Physics Potential of Solar and Atmospheric Neutrino Experiments

S. T. Petcov

SISSA/INFN, Trieste, Italy, and
INRNE, Bulgarian Academy of Sciences, Sofia, Bulgaria

Neutrino Telescopes
Venice
February 23, 2005

Compelling Evidences for $\nu-$Oscillations

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

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

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

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

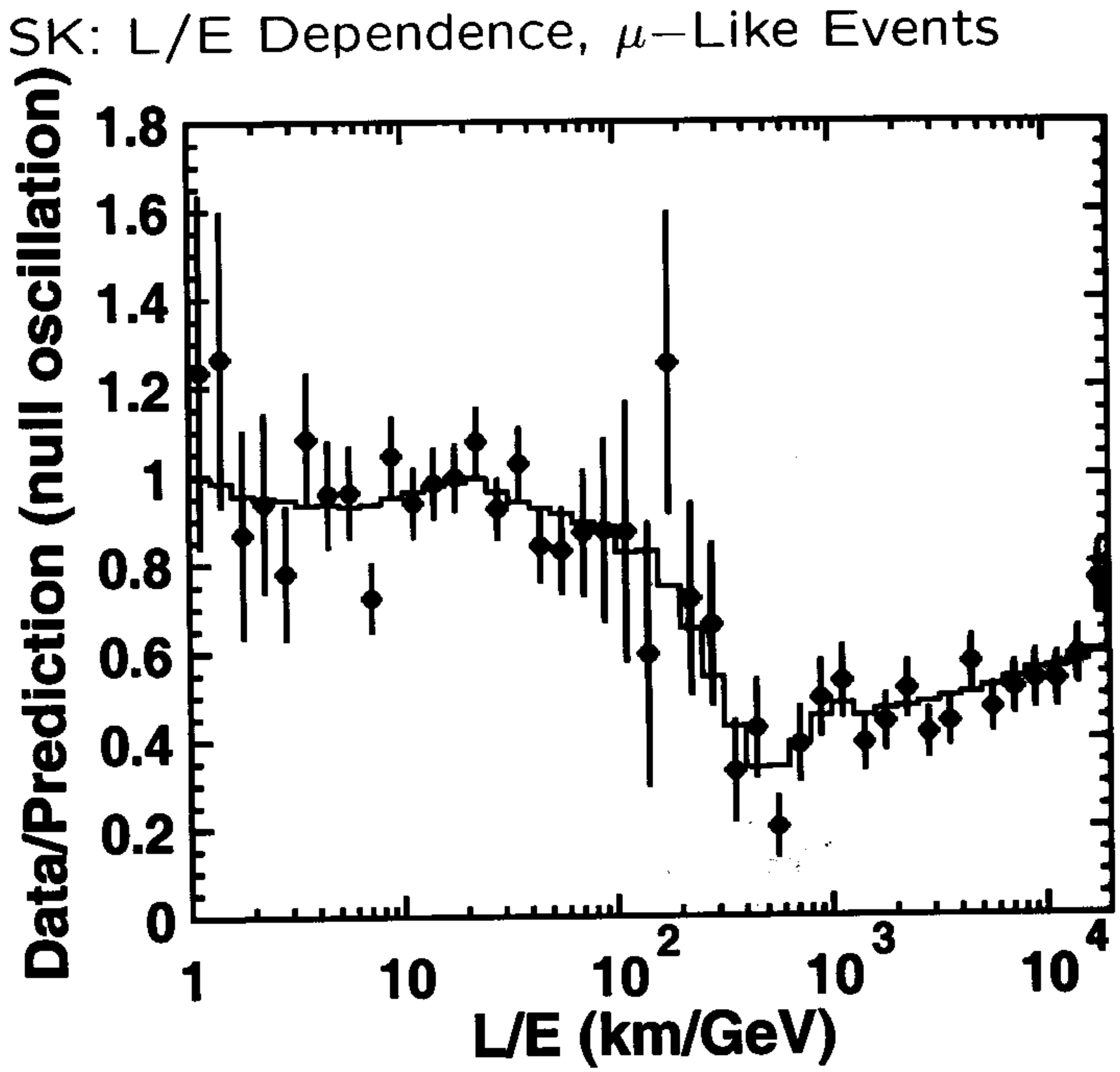
Super-Kamiokande, SNO; KamLAND

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

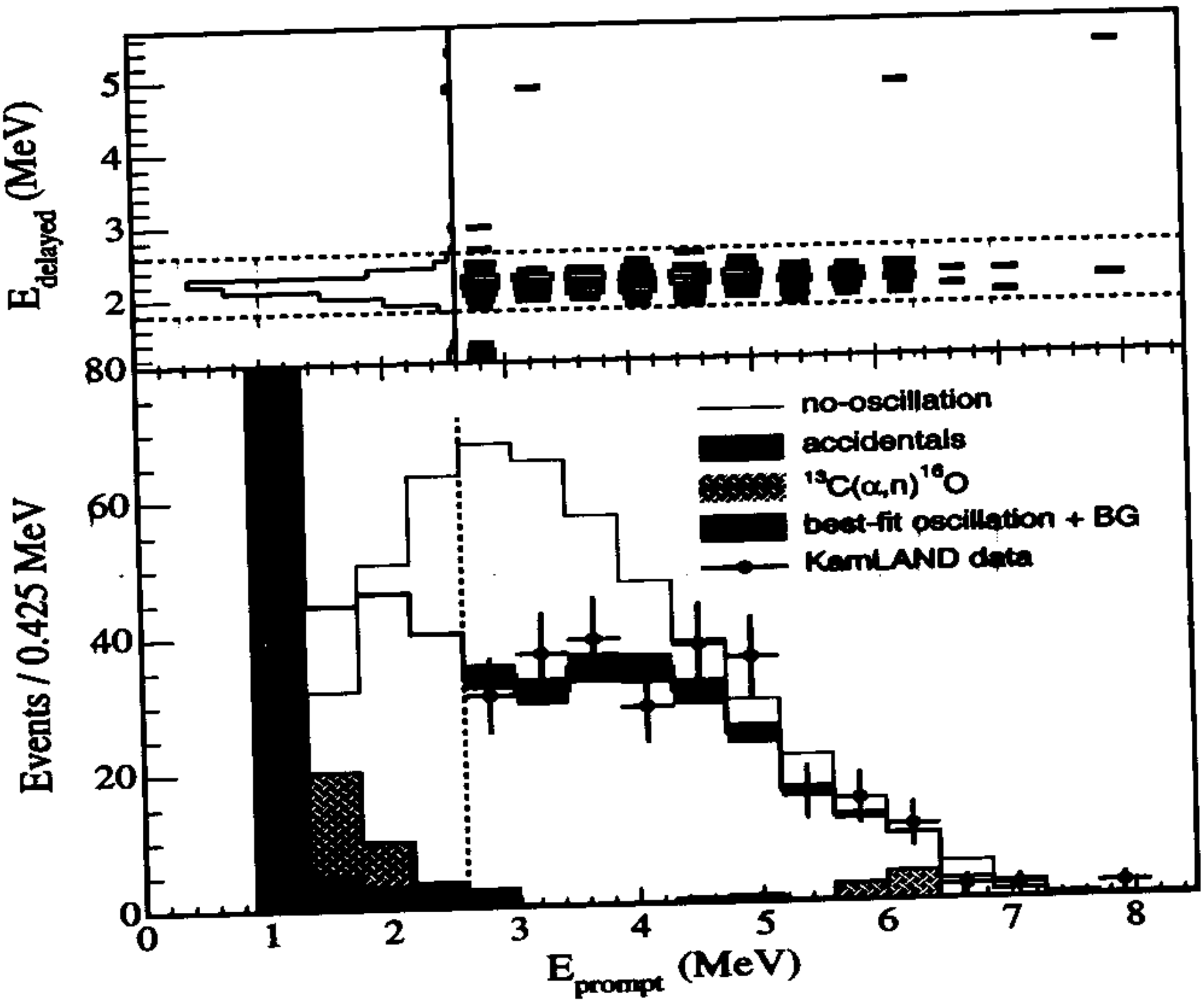
– LSND

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

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

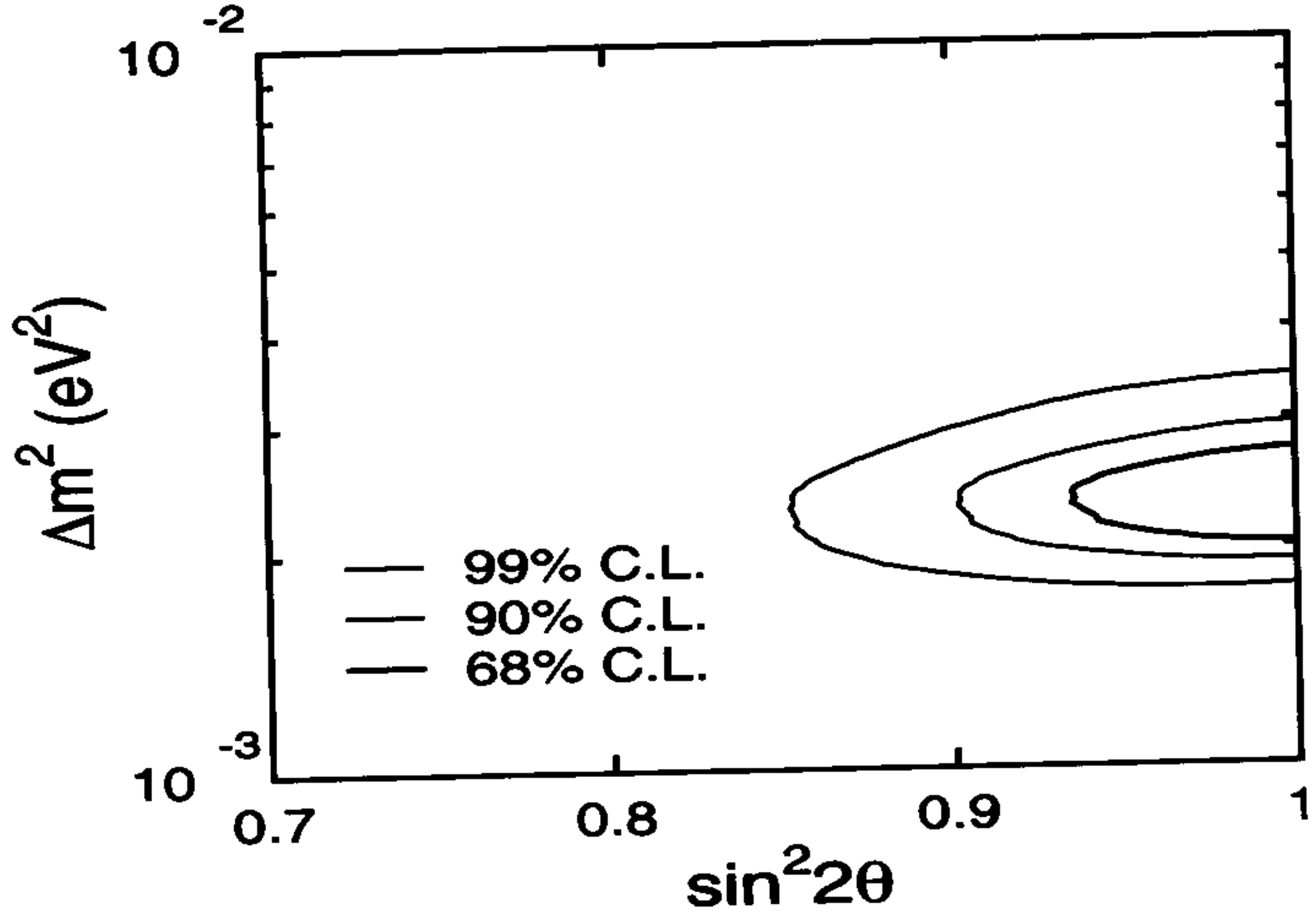


SK: L/E Dependence, μ−Like Events
Data/Prediction (null oscillation)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1
10
10^2
10^3
10^4
L/E (km/GeV)



KamLAND: e^+–Spectrum Deformation

SK: Atmospheric ν Data, L/E



$\Delta m^2_{\rm atm} \equiv \Delta m^2_{31} = 2.1 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{\rm atm} \equiv \sin^2 2\theta_{23} = 1$

$\Delta m^2_{31} = (1.3 - 4.2) \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} \geq 0.85$, 99.73% (

+ K2K : $\Delta m^2_{31} = (1.4 - 3.3) \times 10^{-3}$ eV^2, 99.73% C.L

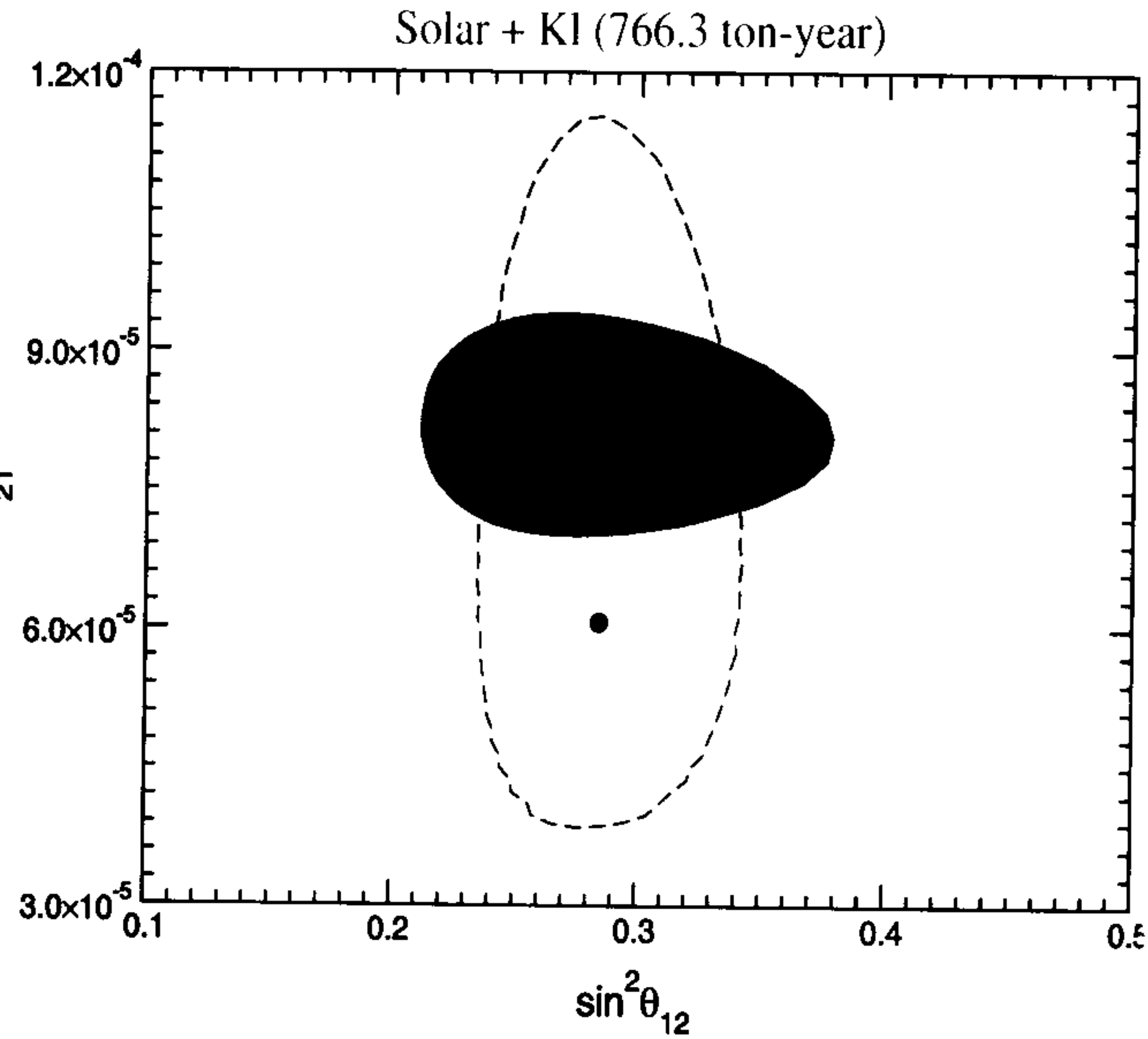
M. Maltoni et al., hep-ph/040517

- 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.



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

$$\sin^2\theta_{\odot} \equiv \sin^2\theta_{12} = 0.26\ ;$$

$$\cos 2\theta_{12} = 0.48; \quad \cos 2\theta_{12} > 0.32, \quad 95\%\ \text{C.L.}$$

- $\sin^2\theta_{12} = 0.50$ excluded at > 6 s.d.
- High-LMA excluded at ~ 3.3 s.d.

A.Bandyopadhyay, S.Choubey, S.Goswami, S.T.P., D.P.Roy
hep-ph/040632

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

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

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

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

W. Haxton, S. Parke, 19ε

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

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

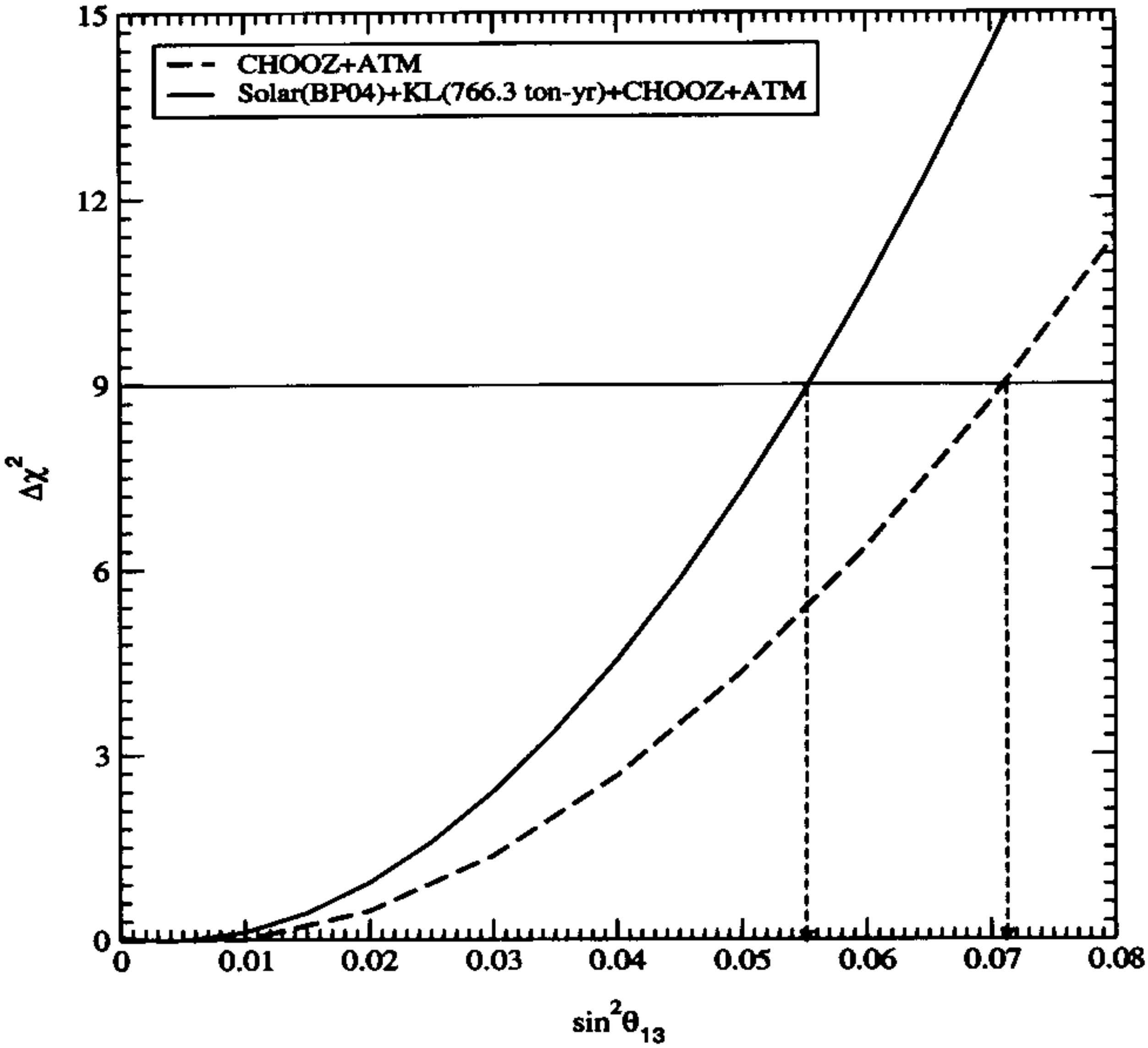
S.T.P., 198

LMA: $P' \ll 1, \quad < P^{2\nu}_{\odot\,\rm osc} > \cong 0$

J. Rich, S.T.P., 198

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

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

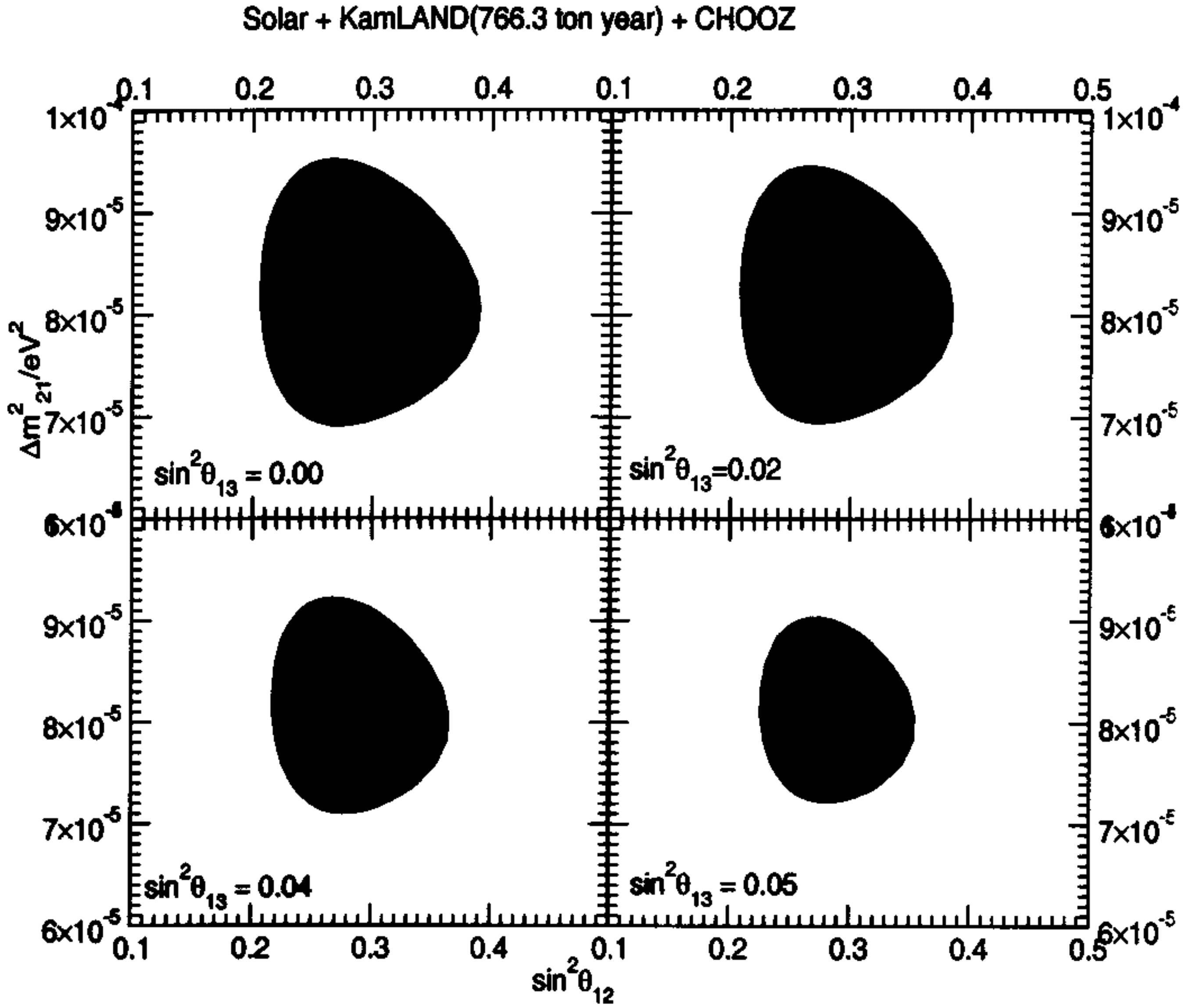


$\Delta m^2_{\text{atm}} \equiv \Delta m^2_{31} = (1.3 - 4.2) \times 10^{-3}$ eV^2, 3 *s.d.* (SK : $\nu'04$)

SK: E. Kearns, talk at $\nu'04$, June 2004, Par

- $\sin^2\theta_{13} < 0.055$ at 99.73% C.L.

A. Bandyopadhyay et al., hep-ph/040632



$\sin^2\theta_{13} = 0$, 95% C.L. :

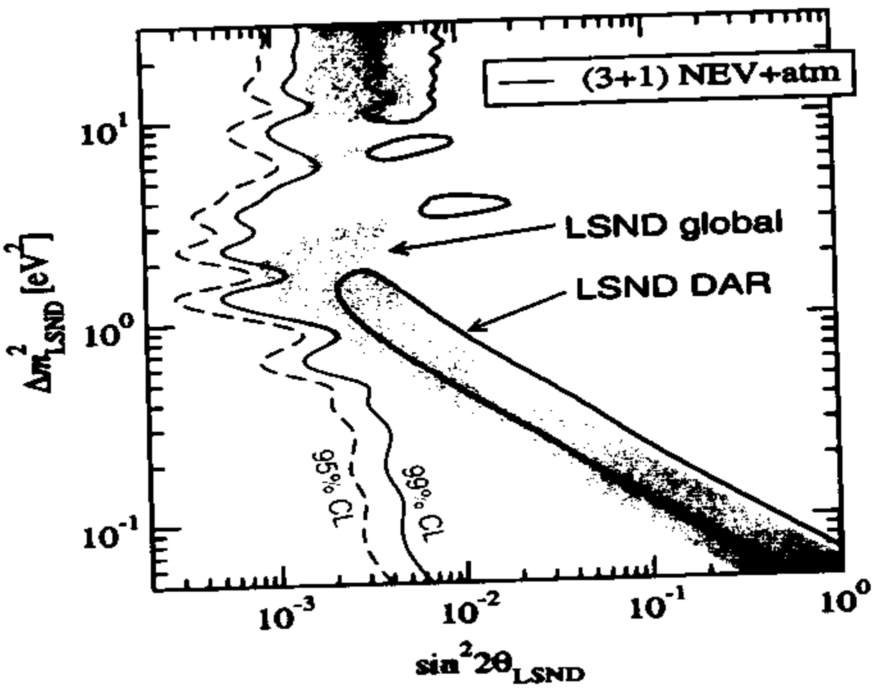
$$\Delta m^2_{21} = (7.2 - 9.1) \times 10^{-5}\ \text{eV}^2\ ,\ \sin^2\theta_{12} = (0.22 - 0.36)$$

$$\cos 2\theta_{12} = 0.44; \quad \cos 2\theta_{12} > 0.28, \quad 95\%\ \text{C.L.};$$

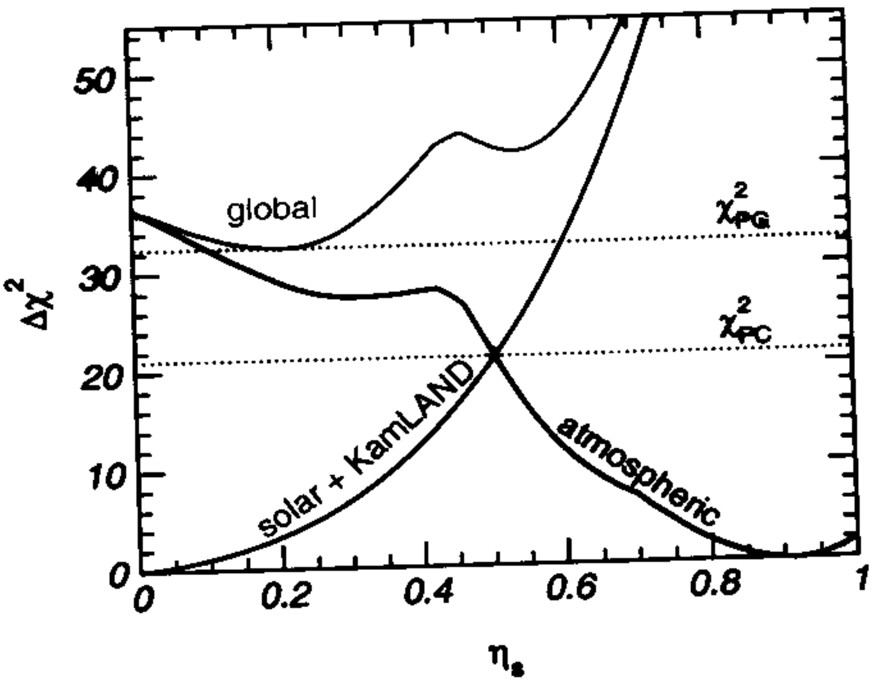
- $\sin^2\theta_{12} = 0.50$ excluded at > 6 s.d.

A. Bandyopadhyay et al, hep-ph/040632

(3+1)



(2+2)



M. Maltoni et al., hep-ph/04051

Standard Parametrization

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

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

- $s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$, $\theta_{ij} = [0, \frac{\pi}{2}]$,
- 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, S.T.P., G. Steigman, S. Toshev, 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: $\alpha_{21,31}$?

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

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

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

$$m_1 \cong m_2 \cong m_3, \quad m^2_{1,2,3} >> \Delta m^2_{\rm atm}, \qquad \text{QD}.$$

- Determining or obtaining significant constraints on the ab solute 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.

Solar Neutrino Experiments

SAGE, SNO, SK (HK, UNO)

BOREXINO, KamLAND: ^{7}Be neutrinos

LowNu (LENS, XMASS, HERON,...): pp neutrinos

- Physics of Dominant $\nu_\odot$–Oscillations
  - Test of the (MSW) mechanism involved
  - High precision determination of $\sin^2\theta_{12}$
  - Further constrain Δm^2_{21}, possibly $\sin^2\theta_{13}$
  - Test of CPT–symmetry: $\nu_e \to \nu_e$ vs. $\bar{\nu}_e \to \bar{\nu}_e$
- Subdominant $\nu_\odot$–Transitions ?
  - $\nu_e \to \nu_s$
  - Neutrino $FDFNNC$, $FCNC$ Interactions
  - Violation of WEP (nonuniversal $\nu_j - \phi_{GRAV}$ couplings)
  - Lorentz Invariance Violation
- Supernova Neutrinos

VO: $\lambda = 4\pi E/\Delta m^2$

VWEP: NONUNIVERSAL $\nu_j - \Phi_{GRAV}$ COUPLI

$\lambda = \pi/(E|\Phi|\delta\gamma)$, $\delta\gamma = \gamma_1 - \gamma_2$

LIV: NONUNIVERSAL ASYMPTOTIC ν_j VELOCI

$\lambda = 2\pi/(E\delta v)$, $\delta v = v_1 - v_2$

LIV DUE TO CPT VIOLATION: $\bar{\nu}_{\alpha L} b^{\mu}_{\alpha\beta} \gamma_\mu \nu_{\beta L}$

$\lambda = \pm 2\pi/\delta b$, $\delta b = b_1 - b_2$

FCNC, FDFNNC: $G_F \varepsilon_{\alpha\beta} \bar{\nu}_{\alpha L} \gamma_\mu \nu_{\beta L} (\bar{f} \gamma^\mu f$

$$\lambda = \frac{2\pi}{2\sqrt{2}\, G_F N_f} \frac{2}{(4\varepsilon_{\alpha\beta}^2 + (\varepsilon_{\alpha\alpha} - \varepsilon_{\beta\beta})^2}$$

MNV: $m_j = m_j(\rho)$

BOSONIC ν'S: $\nu_e \to \nu_\mu$, $\bar{\nu}_e \to \bar{\nu}_\mu$:

$\sqrt{2}\, G_F N_e$ - DOES NOT CHAN SIGN

$$4p \rightarrow \ ^4He + 2e^+ + 2\nu_e.$$

- *pp* neutrinos, $E \leq 0.420$ MeV, $\bar{E} = 0.265$ MeV,
- ^{7}Be neutrinos, E=0.862 MeV (89.7% of the flux), 0.384 MeV (10.3%) ,
- ^{8}B neutrinos, $E \leq 14.40$ MeV, $\bar{E} = 6.71$ MeV,
- *pep* neutrinos, E=1.442 MeV,
- of ^{13}N, $E \leq 1.199$ MeV, $\bar{E} = 0.707$ MeV,
- of ^{15}O, $E \leq 1.732$ MeV, $\bar{E} = 0.997$ MeV.

Solar Neutrino Production: pp Chain

REACTION	TERM. (%)	ν ENERGY (MeV)
$p + p \rightarrow {}^2H + e^+ + \nu_e$	(99.96)	≤ 0.420
or		
$p + e^- + p \rightarrow {}^2H + \nu_e$	(0.44)	1.442
$^2H + p \rightarrow {}^3He + \gamma$	(100)	
$^3He + {}^3He \rightarrow \alpha + 2\,p$	(85)	
or		
$^3He + {}^4He \rightarrow {}^7Be + \gamma$	(15)	
$^7Be + e^- \rightarrow {}^7Li + \nu_e$	(15)	0.861 90% 0.383 10%
$^7Li + p \rightarrow 2\,\alpha$		
or		
$^7Be + p \rightarrow {}^8B + \gamma$	(0.02)	
$^8B \rightarrow {}^8Be^* + e^+ + \nu_e$		< 15
$^8Be^* \rightarrow 2\,\alpha$		
or		
$^3He + p \rightarrow {}^4He + e^+ + \nu_e$	(0.000004)	18.8

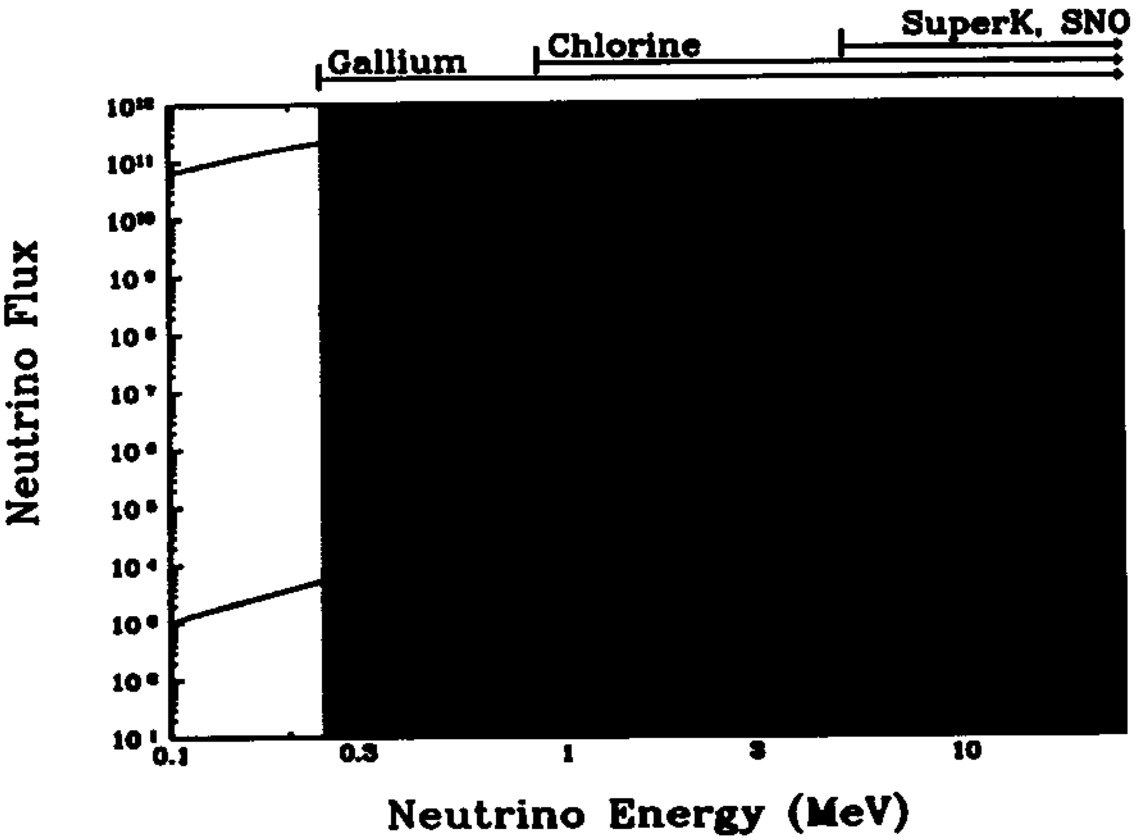


Figure 2: Differential Standard Solar Model neutrino fluxes [14].

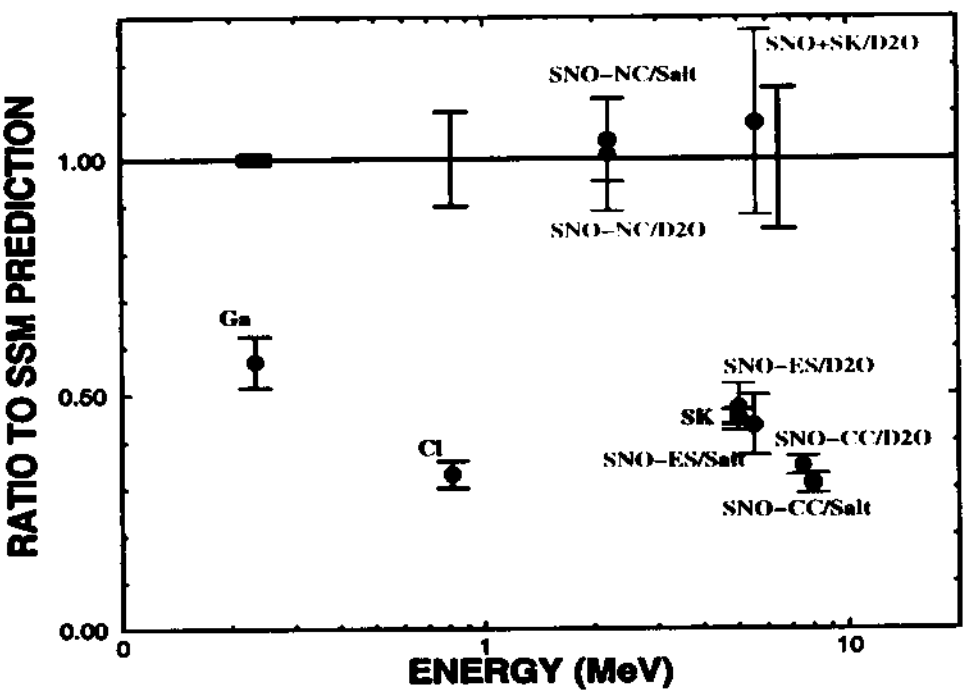


Figure 3: Comparison of measurements to Standard Solar Model predictions

- Physics of the Sun
  - High Precision Measurement of $\Phi_{^7Be}$, Φ_{pp} (~few %)

    SSM: $\Delta(\Phi_{pp}) \cong 1\%$, test of the mechanism of solar energy generation ($pp-$cycle of fusion reactions)

    SSM: $^3He +\ ^3He$ vs. $^3He +\ ^4He$ reaction rates

    SSM: $\Phi(^7Be) + \Phi(pp) = 98\%\Phi(\nu_\odot)$

    Determination of $L_\odot^\nu$ (~8 min)

    Comparison with $L_\odot$ (~ 40 000 yrs)

    Significant tests of

    Thermo-nuclear fusion theory of energy generation

    Theory of stellar evolution

Physics of the Sun

$$f_j \equiv \frac{\Phi(j)}{\Phi_{SSM}(j)},\ \ j = pp, pep, ...,^8B,\ SSM = BP04$$

$\nu_\odot$ + KL data + $L_\odot$–constraint

$$f_{Be} = 1.03^{+0.24\ (+0.77)}_{-1.03\ (-1.03)},\ \ f_{pp} = 1.01 \pm 0.02\ (\pm 0.06)$$

$$f_B = 0.87 \pm 0.04\ {}^{(+0.09)}_{(-0.11)},\ \ L_{CNO} = 0.0^{+2.7\ (+7.3)}_{-0.0\ (-0.0)}\%$$

f_{Be} poorly determined

High precision measurement of Φ_{Be} ($\sim 5\%$)

+ $R(Ga)$: $\Phi(pp)$ with high precision

+ $L_\odot$: $\Delta(\Phi(pp)) \sim (0.5 - 1.0)\%$; important test of SSM

Current data: $L^\nu_\odot / L_\odot = 1.4^{+0.2\ (+0.7)}_{-0.3\ (-0.6)}$

$L^\nu_\odot$: 92% due to pp neutrinos

$\Delta(f_{pp}) \sim 5\%$: $\Delta(L^\nu_\odot / L_\odot) \sim 4\%$

J.N. Bahcall, M.C. Gonzalez-Garcia, C. Peña-Garay, hep-ph/0406294

Current Data on Δm^2_{21} and $\sin^2\theta_{12}$

Data set used	(3σ)Range Δm^2_{21} eV^2	(3σ)spread Δm^2_{21}	(3σ) Range $\sin^2\theta_{12}$	(3σ) spread $\sin^2\theta_{12}$
only sol	3.0 - 17.0	70%	0.21 – 0.39	30%
sol+162 Ty KL	4.9 - 10.7	37%	0.21 – 0.39	30%
sol+ 766.3 Ty KL	7.0 - 9.4	15%	0.21 – 0.38	29%

Table 1: 3σ allowed ranges of Δm^2_{21} and $\sin^2\theta_{12}$ from the analysis of the global solar neutrino, and global solar neutrino + KamLAND (past and present) data. The % spread in the allowed values of the two neutrino oscillation parameters is also shown.

Experiment	Observed rate/BP04 prediction	Predicted Rate at global best-fit	Predicted Rate at solar best-fit
Ga	0.52 ± 0.029	0.546	0.538
Cl	0.301 ± 0.027	0.350	0.346
SK(ES)	0.406 ± 0.014	0.395	0.396
SNO(CC)	0.274 ± 0.019	0.291	0.290
SNO(ES)	0.38 ± 0.052	0.387	0.387
SNO(NC)	0.895 ± 0.08	0.879	0.903

Table 1: The observed rates w.r.t predictions from the latest Standard Solar Model BP04. The predicted rates for the best fit values of Δm^2_{21} and $\sin^2\theta_{12}$, obtained in the analysis of the i) global solar neutrino data, and ii) global solar neutrino +KamLAND data, are also shown.

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

A. Bandyopadhyay et al., hep-ph/04063

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

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: $\sin^2 2\theta_{12}$

Reactor Experiments

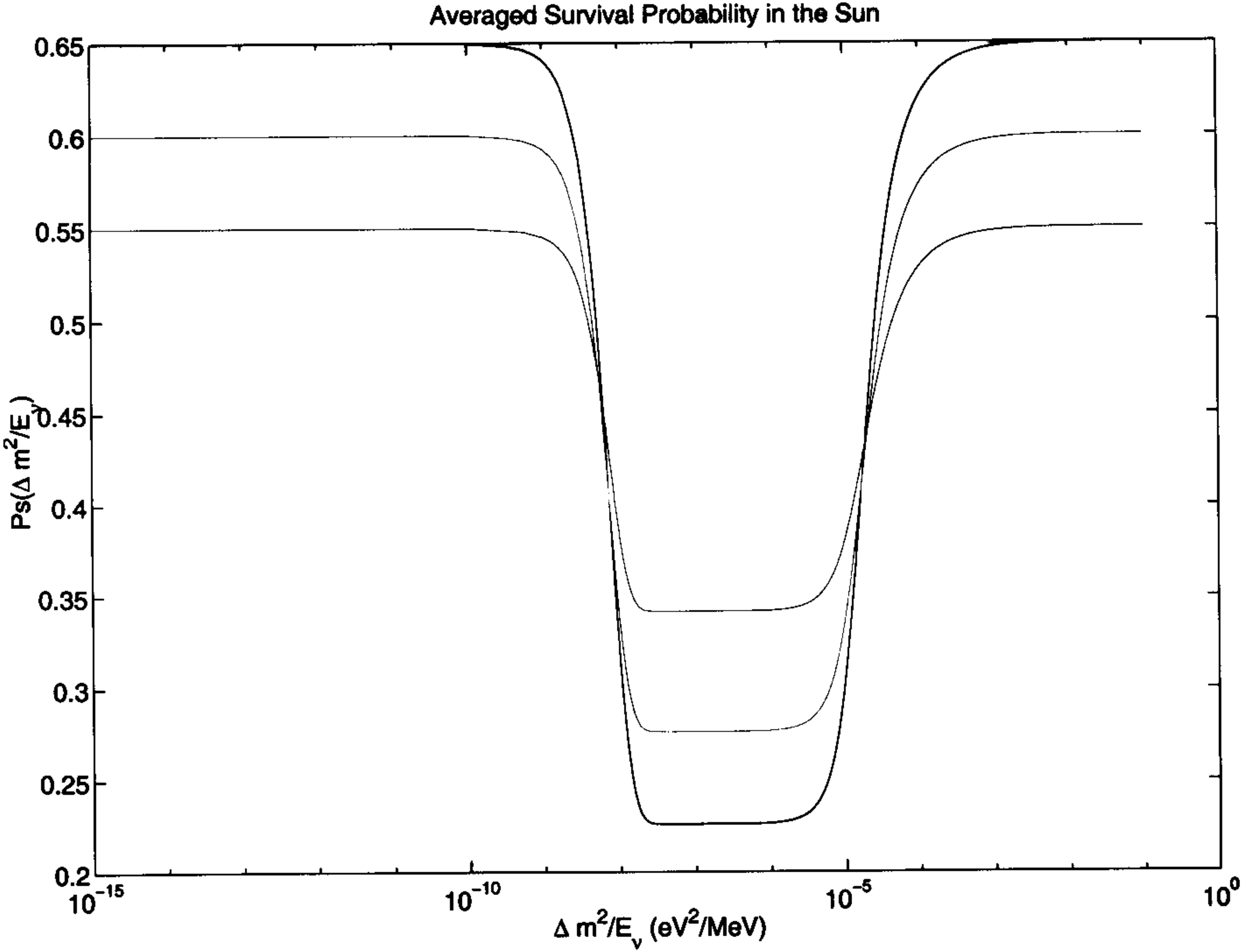
Future more precise KamLAND data

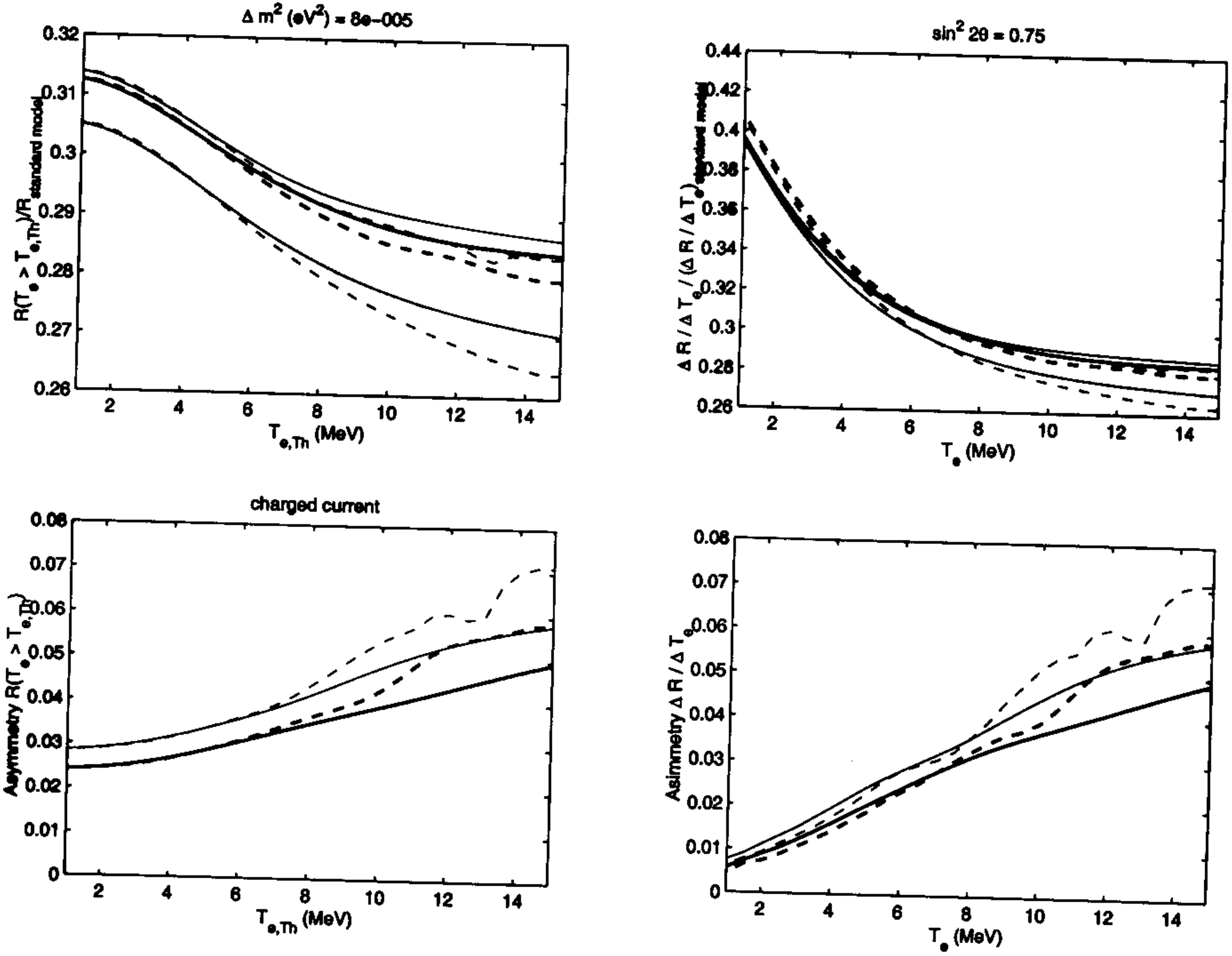
KamLAND: Low-LMA - Δm^2_{21} with higher precision

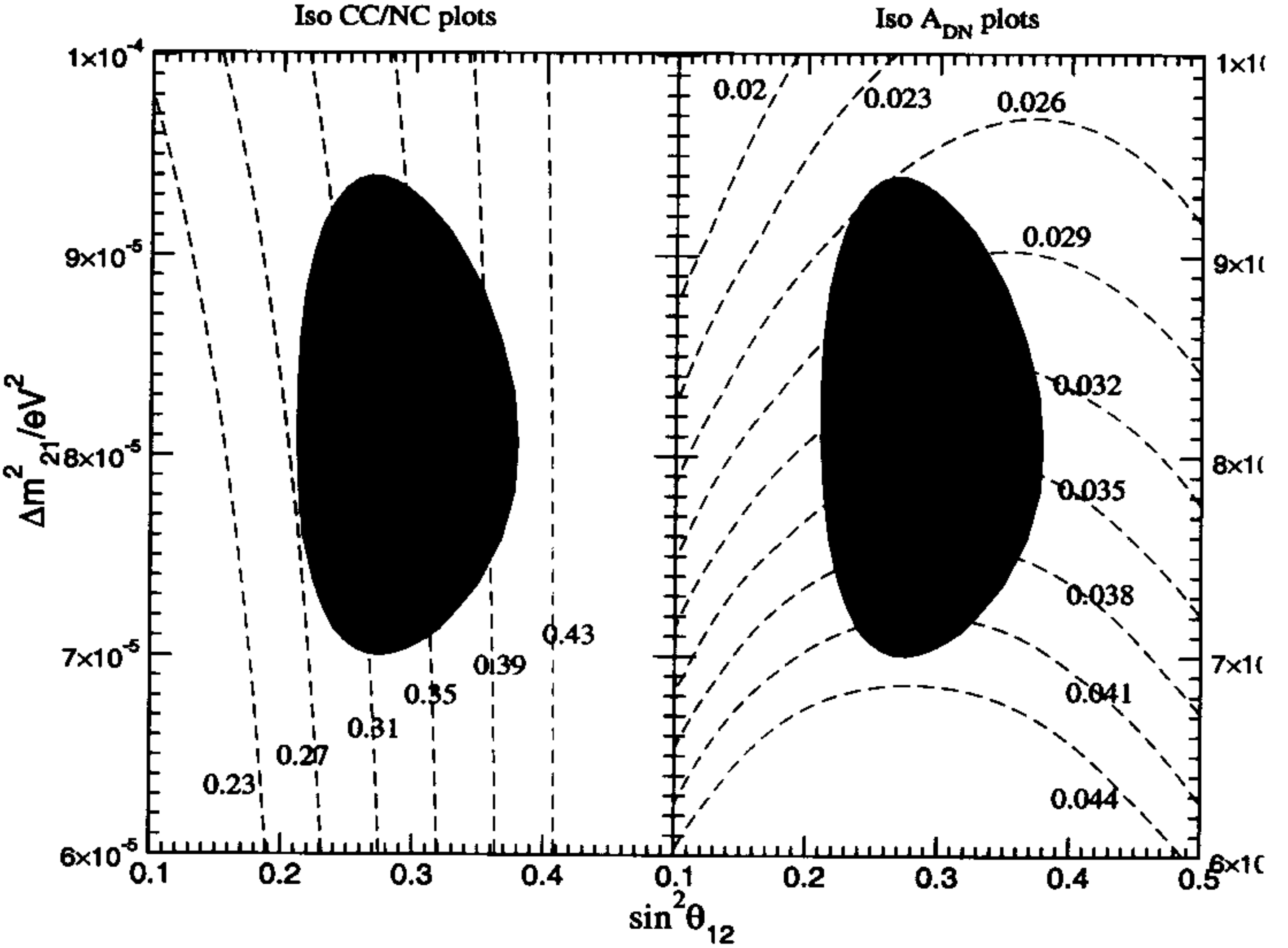
$\sin^2\theta_{12}$ cannot be determined with a high precisio
("wrong distance")

even with SHIGA-2 reactor to be operative in 200
("right distance" but signal too weak)

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


Averaged Survival Probability in the Sun
Ps(Δ m²/Eν)
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
10⁻¹⁵
10⁻¹⁰
10⁻⁵
10⁰
Δ m²/Eν (eV²/MeV)


Δ m² (eV²) = 8e−005
sin² 2θ = 0.75
R(T_e > T_e,Th)/R_standard model
T_e,Th (MeV)
ΔR / ΔT_e / (ΔR / ΔT_e)_standard model
T_e (MeV)
charged current
Asymmetry R(T_e > T_e,Th)
Asimmetry ΔR / ΔT_e

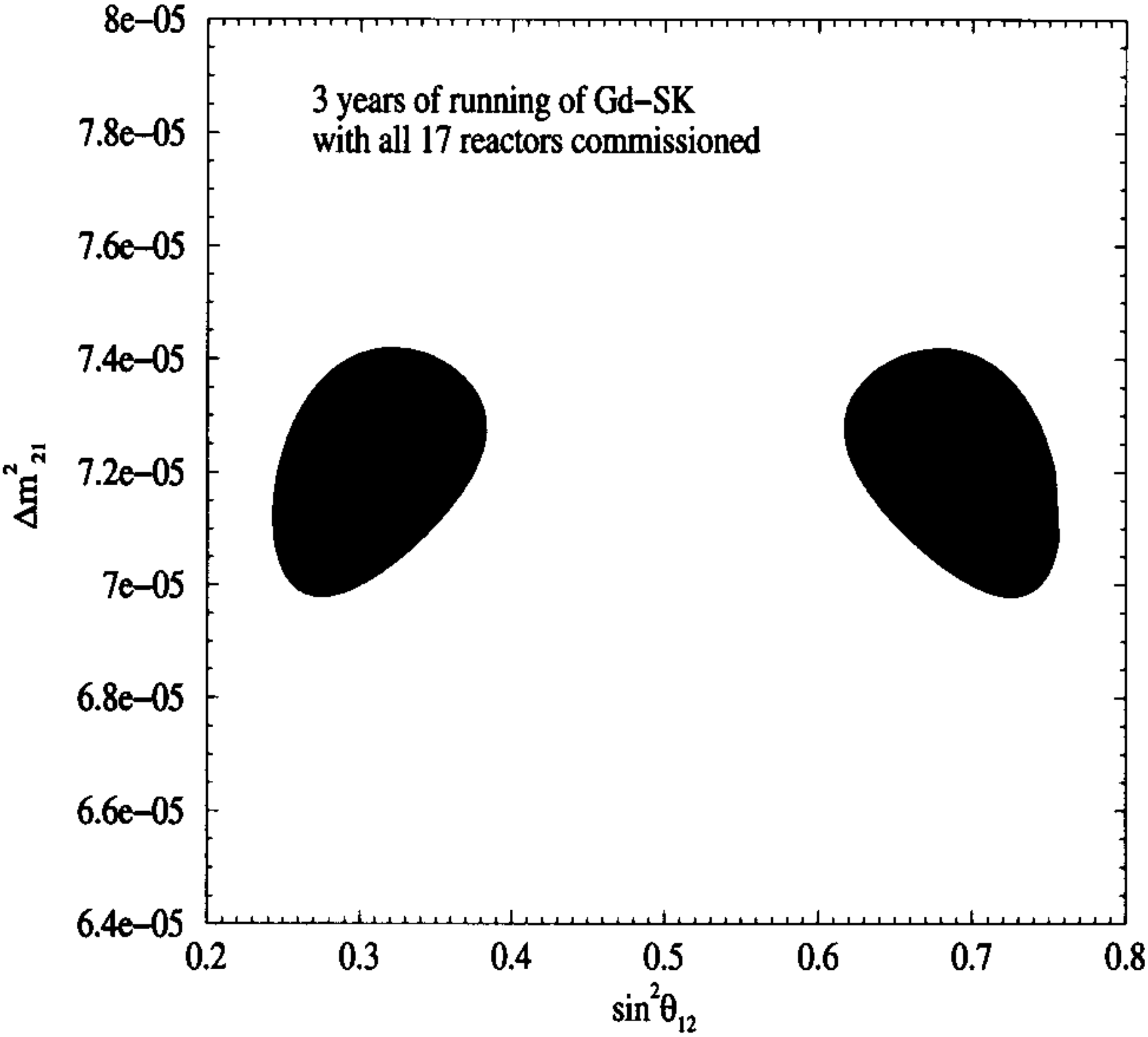


A. Bandyopadhyay et al, hep-ph/0406328

SK + 0.1% Gd

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

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



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

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:** $\sim 6\%$

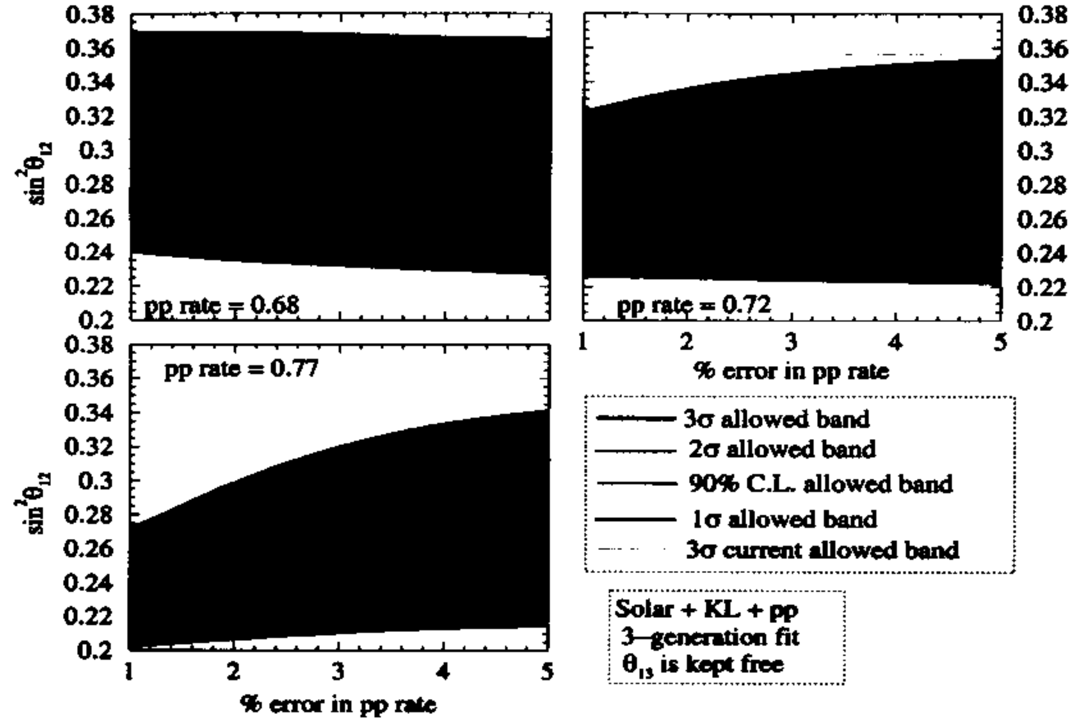
BP04: $R_{pp} \cong 0.71$; 3σ: **0.67 - 0.76**

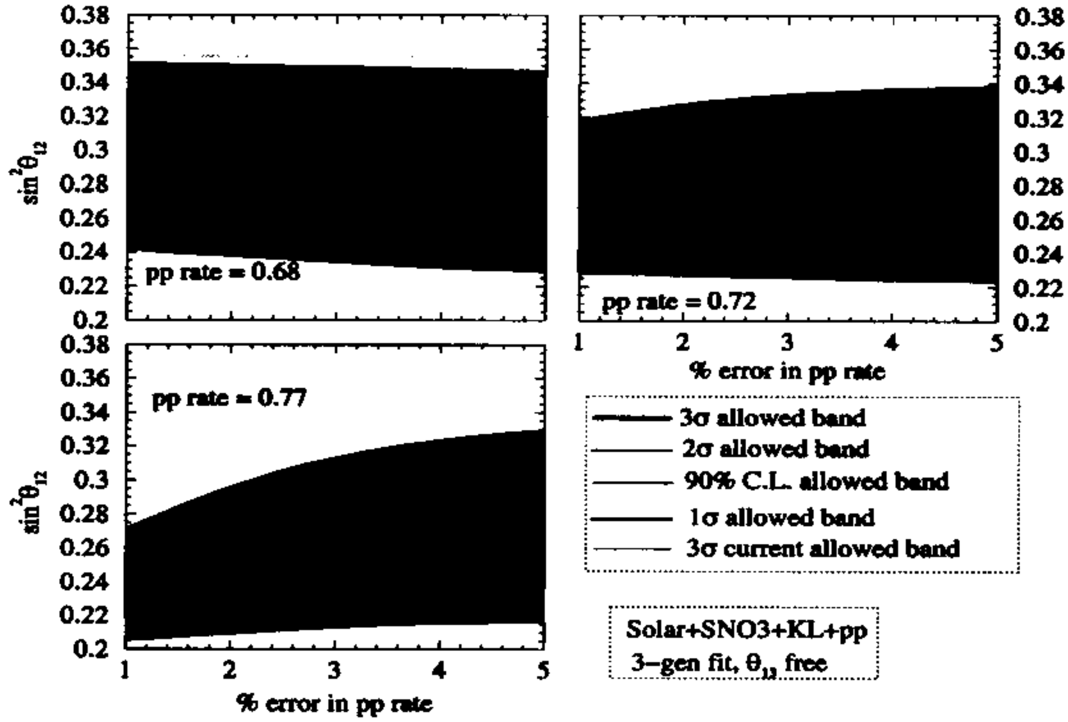
With $\Delta(R_{pp}) = 1\%$, $\Delta(\sin^2\theta_{12}) \gtrsim 15\%$ **at** 3σ

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

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

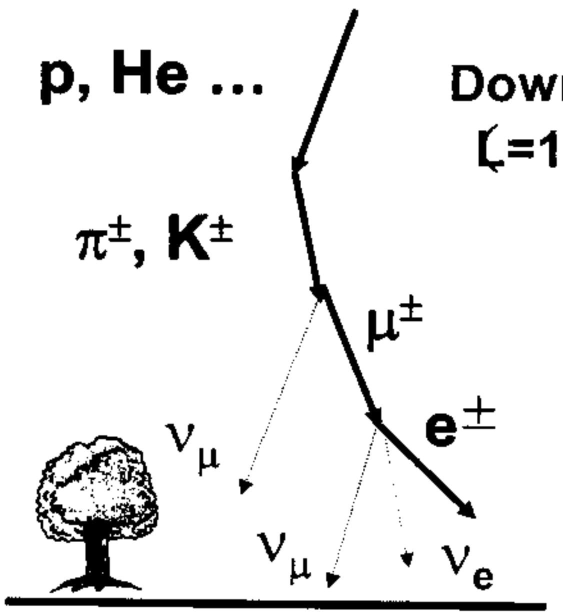
A. Bandyopadhyay et al., hep-ph/0302243 and hep-ph/0410283;
H. Minakata et al., hep-ph/0407326



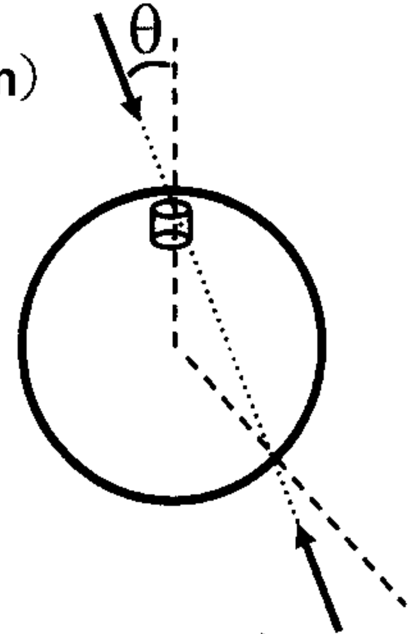


A. Bandyopadhyay, S. Choubey, S. Goswami, S.T. Petco
hep-ph/04102

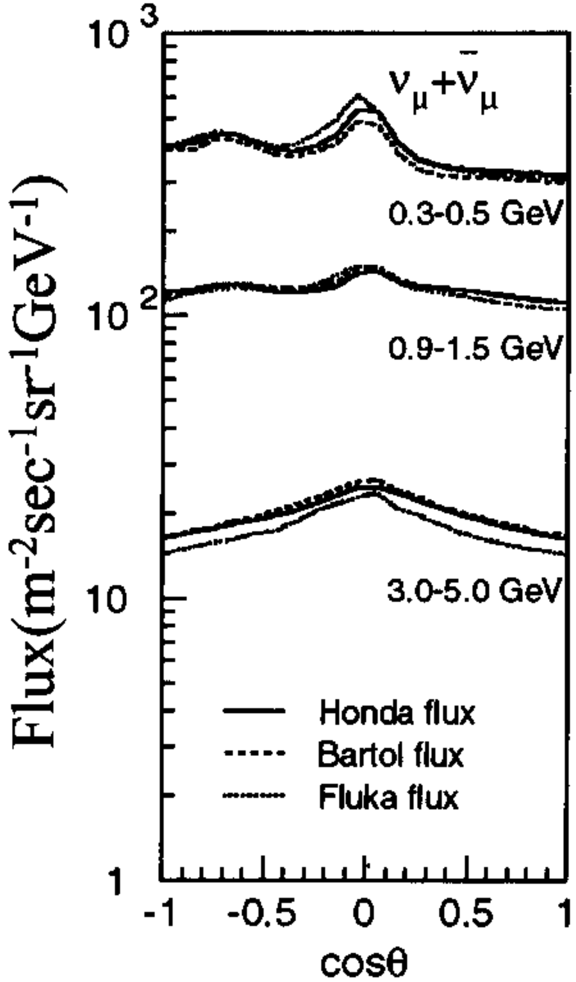
Atmospheric neutrinos



Zenith angle



Zenith angle dist. of Atmospheric ν flux



Eν > a few GeV

Up/Down Symmetry

ATMOSPHERIC NEUTRINOS

SUBDOMINANT $\overset{(-)}{\nu}_{\mu(e)} \to \overset{(-)}{\nu}_{e(\mu)}$

$r = \Phi^\circ(\nu_\mu) / \Phi^\circ(\nu_e)$

SUB-GEV: $(r \cos^2\theta_{23} - 1) P^{2\nu}(\Delta m^2_{21}, \theta_{1}$

NO SENSITIVITY TO θ_{13}, SGN(Δ

SENSITIVE TO $\theta_{23} \neq \pi/4$

($r \simeq 2$)

MULTI-GEV: $(r \sin^2\theta_{23} - 1) P^{2\nu}(\Delta m^2_{31}, \theta_{13})$

SENSITIVE TO θ_{13}, SGN(Δm^2_A)

$\theta_{23} \neq \pi/4$

($r > 2$)

MATTER EFFECTS - LARGE

EARTH MANTLE : MSW

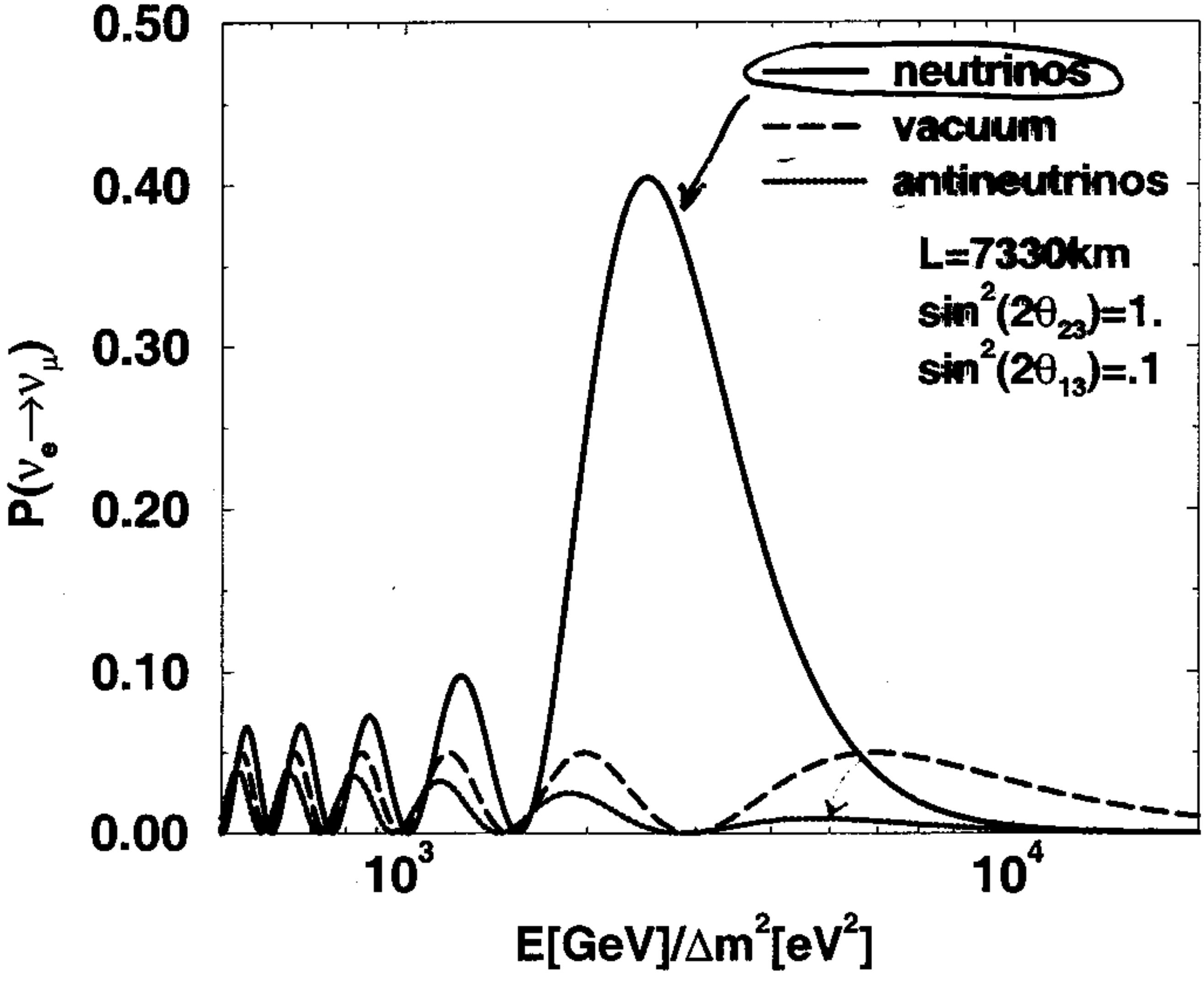
EARTH CORE: NOLR

(CONSTRUCTIVE INTERF RE

SEARCH FOR:

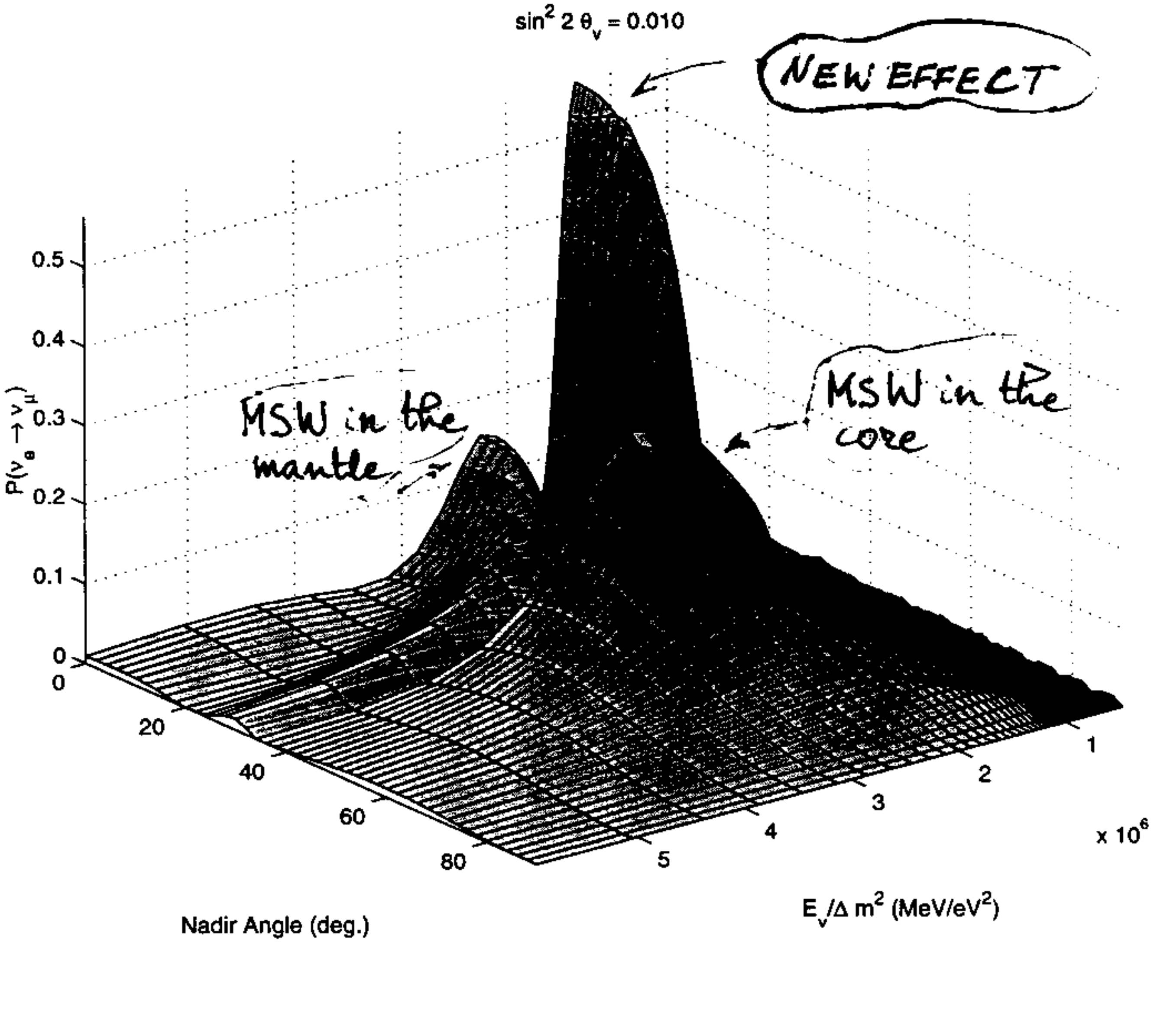
VWEP, LIV, CPTV, MVN, ...

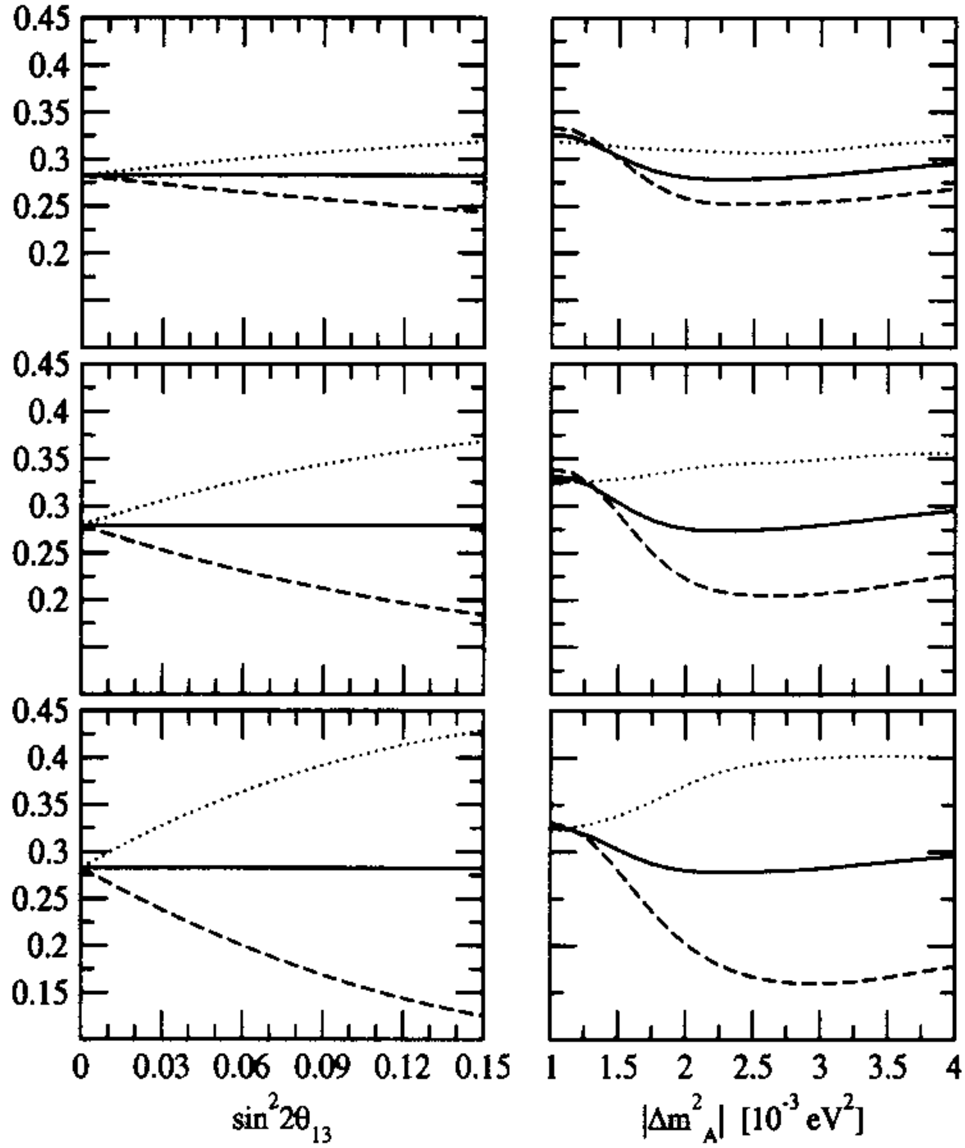
Mocioiu, Shrock: '00



(M. CHIZHOV, M. MARIS, S.T.P.

$\nu_\mu \to \nu_e\ ,\ \nu_e \to \nu_{\mu(\tau)}$





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)**

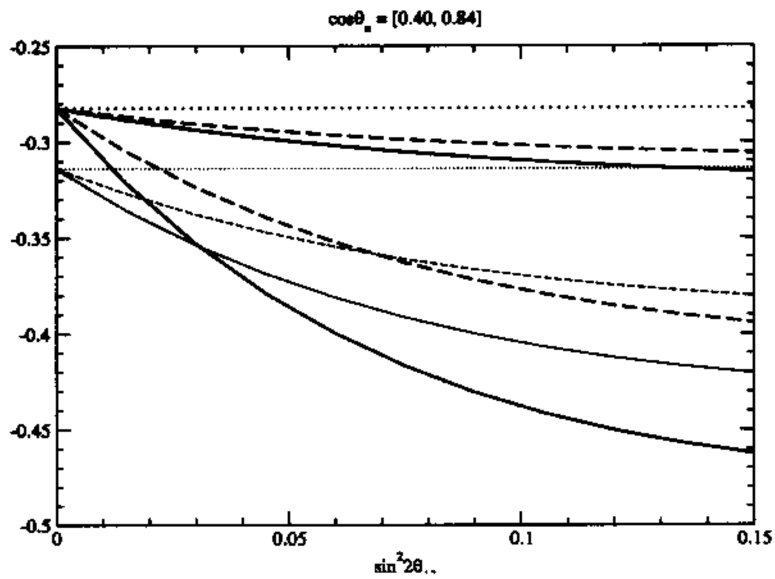
$\cos\theta_n = (0.30 - 0.84)$ **mantle bin, E = [5,20] GeV**

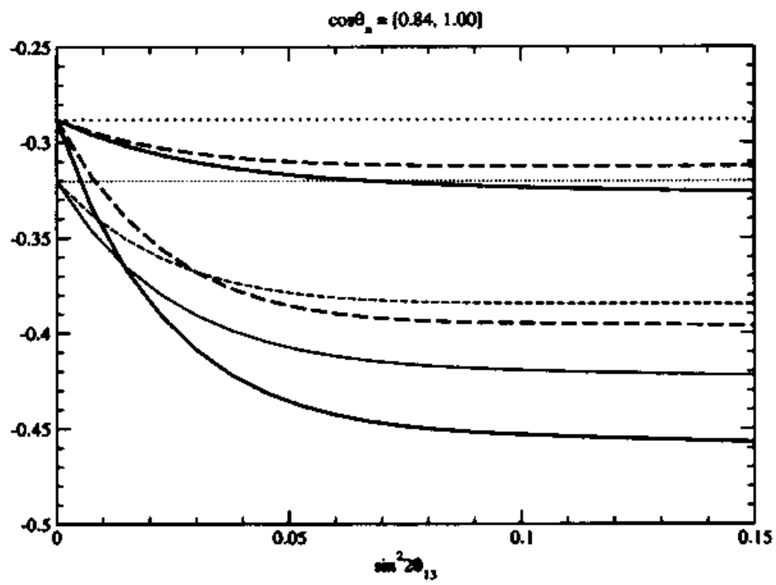
S.T.P., S. Palomares-Ruiz, hep-ph/0406

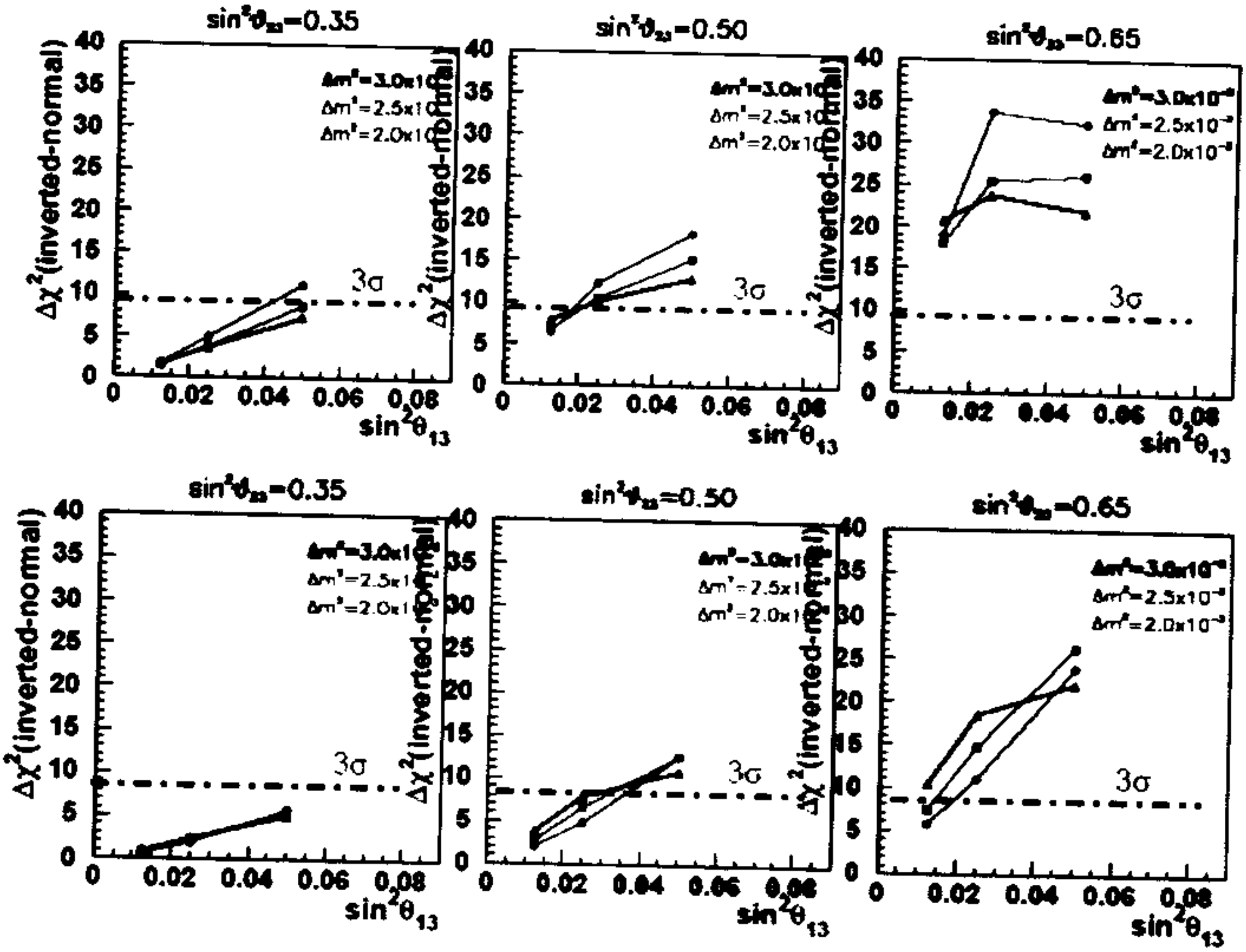
Water-Čerenkov Detectors (SK, etc.): **multi-GeV $\mu-$like and $e-$like event rates, N_μ and N_e**

$A \equiv \frac{U-D}{U+D}$ **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)







Water-Cerenkov detector, 1.8 MTy

T. Kajita et al., 2004

$|\Delta m^2_{31}|$, 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 $\sin^2\theta_1$ **and** δ

J. Burguet-Castell et al., hep-ph/010325
V. Barger, D. Marfatia, K. Whisnant, hep-ph/011211
H. Minakata, H. Nunokawa, S.J. Parke, hep-ph/030121
P. Huber et al., hep-ph/040306
O. Yasuda, hep-ph/04050C

Resolving the ambiguities may require data from

NuMI off-axis, and/or

new off-maximum JHF, and/or

SPL + β–beams experiment(s).

Combining T2K and HK Atmospheric Neutrino Data

P. Huber, M. Maltoni, T. Schwetz, hep-ph/0501037

- **T2K Phase II; $\bar{E}_\nu = 0.76$ GeV; $L = 295$ km**

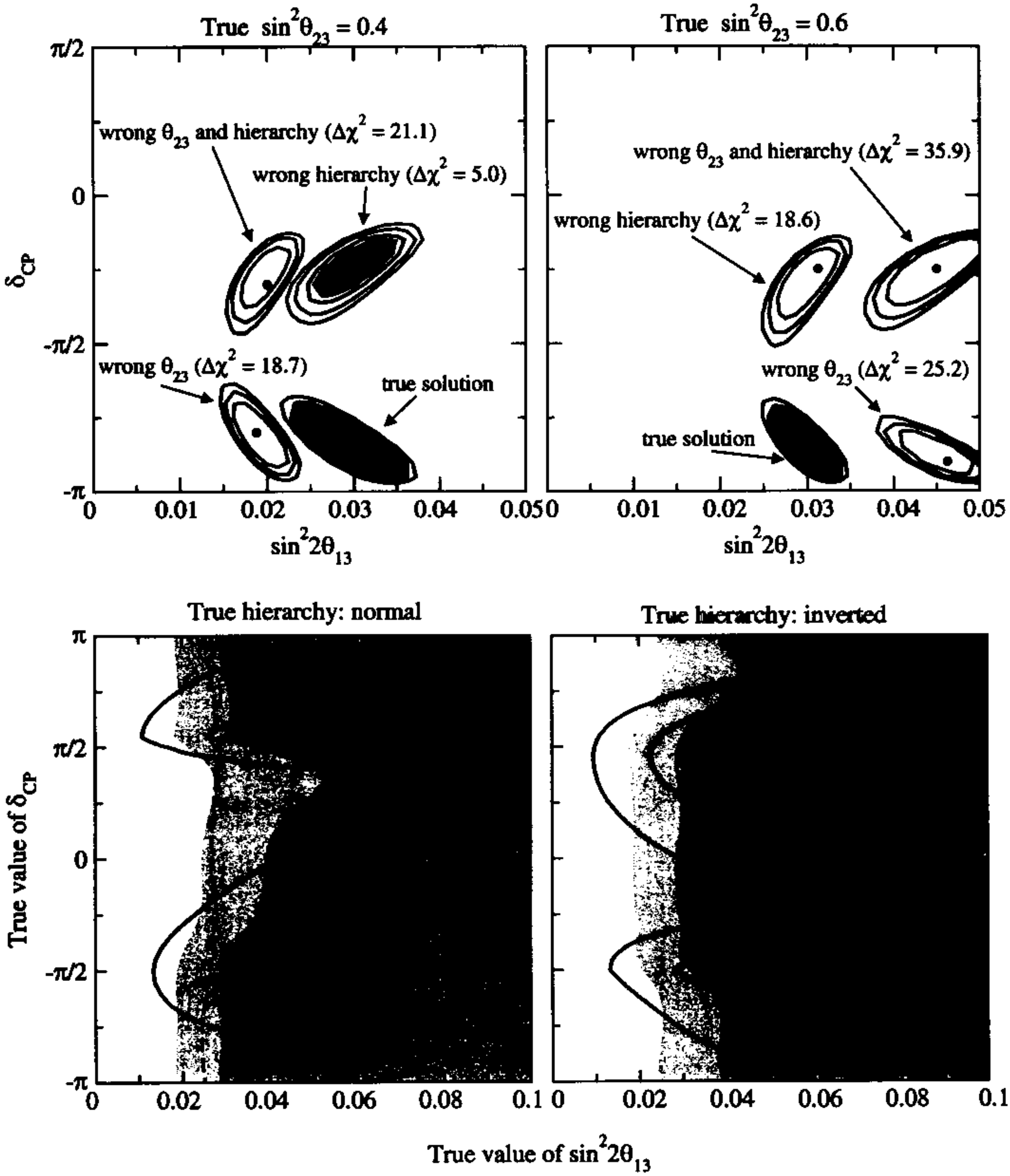
2 years running with ν_μ, 6 years with $\bar{\nu}_\mu$

- **Detector: 1 Megaton Water Cerenkov (HyperK)**

- **Atmospheric Neutrino Data:**

$100\times$ SuperK-I data sample ($\sim$ 90 kT yrs); corresponds to 10 years of data.

Includes $e-$ and $\mu-$ like sub-GeV and multi-GeV contained events + stopping and through-going μ events.


True sin²θ₂₃ = 0.4
True sin²θ₂₃ = 0.6
wrong θ₂₃ and hierarchy (Δχ² = 21.1)
wrong hierarchy (Δχ² = 5.0)
wrong θ₂₃ (Δχ² = 18.7)
true solution
wrong θ₂₃ and hierarchy (Δχ² = 35.9)
wrong hierarchy (Δχ² = 18.6)
wrong θ₂₃ (Δχ² = 25.2)
true solution
δCP
sin²2θ₁₃
π/2
0
-π/2
-π
0.01
0.02
0.03
0.04
0.05
True hierarchy: normal
True hierarchy: inverted
True value of δCP
True value of sin²2θ₁₃
π
0.06
0.08
0.1

INSTEAD OF CONCLUSIONS

- THE FIRST $\nu_\odot$ - EXPERIMENT CONCEIVE (IN 1964) TO PROVIDE INFORMATIO ABOUT THE INTERIOR OF THE SUN
- DISCOVERED THE SOLAR ν_e - DEFICIT (OSCILLATIO
- KAMIOKANDE, IMB : PROTON DECAY
- DETECTED SN' ν'S
- KAMIOKANDE : CONFIRMED $\nu_e^\odot$ DEFICIT
  IMB + KAM-DE : FIRST EVIDENCE FOR ATMOSPHERIC $\overset{(-)}{\nu}_\mu$ OSCILLA
- GIVEN THIS PATTERN, WHAT WILL FUTUR EXPERIMENTS DISCOVER?
  - VIOLATION OF LI?
  - VIOLATION OF WEP?
  - VIOLATION OF CPT?
  - STERILE ν'S?
  - BOSONIC ν'S?
  - MVN?
  - ? ? ?