p) :

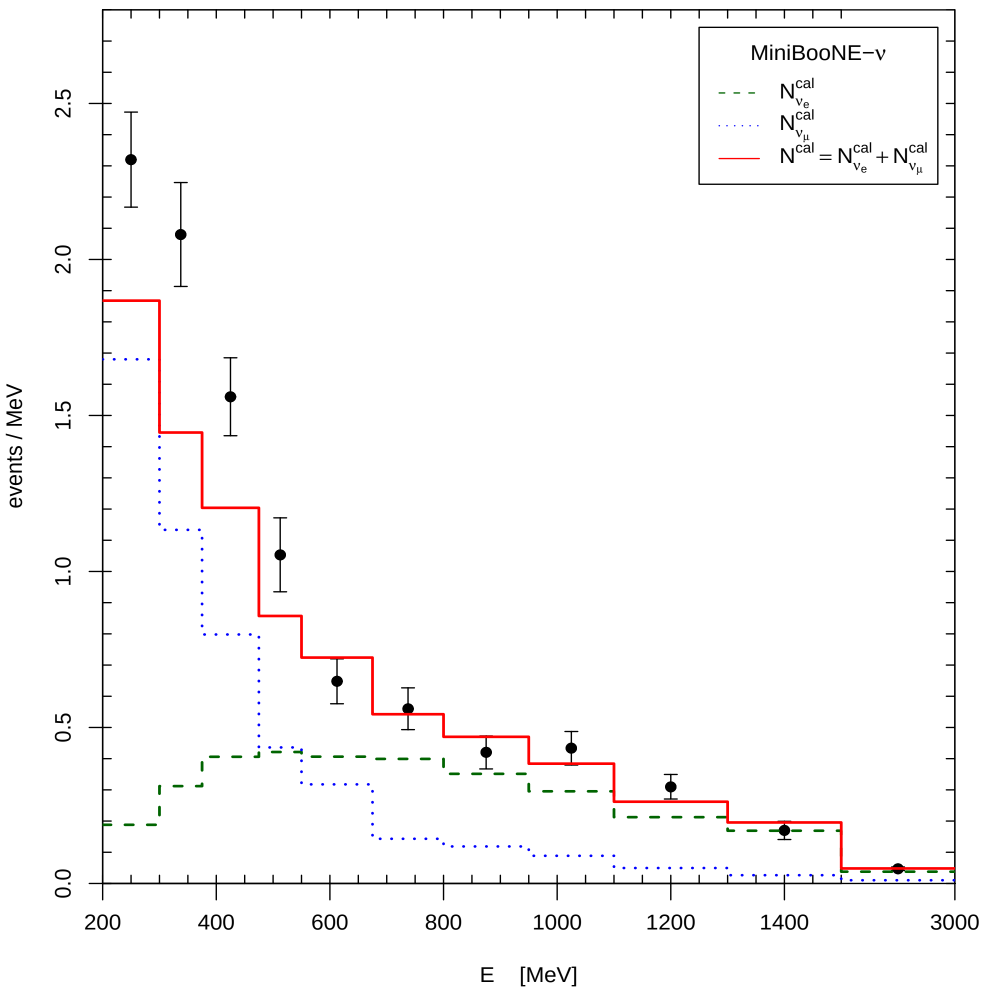
$$R \equiv \frac{\mathrm{p(measured)}}{\mathrm{p(predicted)}} = 0.87 \pm 0.05$$

arXiv:0901.2200[nucl-ex]

Ga radioactive source exp. results may be interpreted as an indication of the disappearance of ν_e due to active-sterile oscillations!

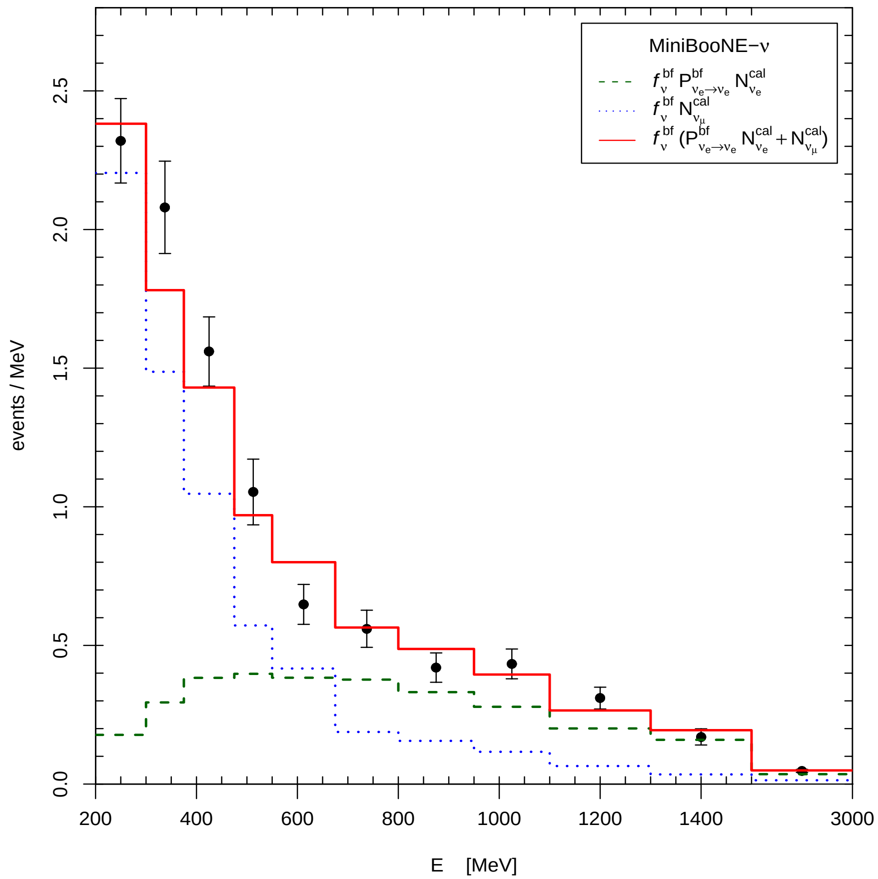
hep-ph/0610352 Carlo Giunti & ML

Miniboone-ν data : Low Energy Excess or ...



arXiv:0812.2243

ν_e Disappearance in Miniboone-ν data



Phys. Rev. D 77, 093002 (2008) C.Giunti & ML

A renormalization of the absolute event rate by a constant factor f_ν ($\Delta f_\nu = 0.15$) with a simultaneous disappearance of the ν_e in the beam .

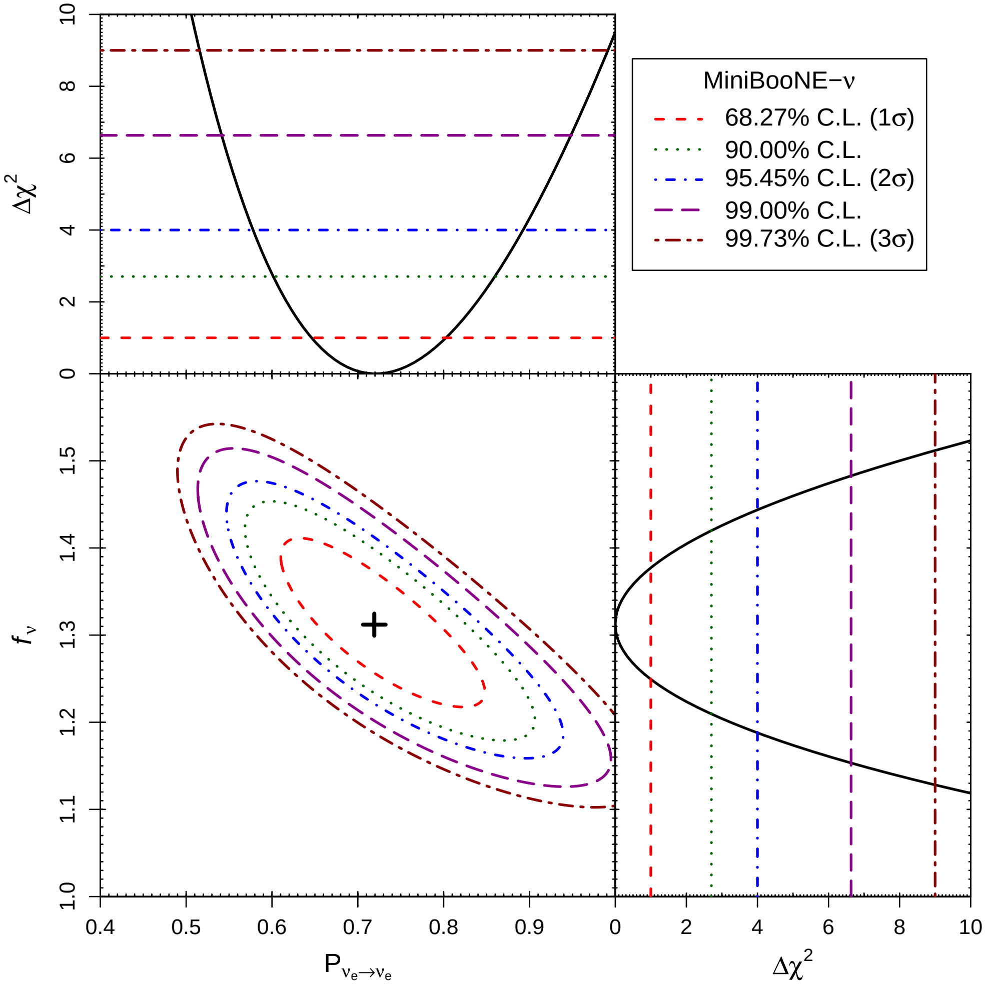
A constant $P_{\nu_e \to \nu_e} \leftrightarrow \Delta m^2 \gtrsim 20\,\mathrm{eV}^2$.

j	Energy Range [MeV]	$N^{\text{cal}}_{\nu_e,j}$	$N^{\text{cal}}_{\nu_\mu,j}$	$N^{\text{cal}}_{\nu,j}$	$N^{\text{exp}}_{\nu,j}$
1	$200 - 300$	24.2	162.4	186.7	232
2	$300 - 375$	21.8	86.4	108.2	156
3	$375 - 475$	39.4	81.2	120.6	156
4	$475 - 550$	29.5	34.5	64.1	79
5	$550 - 675$	47.0	42.4	89.4	82
6	$675 - 800$	47.0	19.7	66.7	70
7	$800 - 950$	49.1	20.0	69.1	64
8	$950 - 1100$	41.8	16.4	58.2	65
9	$1100 - 1300$	41.2	12.1	53.3	63
10	$1300 - 1500$	29.1	9.7	38.8	34
11	$1500 - 3000$	54.5	18.2	72.7	73

We calculate the best fit values of the parameters $P_{\nu_e \to \nu_e}$ and f_ν by minimizing the least-square function :

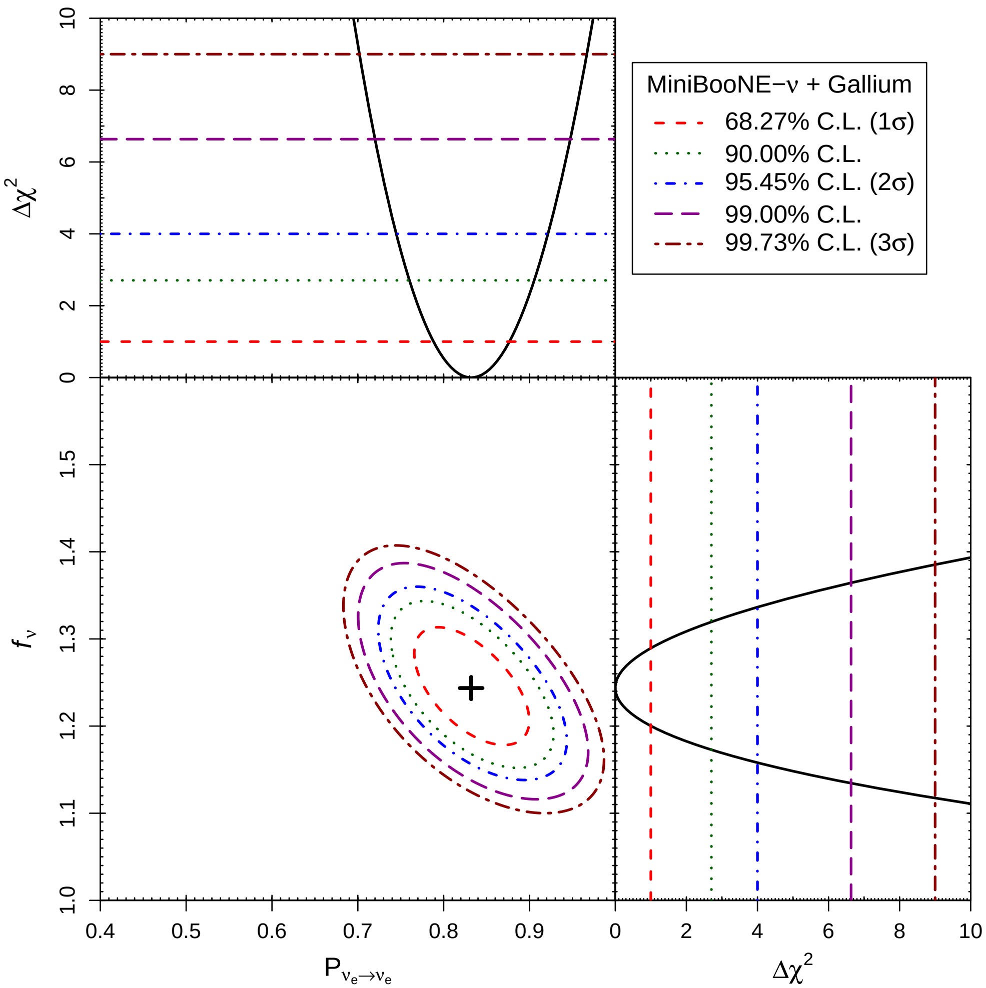
$$\chi^2_{\text{MB-}\nu} = \sum_{j=1}^{11} \frac{\left(N^{\text{the}}_{\nu,j} - N^{\text{exp}}_{\nu,j}\right)^2}{N^{\text{the}}_{\nu,j}} + \left(\frac{f_\nu - 1}{\Delta f_\nu}\right)^2, \qquad N^{\text{the}}_{\nu,j} = f_\nu \left(P_{\nu_e \to \nu_e} N^{\text{cal}}_{\nu_e,j} + N^{\text{cal}}_{\nu_\mu,j}\right)$$

Fit to Miniboone-ν data



$$\chi^2_{min} = 17.7/(9\,\mathrm{dof}) \qquad GoF = 3.8\% \qquad P^{bf}_{\nu_e\to\nu_e} = 0.72^{+0.08}_{-0.07} \qquad f^{bf}_{\nu} = 1.31^{+0.07}_{-0.06}$$

Fit to Miniboone-ν & Gallium data



$$\chi^2_{min} = 20.1/(10\,\mathrm{dof}) \quad GoF = 2.8\% \qquad P^{bf}_{\nu_e\to\nu_e} = 0.83 \pm 0.04 \quad f^{bf}_{\nu} = 1.24^{+0.05}_{-0.04}$$

Miniboone-ν & Gallium : Osc vs No Osc

		MB-ν	MB-ν+Ga
No Osc.	χ^2_{min}	27.2	34.0
	NDF	10	11
	GoF	0.2%	0.04%
	f_ν^{bf}	1.15	1.15
Osc.	χ^2_{min}	17.7	20.1
	NDF	9	10
	GoF	3.8%	2.8%
	$P^{\text{bf}}_{\nu_e\to\nu_e}$	0.72	0.83
	f_ν^{bf}	1.31	1.24
PG	$\Delta\chi^2_{\text{min}}$		2.4
	NDF		1
	GoF		12.4%

Active-Sterile ν_e mixing !

- The parameter goodness-of-fit of 12.4% implies that the results of the MiniBooNE neutrino and the Gallium radioactive source experiments are compatible in the framework of the ν_e disappearance hypothesis.
- The goodness of fit of 2.8% is acceptable and much better than the 0.04% obtained without ν_e disappearance.
- $P_{\nu_e \to \nu_e} = 1$ is disfavored at more than 3σ (the precise value is 99.98% CL).

The large disappearance of ν_e found in Gallium and in Miniboone-ν data, may be due to oscillations into sterile neutrinos $\nu_e \longrightarrow \nu_s$ since

- $\nu_e \longrightarrow \nu_\mu$ transitions are restricted by the results of CCFR , KARMEN , NOMAD and MINIBOONE ;
- $\nu_e \longrightarrow \nu_\tau$ transitions are limited by the results of CHORUS and NOMAD .

SBL Reactor $\overline{\nu}_e$ experiments

$R^{(\text{d})}$ denotes the ratio of measured and predicted event rates at the source-detector distance d:

Gosgen :

$$R^{(37.9\,\text{m})}_{\text{Gosgen}} = 1.018 \pm 0.019(\text{stat}) \pm 0.015(\text{uncorr}) \pm 0.060(\text{corr})\,, \tag{1}$$

$$R^{(45.9\,\text{m})}_{\text{Gosgen}} = 1.045 \pm 0.019(\text{stat}) \pm 0.015(\text{uncorr}) \pm 0.060(\text{corr})\,, \tag{2}$$

$$R^{(64.7\,\text{m})}_{\text{Gosgen}} = 0.975 \pm 0.036(\text{stat}) \pm 0.030(\text{uncorr}) \pm 0.060(\text{corr})\,, \tag{3}$$

Bugey :

$$R^{(15\,\text{m})}_{\text{Bugey}} = 0.988 \pm 0.004(\text{stat}) \pm 0.05(\text{syst})\,, \tag{4}$$

$$R^{(40\,\text{m})}_{\text{Bugey}} = 0.994 \pm 0.010(\text{stat}) \pm 0.05(\text{syst})\,, \tag{5}$$

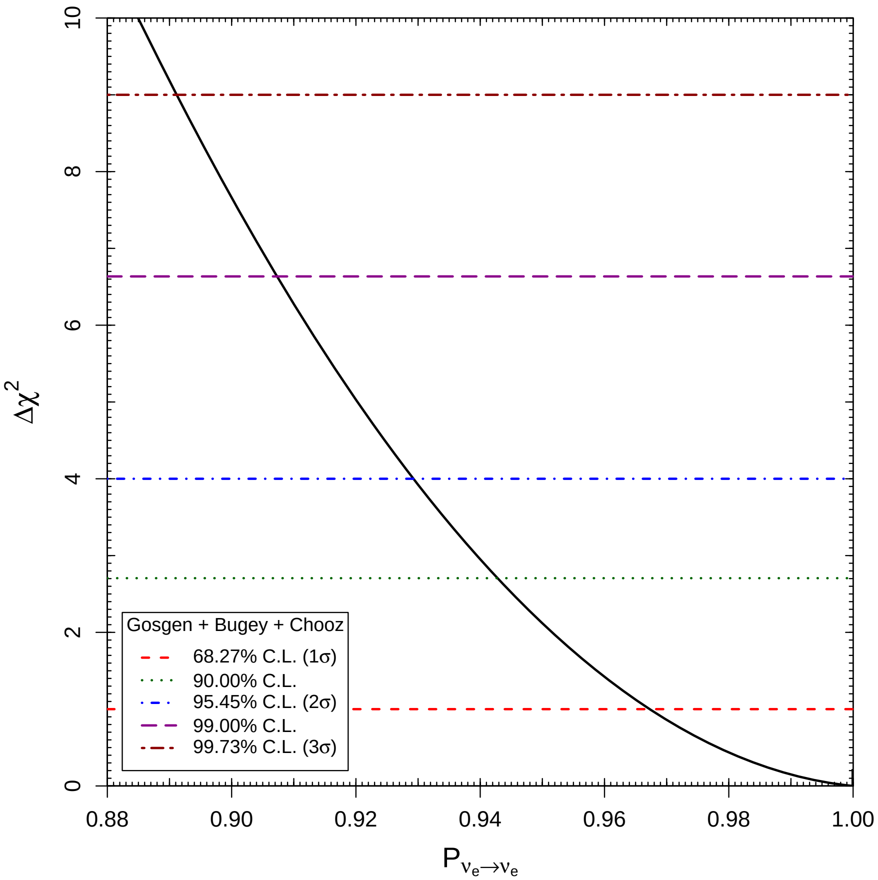
$$R^{(95\,\text{m})}_{\text{Bugey}} = 0.915 \pm 0.132(\text{stat}) \pm 0.05(\text{syst})\,. \tag{6}$$

Chooz :

$$R^{(1\,\text{km})}_{\text{Chooz}} = 1.01 \pm 0.028(\text{stat}) \pm 0.036(\text{syst})\,. \tag{7}$$

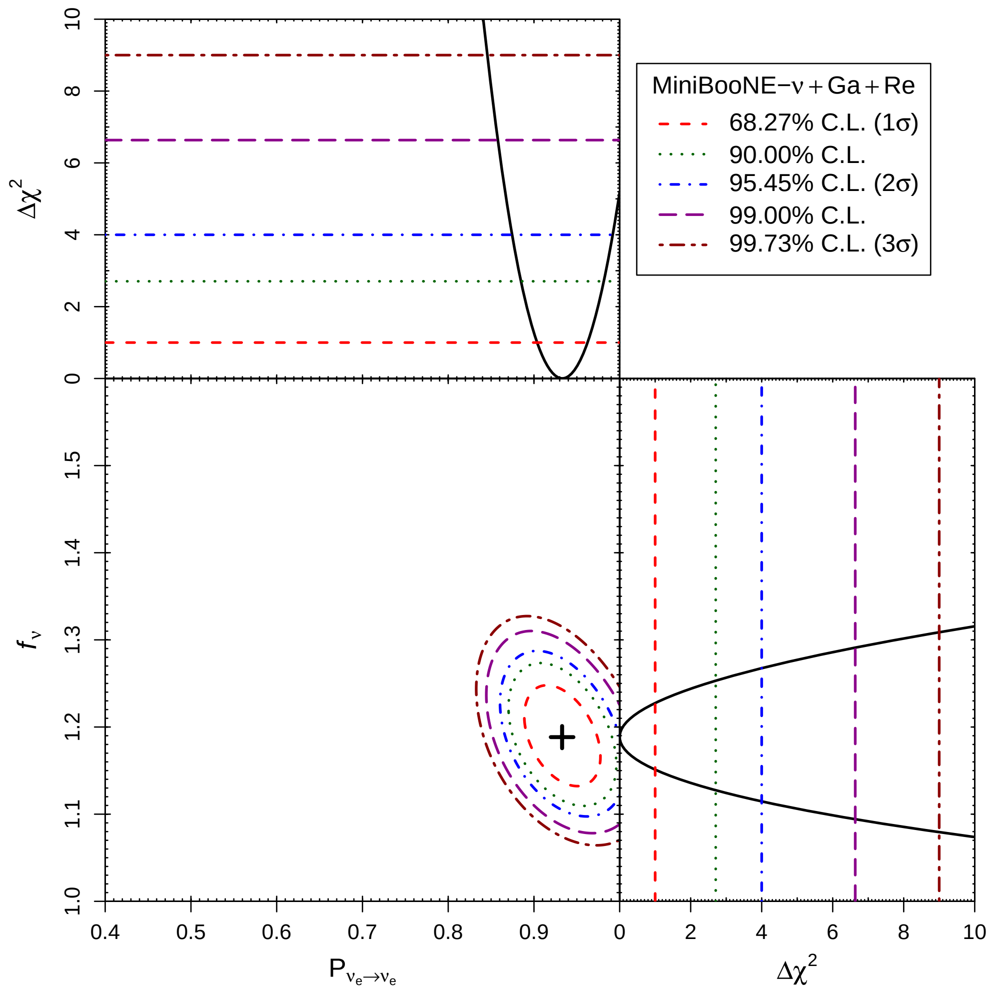
N.B. The Chooz systematic uncertainty of the reactor neutrino flux has the same value as that of Gosgen and Bugey, i.e. approximately 3% (ILL value).

Fit to SBL Reactor $\overline{\nu}_e$ data



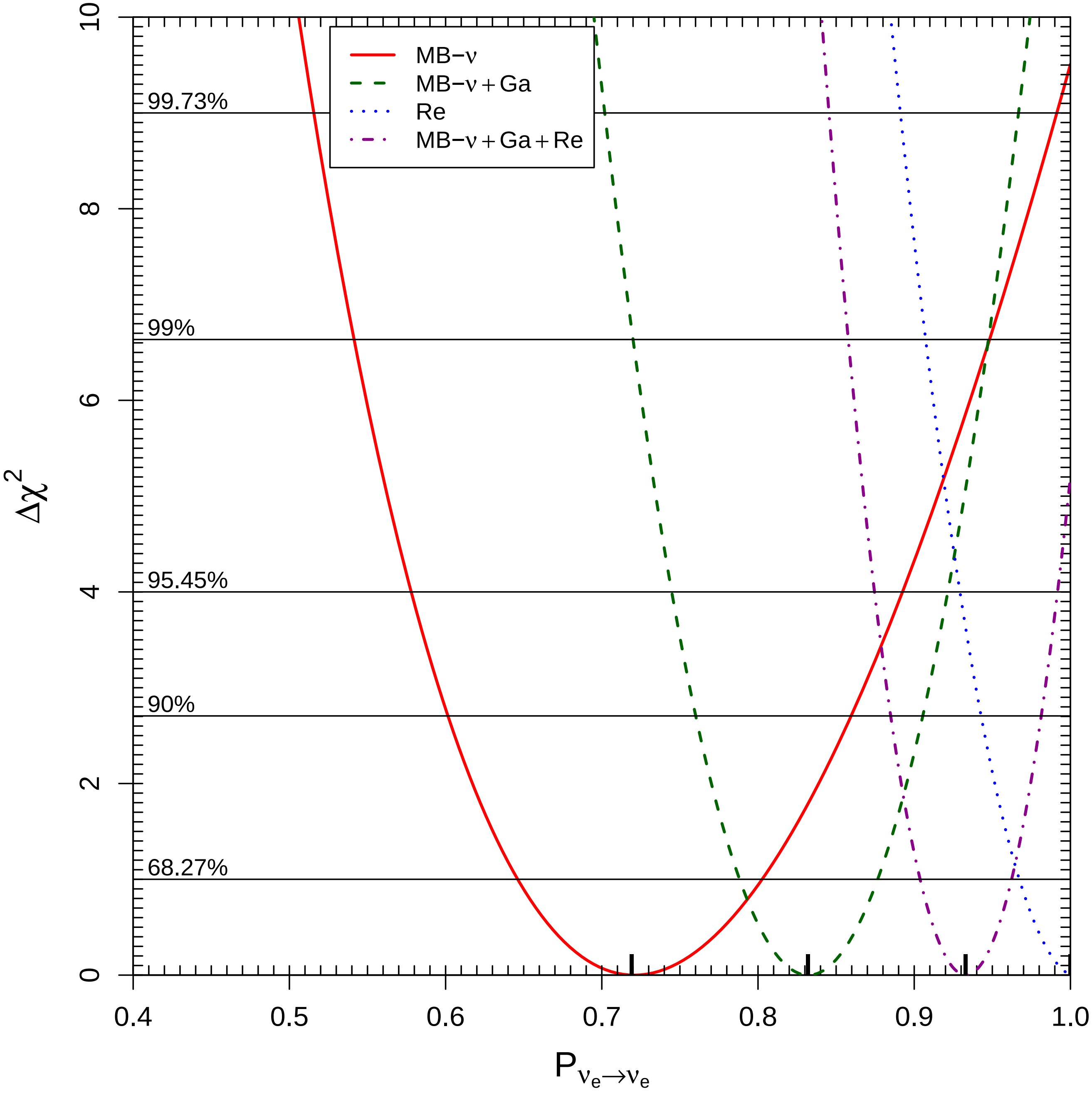
The lower limits for $P_{\nu_e \to \nu_e}$ indicate that reactor data allow a small $\bar{\nu}_e$ disappearance. Therefore, we tried a combined analysis of MiniBooNE neutrino, Gallium and reactor data under the hypothesis of ν_e disappearance with $P_{\nu_e \to \nu_e} = P_{\bar{\nu}_e \to \bar{\nu}_e}$.

Combined fit of Miniboone-ν & Gallium & Reactor (1)



$$\chi^2_{min} = 31.7/(17\,\mathrm{dof}) \quad GoF = 1.7\% \quad P^{bf}_{\nu_e \to \nu_e} = 0.93 \pm 0.03 \quad f^{bf}_{\nu} = 1.19 \pm 0.04$$

Combined fit of Miniboone-ν & Gallium & Reactor (2)



Miniboone-ν & Gallium & Reactor : Osc vs No Osc

		MB-ν	MB-ν+Ga	MB-ν+Ga+Re
No Osc.	χ^2_{min}	27.2	34.0	36.9
	NDF	10	11	18
	GoF	0.2%	0.04%	0.5%
	f_ν^{bf}	1.15	1.15	1.15
Osc.	χ^2_{min}	17.7	20.1	31.7
	NDF	9	10	17
	GoF	3.8%	2.8%	1.7%
	$P^{\text{bf}}_{\nu_e\to\nu_e}$	0.72	0.83	0.93
	f_ν^{bf}	1.31	1.24	1.19
PG	$\Delta\chi^2_{\text{min}}$		2.4	11.1
	NDF		1	2
	GoF		12.4%	0.4%

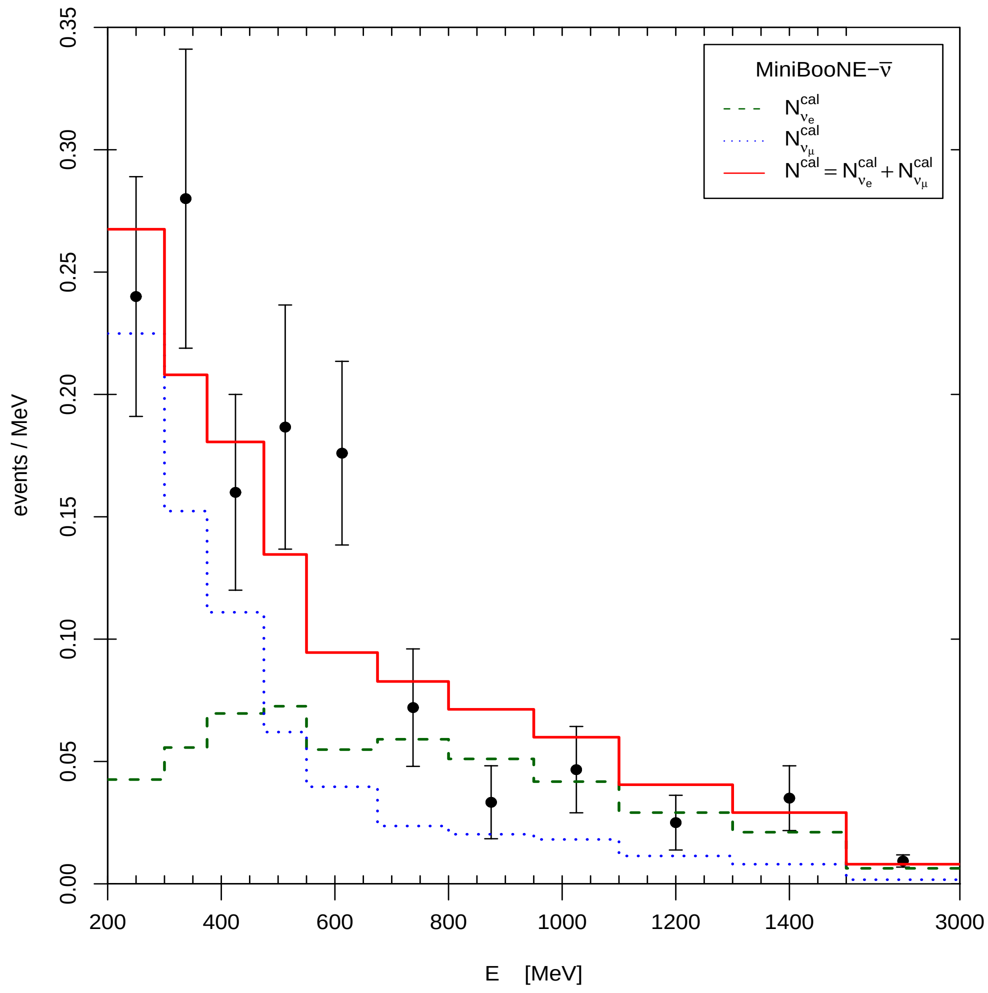
Tension between ν_e and $\overline{\nu}_e$ data

- The rather low parameter goodness-of-fit, 0.4% , shows that there is tension between MiniBooNE and Gallium neutrino data on one side and reactor antineutrino data on the other side.
- The goodness of fit of 1.7% is acceptable and it is better than the 0.5% obtained without ν_e disappearance.
- $P_{\nu_e \to \nu_e} = 1$ is disfavored at more than 2σ (97.74% CL).

Possible explanations of this tension could be:

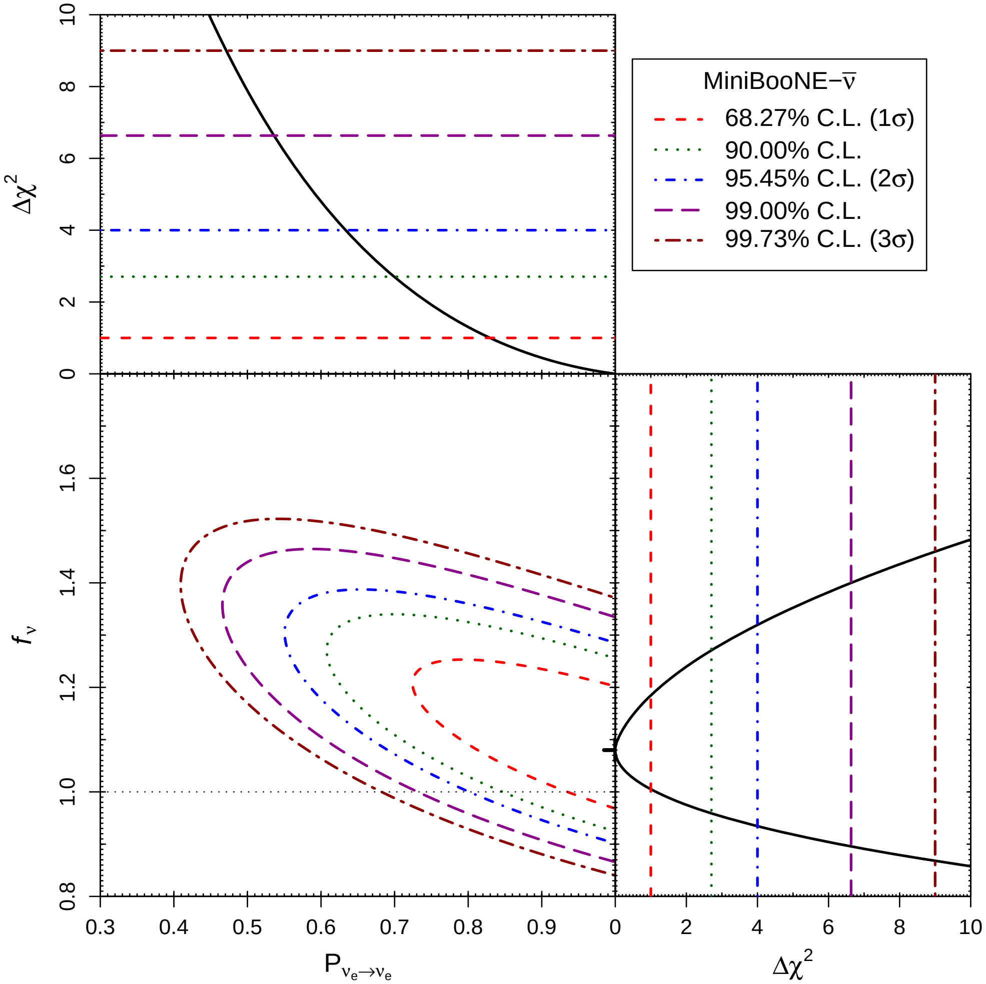
1. Statistical fluctuations.
2. Systematic uncertainties have been underestimated.
3. Our hypothesis of ν_e disappearance is excluded.
4. There is a violation of CPT symmetry leading to $P_{\nu_e \to \nu_e} \neq P_{\bar{\nu}_e \to \bar{\nu}_e}$.

More data : Miniboone-$\bar{\nu}$



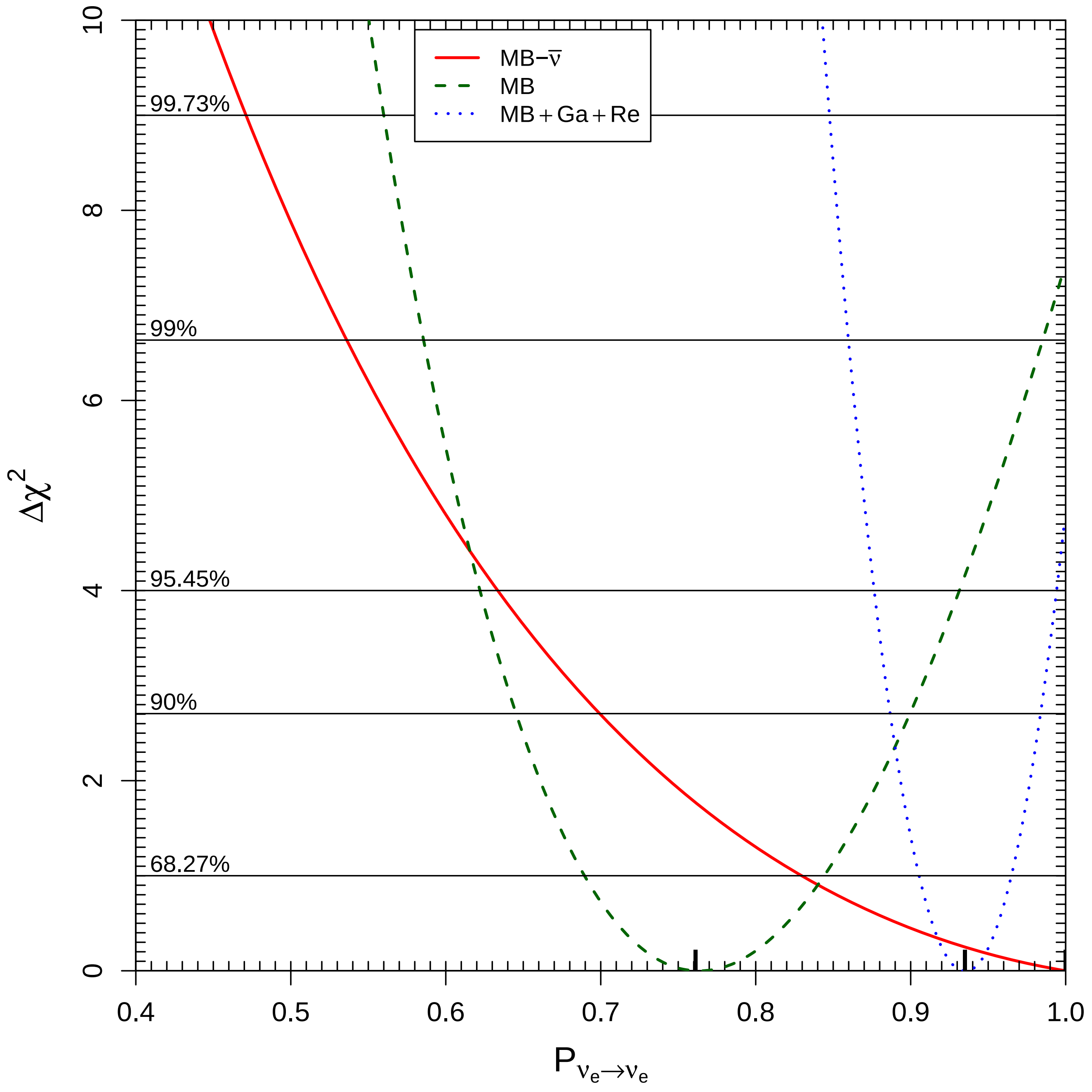
Karagiorgi talk @ FNAL dec 2008

Fit to Miniboone-$\bar{\nu}$ data



$$\chi^2_{min} = 16.9/(9\,\mathrm{dof}) \qquad GoF = 5.0\% \qquad P^{bf}_{\nu_e \to \nu_e} = 1.00^{+0.00}_{-0.17} \qquad f^{bf}_{\bar{\nu}} = 1.08^{+0.10}_{-0.08}$$

Combined fit of Miniboone & Gallium & Reactor



Miniboone & Gallium & Reactor : Osc vs No Osc

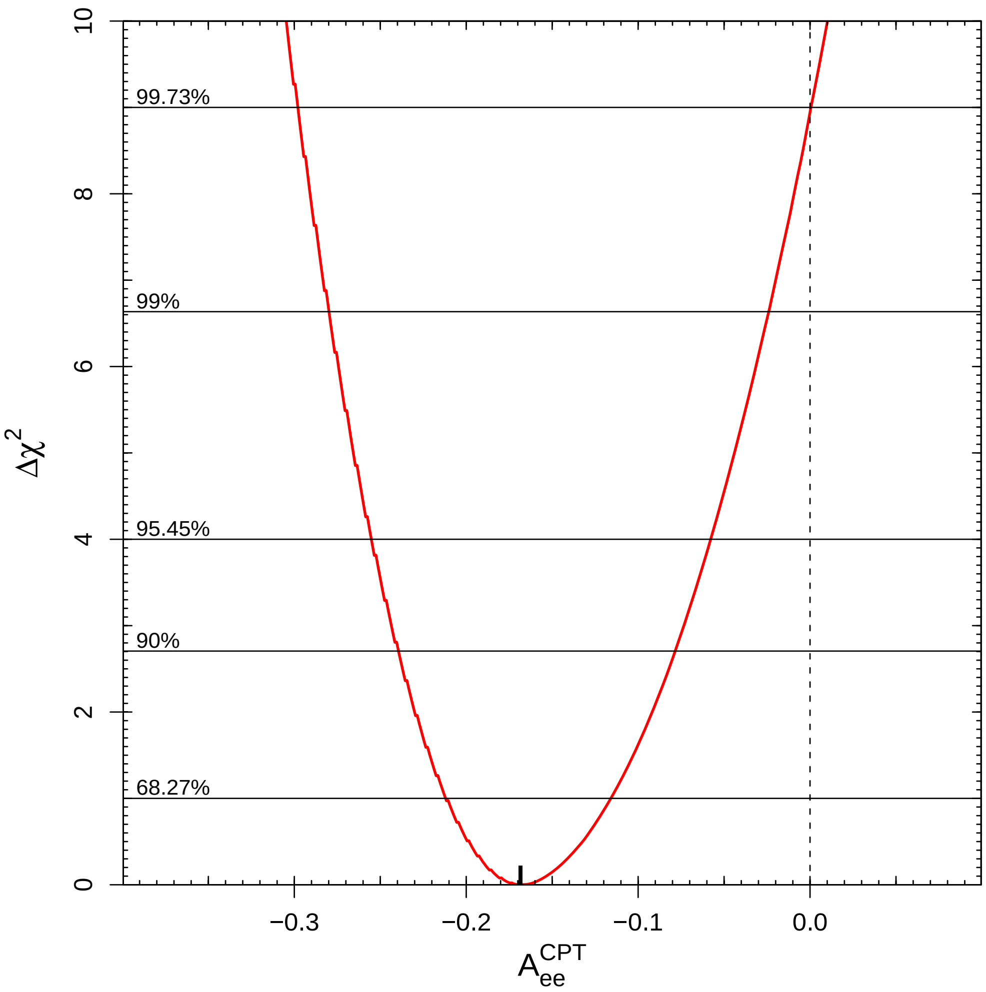
		MB-ν	MB-ν+Ga	MB-ν+Ga+Re	MB+Ga+Re
No Osc.	χ^2_{min}	27.2	34.0	36.9	53.8
	NDF	10	11	18	29
	GoF	0.2%	0.04%	0.5%	0.3%
	f_{ν}^{bf}	1.15	1.15	1.15	1.15
	$f_{\bar{\nu}}^{\text{bf}}$				1.08
Osc.	χ^2_{min}	17.7	20.1	31.7	48.9
	NDF	9	10	17	27
	GoF	3.8%	2.8%	1.7%	0.6%
	$P_{\nu_e\to\nu_e}^{\text{bf}}$	0.72	0.83	0.93	0.93
	f_{ν}^{bf}	1.31	1.24	1.19	1.19
	$f_{\bar{\nu}}^{\text{bf}}$				1.10
PG	$\Delta\chi^2_{\text{min}}$		2.4	11.1	8.3
	NDF		1	2	3
	GoF		12.4%	0.4%	4.1%

Tension between ν_e and $\overline{\nu}_e$data

- The parameter goodness-of-fit of 4.1% do not allow us to reject the compatibility of the data under the hypothesis of ν_e disappearance. This results indicate that the possibility that the tension between MiniBooNE neutrino and Gallium data on one side and reactor data on the other side is due to statistical fluctuations may be correct.
- The goodness of fit of 0.6% is rather low and it is better than the 0.3% obtained without ν_e disappearance.
- $P_{\nu_e\to\nu_e} = 1$ is disfavored at more than 2σ (97.04% CL).
- Next we consider a possible violation of the CPT equality $P_{\nu_e\to\nu_e} = P_{\bar{\nu}_e\to\bar{\nu}_e}$ as a possible explanation of the tension between MiniBooNE and Gallium neutrino data on one side and reactor antineutrino data on the other side under the hypothesis of ν_e disappearance.
- We quantify the amount of CPT violation through the asymmetry

$$A_{ee}^{\text{CPT}} \equiv P_{\nu_e\to\nu_e} - P_{\bar{\nu}_e\to\bar{\nu}_e} \,.$$

CPTV fit of Miniboone & Gallium & Reactor



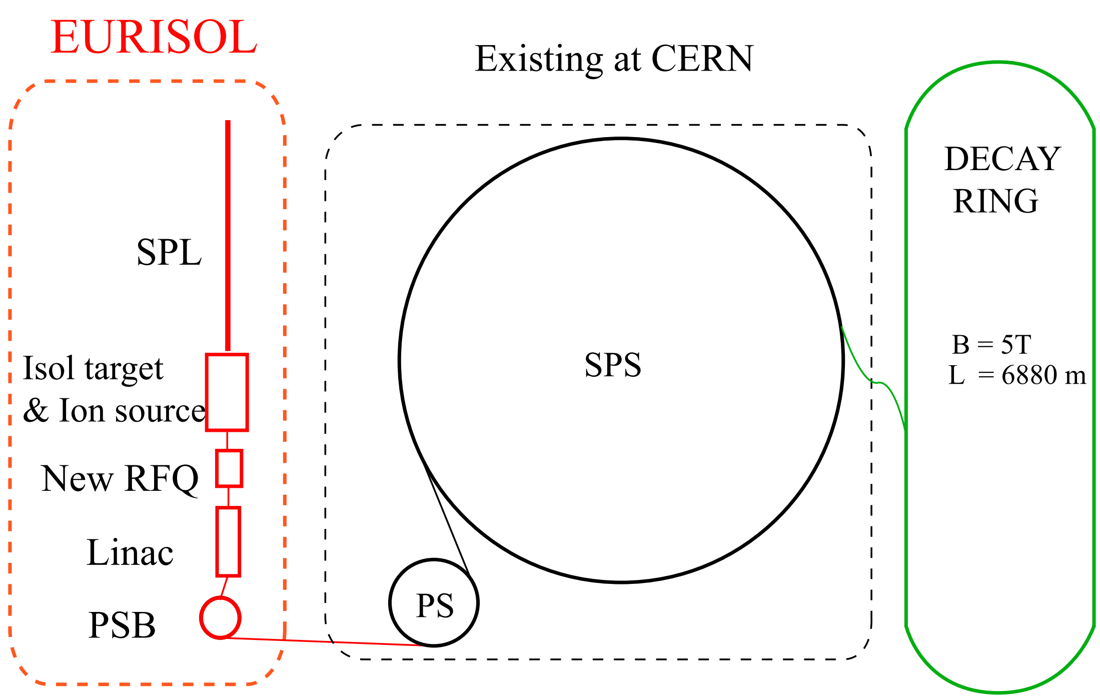
$$\chi^2_{min} = 38.3/(26\,\mathrm{dof}) \qquad GoF = 5.7\% \qquad A_{ee}^{\mathsf{CPT}} = -0.165^{+0.05}_{-0.04}$$

Interesting results !

- The relatively low goodness of fit of 5.7% is due to the relatively low goodness of fit of the MiniBooNE neutrino (3.8%) and antineutrino (5.0%) data.
- There is an indication of CPT violation ($A_{ee}^{\text{CPT}} < 0$) at 99.71% CL.
- Since the indication of CPT violation that we have found has been obtained under the hypothesis of ν_e disappearance into sterile neutrinos, it could be due to very exotic CPT-violating properties of the sterile neutrinos.
- Let us emphasize that the possibility of CPT violation is extremely interesting and should be explored in future experiments by measuring the CPT asymmetries:

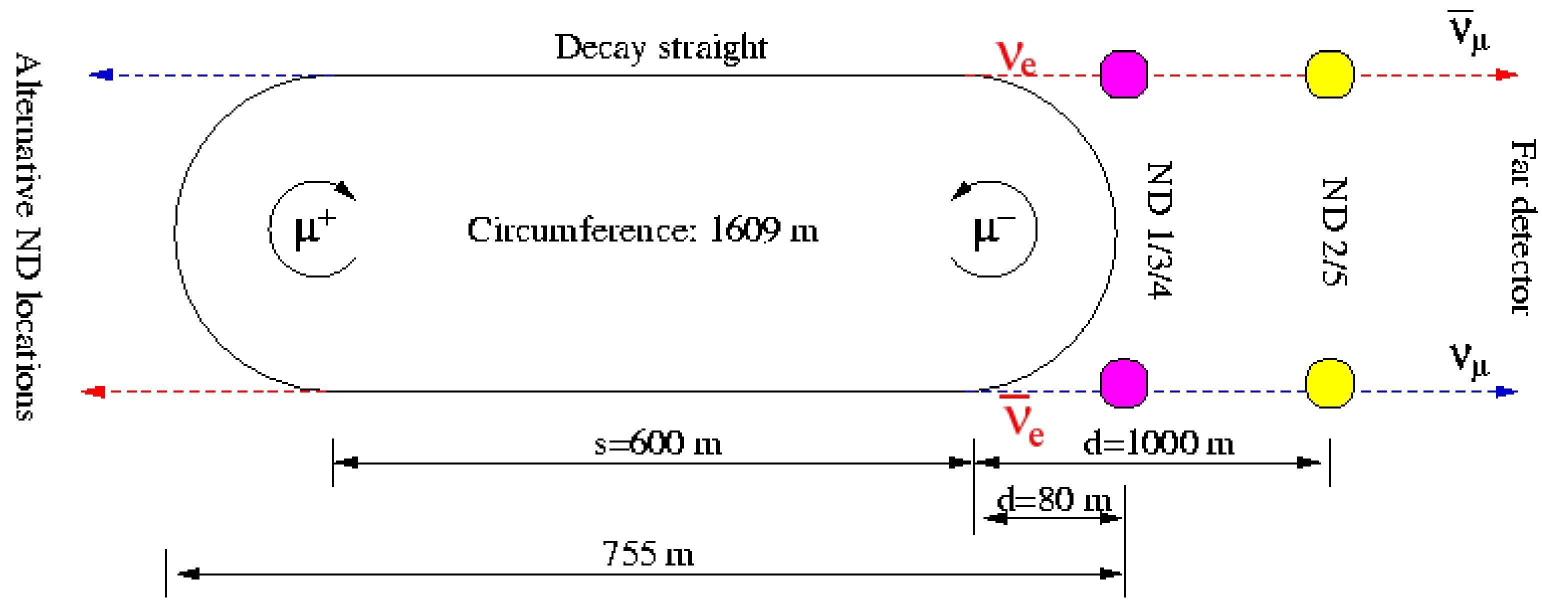
$$A_{\alpha\beta}^{\text{CPT}} \equiv P_{\nu_\alpha \to \nu_\beta} - P_{\bar{\nu}_\beta \to \bar{\nu}_\alpha} \qquad \alpha, \beta = e, \mu.$$

Future SBL experimental CPT tests with a β beam



Future SBL Beta-Beam experiments [P.Zucchelli PLB 532 (2002) 166] with a pure ν_e or $\bar{\nu}_e$ beam from nuclear decay of accelerated ions have the potentiality to check the possible SBL disappearance of ν_e and $\bar{\nu}_e$ with high accuracy .

Future SBL experimental CPT tests with a ν factory



Future SBL ν factory experiments [CERN-Yellow-Report hep-ph/0210192] with pure ν_e AND $\bar{\nu}_e$ beams from muon decay of accelerated muons have the capability to check the possible SBL disappearance of ν_e and $\bar{\nu}_e$ again with high accuracy . Non standard interactions studied from [A.Rubbia, ML et al. JHEP06(2001)032] $\longrightarrow$ [J.Tang and W.Winter arXiv:0903.3039].

Addendum : on the Majorana Theory (1)

- In 1928 Dirac proposed his equation [P.A.M. Dirac, Proceedings of the Royal Society A117 (1928) 610]. As it is well known the physical interpretation of this equation was rather problematic due the existence of negative energy solutions.
- In 1931 Dirac proposed a solution in terms of the hole-theory introducing a new kind of particles with the same mass of the electrons and opposite charge, the positrons [P.A.M. Dirac, Proceedings of the Royal Society A133 (1931) 610].
- The positron was discovered by Anderson at the end of 1931, and the paper with the first picture of a positron appeared at the very beginning of 1932 [C.D. Anderson, Science 76 (1932) 238] and [C.D. Anderson, The Positive Electron, Phys. Rev. 43, 491 - 494 (1933) received on 28 February 1933].
- In 1932 Ettore Majorana published a paper, in italian, by the title ”Relativistic theory of particles with arbitrary angular momentum” [E. Majorana,Relativistic theory of particles with arbitrary intrinsic angular momentum, Nuovo Cim. 9 (1932) 335].

Addendum : on the Majorana Theory (2)

- It is not clear when Majorana wrote this paper (probably during the summer, according to Amaldi) and in which month of 1932 the paper appeared in Il Nuovo Cimento. However it seems that the news of the discovery of the positron arrived in Rome only around the end of 1932.
- So when Majorana conceived his paper the problem of the negative energy states was still in his mind. Therefore the aim of the paper was to construct a Dirac-like equation with only positive energy solutions.
- Majorana found that this is indeed possible, but that it is necessary that the wave function transforms under unitary representations (UR) of the homogeneous Lorentz group. These representations are infinite dimensional, as he discovered.
- There is a connection between composite systems and URs of the Lorentz group.
- The infinite component wave equation shows 3 particular consequences : 1)the presence of redundant tachionic solutions; 2)the CPT theorem does not generally hold ; 3)the spin-statistic theorem does not generally hold ; (for a discussion see [R. Casalbuoni, hep-th/0610252].

Addendum : on the Majorana Theory (3)

- Let's go now to the famous paper [E. Majorana, Symmetrical Theory of Electrons and Positrons, Nuovo Cim. 14 (1937) 171]

  from the Abstract: ... there is no longer any reason to speak of **negative-energy** states nor to assume, for neutral particles, the existence of antiparticles.

- This paper was published in 1937 , **but the results were obtained before the year 1933**. [Esposito-Recami et al. ed."Ettore Majorana - Unpublished Research Notes on Theoretical Physics", Springer, 2009]

- Was Majorana simply wrong ([P.Minkowski hep-ph/0505049]) ...

  or instead he had in mind the results of his general theory of 1932 ?

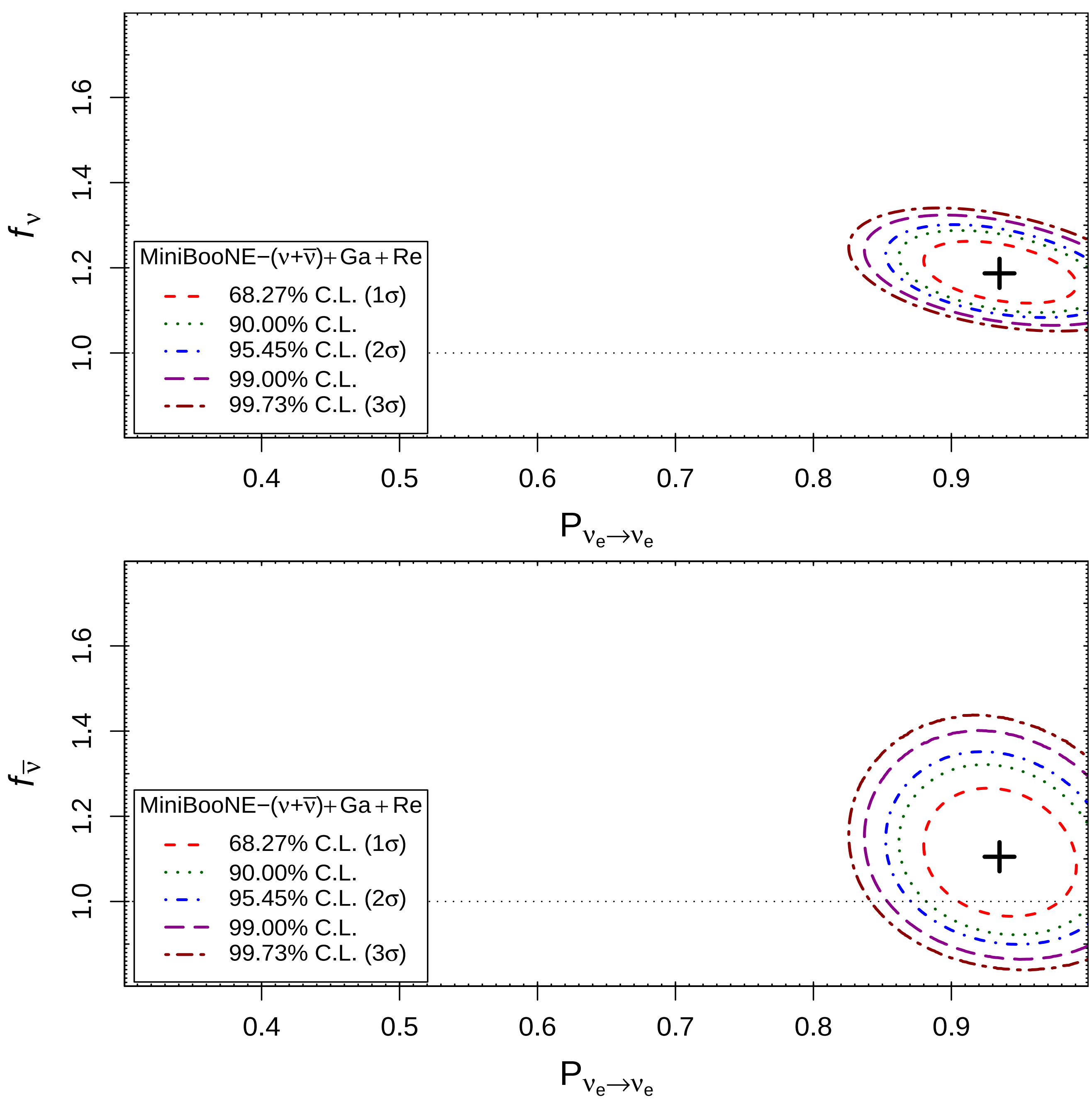
- **If this is the case a CPT violation for ν's is not totally unexpected !**

... if they are roses they'll flower...

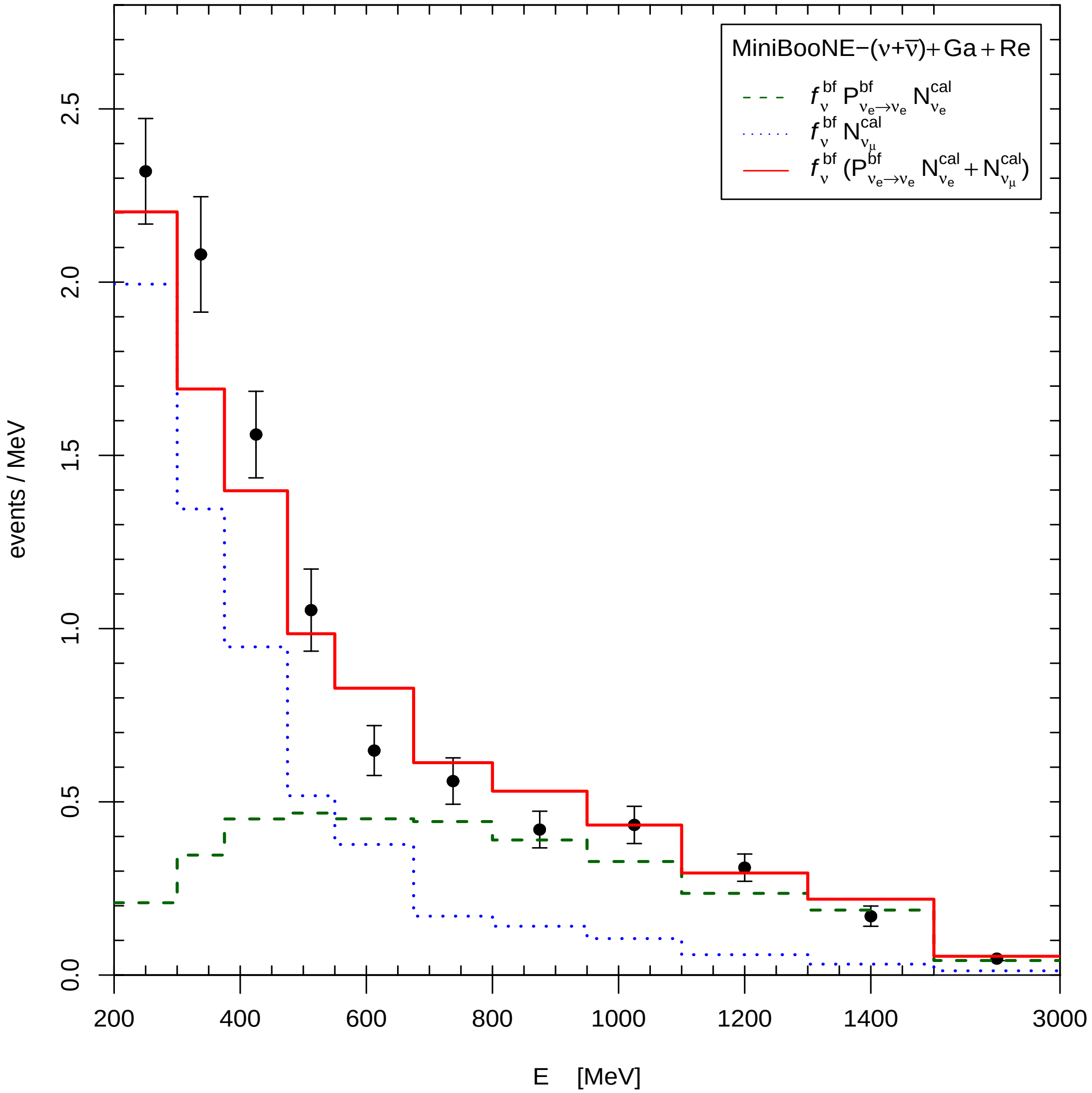
... A BRIGHT FUTURE for Majorana ν physics !!!

Backup slides

Combined fit of Miniboone & Gallium & Reactor



Best fit of Miniboone & Gallium & Reactor vs Miniboone-ν data



	BF	68.27%	90%	95.45%	99%	99.73%
MB-ν	0.72	0.65 - 0.80	0.60 - 0.86	0.58 - 0.89	0.54 - 0.95	0.52 - 0.99
MB-ν+Ga	0.83	0.79 - 0.88	0.76 - 0.91	0.75 - 0.92	0.72 - 0.95	0.70 - 0.97
Re	1.00	0.97 - 1.00	0.94 - 1.00	0.93 - 1.00	0.91 - 1.00	0.89 - 1.00
MB-ν+Ga+Re	0.93	0.90 - 0.96	0.89 - 0.98	0.88 - 0.99	0.86 - 1.00	0.85 - 1.00
MB-$\bar{\nu}$	1.00	0.83 - 1.00	0.70 - 1.00	0.63 - 1.00	0.54 - 1.00	0.47 - 1.00
MB-$\bar{\nu}$+Re	1.00	0.97 - 1.00	0.95 - 1.00	0.93 - 1.00	0.91 - 1.00	0.89 - 1.00
MB	0.76	0.69 - 0.84	0.65 - 0.90	0.62 - 0.93	0.59 - 0.98	0.56 - 1.00
MB+Ga+Re	0.93	0.91 - 0.96	0.89 - 0.98	0.88 - 0.99	0.86 - 1.00	0.85 - 1.00

Table 1: Best-fit values (BF) and allowed ranges of $P_{\nu_e \to \nu_e}$ at the indicated value of confidence level.

		MB-$\bar{\nu}$	MB-$\bar{\nu}$+Re	MB	MB+Ga+Re
No Osc.	$\chi^2_{\rm min}$	16.9	19.8	44.1	53.8
	NDF	10	17	21	29
	GoF	7.6%	28.5%	0.2%	0.3%
	$f_{\bar{\nu}}^{\rm bf}$	1.08	1.08	1.08	1.08
Osc.	$\chi^2_{\rm min}$	16.9	19.8	36.7	48.9
	NDF	9	16	19	27
	GoF	5.0%	23.0%	0.9%	0.6%
	$P^{\rm bf}_{\nu_e\to\nu_e}$	1.00	1.00	0.76	0.93
	$f_{\bar{\nu}}^{\rm bf}$	1.08	1.08	1.19	1.10
	$f_{\nu}^{\rm bf}$			1.28	1.19
PG	$\Delta\chi^2_{\rm min}$		0.0	2.1	8.3
	NDF		1	1	3
	GoF		100.0%	14.8%	4.1%

Table 2: Values of χ^2, number of degrees of freedom (NDF) and goodness-of-fit (GoF) for the fit of MiniBooNE antineutrino (MB-$\bar{\nu}$), MiniBooNE antineutrino and reactor (MB-$\bar{\nu}$+Re), MiniBooNE neutrino and antineutrino (MB) and MiniBooNE neutrino and antineutrino, Gallium and reactor (MB+Ga+Re) data. The first four lines correspond to the case of no oscillations (No Osc.). The following six lines correspond to the case of oscillations (Osc.). The last three lines give the parameter goodness-of-fit (PG) .

Parameter Goodness-of-fit (PG)

- The goodness-of-fit is the probability to obtain a worse fit under the assumption that the model under consideration is correct. It is the standard statistic used for the estimation of the quality of a fit obtained with the least-squares method, assuming the validity of the approximation in which χ^2_{min} has a χ^2 distribution with NDF $= N_{\text{D}} - N_{\text{P}}$ degrees of freedom, where N_{D} is the number of data points and N_{P} is the number of fitted parameters. The fit is usually considered to be acceptable if the goodness-of-fit is larger than about 1%.
- The value of $(\Delta\chi^2_{\text{min}})_{\text{A+B}}$ corresponding to the Parameter Goodness-of-fit (PG) of two experiments A and B is given by $(\chi^2_{\text{min}})_{\text{A+B}} - [(\chi^2_{\text{min}})_{\text{A}} + (\chi^2_{\text{min}})_{\text{B}}]$. It has a χ^2 distribution with number of degrees of freedom NDF $= P_{\text{A}} + P_{\text{B}} - P_{\text{A+B}}$, where P_{A}, P_{B} and $P_{\text{A+B}}$ are, respectively, the number of parameters in the fits of A, B and A+B data.
  [M. Maltoni and T. Schwetz, Phys. Rev. D68 (2003) 033020 (hep-ph/0304176).]