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THE NEW STATUS OF ν OSCILLATION PARAMETERS

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OUTLINE

- ATMOSPHERIC ν OSCILLATIONS : 2ν [1], 3ν [2,3], 4ν [4,5]

- SOLAR ν OSCILLATIONS : 2ν [6-8], 3ν [6-8], 4ν [9]

Refs:

[1] Summer conferences (ν2000 + others)

[2] Fogli, E.L., Marrone, Scioscia, PRD 59, 033001 (1999)

[3] Fogli, E.L., Marrone, Montanino, hep-ph/0009269

[4] G.L.Fogli, E.L., Marrone, hep-ph/0009299

[5] Talk by A.Marrone at NOW2000, www.ba.infn.it/~now2000

[6] G.L.Fogli, E.L., Montanino, Palazzo, PRD 62, 013002 (2000)

[7] Fogli, Lisi, Montanino, Palazzo, hep-ph/0005261

[8] Talks by D.Montanino and A.Palazzo at now 2000

[9] C.Giunti, M.C. Gonzalez-Garcia, C. Peña-Garay, PRD 62, 013005 (2000)

REMARK ON MIXING ANGLES

- Mixing angle range is: $\vartheta_{ij} \in [0, \pi/2]$
  (1st + 2nd OCTANT)

- In general, oscillation physics is different in the two octants.
  Octant symmetry ($\sin\vartheta_{ij} \to \cos\vartheta_{ij}$) is unbroken only for 2ν oscill. in vacuum

- $\sin^2 2\vartheta_{ij}$ maps one octant only
  → not a proper variable → OBSOLETE

- Better variables: $\sin^2\vartheta_{ij}$ (linear scale)
  $\tan^2\vartheta_{ij}$ (log scale)
  - Map both octants
  - Preserve octant symmetry if applicable
  - Avoid pseudo-problems like $\sin^2 2\vartheta > 1$, etc.

Use of both octants and of $\log\tan^2\vartheta_{ij}$ originally advocated in:

Fogli, E.L., Scioscia, PRD 52, 5334 (1995) ← Lab ν
Fogli, E.L., Montanino, PRD 54, 2048 (1996) ← Solar ν
Fogli, E.L., Montanino, Scioscia, PRD 55, 4385 (1997) ← Atm. ν

REMARK ON χ^2 STATISTICS

Two canonical χ^2 tests (PDG):

(A) PARAMETER ESTIMATION

- Uses $\chi^2 - \chi^2_{min} = \Delta\chi^2$
- d.o.f. = N(model param.)
- Tests if parameters are fluctuations of best-fit
- Widely used to draw C.L. contours (including this talk)

(B) HYPOTHESIS TEST

- Uses absolute χ^2
- d.o.f. = N(data) − N(model par.)
- Tests intrinsic goodness of fit, independently of existence of absolute χ^2_{min}

WARNING: Tests (A) and (B) are DIFFERENT. Parameters may fail (A) but pass (B). Information on (B) important when hypothesis rejection is claimed (e.g., SMA, $\nu_\mu \to \nu_s$, etc.)

Atmospheric 2ν oscillations

Well-known results (90% C.L.):

$$\begin{cases} \Delta m^2 \simeq 3^{+3.0}_{-1.5} \times 10^{-3}\, eV^2 \\ \sin^2 2\theta \gtrsim 0.88 \end{cases}$$

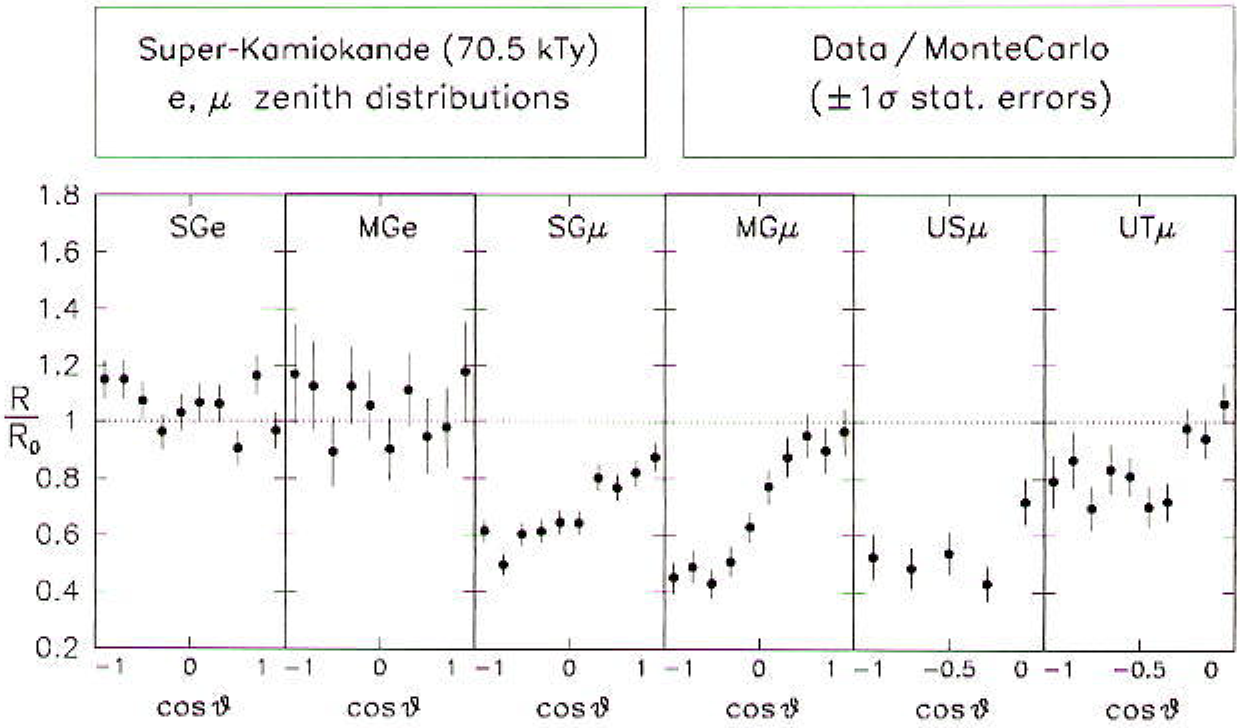
Can be written as:

$$\log_{10} \frac{\Delta m^2}{eV^2} \simeq -2.5 \pm 0.3$$

$$\sin^2 \vartheta \simeq 0.5 \pm 0.17$$

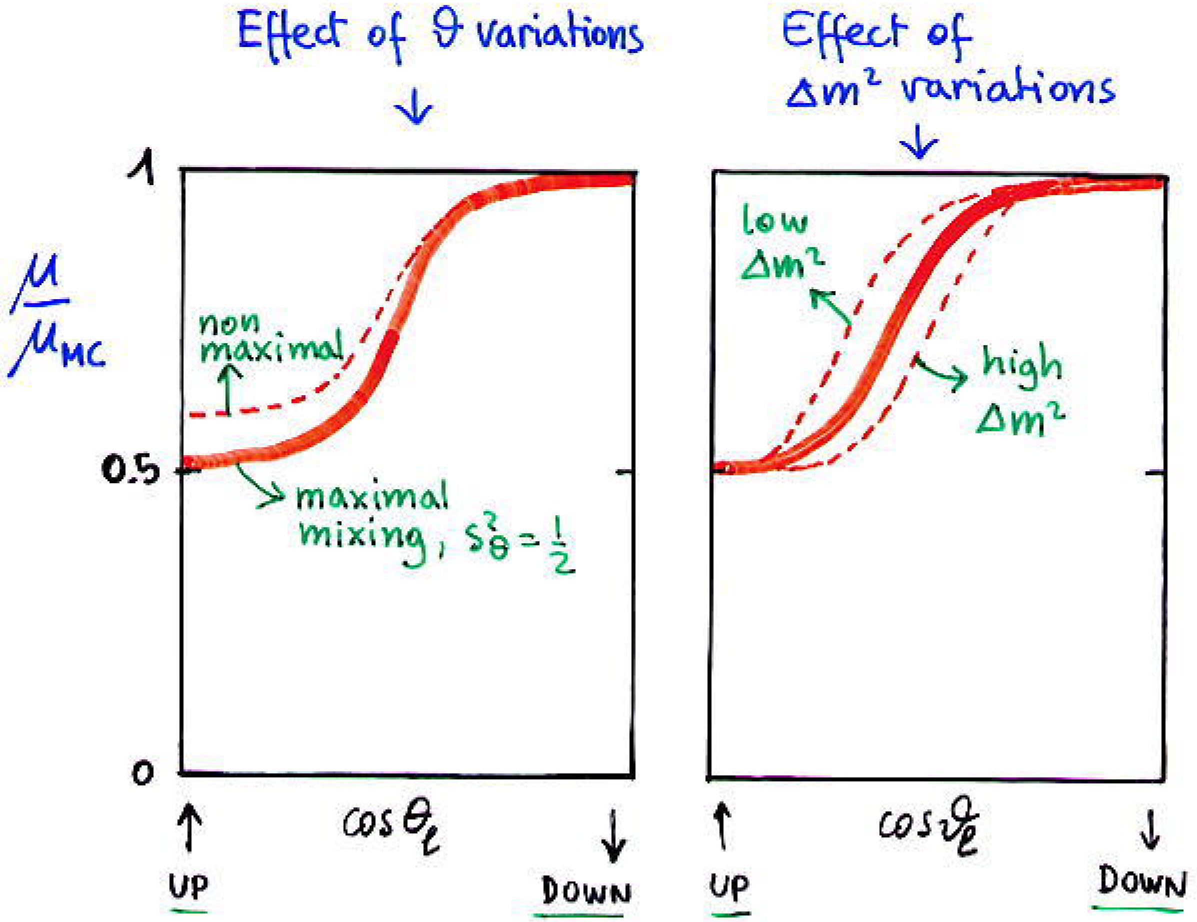
($\Delta m^2, \sin^2\theta$) fit robust because:

- Different SK data consistent with each other
- Different experiments* consistent with each other
- Fit dominated by a single, striking evidence:
  U/D asymmetry of multi GeV muons



* SK, MACRO, SOUDAN2

MGμ events



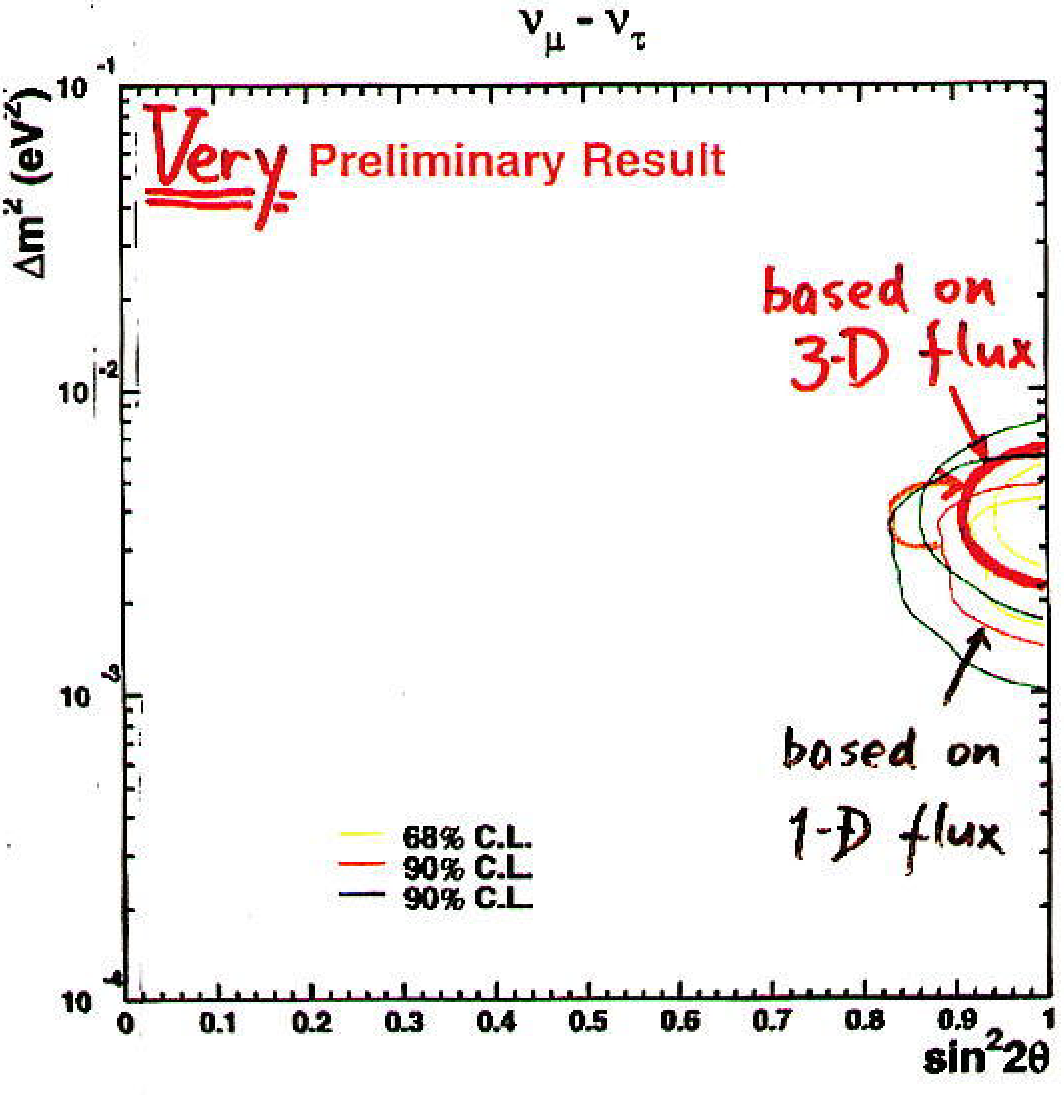
$\frac{\mu_{UP}}{\mu_{MC}} \sim \frac{1}{2}$ fixes $s^2_\theta \sim \frac{1}{2}$

μ decrease at horizon fixes Δm^2

Recent progress: 3D calculations of ν fluxes change nearly horizontal neutrino yield at low energy

→ Expect fractional changes in $(\Delta m^2)_{fit}$ (upwards)

Allowed parameter region based on a 3-D flux



Kajita at NOW 2000

ATMOSPHERIC 3ν OSCILLATIONS

2ν :

$$\nu_2 = s_\psi \nu_\mu + c_\psi \nu_\tau$$

$$\nu_1$$

3ν : Allowance for ν_e mixing

$$\nu_3 = s_\varphi \underline{\underline{\nu_e}} + c_\varphi (s_\psi \nu_\mu + c_\psi \nu_\tau)$$

m^2

ν_2, ν_1

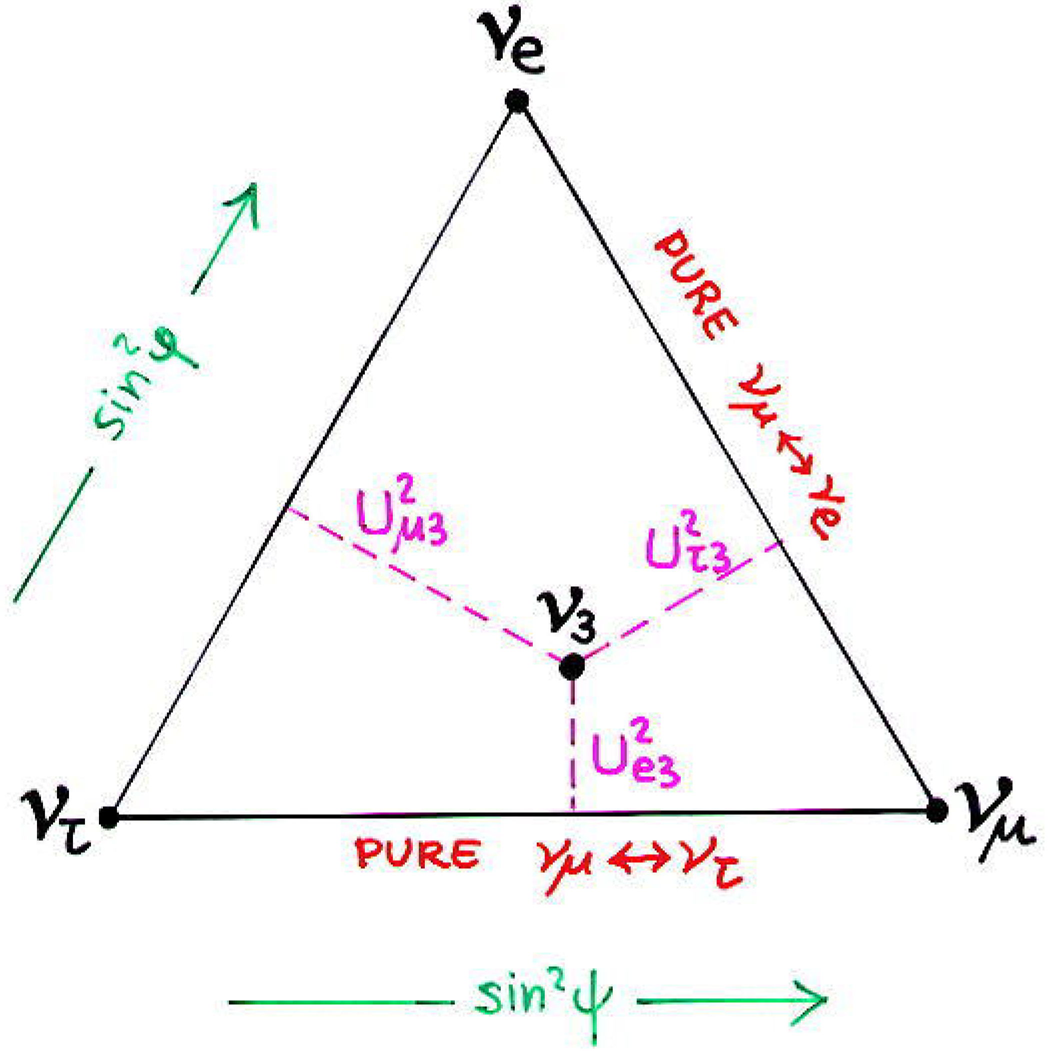
- $\begin{cases} \varphi = \theta_{13} \\ \psi = \theta_{23} \end{cases}$ (using standard CKM ordering)
- Comments on ν_1, ν_2 above ν_3 later

GRAPHICAL REPRESENTATIONS:

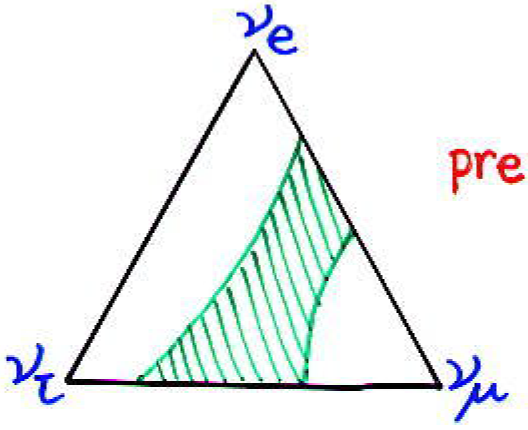
$$\nu_3 = s\varphi\,\nu_e + c\varphi\, s\psi\,\nu_\mu + c\varphi\, c\psi\,\nu_\tau$$

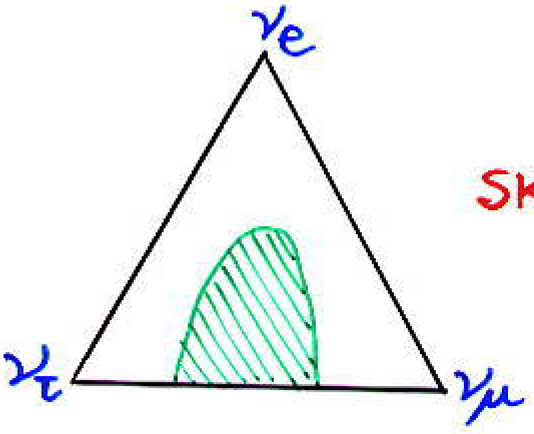
$$= U_{e3}\nu_e + U_{\mu 3}\nu_\mu + U_{\tau 3}\nu_\tau$$

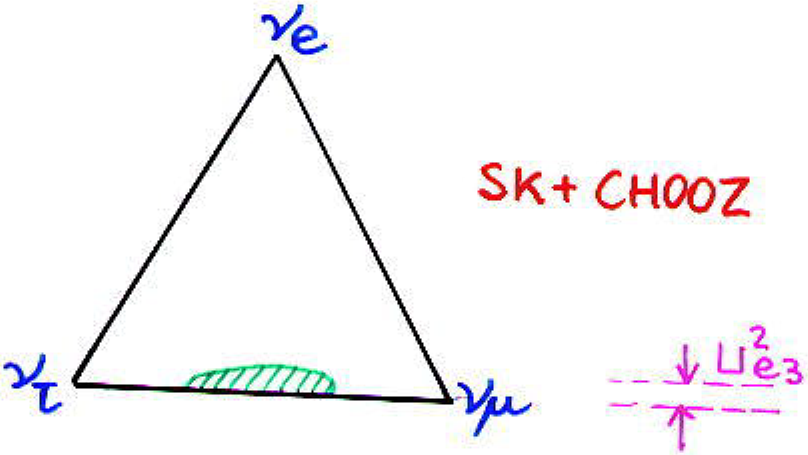
with $U_{e3}^2 + U_{\mu 3}^2 + U_{\tau 3}^2 = 1$



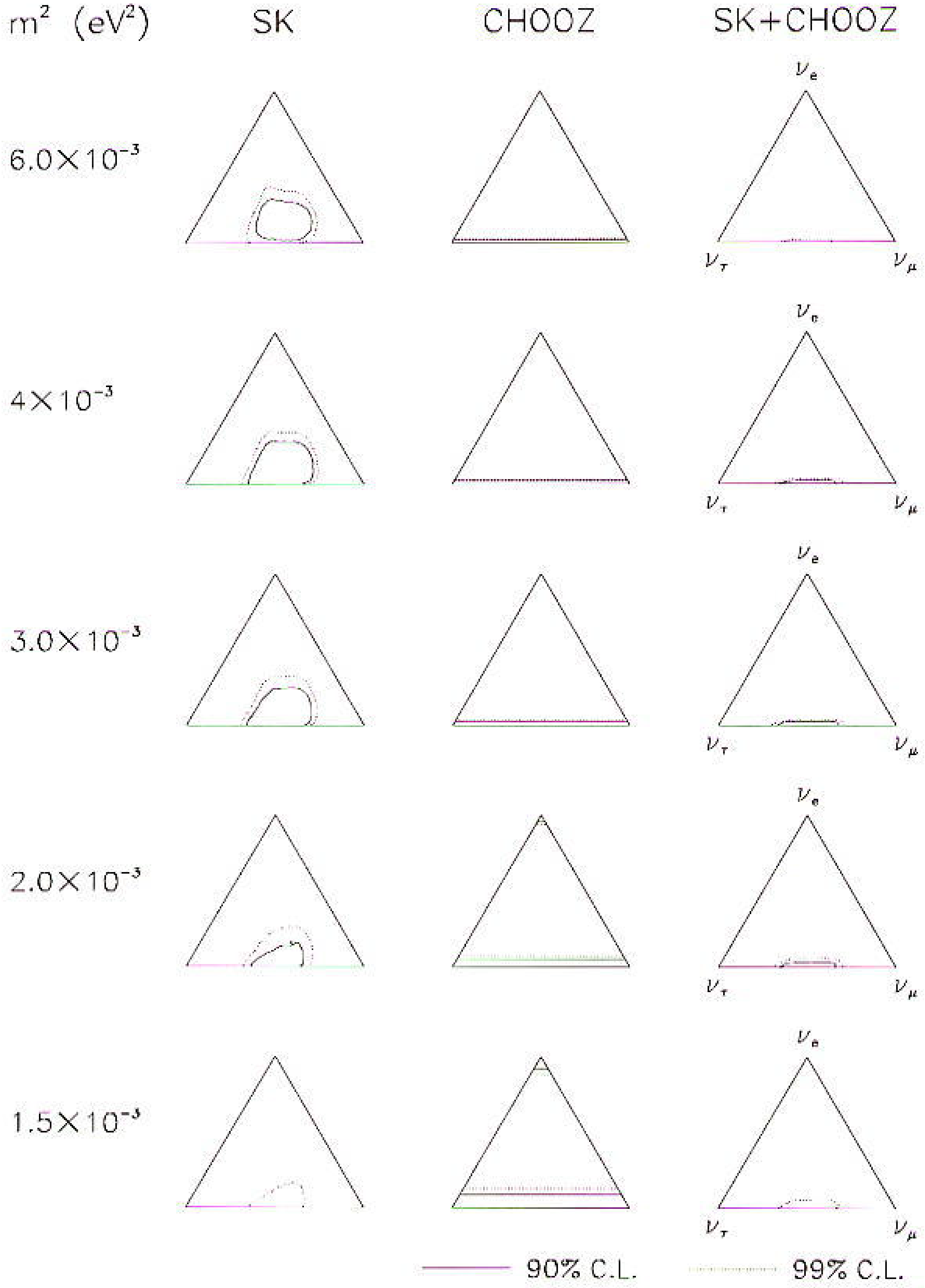
EVOLUTION OF BOUNDS:







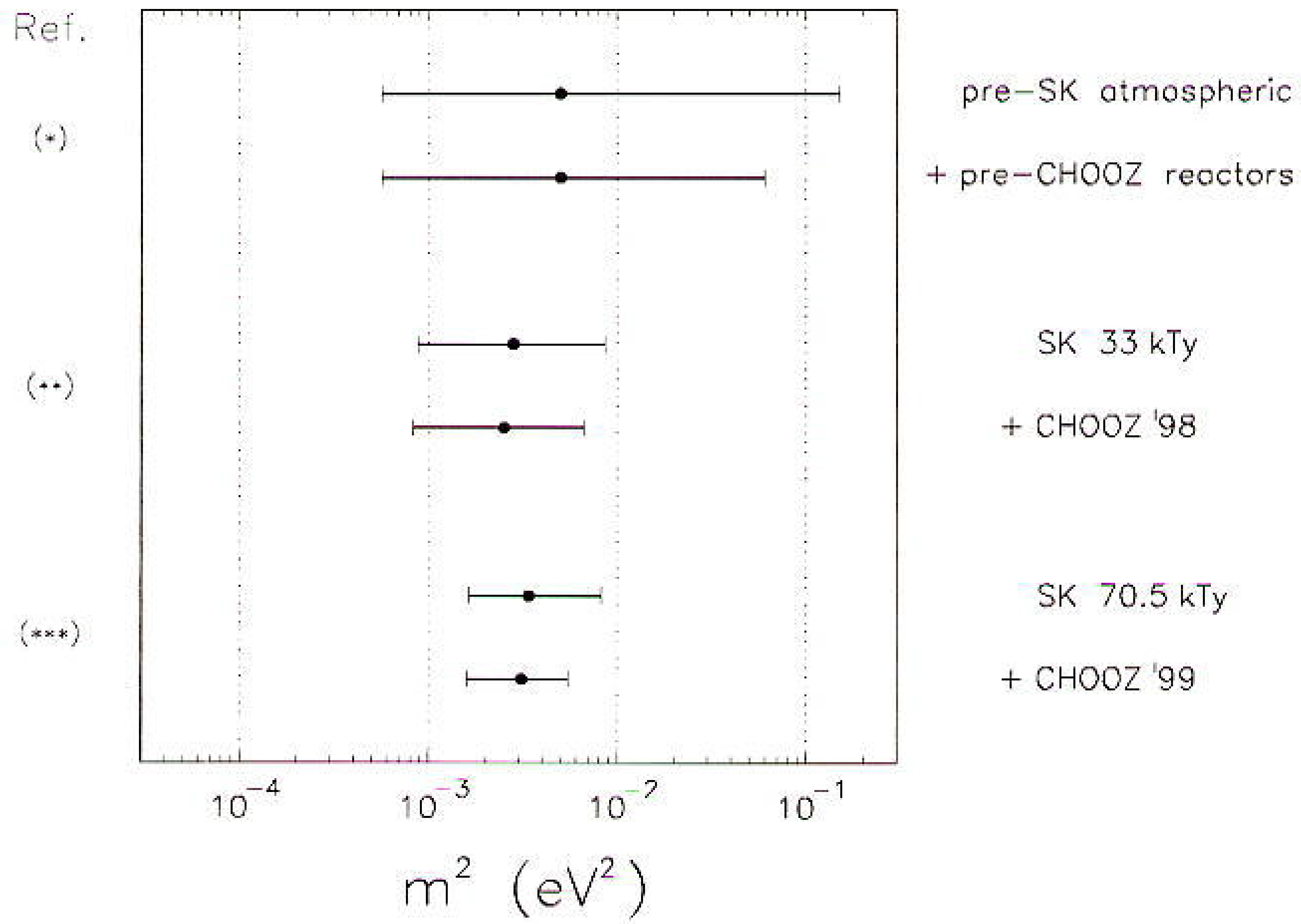
Updated results after ν2000
(Fogli, E.L., Marrone) ⟶



m^2 (eV^2)
SK
CHOOZ
SK+CHOOZ
6.0×10^{-3}
4×10^{-3}
3.0×10^{-3}
2.0×10^{-3}
1.5×10^{-3}
ν_e
ν_τ
ν_μ
90% C.L.
99% C.L.

Progress in m^2 bounds for unconstrained 3ν mixing

(90% C.L., $N_{DF} = 3$)



(*) G.L. Fogli, E. Lisi, D. Montanino, and G. Scioscia, Phys. Rev. D 55, 4385 (1997)

(**) G.L. Fogli, E. Lisi, A. Marrone, and G. Scioscia, Phys. Rev. D 59, 033001 (1999)

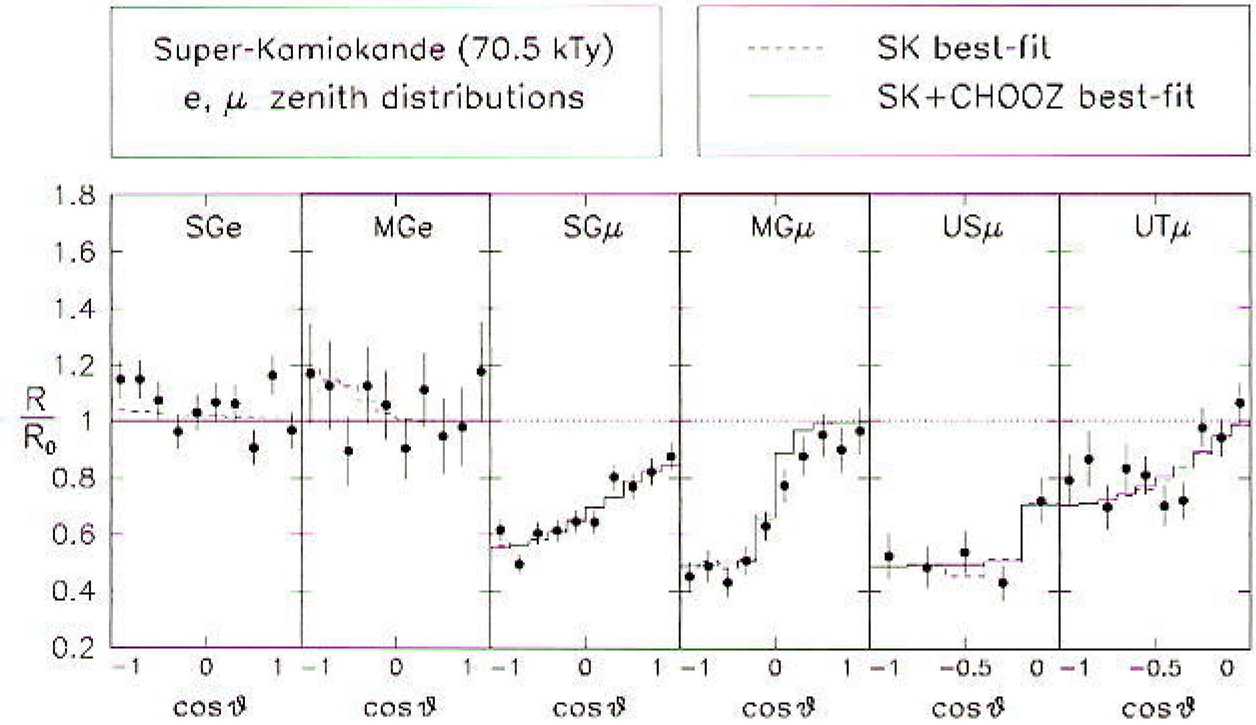
(***) G.L. Fogli, E. Lisi, A. Marrone, and D. Montanino Proceedings of Neutrino2000

BEST-FIT ZENITH DISTRIBUTIONS

---- SK $\quad (m^2, U_{e3}^2, U_{\mu 3}^2, U_{\tau 3}^2) \simeq (3.5, 0.07, 0.57, 0.36)$

—— SK+CHOOZ $\quad$ " $\quad$ " $\quad \simeq (3, 0, 0.5, 0.5)$

No significant evidence for $U_{e3}^2 \neq 0$



→ No evidence for Earth matter effects

→ No real sensitivity to sign(m^2) : or

→ Hard to see $U_{e3}^2 \neq 0$ even with higher SK statistics

SUMMARY OF 3ν CONSTRAINTS

(90% C.L.)

$$\log_{10} \frac{m^2}{\text{eV}^2} \simeq -2.5 \pm 0.3$$

$$s^2_\psi \equiv \sin^2\theta_{23} \simeq 0.5 \pm 0.17$$

} ~ as for 2ν case; very robust

$$s^2_\varphi \equiv \sin^2\theta_{13} \equiv U^2_{e3} \lesssim 0.31 \quad \text{(SK)}$$

$$\lesssim 0.04 \quad \text{(SK + CHOOZ)}$$

ATMOSPHERIC 4ν OSCILLATIONS

- $\exists$ light ν_s motivated by LSND + solar + atmospheric

- 2+2 spectrum favored : $=\ \nu_{3,4}$ / $=\ \nu_{1,2}$
  (1+3 not excluded)

- Recently, pure $\nu_\mu \to \nu_s$ disfavored by atmospheric ν data:

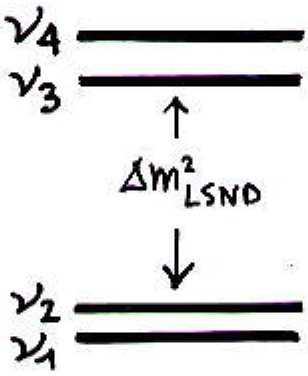
  SK $\to$ no $\nu_\mu \to \nu_s$ matter effects observed
  no suppression of NC events

  MACRO $\to$ no matter effects observed

Q. : How much ν_s can we add to $\nu_\mu \to \nu_\tau$?

Formalism $\longrightarrow$

(Fogli, E.L., Marrone)



ATMOS. OSC.: $\nu_\mu \to \nu_+$

SOLAR OSC.: $\nu_e \to \nu_-$

$$\begin{pmatrix} \nu_+ \\ \nu_- \end{pmatrix} = \begin{pmatrix} \cos\xi & \sin\xi \\ -\sin\xi & \cos\xi \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \nu_s \end{pmatrix}$$

Effective fermion density for neutrino potential in matter, $V_f = \sqrt{2}\, G_F N_f$:

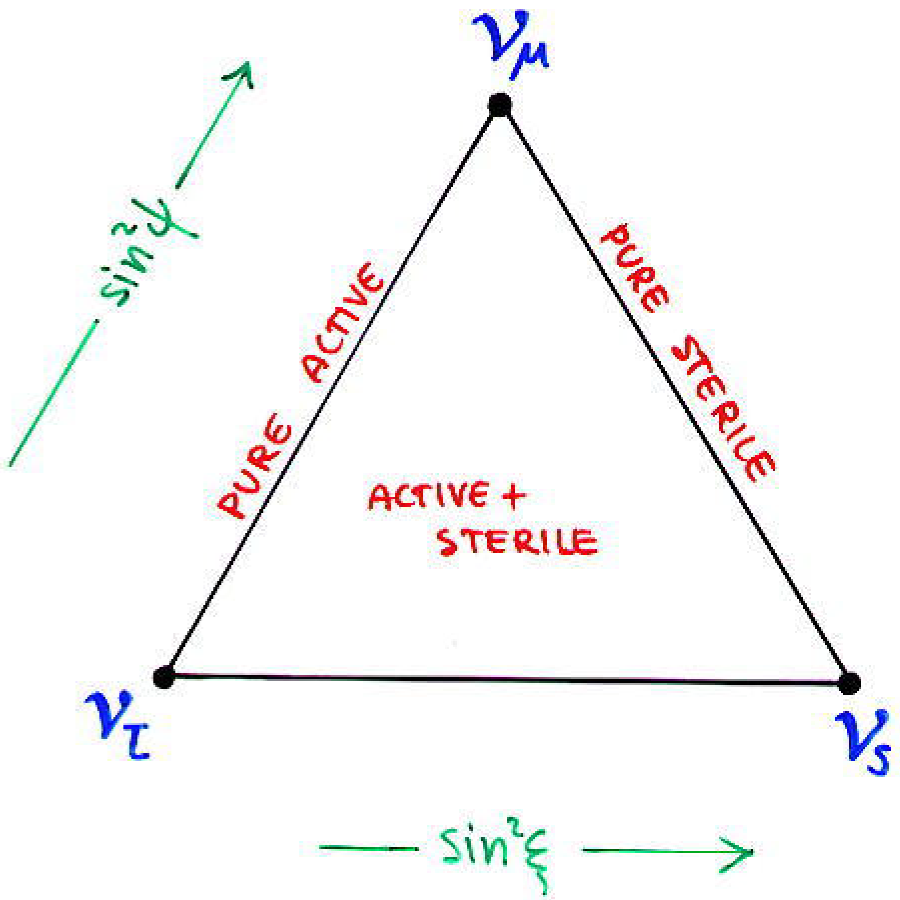
$$N_f = -\frac{1}{2}\sin^2\xi \cdot N_n \qquad \text{(atmos.)}$$

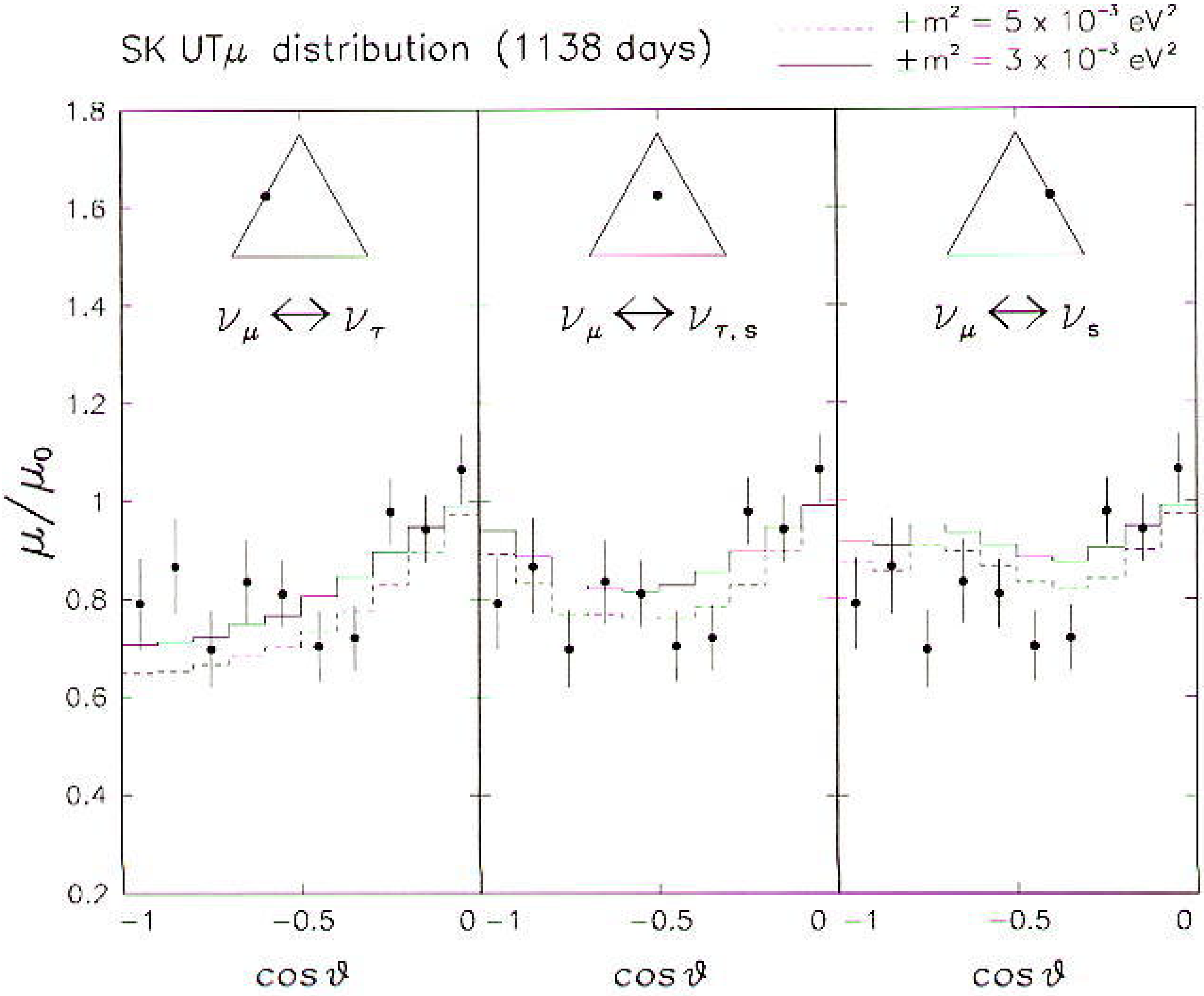
$$N_f = N_e - \frac{1}{2}\cos^2\xi\, N_n \qquad \text{(solar)}$$

ATMOSPHERIC 4ν OSCILLATIONS: GRAPHICAL REPRESENTATION

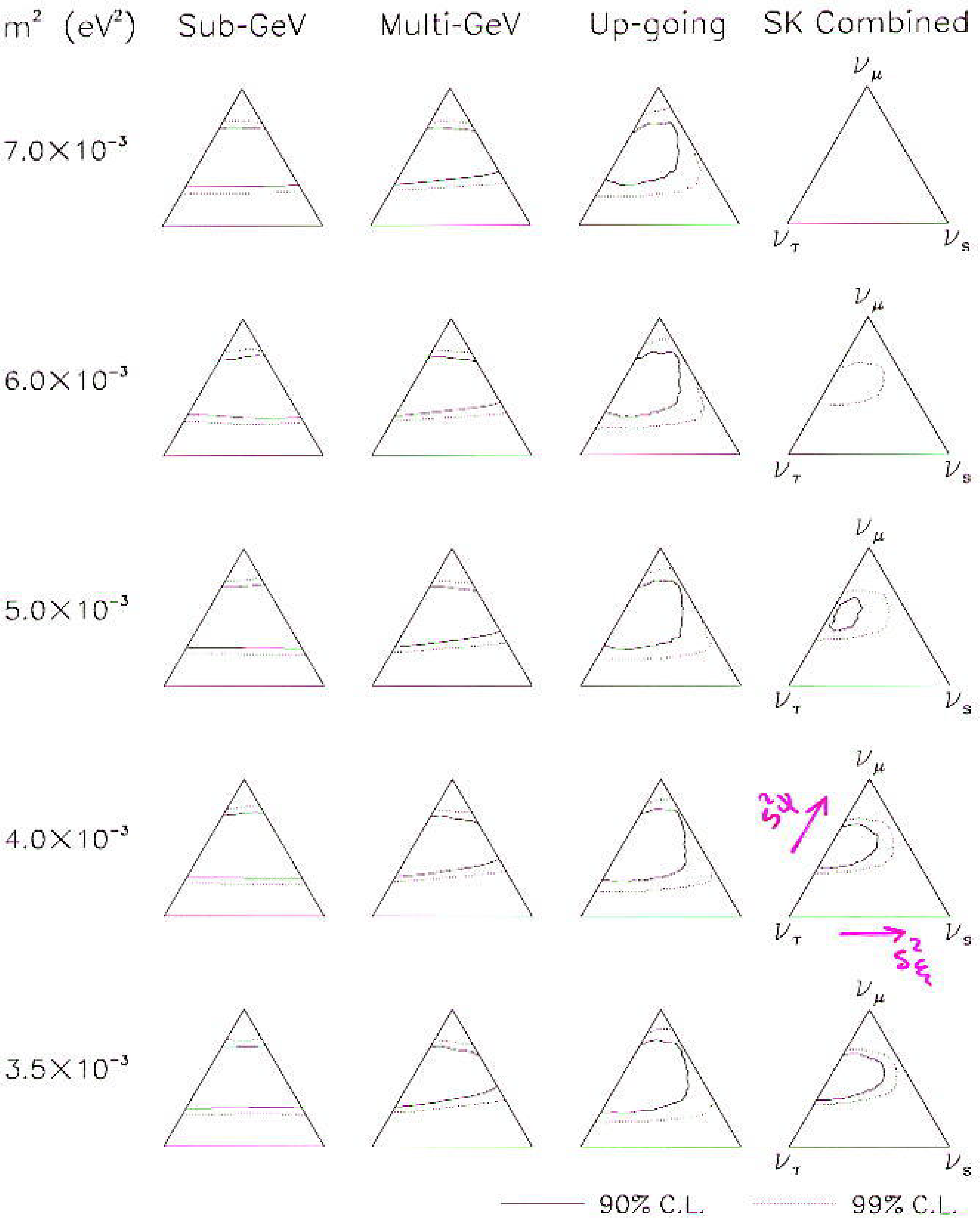
$$\nu_4 = s_\psi \nu_\mu + c_\psi \nu_+$$

$$= s_\psi \nu_\mu + c_\psi c_\xi \nu_\tau + c_\psi s_\xi \nu_s$$



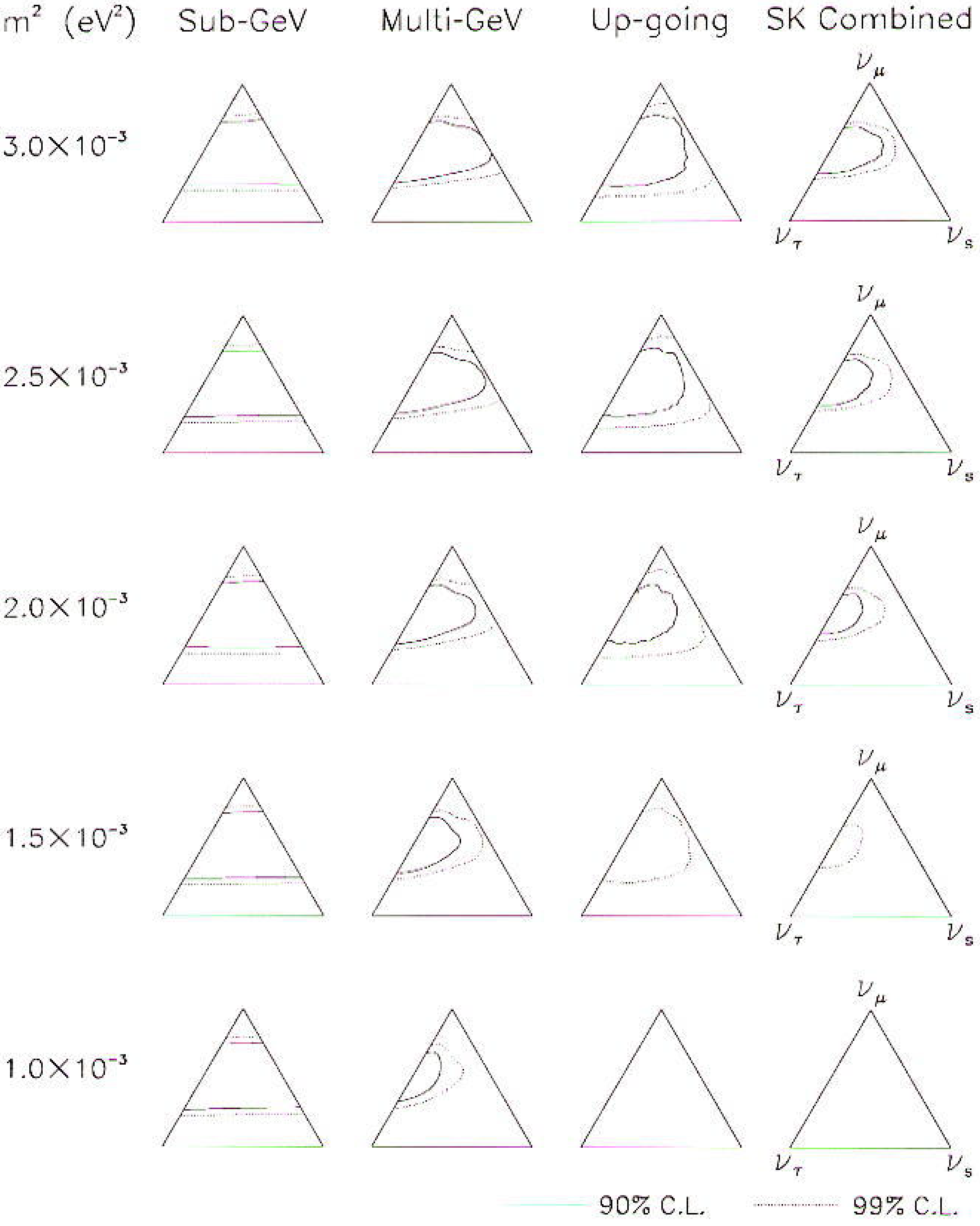

SK UTμ distribution (1138 days)
Δm² = 5 x 10⁻³ eV²
Δm² = 3 x 10⁻³ eV²
νμ ⟷ ντ
νμ ⟷ ντ, s
νμ ⟷ νs
μ/μ0
cos ϑ
cos ϑ
cos ϑ
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
−1
−0.5
0

Bounds from parameter estimation test

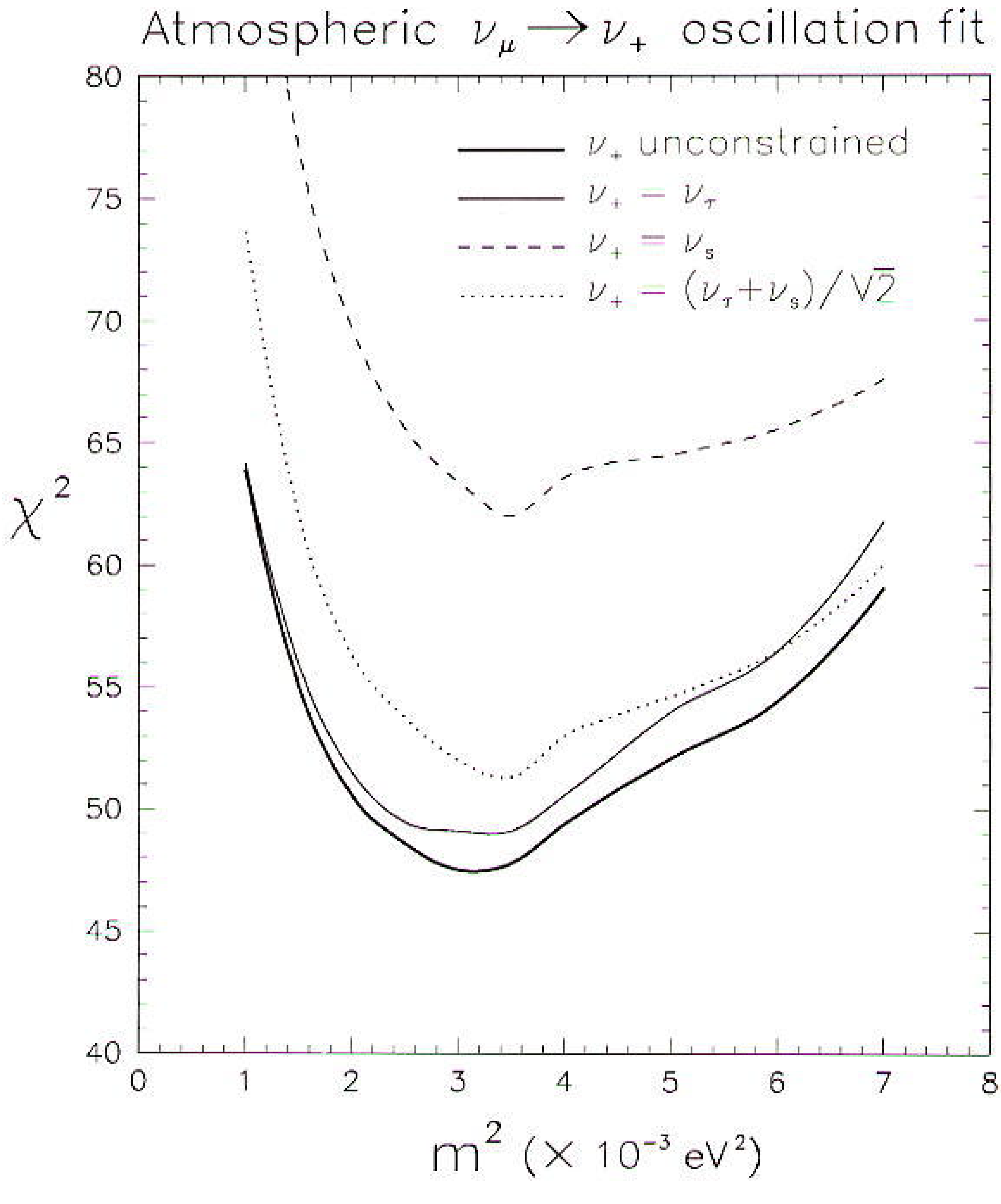


$s^2_\psi \simeq 0.5 \pm 0.17$ (once again)

$s^2_\xi \lesssim 0.67$ (large ν_s mixing tolerated)



Pure $\nu_\mu \to \nu_s$ excluded at 99.8 % by
PARAMETER ESTIMATION ($\equiv \Delta\chi^2$)



Goodness-of-fit for pure $\nu_\mu \to \nu_s$:

$\chi^2/\mathrm{dof} = 62/(55-2) \to P = 18\%$ ← ACCEPTABLE

$\nu_\mu \to \nu_s$ NOT RULED OUT AS AN "A PRIORI" HYPOTHESIS (in our analysis)

SOLAR 2ν OSCILLATIONS

Fogli, E.L., Montanino, Palazzo

ν 2000 data + BP98 S.S.M.

Recent developments :

Detailed study of "quasivacuum" (QV) range, intermediate between "vacuum" and "MSW"

Friedland
Fogli, E.L., Montanino, Palazzo
De Gouvea, Friedland, Murayama
Gonzalez-Garcia, Peña-Garay
Gago, Nunokawa, Zukanovich Funchal

Earlier QV studies :

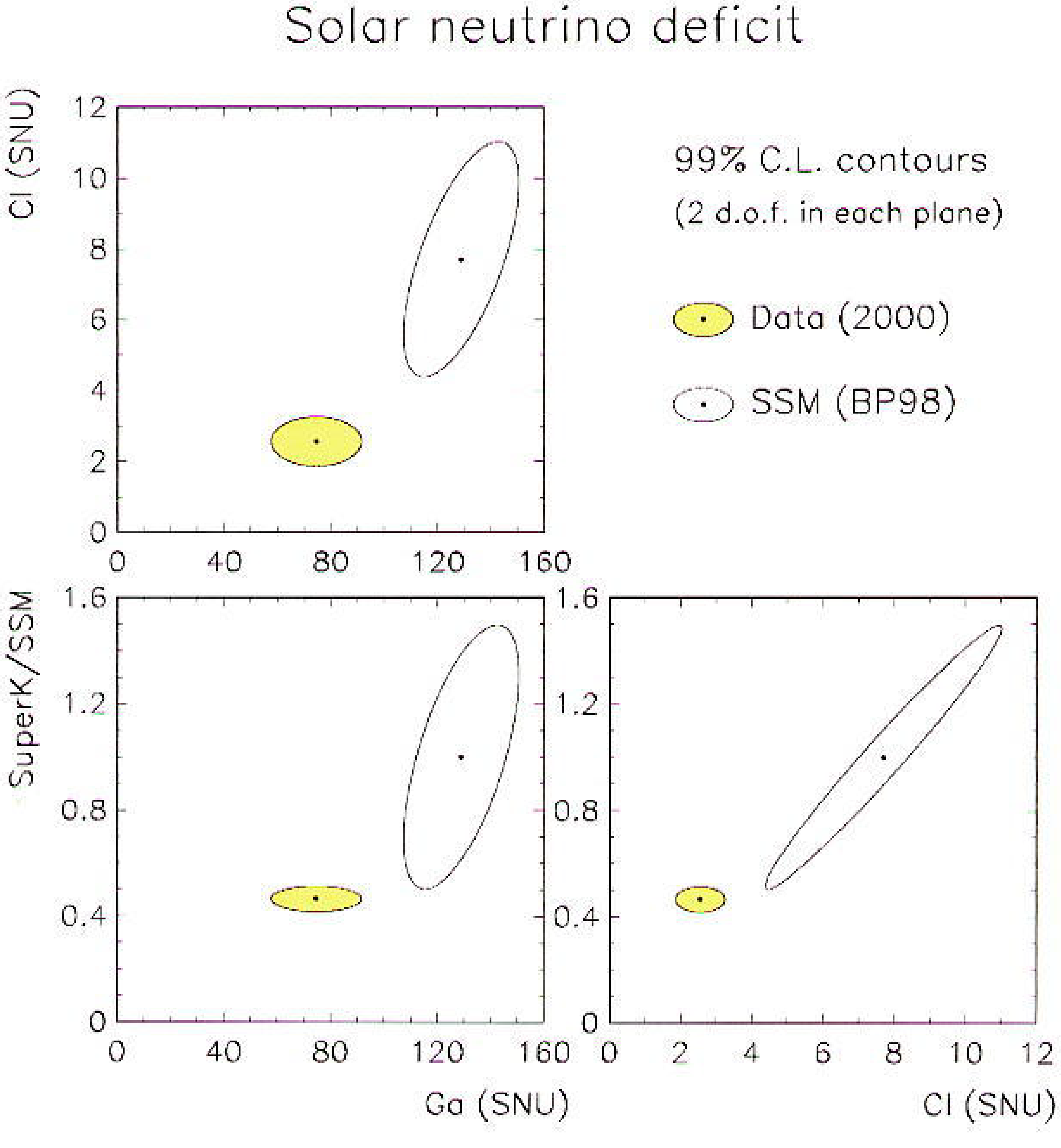
Petcov
Pantaleone
Pakvasa, Pantaleone

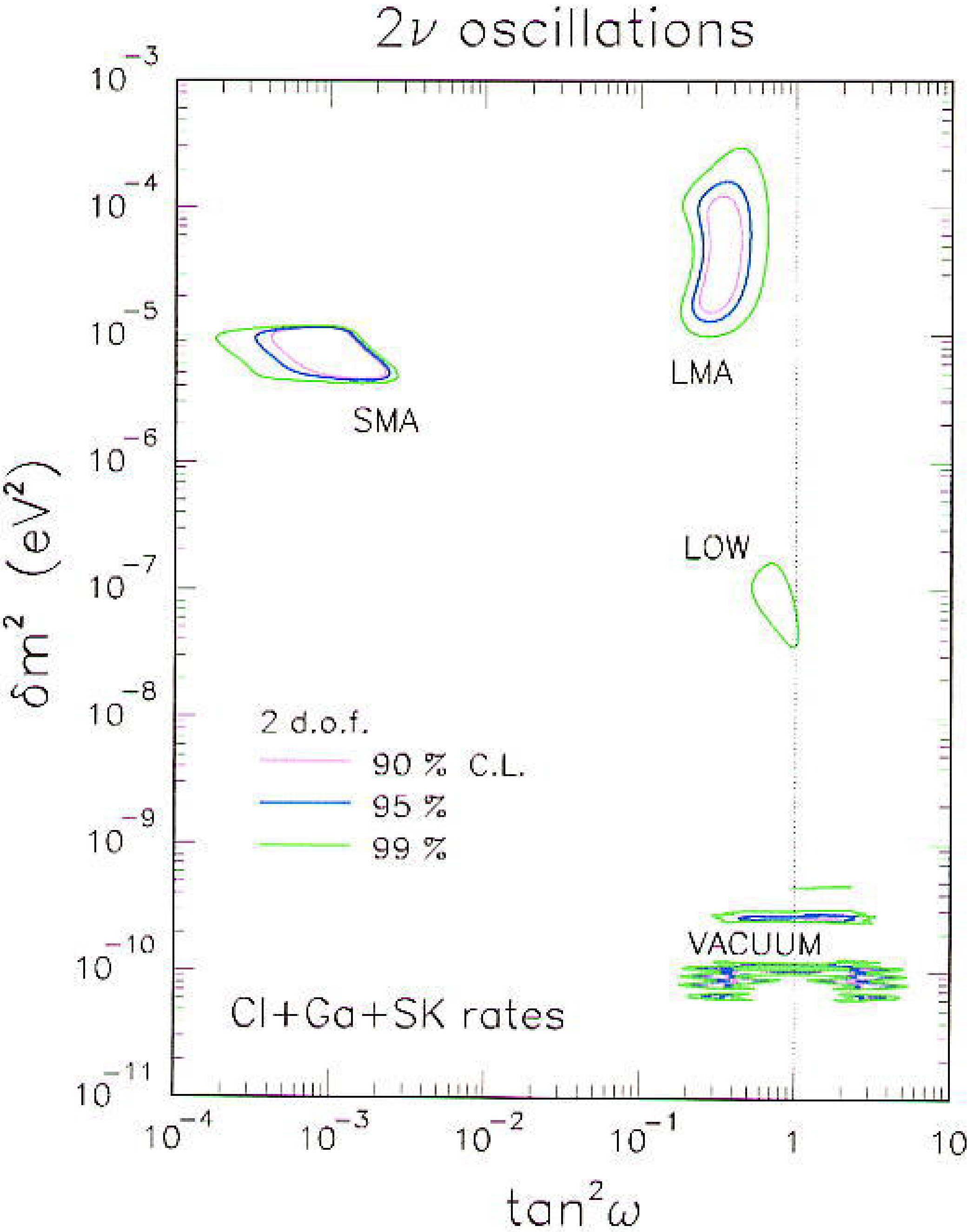
Note : QV effects <u>not</u> octant symmetric

TOTAL RATES

Detector	Units	Exp. data	BP98	BP00
Ga	SNU	74.65 ± 5.13	129^{+8}_{-6}	130^{+9}_{-7}
Cl	SNU	2.56 ± 0.23	$7.7^{+1.2}_{-1.0}$	$8.0^{+1.2}_{-1.0}$
SK	$10^6 cm^{-2} s^{-1}$	2.40 ± 0.08	$5.15^{+0.99}_{-0.72}$	$5.31^{+1.00}_{-0.74}$

- Ga = SAGE $\oplus$ GALLEX $\oplus$ GNO
- Data at ν2000


Solar neutrino deficit
99% C.L. contours
(2 d.o.f. in each plane)
Data (2000)
SSM (BP98)
Cl (SNU)
SuperK/SSM
Ga (SNU)
Cl (SNU)



2ν oscillations
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
δm² (eV²)
SMA
LMA
LOW
VACUUM
2 d.o.f.
90 % C.L.
95 %
99 %
Cl+Ga+SK rates
10^-4
10^-3
10^-2
10^-1
1
10
tan²ω

Fit to rates only
(Ga + Cl + SK)

goodness of fit ↓

Solution	$\delta m^2/eV^2$	$\tan^2\omega$	χ^2	$P(\chi^2, dof)$
SMA	8.8×10^{-6}	9.6×10^{-4}	0.29	59 %
LMA	3.3×10^{-5}	0.33	3.53	6 %
LOW	8.9×10^{-8}	0.71	7.84	0.5 %
VAC	1.01×10^{-10}	0.89	0.30	58 %

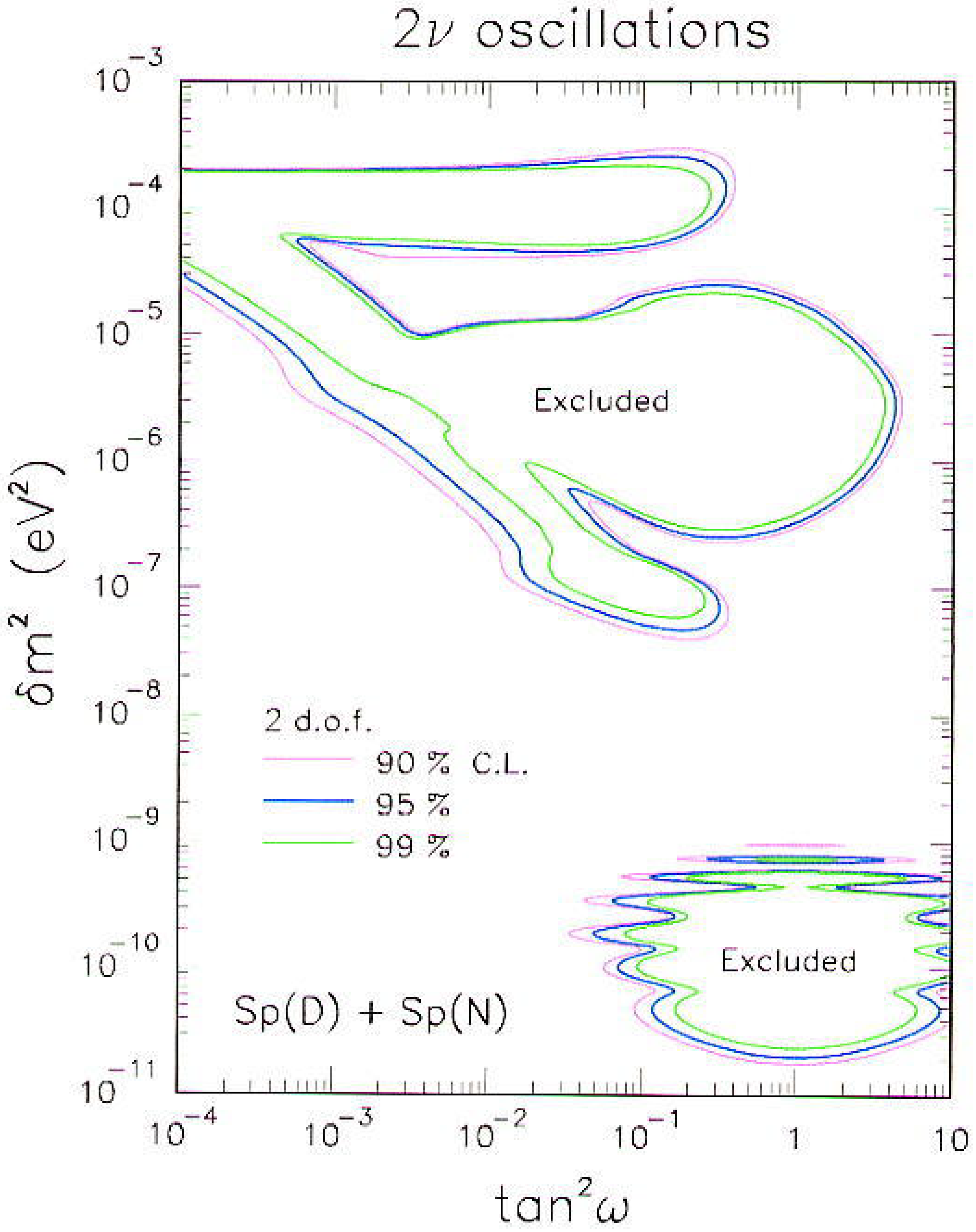
dof = 3 − 2 = 1

Relative likelihood of solutions is radically changed by SK spectrum ($D \oplus N$)

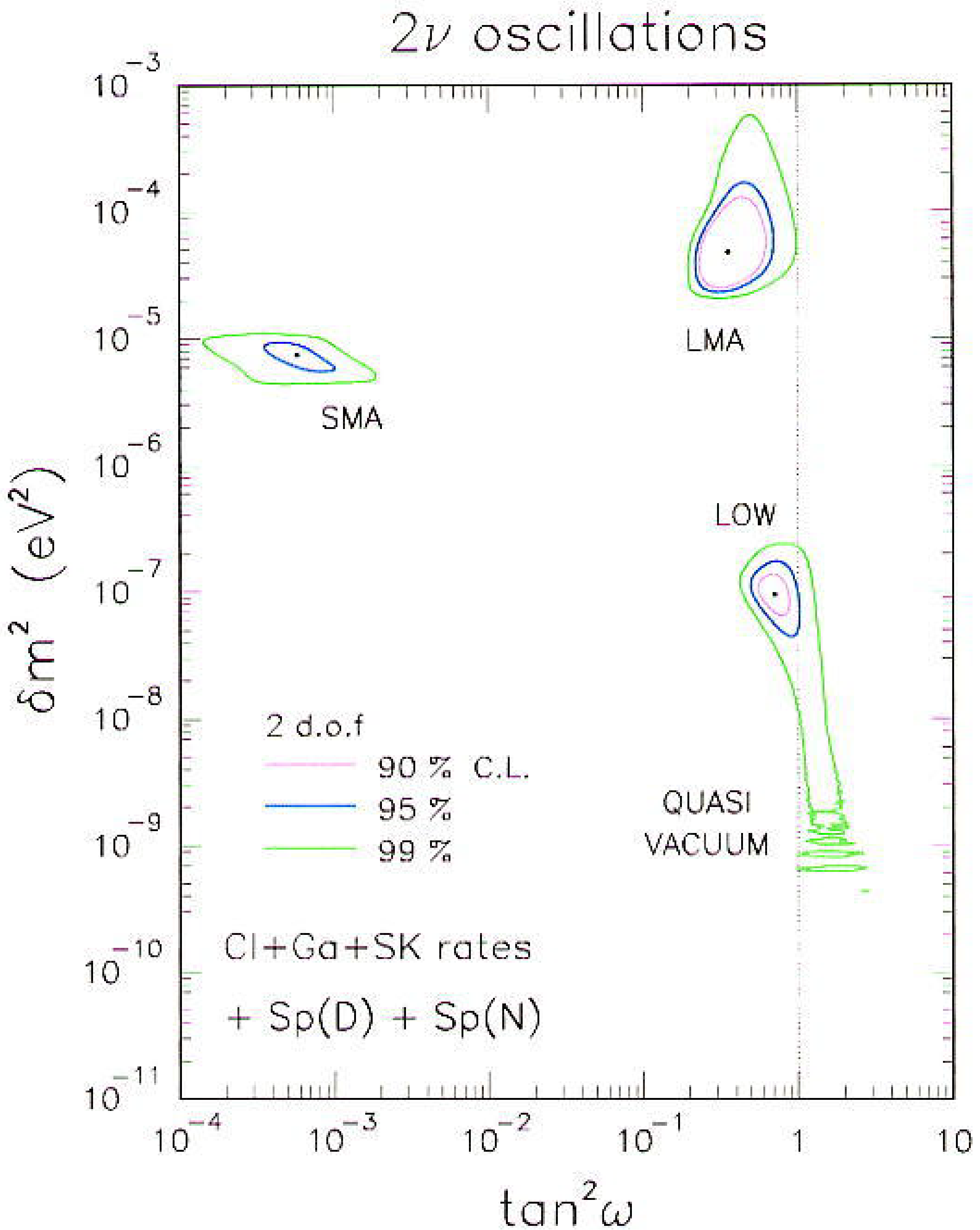
Spectrum is flat : $\chi^2(\text{flat}) = 32.8$

for 18 + 18 data
and free normalization

and is not improved (in χ^2) by oscillations significantly



2ν oscillations
δm² (eV²)
tan²ω
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻⁴
10⁻³
10⁻²
10⁻¹
1
10
Excluded
Excluded
2 d.o.f.
90 % C.L.
95 %
99 %
Sp(D) + Sp(N)



2ν oscillations
δm² (eV²)
tan²ω
LMA
SMA
LOW
QUASI
VACUUM
2 d.o.f
90 % C.L.
95 %
99 %
Cl+Ga+SK rates
+ Sp(D) + Sp(N)

Local χ^2 minima for Ga+Cl+Sk+Sp(D)+Sp(N) fit

Solution	$\delta m^2/eV^2$	$\tan^2\omega$	χ^2	$P(\chi^2, dof=36)$
SMA	7.7×10^{-6}	5.6×10^{-4}	40.7	27 %
LMA	4.6×10^{-5}	0.36	35.1	51 %
LOW	9.7×10^{-8}	0.71	38.7	35 %

↑ goodness of fit

- LMA : reasonable convergence of rates + spectrum fit
- SMA : fits rates much better than spectrum
- LOW : fits spectrum much better than rates
- VAC : disfavored in the lower part (just-so) by spectrum ; better fit for quasi-vacuum
- There are solutions at maximal mixing ($\omega=\pi/4$) and beyond (second octant). Such solutions are not octant symmetric
  → $\sin^2 2\theta$ clearly obsolete for solar ν analysis
- From the point of view of hypothesis test (absolute χ^2) hard to exclude any of the solutions, although LMA appears favored

Nakahata at NNN 00

Very recent results on

Hep neutrino

SSM_{BP98} prediction

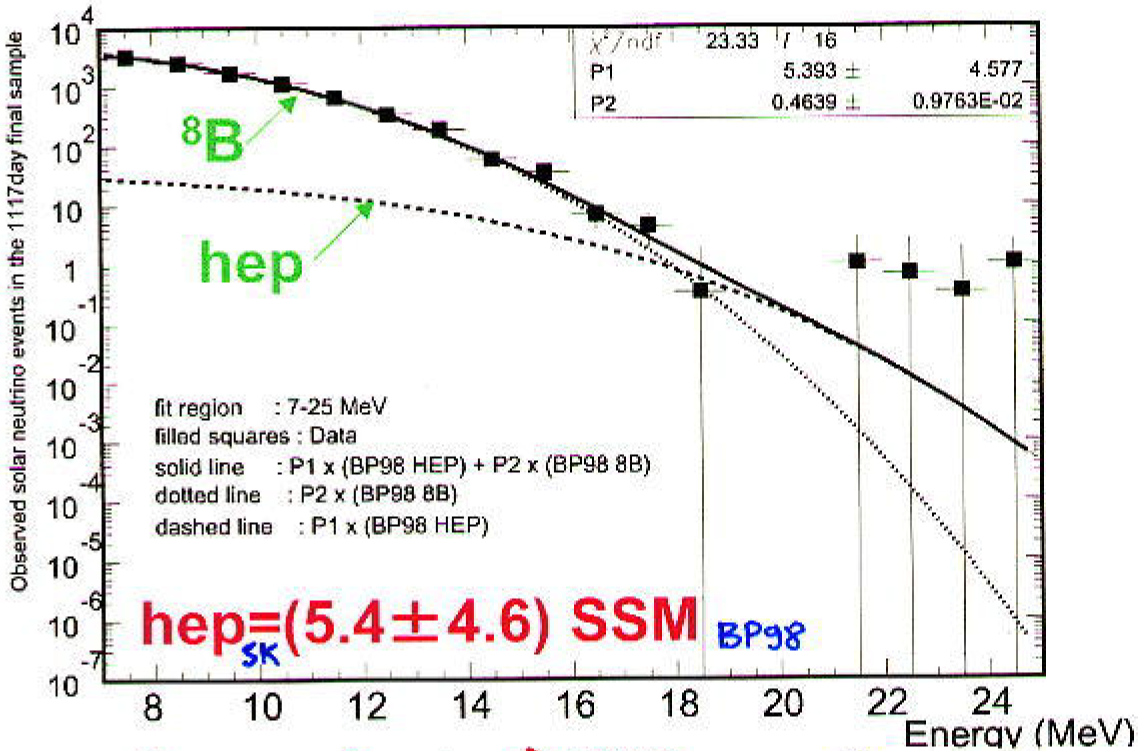
^{8}B-neutrino E_{max} = 15 MeV	$5.15 \times 10^{6}(1.00 \pm ^{0.19}_{0.14})$ /cm^2/s
Hep-neutrino E_{max} = 18.8 MeV ($S(0)_{hep} = 2.3 \times 10^{-20}$ keV·b)	2.10×10^{3} /cm^2/s (no error estimate)

Note: recent work by L.E.Marcucci et al. (nucl-th/0006005)

hep flux : a factor of ~4.5 larger than SSM_{BP98}

$S(0)_{hep}$ = (10.1 ± 0.6 keV·b) ← now incorporated in BP00

SK spectrum fit

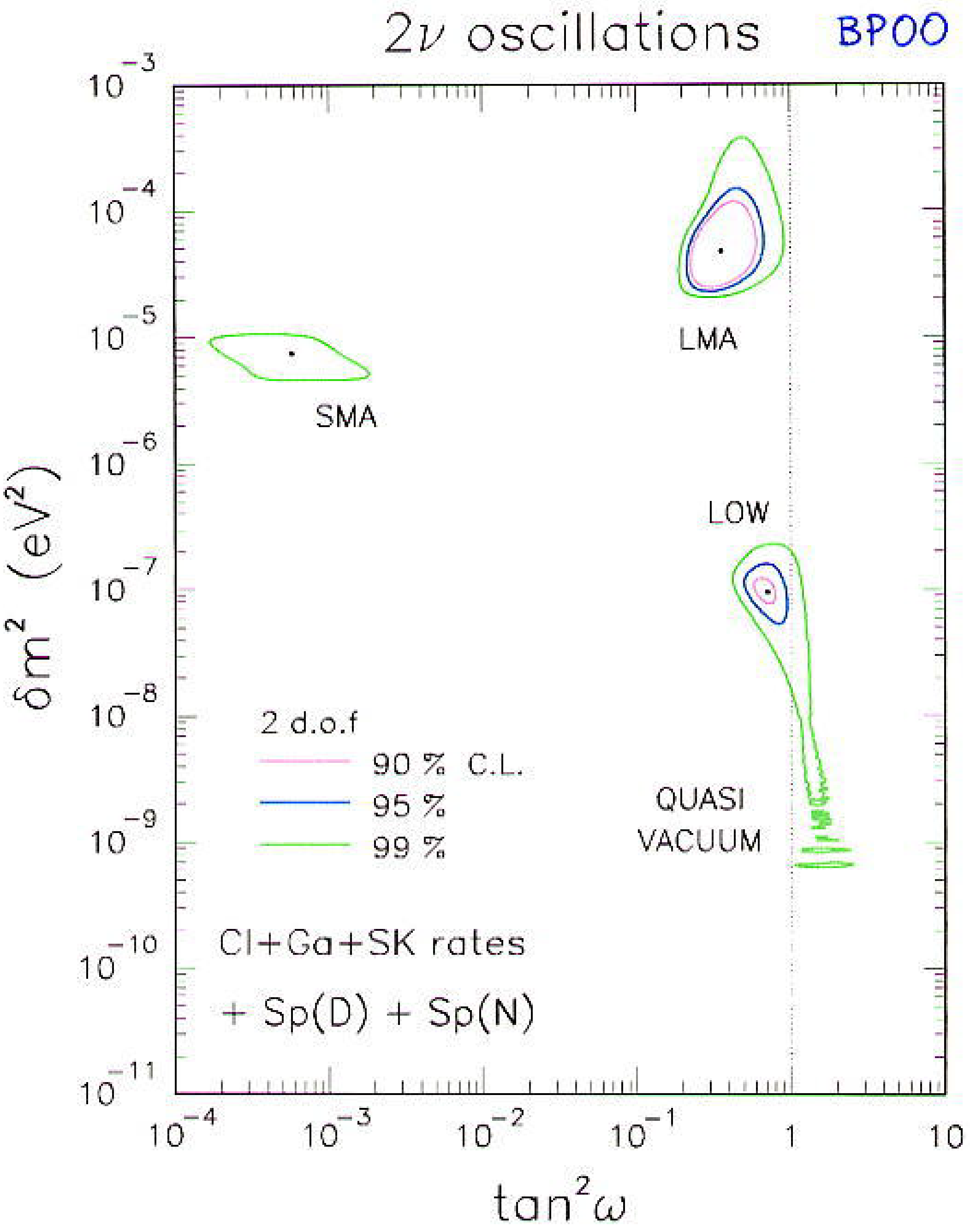


$hep_{SK} \cong (1.2 \pm 1)\ SSM_{BP00}$!!!

Bahcall at NOW 2000

Standard Model Predictions (BP00)

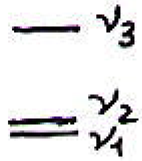
Source	Flux	Cl	Ga
	$(10^{10}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1})$	(SNU)	(SNU)
pp	$5.94(1.00^{+0.01}_{-0.01})$	0.0	69.7
pep	$1.39\times10^{-2}(1.00^{+0.01}_{-0.01})$	0.22	2.8
hep	9.2×10^{-7}	0.04	0.0
^{7}Be	$4.88\times10^{-1}(1.00^{+0.09}_{-0.09})$	1.17	35.0
^{8}B	$5.31\times10^{-4}(1.00^{+0.19}_{-0.14})$	6.06	12.7
^{13}N	$6.18\times10^{-2}(1.00^{+0.19}_{-0.13})$	0.11	3.7
^{15}O	$5.45\times10^{-2}(1.00^{+0.22}_{-0.15})$	0.37	6.2
^{17}F	$6.50\times10^{-4}(1.00^{+0.12}_{-0.11})$	0.0	0.1
		$8.0^{+1.2}$	[illegible]



- larger hep flux in BP00 SSM
  - → SK spectrum excess in high-energy tail "absorbed" by standard predictions
  - → SK/SSM_{00} even flatter than SK/SSM_{98}
  - → SMA, QV solutions shrink slightly

SOLAR 3ν OSCILLATIONS

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



Standard CKM ordering happens to be useful also for neutrino phenomenology:

$$U = \begin{pmatrix}1 & 0 & 0\\ 0 & c_\psi & s_\psi\\ 0 & -s_\psi & c_\psi\end{pmatrix}\begin{pmatrix}c_\varphi & 0 & s_\varphi\\ 0 & 1 & 0\\ -s_\varphi & 0 & c_\varphi\end{pmatrix}\begin{pmatrix}c_\omega & s_\omega & 0\\ -s_\omega & c_\omega & 0\\ 0 & 0 & 1\end{pmatrix}$$

↑

ψ-rotations act in the (ν_μ, ν_τ) subspace → irrelevant for solar ν

Solar ν parameters: $(\delta m^2, \omega, \varphi)$

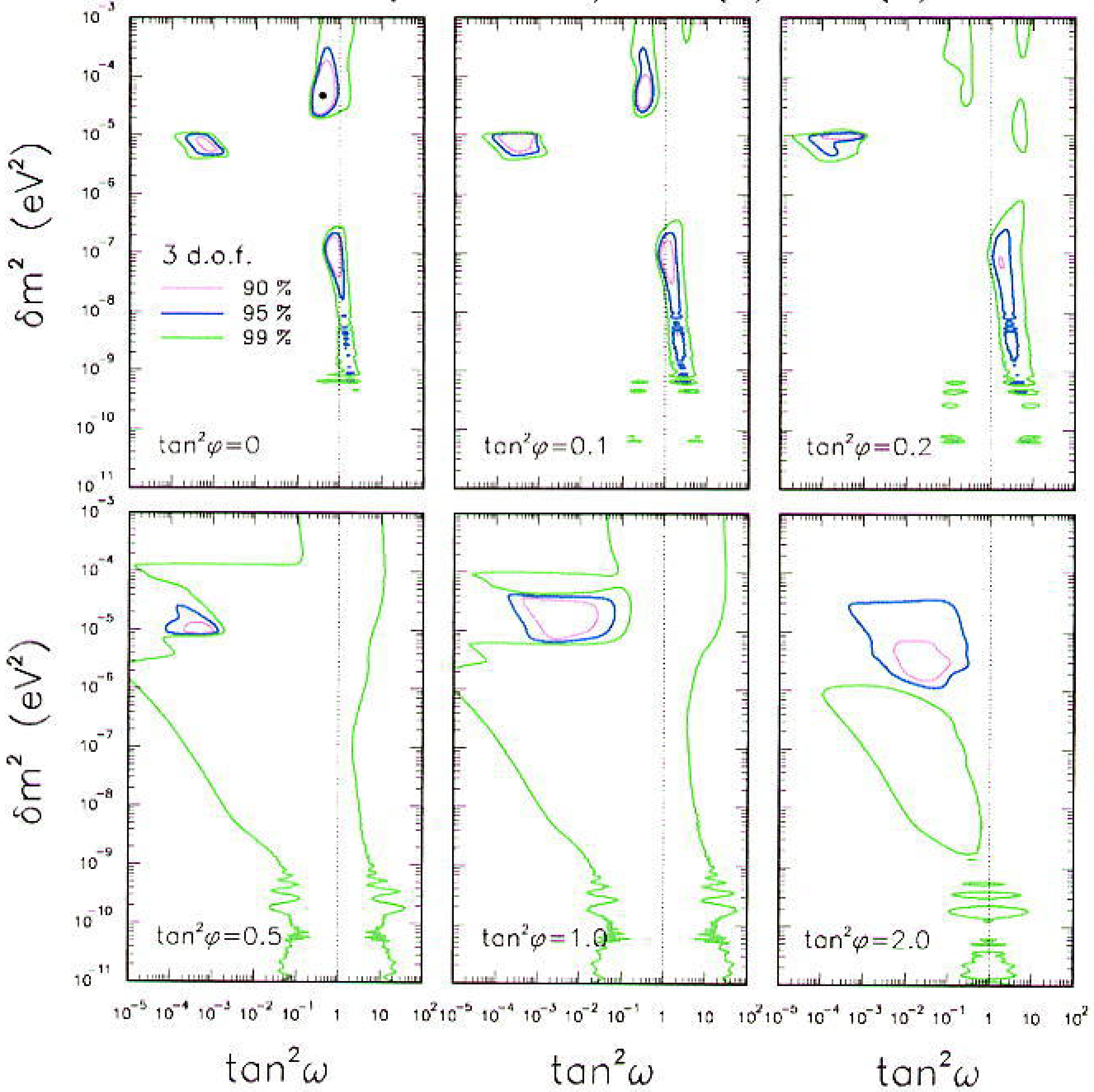
(φ ↑ θ_{13})

Remark: U is more and more often being named after Maki-Nakagawa-Sakata, $U = U_{MNS}$.
I don't see reasons to drop "P" (for Pontecorvo):

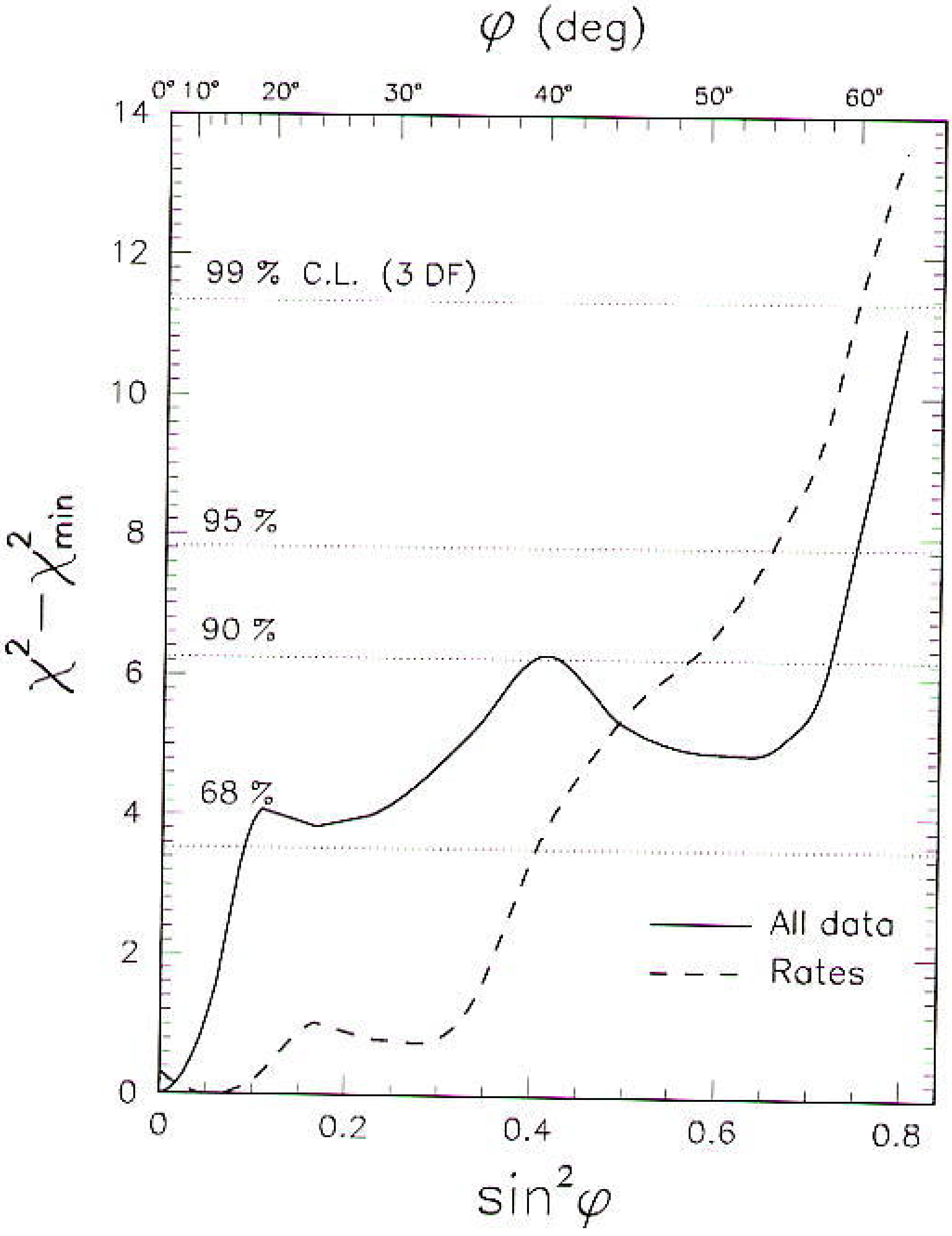
$$U = U_{PMNS} \quad !$$

3ν oscillations:

Rates(Cl+Ga+SK) + SP(D) + SP(N)



- For small φ, interesting changes around $\omega = \pi/4$
- Radical changes for large φ ← but excluded by CHOOZ
- Fit with $\varphi = \theta_{13}$ free important for consistency check



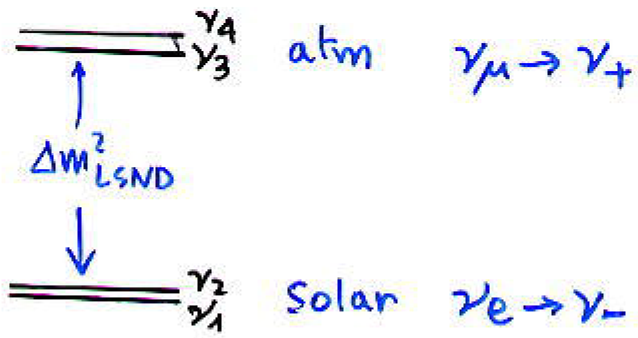
δm^2 and $\tan^2\omega$ unconstrained

- Solar ν data prefer small $\varphi = \theta_{13}$
- → Consistent with atmos. 3ν fit
- → Consistent with CHOOZ
- → OVERALL CONSISTENCY OF 3ν SCENARIO WITH SMALL U^2_{e3}

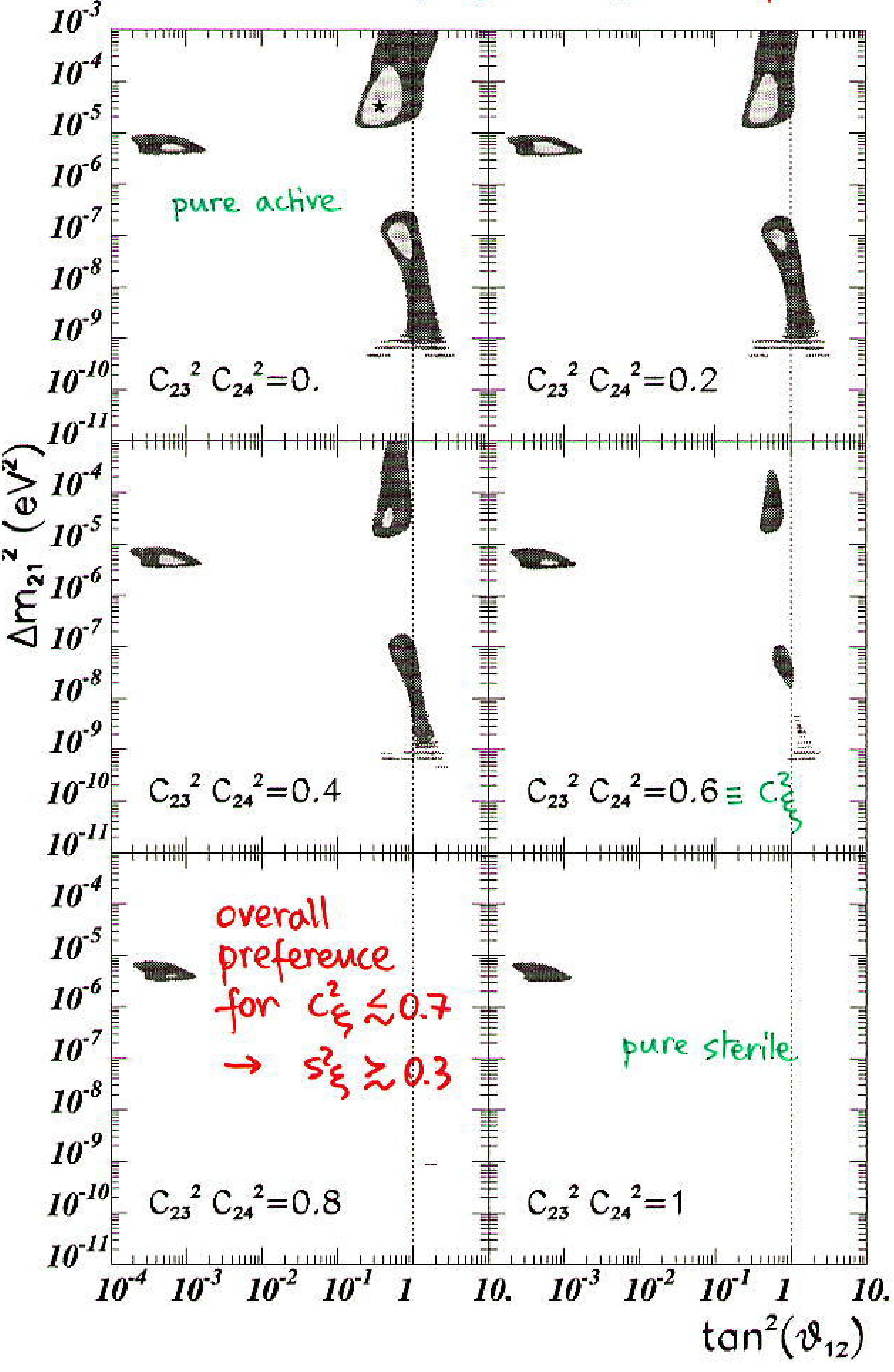
SOLAR 4ν OSCILLATIONS

$$\nu_e \to \nu_- = \cos\xi \, \nu_s - \sin\xi \, \nu_\tau$$

active + sterile
oscillations



Giunti, Peña-Garay, and Gonzalez-Garcia



SUMMARY OF PARAMETER ESTIMATION

(2ν, 3ν, 4ν)

Atmospheric ν data indicate that one mass eigenstate (say, ν_m) must be dominantly coupled with ν_μ :

$$\nu_m = A_e \nu_e + A_\mu \nu_\mu + A_\tau \nu_\tau + A_s \nu_s$$

$A_\mu^2 \sim \mathcal{O}(1/2)$, $A_e^2 + A_\mu^2 + A_\tau^2 + A_s^2 = 1$

We have studied three scenarios :

SCENARIO	A_e	A_μ	A_τ	A_s
2ν ($\nu_m = \nu_2$)	–	S_ψ	C_ψ	–
3ν ($\nu_m = \nu_3$)	S_φ	$C_\varphi S_\psi$	$C_\varphi C_\psi$	–
4ν ($\nu_m = \nu_4$)	–	S_ψ	$C_\xi C_\psi$	$S_\xi C_\psi$

$2\nu, 3\nu, 4\nu$:

$$\log_{10} \frac{m^2}{eV^2} \simeq -2.5 \pm 0.3$$

$$\sin^2\psi \simeq 0.5 \pm 0.17$$

3ν : $\sin^2\varphi \lesssim 0.31$ (SK)

$\lesssim 0.04$ (SK+CHOOZ)

4ν : $\sin^2\xi \lesssim 0.67$

$\sim$ pure $\nu_\mu \leftrightarrow \nu_\tau$ favored. Upper bounds on additional ν_e and ν_s mixing.

ATM 4ν ANALYSIS $\rightarrow$ $\sin^2\xi \lesssim 0.7$
(Fogli, E.L., Marrone)*

SOLAR 4ν ANALYSIS $\rightarrow$ $\sin^2\xi \gtrsim 0.3$
(Giunti, Gonzalez-Garcia, Peña-Garay)

- Consistent for $s^2_\xi \simeq 0.5 \pm 0.2$
- Specific case: $s^2_\xi \equiv 0.5$ $\rightarrow$

$$\nu_e \leftrightarrow \nu_- = \frac{1}{\sqrt{2}}(\nu_s - \nu_\tau)$$

$$\nu_\mu \leftrightarrow \nu_+ = \frac{1}{\sqrt{2}}(\nu_s + \nu_\tau)$$

"Fourfold maximal mixing" !
(50% active + 50% sterile oscillations for both solar and atmospheric ν)

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* See also O. Yasuda

CONCLUSIONS

- Current bounds on 2ν, 3ν, 4ν oscillation parameters have been reviewed
- Atmospheric 2ν bounds on Δm^2_{atm} and one mixing angle (ψ) robust; not altered by extension to 3ν, 4ν
- Solar 2ν analysis still allow multiple solutions for Δm^2_{solar} and another mixing angle (ω); multiplicity still present, to some extent, in 3ν and 4ν extensions
- Overall consistency among solar, atm., CHOOZ data obtained in 3ν scenario for small values of U^2_{e3}. No evidence for $U^2_{e3} \neq 0$
- Overall consistency among solar, atm., LSND data obtained in 4ν scenario (with 2+2 spectrum) for $\sim 50\%\ \nu_s + 50\%\ \nu_\tau$ oscillations of both ν_e (solar) and ν_μ (atm.)
- A lot of exp+theo work to be done to fix unambiguously Δm^2_{ij} and $U_{PMNS}(\theta_{ij})$