

# 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

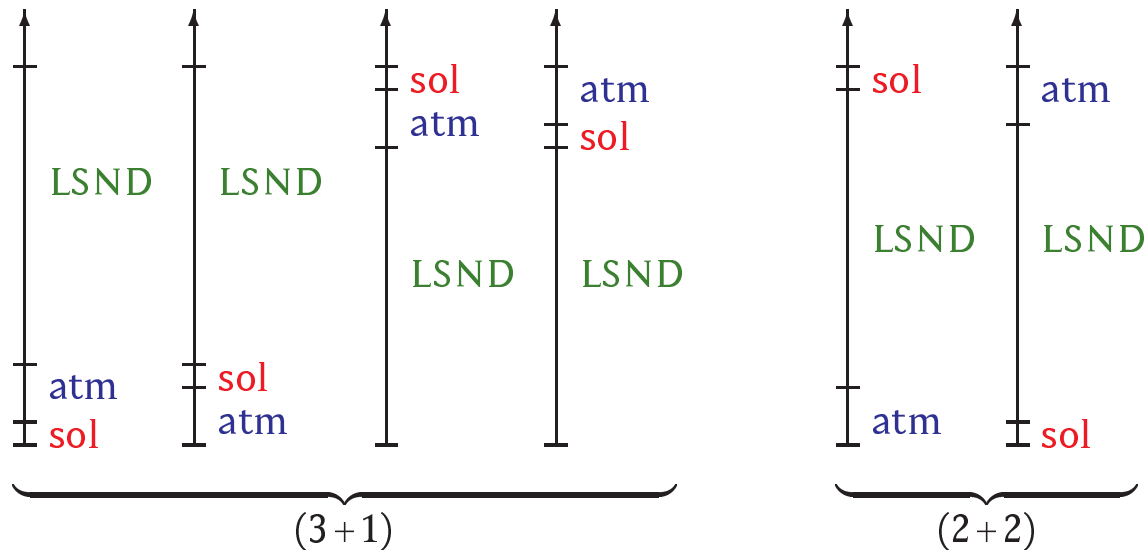
## Outline

- Introduction
- 4-neutrino oscillation parameters
- Analysis of solar and atmospheric neutrino data
- Statistical methods
- $(2+2)$  schemes: ruled out by solar and atmospheric 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:  $\nu_e \rightarrow \nu_\mu, \nu_\tau$   $\Delta m_{\text{sol}}^2 \lesssim 10^{-4} \text{ eV}^2$
- atmospheric neutrinos:  $\nu_\mu \rightarrow \nu_\tau$   $\Delta m_{\text{atm}}^2 \sim 3 \times 10^{-3} \text{ eV}^2$
- LSND:  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$   $\Delta m_{\text{LSND}}^2 \sim 1 \text{ eV}^2$

not possible with 3 neutrinos  $\rightarrow$  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 → 9 parameters

we define:

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

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

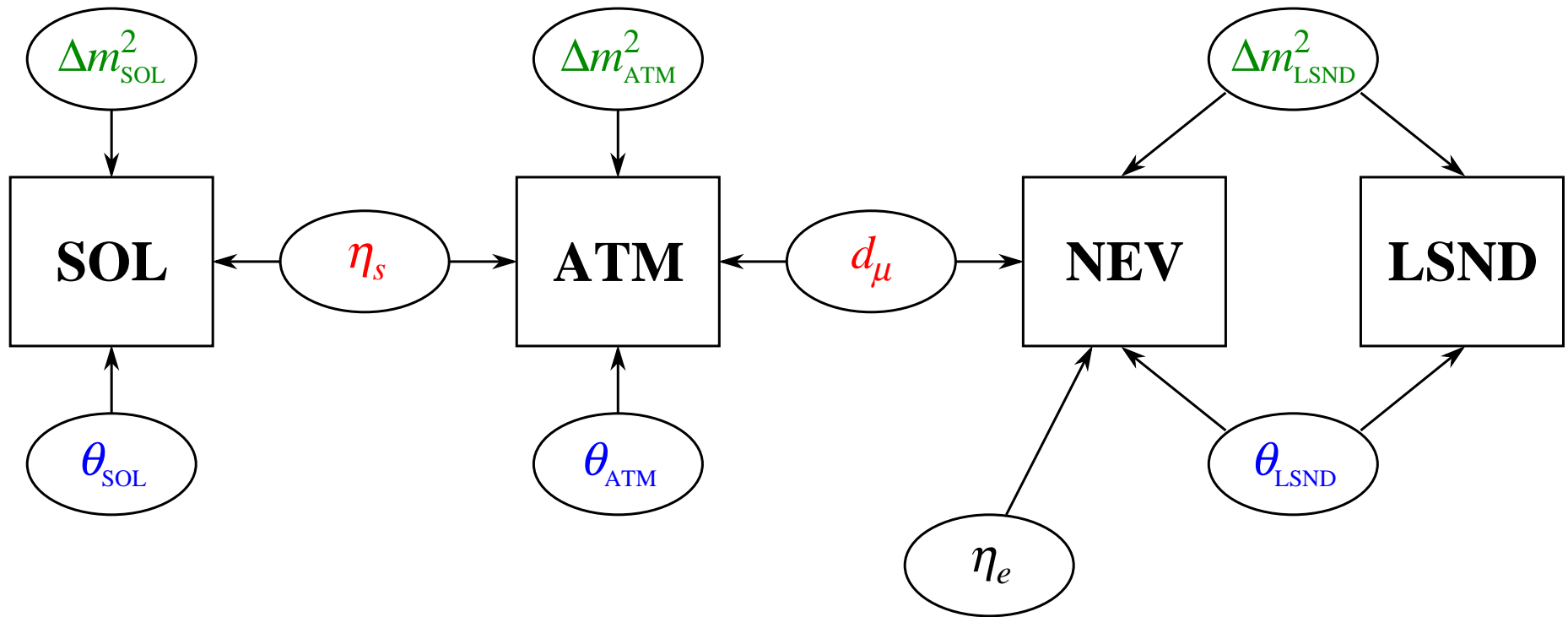
note that in (2+2):  $\eta_\alpha = d_\alpha$

$$\rightarrow \Delta m_{\text{sol}}^2, \Delta m_{\text{atm}}^2, \Delta m_{\text{LSND}}^2, \theta_{\text{sol}}, \theta_{\text{atm}}, \theta_{\text{LSND}}, \eta_s, \eta_e, d_\mu$$

approximations:

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

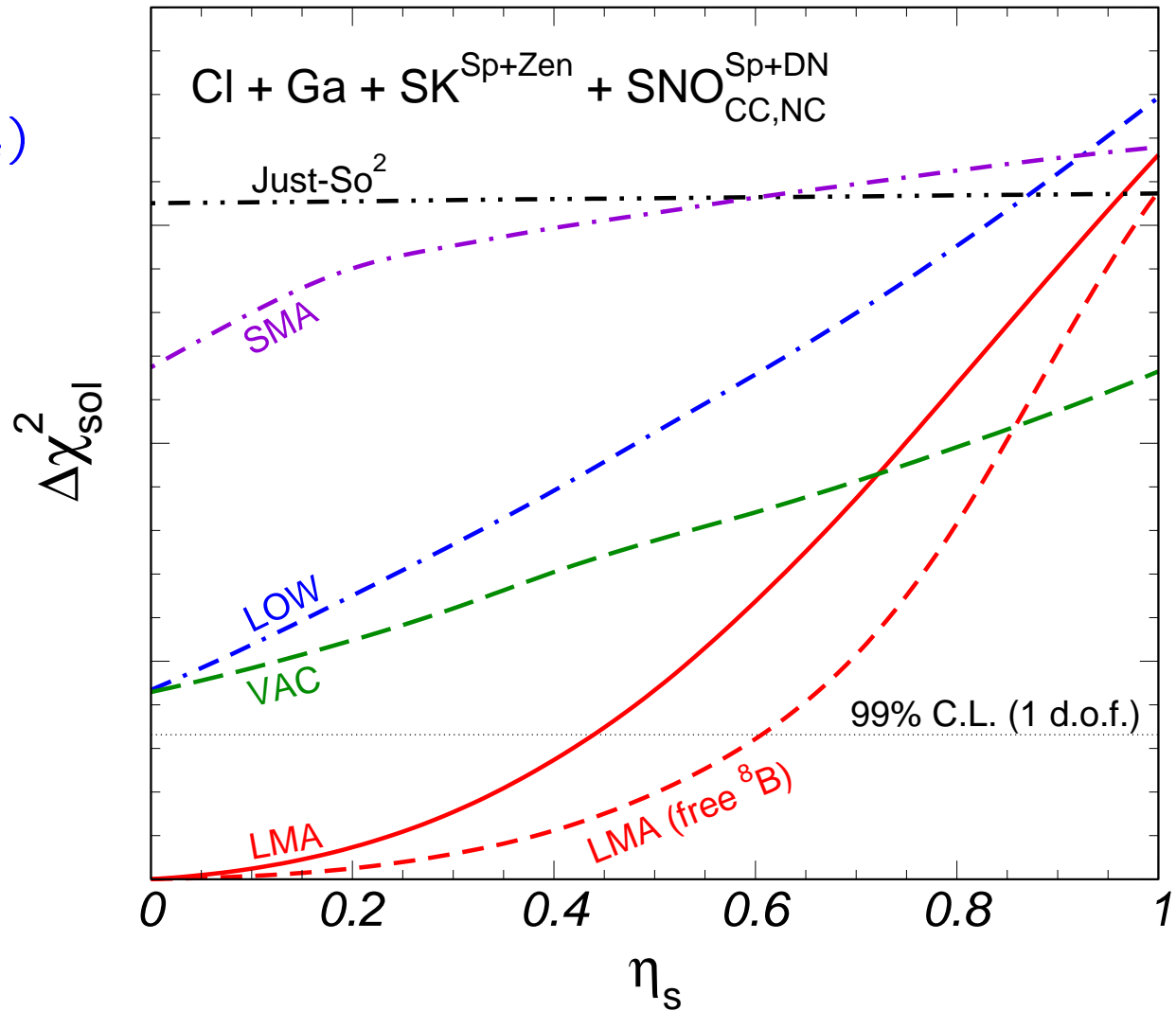
Coupling of the data sets:

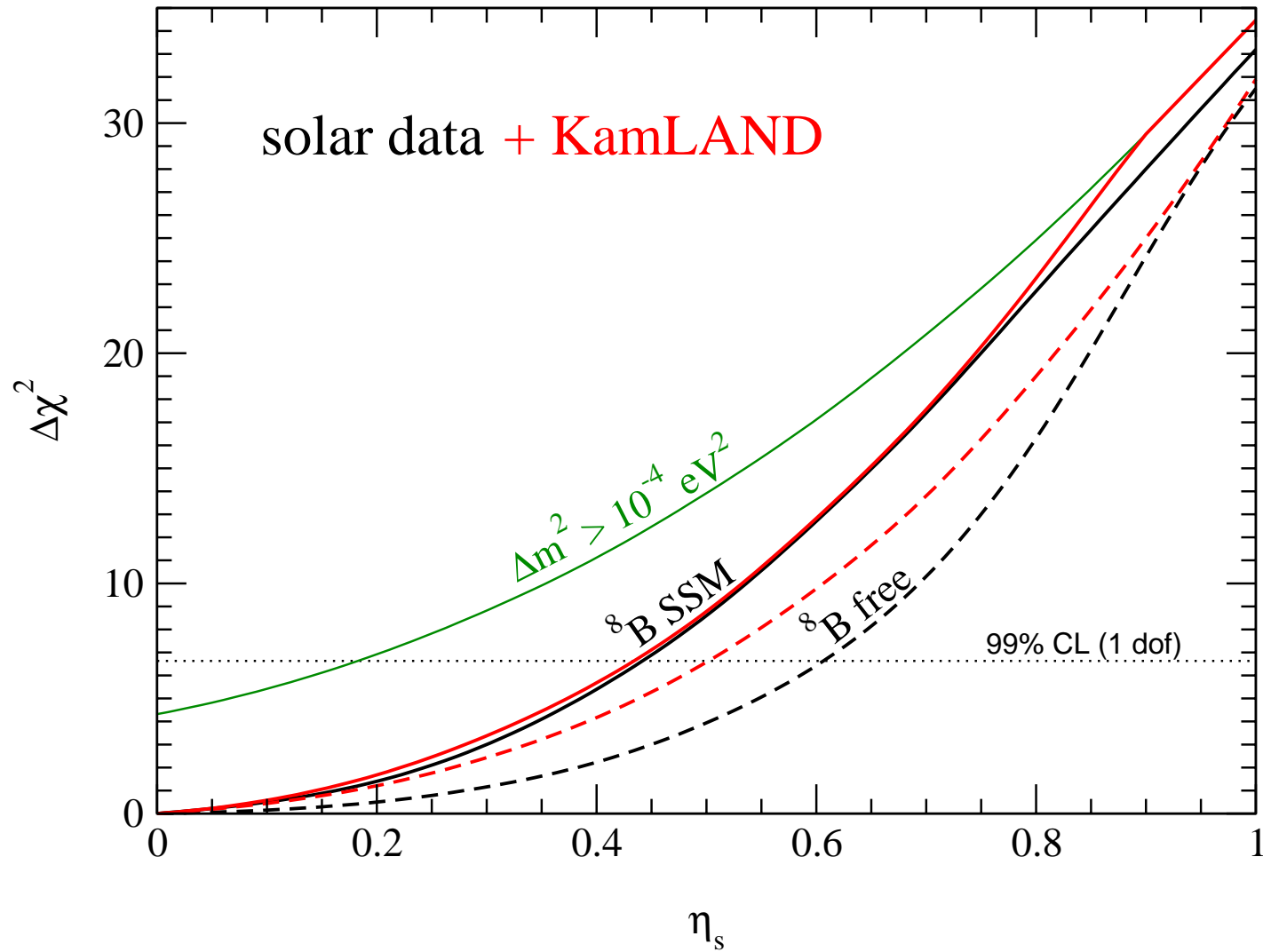


# Solar data

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

$$\chi_{\text{sol}}^2(\Delta m_{\text{sol}}^2, \theta_{\text{sol}}, \eta_s)$$





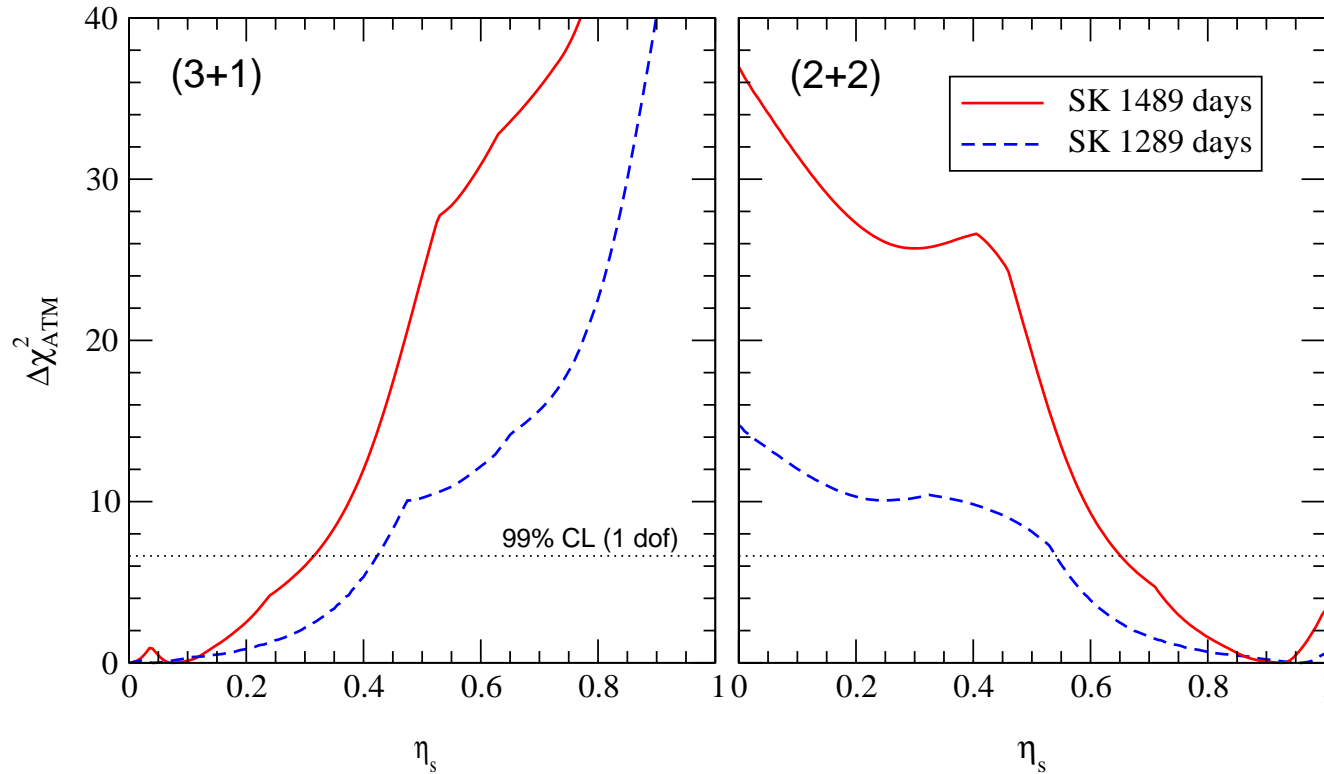
99% CL :

$^8\text{B SSM}$ :	$\eta_s \leq 0.44$	(unchanged)
$^8\text{B free}$ :	$\eta_s \leq \begin{cases} 0.5 & \text{(solar + KamLAND)} \\ 0.61 & \text{(solar only)} \end{cases}$	

# atmospheric data:

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

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



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

SK analysis:

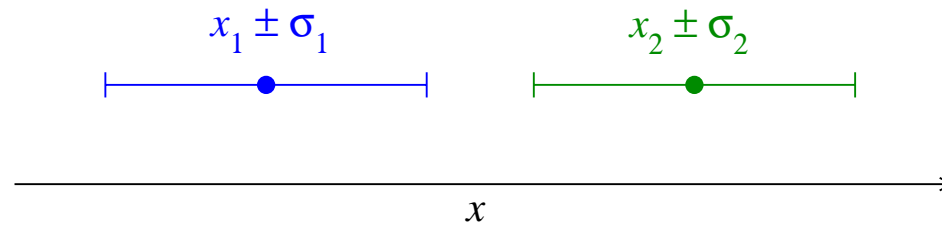
Shiozawa, Neutrino 02

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

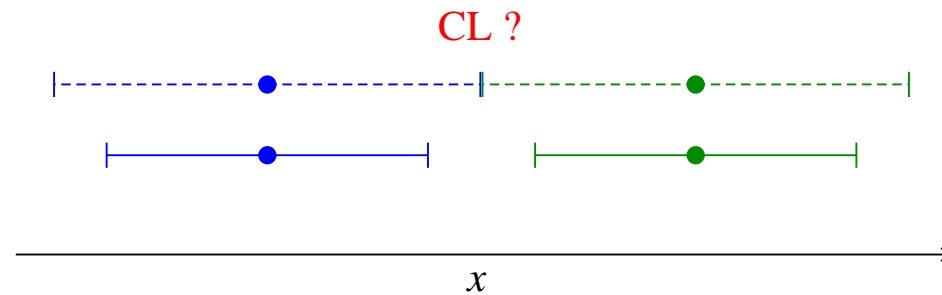
$$\text{atmospheric: } \begin{cases} \eta_s \leq 0.32 & \text{for (3+1)} \\ \eta_s \geq 0.65 & \text{for (2+2)} \end{cases}$$

$$\text{solar: } \eta_s \leq 0.44$$

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



- **Parameter consistency (PC)**



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

## The parameter goodness-of-fit

$K$  data sets:  $\chi_k^2(x^k) = (\chi_k^2)_{\min} + \Delta\chi_k^2(x^k)$ ,  $k = 1 \dots K$

global  $\chi^2$ :  $\chi_{\text{tot}}^2(x) = \sum_{k=1}^K (\chi_k^2)_{\min} + \sum_{k=1}^K \Delta\chi_k^2(x^k)$

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

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

not very usefull for large  $N$

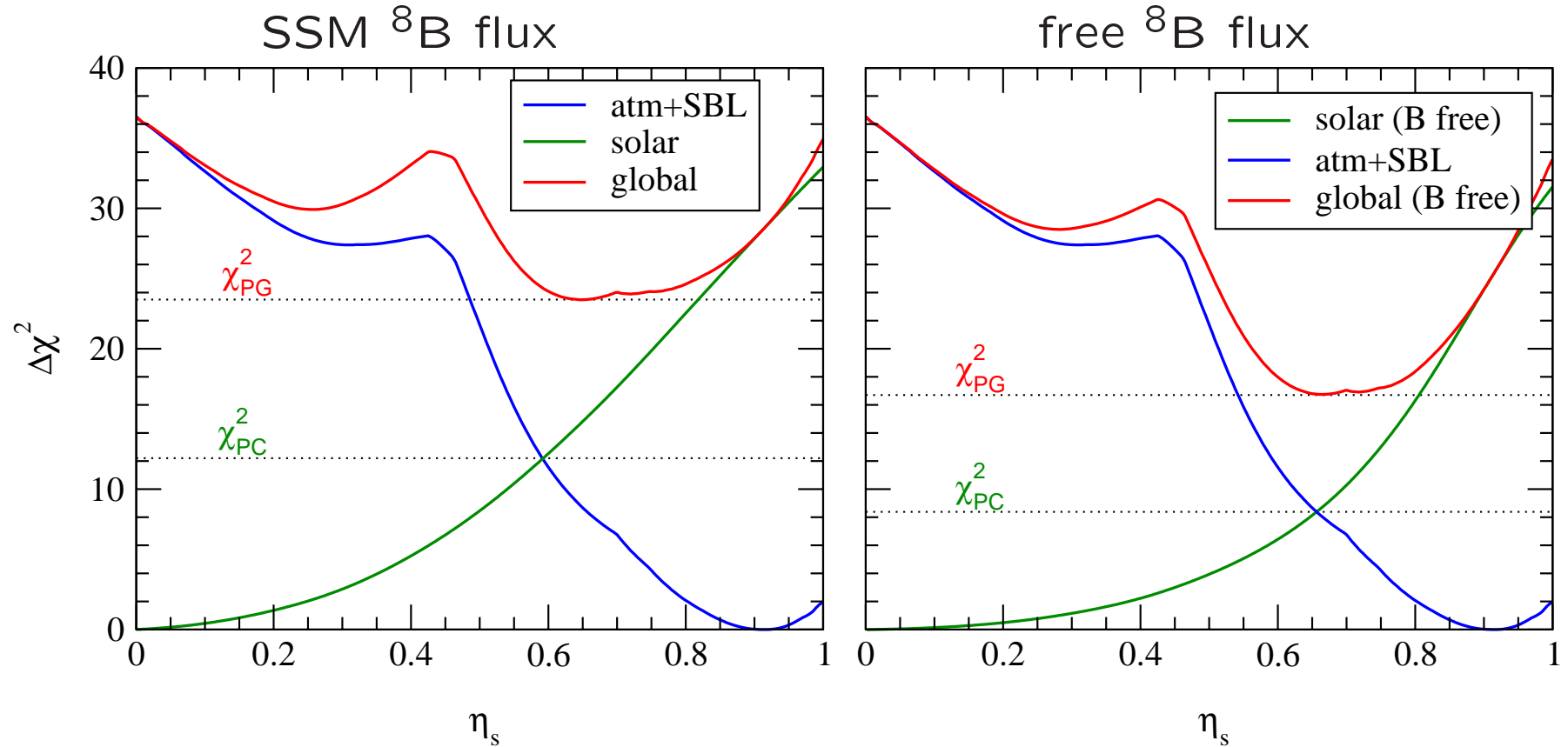
→ we use only  $\bar{\chi}_{\min}^2$ :  $\chi_{\text{PG}}^2 \equiv \bar{\chi}_{\min}^2$  for  $\sum_{k=1}^K P_k - P$  dof

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

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

$\chi_{\text{atm}}^2 = 222$	190 dof	GOF: 5%
$\chi_{\text{LSND}}^2 + \chi_{\text{atm}}^2 = 226$	198 dof	GOF: 8%
$\chi_{\text{sol}}^2 + \chi_{\text{LSND}}^2 + \chi_{\text{atm}}^2 = 291$	276 dof	GOF: 26%
$\chi_{\text{CHOOZ}}^2 + \chi_{\text{sol}}^2 + \chi_{\text{LSND}}^2 + \chi_{\text{atm}}^2 = 296$	290 dof	GOF: 39%
$\chi_{\text{Bugey}}^2 + \chi_{\text{CHOOZ}}^2 + \chi_{\text{sol}}^2 + \chi_{\text{LSND}}^2 + \chi_{\text{atm}}^2 = 344$	350 dof	GOF: 58%

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



$\chi_{PC}^2 = 12.2$  (99.95% CL)

B free:  $\chi_{PC}^2 = 8.4$  (99.6% CL)

$\chi_{PG}^2 = 23.5$  (PG  $1.3 \times 10^{-6}$ )

B free:  $\chi_{PG}^2 = 16.7$  (PG  $4.4 \times 10^{-5}$ )

## SBL data

- LSND:

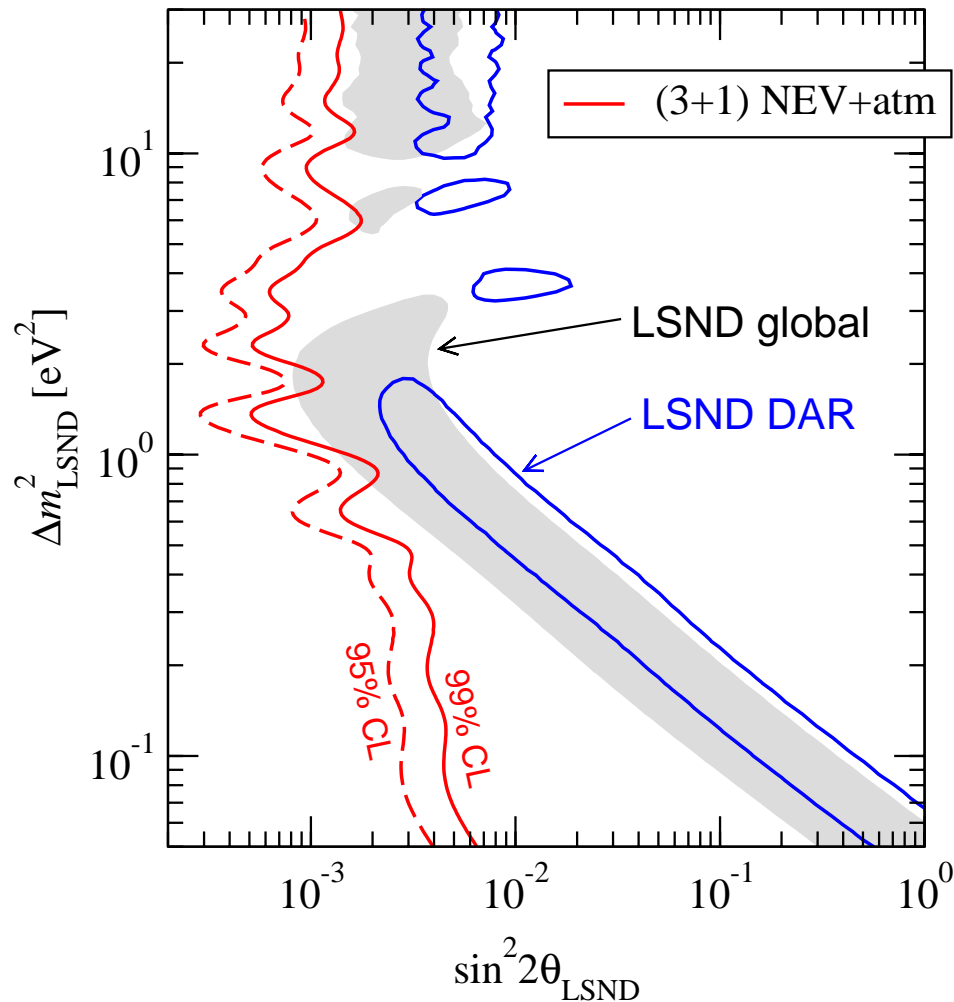
- LSND global: LSND Coll., A. Aguilar *et al.*, PRD 64 (2001) 112007  
20 MeV <  $E_e$  < 200 MeV, DAR ( $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ ) + DIF ( $\nu_\mu \rightarrow \nu_e$ )
- LSND DAR: E.D. Church *et al.*, PRD 66 (2002) 013001  
20 MeV <  $E_e$  < 60 MeV,  $R_\gamma > 10^{-5}$ , DAR ( $\bar{\nu}_\mu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

- NEV:

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

**(3+1): strongly disfavoured by SBL data**

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



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

Bilenky, Giunti, Grimus, 96, 98

Okada, Yasuda, 1997

Barger *et al.*, 1998, 2000

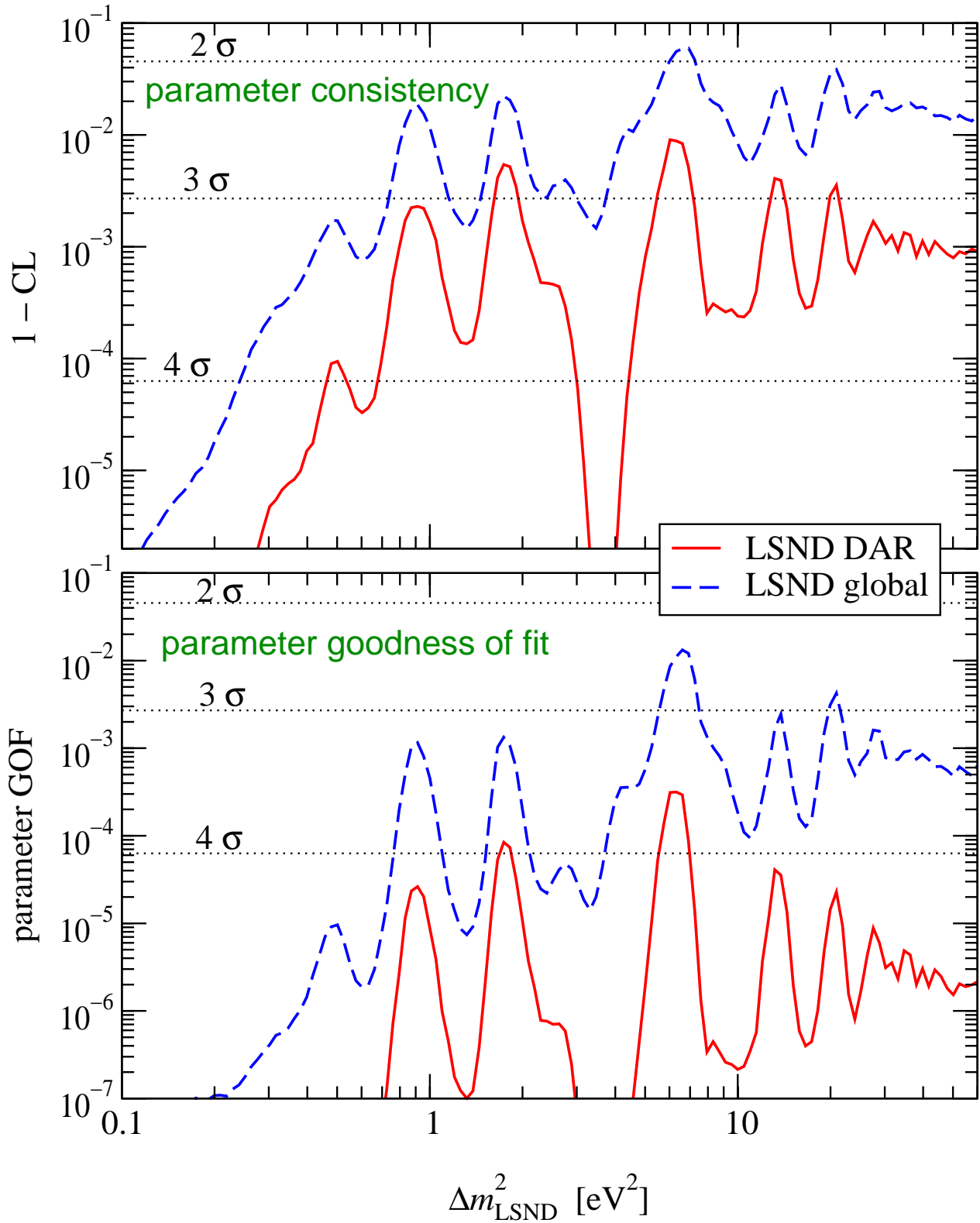
Bilenky, Giunti, Grimus, T.S., 99

Giunti, Laveder, 2001

Peres, Smirnov, 2001

Grimus, T.S., 2001

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



## Global analysis

$$\bar{\chi}^2(\eta_s, d_\mu, \theta_{\text{LSND}}, \Delta m_{\text{LSND}}^2) = \Delta\chi_{\text{sol}}^2 + \Delta\chi_{\text{atm}}^2 + \Delta\chi_{\text{NEV}}^2 + \Delta\chi_{\text{LSND}}^2$$

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

	LSND global			LSND DAR		
	(3+1)	(2+2)	(2+2) <sub>Bfr</sub>	(3+1)	(2+2)	(2+2) <sub>Bfr</sub>
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
$\chi_{\text{PG}}^2$	14.6	32.4	27.6	24.1	35.6	30.8
PG	$5.6 \times 10^{-3}$	$1.6 \times 10^{-6}$	$1.5 \times 10^{-5}$	$7.6 \times 10^{-5}$	$3.5 \times 10^{-7}$	$3.4 \times 10^{-6}$

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

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

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

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

# 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  $\nu_e/\nu_\mu$  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