VIII International Workshop
on "Neutrino Telescopes"

Venice, February 24, 1999

A Combined Analysis
of
Atmospheric Neutrino Results

GLF

1. Introduction
2. Atmospheric ν: 2ν and 3ν oscillations
3. Updating the SuperKamiokande data (45 kTy)
4. Neutrino decay and Superkamiokande data
5. Solar + Atmospheric ν solutions
6. Established facts and open questions

1. Introduction

Neutrino oscillation evidence

Two kinds of observables:

- total neutrino event rates

  ⇒ give information on "averaged" neutrino oscillation probability $< P_{\alpha\beta} >$

- neutrino event spectra (as a function of E, L, L/E, or t)

  ⇒ give information on $\frac{\partial P_{\alpha\beta}}{\partial x}$ $x = \left| \begin{array}{l} E \\ L \\ L/E \\ t \\ \ldots \end{array} \right.$

crucial to assess oscillations unambiguously !!!

Present evidence

	total rate	spectra
LSND	$P(\nu_\mu \rightarrow \nu_e) > 0$ (controversial)	no significant info
solar	$P(\nu_e \rightarrow \nu_e) < 1$ (robust)	$\frac{\partial P_{ee}}{\partial E} \neq 0$ preferred no indication for $\frac{\partial P_{ee}}{\partial t} \neq 0$, $\frac{\partial P_{ee}}{\partial L} \neq 0$
atmospheric	$P(\nu_\mu \rightarrow \nu_\mu) < 1$ (ambiguous)	$\frac{\partial P_{\mu\mu}}{\partial L} \neq 0$ (robust)

2. Atmospheric neutrinos: 2ν and 3ν analysis of the SK data

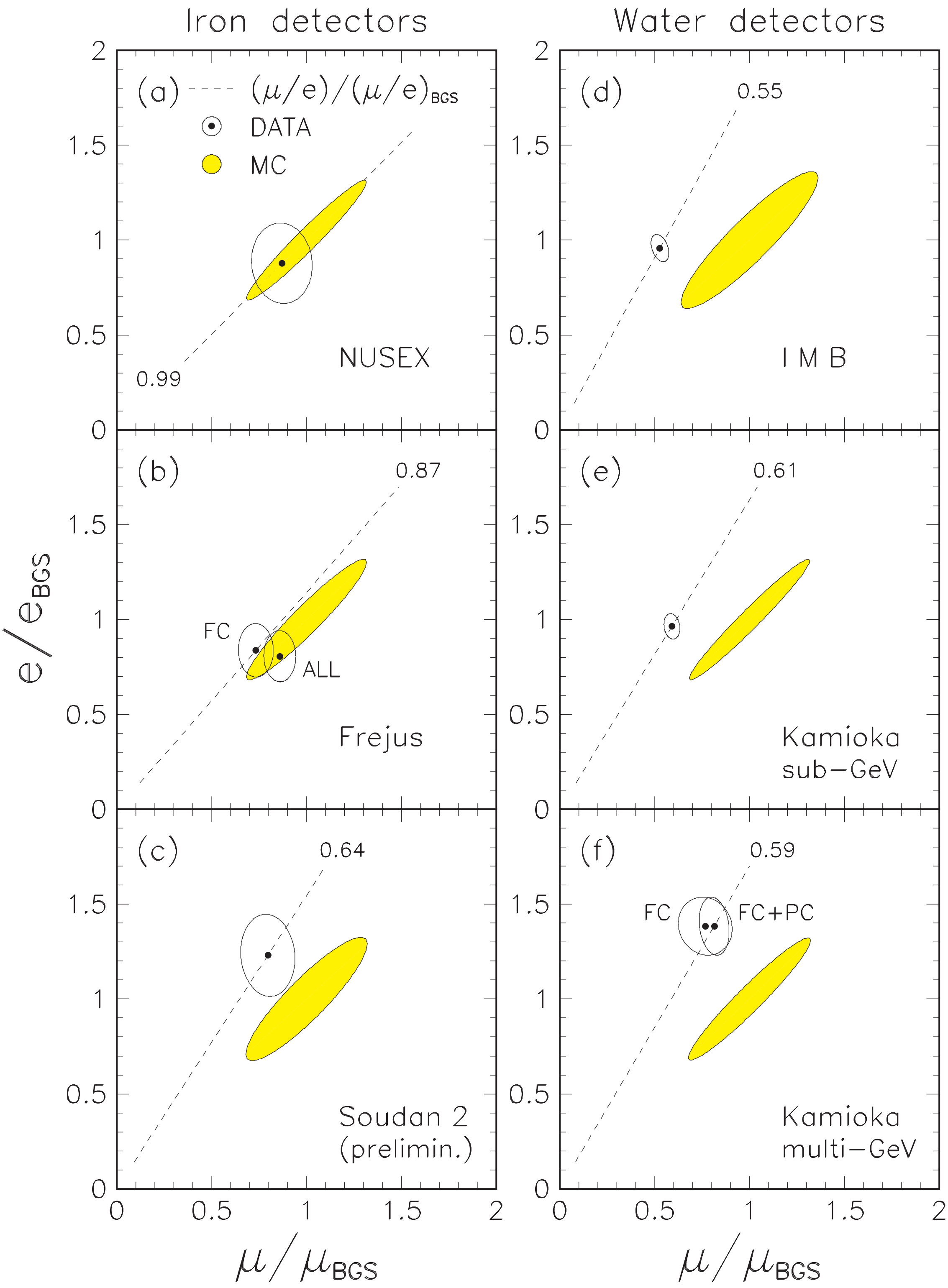
- Experimental data
- Total rates and zenithal distributions
- Two-flavor and three-flavor analysis

GLF, E. Lisi, A. Marrone and G. Scioscia,
Physical Review D 59, 033001 (1999)

Atmospheric neutrinos: pre-SK data (total rates)

Separate analysis of μ–like and e-like events in the (μ/μ_{BGS} , e/e_{BGS}) plane

- normalized to the BGS flux (Barr, Gaisser & Stanev)
- correlation effects taken into account

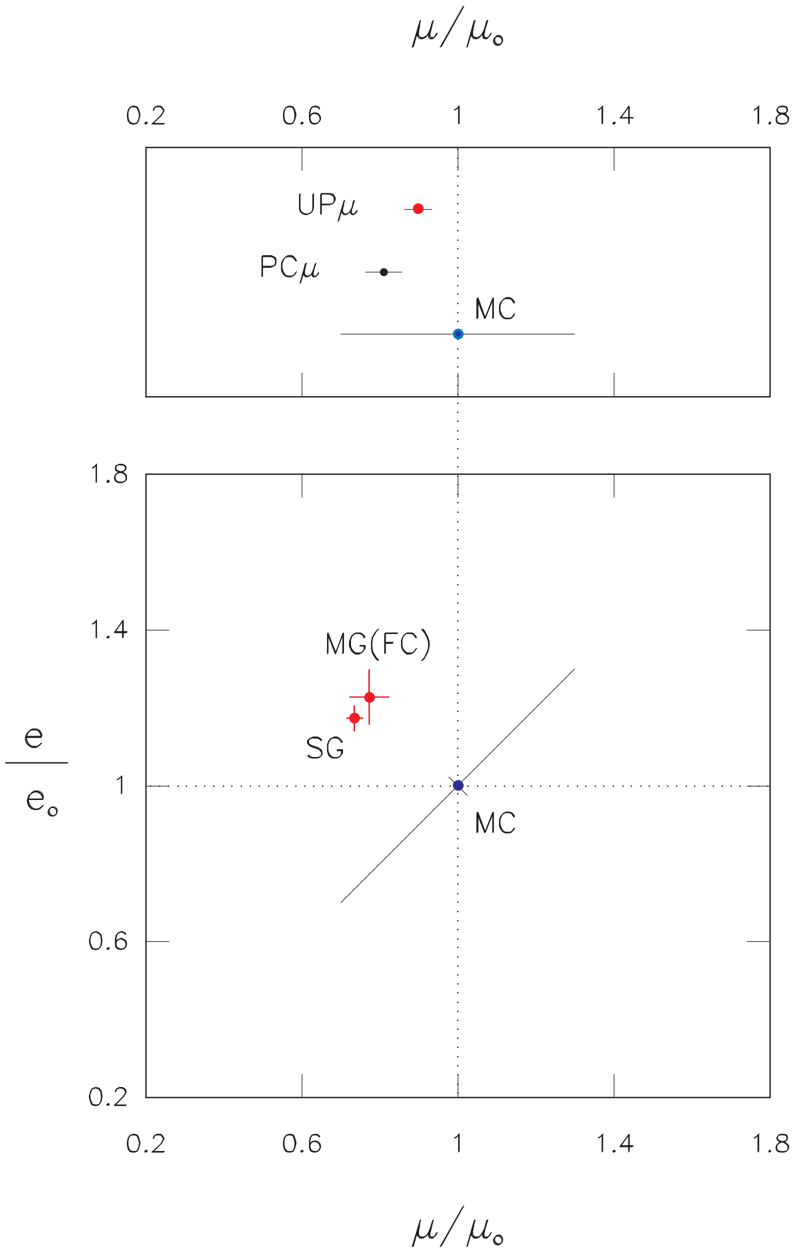


GLF and E. Lisi, Phys. Rev. D52 (1995) 2775

Atmospheric neutrinos: SK total rates

SuperKamiokande total lepton rates, as presented @ ν '98

(33.0 kTy, preliminary)

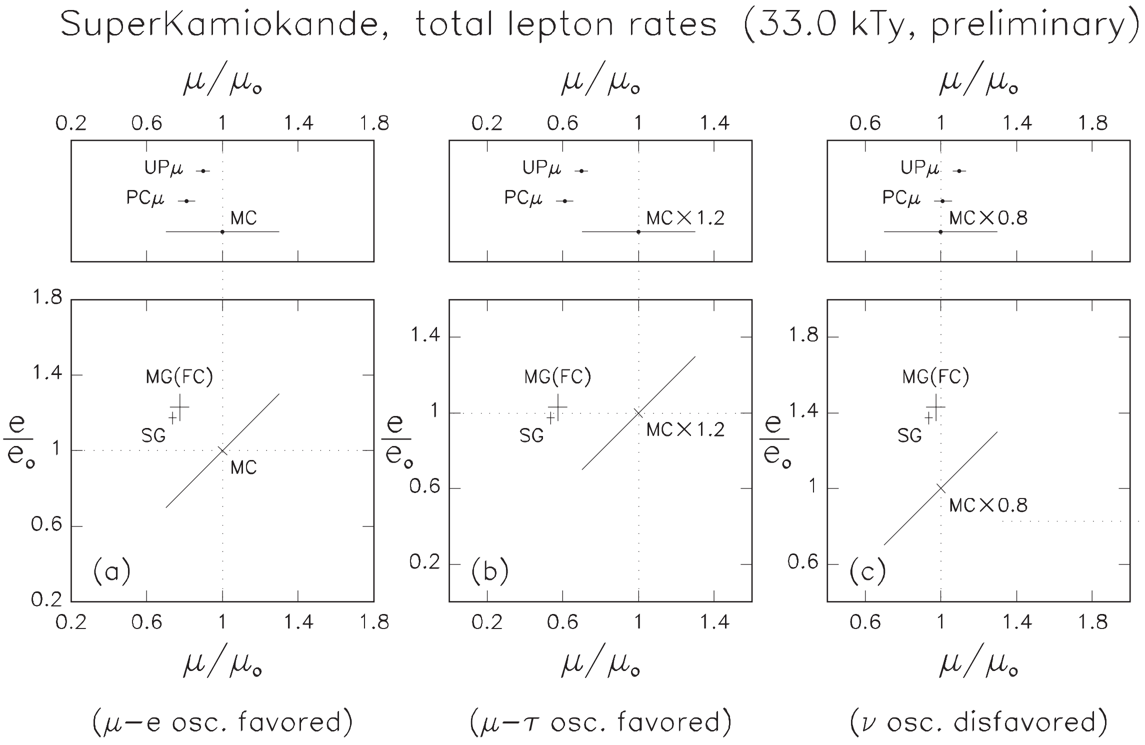


Comparison of SubGeV (SG), MultiGeV (MG) and Upgoing μ (Up-μ) with the SuperKamiokande MonteCarlo

HKKM '95 ν fluxes with { 30% μ–e normalization error; 5% μ/e ratio error

Total rate ambiguity

Effect of a 20% shift of the ν fluxes



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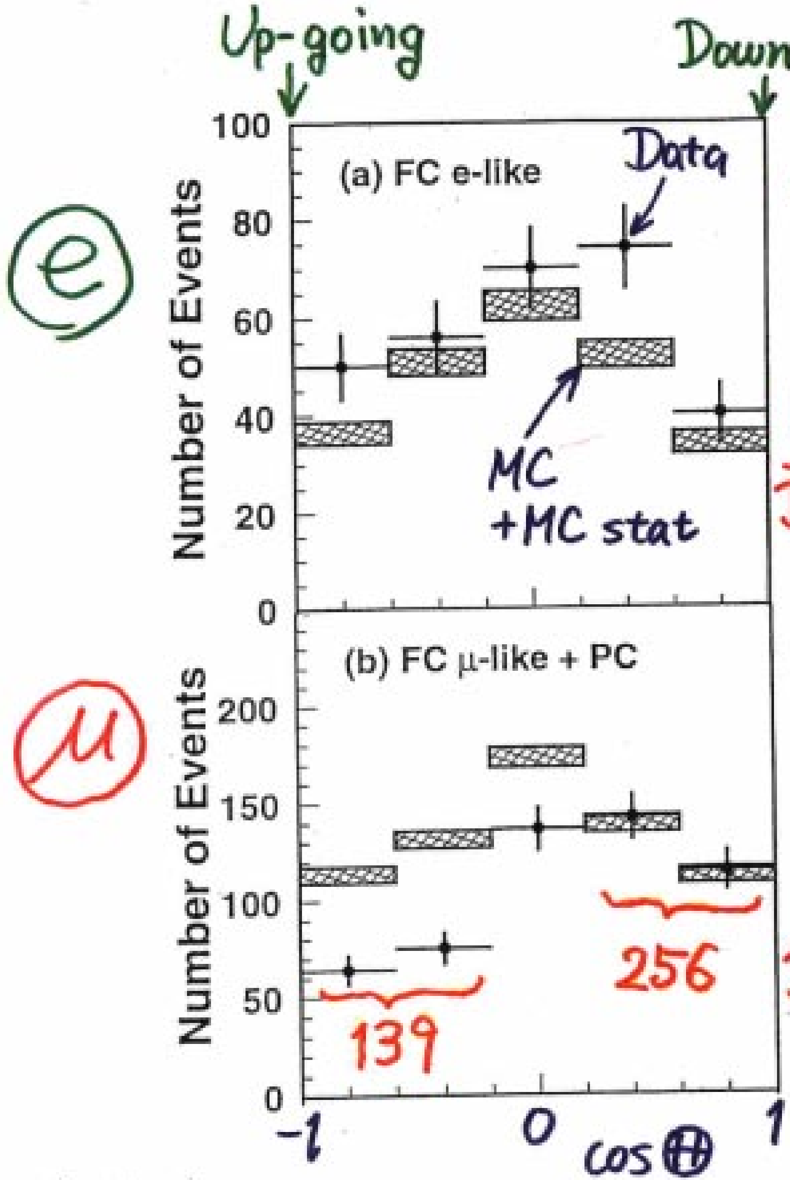
MonteCarlo flux — increased by 20% — reduced by 20%

We expect less ambiguous information from spectral distorsions

SuperKamiokande data @ ν '98

1998 particle physics hit: up/down asymmetry in SK !

Zenith angle dependence
(Multi-GeV)



χ^2(shape) $= 2.8/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.93^{+0.13}_{-0.12}$

χ^2(shape) $= 30/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.54^{+0.06}_{-0.05}$

(6.2σ!!)

※ Up/Down syst. error for μ-like

Prediction (flux calculation …… ≲ 1%
1km rock above SK …. 1.5%) 1.8%

Data (Energy calib. for ↑↓ …. 0.7%
Non ν Background …..< 2%) 2.1%

Comments

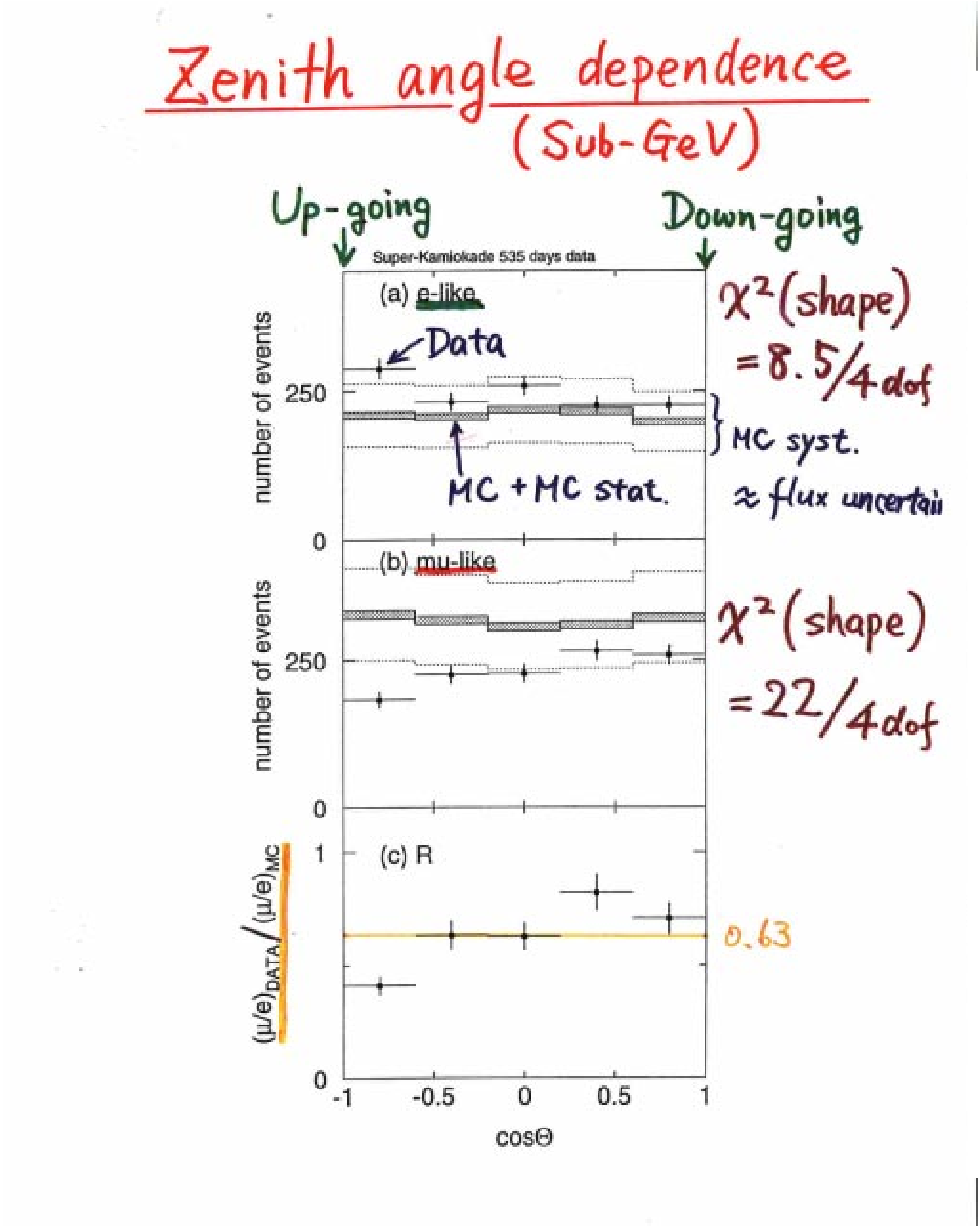
- Clear evidence in favor of $\frac{\partial P(\nu_\mu \rightarrow \nu_\mu)}{\partial L} \neq 0$

- Evidence is robust since MultiGev leptons are relatively good "tracers" of the energy and direction of parent neutrinos

- Geomagnetic effects small for MultiGev events

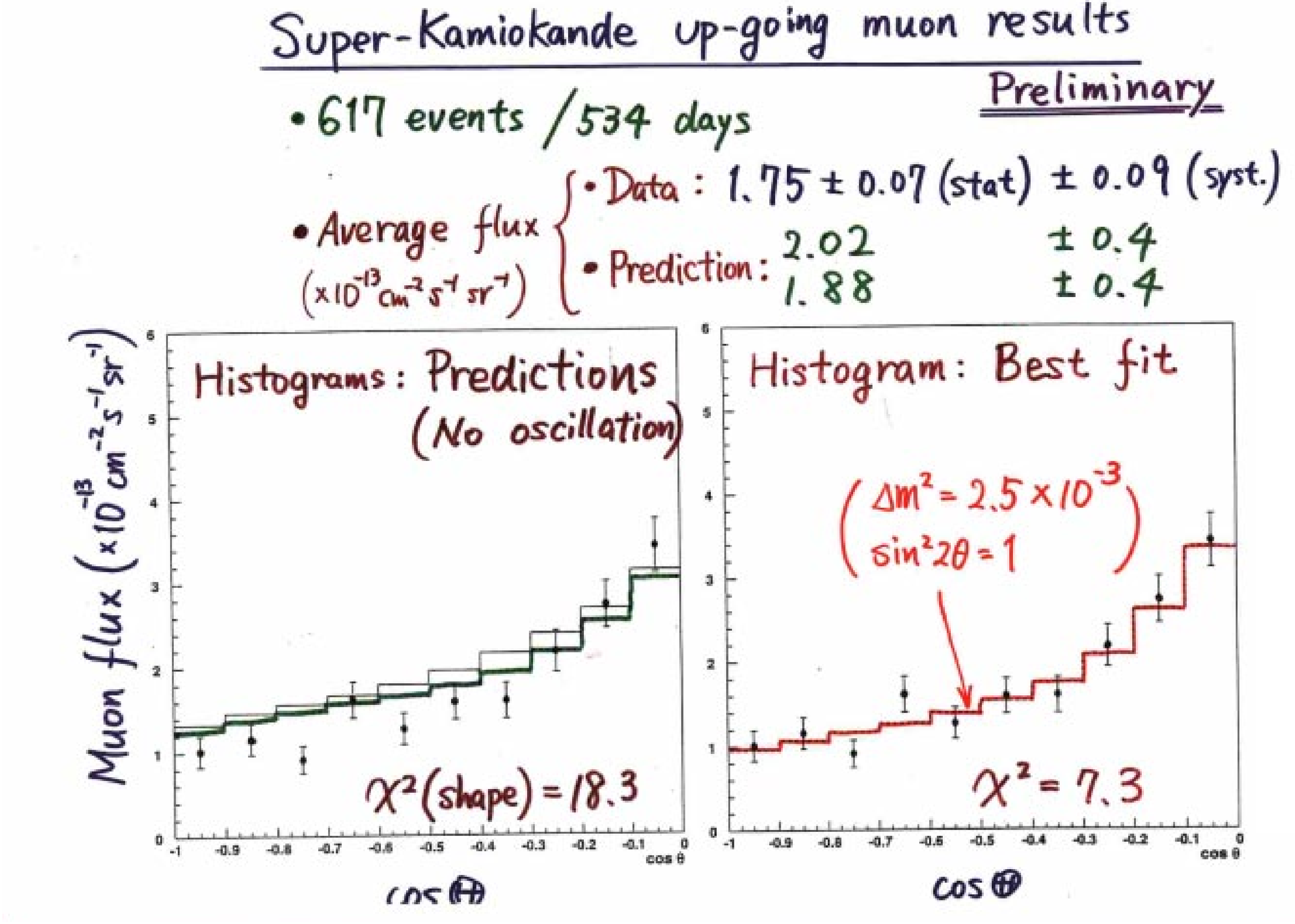
SuperKamiokande data @ ν '98

Evidence is weaker, but consistent with MultiGeV



SuperKamiokande data @ ν '98

Evidence is weaker, but
consistent with MultiGeV



Super-Kamiokande up-going muon results

Preliminary

- 617 events / 534 days
- Average flux ($\times 10^{-13}$ cm^{-2} s^{-1} sr^{-1})
  - Data : 1.75 ± 0.07 (stat) ± 0.09 (syst.)
  - Prediction : 2.02 ± 0.4
    1.88 ± 0.4

Histograms : Predictions (No oscillation)

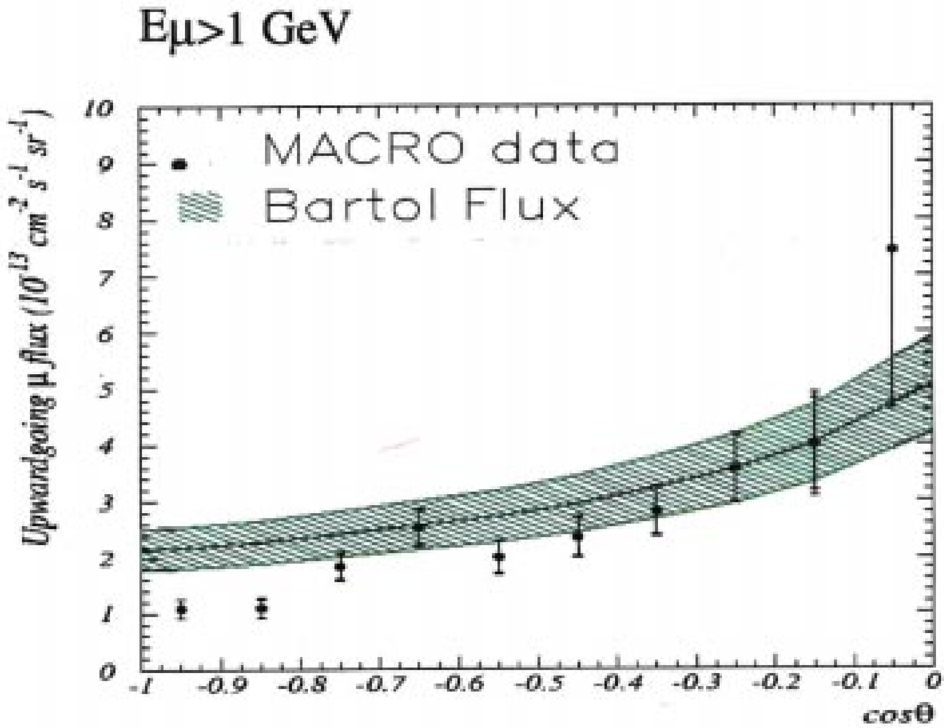
χ^2(shape) = 18.3

Histogram : Best fit

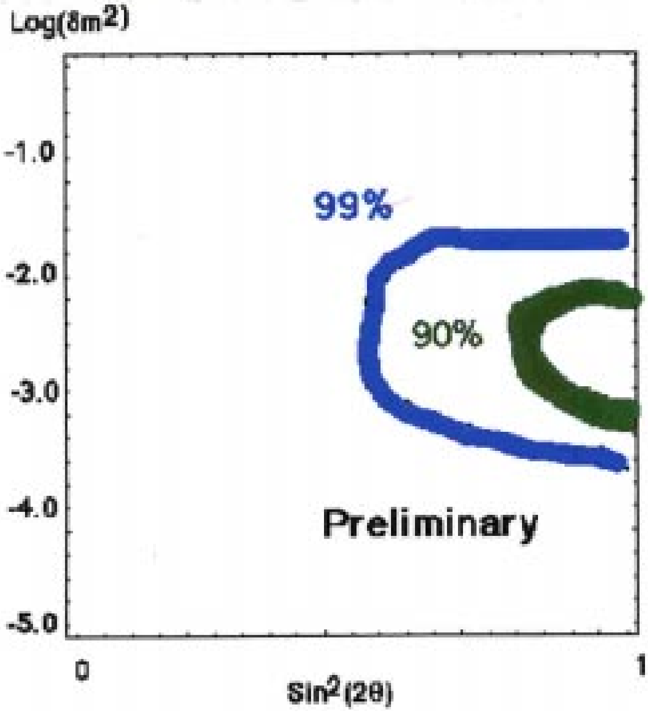
$\left(\Delta m^2 = 2.5 \times 10^{-3} \quad \sin^2 2\theta = 1 \right)$

$\chi^2 = 7.3$

Atmospheric ν: new MACRO data @ ν '98



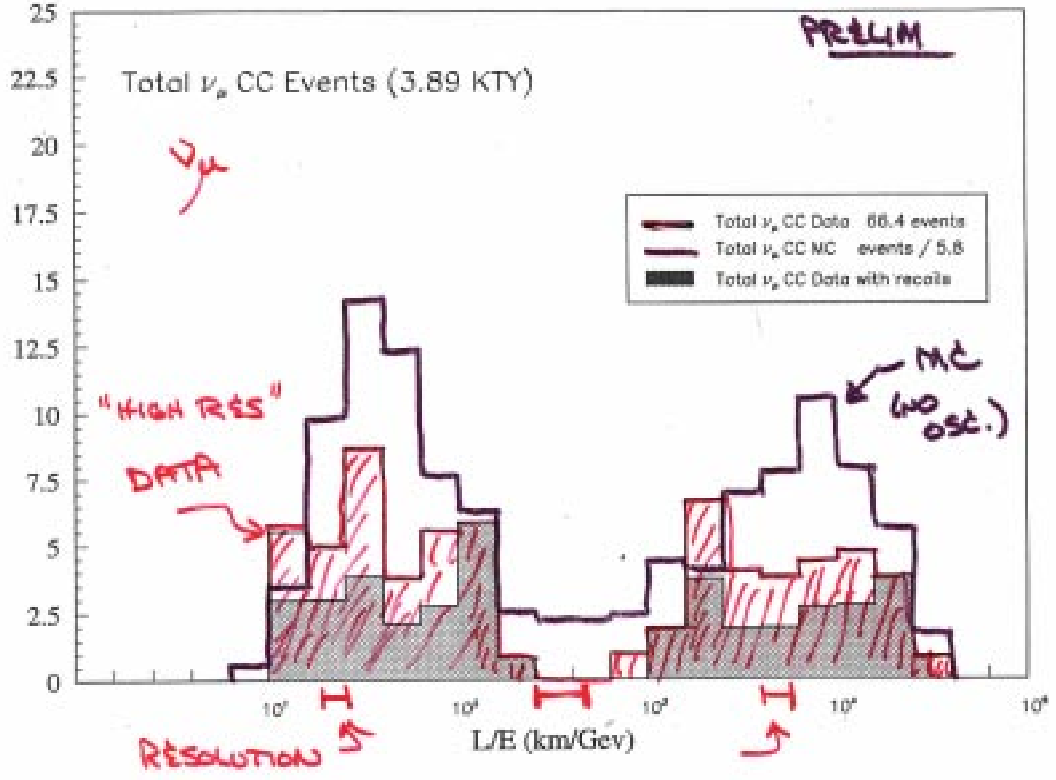
Confidence regions for oscillation parameters (Feldman-Cousins)

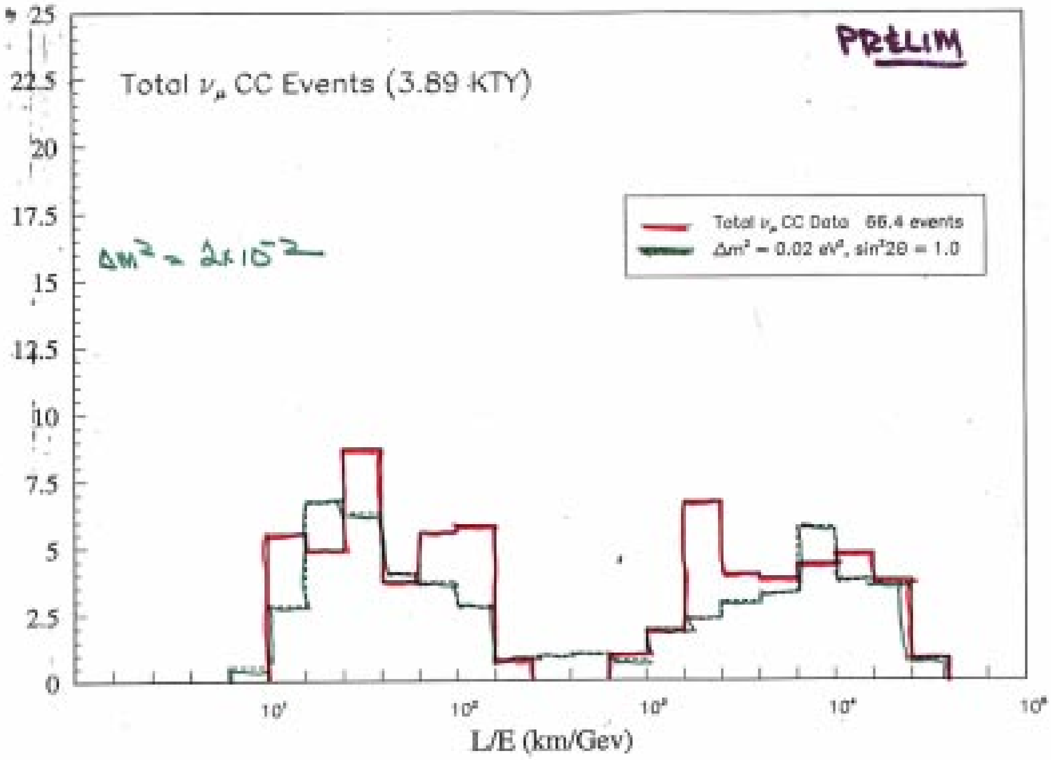


additional information ...

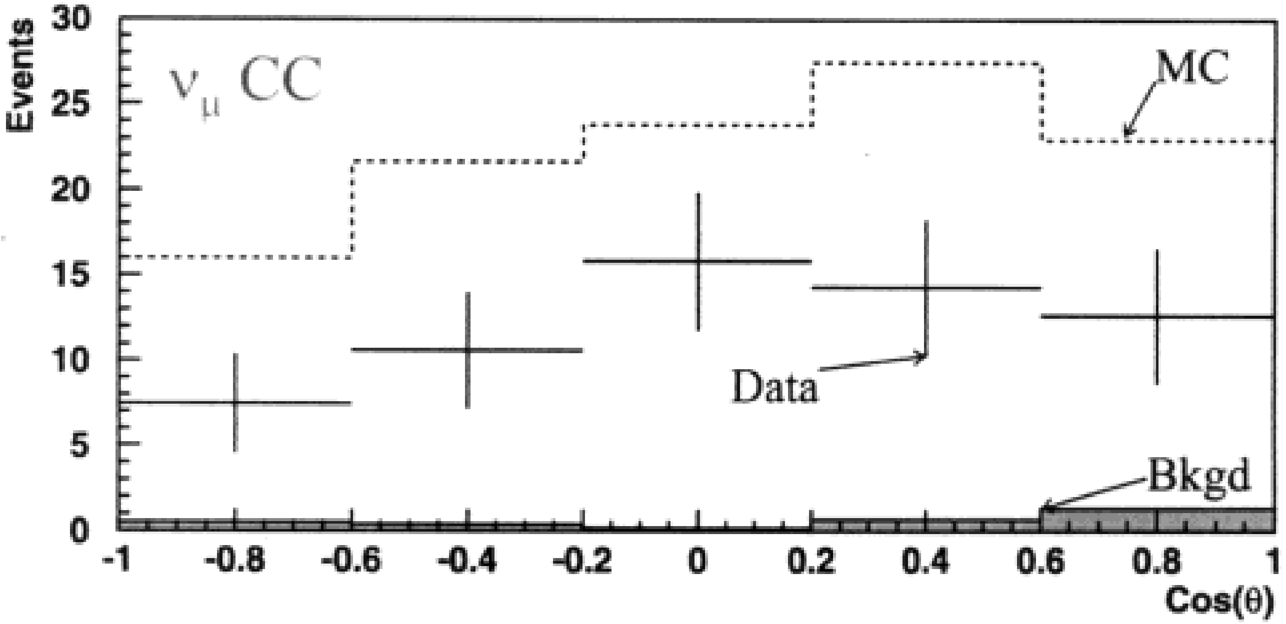
Atmospheric ν: new SOUDAN2 data @ ν '98

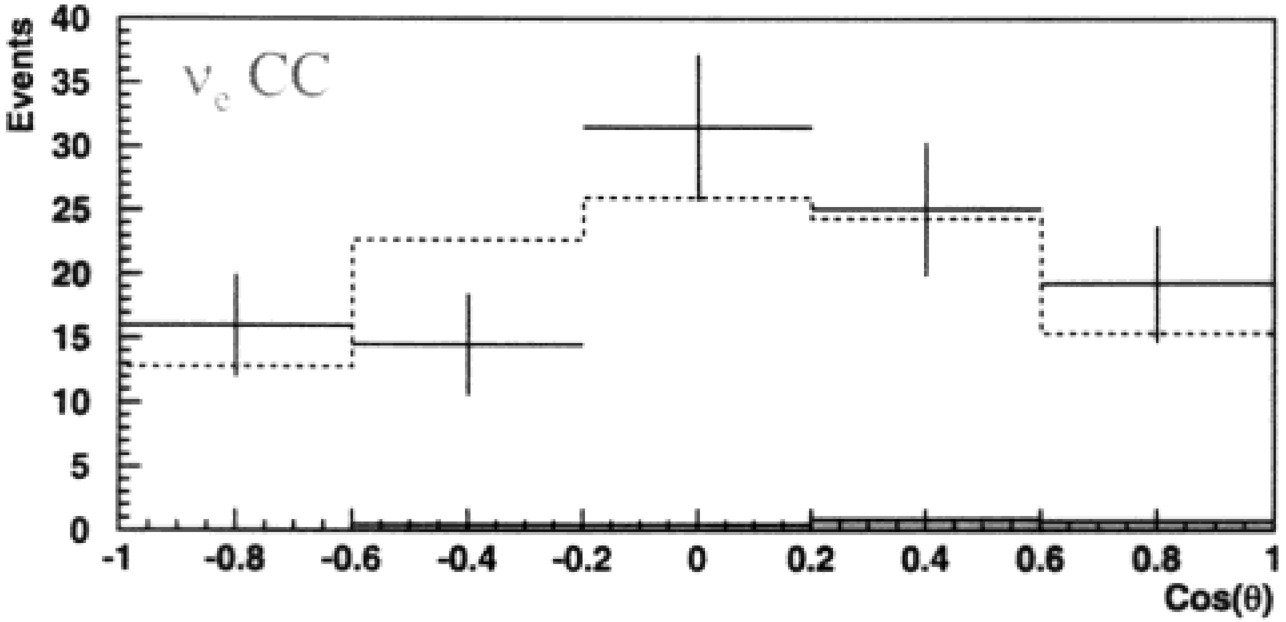
anomaly confirmed, but no significant
evidence for UP/DOWN asymmetry





Zenith Angles



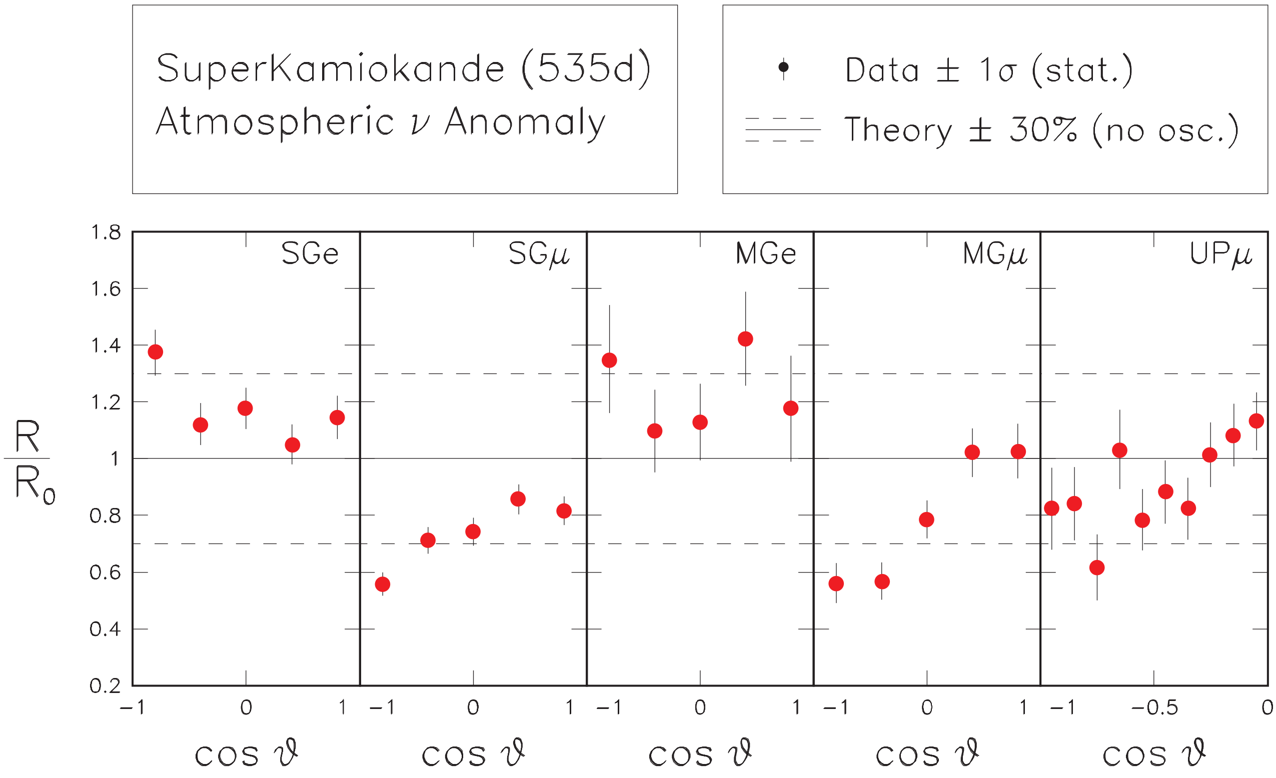


MC normalized to 3.89 kty data.

Flux is Barr, Gaisser, Stanev.

Superkamiokande zenithal distributions

(normalized to NO OSCILLATION in each bin)



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SubGeV (SG)
e and μ

MultiGeV (MG)
e and μ

Upgoing-μ

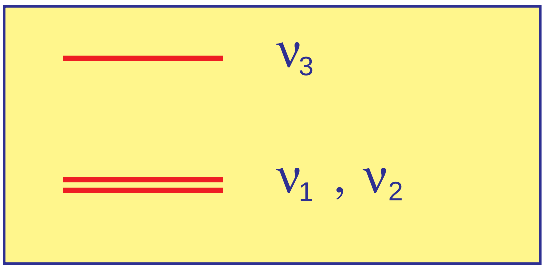
electrons: no significant deviation from a flat shape
(slight excess of upgoing SGe)

muons: significant distorsion, in particular MGμ

analyzed in the following in a three-flavour approach

Parametrization

$\boxed{3\nu}$ $\longrightarrow$ parameter space in the "one-dominant mass scale approximation", by assuming the mass spectrum



$$\begin{cases} m^2 = |m_3^2 - m_{1,2}^2| \\ \delta m^2 = |m_2^2 - m_1^2| \end{cases}$$

(responsible of solar ν deficit)

$$\begin{Vmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{Vmatrix} = U(\theta_{ij}, \delta_{CP}) \begin{Vmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{Vmatrix}$$

in the following

$\omega = \theta_{12}$
$\phi = \theta_{13}$
$\psi = \theta_{23}$

Up to terms of order $(\delta m^2 / m^2)$, the parameter space is spanned by three variables only

$(m^2, \psi, \phi) \Leftrightarrow (m^2, U_{e3}^2, U_{\mu3}^2, U_{\tau3}^2)$ with $U_{e3}^2 + U_{\mu3}^2 + U_{\tau3}^2 = 1$

or equivalently

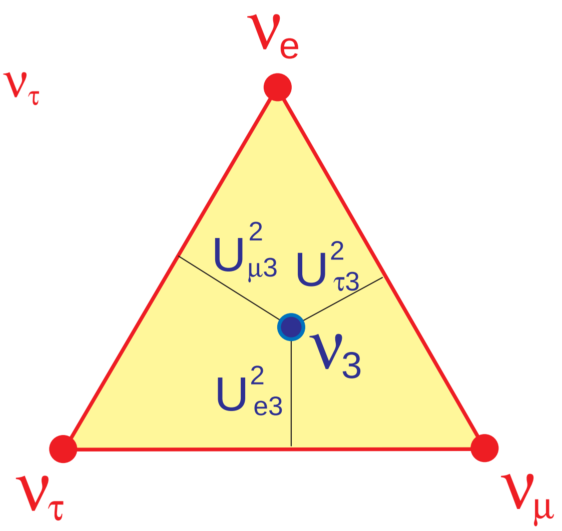
(unitarity)

What is relevant is the flavour composition of ν_3 :

$$\nu_3 = U_{e3}\,\nu_e + U_{\mu3}\,\nu_\mu + U_{\tau3}\,\nu_\tau$$

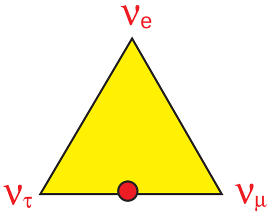
with

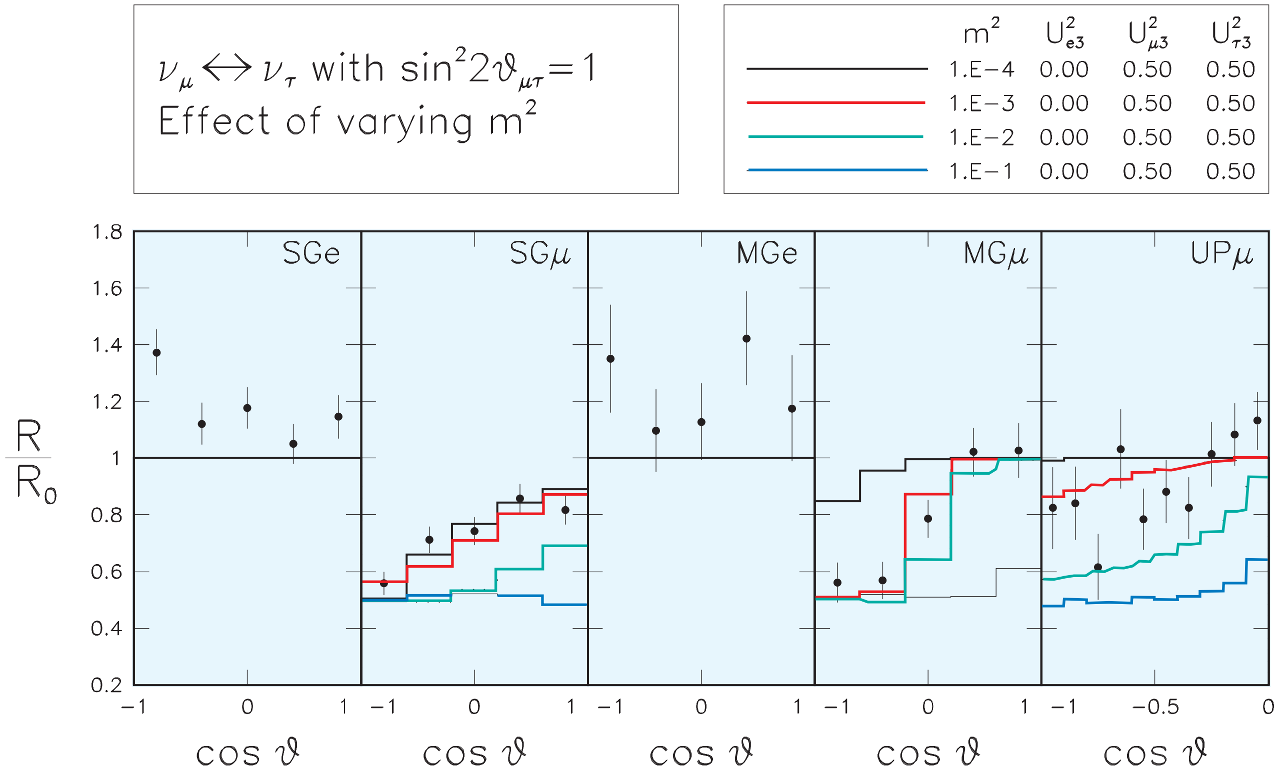
$U_{e3}^2 = s_\phi^2$
$U_{\mu3}^2 = c_\phi^2\, s_\psi^2$
$U_{\tau3}^2 = c_\phi^2\, c_\psi^2$



the unitarity being automatically enforced by means of a "triangular representation" for m^2 fixed

Comparing expectations with the experimental SK zenithal distributions for specific choices of $(m^2, U^2_{e3}, U^2_{\mu3}, U^2_{\tau3})$





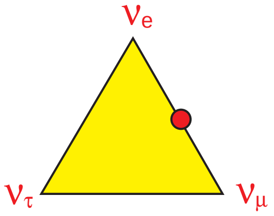
Examples of $\nu_\mu \Leftrightarrow \nu_\tau$ distorted distributions:

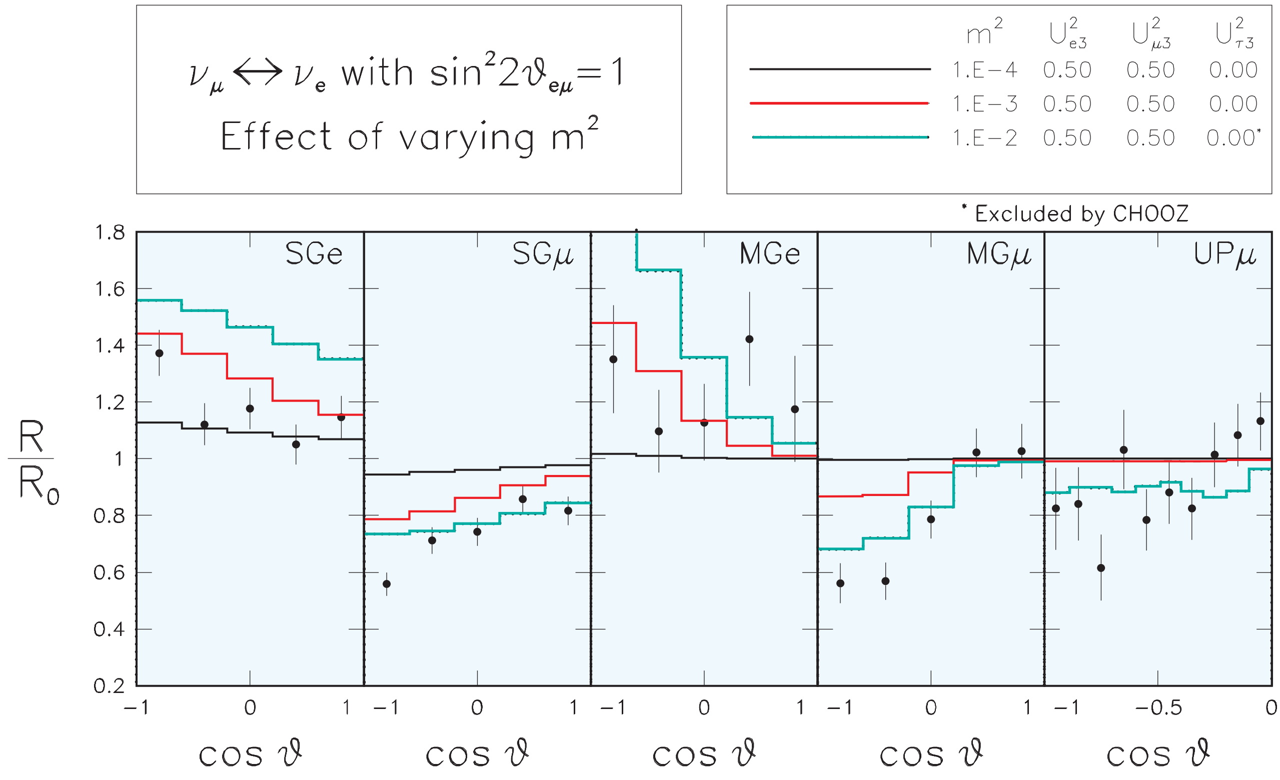
- no distorsion of e-like events (but some excess)
- just the right distortion for μ-like events

⇓

$\nu_\mu \rightarrow \nu_\tau$ good fit

Comparing expectations with the experimental SK zenithal distributions for specific choices of $(m^2, U^2_{e3}, U^2_{\mu 3}, U^2_{\tau 3})$





Examples of $\nu_\mu \Leftrightarrow \nu_e$ distorted distributions:

- too strong distorsion of e-like events
- too weak distortion of μ-like events

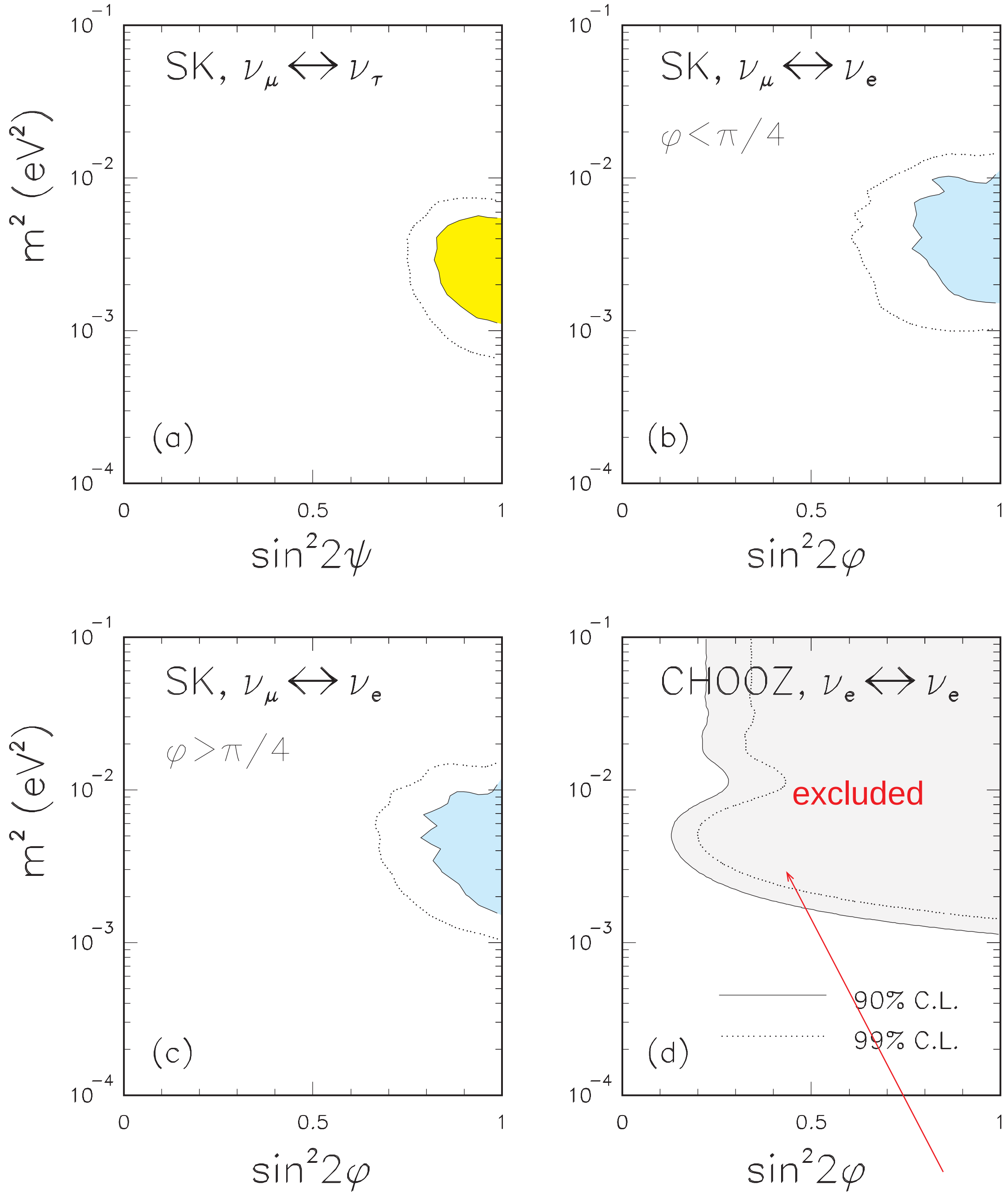
$\Downarrow$

$\nu_\mu \rightarrow \nu_e$ bad fit

Two-flavor analysis of the SK ν'98 data

SubGeV, MultiGeV and Upgoing μ combined

GLF, Lisi, Marrone & Scioscia hep-ph/9808205



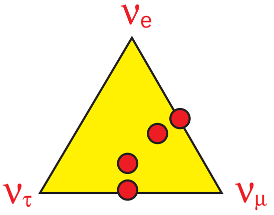
additional evidence against $\nu_\mu \to \nu_e$

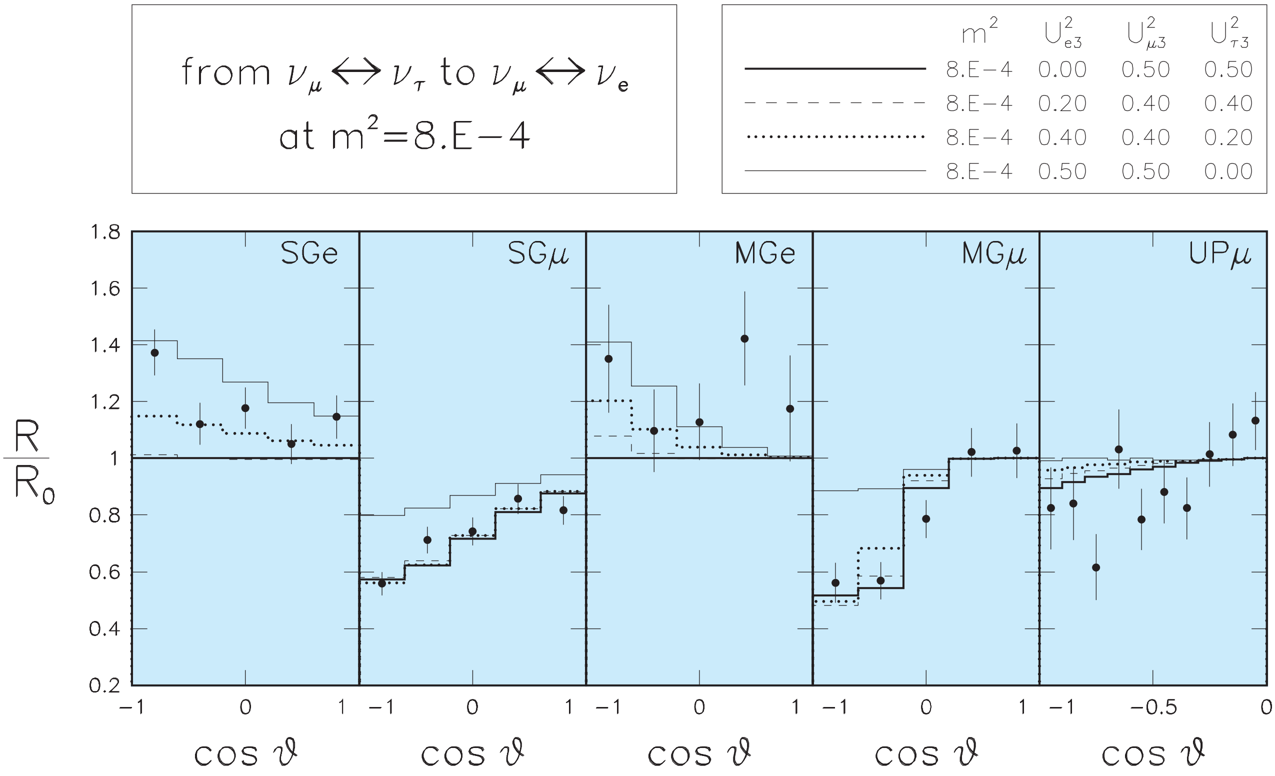
$\chi^2_{min}(\nu_\mu \to \nu_\tau) \approx 30$ (for 28 d.o.f)

$\chi^2_{min}(\nu_\mu \to \nu_e) \approx 68$

χ^2(no oscill.) ≈ 126 !!!

Comparing expectations with the experimental SK zenithal distributions for specific choices of $(m^2, U^2_{e3}, U^2_{\mu3}, U^2_{\tau3})$





from $\nu_\mu \leftrightarrow \nu_\tau$ to $\nu_\mu \leftrightarrow \nu_e$ at m^2=8.E−4

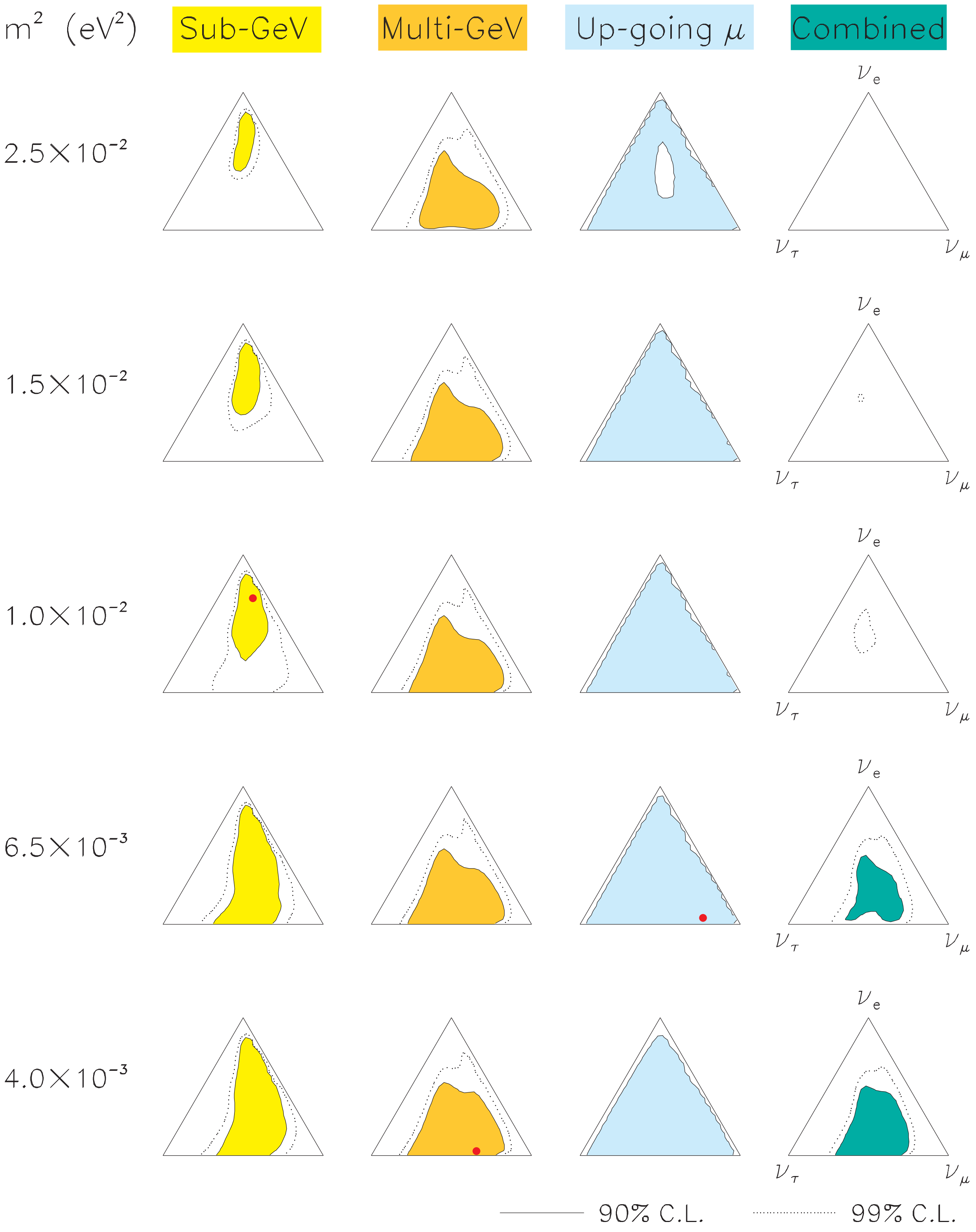
	m^2	U^2_{e3}	$U^2_{\mu3}$	$U^2_{\tau3}$
———	8.E−4	0.00	0.50	0.50
– – – –	8.E−4	0.20	0.40	0.40
······	8.E−4	0.40	0.40	0.20
——	8.E−4	0.50	0.50	0.00

Examples of 3ν distorted distributions

⇓

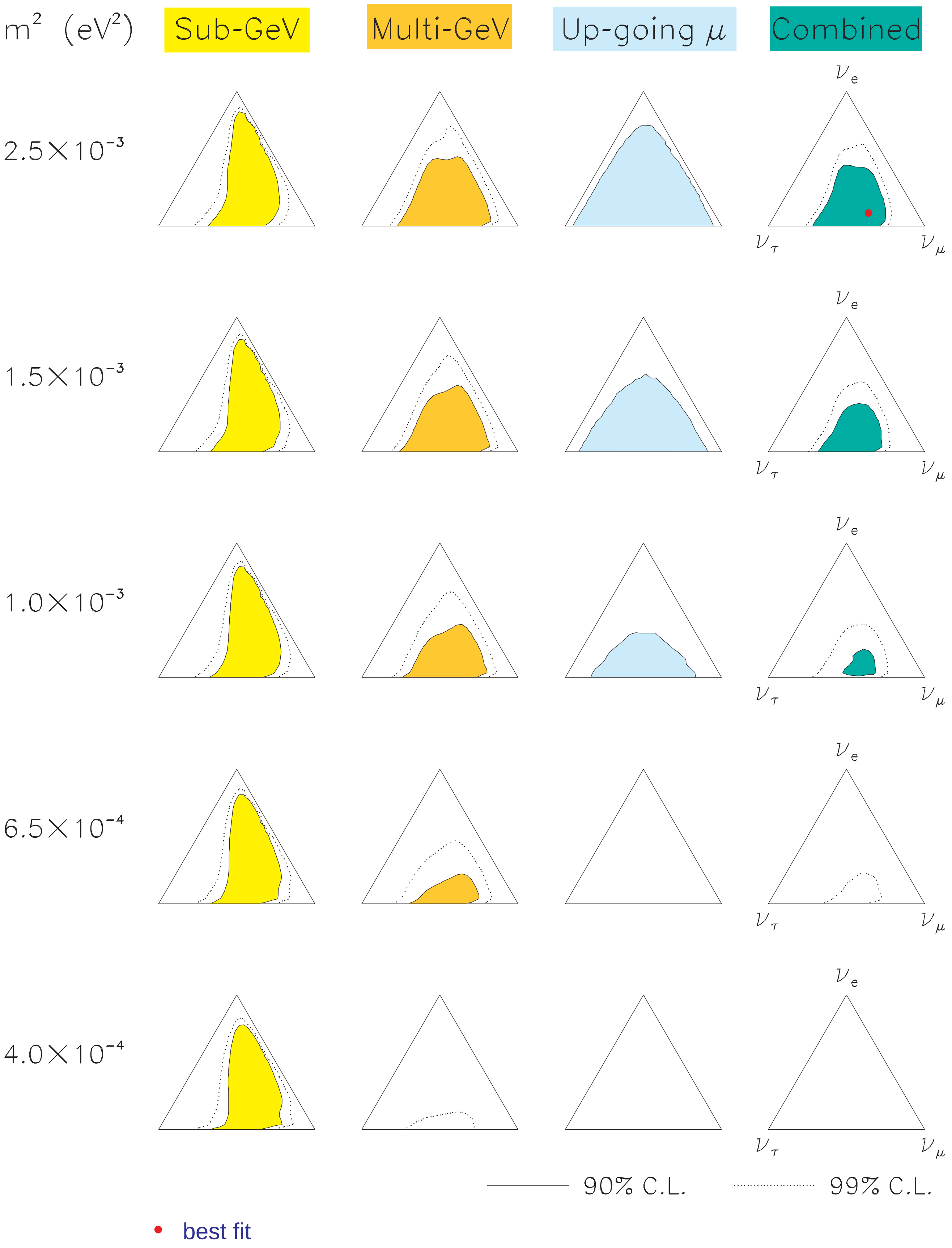
3ν mixing "helps" to explain part of the electron excess without perturbing too much the muon distribution

Allowed regions in a three-flavour approach

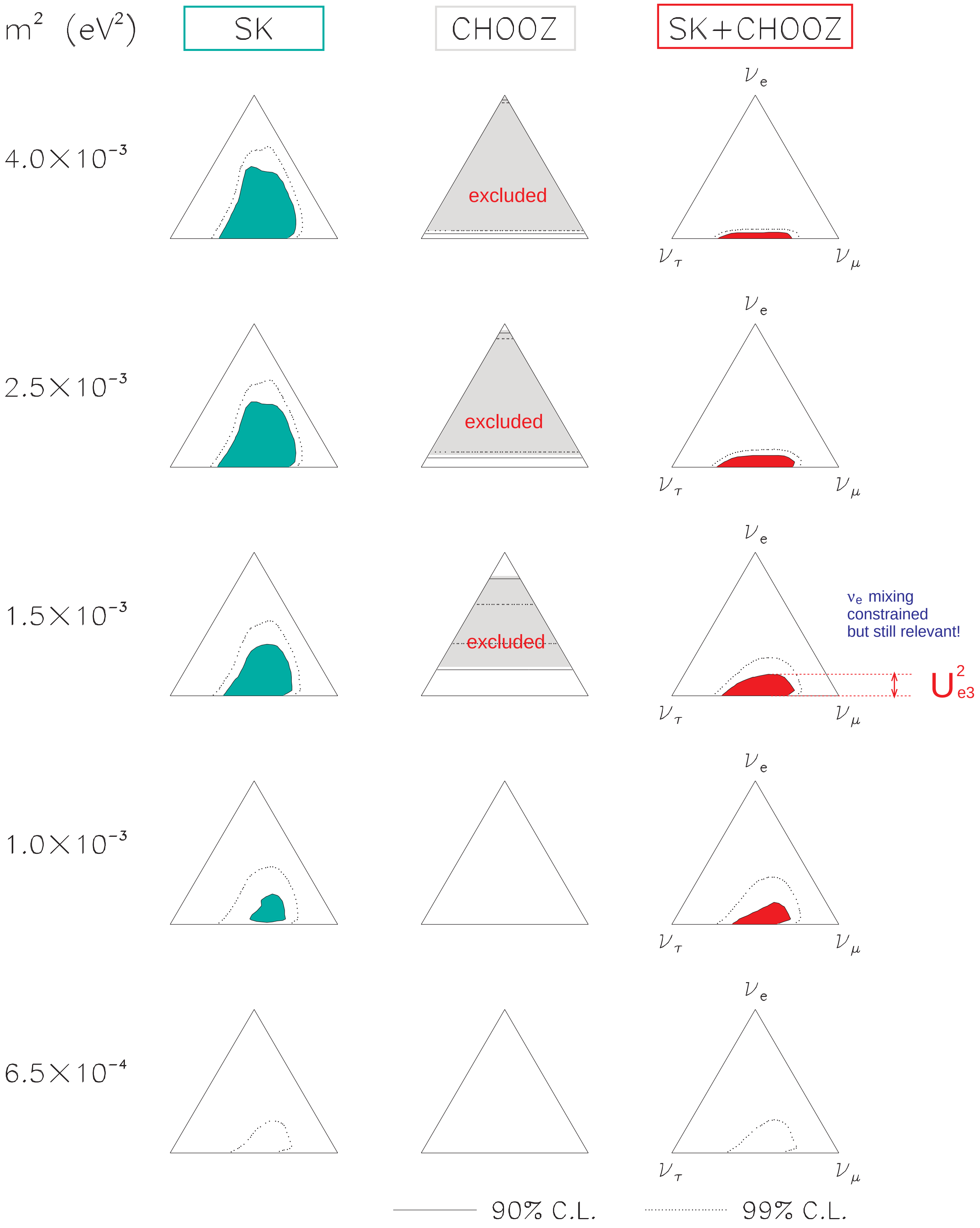


● best fit

Allowed regions in a three-flavour approach

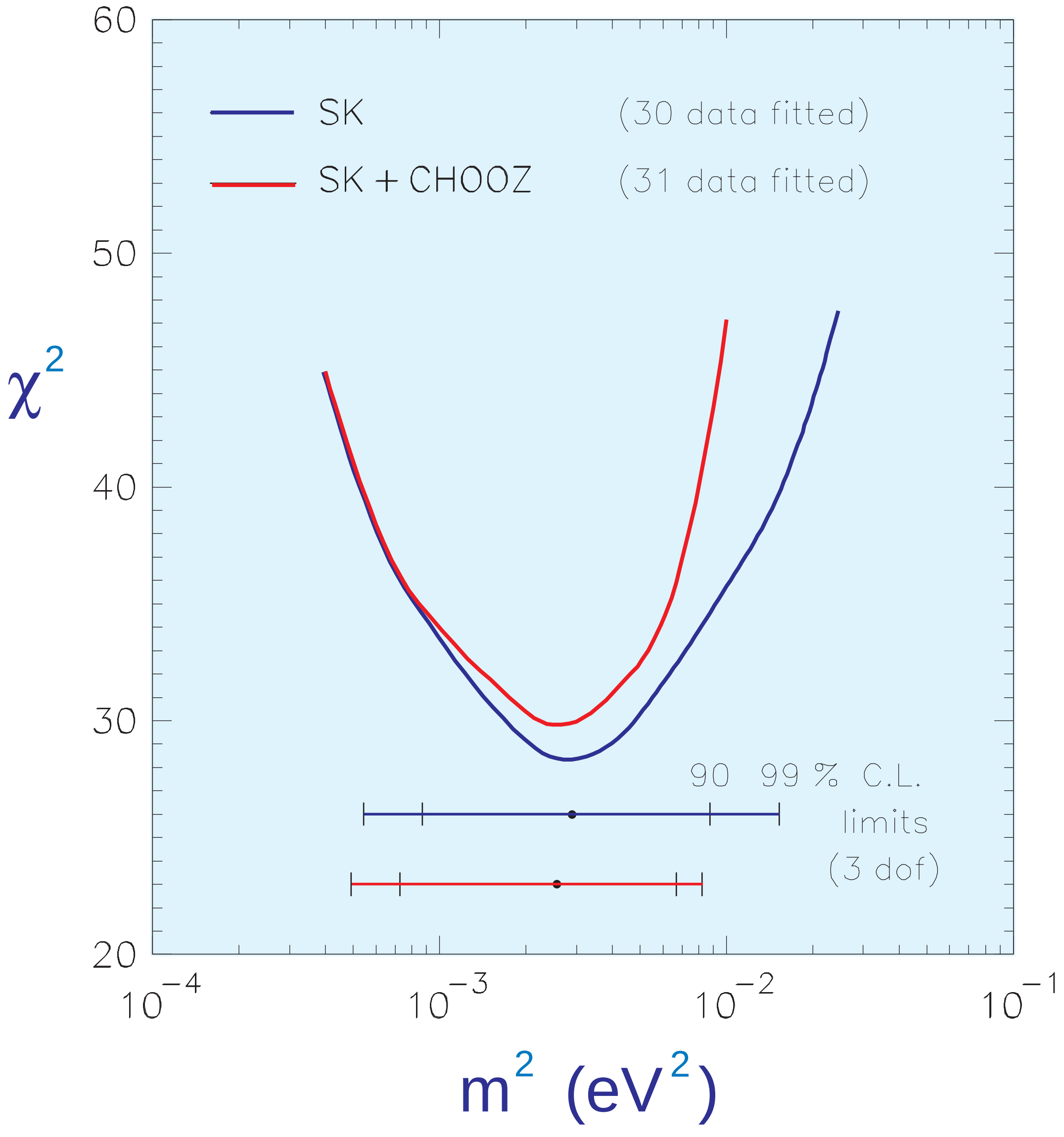


Combining Superkamiokande and CHOOZ



ν_e mixing
constrained
but still relevant!

Bounds on m^2 for unconstrained 3ν mixing

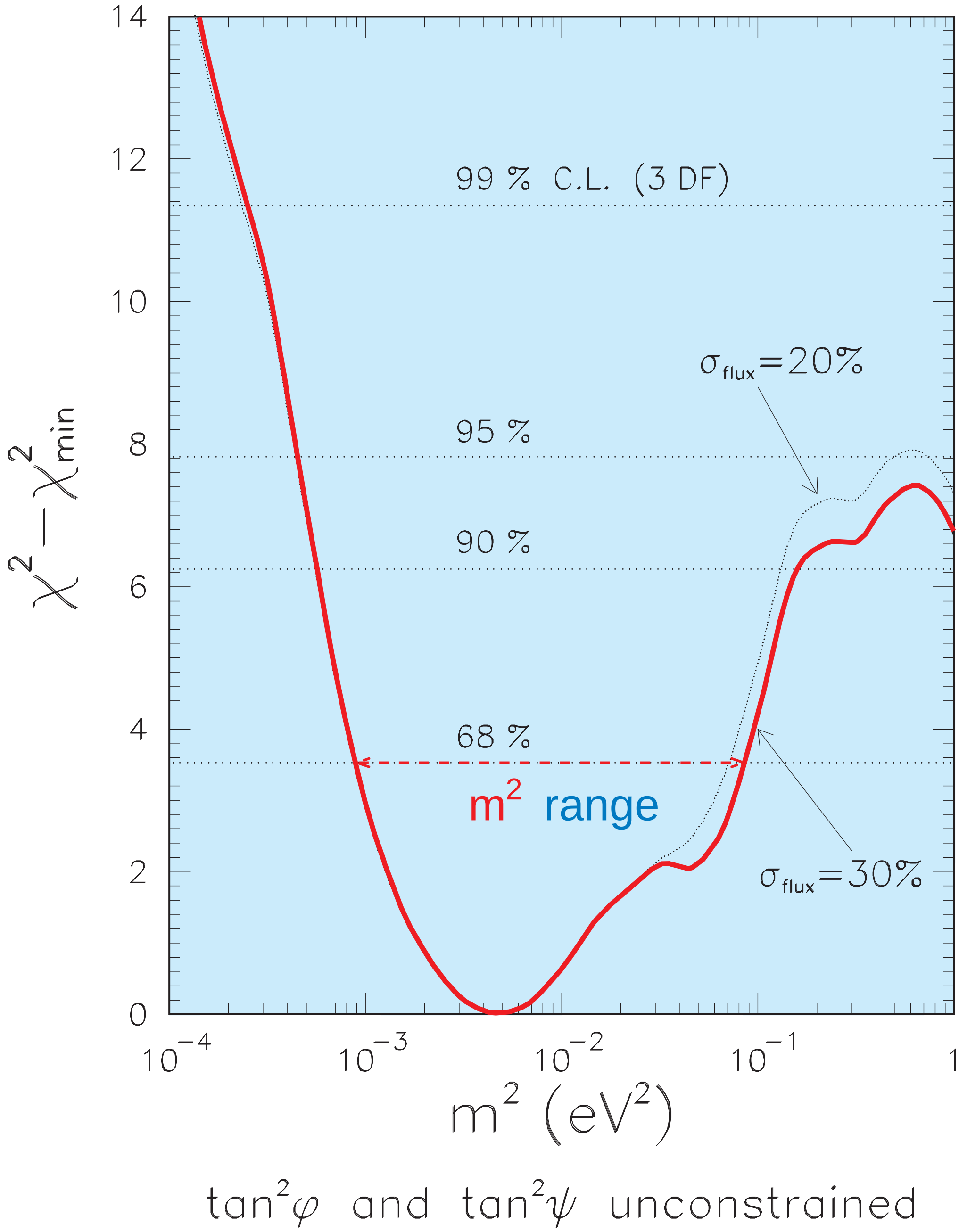


in good agreement with the analysis of the old atmospheric data ...

Atmospheric neutrinos: fit to m^2

IMB + Frejus + NUSEX + Kamiokande (SubGeV + MultiGeV)

3ν atmospheric sub-GeV
& Multi-GeV binned data

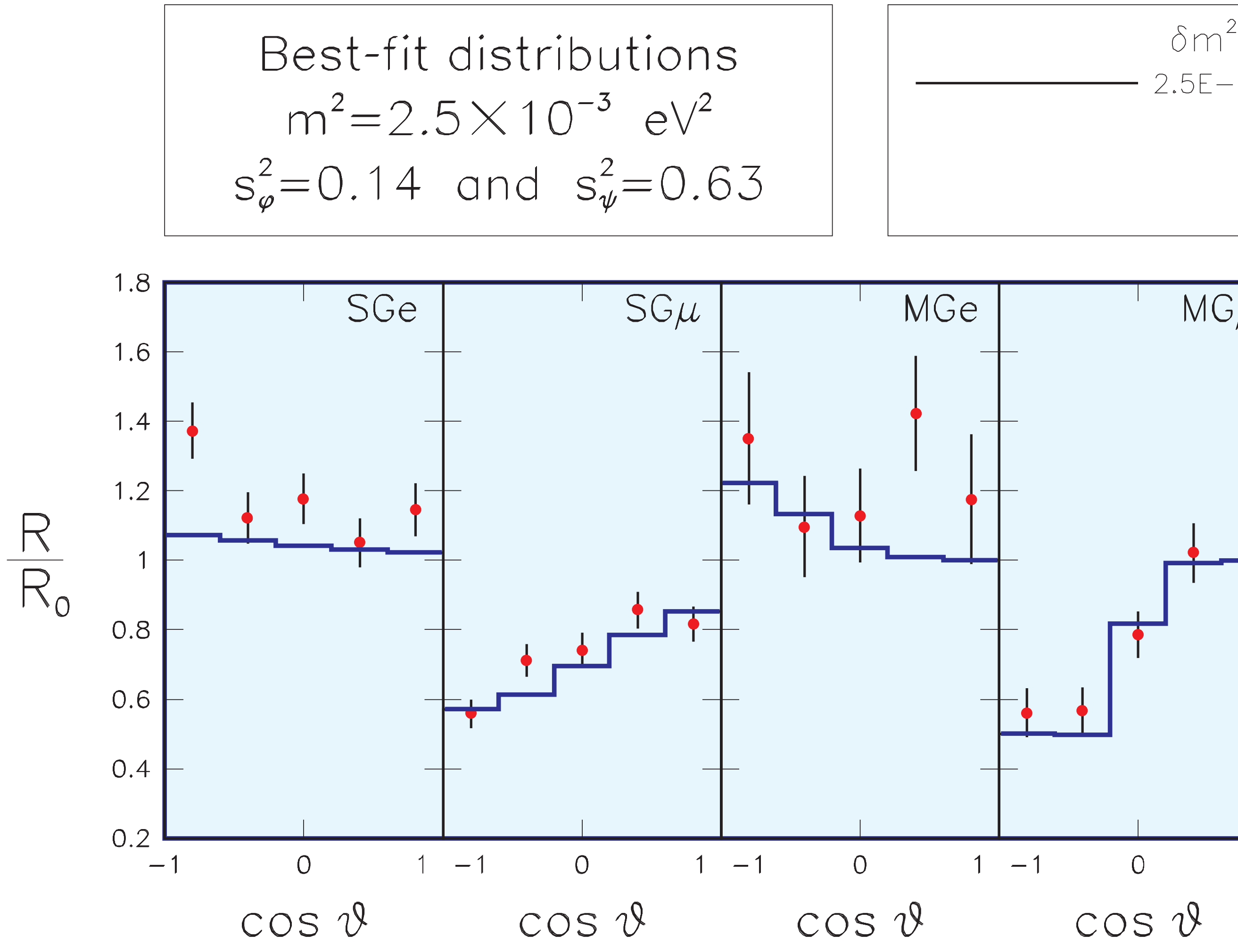


Our pre-SK fit already indicated $m^2 \sim 5 \times 10^{-3}$ eV^2 !

GLF, Lisi, Montanino and Scioscia, PRD 55 (1997) 4358

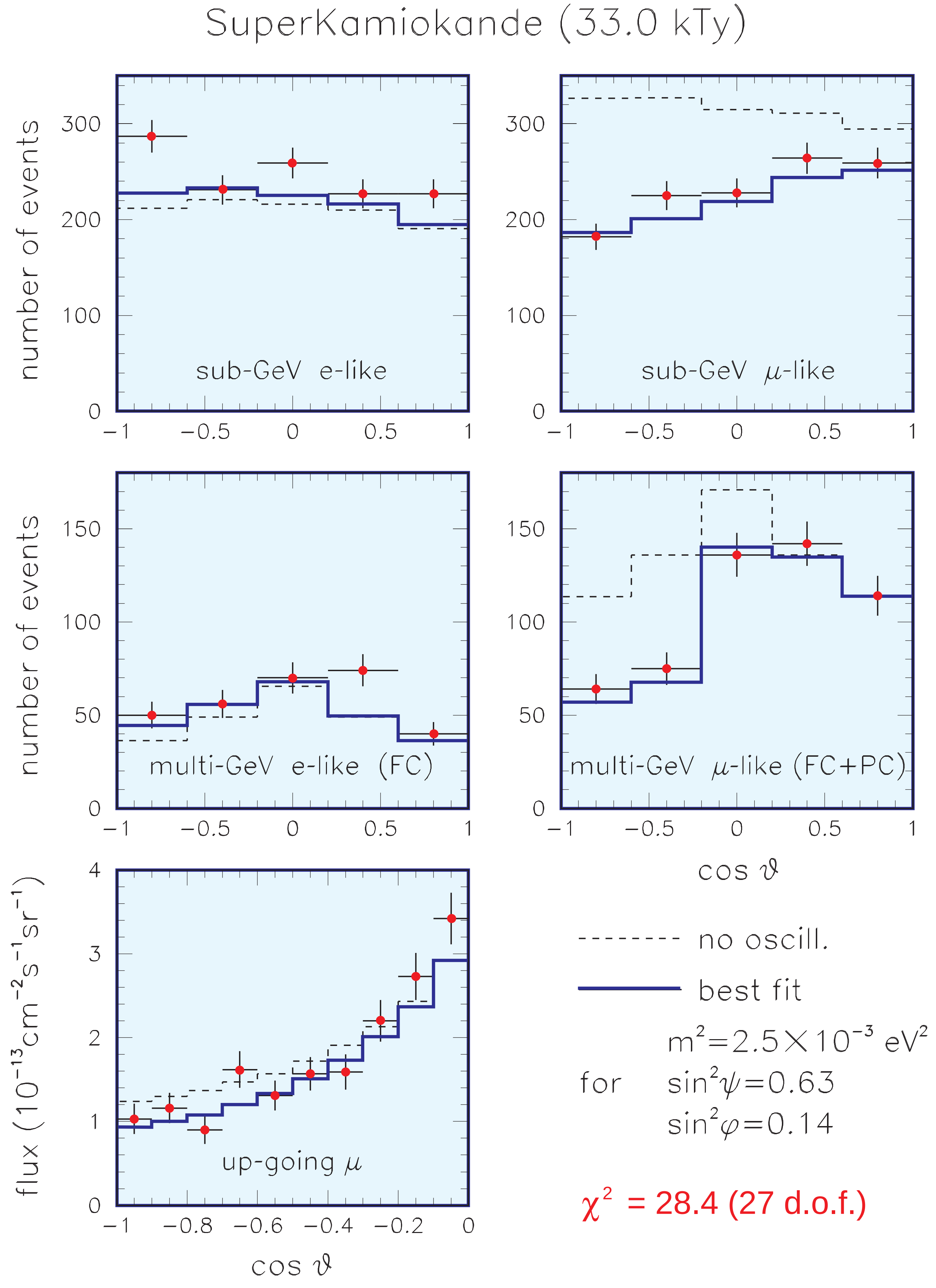
Three-flavor best-fit to the SK ν'98 data

χ^2 = 28.4



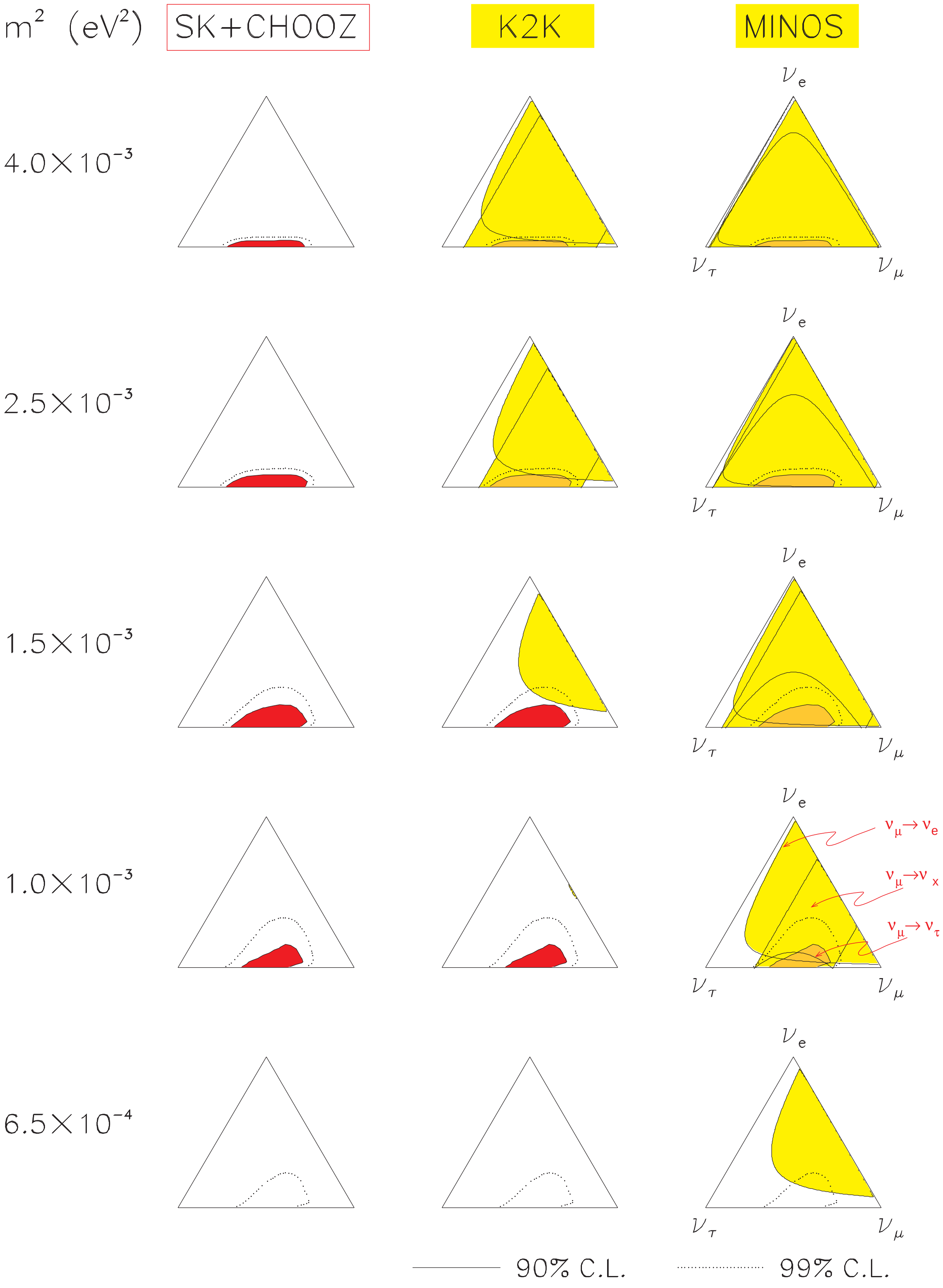
Best-fit distributions
$m^2 = 2.5 \times 10^{-3}$ eV^2
$s^2_\varphi = 0.14$ and $s^2_\psi = 0.63$

Three-flavor best-fit to the SK ν'98 data



χ^2 = 28.4 (27 d.o.f.)

Comparing SK+CHOOZ with K2K and MINOS



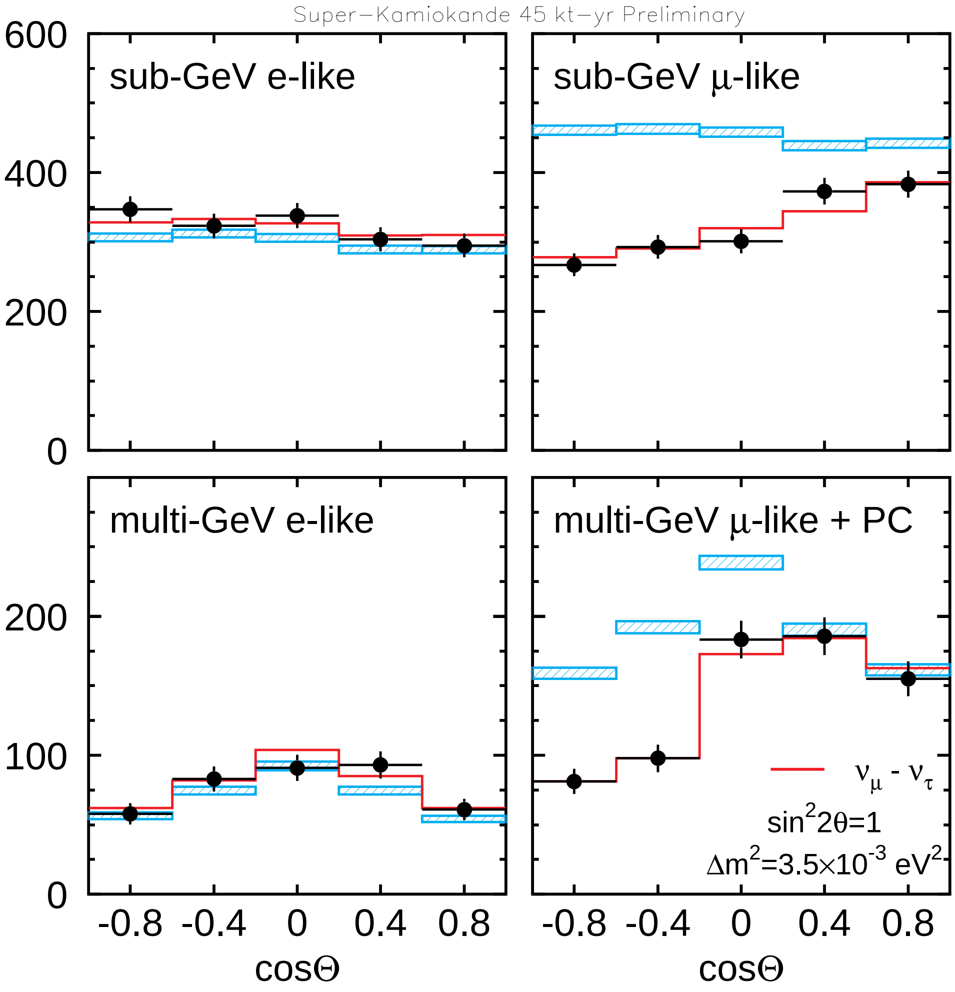
3. Updating the SK data (45 kTy, January '99)

- The new experimental data
- A three-flavor analysis

GLF, E. Lisi, A. Marrone and G. Scioscia,
preliminary

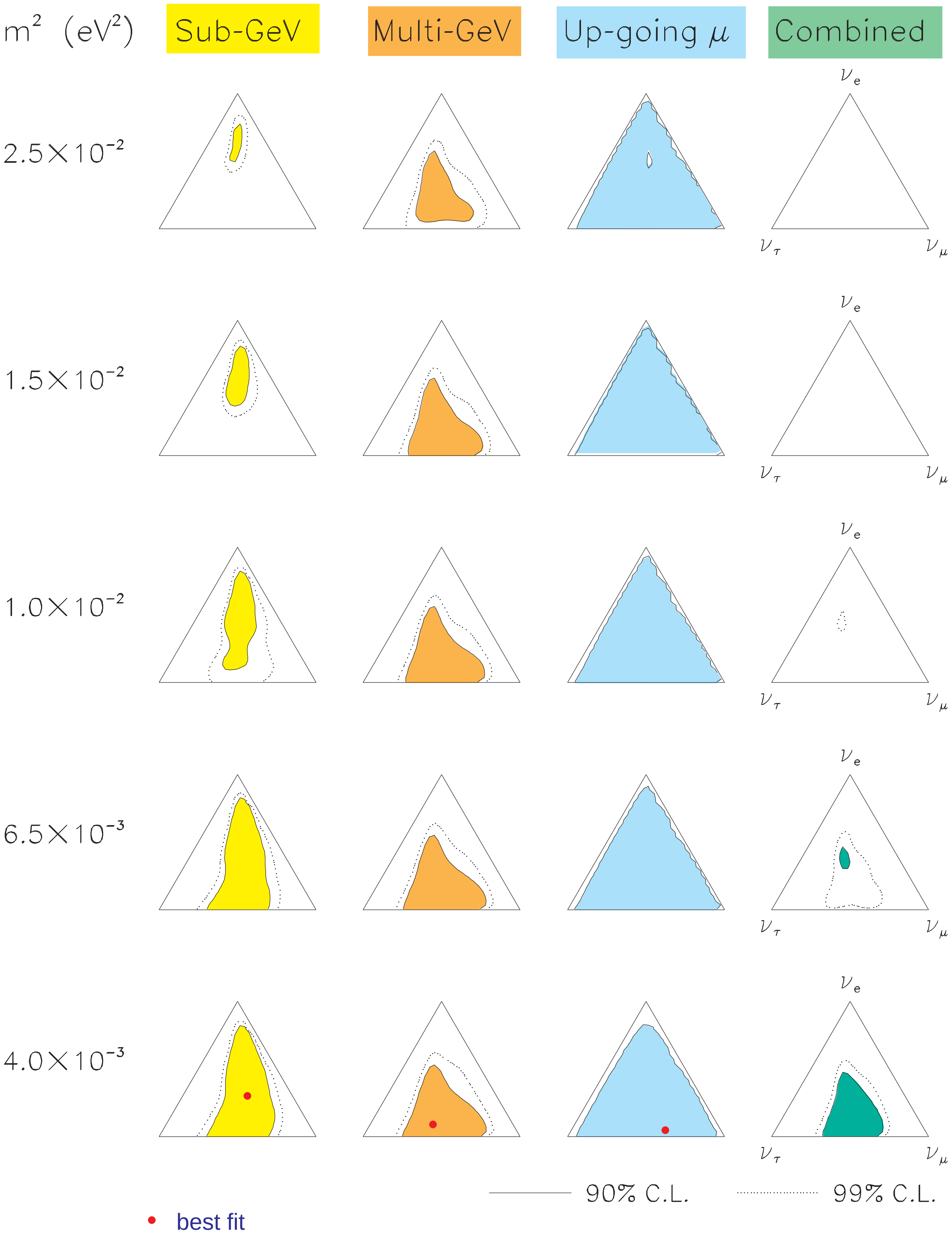
Update of the SK data: SG and MG zenithal distributions

ν_μ ν_τ Best Fit Zenith Angle Rates



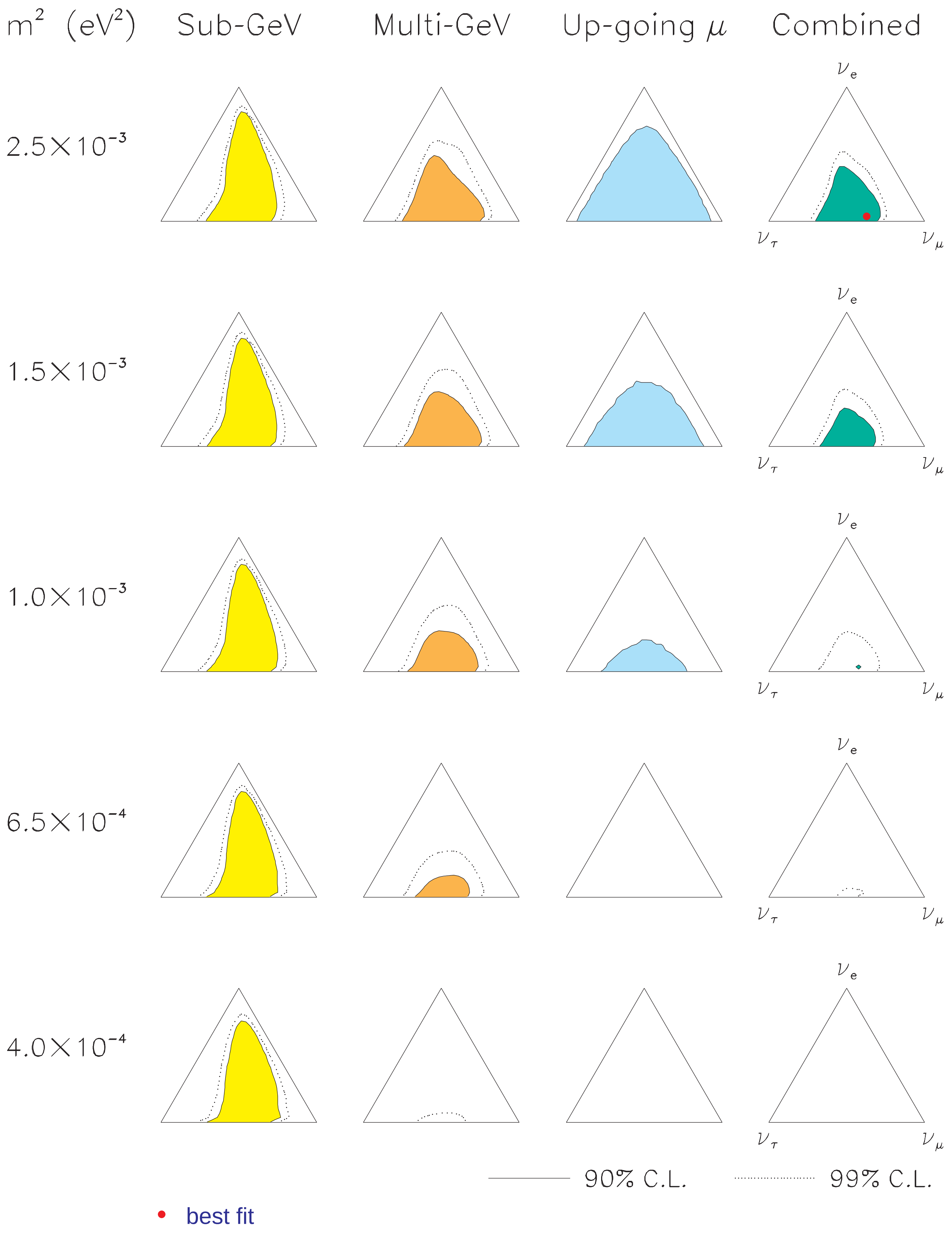
SK99_1

Allowed regions in a three-flavour approach



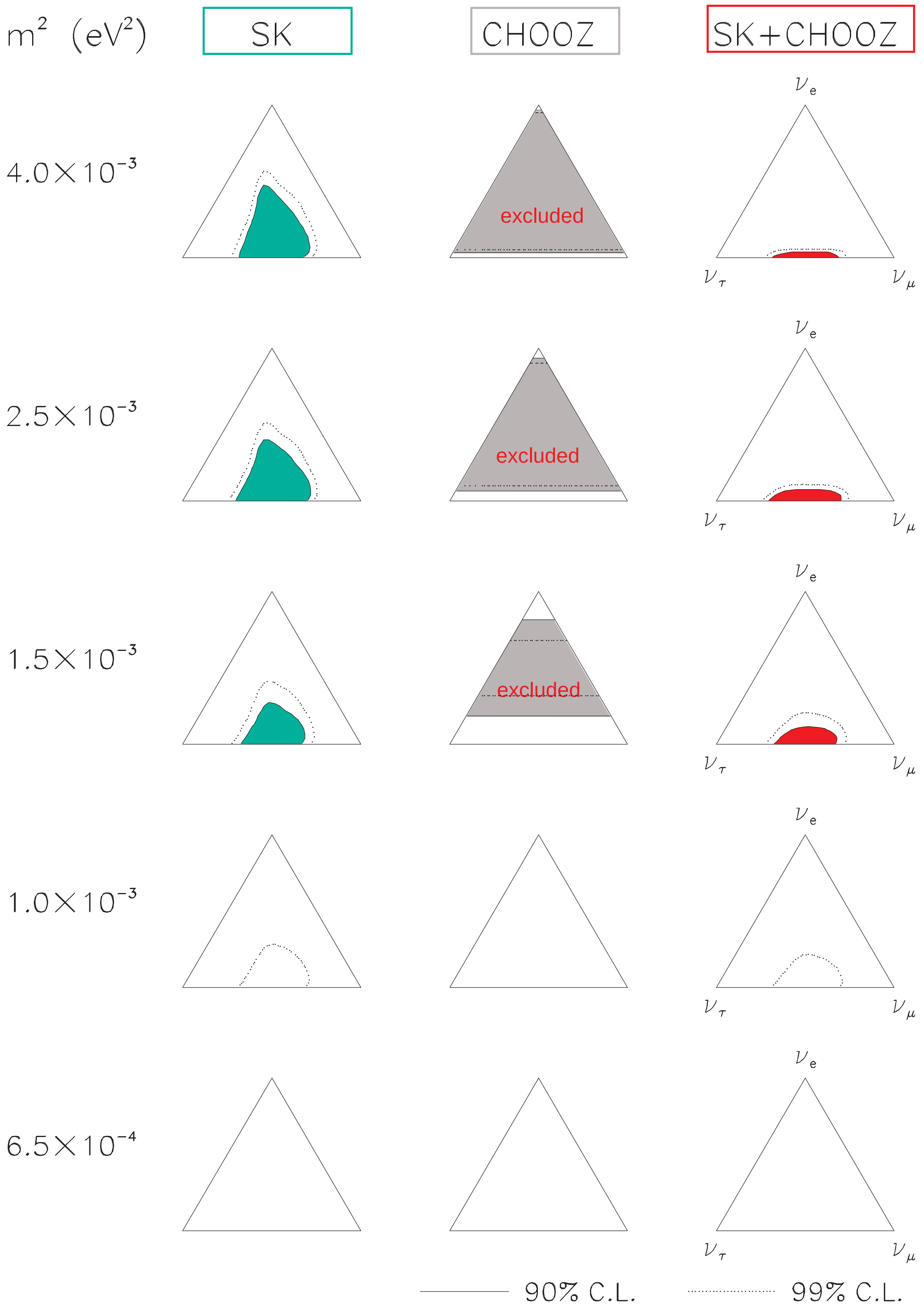
VERY PRELIMINARY!

Allowed regions in a three-flavour approach



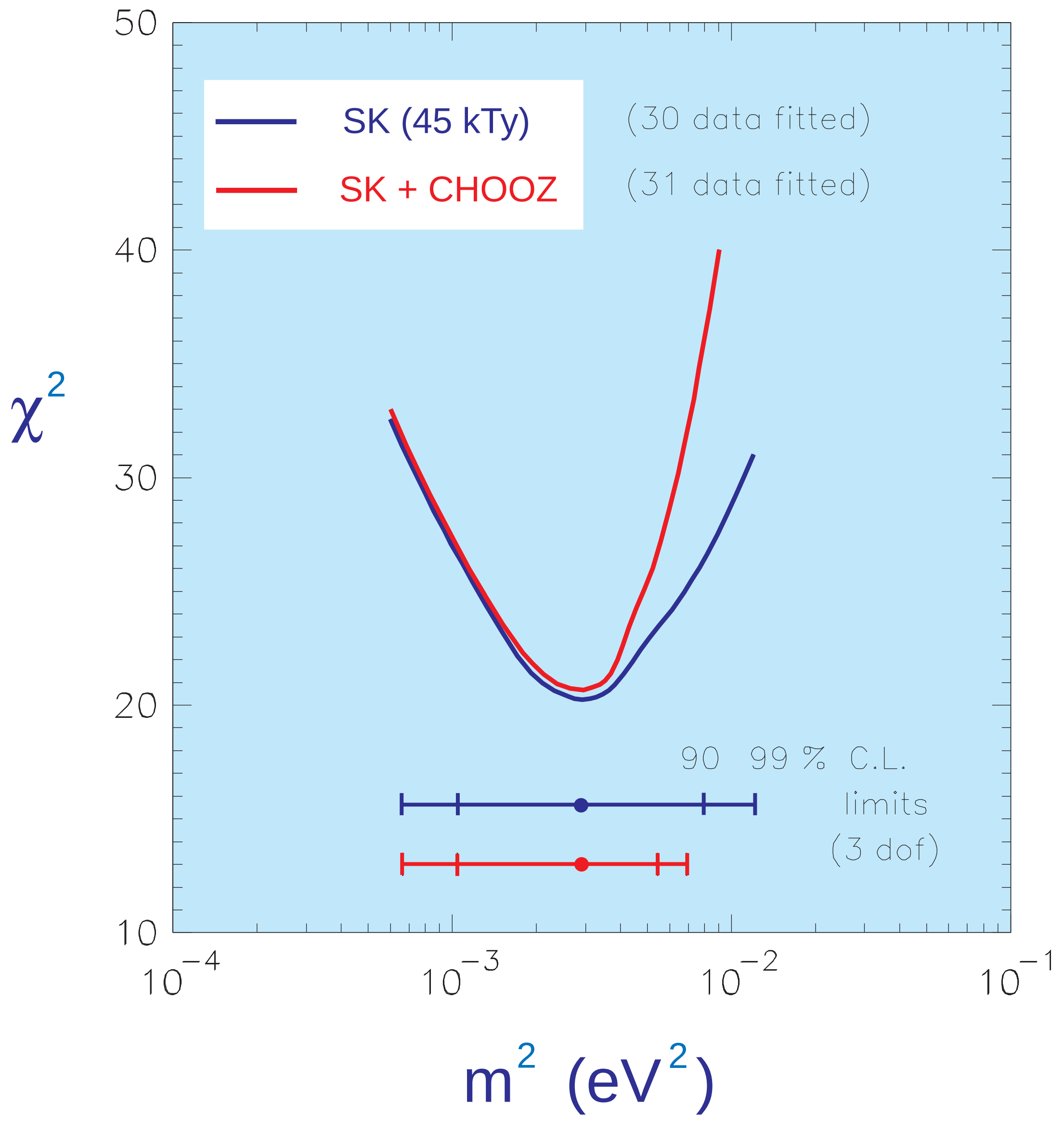
VERY PRELIMINARY!

Combining Superkamiokande and CHOOZ



VERY PRELIMINARY!

Bounds on m^2 for unconstrained 3ν mixing



best-fit for both cases @ $m^2 = 2.8 \times 10^{-3}$ eV^2

VERY PRELIMINARY!

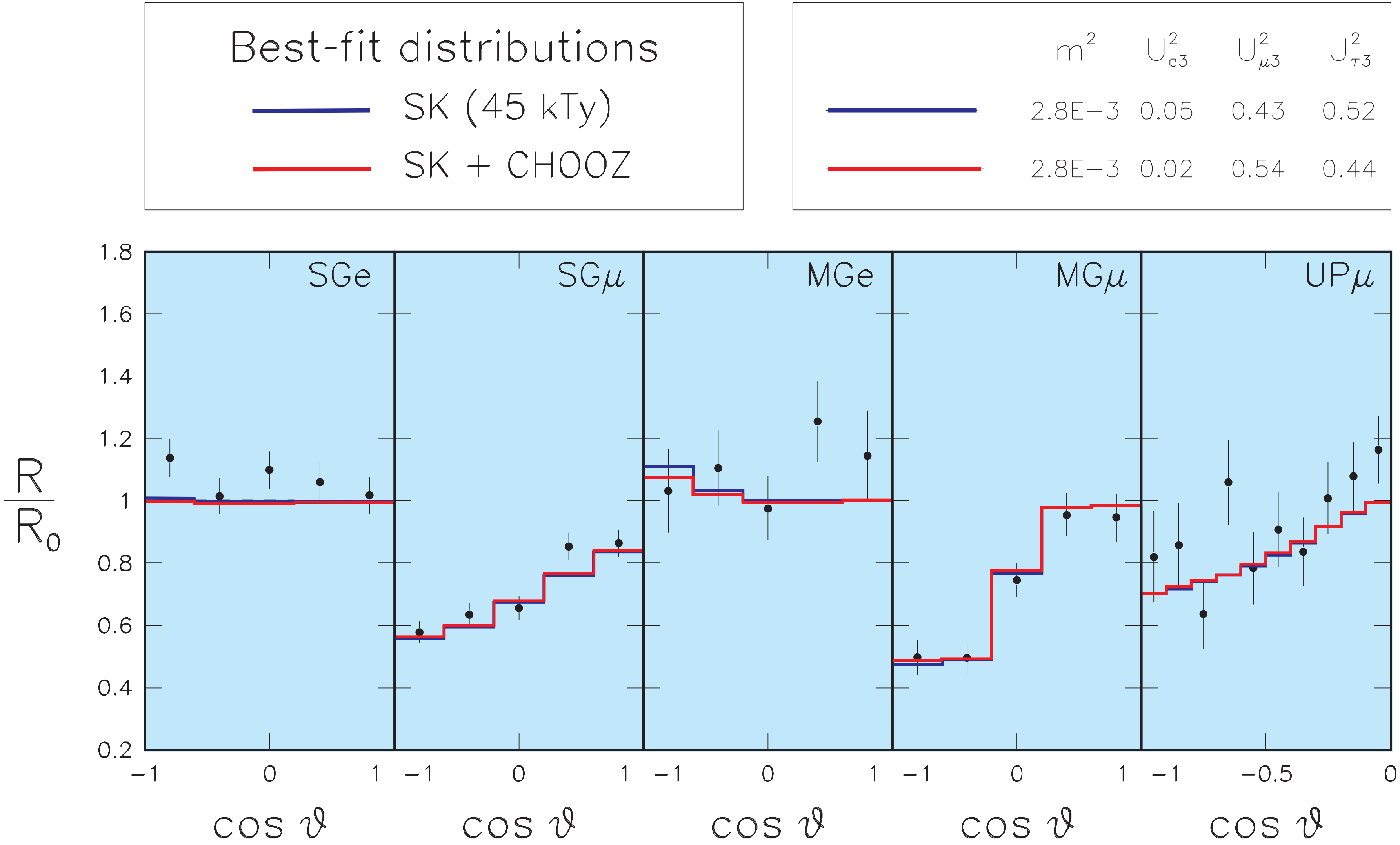
With respect to the 33 kTy data:

- best fit stable around $m^2 \sim 3 \times 10^{-3}$ eV^2
- log(m^2) range reduced of ~ 15%

⇒ Further improvements in statistics might be increasingly hindered by the systematics uncertainties in fluxes and cross-sections

Best-fit distributions

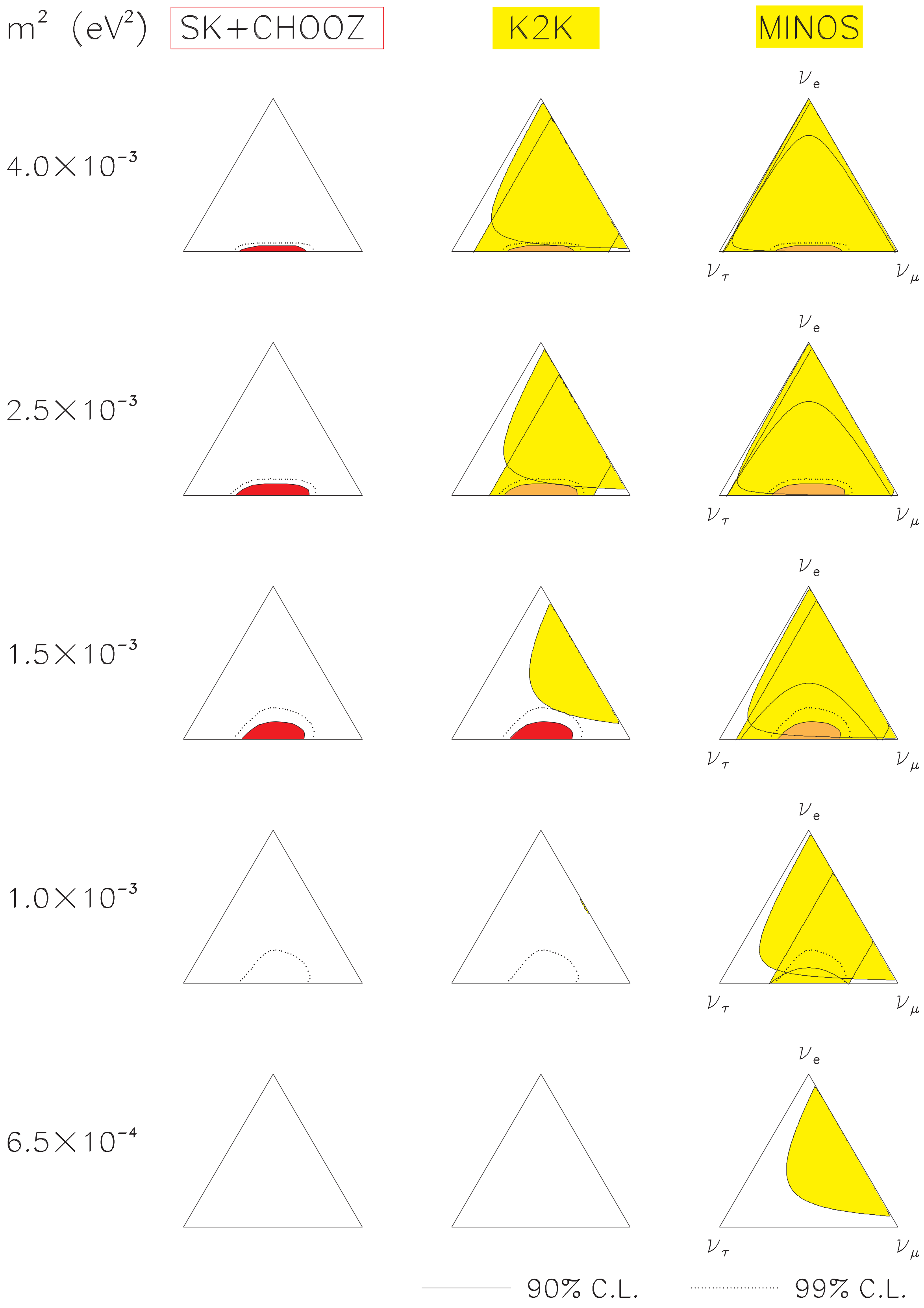
The slight up-down asymmetry in the MGe distribution is due to $U_{e3}^2 \neq 0$. Much higher statistics needed to check it.



	m^2	U_{e3}^2	$U_{\mu3}^2$	$U_{\tau3}^2$
🟦	2.8E−3	0.05	0.43	0.52
🟥	2.8E−3	0.02	0.54	0.44

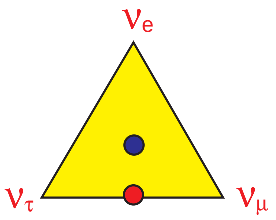
VERY PRELIMINARY!

Comparing SK+CHOOZ with K2K and MINOS

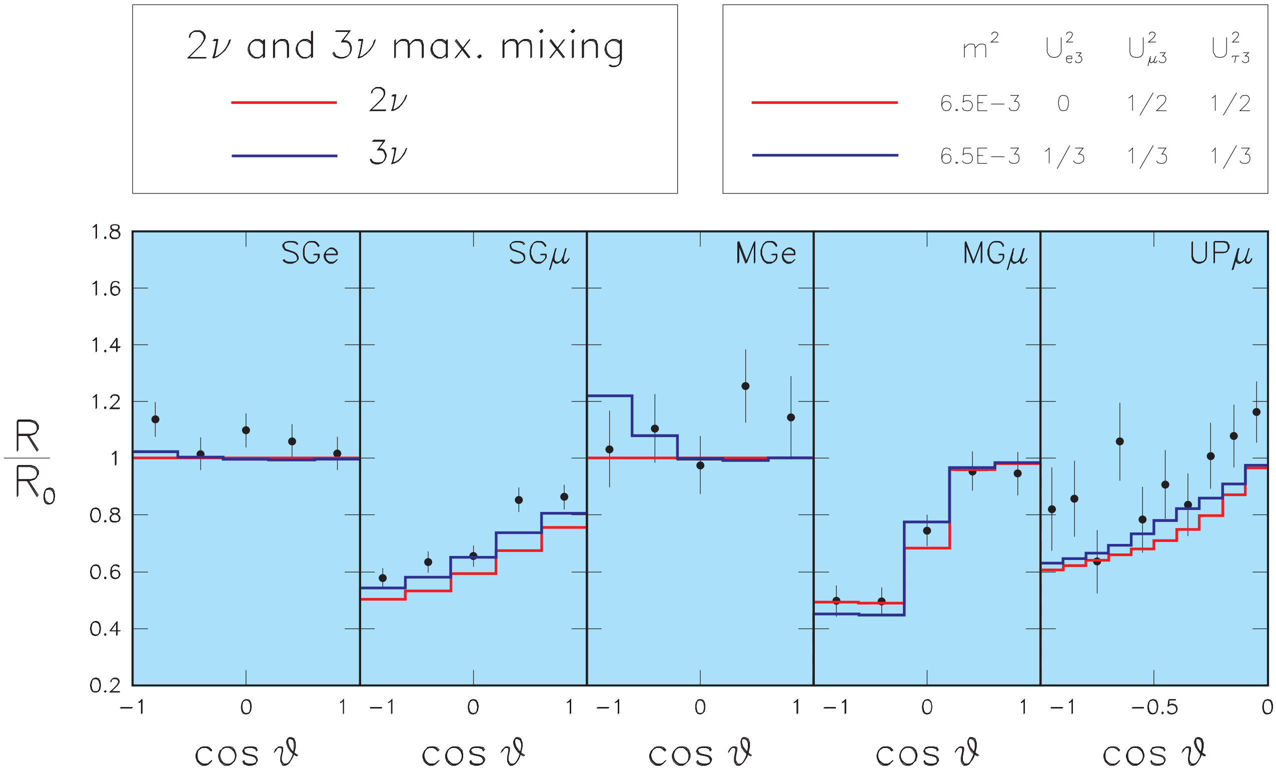


VERY PRELIMINARY!

Comparing SK data with 2ν and 3ν maximal mixing



$@\ m^2 = 6.5 \infty 10^{-3}\ eV^2$



	m^2	U^2_{e3}	$U^2_{\mu 3}$	$U^2_{\tau 3}$
🟥	6.5E−3	0	1/2	1/2
🟦	6.5E−3	1/3	1/3	1/3

Without including the CHOOZ constraints,

$$\chi^2(3\nu) < \chi^2(2\nu)$$

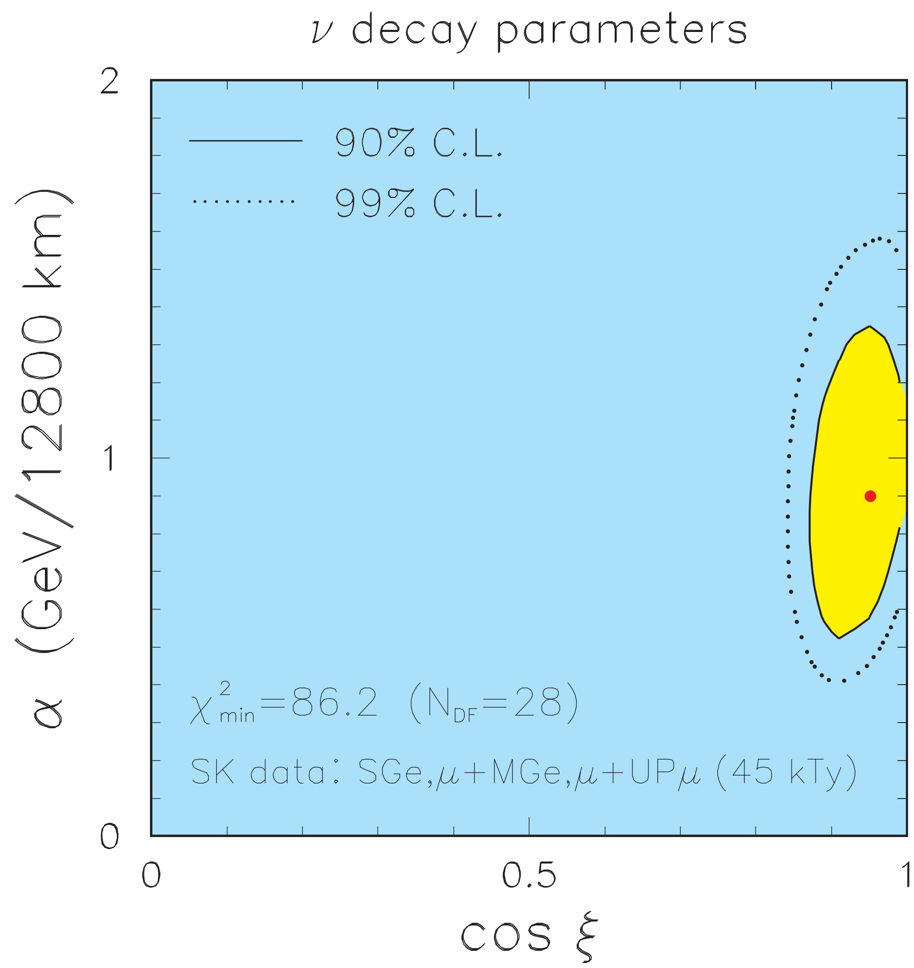
for relatively high values of m^2. Not a great variation in MGμ, but SGμ and Upμ are fitted better with 3ν oscillations

neutrino decay interpretation of the atmospheric neutrino anomaly

ν_μ assumed to have un instable component ν_d
with mass m_d and lifetime τ_d

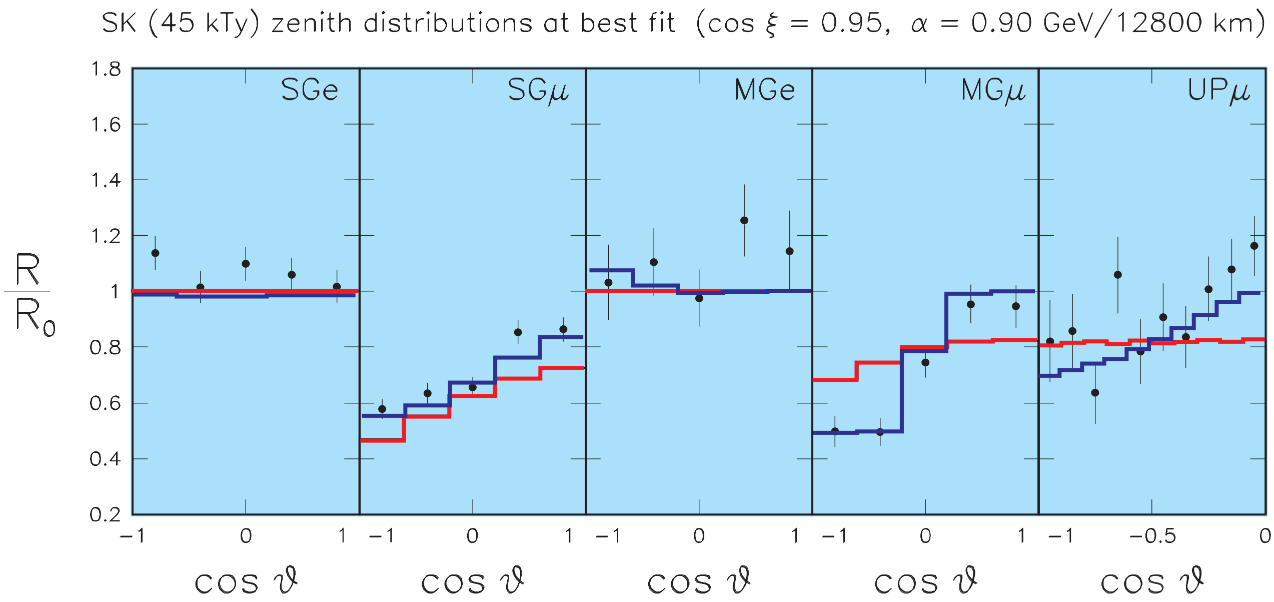
parameters

$$\left\{ \begin{array}{l} \cos\xi \equiv \langle \nu_\mu | \nu_d \rangle \\ \alpha = m_d / \tau_d \end{array} \right.$$



neutrino decay interpretation of the atmospheric neutrino anomaly

GLF, E. Lisi, A. Marrone and G. Scioscia
hep-ph/9902267



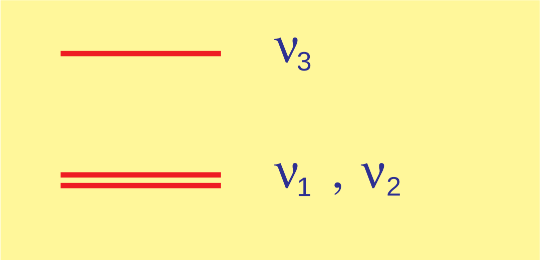
SK (45 kTy) zenith distributions at best fit (cos $\xi = 0.95$, $\alpha = 0.90$ GeV/12800 km)

— neutrino decay: $\chi^2 = 86.2$ ($N_{df} = 28$)

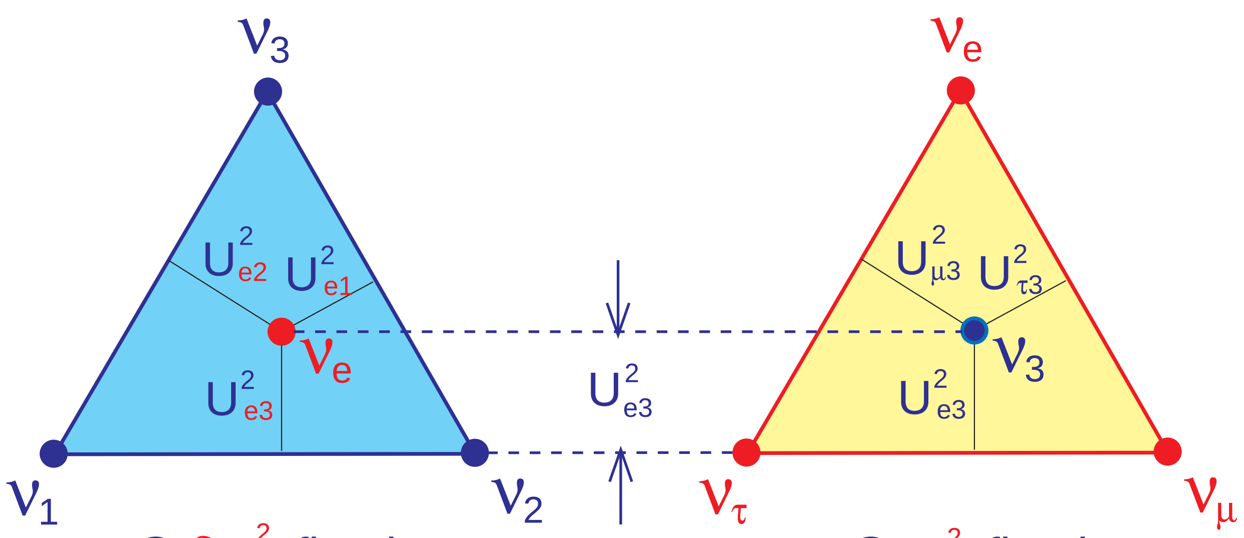
— neutrino oscillation: $\chi^2 = 20.7$ ($N_{df} = 28$)

5. Solar + atmospheric ν solutions

Within the scheme discussed before:



$$\begin{cases} m^2 = |m_3^2 - m_{1,2}^2| & \text{(responsible of "terrestrial" } \nu) \\ \delta m^2 = |m_2^2 - m_1^2| & \text{(responsible of solar } \nu \text{ deficit)} \end{cases}$$



Solar ν

@ δm^2 fixed

Atmospheric ν

@ m^2 fixed

U_{e3}^2 probed by solar AND atmospheric ν experiments

$\Downarrow$

U_{e3}^2 must be the SAME in both triangles !!!

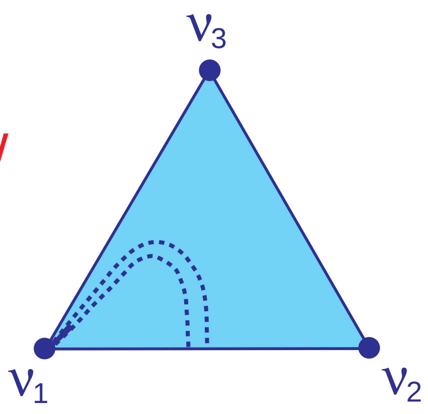
Possible solutions

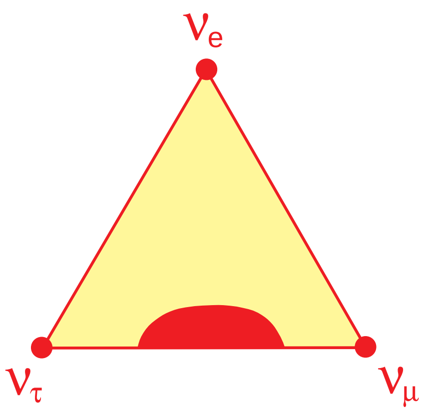
Solar

Atm. + CHOOZ

1.

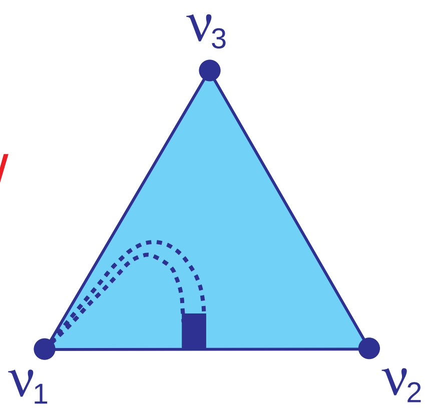
MSW
SMA

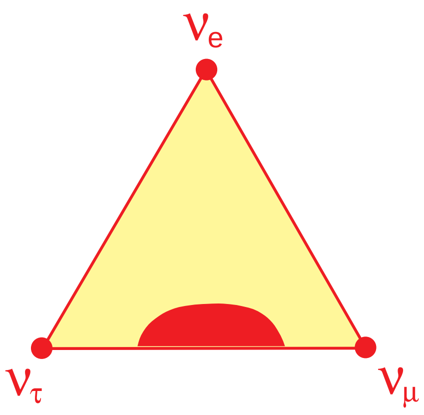




2.

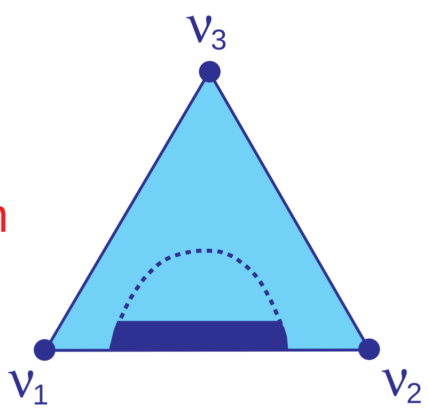
MSW
LMA

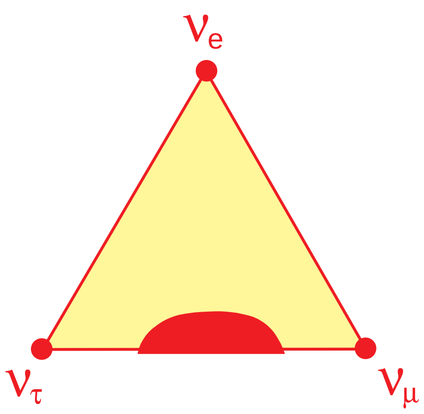




3.

vacuum





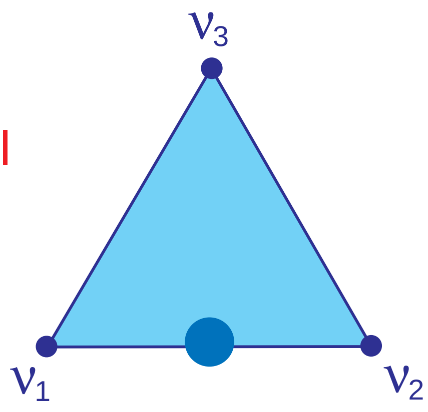
Example of models

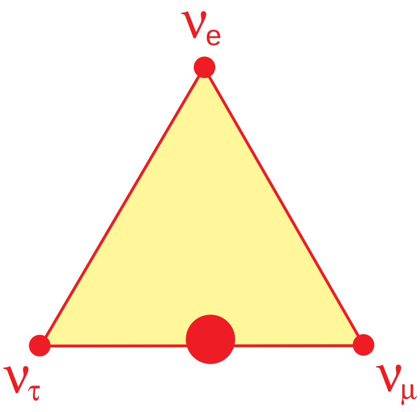
Solar

Atm. + CHOOZ

1.

"bimaximal mixing"

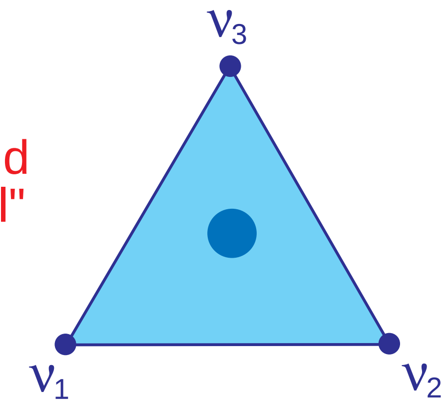


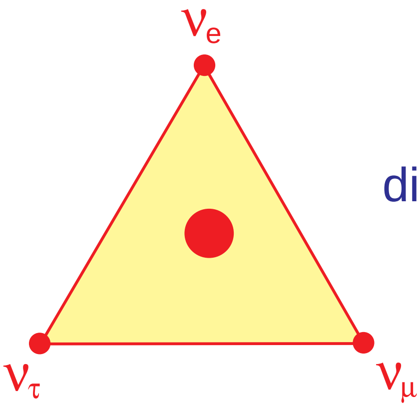


allowed

2.

"threefold maximal" mixing





disfavored

6. Established facts and open questions

- angular distribution information is robust: it drives the fit, narrowing the m^2 range and excluding scenarios different from "standard" oscillations (see also the Pakvasa 's talk and Lipari-Lusignoli, hep-ph/9901350)

- good fit provided by dominant $\nu_\mu \rightarrow \nu_\tau$ with a "bit" of ν_e

however ...

- e-like distributions have (at present) a too low statistics to probe the distorsions induced by the ν_e mixing

- Total rate information is ambiguous: it is not inconsistent with $\nu_\mu \Leftrightarrow \nu_e$, MC × 1.1 is required by $\nu_\mu \Leftrightarrow \nu_\tau$ interpretation, but MC × 0.8 would jeopardize the oscillation interpretation!

⇒ NEED TO IMPROVE AND CONSTRAIN THEORETICAL CALCULATION OF FLUXES

⇒ NEED TO TEST THE ROLE OF ν_e MIXING WITH HIGHER STATISTICS

LBL experiments

- may be difficult if $\Delta m^2 \sim 10^{-3}$ eV^2 (not yet excluded)

- most of the signal expected in the disappearance channel

  $\nu_\mu \rightarrow \nu_\mu$ $\Rightarrow$ a near detector would be useful

- ν_τ appearance is the main goal, but not the only one: LBL expts. are our only chance to measure some oscillation parameters !

  $$\Longrightarrow \quad m^2, U_{e3}^2, U_{\mu 3}^2, U_{\tau 3}^2$$

- ν_e appearance is also important!

$\Longrightarrow$ LBL PROPOSALS SHOULD PROVE HOW WELL THEY CAN MEASURE OSCILLATION PARAMETERS, RATHER THAN JUST CONFIRM THE SK DISAPPEARANCE SIGNAL