The Current Status and Prospetcs of Neutrino Masses, Mixing and Oscillations

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Compelling Evidences for $\nu-$Oscillations

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

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

Dominant $\nu_\mu \longrightarrow \nu_\tau$ K2K, MINOS; CNGS (OPERA)

$-\nu_\odot$: **Homestake, Kamiokande, SAGE, GALLEX/GNO**

Super-Kamiokande, SNO; KamLAND

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

– LSND

Dominant $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$ **MiniBOONE**

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

B. Pontecorvo, 1957; 1958; 1967;

Z. Maki, M. Nakagawa, S. Sakata, 1962;

The ν−Oscillation Data: 3−ν Mixing

$$\nu_{l\mathrm{L}} = \sum_{j=1,2,3} U_{lj}\,\nu_{j\mathrm{L}} \qquad l = e, \mu, \tau.$$

B. Pontecorvo, 1957; 1958; 1967;

Z. Maki, M. Nakagawa, S. Sakata, 1962;

Three Neutrino Mixing

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

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

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

- U - $n \times n$ unitary:

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

PMNS Matrix: Standard Parametrization

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

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

- $s_{ij} \equiv \sin\theta_{ij},\ c_{ij} \equiv \cos\theta_{ij},\ \theta_{ij} = [0, \frac{\pi}{2}]$,
- δ - Dirac CP-violation phase, $\delta = [0, 2\pi]$,
- α_{21}, α_{31} - the two Majorana CP-violation phases.
- $\Delta m^2_{\odot} \equiv \Delta m^2_{21} \cong 8.0 \times 10^{-5}$ eV$^2 > 0$, $\sin^2\theta_{12} \cong 0.30$, $\cos 2\theta_{12} \gtrsim 0.28$ (2σ),
- $|\Delta m^2_{\rm atm}| \equiv |\Delta m^2_{31}| \cong 2.5 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} \cong 1$,
- θ_{13} - the CHOOZ angle: $\sin^2\theta_{13} < 0.027$ (0.041) 2σ (3σ).

A.Bandyopadhyay, S.Choubey, S.Goswami, S.T.P., D.P.Roy, hep-ph/0406328 (updated)

T. Schwetz, hep-ph/0606060.

- $\text{sgn}(\Delta m^2_{\text{atm}}) = \text{sgn}(\Delta m^2_{31})$ not determined

$$\Delta m^2_{\text{atm}} \equiv \Delta m^2_{31} > 0, \quad \text{normal mass ordering}$$

$$\Delta m^2_{\text{atm}} \equiv \Delta m^2_{32} < 0, \quad \text{inverted mass ordering}$$

Convention: $m_1 < m_2 < m_3$ - NMO, $m_3 < m_1 < m_2$ - IMO

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

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

$$m_1 \cong m_2 \cong m_3, \; m^2_{1,2,3} >> \Delta m^2_{\text{atm}}, \; \text{QD}; \; m_j \gtrsim 0.10 \text{ eV}.$$

- Majorana phases 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, S.T.P., G. Steigman, S. Toshev, 1987
  - $|<m>|$ in $(\beta\beta)_{0\nu}$−decay depends on α_{21}, α_{31};
  - $\Gamma(\mu \rightarrow e + \gamma)$ etc. in SUSY theories depend on $\alpha_{21,31}$;
  - BAU, leptogenesis scenario: $\alpha_{21,31}$!

Neutrino Mixing Parameters

$\theta_{12},\ \theta_{23},\ \theta_{13}$

ν_j Dirac Majorana

δ $\delta,\ \alpha_{21},\ \alpha_{31}$

$m_1, \quad m_2, \quad m_3$

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

Conventions

A. $m_1 < m_2 < m_3$ (NO) or $m_3 < m_1 < m_2$ (IO)

- $\Delta m^2_{\odot} = \Delta m^2_{21} > 0$
- $\Delta m^2_{\rm atm} = \Delta m^2_{31} > 0$ (NO), $\Delta m^2_{\rm atm} = \Delta m^2_{32} < 0$ (IO)
- $m_2 = \sqrt{m_1^2 + \Delta m^2_{21}}, \ \ m_3 = \sqrt{m_1^2 + \Delta m^2_{31}}$

B. $m_1 < m_2 < m_3$

- $\Delta m^2_{\rm atm} = \Delta m^2_{31} > 0$
- $\Delta m^2_{\odot} = \Delta m^2_{21} > 0$, NO; $\Delta m^2_{\odot} = \Delta m^2_{32} > 0$, IO

Neutrino Oscillation Parameters

parameter	bf$\pm 1\sigma$	1σ acc.	2σ range	3σ range
Δm^2_{21} [$10^{-5} eV^2$]	7.9 ± 0.3	4%	$7.3 - 8.5$	$7.1 - 8.9$
$\|\Delta m^2_{31}\|$ [$10^{-3} eV^2$]	$2.5^{+0.20}_{-0.25}$	10%	$2.1 - 3.0$	$1.9 - 3.2$
$\sin^2 \theta_{12}$	$0.30^{+0.02}_{-0.03}$	9%	$0.26 - 0.36$	$0.24 - 0.40$
$\sin^2 \theta_{23}$	$0.50^{+0.08}_{-0.07}$	16%	$0.38 - 0.64$	$0.34 - 0.68$
$\sin^2 \theta_{13}$	–	–	≤ 0.025	≤ 0.041

Best fit values (bf), 1σ errors, relative accuracies at 1σ, and 2σ and 3σ allowed ranges of three-flavor neutrino oscillation parameters from a combined analysis of global data.

T. Schwetz, hep-ph/0606060

Absolute Neutrino Mass Measurements

Troitzk and Mainz ^{3}H β-decay experiments, $3\text{H} \rightarrow ^3\text{He} + e^- + \bar{\nu}_e$,

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

There are prospects to reach sensitivity

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

Cosmological and astrophysical data: the WMAP result combined with data from large scale structure surveys (2dFGRS, SDSS)

$$\sum_j m_j \equiv \Sigma < (0.4 - 1.7) \text{ eV}$$

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

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

Future Progress

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

• Determination of sgn($\Delta m^2_{\rm atm}$), type of $\nu-$ mass spectrum

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

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

$$m_1 \cong m_2 \cong m_3,\; m^2_{1,2,3} >> \Delta m^2_{\rm atm},\; \text{QD};\; m_j \gtrsim 0.10 \text{ eV}.$$

• Determining, or obtaining significant constraints on, the absolute scale of ν_j-masses, or min(m_j).

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

• 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, $\sin^2\theta_{13}$.

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

• Understanding at fundamental level the mechanism giving rise to the $\nu-$ masses and mixing and to the L_l-non-conservation. Includes understanding

– the origin of the observed patterns of ν-mixing and ν-masses ;

– the physical origin of CPV phases in U_{PMNS} ;

– Are the observed patterns of ν-mixing and of $\Delta m^2_{21,31}$ related to the existence of a new symmetry?

– Is there any relations between $q-$mixing and $\nu-$ mixing? Is $\theta_{12} + \theta_c = \pi/4$?

– Is $\theta_{23} = \pi/4$, or $\theta_{23} > \pi/4$ or else $\theta_{23} < \pi/4$?

– Is there any correlation between the values of CPV phases and of mixing angles in U_{PMNS}?

• Progress in the theory of ν-mixing might lead to a better understanding of the origin of the BAU.

– Can the Majorana and/or Dirac CPVP in U_{PMNS} be the leptogenesis CPV parameters at the origin of BAU?

HOW?

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

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

  SNO

  SAGE

  BOREXINO

  LowNu (XMASS, LENS,...)

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

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

  OPERA, ICARUS 732 km

- Super Beams

  T2K, SK (HK) 295 km

  NOνA $\sim$800 km

  SPL+$\beta-$beams, MEMPHYS (0.5 megaton):
  CERN-Frejus $\sim$140 km

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

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

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

Data from $\nu_\odot$- experiments

- **SNO**: $A_{\mathrm{D-N}} < 4.3\%$

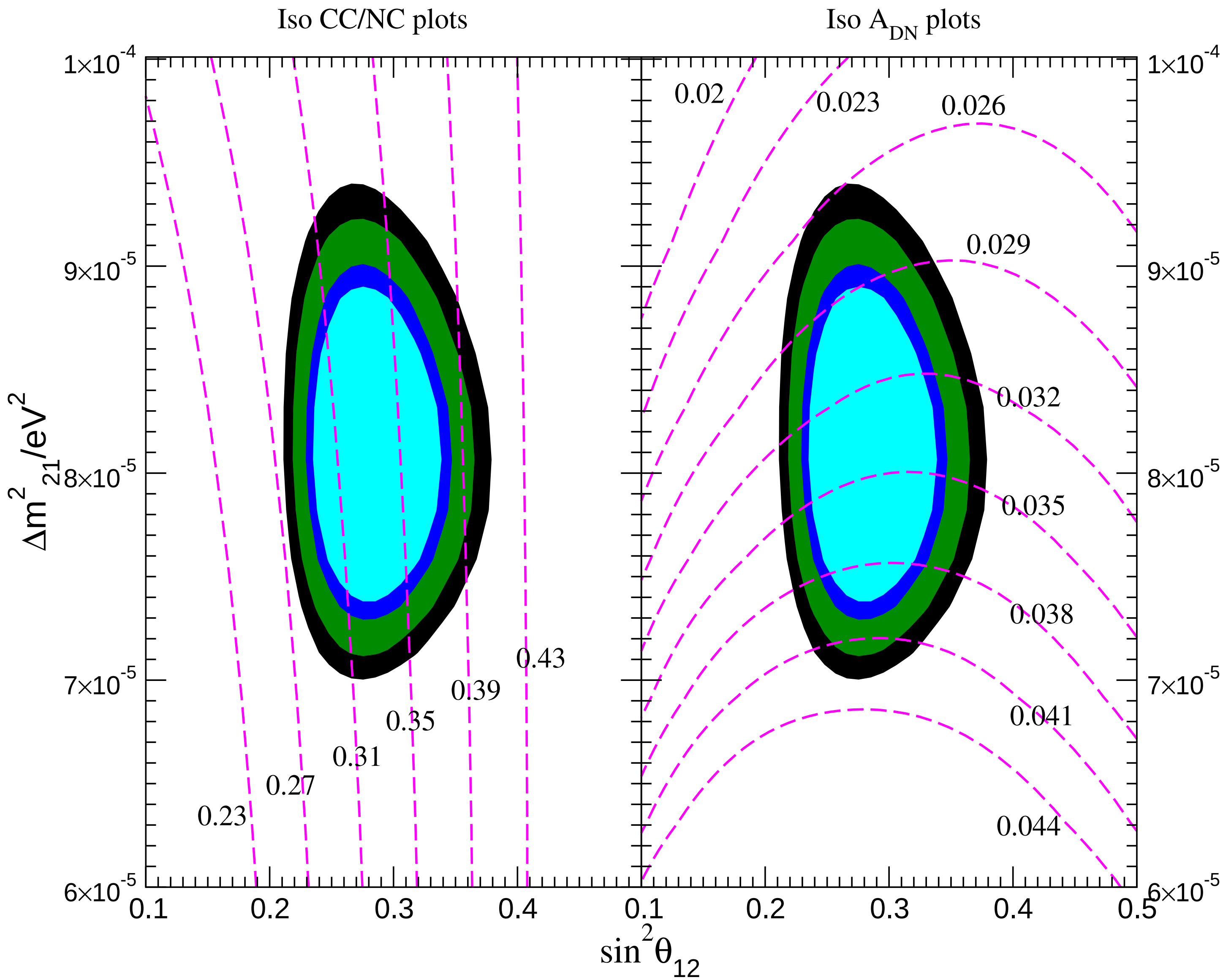
  would restrict further Δm^2_{21} from below

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

  would restrict further

  the range of $\sin^2\theta_{12}$

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



A.Bandyopadhyay,S.Choubey,S.Goswami,S.T.P.,D.P.Roy, hep-ph/0309174

LowNu: generic $\nu - e^-$ ES experiment

pp: $E_\nu \leq 0.42$ **MeV,** $\bar{E}_\nu = 0.286$ **MeV**

Assume $T_e \geq 50$ **keV**

$R_{pp} \cong \bar{P} + r_{pp}(1 - \bar{P})$, $\bar{P} \cong \cos^4\theta_{13}(1 - \frac{1}{2}\sin^2 2\theta_{12})$, $r_{pp} \cong 0.3$

$R_{CC/NC}(SNO) \cong \sin^2\theta_{12}\cos^4\theta_{13}$

$\Delta(R_{pp}) < \Delta(R_{CC/NC})$ **to reduce** $\Delta(\sin^2\theta_{12})$**; SNO3:** $\sim 6\%$

BP04: $R_{pp} \cong 0.71$; 3σ: **0.67 - 0.76**

With $\Delta(R_{pp}) = 1\%$, $\Delta(\sin^2\theta_{12}) \gtrsim 15\%$ **at** 3σ

Dedicated reactor experiment with $L \sim 60$ **km:**

$\Delta(\sin^2\theta_{12}) = (6 - 9)\%$ **at** 3σ

A. Bandyopadhyay et al., hep-ph/0302243 and hep-ph/0410283;

H. Minakata et al., hep-ph/0407326

Reactor Experiments

Future more precise KamLAND data: Δm^2_{21} **with higher precision**

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

("wrong distance")

even with SHIKA-2 reactor to be operative in 2006

("right distance", L = 88 km, but signal too weak (3.926 GW))

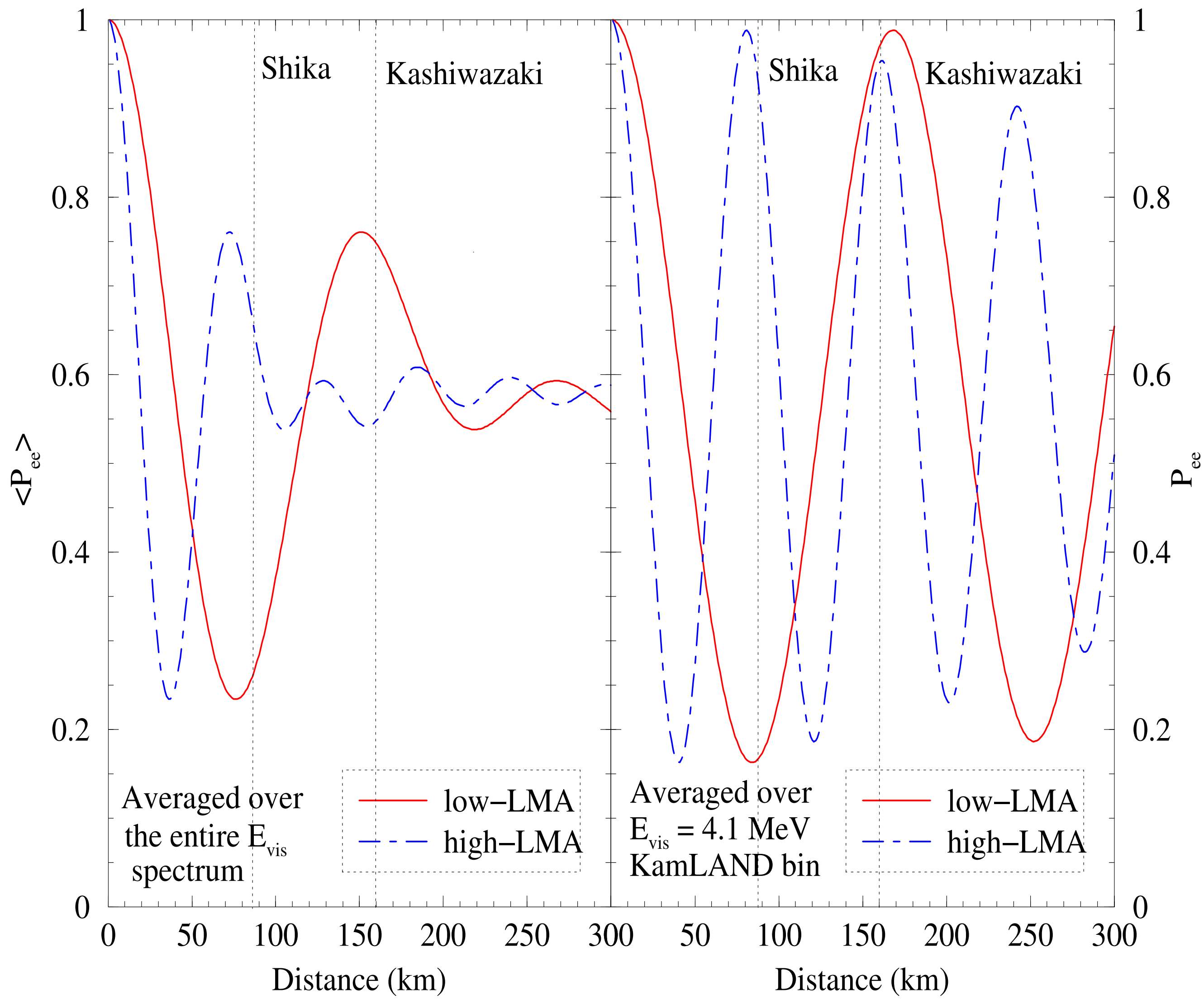
$$P^{3\nu}_{\mathrm{KL}} \cong \sin^4\theta_{13} + \cos^4\theta_{13}\left[1 - \sin^2 2\theta_{12}\sin^2(\frac{\Delta m^2_{\odot}}{4E}L)\right]$$

$\sin^2(\frac{\Delta m^2_{\odot}}{4E}L) \cong 0$ **(SPMAX; KamLAND):**

strong sensitivity to $\Delta m^2_{\odot} \equiv \Delta m^2_{21}$**, weak sensitivity to** $\sin^2\theta_{12}$

$\sin^2(\frac{\Delta m^2_{\odot}}{4E}L) \cong 1$ **(SPMIN): E = 4 MeV,** $L \cong 60$ **km,**

strong sensitivity to $\sin^2\theta_{12}$



Shika
Kashiwazaki
$<P_{ee}>$
P_{ee}
Averaged over
the entire E_{vis}
spectrum
Averaged over
E_{vis} = 4.1 MeV
KamLAND bin
low–LMA
high–LMA
Distance (km)

SK + 0.1% Gd

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

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

3 years statistics in SK-Gd, 99% C.L.:

$$\Delta m^2_{21} = (8.01 - 8.61) \times 10^{-5} \text{eV}^2; \quad \text{spread} = 3.6\%$$
$$\sin^2\theta_{12} = (0.22 - 0.34); \quad \text{spread} = 21\%$$

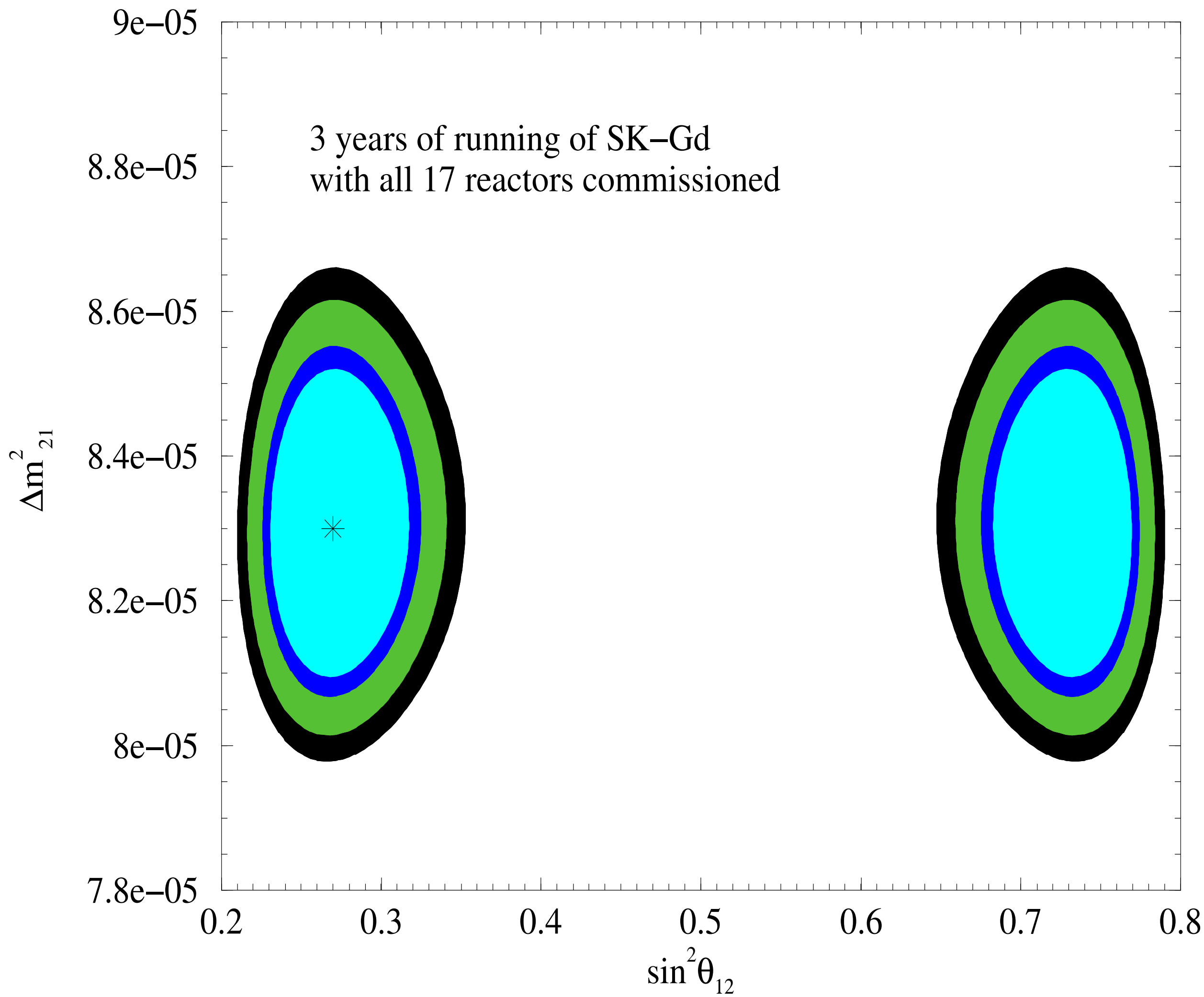
5 years statistics in SK-Gd, 99% C.L.:

$$\Delta m^2_{21} = (8.07 - 8.53) \times 10^{-5} \text{eV}^2; \quad \text{spread} = 2.8\%$$
$$\sin^2\theta_{12} = (0.22 - 0.32); \quad \text{spread} = 18\%$$

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

Comment: SK-Gd data simulated at $\Delta m^2_{21} = 8.3 \times 10^{-5}$ eV^2, $\sin^2\theta_{12} = 0.27$ (the "old" global best-fit point). The precision on Δm^2_{21} and $\sin^2\theta_{12}$ for a given statistics remains approximately the same for $\Delta m^2_{21} = 8.0 \times 10^{-5}$ eV^2, $\sin^2\theta_{12} = 0.30$ (the new global best-fit point).

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



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

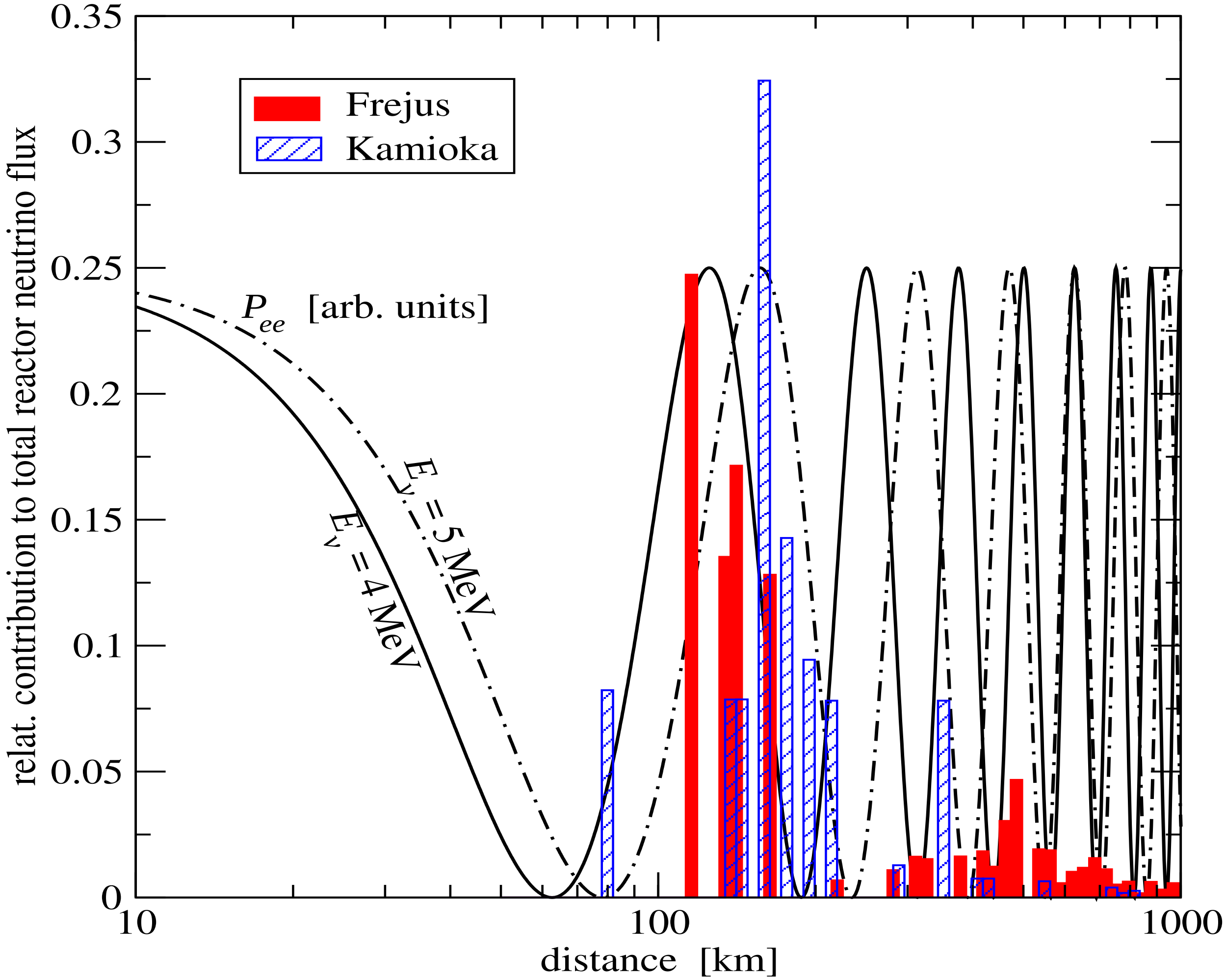
Sensitivity to Δm^2_{21} and $\sin^2\theta_{12}$

Data set used	99% CL range of $\Delta m^2_{21} \times 10^{-5}\mathrm{eV}^2$	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 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	7.0 - 7.4	3%	0.25 – 0.37	19%
5 yrs SK-Gd	7.0 – 7.3	2%	0.26 – 0.35	15%
solar+3 yrs SK-Gd(low-LMA)	7.0 – 7.4	3%	0.25 – 0.34	15%
solar with future SNO+3 yrs SK-Gd(low-LMA)	7.0 – 7.4	3%	0.25 – 0.335	14%
7 yrs SK-Gd with *only* Shika-2 “up”	7.0 – 7.3	2%	0.28 – 0.32	6.7%

Future SNO: 5% on R_{CC}, 6% on R_{NC}

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

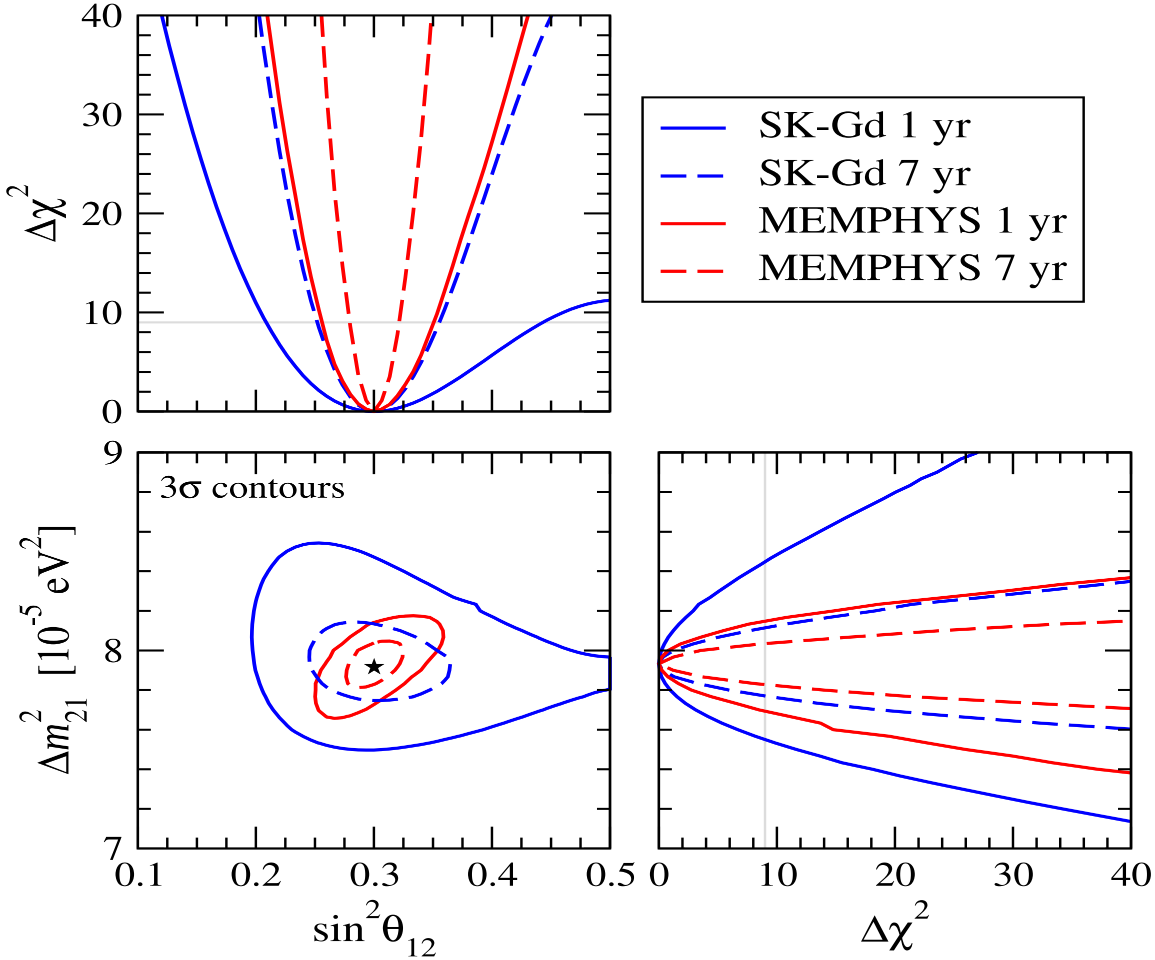
MEMPHYS (Frejus) + 0.1% Gd



MEMPHYS (Frejus): 147 kt water-Čerenkov detector, ~6.5×SK

56 reactors within 1000 km; 65% of the flux from reactors within 160 km

MEMPHYSGd vs SKGd



1 year MEMGd ≅ 7 years SKGd: **3**$\sigma(\Delta m^2_{21}) \cong 3\%$**,** **3**$\sigma(\sin^2_{21}) \cong 20\%$

7 years MEMPHYSGd: **3**$\sigma(\Delta m^2_{21}) \cong 1.4\%$**,** **3**$\sigma(\sin^2_{21}) \cong 13\%$

S.T.P. and T. Schwetz, hep-ph/0607155

Dedicated Reactor Experiment on $\sin^2 2\theta_{12}$

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

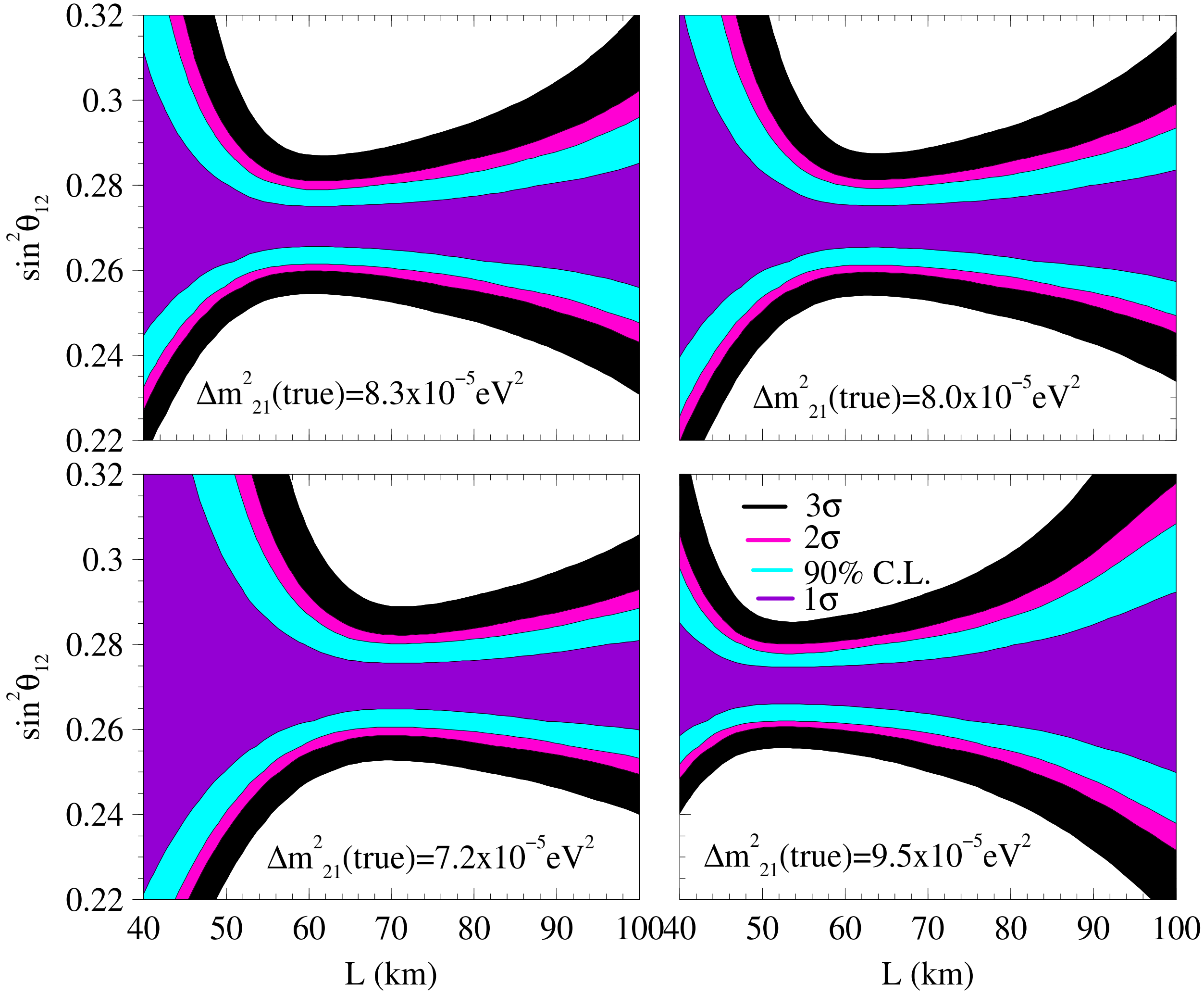
SPMIN: $L \sim 60$ **km:** $\sin^2 2\theta_{12}$

$\Delta(\sin^2\theta_{12}) = (6-9)\%$ **at** 3σ

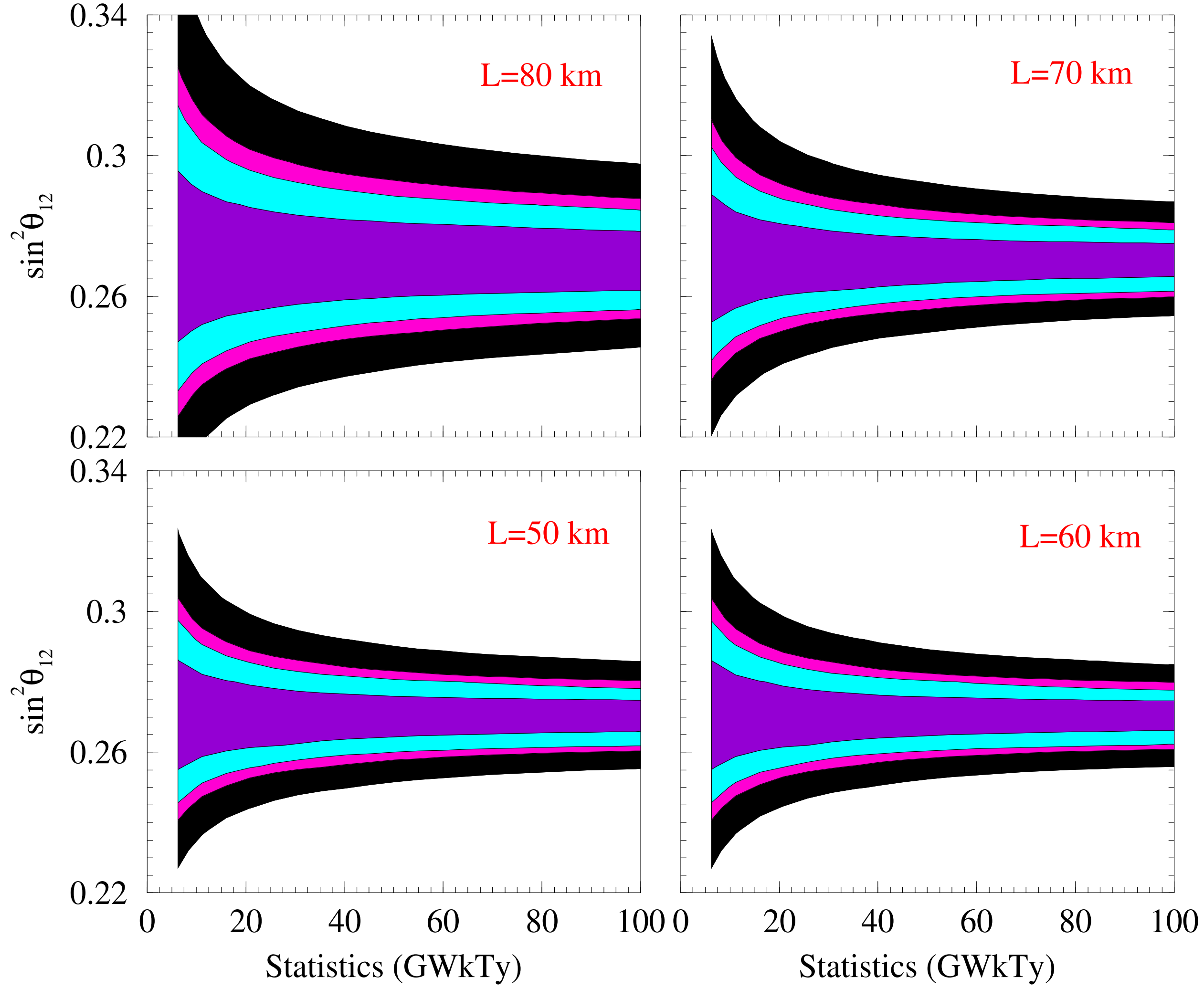
A. Bandyopadhyay, S. Choubey, S. Goswami, hep-ph/0302243;

A. Bandyopadhyay, S. Choubey, S. Goswami, S.T.P., hep-ph/0410283;

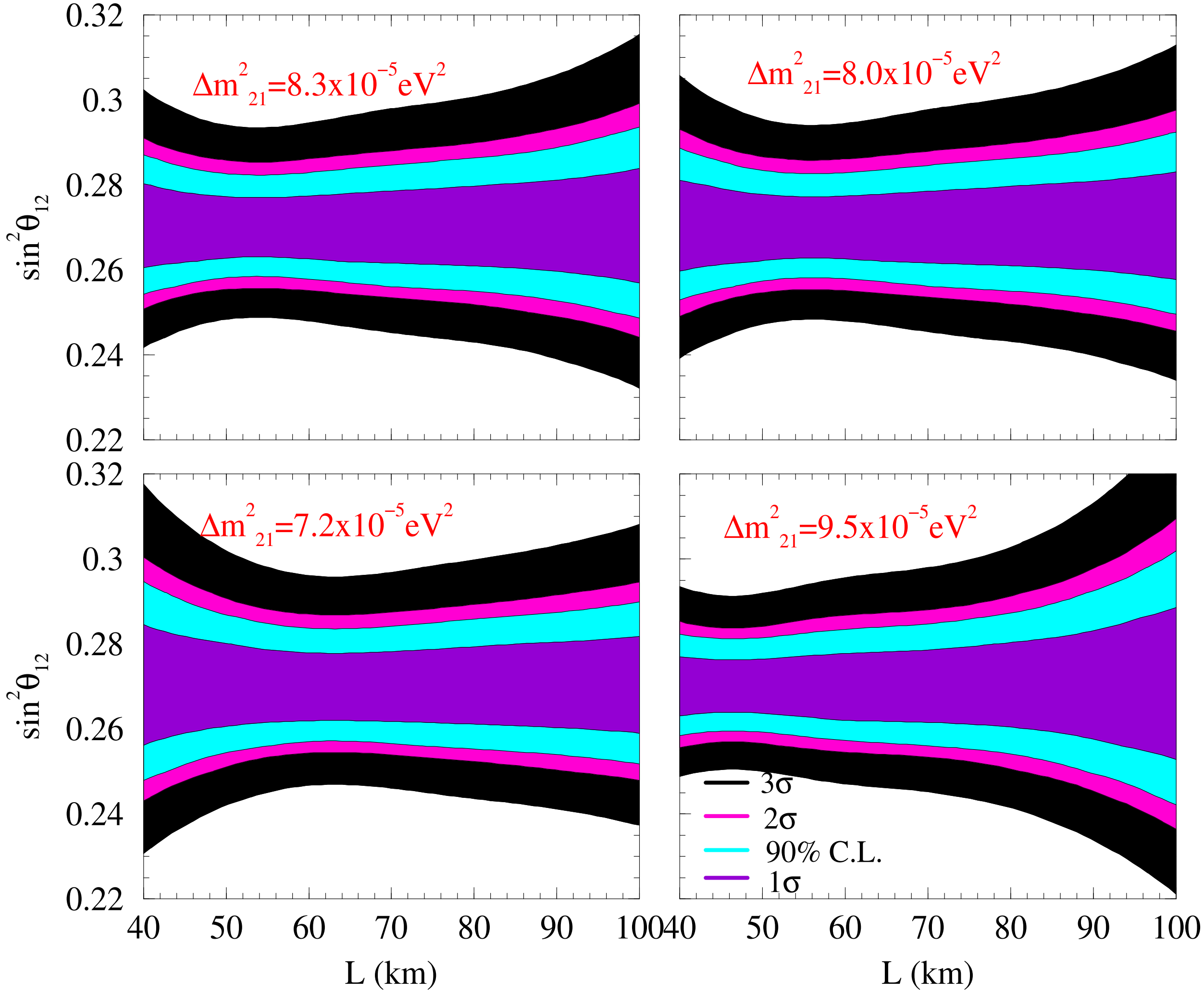
H. Minakata et al., hep-ph/0407326



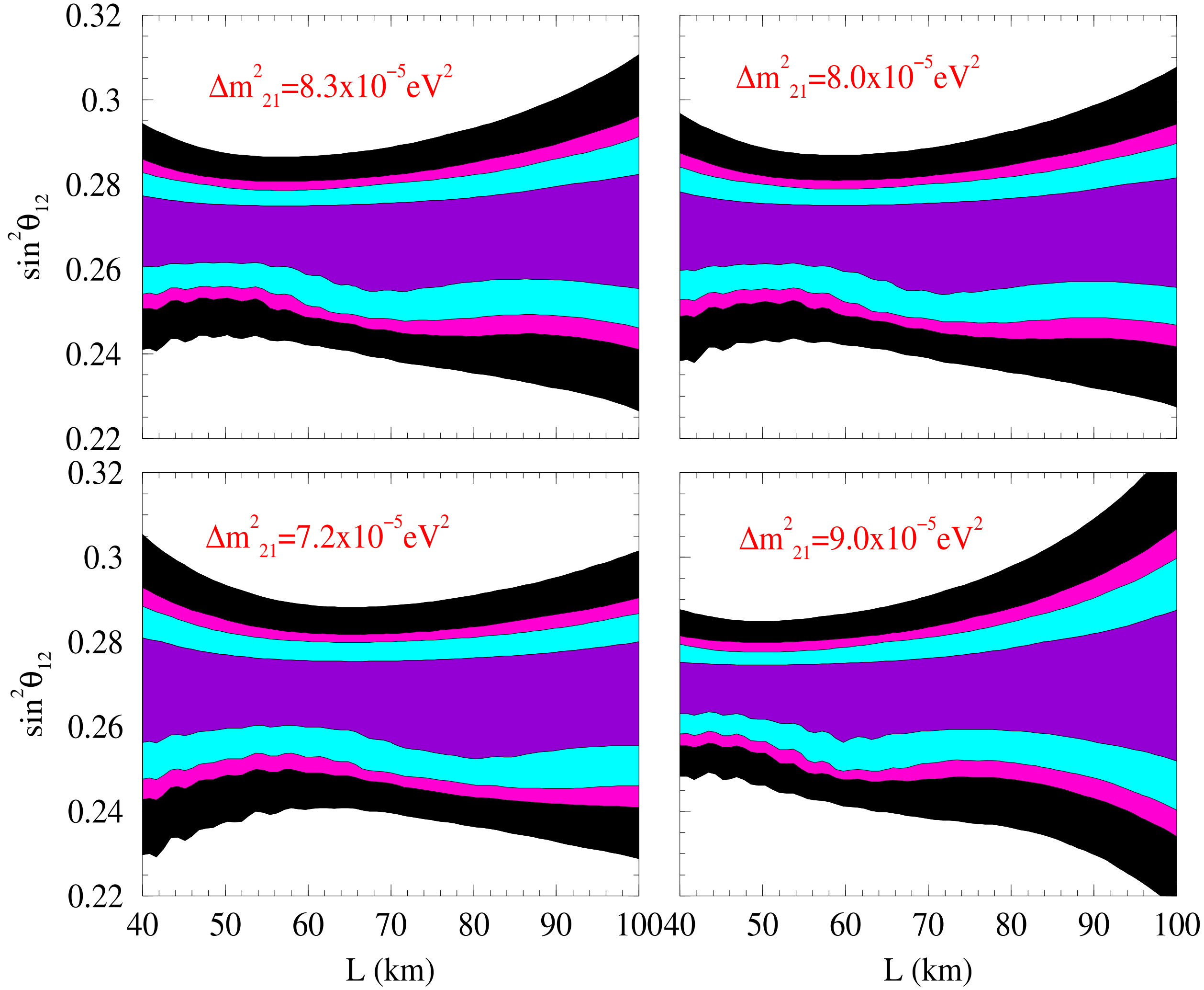
Systematic uncertainty 2%; statistics 73 GWkTy; KamLAND-like detector



The effect of statistics



Fixed Δm^2_{21}; systematic error 5%



$\sin^2\theta_{13}$ - **free within the 3σ allowed range**

SPMIN: $\delta(\sin^2 2\theta_{12}) \approx 2\Delta P_{ee} \sin^2\theta_{13} + 2\ \cos^2 2\theta_{12}\ \Delta(\sin^2\theta_{13})$

Oscillation Parameters

$$\Delta m^2_\odot = 8.0 \times 10^{-5}\ \text{eV}^2\ ,\quad 3\sigma(\Delta m^2_\odot) = 12\%\ ,$$

$$\sin^2\theta_\odot = 0.30\ ,\quad 3\sigma(\sin^2\theta_\odot) = 24\%\ ,$$

$$|\Delta m^2_{\text{atm}}| = 2.5 \times 10^{-3}\ \text{eV}\ ,\quad 3\sigma(|\Delta m^2_{\text{atm}}|) = 26\%.$$

Future:

SNO III: $3\sigma(\sin^2\theta_\odot) = 21\%$ **;**

3 kTy KamLAND: $3\sigma(\Delta m^2_\odot) = 7\%$, $3\sigma(\sin^2\theta_\odot) = 18\%$ **;**

A. Bandyopadhyay et al., hep-ph/0410283

SK-Gd (0.1% Gd: 43×(KL $\bar{\nu}_e$ rate)), 3y: $3\sigma(\Delta m^2_\odot) \cong 4\%$

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

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

KL type reactor $\bar{\nu}_e$ detector, $L \sim 60$ km, ~ 60 GW kTy:

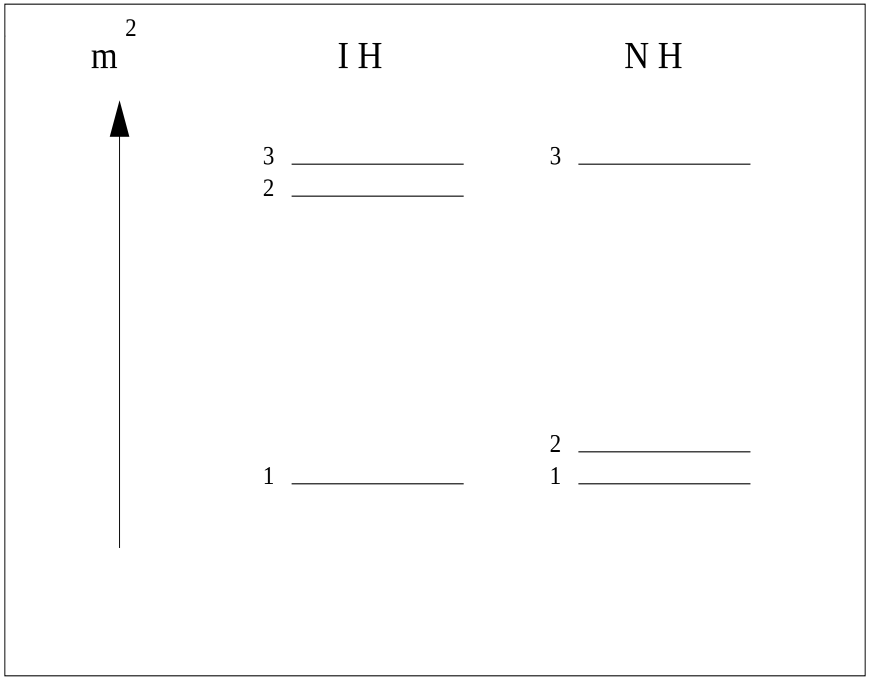
$3\sigma(\sin^2\theta_\odot) \cong 6\%$ (9%) **for 2% (5%) syst. error; +** $\delta(\sin^2\theta_{13}) : 9\%$ (11%)

A. Bandyopadhyay, et al., hep-ph/0410283

T2K (SK): $3\sigma(|\Delta m^2_{\text{atm}}|) \cong 12\%$

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

Determining the $\nu-$Mass Hierarchy (sgn($\Delta m^2_{\mathrm{atm}}$))



- Reactor $\bar{\nu}_e$ Oscillations in vacuum.
- Atmospheric ν experiments: subdominant $\nu_{\mu(e)} \to \nu_{e(\mu)}$ and $\bar{\nu}_{\mu(e)} \to \bar{\nu}_{e(\mu)}$ oscillations (matter effects).
- LBL $\nu-$oscillation experiments (T2KK, NOνA); $\nu-$factory.
- ^{3}H β-decay Experiments (sensitivity to 5×10^{-2} eV).
- $(\beta\beta)_{0\nu}-$Decay Experiments (ν_j- Majorana particles).

Reactor $\bar{\nu}_e$ Oscillations in vacuum

$$P_{\mathrm{NH}}(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \frac{1}{2}\sin^2 2\theta_{13}\left(1 - \cos\frac{\Delta m^2_{\mathrm{A}}\,L}{2\,E_\nu}\right) - \frac{1}{2}\cos^4\theta_{13}\,\sin^2 2\theta_\odot\left(1 - \cos\frac{\Delta m^2_\odot\,L}{2\,E_\nu}\right)$$
$$+ \sin^2 2\theta_{13}\,\sin^2\theta_\odot\,\sin\frac{\Delta m^2_\odot\,L}{4\,E_\nu}\,\sin\left(\frac{\Delta m^2_{\mathrm{A}}\,L}{2\,E_\nu} - \frac{\Delta m^2_\odot\,L}{4\,E_\nu}\right),$$

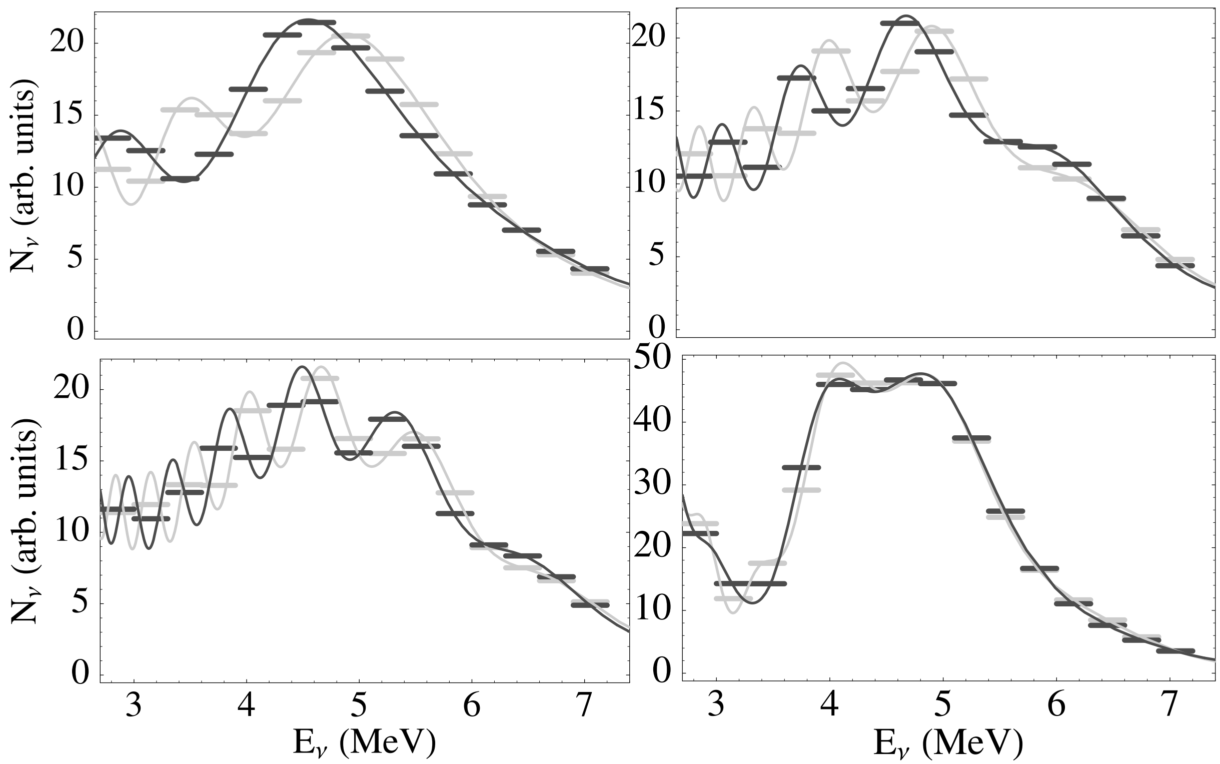
$$P_{\mathrm{IH}}(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \frac{1}{2}\sin^2 2\theta_{13}\left(1 - \cos\frac{\Delta m^2_{\mathrm{A}}\,L}{2\,E_\nu}\right) - \frac{1}{2}\cos^4\theta_{13}\,\sin^2 2\theta_\odot\left(1 - \cos\frac{\Delta m^2_\odot\,L}{2\,E_\nu}\right)$$
$$+ \sin^2 2\theta_{13}\,\cos^2\theta_\odot\,\sin\frac{\Delta m^2_\odot\,L}{4\,E_\nu}\,\sin\left(\frac{\Delta m^2_{\mathrm{A}}\,L}{2\,E_\nu} - \frac{\Delta m^2_\odot\,L}{4\,E_\nu}\right),$$

$\theta_\odot = \theta_{12}\,,\ \Delta m^2_\odot = \Delta m^2_{21} > 0\,;$ $\sin^2\theta_{12} \leq 0.38$ at 3σ;

$\Delta m^2_{\mathrm{A}} = \Delta m^2_{31} > 0\,,$ NH spectrum,

$\Delta m^2_{\mathrm{A}} = \Delta m^2_{23} > 0\,,$ IH spectrum

S.M. Bilenky, D. Nicolo, S.T.P., hep-ph/0112216;
M. Piai, S.T.P., hep-ph/0112074;

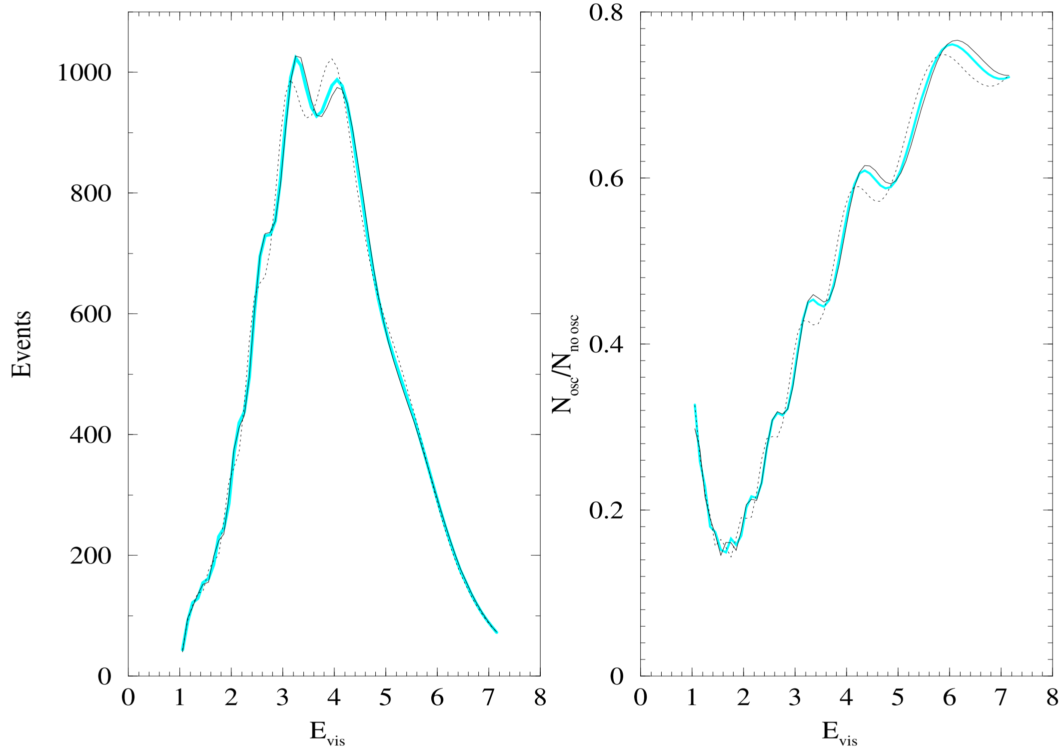


M. Piai, S.T.P., 2001

$\sin^2\theta_{13} = 0.05$, $\Delta m^2_{21} = 2 \times 10^{-4}$ **eV**^{2}**;** $\Delta m^2_{\rm A} = 1.3;\ 2.5;\ 3.5 \times 10^{-3}$ **eV**^{2}

$L = 20$ **km;** $\Delta E_\nu = 0.3$ **MeV**

NH – light grey; IH – dark grey

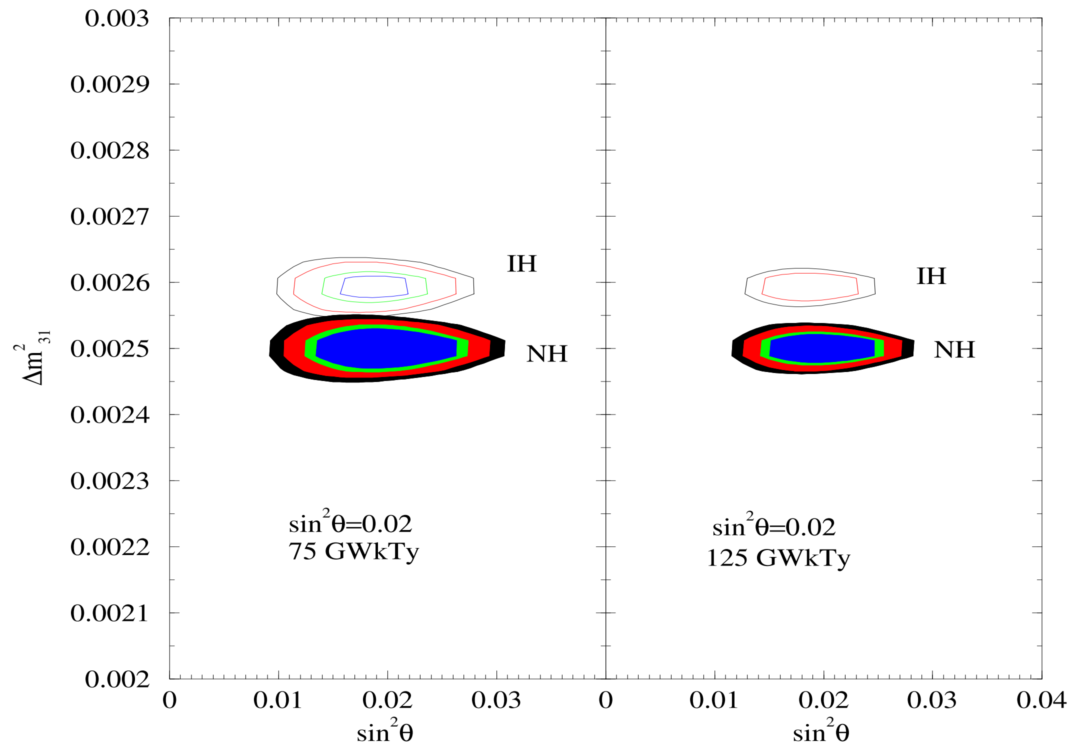


S. Choubey, S.T.P., 2003

$\sin^2\theta_{13} = 0.03$, $\sin^2\theta_{\odot} = 0.30$, $\Delta m^2_{21} = 1.5 \times 10^{-4}$ **eV**^{2}, $\Delta m^2_{\rm A} = 2.5 \times 10^{-3}$ **eV**^{2}

$L = 20$ **km;** $\Delta E_\nu = 0.1$ **MeV; 75 GWkTy**

NH – thick cyan; IH – dotted, thin solid ($\Delta m^2_{\rm A} = 2.6 \times 10^{-3}$ **eV**^{2}**)**

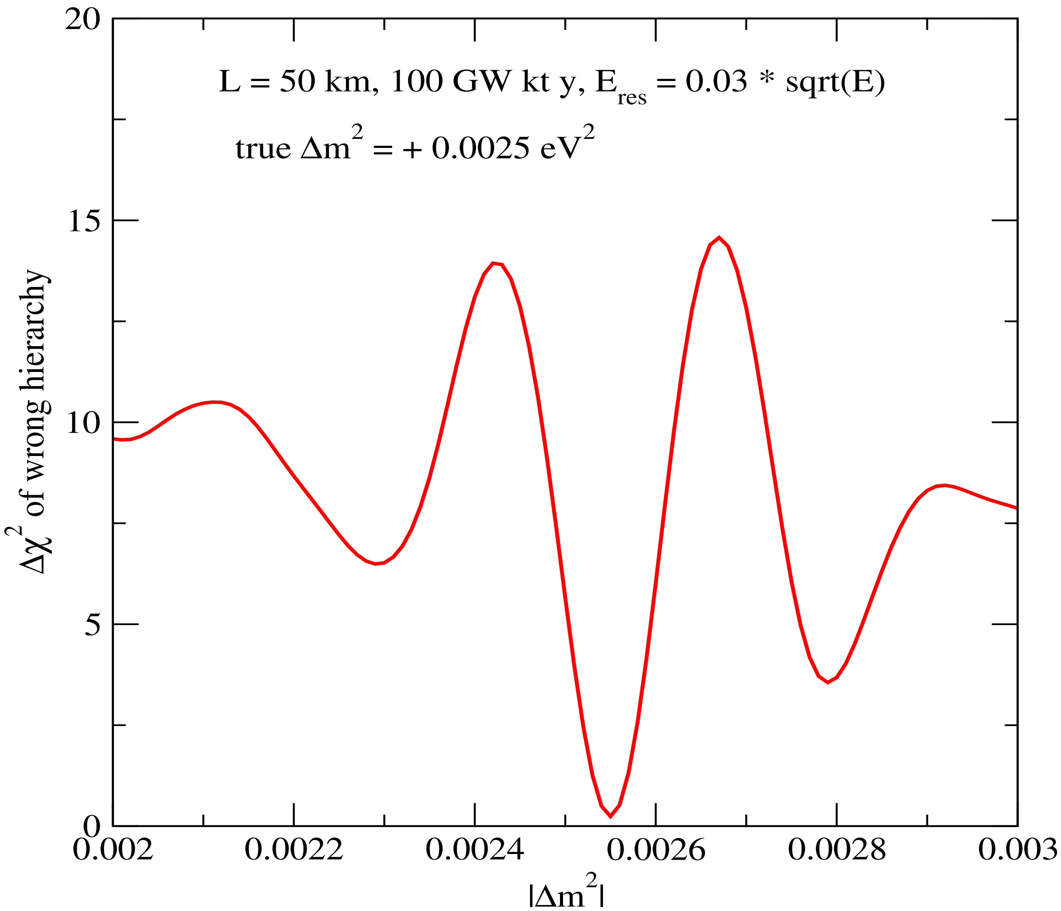


S. Choubey, S.T.P., 2003

$\sin^2\theta_\odot = 0.30$, $\Delta m^2_{21} = 1.5 \times 10^{-4}$ **eV**^{2}, $\Delta m^2_{\mathrm{A}} = 2.5 \times 10^{-3}$ **eV**^{2}

$L = 20$ **km**; $\Delta E_\nu = 0.1$ **MeV; syst. error 2%**

"True": NH; 90%, 95%, 99% and 99.73% solution regions



T. Schwetz, September 2006

$\sin^2\theta_\odot = 0.30$, $\Delta m^2_{21} = 8 \times 10^{-5}$ **eV**^{2}; **"true"** $\Delta m^2_{\mathrm{A}} = 2.50 \times 10^{-3}$ **eV**^{2} **(NH)**

Minimum at $\Delta m^2_{\mathrm{A}} = -\ 2.55 \times 10^{-3}$ **eV**^{2} **(IH)**

Precision of $\sim$ **1%** **on** $|\Delta m^2_{\mathrm{A}}|$ **required**

Atmospheric ν experiments

Subdominant $\nu_{\mu(e)} \rightarrow \nu_{e(\mu)}$ and $\bar{\nu}_{\mu(e)} \rightarrow \bar{\nu}_{e(\mu)}$ oscillations in the Earth.

$$P_{3\nu}(\nu_e \rightarrow \nu_\mu) \cong P_{3\nu}(\nu_\mu \rightarrow \nu_e) \cong s^2_{23}\, P_{2\nu}\,, P_{3\nu}(\nu_e \rightarrow \nu_\tau) \cong c^2_{23}\, P_{2\nu}\,,$$

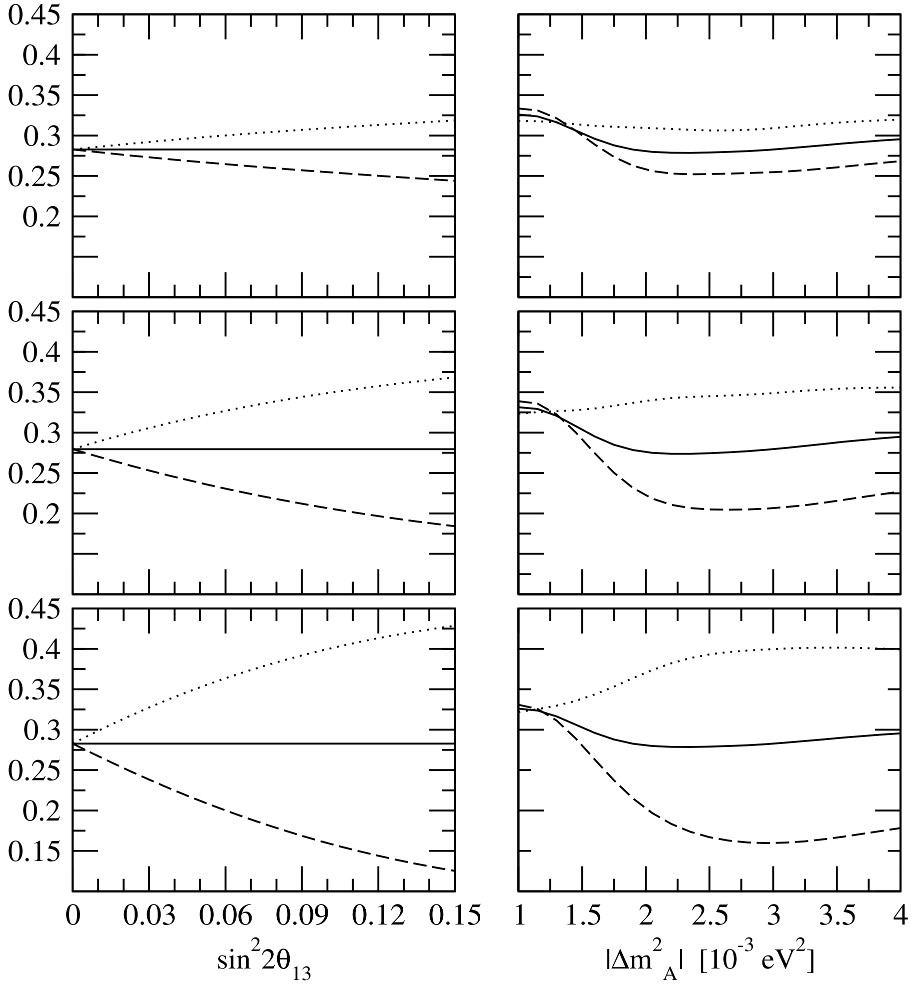
$$P_{3\nu}(\nu_\mu \rightarrow \nu_\mu) \cong 1 - s^4_{23}\; P_{2\nu} - 2c^2_{23}s^2_{23}\; \left[1 - Re\; (e^{-i\kappa} A_{2\nu}(\nu_\tau \rightarrow \nu_\tau))\right]\,,$$

$P_{2\nu} \equiv P_{2\nu}(\Delta m^2_{31}, \theta_{13}; E, \theta_n; N_e)$**: 2-$\nu$ $\nu_e \rightarrow \nu'_\tau$ oscillations in the Earth,**
$\nu'_\tau = s_{23}\,\nu_\mu + c_{23}\,\nu_\tau$**;**

κ **and** $A_{2\nu}(\nu_\tau \rightarrow \nu_\tau) \equiv A_{2\nu}$ **are known phase and 2-ν amplitude.**

NH: $\nu_{\mu(e)} \rightarrow \nu_{e(\mu)}$ **matter enhanced,** $\bar{\nu}_{\mu(e)} \rightarrow \bar{\nu}_{e(\mu)}$ **- suppressed**

IH: $\bar{\nu}_{\mu(e)} \rightarrow \bar{\nu}_{e(\mu)}$ **matter enhanced,** $\nu_{\mu(e)} \rightarrow \nu_{e(\mu)}$**−suppressed**

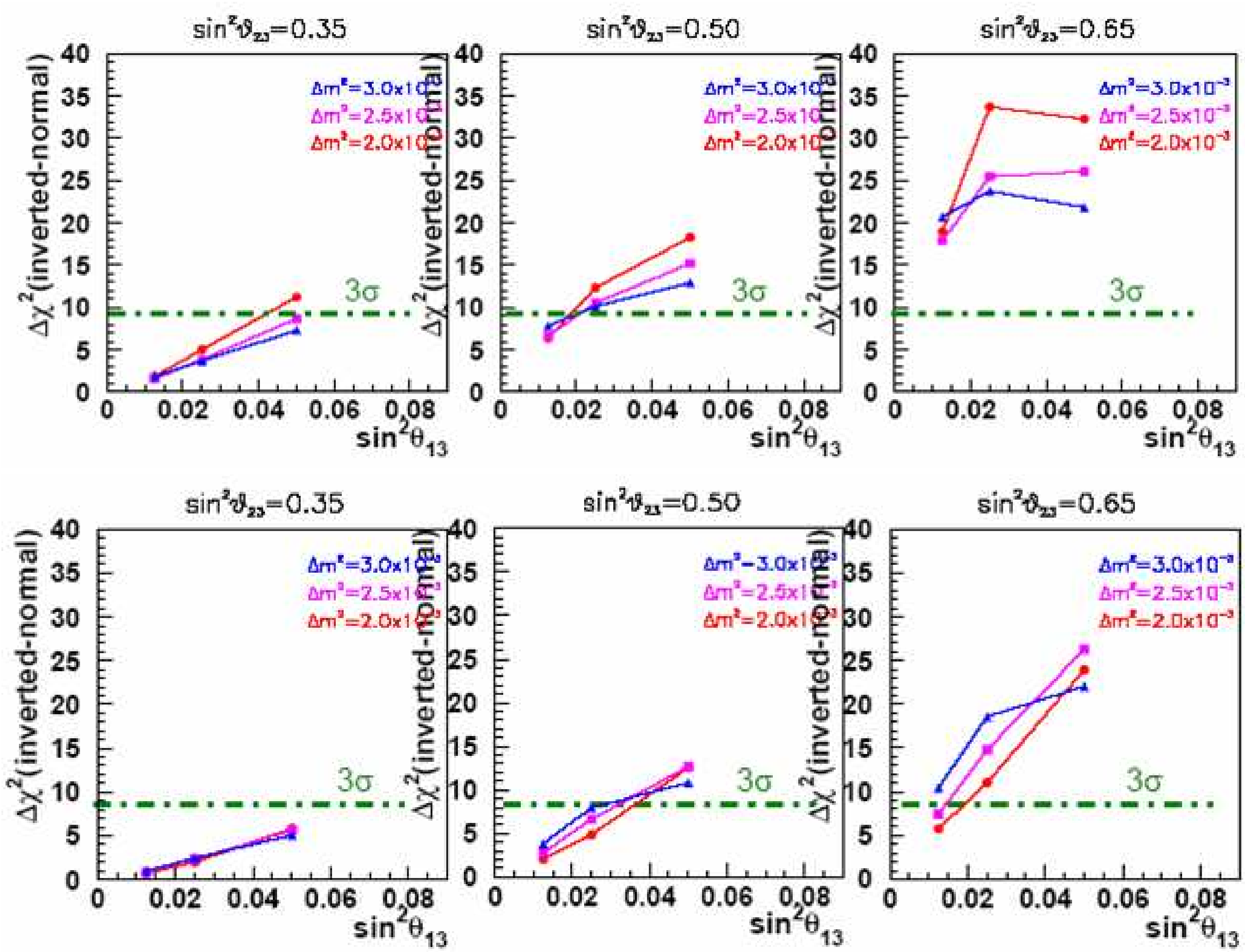


Iron Magnetized Detectors (MINOS, INO): multi-GeV μ^- and μ^+ event rates, N_{μ^-} and N_{μ^+}; $\cos\theta_n = (0.30 - 0.84)$ mantle bin, E = [5,20] GeV

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

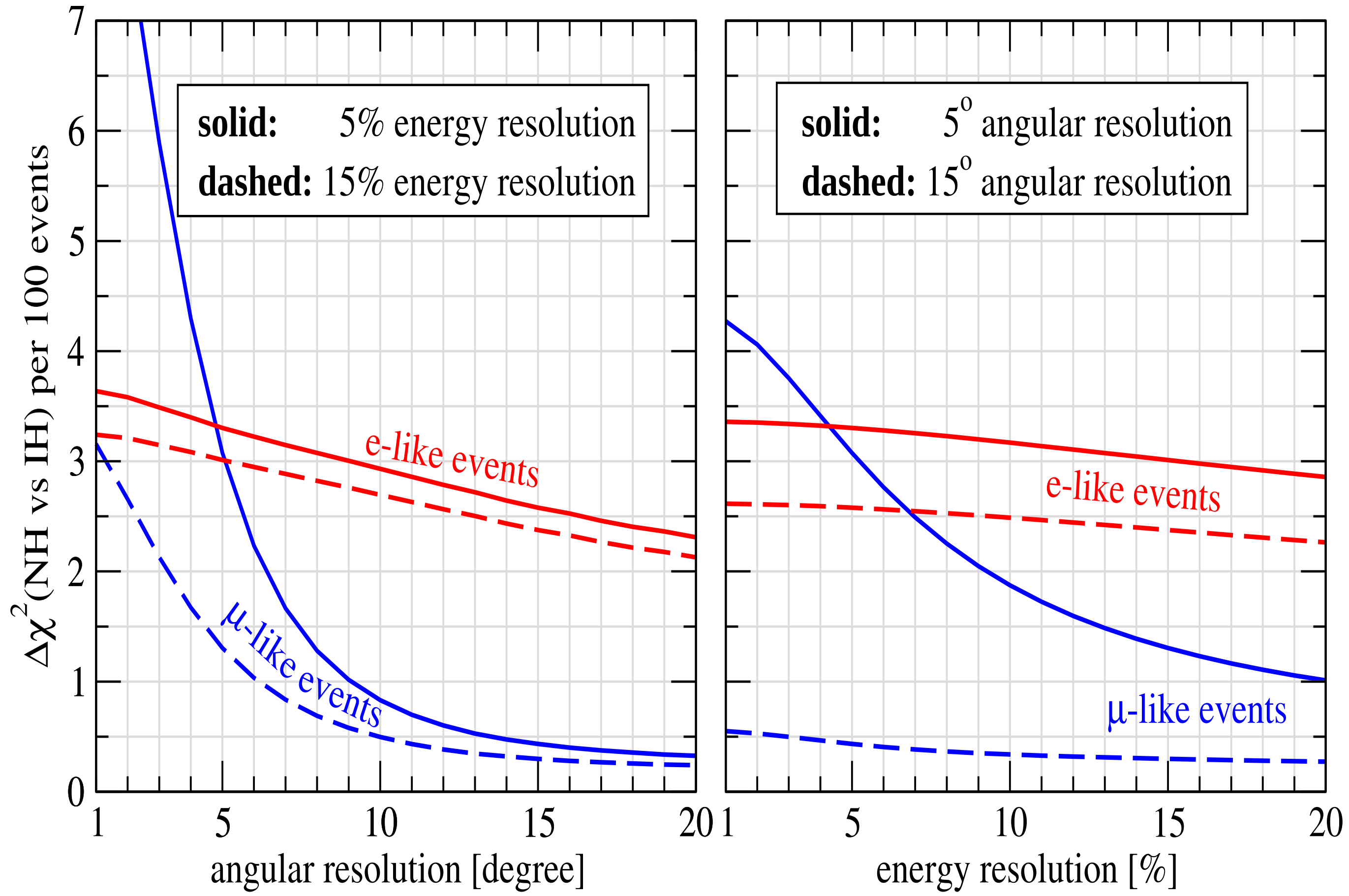
- $|\Delta m^2_{31}| = 3 \times 10^{-3}$ eV^2, $\sin^2\theta_{23}$ =**0.36, 0.50, 0.64**
- $\Delta m^2_{31} > 0$-**NH (dashed)**, $\Delta m^2_{31} < 0$-**IH (dotted)**, 2$-\nu$ **(solid)**

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



Water-Cerenkov detector, 1.8 MTy

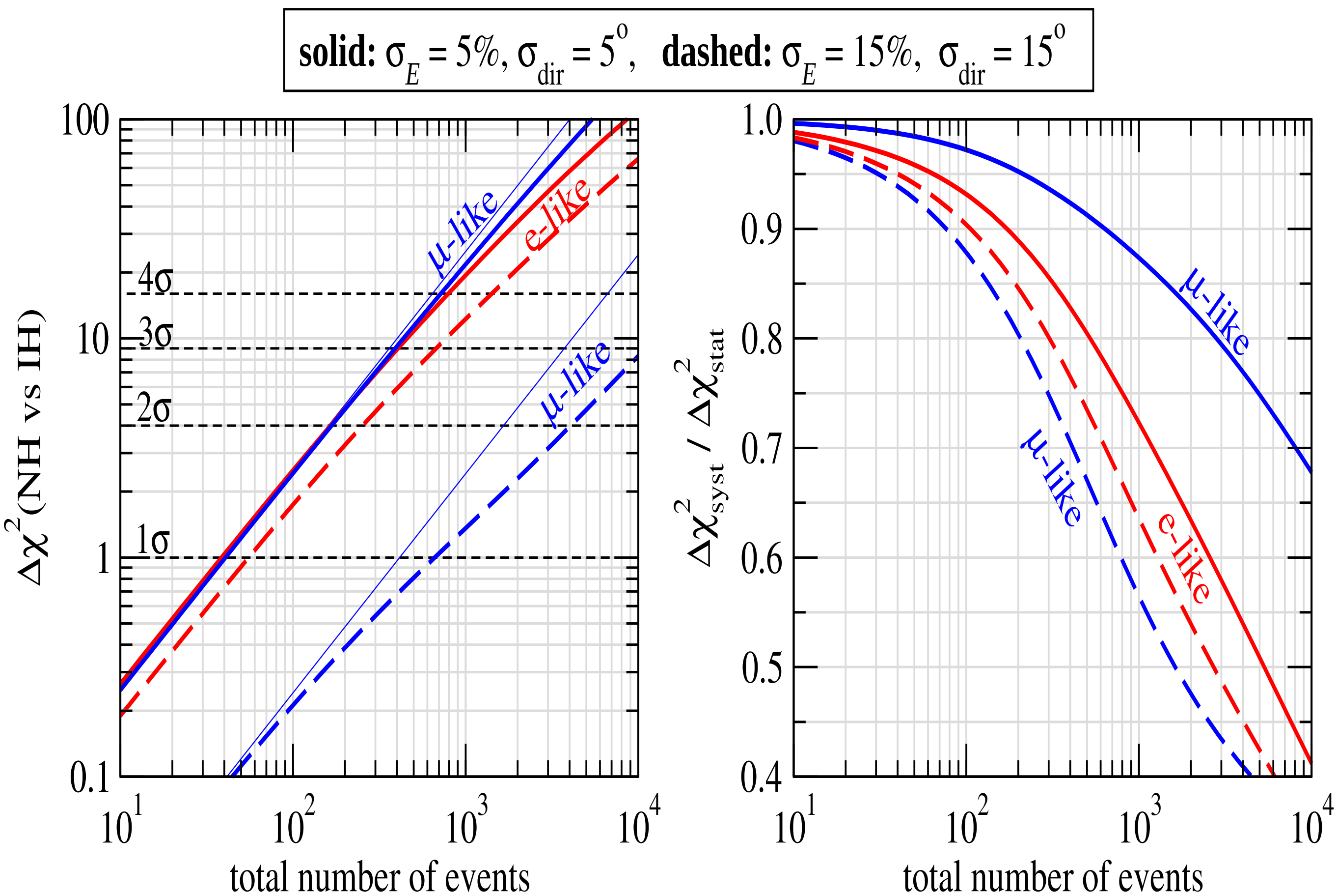
T. Kajita et al., 2004



T. Schwetz, S.T.P., 2005

$\sin^2 2\theta_{13} = 0.10$, $\sin^2\theta_{23} = 0.50$, $|\Delta m^2_{\rm A}| = 2.4 \times 10^{-3}$ **eV**^{2}

$E_\nu = (2-10)$ **GeV;** $0.1 \leq \cos\theta_n \leq 1.0$



$\sin^2 2\theta_{13} = 0.10$, $\sin^2 \theta_{23} = 0.50$, $|\Delta m^2_A| = 2.4 \times 10^{-3}$ **eV^2**

$E_\nu = (2 - 10)$ **GeV;** $0.1 \leq \cos\theta_n \leq 1.0$

Thin solid lines - stat. errors only (for μ-like events)

INO; ATLAS, CMS (?)

$(\beta\beta)_{0\nu}-$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 (QD, IH)

- CPV due to Majorana CPV phases

ν_j- Dirac or Majorana particles, fundamental problem

ν_j-Dirac: conserved lepton charge exists, $L = L_e + L_\mu + L_\tau$, $\nu_j \neq \bar{\nu}_j$

ν_j-Majorana: no lepton charge is exactly conserved, $\nu_j \equiv \bar{\nu}_j$

The observed patterns of $\nu-$mixing and of Δm^2_{atm} and $\Delta m^2_{\odot}$ can be related to Majorana ν_j and an approximate symmetry:

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

S.T.P., 1982

See-saw mechanism: ν_j- Majorana

Establishing that ν_j are Majorana particles would be as important as the discovery of $\nu-$ oscillations.

If $\nu_j -$ Majorana particles, U_{PMNS} **contains (3-ν mixing)**

δ-Dirac, α_{21}, α_{31} - Majorana **physical CPV phases**

ν-oscillations $\nu_l \leftrightarrow \nu_{l'}$, $\bar{\nu}_l \leftrightarrow \bar{\nu}_{l'}$, $l, l' = e, \mu, \tau$,

- **are not sensitive to the nature of ν_j,**

S.M. Bilenky et al.,1980;
P. Langacker et al., 1987

- **provide information on $\Delta m^2_{jk} = m^2_j - m^2_k$, but not on the absolute values of ν_j masses.**

The Majorana nature of ν_j can manifest itself in the existence of $\Delta L = \pm 2$ processes:

$$K^+ \rightarrow \pi^- + \mu^+ + \mu^+$$
$$\mu^- + (\mathrm{A,Z}) \rightarrow \mu^+ + (\mathrm{A,Z}-2)$$

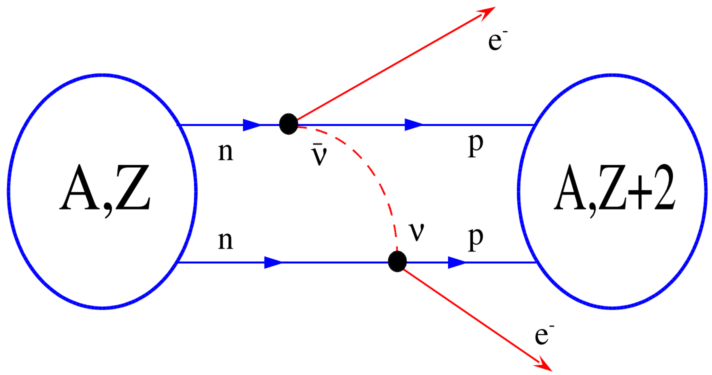
The process most sensitive to the possible Majorana nature of ν_j - $(\beta\beta)_{0\nu}$-decay

$$(\mathrm{A,Z}) \rightarrow (\mathrm{A,Z}+2) + e^- + e^-$$

of even-even nuclei, ^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe, ^{150}Nd.

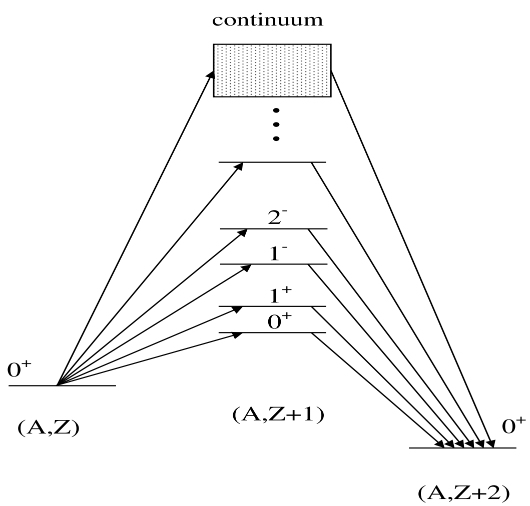
$2n$ from (A,Z) exchange a virtual Majorana ν_j (via the CC weak interaction) and transform into $2p$ of (A,Z+2) and two free e^-.

Nuclear $0\nu\beta\beta$-decay



strong in-medium modification of the basic process

$dd \rightarrow uue^-e^-(\bar{\nu}_e\bar{\nu}_e)$



virtual excitation
of states of all multipolarities
in (A,Z+1) nucleus

V. Rodin, talk at Gran Sasso, 2006

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

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

$$= \left| m_1 \; c_{12}^2 \; c_{13}^2 + m_2 \; s_{12}^2 \; c_{13}^2 \; e^{i\alpha_{21}} + m_3 \; s_{13}^2 \; e^{i\alpha_{31}} \right|,$$ $\theta_{12} \equiv \theta_{\odot}$, θ_{13}- CHOOZ

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

CP-invariance: $\alpha_{21} = 0, \pm\pi$, $\alpha_{31} = 0, \pm\pi$;

$$\eta_{21} \equiv e^{i\alpha_{21}} = \pm 1, \quad \eta_{31} \equiv e^{i\alpha_{31}} = \pm 1$$

relative CP-parities of ν_1 and ν_2, and of ν_1 and ν_3 .

L. Wolfenstein, 1981;

S.M. Bilenky, N. Nedelcheva, S.T.P., 1984;

B. Kayser, 1984.

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

$$\left|<m>\right| \cong \left|\sqrt{\Delta m^2_{\odot}}\,\sin^2\theta_{12} e^{i\alpha} + \sqrt{\Delta m^2_{31}}\,\sin^2\theta_{13} e^{i\beta_M}\right| \;,\; m_1 \ll m_2 \ll m_3 \text{ (NH)},$$

$$\left|<m>\right| \cong \sqrt{m_3^2 + \Delta m^2_{13}}\left|\cos^2\theta_{12} + e^{i\alpha}\ \sin^2\theta_{12}\right| \;,\; m_3 < (\ll) m_1 < m_2 \text{ (IH)},$$

$$\left|<m>\right| \cong m\left|\cos^2\theta_{12} + e^{i\alpha}\ \sin^2\theta_{12}\right| \;,\; m_{1,2,3} \cong m \gtrsim 0.10 \text{ eV} \;\; \text{(QD)},$$

$\theta_{12} \equiv \theta_{\odot}$, θ_{13}-CHOOZ; $\alpha \equiv \alpha_{21}$, $\beta_M \equiv \alpha_{31}$.

CP-invariance: $\alpha = 0, \pm\pi$, $\beta_M = 0, \pm\pi$;

$\left|<m>\right| \lesssim 5 \times 10^{-3}$ eV, **NH;**

$\sqrt{\Delta m^2_{13}}\cos 2\theta_{12} \cong 0.013$ eV $\lesssim \left|<m>\right| \lesssim \sqrt{\Delta m^2_{13}} \cong 0.055$ eV, **IH;**

$m\cos 2\theta_{12} \lesssim \left|<m>\right| \lesssim m$, $m \gtrsim 0.10$ eV, **QD** .

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.).**

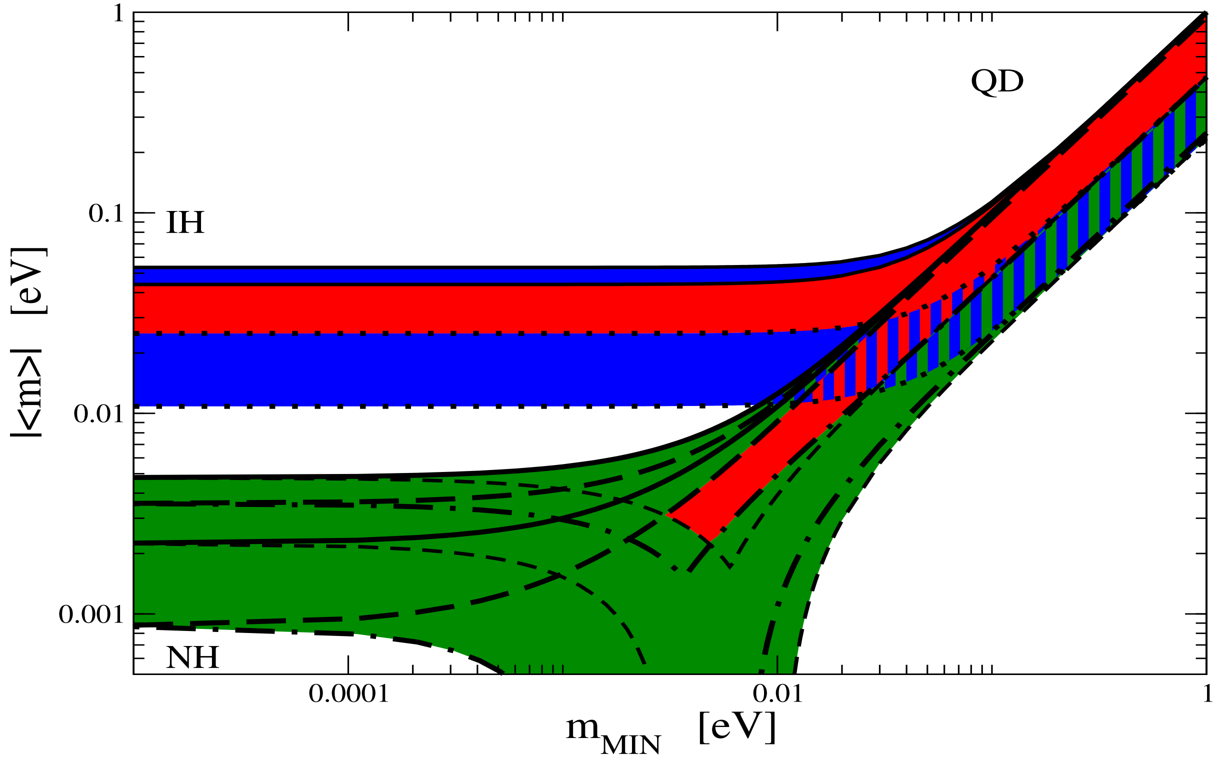
IGEX ^{76}Ge: $|{<}m{>}| < (0.33 - 1.35)$ eV **(**90% **C.L.).**

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

$|{<}m{>}|$ **<(0.7–1.2) eV,** $|{<}m{>}|$ **<(0.18–0.90) eV (90% C.L.).**

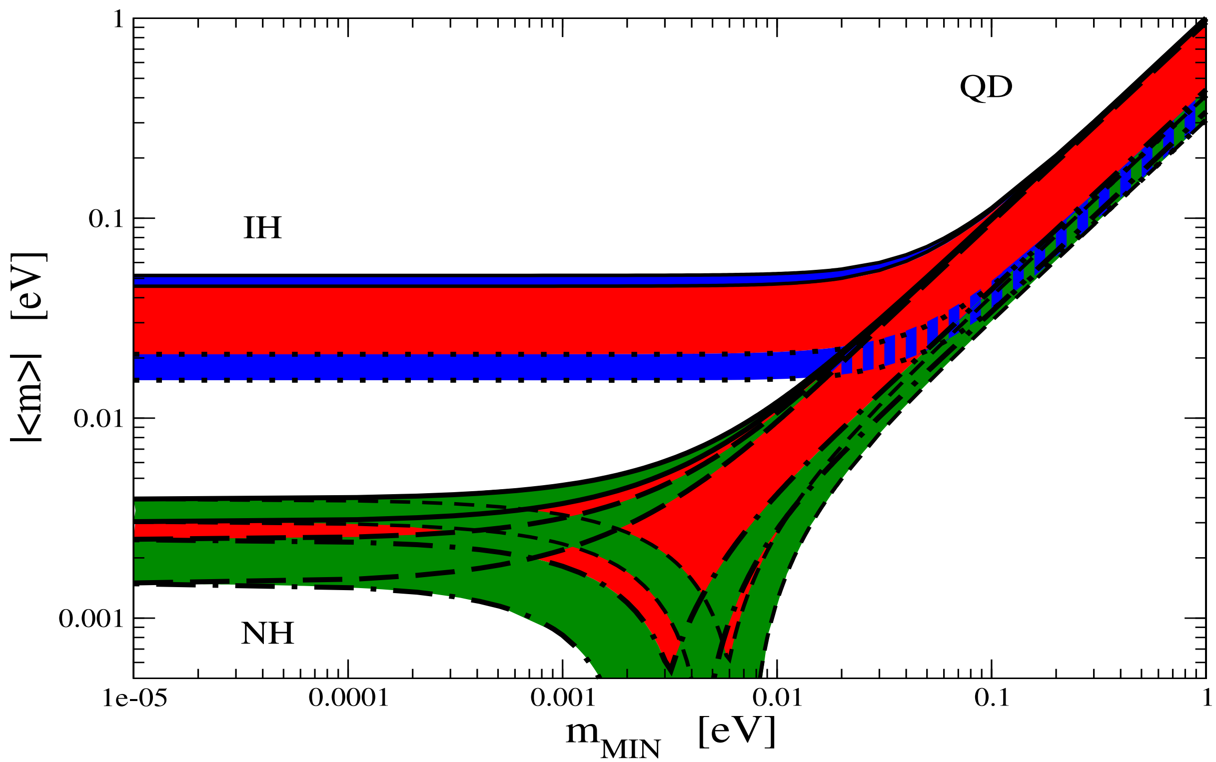
Large number of projects: $|{<}m{>}| \sim (0.01 - 0.05)$ **eV**

CUORE - ^{130}Te,
GERDA - ^{76}Ge,
SuperNEMO - ^{82}Se,
EXO - ^{136}Xe,
MAJORANA - ^{76}Ge,
MOON - ^{100}Mo,
CANDLES - ^{48}Ca,
XMASS - ^{136}Xe.



S. Pascoli, S.T.P., 2006

The current 2σ ranges of values of the parameters used.



S. Pascoli, S.T.P., 2006

$\sin^2\theta_{13} = 0.015 \pm 0.006$; $1\sigma(\Delta m^2_\odot) = 4\%$, $1\sigma(\sin^2\theta_\odot) = 4\%$, $1\sigma(|\Delta m^2_{\rm atm}|) = 6\%$;

$2\sigma(|<m>|\ )$ **used.**

^{3}H β-decay: $3\mathrm{H} \to ^3\mathrm{He} + e^- + \bar{\nu}_e$

$$\frac{d\,\Gamma}{d\,E_e} = \sum_i |U_{ei}|^2 \; \frac{d\,\Gamma(m_i)}{d\,E_e}\;,$$

$$\frac{d\,\Gamma(m_i)}{d\,E_e} = C\,p_e\,(E_e + m_e)\,(E_0 - E_e)\,\sqrt{(E_0 - E_e)^2 - m_i^2}\,F(E_e)\,\theta(E_0 - E_e - m_i)\;.$$

NH: $m_1 << m_2 < m_3$, $m_2 \cong \sqrt{\Delta m^2_{21}} \cong 9 \times 10^{-3}$ **eV,** $m_3 \cong \sqrt{\Delta m^2_{31}} \cong 5 \times 10^{-2}$ eV

IH: $m_3 << m_1 \cong m_2$, $m_{1,2} \cong \sqrt{\Delta m^2_{23}} \cong 5 \times 10^{-2}$ eV

Assume sensitivity to 5×10^{-2} eV.

- **NH:** m_1, m_2 - **below the sensitivity; the effect of** m_3 - **unobservable, suppressed by** $\sin^2\theta_{13}$:

$$\frac{d\,\Gamma}{d\,E_e} \cong \frac{d\,\Gamma(m_i = 0)}{d\,E_e}$$

- **IH:** m_3 - **below the sensitivity;** $m_2 - m_1 \cong 1.6 \times 10^{-3}$ **eV - unobservable:**

$$\frac{d\,\Gamma}{d\,E_e} \cong \frac{d\,\Gamma(m_{1,2})}{d\,E_e} \cong \frac{d\,\Gamma(\sqrt{\Delta m^2_{23}})}{d\,E_e}$$

No e^-spectrum deformation observed: NH spectrum.

Deformations observed:

1) spectrum with inverted neutrino mass ordering, $\Delta m^2_{23} < 0$,
a) inverted hierarchical (IH), $m_3 \ll m_1 < m_2$, or
b) partial inverted hierarchy, $m_3 < m_1 < m_2$;

2) spectrum with normal neutrino mass ordering, $\Delta m^2_{23} > 0$, but with partial neutrino mass hierarchy, $m_1 < m_2 < m_3$.

Example (hypothetical) of the possibility 2): $m_1 = 5.0 \cdot 10^{-2}$ eV,

$m_2 = \sqrt{m_1^2 + \Delta m^2_{12}} \cong 5.1 \cdot 10^{-2}$ **eV,** $m_3 = \sqrt{m_1^2 + \Delta m^2_{13}} \cong 6.9 \cdot 10^{-2}$ **eV**

$m_1 + m_2 + m_3 \cong 0.17$ **eV**

$$\frac{d\,\Gamma}{d\,E_e} \cong (1 - |U_{e3}|^2)\,\frac{d\,\Gamma(m_{1,2})}{d\,E_e} + |U_{e3}|^2\,\frac{d\,\Gamma(m_3)}{d\,E_e} \cong \frac{d\,\Gamma(m_{1,2})}{d\,E_e}$$

S.M. Bilenky, M. Mateyev, S.T.P., 2006

Conclusions

Experiments with reactor $\bar{\nu}_e$ have remarkable physics potential:

– **Can provide high precision determination of** $\sin^2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{31}|$

– **Can provide important constraint or measure** $\sin^2\theta_{13}$

– **Can determine the type of ν mass spectrum**

We are at the beginning of the Road...