Neutrino Oscillations: A Global Analysis

XXIII Physics in Collision

Zeuthen, June 26, 2003

Outline:

- The three-neutrino parameters
- Impact of atmospheric + K2K experiments
- Impact of CHOOZ
- Impact of solar neutrino experiments + KamLAND
- Conclusions

Based on work done in collaboration with:
E. Lisi, A. Marrone, D. Montanino, A. Palazzo, A.M. Rotunno

Introduction

- We have now compelling evidence that the Hamiltonian of ν flavor evolution

$$i\,\frac{d\nu_{\alpha}}{dt} = H^{\beta}_{\alpha}\,\nu_{\beta} \qquad \text{is non-trivial:} \qquad H^{\beta}_{\alpha} \neq E_{\nu}\bullet\delta^{\beta}_{\alpha}$$

- Barring LSND data, all differences from triviality ($\equiv$ massless neutrinos) are consistent with a 3ν oscillation framework:

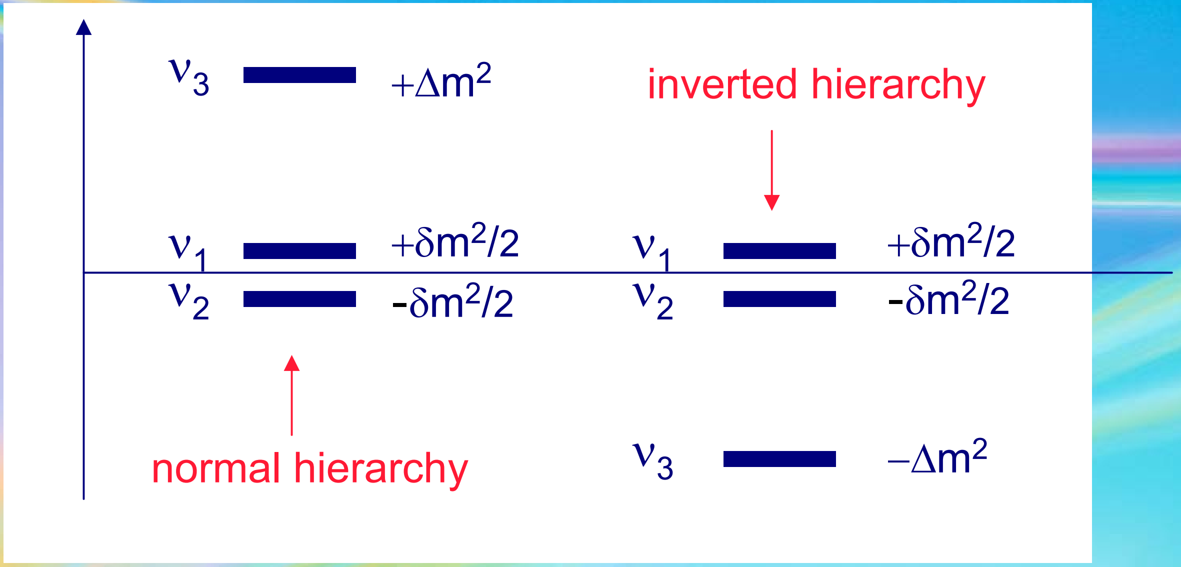
$$\Delta H^{\beta}_{\alpha} = (\Delta H_{kin} + \Delta H_{dyn})^{\beta}_{\alpha} = \left(\underbrace{\frac{UM^{2}U^{+}}{2E}}_{\text{kinematical mass-mixing term}} + \underbrace{V}_{\text{dynamical MSW term (in matter)}}\right)_{3\times3}$$

- We have entered the precision era in the determination of ΔH_{kin}, and we are starting to probe the features of ΔH_{dyn} in matter. In the following we review the current status of (kin + dyn) constraints.

Notation

- Mixing parameters: $U = U(\theta_{12}, \theta_{13}, \theta_{23}, \delta)$ as for CKM matrix

- Mass-gap parameters: $$M^2 = \left(\underbrace{-\frac{\delta m^2}{2}, +\frac{\delta m^2}{2}}_{\text{“solar”}}, \underbrace{\pm \Delta m^2}_{\text{“atmospheric”}} \right)$$



ν_3 $+\Delta m^2$

inverted hierarchy

ν_1 $+\delta m^2/2$ ν_1 $+\delta m^2/2$

ν_2 $-\delta m^2/2$ ν_2 $-\delta m^2/2$

normal hierarchy

ν_3 $-\Delta m^2$

conventional zero

⇩

Should be set by direct mass measurements:

- β-decay
- 0ν2β-decay
- “W-MAP”

- Dynamical term (MSW): $$\begin{pmatrix} \pm 2^{1/2} G_F N_e E_\nu & & \\ & 0 & \\ & & 0 \end{pmatrix}$$

Impact of atmospheric + K2K neutrinos

$\left\{\begin{array}{l}\Delta m^2\\ \theta_{23}\end{array}\right.$ can be basically taken from the 2ν analysis of $\left\{\begin{array}{l}\text{SK}\\ \text{K2K}\end{array}\right.$ data

since they are not significantly perturbed by 3ν effects induced by small θ_{13} or $\delta m^2/\Delta m^2$ (at least within the current picture).

⇓

this also implies no real sensitivity to sign(Δm^2) or δ_{CP}

Let us anticipate the results of SK + K2K constraints:

$$\left\{\begin{array}{l}\Delta m^2 = (2.6 \pm 0.4) \times 10^{-3}\ \text{eV}^2\\ \sin^2 2\theta_{23} = 1.00\ {}^{+\,0.00}_{-\,0.05}\end{array}\right.$$

→

new feature:
these errors now scale linearly up to ~3σ (it was not the case prior to K2K and with the older SK data)

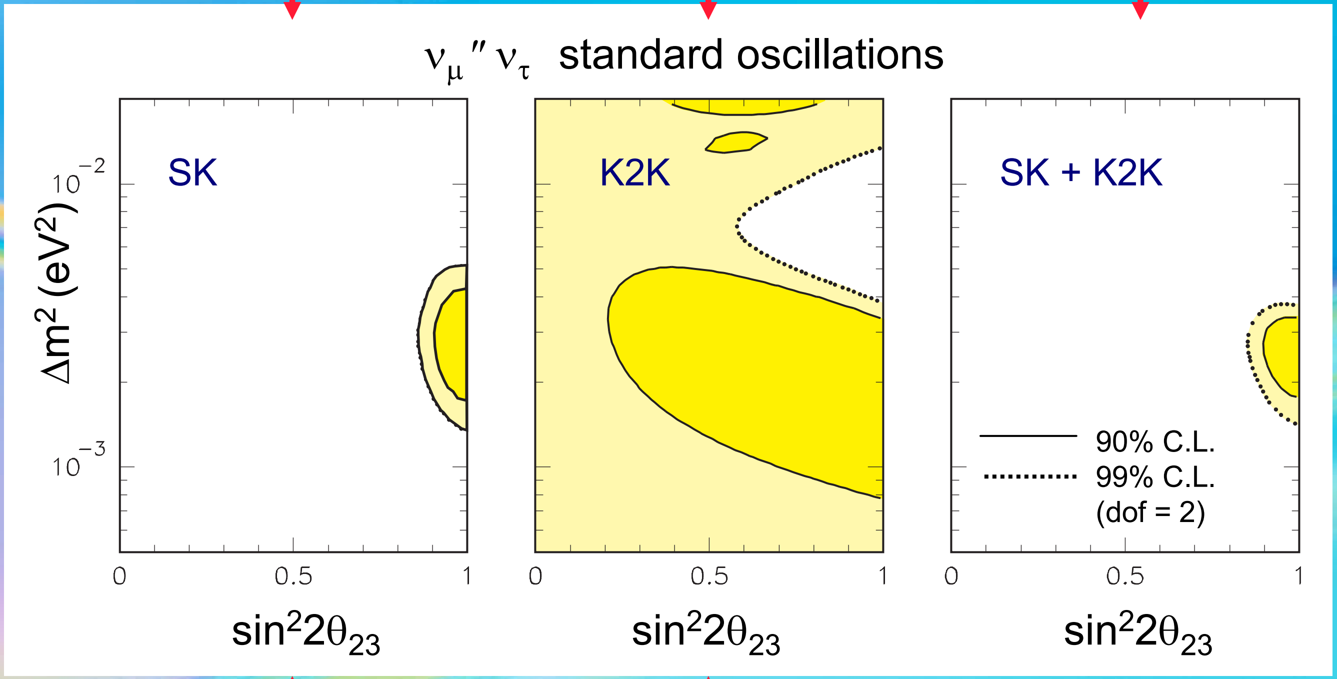
2ν analysis of SK + K2K

(GLF, E. Lisi, A. Marrone and D. Montanino, hep-ph/0303064)

our reanalysis of SK zenith distributions (92 kTy data)

our reanalysis of K2K spectral data (29 spectrum events)

combination of SK + K2K



new: ⇨

Contains a detailed analysis of systematic uncertainties

new analysis of K2K spectrum in 6 bins

Bounds on Δm^2 from SK and K2K

Combination of SK and K2K:

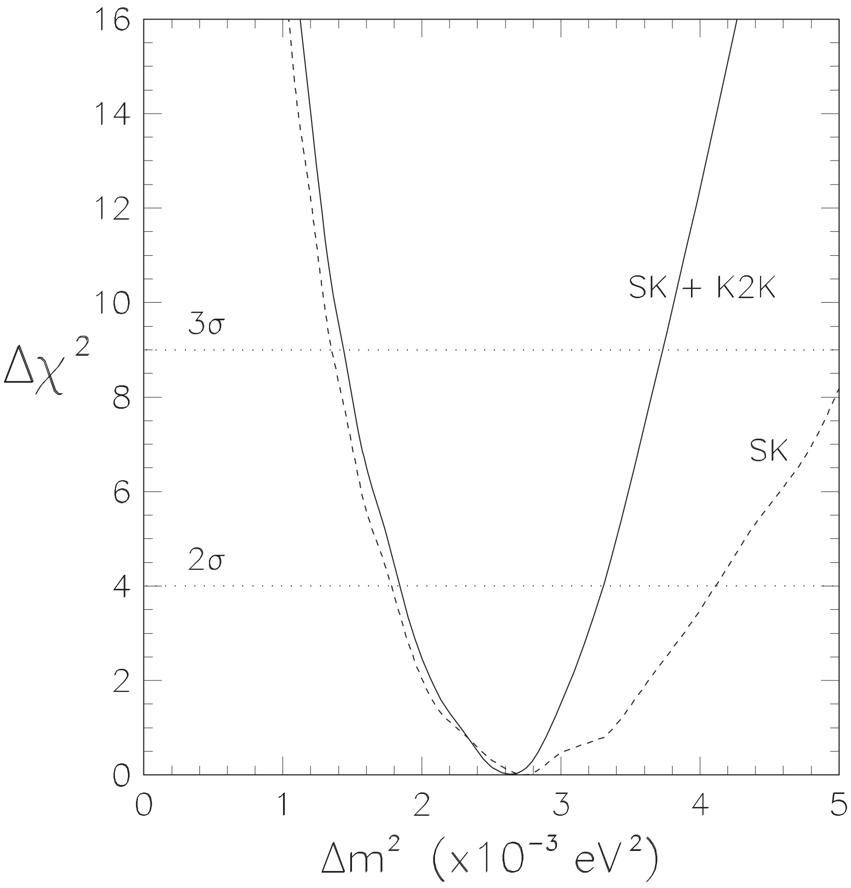
- almost “parabolic” likelihood
- errors well-defined

$\Delta m^2 \approx (2.6 \pm 0.4) \times 10^{-3}$ eV^2 (at 1σ!)

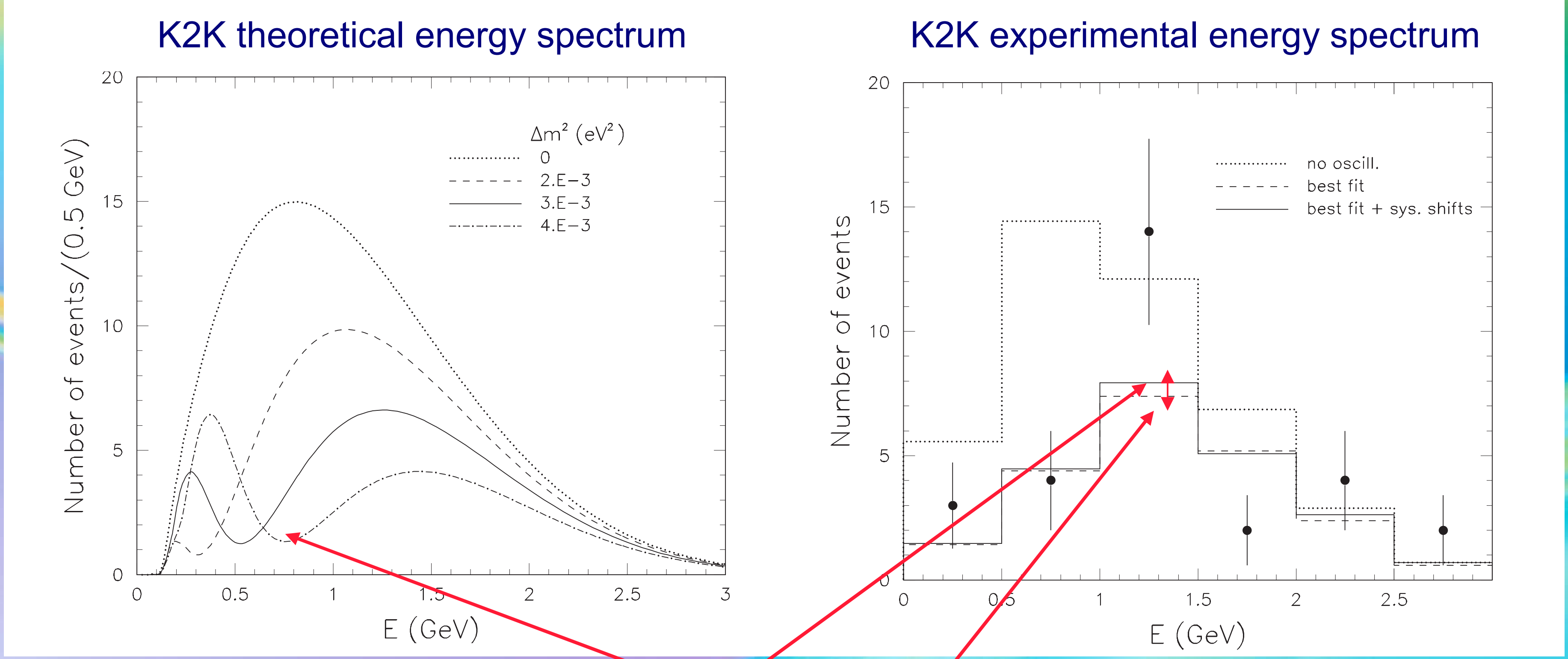
- K2K decisive to strengthen the upper bound on Δm^2

Why?

Bounds on Δm^2 for unconstrained $\sin^2\theta$



K2K energy spectrum


K2K theoretical energy spectrum

K2K experimental energy spectrum

- For Δm^2 slightly above 3×10^{-3} eV^2 (e.g. 4×10^{-3} eV^2) the oscillation minimum is just at the K2K spectrum peak, giving excessive suppression, while $2\div3\times10^{-3}$ eV^2 gives the right amount of ν_μ disappearance

- The amount of systematic error shifts preferred by data is very small if compared to stat. errors: K2K is dominated by stat. errors, and can be largely improved by higher statistics

SK zenith distributions

In SK data, statistics is instead high enough to make systematic errors comparable

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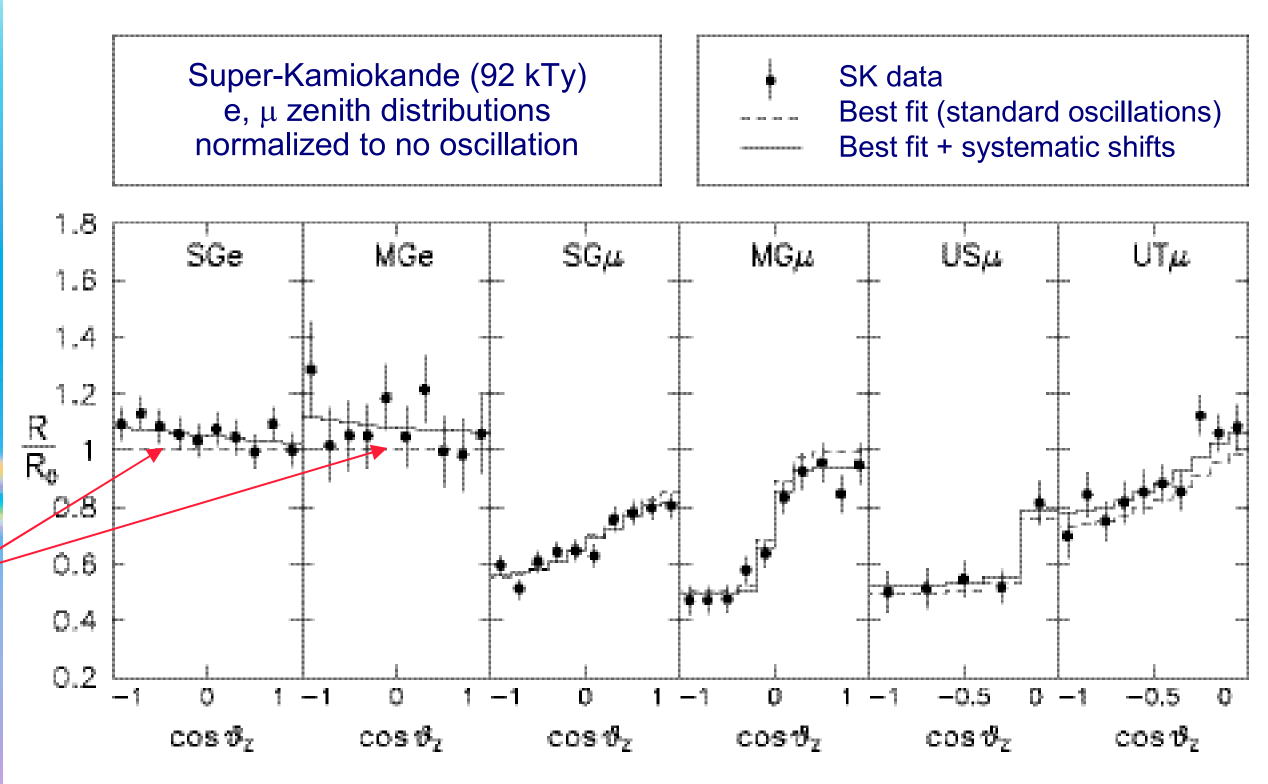
Note how systematic shifts pull e-like events to higher normalization, due to the still unsettled feature of “electron event excess”


Super-Kamiokande (92 kTy)
e, μ zenith distributions
normalized to no oscillation

⬇

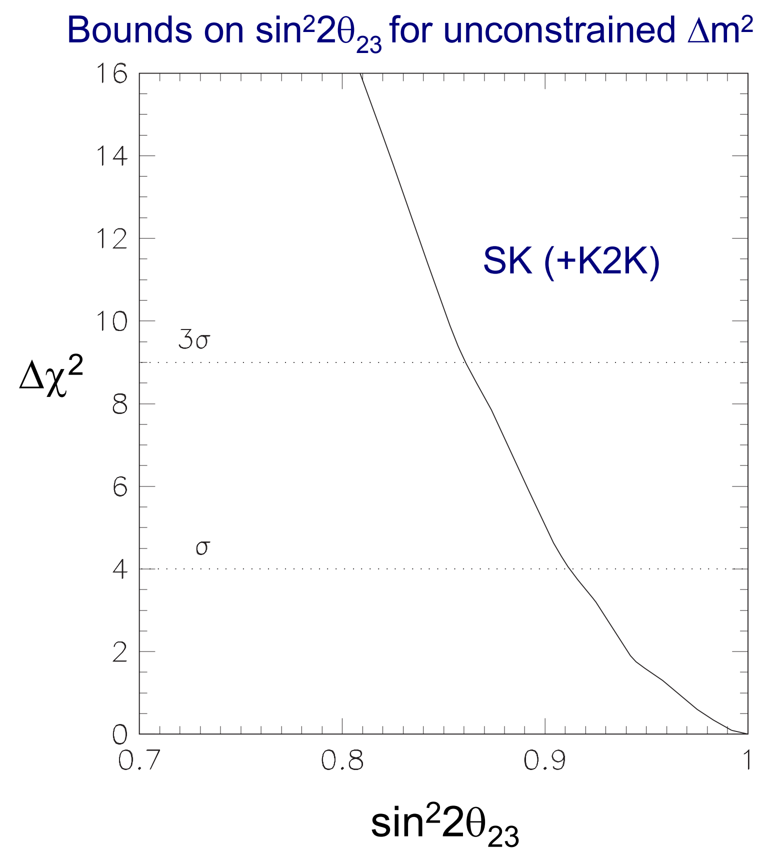
Difficult to assess a possible relation with subleading 3ν effects

$\theta_{13} \neq 0$?

high-δm^2 ?

➡ whose size is comparable to systematic errors

Bounds on $\sin^2 2\theta_{23}$



As for Δm^2, we can bound $\sin^2 2\theta_{23}$:

- likelihood "parabolic" also in this case.
- K2K impact negligible in this case

$$\sin^2 2\theta_{23} = 1.00 \begin{matrix} + 0.00 \\ - 0.05 \end{matrix} \qquad (1\sigma)$$

Impact of CHOOZ

While atmospheric (SK) and K2K bounds on $(\Delta m^2, \theta_{23})$ can be studied well in the 2ν approximation, a 3ν analysis is mandatory for CHOOZ:

$$P_{ee}^{\mathrm{CHOOZ}} = P_{ee}^{\mathrm{CHOOZ}} (\delta m^2, \theta_{12}, \theta_{13}, \Delta m^2)$$ survival ν_e probability

In practice, Δm^2 is marginalized away in the χ^2 construction, by adding the "atmospheric + K2K" likelihood:

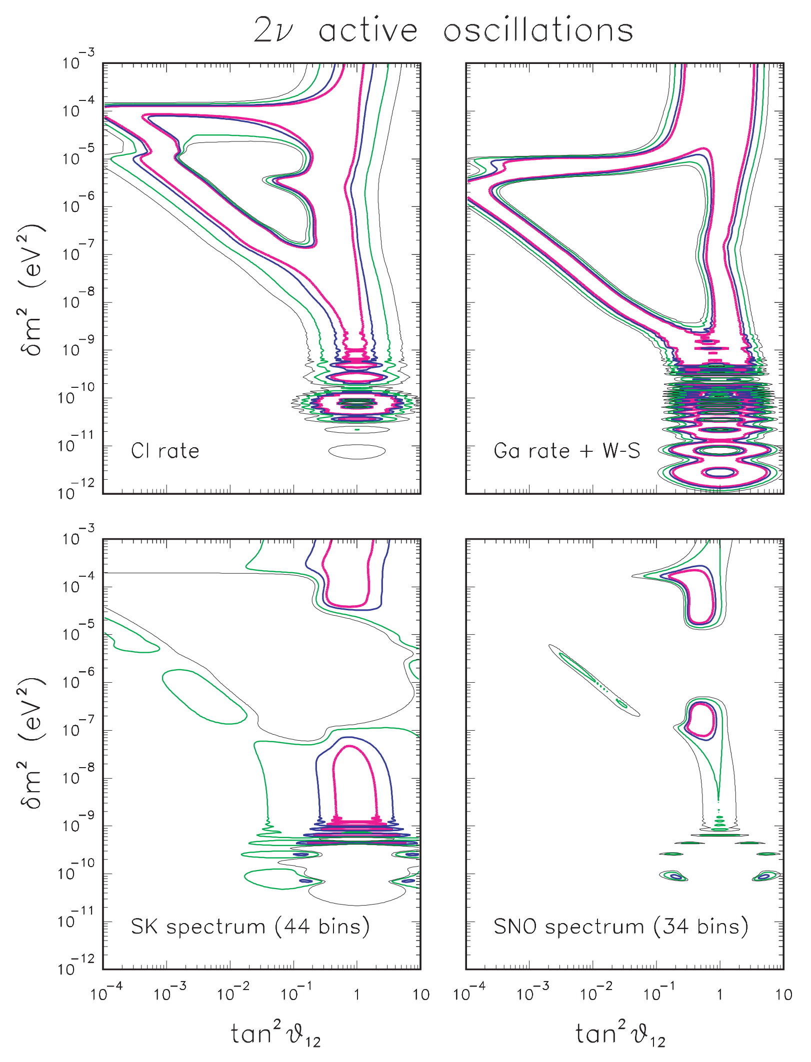
$$\chi^2_{\substack{\mathrm{CHOOZ,}\\ \mathrm{ATM,}\\ \mathrm{K2K}}} = \min_{(\Delta m^2,\, \theta_{23})} \left[\chi^2_{\mathrm{CHOOZ}} (\delta m^2, \theta_{12}, \theta_{13}, \Delta m^2) + \chi^2_{\mathrm{ATM,\ K2K}} (\Delta m^2, \theta_{23})\right] =$$

$$= \chi^2 (\delta m^2, \theta_{12}, \theta_{13})$$

This is what is effectively combined with "solar + KamLAND" data that depend on

$$(\delta m^2, \theta_{12}, \theta_{13})$$

Solar neutrinos before KamLAND



Four types of solar neutrino experiments:

- Chlorine (rate)
- Gallium (Ga rate + W-S effect)
- SK spectrum (44 bins)
- SNO spectrum (34 bins)

An interesting point:

High δm^2 or, equivalently, $<P_{ee}> \sim 1/2$ not ruled out by any single experiment yet, although Cl and SNO disfavor this solution

Solar problem: status before KamLAND

By combining the four solar experiments, only the large mixing angle solutions are seen to survive:

- LMA: preferred by data, below the maximal mixing line
- LOW: at lower δm^2, with a long tail in the quasi-vacuum region

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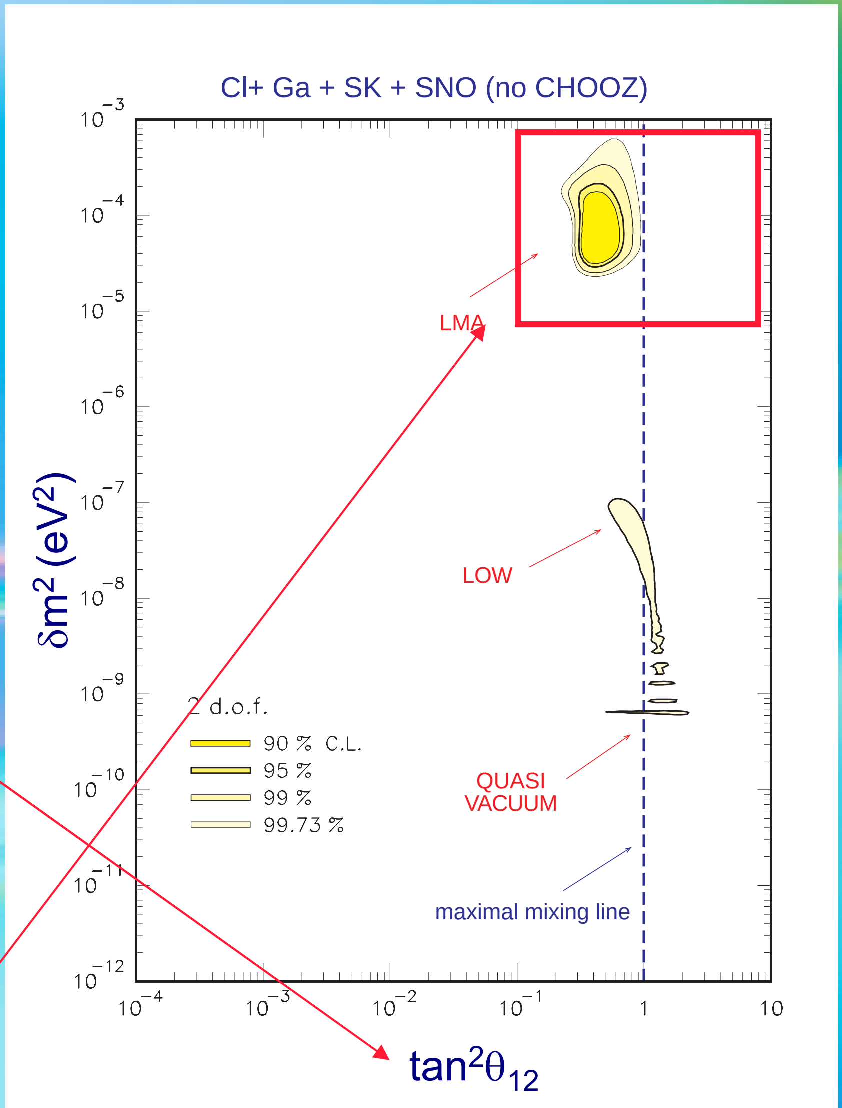
Large mixing: $$\underset{\text{(log)}}{\tan^2\theta_{12}} \longrightarrow \underset{\text{(linear)}}{\sin^2\theta_{12}}$$



Moreover, KamLAND selects only relatively high values of δm^2

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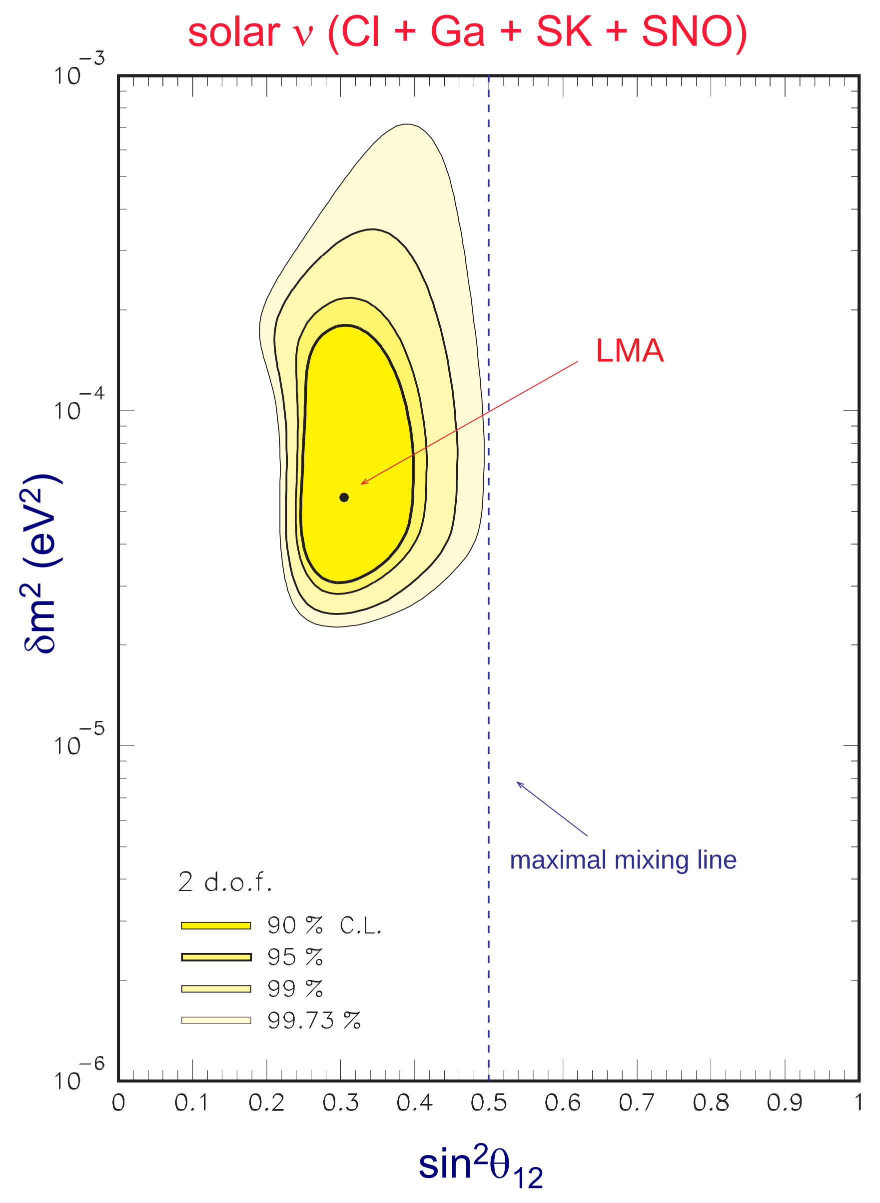
We are restricted to a very small region in the parameter space!

Solar data with and without CHOOZ

Concerning the upper bound on δm^2 coming from solar ν experiments:

- There exists an upper bound on δm^2 from all solar ν exps. combined



Solar data with and without CHOOZ

Concerning the upper bound on δm^2 coming from solar ν experiments:

- There exists an upper bound on δm^2 from all solar ν exps. combined
- Not very dissimilar to the safe upper bound on δm^2 from CHOOZ

However, we cannot exclude yet rather high values of δm^2 (~few×10^{-4} eV^2), consistent with

$$\boxed{\langle P_{ee} \rangle \sim 1/2}$$

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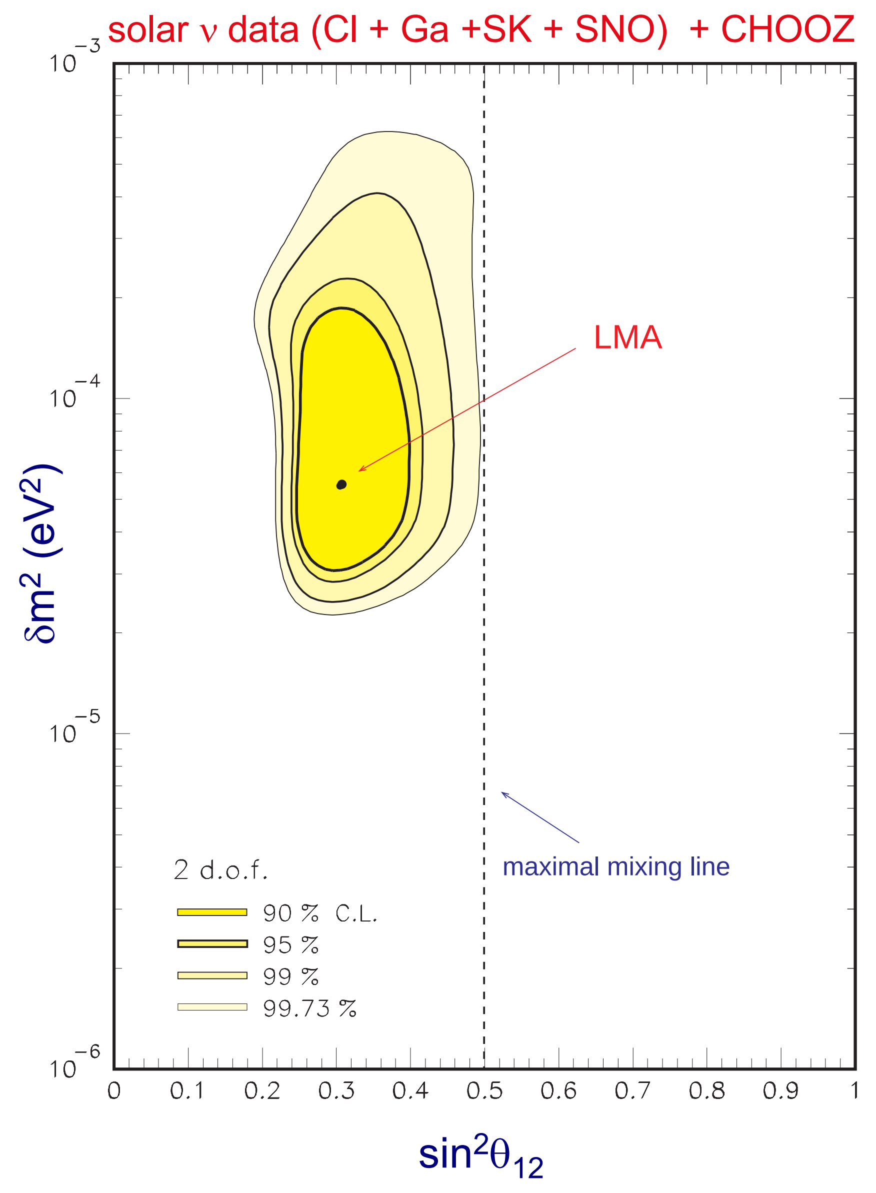
not easy to see MSW effects responsible for $P_{ee} < 1/2$



Role of SNO in constraining $\langle P_{ee} \rangle$

By comparing ES, CC and NC fluxes measured by SNO:

- extremely good confirmation of the SSM
- clear evidence of active oscillations
- preferred $\langle P_{ee} \rangle \sim 1/3$
- but current data not compelling yet

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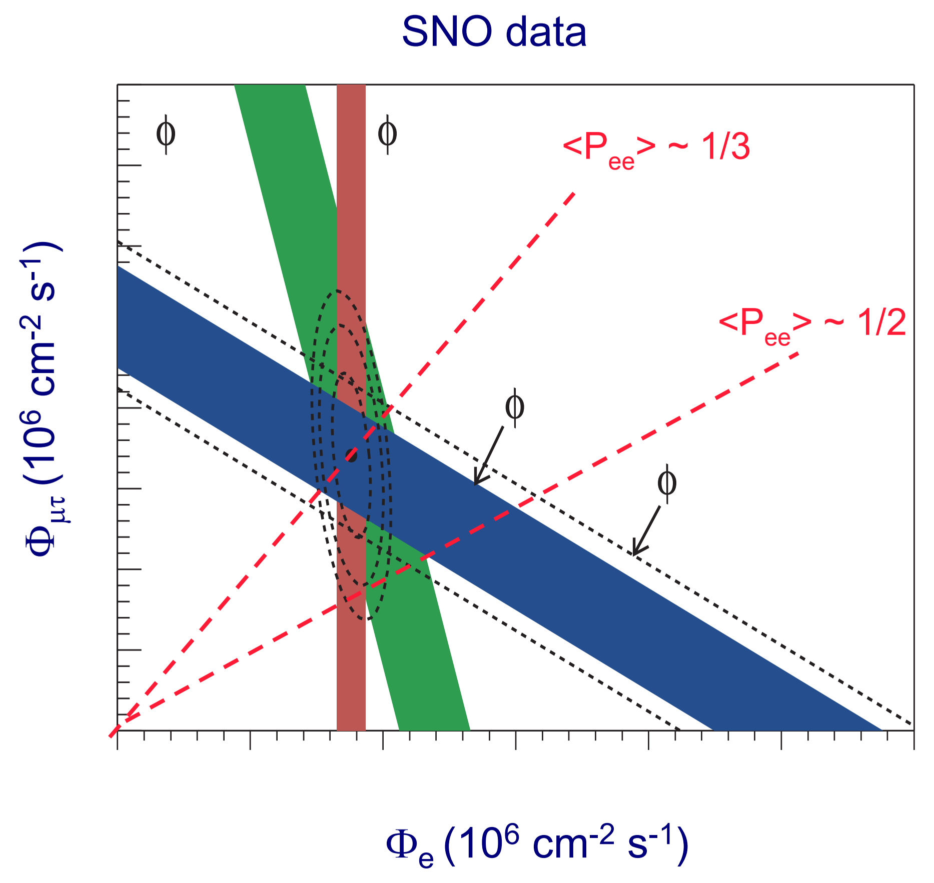
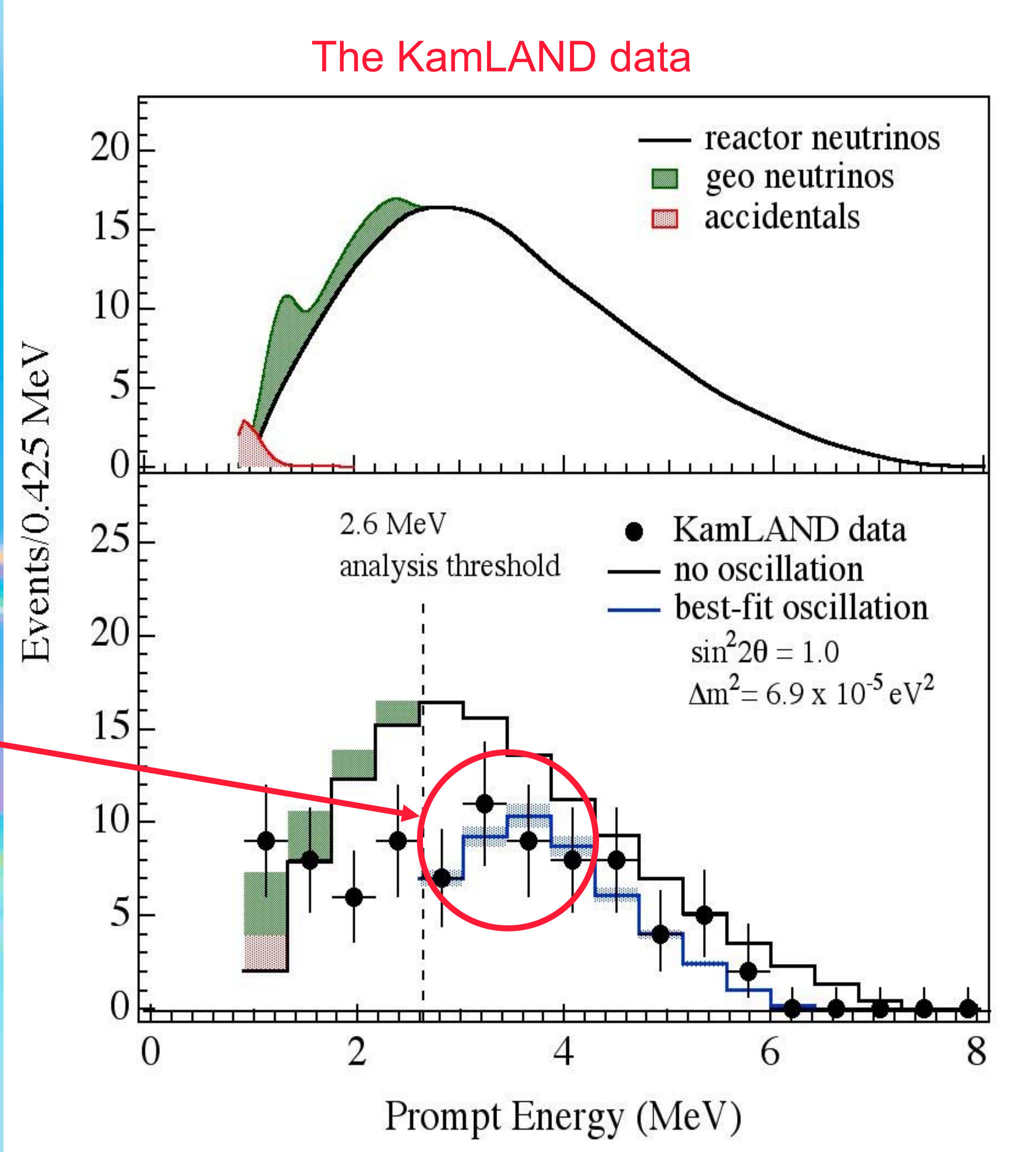
$\langle P_{ee} \rangle \sim 1/2$ not ruled out



The KamLAND data

- The KamLAND total rate singles LMA out
- The KamLAND spectrum fixes the LMA sub-structure:

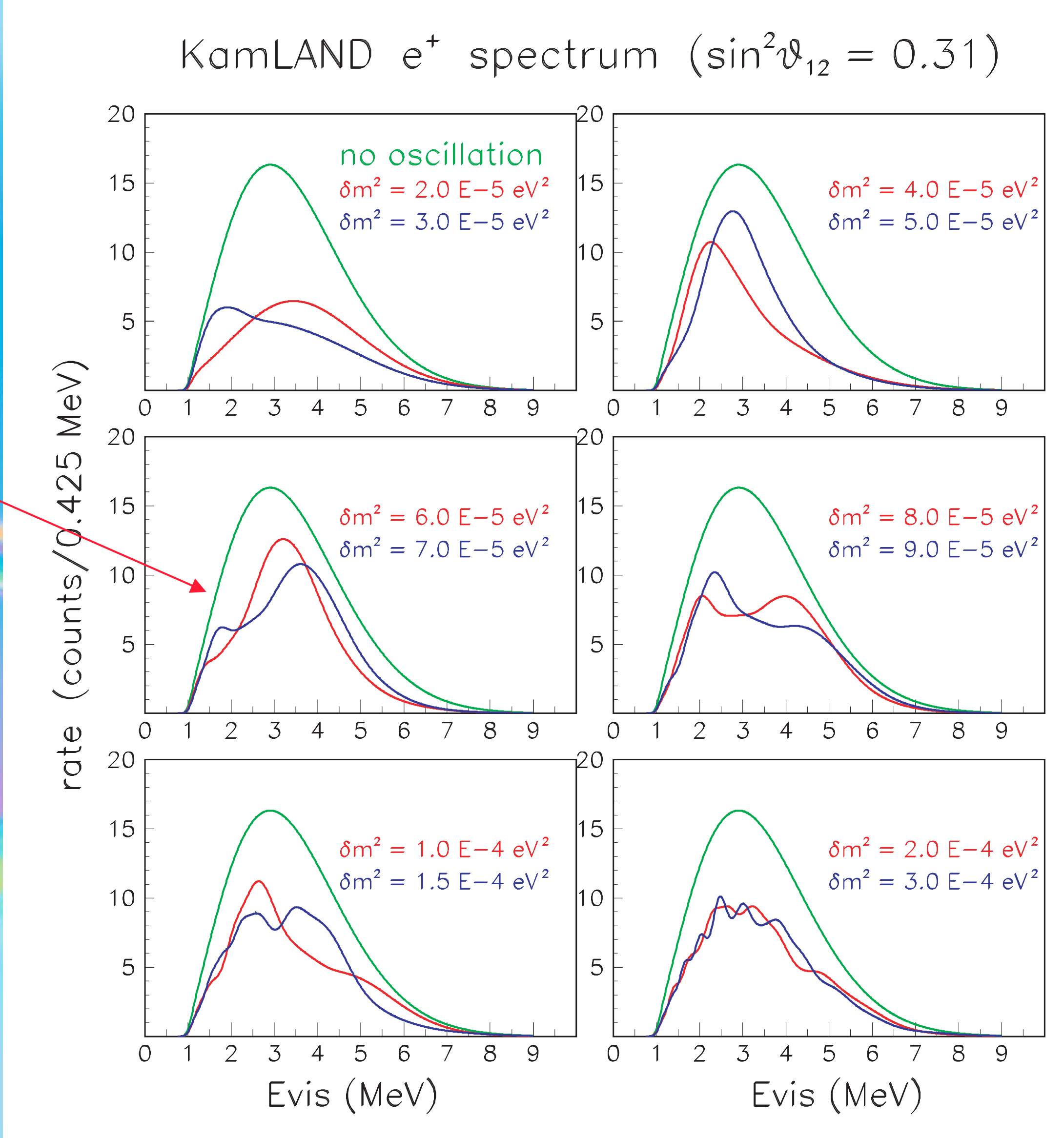
Above the analysis threshold (2.6 MeV) the “bulk” of the spectrum (first 4 bins above threshold) seems more suppressed than the “tail”



The KamLAND e^+ spectrum

For given $\sin^2\theta_{12}$ we can compare the spectra expected for different values of δm^2.

In particular we can select the values near to the best fit.



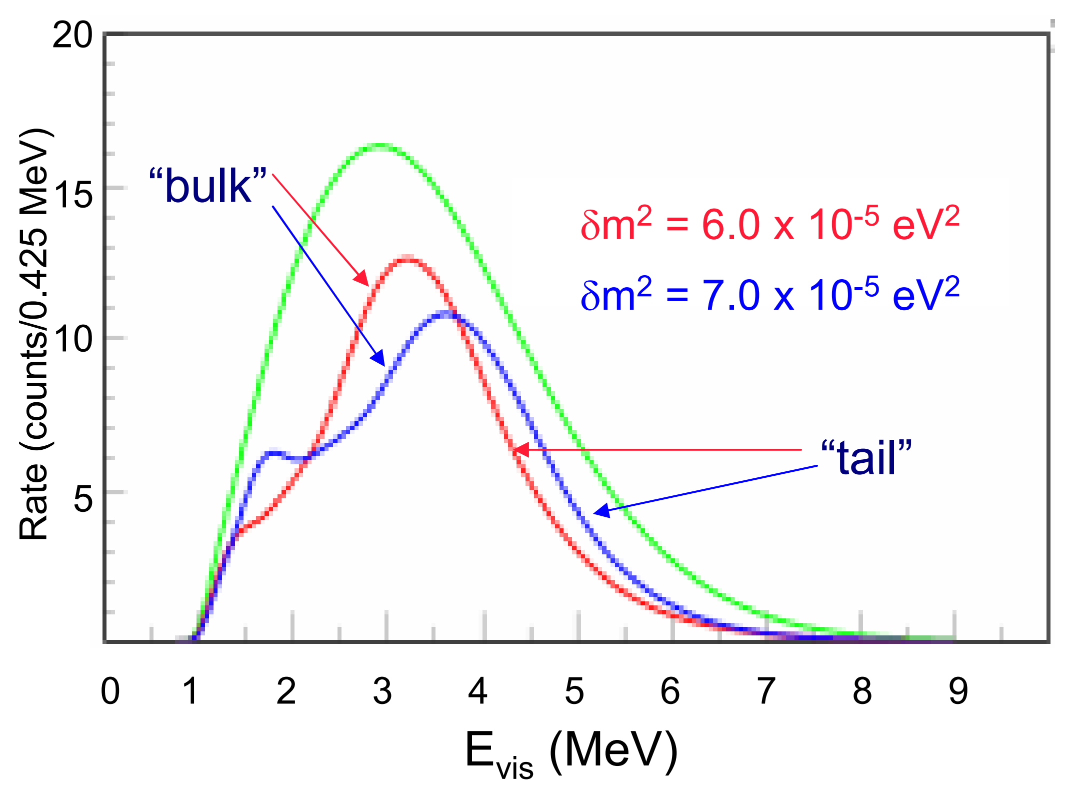
The KamLAND e^+ spectrum

For given $\sin^2\theta_{12}$ we can compare the spectra expected for different values of δm^2.

In particular we can select the values near to the best fit.

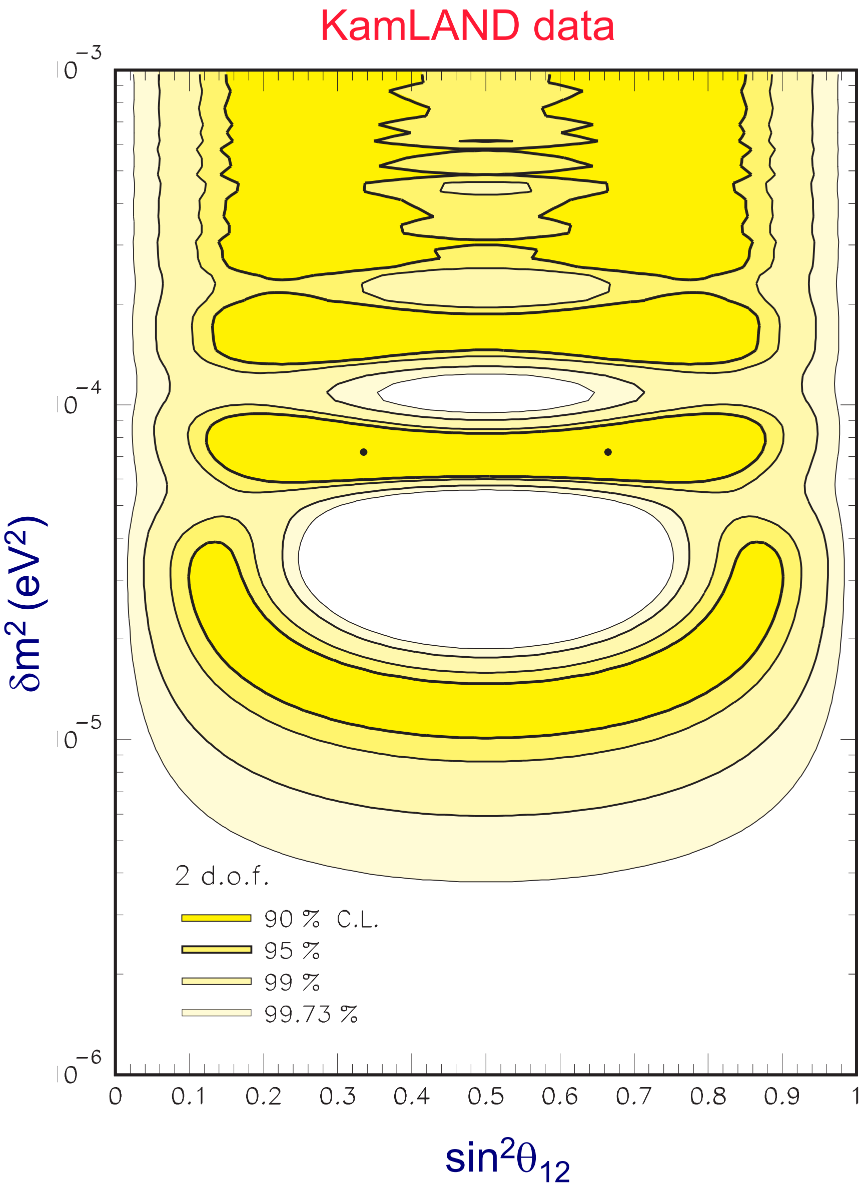
There is a specific behaviour of the “bulk” and “tail” suppression for each spectrum.

The emerging sub-structure in the KamLAND allowed regions depends on the “bulk-tail” relative suppression and might be altered by future KamLAND data.



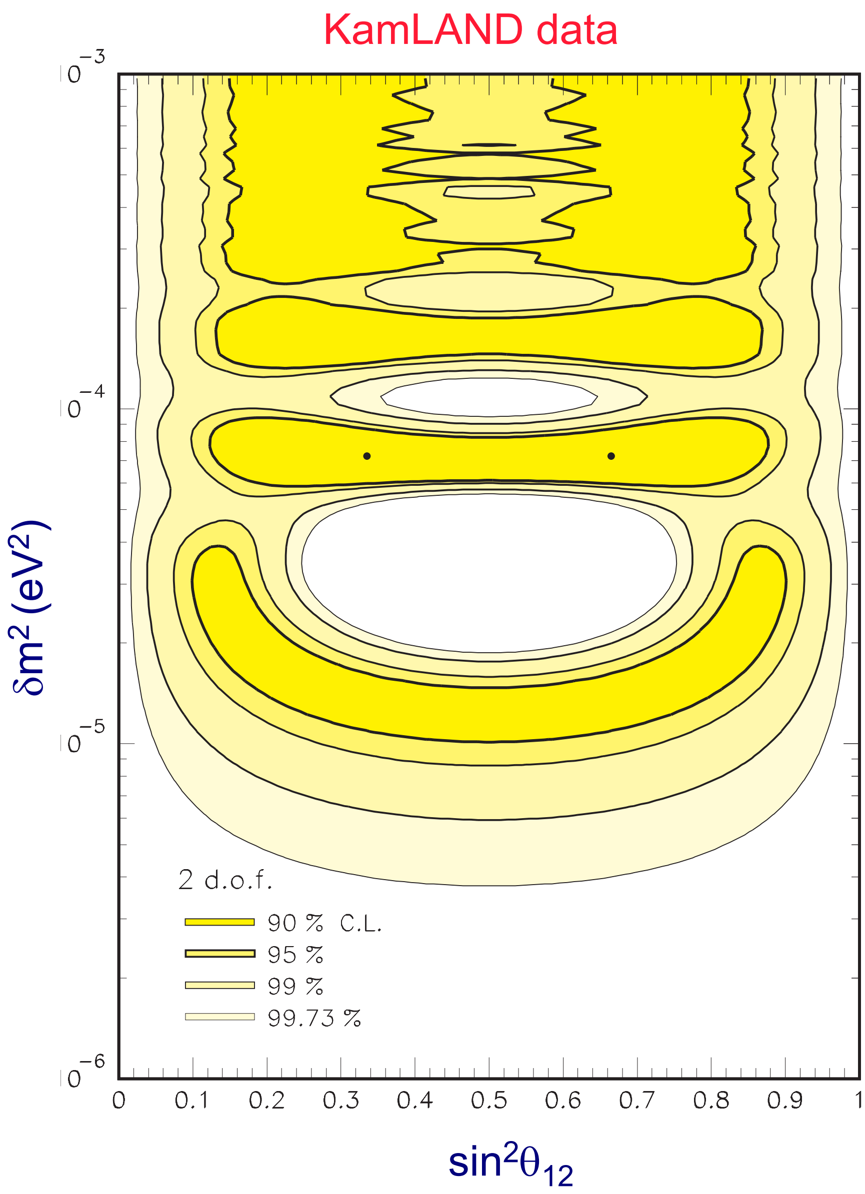
The KamLAND parameter space

- strong lower limit on δm^2
- no upper limit on δm^2
- bounds on θ_{12} still weak
- the region allowed shows a sub-structure related to the specific “bulk”/”tail” relative suppression



Combining all solar data + CHOOZ with KamLAND

The KamLAND data …



Gianluigi Fogli

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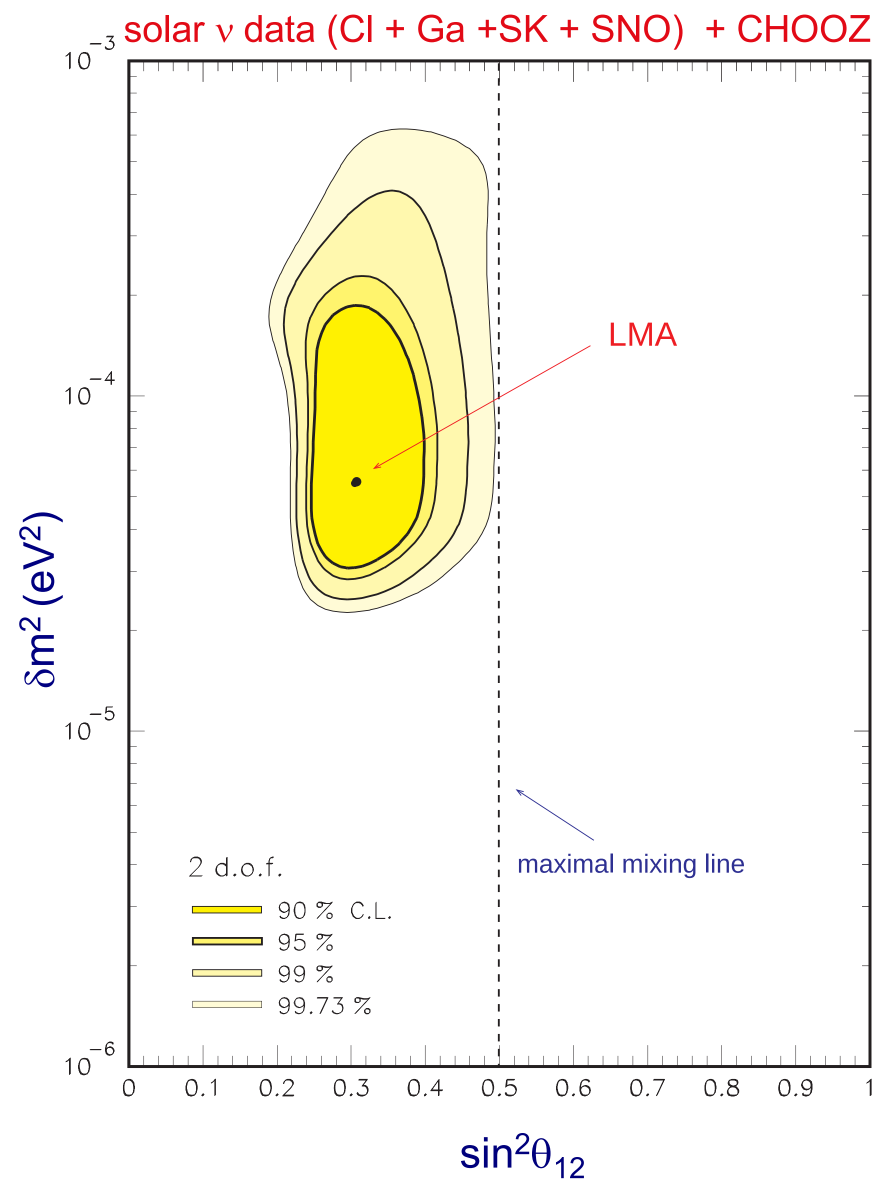
Combining all solar data + CHOOZ with KamLAND

The KamLAND data …

…. can now be combined with the solar data, including the CHOOZ constraint …

…. and (at least) two solutions emerge,



Combining all solar data + CHOOZ with KamLAND

The KamLAND data …

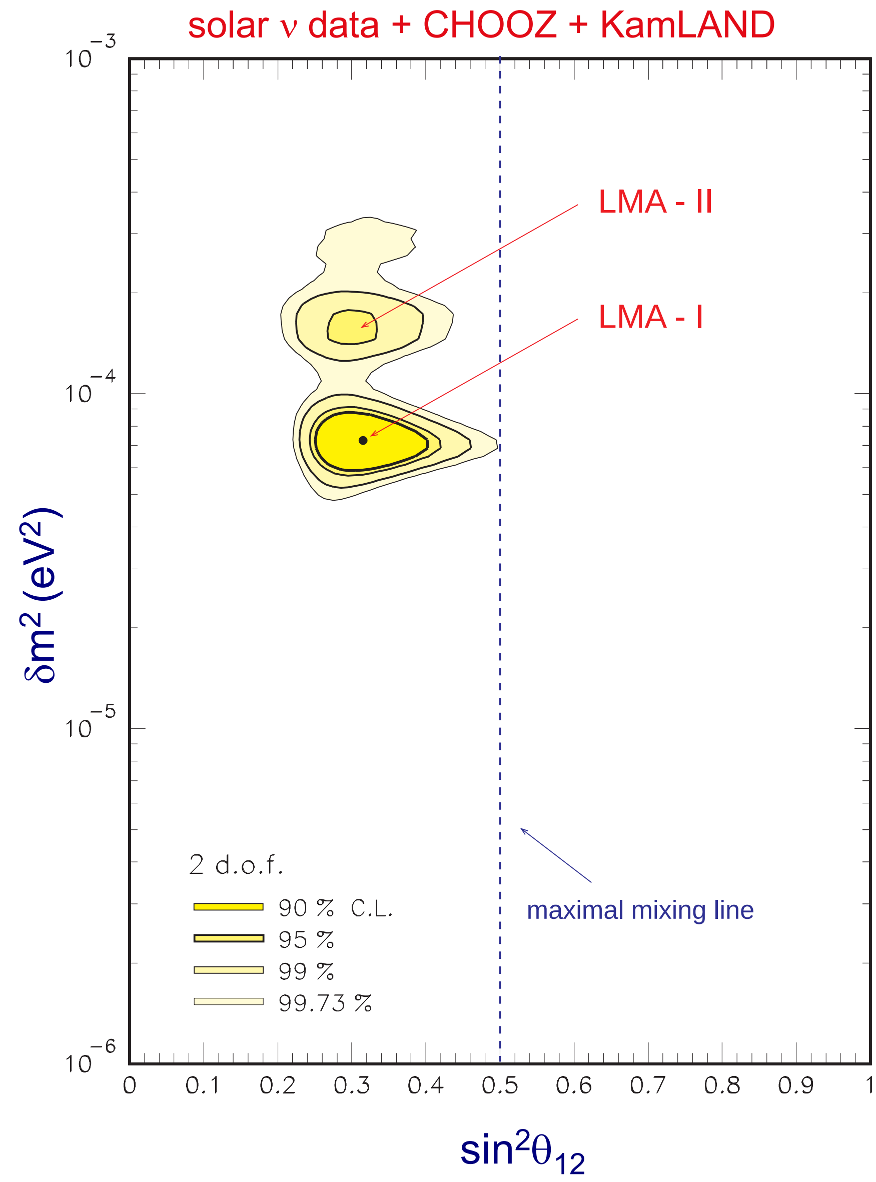
…. can now be combined with the solar data, including the CHOOZ constraint …

…. and (at least) two solutions emerge,

LMA - I (best fit)

LMA - II (second best fit)

…. strictly related to the substructure shown by the KamLAND data analysis.



LMA-I and LMA-II energy spectra

From a comparison of the LMA-I and LMA-II energy spectra …

- It is seen that bins near threshold are decisive to discriminate between LMA-I and LMA-II

- this requires to include geo-ν analysis

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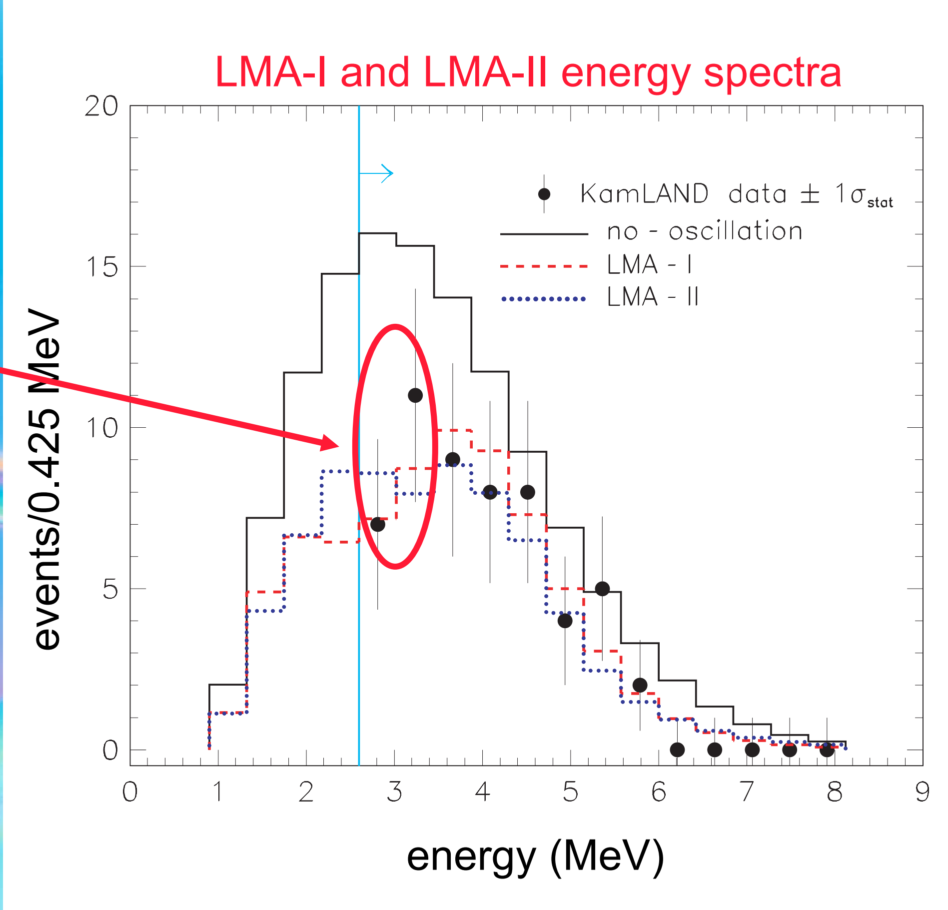
Progress and consensus in modeling geo-neutrinos are needed



Matter effects: how to test their presence

We can write the Hamiltonian for solar 2ν oscillations in the form:

$$H = H_{kin} + H_{dyn} = \frac{k}{2}\begin{bmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12} \end{bmatrix} + \frac{V}{2}\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

with $\begin{cases} k = \delta m^2/2E \\ V = 2^{1/2}\, G_F N_e \end{cases}$

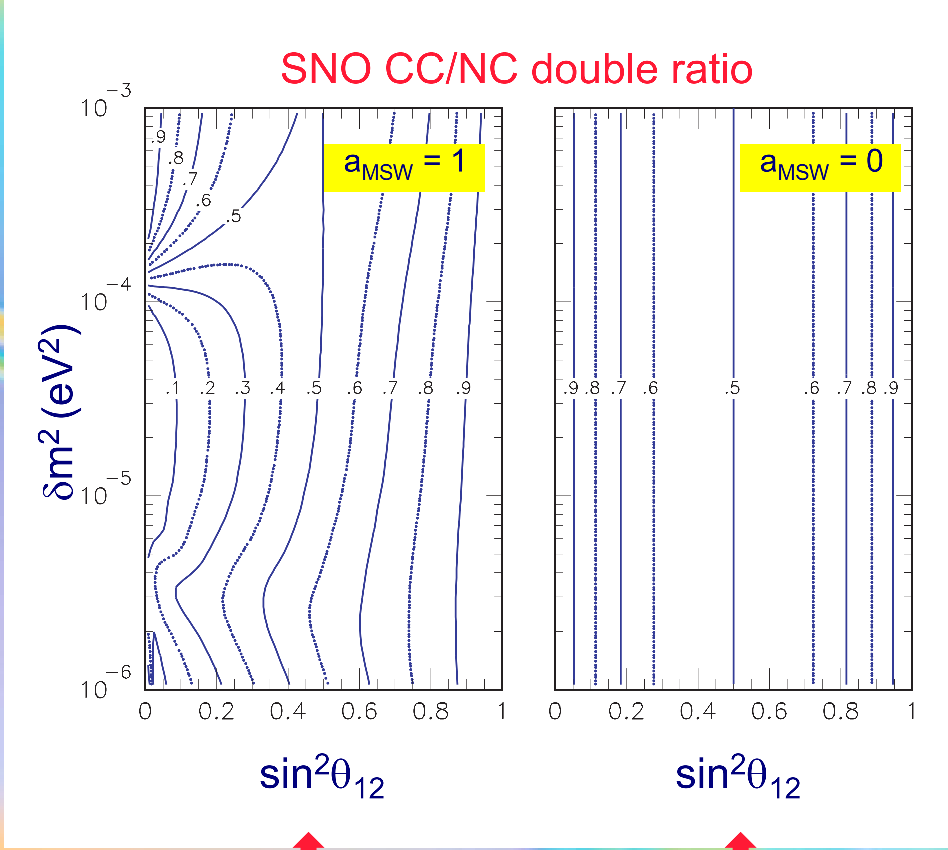
free parameter

Let the dynamical (MSW) term be rewritten in the form: $V \longrightarrow V \bullet a_{MSW}$

we can check if the data $\begin{cases} \text{exclude } a_{MSW} = 0 \quad \text{(no MSW effect)} \\ \text{prefer } a_{MSW} = 1 \quad \text{(standard MSW effect)} \end{cases}$

A similar exercise was made to test the kinematical term in atmospheric ν:
rewriting $L/E \longrightarrow L\, E^n$, test if $n = -1$

Matter effects and the SNO CC/NC double ratio



with standard matter effects

no matter effects

The SNO CC/NC double ratio is particularly useful to test matter effects

In fact, in the LMA region CC/NC values lower than 0.5 are reachable in presence of standard matter effects ($a_{MSW} = 1$), while they are excluded if $a_{MSW} = 0$.

Future upper limit $(CC/NC)_{max}$ by SNO decisive to:

- Place improved limits $(\delta m^2)_{max}$
- Provide compelling evidence for matter effects

Global fit to solar matter effects

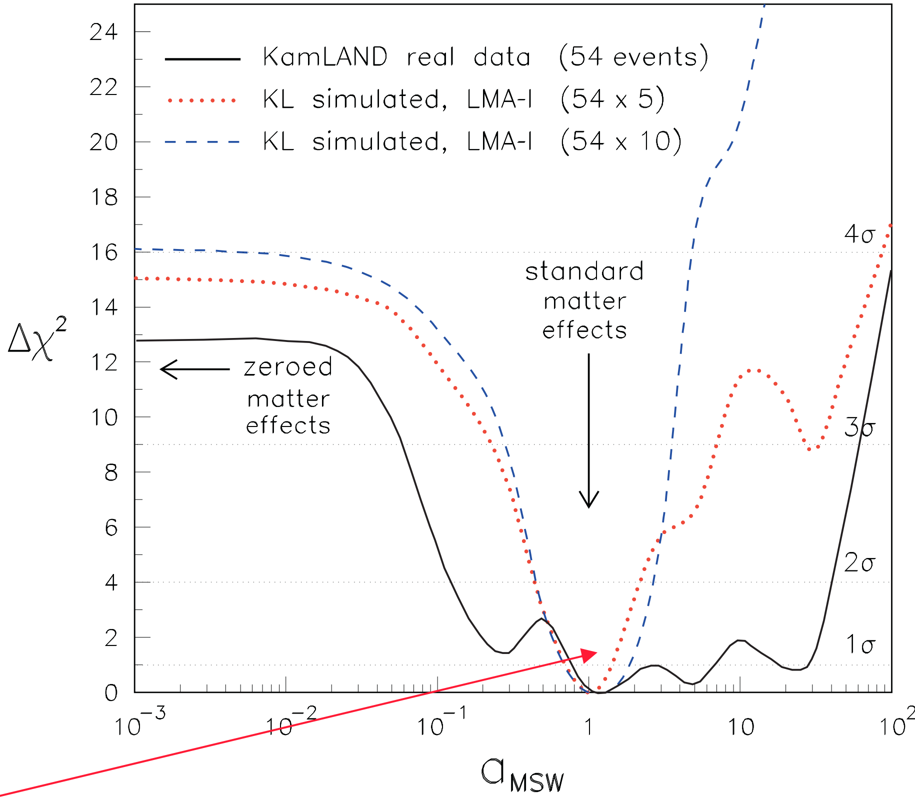
A global fit to solar ν including CHOOZ and KamLAND data (with δm^2 and θ_{12} as free parameters) shows that:

- $a_{MSW} = 0$ strongly disfavored
- $a_{MSW} \sim O(1)$ favored
- but still large ±3σ uncertainty on a_{MSW} (~ 3 decades)

However, the situation may dramatically improve in a near future! Indications can be found by simulating a higher KamLAND statistics (×5 and ×10 the present data)

➡ from LMA-I: $a_{MSW} \sim 1$

Bounds on a_{MSW} (solar + CHOOZ + KamLAND)



Solar and reactors 2ν analysis: summary

- Current LMA sub-structure determined by bulk-tail suppression pattern in KamLAND spectrum. Some pattern change with higher statistics cannot be excluded.

- Bounds on $\sin^2\theta_{12}$ dominated by solar neutrinos.

- Upper bounds on δm^2 from solar ν data alone stronger than - but not as compelling as - the CHOOZ limit.

- Near-future SNO data (CC/NC) decisive to assess upper bound on δm^2 and (related) upper bounds on $\langle P_{ee} \rangle$ and $\sin^2\theta_{12}$, as well as to confirm emerging evidence for matter effects. Higher KamLAND statistics also very important.

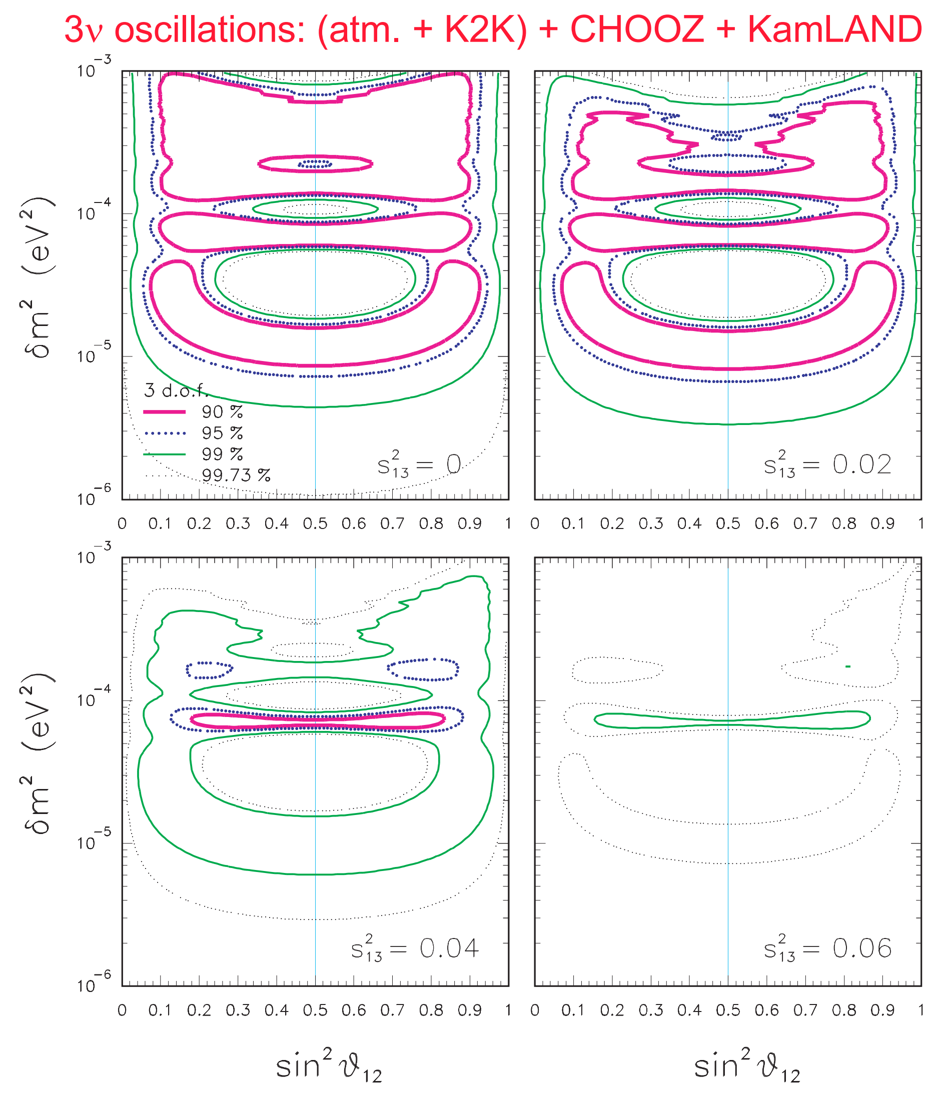
- In the meantime, a conservative attitude allowing $\delta m^2 \sim$ few × 10^{-4} eV^2, quasi-maximal mixing, ,$\langle P_{ee} \rangle \sim 1/2$, and vanishing matter effects is still admissible at the $\sim 3\sigma$ level.

3ν analysis: terrestrial data only

Purely "terrestrial" neutrino data from atmospheric (SK) accelerator (K2K) and reactor (CHOOZ + KamLAND) neutrino experiments are now able to put both upper and lower bounds on the solar parameters (δm^2, θ_{12})

In particular …

- the CHOOZ upper bound on δm^2 becomes stronger when $\sin^2\theta_{13}$ increases

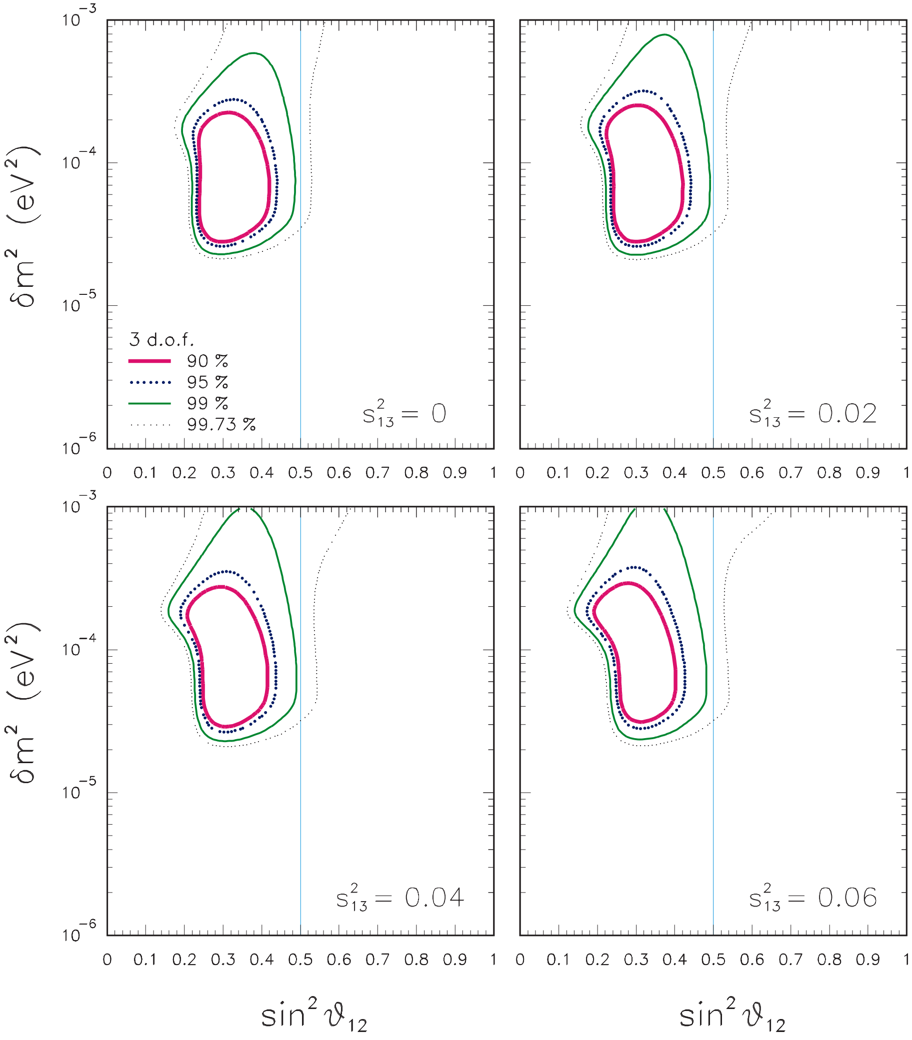


3ν analysis: solar data only

In a similar way, we can consider solar data in a three-generation framework:

- there is weaker sensitivity to $\sin^2\theta_{13}$ from solar ν data
- the upper bound on δm^2 appears to be weakened when $\sin^2\theta_{13} \neq 0$

3ν oscillations: solar data only



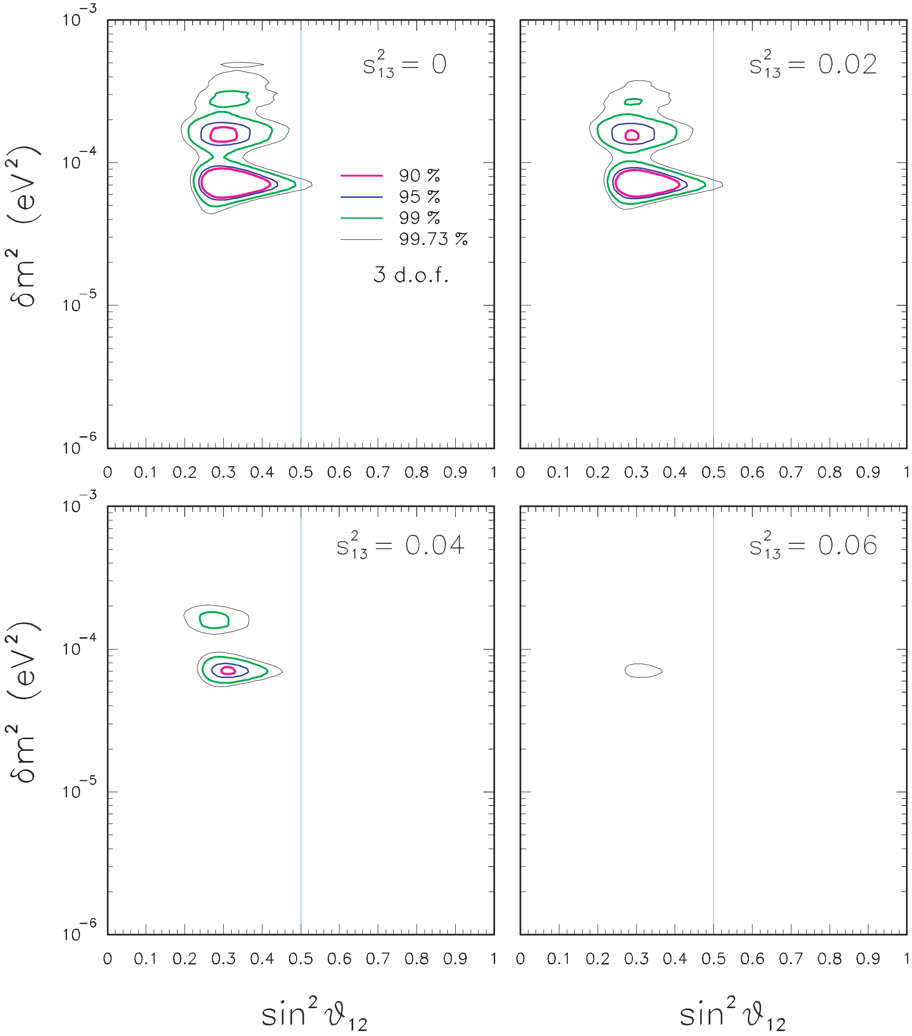
Combining solar and terrestrial data

Combining all data …

↓

- the best fit is reached in the 2ν limit ($s^2_{13} = 0$)
- we recover the safe upper bound on δm^2, imposed by the CHOOZ data
- the higher $\Delta\chi^2$ tolerance due to the extra degree of freedom marginally allows a solution "LMA-III" (at $\delta m^2 \sim 2.5\text{-}3.2 \times 10^{-4}$ eV^2)

3ν oscillations: world data (solar + "terrestrial")



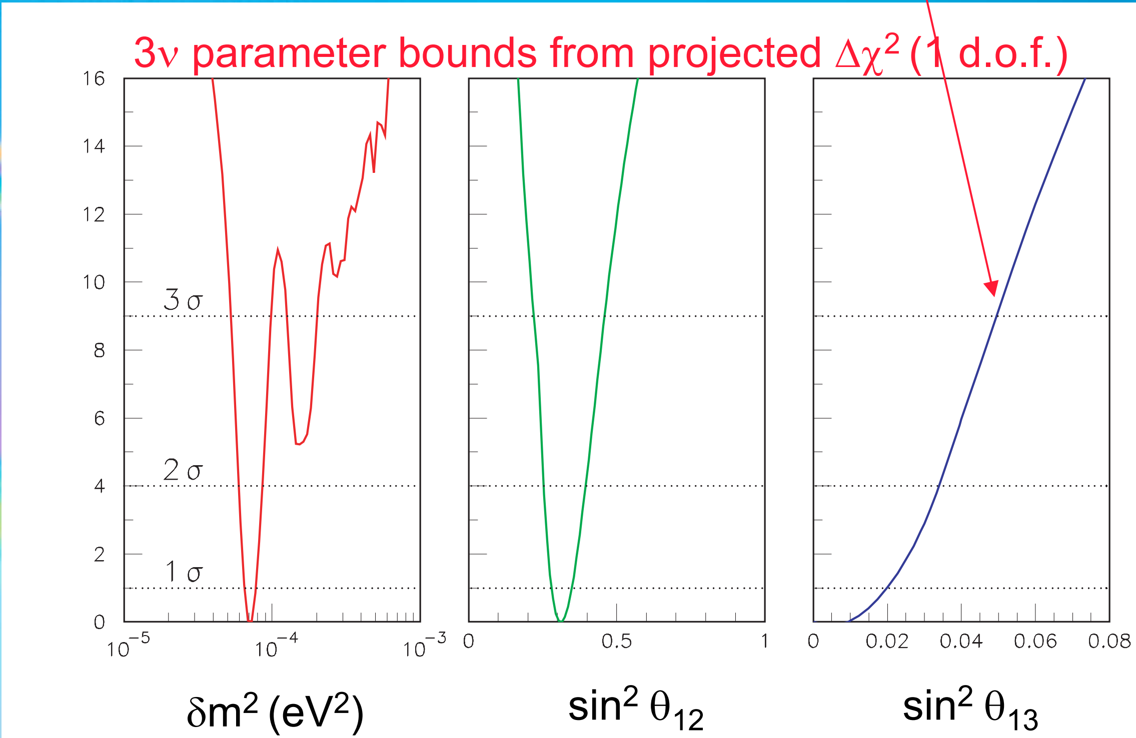
Bounds on the parameters (δm^2, θ_{12}, θ_{13})

Taking LMA-I as the reference solution, we can extract the following ±1σ estimate for the relevant solar 3ν parameters:

$$\text{LMA-I } (\sim 1\sigma): \begin{cases} \delta m^2 \approx (7.3 \pm 0.8) \times 10^{-5}\ \text{eV}^2 \\ \sin^2\theta_{12} \approx 0.315 \pm 0.035 \\ \sin^2\theta_{13} \leq 0.017 \end{cases}$$

$\sin^2\theta_{13} < 0.05$ (3σ)

However, the most complete information comes from the $\Delta\chi^2$ functions for each parameter, the other two being projected away


3ν parameter bounds from projected $\Delta\chi^2$ (1 d.o.f.)

Conclusions

- We have entered the precision era in the determination of the parameters governing the neutrino flavor evolution.
- Upper and lower bounds exist on the kinematical parameters:

$$\Delta m^2 \qquad \theta_{23} \qquad \delta m^2 \qquad \theta_{12}$$

→ concerning the "atmospheric parameters" (Δm^2 and $\sin^2 2\theta_{23}$), bounds are sufficiently strong to allow a meaningful definition of $\pm 1\sigma$ errors (improvable by K2K)

→ concerning the "solar parameters" (δm^2 and $\sin^2\theta_{12}$), the main issue is the resolution of the LMA-n ambiguity (improvable by KamLAND, SNO)

- Evidence starts to emerge for dynamical MSW effect in the Sun (improvable by KamLAND, SNO).
- But:
  - → only upper bound on $\sin^2\theta_{13}$
  - → no sensitivity to sign(Δm^2)
  - → no sensitivity to δ_{CP}

- Placing a lower bound on $\sin^2\theta_{13}$ will be a decisive step to attack the problem of estimating sign(Δm^2) and δ_{CP} with (far) future experiments, completing the determination of the 3ν parameters.

- Many ideas to test θ_{13}:
  - reactors
  - (very) LBL experiments
  - supernovae
  - ……..

… but the precision program will require its time:

patience is needed with ν Physics!