Short Baseline Oscillations: what to look for?

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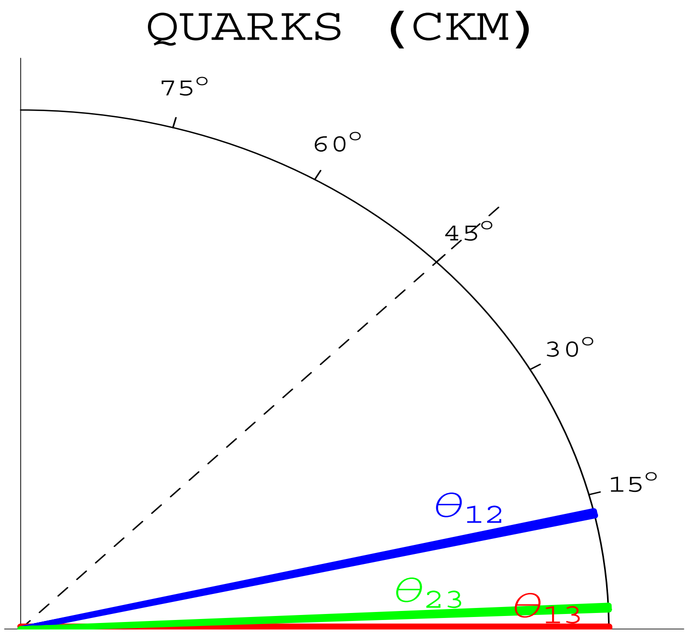
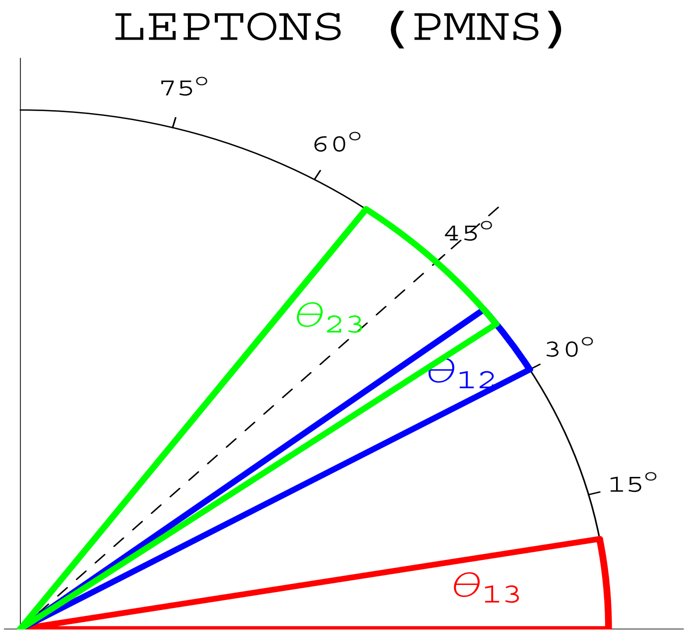
LAGUNA 2011

LAGUNA/LAGUNA-LBNO General Meeting

3-5 March 2011, CERN

WHICH NEUTRINO MIXING ?


QUARKS (CKM)

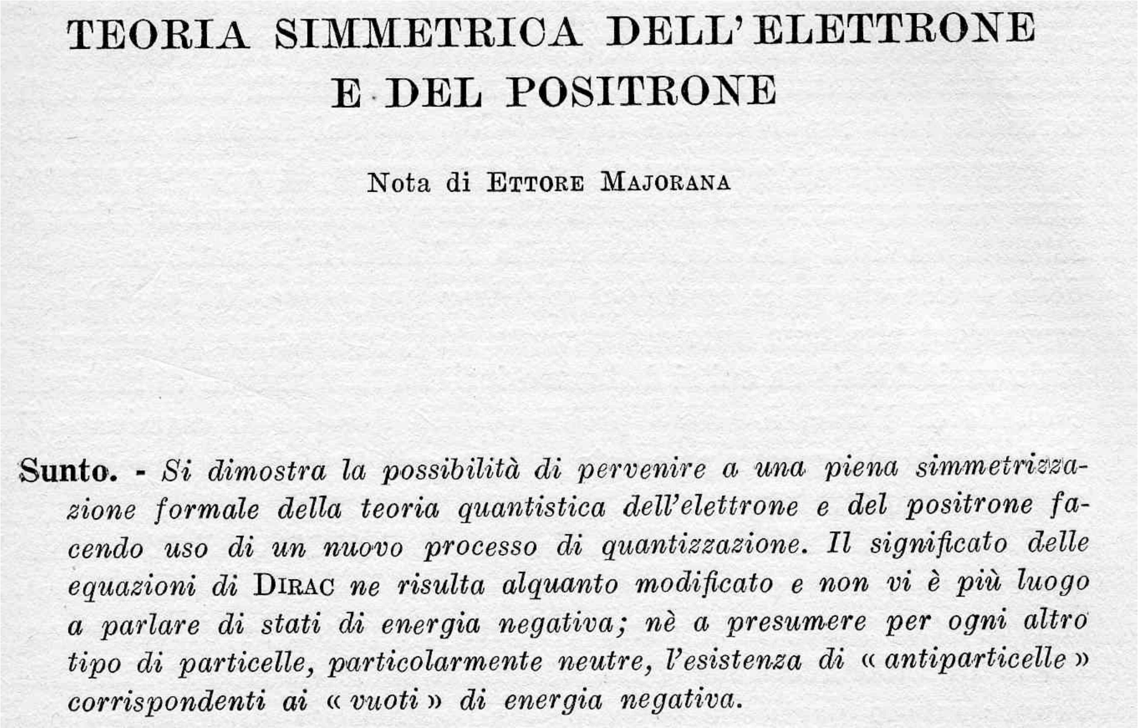

LEPTONS (PMNS)

Experimental ν mixing angles between active ν are BI-LARGE:

$$\theta_{12} \sim 32^o \qquad \theta_{23} \sim 45^o \qquad \theta_{13} \leq 13^o$$

Natura del neutrino

Nuovo Cimento **14** (1937) 171-184



TEORIA SIMMETRICA DELL'ELETTRONE E DEL POSITRONE

Nota di ETTORE MAJORANA

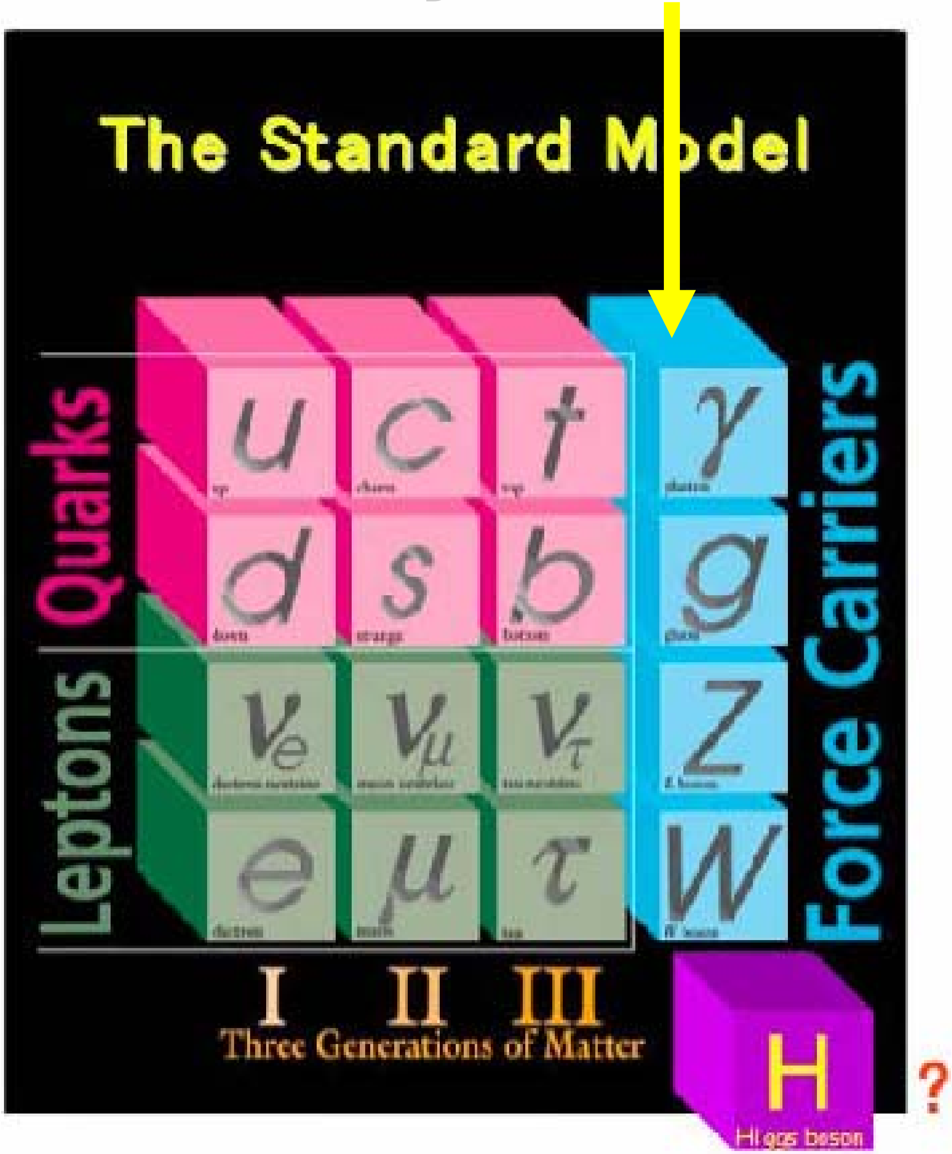
Sunto. - *Si dimostra la possibilità di pervenire a una piena simmetrizzazione formale della teoria quantistica dell'elettrone e del positrone facendo uso di un nuovo processo di quantizzazione. Il significato delle equazioni di* DIRAC *ne risulta alquanto modificato e non vi è più luogo a parlare di stati di energia negativa; nè a presumere per ogni altro tipo di particelle, particolarmente neutre, l'esistenza di «antiparticelle» corrispondenti ai «vuoti» di energia negativa.*

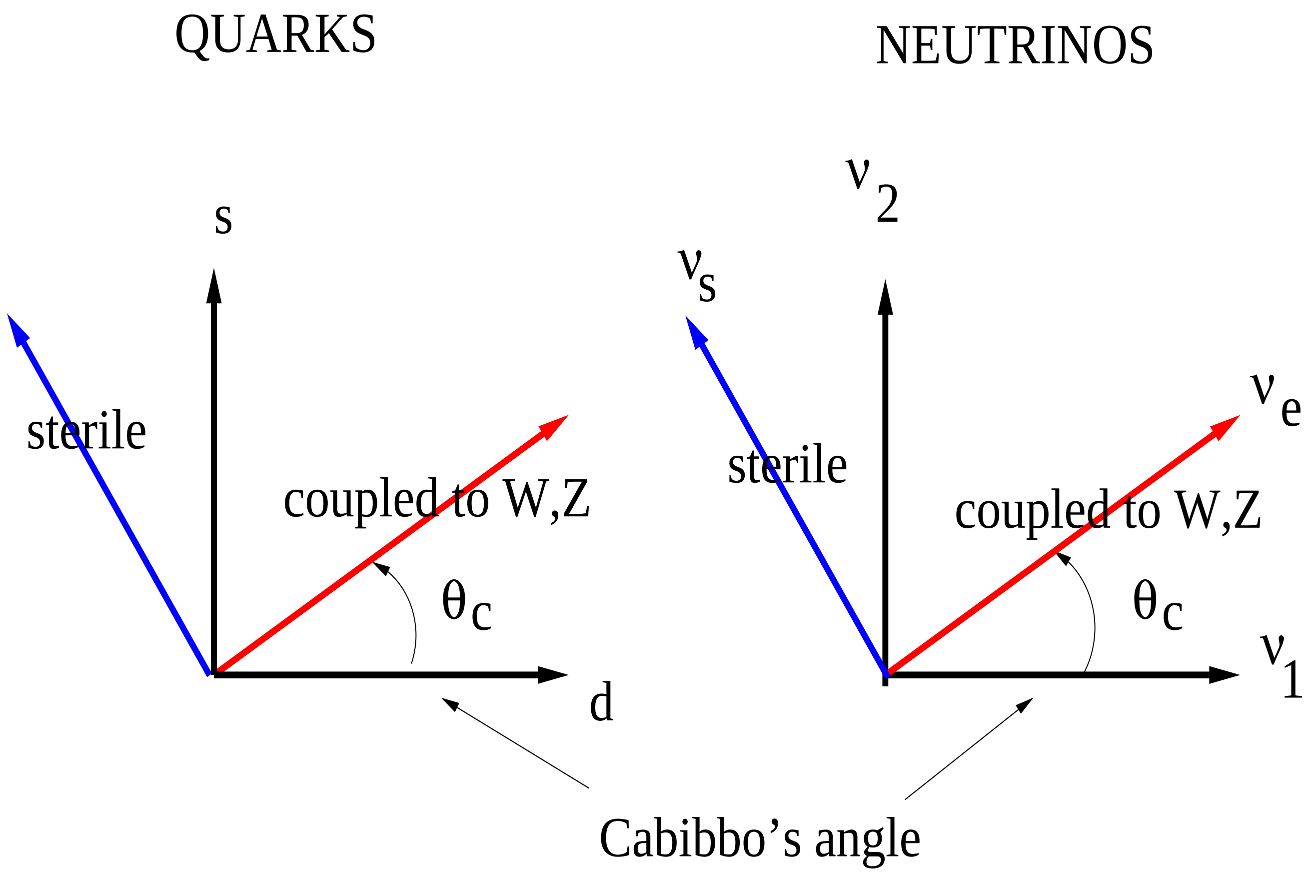
We show that it is possible to achieve complete formal symmetrization in the electron and positron quantum theory by means of a new quantization process. The meaning of Dirac equations is somewhat modified and it is no more necessary to speak of negative-energy states; nor to assume, for any other type of particles, especially neutral ones, the existence of antiparticles, corresponding to the "holes" of negative energy.

Majorana Neutrino

Gravity

?

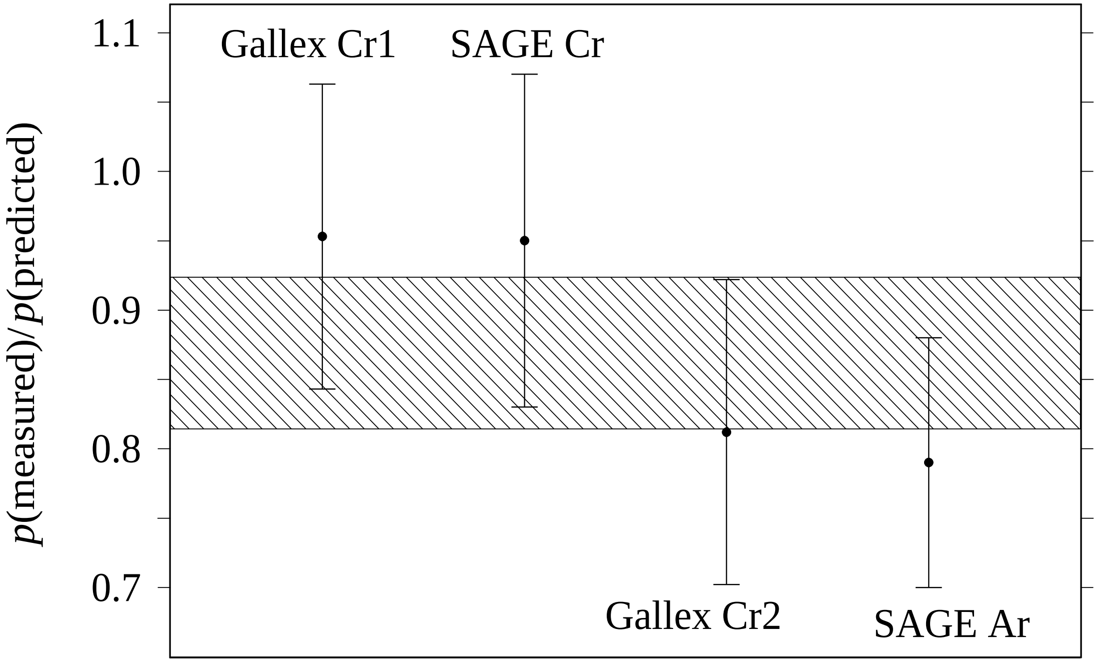




COMPLEMENTARITY relation :

$$\theta_{12} \sim 32^o \qquad \theta_{es} \sim 13^o \qquad \theta_{12} + \theta_{es} = 45^o$$

ν_e Disappearance in Gallium radioactive source experiments



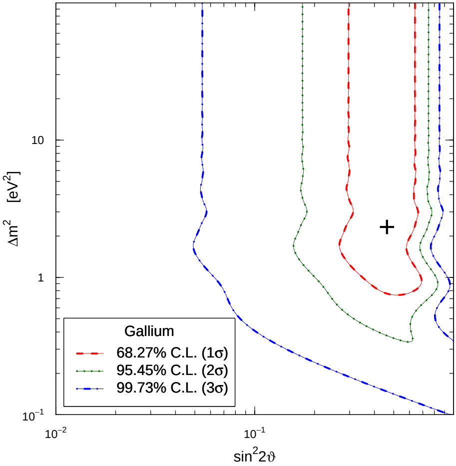
$R \equiv$ wheighted average value of the ratio of measured and predicted ${}^{71}Ge$ production rates (p) :

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

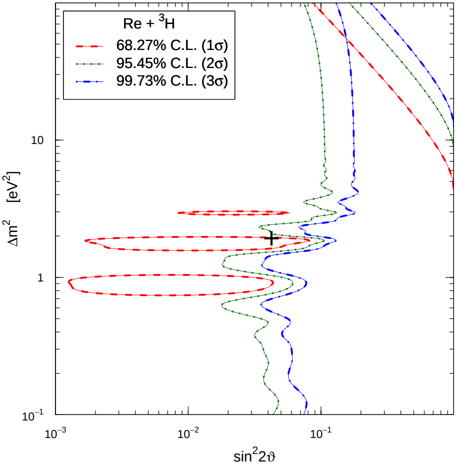
arXiv:0901.2200[nucl-ex]

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



[Giunti, Laveder, arXiv:1006.3244]



[Giunti, Laveder, PRD 82 (2010) 053005, arXiv:1005.4599]

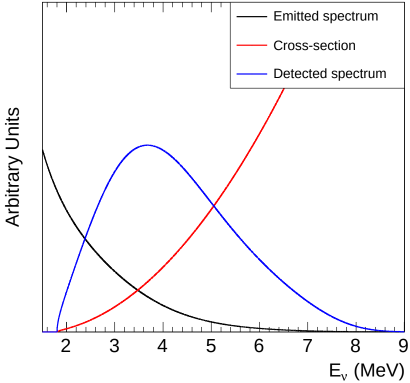
$\Delta m^2_{\rm SBL} \gtrsim 1\,{\rm eV}^2$ is OK, but $\sin^2 2\vartheta_{\nu} > \sin^2 2\vartheta_{\bar\nu}$

Parameter Goodness of Fit = 0.2%

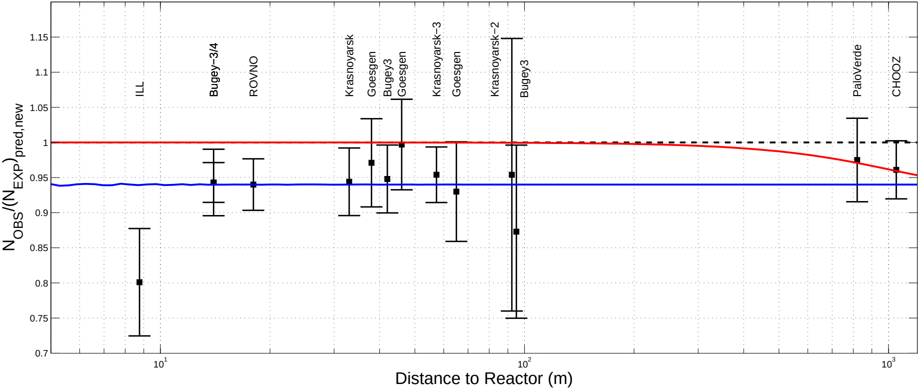
CPT violation? [Giunti, Laveder, PRD 82 (2010) 113009, arXiv:1008.4750]

New Calculation of Reactor $\bar{\nu}_e$ Flux

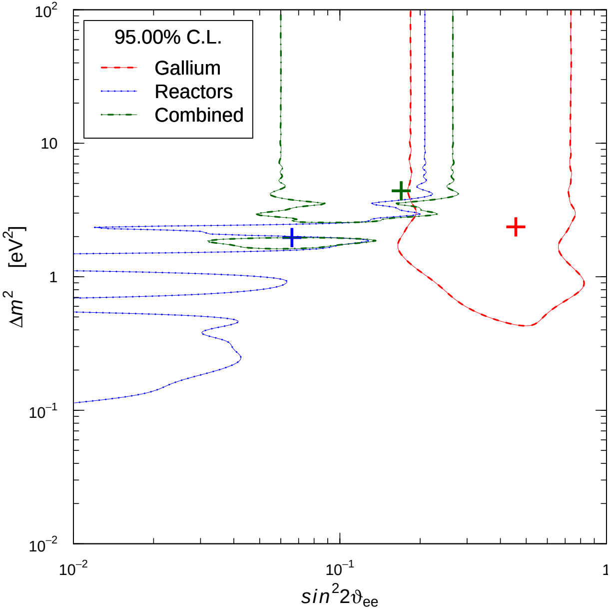
- Th. A. Mueller, D. Lhuillier, M. Fallot, A. Letourneau, S. Cormon, M. Fechner, L. Giot, T. Lasserre, J. Martino, G. Mention, A. Porta, F. Yermia, Improved Predictions of Reactor Antineutrino Spectra, arXiv:1101.2663
- detected flux normalization is increased by about 3%



- G. Mention, M. Fechner, Th. Lasserre, Th. A. Mueller, D. Lhuillier, M. Cribier, A. Letourneau, The Reactor Antineutrino Anomaly, arXiv:1101.2755
- ratio of observed and predicted event rates: 0.937 ± 0.027
- deviation from unity at 98.4% C.L.: reactor antineutrino anomaly



Gallium Anomaly + Reactor Anomaly



$\chi^2_{\text{min}} = 59.8$

$\text{NdF} = 65$

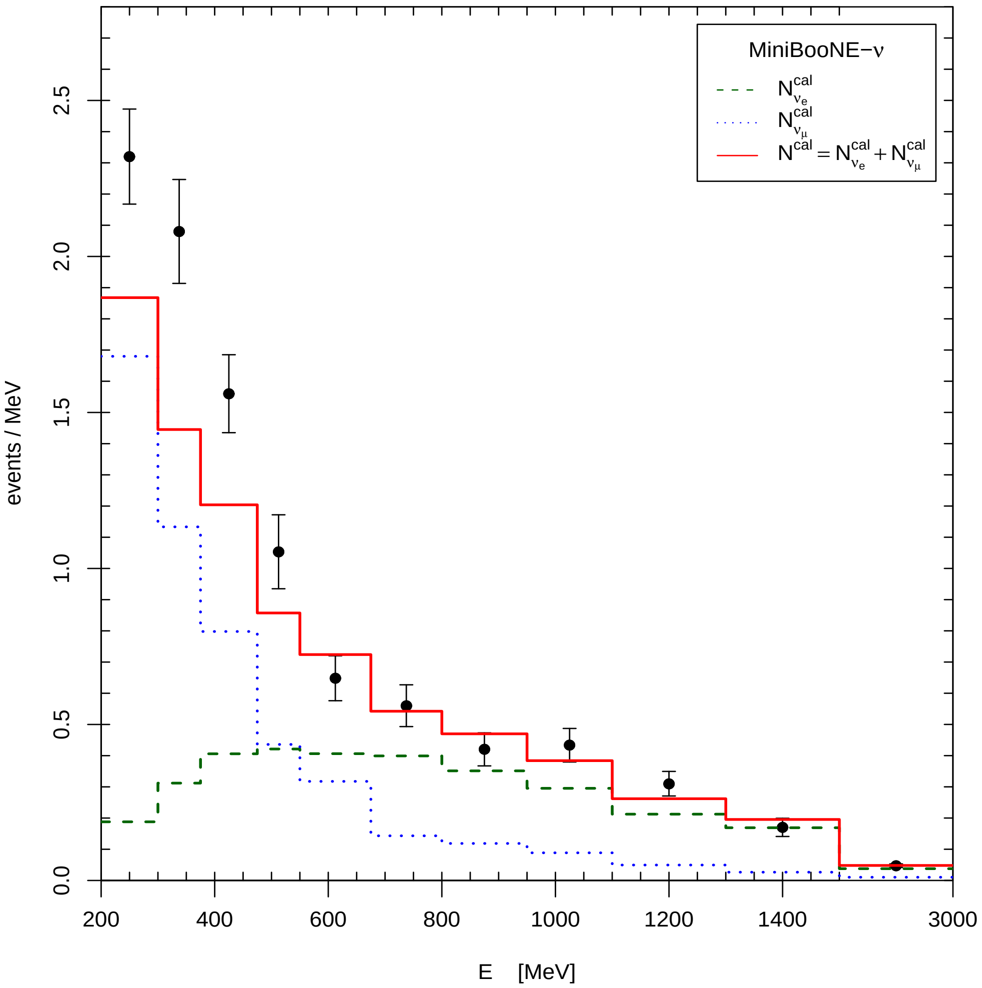
$\text{GoF} = 66\%$

$\sin^2 2\vartheta = 0.17$

$\Delta m^2 = 4.17\,\text{eV}^2$

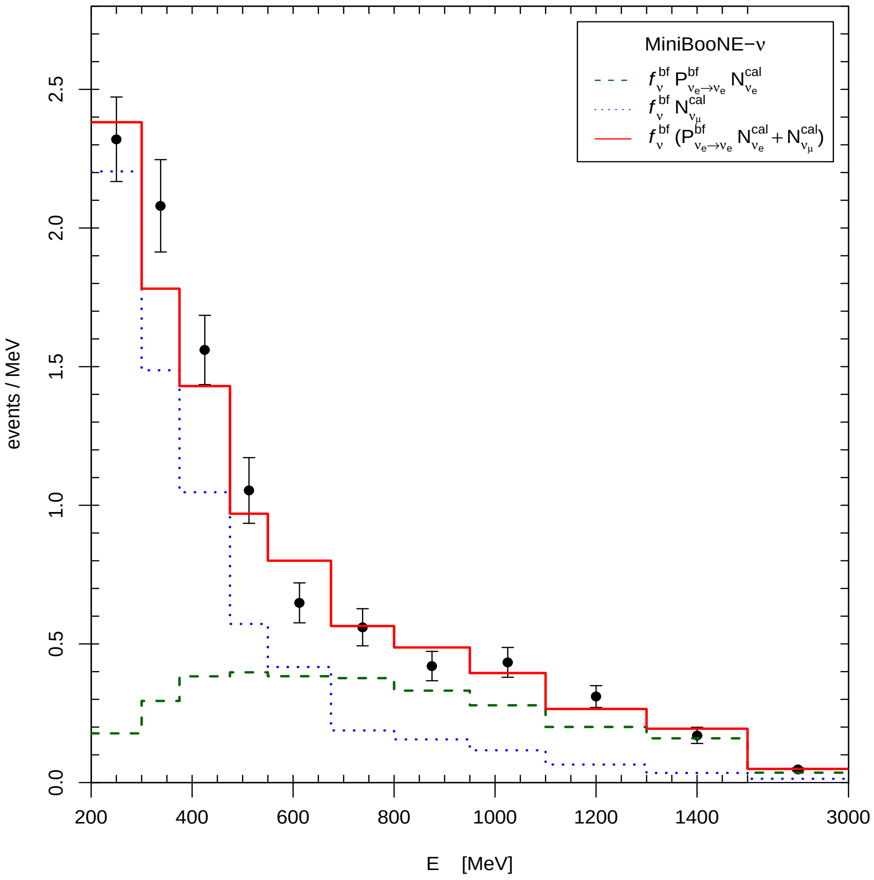
$\text{PGoF} = 1.1\%$

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

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 .

Miniboone & Gallium & Reactor : Osc vs No Osc

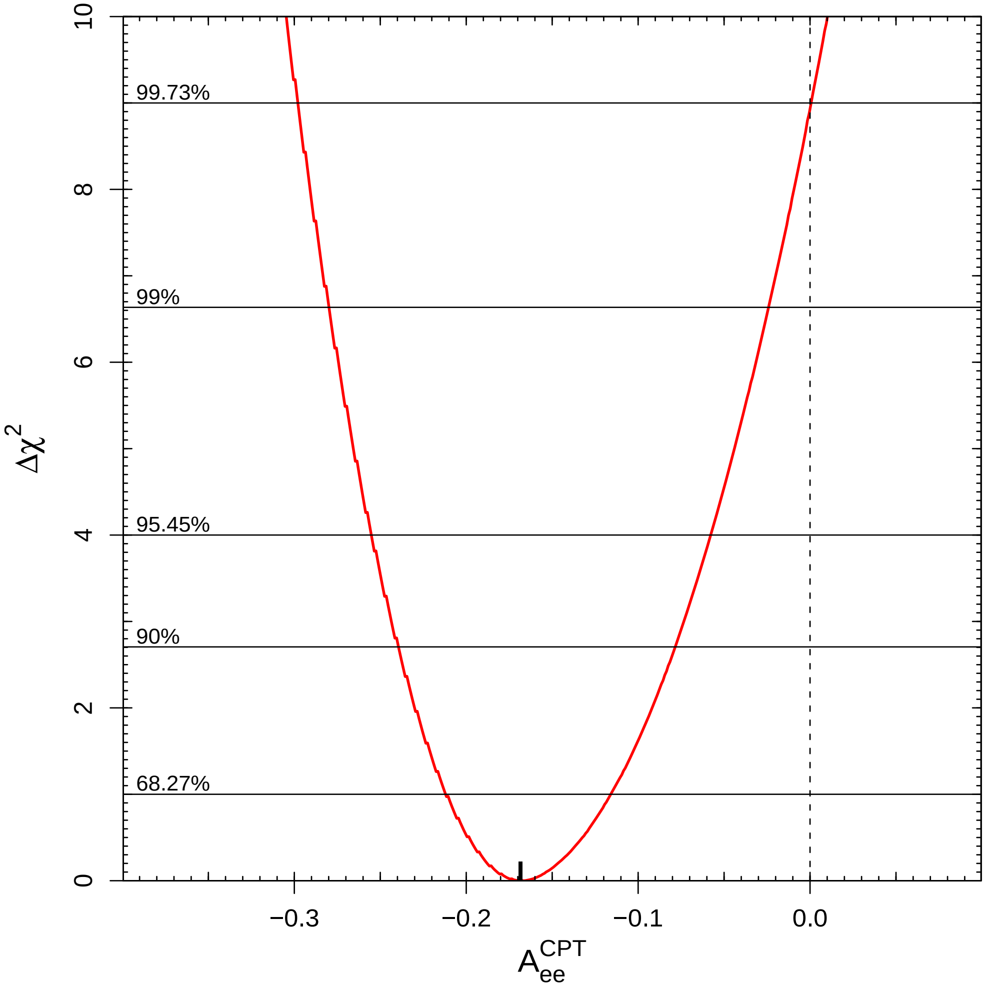
		MB-ν	MB-ν+Ga	MB-ν+Ga+Re	MB+Ga+Re
No Osc.	χ^2_{min}	27.2	34.0	36.9	53.8
	NDF	10	11	18	29
	GoF	0.2%	0.04%	0.5%	0.3%
	f^{bf}_{ν}	1.15	1.15	1.15	1.15
	$f^{\text{bf}}_{\bar{\nu}}$				1.08
Osc.	χ^2_{min}	17.7	20.1	31.7	48.9
	NDF	9	10	17	27
	GoF	3.8%	2.8%	1.7%	0.6%
	$P^{\text{bf}}_{\nu_e\to\nu_e}$	0.72	0.83	0.93	0.93
	f^{bf}_{ν}	1.31	1.24	1.19	1.19
	$f^{\text{bf}}_{\bar{\nu}}$				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



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

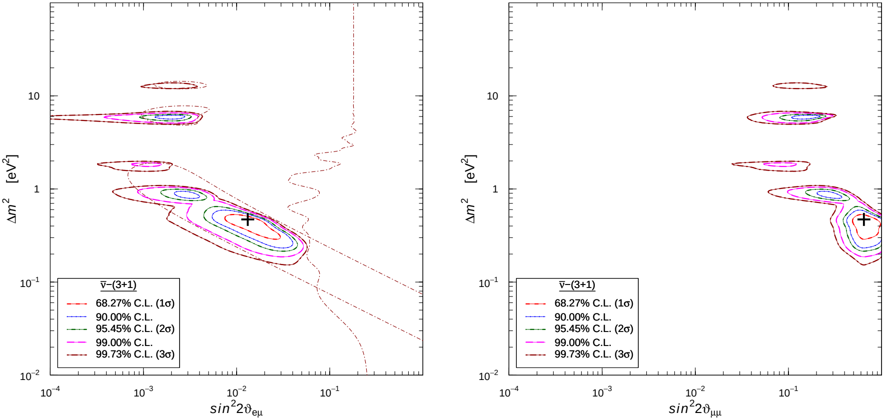
SBL future experiments at CERN-PS beam

detector mass	0.6 kton	1.0 kton
detector distance	850 m	850 m
references	C.Rubbia et al.	A. Rubbia et al.
ν_μ CC	720000	1200000
ν_e CC	18000	30000
stat error	134	173
syst error	360	600
total error	384	624
expected deficit	2970	4950
n. of sigma	7.73	7.93

Event rates presented at CERN workshop ”Neutrino detector studies and possible experiment at CERN PS”, 17-18 march 2010 .

A ν_e contamination of 2.5 % is assumed here (tagged kaons - F.Terranova private communication) with a 2% systematic error on the ν_e flux .

Antineutrino Oscillations in 3+1 Schemes



$\chi^2_{\text{min}} = 82.0 \qquad \text{NdF} = 83 \qquad \text{GoF} = 51\%$

$\Delta m^2 = 0.45\,\text{eV}^2 \quad \sin^2 2\vartheta_{e\mu} = 0.013 \quad \sin^2 2\vartheta_{ee} = 0.017 \quad \sin^2 2\vartheta_{\mu\mu} = 0.65$

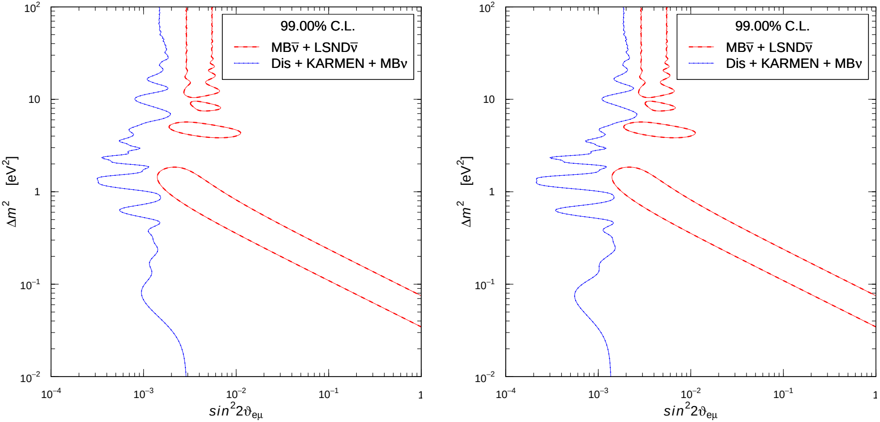
Prediction: large SBL $\bar{\nu}_\mu$ disappearance at $0.1 \lesssim \Delta m^2 \lesssim 1\,\text{eV}^2$

[Giunti, Laveder, arXiv:1012.0267]

SBL Oscillations in 3+1 Spectra

Standard Reactor $\bar{\nu}_e$ Fluxes

New Reactor $\bar{\nu}_e$ Fluxes



PGoF = 0.0052%

PGoF = 0.010%

- Tension between $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance and disappearance limits is decreased, but still strong

Conclusions

- Suggestive LSND and MiniBooNE agreement on SBL $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations
- Hint in favor of sterile neutrinos is compatible with cosmological data, but mass is limited
- Three experimental tensions:
  - LSND and MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$ vs MiniBooNE $\nu_\mu \to \nu_e$ (CP violation?)
  - LSND and MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$ vs $\bar{\nu}_e$ and ν_μ disappearance limits
  - Gallium Anomaly (ν_e disappearance) vs Reactor ($\bar{\nu}_e$ disappearance), maybe resolved by Reactor Anomaly
- CPT-invariant 3+1 Four-Neutrino Mixing is strongly disfavored (no CP violation and tension between appearance and disappearance)
- 3+2 Five-Neutrino Mixing can explain CP violation but tension between appearance and disappearance persists (reduced by NSI)
- CPT-violating 3+1 Mixing $\Longrightarrow$ large SBL $\bar{\nu}_\mu$ disappearance
- Work in Progress: combined explanation of LSND and MiniBooNE + Gallium and Reactor Anomaly
- New short-baseline neutrino oscillation experiments are needed!

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

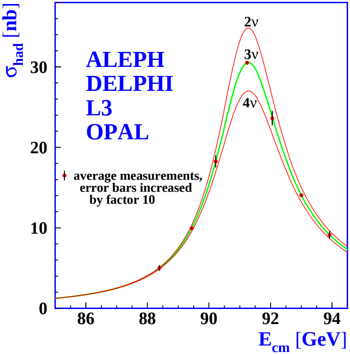
... A BRIGHT FUTURE for Majorana ν physics !!!

Backup Slides

How many Sterile Neutrinos?

$$e^+e^- \to Z \xrightarrow{\text{invisible}} \sum_{a=\text{active}} \nu_a \bar{\nu}_a$$

[LEP, Phys. Rept. 427 (2006) 257, hep-ex/0509008]



3 light active flavor neutrinos

$$\nu_e \quad \nu_\mu \quad \nu_\tau$$

mixing $\Rightarrow$ $$\nu_{\alpha L} = \sum_{k=1}^{N} U_{\alpha k} \nu_{kL} \qquad \alpha = e, \mu, \tau$$

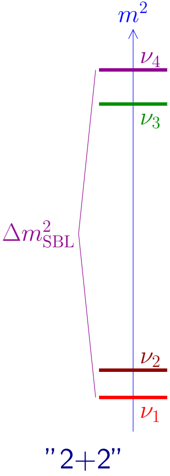
$N \geq 3$
no upper limit!

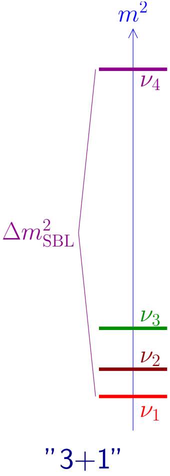
Mass Basis: $\nu_1 \quad \nu_2 \quad \nu_3 \quad \nu_4 \quad \nu_5 \quad \cdots$

Flavor Basis: $\nu_e \quad \nu_\mu \quad \nu_\tau \quad \nu_{s_1} \quad \nu_{s_2} \quad \cdots$

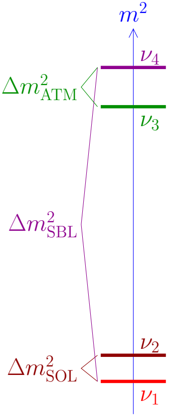
ACTIVE STERILE

Four-Neutrino Schemes: 2+2 and 3+1

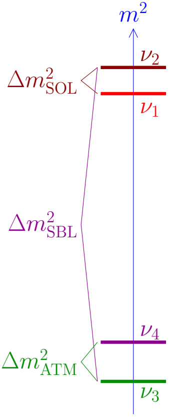




2+2 Four-Neutrino Schemes

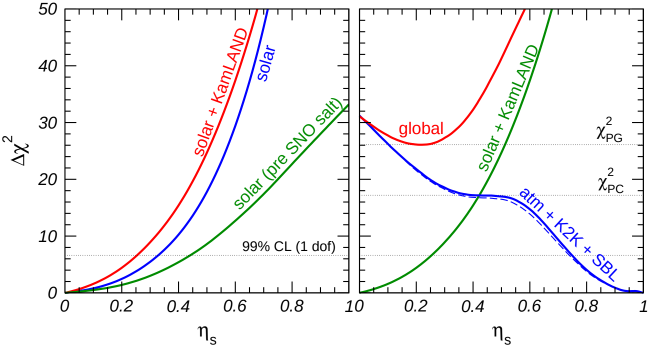


"normal"



"inverted"

2+2 Schemes are strongly disfavored by solar and atmospheric data

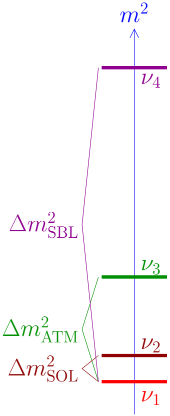


[Maltoni, Schwetz, Tortola, Valle, New J. Phys. 6 (2004) 122, arXiv:hep-ph/0405172]

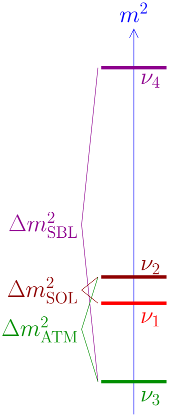
$\eta_s = |U_{s1}|^2 + |U_{s2}|^2$

$$99\%\ \text{CL:} \begin{cases} \eta_s < 0.25 & \text{(solar + KamLAND)} \\ \eta_s > 0.75 & \text{(atmospheric + K2K)} \end{cases}$$

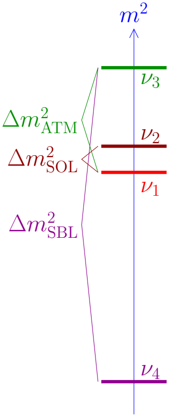
3+1 Four-Neutrino Schemes



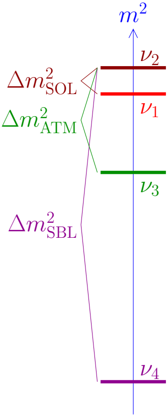
"normal"



"3ν-inverted"



"4ν-inverted"

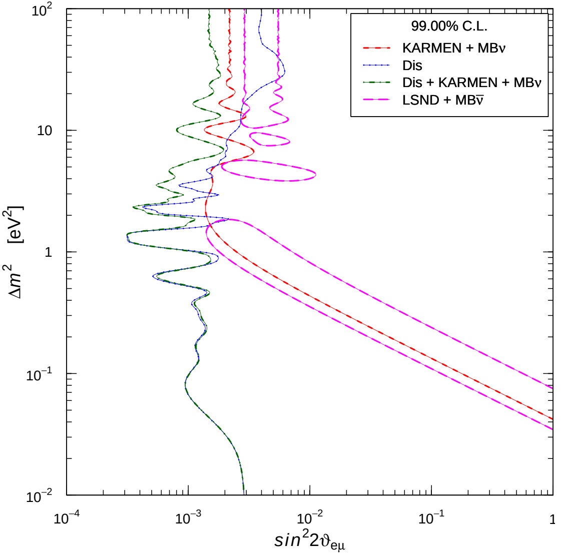


"fully-inverted"

Perturbation of 3-ν Mixing

$|U_{e4}|^2 \ll 1$ $\quad$ $|U_{\mu4}|^2 \ll 1$ $\quad$ $|U_{\tau4}|^2 \ll 1$ $\quad$ $|U_{s4}|^2 \simeq 1$

3+1 Schemes

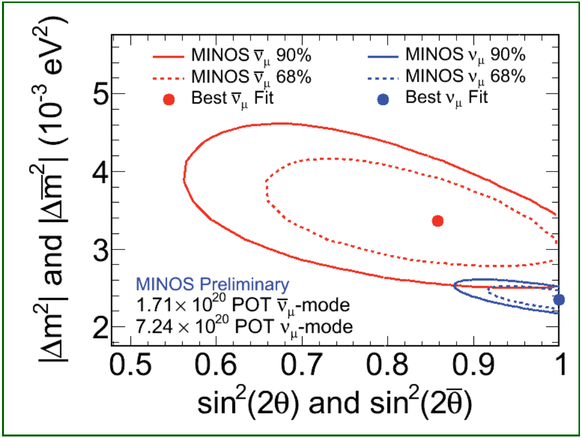


99.00% C.L.
KARMEN + MBν
Dis
Dis + KARMEN + MBν
LSND + MB$\bar{\nu}$
10^2
10
1
10^{-1}
10^{-2}
Δm^2 [eV^2]
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$sin^2 2\vartheta_{e\mu}$

MINOS Hint of CPT Violation

LBL ν_μ disappearance $E \sim 3\,\text{GeV}$

Near Detector at 1.04 km Far Detector at 734 km



[MINOS, Neutrino 2010, 14 June 2010]

Gallium Anomaly

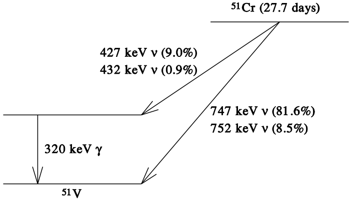
Gallium Radioactive Source Experiments

Tests of the solar neutrino detectors GALLEX (Cr1, Cr2) and SAGE (Cr, Ar)

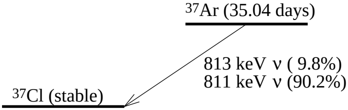
Detection Process: $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$

ν_e Sources: $e^- + {}^{51}\text{Cr} \to {}^{51}\text{V} + \nu_e$ $e^- + {}^{37}\text{Ar} \to {}^{37}\text{Cl} + \nu_e$

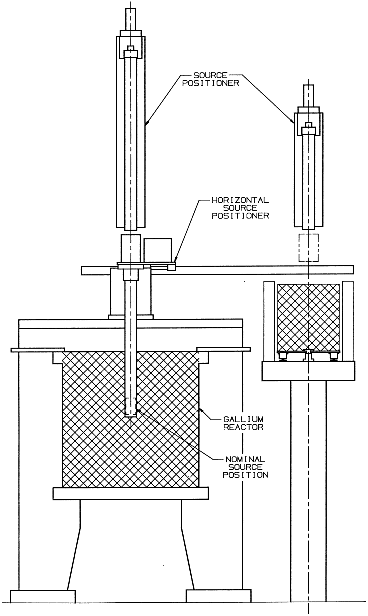
	^{51}Cr				^{37}Ar	
E [keV]	747	752	427	432	811	813
B.R.	0.8163	0.0849	0.0895	0.0093	0.902	0.098



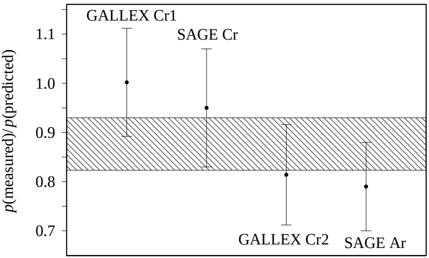
[SAGE, PRC 59 (1999) 2246, hep-ph/9803418]



[SAGE, PRC 73 (2006) 045805, nucl-ex/0512041]



[SAGE, PRC 59 (1999) 2246, hep-ph/9803418]

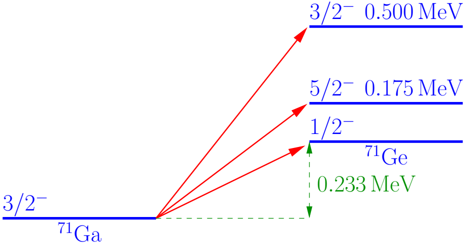


[SAGE, PRC 73 (2006) 045805, nucl-ex/0512041]

$$\boxed{R_{\text{Ga}} = 0.86 \pm 0.05}$$

- Deficit could be due to overestimate of
$$\sigma(\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-)$$

- Calculation: Bahcall, PRC 56 (1997) 3391, hep-ph/9710491



- $\sigma_{\mathrm{G.S.}}$ related to measured $\sigma(e^- + {}^{71}\mathrm{Ge} \to {}^{71}\mathrm{Ga} + \nu_e)$:

$$\sigma_{\mathrm{G.S.}}({}^{51}\mathrm{Cr}) = 55.3 \times 10^{-46}\,\mathrm{cm}^2\,(1 \pm 0.004)_{3\sigma}$$

- $\sigma({}^{51}\mathrm{Cr}) = \sigma_{\mathrm{G.S.}}({}^{51}\mathrm{Cr}) \left(1 + 0.669\,\frac{\mathrm{BGT}_{175\,\mathrm{keV}}}{\mathrm{BGT}_{\mathrm{G.S.}}} + 0.220\,\frac{\mathrm{BGT}_{500\,\mathrm{keV}}}{\mathrm{BGT}_{\mathrm{G.S.}}}\right)$

- Contribution of Excited States only 5%!

- Bahcall: [Bahcall, PRC 56 (1997) 3391, hep-ph/9710491]

  from $p + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + n$ measurements [Krofcheck et al., PRL 55 (1985) 1051]

$$\frac{\text{BGT}_{175\,\text{keV}}}{\text{BGT}_{\text{G.S.}}} < 0.056 \Rightarrow \frac{\text{BGT}_{175\,\text{keV}}}{\text{BGT}_{\text{G.S.}}} = \frac{0.056}{2} \qquad \frac{\text{BGT}_{500\,\text{keV}}}{\text{BGT}_{\text{G.S.}}} = 0.146$$

3σ lower limit: $\dfrac{\text{BGT}_{175\,\text{keV}}}{\text{BGT}_{\text{G.S.}}} = \dfrac{\text{BGT}_{500\,\text{keV}}}{\text{BGT}_{\text{G.S.}}} = 0$

3σ upper limit: $\dfrac{\text{BGT}_{175\,\text{keV}}}{\text{BGT}_{\text{G.S.}}} < 0.056 \times 2 \qquad \dfrac{\text{BGT}_{500\,\text{keV}}}{\text{BGT}_{\text{G.S.}}} = 0.146 \times 2$

$$\sigma({}^{51}\text{Cr}) = 58.1 \times 10^{-46}\,\text{cm}^2 \left(1^{+0.036}_{-0.028}\right)_{1\sigma} \qquad \Longrightarrow \qquad \boxed{R_{\text{Ga}} = 0.86 \pm 0.05}$$

- Haxton: [Hata, Haxton, PLB 353 (1995) 422, nucl-th/9503017; Haxton, PLB 431 (1998) 110, nucl-th/9804011]

  “a sophisticated shell model calculation is performed ... for the transition to the first excited state in ^{71}Ge. The calculation predicts destructive interference between the (p, n) spin and spin-tensor matrix elements.”

$$\sigma({}^{51}\text{Cr}) = 63.9 \times 10^{-46}\,\text{cm}^2 \,(1 \pm 0.106)_{1\sigma} \qquad \Longrightarrow \qquad \boxed{R_{\text{Ga}} = 0.76^{+0.09}_{-0.08}}$$

Future

- New Gallium source experiments: ν_e disappearance [Gavrin et al, arXiv:1006.2103]

- CPT test: ν_e and $\bar{\nu}_e$ disappearance

- Beta-Beam experiments: [Antusch, Fernandez-Martinez, PLB 665 (2008) 190, arXiv:0804.2820]

$$N(A, Z) \to N(A, Z+1) + e^- + \bar{\nu}_e \qquad (\beta^-)$$

$$N(A, Z) \to N(A, Z-1) + e^+ + \nu_e \qquad (\beta^+)$$

- Neutrino Factory experiments: [Giunti, Laveder, Winter, PRD 80 (2009) 073005, arXiv:0907.5487]

$$\mu^+ \to \bar{\nu}_\mu + e^+ + \nu_e$$

$$\mu^- \to \nu_\mu + e^- + \bar{\nu}_e$$

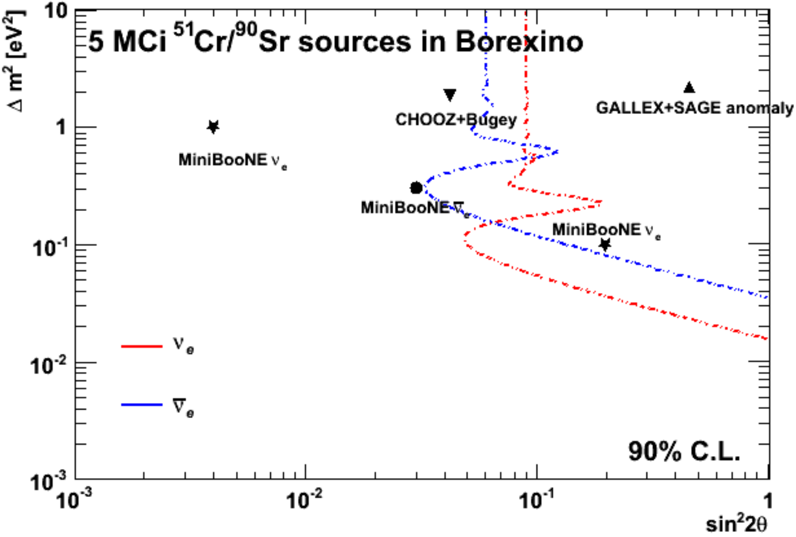
- New ν_e and $\bar{\nu}_e$ radioactive source experiments with low-threshold neutrino elastic scattering detectors.

- LENS (Low Energy Neutrino Spectroscopy): [Agarwalla, Raghavan, arXiv:1011.4509]

$$\nu_e + {}^{115}\mathrm{In} \to {}^{115}\mathrm{Sn} + e^- + 2\gamma \qquad E_{\mathrm{th}} = 0.1\,\mathrm{MeV}$$

$$\bar{\nu}_e + p \to n + e^+ \qquad E_{\mathrm{th}} = 1.8\,\mathrm{MeV}$$

- Borexino: [Ianni, Montanino, Scioscia, EPJC 8 (1999) 609, arXiv:hep-ex/9901012]



[A. Ianni, Private Communication]

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).]