Theory of Neutrino Masses and Mixing

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Conclusions

- Big experimental effort: flavor conversion proved

  Solar $\nu' s$: Verification of Flavour Conversion ν_e to ν_μ or ν_τ at 5 σ

  Atmospheric ν_μ's disappear ($> 15\sigma$) most likely to ν_τ

- Most likely explanation is neutrino oscillation and soon this will be tested with "man-made" neutrino beams from reactor and accelerators

- ν masses imply physics beyond the standard model

- Further advance requires more and more precise data

OUTLINE

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The Parameters: What We Want to Know

What and How We Learn From Oscillations

II. Global Fits:

Solar Neutrinos

Atmospheric Neutrinos: 3ν Mixing

LSND+Karmen and Sterile neutrinos: 4ν Mixing

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The Scale of New Physics: SeeSaw Mechanism

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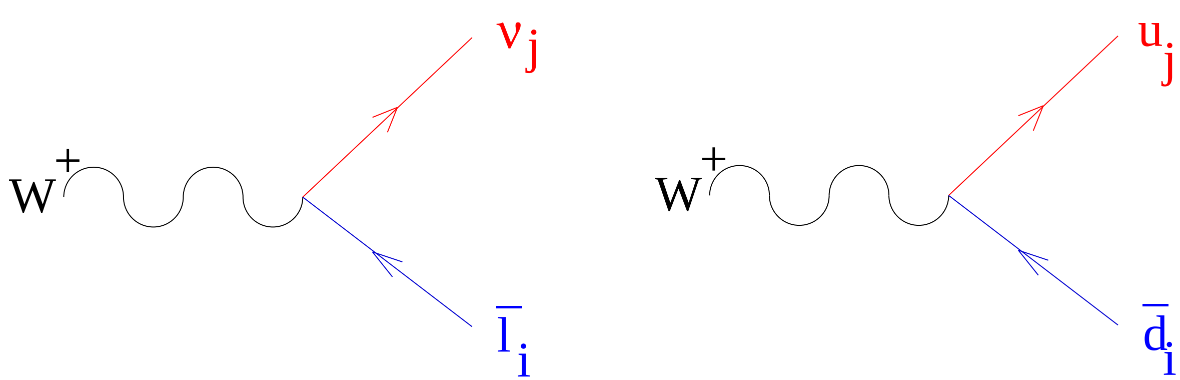
I. Introduction

• If neutrinos have a mass the charged current interactions of leptons are not flavour diagonal (same as quarks)

$$\frac{g}{\sqrt{2}} W^+_\mu \sum_{ij} \left(U^{ij}_{LEP} \overline{l^i_L} \gamma^\mu \nu^j_L + U^{ij}_{CKM} \overline{U^i_L} \gamma^\mu D^j_L \right) + h.c.$$



$$\frac{g}{\sqrt{2}} W^+_\mu \sum_{ij} \left(U^{ij}_{LEP} \overline{l^i_L} \gamma^\mu \nu^j_L + U^{ij}_{CKM} \overline{U^i_L} \gamma^\mu D^j_L \right) + h.c.$$

- To fully determine the lepton flavour sector we want to know:

  * How many, N, neutral states ν_i and their masses m_i

  * Their mixings: # angles $= \frac{N(N-1)}{2} = \begin{cases} 1 \text{ for } N=2 \\ 3 \text{ for } N=3 \\ 6 \text{ for } N=4 \end{cases}$

  * Their CP properties:

Dirac: $\nu^C \neq \nu$ # phases $= \frac{(N-1)(N-2)}{2} = \begin{cases} 0 \text{ for } N=2 \\ 1 \text{ for } N=3 \\ 3 \text{ for } N=4 \end{cases}$

Majorana: $\nu^C = \eta\, \nu$ (η=phase) # extra phases $= (N-1) = \begin{cases} 1 \text{ for } N=2 \\ 2 \text{ for } N=3 \\ 3 \text{ for } N=4 \end{cases}$

$$U^{\rm Maj}_{\alpha j} = U^{\rm Dir}_{\alpha j} \times {\rm e}^{-i\eta_j}$$

- We have learned:
  - $*$ Solar ν_e convert to ν_μ or ν_τ ($> 5\sigma$)

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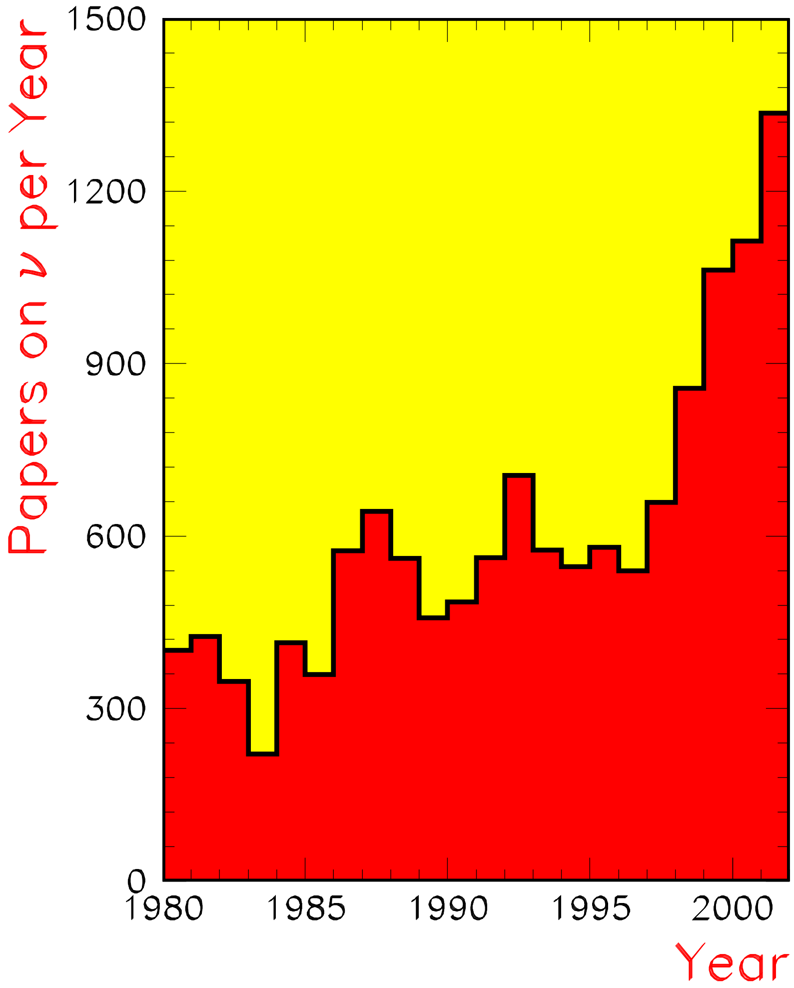
  - $*$ Atmospheric ν_μ disappear ($> 15\sigma$) most likely to ν_τ
  - $*$ Most likely explanation is neutrino oscillation
  - $*$ LSND found evidence for $\overline{\nu_\mu} \to \overline{\nu_e}$
- We have important information (mostly constraints) from:
  - $*$ The line shape of the Z: $N_{\rm weak} = 3$
  - $*$ Direct kinematic mass measurements: ${}^3H \to {}^3He + e^- + \bar{\nu}_e$

    $m_{\nu_e} < 2.2$ eV (95% CL) $\qquad m_{\nu_e} = f(m_i, U_{LEP})$
  - $*$ ν-less $\beta\beta$ decay (If Majorana ν's): $(A,Z) \to (A, Z+2) + e^- + e^-$

    $|\langle m_{ee}\rangle| = |\sum_{i=1}^{N} U_{ei}^2 m_i| < 0.35$ eV + theor. uncert. < 1.05 eV
  - $*$ Limits from Oscillation Searches at Reactor and Accelerators
- From Astrophysics and Cosmology: BBN, CMBR, Dark matter ...

- We know for sure that:



This is an exciting topic !

Neutrino Oscillations

- If neutrinos have mass, a weak eigenstate $|\nu_\alpha\rangle$ produced in $l_\alpha + N \to \nu_\alpha + N'$

  is a linear combination of the mass eigenstates ($|\nu_i\rangle$) : $|\nu_\alpha\rangle = \sum_{i=1}^{n} U_{\alpha i}\, |\nu_i\rangle$

- After a distance L (or time t) it evolves $|\nu(t)\rangle = \sum_{i=1}^{n} U_{\alpha i}\, \mathrm{e}^{\,-i\, E_i t} |\nu_i\rangle$

  it can be detected with flavour β with probability $P_{\alpha\beta} = |\langle\nu_\beta|\nu(t)\rangle|^2$

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_{j\neq i}^{n} \mathrm{Re}[U^\star_{\alpha i} U_{\beta i} U_{\alpha j} U^\star_{\beta j}] \sin^2\left(\frac{\Delta_{ij}}{2}\right) + 2 \sum_{j\neq i} \mathrm{Im}[U^\star_{\alpha i} U_{\beta i} U_{\alpha j} U^\star_{\beta j}] \sin(\Delta_{ij})$$

$$\frac{\Delta_{ij}}{2} = \frac{(E_i - E_j)L}{2} = 1.27 \frac{(m_i^2 - m_j^2)}{\mathrm{eV}^2} \frac{L/E}{\mathrm{Km/GeV}}$$

- $P_{\alpha\beta}$ depends on Theoretical Parameters
  - $\Delta m^2_{ij} = m_i^2 - m_j^2$ The mass differences
  - $U_{\alpha j}$ The mixing angles (and Dirac phases)

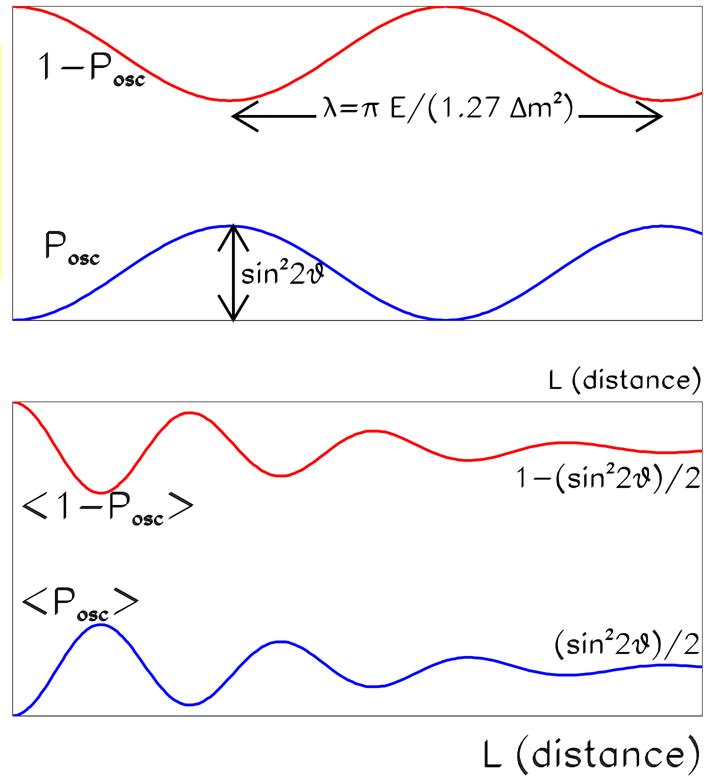
  and on Two *Experimental* Parameters:
  - E The neutrino energy
  - L Distance ν source to detector

- No information on mass scale nor Majorana phases

- For 2-ν: Convention $\Delta m^2 > 0$, $U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$ with $0 \leq \theta \leq \frac{\pi}{2}$

$P_{osc} = \sin^2(2\theta)\,\sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$ Appear

$P_{\alpha\alpha} = 1 - P_{osc}$ Disappear

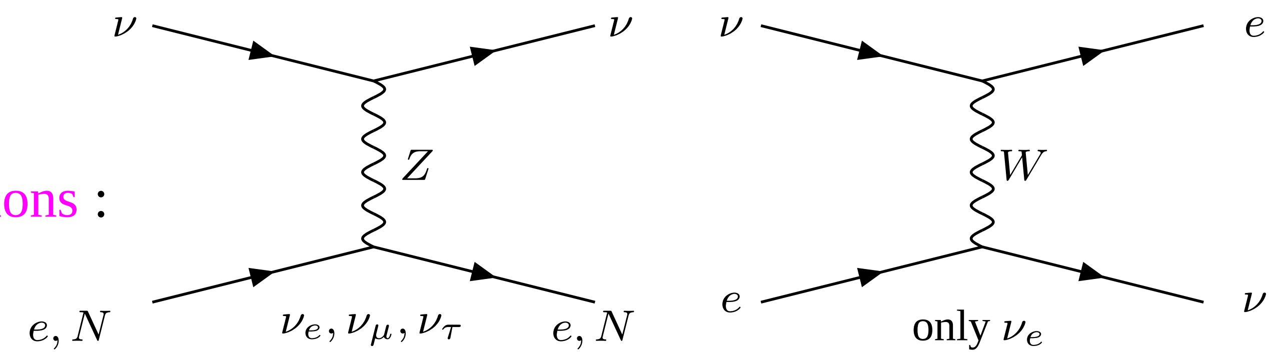


- In real experiments
  neutrinos are not monochromatic

$\Rightarrow \langle P_{\alpha\beta}\rangle = \int dE_\nu \frac{d\Phi}{dE_\nu}\sigma_{CC}(E_\nu)P_{\alpha\beta}(E_\nu)$

- Maximal sensitivity for $\Delta m^2 \sim E/L$
  - $\Delta m^2 \ll E/L$ $\Rightarrow$ No time to oscillate
    $\langle\sin^2(1.27\Delta m^2 L/E)\rangle \simeq 0 \rightarrow \langle P_{osc}\rangle \simeq 0$
  - $\Delta m^2 \gg E/L$ $\Rightarrow$ Averaged oscillations
    $\langle\sin^2(1.27\Delta m^2 L/E)\rangle \simeq \frac{1}{2} \rightarrow \langle P_{osc}\rangle \simeq \frac{1}{2}\sin^2(2\theta)$

- In vacuum $\langle P^{vac}_{osc}\rangle = \sin^2(2\theta)\langle\sin^2\left(1.27\Delta m^2 L/E\right)\rangle$ symmetric for $\theta \to \frac{\pi}{2} - \theta$
- If ν cross matter regions (Sun, Earth...) it interacts *coherently*



– But Different flavours have different interactions :

$\Rightarrow$ potential in the evolution equation $V_e \neq V_\mu = V_\tau \neq V_{sterile}$

$\Rightarrow$ *Modification of mixing angle and oscillation wavelength*

$$\sin(2\theta_m) = \frac{\Delta m^2 \sin(2\theta)}{\sqrt{(\Delta m^2\cos(2\theta) - A)^2 + (\Delta m^2 \sin(2\theta))^2}} \qquad A = 2\,E\,(V_\alpha - V_\beta)$$

– When $\Delta m^2\cos(2\theta) \sim A \Rightarrow$ Enhancement of Oscillation (MSW Effect)

– P^{mat}_{osc} not symmetric for $\theta \to \frac{\pi}{2} - \theta \Rightarrow \sin^2(2\theta)$ Not good
(also if more than 2-ν mixing)

$\Rightarrow$ Use $\tan^2(\theta)$ (or $\sin^2(\theta)$) to cover full space $0 \leq \theta \leq \frac{\pi}{2}$

(Fogli *et al.*; Friedland, de Gouvea, Murayama; M.C.G-G and Peña-Garay)

- If experiment does not see oscillations:

  $\langle P_{osc}\rangle < P_L \rightarrow$ excluded region

- If the experiment detects oscillation

  $\rightarrow$ allowed region

- If data at fixed $\langle L\rangle$ and $\langle E\rangle$

  (like most laboratory searches)

  $\rightarrow$ region is open in large Δm^2

- If data at several $\langle L\rangle$ and/or $\langle E\rangle$

  $\rightarrow$ region may be closed

– If no matter effects:

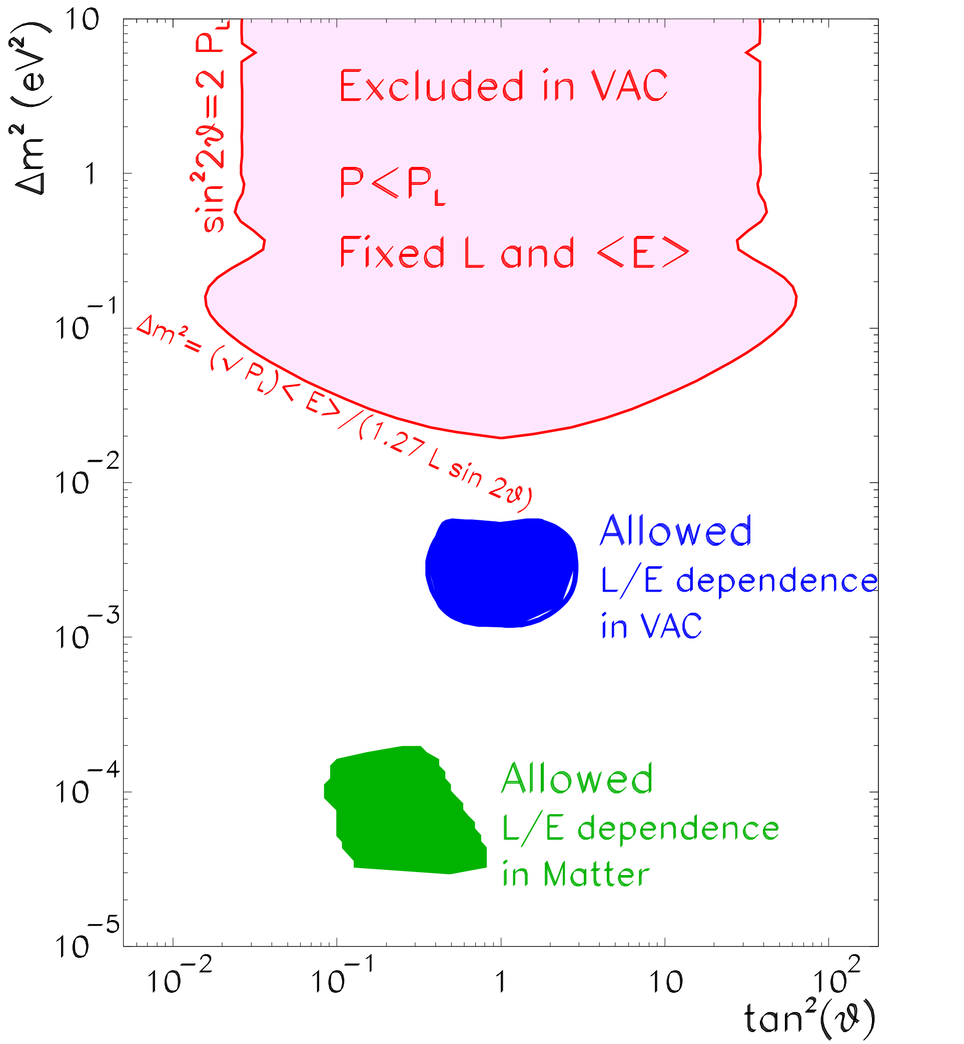
  (like Atmospheric $\nu_\mu \rightarrow \nu_\tau$)

  $\rightarrow$ region is symmetric around $\theta = \frac{\pi}{4}$

– If matter effects

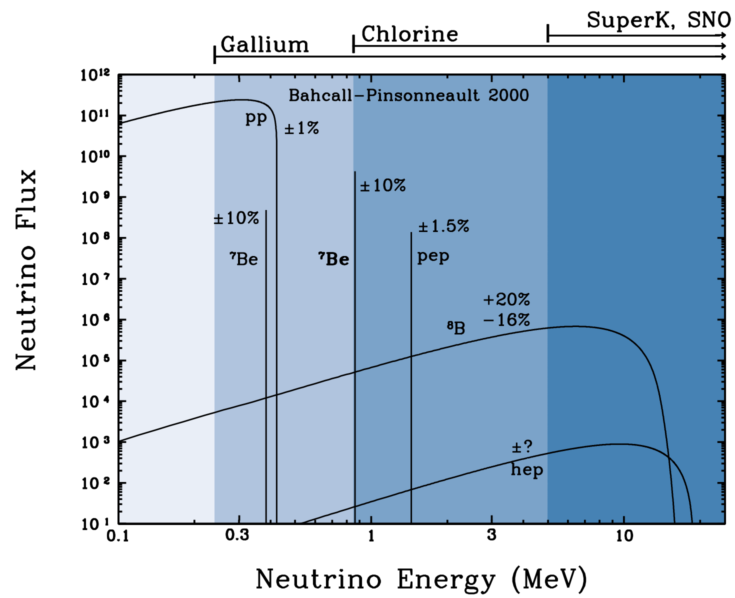
  (like Solar $\nu_e \rightarrow \nu_x$)

  $\rightarrow$ region not symmetric around $\theta = \frac{\pi}{4}$



II. Global Fits

Solar Neutrinos



- The sun emits $\nu_e's$.

- Detected at

	Experiment	Detection	Flavour	$E_{\rm th}$ (MeV)	$\frac{\rm Data}{\rm BP00}$
radio-chemical	Homestake	$^{37}{\rm Cl}(\nu,e^-)^{37}{\rm Ar}$	ν_e	$E_\nu > 0.81$	0.35 ± 0.06
	Sage + Gallex+GNO	$^{71}{\rm Ga}(\nu,e^-)^{71}{\rm Ge}$	ν_e	$E_\nu > 0.23$	0.55 ± 0.05
real time	Kam ⇒ SK	ES $\nu_x e^- \to \nu_x e^-$	$\nu_e, \nu_{\mu/\tau}$ $\left(\frac{\sigma_{\mu\tau}}{\sigma_e} \simeq \frac{1}{6}\right)$	$E_e > 5$	0.46 ± 0.09
	SNO	CC $\nu_e d \to p p e^-$	ν_e	$T_e > 5$	$0.35 \pm 0.07^*$
		NC $\nu_x d \to \nu_x d$	$\nu_e, \nu_{\mu/\tau}$	$T_\gamma > 5$	$1.01 \pm 0.23^*$
		ES $\nu_x e^- \to \nu_x e^-$	$\nu_e, \nu_{\mu/\tau}$	$T_e > 5$	$0.46 \pm 0.23^*$

(* For undistorted ^{8}B spectrum)

SSM Independent Tests

SK and SNO measure $\Phi_{^8\mathrm{B}}$:

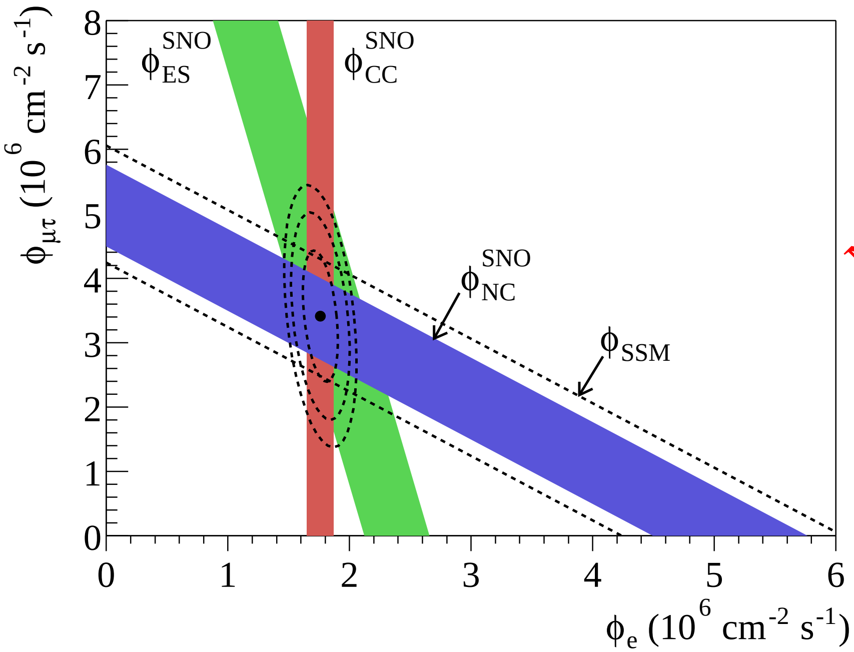
$*$ If flavour conversion:

$$\Phi^{CC} = \Phi_e$$

$$\Phi^{ES} = \Phi_e + \frac{1}{6}\,\Phi_{\mu\tau}$$

$$\Phi^{NC} = \Phi_e + \Phi_{\mu\tau}$$

Evidence for Flavour Conversion !



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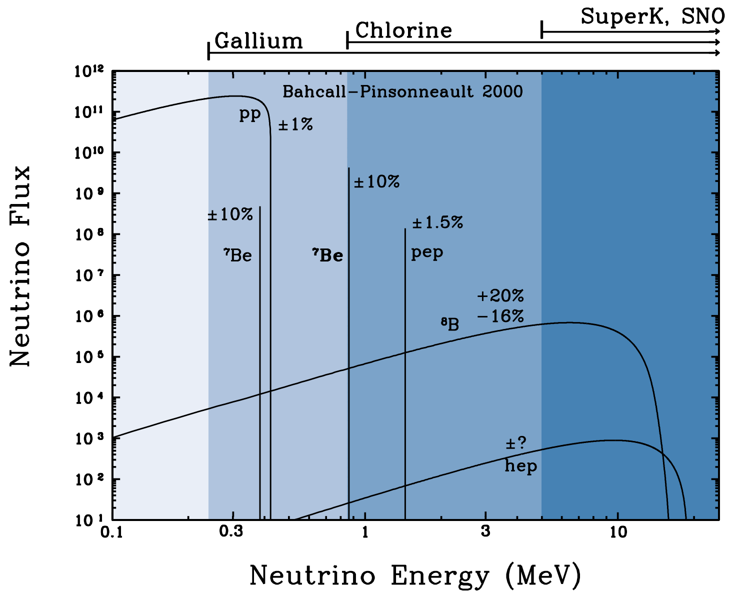
$*$ No flavour conversion $\Rightarrow \Phi_{\mu\tau} = 0$ $\begin{cases} \Phi^{ES}_{SK} = \Phi^{CC}_{SNO} \Rightarrow 3.2\sigma \text{ out} \\ \Phi^{NC}_{SNO} = \Phi^{CC}_{SNO} \Rightarrow 5.3\sigma \text{ out} \end{cases}$

$*$ $\nu_e \to \nu_{\rm sterile} \Rightarrow \Phi_{\mu\tau} = 0 \Rightarrow \Phi^{NC}_{SNO} \simeq \Phi^{CC}_{SNO} \sim 5\sigma$ out

Limited subdominant ν_s contribution in 4ν mixing

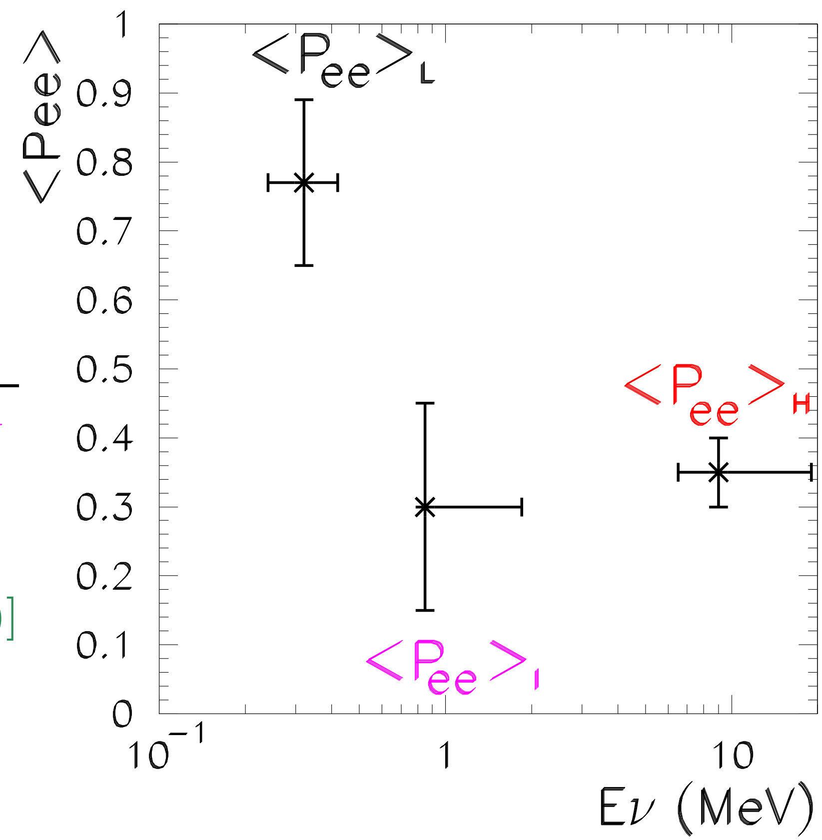
Model Independent Extracted Survival Probabilities

Barger, Marfatia, Whisnant; Berezinsky and Lissia



Dividing the ν spectrum in three parts:

- Low E: pp with survival $\langle P_{ee}\rangle_L$
- Intermediate E: ^{7}B, pep, CNO with $\langle P_{ee}\rangle_I$
- High E: ^{8}B with survival $\langle P_{ee}\rangle_H$



Barger *et al.*, hep-ph/0204253

- Fitting the observed rates:

		$\frac{\text{Data}}{\text{SSM}}$	R_{th}
Cl		0.35 ± 0.06	$0.76\ f_B\ \langle P_{ee}\rangle_H\ +\ 0.24\ \langle P_{ee}\rangle_I$
Ga		0.55 ± 0.05	$0.1\ f_B\ \langle P_{ee}\rangle_H\ +\ 0.36\ \langle P_{ee}\rangle_I\ +\ 0.54\ \langle P_{ee}\rangle_L$
SK		0.46 ± 0.09	$f_B\ [\langle P_{ee}\rangle_H\ +\ \frac{1}{6}\ (1 - \langle P_{ee}\rangle_H)]$
SNO	CC	0.35 ± 0.07	$f_B\ \langle P_{ee}\rangle_H$
	NC	1.01 ± 0.23	f_B

Solar Oscillations: Impact of SNO

SNO coll., nucl-ex/0204009

Barger *et al.*, hep-ph/0204253

Bandyopadhysy *et al*, hep-ph/0204286

Bahcall *et al*, hep-ph/0204314

Creminelli *et al*, hep-ph/0102234

Aliani *et al* hep-ph/0205053

de Holanda, Smirnov, hep-ph/0205241

Strumia *et al*, hep-ph/0205262

Fogli *et al*, hep-ph/0206162

Maltoni *et al*,hep-ph/0207227

Solar Oscillations

ICHEP00 → **ICHEP02**

Detailed SK E and t dependence

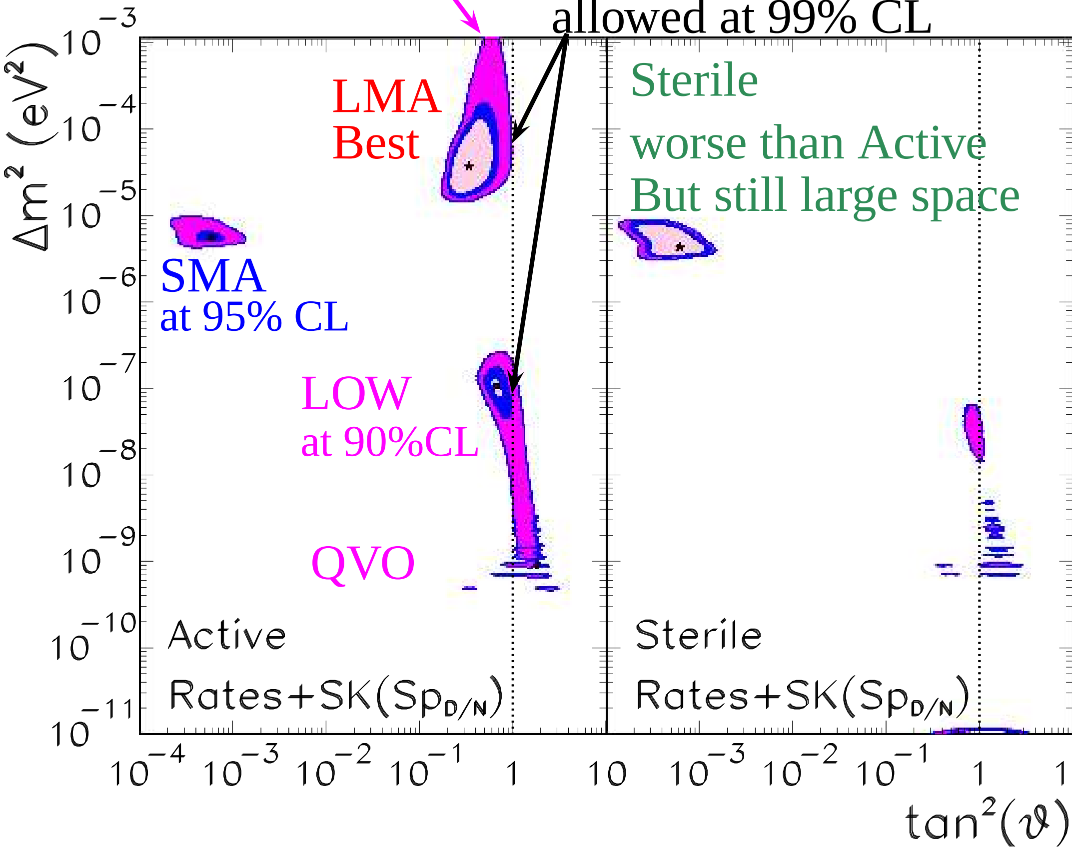
New SNO day-night spectrum

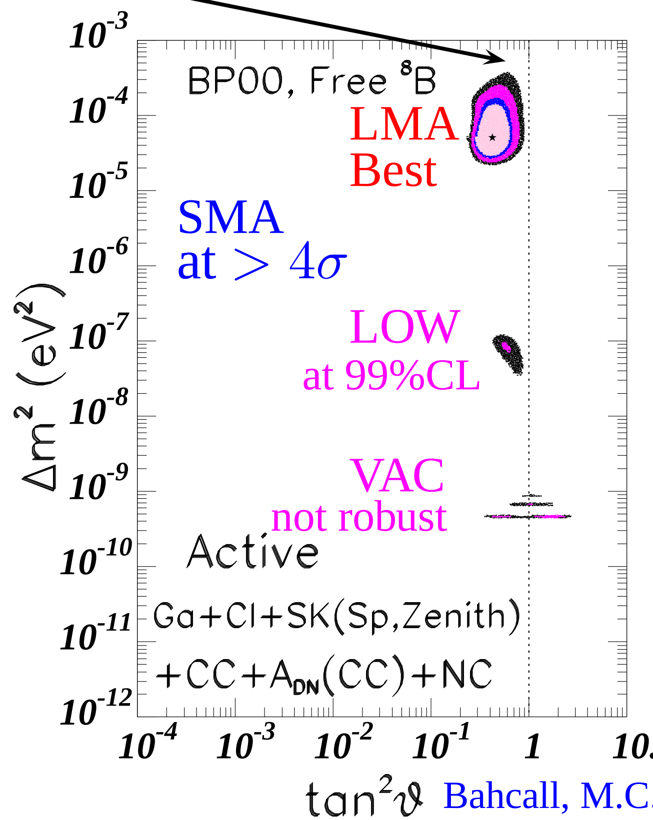
No upper Δm^2 bound at 99% CL

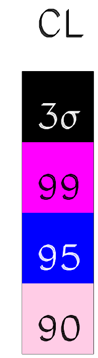
CHOOZ $\Rightarrow \Delta m^2 \lesssim 8 \times 10^{-4}$ eV^2

Maximal mixing allowed at 99% CL

At 3 σ: $\Delta m^2 \lesssim 4 \times 10^{-4}$ eV^2



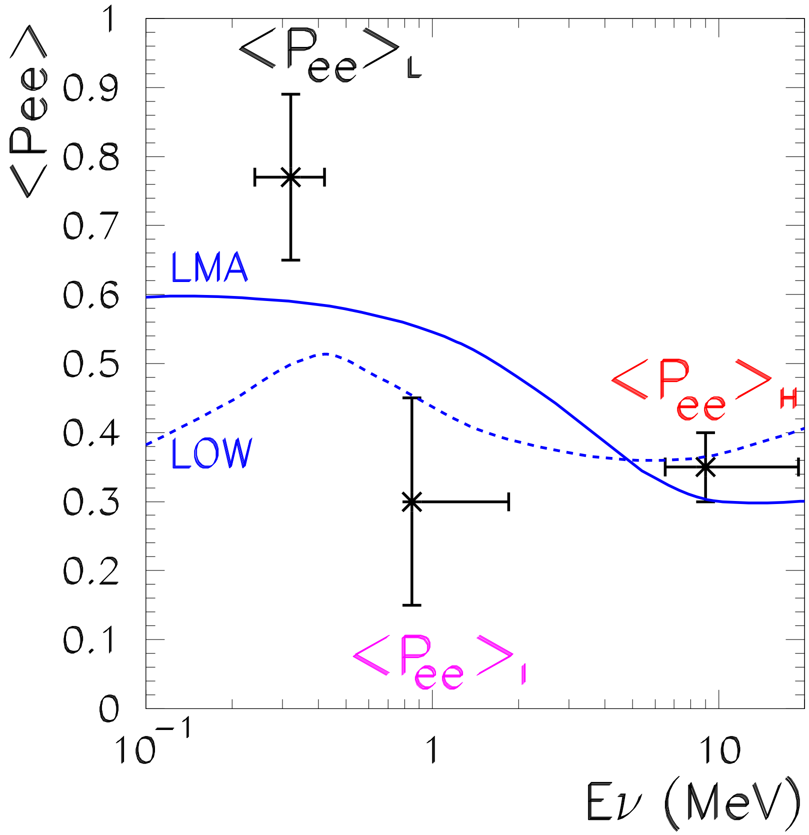




Sterile $\gtrsim 5\sigma$

Bahcall, M.C. G-G and Peña-Garay

LMA/LOW Comparison



LOW gives worse fit to low energies rate

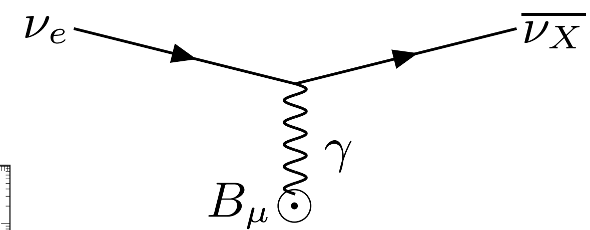
Also worse fit to SK zenith-spectrum

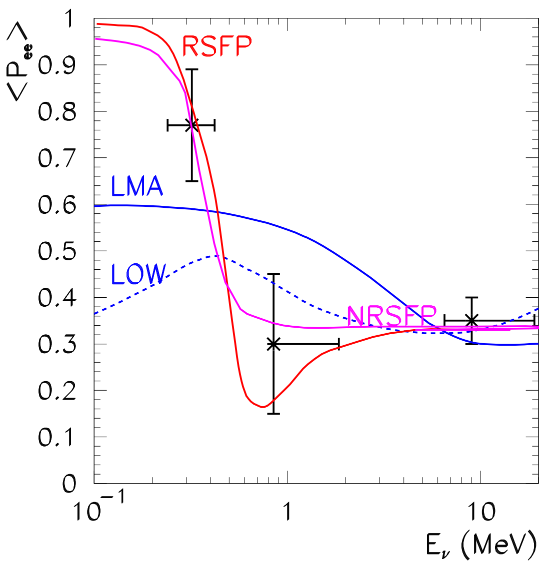
How sure are we of solar oscillations?

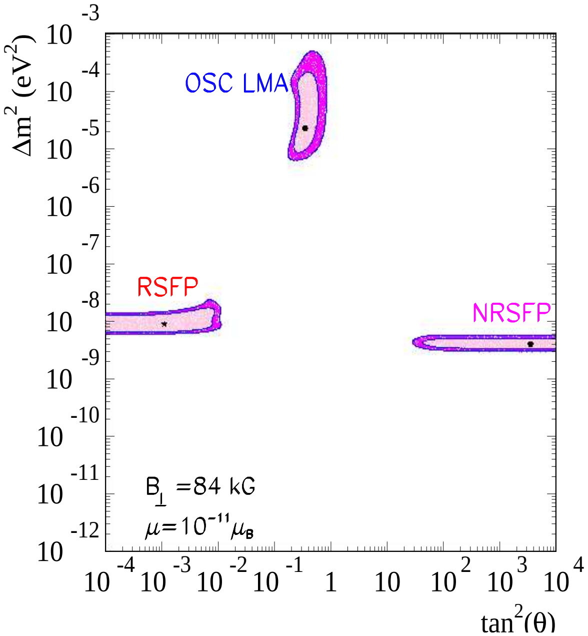
- Other mechanisms of flavour conversion fit the data well

– Spin Flavour Precession: (Lim, Marciano; Akhmedov)

Miranda *et al* hep-ph/0108145; Friedland and Gruzinov hep-ph/0202095; Chauhan and Pulido, hep-ph/0206193



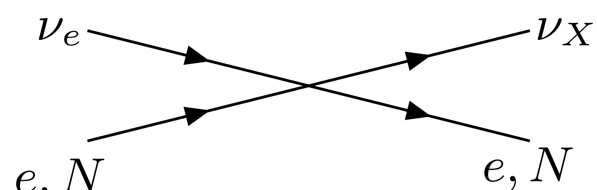




Good Fit with different mass and mixing than oscillations

– Flavour Changing ν interactions (Wolfenstein)

Guzzo *et al* hep-ph/0112310; Gago *et al* hep-ph/0112060



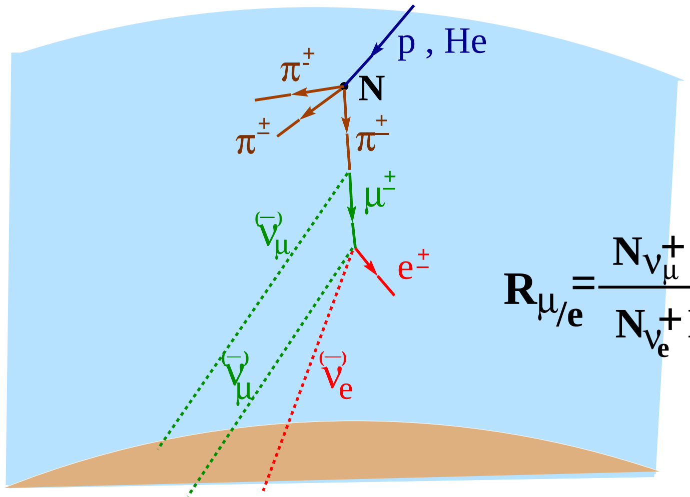
Good Fit with massless ν

- In general additional parameters: ν magnetic moment, magenetic field, FC couplings etc…are not very "natural"

- **Oscillation signal in KamLAND [would] rule them out**

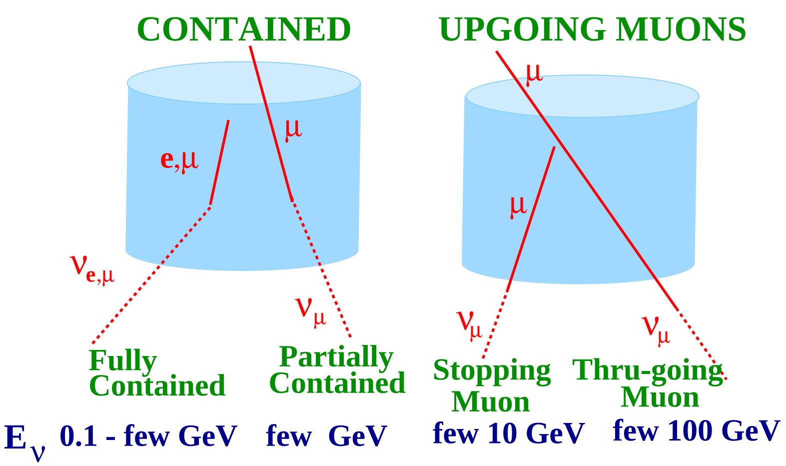
Atmospheric Neutrinos

$\nu_{e,\mu}$ are produced by interaction of cosmic rays (p, He . . .) with the atmosphere



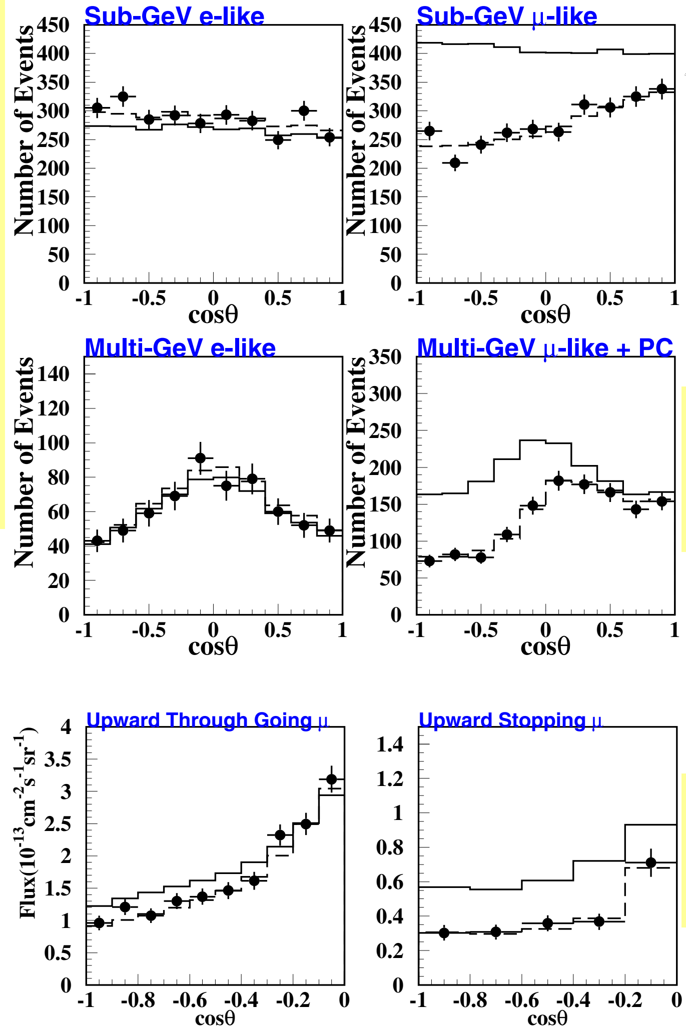
$$R_{\mu/e} = \frac{N_{\nu_\mu} + N_{\bar{\nu}_\mu}}{N_{\nu_e} + N_{\bar{\nu}_e}} \sim 2$$

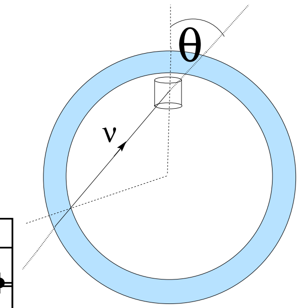
EVENT CLASSIFICATION



Angular Distribution at SK

ν_e in agreement with SM



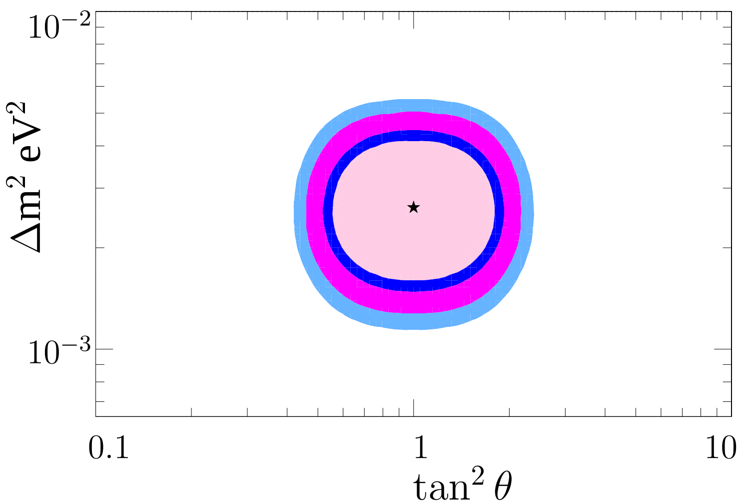


→ Deficit grows with L

→ Decreases with E

Atmospheric Oscillation Solutions

- $\nu_\mu \to \nu_\tau$: best channel



Best fit:

$\Delta m^2 = 2.6 \times 10^{-3}$ eV^2

$\tan^2\theta = 1$

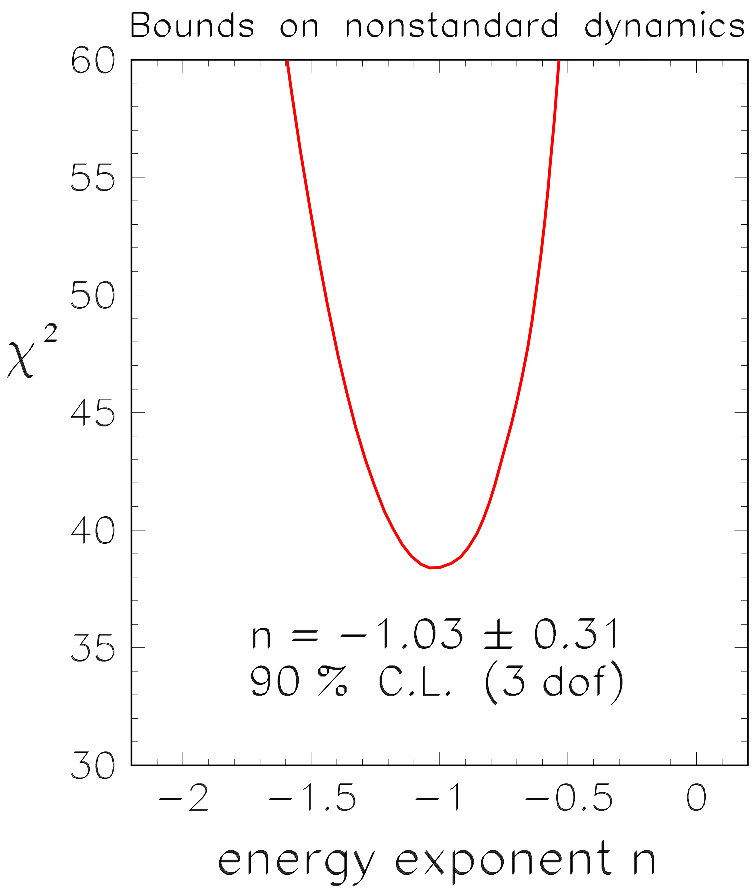
Confirmed within statistics by K2K

- $\nu_\mu \to \nu_{\rm e}$: Excluded at more than 5σ
  Bad fit to observed SM like ν_e distributions
  Ruled out by CHOOZ : ATM $\nu_\mu \to \nu_{\rm e} \Rightarrow \overline{\nu_e}$ disappearance
  Limited subdominant contribution in 3ν mixing

- $\nu_\mu \to \nu_{\rm sterile}$: Disfavoured at more than 99% CL
  Matter effects $\Rightarrow$ Flatter upgoing-μ distribution
  Limited subdominant contribution in 4ν mixing

Atmospheric Neutrinos

- Other exotic no-oscillation explanations:



Fogli, Lisi and Marrone hep-ph/0105139

Different L/E dependence:

$$P_{\mu\tau} = \alpha \sin^2(\beta L E^n)$$

$n = -1$ oscillations

$n = 1$ Viol Equiv. Principle

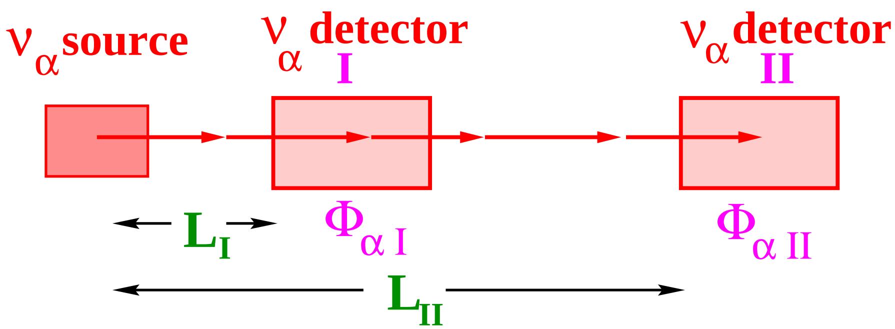
$n = 1$ Viol Lorentz invariance

Fit : $n = -1.03 \pm 0.31$ 90%CL

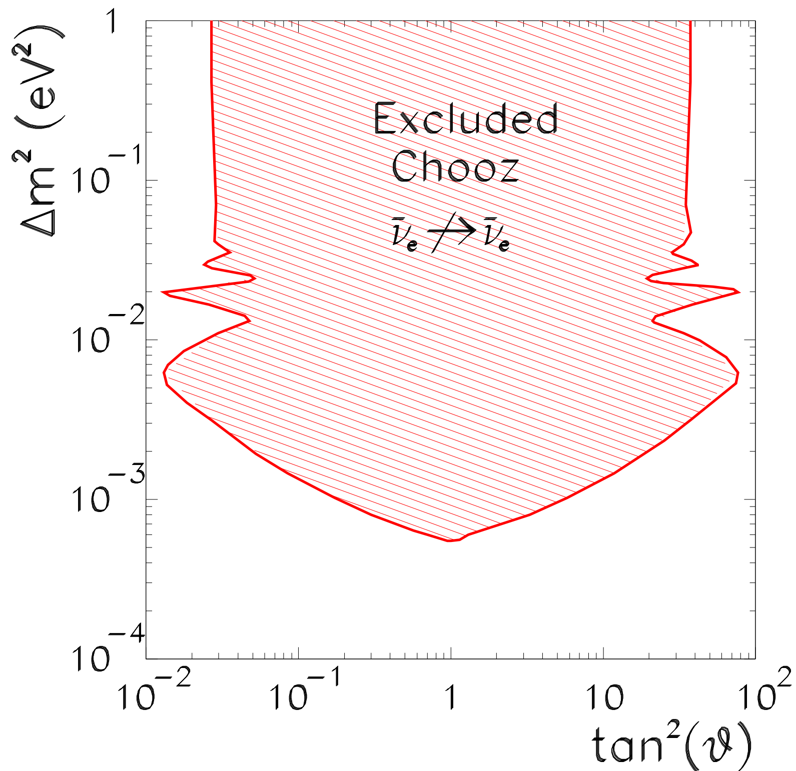
Chooz

• Disappearance Experiment

Negative search with $\overline{\nu_e}$ source: Nuclear Reactor



Compares $\Phi_{\alpha\,I}$ and $\Phi_{\alpha\,II}$ to look for loss

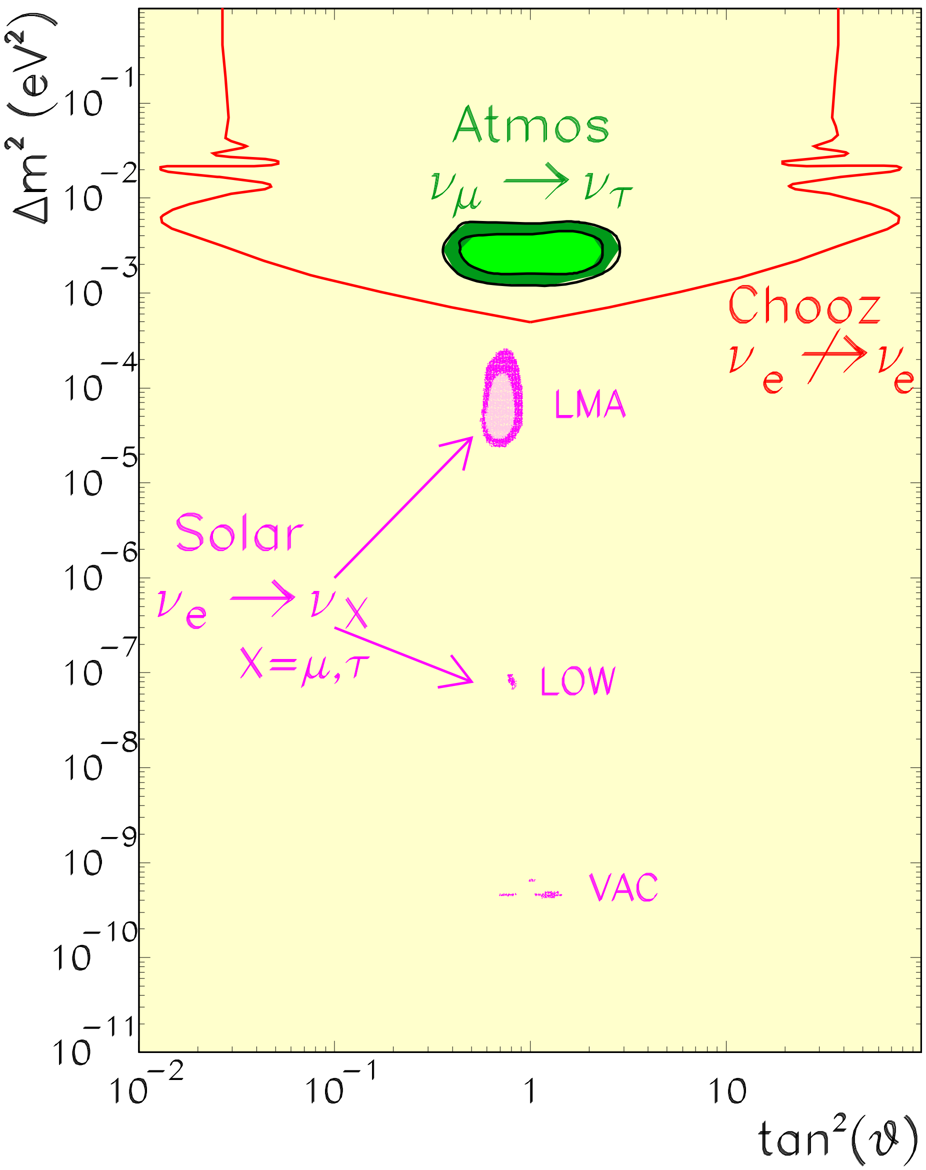


If CPT is conserved:

– Constraints solar oscillations for $\Delta m^2_\odot \gtrsim 8 \times 10^{-4}$ eV^2.

– Constraints $\nu_\mu \to \nu_e$ component of atmospheric oscillations

Solar + Atmospheric 3ν Oscillations



Goal: to fit this with 3ν mixing

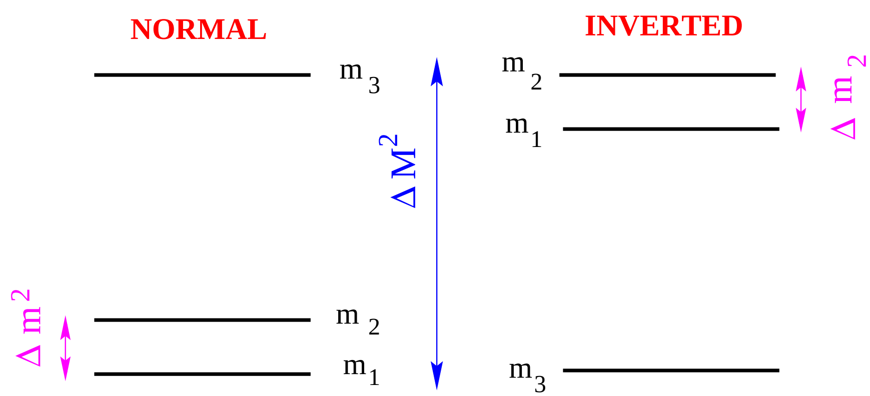
Hope: to learn more than with separate 2ν solar and 2ν atm analysis

Solar + Atmospheric 3ν Oscillations

U: 3 angles, 1 CP-phase
+ (2 Majorana phases)

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Two mass schemes



2ν oscillation analysis $\Rightarrow \Delta m^2 = \Delta m^2_\odot \ll \Delta M^2 \simeq \pm\Delta m^2_{atm} \simeq \pm\Delta m^2_{32} \simeq \pm\Delta m^2_{31}$

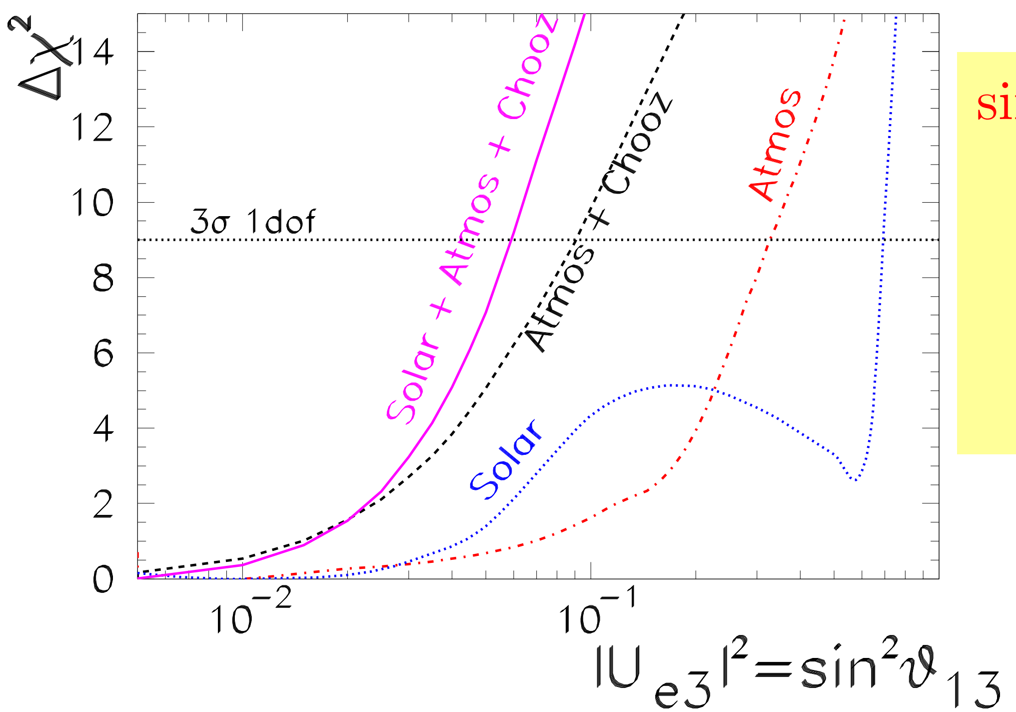
$\Rightarrow$ Generic 3ν effects in ATM+SOLAR+CHOOZ oscillations :

	Potential Dependence							$\Delta m^2 \ll \Delta M^2$						
	θ_{12}	θ_{13}	θ_{23}	Δm^2	ΔM^2	δ	N/I	θ_{12}	θ_{13}	θ_{23}	Δm^2	ΔM^2	δ	N/I
Solar	X	X		X	X		X	X	X		X			
Atmos	X	X	X	X	X	X	X		X	X		X		X?
Chooz	X	X		X	X		X	X	X		X			

CP violation $Unobservable$
2 wavelengths $Unobservable$
N versus I $Below\ sensitivity$
θ_{13}?

- In the Hierarchical approximation $\Delta m^2 \ll \Delta M^2$
  - $*$ For $\theta_{13} = 0$ solar and atmospheric oscillations decouple $\Rightarrow$ Normal$\equiv$ Inverted
    - – Solar $\rightarrow \Delta m^2 = \Delta m^2_\odot \quad \theta_{12} = \theta_\odot$
    - – Atmospheric $\rightarrow \Delta M^2 = \Delta m^2_{atm} \quad \theta_{23} = \theta_{atm}$
  - $*$ For $\theta_{13} \neq 0$ solar and atmospheric couple throught θ_{13}

But all data prefers θ_{13} small



$\sin^2\theta_{13} < 0.06$ (3σ 1dof)

$\Downarrow$

$\Delta m^2, \tan^2\theta_{12}$

ΔM^2 , $\tan^2\theta_{23}$

very similar to 2ν analysis

Solar + Atmospheric 3ν Oscillations

The emerging: $|U_{\rm LEP}| = \begin{pmatrix} 0.73-0.89 & 0.44-0.66 & <0.24 \\ 0.23-0.66 & 0.24-0.75 & 0.51-0.87 \\ 0.06-0.57 & 0.40-0.82 & 0.48-0.85 \end{pmatrix}.$

with structure
$$|U_{\rm LEP}| \simeq \begin{pmatrix} \frac{1}{\sqrt{2}}(1+\mathcal{O}(\lambda)) & \frac{1}{\sqrt{2}}(1-\mathcal{O}(\lambda)) & \epsilon \\ -\frac{1}{2}(1-\mathcal{O}(\lambda)+\epsilon) & \frac{1}{2}(1+\mathcal{O}(\lambda)-\epsilon) & \frac{1}{\sqrt{2}} \\ \frac{1}{2}(1-\mathcal{O}(\lambda)-\epsilon) & -\frac{1}{2}(1+\mathcal{O}(\lambda)-\epsilon) & \frac{1}{\sqrt{2}} \end{pmatrix} \quad \lambda\sim 0.2 \quad \epsilon < 0.25$$

very different from quark's
$$|U_{\rm CKM}| \simeq \begin{pmatrix} 1 & \mathcal{O}(\lambda) & \mathcal{O}(\lambda^3) \\ \mathcal{O}(\lambda) & 1 & \mathcal{O}(\lambda^2) \\ \mathcal{O}(\lambda^3) & \mathcal{O}(\lambda^2) & 1 \end{pmatrix} \quad \lambda\sim 0.2$$

Still open questions

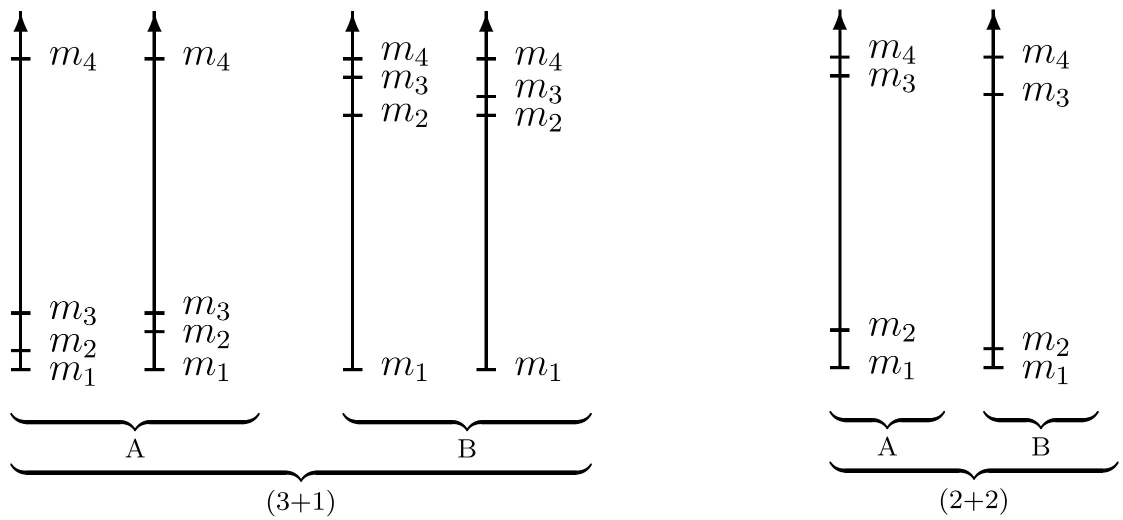
- Is $\theta_{13} \neq 0$?
- Is there CP violation in the leptons (is $\delta \neq 0, \pi$)?
- Are neutrino masses:
  - hierarchical: $m_i - m_j \sim m_i + m_j$?
  - degenerated: $m_i - m_j \ll m_i + m_j$?
- Dirac or Majorana? what about the Majorana Phases?

LSND: Sterile Neutrinos and 4 ν mixing

- $\overline{\nu_\mu} \to \overline{\nu_e}$ at $L/E \sim 1$ m/MeV $\Rightarrow \Delta m^2_{\rm LSND} \simeq 1$ eV^2

$$\Delta m^2_{\rm LSND} \gg \Delta m^2_{atm} \gg \Delta m^2_{\odot}$$

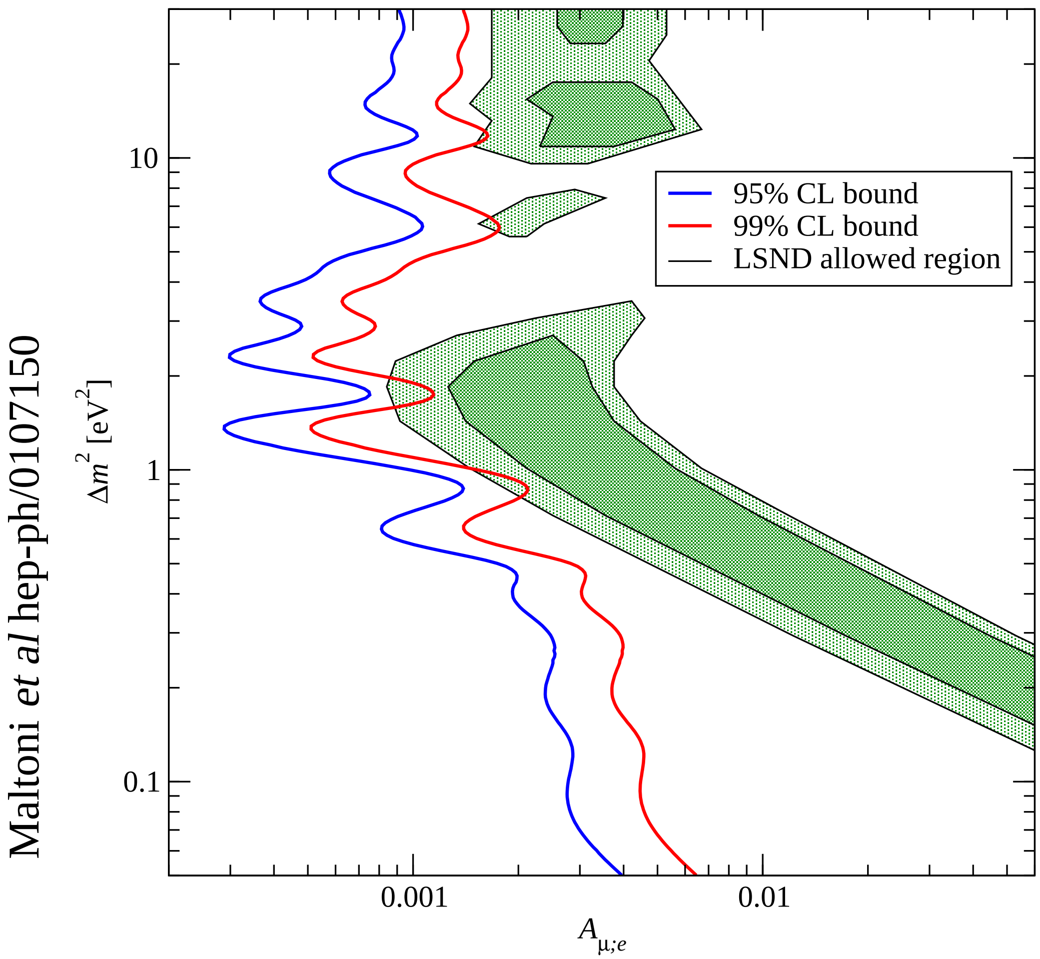
- To fit solar, atmospheric and LSND $\Rightarrow 3\ \Delta m^2 \to$ 4th sterile ν
- U: 6 mixing angles and 3 CP Dirac phases
- 6 mass spectra of two type: $3+1$ and $2+2$



- None of them gives satisfactory description of data (Talk by Giunti at NEU2)

Wait for MiniBooNE

- $3+1$:



$\sin^2 2\theta_{\rm LSND} = 4|U_{e4}|^2|U_{\mu 4}|^2$

$|U_{e4}|^2$ constrained by Bugey

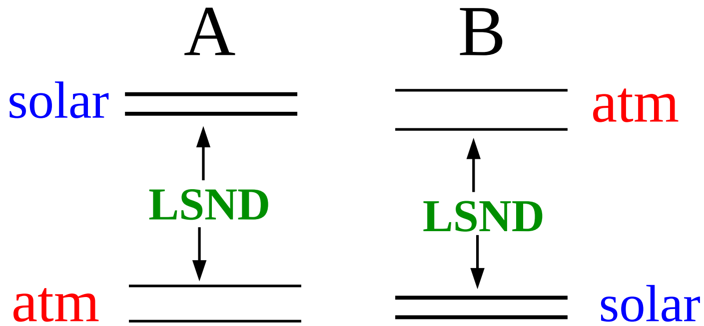
$|U_{\mu 4}|^2$ constrained

by CDHSW+ATM

$\Rightarrow$ only tiny regions at 99%CL

Grimus and Schwetz; Maltoni, Schwetz and Valle; Maltoni, Schwetz, Tortola and Valle

- In 2+2 Schemes:



Dooling, Giunti, Kang and Kim; Giunti, M.C. G-G and Peña-Garay; Fogli, Lisi and Marrone

Mixed active-sterile oscillations

Naively: Solar: $\nu_e \to \nu_+ \quad \nu_+ \simeq \sin\eta\,\nu_s + \cos\eta\,\nu_\tau$

Atm: $\nu_\mu \to \nu_- \quad \nu_- \simeq \cos\eta\,\nu_s - \sin\eta\,\nu_\tau$

– From atmospheric neutrinos: $\nu_\mu \to \nu_s$ disfavoured $\gtrsim$ 99% CL

sterile mixing allowed if all U angles are included in fit

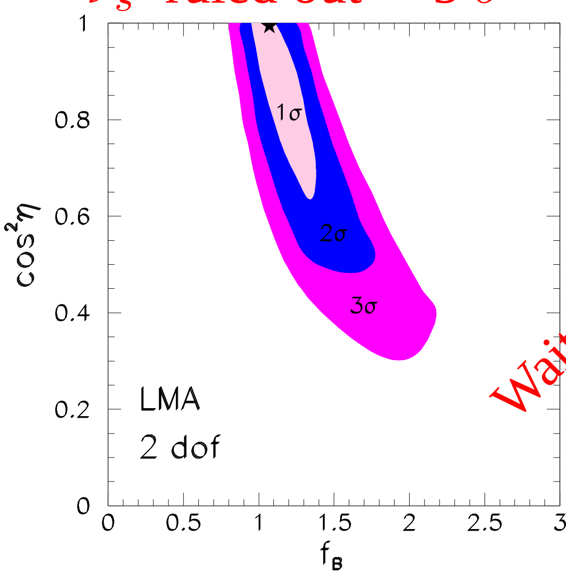
– From solar neutrinos: $\nu_e \to \nu_s$ ruled out $\sim 5\,\sigma$

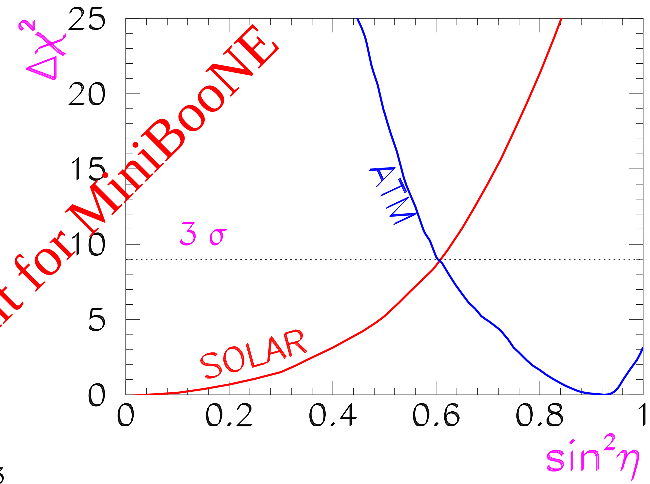
Difficult compromise

SNO measures flux of active neutrino

Larger sterile mixing if $\Phi_{^8B} > \Phi_{^8B,SSM}$

Barger, Marfatia and Wistnant; Bahcall, M.C.G-G, Peña-Garay





Wait for MiniBooNE

Maltoni *et al* hep-ph/0207157

Bahcall *et al* hep-ph/0204194

Alternative Explanations for LSND

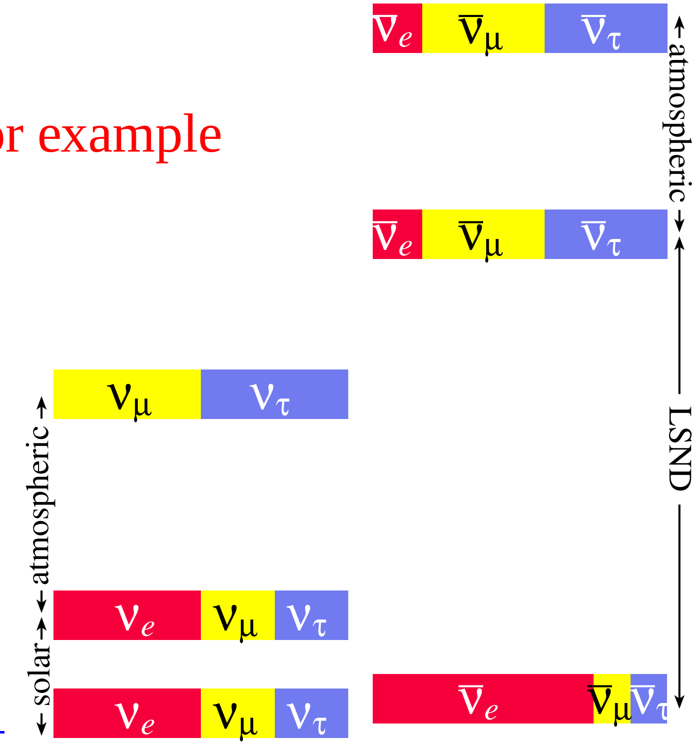
- Lepton Number violation μ decay: $\mu^+ \to e^+ \overline{\nu_e \nu_i}$

  Pakvasa; Bergman, Klapdor and Paes; Babu and Pakvasa

  Talk by Babu at NEU2

- CPT Violation: $(\Delta m^2_\nu, \theta_\nu) \neq (\Delta m^2_{\bar\nu}, \theta_{\bar\nu})$ For example

  Murayama and Yanagida PLB (2001);
  Pakvasa hep-ph/0110175;
  Barenboim etal hep-ph/0108199, hep-ph/0201134
  , Skadghauge hep-ph/0112189



Murayama and Yanagida
Strumia hep-ph 0201134

– Imminent tests of CPT in neutrinos:

  * KamLAND $\overline{\nu_e}$ versus solar ν_e disappearance
  * MiniBooNE $\nu_\mu \to \nu_e$ versus LSND $\overline{\nu_\mu} \to \overline{\nu_e}$
  * a signal at KamLAND or MiniBooNE will put serious constraints on CPT for ν's

– Further precision test at future facilities such as ν factories
  Talk by T. Ohlsson at NEU3

III. Some Implications

In the SM:

– There are no right-handed neutrinos

$\Rightarrow$ No renormalizable (ie dim$\leq$ 4) gauge-invariant operator for tree level ν mass

– SM gauge invariance also implies an accidental symmetry

$$G_{\rm SM}^{\rm global} = U(1)_{\rm B} \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$$

$\Rightarrow$ *neutrinos are strictly massless to all orders*

Thus the most striking implication of ν masses:

There is New Physics Beyond the SM

And it is also the only solid evidence.

To go further one has to be cautious…

Remember what was "implied" 10 years ago:

– Solar neutrino solution had to be "naturally" SMA

– Leptonic mixing should be of the order of quark mixing

$\Rightarrow$ Atmospheric ν anomaly was an experimental problem

– Scale of m_ν should be around 10-100 eV for Dark Matter

Still let's risk it. . .

The scale of New Physics : $\Lambda_{\rm NP}$

If SM is an effective low energy theory, for $E \ll \Lambda_{\rm NP}$

– The same particle content as the SM and same pattern of symmetry breaking

– But there can be non-renormalizable (dim> 4) operators

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_n \frac{1}{\Lambda_{\rm NP}^{n-4}} \mathcal{O}_n$$

First NP effect $\Rightarrow$ dim=5 operator

There is only one!

$$\mathcal{O}_5 = \frac{Z^\nu_{ij}}{\Lambda_{\rm NP}} \phi\phi L_i L_j$$

which after symmetry breaking

induces a ν Majorana mass

$$(M_\nu)_{ij} = \frac{Z^\nu_{ij}}{2} \frac{v^2}{\Lambda_{\rm NP}}$$

$\mathcal{O}_5$ breaks total lepton and lepton flavour numbers

Implications:

– It is natural that ν mass is the first evidence of NP

– Naturally $m_\nu \ll$ other fermions masses $\sim \lambda^f v$

– $m_\nu > \sqrt{\Delta m^2_{atm}} \sim 0.05$ eV $\Rightarrow \Lambda_{\rm NP} < 10^{15}$ GeV

– If $Z^\nu_{ij} \gtrsim 10^{-4} \Rightarrow 10^{10} < \Lambda_{\rm NP} < 10^{15}$ GeV

– Lepton flavour violation and CP violation expected

New Physics Scale close to GUT scale

The See-Saw Ramond, Gell-Mann, Slansky, Yanagida

Simplest NP: add right-handed ν_R (=SM singlet) neutrinos -

Well above the electroweak (EW) scale

$$-\mathcal{L}_{\rm NP} = \frac{1}{2} M_{Rij} \overline{\nu_{R}{}^c_i} \nu_{Rj} + \lambda^\nu_{ij} \overline{L_{Li}} \tilde{\phi} \nu_{Rj} + \text{h.c.}.$$

ν_R is a EW singlet $\Rightarrow M_{Rij} >> $ EW scale

Below EW symmetry breaking scale ($E \ll M_R$):

a) $m_D = \lambda^\nu v \sim$ mass of other fermions is generated

b) ν_R are so heavy that can be "integrated out"

$$\Downarrow \quad E \ll M_R$$

$$\mathcal{L}_{\rm NP} \Rightarrow \mathcal{O}_5 = \frac{Z^\nu_{ij}}{\Lambda_{\rm NP}} \phi\phi L_i L_j \Rightarrow m_\nu = m_D^T \frac{1}{M_R} m_D$$

This is the see-saw

Lessons:

– $\mathcal{L}_{\rm NP}$ contains 18 parameters which we want to know

– $\mathcal{O}_5$ contains 9 parameters which we can measure

$\Rightarrow$ Same $\mathcal{O}_5$ can give very different $\mathcal{L}_{\rm NP}$

$\Rightarrow$ It is *difficult* to "imply" bottom-up (model independently)

Going Top-Down:

(1) Choose your model of NP: particle content and symmetry

(2) Compute the neutrino mass matrix:

(3) Diagonalize it, make predictions and compare to data

(4) Back to (1)...

So many models so little time ...

Reconstructing Neutrino Mass Matrix

Barbieri, Hall, Smith, Strumia, Weiner; Altarelli, Feruglio...

Alternatively (in between):

– Classify the predicted neutrino mass matrix (textures)

– Identify differentiating predictions, and when data comes ...

– Constraint/rule out the texture & accept/rule out the models

Still several neutrino mass matrix (textures) fit the data:

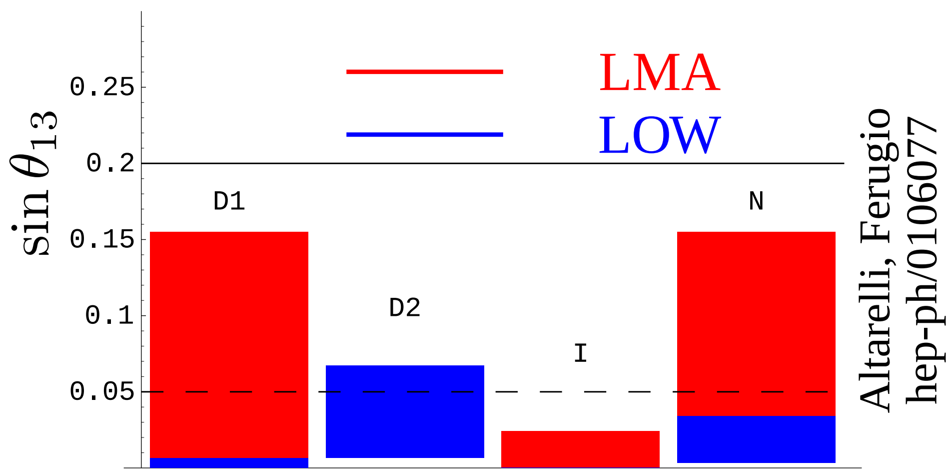
Degenerate 1	Degenerate 2	Normal	Inverted
$m\begin{pmatrix} \delta & -\frac{1}{\sqrt{2}} & \frac{(1-\epsilon)}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} & \frac{(1+\eta)}{2} & \frac{(1+\eta-\epsilon)}{2} \\ \frac{(1-\epsilon)}{\sqrt{2}} & \frac{(1+\eta-\epsilon)}{2} & \frac{(1+\eta-2\epsilon)}{2} \end{pmatrix}$	$m\,1_{3\times3} + r\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} + \delta m_\nu$	$m\begin{pmatrix} \delta & \epsilon & \epsilon \\ \epsilon & 1+\eta & 1+\eta \\ \epsilon & 1+\eta & 1+\eta \end{pmatrix}$	$m\begin{pmatrix} \delta & -1 & 1 \\ -1 & \eta & \eta \\ 1 & \eta & \eta \end{pmatrix}$

They Predict :

Different ν-less $\beta\beta$ rate

Different between masses and mixing

Need more data



Other Side Effects

Side Effect 1: Lepton Flavour Violation

– ν oscillation $\Rightarrow$ Lepton Family Number is not conserved

– Can be seen in charged leptons?

If only $m_\nu \simeq \sqrt{\Delta m^2_{\rm atm}} \Rightarrow Br(\tau \rightarrow \mu\gamma) \sim 10^{-41}$ too small!

But if there is an intermediate scale (for example SUSY)
$\Rightarrow Br(\tau \rightarrow \mu\gamma)$ or $Br(\mu \rightarrow e\gamma)$ could be observable

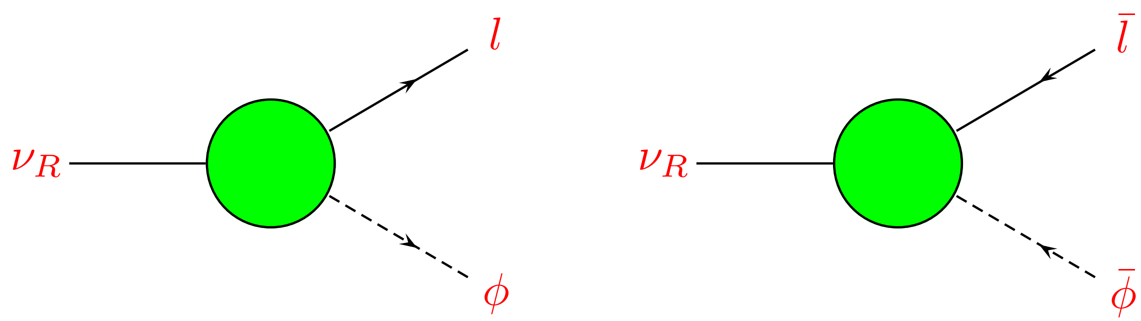
Other Side Effects

Side Effect 2: We are here! (Leptogenesis)

– Majorana $m_\nu \Rightarrow \not{L} \Rightarrow$ Baryon asymmetry can be generated

– How? In the Early Universe via decay of heavy ν_R

Fukugita and Yanagida



If $\not{C}$P : $\Gamma(\nu_R \to \phi\, l_L) \neq \Gamma(\nu_R \to \overline{\phi}\, \overline{l_L})$

And decay is out of equilibrium:

($\Gamma_{\nu_R} \ll$ Universe expansion rate)

} Δ L is generated

At the electroweak transition sphaleron processes

$\Rightarrow \Delta$ L is transformed in $\Delta B \simeq -\frac{\Delta \mathrm{L}}{2}$

– Details are model dependent (Buchmüler, Plümacher... Talk by Zing) but

$M_R \sim 10^{10}$ GeV $\Rightarrow$ OK to explain observed η_B/η_γ

IV. Future

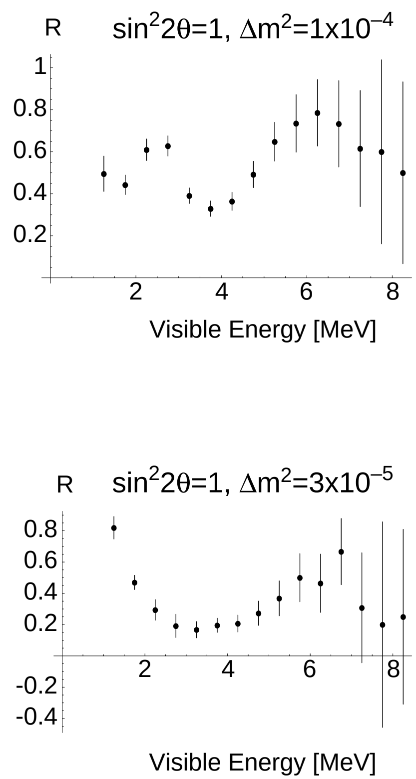
KamLAND

First terrestrial experiment to test solar problem

– Search $\overline{\nu_e}$ from L$\sim$ 200 km (17 reactors), $E_\nu \sim$ few MeV

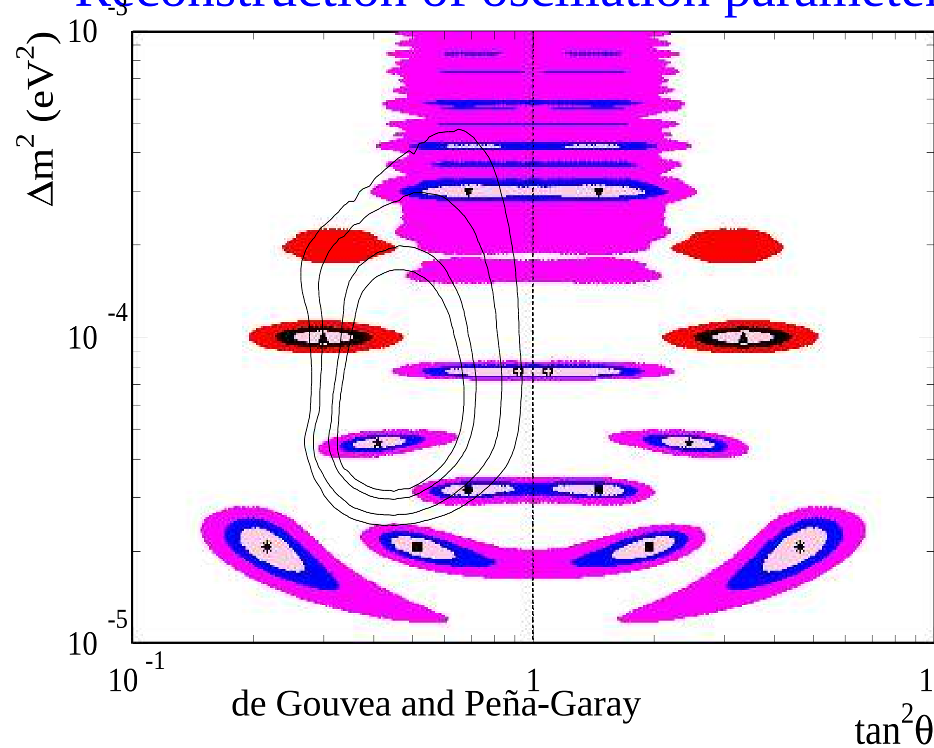
– Defnite test of LMA: It will verify/exclude it SOON

Dip in spectrum if $\Delta m^2 > 2 \times 10^{-5}$ eV^2



Murayama and Pierce; Barger, Marfatia and Wood

Reconstruction of oscillation parameters



– If LMA is confirmed:

CP violation is observable at SuperBeams/ν-factory

Solar ν experiments will be able to test solar physics

– If LMA is excluded: $\Rightarrow$ Borexino

Sensitive to the LOW region: D/N, Zenith dependence

Sensitive to the VAC region: Seasonal dependence

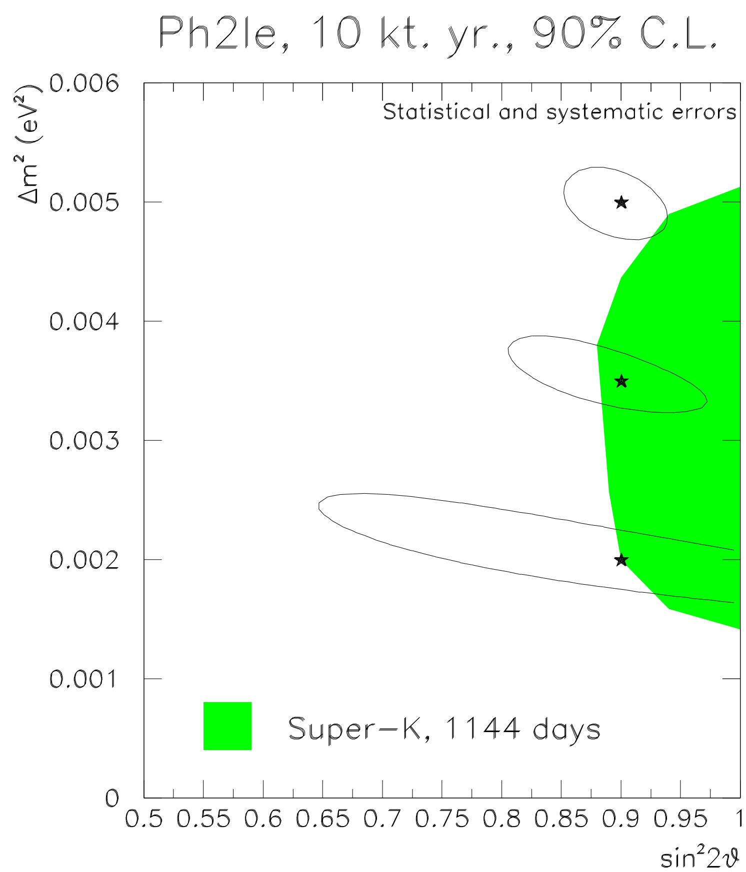
Future LBL: MINOS and CNGS

– K2K : confirms so far Atmospheric Oscillations

– MINOS:

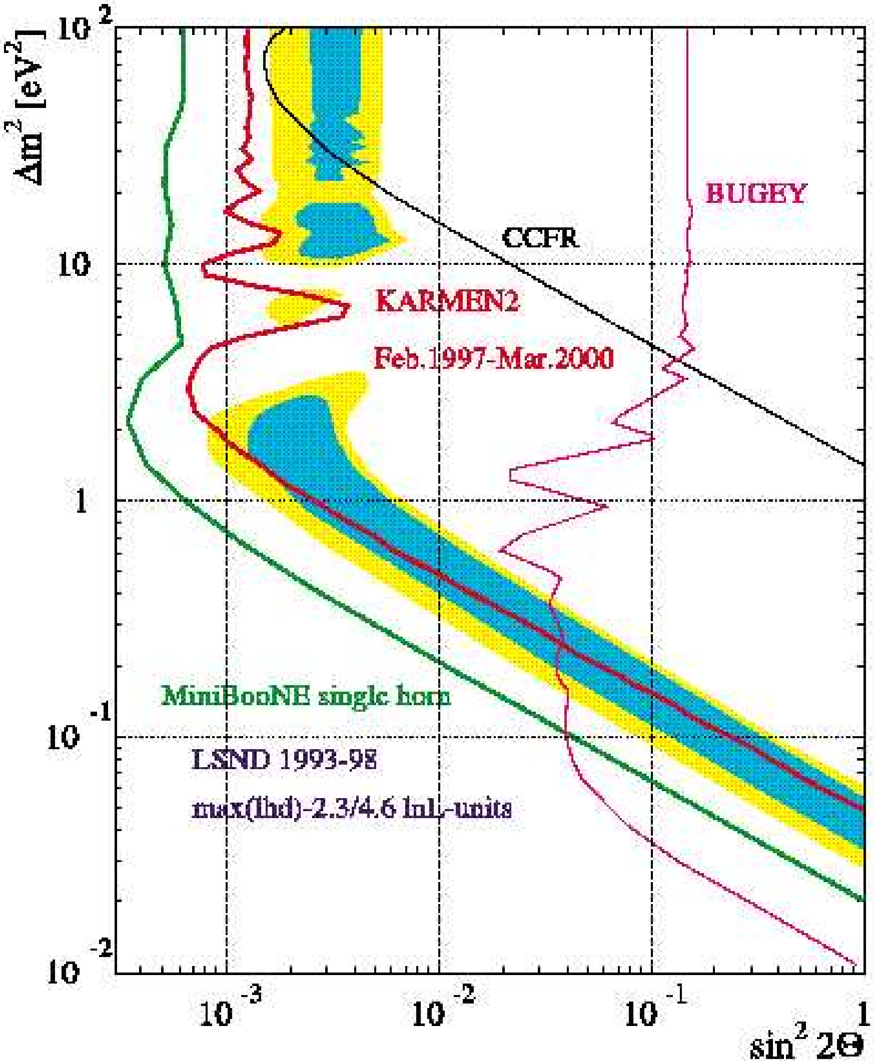
Precision measurement of Δm^2_{23}, $\tan^2\theta_{23}$

Some sensitivity to θ_{13} if close to upper bound



– CNGS: τ appearance searches

Future:MiniBooNE



It will settle the issue of LSND/Karmen

It will boost the case for sterile neutrino

Future: Mass scheme, θ_{13}, CP violation

- Normal/Inverted: Need of matter effects $\Rightarrow$ very long L [(**)]
- θ_{13}: Very intense ν_μ beam with low background [(*), (**)]
- $\not{C}$P: Δm^2_{21} and $\tan^2\theta_{21}$ (LMA) and θ_{13} not too small
  Intense beams with exchangeable initial state $(\nu/\bar{\nu})$ [(*), (**)]

Possible with:

$*$ Conventional (=from π decay)

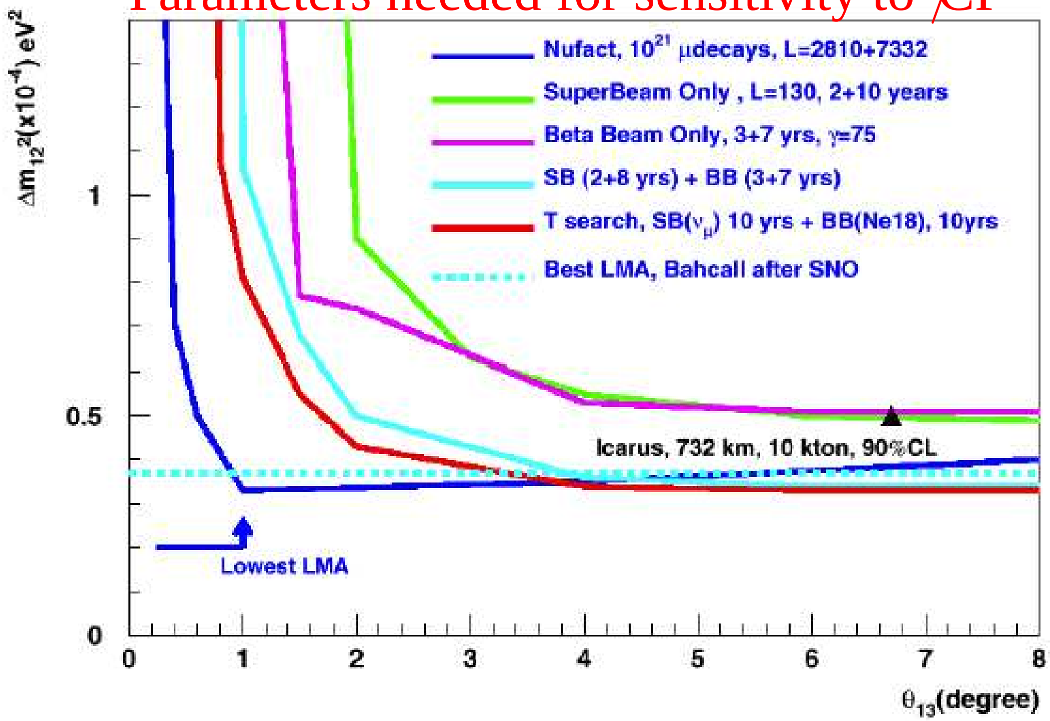
Superbeams: JHF ...

$**$ ν-factory:

clean ν beam from μ decay

Cervera, Burguet-Castell, Gavela, Gomez-Cadenas, Hernandez, Mena
Barger Geer, Marfatia, Raja, Whisnant
Huber, Lindner, Winter
...

Parameters needed for sensitivity to $\not{C}$P



M. Mezzetto, CERN/NuFact ν Oscillation Working Group

Future: Neutrino Mass Scale

- Oscillation data only gives lower bound on heaviest ν mass
- At present only upper limits from:

$^3H \to ^3He + e + \overline{\nu}_e$: for both Dirac or Majorana ν's

$$m_{\nu_e} = m^{\beta}_{eff} = \sum m_j |U_{ej}|^2 < 2.2 \text{ eV}$$

(at 95 % CL)
(Mainz & Troisk experiments)

– Katrin proposed to improve present sensitivity to $m^{\beta}_{eff} \sim 0.3\,\text{eV}$

ν-less Double-β decay: only for Majorana ν's $(A, Z) \to (A, Z+2) + e^- + e^-$

$$|\langle m_{ee}\rangle| = |\sum U^2_{ej} m_j| < 0.35 \text{ eV}$$

$$+\text{theor. uncert.} < 1.05 \text{ eV}$$

(^{75}Ge Heidelberg-Moscow experiment) (at 90% CL)

Dependence on 3 CP violating phases (unlike m^{β}_{eff})

– Several proposed experiments to improve sensitivity to $|\langle m_{ee}\rangle| \sim 10^{-2}\,\text{eV}$

- If a signal is observed in principle comparison of $|\langle m_{ee}\rangle|$ and m^{β}_{eff} may allow to discriminate between mass schemes and give information on Majorana CP phases

Bilenky, Farzan, Giunti, Grimmus, Kayser, Klapdorm, Pas, Peres, Pascoli, Petcov, Smirnov . . .

But expected experimental and theoretical precision may not be enough

Barger, Glashow, Langacker and Marfatia, hep-ph/0205290

V. Conclusions

- Big experimental effort: flavor conversion proved; oscillation being probed

  Solar $\nu' s$: Verification of Flavour Conversion at 5 σ

  Atmospheric $\nu' s$: high confidence of L/E dependence

- Soon these signals will be confirmed with "man-made" neutrino beams from reactor and accelerators.

  Solar $\nu' s$: Imminently KamLAND and soon BOREXINO should be able to approach us to the final answer

  Atmospheric $\nu' s$: K2K confirms and MINOS should measure parameters with precision.

- ν masses suggest new physics scale close to GUT scale.

- Determining the parameters of the neutrino mass matrix will provide fundamental information to understand the dynamics at this new physics scale

- This is a challenging task which requires a new generation of neutrino experiments

$\nu' s$ may help us to answer some *philosophical* question:

Why are we *here*?

Special thanks to:

J.N. Bahcall, J.J. Gomez-Cadenas, P. Hernandez, M. Maltoni, A. Marrone and C. Peña-Garay