Towards the Complete Neutrino Mixing Matrix and CP-Violation

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2001– Remarkable progress in the studies of $\nu-$ mixing and oscillations

- **June, 2001: SNO CC data + SK data $\rightarrow$ $\nu_{\mu,\tau}$ and/or $\bar{\nu}_{\mu,\tau}$ in $\Phi_E(\nu_\odot)$**

- **April, 2002: SNO NC data $\rightarrow$ evidences for $\nu_{\mu,\tau}$ and/or $\bar{\nu}_{\mu,\tau}$ in $\Phi_E(\nu_\odot)$ strengthen**

- **December, 2002: KamLAND**

  – First compelling evidence for $\nu-$oscillations in an experiment with terrestrial ν's

  – Evidence for ν_e-mixing in vacuum

  – $\nu_\odot$: LMA solution (CPT)

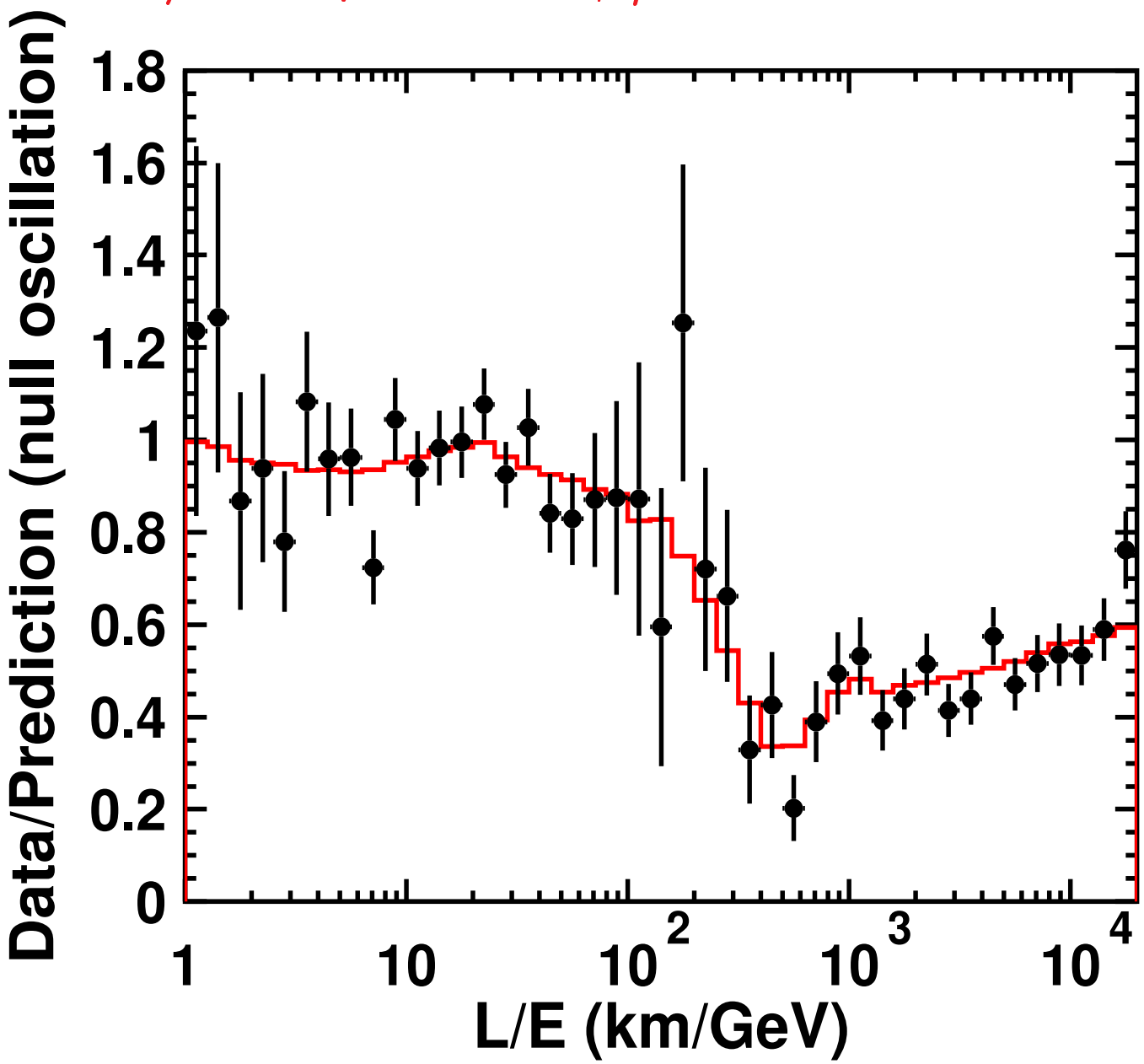
  – KamLAND "massacre":

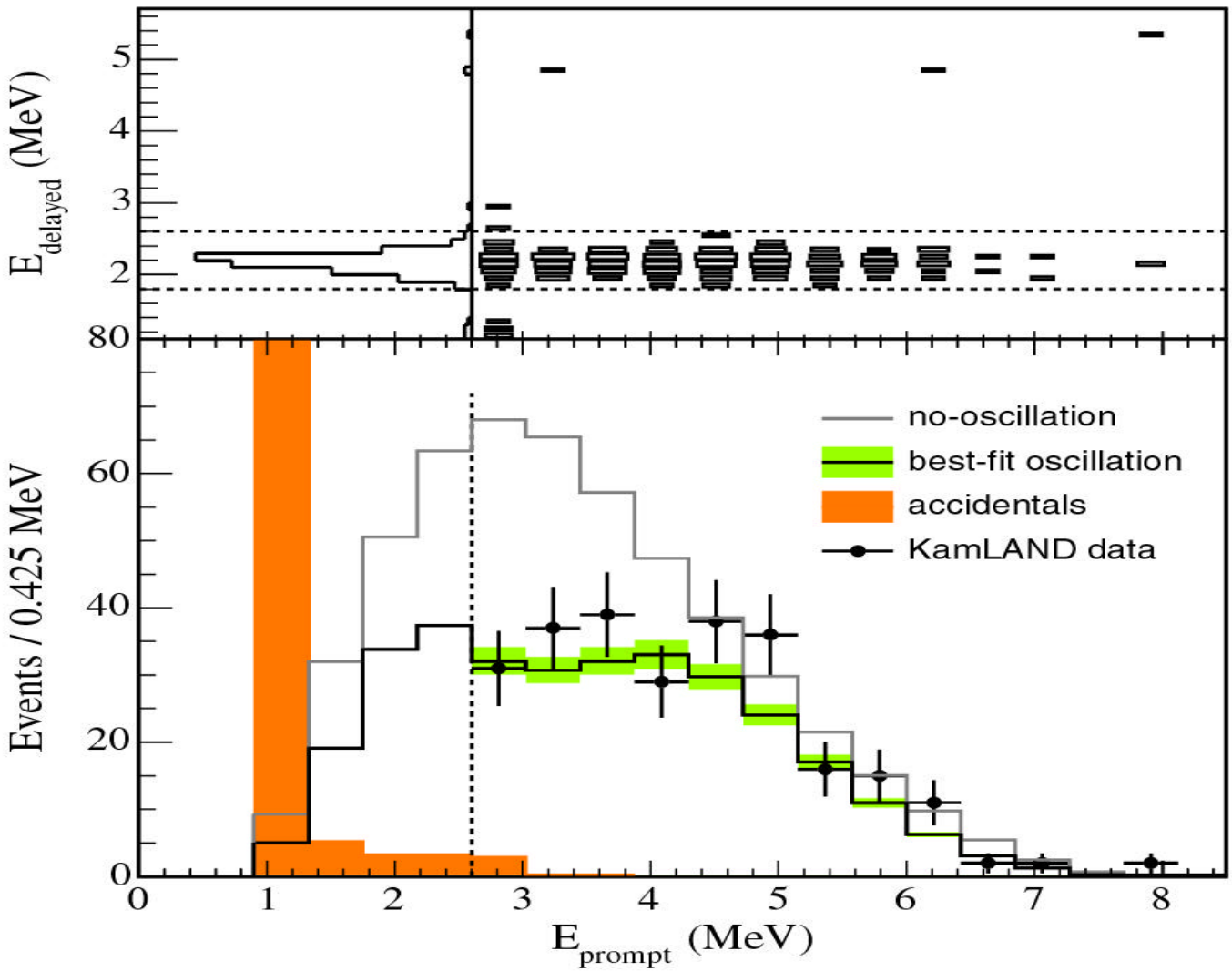
  VO, QVO, LOW, SMA MSW, RSFP, FCNC, WEPV, LIV,...

- **September, 2003: SNO salt phase data,**

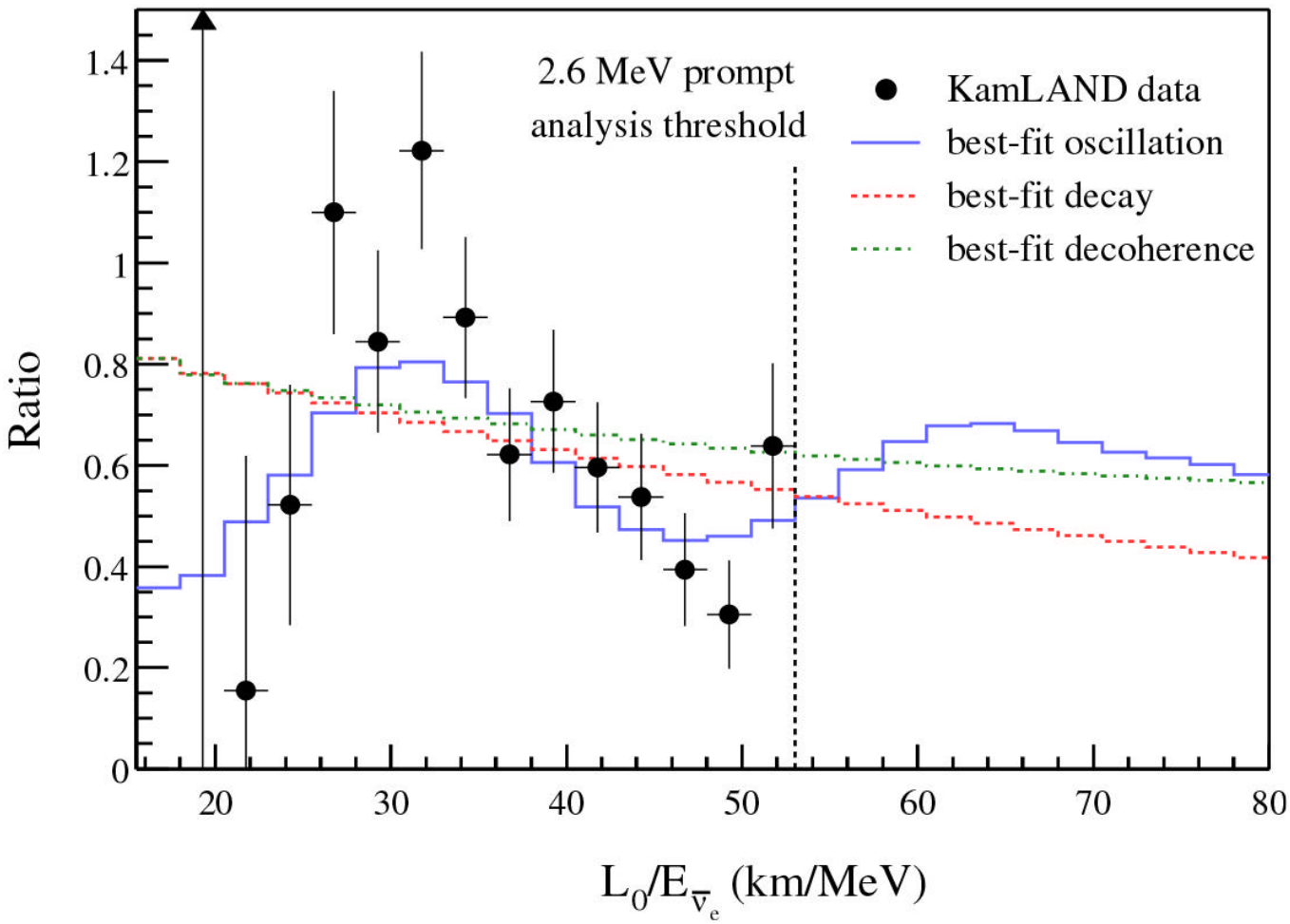
  higher precision measurement of $\Phi_B(\nu_\odot)$

SK: L/E Dependence, μ−Like Events





KamLAND: e^+−Spectrum Deformation



KamLAND: e^+−Spectrum Deformation

K2K: Spectrum Deformation

Evidences for $\nu-$Oscillations

$-\nu_{\text{atm}}$: SK UP-DOWN ASYMMETRY

θ_Z-, $L/E-$ dependences of $\mu-$like events

Dominant $\nu_\mu \to \nu_\tau$ K2K; MINOS, CNGS

$-\nu_\odot$: Homestake, Kamiokande, SAGE, GALLEX/GNO
Super-Kamiokande, SNO; KamLAND

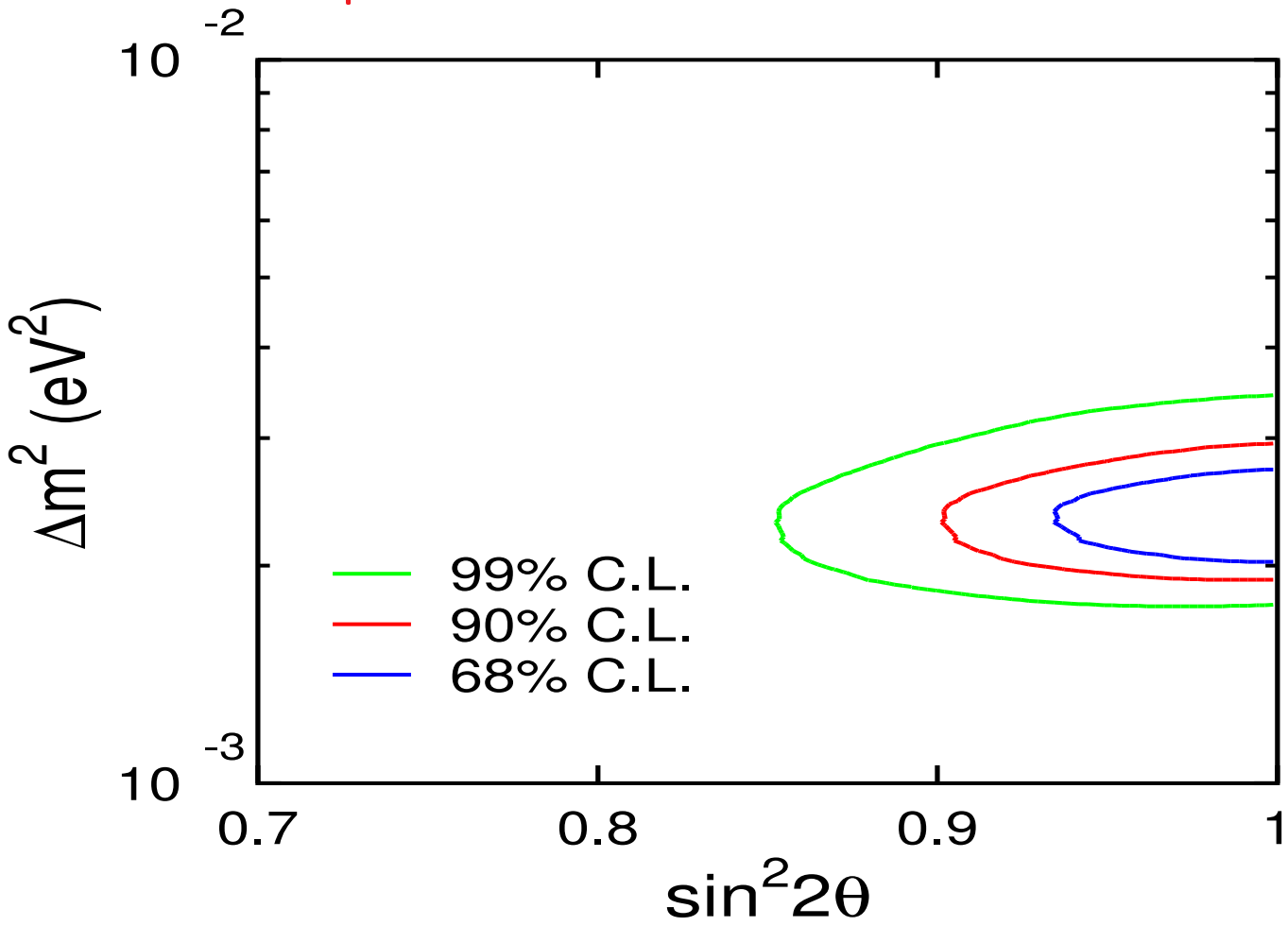
Dominant $\nu_e \to \nu_{\mu,\tau}$ BOREXINO,..., LowNu

– LSND

Dominant $\bar{\nu}_\mu \to \bar{\nu}_e$ MiniBOONE

$$\nu_{l\text{L}} = \sum_{j=1} U_{lj}\, \nu_{j\text{L}} \qquad l = e, \mu, \tau. \qquad (1)$$

SK: Atmospheric ν Data



$\Delta m^2_{\rm atm} \equiv \Delta m^2_{31} = 2.1 \times 10^{-3}$ eV^2, $\sin^2\theta_{\rm atm} \equiv \sin^2 2\theta_{23} = 1.0$;

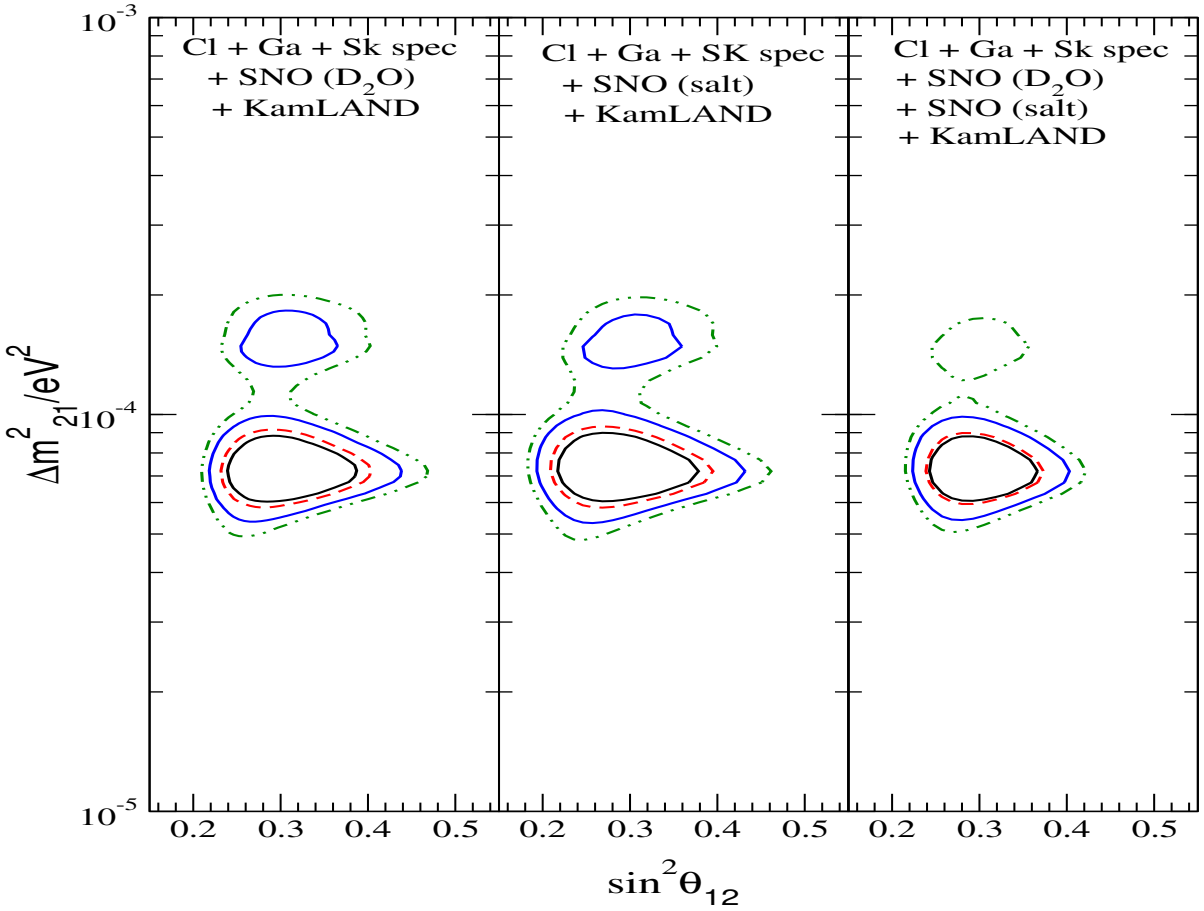
$\Delta m^2_{31} = (1.5 - 3.4) \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} \geq 0.92$, 90% C.L.

- sign of $\Delta m^2_{\rm atm}$ not determined;

  3-ν mixing: $\Delta m^2_{31} > 0$, $m_1 < m_2 < m_3$ (NH);

  $\Delta m^2_{31} < 0$, $m_3 < m_1 < m_2$ (IH).

- If $\theta_{23} \neq \frac{\pi}{4}$: θ_{23}, $(\frac{\pi}{4} - \theta_{23})$ ambiguity.



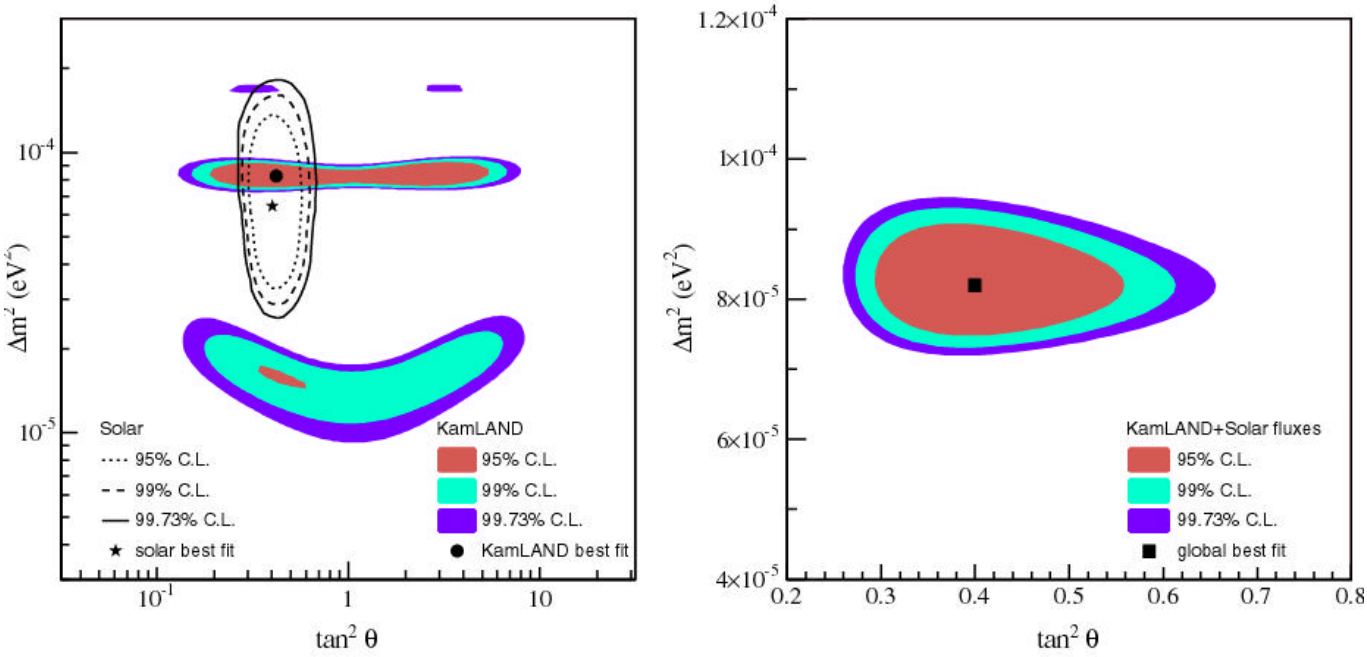
$$\Delta m^2_{\odot} \equiv \Delta m^2_{21} = 7.2 \times 10^{-5}\ \text{eV}^2\ ,$$

$$\sin^2\theta_{\odot} \equiv \sin^2\theta_{12} = 0.30\ ;$$

$$\cos 2\theta_{12} = 0.40; \quad \cos 2\theta_{12} > 0.20, \quad 99\%\ \text{C.L.}$$

- $\sin^2\theta_{12} = 0.50$ excluded at > 5 s.d.
- Low-LMA statistically favored
- High-LMA allowed only at $\sim 99.15\%$ C.L.

A. Bandyopadhyay et al, hep-ph/0309174



Impact of KamLAND Results on $\nu_\odot$ Oscillation Parameters

- High-LMA excluded at $> 3\sigma$

$$\Delta m^2_\odot \equiv \Delta m^2_{21} = (8.2^{+0.6}_{-0.5}) \times 10^{-5}\ \text{eV}^2\ ,$$

$$\tan^2\theta_\odot \equiv \tan^2\theta_{12} = (0.40^{+0.09}_{-0.07})\ ,$$

$$\cos 2\theta_{12} = 0.43; \quad \cos 2\theta_{12} > 0.21, \quad 99\%\ \text{C.L.}$$

$3-\nu$ Mixing Analysis: $\Delta m^2_{\odot} \ll |\Delta m^2_{\rm atm}|$

$P^{3\nu}_{\odot} \cong \sin^4\theta_{13} + \cos^4\theta_{13}\ P^{2\nu}_{\odot}$,

$P^{2\nu}_{\odot} = \bar{P}^{2\nu}_{\odot} + P^{2\nu}_{\odot\,\rm osc}$,

$\bar{P}^{2\nu}_{\odot} = \frac{1}{2} + (\frac{1}{2} - P')\cos 2\theta^m_{12}(t_0)\cos 2\theta_{12} \qquad (\theta_{12} \equiv \theta_{\odot})$,

S. Parke, 1986

$N_e \to N_e \cos^2\theta_{13}$,

$$P' = \frac{e^{-2\pi r_0 \frac{\Delta m^2}{2E}\sin^2\theta} - e^{-2\pi r_0 \frac{\Delta m^2}{2E}}}{1 - e^{-2\pi r_0 \frac{\Delta m^2}{2E}}}$$

S.T.P., 1988

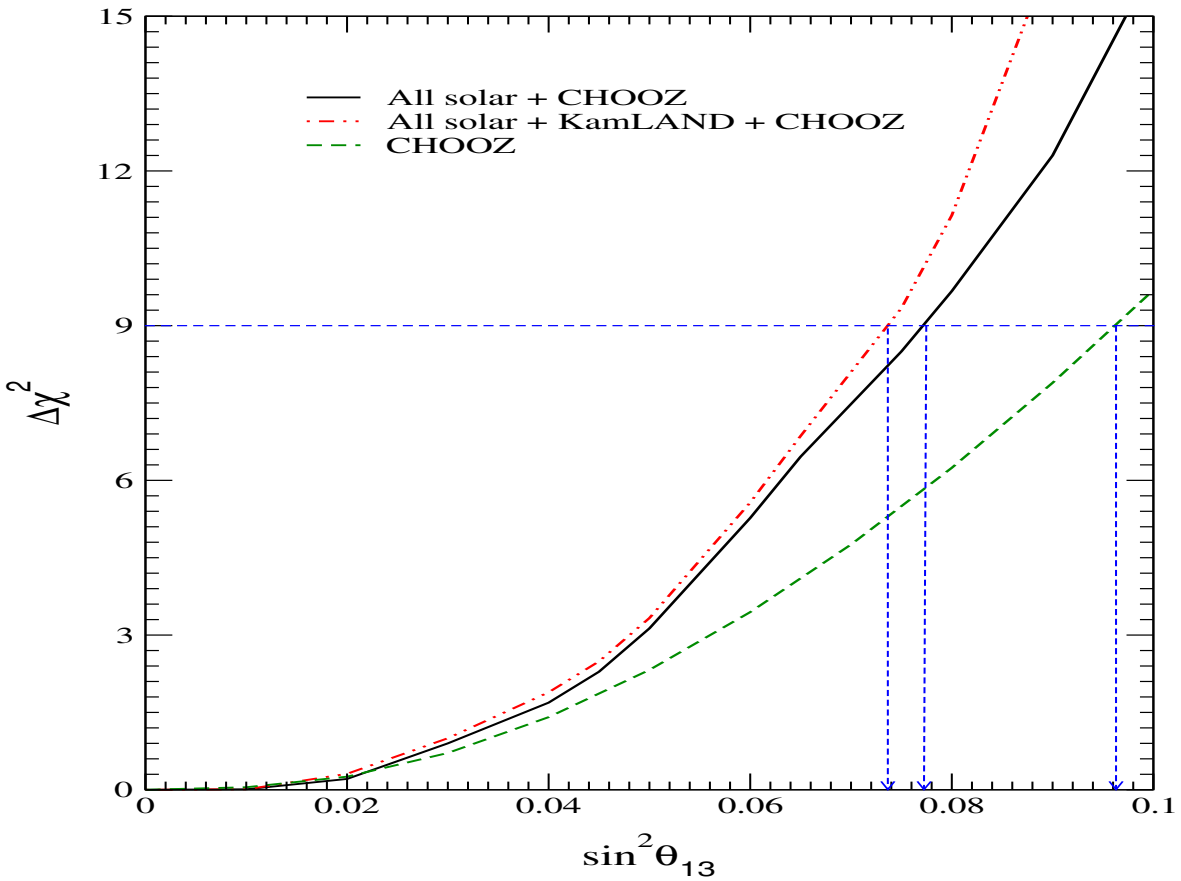
LMA: $P' \cong 0, \quad < P^{2\nu}_{\odot\,\rm osc} > \cong 0$

$$P^{2\nu}_{\odot} \cong \bar{P}^{2\nu}_{\odot} = \frac{1}{2} + \frac{1}{2}\cos 2\theta^m_{12}(t_0)\cos 2\theta_{12}$$

S. Mikheev, A.Yu. Smirnov, 1985

$$P^{3\nu}_{\rm KL} \cong \sin^4\theta_{13} + \cos^4\theta_{13}\left[1 - \sin^2 2\theta_{12}\sin^2(\frac{\Delta m^2_{\odot}}{4E}L)\right]$$

$$P^{3\nu}_{\rm CHOOZ} \cong 1 - \sin^2 2\theta_{13}\sin^2(\frac{\Delta m^2_{\rm atm}}{4E}L)$$



$\Delta m^2_{\rm atm} \equiv \Delta m^2_{31} = (1.1 - 3.2) \times 10^{-3}$ eV^2, 3 $s.d.$ (SK + K2K)

G.L. Fogli et al, hep-ph/0308055

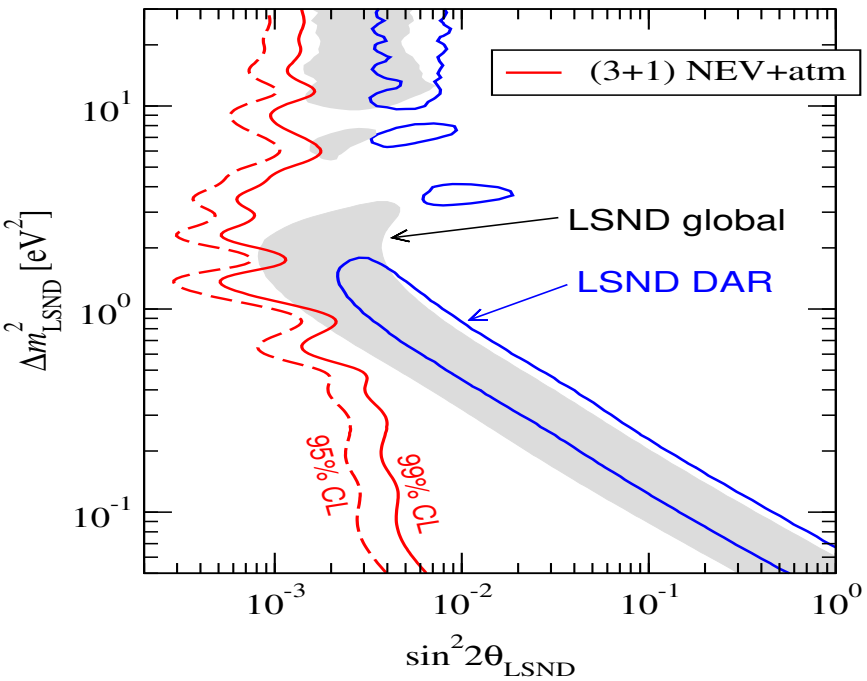
- $\sin^2\theta_{13} < 0.74$ at 99.73% C.L.

A. Bandyopadhyay et al., hep-ph/0309174

- Global analysis: $\sin^2\theta_{13} < 0.54$ at 99.73% C.L.

M.C. Gonzalez-Garcia and M. Maltoni, NOON2004

(3+1)



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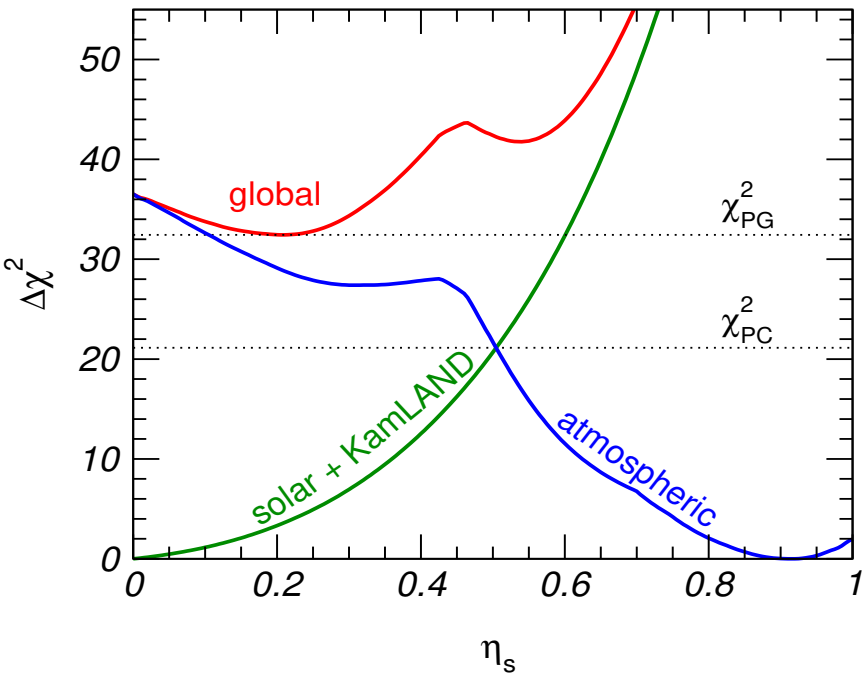


M. Maltoni et al., hep-ph/0405172

Three Neutrino Mixing

$$\nu_{l\mathrm{L}} = \sum_{j=1}^{3} U_{lj}\, \nu_{j\mathrm{L}} \ . \tag{2}$$

U is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix,

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \tag{3}$$

- U - $n \times n$ unitary:

	n	2	3	4
mixing angles:	$\frac{1}{2}n(n-1)$	1	3	6
CP-violating phases:				
• ν_j- Dirac:	$\frac{1}{2}(n-1)(n-2)$	0	1	3
• ν_j- Majorana:	$\frac{1}{2}n(n-1)$	1	3	6

$n = 3$: 1 Dirac and
2 additional CP-violating phases, Majorana phases

S.M. Bilenky, J. Hosek, S.T.P.,1980;
J. Schechter, J.W.F. Valle,1980;
M. Doi, T. Kotani, E. Takasugi,1981

Standard Parametrization

$$U = V \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix} \tag{4}$$

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13}e^{i\delta} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}e^{i\delta} \end{pmatrix} \tag{5}$$

- $s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$, $\theta_{ij} = [0, \frac{\pi}{2}]$,
- δ - Dirac CP-violation phase, $\delta = [0, 2\pi]$,
- α_{21}, α_{31} - the two Majorana CP-violation phases.
- If $\Delta m^2_{\odot} = \Delta m^2_{21} > 0$, $\Delta m^2_{\text{atm}} = \Delta m^2_{31}$,

then $\theta_{12} = \theta_{\odot}$, $\theta_{23} = \theta_{\text{atm}}$, $\theta_{13} = \theta$.

The angle θ is limited by the data from the CHOOZ and Palo Verde experiments.

- α_{21}, α_{31}:
  - $\nu_l \leftrightarrow \nu_{l'}$, $\bar{\nu}_l \leftrightarrow \bar{\nu}_{l'}$ not sensitive;
    S.M. Bilenky, J. Hosek, S.T.P.,1980;
    P. Langacker et al.,1987;
  - $|<m>|$ in $(\beta\beta)_{0\nu}-$decay depends on α_{21}, α_{31};
  - $\Gamma(\mu \to e + \gamma)$ etc. in SUSY theories depend on $\alpha_{21,31}$;
  - BAU, leptogenesis scenario: $\alpha_{21,31}$?

Neutrino Mixing Parameters

θ_{12}, θ_{23}, θ_{13}

ν_j Dirac Majorana

δ δ, α_{21}, α_{31}

m_1, m_2, m_3

m_2, m_3 - in terms of $\Delta m^2_{\odot}$, $\Delta m^2_{\rm atm}$ and m_1

Conventions

A. $m_1 < m_2 < m_3$ (NH) or $m_3 < m_1 < m_2$ (IH)

- $\Delta m^2_{\odot} = \Delta m^2_{21} > 0$
- $\Delta m^2_{\rm atm} = \Delta m^2_{31} > 0$ (NH), $\Delta m^2_{\rm atm} = \Delta m^2_{32} < 0$ (IH)
- $m_2 = \sqrt{m_1^2 + \Delta m^2_{21}}$, $m_3 = \sqrt{m_1^2 + \Delta m^2_{31}}$

B. $m_1 < m_2 < m_3$

- $\Delta m^2_{\rm atm} = \Delta m^2_{31} > 0$

Two possibilities:

$\Delta m^2_{\odot} = \Delta m^2_{21} > 0$, NH

$\Delta m^2_{\odot} = \Delta m^2_{32} > 0$, IH

"discrete" parameter

Future Progress

- High precision determination of $\Delta m^2_{\odot}$, $\theta_{\odot}$, $\Delta m^2_{\rm atm}$, θ_{atm}.

- Measurement of, or improving by at least a factor of (5 - 10) the existing upper limit on, $\sin^2\theta_{13}$.

- Determination of the type of the $\nu-$ mass spectrum

$$m_1 \ll m_2 \ll m_3, \qquad \text{NH},$$

$$m_1 \ll m_2 \cong m_3, \qquad \text{IH},$$

$$m_1 \cong m_2 \cong m_3,\ m^2_{1,2,3} >> \Delta m^2_{\rm atm},\ \text{QD};\ m_j \gtrsim 0.20\ \text{eV}.$$

- Determining or obtaining significant constraints on the absolute scale of neutrino masses, or on m_1.

- Determination of the nature - Dirac or Majorana, of ν_j .

- Status of the CP-symmetry in the lepton sector: violated due to δ (Dirac), and/or due to α_{21}, α_{31} (Majorana)?

- Searching for possible manifestations, other than ν_l-oscillations, of the non-conservation of L_l, $l = e, \mu, \tau$, such as $\mu \to e + \gamma$, $\tau \to \mu + \gamma$, etc. decays.

- Understanding at fundamental level the mechanism giving rise to the $\nu-$ masses and mixing and to the L_l-non-conservation, i.e., finding The Theory of $\nu-$mixing.

$\nu_\odot$, $\Delta m^2_{\rm atm}$, CHOOZ Data:

- $\theta_{12} = \theta_\odot \cong \frac{\pi}{6}$, $\quad \theta_{23} = \theta_{\rm atm} \cong \frac{\pi}{4}$, $\quad \theta_{13} < \frac{\pi}{12}$

$$U = \begin{pmatrix} \frac{\sqrt{3}}{2} & \frac{1}{2} & \epsilon \\ -\frac{1}{2\sqrt{2}} & \frac{\sqrt{3}}{2\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{2\sqrt{2}} & -\frac{\sqrt{3}}{2\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \tag{6}$$

Very different from the CKM-matrix!

- $\cos\theta_{12} \cong \cos(\frac{\pi}{4} - \frac{\pi}{12}) = \frac{1}{\sqrt{2}}(1+\lambda)$, $\quad \sin\theta_{12} \cong \frac{1}{\sqrt{2}}(1-\lambda)$,
- $\lambda \cong (0.20 - 0.25)$: $\quad \theta_\odot + \theta_{\rm c} = \pi/4$?

Natural Possibility:

$$U = U^\dagger_{\rm lep}(\lambda)\ U_{\rm bimax} \tag{7}$$

with

$$U_{\rm bimax} = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & -\frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix} \tag{8}$$

- $U^\dagger_{\rm lep}(\lambda)$ - from diagonalization of the l^- mass matrix,
- $U_{\rm bimax}$ - from diagonalization of the $\nu-$mass matrix

Further, $\Delta m^2_\odot \ll |\Delta m^2_{\rm atm}|$.

- $U_{\rm bimax}$ can be associated with a symmetry:

$$L' = L_e - L_\mu - L_\tau$$

S.T.P., 1982

This symmetry cannot be exact.

Deviations from bimaximal mixing:

- Charged lepton mixing ($U_{\rm PMNS} = U_{\rm lep}^{\dagger}\ U_{\nu}^{\rm bimax}$):
  - Jezabek & Sumino '99
  - Xing '01
  - Giunti & Tanimoto '02
  - King '02
  - Rodejohann '03 $\quad(\theta_{\odot} + \theta_{\rm C} = \pi/4\ \ ?)$
  - Frampton, Petcov & Rodejohann '04
  - Altarelli, Feruglio & Masina '04
  - Romanino '04
  - Raidal '04 $\quad(\theta_{\odot} + \theta_{\rm C} = \pi/4)$
  - de S. Pires '04 $\quad(U_{\rm lep} = U^{\rm bimax})$
  - Minakata & Smirnov '04 $\quad(\theta_{\odot} + \theta_{\rm C} = \pi/4)$
- Radiative Corrections:
  - Antusch *et al.* '02
  - Miura, Shindou & Takasugi '03
  - Stech & Tavartkiladze '03
- Perturbation from textures:
  - de Gouvea '04
  - Rodejohann '04

- $U^{\dagger}_{\rm lep}(\lambda)$: θ^{lep}_{ij}, $\qquad \sin\theta^{lep}_{ij} \equiv \lambda_{ij}$
- Data used - 90% (99.73%) C.L.:

$$0.35\ (0.27) \leq \tan^2\theta_{\rm sol} \equiv \tan^2\theta_{12} \leq 0.52\ (0.72)\ ,$$
$$|U_{e3}|^2 = \sin^2\theta_{13} < 0.029\ (0.074)\ ,$$
$$\sin^2 2\theta_{\rm atm} \equiv \sin^2 2\theta_{23} \geq 0.95\ (0.85)\ .$$

Three cases possible:

P. Frampton, S.T.P., W. Rodejohann, 2004

- All λ_{ij} small, $\lambda_{ij} \lesssim 0.35$
- $\lambda_{23} = 1$, λ_{12}, λ_{13} small
- All λ_{ij} large, e.g., $\lambda_{ij} \geq \frac{1}{\sqrt{2}}$

In the case of small λ_{ij}:

$$\tan^2\theta_{\rm sol} \cong 1 - 2\sqrt{2}\,(\lambda_{12}-\lambda_{13}) + 4\,(\lambda_{12}-\lambda_{13})^2 - 2\sqrt{2}\,\lambda_{23}\,(\lambda_{12}+\lambda_{13}) + \mathcal{O}(\lambda^3)\ ,$$

$$|U_{e3}| \cong \left| \frac{\lambda_{12}+\lambda_{13}}{\sqrt{2}} - \frac{\lambda_{23}}{\sqrt{2}}\,(\lambda_{12}-\lambda_{13}) + \mathcal{O}(\lambda^3) \right|\ ,$$

$$\sin^2 2\theta_{\rm atm} \cong 1 - 4\,\lambda^2_{23} + \mathcal{O}(\lambda^3)$$

The data implies:

- $\lambda_{23} \lesssim 0.19\ (0.11)$
- $\lambda_{12} \gg \lambda_{13}$ $\quad$ (for $\lambda_{12,13} > 0$):

$\lambda_{12} \cong (0.21 - 0.26)$, $\quad \lambda_{13} \lesssim 0.03$;

$\tan^2\theta_{\rm sol} \gtrsim 0.42$, $|U_{e3}|^2 \gtrsim 0.017$ $\quad (1\ \sigma)$

Simple Possibilities:

- $\lambda_{12} \equiv \lambda,\ \lambda_{23} \sim \lambda^2,\ \lambda_{13} \sim \lambda^3$ (hierarchy)

$$U_{\rm lep}(\lambda) \sim \begin{pmatrix} 1-\lambda^2/2 & \lambda & \lambda^3 \\ -\lambda & 1-\lambda^2/2 & \lambda^2 \\ \lambda^3 & -\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4) \qquad (9)$$

$U_{\rm lep}(\lambda)-$CKM-like.

$$|U_{e3}| \simeq \frac{\lambda}{\sqrt{2}}\ ,$$
$$\tan^2\theta_{\rm sol} \simeq 1 - 4\,|U_{e3}| + 8\,|U_{e3}|^2 - 8\,|U_{e3}|^3,$$
$$\sin^2 2\theta_{\rm atm} \simeq 1 - 4\,\lambda^4 = 1 - 16|U_{e3}|^4;$$

$\tan^2\theta_{\rm sol} \lesssim 0.52\ (0.72):\ |U_{e3}|^2 \gtrsim 0.027\ (0.006)$

$\sin^2 2\theta_{\rm atm} \gtrsim 0.96$

- $\lambda_{12} \equiv \lambda,\ \lambda_{23} \sim \frac{1}{2}\lambda$ (mild hierarchy), $\lambda_{13} \sim \lambda^3$

$\sin^2 2\theta_{\rm atm} \simeq 1 - 2|U_{e3}|^2 \simeq 0.90-$ possible $\quad (|U_{e3}|^2 = 0.05)$

The Case of $\lambda_{23} = 1$, $\lambda_{12}, \lambda_{13} \lesssim 0.35$ ("small")

$U_{\rm lep}(\lambda)$: the 23 block is antidiagonal.

- In this case $\sin^2 2\theta_{\rm atm} \gtrsim 0.997$

The Case of CP Nonconservation

$M_{\rm lep} = U_L^\dagger \, m_{\rm lep}^{\rm diag} \, U_R$, $M_\nu = U_\nu^T \, m_\nu^{\rm diag} \, U_\nu$; $\quad U = e^{i\Phi} \, P \, \tilde{U} \, Q$

$U_{\rm PMNS} = U_{\rm L}^\dagger \, U_\nu = \tilde{U}_{\rm lep}^\dagger \; P_\nu \; \tilde{U}_\nu \; Q_\nu$

- $\tilde{U}_{\rm lep}$, $\tilde{U}_\nu$ - CKM-like: (3+3) angles, (1+1) CPVP
- $P_\nu = {\rm diag}(1, e^{i\phi}, e^{i\omega})$, $Q_\nu = {\rm diag}(1, e^{i\rho}, e^{i\sigma})$: 4 CPVP

$U_{\rm PMNS}$: 3 angles, 3 CPVP

$\tilde{U}_{\rm lep}^\dagger \; P_\nu \; \tilde{U}_\nu \; Q_\nu$: 6 angles, 6 CPVP; textures, symmetries

Suppose $\tilde{U}_\nu$ - bimaximal (real) and arises from

$$M_\nu = \frac{m}{\sqrt{2}} \begin{pmatrix} 0 & e^{-i\alpha'} & e^{-i\beta'} \\ e^{-i\alpha'} & 0 & \epsilon \; e^{-i\gamma'} \\ e^{-i\beta'} & \epsilon \; e^{-i\gamma'} & 0 \end{pmatrix} ,$$

α', β', γ' - phases, $\epsilon \ll 1$

$\Delta m^2_{\rm atm} \cong m^2$, $\Delta m^2_\odot \cong \sqrt{2} \epsilon \Delta m^2_{\rm atm}$, $\epsilon \sim 0.025$, IH $\nu-$ masses

In the limit $\epsilon = 0$ and $U_{\rm lep} = 1$,

$L' = L_e - L_\mu - L_\tau$ is conserved.

For $U_{\rm lep} \neq 1$, $(\alpha' - \gamma')$, $(\beta' - \gamma')$ physical CPVP,

$Q_\nu = 1$, $P_\nu = {\rm diag}(1, e^{i(\beta' - \gamma')}, e^{i(\alpha' - \gamma')})$

$U_{\rm PMNS} = \tilde{U}_{\rm lep}^\dagger P_\nu U_{\rm bimax}$: 3 angles, 3 CPVP

Rephasing Invariants Associated with CPVP

Dirac phase δ:

$$J_{CP} = \text{Im}\left\{U_{e1}\, U_{\mu 2}\, U^*_{e2}\, U^*_{\mu 1}\right\} \ .$$

C. Jarlskog, 1985

CP-, T- violation effects in neutrino oscillations

P. Krastev, S.T.P., 1988

Majorana phases α_{21}, α_{31}:

$$S_1 = \text{Im}\left\{U_{e1}U^*_{e3}\right\}, \quad S_2 = \text{Im}\left\{U_{e2}U^*_{e3}\right\} \quad \text{(not unique)}$$

J.F. Nieves and P. Pal, 1987, 2001
G.C. Branco et al., 1986
J.A. Aguilar-Saavedra and G.C. Branco, 2000

S_1, S_2 appear in $|<m>|$ in $(\beta\beta)_{0\nu}$-decay.

In general, J_{CP}, S_1 and S_2 are independent.

However, for, e.g., all $\lambda_{ij} \lesssim \lambda$ small, in the model we are considering and to leading order in λ,

$$J_{CP} \simeq \frac{S_1}{2\sqrt{2}} \simeq \frac{S_2}{2\sqrt{2}}$$

If in addition $(\beta' - \gamma') \cong 0$,

$$|<m>| \ \cong \sqrt{|\Delta m^2_{\text{atm}}|}\ \left|\cos 2\theta_\odot - i\, 8\, J_{CP}\right| \ .$$

HOW?

- $\nu_\odot-$, $\nu_{\rm atm}-$ experiments

  SK ($\nu_{\rm atm}$), INO ($\nu_{\rm atm}$)

  SNO

  GNO, SAGE

  BOREXINO

  LowNu (XMASS, LENS,...)

- Reactor Experiments $\sim (1-180)$ km

- Accelerator Experiments

  K2K 250 km

  MINOS ($\nu_{\rm atm}$) 732 km

  OPERA, ICARUS 732 km

- Super Beams

  JHF (T2K), SK (HK) 295 km

  NuMI (NOνA) $\sim$800 km

  SPL+$\beta-$beams, UNO (1 megaton):
  CERN-Frejus $\sim$140 km

  $\nu-$Factories $\sim$ 3000, 7000 km

- $(\beta\beta)_{0\nu}-$Decay, ^{3}H $\beta-$Decay

- Astrophysics, Cosmology

Absolute Neutrino Mass Measurements

The Troitzk and Mainz ^{3}H β-decay experiments

$$m_{\nu_e} < 2.2 \text{ eV} \qquad (95\% \text{ C.L.})$$

There are prospects to reach sensitivity

KATRIN : $\qquad m_{\nu_e} \sim 0.2$ eV

Cosmological and astrophysical data: the WMAP result

$$\sum_j m_j < 0.70 \text{ eV} \quad (95\% \text{ C.L.}) \quad (X \sim 2)$$

The WMAP and future PLANCK experiments can be sensitive to

$$\sum_j m_j \cong 0.4 \text{ eV}$$

Data on weak lensing of galaxies by large scale structure, combined with data from the WMAP and PLANCK experiments may allow to determine

$$\sum_j m_j : \qquad \delta \cong 0.04 \text{ eV}.$$

$(\beta\beta)_{0\nu}-$Decay Experiments:

- Majorana nature of ν_j
- Type of $\nu-$mass spectrum (NH, IH, QD)
- Absolute neutrino mass scale

^{3}H β-decay , cosmology: m_ν

- CPV due to Majorana CPV phases

$A(\beta\beta)_{0\nu} \sim <m>$ M, M – NME,

$|<m>| = \left|m_1|U_{e1}|^2 + m_2|U_{e2}|^2\ e^{i\alpha_{21}} + m_3|U_{e3}|^2\ e^{i\alpha_{31}}\right|$,

α_{21}, α_{31} - the two Majorana CPVP of the PMNS matrix.

Best sensitivity: Heidelberg-Moscow ^{76}Ge experiment.
Claim for a positive signal at $> 3\sigma$:
H. Klapdor-Kleingrothaus et al., PL B586 (2004),

$|<m>| = (0.1 - 0.9)$ eV (99.73% C.L.).

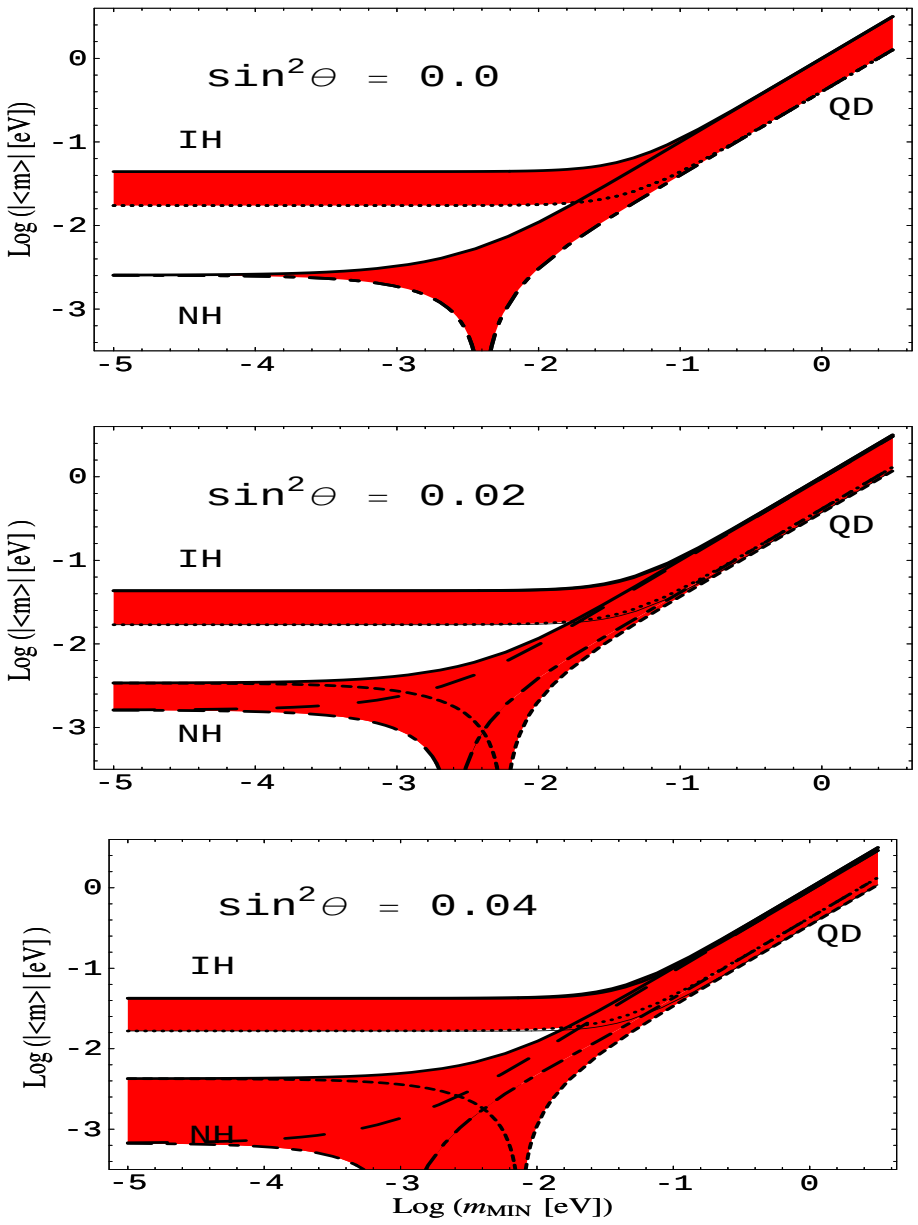
IGEX ^{76}Ge: $|<m>| < (0.33 - 1.35)$ eV (90% C.L.).

Taking data - NEMO3 (^{100}Mo), CUORICINO (^{130}Te):

$|<m>| \sim (0.2 - 0.3)$ eV

Large number of projects: $|<m>| \sim (0.01 - 0.05)$ eV

CUORE - ^{130}Te,
GENIUS - ^{76}Ge,
EXO - ^{136}Xe,
MAJORANA - ^{76}Ge,
MOON - ^{100}Mo,
CANDLES - ^{48}Ca,
XMASS - ^{136}Xe.



S. Pascoli, S.T.P., hep-ph/0310003

Highest Priority: θ_{13}

- Controls the sub-dominant $\nu_\mu \leftrightarrow \nu_e$ and $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ oscillations

  - of the atmospheric ν's

  - in LBL experiments MINOS, OPERA,...

  - in VLBL experiments at $\nu-$factories

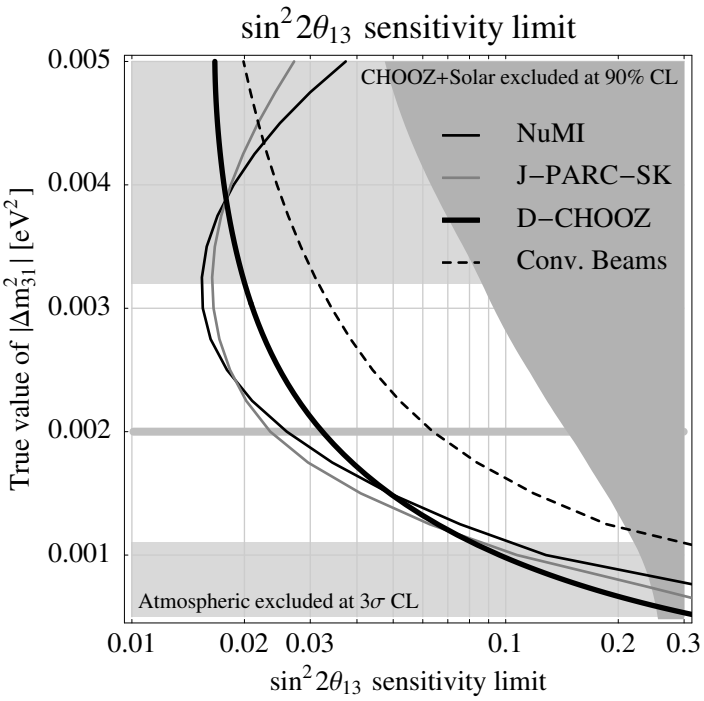
- Controls together with $\sin\delta$ the magnitude of CP- and T-violating effects in $\nu-$oscillations

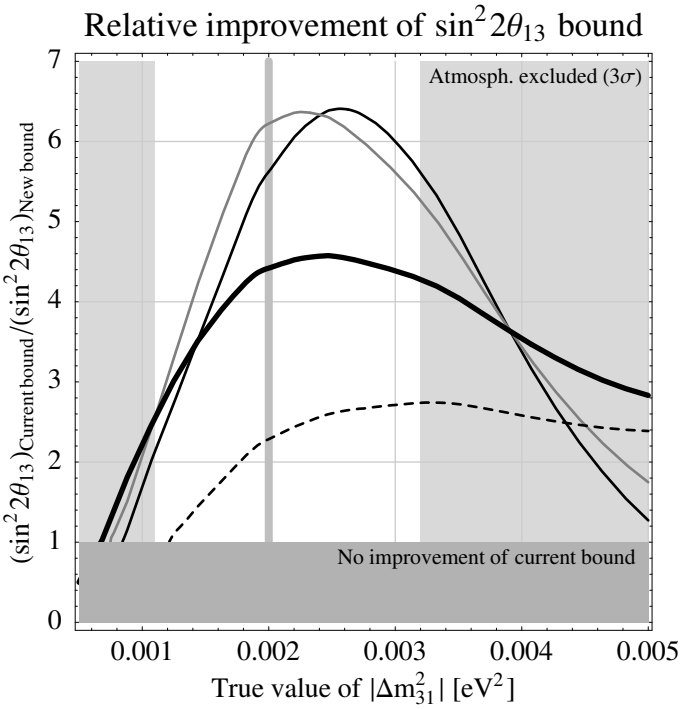
- $|<m>|$ in $(\beta\beta)_{0\nu}$-decay for NH

- The knowledge of the value of θ_{13} is crucial for the searches for correct theory of $\nu-$masses and mixing

Sensitivity of future experiments to $\sin^2 2\theta_{13}$

Conventional beams: MINOS, ICARUS, OPERA
Reactor experiments: Double-CHOOZ
Super beam off-axis experiments: T2K, NOνA (NuMI)



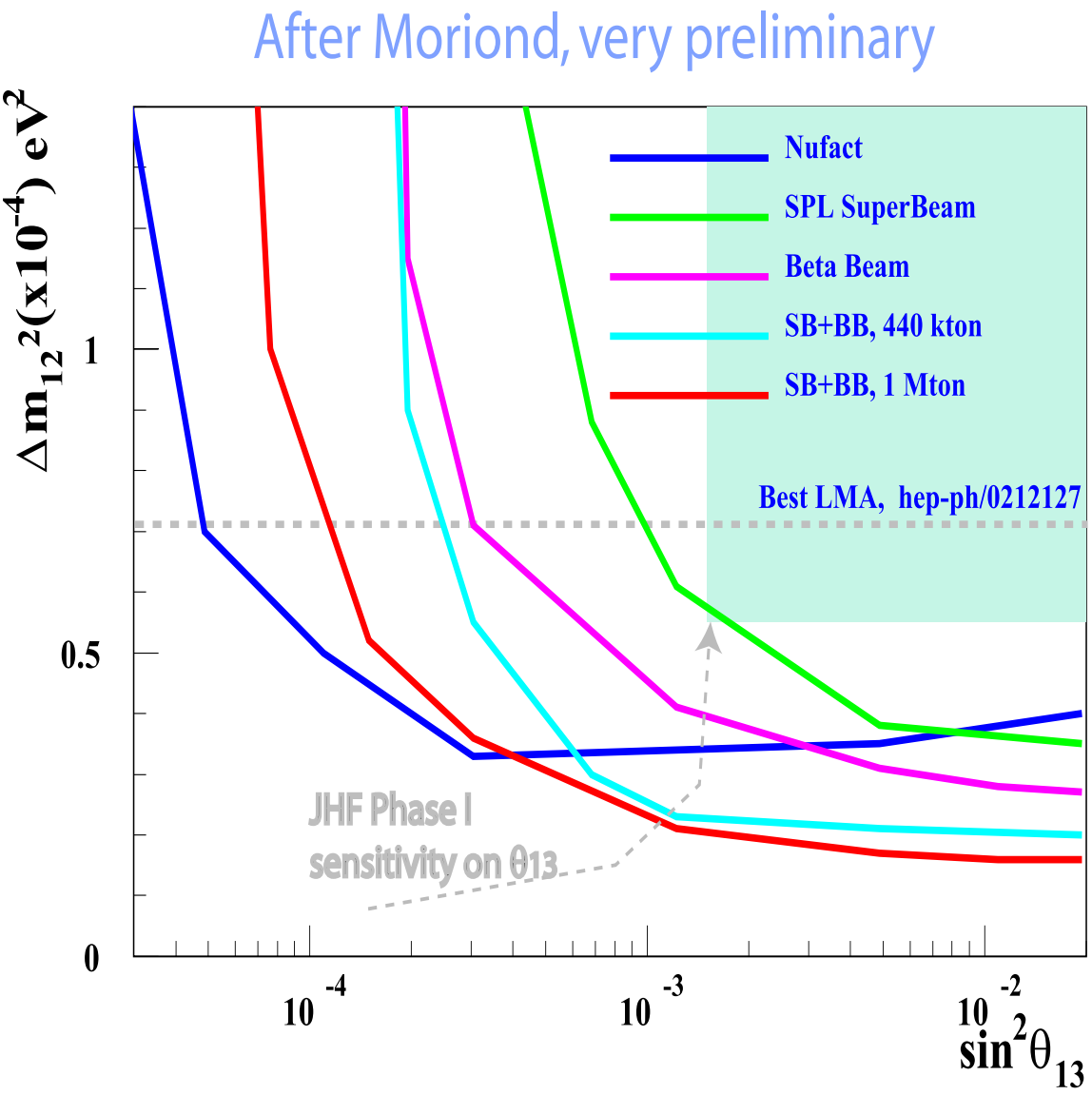


P.Huber et al., hep-ph/0403068

Proposals for reactor experiments: KASKA (Japan), U.S.A.

L.A. Mikhaelyan et al., hep-ex/9908047 and 0211070

H. Minakata et al., hep-ph/0211111


After Moriond, very preliminary
$\Delta m_{12}^2 (x10^{-4})\ eV^2$
1
0.5
0
10^{-4}
10^{-3}
10^{-2}
$\sin^2\theta_{13}$
Nufact
SPL SuperBeam
Beta Beam
SB+BB, 440 kton
SB+BB, 1 Mton
Best LMA, hep-ph/0212127
JHF Phase I
sensitivity on θ13

$$\Delta m^2_{\odot} = \Delta m^2_{21},\ \theta_{\odot} = \theta_{12}$$

Data from $\nu_{\odot}$- experiments

- **SNO**: $A_{\mathrm{D-N}} < 6\%$

  would restrict further Δm^2_{21} from below

  $R_{\mathrm{CC/NC}} = 0.306 \pm 0.035$, **reducing the error**

  would restrict further

  i) Δm^2_{21} from above, ii) the range of $\sin^2\theta_{12}$

- **BOREXINO**
- **LowNu (pp neutrinos) - LENS, XMASS: $\sin^2 2\theta_{12}$**

  (uncertainty due to $\sin^2\theta_{13}$)

Reactor Experiments

Future more precise KamLAND data

KamLAND: Low-LMA - Δm^2_{21} with high precision

$\sin^2\theta_{12}$ cannot be determined with a high precision

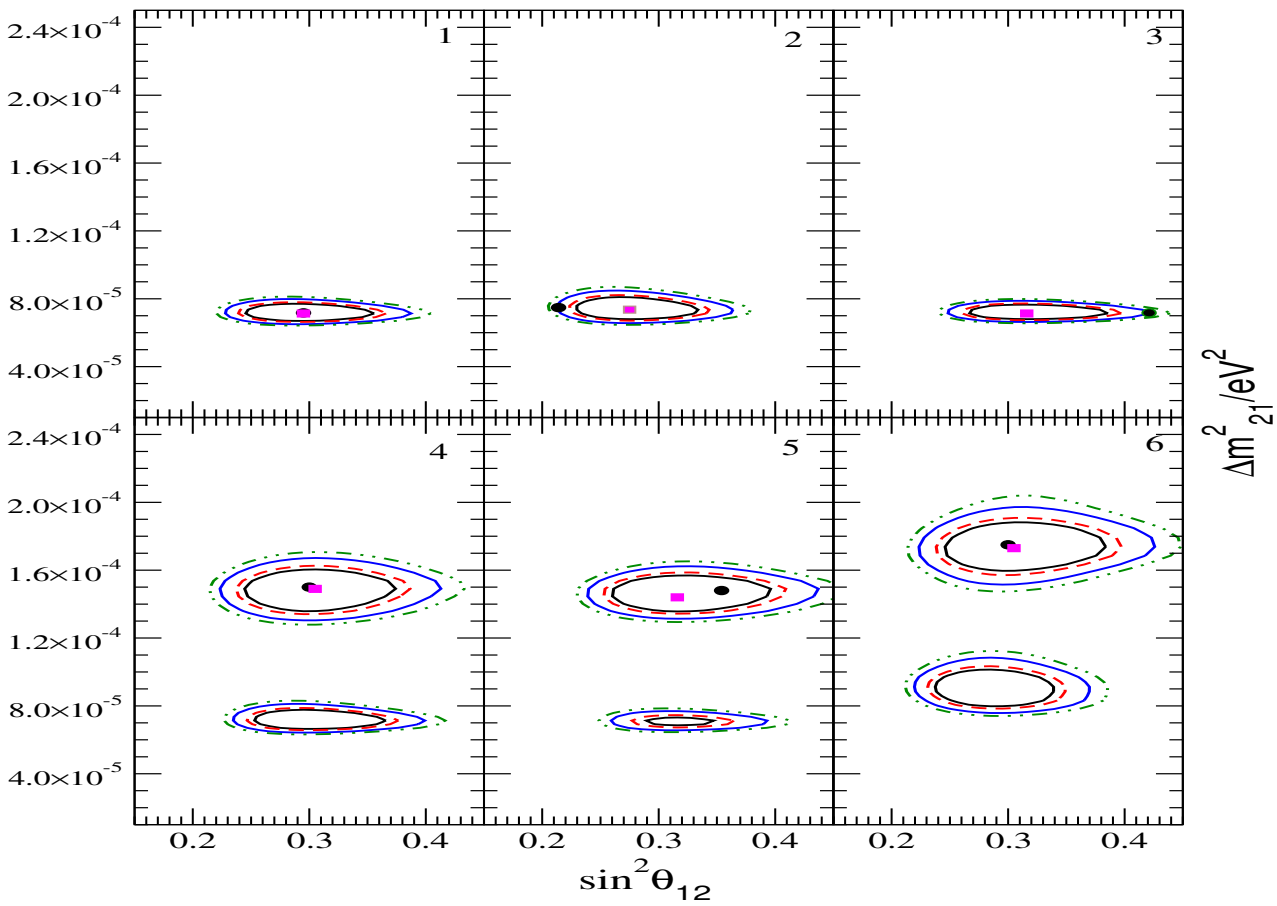
("wrong distance")

even with SHIGA-2 reactor to be operative in 2006

("right distance" but signal too weak)

Low-LMA: $L \sim 60$ km: $\sin^2 2\theta_{12}$

KamLAND 1 kTy

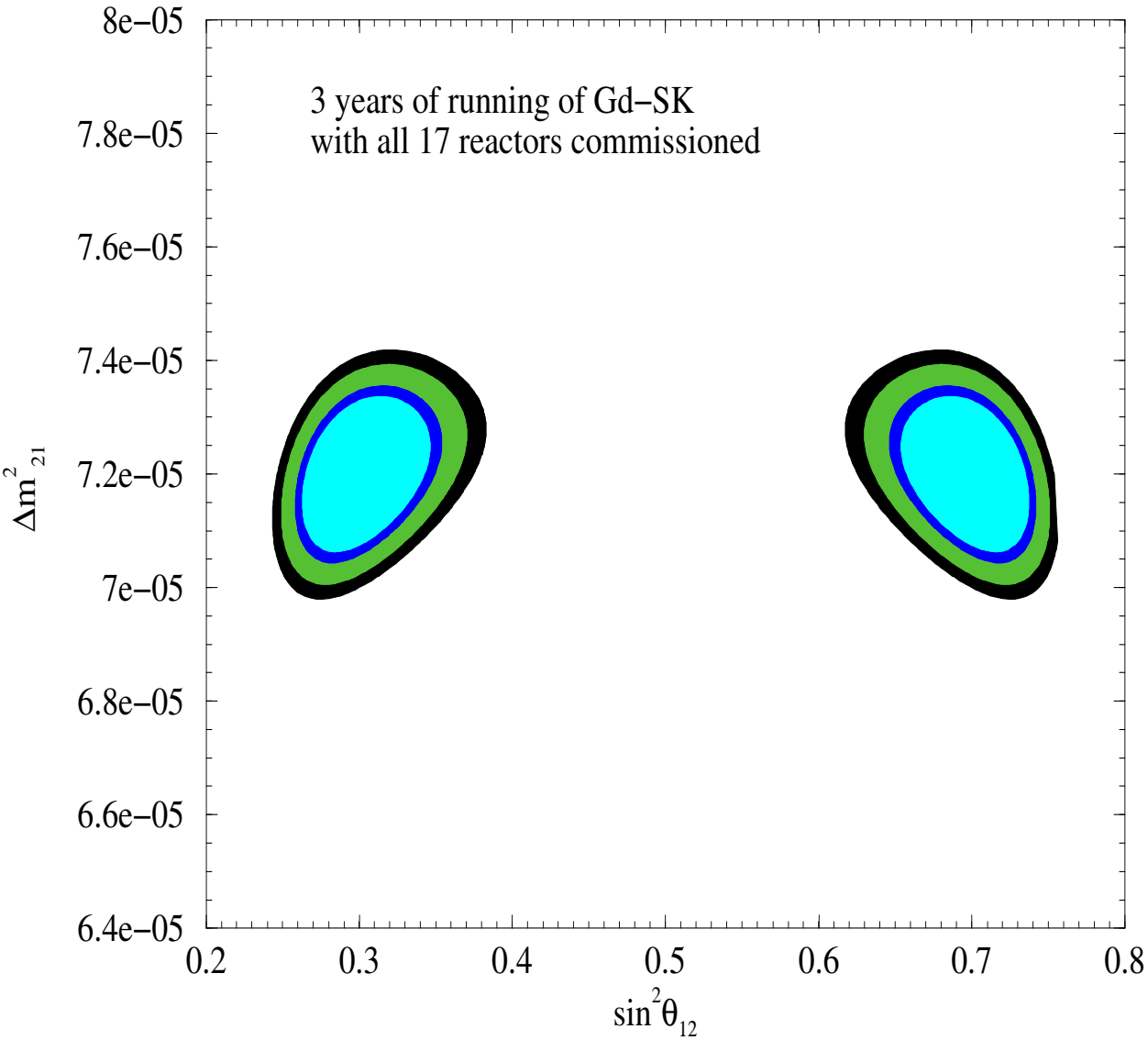


A. Bandyopadhyay et al, hep-ph/0309174

SK + 0.2% Gd

J.F. Beacom and M.R. Vagins, hep-ph/0309300

SK-Gd reactor $\bar{\nu}_e$ rate $\sim$ 43 times KamLAND rate



S.T.P. and S. Choubey, hep-ph/0404103

Sensitivity to Δm^2_{21} and $\sin^2\theta_{12}$

$$\text{spread} = \frac{a_{max} - a_{min}}{a_{max} + a_{min}},\ p \equiv \Delta m^2_{21} \text{ or } \sin^2\theta_{12}$$

Data set used	99% CL range of $\Delta m^2_{21}\times 10^{-5}\text{eV}^2$	99% CL spread of Δm^2_{21}	99% CL range of $\sin^2\theta_{12}$	99% CL spread in $\sin^2\theta_{12}$
only solar	3.2 - 14.9	65%	0.22 – 0.37	25%
solar+162 Ty KL	5.2 - 9.8	31%	0.22 – 0.37	25%
solar with future SNO	3.3 – 11.9	57%	2.2 – 0.34	21%
solar+1 kTy KL(low-LMA)	6.5 - 8.0	10%	0.23 – 0.37	23%
solar+2.6 kTy KL(low-LMA)	6.7 – 7.7	7%	0.23 – 0.36	22%
solar with future SNO+1.3 kTy KL(low-LMA)	6.7 – 7.8	8%	0.24 – 0.34	17%
3 yrs SK-Gd	7.2 - 7.4	1.4%	0.25 – 0.37	19%
5 yrs SK-Gd	7.0 – 7.3	$< 1\%$	0.26 – 0.35	15%
solar+3 yrs SK-Gd(low-LMA)	7.0 – 7.4	3%	0.25 – 0.34	15%
solar+3 yrs SK-Gd(high-LMA)	14.5 – 15.4	3%	0.24 – 0.37	21%
solar with future SNO+3 yrs SK-Gd(low-LMA)	7.0 – 7.4	3%	0.25 – 0.335	14%
solar with future SNO+3 yrs SK-Gd(high-LMA)	14.5 – 15.4	3%	0.24 – 0.35	19%
3 yrs SK-Gd with Kashiwazaki "down"	6.8 – 7.6	6%	0.23 – 0.40	27%
7 yrs SK-Gd with *only* Shika-2 "up"	7.0 – 7.3	$< 1\%$	0.28 – 0.32	6.7%

Table 1: The range of parameter values allowed at 99% C.L. and their corresponding spread.

$|\Delta m^2_{31}|$, sign(Δm^2_{31}), θ_{23}

MINOS: $|\Delta m^2_{31}|$ $\sim 10\%$

JHF (T2K), SK: $P(\nu_\mu \to \nu_\mu)$; $P(\nu_\mu \to \nu_e)$, $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ **at maximum:** $|\Delta m^2_{31}|\ L/(4E) = \pi/2$

- $|\Delta m^2_{31}|$, $\sin^2 2\theta_{23}$ **high precision**
- **The sign(Δm^2_{31}) - a problem**
- **Exact** $\delta \leftrightarrow (\pi - \delta)$ **degeneracy**
- **If** $\sin^2 2\theta_{23} < 1$: $\sin^2\theta_{23} > 0.5$, $\sin^2\theta_{23} < 0.5$ **ambiguity**

Lead to ambiguities in the measurements of $\sin^2\theta_{13}$ **and** δ

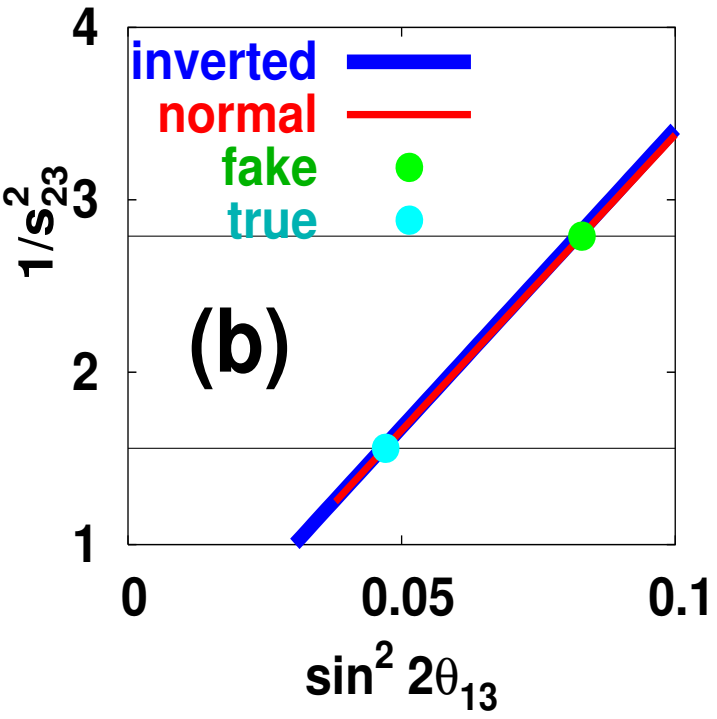
J. Burguet-Castell et al., hep-ph/0103258
V. Barger, D. Marfatia, K. Whisnant, hep-ph/0112119
H. Minakata, H. Nunokawa, S.J. Parke, hep-ph/0301210
P. Huber et al., hep-ph/0403068
O. Yasuda, hep-ph/0405005

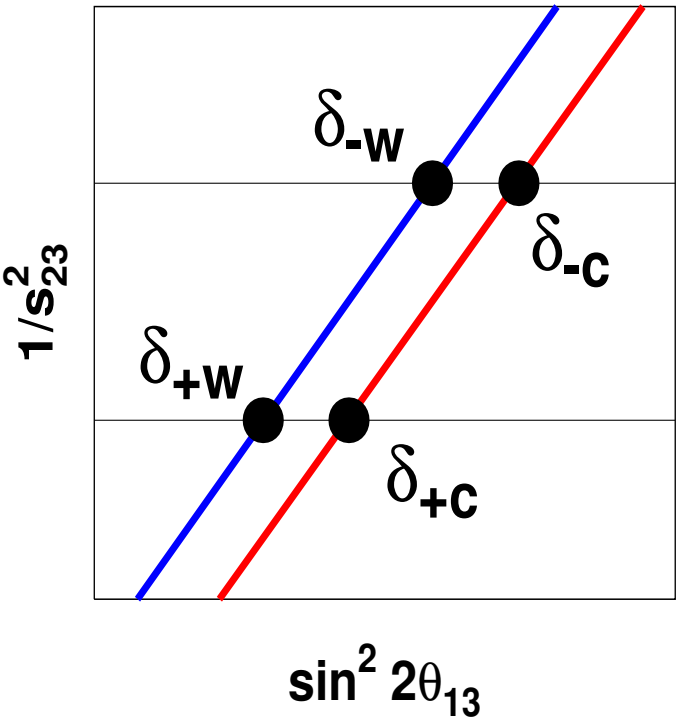
Resolving the ambiguities may require data from

NuMI off-axis, and/or

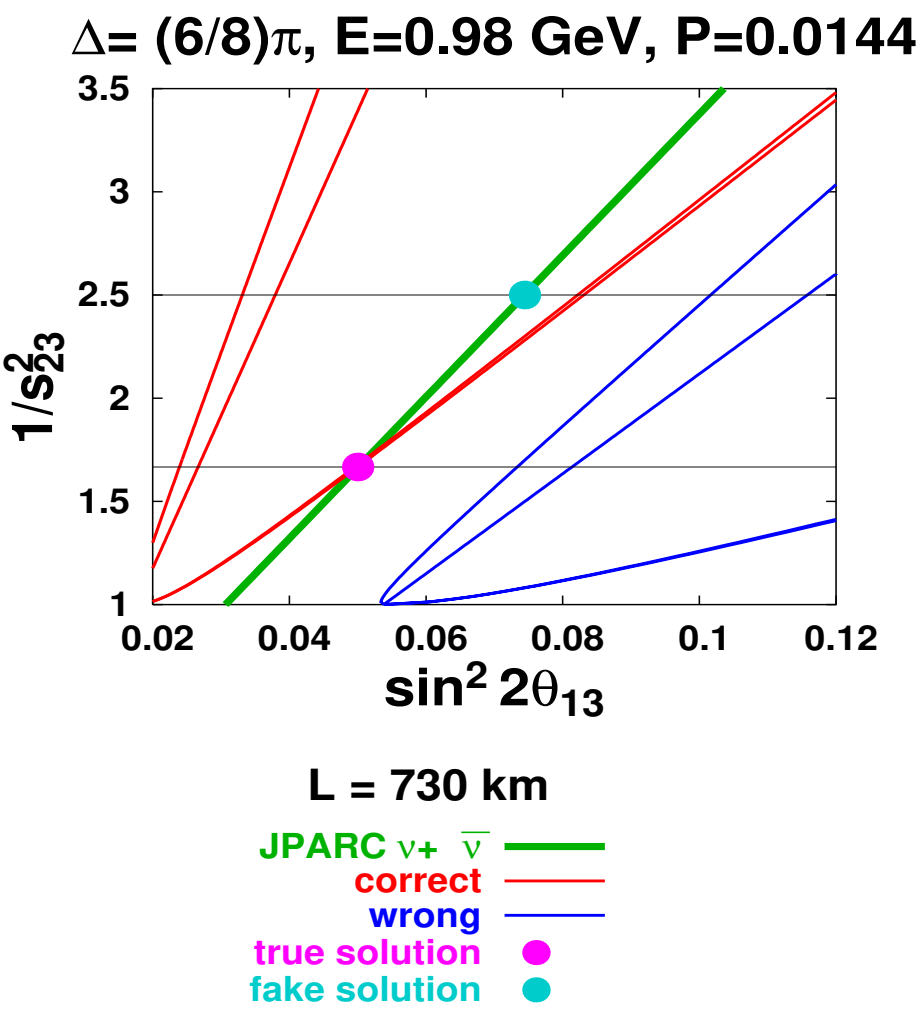
new off-maximum JHF, and/or

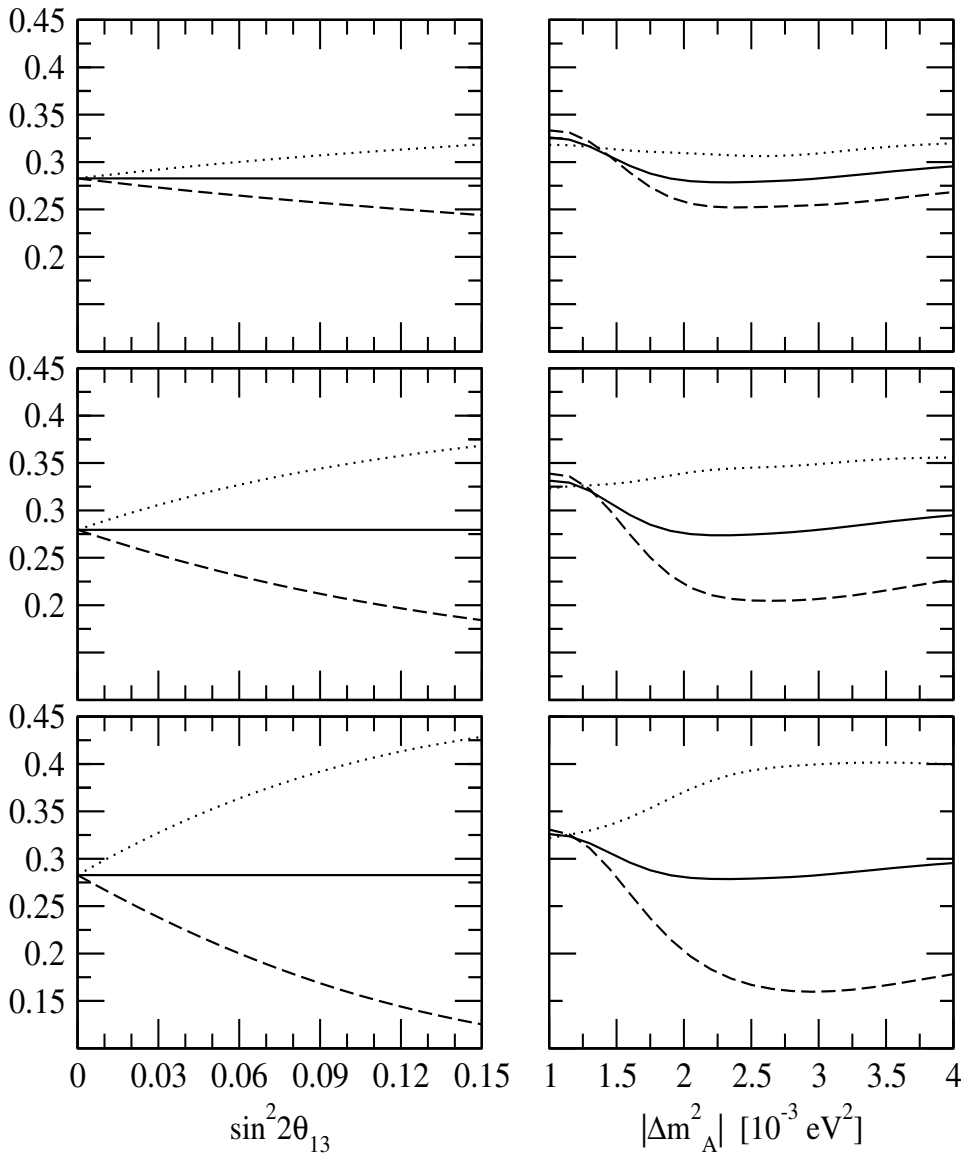
SPL + β−beams experiment(s).





O. Yasuda, hep-ph/0405005


Δ= (6/8)π, E=0.98 GeV, P=0.0144
3.5
3
2.5
2
1.5
1
0.02
0.04
0.06
0.08
0.1
0.12
1/s²₂₃
sin² 2θ₁₃
L = 730 km
JPARC ν+ ν̄
correct
wrong
true solution
fake solution



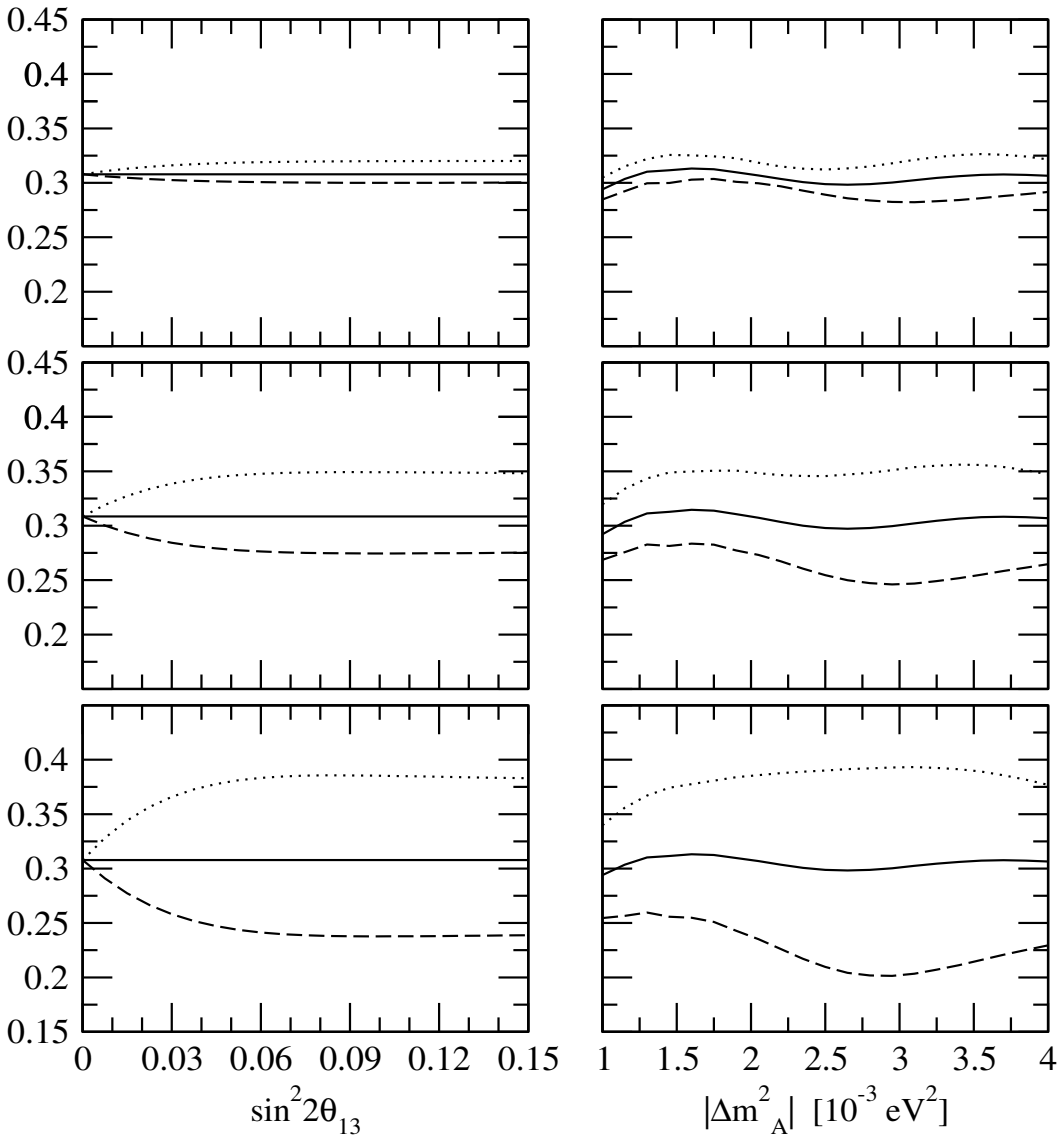
Iron Magnetized Detectors (MINOS, INO): multi-GeV μ^- and μ^+ event rates, N_{μ^-} and N_{μ^+}

$A \equiv \frac{U-D}{U+D}$ in the θ_n- dependence of $\frac{N_{\mu^-}}{N_{\mu^+}}$

- $|\Delta m^2_{31}| = 3 \times 10^{-3}$ eV^2, $\sin^2\theta_{23}$ =0.36, 0.50, 0.64
- $\Delta m^2_{31} > 0$-NH (dashed), $\Delta m^2_{31} < 0$-IH (dotted), 2-ν (solid)

$\cos\theta_n = (0.30 - 0.84)$ mantle bin, E = [5,20] GeV

S.T.P., S. Palomares-Ruiz, hep-ph/0406

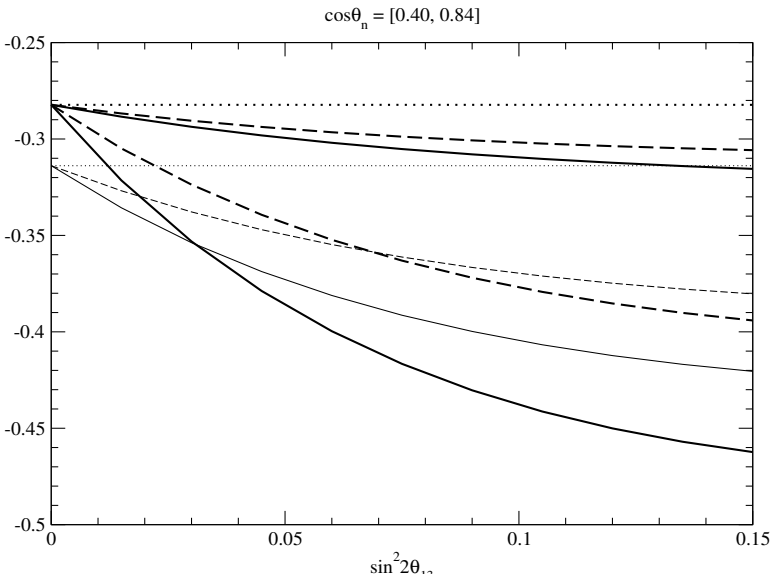


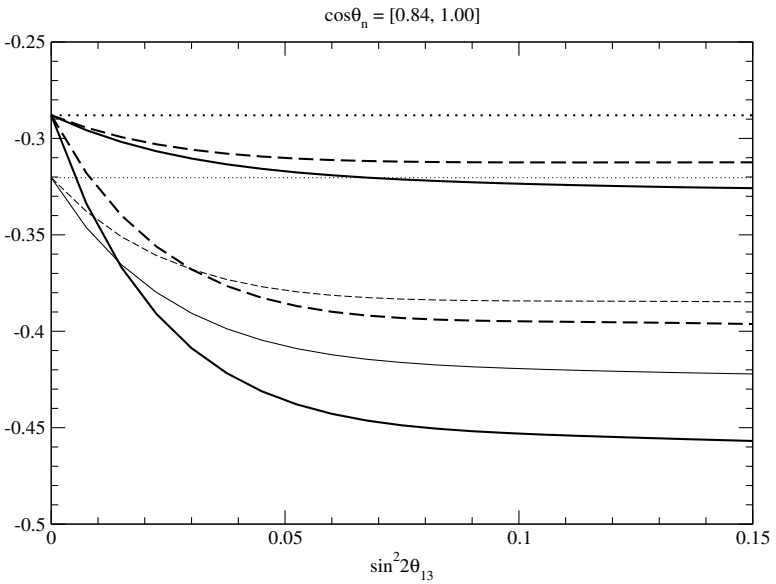
$\cos\theta_n = (0.84 - 1.0)$ **core bin, E = [2,10] GeV**

Water-Čerenkov Detectors (SK, etc.): multi-GeV $\mu-$like and $e-$like event rates, N_μ and N_e

$A \equiv \frac{U-D}{U+D}$ **in the** θ_n- **dependence of** $\frac{N_\mu}{N_e}$

- $|\Delta m^2_{31}| = 2 \times 10^{-3}$ eV^2, $\sin^2\theta_{23}$ **=0.36, 0.50, 0.64**
- $\Delta m^2_{\rm atm} > 0$**-NH (solid),** $\Delta m^2_{\rm atm} < 0$**-IH (dashed),** $2-\nu$ **(dotted)**





Instead of Conclusions

We are at the beginning of the Road...

諸國名所古景
近江
堅田
落雁

Hiroshige (Ukiyoe master), Landscape, Edo Epoch