Can four neutrinos explain global oscillation data including LSND?

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based on:

M. Maltoni, T.S., M.A. Tórtola, J.W.F. Valle, Nucl. Phys. B 643 (2002) 321
M. Maltoni, T.S., M.A. Tórtola, J.W.F. Valle, hep-ph/0207227, PRD
M. Maltoni, T.S., J.W.F. Valle, Phys. Rev. D 65 (2002) 093004
M. Maltoni, T.S., J.W.F. Valle, Phys. Lett. B 518 (2001) 252
W. Grimus, T.S., Eur. Phys. J. C 20 (2001) 1

NOON2003, 10 Feb. 2003, Kanazawa, Japan

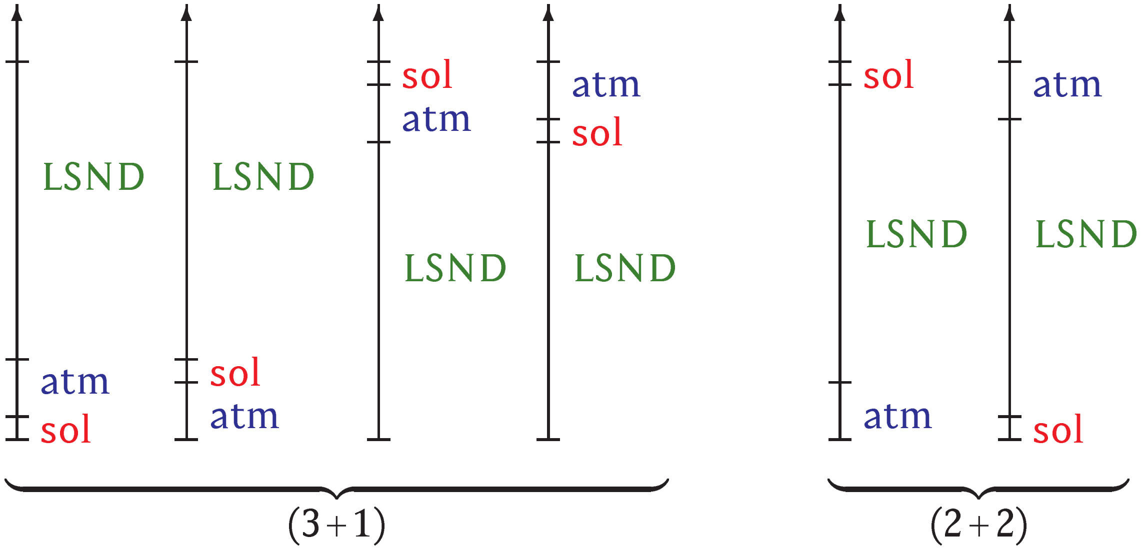
Outline

- Introduction
- 4-neutrino oscillation parameters
- Analysis of solar and atmsopheric neutrino data
- Statistical methods
- (2+2) schemes: ruled out by solar and atmsopheric data
- SBL data and the disfavouring of (3+1) schemes
- Analysis of global oscillation data in (3+1), (2+2) and (3+0)
- Summary and outlook

Introduction

- solar neutrinos: $\nu_e \to \nu_\mu, \nu_\tau$ $\Delta m^2_{\text{sol}} \lesssim 10^{-4}\ \text{eV}^2$
- atmospheric neutrinos: $\nu_\mu \to \nu_\tau$ $\Delta m^2_{\text{atm}} \sim 3 \times 10^{-3}\ \text{eV}^2$
- LSND: $\bar{\nu}_\mu \to \bar{\nu}_e$ $\Delta m^2_{\text{LSND}} \sim 1\ \text{eV}^2$

not possible with 3 neutrinos → sterile neutrino



(3+1): include 3-active neutrino scenario
(2+2): sterile neutrino is important for solar and/or atmospheric

4-neutrino oscillation parameters

3 mass-squared differences + 6 mixing angles → $\boxed{\text{9 parameters}}$

we define:

$$\eta_\alpha = \sum_i |U_{\alpha i}|^2 \quad \text{with } i \in \text{solar mass states}$$

$$d_\alpha = 1 - \sum_i |U_{\alpha i}|^2 \quad \text{with } i \in \text{atmospheric mass states}$$

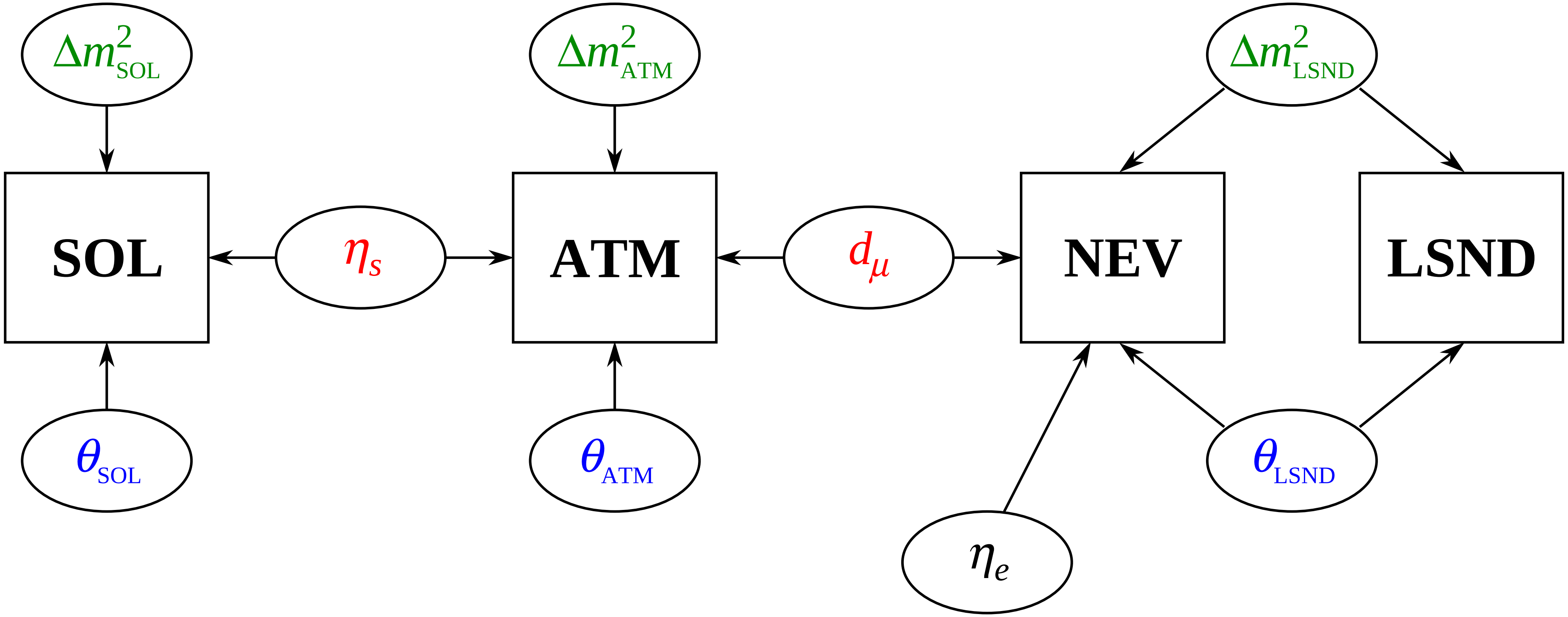
note that in (2+2): $\eta_\alpha = d_\alpha$

$$\longrightarrow \quad \boxed{\Delta m^2_{\text{sol}},\ \Delta m^2_{\text{atm}},\ \Delta m^2_{\text{LSND}},\ \theta_{\text{sol}},\ \theta_{\text{atm}},\ \theta_{\text{LSND}},\ \eta_s,\ \eta_e,\ d_\mu}$$

approximations:

- $\Delta m^2_{\text{sol}} \ll \Delta m^2_{\text{atm}} \ll \Delta m^2_{\text{LSND}}$
- $\eta_e \approx 1$ for solar and atmospheric oscillations (reactor data)

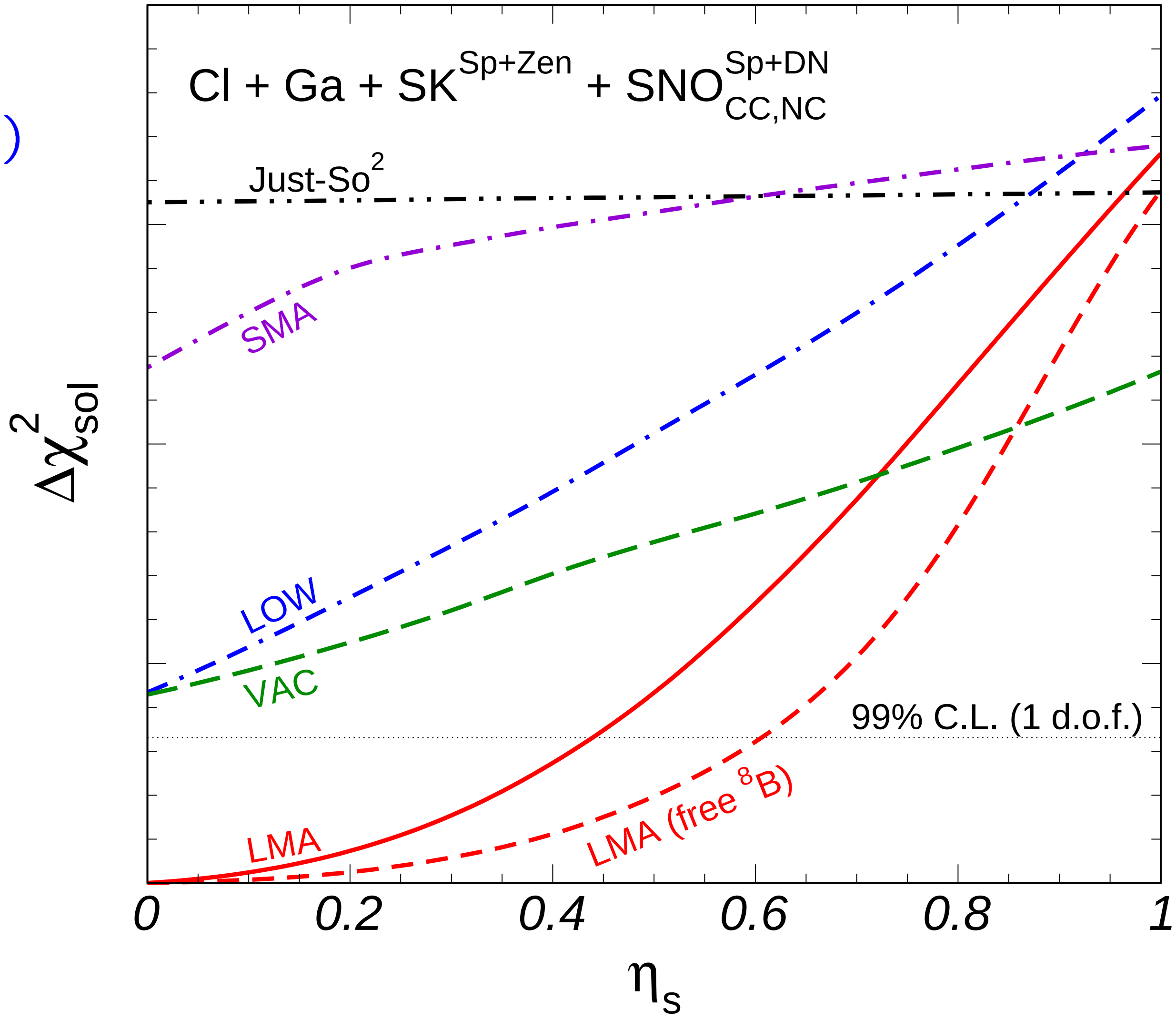
Coupling of the data sets:

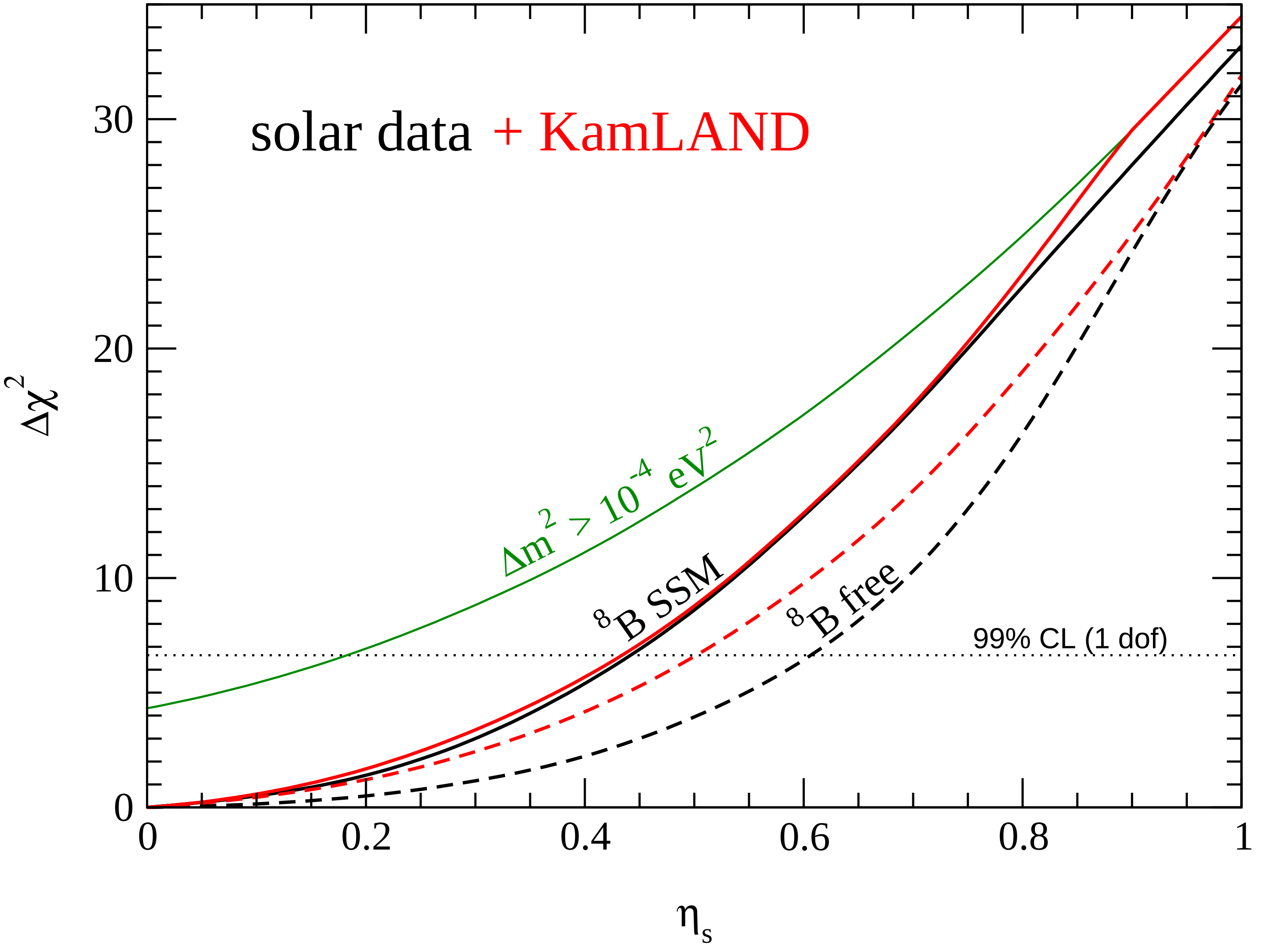


Solar data

M. Maltoni, T.S., M.A. Tórtola, J.W.F. Valle, hep-ph/0207227, PRD

$\chi^2_{\text{sol}}(\Delta m^2_{\text{sol}},\, \theta_{\text{sol}},\, \eta_s)$





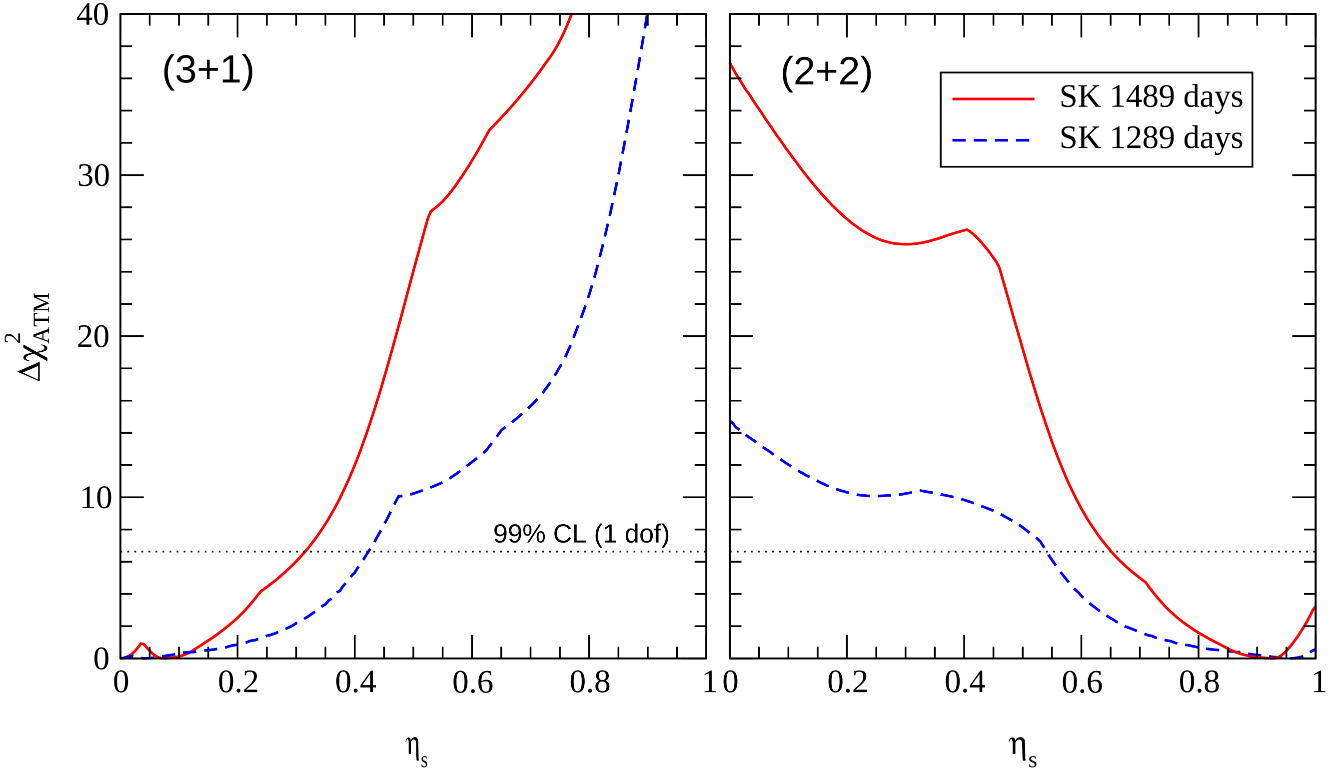
99% CL : ^{8}B SSM: $\eta_s \leq 0.44$ (unchanged)

^{8}B free: $\eta_s \leq \begin{cases} 0.5 & \text{(solar + KamLAND)} \\ 0.61 & \text{(solar only)} \end{cases}$

atmospheric data:

SK sub/multi-GeV e/μ, upwd. stopp/thr μ (55 dof) + **MACRO** through μ (10 dof)

$\chi^2_{\text{atm}}(\eta_s)$ depends on the mass scheme:



$\Delta\chi^2_{\text{st-act}} = 34.6$

SK analysis:

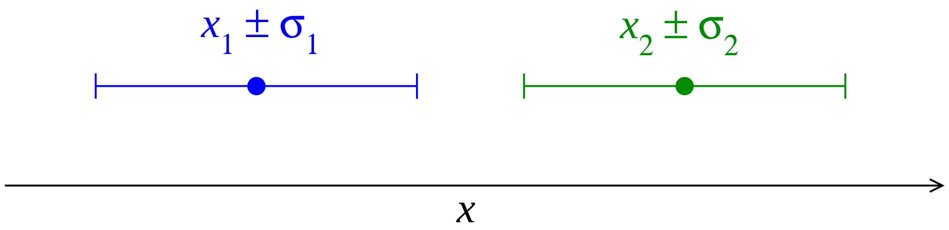
Shiozawa, Neutrino 02

$\Delta\chi^2_{\text{st-act}} = 50.1$

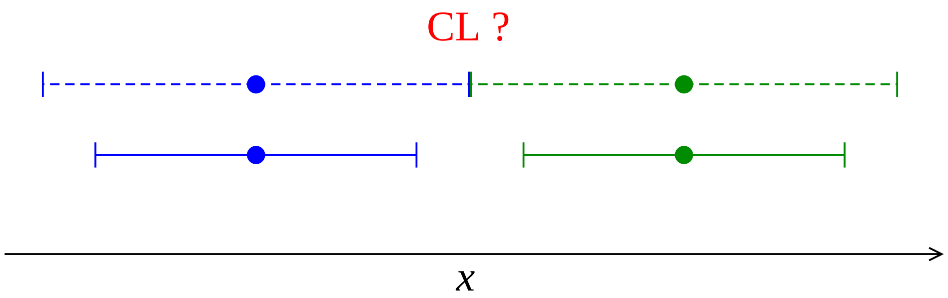
$$\text{atmospheric:} \begin{cases} \eta_s \leq 0.32 & \text{for (3+1)} \\ \eta_s \geq 0.65 & \text{for (2+2)} \end{cases}$$

solar: $\eta_s \leq 0.44$

A bit of statistics: Two measuremts of the same parameter:



- **Parameter consistency (PC)**



- **Parameter goodness-of-fit (PG)**

The parameter goodness-of-fit

K data sets: $\chi^2_k(x^k) = (\chi^2_k)_{\mathrm{min}} + \Delta\chi^2_k(x^k)\,, \quad k = 1 \ldots K$

global χ^2 : $\chi^2_{\mathrm{tot}}(x) = \sum_{k=1}^{K} (\chi^2_k)_{\mathrm{min}} + \sum_{k=1}^{K} \Delta\chi^2_k(x^k)$

define: $\bar{\chi}^2(x) \equiv \sum_{k=1}^{K} \Delta\chi^2_k(x^k) = \bar{\chi}^2_{\mathrm{min}} + \Delta\bar{\chi}^2(x)$

usuall GOF: $\min\left[\chi^2_{\mathrm{tot}}\right] = \sum_{k=1}^{K} (\chi^2_k)_{\mathrm{min}} + \bar{\chi}^2_{\mathrm{min}}$ for $N - P$ dof

not very usefull for large N

→ we use only $\bar{\chi}^2_{\mathrm{min}}$: $\boxed{\chi^2_{\mathrm{PG}} \equiv \bar{\chi}^2_{\mathrm{min}} \quad \text{for} \quad \sum_{k=1}^{K} P_k - P \text{ dof}}$

Why not use standard GOF ? [R. Foot, hep-ph/0210393]

Consider (2+2) with $\eta_s = 0$
(pure active–sterile atmospheric oscillations)

$\chi^2_{\text{atm}} = 222$ 190 dof GOF: 5%

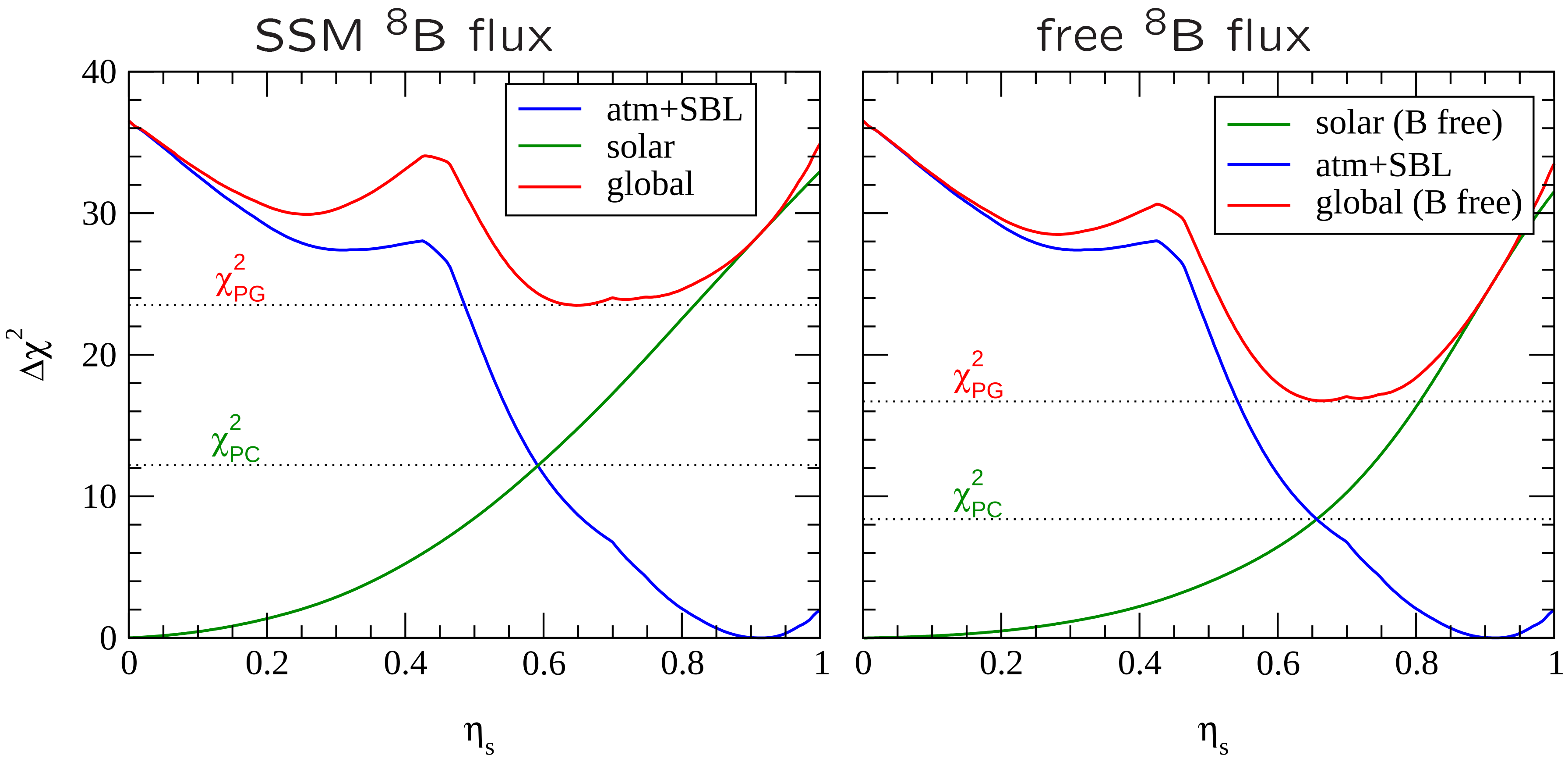
$\chi^2_{\text{LSND}} + \chi^2_{\text{atm}} = 226$ 198 dof GOF: 8%

$\chi^2_{\text{sol}} + \chi^2_{\text{LSND}} + \chi^2_{\text{atm}} = 291$ 276 dof GOF: 26%

$\chi^2_{\text{CHOOZ}} + \chi^2_{\text{sol}} + \chi^2_{\text{LSND}} + \chi^2_{\text{atm}} = 296$ 290 dof GOF: 39%

$\chi^2_{\text{Bugey}} + \chi^2_{\text{CHOOZ}} + \chi^2_{\text{sol}} + \chi^2_{\text{LSND}} + \chi^2_{\text{atm}} = 344$ 350 dof GOF: 58%

(2+2): ruled out by solar and atmospheric



$\chi^2_{PC} = 12.2$ (99.95% CL) B free: $\chi^2_{PC} = 8.4$ (99.6% CL)

$\chi^2_{PG} = 23.5$ (PG 1.3×10^{-6}) B free: $\chi^2_{PG} = 16.7$ (PG 4.4×10^{-5})

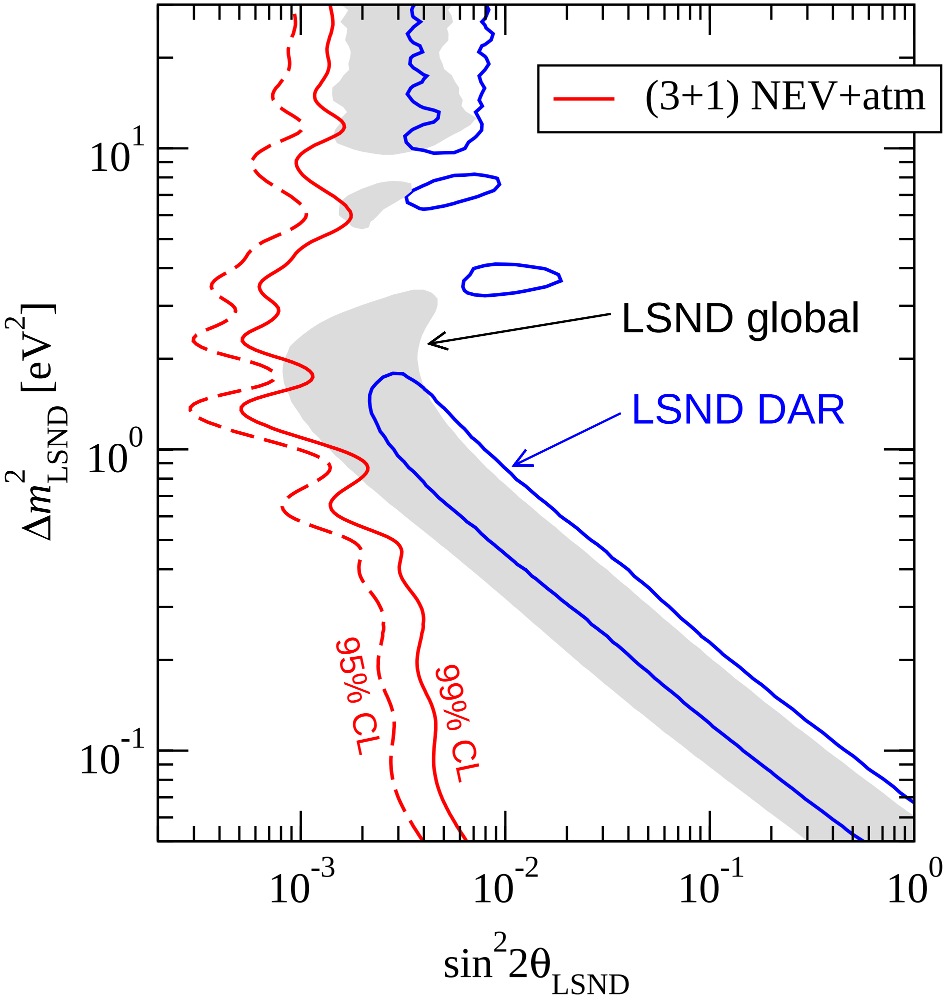
SBL data

- LSND:
  - LSND global: LSND Coll., A. Aguilar *et al.*, PRD 64 (2001) 112007
    20 MeV $< E_e <$ 200 MeV, DAR $(\bar{\nu}_\mu \to \bar{\nu}_e)$ + DIF $(\nu_\mu \to \nu_e)$
  - LSND DAR: E.D. Church *et al.*, PRD 66 (2002) 013001
    20 MeV $< E_e <$ 60 MeV, $R_\gamma > 10^{-5}$, DAR $(\bar{\nu}_\mu \to \bar{\nu}_e)$

- NEV:
  - disappearance: W. Grimus, T.S., Eur. Phys. J. C 20 (2001) 1
    Bugey, CHOOZ $(\bar{\nu}_e)$, CDHS (ν_μ)
  - KARMEN: KARMEN Coll., B. Armbruster *et al.*, PRD 65 (2002) 112001
    $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance

(3+1): strongly disfavoured by SBL data

M. Maltoni, T.S., J.W.F. Valle, PLB 518 (2001) 252



$$\sin^2 2\theta_{\mathrm{LSND}} = 4\, d_e\, d_\mu$$

Bilenky, Giunti, Grimus, 96, 98

Okada, Yasuda, 1997

Barger *et al.*, 1998, 2000

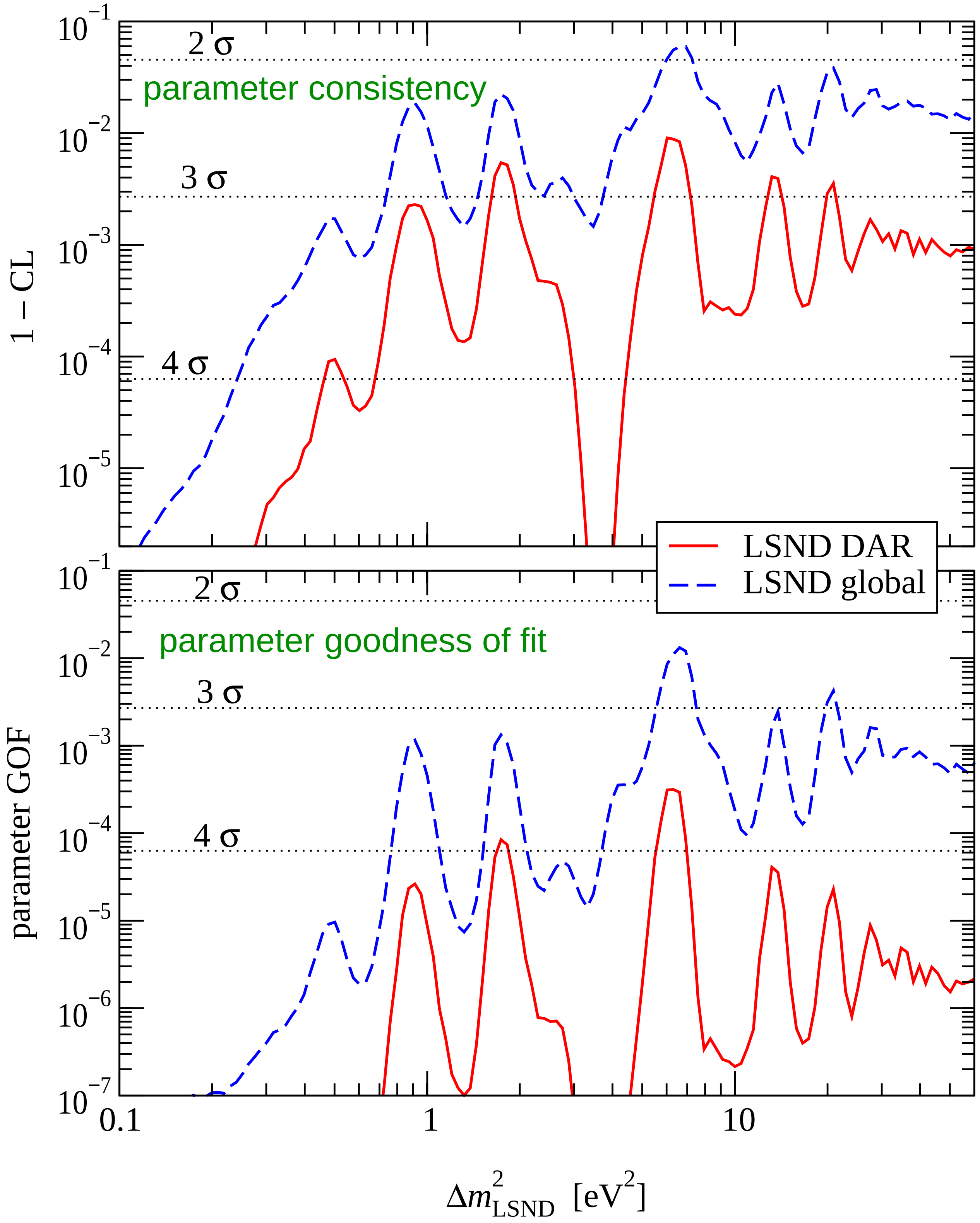
Bilenky, Giunti, Grimus, T.S., 99

Giunti, Laveder, 2001

Peres, Smirnov, 2001

Grimus, T.S., 2001

LSND vs sol+atm+NEV data
in (3+1) schemes



Global analysis

$$\bar{\chi}^2(\eta_s, d_\mu, \theta_{\mathsf{LSND}}, \Delta m^2_{\mathsf{LSND}}) = \Delta\chi^2_{\mathsf{sol}} + \Delta\chi^2_{\mathsf{atm}} + \Delta\chi^2_{\mathsf{NEV}} + \Delta\chi^2_{\mathsf{LSND}}$$

number of dof: $3_{\mathsf{sol}} + 4_{\mathsf{atm}} + 4_{\mathsf{NEV}} + 2_{\mathsf{LSND}} - 9_{\mathsf{total}} = 4$

	LSND global			LSND DAR		
	(3+1)	(2+2)	$(2+2)_{\mathsf{Bfr}}$	(3+1)	(2+2)	$(2+2)_{\mathsf{Bfr}}$
SOL	0.0	14.8	8.7	0.0	14.8	8.7
ATM	0.4	6.7	8.0	0.2	6.7	8.0
NEV	7.0	9.7	9.7	17.1	12.2	12.2
LSND	7.2	1.2	1.2	6.8	1.9	1.9
χ^2_{PG}	14.6	32.4	27.6	24.1	35.6	30.8
PG	5.6×10^{-3}	1.6×10^{-6}	1.5×10^{-5}	7.6×10^{-5}	3.5×10^{-7}	3.4×10^{-6}

relative comparison of (3+1), (2+2) and (3+0)

$$\chi^2_{(2+2)} - \chi^2_{(3+1)} = \begin{cases} 17.8 & (99.87\%\ \mathrm{CL}/4\ \mathrm{dof}) \quad \text{LSND global} \\ 11.5 & (97.9\%\ \mathrm{CL}/4\ \mathrm{dof}) \quad \text{LSND DAR} \end{cases}$$

$$\chi^2_{(2+2)_{\mathrm{Bfr}}} - \chi^2_{(3+1)} = \begin{cases} 12.0 & (98.3\%\ \mathrm{CL}/4\ \mathrm{dof}) \quad \text{LSND global} \\ 6.7 & (84.7\%\ \mathrm{CL}/4\ \mathrm{dof}) \quad \text{LSND DAR} \end{cases}$$

$$\chi^2_{(3+0)} - \chi^2_{(3+1)} = \begin{cases} 20.0 & (99.95\%\ \mathrm{CL}/4\ \mathrm{dof}) \quad \text{LSND global} \\ 28.5 & (99.999\%\ \mathrm{CL}/4\ \mathrm{dof}) \quad \text{LSND DAR} \end{cases}$$

Can four neutrinos explain global oscillation data including LSND?

- careful answer:

  Not very well.

- stronger statement:

  No! Ruled out at the 99.4% CL!

  PG of 0.6% for (3+1) and LSND global data

Outlook

- MiniBooNE will check LSND E.D.Zimmerman, hep-ex/0211039
  started data taking Aug. 2002, results maybe this year

- (2+2) schemes are ruled out by solar and atmospheric data, independently of LSND

- if LSND should be confirmed we need more data on
  SBL ν_e/ν_μ disappearance to decide about (3+1)

- alternative explanations
  - CPT violation – disfavoured by KamLAND
    however: Barenboim et al., hep-ph/0213116
  - explain LSND by anomalous muon decay (KARMEN ?)
    Babu, Pakvasa, hep-ph/0204236