Neutrino experiments and nonstandard interactions

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Cinvestav

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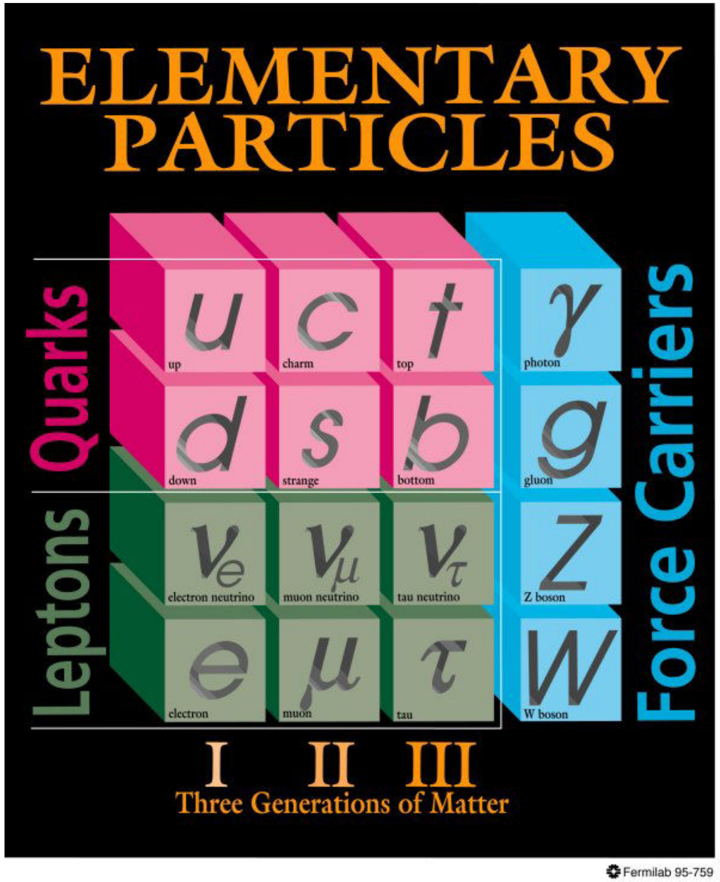
- Neutrino flavors
- Neutrino oscillations
- Solar and atmospheric Neutrinos
- Beyond the Standard Model

Neutrino flavors



Neutrino flavors

- For neutrinos coming from the decay:

$$n \to p + e^- + \bar{\nu}$$

we observe the reaction

$$\bar{\nu} + p \to n + e^+$$

- When neutrinos are coming from the decay:

$$\pi^- \to \mu^- + \bar{\nu}$$

we observe the reaction

$$\bar{\nu} + p \to n + \mu^+$$

Neutrino experiments without oscillations

- Muon neutrinos on nuclei
  CHARM, CDHS, NuTeV

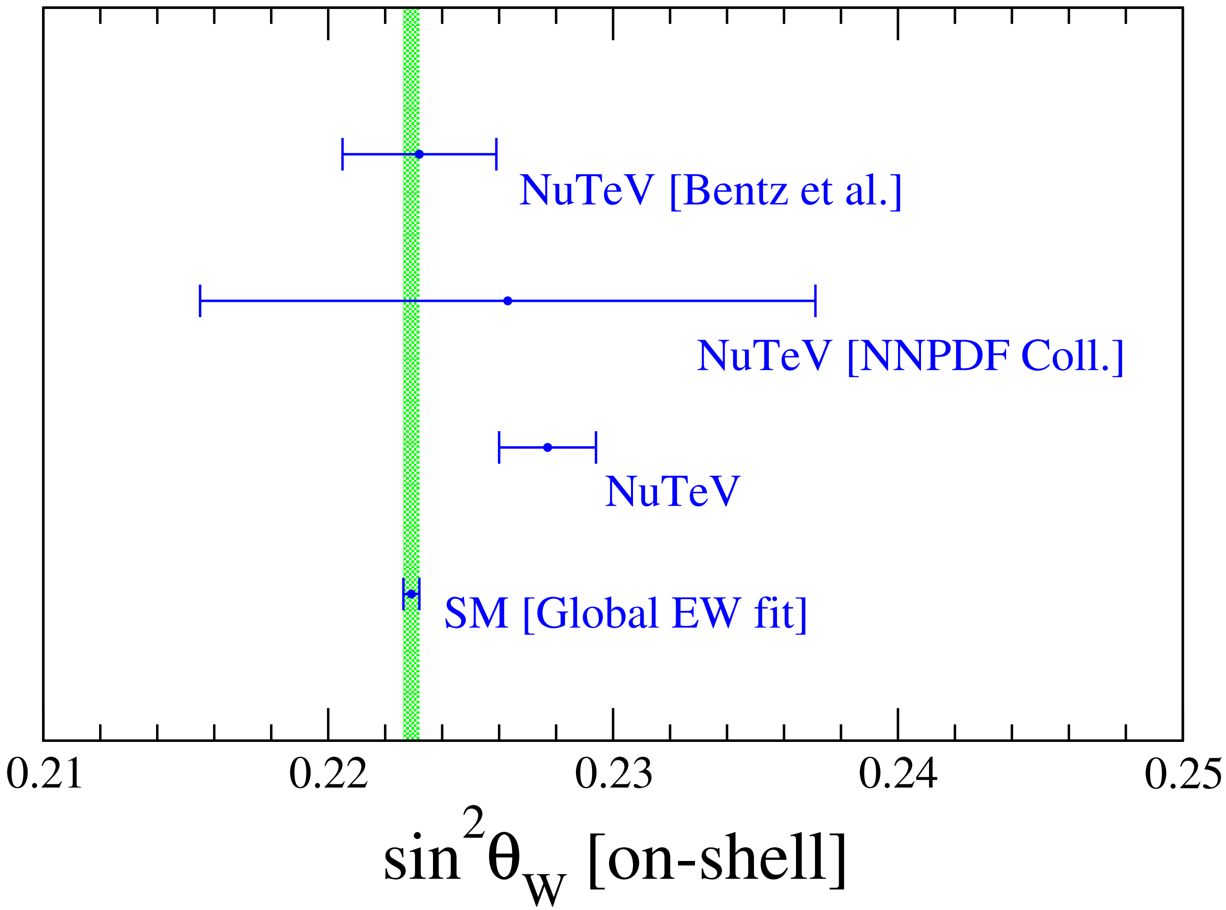
$$R^{\nu} = \frac{\sigma(\nu_\mu N \to \nu_\mu X)}{\sigma(\nu_\mu N \to \mu^- X)}$$

- Muon neutrinos on electrons
  CHARM II

$$\sigma(\nu_\mu e^- \to \nu_\mu e^-)$$

Neutrino experiments without oscillations

NuTeV PRL **88** 091802 (2002); NNPDF NPB **823** 195 (2009); Bentz et al PLB **693** 462 (2010)



Neutrino experiments without oscillations

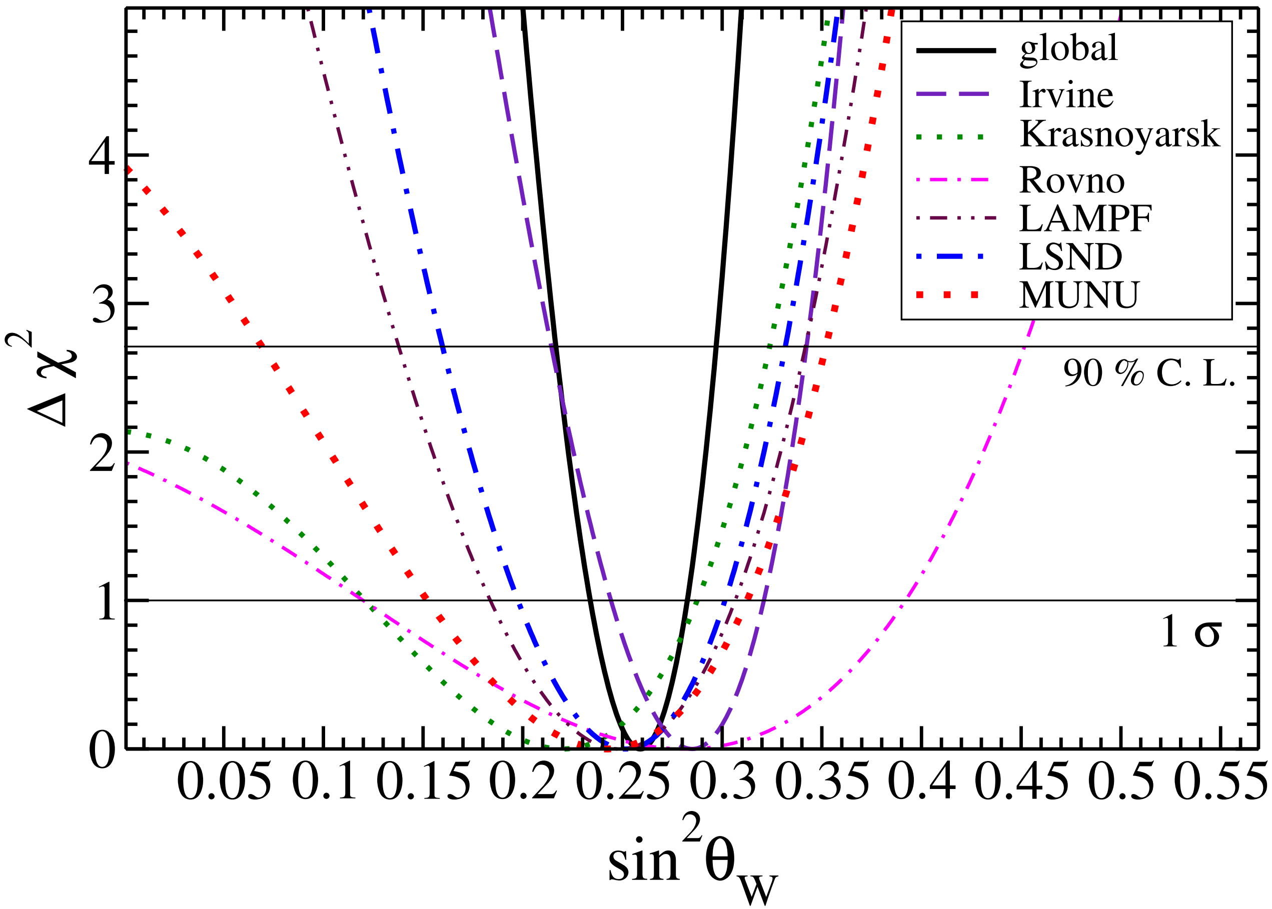
- Electron neutrinos on nuclei
  Bugey, Chooz...
- Electron neutrinos on electrons
  LAMPF, Irvine (Reines, Gurr, Sobel), ..., MUNU, Texono

$$\sigma(\nu_e e^- \to \nu_e e^-)$$

Neutrino experiments without oscillations

Barranco, OGM, Rashba PLB **662** 431 (2008): $\sin^2\theta_W = 0.259 \pm 0.025$

TEXONO PRD **81** 072001 (2010): $\sin^2\theta_W = 0.251 \pm 0.039$



Neutrino oscillations

Pontecorvo (1957,1967), Maki, Nakagawa, Sakata (1962)

Massive ν's :

the massive states ν_i (i=1,2,3) are not equal to the flavor states (weak interactions) ν_a (e, μ, τ)

$$|\nu_a\rangle = \sum_i U_{ai}\,|\nu_i\rangle$$

Time: $t = 0 \quad |\nu_a(x, t = 0)\rangle = \sum_i U_{ai} e^{ip_i x}\,|\nu_i\rangle$

Time: $t > 0 \quad |\nu_a(x, t)\rangle = \sum_i U_{ai} e^{ip_i x - iE_i t}\,|\nu_i\rangle$

Ultrarrelativistic ν-s $m_i \ll p_i \qquad E_i = \sqrt{m_i^2 + p_i^2} \approx p_i + \frac{m_i^2}{2p_i}$

y $x \approx t \quad |\nu_a(x, t)\rangle = \sum_i U_{ai} e^{-i\frac{m_i^2}{2p_i}t}\,|\nu_i\rangle$

Two neutrinos

conversion Probability $\nu_e \to \nu_\mu$

$$P_{\nu_e \to \nu_\mu}(x) = \sin^2(2\theta) \sin^2 \frac{\pi x}{L_{\text{osc}}}$$

oscillation lenght

$$L_{\text{osc}} \approx 250\,\text{km} \left(\frac{E}{\text{MeV}}\right) \left(\frac{10^{-5}\text{eV}^2}{\Delta m^2}\right)$$

Oscillations in matter

Wolfenstein 1978, Mikheev & Smirnov 1985

- Neutral currents (NC): exchange of Z_0
- Charge currents (CC): exchange of $W_\pm$

$$V_e = \sqrt{2}\,G_F\left(N_e - \frac{N_n}{2}\right), \qquad V_\mu = V_\tau = \sqrt{2}\,G_F\left(-\frac{N_n}{2}\right).$$

Evolution equation

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \sqrt{2}\,G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}.$$

Constant density case

Conversion probabilitiy $\nu_e \leftrightarrow \nu_\mu$:

$$P(\nu_e \to \nu_\mu;\, L) = \sin^2 2\theta_m \, \sin^2\left(\pi \frac{L}{l_m}\right) \,,$$

Mixing angle in matter

$$\sin^2 2\theta_m = \frac{\left(\frac{\Delta m^2}{2E}\right)^2 \sin^2 2\theta}{\left(\frac{\Delta m^2}{2E}\cos 2\theta - \sqrt{2}\, G_F\, N_e\right)^2 + \left(\frac{\Delta m^2}{2E}\right)^2 \sin^2 2\theta}$$

Resonance $\quad \sqrt{2}\, G_F\, N_e = \frac{\Delta m^2}{2E} \cos 2\theta$

Three families

$$U = R_{23}(\theta_{23};0)\,R_{13}(\theta_{13};\delta)\,R_{23}(\theta_{23};0)\,P\,,$$

$$R_{13}(\theta_{13};\delta) = \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}\,\mathsf{e}^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}\,\mathsf{e}^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix}.$$

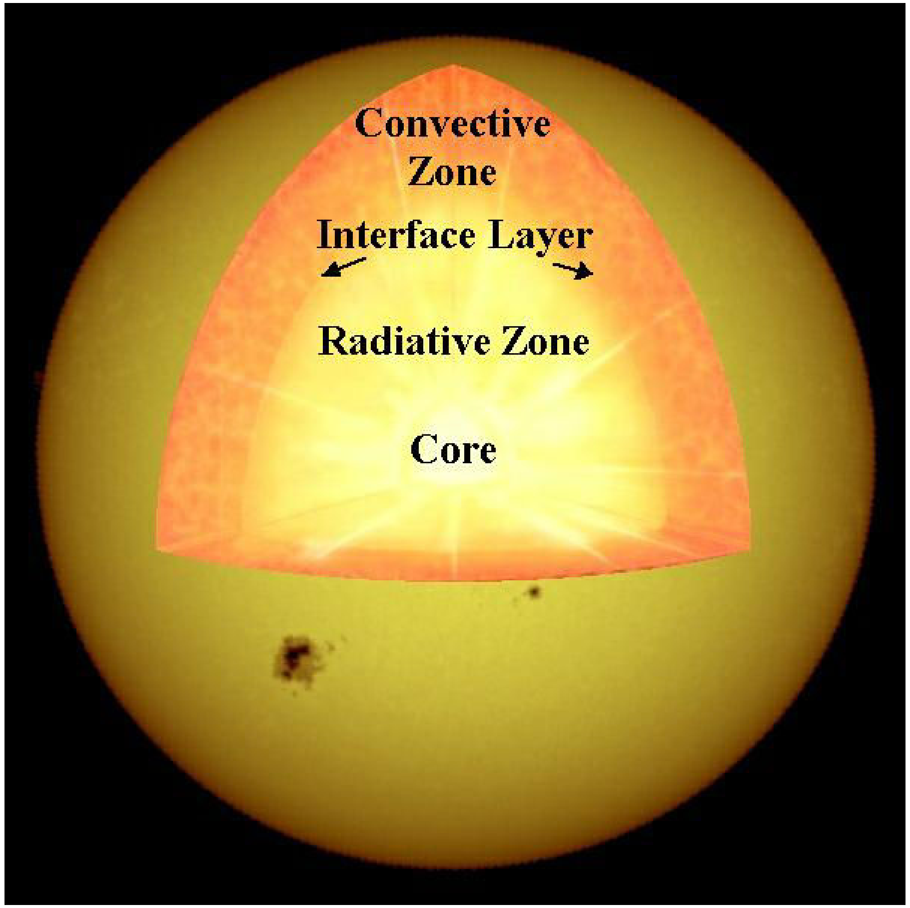
$P = \mathrm{diag}(\mathsf{e}^{i\alpha}, \mathsf{e}^{i\beta}, 1)$

Three families

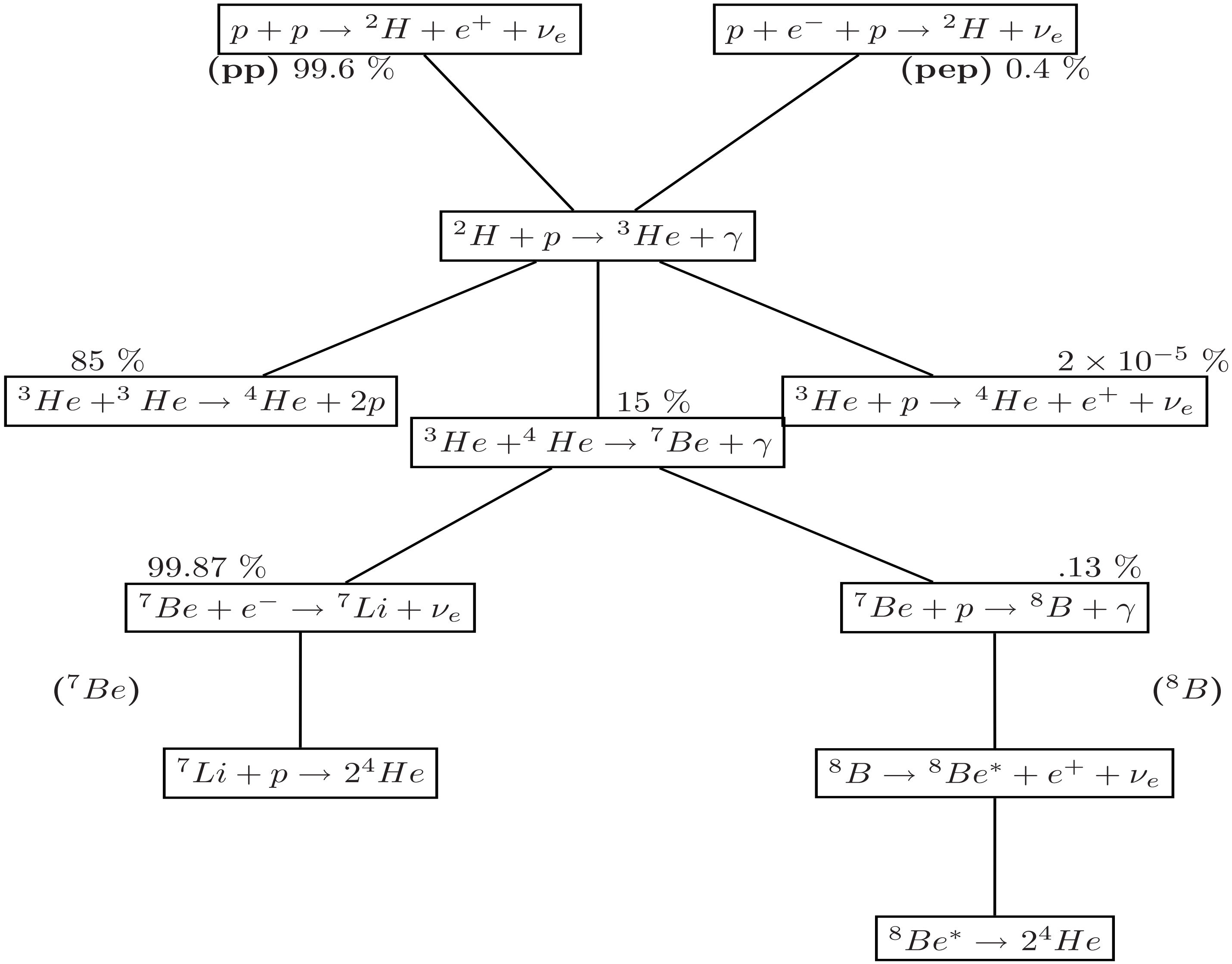
$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}\,\mathrm{e}^{-i\delta} \\ -(s_{12}c_{23}+c_{12}s_{23}s_{13}\,\mathrm{e}^{i\delta}) & (c_{12}c_{23}-s_{12}s_{23}s_{13}\,\mathrm{e}^{i\delta}) & s_{23}c_{13} \\ (s_{12}s_{23}-c_{12}c_{23}s_{13}\,\mathrm{e}^{i\delta}) & -(c_{12}s_{23}+s_{12}c_{23}s_{13}\,\mathrm{e}^{i\delta}) & c_{23}c_{13} \end{pmatrix}$$

$$\begin{aligned} P(\nu_\alpha \to \nu_\beta) &= \left| \sum_j U^*_{\alpha j} U_{\beta j}\,\mathrm{e}^{-i\frac{m_j^2}{2E}L} \right|^2 = \\ \delta_{\alpha\beta} &- 4\sum_{i>j} \Re\left\{U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}\right\} \sin^2\left(\frac{\Delta m^2_{ij}}{4E}L\right) \qquad (1) \\ &+ 2\sum_{i>j} \Im\left\{U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}\right\} \sin\left(\frac{\Delta m^2_{ij}}{2E}L\right) \end{aligned}$$

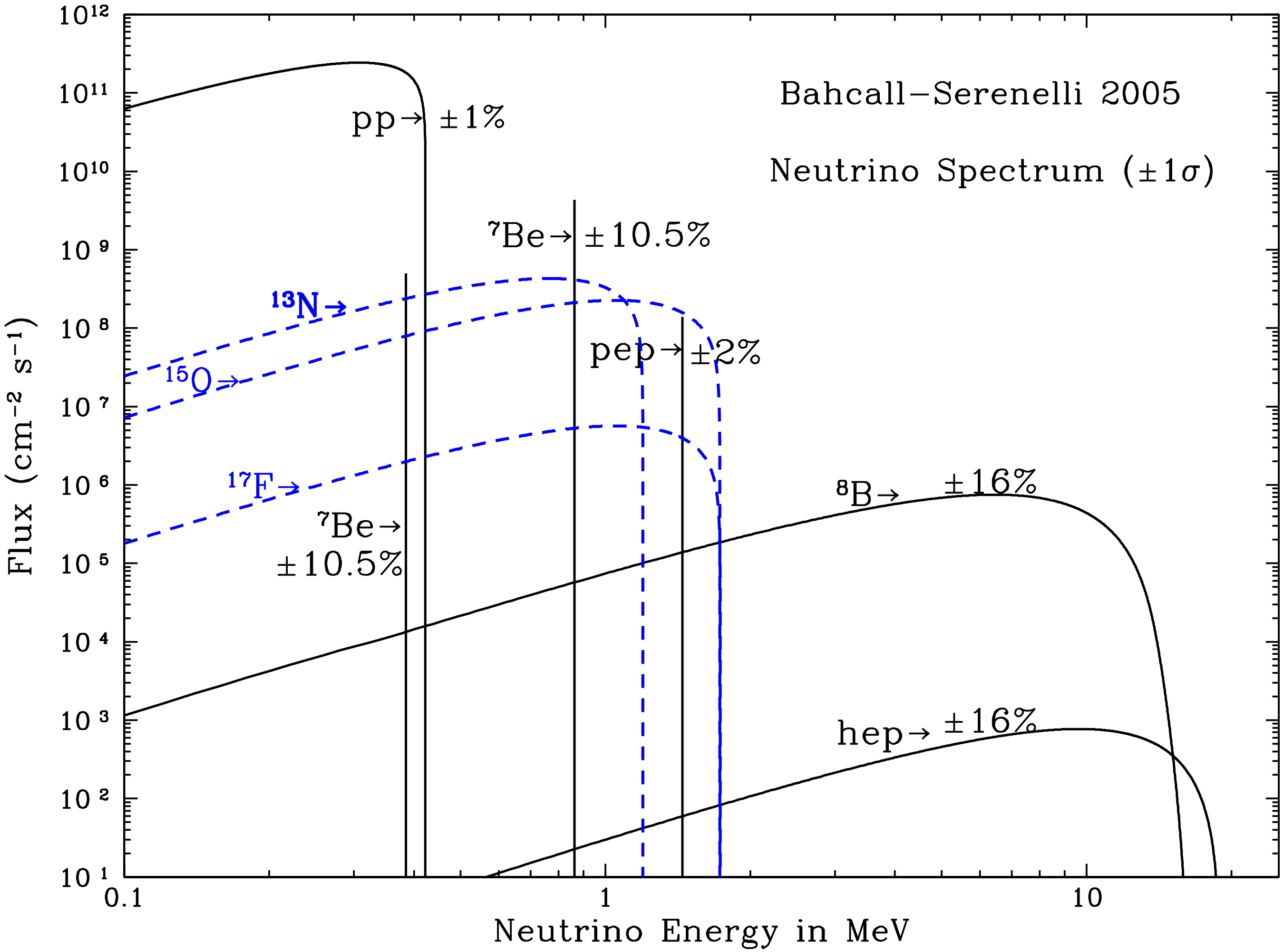
The solar interior



Nuclear reactions in the Sun



solar neutrino spectrum



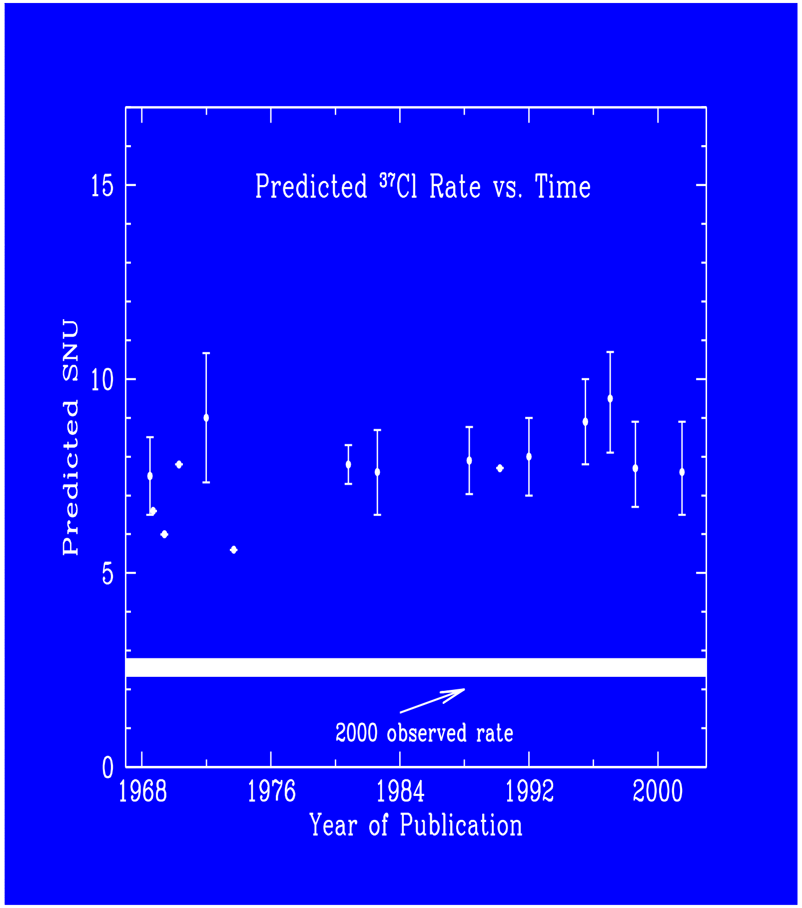
Bahcall's home page

Homestake Experiment, R.Davis'68

$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$ *Pontecorvo'46*

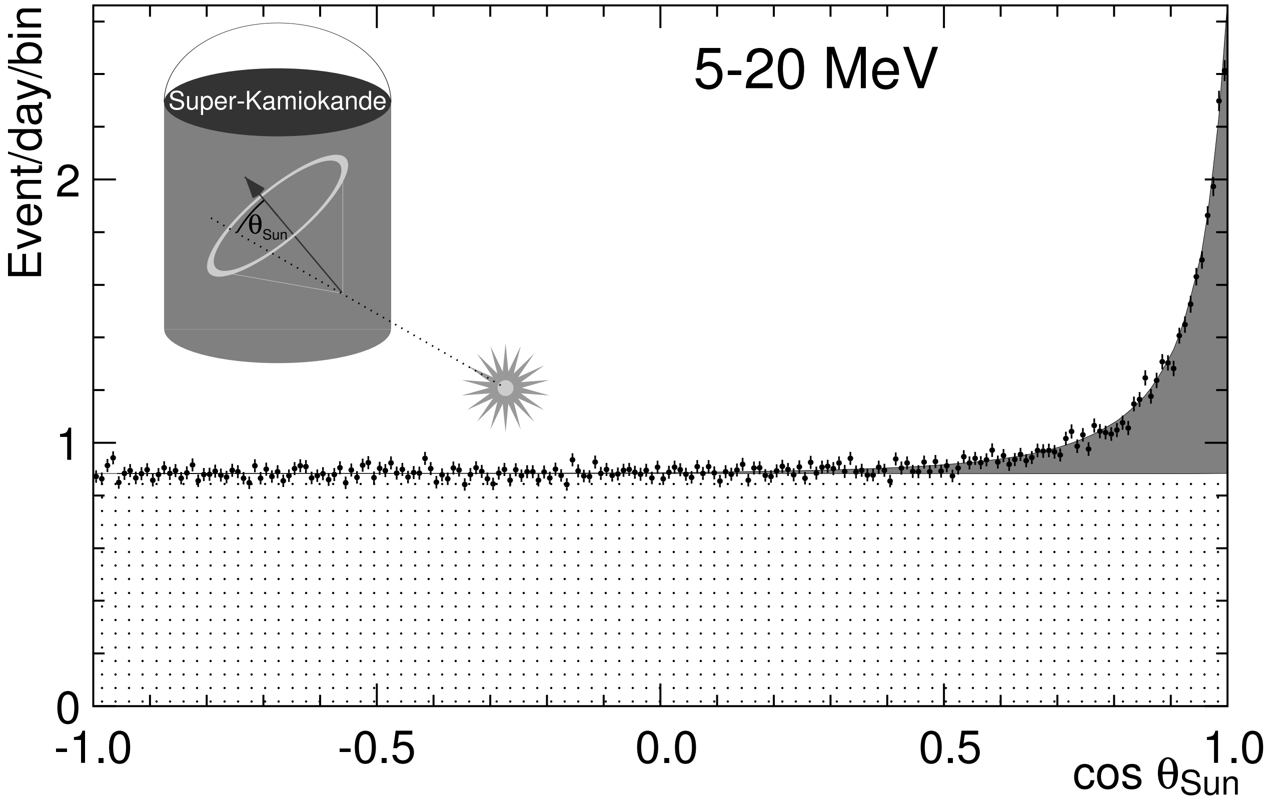
Homestake Experiment, R. Davis'68

$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$ *Pontecorvo'46*



Super-Kamiokande

$\nu_e + e \to \nu_e + e$ and $\nu_x + e \to \nu_x + e$



Super-Kamiokande

- Predicted ^{8} B neutrino flux: $4.85 \times 10^6 cm^{-2} s^{-1}$
- Super-Kamiokande I PLB **539** 179 (2002); PRD **73** 112001 (2006)

$$\phi = 2.35 \pm 0.02\,(\text{stat}\ \pm 0.08\,(\text{syst})\ \times 10^6 cm^{-2} s^{-1}$$

- Super-Kamiokande II PRD **78** 032002 (2008)

$$\phi = 2.38 \pm 0.05\,(\text{stat}\ \pm 0.16\,(\text{syst})\ \times 10^6 cm^{-2} s^{-1}$$

- Super-Kamiokande III PRD **83** 052010 (2011)

$$\phi = 2.32 \pm 0.04\,(\text{stat}\ \pm 0.05\,(\text{syst})\ \times 10^6 cm^{-2} s^{-1}$$

SNO '02

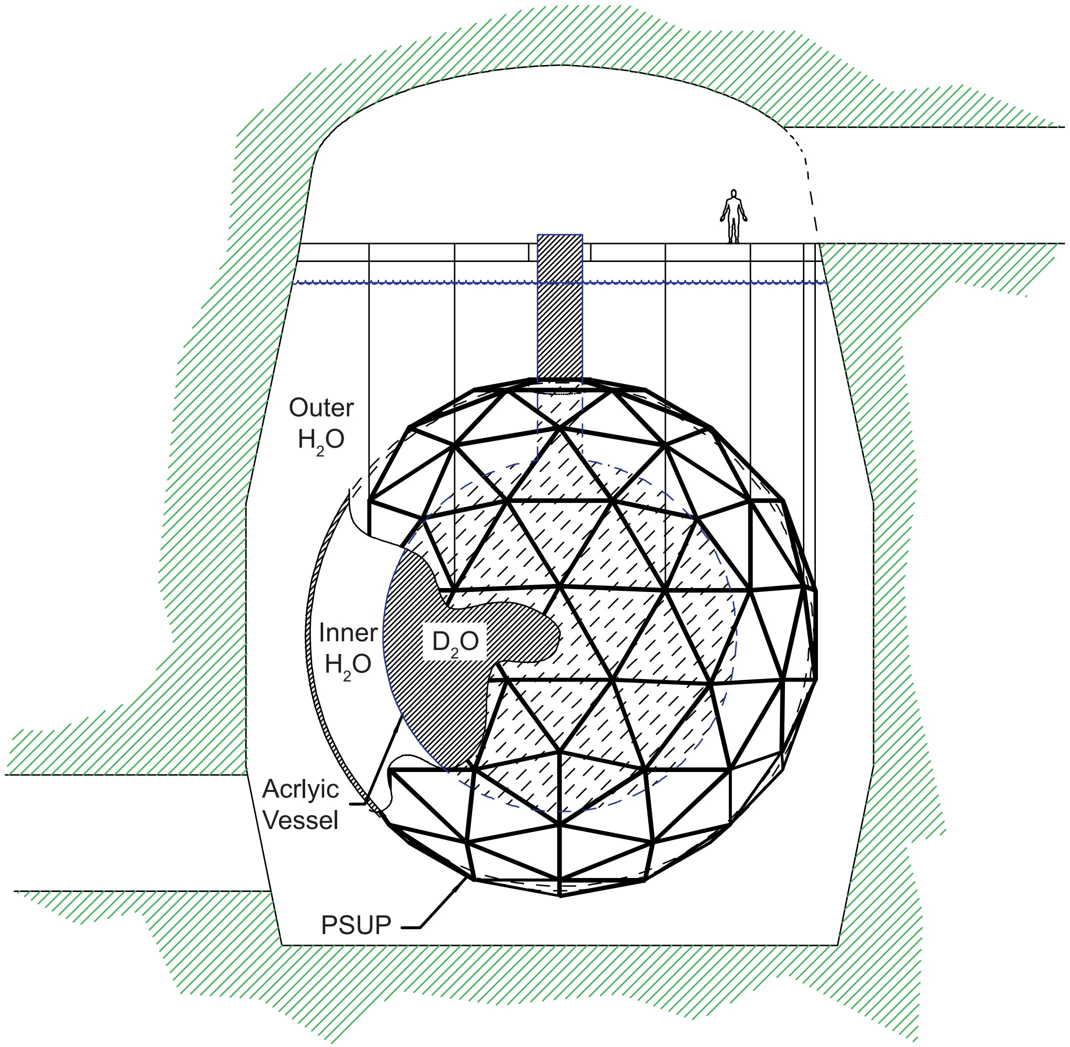
PRL **89** 011301 '02

$$\begin{aligned} \nu_e + \mathrm{d} &\rightarrow \mathrm{p} + \mathrm{p} + \mathrm{e}^- && \text{(CC)}, \\ \nu_x + \mathrm{d} &\rightarrow \mathrm{p} + \mathrm{n} + \nu_x && \text{(NC)}, \\ \nu_x + \mathrm{e}^- &\rightarrow \nu_x + e^- && \text{(ES)}. \end{aligned}$$

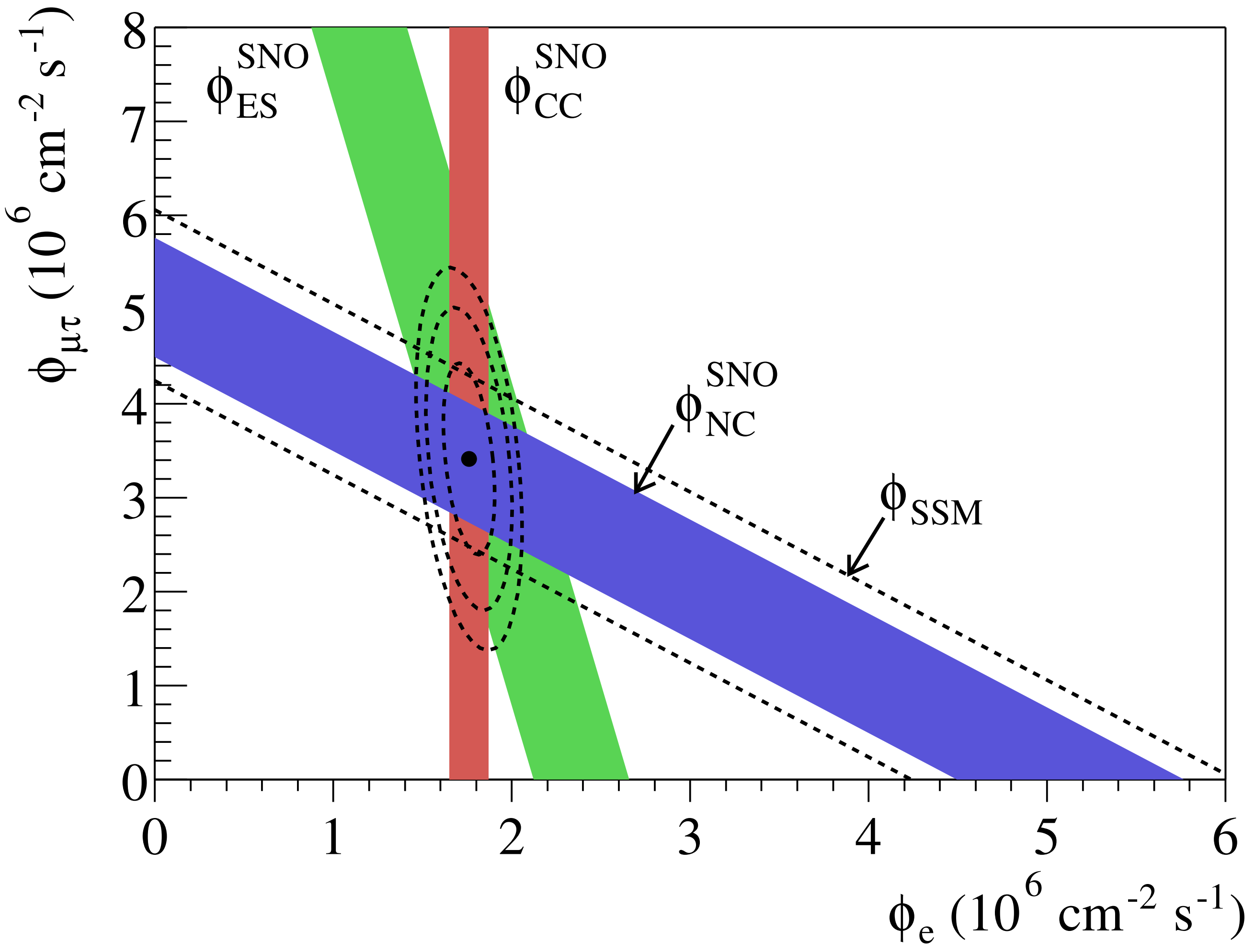
$$\begin{aligned} \phi_e &= 1.76^{+0.05}_{-0.05}\text{(stat.)}^{+0.09}_{-0.09}\text{ (syst.)} \\ \phi_{\mu\tau} &= 3.41^{+0.45}_{-0.45}\text{(stat.)}^{+0.48}_{-0.45}\text{ (syst.)} \end{aligned}$$

$$\phi^{\text{SNO}}_{\text{NC}} = 6.42^{+1.57}_{-1.57}\text{(stat.)}^{+0.55}_{-0.58}\text{ (syst.)}$$

SNO '02

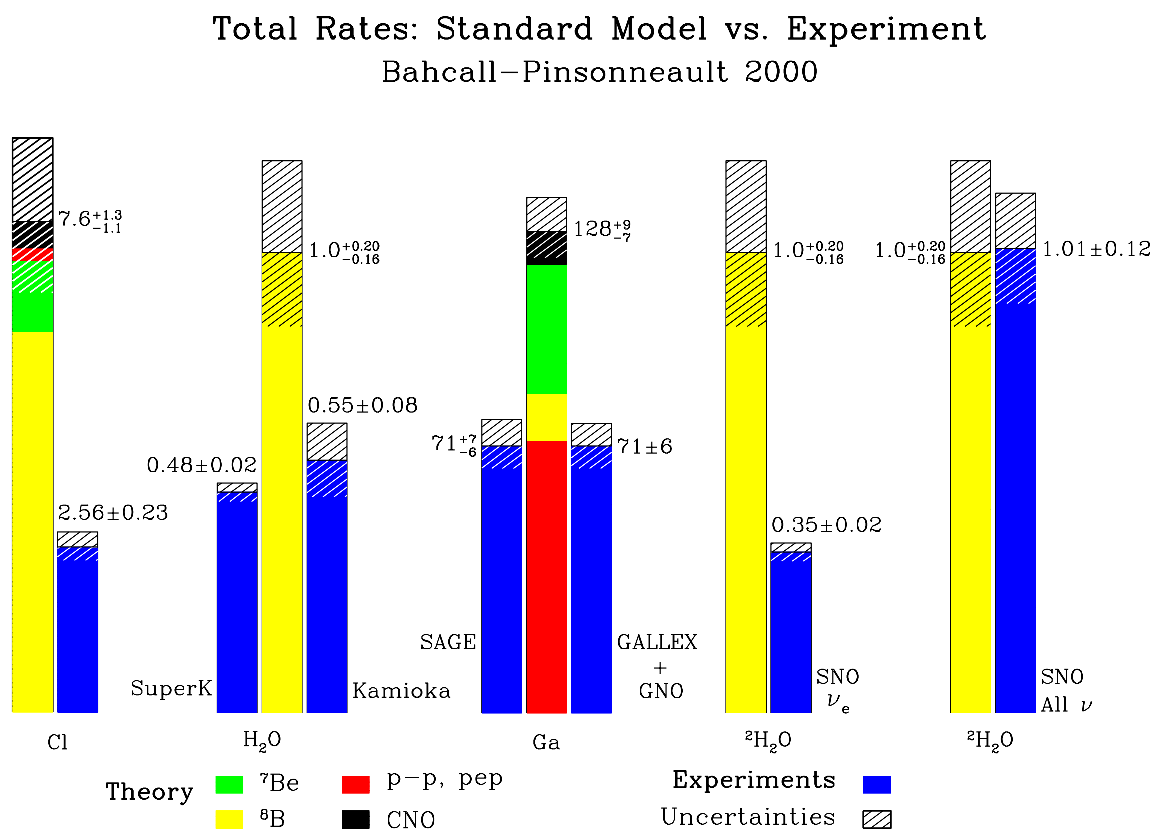


SNO ’02



ϕ_{ES}^{SNO}
ϕ_{CC}^{SNO}
ϕ_{NC}^{SNO}
ϕ_{SSM}
$\phi_{\mu\tau}$ (10^6 cm^{-2} s^{-1})
ϕ_e (10^6 cm^{-2} s^{-1})
0
1
2
3
4
5
6
7
8

theory vs. experiment



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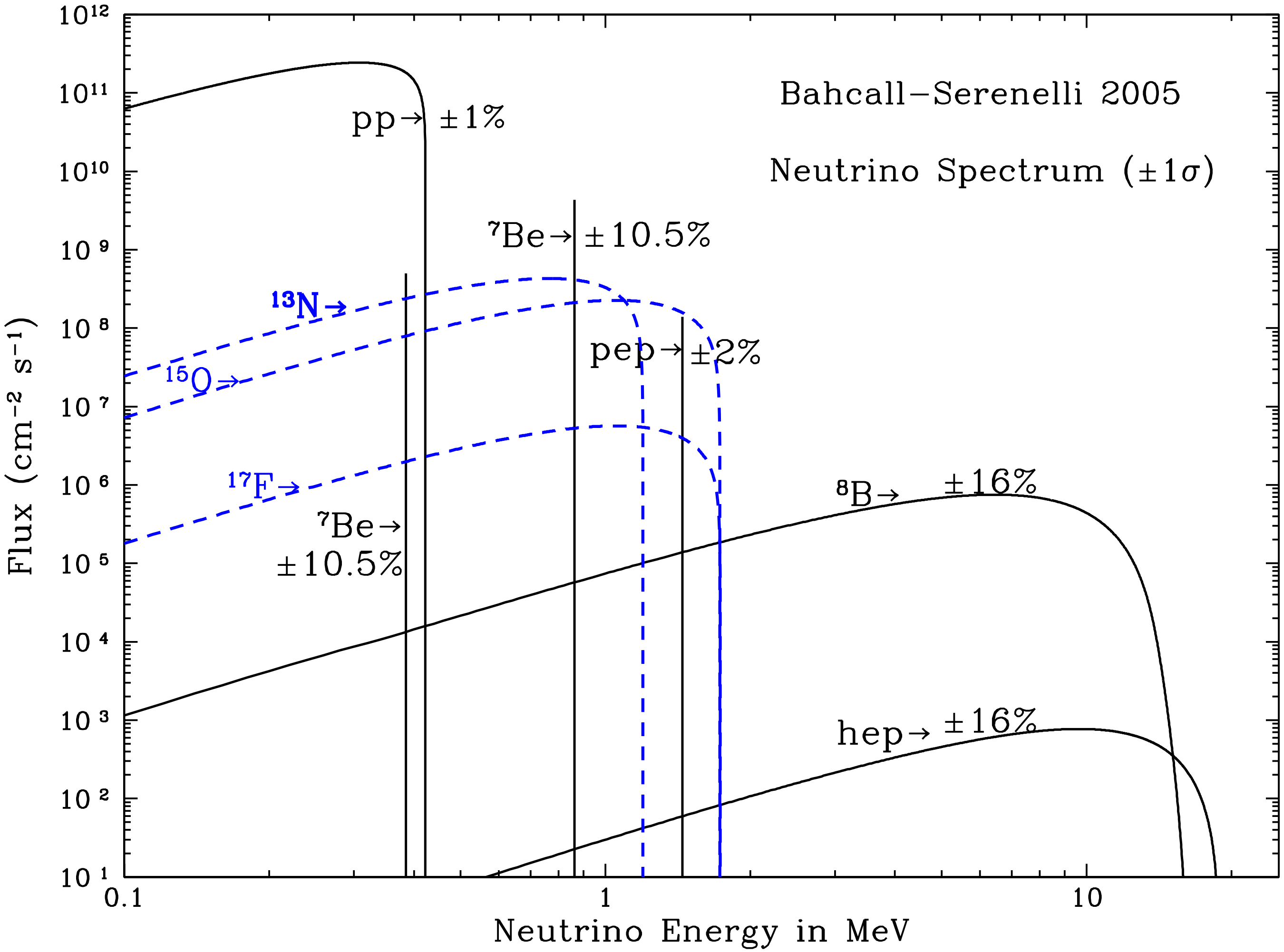
solar neutrino spectrum



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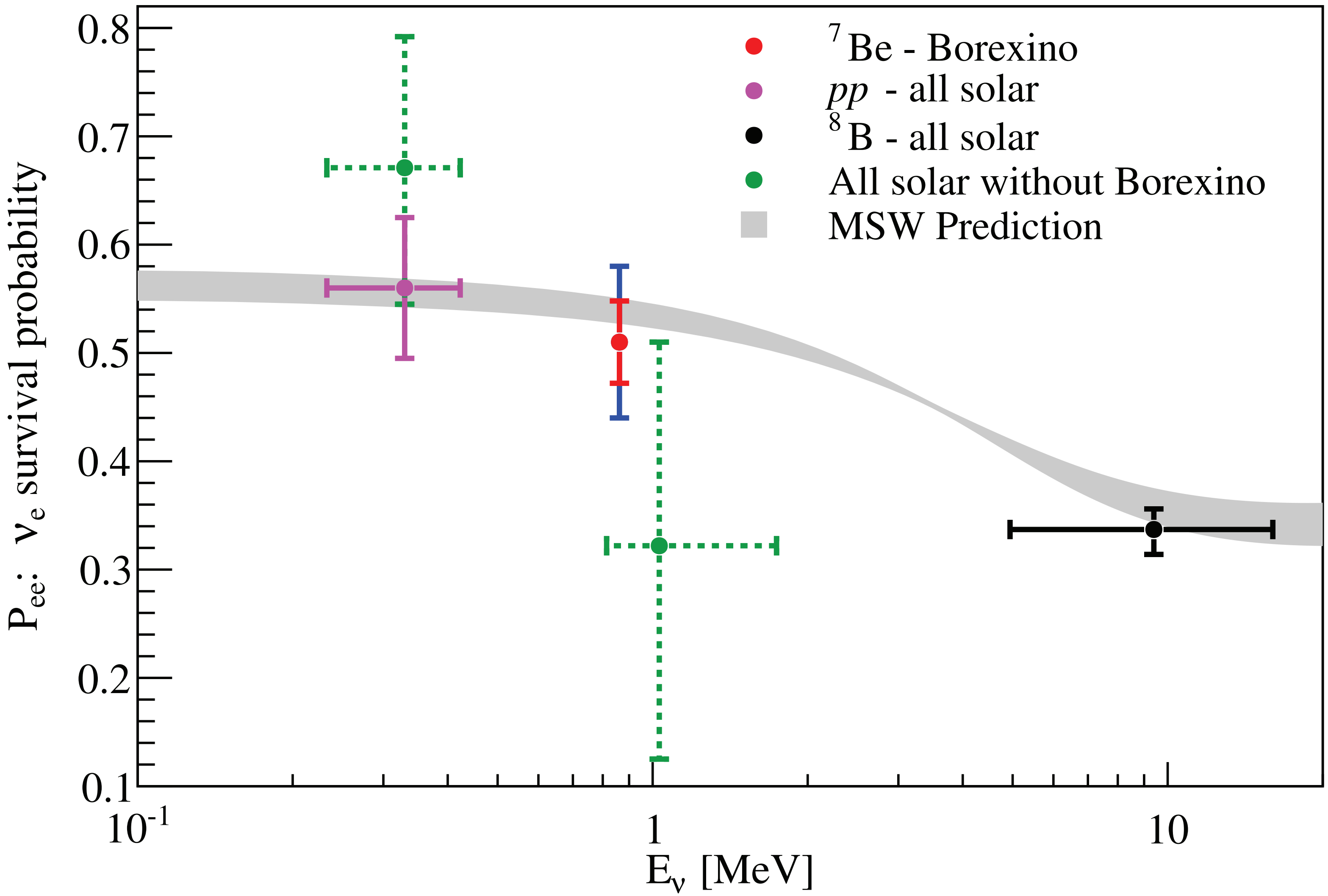
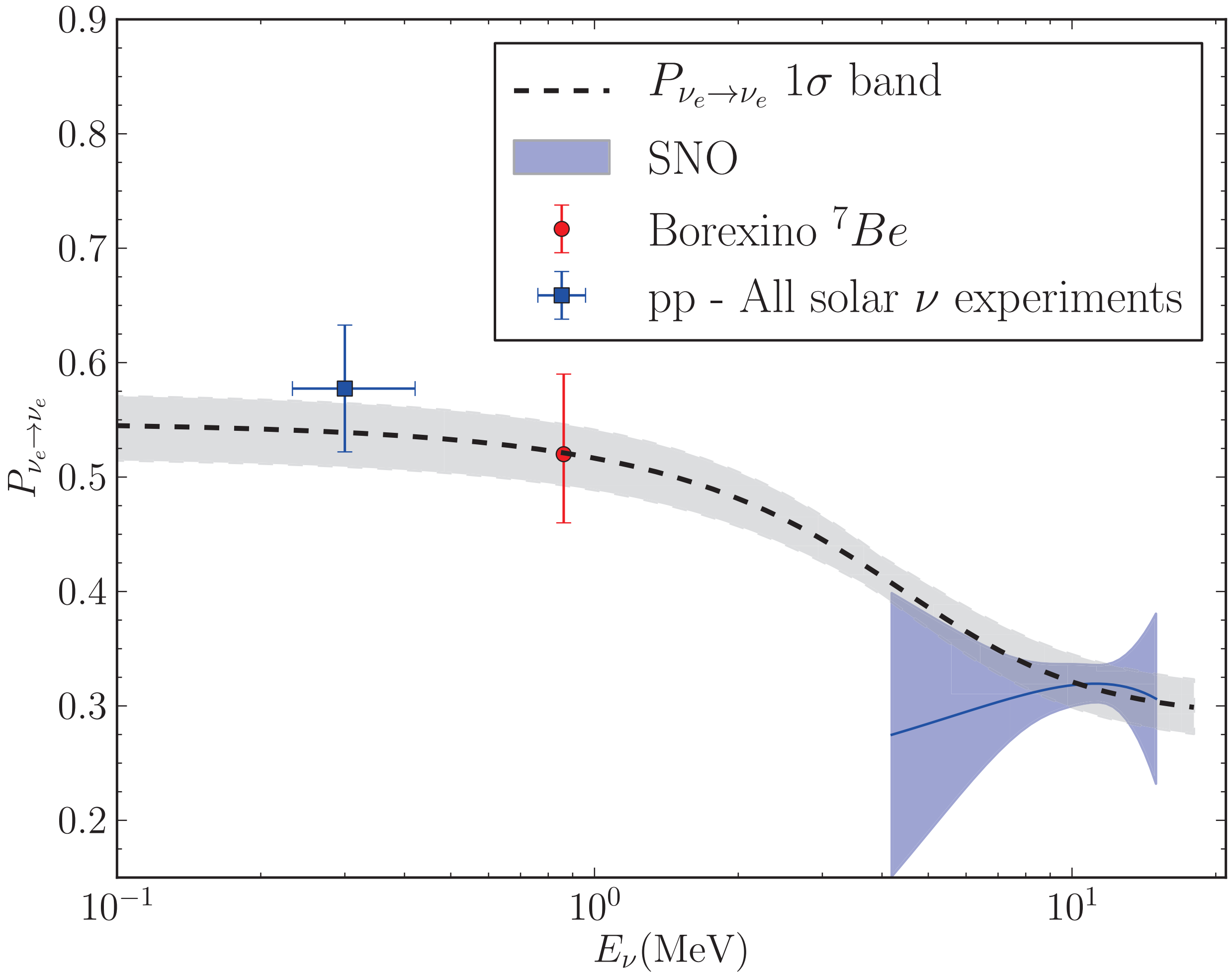
Borexino experiment



Borexino PRL **107** *141302 (2011)*

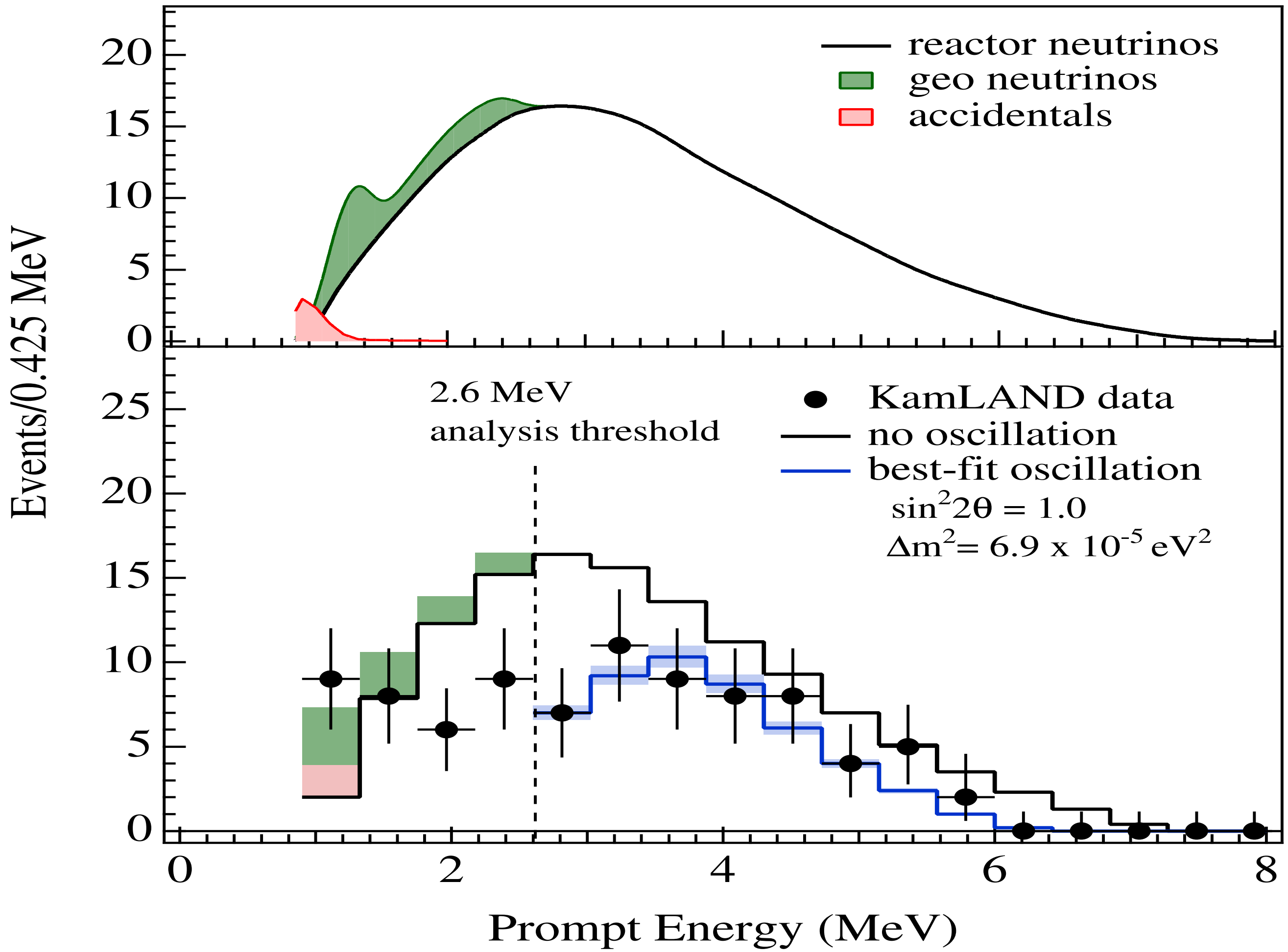
SNO experiment



SNO 1109.0763

KamLAND ’02

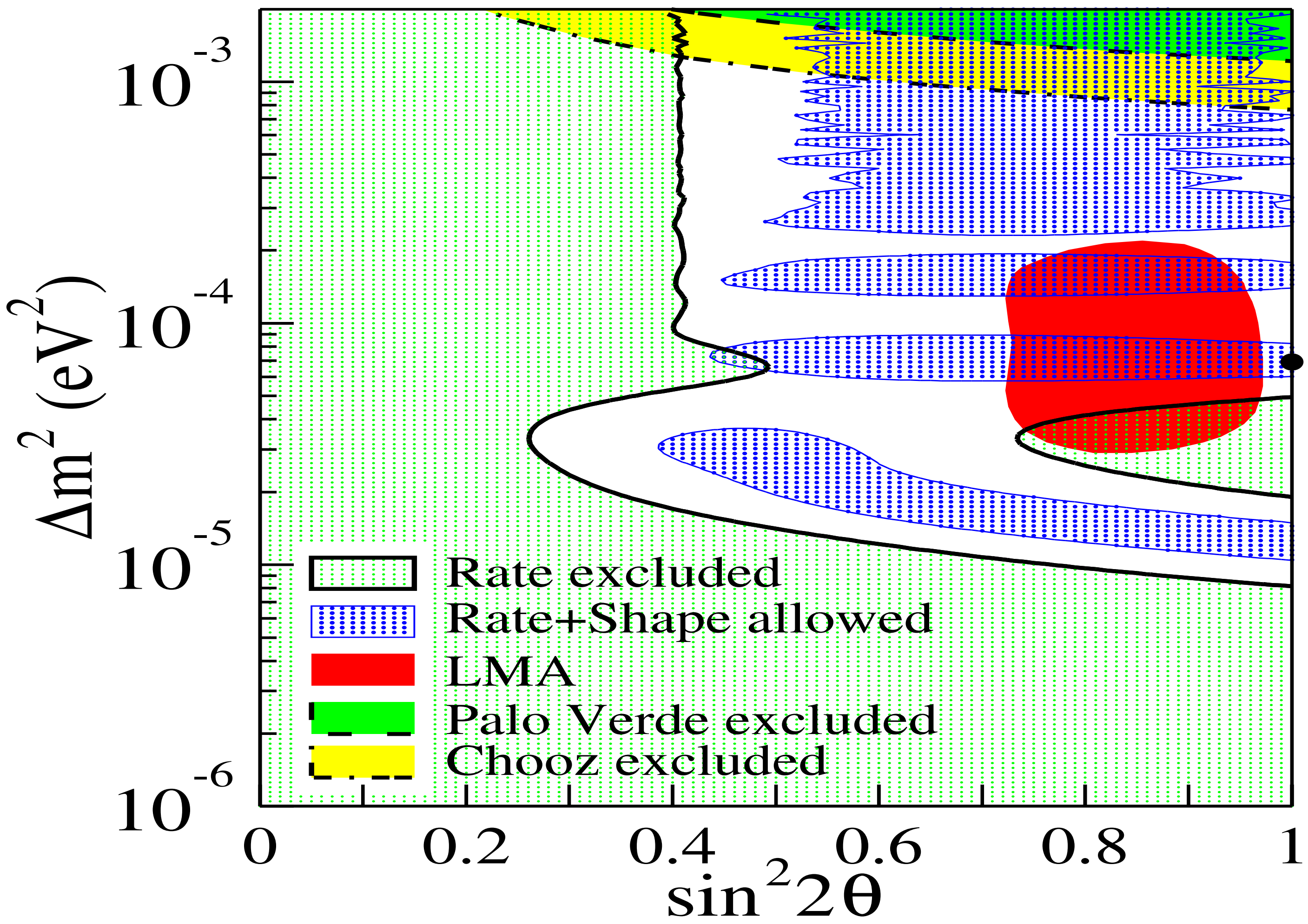
PRL **90** 021802 ’03



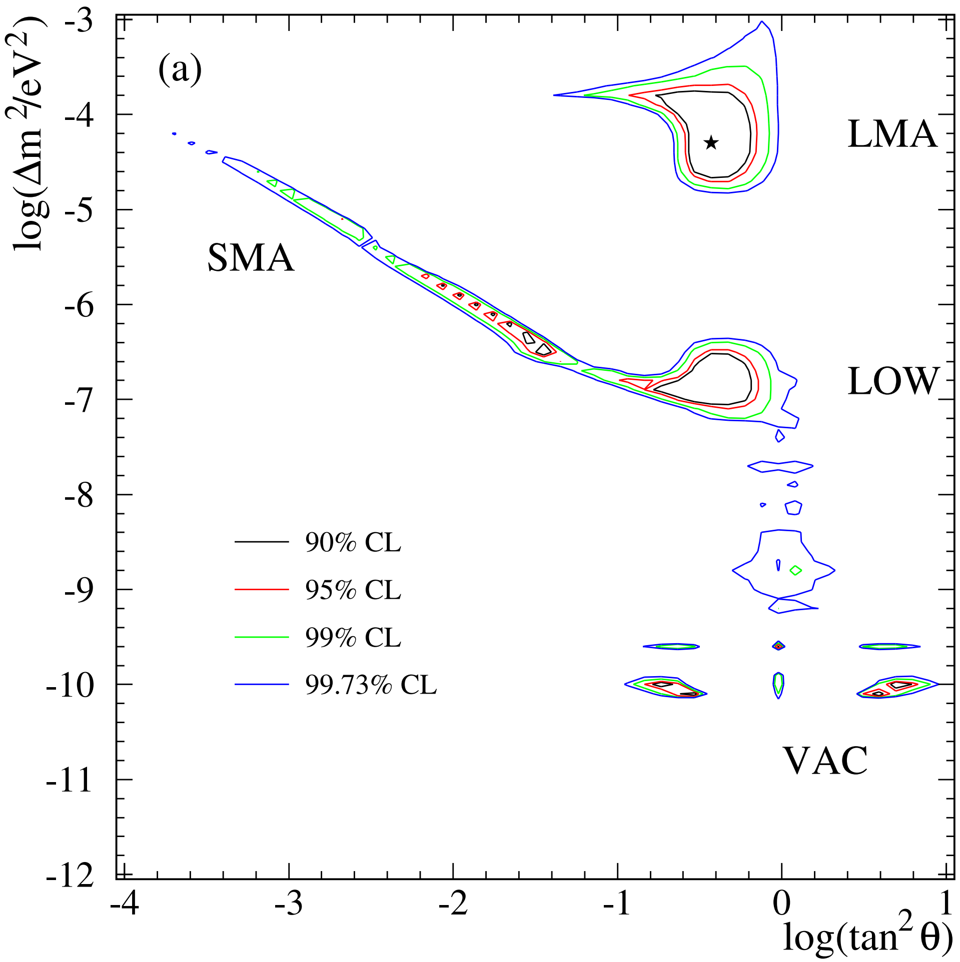
$\bar{\nu}_e + p \to n + e^+ :$ $\quad P_{\bar{\nu}_e \to \bar{\nu}_\mu}(x) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2}{4E}x\right)$

KamLAND '02

PRL **90** 021802 '03

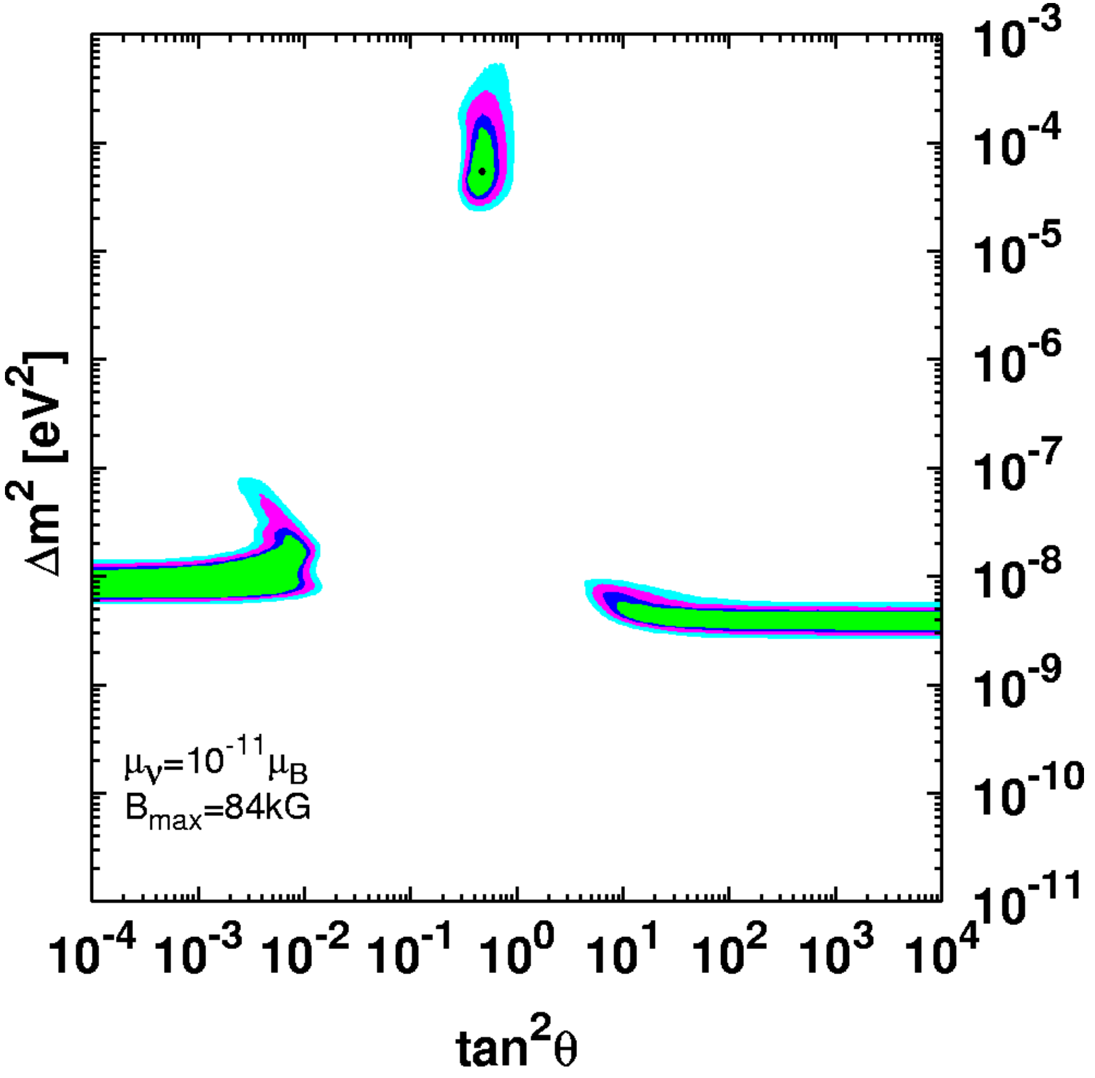


SNO '02



(a)
LMA
SMA
LOW
VAC
90% CL
95% CL
99% CL
99.73% CL
$\log(\Delta m^2/eV^2)$
$\log(\tan^2\theta)$
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-4
-3
-2
-1
0
1

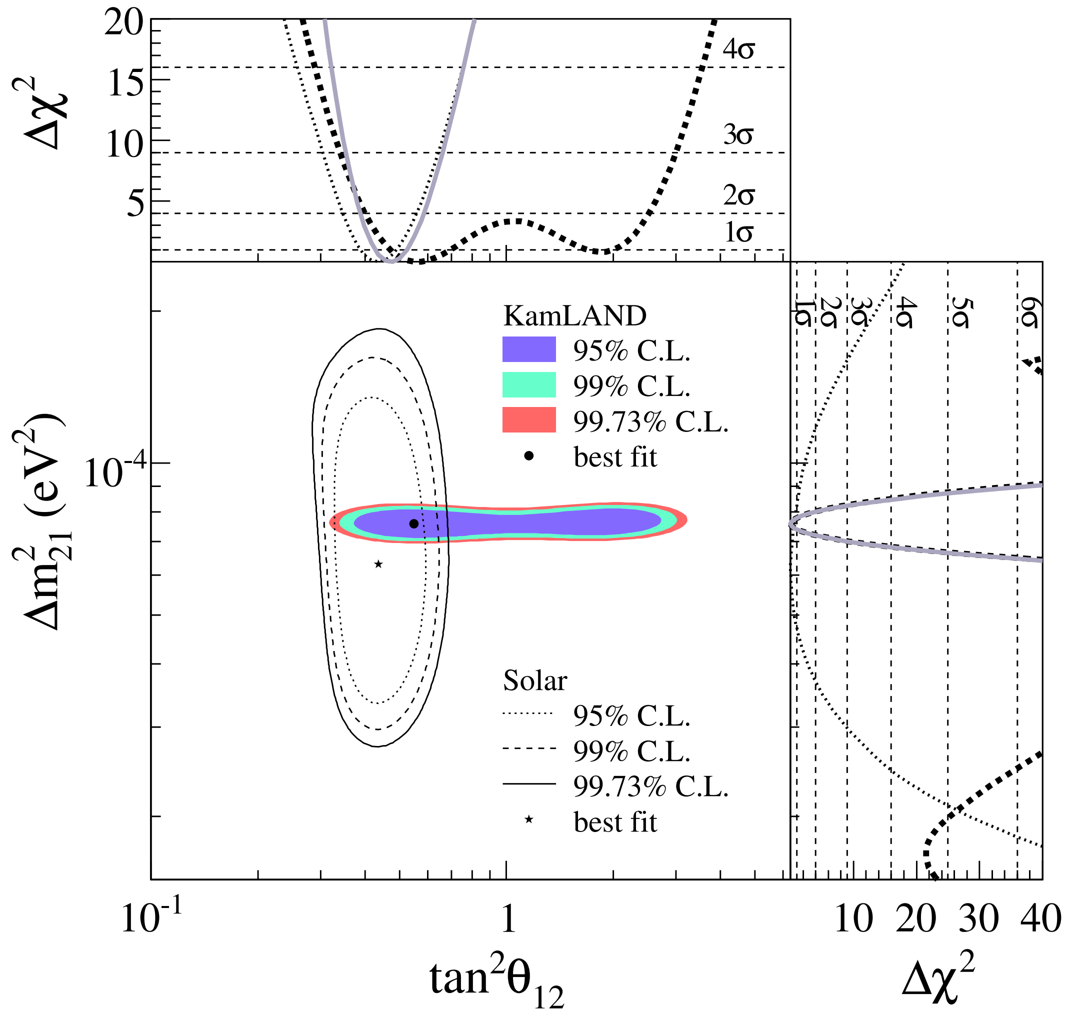
Other solutions



Barranco et al PRD **66** *093009 (2002)*

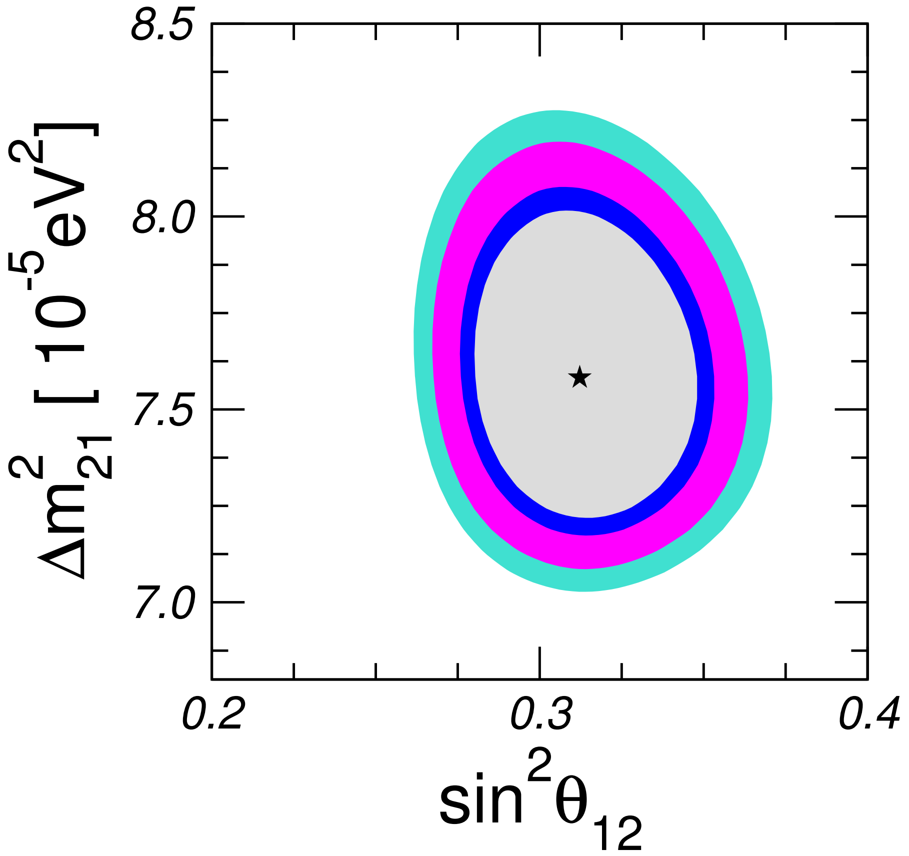
Data fit

KamLAND PRL **100** 221803 (2008)



$\Delta m^2 = 7.59 \times 10^{-5}$ eV ^{2}, $\tan^2\theta_\odot = 0.47$

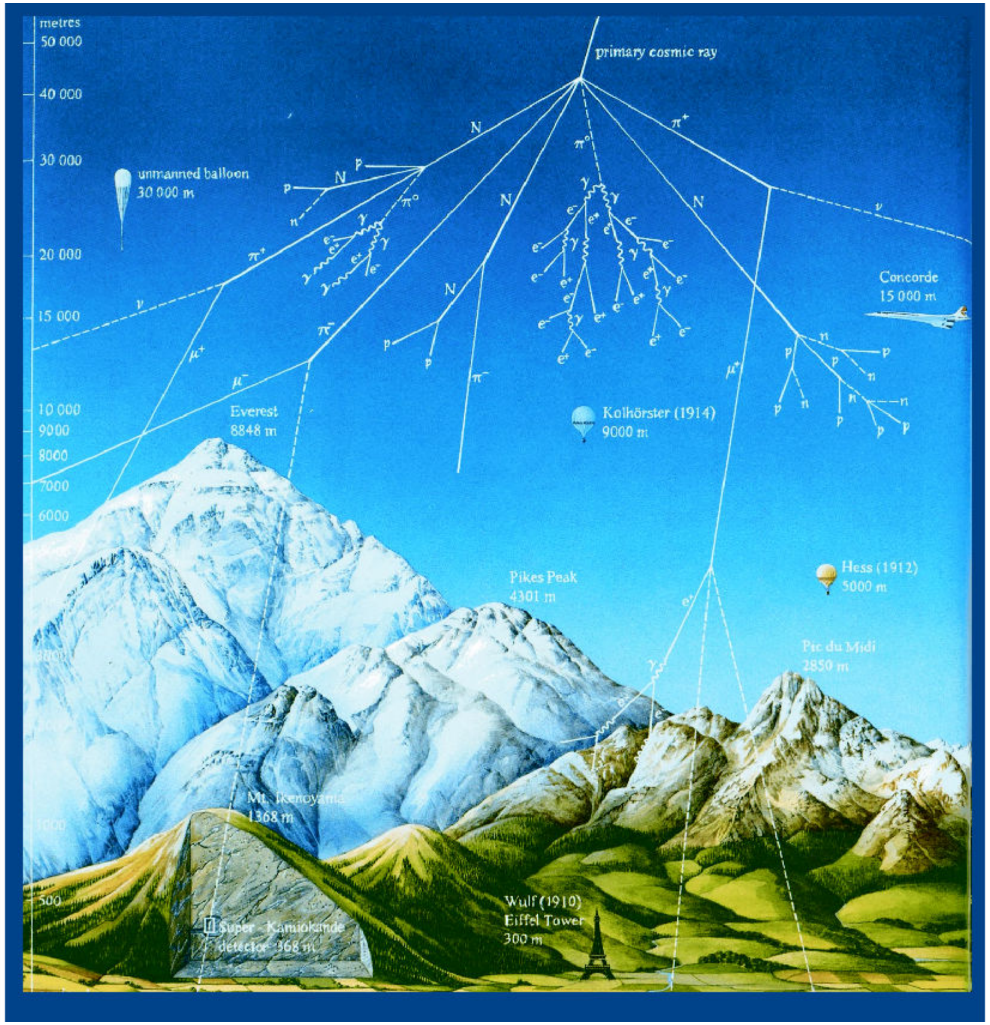
Δm^2_{21} and $\sin^2\theta_{12}$



$\sin^2\theta_{12} = 0.312^{+0.017}_{-0.015}$, $\quad \Delta m^2_{21} = 7.59^{+0.20}_{-0.18} \times 10^{-5}$ eV ^{2}

Schwetz, Tortola, Valle New J.Phys. 13 (2011) 063004

Atmospheric Neutrinos



Atmospheric Neutrinos

We will have the decays:

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

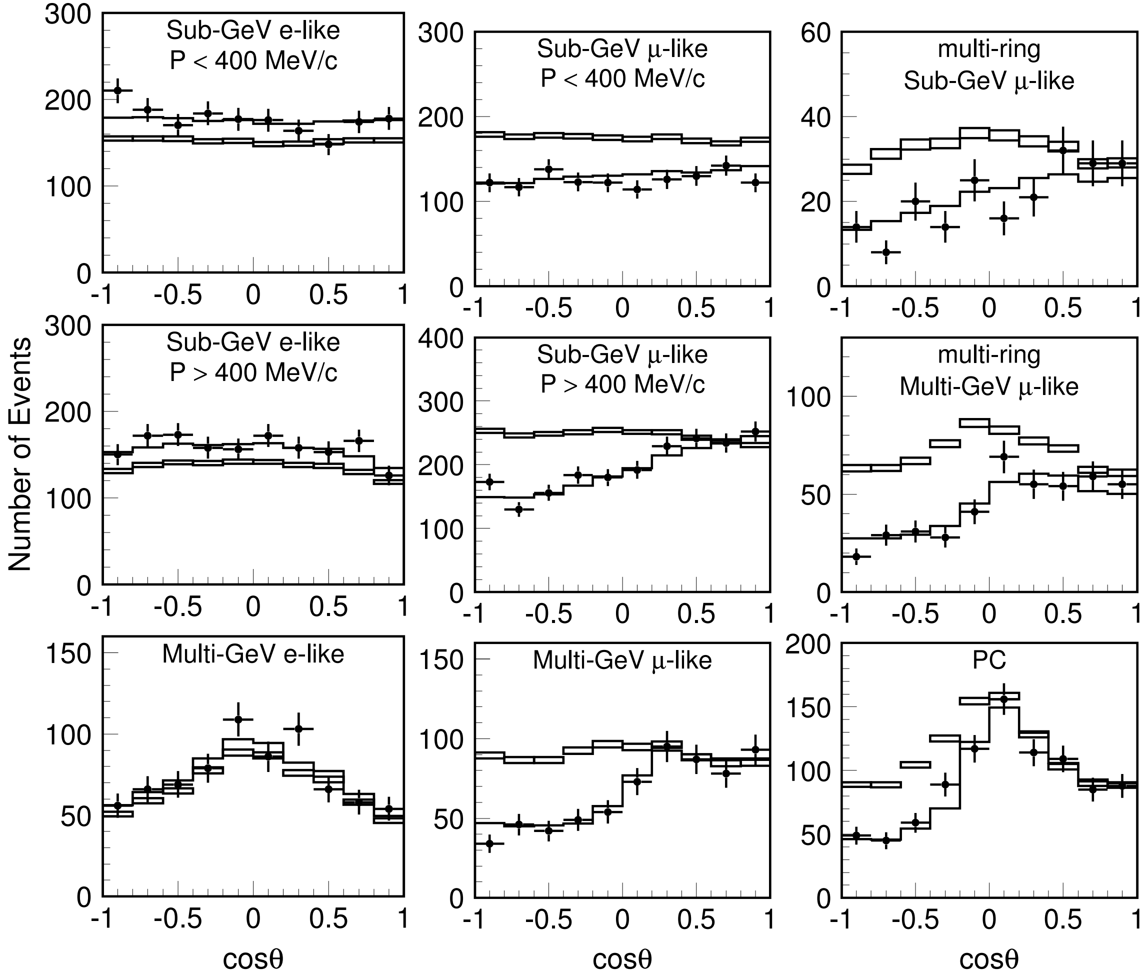
$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

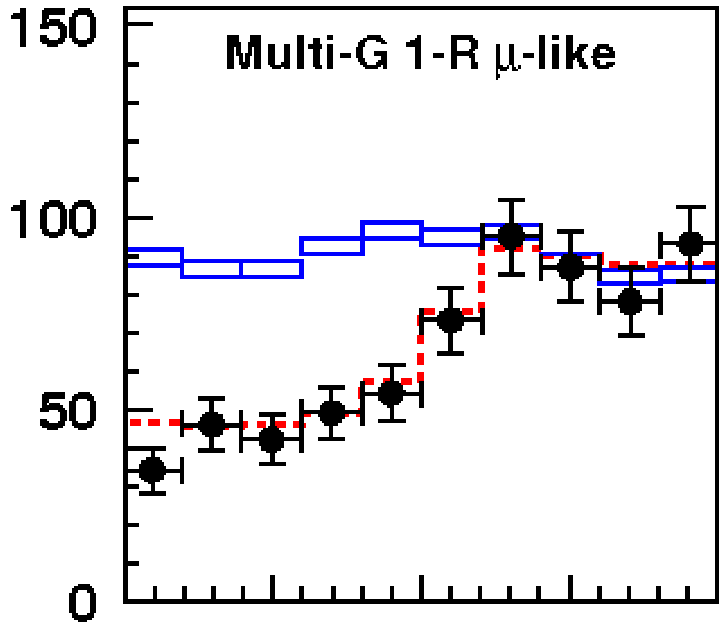
and

$$\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu$$

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

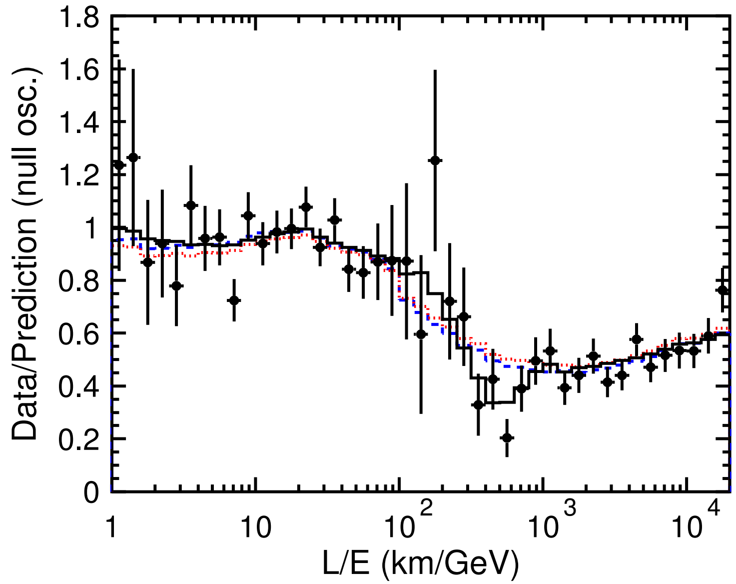
Atmospheric Neutrinos





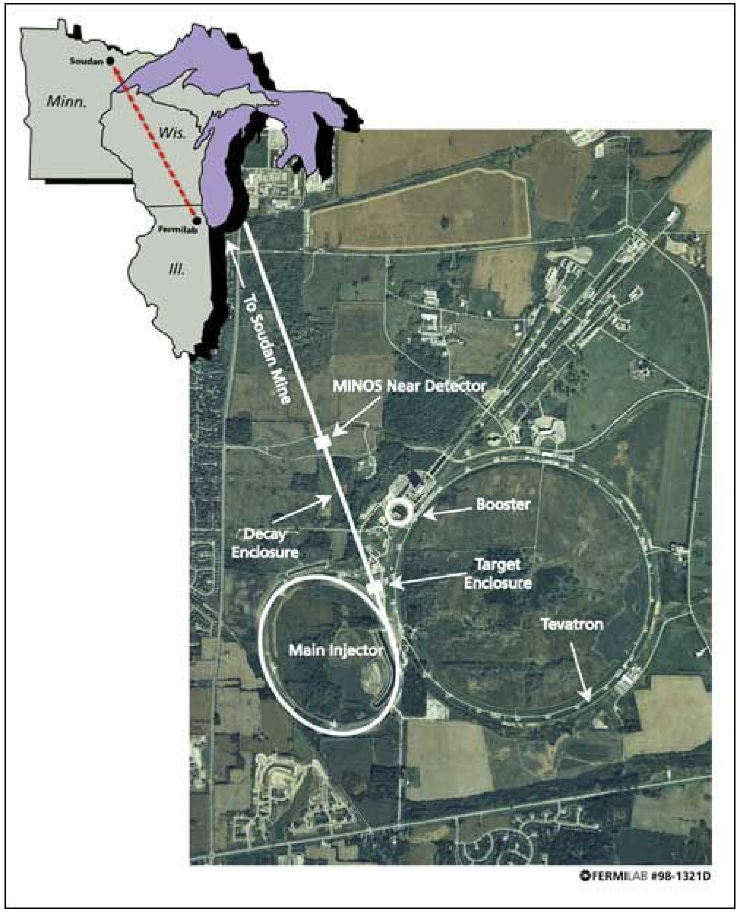
Super-Kamiokande PRD ***74*** *032002 (2006)*

Atmospheric Neutrinos



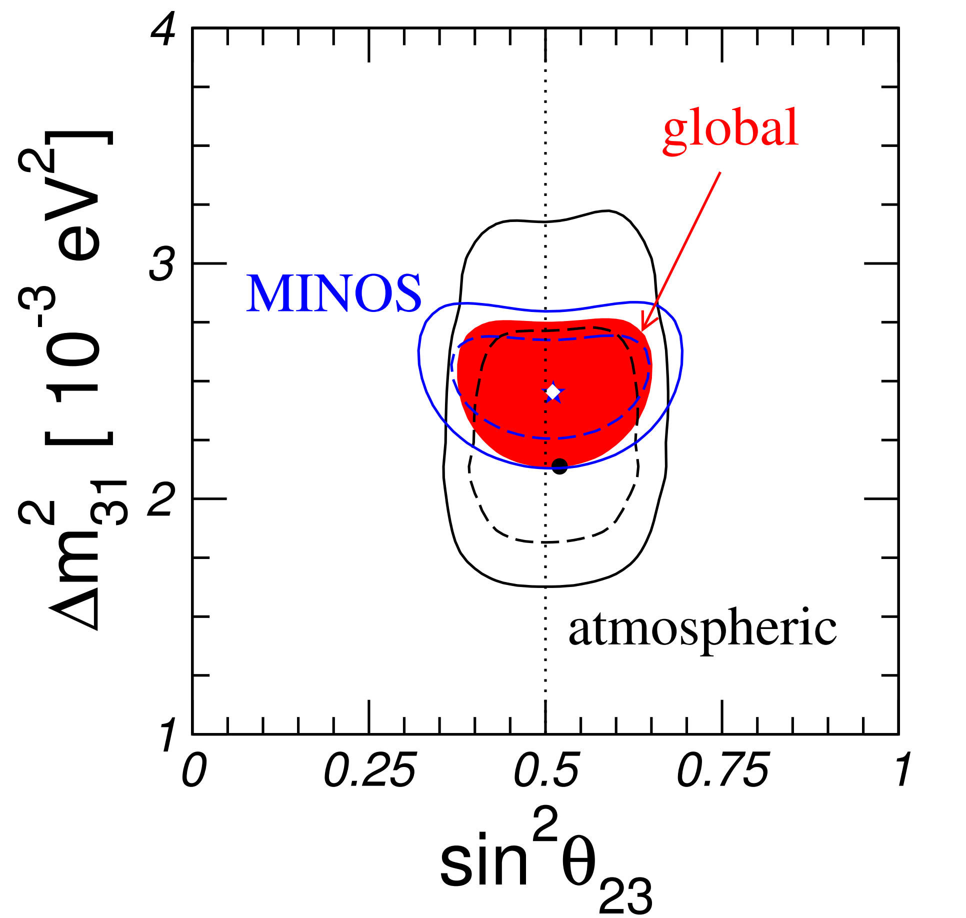
Super-Kamiokande PRL **93** *101801 (2004)*

Accelerator Neutrinos



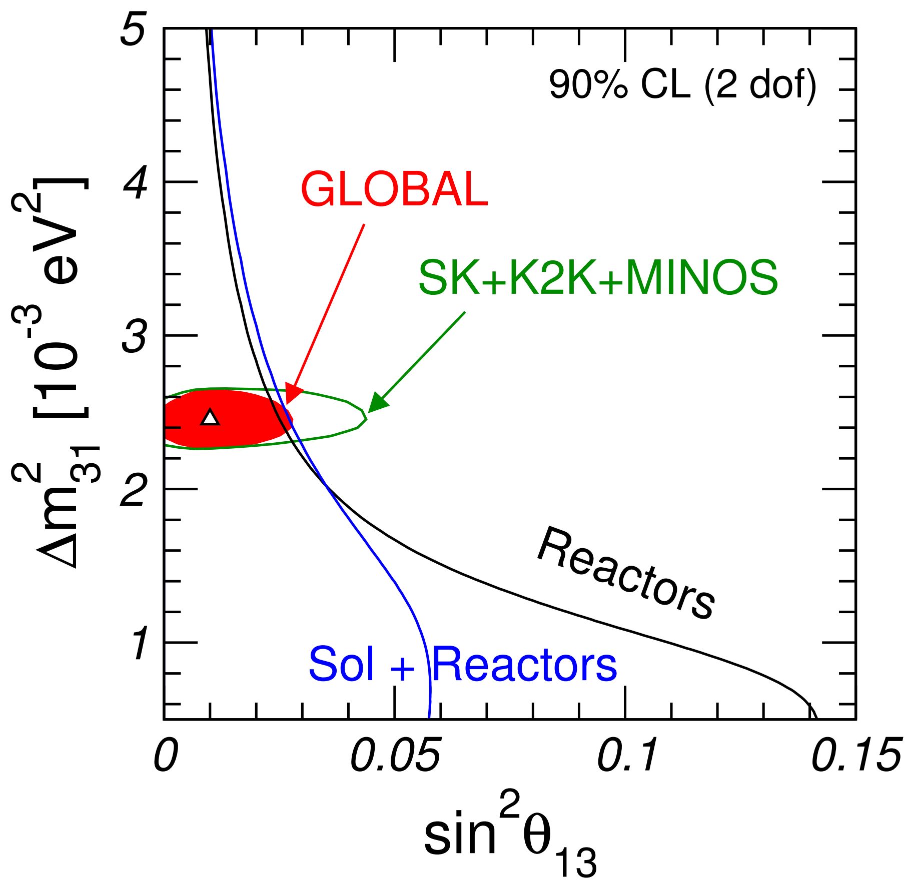
neutrino oscillations

Schwetz, Tortola, Valle New J. Phys. **13** 063004 (2011)



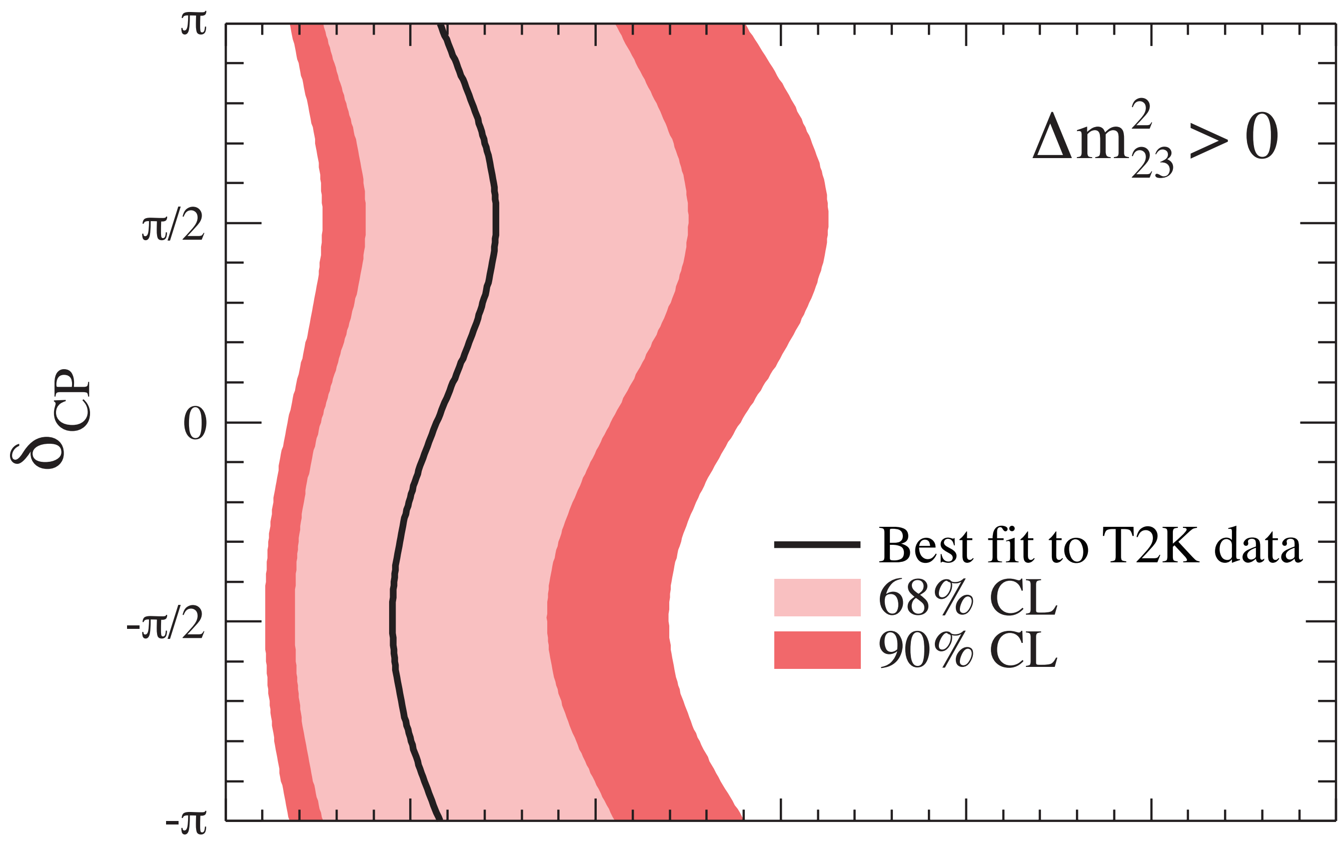
neutrino oscillations

Schwetz, Tortola, Valle New J. Phys. **13** 063004 (2011)



neutrino oscillations

T2K PRL **107** 041801 (2011)



neutrino oscillations

Schwetz, Tortola, Valle New J. Phys. **13** 063004 (2011)

parameter	best fit $\pm 1\sigma$	2σ	3σ
Δm^2_{21} $[10^{-5} eV^2]$	$7.59^{+0.20}_{-0.18}$	7.24–7.99	7.09–8.19
Δm^2_{31} $[10^{-3} eV^2]$	$2.50^{+0.09}_{-0.16}$ $-(2.40^{+0.08}_{-0.09})$	$2.25 - 2.68$ $-(2.23 - 2.58)$	$2.14 - 2.76$ $-(2.13 - 2.67)$
$\sin^2 \theta_{12}$	$0.312^{+0.017}_{-0.015}$	0.28–0.35	0.27–0.36
$\sin^2 \theta_{23}$	$0.52^{+0.06}_{-0.07}$ 0.52 ± 0.06	0.41–0.61 0.42–0.61	0.39–0.64
$\sin^2 \theta_{13}$	$0.013^{+0.007}_{-0.005}$ $0.016^{+0.008}_{-0.006}$	0.004–0.028 0.005–0.031	0.001–0.035 0.001–0.039
δ	$\left(-0.61^{+0.75}_{-0.65}\right)\pi$ $\left(-0.41^{+0.65}_{-0.70}\right)\pi$	$0 - 2\pi$	$0 - 2\pi$

Nonstandar interactions

Beside the Standard Model Lagrangian:

$$\mathcal{L}_{eff} = -2\sqrt{2}G_F([\bar{\nu}_\beta \gamma_\rho L \ell_\beta][\bar{f}\gamma^\rho L f'] + \text{h.c.})$$

$$-2\sqrt{2}G_F \sum_{P,f,\beta} g_P^f [\bar{\nu}_\beta \gamma_\rho L \nu_\beta][\bar{f}\gamma^\rho P f]$$

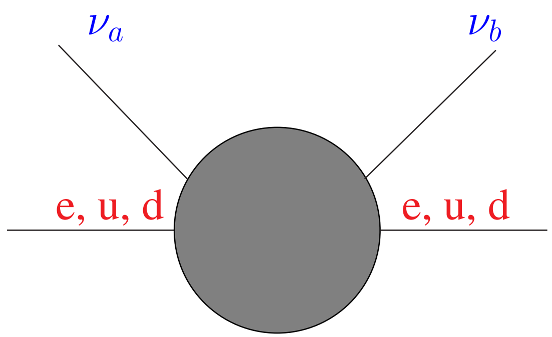
$$\begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \sqrt{2}\,G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}$$

Non Standard Interactions (NSI)

Most extensions of the SM predict neutral current non-standard interactions (NSI) of neutrinos which can be either flavor preserving (FD or NU) or flavor-changing (FC).

NSI effective Lagragian:

$$\mathcal{L}_{eff}^{NSI} = -\sum_{\alpha\beta f P} \varepsilon_{\alpha\beta}^{fP} 2\sqrt{2} G_F (\bar{\nu}_\alpha \gamma_\rho L \nu_\beta)(\bar{f} \gamma^\rho P f)$$



Here $\alpha, \beta = e, \mu, \tau$; $f = e, u, d$; $P = L, R$; $L = (1 - \gamma_5)/2$; $R = (1 + \gamma_5)/2$

$\not{R}_p$ parity violating SUSY

An example of non-standard neutrino-electron and neutrino quark interactions:

$$\mathcal{L} = \lambda_{ijk} \tilde{e}^{k*}_R (\bar{\nu}^i_L)^c e^j_L + \lambda'_{ijk} \tilde{d}^j_L \bar{d}^k_R \nu^i_L + \ldots$$

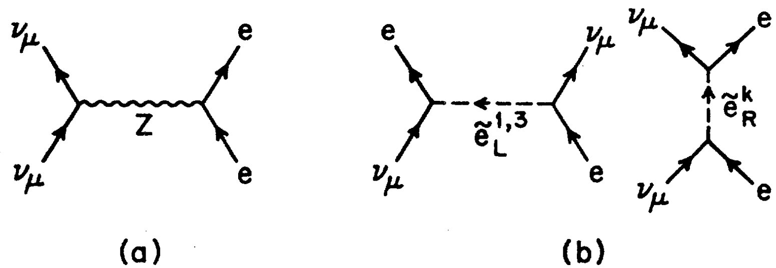
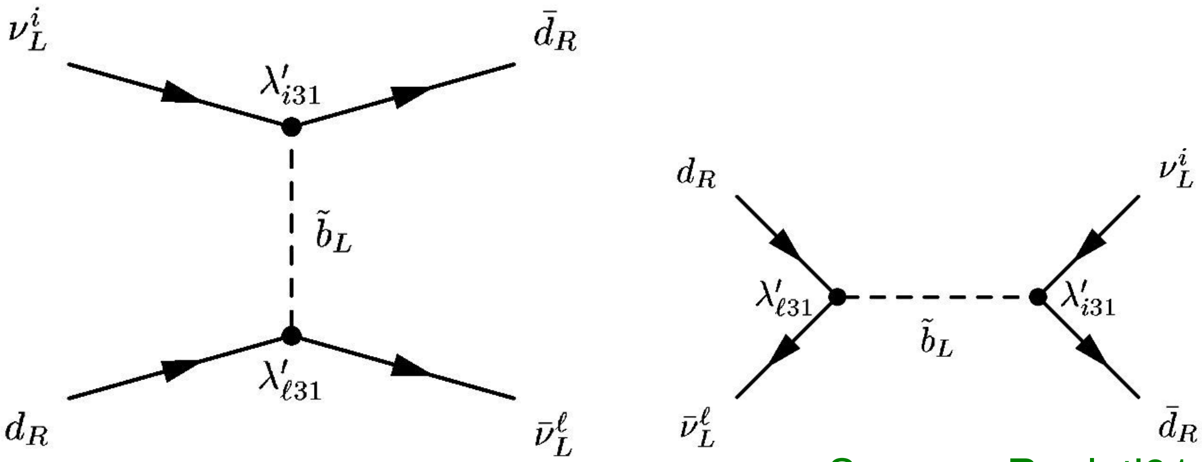


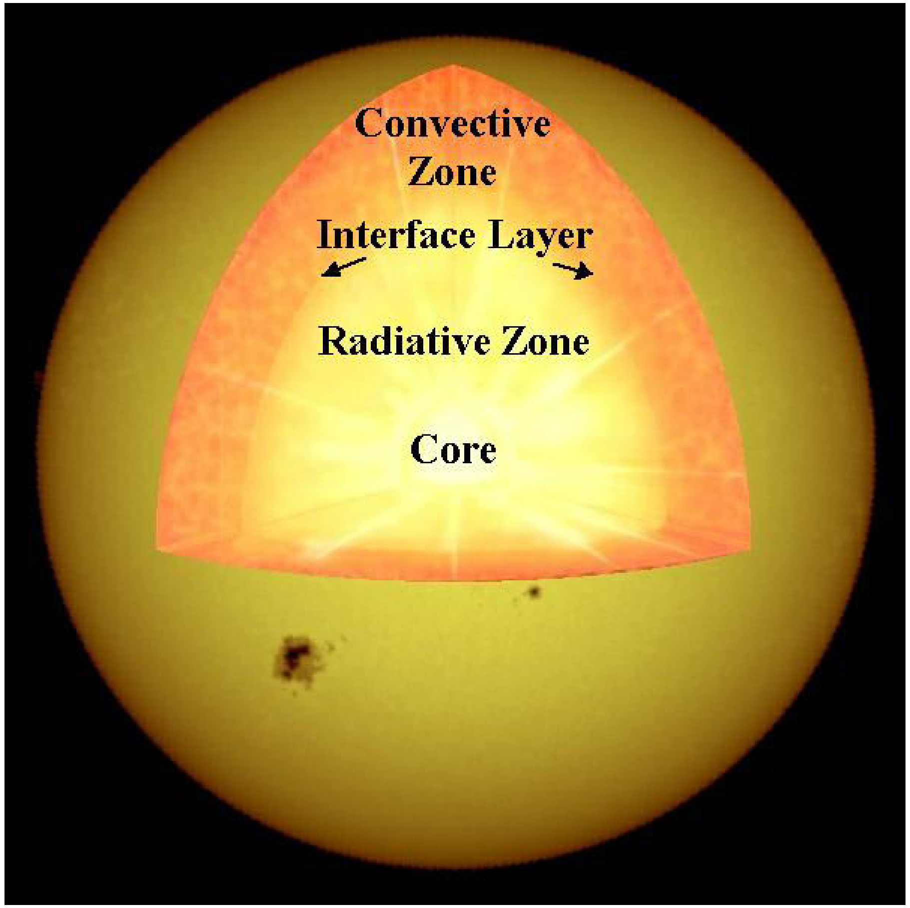
FIG. 2. Feynman diagrams for $\nu_\mu e$ scattering from (a) the standard model, and (b) the R-breaking interactions.

Barger, Giudice & Han'89



See e.g. Roulet'91, Amanik et al'05

Solar ν Oscillations and NSI with quarks



Solar ν Oscillations and NSI with quarks

$$H_{\rm NSI} = \sqrt{2} G_F N_f \begin{pmatrix} 0 & \varepsilon \\ \varepsilon & \varepsilon' \end{pmatrix} .$$

with

$$\varepsilon = -\sin\theta_{23}\,\varepsilon_{e\tau}^{fV} \qquad \varepsilon' = \sin^2\theta_{23}\,\varepsilon_{\tau\tau}^{fV} - \varepsilon_{ee}^{fV}$$

and

$$\varepsilon_{\tau\tau}^{fV} = \varepsilon_{\tau\tau}^{fL} + \varepsilon_{\tau\tau}^{fR}$$

Non Standard Interactions

$$H_{\rm NSI} = \sqrt{2} G_F N_f \begin{pmatrix} 0 & \varepsilon \\ \varepsilon & \varepsilon' \end{pmatrix} .$$

Mixing angle in matter + NSI

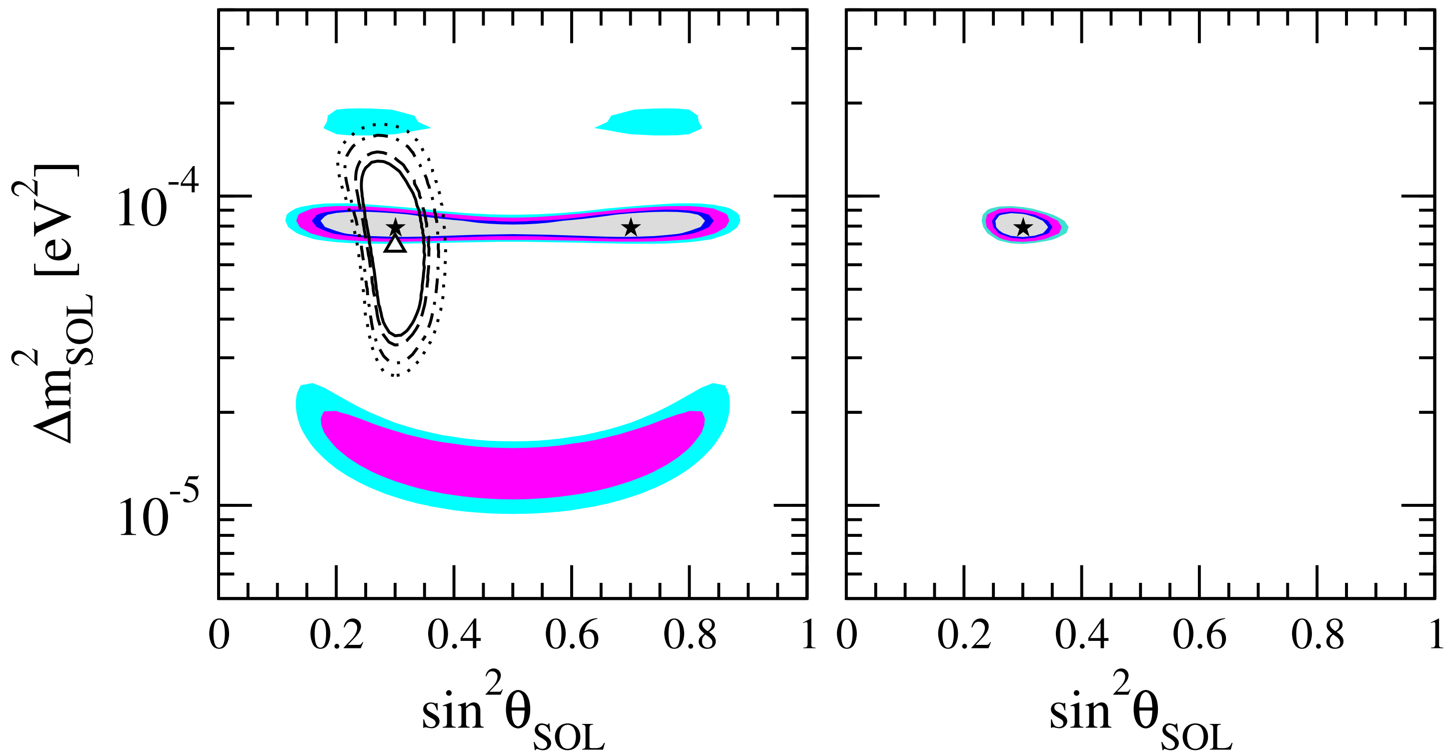
$$\tan 2\theta_m = \frac{\left(\frac{\Delta m^2}{2E}\right) \sin 2\theta + 2\sqrt{2} G_F \varepsilon N_d}{\frac{\Delta m^2}{2E} \cos 2\theta - \sqrt{2}\, G_F\, N_e + \sqrt{2}\, G_F \varepsilon'\, N_d} .$$

Resonance $\frac{\Delta m^2}{2E} \cos 2\theta - \sqrt{2}\, G_F\, N_e + \sqrt{2}\, G_F\, \varepsilon'\, N_d = 0\,.$

$$\varepsilon' > \frac{N_e}{N_d}$$

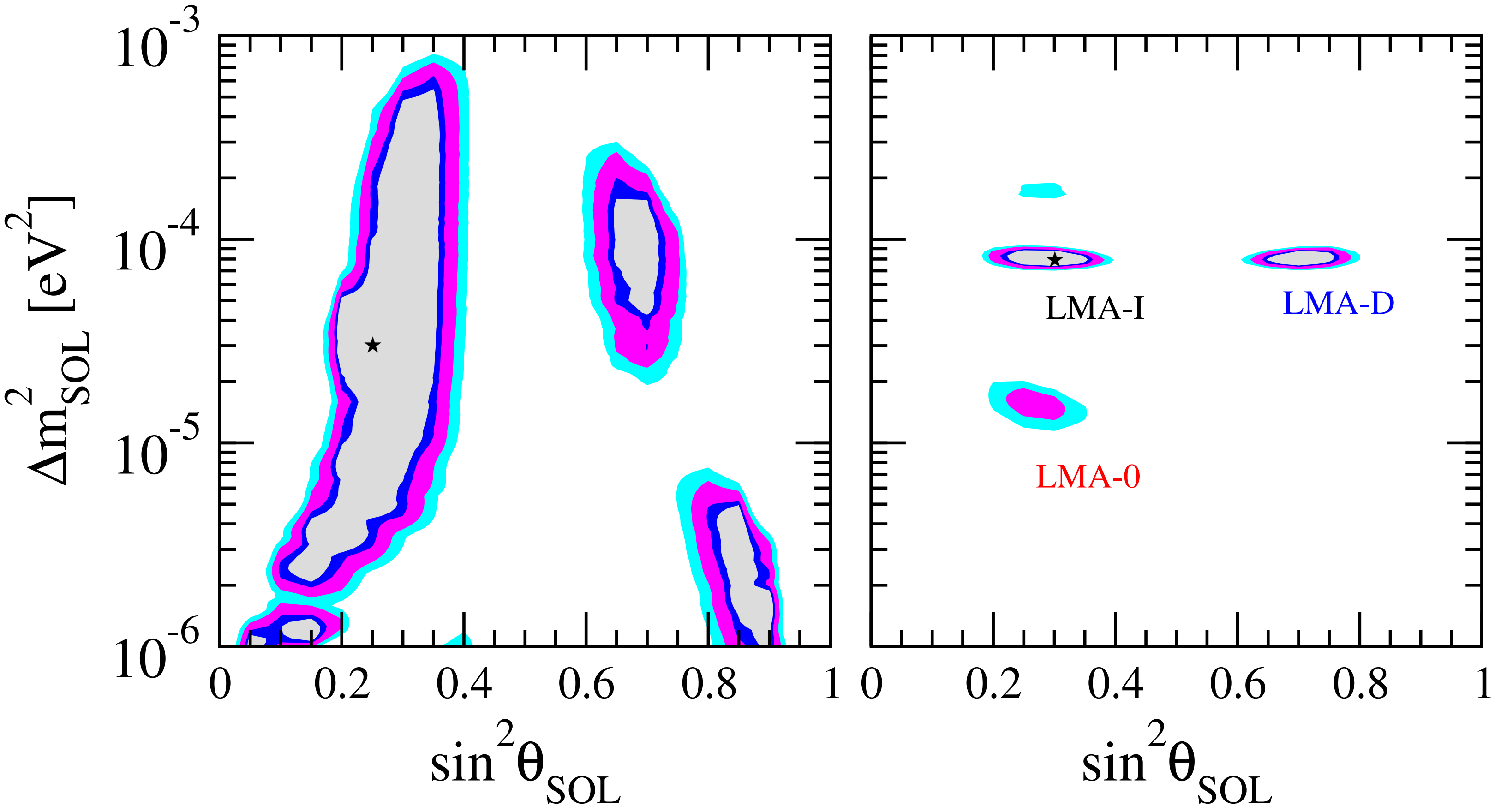
Data fit

OGM, Tortola, Valle JHEP 0610:008,2006

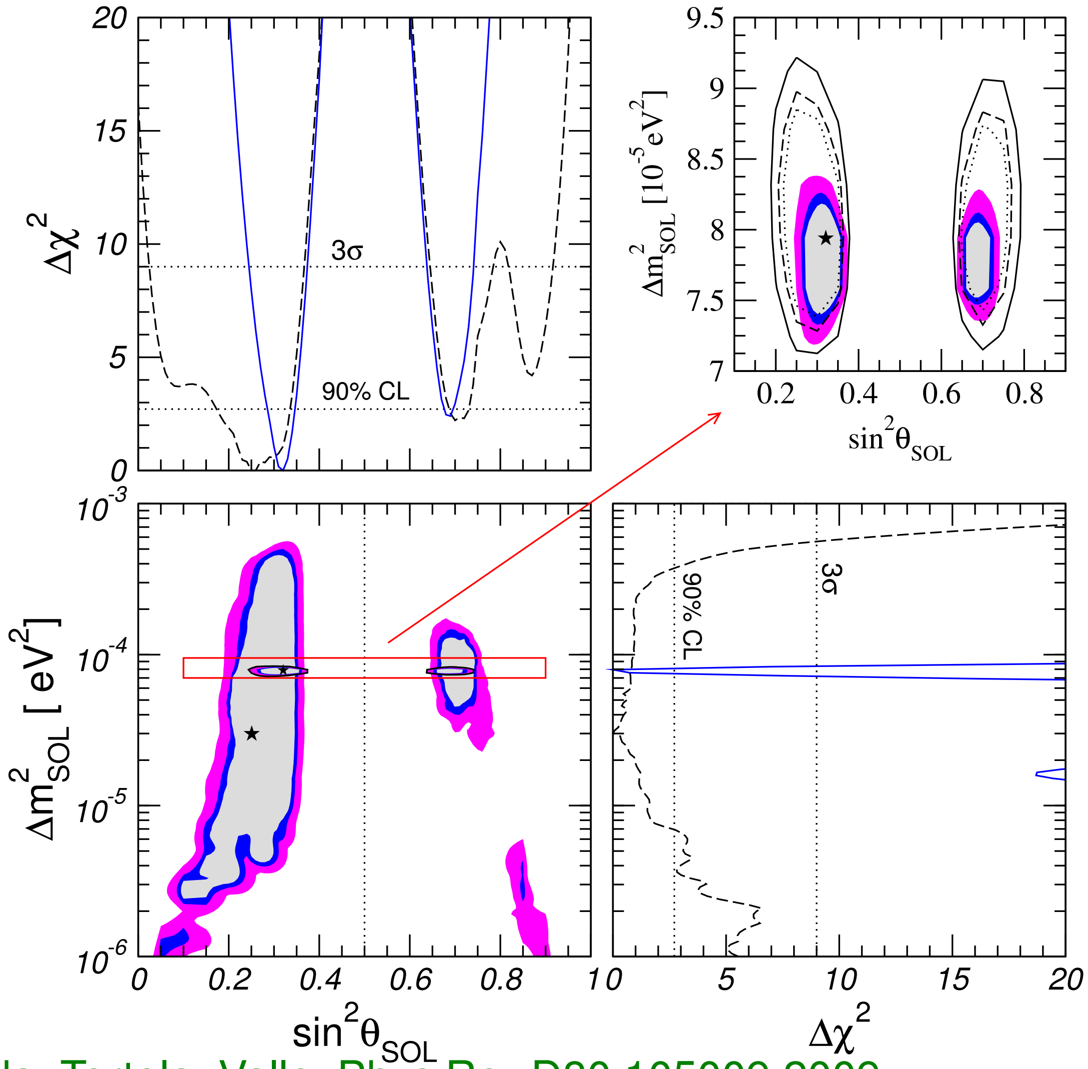


Data fit

Tortola, OGM, Valle, JHEP 0610:008,2006

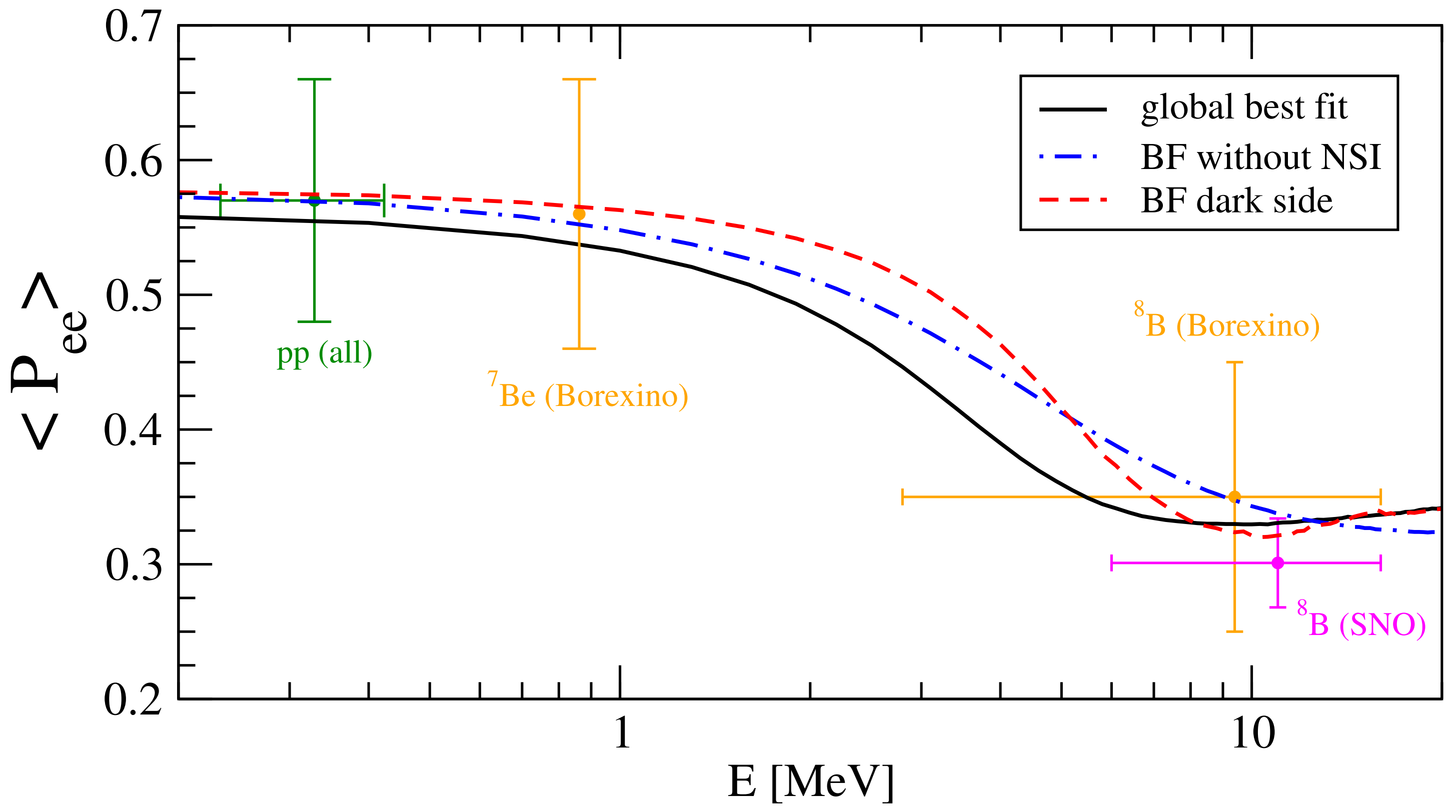


Nonstandar interactions

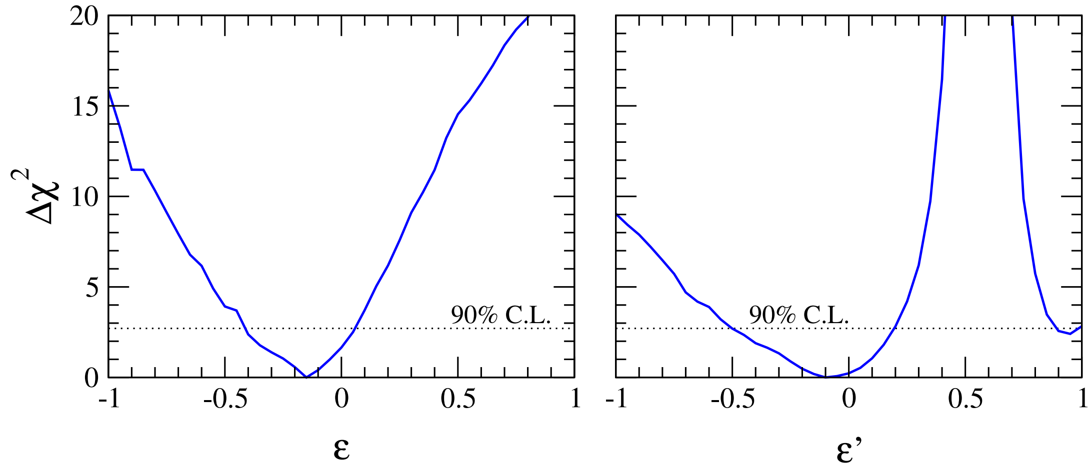


Escrihuela, Miranda, Tortola, Valle, Phys.Rev.D80:105009,2009

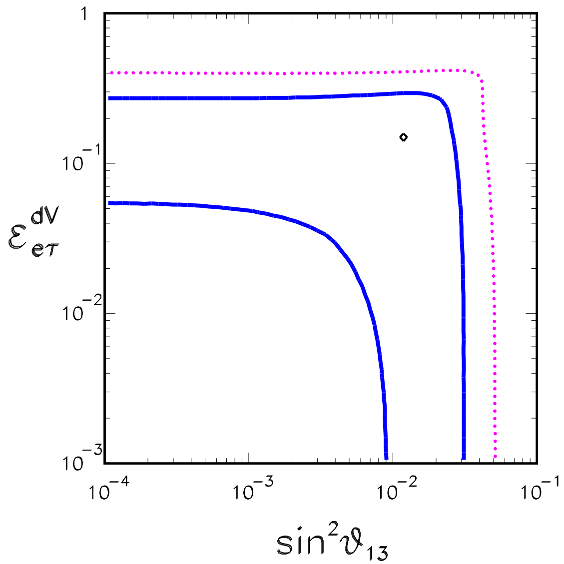
Predictions for the probability



NSI-d constraints from Solar + Kamland



NSI-d constraints from Solar + Kamland



Palazzo, Valle PRD **80** 091301 (2009)

NSI-d constraints for ν_e and ν_τ

$$R^e = \frac{\sigma(\nu_e N \to \nu X) + \sigma(\bar{\nu_e} N \to \bar{\nu} X)}{\sigma(\nu_e N \to e X) + \sigma(\bar{\nu_e} N \to \bar{e} X)} = (\tilde{g}_{Le}) + (\tilde{g}_{Re})$$

	Constraints from CHARM II experiment
ε^L_{ee}	$-0.3 < \lvert\varepsilon^L_{ee}\rvert < 0.3$
ε^R_{ee}	$-0.6 < \lvert\varepsilon^R_{ee}\rvert < 0.5$
$\varepsilon^L_{e\mu}$	$\lvert\varepsilon^L_{e\mu}\rvert < 0.5$
$\varepsilon^R_{e\mu}$	$\lvert\varepsilon^R_{e\mu}\rvert < 0.5$
$\varepsilon^L_{e\tau}$	$\lvert\varepsilon^L_{e\tau}\rvert < 0.5$
$\varepsilon^R_{e\tau}$	$\lvert\varepsilon^R_{e\tau}\rvert < 0.5$

CHARM II Collaboration, P. Vilain et. al. Phys. Lett. **B335** 246 (1994)

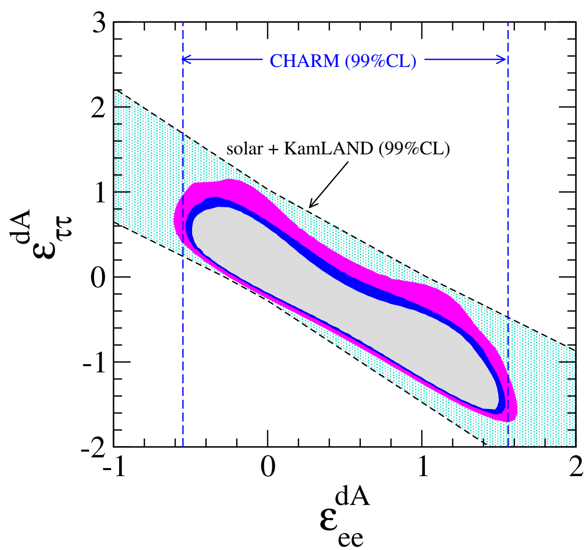
Davidson, Peña-Garay,Rius,Santamaria JHEP 0303:011 (2003) hep-ph/0302093

NSI-d constraints for ν_e

$$\nu + d \rightarrow \nu + p + n$$

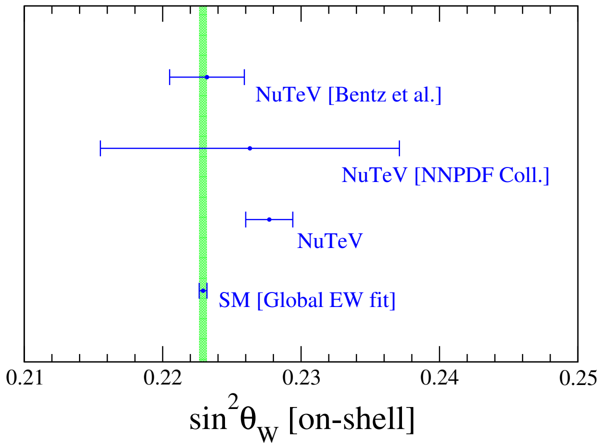
SNO NC is proportional to g_A^2

$$\epsilon_A = - \sum_{\alpha=e,\mu,\tau} \langle P_{e\alpha} \rangle_{NC} \, \epsilon_{\alpha\alpha}^{dA} \, ,$$



NSI-d constraints for ν_μ

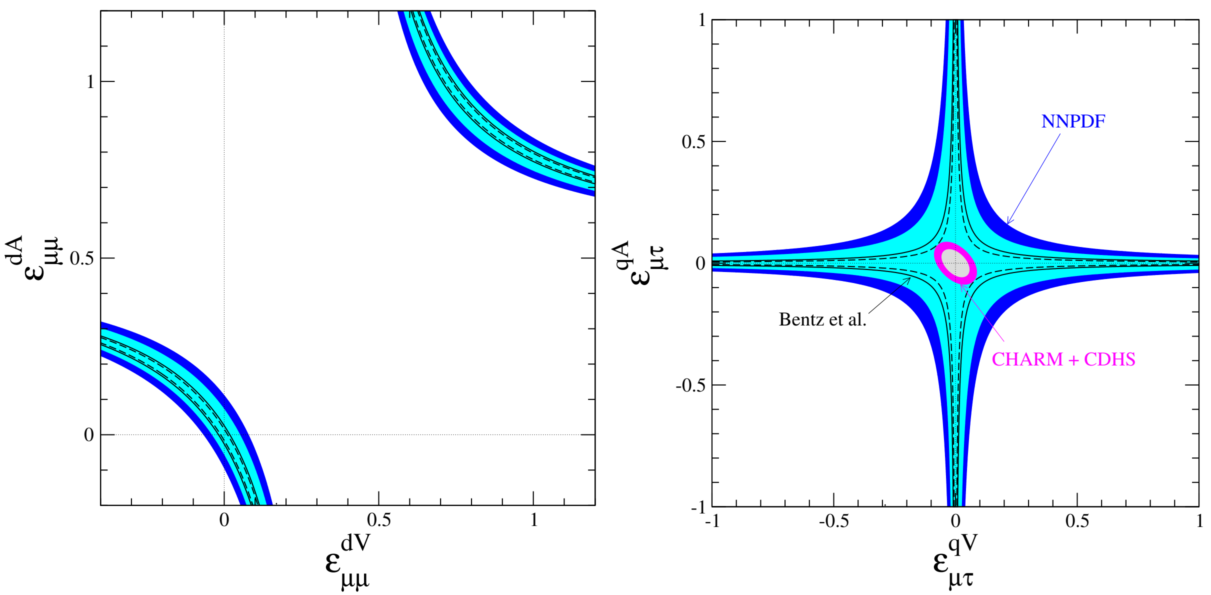
$$R^\mu = \frac{\sigma(\nu_\mu N \to \nu X) + \sigma(\bar{\nu_\mu} N \to \bar{\nu} X)}{\sigma(\nu_\mu N \to \mu X) + \sigma(\bar{\nu_\mu} N \to \bar{\mu} X)} = (\tilde{g}_{L\mu}) + (\tilde{g}_{R\mu})$$



Escrihuela, Miranda, Tortola, Valle, PRD **83** 093002 (2011)

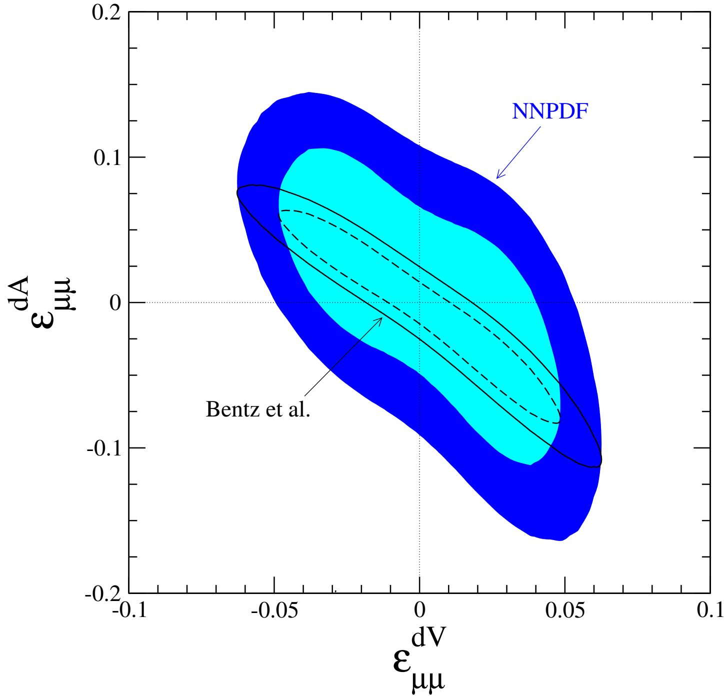
NSI-d constraints for ν_μ

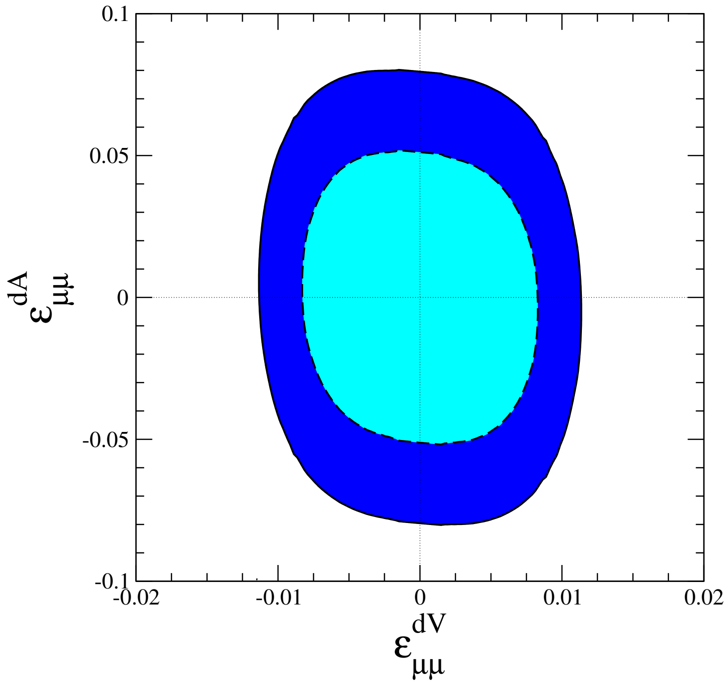
$$R^\mu = \frac{\sigma(\nu_\mu N \to \nu X) + \sigma(\bar{\nu_\mu} N \to \bar{\nu} X)}{\sigma(\nu_\mu N \to \mu X) + \sigma(\bar{\nu_\mu} N \to \bar{\mu} X)} = (\tilde{g}_{L\mu}) + (\tilde{g}_{R\mu})$$



Escrihuela, Miranda, Tortola, Valle, PRD **83** 093002 (2011)

NSI-d constraints for ν_μ





NSI-d constraints for ν_μ

Global with NuTeV reanalysis	NSI with down	NSI with up
	NU	NU
NNPDF	$-0.042 < \epsilon^{dV}_{\mu\mu} < 0.042$	$-0.044 < \epsilon^{uV}_{\mu\mu} < -0.044$
	$-0.091 < \epsilon^{dA}_{\mu\mu} < 0.091$	$-0.15 < \epsilon^{uA}_{\mu\mu} < 0.18$
Bentz at al.	$-0.042 < \epsilon^{dV}_{\mu\mu} < 0.042$	$-0.044 < \epsilon^{uV}_{\mu\mu} < -0.044$
	$-0.072 < \epsilon^{dA}_{\mu\mu} < 0.057$	$-0.094 < \epsilon^{uA}_{\mu\mu} < 0.14$
	FC	FC
NNPDF/Bentz et al.	$-0.007 < \epsilon^{dV}_{\mu\tau} < 0.007$	$-0.007 < \epsilon^{uV}_{\mu\tau} < 0.007$
	$-0.039 < \epsilon^{dA}_{\mu\tau} < 0.039$	$-0.039 < \epsilon^{uA}_{\mu\tau} < 0.039$

Escrihuela, Miranda, Tortola, Valle, PRD **83** 093002 (2011)

NSI-e Laboratory constraints

- Laboratory experiments:
  1. Reactor neutrinos
  2. LEP data ($e^+e^- \to \nu\bar{\nu}\gamma$)
  3. CHARM

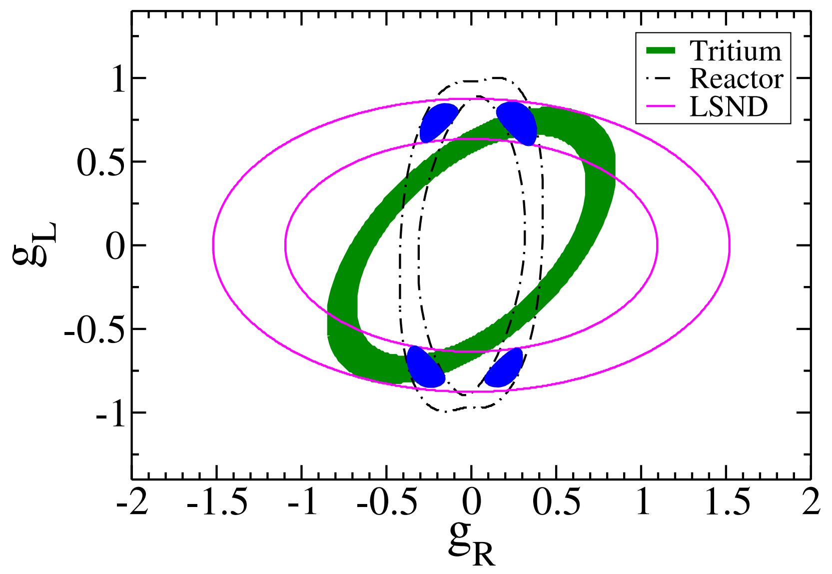
The $\nu_e e$ interaction

$$\sigma(\nu_e e \to \nu e) = \frac{2G_F^2 m_e E_\nu}{\pi}\left[(1+g_L^e+\varepsilon_{ee}^{eL})^2 + \sum_{\alpha\neq e}|\varepsilon_{\alpha e}^{eL}|^2 + \frac{1}{3}(g_R^e+\varepsilon_{ee}^{eR})^2 + \frac{1}{3}\sum_{\alpha\neq e}|\varepsilon_{\alpha e}^{eR}|^2\right]$$

- Davidson, Peña-Garay,Rius,Santamaria JHEP 0303:011 (2003) hep-ph/0302093:
  $-0.07 < \varepsilon_{ee}^{eL} < 0.1 \qquad -1.0 < \varepsilon_{ee}^{eR} < 0.50$ at 90 % C L
- Berezhiani, Raghavan, Rossi PLB **535** 207 (2002) hep-ph/0111138:
  $-0.15 < \varepsilon_{ee}^{eL} < 0.17 \qquad -0.95 < \varepsilon_{ee}^{eR} < 0.50$ at 99 % C L

The $\nu_e e$ interaction

Experiment	Energy (MeV)	events	measurement
LSND $\nu_e e$	10-50	191	$\sigma = [10.1 \pm 1.5] \times E_{\nu_e}(\mathrm{MeV}) \times 10^{-45}\mathrm{cm}^2$
Irvine $\bar{\nu}_e - e$	1.5 - 3.0	381	$\sigma = [0.86 \pm 0.25] \times \sigma_{V-A}$
Irvine $\bar{\nu}_e - e$	3.0 - 4.5	77	$\sigma = [1.7 \pm 0.44] \times \sigma_{V-A}$
Rovno $\bar{\nu}_e - e$	0.6 - 2.0	41	$\sigma = (1.26 \pm 0.62) \times 10^{-44}\mathrm{cm}^2/\mathrm{fission}$
MUNU $\bar{\nu}_e - e$	0.7 - 2.0	68	1.07 ± 0.34 events day $^{-1}$



The $\nu_\mu e \to \nu_\mu e$ interaction

$$\frac{\mathrm{d}\sigma^{\mathrm{theo}}_{\mathrm{CHARM}}}{\mathrm{d}y} = \frac{2G_F^2 m_e}{\pi} E_\nu \left[\left(\tilde{g}_L^2 + \sum_{\alpha \neq \mu} |\varepsilon^L_{\alpha\mu}|^2 \right) + \left(\tilde{g}_R^2 + \sum_{\alpha \neq \mu} |\varepsilon^R_{\alpha\mu}|^2 \right) (1-y)^2 \right]$$

The $e^+e^- \to \nu\bar{\nu}\gamma$ interaction

$$\sigma_{\mathrm{LEP}}^{\mathrm{theo}}(s) = \int \mathrm{d}x \int \mathrm{d}c_\gamma \; H(x, s_\gamma; s) \; \sigma_0^{\mathrm{theo}}(\hat{s}) \,,$$

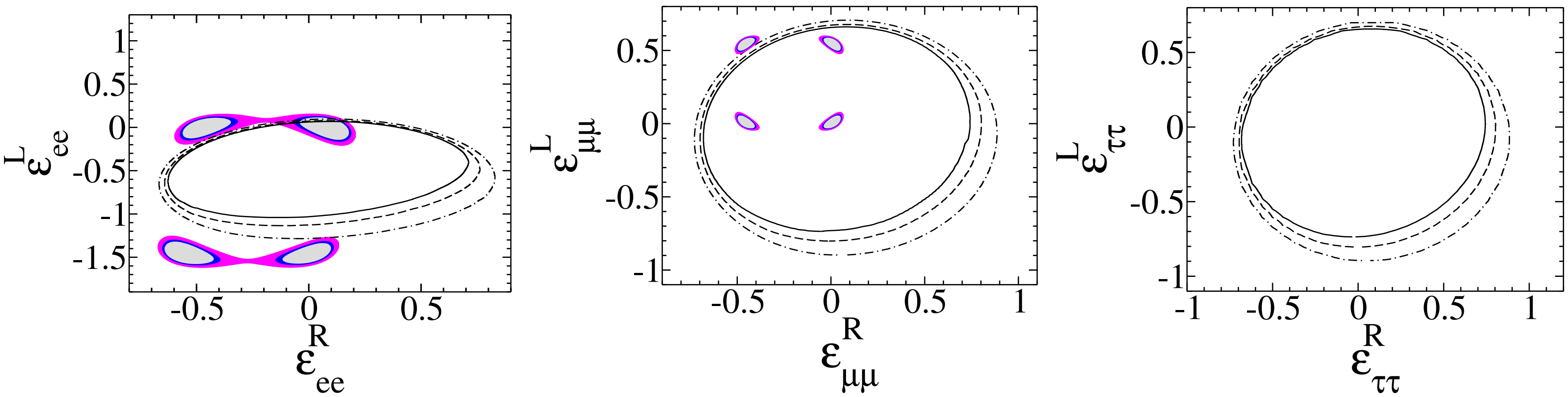
$$H(x, s_\gamma; s) = \frac{2\alpha}{\pi x s_\gamma} \left[\left(1 - \frac{x}{2}\right)^2 + \frac{x^2 c_\gamma^2}{4} \right] ,$$

$$\begin{aligned}
\sigma_0^{\mathrm{SM}} \quad (s) &= \frac{N_\nu G_F^2}{6\pi} M_Z^4 (g_R^2 + g_L^2) \frac{s}{[(s - M_Z^2)^2 + (M_Z \Gamma_Z)^2]} \\
+ \quad & \frac{G_F^2}{\pi} M_W^2 \left\{ \frac{s + 2M_W^2}{2s} - \frac{M_W^2}{s} \left(\frac{s + M_W^2}{s} \right) \log \left(\frac{s + M_W^2}{M_W^2} \right) \right. \\
- \quad & \left. \frac{g_L M_Z^2 (s - M_Z^2)}{(s - M_Z^2)^2 + (M_Z \Gamma_Z)^2} \left[\frac{(s + M_W^2)^2}{s^2} \log \left(\frac{s + M_W^2}{M_W^2} \right) - \frac{M_W^2}{s} - \frac{3}{2} \right] \right\} ,
\end{aligned}$$

The $e^+e^- \to \nu\bar{\nu}\gamma$ interaction

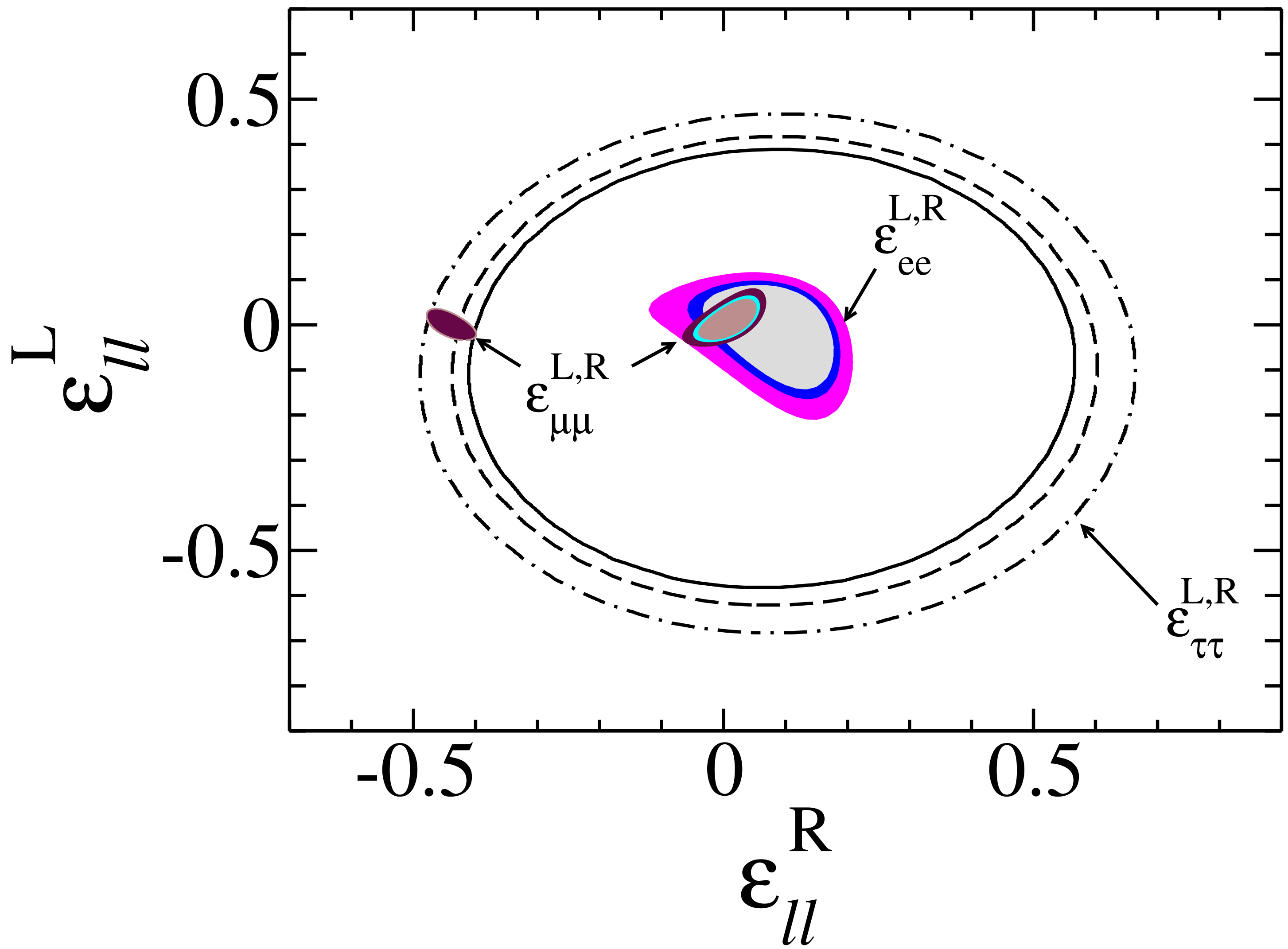
$$
\begin{aligned}
\sigma_0^{\mathrm{NU}}(s) &= \sum_{\alpha=e,\mu,\tau} \frac{G_F^2}{6\pi} s \left[(\varepsilon_{\alpha\alpha}^L)^2 + (\varepsilon_{\alpha\alpha}^R)^2 - 2(g_L \varepsilon_{\alpha\alpha}^L + g_R \varepsilon_{\alpha\alpha}^R) \frac{M_Z^2 (s - M_Z^2)}{(s - M_Z^2)^2 + (M_Z \Gamma_Z)^2} \right] \\
&+ \frac{G_F^2}{\pi} \varepsilon_{ee}^L M_W^2 \left[\frac{(s + M_W^2)^2}{s^2} \log\left(\frac{s + M_W^2}{M_W^2} \right) - \frac{M_W^2}{s} - \frac{3}{2} \right] , \\
\sigma_0^{\mathrm{FC}}(s) &= \sum_{\alpha \neq \beta = e,\mu,\tau} \frac{G_F^2}{6\pi} s \left[(\varepsilon_{\alpha\beta}^L)^2 + (\varepsilon_{\alpha\beta}^R)^2 \right] .
\end{aligned}
$$

Laboratory constraints



Barranco, Miranda, Moura, Valle PRD **77** 093014 ’08

Laboratory constraints



Laboratory constraints

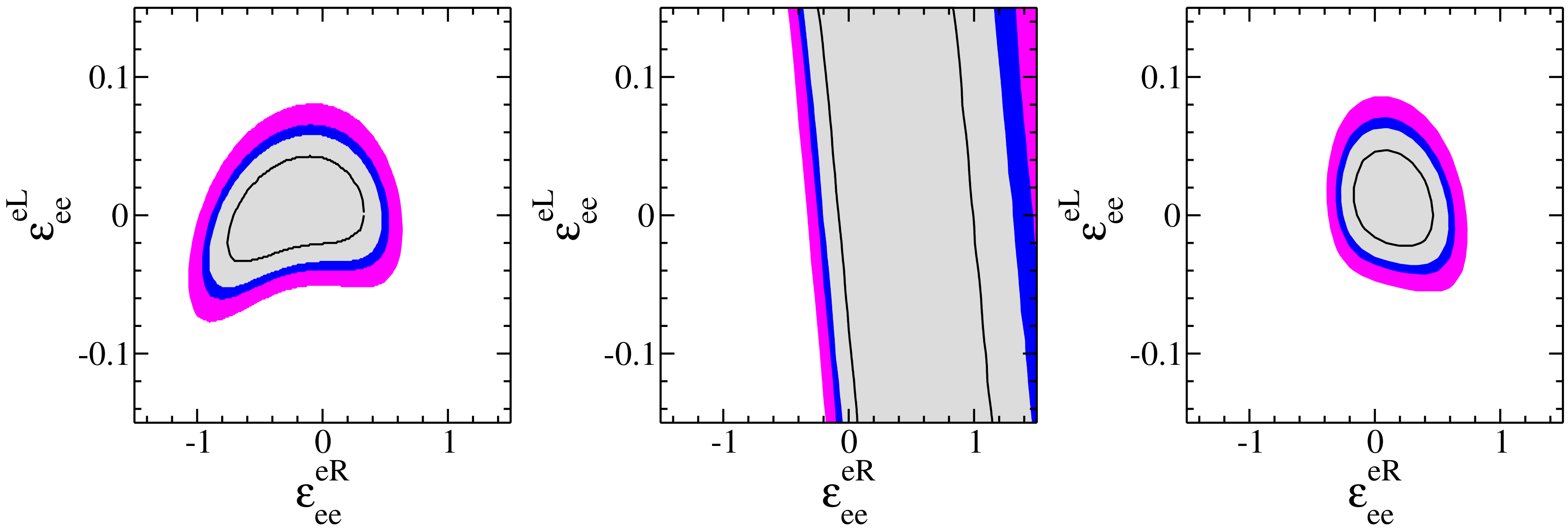
	Region at 90% C. L.	one parameter	previous limits
ε^L_{ee}	$-0.14 < \varepsilon^L_{ee} < 0.09$	$-0.03 < \varepsilon^L_{ee} < 0.08$	$-0.05 < \varepsilon^L_{ee} < 0.1$
ε^R_{ee}	$-0.03 < \varepsilon^R_{ee} < 0.18$	$0.004 < \varepsilon^R_{ee} < 0.15$	$0.04 < \varepsilon^R_{ee} < 0.14$
$\varepsilon^L_{\mu\mu}$	$-0.033 < \varepsilon^L_{\mu\mu} < 0.055$	$\vert\varepsilon^L_{\mu\mu}\vert < 0.03$	$\vert\varepsilon^L_{\mu\mu}\vert < 0.03$
$\varepsilon^R_{\mu\mu}$	$-0.040 < \varepsilon^R_{\mu\mu} < 0.053$	$\vert\varepsilon^R_{\mu\mu}\vert < 0.03$	$\vert\varepsilon^R_{\mu\mu}\vert < 0.03$
$\varepsilon^L_{\tau\tau}$	$-0.6 < \varepsilon^L_{\tau\tau} < 0.4$	$-0.5 < \varepsilon^L_{\tau\tau} < 0.2$	$\vert\varepsilon^L_{\tau\tau}\vert < 0.5$
$\varepsilon^R_{\tau\tau}$	$-0.4 < \varepsilon^R_{\tau\tau} < 0.6$	$-0.3 < \varepsilon^R_{\tau\tau} < 0.4$	$\vert\varepsilon^R_{\tau\tau}\vert < 0.5$

Barranco, Miranda, Moura, Valle PRD **77** 093014 ’08

Solar neutrinos

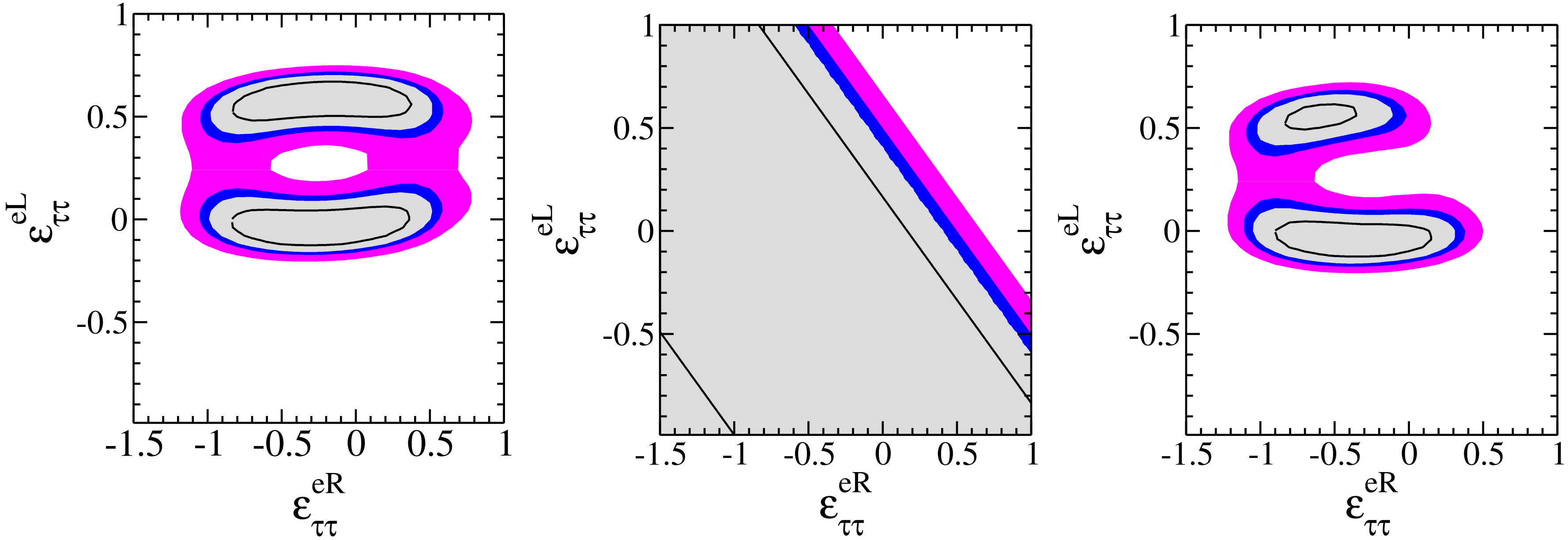
- solar neutrinos could be sensitive to the NSI with electrons
- Propagation could be affected
- Detection could also be affected! especially in SuperKamiokande

Solar neutrinos



Bolaños, OGM, Palazzo, Tortola, Valle PRD79:113012,2009

Solar neutrinos



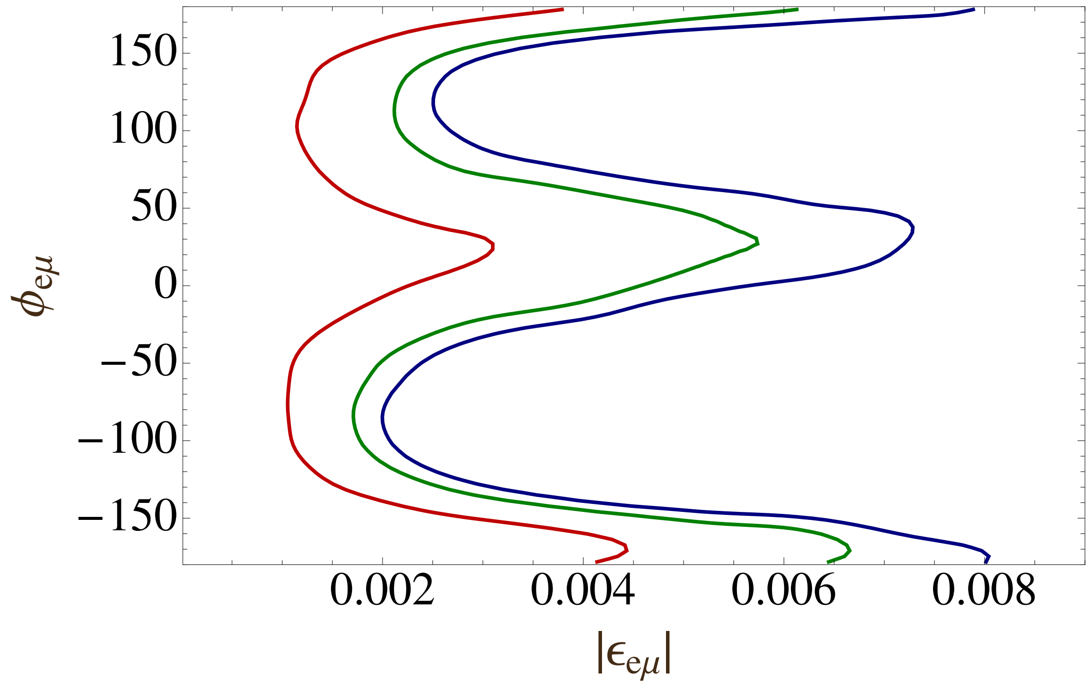
Bolaños, Miranda, Palazzo, Tortola, Valle Phys.Rev.D79:113012,2009

Solar neutrinos

	Solar analysis	Laboratory	Previous limits
ε_{ee}^{L}	$-0.036 < \varepsilon_{ee}^{L} < 0.063$	$-0.14 < \varepsilon_{ee}^{L} < 0.09$	$-0.05 < \varepsilon_{ee}^{L} < 0.1$
ε_{ee}^{R}	$-0.27 < \varepsilon_{ee}^{R} < 0.59$	$-0.03 < \varepsilon_{ee}^{R} < 0.18$	$0.04 < \varepsilon_{ee}^{R} < 0.14$
$\varepsilon_{\mu\mu}^{L}$		$-0.033 < \varepsilon_{\mu\mu}^{L} < 0.055$	$\lvert\varepsilon_{\mu\mu}^{L}\rvert < 0.03$
$\varepsilon_{\mu\mu}^{R}$		$-0.040 < \varepsilon_{\mu\mu}^{R} < 0.053$	$\lvert\varepsilon_{\mu\mu}^{R}\rvert < 0.03$
$\varepsilon_{\tau\tau}^{L}$	$-0.16 < \varepsilon_{\tau\tau}^{L} < 0.11$	$-0.6 < \varepsilon_{\tau\tau}^{L} < 0.4$	$\lvert\varepsilon_{\tau\tau}^{L}\rvert < 0.5$
$\varepsilon_{\tau\tau}^{R}$	$-1.05 < \varepsilon_{\tau\tau}^{R} < 0.31$	$-0.4 < \varepsilon_{\tau\tau}^{R} < 0.6$	$\lvert\varepsilon_{\tau\tau}^{R}\rvert < 0.5$

Bolaños, OGM, Palazzo, Tortola, Valle PRD79:113012,2009

Improving NSI constraints

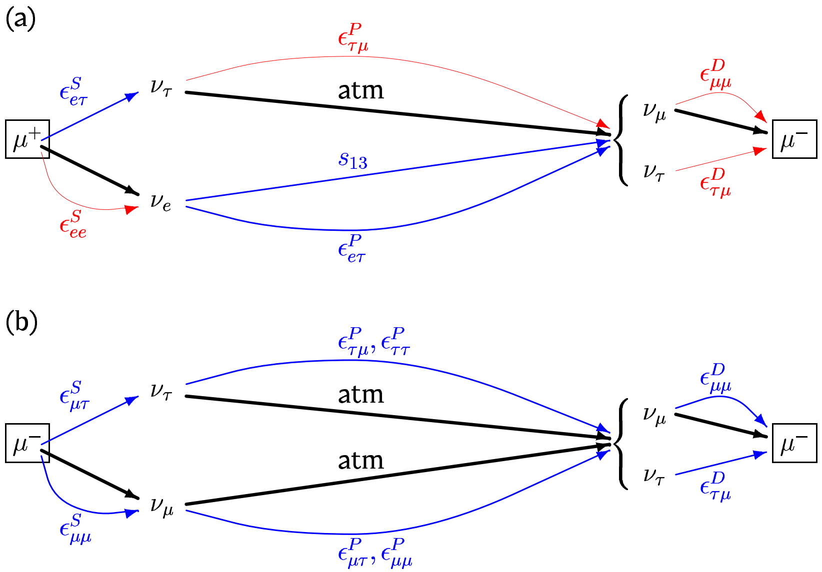


Coloma, Donini, López-Pavón, Minakata 1105.5936

Confusion problem for θ_{13}

$$\mathcal{R}_{e\mu} \approx A\, s_{13}^2 + B\, s_{13}\epsilon_P + C\,\epsilon_P^2 + D\,\epsilon_P\epsilon_S + E\,\epsilon_S^2 + F\, s_{13}\epsilon_S$$

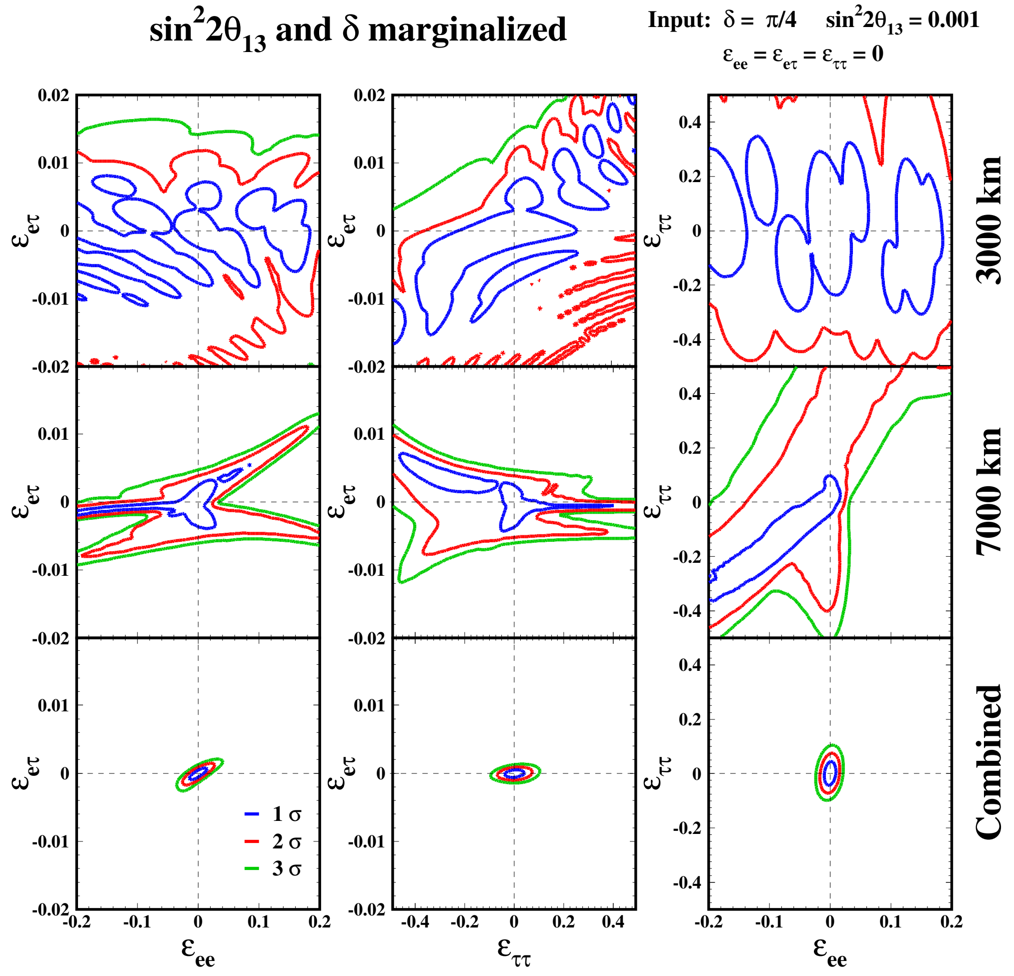
$$\epsilon_S \equiv \epsilon_{e\tau}^S\,, \qquad \epsilon_P \equiv \epsilon_{e\tau}^P\,.$$



Huber, Schwetz, Valle, PRD **66** 013006 '02.

Confusion problem for θ_{13}

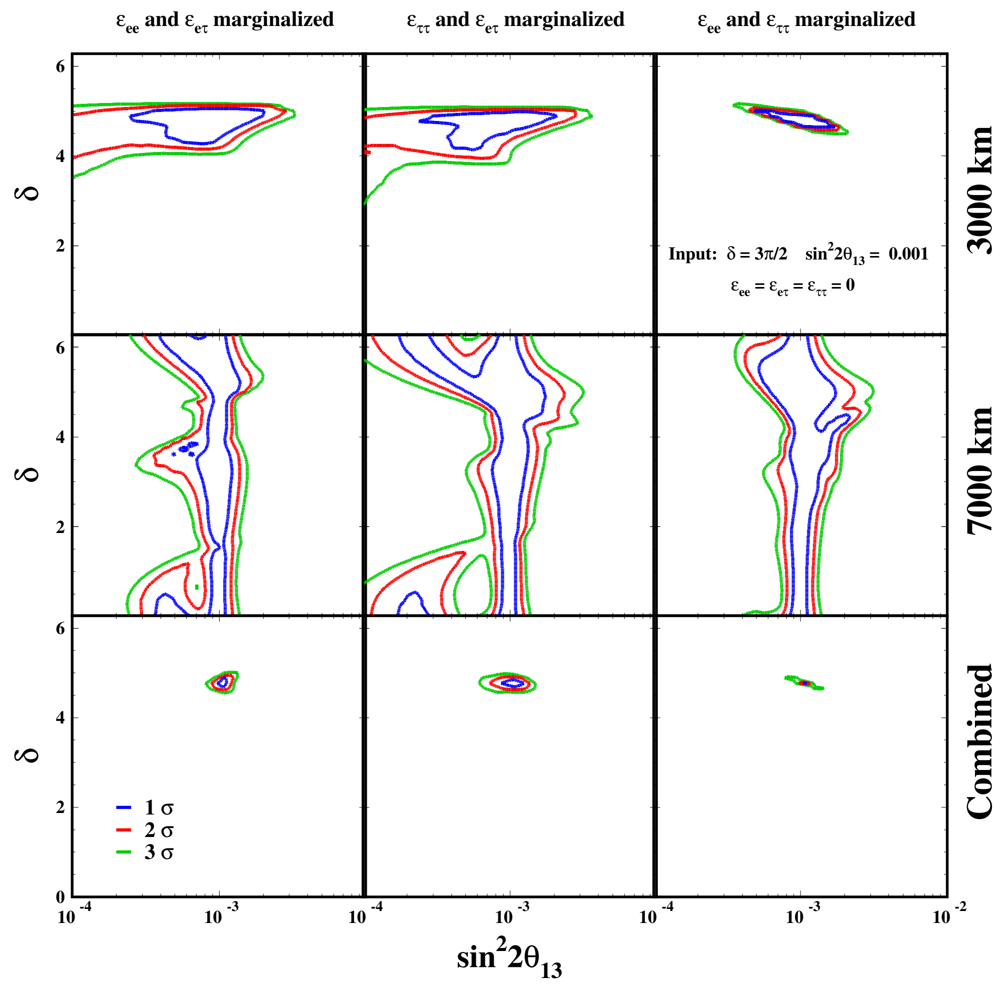
Neutrino factory + two different neutrino detectors



Ribeiro, Minakata, Nunokawa, S. Uchinami , R. Zukanovich-Funchal JHEP 0712:002,2007.

Confusion problem for θ_{13}

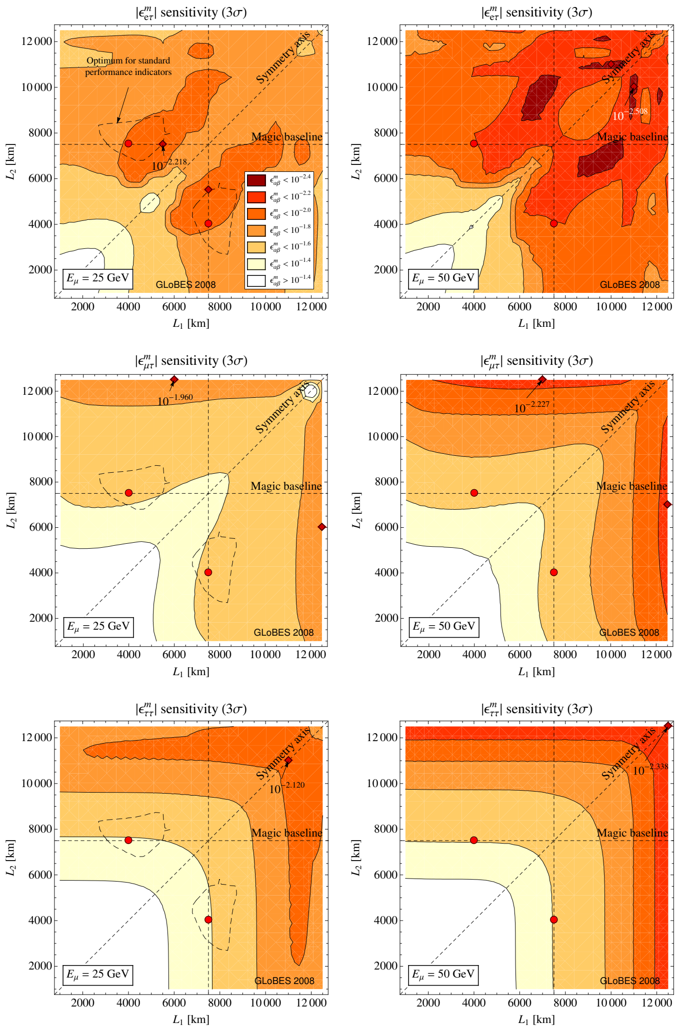
Neutrino factory + two different neutrino detectors



Ribeiro, Minakata, Nunokawa, S. Uchinami , R. Zukanovich-Funchal JHEP 0712:002,2007.

Confusion problem for θ_{13}

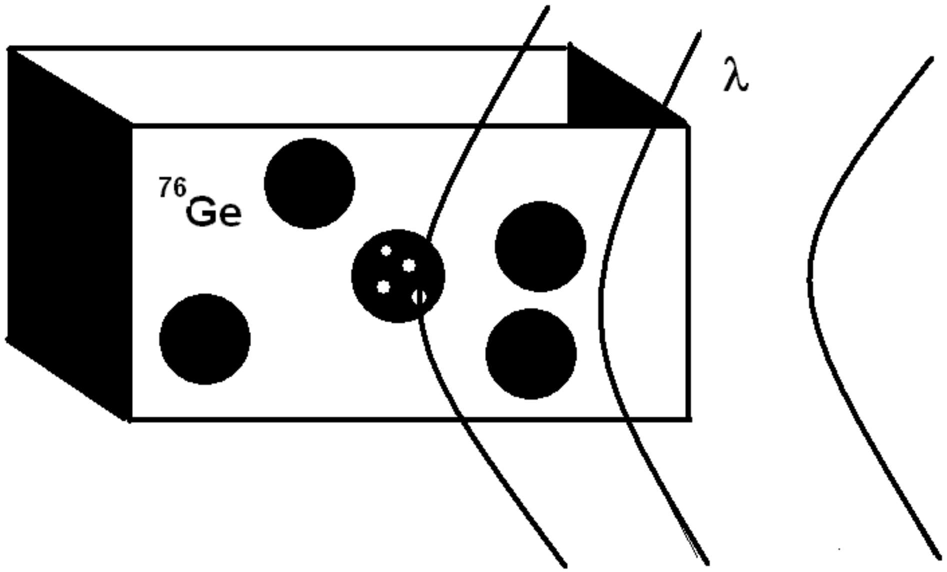
Neutrino factory + two different neutrino detectors



Kopp, Ota, Winter, PRD **78** 053007 '08

Improving NSI constraints

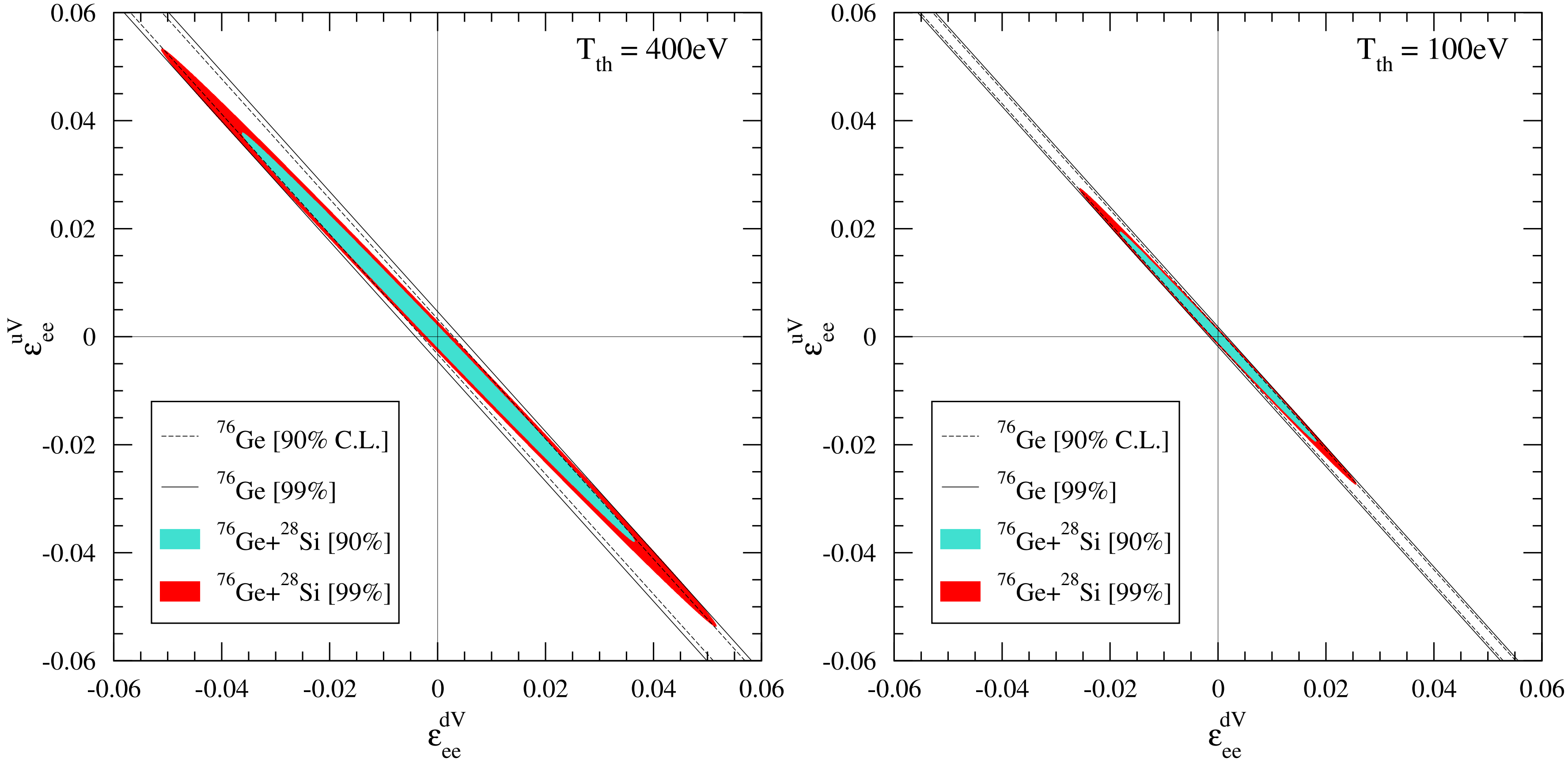
[J. Barranco, OGM, T.I. Rashba JHEP 0512:021 '05] Neutrino-nuclei coherent scattering (for $qR << 1$)



$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi}\left\{(G_V + G_A)^2 + (G_V - G_A)^2\left(1 - \frac{T}{E_\nu}\right)^2 - (G_V^2 - G_A^2)\frac{MT}{E_\nu^2}\right\},$$

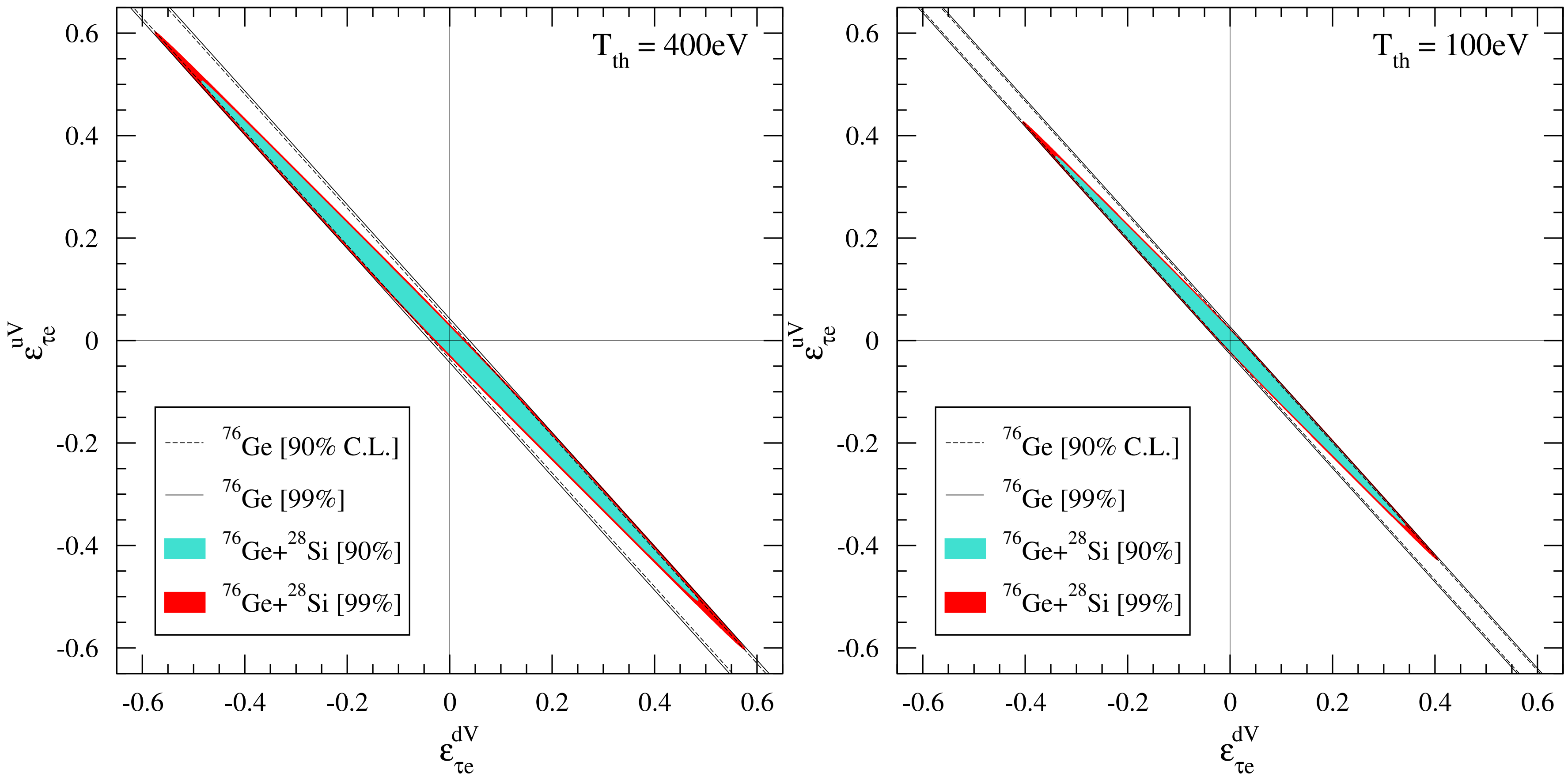
M is the nucleus mass; T recoil nucleus energy (from 0 to $T_{max} = 2E_\nu^2/(M + 2E_\nu)$); E_ν neutrino energy.

Coherent scattering



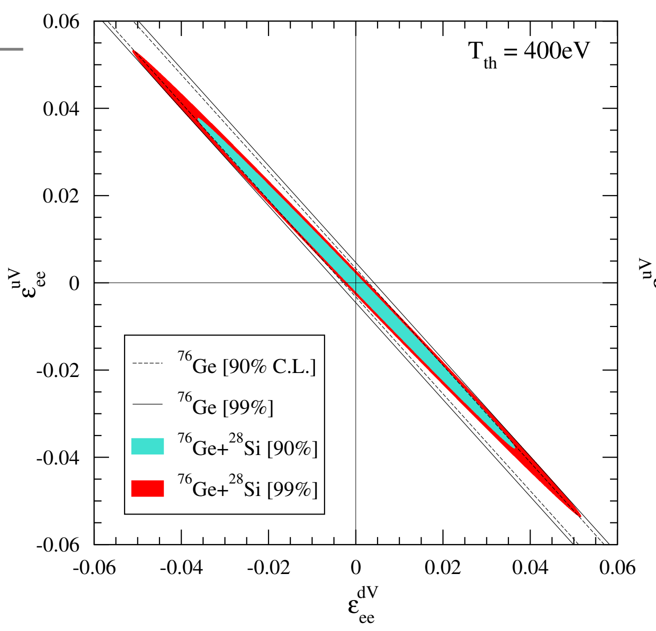
J. Barranco, OGM, T.I. Rashba JHEP 0512:021 ’05

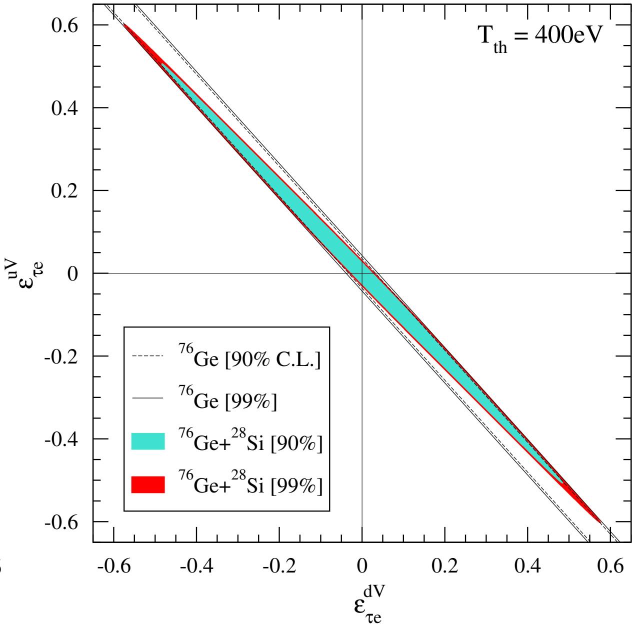
Coherent scattering



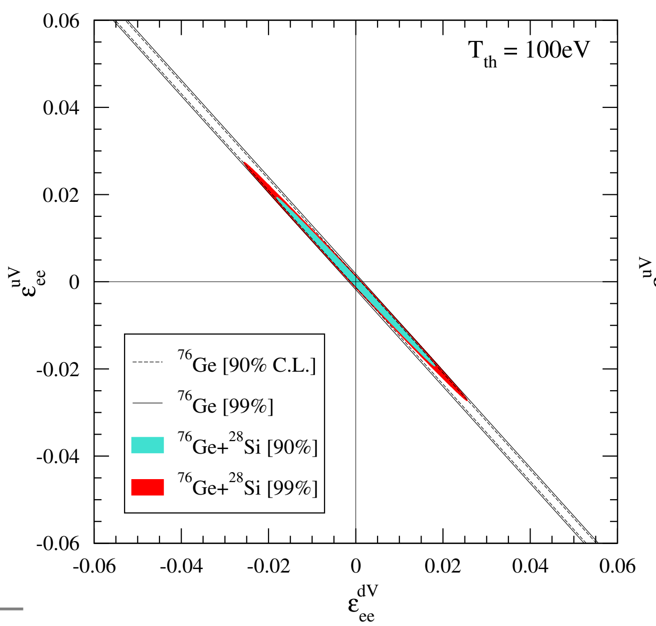
J. Barranco, OGM, T.I. Rashba JHEP 0512:021 ’05

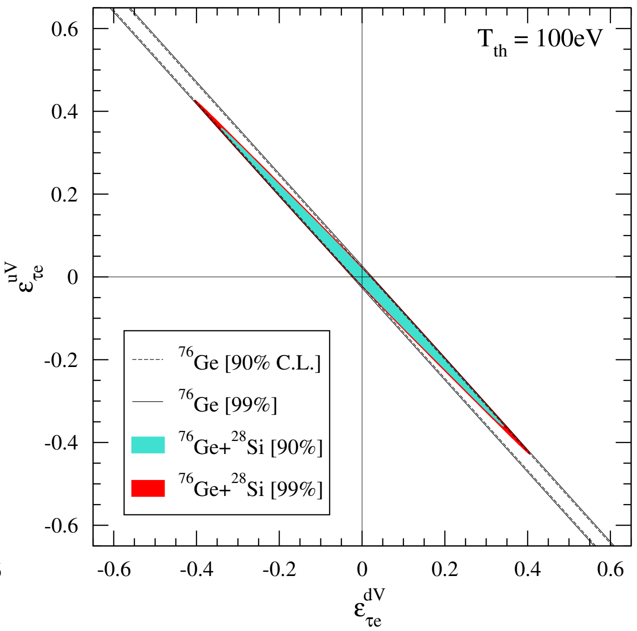
Estimated bounds on NSI from TEXONO-like experiment (Ge+Si)





^{76}Ge+^{28}Si $T_{th}=400eV$
$\lvert\epsilon^{dV}_{ee}\rvert < 0.036$
$\lvert\epsilon^{uV}_{ee}\rvert < 0.038$
$\lvert\epsilon^{dV}_{\tau e}\rvert < 0.48$
$\lvert\epsilon^{uV}_{\tau e}\rvert < 0.50$





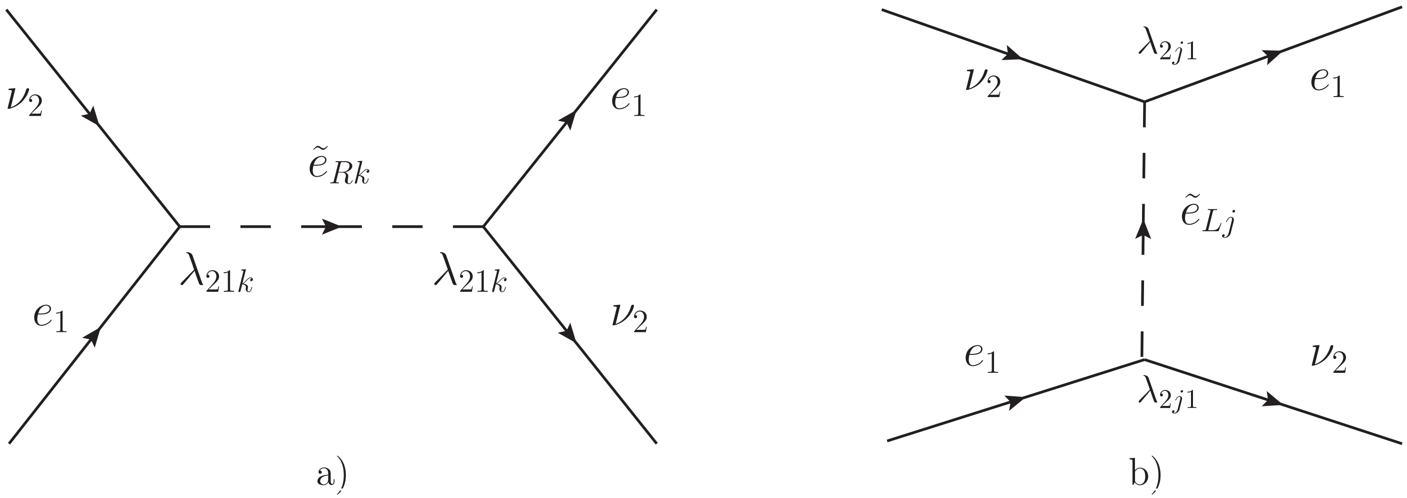
^{76}Ge+^{28}Si $T_{th}=100eV$
$\lvert\epsilon^{dV}_{ee}\rvert < 0.018$
$\lvert\epsilon^{uV}_{ee}\rvert < 0.019$
$\lvert\epsilon^{dV}_{\tau e}\rvert < 0.34$
$\lvert\epsilon^{uV}_{\tau e}\rvert < 0.37$

Conclusions

- The solar neutrino problem remained unsolved for more than 30 years.
- It was the motivation, together with the atmospheric neutrino puzzle, for several experiments that have allowed to get a better knowledge of the Standard Model and of the neutrino properties.
- Neutrino physics counts now with several experiments that are improving the measurements of neutrino parameters and it is expected that new generation experiments could give a clue of the direction for physics beyond the Standard Model.
- Although we now better the neutrino masses diferences and mixings, there are many open question.

R-parity breaking Susy

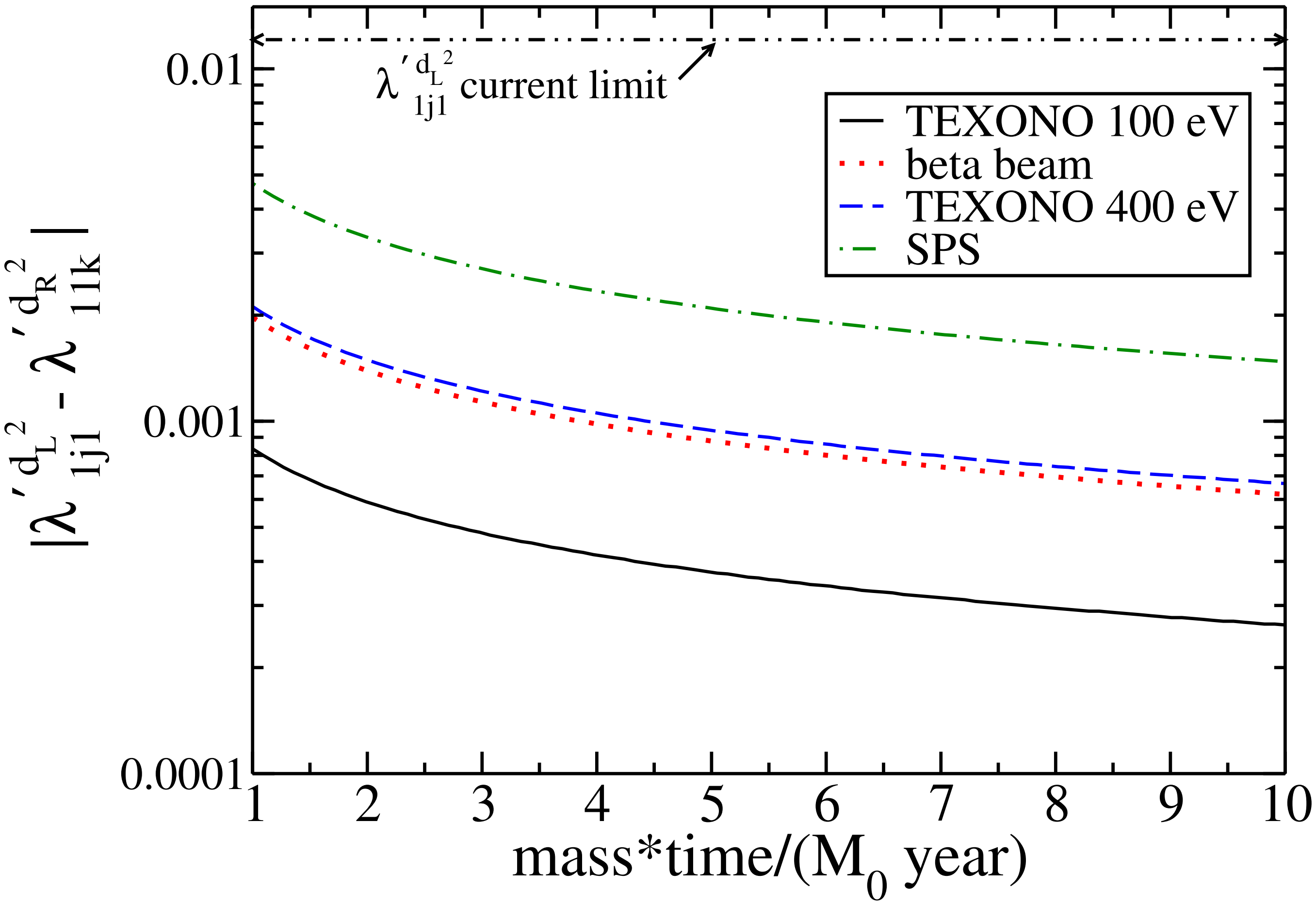
$$
\begin{aligned}
&\lambda_{ijk} L_L^i L_L^j \bar{E}_R^k \\
&\lambda'_{ijk} L_L^i Q_L^j \bar{D}_R^k,
\end{aligned}
\qquad (2)
$$



J. Barranco, OGM, T.I. Rashba PRD **76** 073008 (2007)

R-parity breaking Susy

J. Barranco, OGM, T I Rashba hep-ph/0702175



J. Barranco, OGM, T.I. Rashba PRD **76** 073008 (2007)