Unified Analysis of Solar and Atmospheric Neutrino Data

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OUTLINE

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3. Four-neutrino oscillations
   - *Active vs sterile in solar and atmospheric experiments*
   - *Combined analysis of solar and atmospheric ν*
4. Conclusions

Based on

⇒ M.C. Gonzalez-Garcia, M.M., C. Peña-Garay, J.W.F. Valle, *Global three-neutrino oscillation analysis of neutrino data, Phys. Rev.* **D63** (2001) 033005, *hep-ph/0009350.*

⇒ M.C. Gonzalez-Garcia, M.M, C. Peña-Garay, *Solar and Atmospheric Four–Neutrino Oscillations, hep-ph/0105269* (to appear in PRD).

Three–neutrino oscillation parameters

- Equation of motion: 5 parameters (neglecting CP violating effects):

$$i\frac{d\vec{\nu}}{dt} = \mathbf{H}\,\vec{\nu}; \qquad \mathbf{H} = \mathbf{O}\cdot\mathbf{H}_0^d\cdot\mathbf{O}^\dagger + \mathbf{V};$$

$$\mathbf{O} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23} & c_{12}c_{23} - s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23} & -c_{12}s_{23} - s_{12}s_{13}c_{23} & c_{13}c_{23} \end{pmatrix}, \qquad \vec{\nu} = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix};$$

$$\mathbf{H}_0^d = \frac{1}{2E_\nu}\mathbf{diag}\left(-\Delta m^2_{21}, 0, \Delta m^2_{32}\right);$$

$$\mathbf{V} = \mathbf{diag}\left(\pm\sqrt{2}G_F N_e, 0, 0\right);$$

- from <u>solar</u> ν data: $\Delta m^2_{21} \ll \Delta m^2_{32}$.

Atmospheric case

- Simplifying assumption: $\Delta m^2_{21} \approx 0 \Rightarrow$ get rid also of θ_{12}:

$$\mathbf{O} = \begin{pmatrix} c_{13} & 0 & s_{13} \\ -s_{13}s_{23} & c_{23} & c_{13}s_{23} \\ -s_{13}c_{23} & -s_{23} & c_{13}c_{23} \end{pmatrix}, \qquad \mathbf{H}_0^d = \frac{1}{2E_\nu}\mathbf{diag}\left(0, 0, \Delta m^2_{32}\right);$$

$\Rightarrow$ only 3 parameters left.

Solar case

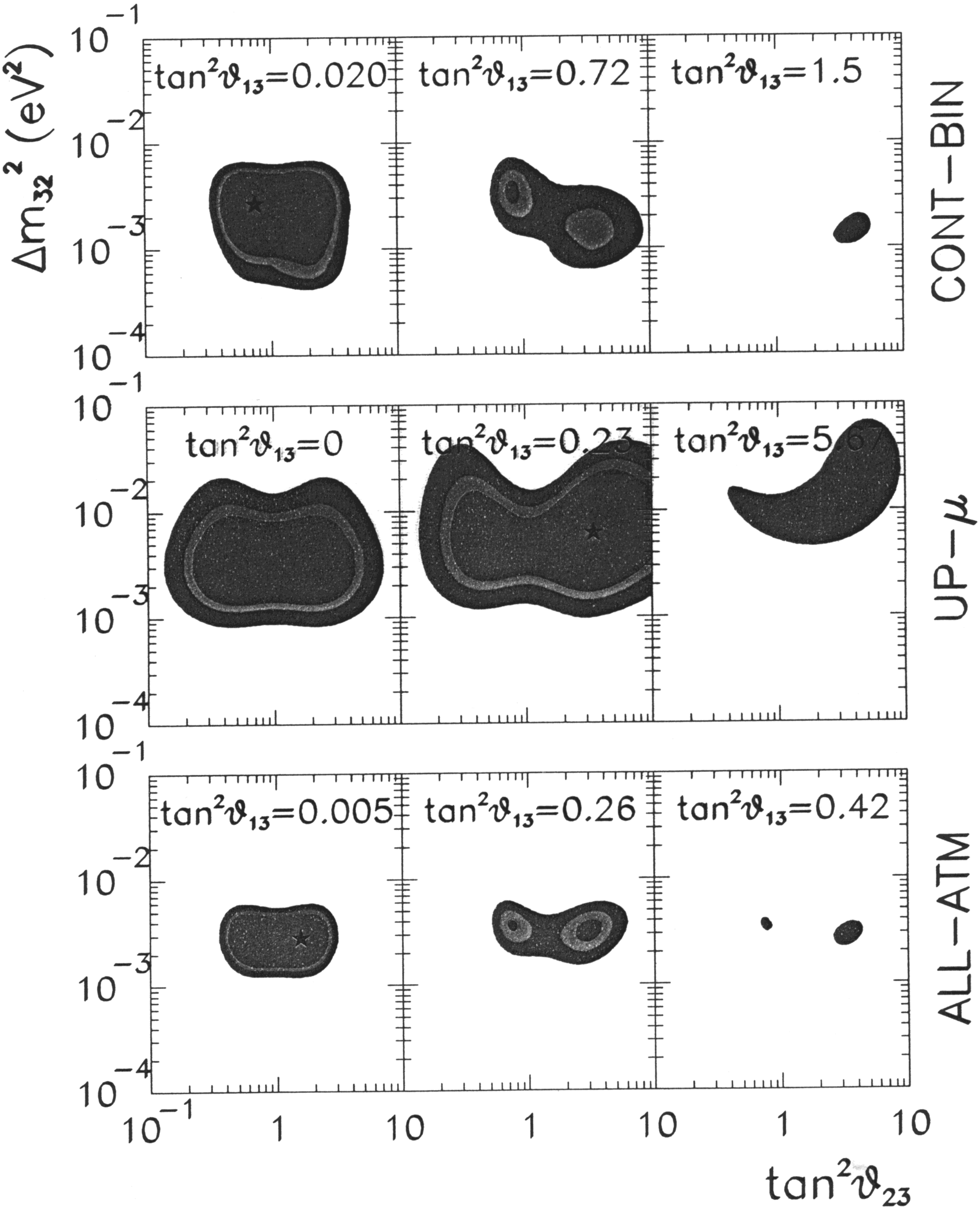
- Simplifying assumption: $\Delta m^2_{32} \approx \infty$;
- moreover, θ_{23} cancels out from P_{ee}:

$$\mathbf{O} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12} & c_{12} & 0 \\ -c_{12}s_{13} & -s_{12}s_{13} & c_{13} \end{pmatrix}, \qquad \mathbf{H}_0^d = \frac{1}{2E_\nu}\mathbf{diag}\left(-\Delta m^2_{21}, 0, \infty\right);$$

$\Rightarrow$ again, only 3 parameters left.

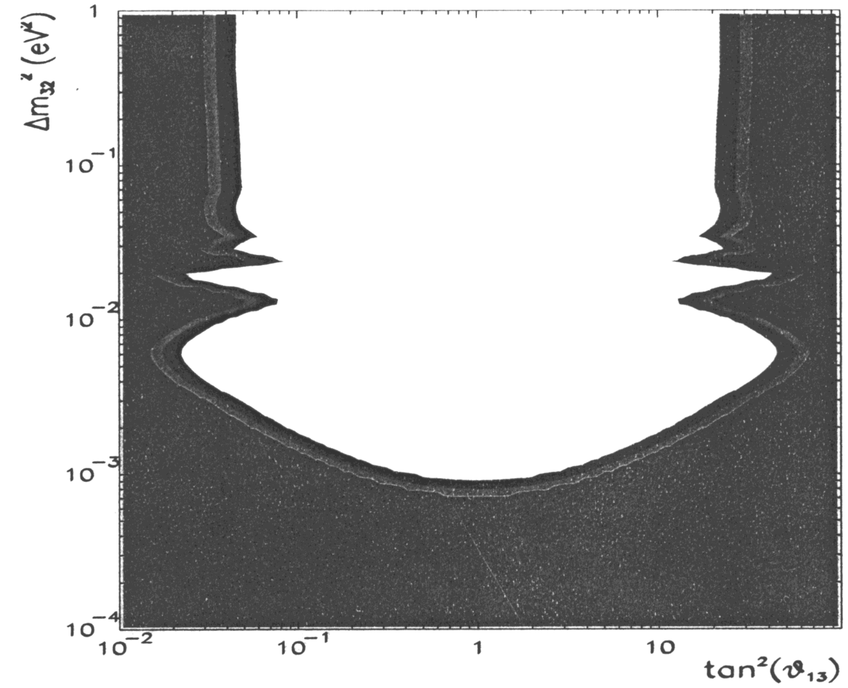
Contained and Upgoing events

Bound	Contained	Upgoing-μ	Combined
Δm^2_{32}, upper	strong	weak	strong
Δm^2_{32}, lower	weak	strong	strong
$\tan^2\theta_{13}$	mild	weak	strong

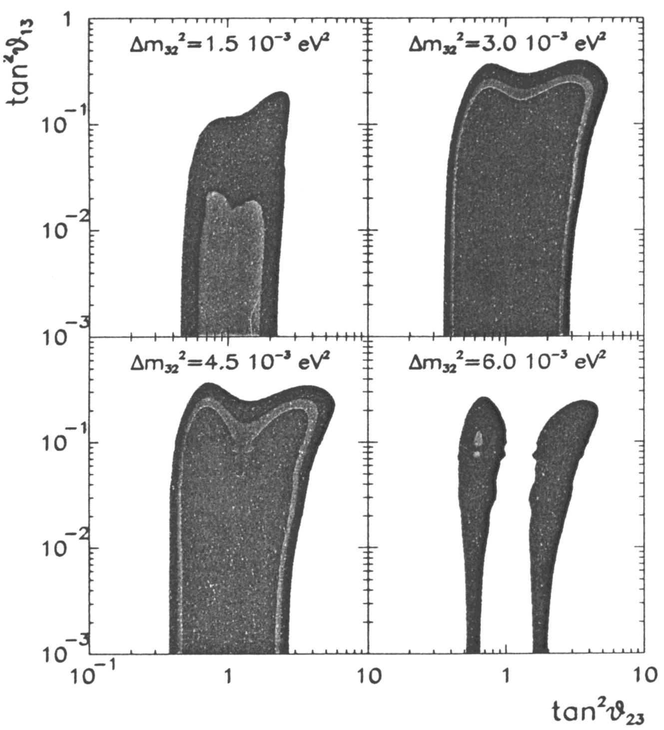


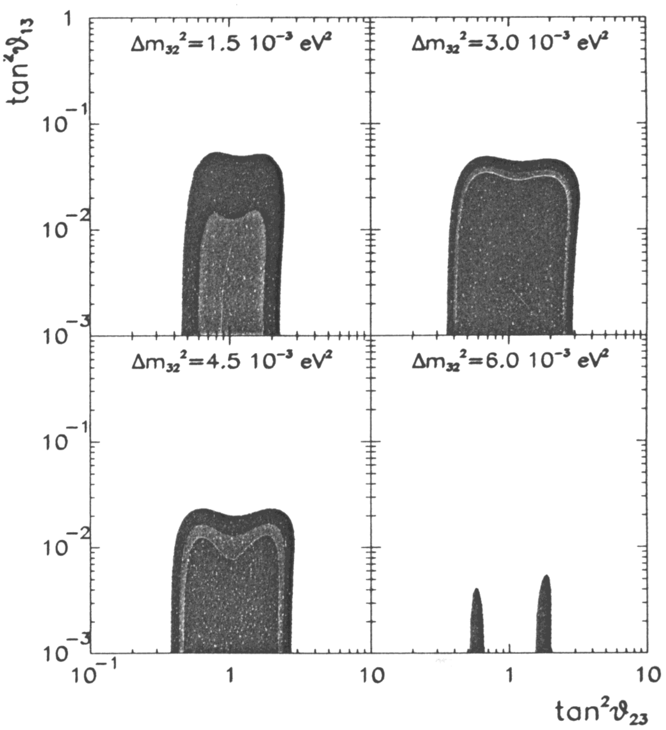
The CHOOZ experiment

- Bound from *non-observation* of $\bar{\nu}_e$ disappearance;
- from solar data: $\Delta m^2_{21} \ll 10^{-3}\ \mathrm{eV}^2 \Rightarrow$ **NO bound** on $\tan^2\theta_{23}$;
- Excluded region: $\Delta m^2_{32} \gtrsim 10^{-3}\ \mathrm{eV}^2$, $0.03 \lesssim \tan^2\theta_{13} \lesssim 30$.



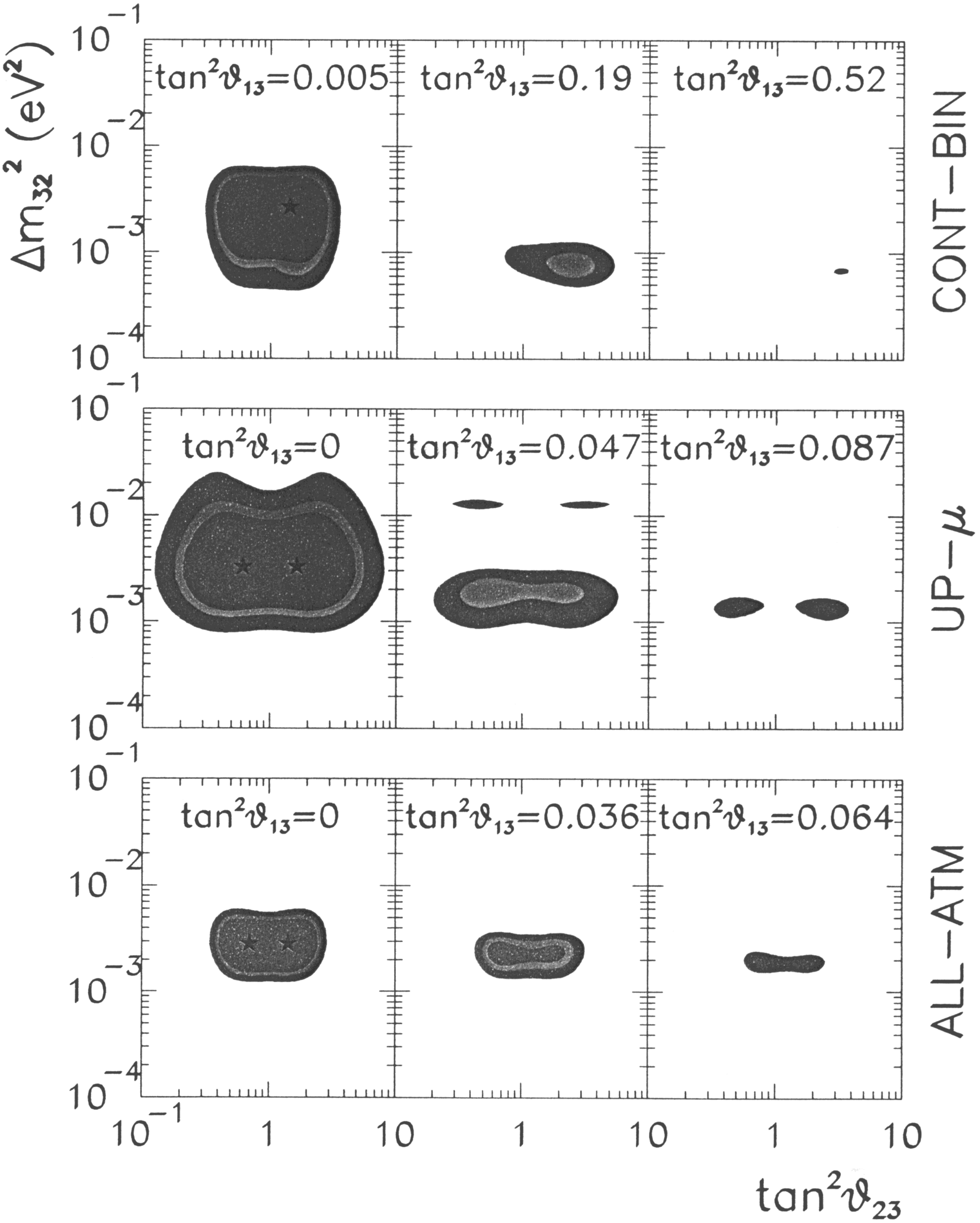
Contour regions in the $(tan^2\theta_{13}, tan^2\theta_{23})$ plane



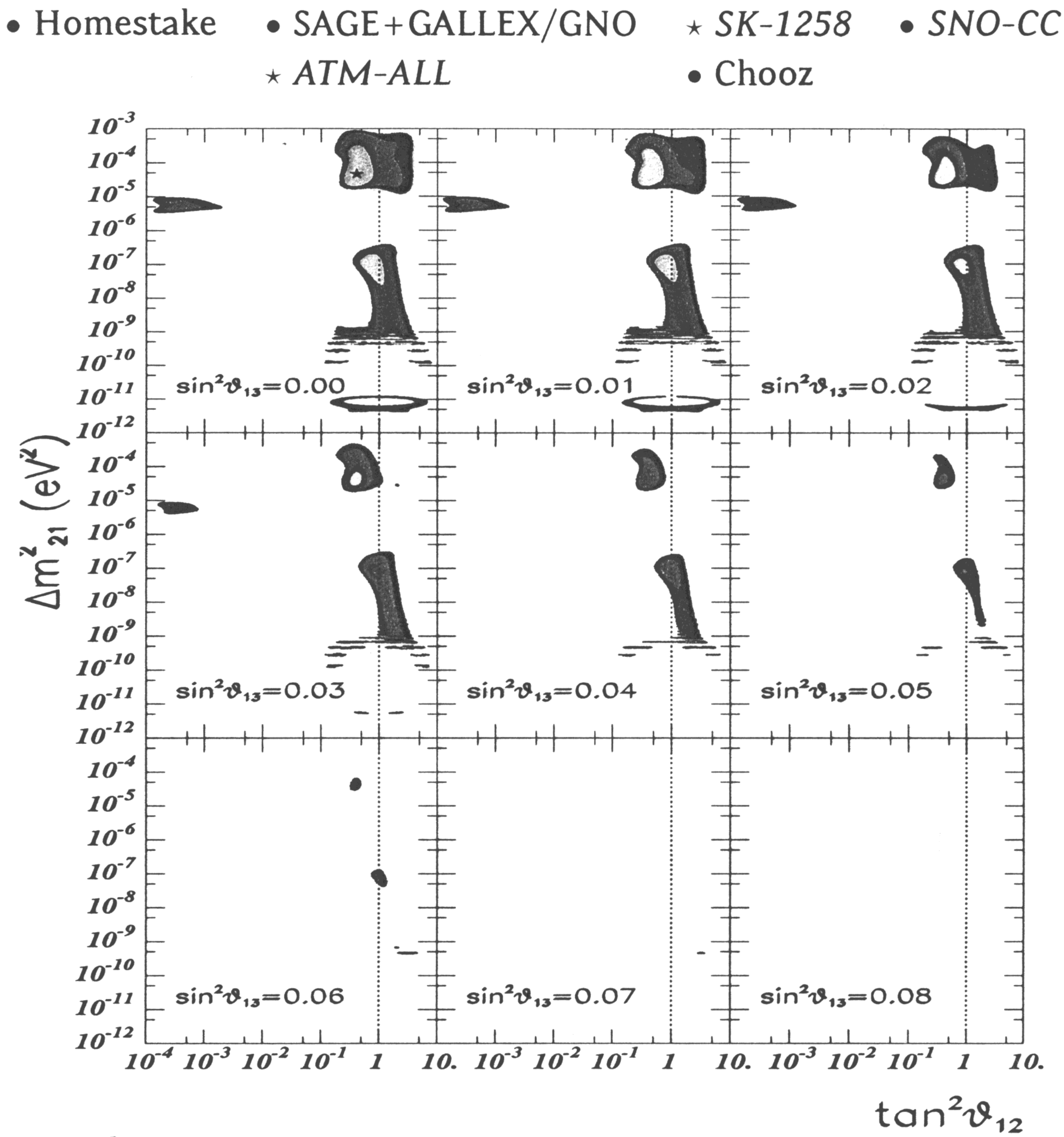


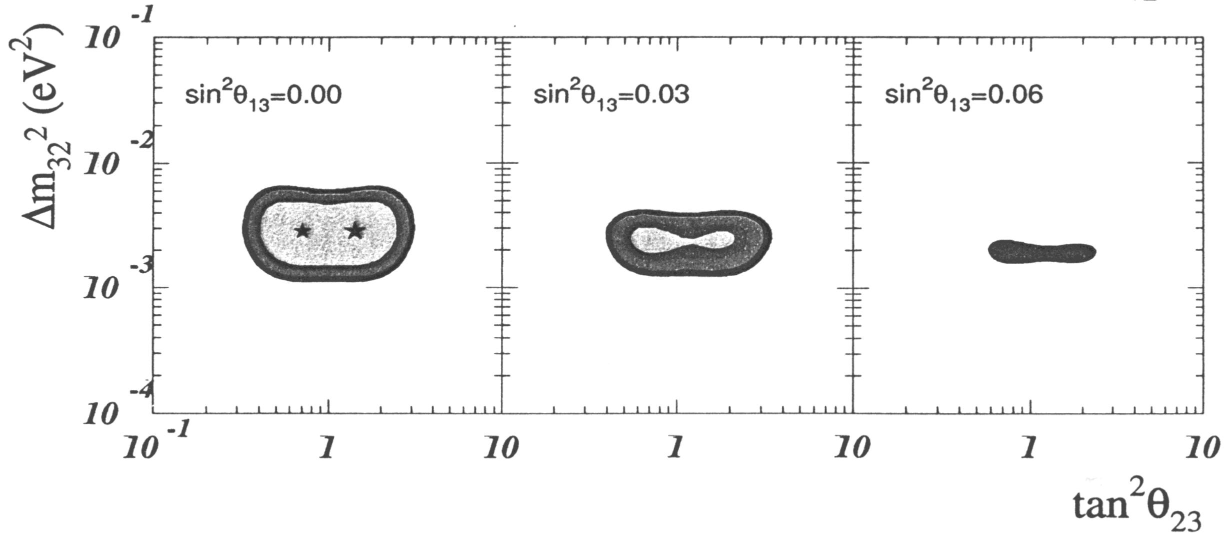
Effect of Chooz on the Atmospheric results

Bound	Contained	Upgoing-μ	Combined
Δm^2_{32}, upper	strong	weak	strong
Δm^2_{32}, lower	weak	strong	strong
$\tan^2\theta_{13}$	mild	very strong	very strong



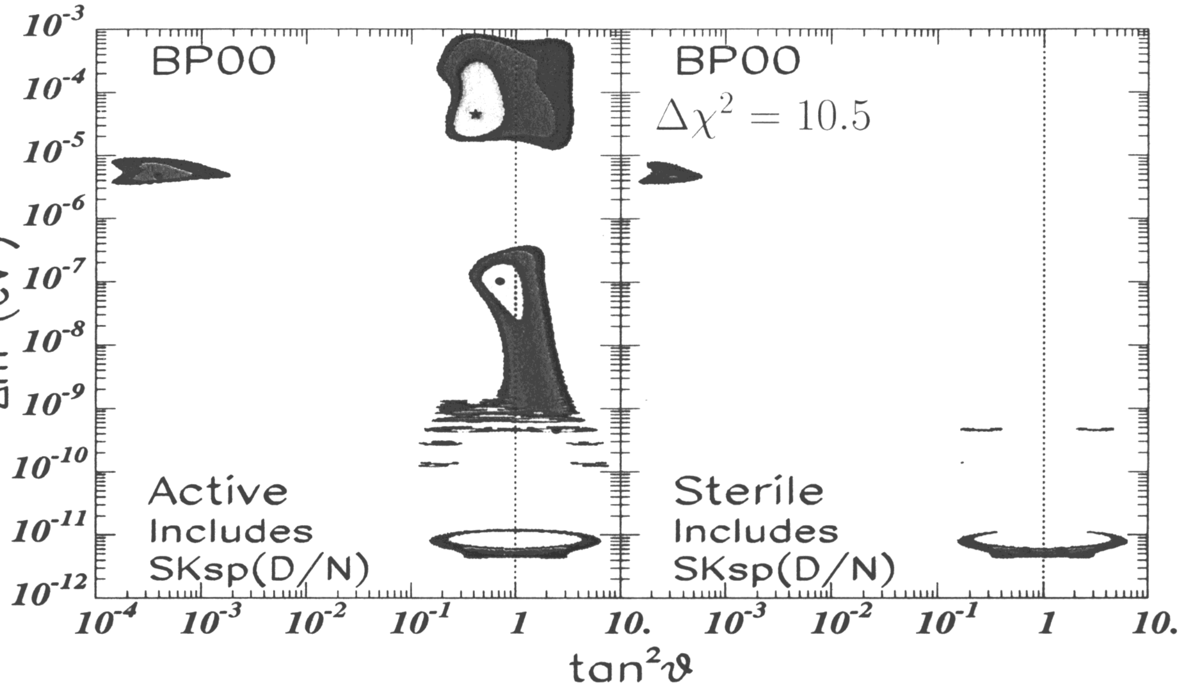
GLOBAL: combined Solar + ATM + Reactor analysis



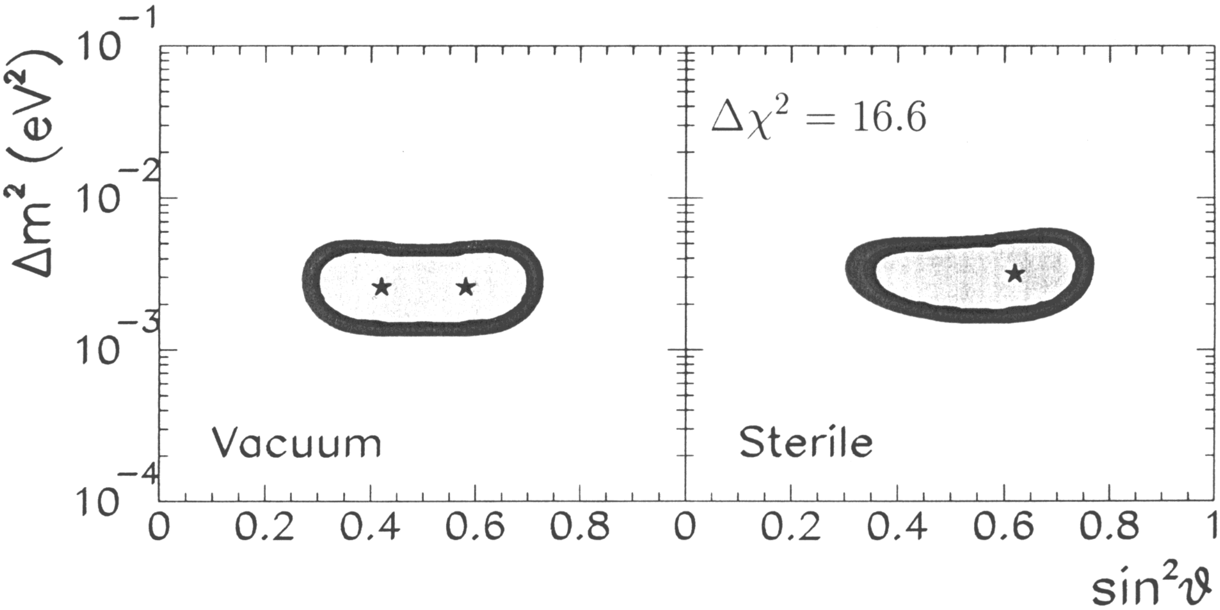


Four neutrino oscillations

- A 4^{th} light ν is needed to reconcile LSND with Solar and ATM results;
- Z width in agreement with SM $\Rightarrow$ new neutrino must be *sterile*;
- however, solar data disfavour ν_e oscillations into a sterile state...



- ...and atmospheric data also disfavour $\nu_\mu \to \nu_s$ oscillations:



- therefore, 2ν analyses of solar and atmospheric data seems incompatible;

$\Rightarrow$ a global and unified 4ν analysis is needed.

Four–neutrino oscillation parameters

- Equation of motion: 9 parameters (neglecting CP violating effects):

$$i\frac{d\vec{\nu}}{dt} = \mathbf{H}\,\vec{\nu}; \qquad \mathbf{H} = \mathbf{O}\cdot\mathbf{H}_0^d\cdot\mathbf{O}^\dagger + \mathbf{V};$$

$$\mathbf{O} = \mathbf{O}_{24}(\theta_{24})\cdot\mathbf{O}_{23}(\theta_{23})\cdot\mathbf{O}_{14}(\theta_{14})\cdot\mathbf{O}_{13}(\theta_{13})\cdot\mathbf{O}_{34}(\theta_{34})\cdot\mathbf{O}_{12}(\theta_{12}); \quad \vec{\nu} = \begin{pmatrix}\nu_e\\ \nu_s\\ \nu_\mu\\ \nu_\tau\end{pmatrix};$$

$$\mathbf{H}_0^d = \frac{1}{2E_\nu}\mathbf{diag}\left(-\Delta m^2_{21}, 0, \Delta m^2_{32}, \Delta m^2_{32} + \Delta m^2_{43}\right);$$

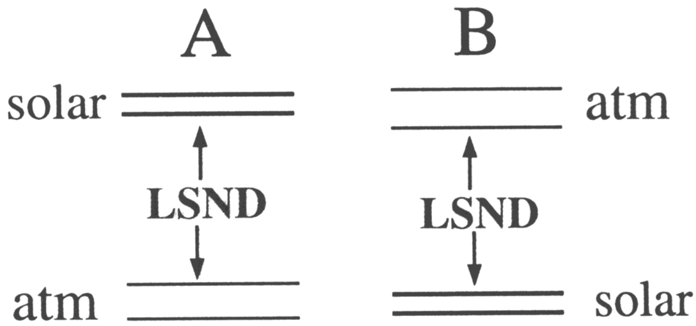
$$\mathbf{V} = \pm\sqrt{2}G_F\,\mathbf{diag}\left(N_e, \frac{1}{2}N_n, 0, 0\right);$$

- **3 + 1** models are now disfavoured. In **2 + 2** models:

$$\Delta m^2_\odot \ll \Delta m^2_{atm} \ll \Delta m^2_{LSND}$$

$$\Downarrow \mathbf{B}$$

$$\Delta m^2_{21} = \Delta m^2_\odot$$
$$\Delta m^2_{32} = \Delta m^2_{LSND}$$
$$\Delta m^2_{43} = \Delta m^2_{atm}$$



- from the result of the **Bugey** experiment:

$$|O_{e3}|^2 + |O_{e4}|^2 = c^2_{14}s^2_{13} + s^2_{14} \lesssim 10^{-2} \quad \Rightarrow \quad \theta_{13} \approx \theta_{14} \approx 0;$$

- simplified form of the O matrix:

$$\mathbf{O} = \begin{pmatrix} c_{12} & s_{12} & 0 & 0 \\ -s_{12}c_{23}c_{24} & c_{12}c_{23}c_{24} & -s_{34}s_{24} + c_{34}s_{23}c_{24} & c_{34}s_{24} + s_{34}s_{23}c_{24} \\ s_{12}s_{23} & -c_{12}s_{23} & c_{34}c_{23} & s_{34}c_{23} \\ s_{12}c_{23}s_{24} & -c_{12}c_{23}s_{24} & -s_{34}c_{24} - c_{34}s_{23}s_{24} & c_{34}c_{24} - s_{34}s_{23}s_{24} \end{pmatrix}.$$

Atmospheric case

- $\Delta m^2_{21} \approx 0$, $\Delta m^2_{32} \approx \infty$;
- θ_{12} cancels out $\Rightarrow \nu_e$ decouples;
- θ_{23} and θ_{24} contribute separately;

$\Rightarrow$ **4** $(= 1_m + 3_\theta)$ parameters left.

Solar case

- $\Delta m^2_{32} \approx \infty$, $\Delta m^2_{43} \approx \infty$;
- θ_{34} does not contribute to P_{ee};
- only $c^2_{23}c^2_{24}$ appears in P_{ee};

$\Rightarrow$ **3** $(= 1_m + 2_\theta)$ parameters left.

SOLAR PARAMETERS

- $\Delta m^2_{\odot}$, ϑ_{12} : RELEVANT MASS-SQUARED DIFF., MIXING ANGLES;
- $c^2_{23} c^2_{24} = |U_{s1}|^2 + |U_{s2}|^2$: ACTIVE-STERILE ADMIXTURE;
- CASES:
  - $c^2_{23} c^2_{24} = 0 \Rightarrow$ PURE $\nu_e \rightarrow \nu_{ACTIVE}$ OSCILLATIONS;
  - $c^2_{23} c^2_{24} = 1 \Rightarrow$ PURE $\nu_e \rightarrow \nu_{STERILE}$ OSCILLATIONS.

ATMOSPHERIC PARAMETERS

- Δm^2_{ATM}, ϑ_{34} : RELEVANT OSCILLATION-PARAMETERS;
- $c^2_{23} c^2_{24} = |U_{s1}|^2 + |U_{s2}|^2$: ACTIVE-STERILE ADMIXTURE;
- $c^2_{23} = |U_{\mu 3}|^2 + |U_{\mu 4}|^2$: ν_μ PROJECTION ON ATM STATES.
- CASES:
  - $c^2_{23} = 0 \Rightarrow$ NO ATMOSPHERIC ν_μ OSCILLATIONS;
  - $c^2_{23} = 1 \Rightarrow$ "RESTRICTED" CASE :
    - $c^2_{23} c^2_{24} = 0 \Rightarrow$ PURE $\nu_\mu \rightarrow \nu_s$ OSCILLATIONS;
    - $c^2_{23} c^2_{24} = 1 \Rightarrow$ PURE $\nu_\mu \rightarrow \nu_\tau$ OSCILLATIONS.

★ s^2_{23} LIMITED BY THE ATM ANALYSIS;

★ ALSO ν_μ DISAPP. SEARCHES AT CDHSW $\Rightarrow s^2_{23} \lesssim 0.2$.

PARAMETER RANGES.

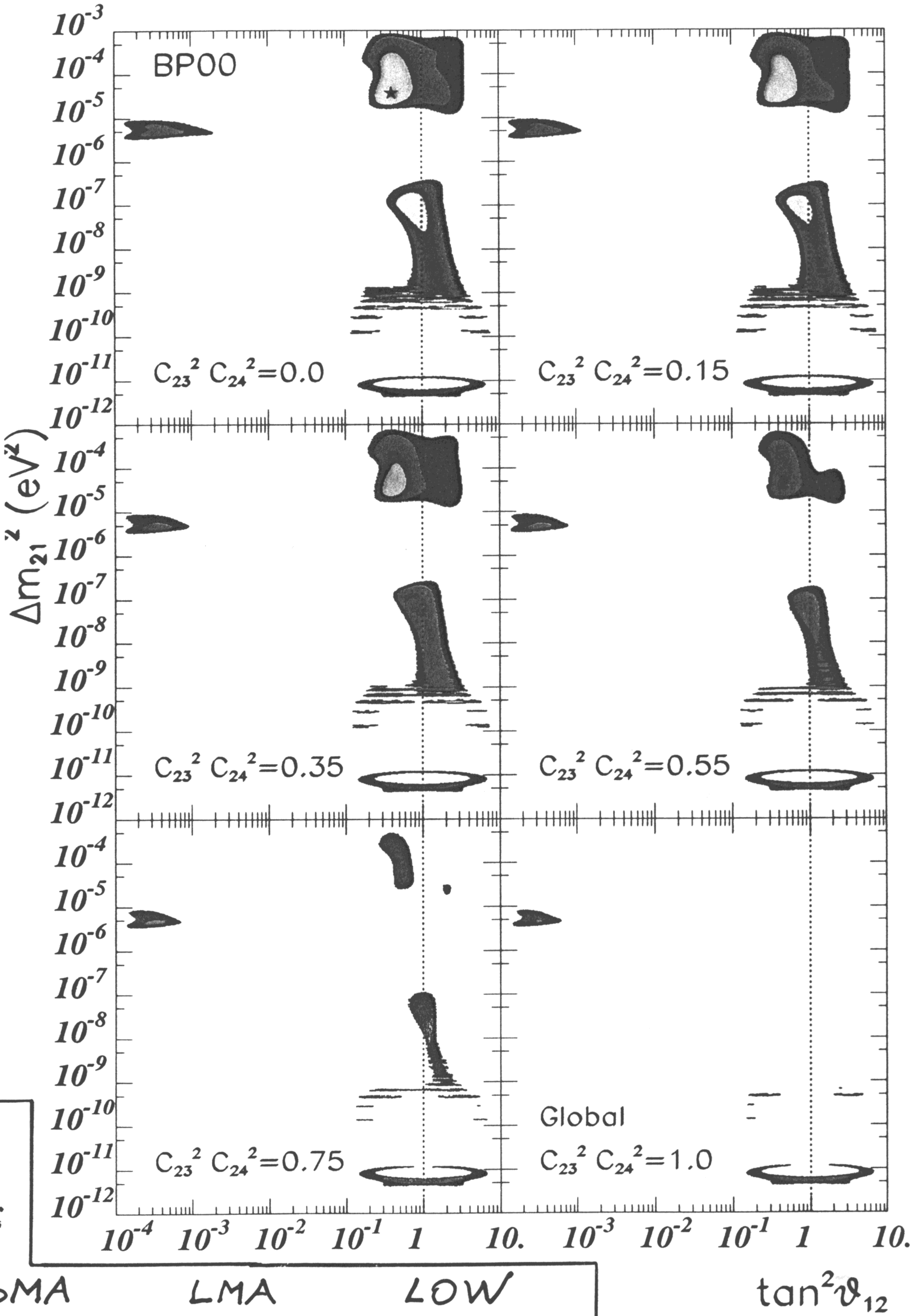
- $\Delta m^2_{\odot} \geq 0$; $\Delta m^2_{ATM} \geq 0$;
- $0 \leq \vartheta_{12} \leq \pi/2 \Rightarrow 0 \leq tg^2 \vartheta_{12} \leq +\infty$;
- $0 \leq \vartheta_{23} \leq \pi/2$ & $0 \leq \vartheta_{24} \leq \pi/2 \Rightarrow 0 \leq c^2_{23} c^2_{24} \leq 1$ & $0 \leq s^2_{23} \leq 1$;
- $-\pi/2 \leq \vartheta_{34} \leq \pi/2 \Rightarrow -1 \leq sgn(\vartheta_{34}) \sin^2(\vartheta_{34}) \leq +1$.

Active vs Sterile: Solar case

- Homestake • SAGE+GALLEX/GNO ⋆ *SK-1258* • *SNO-CC*

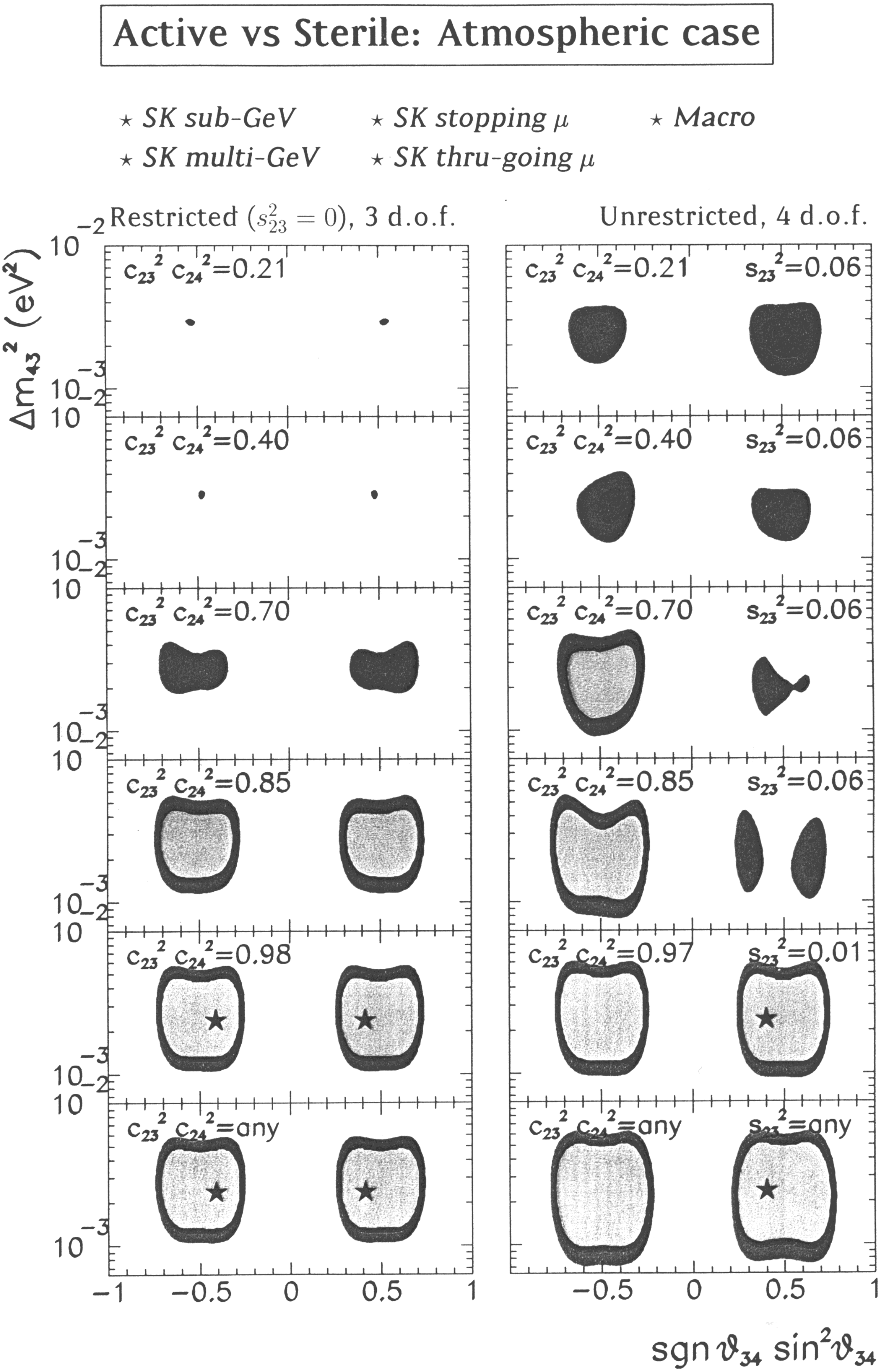
⇒ Best fit point: LMA, $c_{23}^2 c_{24}^2 = 0$; SMA strongly disfavoured;

⇒ however, for large values of $c_{23}^2 c_{24}^2$ the LMA region disappears.



REGION DISAPPEAR FOR $c_{23}^2 c_{24}^2$:

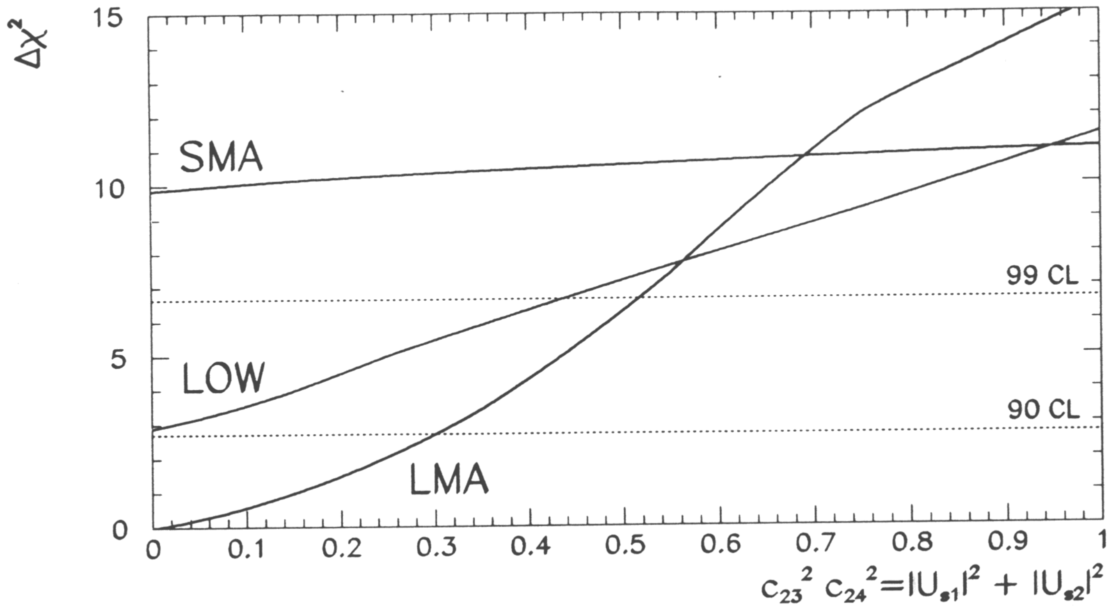
C.L.	SMA	LMA	LOW
90%	≥0.0	≥0.45	≥0.4
99%	NEVER	≥0.72	≥0.99



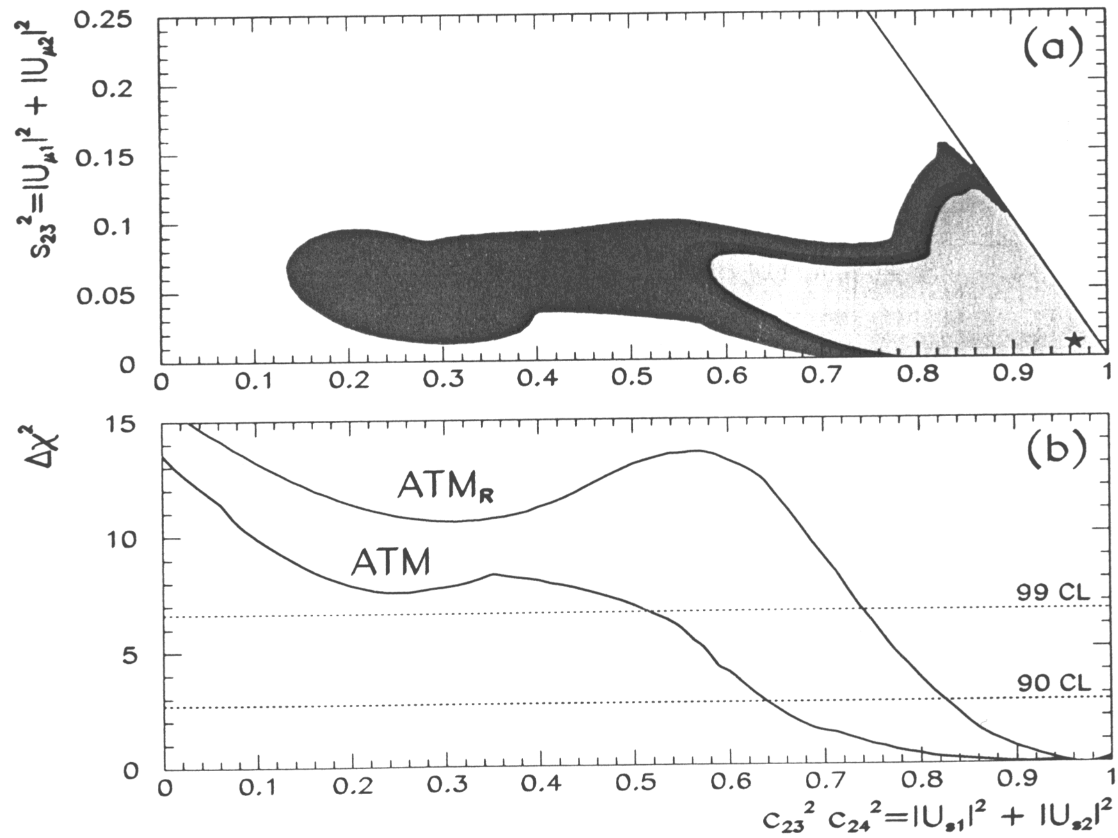
Active vs Sterile: Atmospheric case
⋆ SK sub-GeV
⋆ SK stopping μ
⋆ Macro
⋆ SK multi-GeV
⋆ SK thru-going μ
Restricted ($s_{23}^2 = 0$), 3 d.o.f.
Unrestricted, 4 d.o.f.
$c_{23}^2\ c_{24}^2$=0.21
$c_{23}^2\ c_{24}^2$=0.40
$c_{23}^2\ c_{24}^2$=0.70
$c_{23}^2\ c_{24}^2$=0.85
$c_{23}^2\ c_{24}^2$=0.98
$c_{23}^2\ c_{24}^2$=any
$c_{23}^2\ c_{24}^2$=0.97
s_{23}^2=0.06
s_{23}^2=0.01
s_{23}^2=any
Δm_{43}^2 (eV^2)
10^{-2}
10^{-3}
−1
−0.5
0
0.5
1
sgn ϑ_{34} $\sin^2\vartheta_{34}$

Active/sterile admixture in Solar & Atmospheric

- Solar case: $c_{23}^2 c_{24}^2 = 0$ preferred, but larger values allowed:

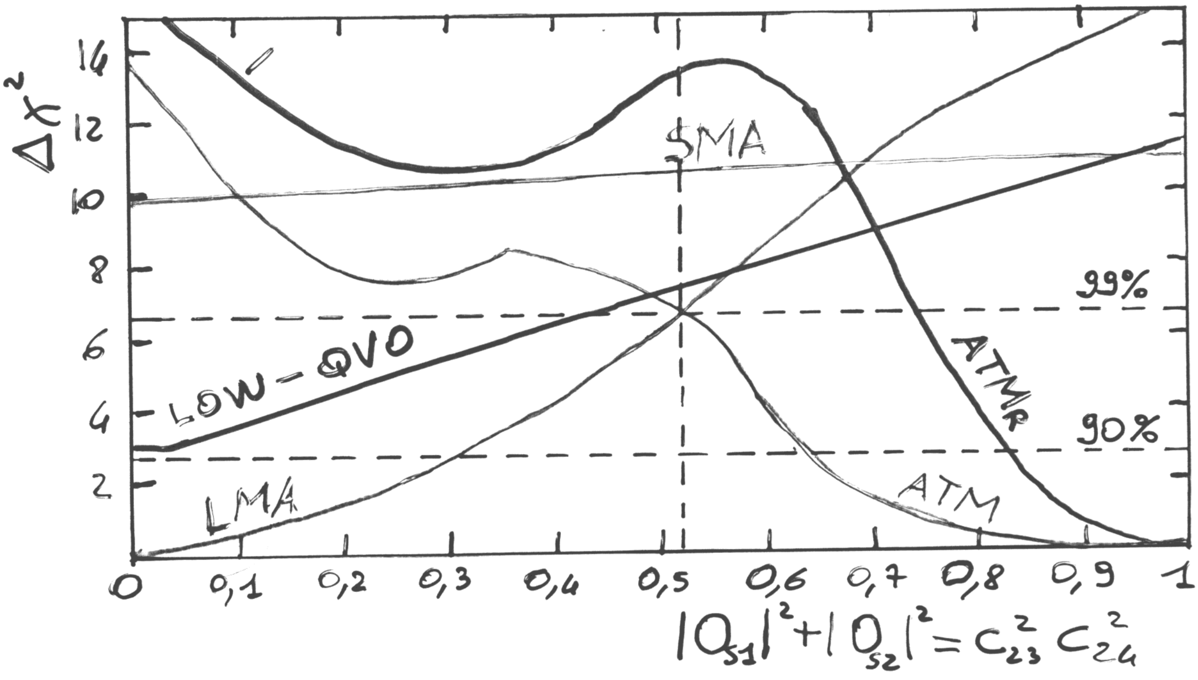


- Atmospheric case: $c_{23}^2 c_{24}^2 \approx 1$ preferred, but smaller values possible:



$\Rightarrow$ a chance for *maximal active-sterile admixture*?

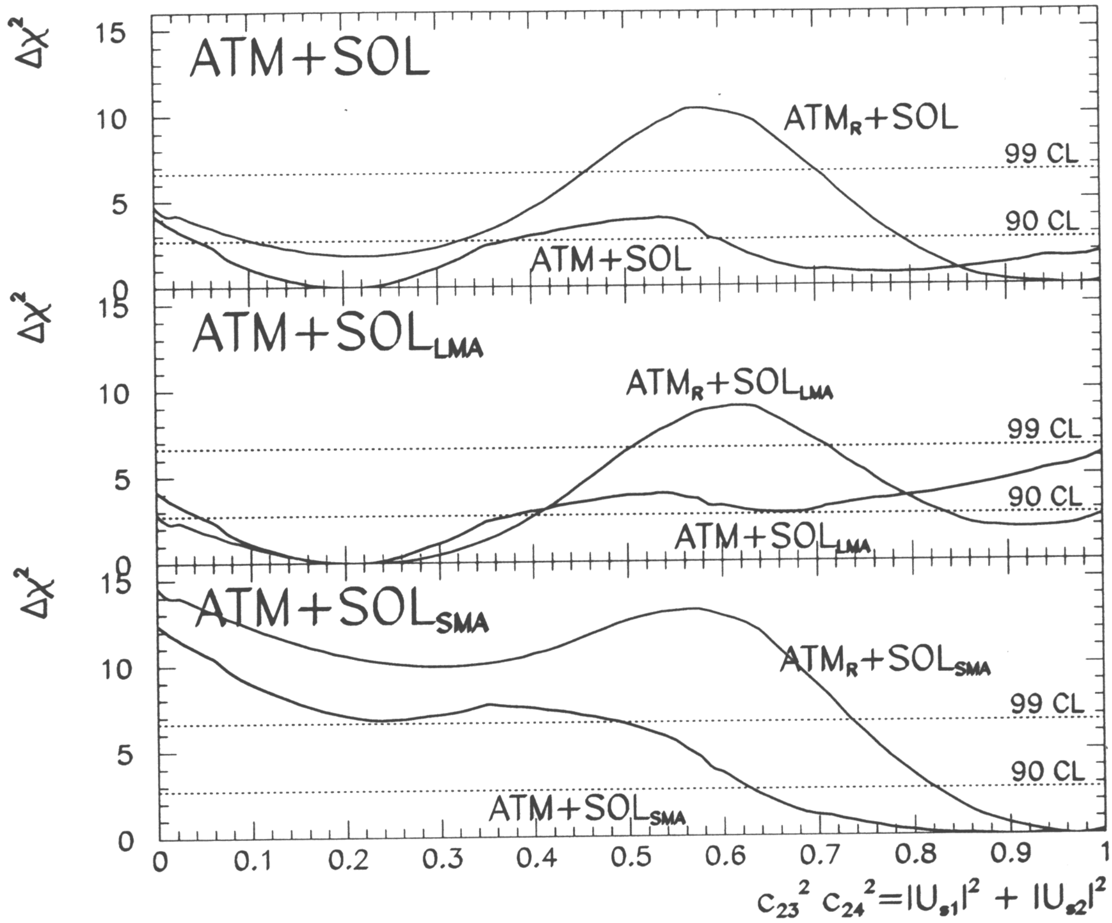
SOLAR VS. ATMOSPHERIC DATA



- NAIVELY:
  - SOLAR: $c_{23}^2 c_{24}^2 \leq 0.52$ AT 99% C.L.
  - ATM: $c_{23}^2 c_{24}^2 \geq 0.52$ AT 99% C.L.

Combined analysis

- Maximal active-sterile admixture *is newer preferred*:



- there are always two local minima;
- in the *unconstrained* and *LMA* cases, $c_{23}^2 c_{24}^2 \approx 0.2$ is preferred;
- in the *SMA* case, $c_{23}^2 c_{24}^2 \approx 1$ is preferred;

⋆ after SNO, the *SMA* solution is (slightly) disfavoured;

⋆ however, in the ATM$_R$ case the *SMA* solution is still preferred.

Scenario	d.o.f.	s_{23}^2	$c_{23}^2 c_{24}^2$	χ^2_{min}	GOF
ATM+SOL$_{unc}$	$85-6$	0.065	0.21	73.8	64%
ATM$_R$+SOL$_{unc}$	$85-5$	0.	0.98	75.5	62%
ATM+SOL$_{LMA}$	$85-6$	0.065	0.21	73.8	64%
ATM$_R$+SOL$_{LMA}$	$85-5$	0.	0.22	77.4	56%
ATM+SOL$_{SMA}$	$85-6$	0.030	0.91	75.4	59%
ATM$_R$+SOL$_{SMA}$	$85-5$	0.	0.98	75.5	62%

Conclusions

- We have performed a global and unified analysis of both solar and atmospheric neutrino data in the context:
  - of 3ν oscillations, using taking into account also the **Chooz** result;
  - of 4ν oscillations, in the framework of $2+2$ schemes.
- we included in our fit:
  - all the solar experiments, with SK-1258 data and SNO_{CC} rates;
  - all the atmospheric experiments for the 3ν analysis, and SK (1289 days) + MACRO for the 4ν analysis.

3ν results

- both solar and atmospheric data are in strong disagreement with the SM, however can be perfectly explained by the *oscillation hypothesis*;
- even without the reactor data $\theta_{13} \approx 0$ is preferred;
- there is *full agreement* between solar, atmospheric and reactor results.

⇒ M.C. Gonzalez-Garcia, M.M., C. Peña-Garay, J.W.F. Valle, *Global three-neutrino oscillation analysis of neutrino data, Phys. Rev.* **D63** (2001) 033005, *hep-ph/0009350.*

4ν results

- neither solar nor atm data favour oscillations into a sterile neutrino;
- maximal active/sterile admixture is *always* disfavoured;

⋆ the best fit point has $|U_{s1}|^2 + |U_{s2}|^2 \approx 0.2$, is dominated by solar data and favours in the *LMA* solution;

⋆ however, another configuration with $|U_{s1}|^2 + |U_{s2}|^2 \approx 1$, dominated by atmospheric data and favoured by the *SMA* solution, is also possible.

⇒ M.C. Gonzalez-Garcia, M.M, C. Peña-Garay, *Solar and Atmospheric Four–Neutrino Oscillations, hep-ph/0105269* (to appear in PRD).