Global Analysis of Neutrino Oscillation

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Acknowledgment:

A. Bandyopadhyay, S. Choubey,

S.T. Petcov, D.P.Roy

Plan of Talk

- Two flavour oscillation analysis
  - Solar +KamLAND – constraints on $\Delta m^2_\odot$ and $\sin^2\theta_\odot$
  - Atmospheric+K2K – constraints on Δm^2_{atm} and $\sin^2\theta_{atm}$
- Three flavour oscillation analysis
  - solar+KL+chooz+atmospheric+K2K - constraints on θ_{13}, $\Delta m^2_\odot/\Delta m^2_{atm}$
- Sterile Neutrinos – LSND ✕
- Summary and Future Goals

ν *Oscillation: experimental evidences . . .*

- Atmospheric Neutrino data from SuperKamiokande
- Solar Neutrino Data from Homestake,SAGE, Gallex, GNO, Kamiokande, SuperKamiokande, SNO (Phase-I,Phase-II)
- Data from Long baseline accelerator based experiment K2K
- Long baseline reactor experiment KamLAND
- Accelerator based oscillation experiment LSND

  –not confirmed by Karmen

  —Miniboone will provide independent check

Global Analysis — Ingredients . . .

- Experimental Data
  –statistical error
  –systematic errors and their correlations
- Theoretical Predictions
  –the fluxes and their uncertainties
  –the interaction cross-sections and their uncertainties
  –the oscillation probabilities (depends on the density profile of the propagating medium Δm^2 , θ, E_ν ....)
- $\mathrm{rate} = \mathrm{flux} \times \mathrm{cross} - \mathrm{section} \times \mathrm{probability}$
- Minimisation of χ^2_{global}
  — covariance method
  — pull method *Fogli et al.,2002*
- Frequentist method *Creminelli,Signorelli,Strumia*
- Baysian Analysis *M.V.Grazalli and C. Giunti*

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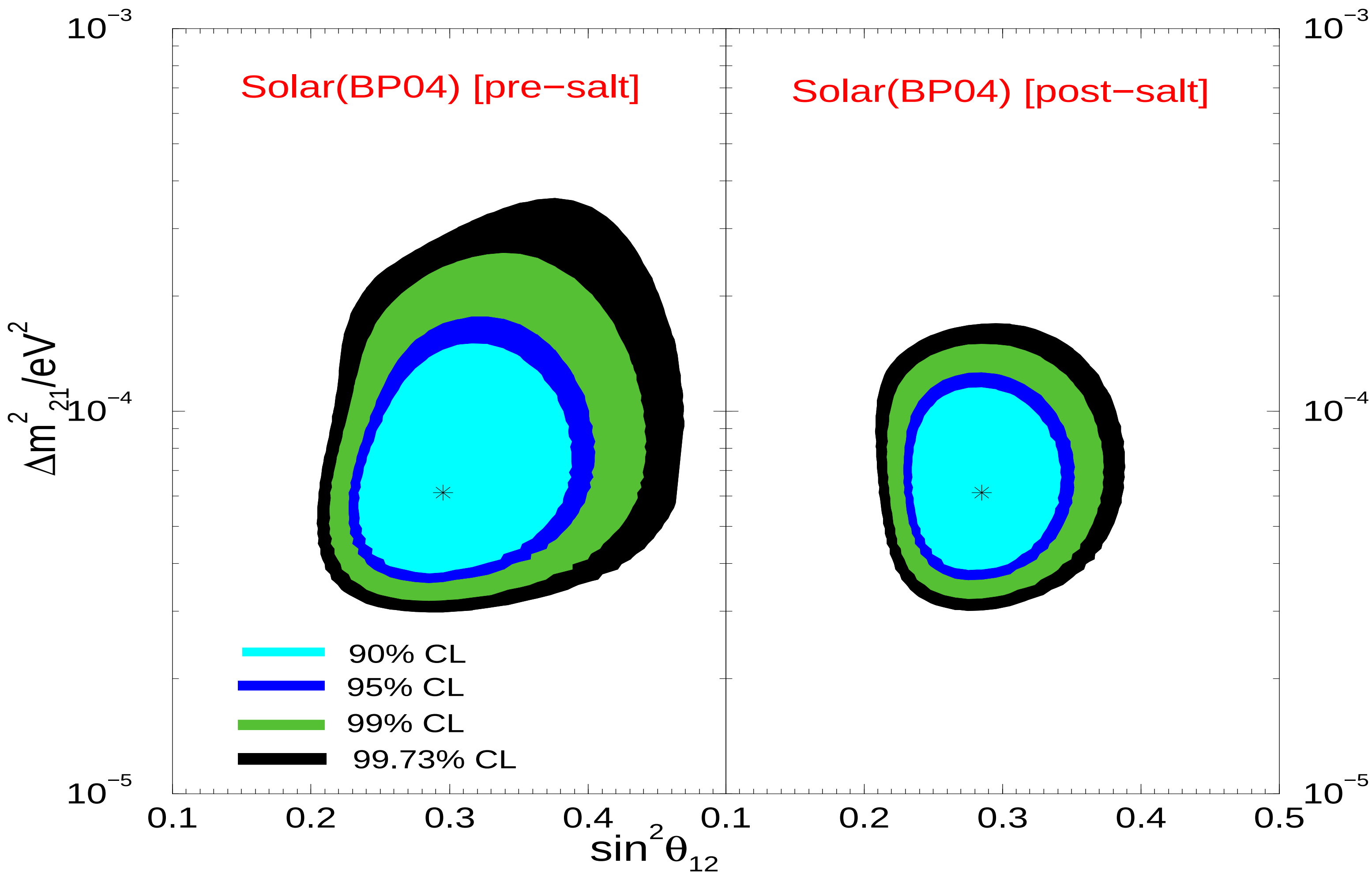
Best-fit values of parameters $\Delta m^2, \sin^2\theta \ldots$

Solar Neutrino Oscillation Parameters:two flavour analysis

Allowed area from global Solar Data . . . $\nu_e - \nu_{\rm active}$

- Solar Neutrino Oscillation Parameters : $\Delta m^2_\odot \equiv \Delta m^2_{21}$, $\theta_\odot \equiv \theta_{12}$
- BP04 fluxes, ^8B flux normalisation free



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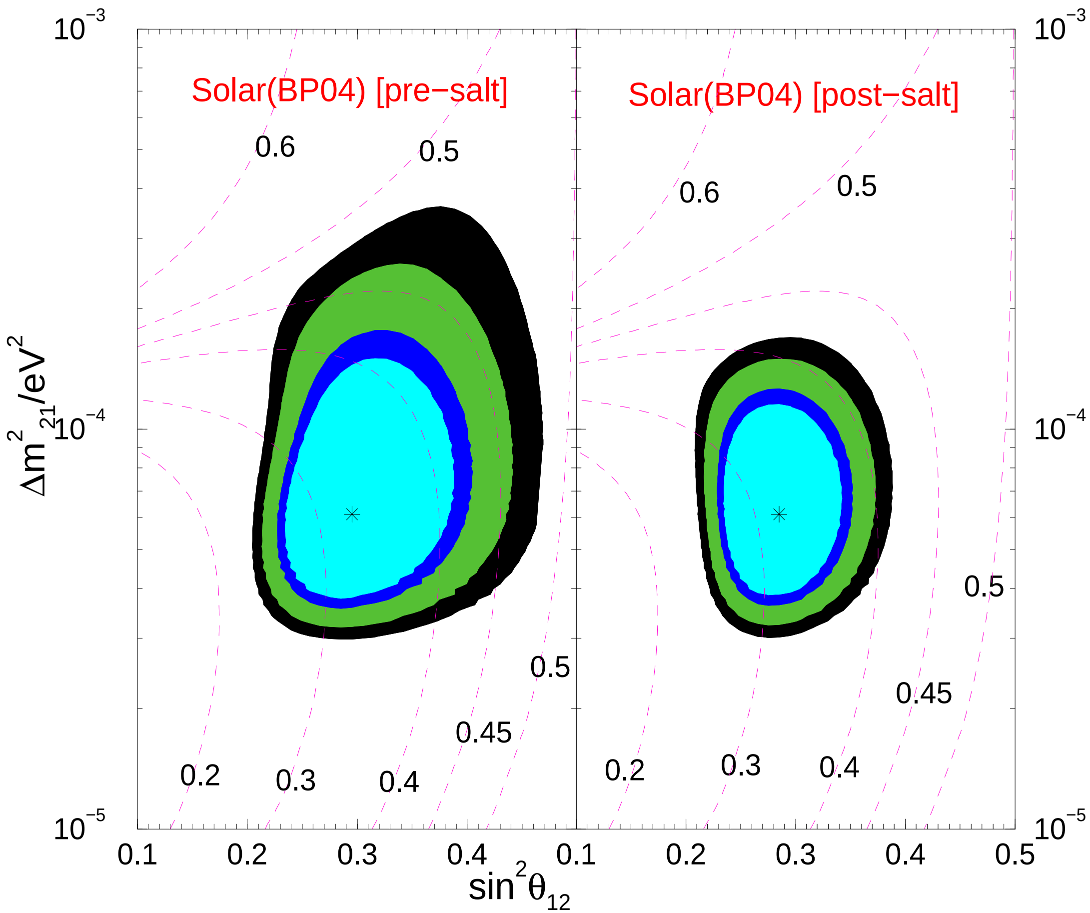

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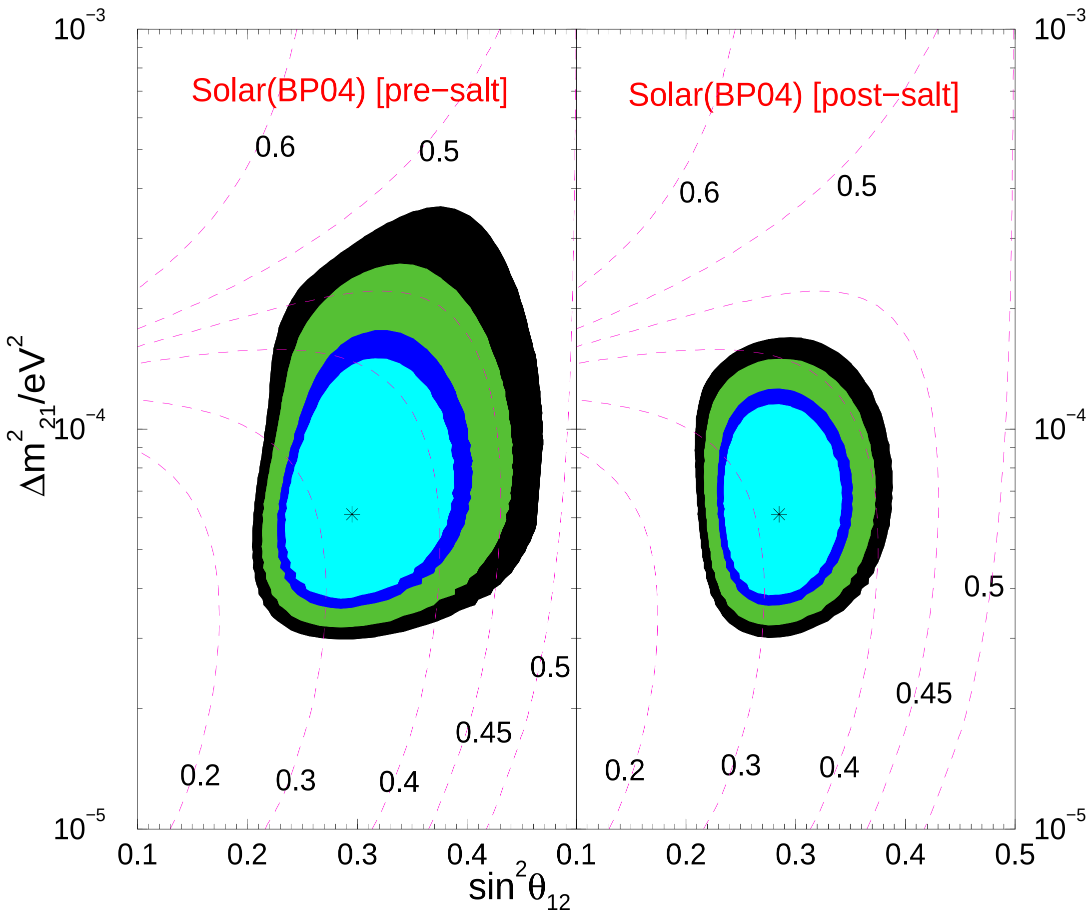

•Best fit

Δm^2_{21} =6.06 $\times 10^{-5}$eV^2
$\sin^2\theta_{12}$ = 0.29 f_B=0.89

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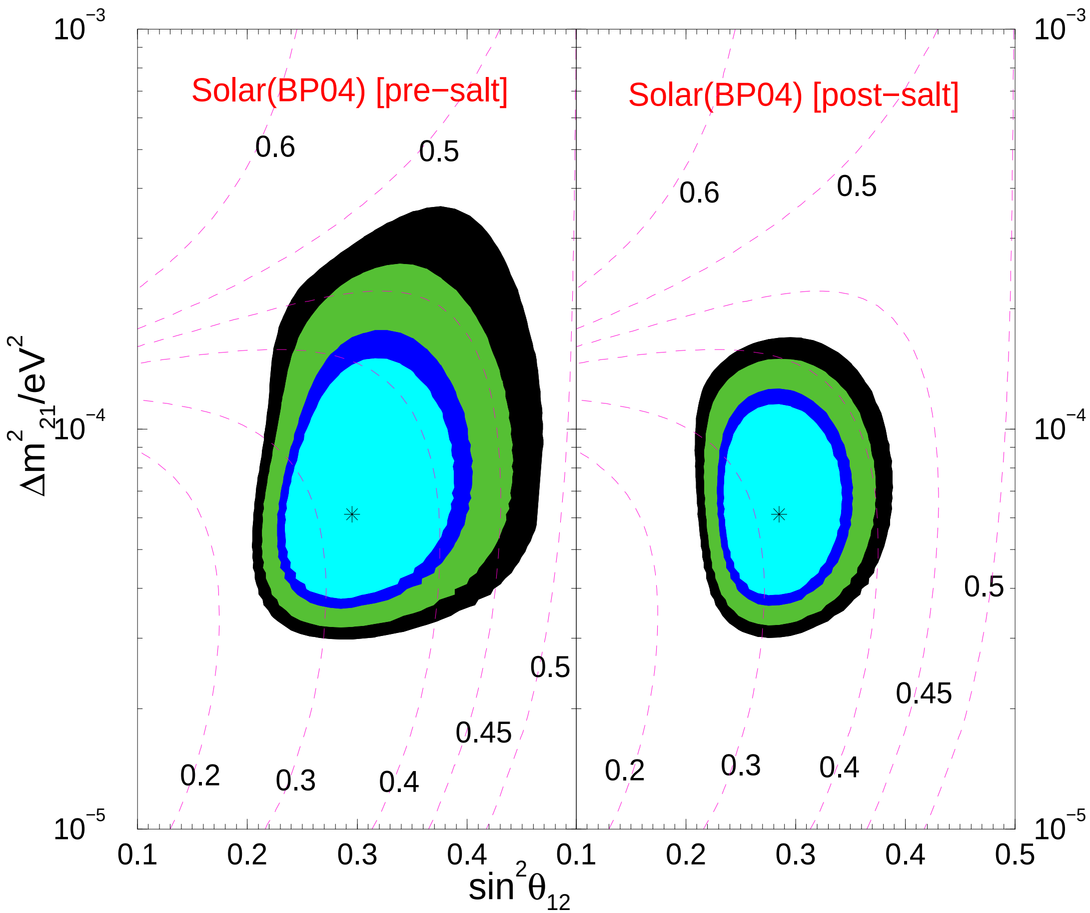

•99% C.L. range

Δm^2_{21} =(3.1-25.7) $\times 10^{-5}$eV^2
$\sin^2\theta_{12}$ = 0.21 -0.44
....(before salt)

Δm^2_{21} =(3.2-14.8) $\times 10^{-5}$eV^2
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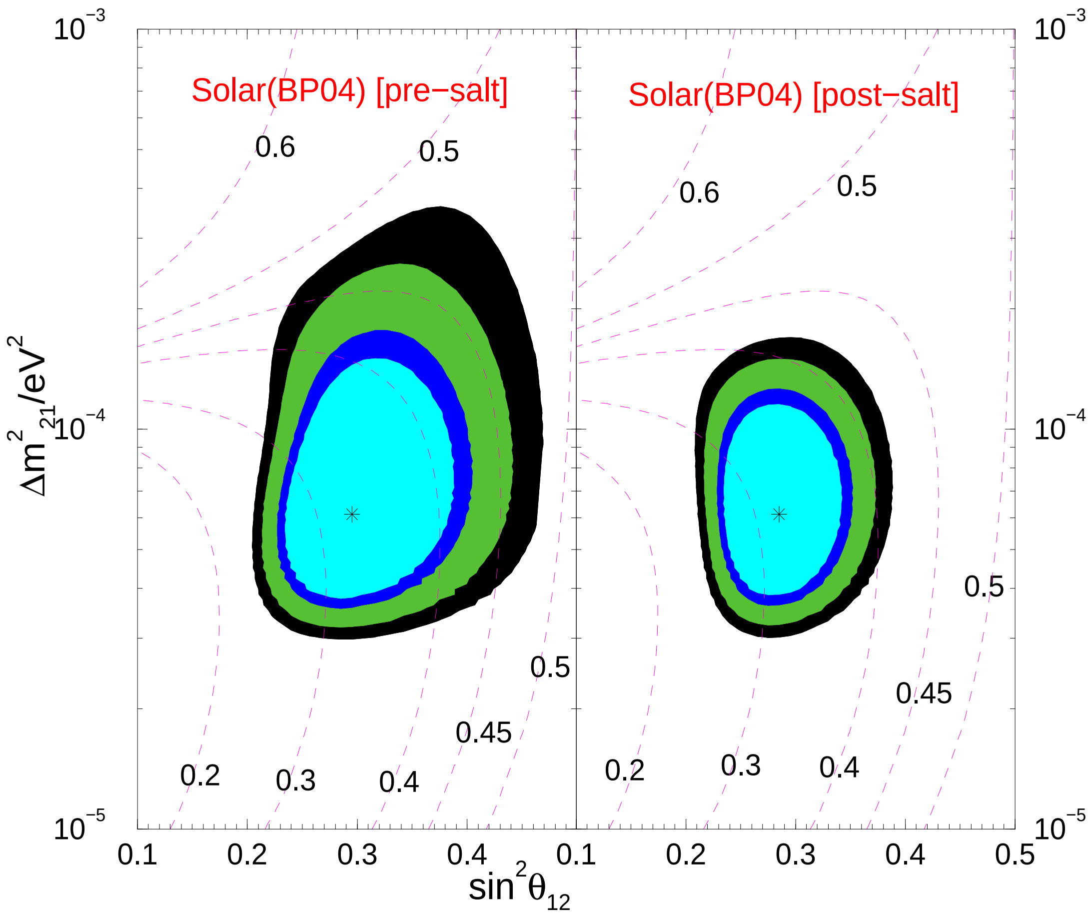

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- Upper limit on Δm^2_{21} and $\sin^2\theta_{12}$ tightens with salt data

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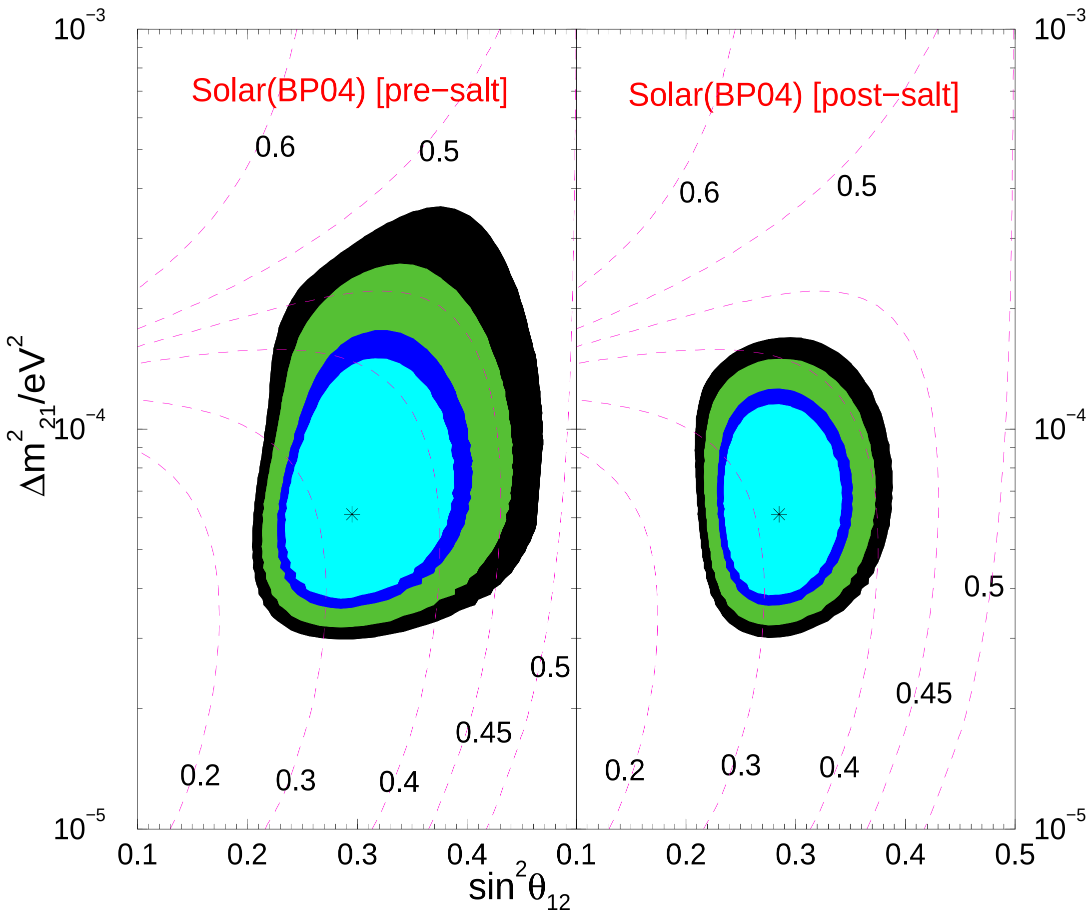

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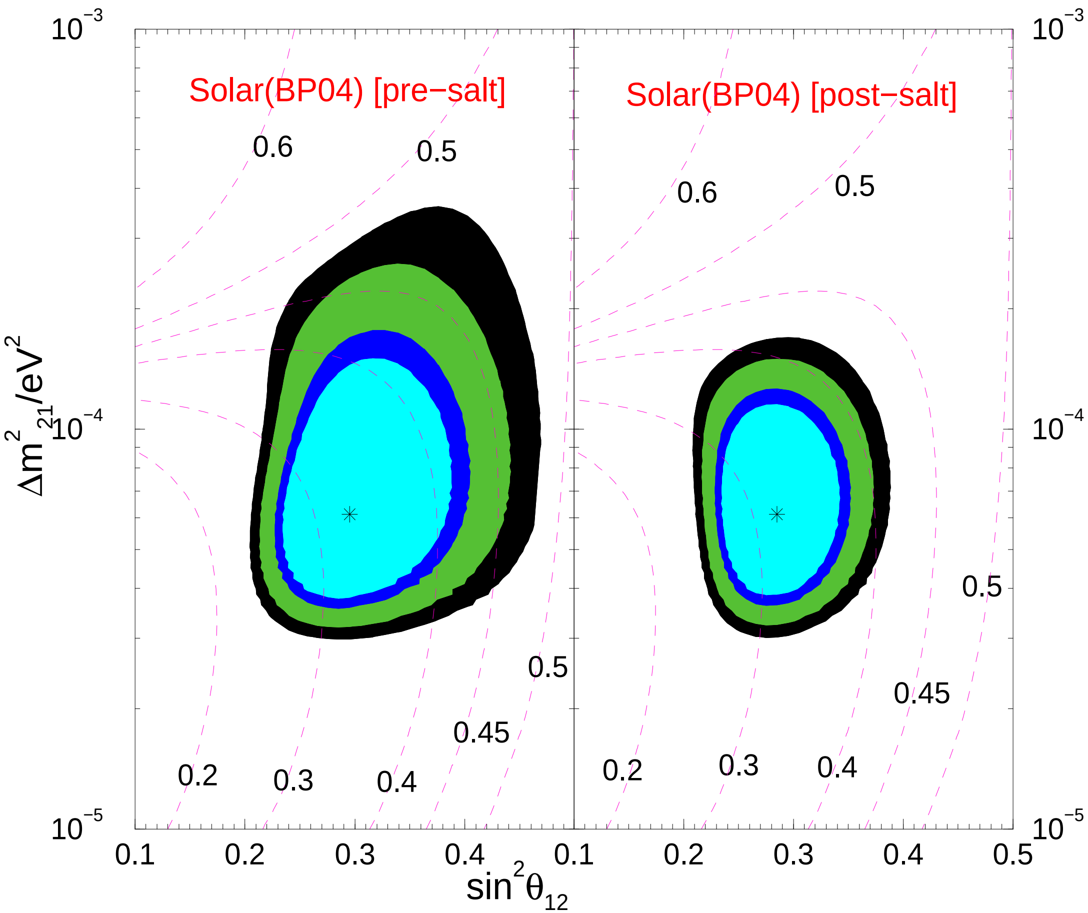

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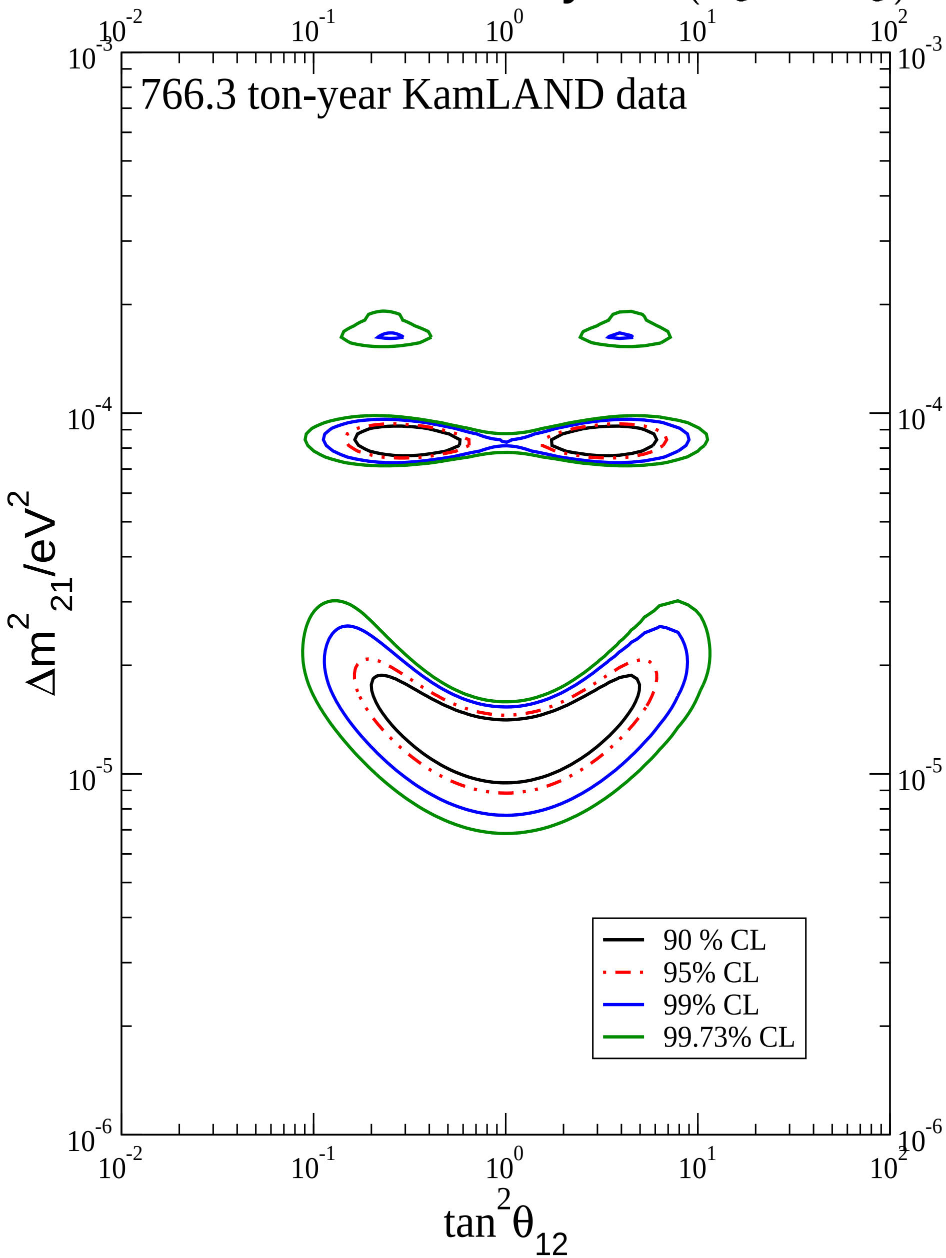
- Upper limit on Δm^2_{21} and $\sin^2\theta_{12}$ tightens with salt data
- No significant change due to BP04

Allowed area from KamLAND spectra

- Survival Probability : $P(\bar{\nu}_e \leftrightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta \sin^2 \left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$



- sensitive to LMA region (assuming CPT conservation)
- higher Δm^2 regions reduce in size with new KamLAND data

- New Best fit

$\Delta m^2_\odot$ = 8.3 $\times 10^{-5}$ eV^2
$\sin^2\theta_\odot$ = 0.44

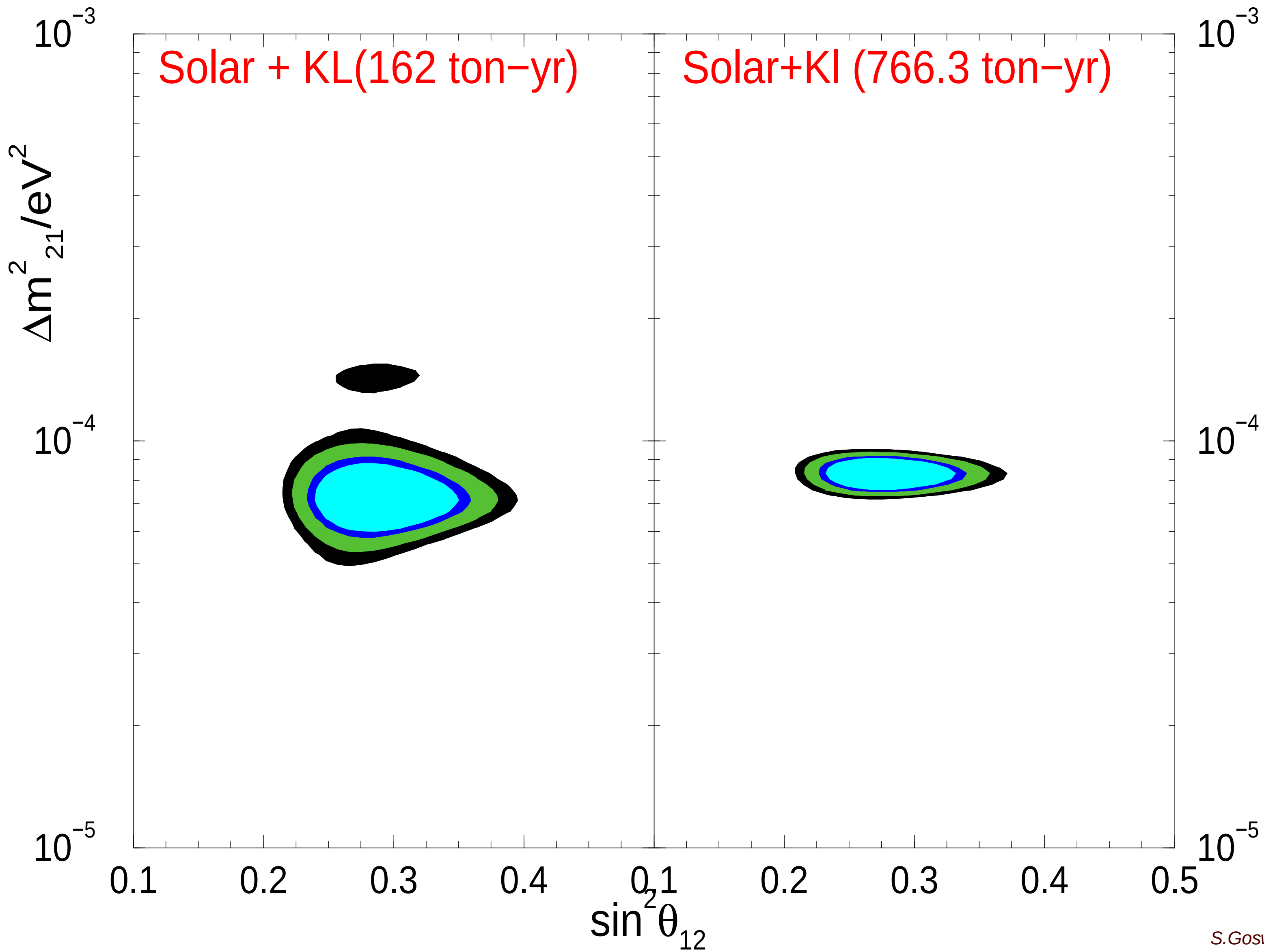
KL collaboration, 2004

- New Best fit

$\Delta m^2_\odot$ = 8.4 $\times 10^{-5}$ eV^2
$\sin^2\theta_\odot$ = 0.32

Bandyopadhyay et. al. 2004

Allowed area from Solar+KamLAND . . .



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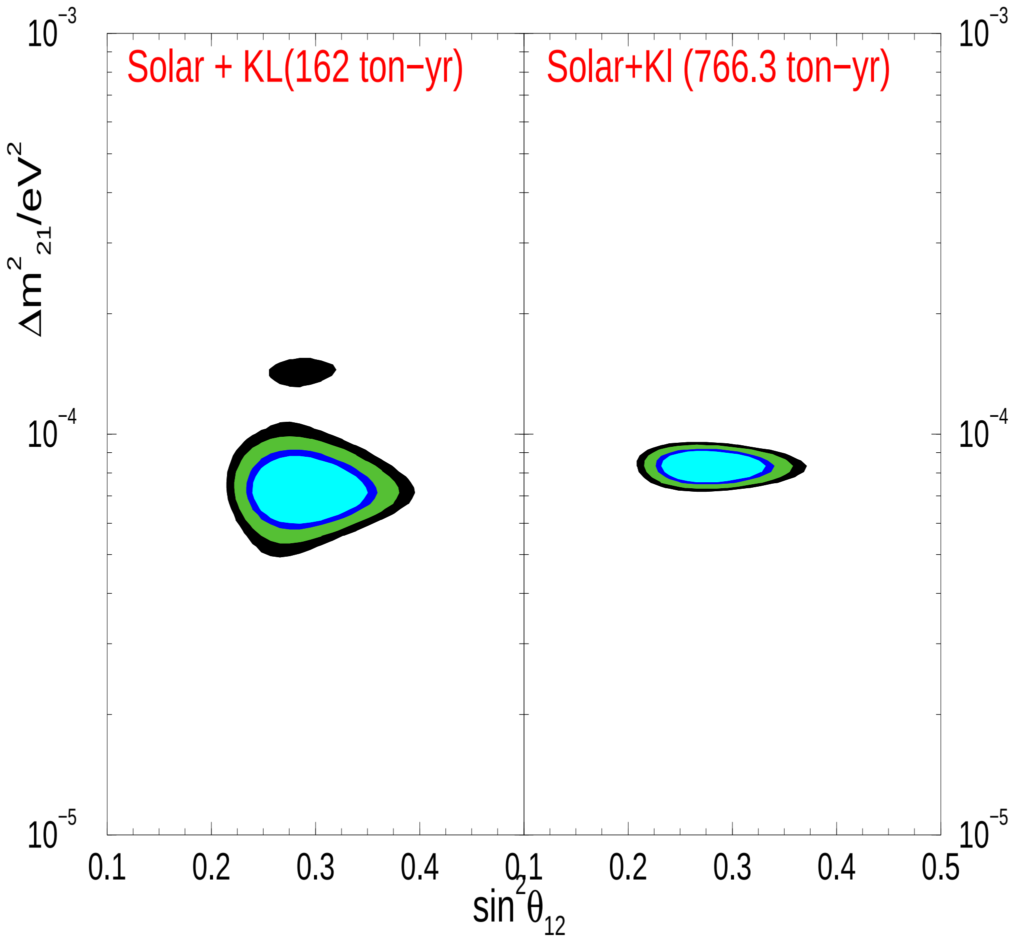
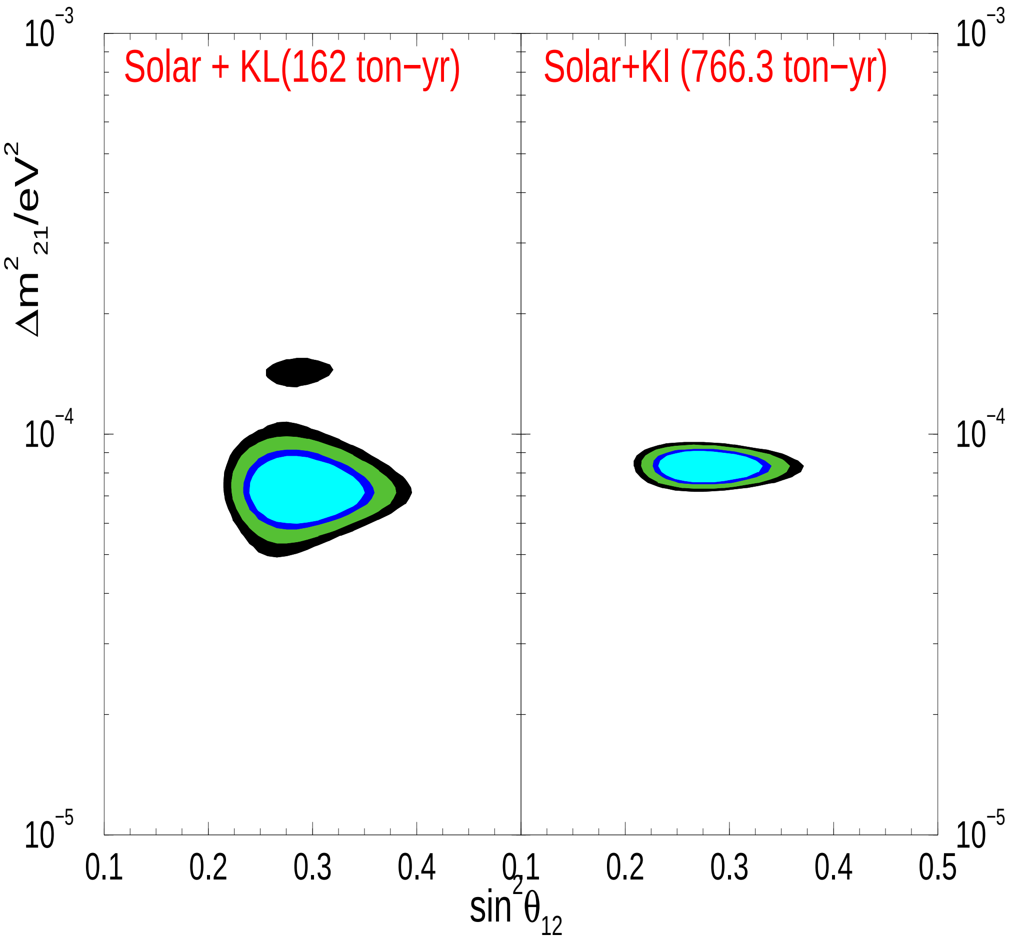


Allowed area from Solar+KamLAND ...



- **Best fit (KL 162Ty)**

Δm^2_{21} = 7.2 $\times 10^{-5}$eV^2
$\sin^2\theta_{12}$ = 0.29, f_B= 0.89

- **New Best fit (KL 766.3Ty)**

Δm^2_{21} = 8.3 $\times 10^{-5}$eV^2
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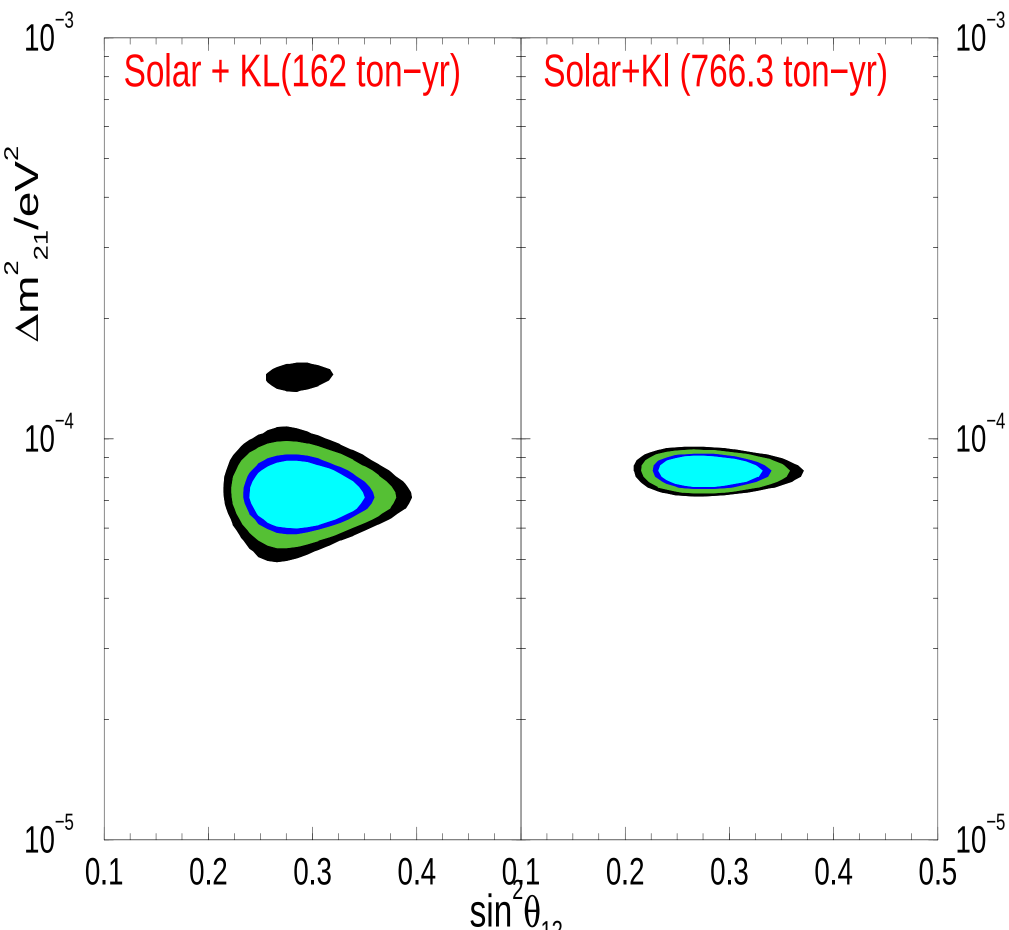
Bandyopadhyay et al., 2004

- **New Best fit (KL 766.3Ty)**

Δm^2_{21} = 8.2 $\times 10^{-5}$ eV^2
$\sin^2\theta_{12}$ = 0.28

KamLAND collaboration 2004

Allowed area from Solar+KamLAND ...



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- The high-LMA region is excluded at more than 3σ

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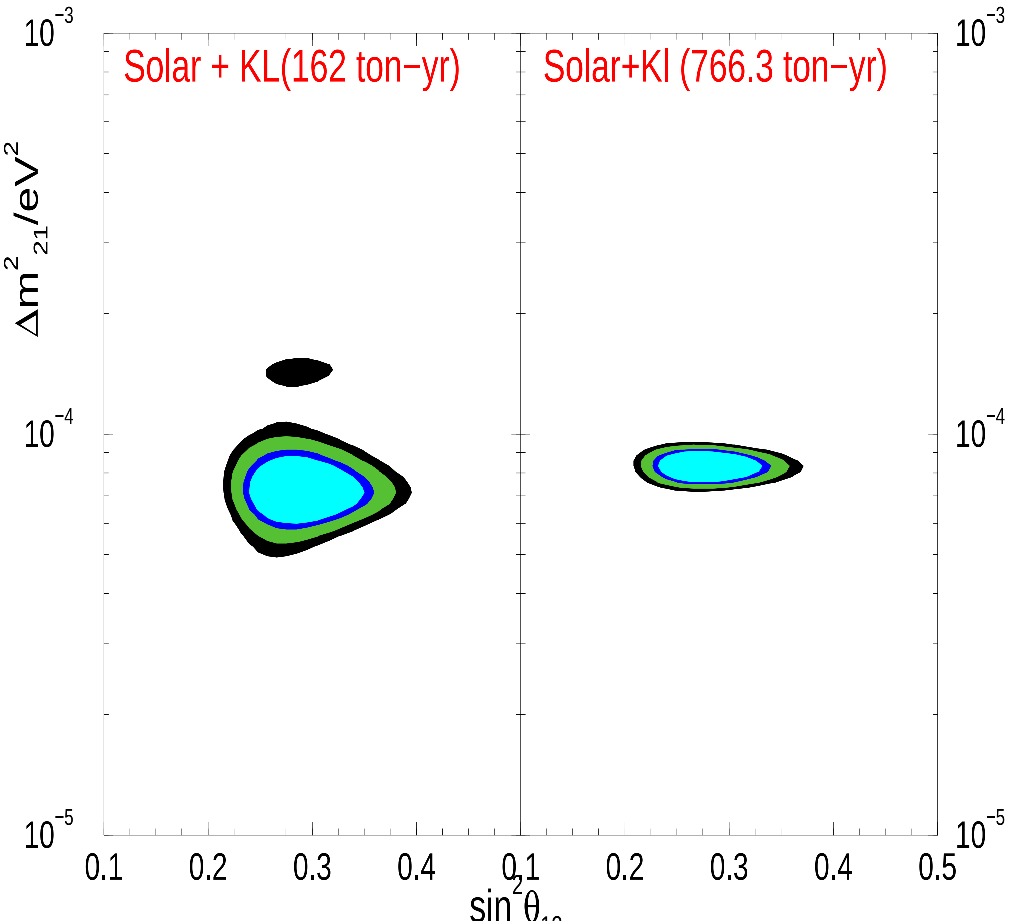

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KamLAND collaboration 2004

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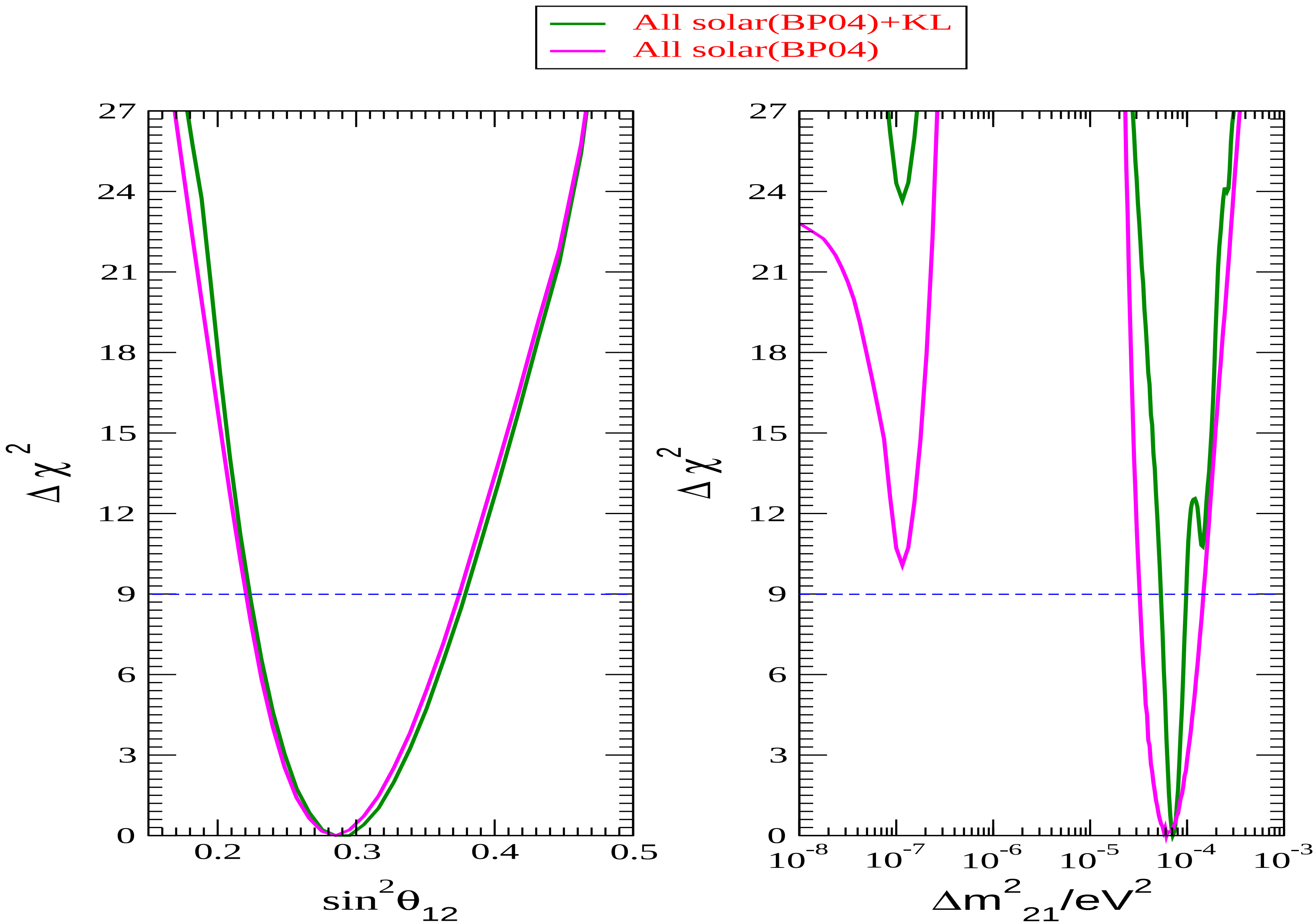
- Solar data disallows $\theta > \pi/4$ (Dark-Side) solutions ⇨ $\Delta m^2_{21} > 0$

Allowed area from Solar+KamLAND . . .



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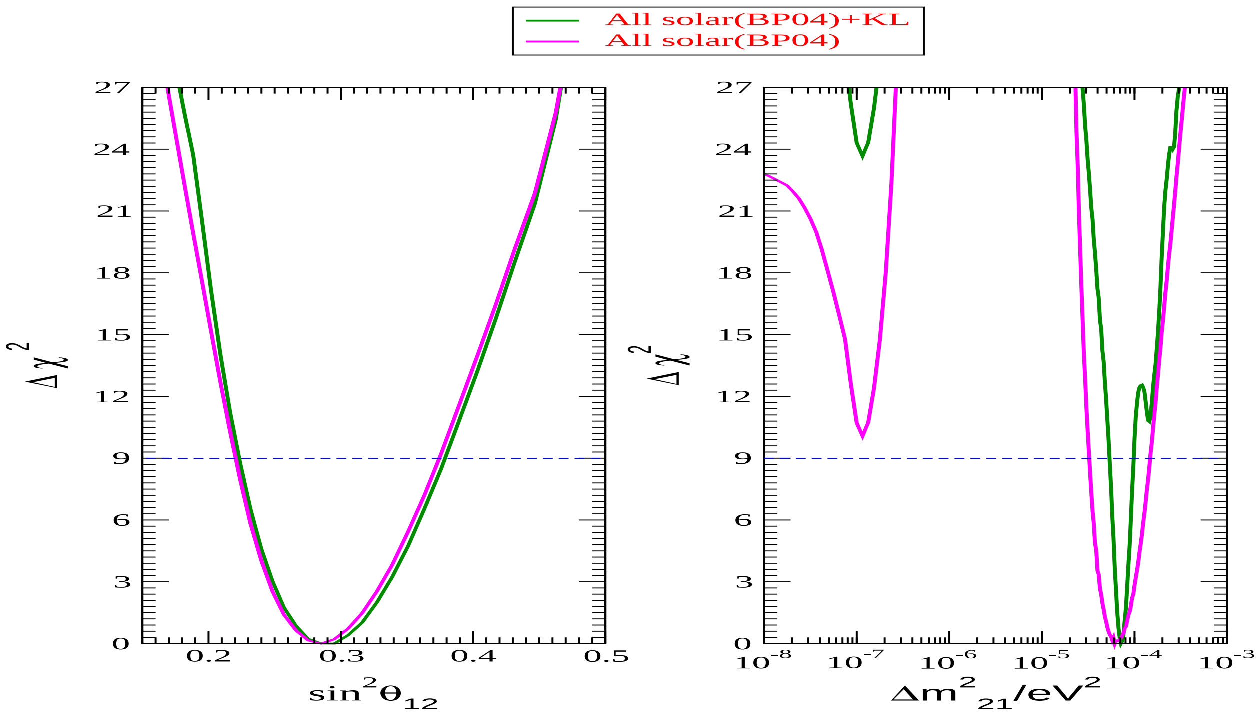

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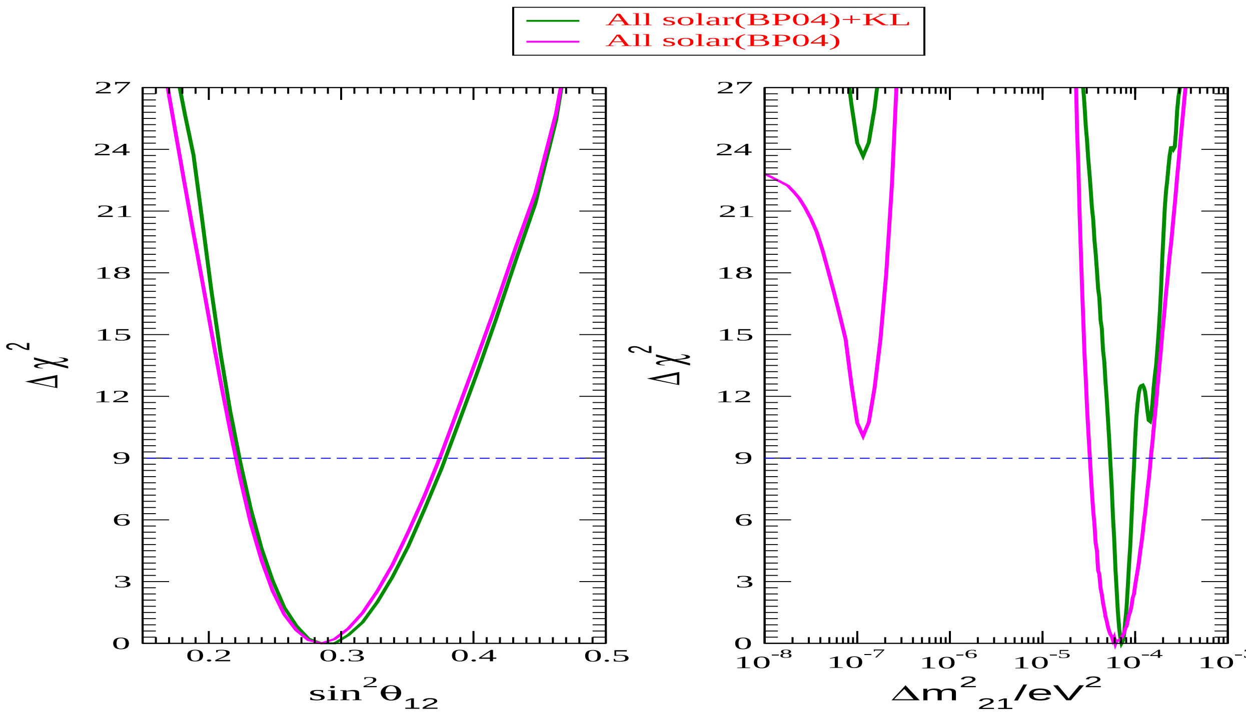

- Δm^2_{21} further constrained by KamLAND

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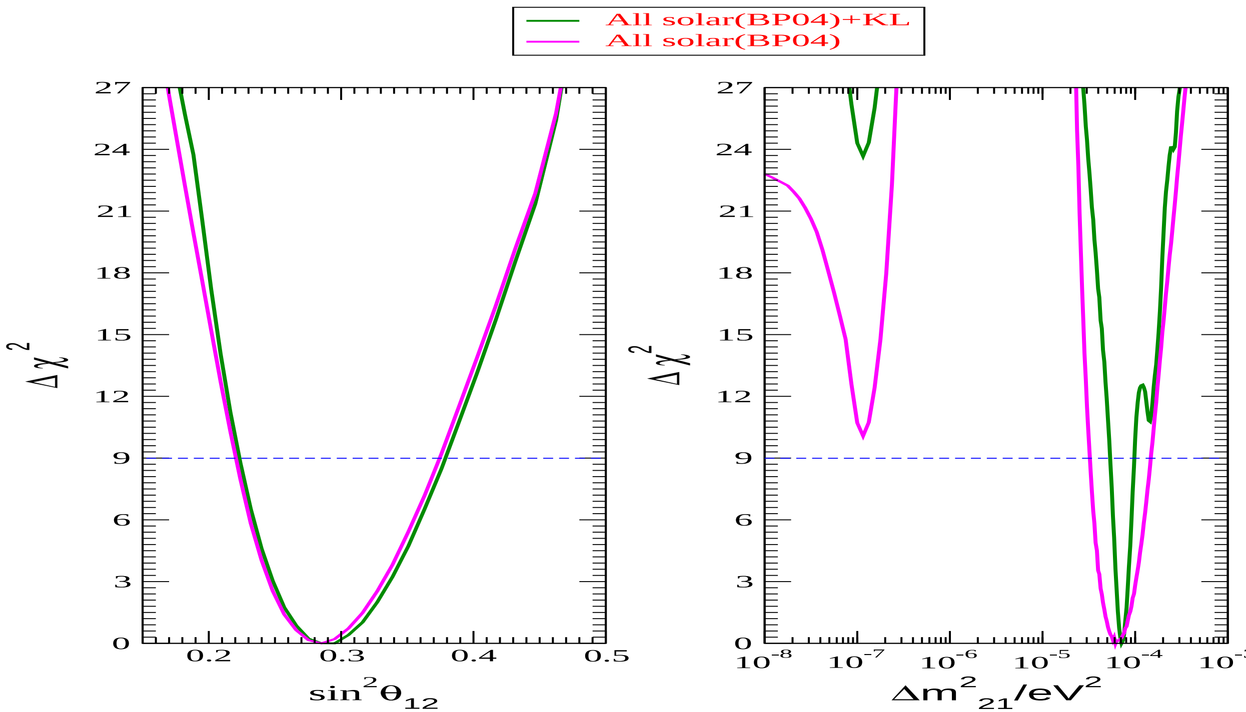

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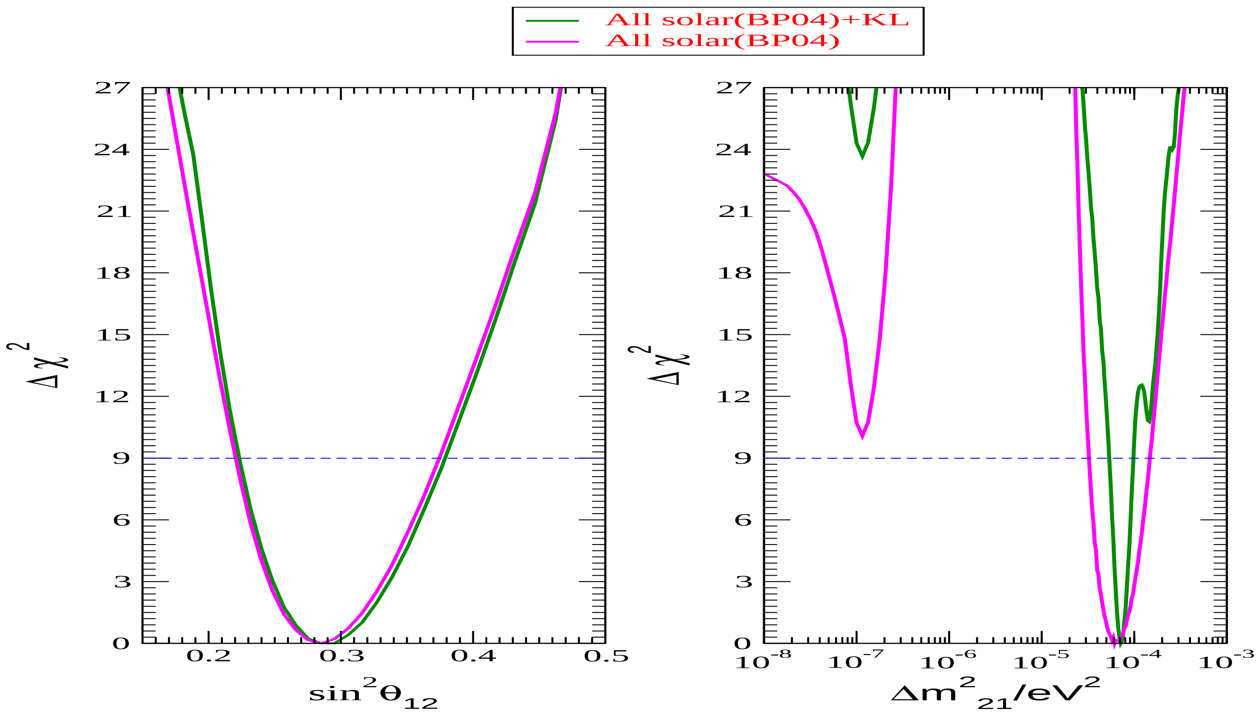
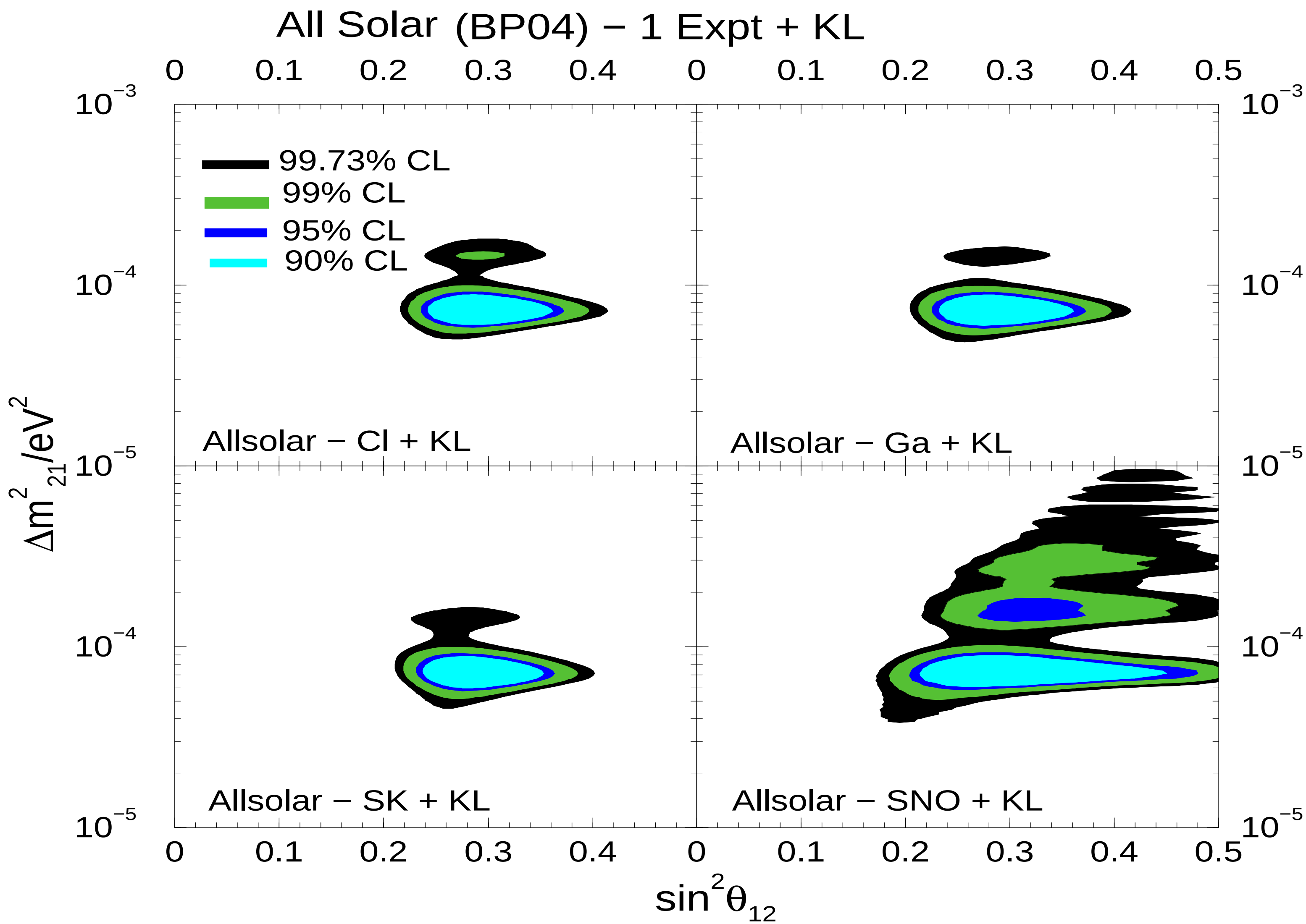


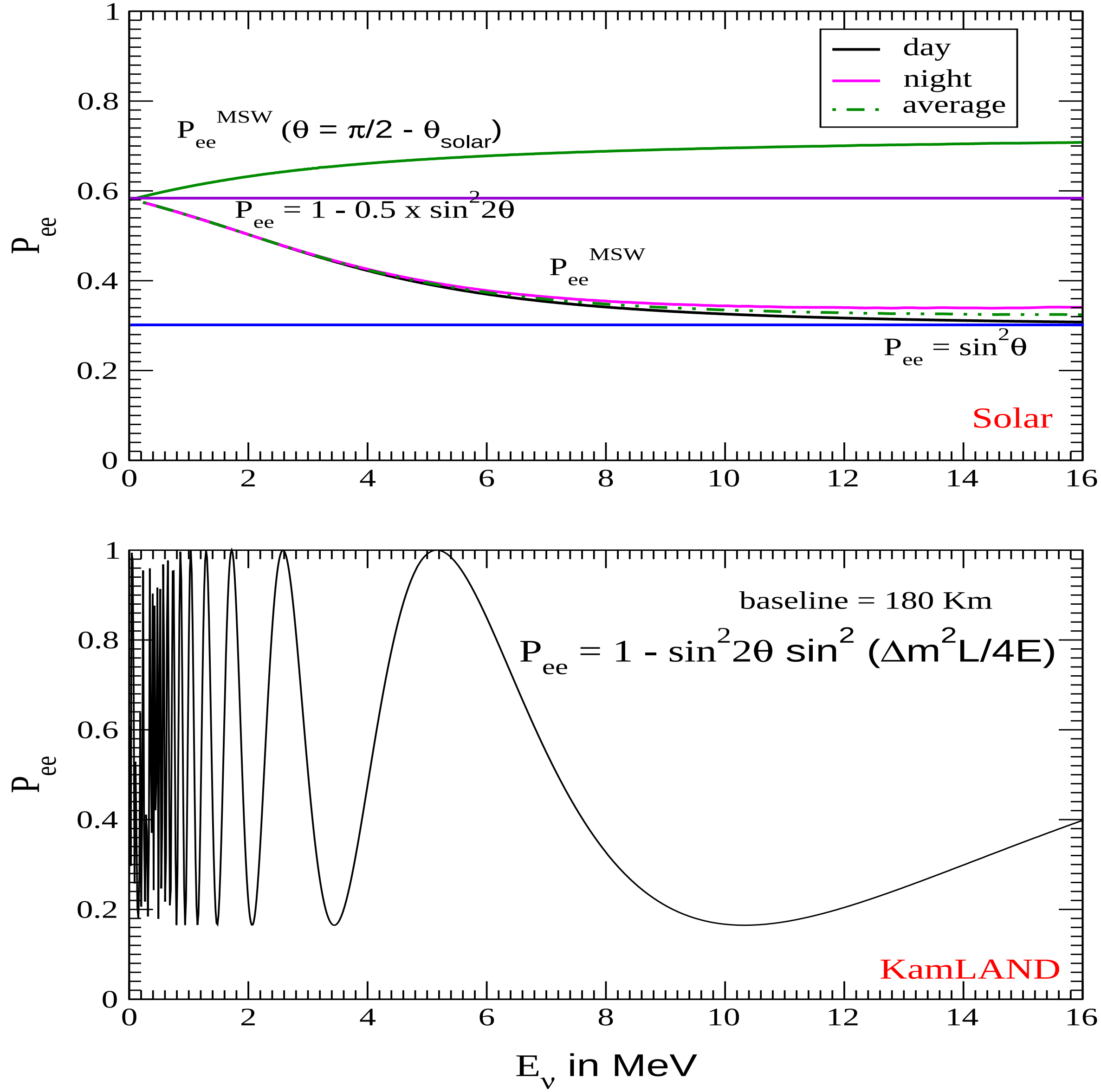
- Δm^2_{21} further constrained by KamLAND
- $\sin^2\theta_{12}$ not constrained any further
- LOW solution is disfavoured at more than 3σ by only solar data and at about 5σ by solar+KL data
- Maximal mixing is disfavoured at more than 5σ

Impact of each solar experiment . . .



- SNO instrumental in disfavouring maximal mixing, Dark side and higher Δm^2 solutions

Survival Probabilites for solar and KamLAND



On the precision of $\nu_\odot$ oscillation parameters

- 6%(5%) total error for future SNO NC(CC) data

$$\text{spread} = \frac{a_{max} - a_{min}}{a_{max} + a_{min}} \times 100\ \%$$

Data set used	Range* of $\Delta m^2_{21} \times 10^{-5}$ eV^2	spread in Δm^2_{21}	Range* of $\sin^2\theta_{12}$	spread in $\sin^2\theta_{12}$
only sol	3.2 - 14.9	65%	$0.22 - 0.37$	25%
sol+162 Ty KL	5.2 - 9.8	31%	$0.22 - 0.37$	25%
sol+ 766.3 Ty KL	7.3 - 9.4	13%	$0.22 - 0.36$	24%
future sol+1.3 kTy KL	6.7 - 7.8	8%	$0.24 - 0.34$	17%

* 99% C.L.

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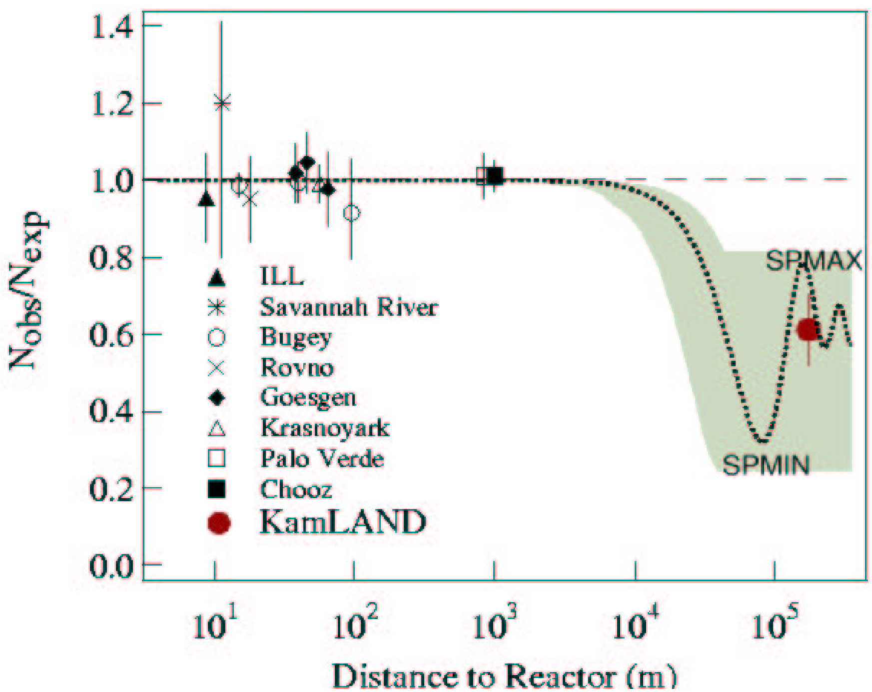
- KamLAND has tremendous sensitivity to Δm^2_{21}
- Does not constrain θ_{12} much better than the current set of solar experiments

Still closer look at KamLAND sensitivity

- $P_{ee} = 1 - \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2_{21} L}{4E} \right)$
- $\sin^2 \left(\frac{\Delta m^2_{21} L}{4E} \right) \to 1 \Rightarrow$ SPMIN, $\sin^2 \left(\frac{\Delta m^2_{21} L}{4E} \right) \to 0 \Rightarrow$ SPMAX
- SPMIN best for $\sin^2 \theta_\odot$ for $\sin^2 \theta_\odot \lesssim 0.37$



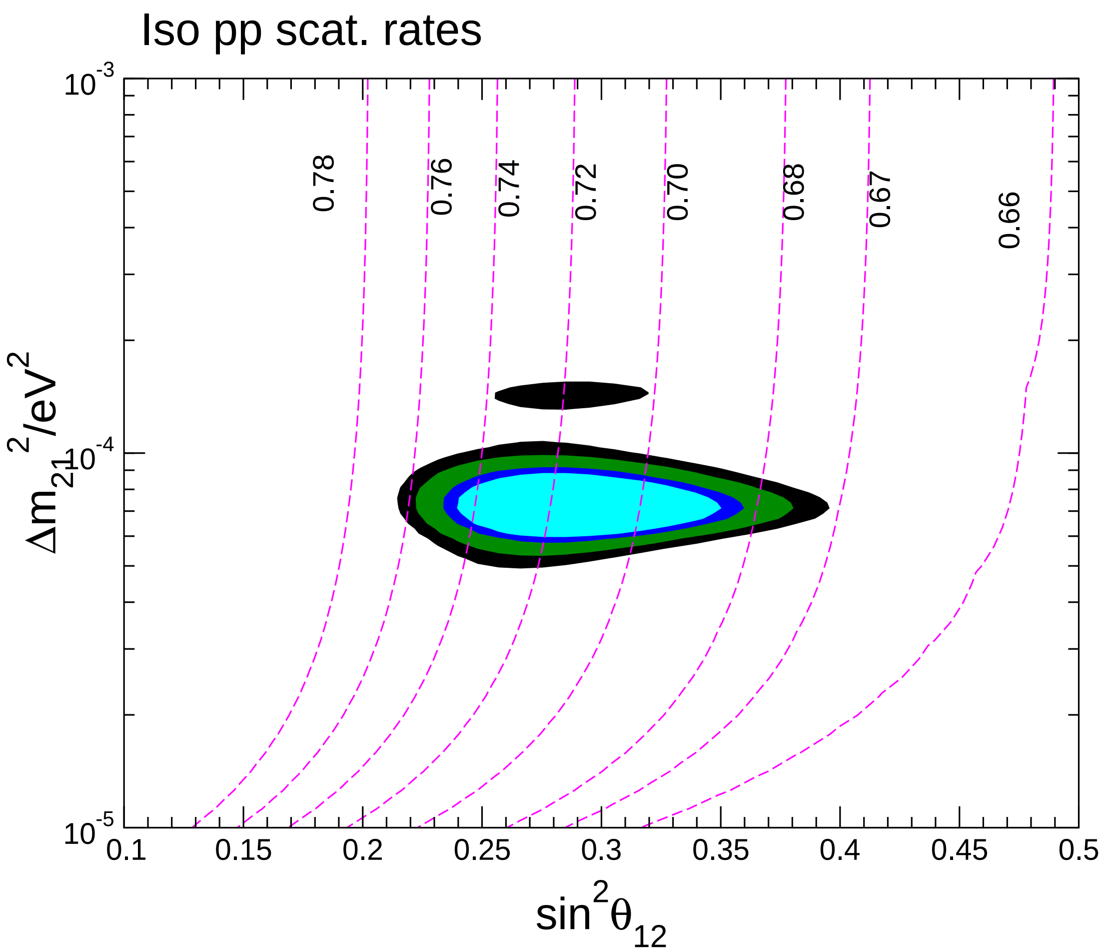
(KamLAND Collaboration, hep-ex/0212021)

Best-Fit: $\sin^2 \theta_\odot = 0.3$
Range: $0.22 < \sin^2 \theta_\odot < 0.37$

- KamLAND is at SPMAX
- The θ_{12} sensitivity gets smothered
- KamLAND is not at best position for θ_{12}
- SPMIN comes at $L \sim 70$ km for low-LMA
- Reactor Experiment at $L \sim 70$ km

A. Bandyopadhyay , S.Choubey, S.G. PRD, 2003

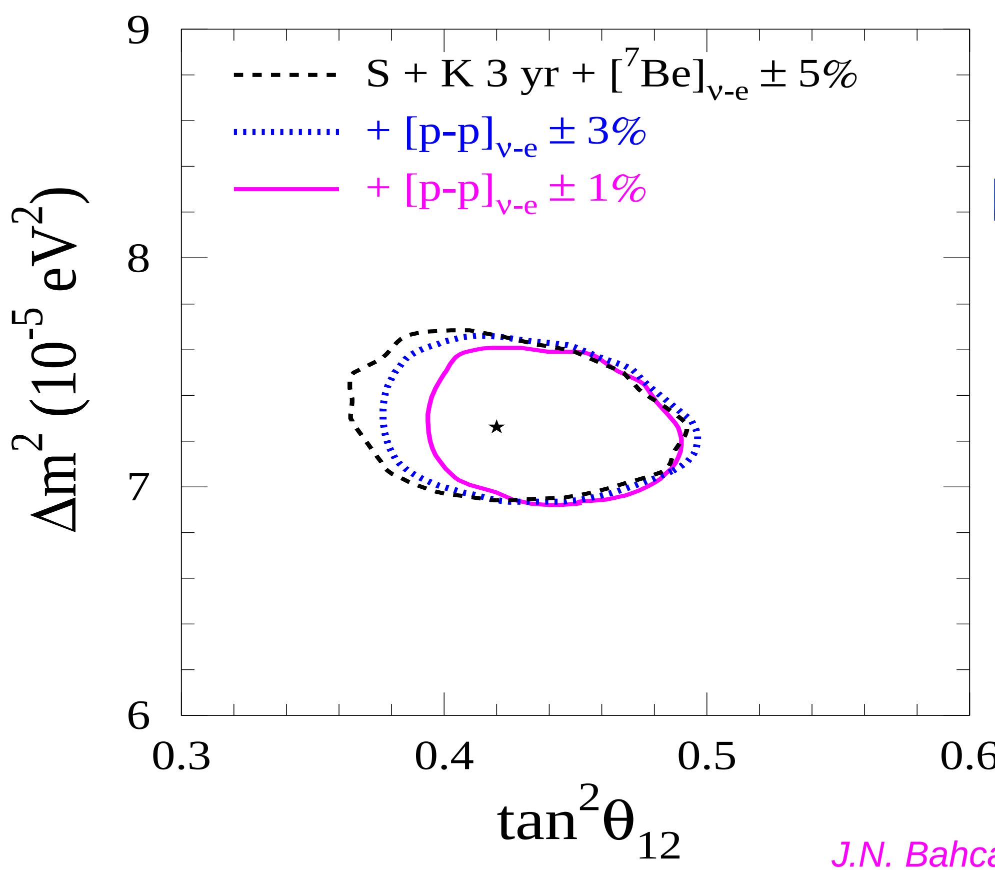
Potential of LowNU experiments for $\theta_\odot$



- The pp flux is known with 1% accuracy from Standard Solar Models ($^8B \sim$ 20%, $^7Be \sim$ 10%)
- Can pin down θ_{12} if experimental errors are low

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

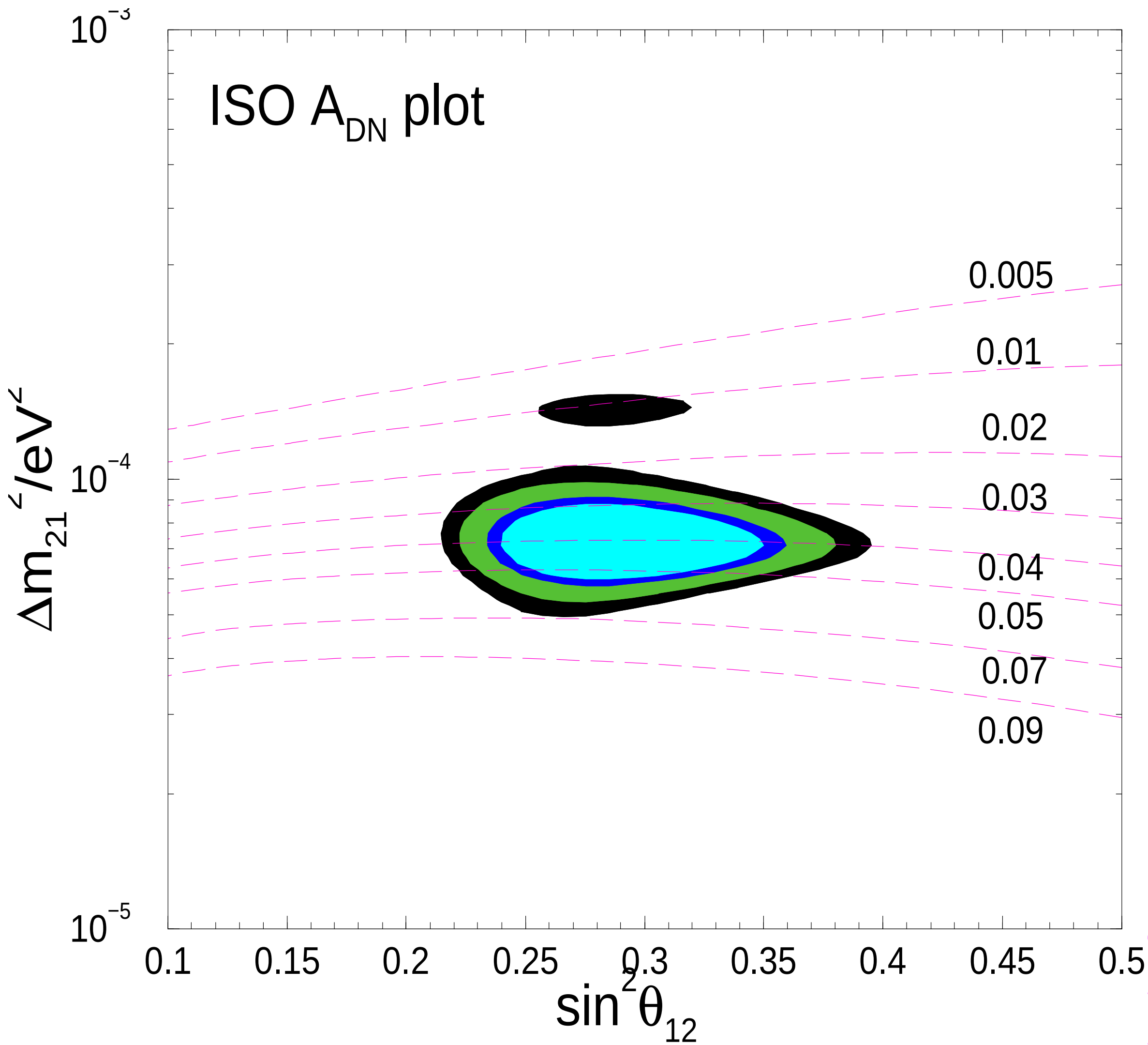
Potential of LowNU experiments for $\theta_\odot$



- Precision in θ_{12} increases with reduced error in pp flux measurement

J.N. Bahcall and C. Pena-Garay, hep-ph/0305159

Potential of day/night asymmetry for Δm^2_{21}



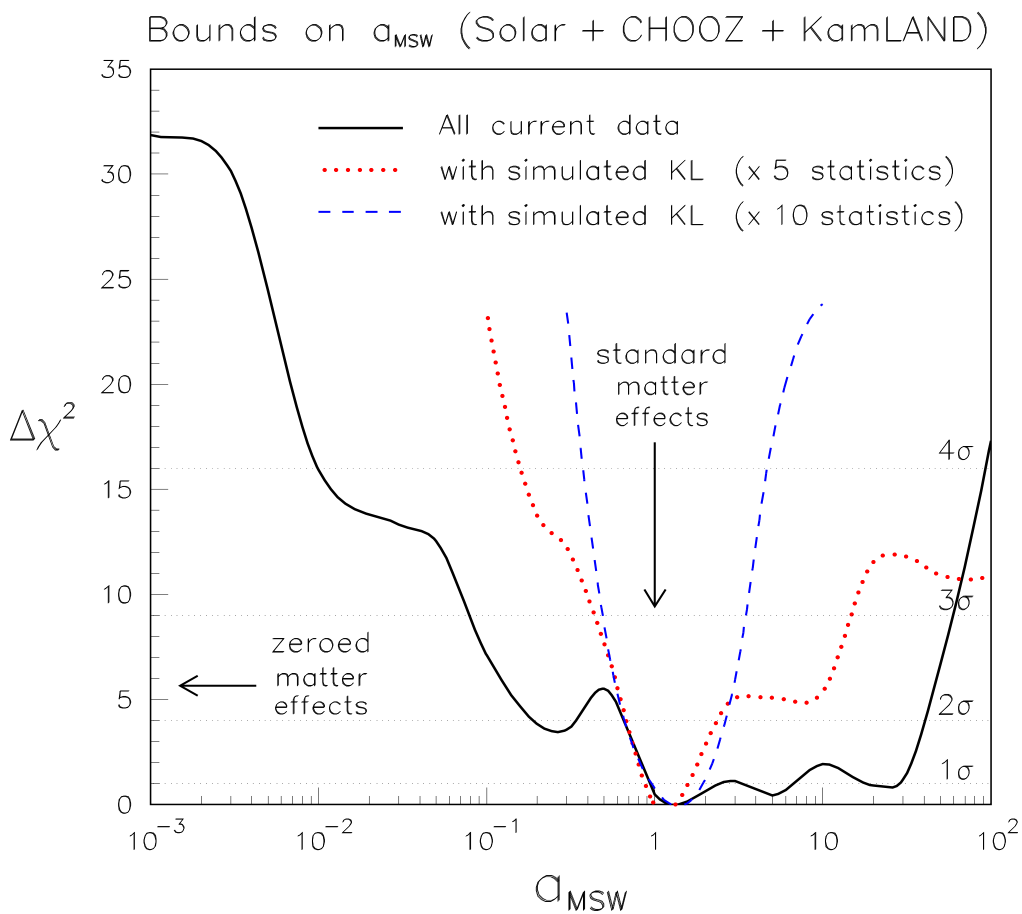
$$A_{D/N} = 2\frac{N - D}{N + D}.$$

Maris, Petcov
de. Hollanda, Smrinov
Blennow, Ohlsson,Snellman
Bandyopadhyay et al.

A^{SNO}_{DN}=0.04, 3σ range:0.02-0.07,(low-LMA)

$A^{SNO}_{DN} \approx$ 0.01, 3σ range: 0.009-0.014, (high-LMA).

Evidence for MSW effect in Sun . . .



$$V_{MSW} = \sqrt{2} G_F n_e$$
$$V_{MSW} \rightarrow \alpha_{MSW} . V$$

- "No MSW" rejected at several σ

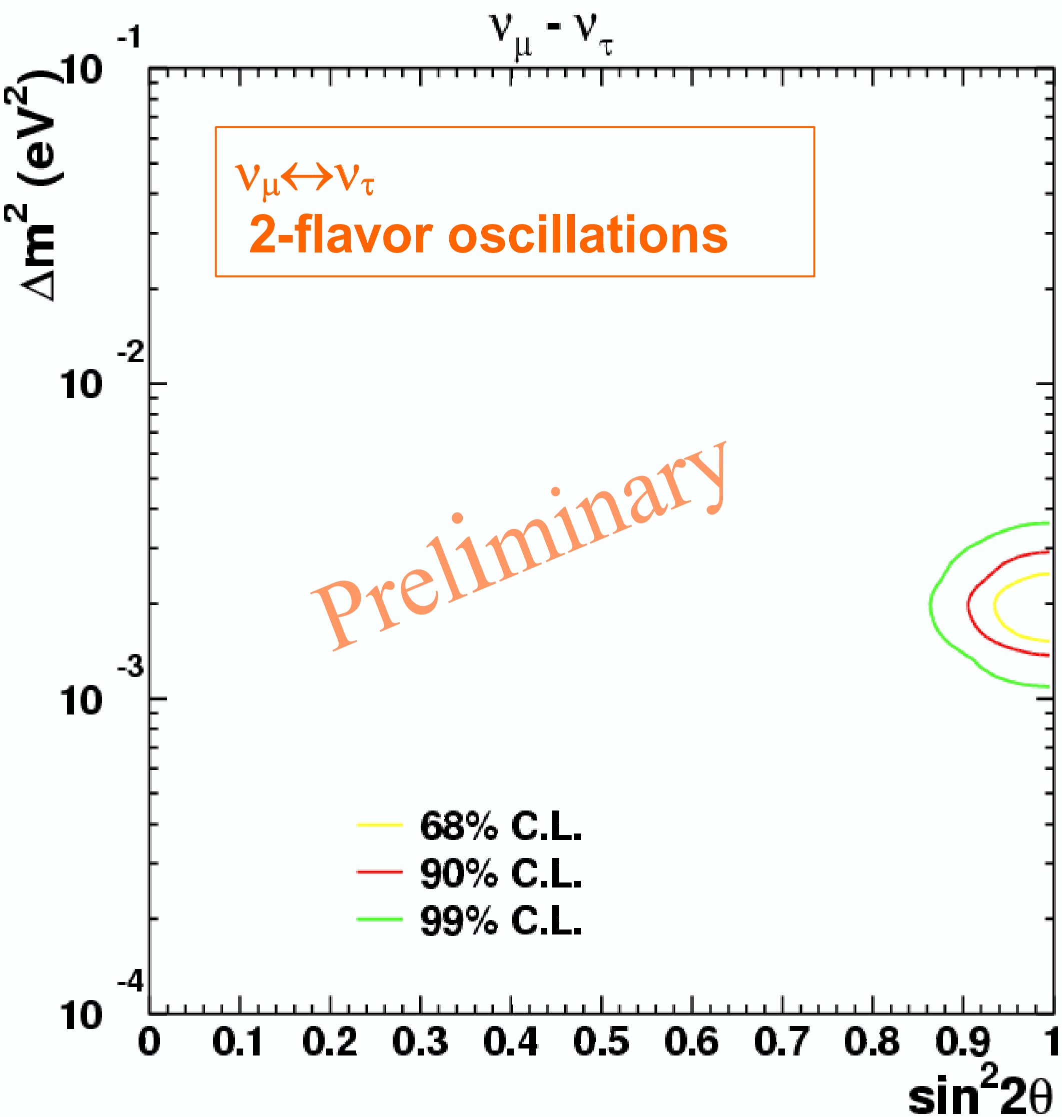
Fogli et al. 2003

- Increased statistics from KL can put stronger constraints
- More precise test of MSW and "new" physics beyond MSW

Atmospheric Neutrino Oscillation Parameters: two flavour analysis of SK +K2K data

Oscillation Analysis Results

(FC + PC + UP-μ)



C.Saji NOON2004

- **Best fit:**
  $\sin^2 2\theta = 1.0$
  $\Delta m^2 = 2.0\times10^{-3}$ eV^2
  $\chi^2 = 170.8/170$ dof

- **90% C.L. region:**
  $\sin^2 2\theta > 0.90$
  $1.3 < \Delta m^2 < 3.0\times10^{-3}$ eV^2

Best-fit ⇨ 2.1×10^{-3} eV^2

E. Kearns, Neutrino 2004

Analysis of SK Atmospheric Data

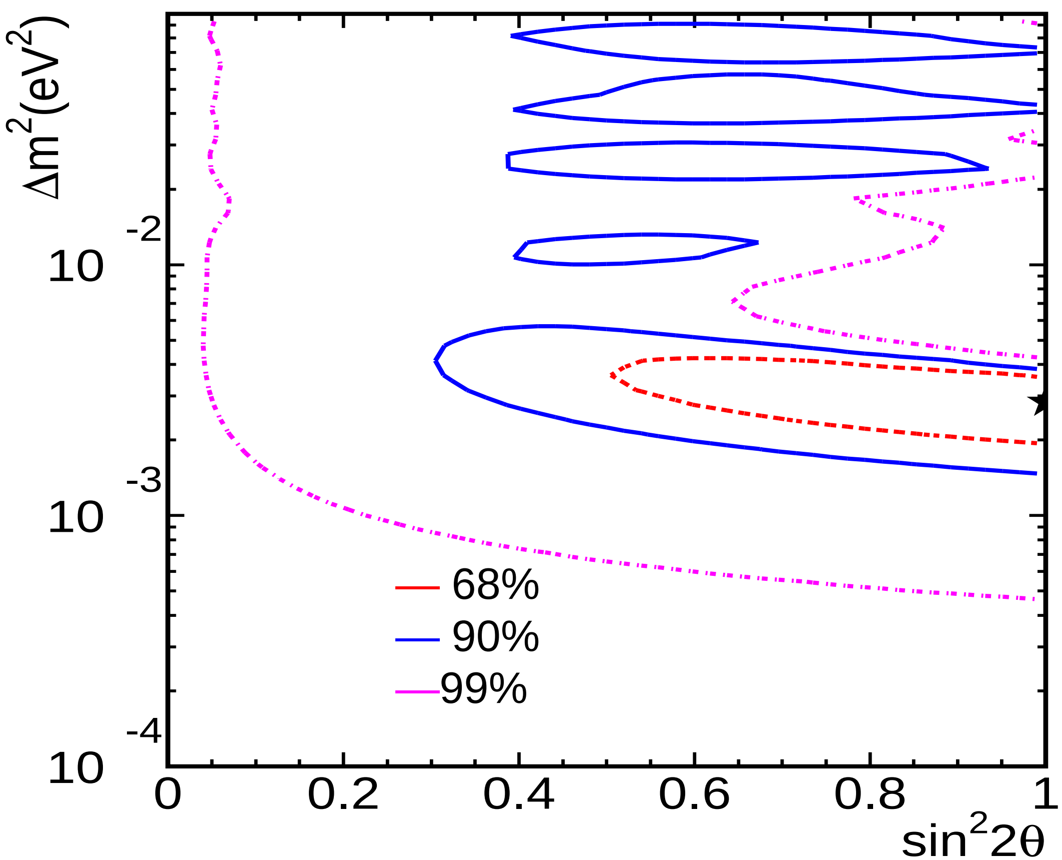
- Analysis of SuperKamiokande data by two groups * confirm this downward shift of Δm^2_{atm}
- Three-Dimensional Honda Atmospheric Fluxes
- Normalisation to SK Monte Carlo to include the effect of revised efficiencies and cross-sections
- Pull approach for systematic uncertainties
  — provides useful information on the role of systematic uncertainties on the best-fit rates.

∗*Maltoni et al.,hep-ph/0405172*

∗*Gonzalez-Garcia et al., hep-ph/0404085*

Allowed area from K2K Experiment

- $P_{\mu\mu} = 1 - \sin^2 2\theta_{atm} \sin^2\left(\frac{\Delta m^2_{atm} L}{4E}\right)$
- L $\sim$ 250 km, $E_\nu \sim$ 1.3 GeV



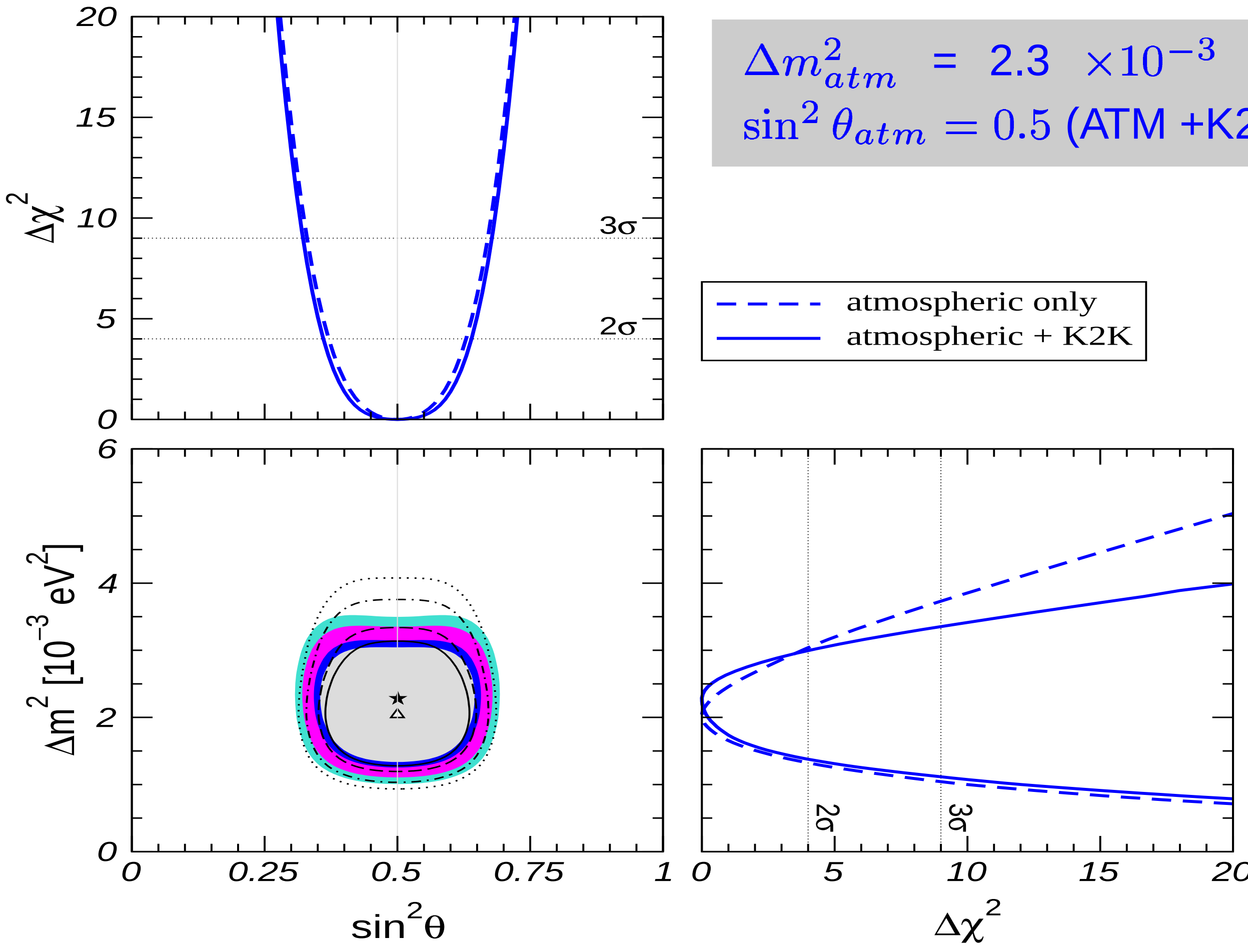
- **Best-fit**

Δm^2_{atm} = 2.8 $\times 10^{-3}$ eV^2

$\sin^2 2\theta_{atm} = 1.0$

K2K collaboration, 2003

Allowed parameters from SK+K2K analysis

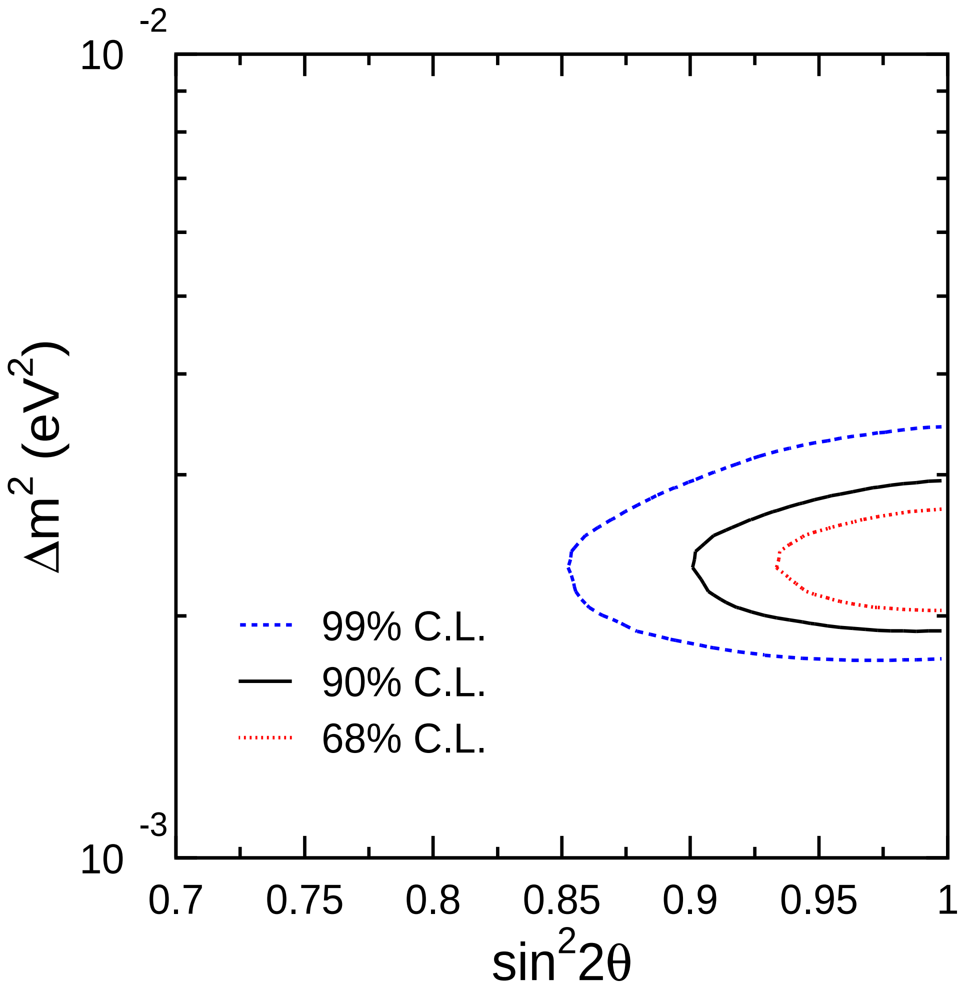


Δm^2_{atm} = 2.3 $\times 10^{-3}$ eV^2,
$\sin^2\theta_{atm} = 0.5$ (ATM +K2K)

Maltoni et al.,hep-ph/0405172

- Higher Δm^2 values are constrained by K2K
- K2K data does not constrain θ_{atm} any better

Allowed area from SK L/E data . . .



- Best-fit

Δm^2_{atm} = 2.4 $\times 10^{-3}$ eV^2,
$\sin^2 2\theta_{atm} = 1.0$ (SK L/E)

- 90% C.L. range

Δm^2_{atm} = 1.9 - 3.0 $\times 10^{-3}$ eV^2,
$\sin^2 2\theta_{atm} >$ 0.9 (SK L/E)

spread in Δm^2_{atm} = 22%

- 90% C.L. range

Δm^2_{atm} = 1.3 - 3.0 $\times 10^{-3}$ eV^2,
$\sin^2 2\theta_{atm} >$ 0.9 (SK Zenith)

spread in Δm^2_{atm} = 39%

- Improved precision in Δm^2_{atm} with L/E data
- Range of $\sin^2 \theta_{atm}$ unchanged $\rightarrow \delta(\sin^2 2\theta_{23}) \sim 5\%$

Y. Ashie et al. SK collaboration, hep-ex/0404034

Precision of atmospheric neutrino oscillation parameters

- $\delta(\sin^2\theta_{23}) \sim 32\%$ ⇨ $\sin^2\theta_{23}$ precision is worse than $\sin^2 2\theta_{23}$ precision near maximal mixing
- $\delta(\sin^2 2\theta_{23})$ = $\sqrt{(\text{exposure})}$ ⇨ more statistics from SK
  - $\delta(\sin^2\theta_{23}) \sim$ 22% in SK 20 years at 90% C.L..
- Increased statistics in L/E data can improve $\delta(\Delta m^2_{32})$
  - $\delta(\Delta m^2_{32}) \sim$ 10% in SK 20 years at 90% C.L..
- Effect sensitive to the true Δm^2_{32} chosen (Δm^2_{32}=2.5 $\times 10^{-3}$ eV^2)

T.Kajita, Talk in NOON2004

Precision of atmospheric neutrino oscillation parameters

- Large Magnetized Iron (30-100 kT) calorimeters have very good L/E resolution
  - excellent muon track and charge identification
  - $\sim$ 5% energy resolution
- MONOLITH was first proposed for GranSasso

  MONOLITH proposal, http://castore.mi.infn.it/∼monolith
- INO : currently planned for location in India
  $\delta(\Delta m^2) \sim$ 10% for 150 kTy $\sim$ 5 yrs of INO
  (at $\Delta m^2_{atm} \sim$ 3.0 $\times 10^{-3}$ eV^2)

  http:/www.imsc.res.in/∼ino
- Longbaseline, Superbeam . . .

Three Flavour Oscillation

- Two mass squared differences

$$\Delta m^2_{21} = \Delta m^2_{\odot}, \quad \Delta m^2_{31} = \Delta m^2_{CHOOZ} \simeq \Delta m^2_{atm} = \Delta m^2_{32}$$

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- Three mixing Angles

Three Flavour Oscillation

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- Three mixing Angles
- $U = R_{23} R_{13} R_{12}$ =

$$\begin{pmatrix} c_{13}c_{12} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - s_{23}s_{13}c_{12} & c_{23}c_{12} - s_{23}s_{13}s_{12} & s_{23}c_{13} \\ s_{23}s_{12} - s_{13}c_{23}c_{12} & -s_{23}c_{12} - s_{13}s_{12}c_{23} & c_{23}c_{13} \end{pmatrix}$$

Three Flavour Oscillation

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  $\Delta m^2_{21} = \Delta m^2_{\odot}, \quad \Delta m^2_{31} = \Delta m^2_{CHOOZ} \simeq \Delta m^2_{atm} = \Delta m^2_{32}$
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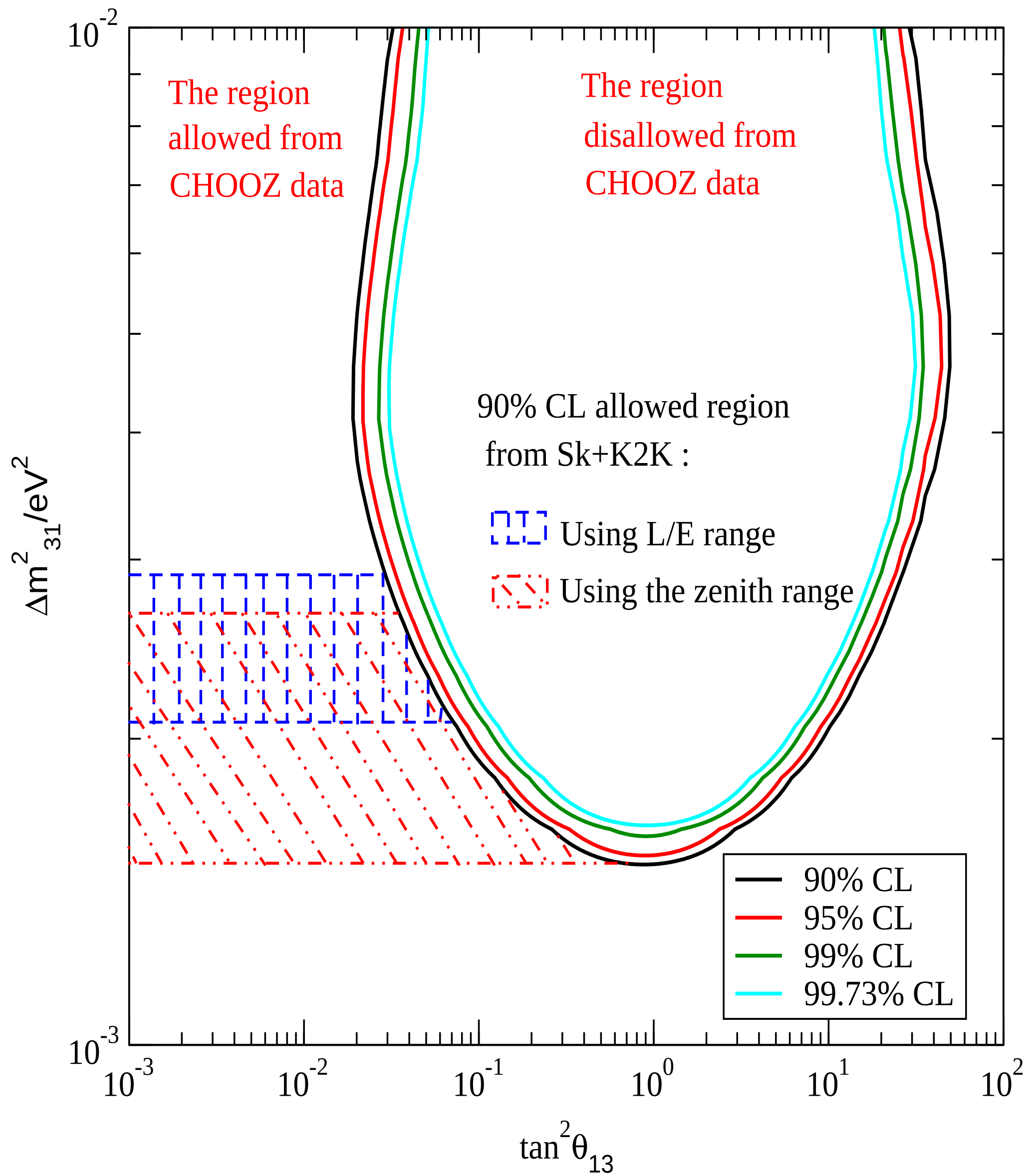
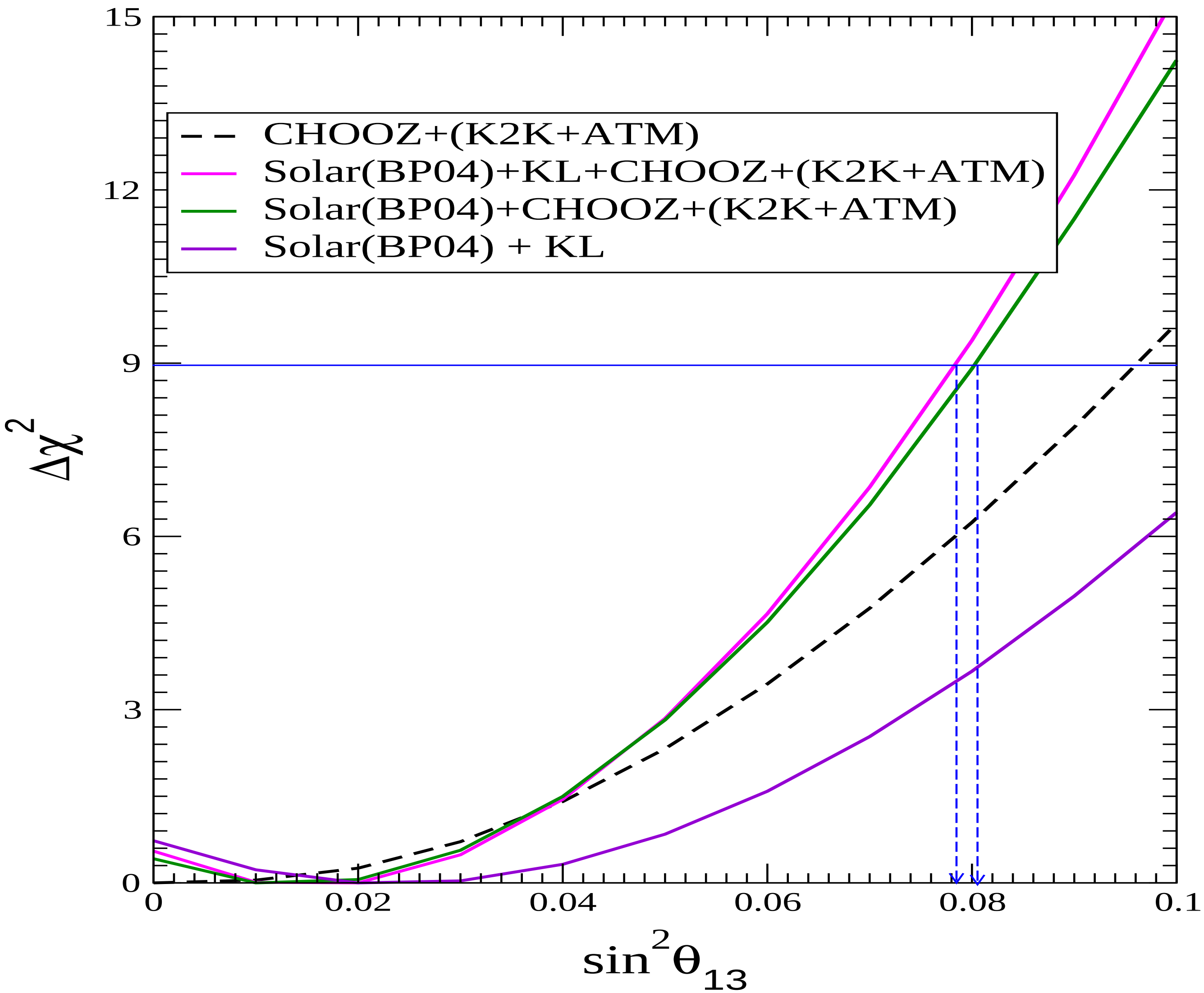
- Three mixing Angles
- $\Delta m^2_{21} << \Delta m^2_{32}$
  - Atmospheric probabilites depend on Δm^2_{32}, θ_{13}, θ_{23}
  - Solar neutrino probabilites depend on Δm^2_{21}, θ_{12}, θ_{13}
  - CP violation phases can be neglected
  - $\theta_{13} = 0 \Rightarrow$ solar and atmospheric neutrinos decouple
  - CHOOZ probability depends on Δm^2_{31}, θ_{13}

Allowed area from CHOOZ

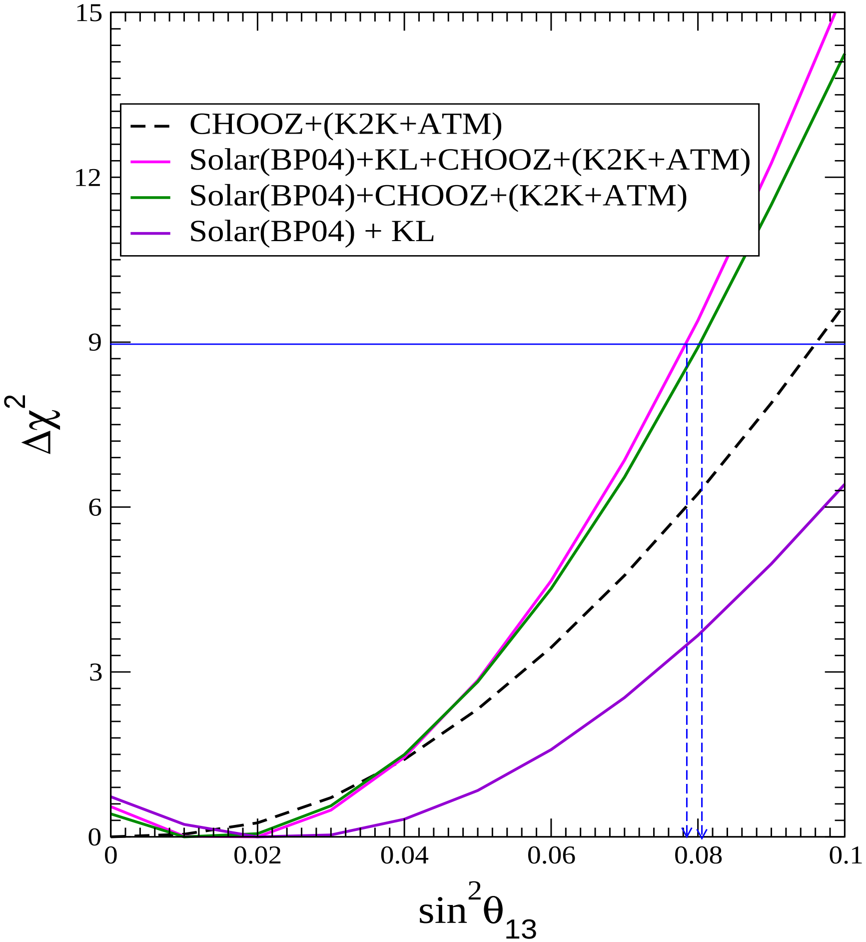


- CHOOZ/PaloVarde $\rightarrow$ bound on θ_{13} from non-observation of $\bar{\nu_e}$ disappearance
- The θ_{13} bound from CHOOZ depends on Δm^2_{31}
- Stronger bounds for higher Δm^2_{31}

Bounds on $\sin^2\theta_{13}$



Bounds on $\sin^2\theta_{13}$



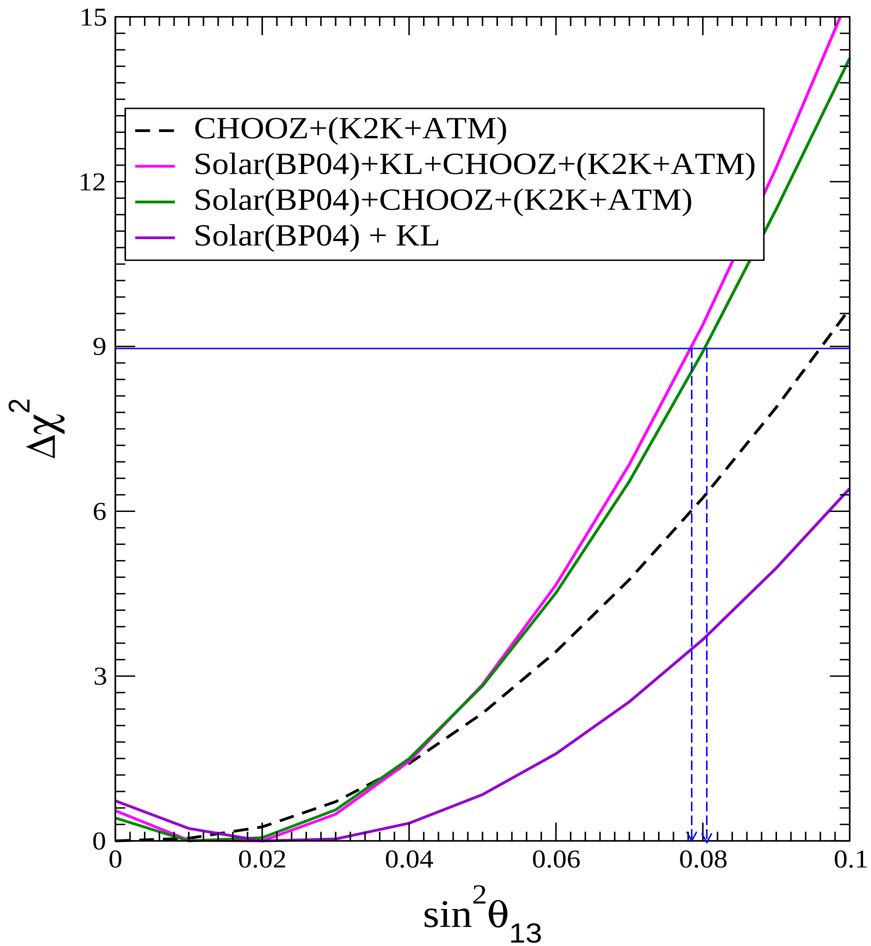
3σ Bounds ($\Delta\chi^2 = 9$)

- **Assuming the Δm^2_{32} range from SK+K2K analysis**

$\sin^2\theta_{13} < 0.096$	(CHOOZ+ ATM+K2K)
$\sin^2\theta_{13} < 0.077$	(Sol+CHOOZ+ ATM+K2K)
$\sin^2\theta_{13} < 0.074$	(all data)

Bandyopadhyay et al., 2003

Bounds on $\sin^2\theta_{13}$



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$\sin^2\theta_{13} < 0.074$ (all data)

Bandyopadhyay et al., 2003

- **Assuming the SK zenith analysis**

$\sin^2\theta_{13} < 0.067$ (all data)

Fogli et al., 2003

- **Assuming SK L/E analysis**

$\sin^2\theta_{13} < 0.05$ (all data)

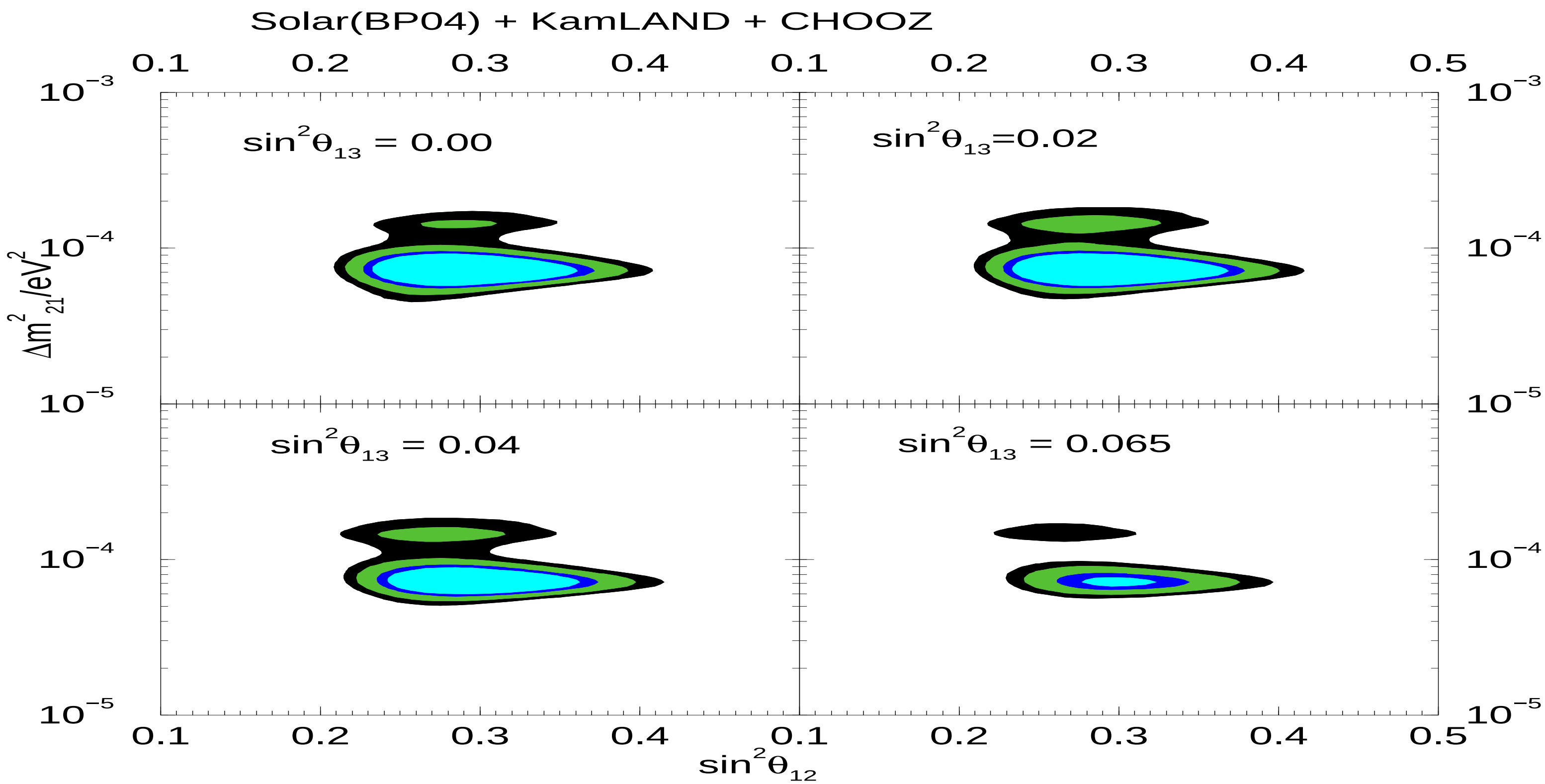
Fogli, Lisi, Marrone, Palazo, 2004

- **SK zenith+K2K+solar+reactor analysis**

$\sin^2\theta_{13} < 0.061$ (all data)

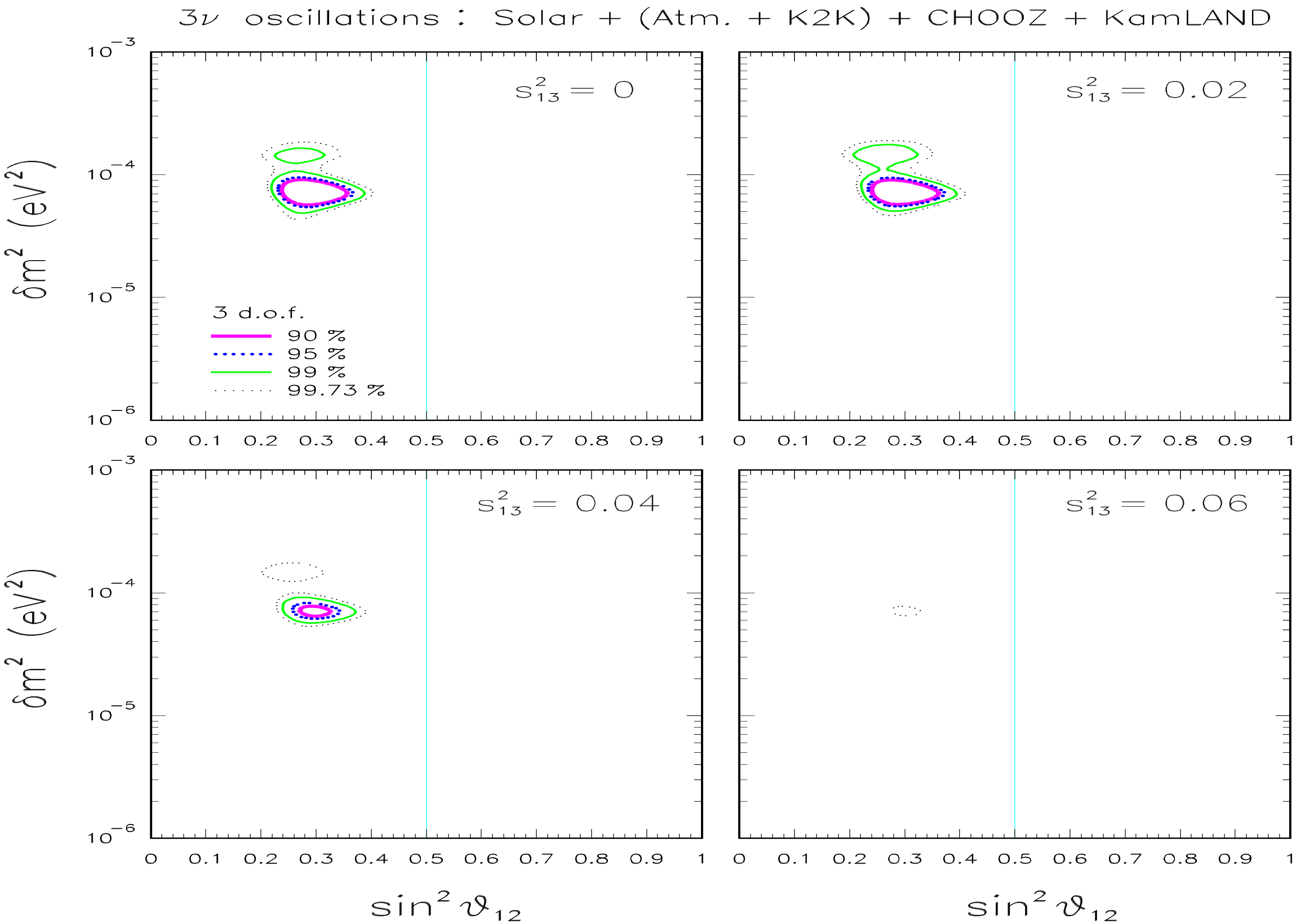
Maltoni et al,2004

Effect of $\sin^2\theta_{13}$ *on Solar Parameters*



- **Solar:** $P_{ee} \approx \cos^4\theta_{13}\sin^2\theta_{12}$
- **KamLAND** $P_{ee} = \cos^4\theta_{13}\left(1 - \sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{21}\,L}{4\,E_\nu}\right)$
- **CHOOZ** $P_{ee} = \left(1 - \sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}\,L}{4\,E_\nu}\right)$

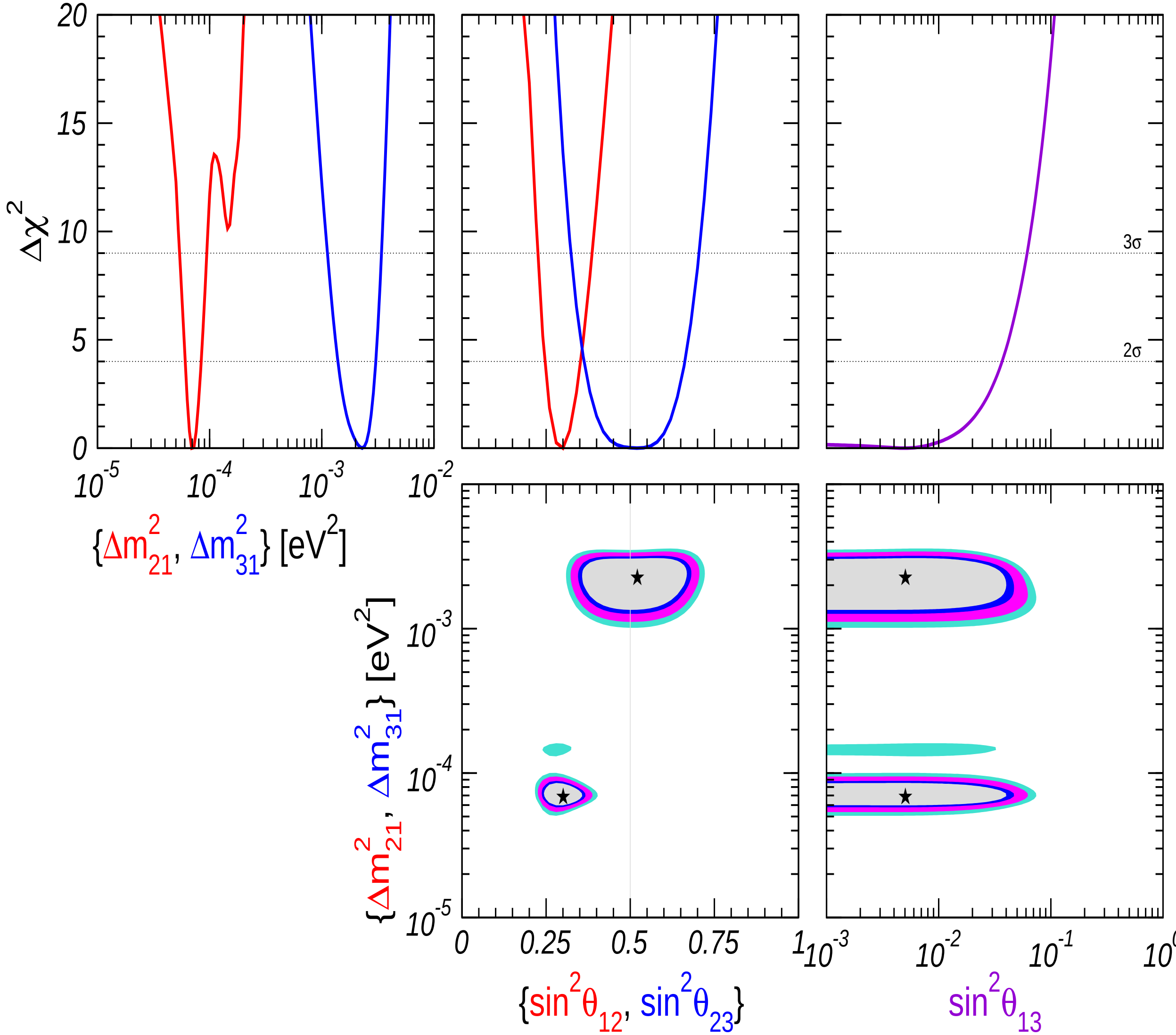
Effect of $\sin^2\theta_{13}$ *on Solar Parameters*



- Using the SK likelihood function of Δm^2_{32},$\sin^2\theta_{23}$ from the SK L/E analysis by graphical reduction

Fogli, Lisi, Marrone, Palazo, 2004

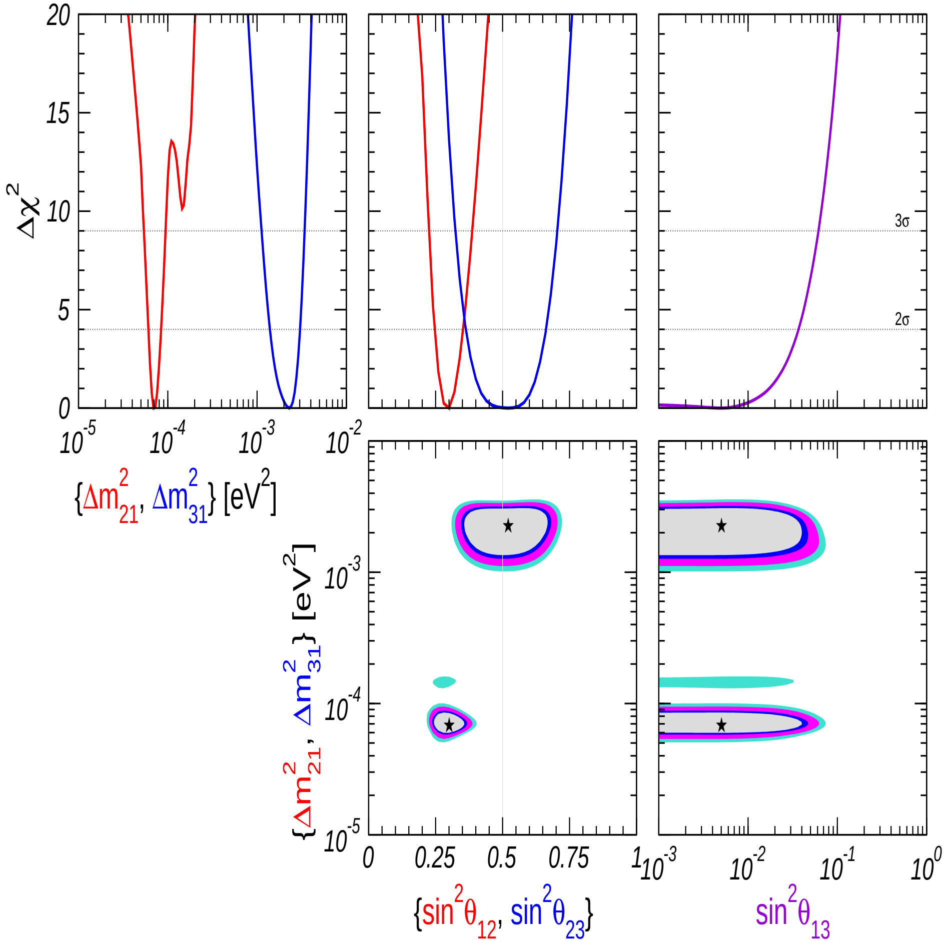
Three generation parameters



Maltoni et al., 2004

- Minimised w.r.t undisplayed parameters

Three generation parameters



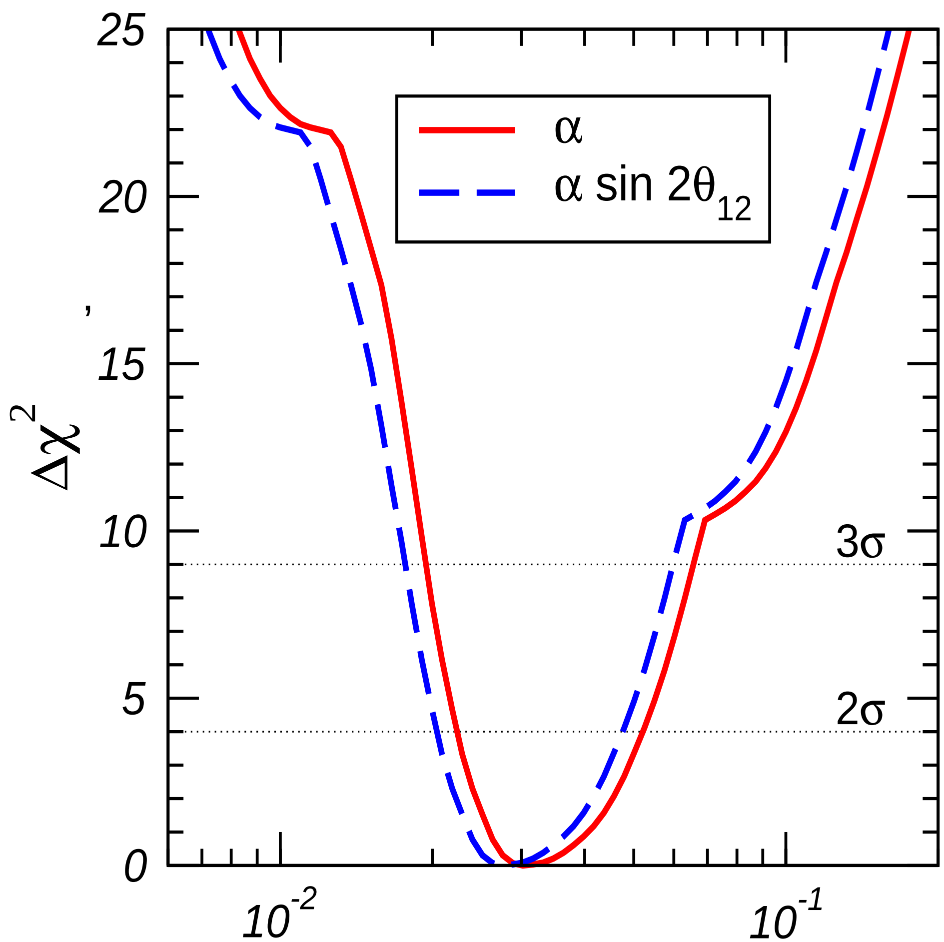
- 3σ range: 3-flavour analysis

Δm^2_{31} = 1.1 -3.4 $\times 10^{-3}$ eV^2
$\sin^2\theta_{23}$ = 0.32 -0.7
Δm^2_{21} = 5.4 -9.4 $\times 10^{-5}$ eV^2
$\sin^2\theta_{12}$ = 0.23 -0.39

- 3σ range: 2-flavour analysis

Δm^2_{31} = 1.1 -3.4 $\times 10^{-3}$ eV^2
$\sin^2\theta_{23}$ = 0.32 -0.68
Δm^2_{21} = 5.4 -9.4 $\times 10^{-5}$ eV^2
$\sin^2\theta_{12}$ = 0.23 -0.39

Bound on $\Delta m^2_{21}/\Delta m^2_{31}$



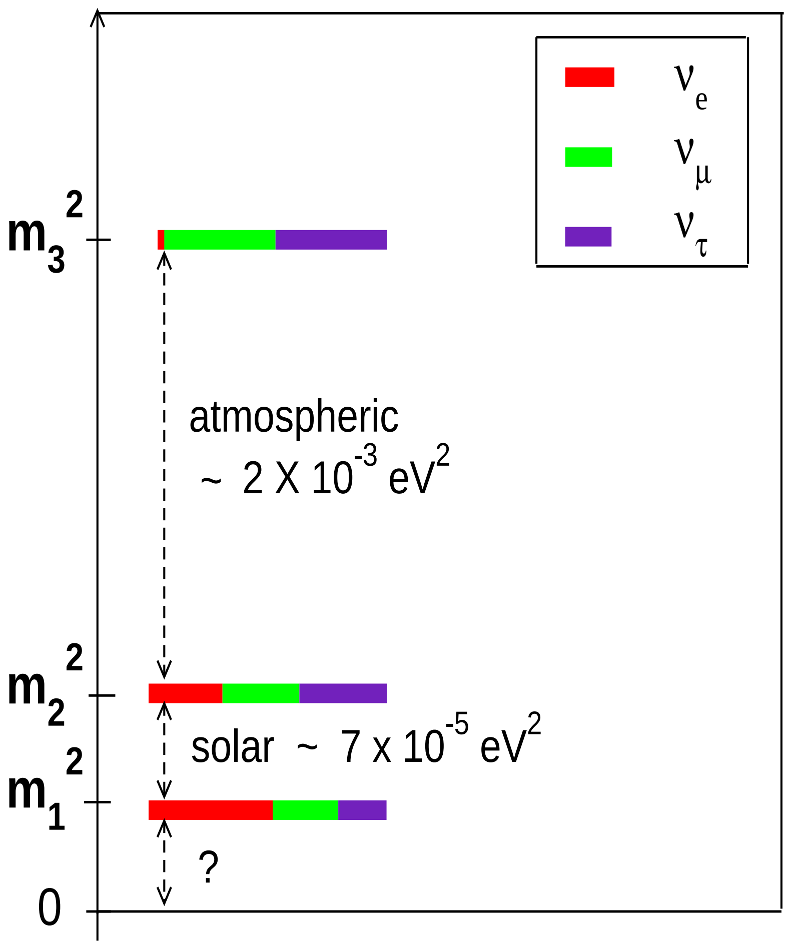
- $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$ ⇨ the hierarchy parameter associated with subleading oscillations
- Best-fit

  α = 0.03

  $\alpha \sin 2\theta_{12}$ = 0.028

Maltoni et al. 2004

Three neutrino oscillation parameters



- **Best-fit**

Δm^2_{21} =7.1 $\times 10^{-5}$ eV^2, $\sin^2\theta_{12} = 0.29$
Δm^2_{32} = 2.4 $\times 10^{-3}$ eV^2, $\sin^2\theta_{23} = 0.5$,
$\sin^2\theta_{13} = 0.01$

Fogli, Lisi, Marrone, Palazzo,2004

$$U = \begin{pmatrix} 0.84 & 0.54 & 0.1 \\ -0.44 & 0.56 & 0.71 \\ 0.32 & -0.63 & 0.71 \end{pmatrix}$$

- Δm^2_{32} can be positive or negative
- $\Delta m^2_{21} > 0$ (from solar data)

Summary-Current status

Solar+KamLAND

- MSW effect in sun is confirmed.
- Salt phase data from SNO further restricts $\Delta m^2_\odot$ and $\sin^2\theta_\odot$
- Solar + new KamLAND data favours low-LMA
- Best-fit $\Delta m^2_\odot$ = 8.3 $\times 10^{-5}$ eV^2, $\sin^2\theta_\odot$ =0.28
- high-LMA disallowed at more than 3σ
- Maximal mixing disfavoured at more than 5σ
- Solar Neutrino physics enters precision era

Atmospheric+K2K

- Analysis of SK zenith angle data gives $\Delta m^2_{atm} \sim$ 2.1 $\times 10^{-3}$ eV^2, $\sin^2\theta_{atm}$ =0.5
- K2K constrains the higher Δm^2 part
- The L/E data gives Δm^2_{atm} = 2.4 $\times 10^{-3}$ eV^2, $\sin^2\theta_{atm}$ =0.5
- Increased precision in Δm^2_{atm} with L/E data

Summary -Current status

Three Generation Analysis

- Solar,KamLAND ,atmospheric,K2K,CHOOZ data compatible
- The bound on θ_{13} is sensitive to the allowed Δm^2_{32} range and $\sin^2\theta_{13} <$ 0.05 -0.07
- Best fit value of $\Delta m^2_{21}/\Delta m^2_{31}$ = 0.03
- The two generation allowed parameter regions are stable

Future goals

- Improve the precision of parameters we already know
- Obtain some measure of smallness of θ_{13}
- Determine the sign of Δm^2_{32}
- Search for CP violation in the lepton sector;
- Subleading effects in solar and atmospheric neutrinos
  - Sterile neutrinos, discrete symmetries, Nonstandard Interactions . . .

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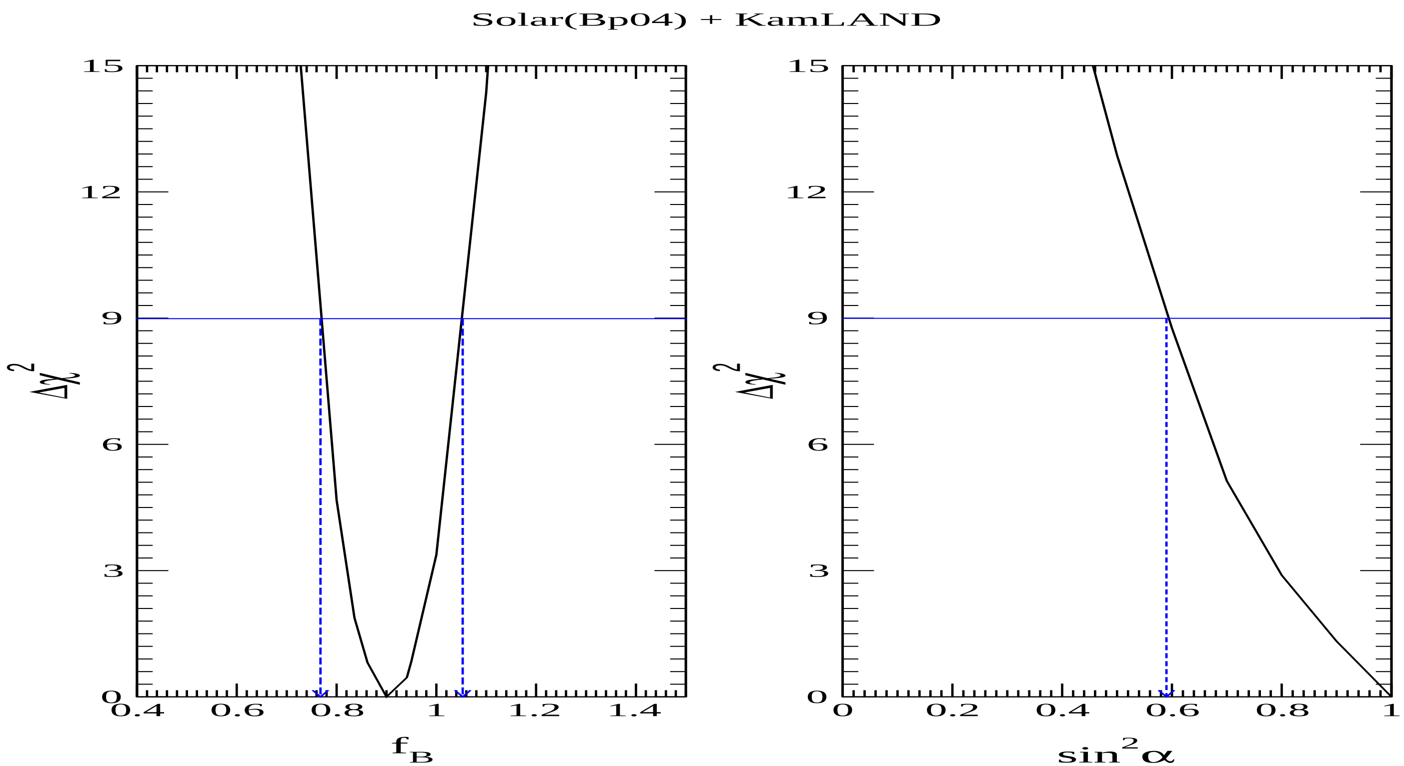
Thanks to T.Kajita, E. Lisi, M. Maltoni for disucssions

Sterile component in solar ν_e flux



$\nu_e \to \sin\alpha \;\; \nu_a + \cos\alpha\nu_s$

$\sin^2\alpha = 1$, pure $\nu_e \to \nu_a$

$\sin^2\alpha = 0$, pure $\nu_e \to \nu_s$

- Best-fit $\sin^2\alpha = 1.0$
- sterile fraction $\cos^2\alpha < 0.41$ at 3σ

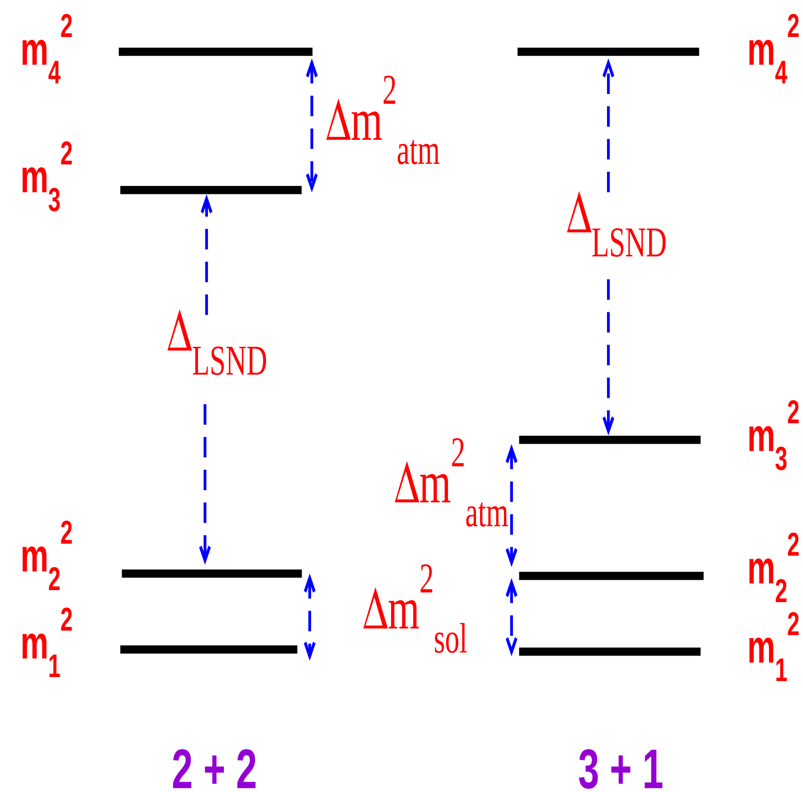
A.Bandyopadhyay,S.Choubey,S.Goswami,S.T.Petcov,D.P.Roy, hep-ph/0309174

Accommodating LSND

- Adding extra sterile neutrinos
- CPT violation

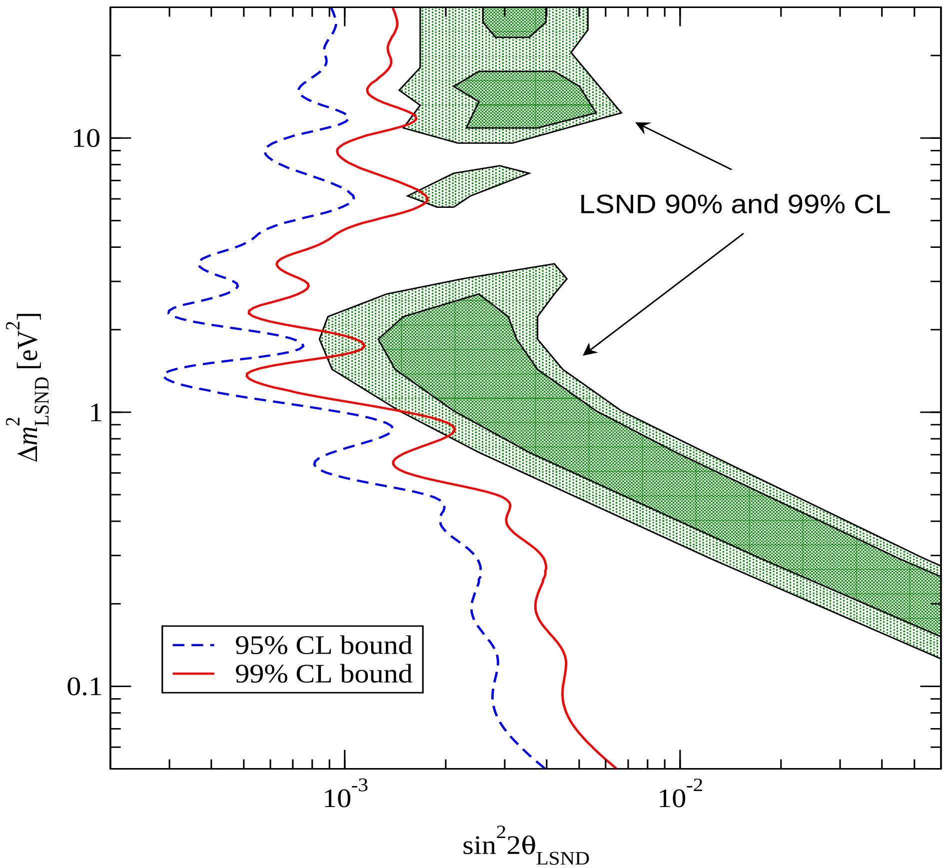
<u>One additional sterile neutrino</u>

- 6 mixing angles
- two possible mass schemes



One additional sterile neutrino:3+1 vs 2+2

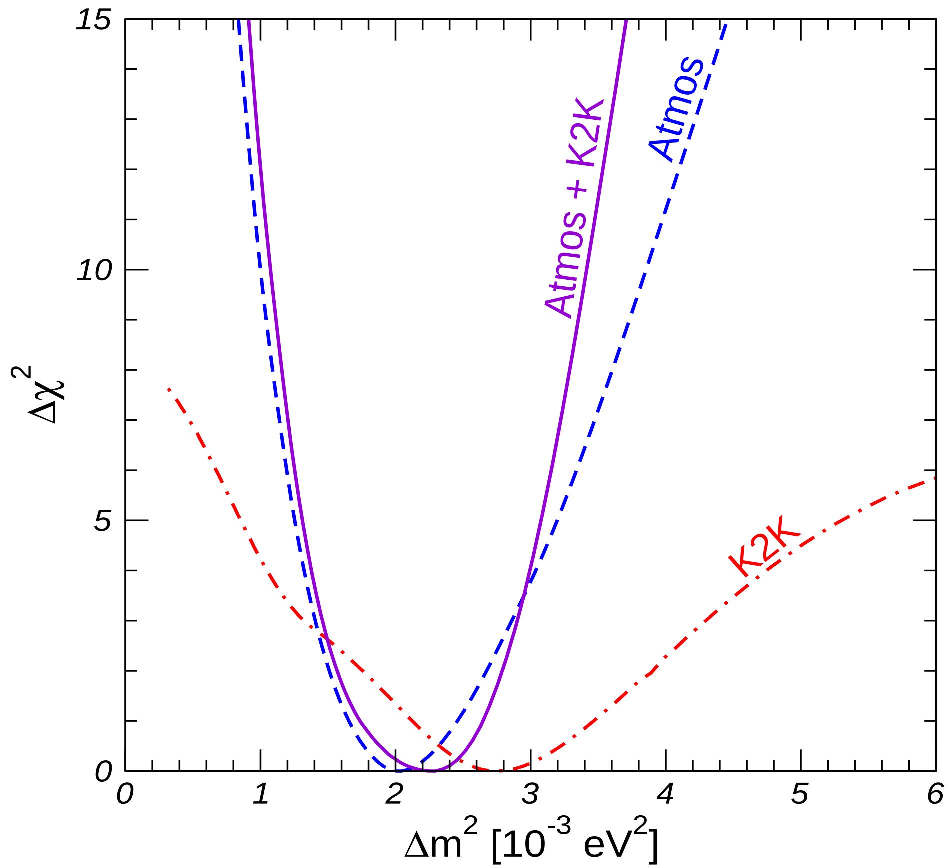
- 3+1 disfavoured from SBL accelerator and reactor experiments Karmen+Bugey+CDHS+NOMAD



- Two small areas consistent at 99% C.L.
- 2+2 disfavored irrespective of LSND is confirmed or not
—oscillation to almost pure sterile state is disfavoured in both solar and atmospheric

M.Maltoni *et al.,hep-ph/0209368*

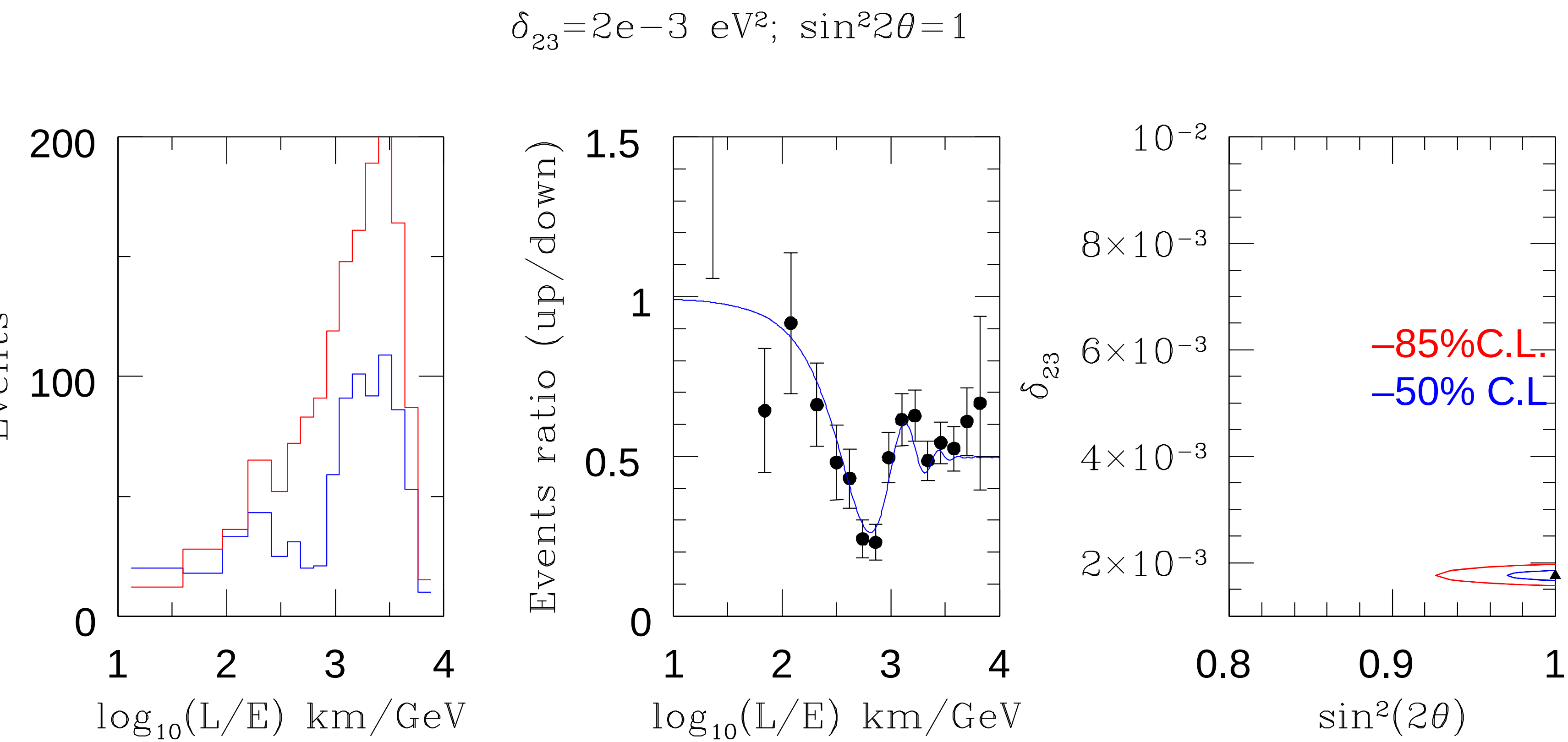
Effect of K2K on Δm^2_{atm}



Maltoni et al

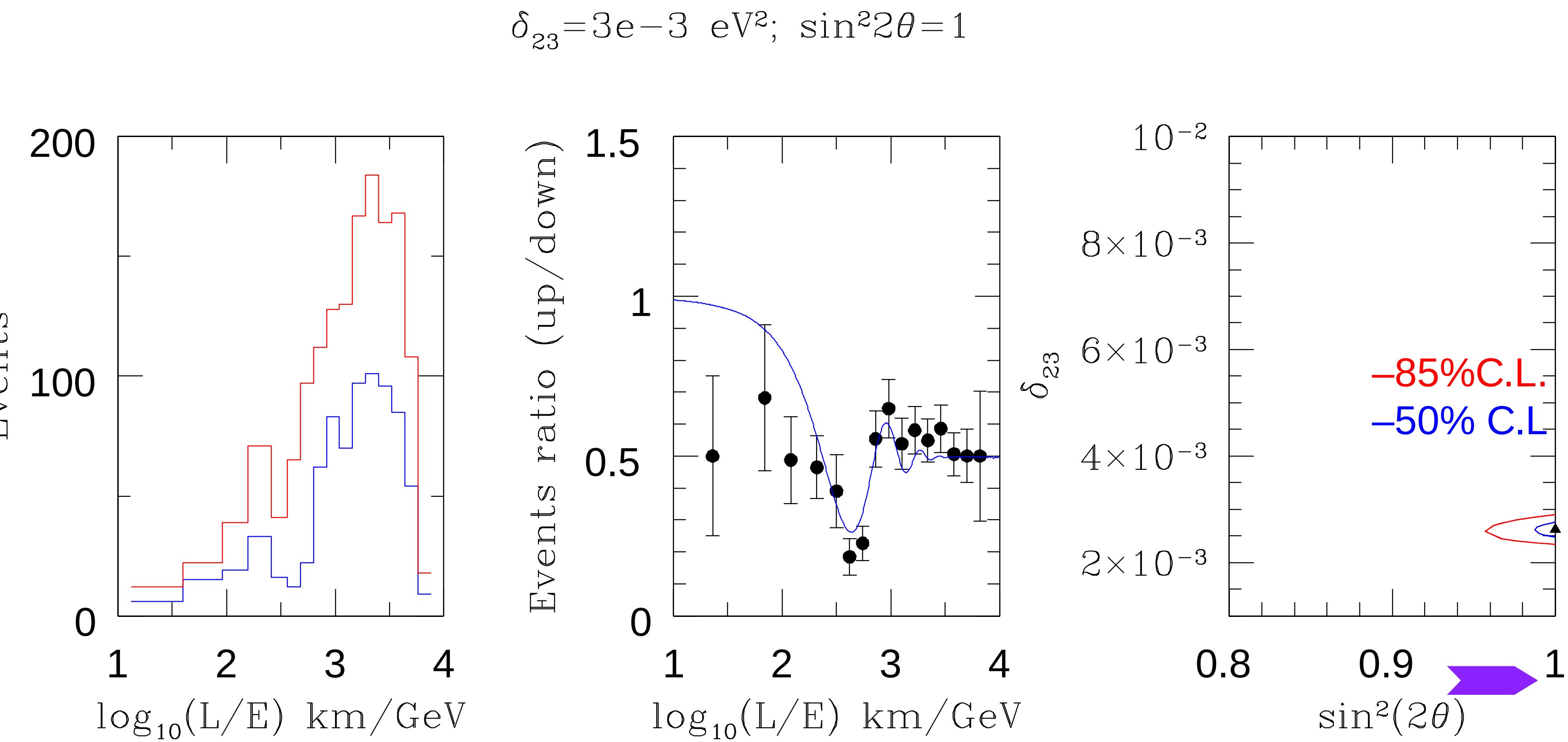
$\delta = 2 \times 10^{-3}\ eV^2$

INO:Preliminary



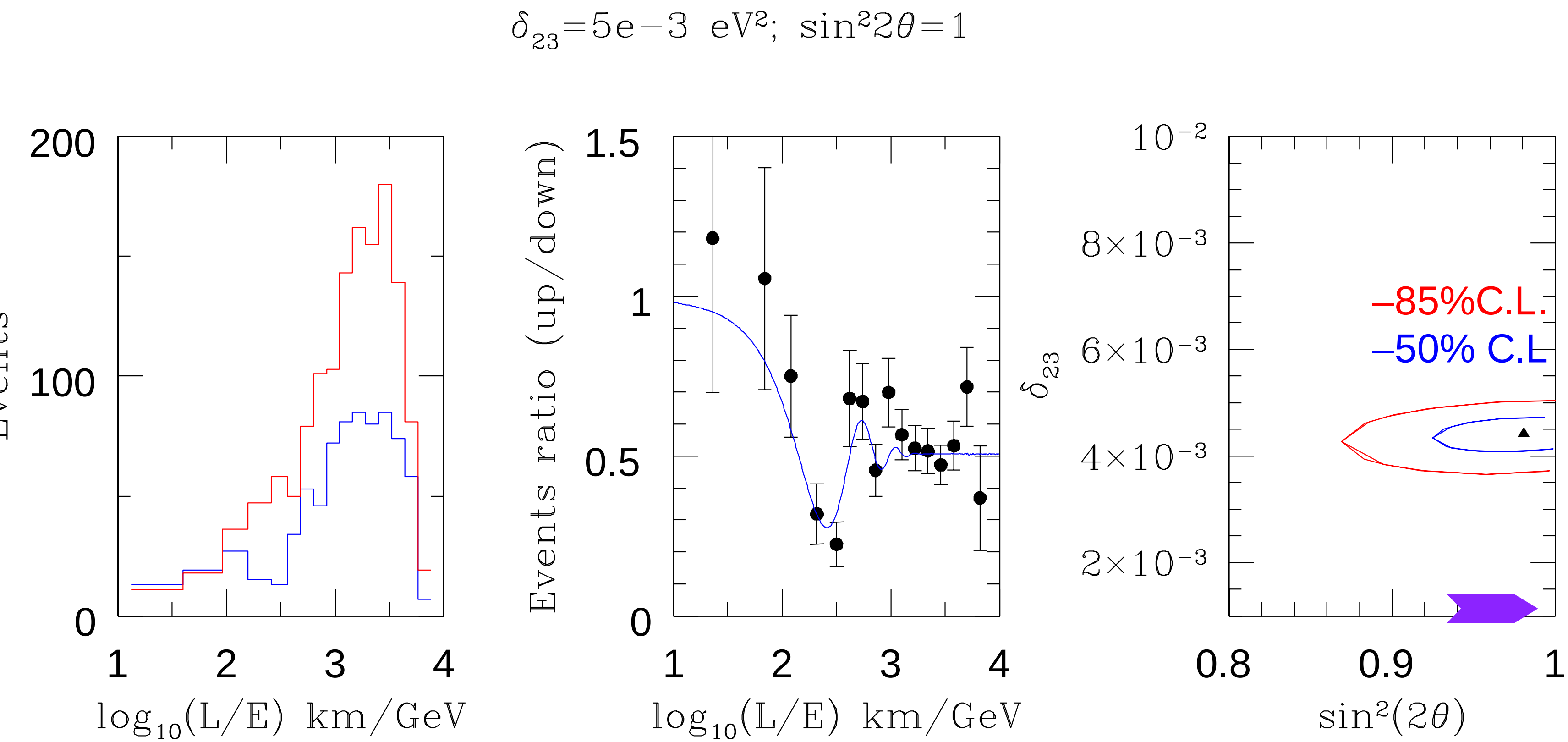
$\delta = 3 \times 10^{-3}\ eV^2$

INO:Preliminary



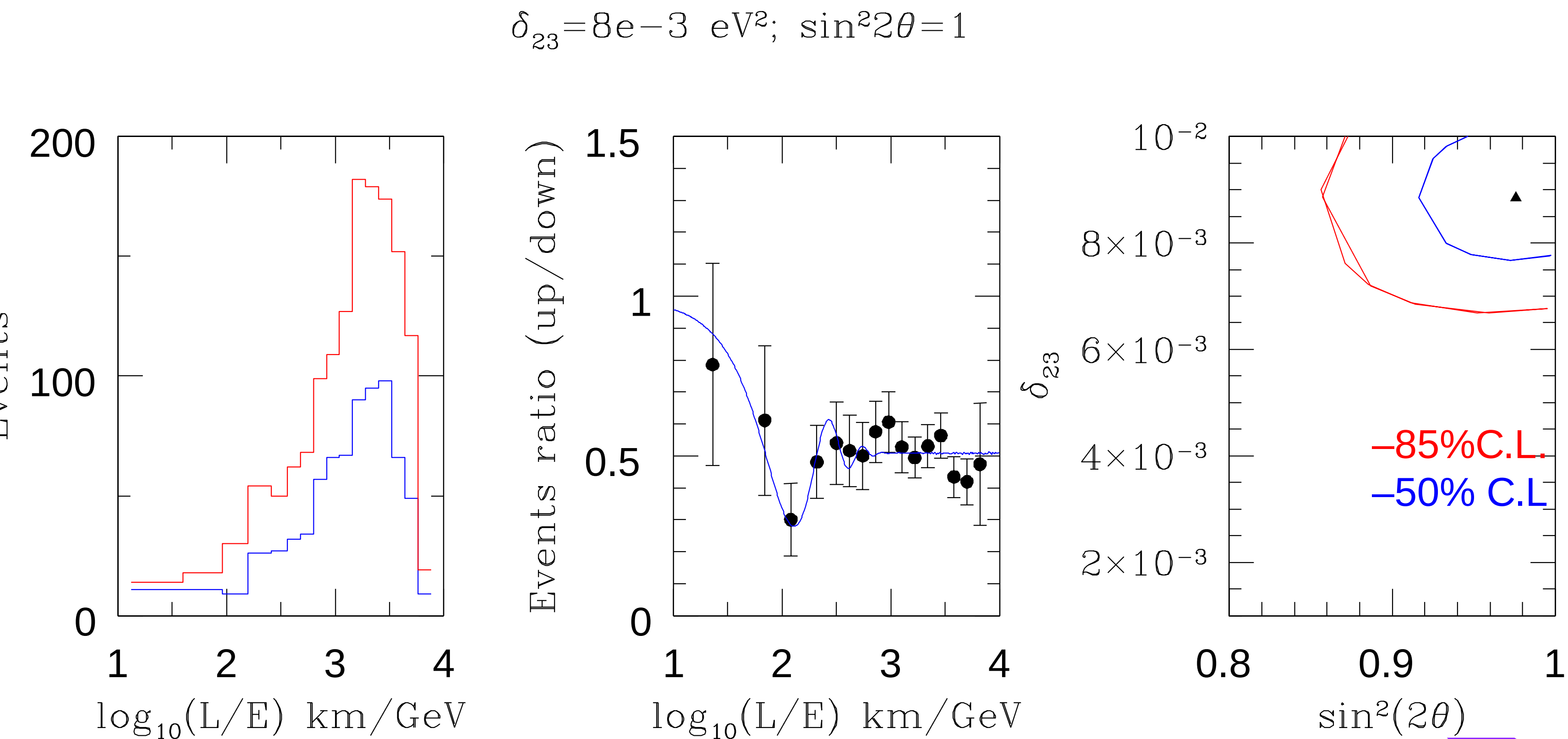
$\delta = 5 \times 10^{-3}\ eV^2$

INO:Preliminary

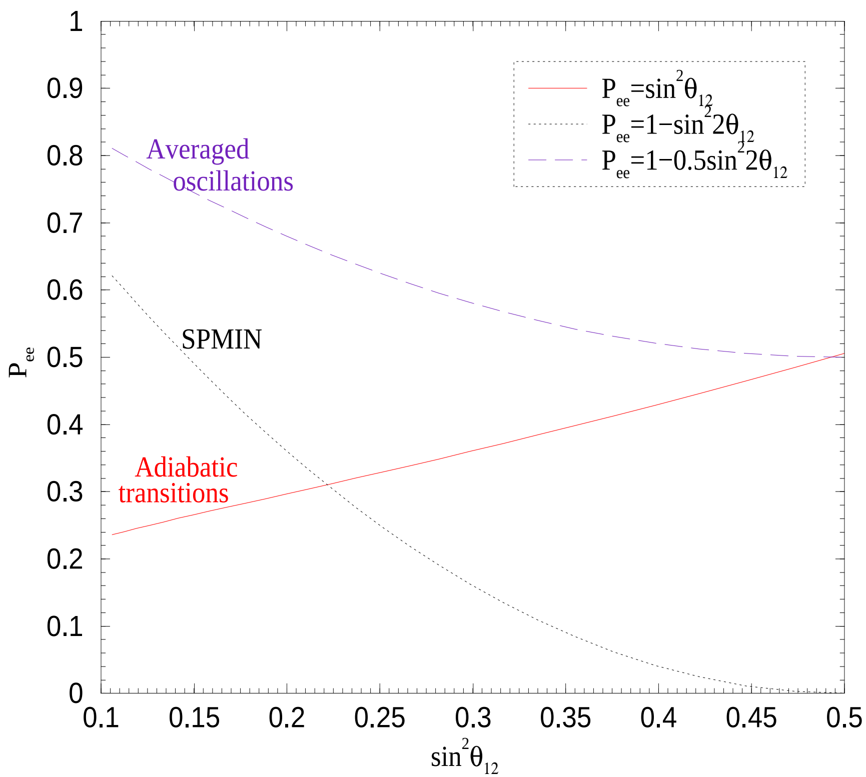


$\delta = 8 \times 10^{-3}\ eV^2$

INO:Preliminary



Sensitivity of $\sin^2\theta_\odot$



- For ^8B neutrinos undergoing matter enhanced resonance
  $P_{ee}^{AD} \approx \sin^2\theta_\odot$ LMA(AD)
- For VO ⇨ $\sin^2(\Delta m^2_\odot L/E) = 1/2$
  $P_{ee}^{AV} = 1 - \frac{1}{2}\sin^2 2\theta_\odot$
  Averaged Oscillations(AV)
- For VO ⇨ $\sin^2(\Delta m^2_\odot L/E) = 1$
  $P_{ee}^{SPMIN} = 1 - \sin^2 2\theta_\odot$
  Survival Prob. MINima(SPMIN)

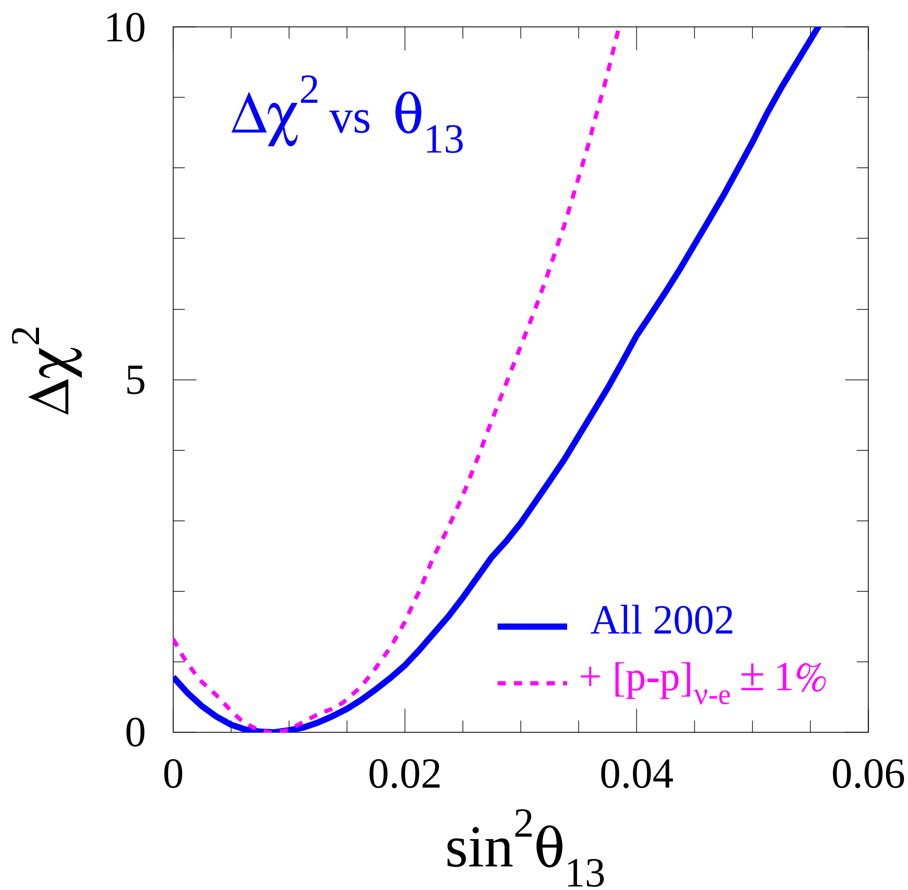
$(\Delta\sin^2\theta_\odot)_{AD} \sim \Delta P_{ee}$; good if $\sin^2\theta_\odot \sim 0.5$

$(\Delta\sin^2\theta_\odot)_{AV} \sim \frac{\Delta P_e{}^e}{-2\cos 2\theta_\odot}$; better if $\cos 2\theta \gtrsim 0.5 (\sin^2\theta_\odot \lesssim 0.25)$

$(\Delta\sin^2\theta_\odot)_{spmin} \sim \frac{\Delta P_e{}^e}{-4\cos 2\theta_\odot}$; best if $\cos 2\theta_\odot \gtrsim 0.25 (\sin^2\theta_\odot \lesssim 0.375)$

Future precision of three neutrino oscillation parameters

- θ_{13} from solar



J.N. Bahcall and C. Pena-Garay, hep-ph/0305159

- Reactors, Superbeams...

Future precision of three neutrino oscillation parameters

- θ_{13}, θ_{23}, sign of Δ_{23} from observation of earth matter effects in atmospheric neutrinos
- Detectors with charge identification capability
- MINOS, INO....

  Palomarez-Ruiz, Petcov, 2004