Neutrino oscillations and non-standard neutrino-matter interactions (NSI)

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A. Friedland, C.L. & Carlos Pena-Garay, Phys.Lett.B594:347,2004 (solar n.)
A.Friedland, C.L. & M.Maltoni, PRD 70:111301, 2004 (atmospheric n.),
A. Friedland, C.L., hep-ph/0506143

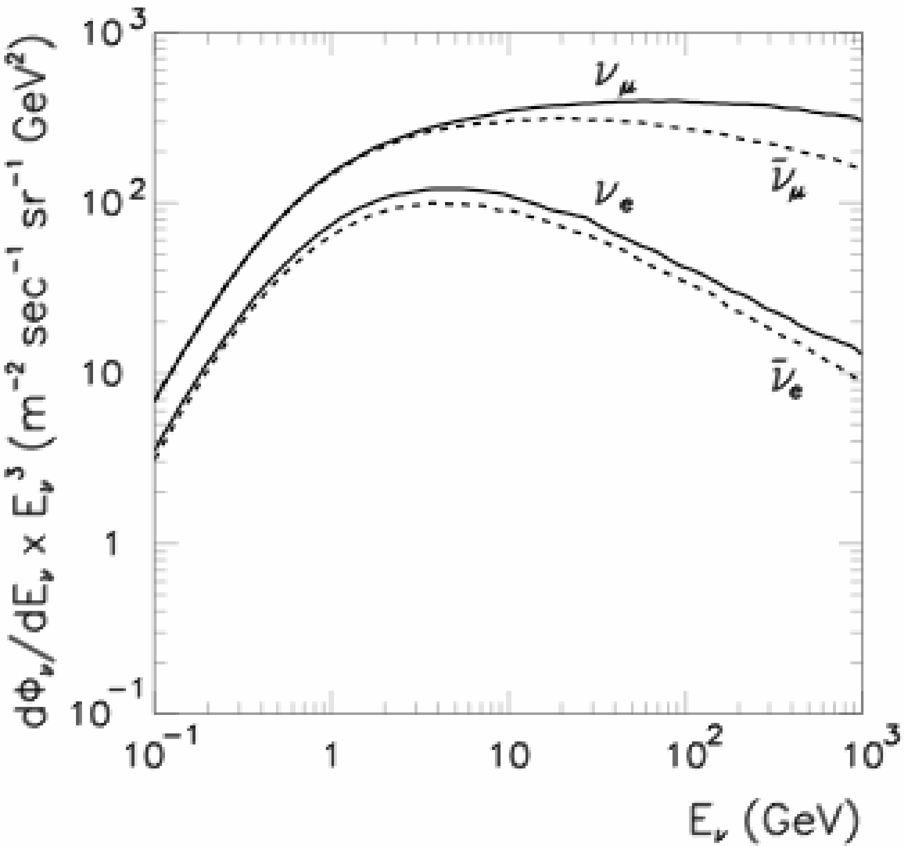
Contents

- Neutrino oscillations and matter effects
- Non standard interactions (NSI)?
- Testing NSI with oscillation experiments
  - Atmospheric neutrinos

Neutrino oscillations and matter effects

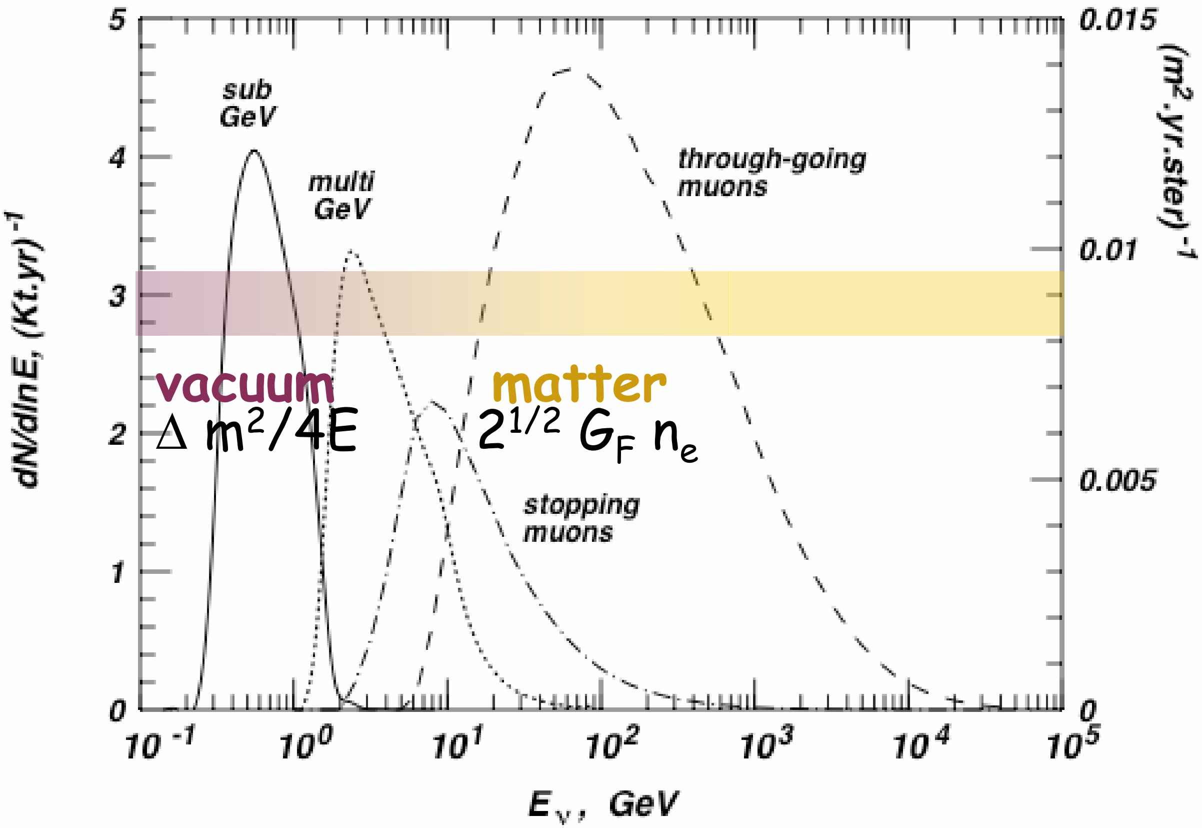
Atmospheric neutrinos as probes of neutrino interactions

From: M.C. Gonzalez Garcia and Y. Nir, Rev.Mod.Phys.75:345-402,2003



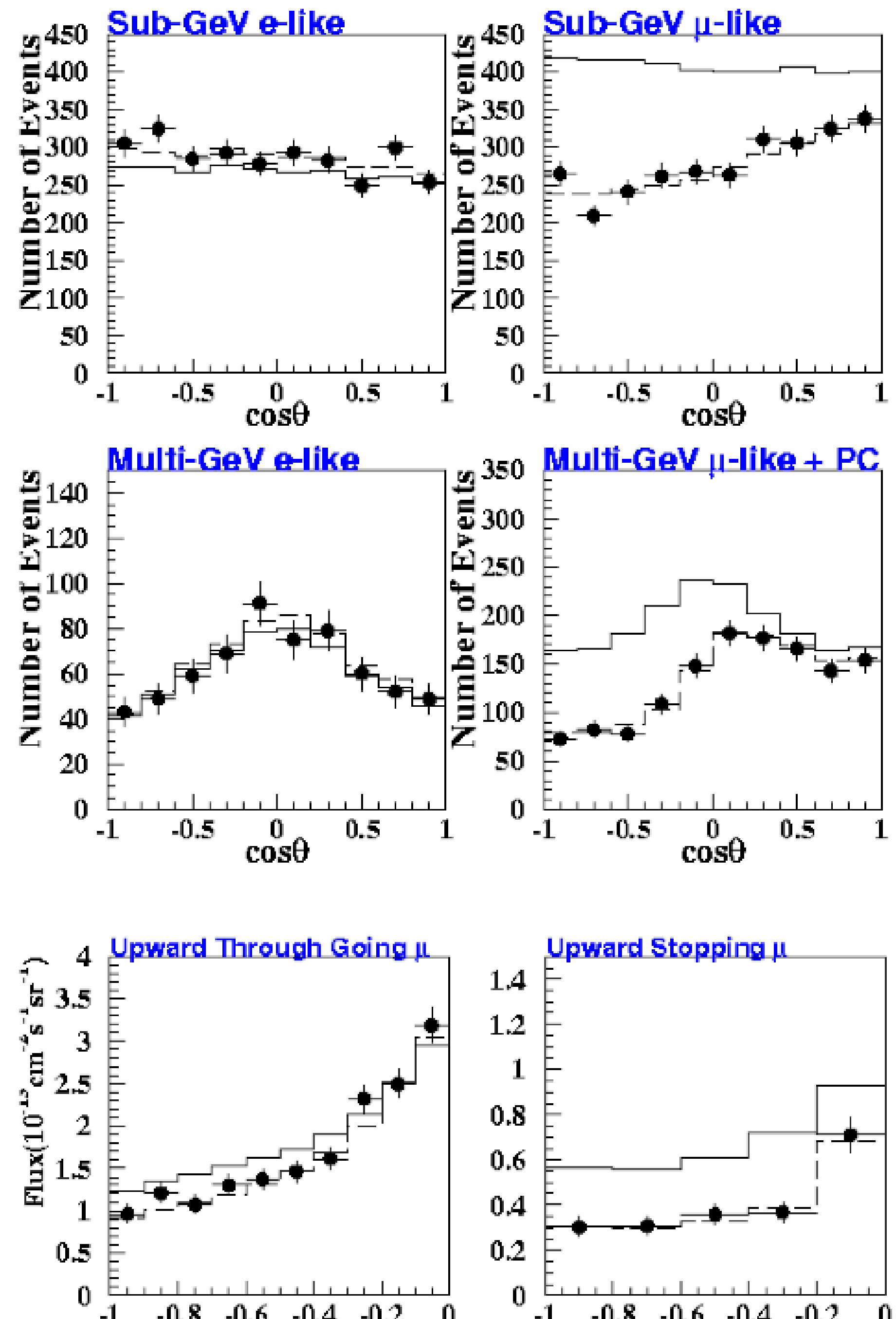
Event rates at SuperKamiokande

From: M.C. Gonzalez Garcia and
Y. Nir, Rev.Mod.Phys.75:345-402,2003



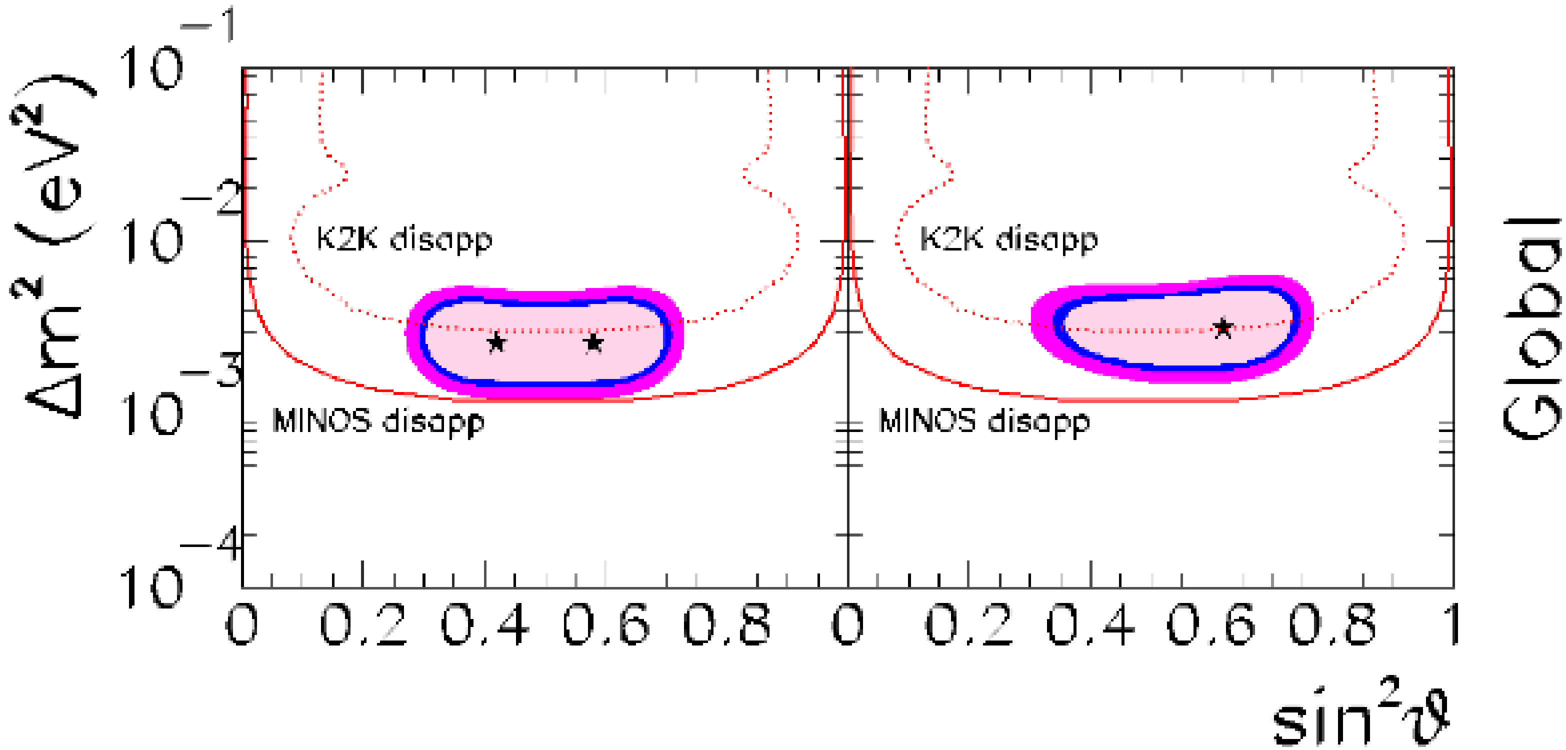
Zenith distribution

- ν_e, unsuppressed -> small ν_e mixing (θ_{13}, bound from reactors)
- ν_μ has zenith-dependence suppression -> large ν_μ - ν_τ mixing



Results: $\theta \sim \pi/4$, $\Delta m^2 = 2.1\ 10^{-3}$ eV^2

From: M.C. Gonzalez Garcia and
Y. Nir, Rev.Mod.Phys.75:345-402,2003



The Hamiltonian
2×2 "effective vacuum"

ν_e,ν_μ,ν_τ basis:

$$H_{eff} = \frac{\Delta m^2}{4E_\nu}\begin{pmatrix} -1+.. & .. & .. \\ .. & -\cos 2\theta + .. & \sin 2\theta \\ .. & \sin 2\theta & \cos 2\theta \end{pmatrix} + \sqrt{2}G_F N_e \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}.$$

Small corrections due to solar mass splitting ($\Delta m^2_{sol} \sim 8 \cdot 10^{-5}\ eV^2$) and mixing, and to θ_{13}

Non standard interactions?

Effects of NSI on neutrino oscillations

New interactions (NSI)

- Predicted by physics beyond the standard model
- Can be flavor-preserving or flavor violating
- How large NSI ?
  - Theory: most likely "small", but "large" values not impossible
  - Experiments: poor direct bounds from neutrinos (strong bounds from charged leptons not directly applicable because SU(2) is violated)

The Lagrangian

$$L^{NSI} = -2\sqrt{2}G_F(\bar{\nu}_\alpha\gamma_\rho\nu_\beta)(\epsilon^{f\tilde{f}L}_{\alpha\beta}\bar{f}_L\gamma^\rho\tilde{f}_L+\epsilon^{f\tilde{f}R}_{\alpha\beta}\bar{f}_R\gamma^\rho\tilde{f}_R)+ h.c. \quad .$$

vertex	Current bound
$(\bar{e}\gamma^\rho Pe)(\bar{\nu}_\tau\gamma_\rho L\nu_\tau)$	$\lvert\varepsilon^{e\,P}_{\tau\,\tau}\rvert<0.5$ LEP
$(\bar{d}\gamma^\rho Pd)(\bar{\nu}_\tau\gamma_\rho L\nu_e)$	$\lvert\varepsilon^{d\,P}_{\tau e}\rvert<1.6$ CHARM
$(\bar{u}\gamma^\rho Ru)(\bar{\nu}_e\gamma_\rho L\nu_e)$	$-0.4 < \varepsilon^{u\,R}_{ee} < 0.7$ CHARM

From: S.Davidson, C.Pena-Garay and N.Rius, JHEP 0303:011,2003

Phenomenological approach…

- We want to test NSI in a 3-flavor context, with NSI in e,τ sector
- The oscillation Hamiltonian

$$
\begin{aligned}
H_{eff} &= \frac{\Delta m^2}{4E_\nu}\begin{pmatrix} -1+.. & .. & .. \\ .. & -\cos 2\theta + .. & \sin 2\theta \\ .. & \sin 2\theta & \cos 2\theta \end{pmatrix} \\
&+ \sqrt{2}G_F N_e \begin{pmatrix} 1+\epsilon_{ee} & .. & \epsilon^*_{e\tau} \\ .. & 0 & .. \\ \epsilon_{e\tau} & .. & \epsilon_{\tau\tau} \end{pmatrix} \qquad \epsilon_{\alpha\beta} = \sum_{P,f} \epsilon^{ffP}_{\alpha\beta} \,.
\end{aligned}
$$

Important differences…

- If $\varepsilon_{e\tau} \neq 0$, H_{mat} is *NOT flavor diagonal* -> conversion in the matter-dominated regime (high E)
- If $\varepsilon_{\tau\tau} \neq 0$, *$\nu_\mu$ -ν_τ oscillations are matter-affected ->* suppression of mixing in the matter-dominated regime
- ν_e is coupled (mixed) to ν_μ - ν_τ by interplay of $\varepsilon_{e\tau}$ and θ

Testing NSI with oscillation experiments

What do we learn from atmospheric neutrinos?

- What is the region of NSI allowed by the data?
- Is this region interesting? More restricted than existing limits?
- If NSI are there, maybe the values of Δm^2 and θ are different from what we think?
- Fully general analysis (3-neutrinos)?

"Predicting" the fit to data...

- Consider the Hamiltonian in the matter eigenbasis: (ν_2=cosβ ν_e + sin β $e^{i\,2\psi}$ ν_τ, ...)

$$\frac{H}{\Delta} = \begin{pmatrix} -c_\beta^2 + s_\beta^2 c_{2\theta} + \frac{\lambda_2}{\Delta} & s_\beta s_{2\theta} e^{-2i\psi} & c_\beta s_\beta (1 + c_{2\theta}) e^{-2i\psi} \\ s_\beta s_{2\theta} e^{2i\psi} & -c_{2\theta} & s_{2\theta} c_\beta \\ c_\beta s_\beta (1 + c_{2\theta}) e^{2i\psi} & s_{2\theta} c_\beta & -s_\beta^2 + c_\beta^2 c_{2\theta} + \frac{\lambda_1}{\Delta} \end{pmatrix}$$

- λ_2,λ_1 matter eigenvalues , $\Delta \equiv \Delta m^2_{32}/(4E)$

$$2\lambda_2 = 1 + \varepsilon_{ee} + \varepsilon_{\tau\tau} + \sqrt{(1 + \varepsilon_{ee} - \varepsilon_{\tau\tau})^2 + 4|\varepsilon_{e\tau}|^2}$$

$$2\lambda_1 = 1 + \varepsilon_{ee} + \varepsilon_{\tau\tau} - \sqrt{(1 + \varepsilon_{ee} - \varepsilon_{\tau\tau})^2 + 4|\varepsilon_{e\tau}|^2}$$

1. "Small" NSI should be OK...

- If $|\lambda_1|, |\lambda_2| \ll \Delta$, (-> $\beta \sim 0$) , the standard case is recovered

$$\frac{H}{\Delta} = \begin{pmatrix} -c_\beta^2 + s_\beta^2 c_{2\theta} + \frac{\lambda_2}{\Delta} & s_\beta s_{2\theta} e^{-2i\psi} & c_\beta s_\beta (1 + c_{2\theta}) e^{-2i\psi} \\ s_\beta s_{2\theta} e^{2i\psi} & -c_{2\theta} & s_{2\theta} c_\beta \\ c_\beta s_\beta (1 + c_{2\theta}) e^{2i\psi} & s_{2\theta} c_\beta & -s_\beta^2 + c_\beta^2 c_{2\theta} + \frac{\lambda_1}{\Delta} \end{pmatrix}$$

2. "Large" NSI generally bad…

- If $|\lambda_1|, |\lambda_2| \gg \Delta$, ν_μ oscillations are suppressed at high energy ->incompatible with data

$$\frac{H}{\Delta} = \begin{pmatrix} -c_\beta^2 + s_\beta^2 c_{2\theta} + \frac{\lambda_2}{\Delta} & s_\beta s_{2\theta} e^{-2i\psi} & c_\beta s_\beta (1 + c_{2\theta}) e^{-2i\psi} \\ s_\beta s_{2\theta} e^{2i\psi} & -c_{2\theta} & s_{2\theta} c_\beta \\ c_\beta s_\beta (1 + c_{2\theta}) e^{2i\psi} & s_{2\theta} c_\beta & -s_\beta^2 + c_\beta^2 c_{2\theta} + \frac{\lambda_1}{\Delta} \end{pmatrix}$$

3. With an exception!

- If $|\lambda_2| \gg \Delta$, AND $|\lambda_1| \ll \Delta$, ν_μ oscillations are NOT suppressed at high energy : $\nu_\mu \leftrightarrow \nu_1$ oscillations.

$$\frac{H}{\Delta} = \begin{pmatrix} -c_\beta^2 + s_\beta^2 c_{2\theta} + \frac{\lambda_2}{\Delta} & s_\beta s_{2\theta} e^{-2i\psi} & c_\beta s_\beta (1 + c_{2\theta}) e^{-2i\psi} \\ s_\beta s_{2\theta} e^{2i\psi} & -c_{2\theta} & s_{2\theta} c_\beta \\ c_\beta s_\beta (1 + c_{2\theta}) e^{2i\psi} & s_{2\theta} c_\beta & -s_\beta^2 + c_\beta^2 c_{2\theta} + \frac{\lambda_1}{\Delta} \end{pmatrix}$$

- Suppression ; reduction to 2 neutrinos

Why does this work?

- Right pattern of ν_μ disappearance at high energy (E ~ 5 -100 GeV)

- Similar to standard at lower energy (vacuum terms dominate)

The χ^2 test

- Parameters: $\Delta m^2, \theta, \varepsilon_{ee}, \varepsilon_{e\tau}, ,\varepsilon_{\tau\tau}$ per electron
- Data: K2K (accelerator) + 1489 days SuperKamiokande-I , 55 d.o.f.
  - μ , e contained
  - Stopping and through going muons
- New 3D fluxes by Honda et al. (astro-ph/0404457)

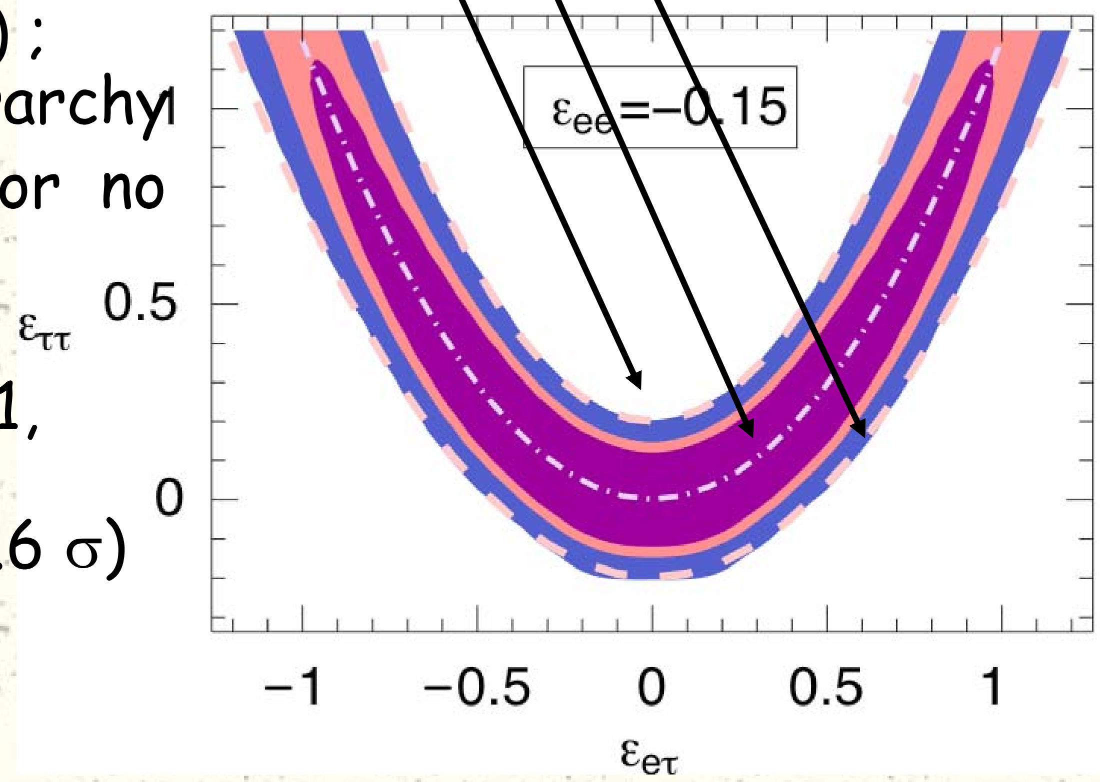
A "smile"...

- Section of 3D region at $\varepsilon_{e\varepsilon}$=-0.15 (others marginalized) ; inverted hierarchy
- χ^2_{min}=48.50 for no NSI
- Contours: $\chi^2 - \chi^2_{min}$=7.81, 11.35, 18.80 (95%,99%, 3.6 σ)

λ_1=0.2 × (standard)

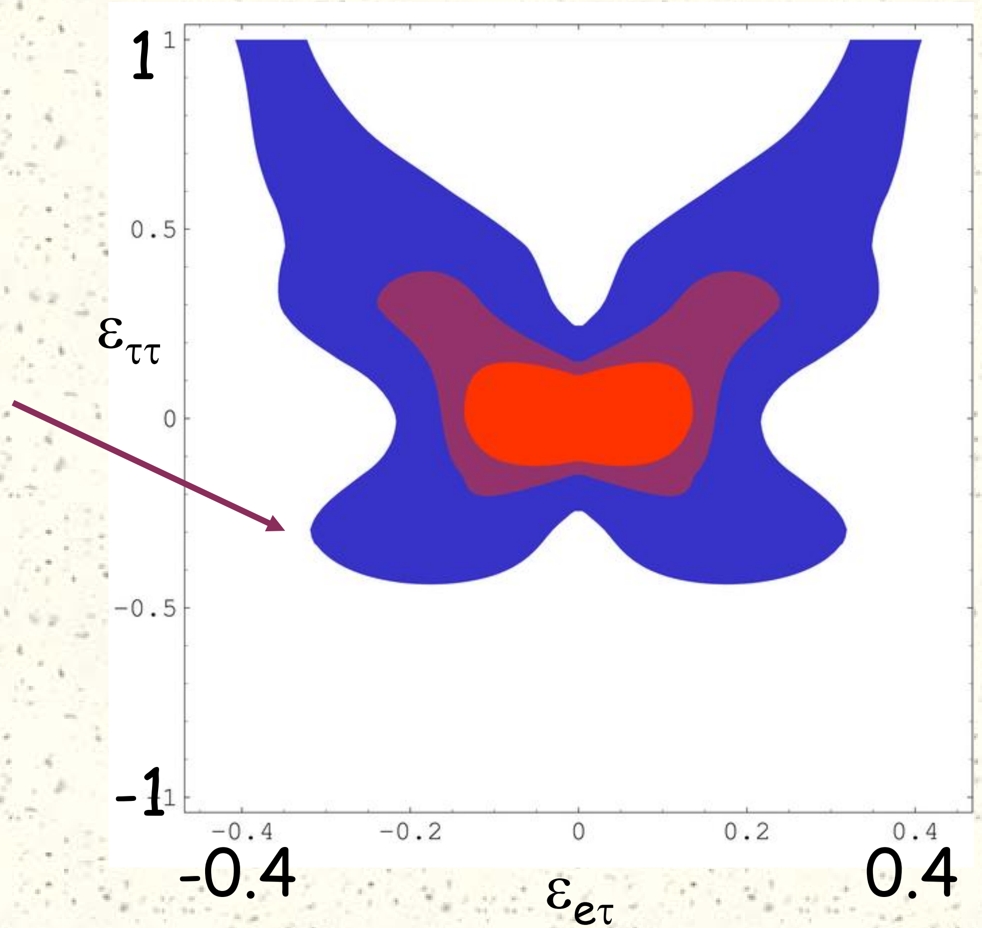
λ_1=0 ($\varepsilon_{\tau\tau}=\varepsilon^2_{e\tau}/(1+\varepsilon_{ee})$)

λ_1=-0.2 × (standard)



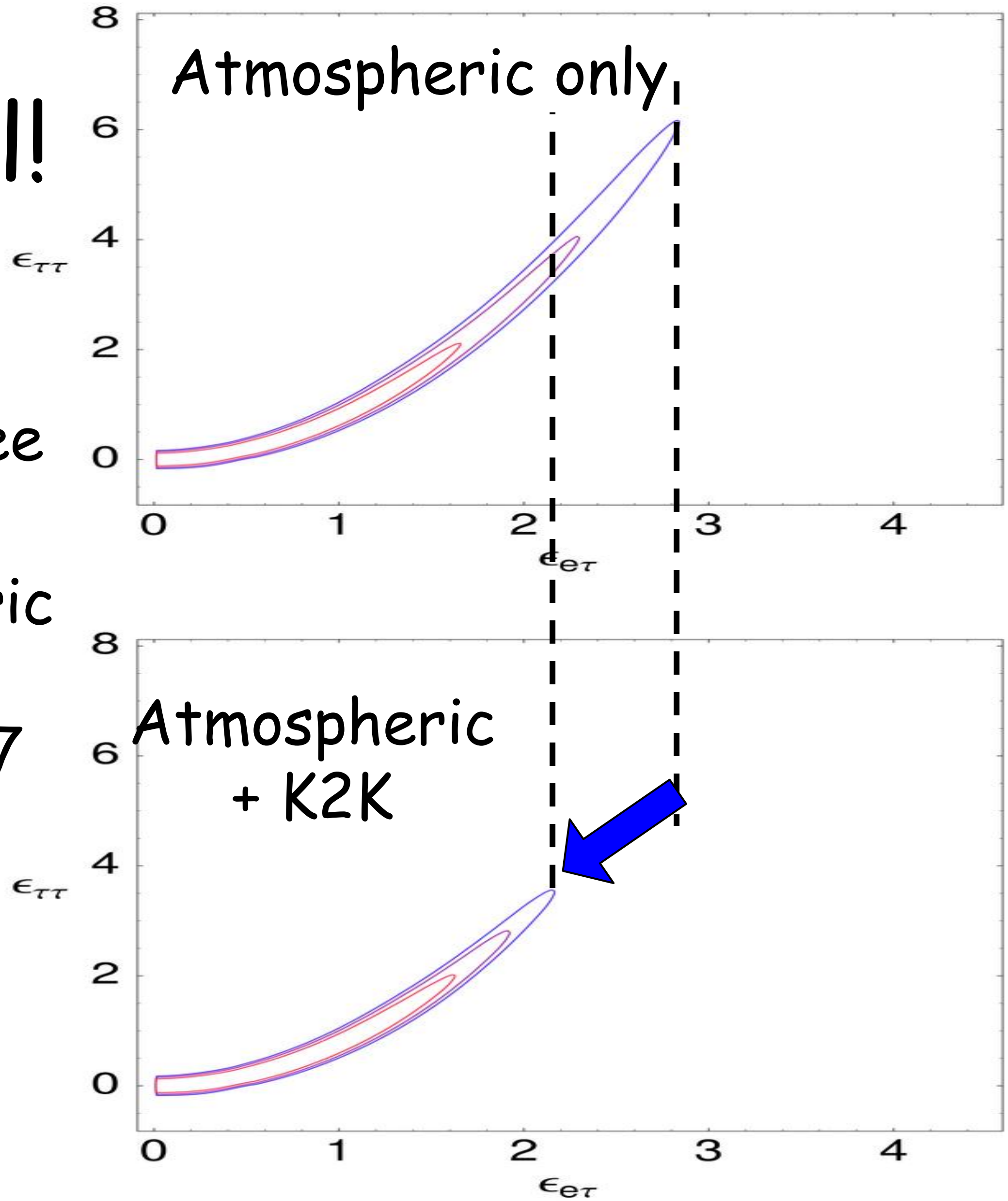
And a butterfly

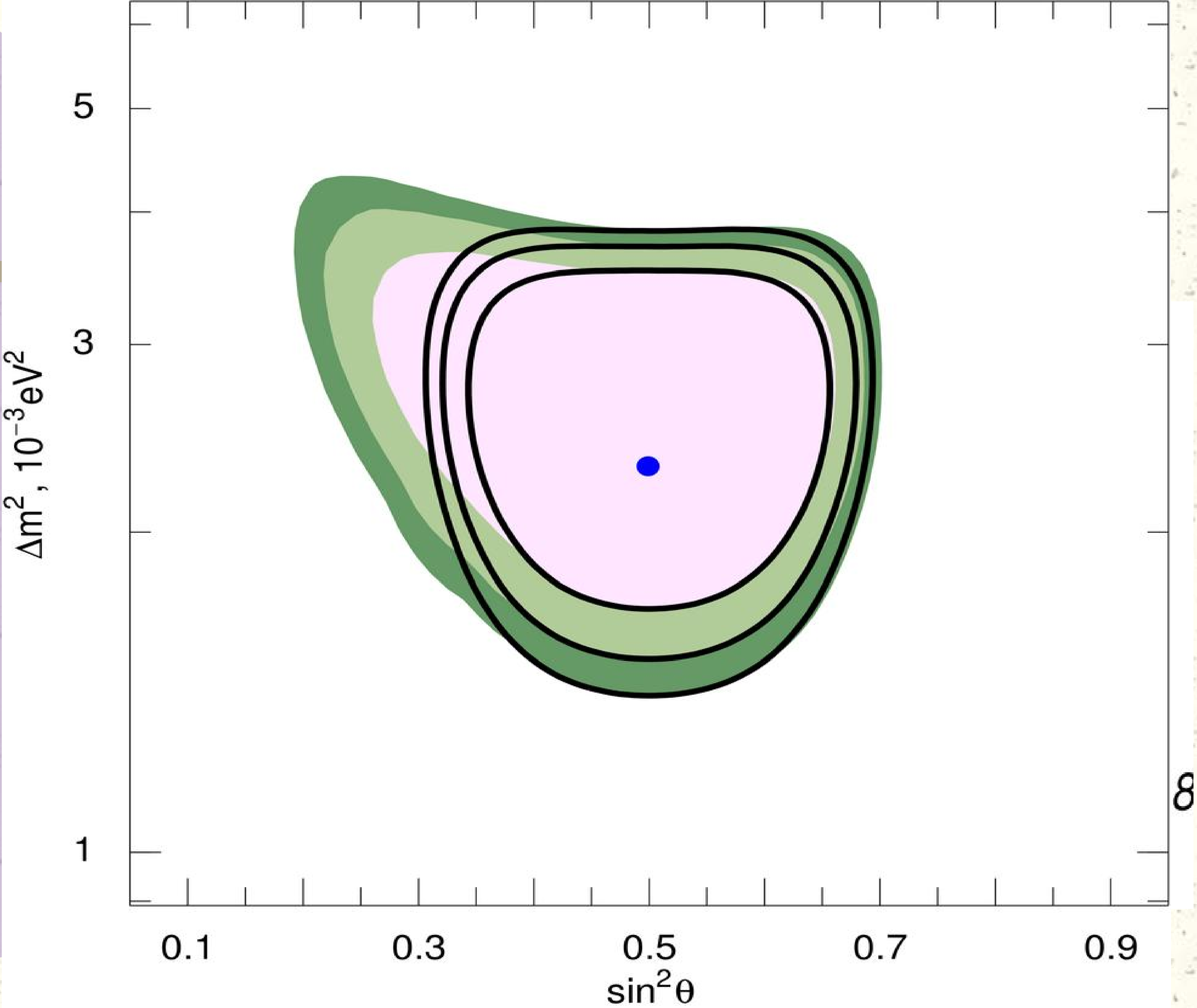
- Section of 3D region at $\varepsilon_{e\varepsilon}$=-1
- Transition to case $|\lambda_2| \ll \Delta$, AND $|\lambda_1| \gg \Delta$



K2K crucial!

- K2K matter-free
- Consistency K2K/atmospheric
  $\rightarrow \theta \sim \theta_m \sim \pi/4$
  $\rightarrow \cos\beta > \sim 0.47$



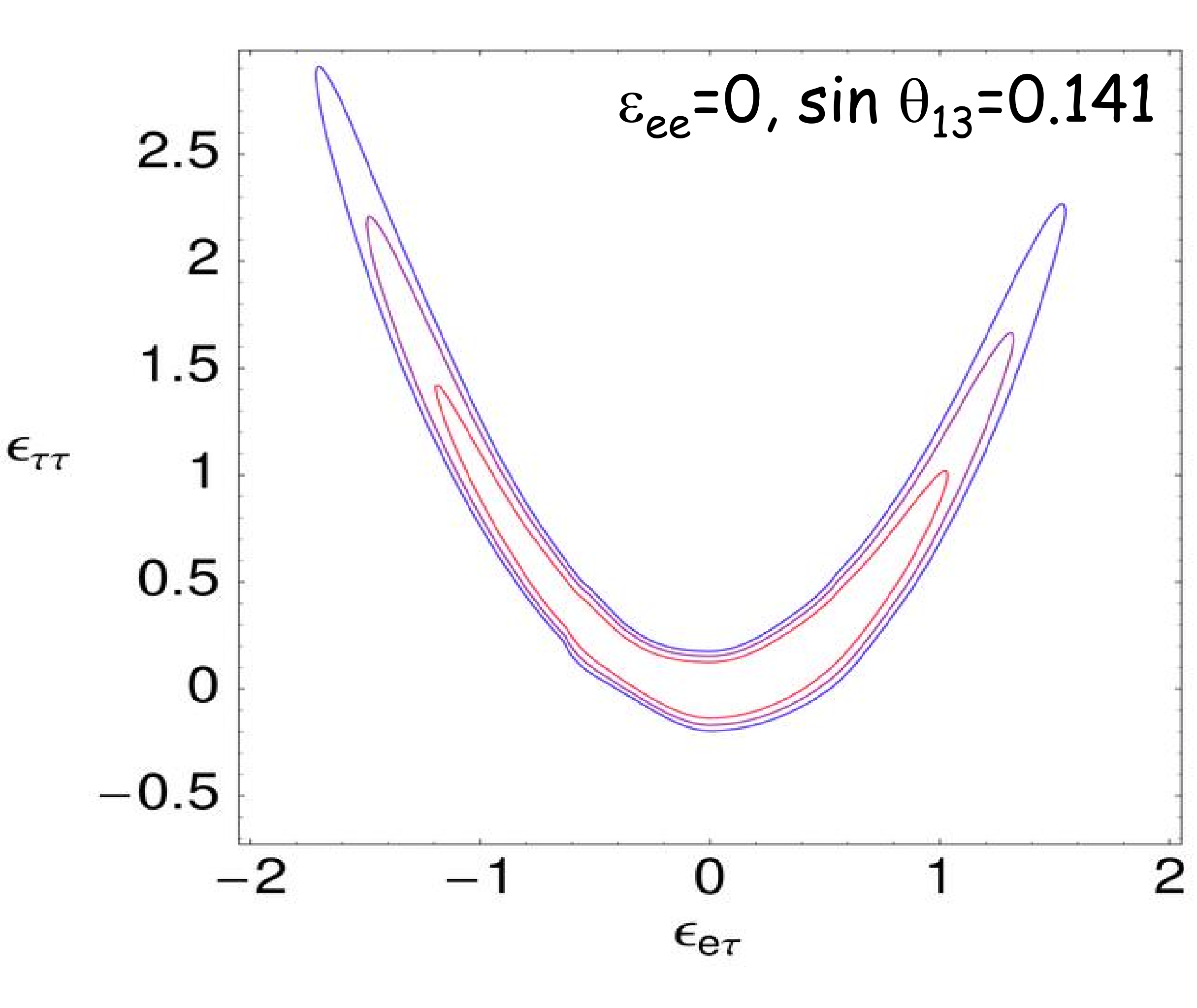


5
3
1
0.1
0.3
0.5
0.7
0.9
$\sin^2\theta$
Δm^2, 10^{-3}eV^2
8

Taking into account NSI:

- Mixing in matter maximal ($\theta_{eff} = \pi/4$) -> smaller vacuum mixing: $\theta < \pi/4$
- Oscillation length in matter (zenith dependence) require $\Delta m^2_{eff} = 2.2 \cdot 10^{-3}$ eV -> larger Δm^2: $\Delta m^2 = 2.6 - 2.8 \cdot 10^{-3}$ eV

θ_{13} makes an asymmetric smile



Comments & open issues

- Surprise! *Atmospheric neutrinos allow large NSI in the e-τ sector* (NOT in the ν_μ - ν_τ sector)
- "zeroth" order effects are (surprisingly!) well predicted by analytics
- Subdominant effects calculable (in part): θ_{13}, "solar" parameters, $\varepsilon_{\mu\tau}$, 3-neutrino effects,…

- What NSI are compatible with everything?
  - Combine with solar neutrinos? Smile becomes restricted and asymmetric; "large" NSI still allowed (work in progress)
- How to test the e-τ NSI?
  - Minos, LBL experiments, supernovae…

Conclusions

- Neutrino oscillations experiments put competitive constraints on NSI
- Atmospheric neutrinos allow large NSI in the e - τ sector, along the parabolic direction $|\lambda_2| \gg \Delta$, AND $|\lambda_1| \ll \Delta$ ($|\lambda_2| \ll \Delta$, AND $|\lambda_1| \gg \Delta$)
- NSI at the allowed level can change the vacuum parameters extracted from the data by (at least) few 10%.
- They can be tested with neutrino beams (intermediate and long base lines)

Solar neutrinos : a new solution!

- LMA-0 : Day/Night suppressed by $(\theta - \alpha) \simeq 0.15$
  - $\varepsilon^u_{11}=\varepsilon^d_{11}=-0.065$; $\varepsilon^u_{12} = \varepsilon^d_{12}=-0.15$