

THEORY OF NEUTRINO MASSES AND MIXING

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Conclusions

- Big experimental effort: flavor conversion proved
Solar ν 's : Verification of Flavour Conversion ν_e to ν_μ or ν_τ at 5σ
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

I. Introduction:

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

III. Some Implications:

The Scale of New Physics: SeeSaw Mechanism

Reconstructing the Neutrino Mass Matrix

Side Effects

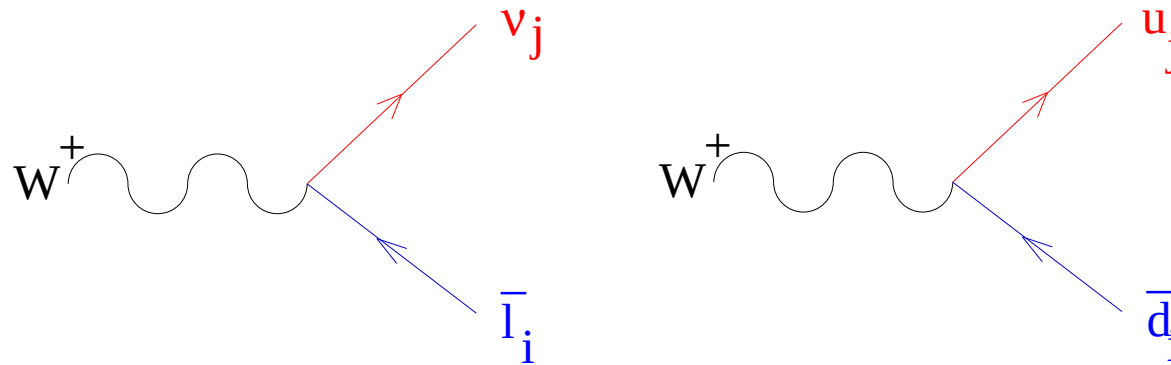
IV. Future

V. Conclusions

I. Introduction

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

$$\frac{g}{\sqrt{2}} W_\mu^+ \sum_{ij} (U_{LEP}^{ij} \bar{l}_L^i \gamma^\mu \nu_L^j + U_{CKM}^{ij} \bar{U}_L^i \gamma^\mu D_L^j) + h.c.$$



$$\frac{g}{\sqrt{2}} W_\mu^+ \sum_{ij} (U_{LEP}^{ij} \bar{l}_L^i \gamma^\mu \nu_L^j + U_{CKM}^{ij} \bar{U}_L^i \gamma^\mu D_L^j) + h.c.$$

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

- * Their CP properties:

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

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

$$U_{\alpha j}^{\text{Maj}} = U_{\alpha j}^{\text{Dir}} \times e^{-i\eta_j}$$

- 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 $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$

- We have important information (mostly constraints) from:

- * The line shape of the Z: $N_{\text{weak}} = 3$

- * Direct kinematic mass measurements: ${}^3\text{H} \rightarrow {}^3\text{He} + e^- + \bar{\nu}_e$

$$m_{\nu_e} < 2.2 \text{ eV (95\% CL)} \quad m_{\nu_e} = f(m_i, U_{LEP})$$

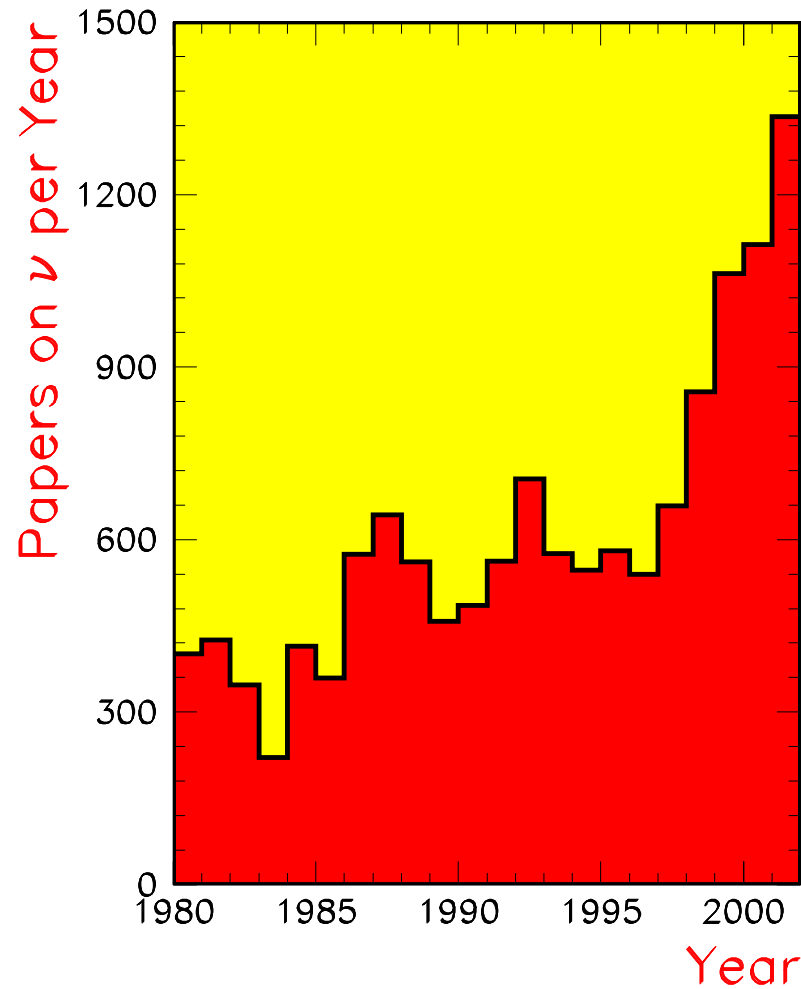
- * ν -less $\beta\beta$ decay (If Majorana ν 's): $(A, Z) \rightarrow (A, Z + 2) + e^- + e^-$

$$|\langle m_{ee} \rangle| = \left| \sum_{i=1}^N U_{ei}^2 m_i \right| < 0.35 \text{ eV} + \text{theor. uncert.} < 1.05 \text{ eV}$$

- * 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 $l_\alpha + N \rightarrow \nu_\alpha + N'$

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 $|\nu(t)\rangle = \sum_{i=1}^n U_{\alpha i} e^{-i E_i t} |\nu_i\rangle$

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

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

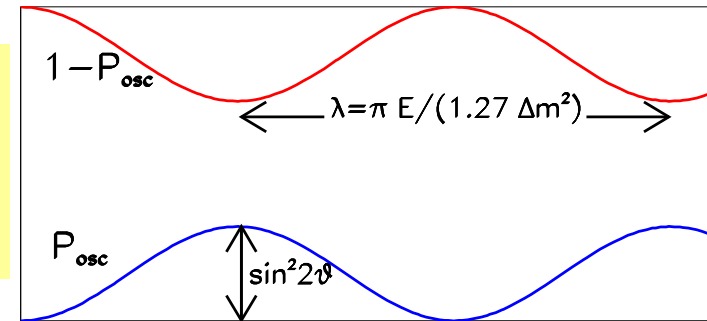
$$\frac{\Delta_{ij}}{2} = \frac{(E_i - E_j)L}{2} = 1.27 \frac{(m_i^2 - m_j^2)}{\text{eV}^2} \frac{L/E}{\text{Km/GeV}}$$

- $P_{\alpha\beta}$ depends on Theoretical Parameters and on Two *Experimental* Parameters:
 - $\Delta m_{ij}^2 = m_i^2 - m_j^2$ The mass differences
 - $U_{\alpha j}$ The mixing angles (and Dirac phases)
 - 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 $0 \leq \theta \leq \frac{\pi}{2}$

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

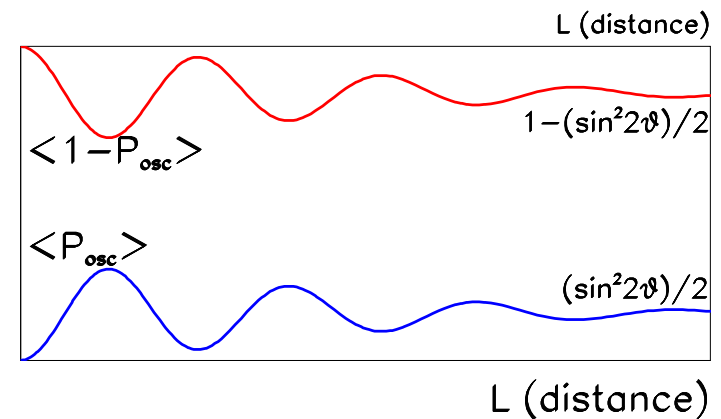
$$P_{\alpha\alpha} = 1 - P_{osc} \text{ Disappear}$$



- 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 $\Delta m^2 \sim E/L$

$$-\Delta m^2 \ll E/L \Rightarrow \text{No time to oscillate}$$

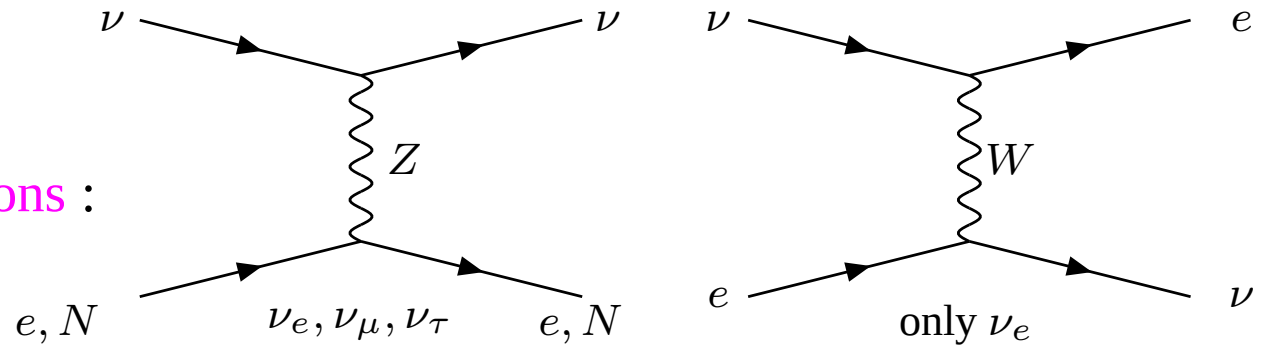
$$\langle \sin^2 (1.27 \Delta m^2 L/E) \rangle \simeq 0 \rightarrow \langle P_{osc} \rangle \simeq 0$$

$$-\Delta m^2 \gg E/L \Rightarrow \text{Averaged oscillations}$$

$$\langle \sin^2 (1.27 \Delta m^2 L/E) \rangle \simeq \frac{1}{2} \rightarrow \langle P_{osc} \rangle \simeq \frac{1}{2} \sin^2(2\theta)$$

- In vacuum $\langle P_{osc}^{vac} \rangle = \sin^2(2\theta) \langle \sin^2(1.27 \Delta m^2 L/E) \rangle$ symmetric for $\theta \rightarrow \frac{\pi}{2} - \theta$
- 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

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

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

– P_{osc}^{mat} not symmetric for $\theta \rightarrow \frac{\pi}{2} - \theta \Rightarrow \sin^2(2\theta)$ 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:

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

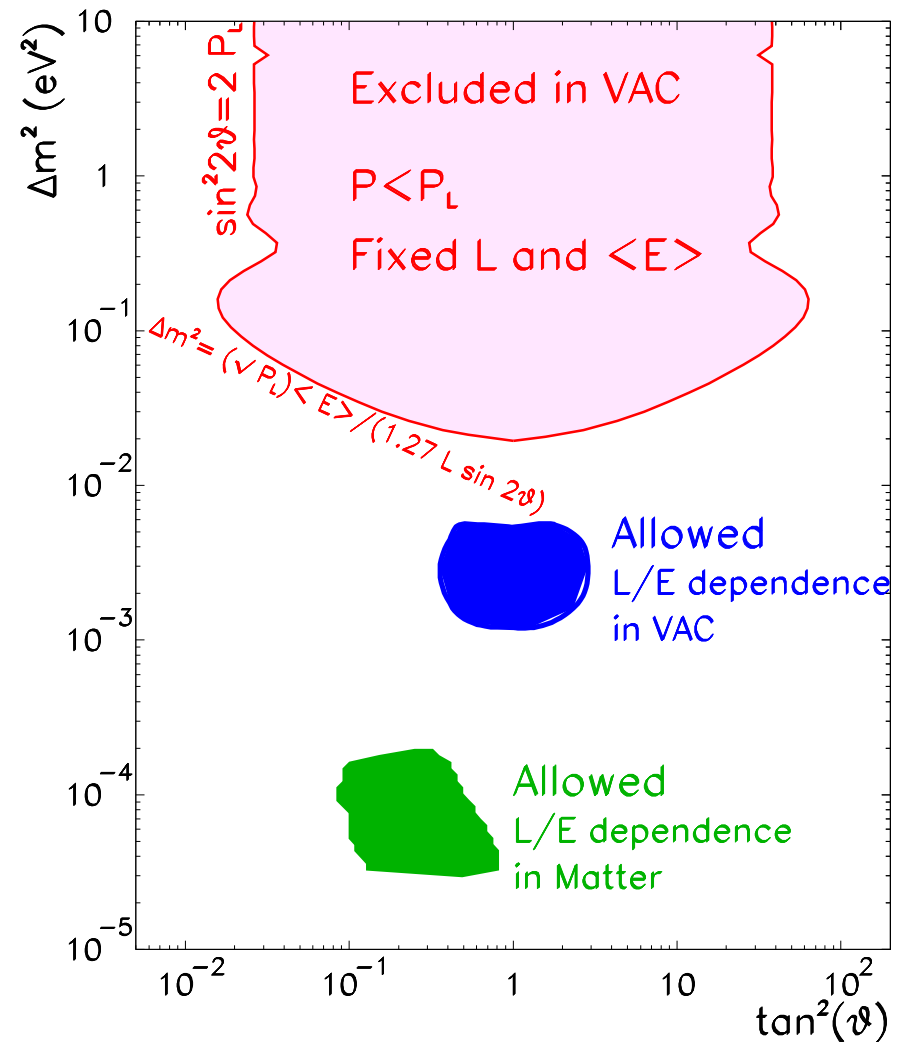
- If the experiment detects oscillation
→ allowed region

- If data at fixed $\langle L \rangle$ and $\langle E \rangle$
(like most laboratory searches)
→ region is open in large Δm^2

- If data at several $\langle L \rangle$ and/or $\langle E \rangle$
→ region may be closed

- If no matter effects:
(like Atmospheric $\nu_\mu \rightarrow \nu_\tau$)
→ region is symmetric around $\theta = \frac{\pi}{4}$

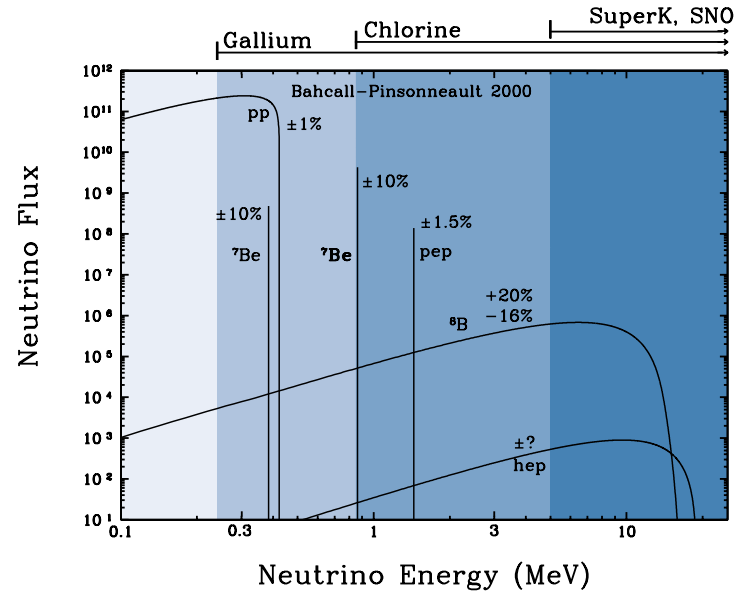
- If matter effects
(like Solar $\nu_e \rightarrow \nu_x$)
→ region not symmetric around $\theta = \frac{\pi}{4}$



II. Global Fits

Solar Neutrinos

- The sun emits ν_e 's.
- Detected at



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

(* For undistorted ^8B spectrum)

SSM Independent Tests

SK and SNO measure Φ_{8B} :

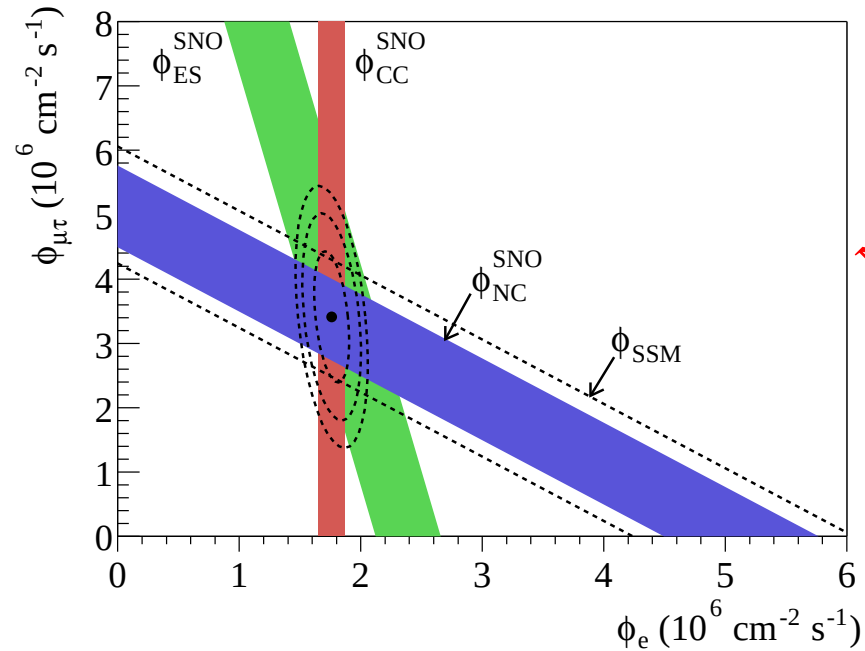
* If flavour conversion:

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

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

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

Evidence for Flavour Conversion !



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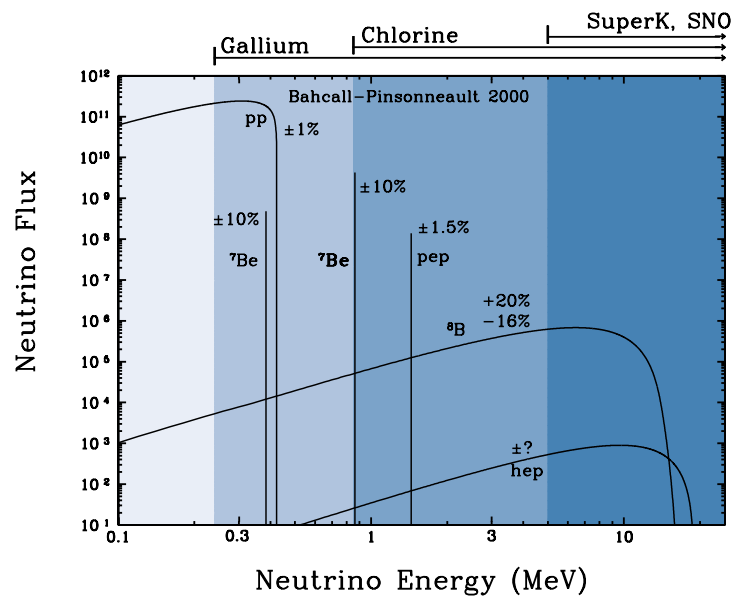
* No flavour conversion $\Rightarrow \Phi_{\mu\tau} = 0$ $\left\{ \begin{array}{l} \Phi_{SK}^{ES} = \Phi_{SNO}^{CC} \Rightarrow 3.2\sigma \text{ out} \\ \Phi_{SNO}^{NC} = \Phi_{SNO}^{CC} \Rightarrow 5.3\sigma \text{ out} \end{array} \right.$

* $\nu_e \rightarrow \nu_{\text{sterile}} \Rightarrow \Phi_{\mu\tau} = 0 \Rightarrow \Phi_{SNO}^{NC} \simeq \Phi_{SNO}^{CC} \sim 5\sigma \text{ out}$

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:

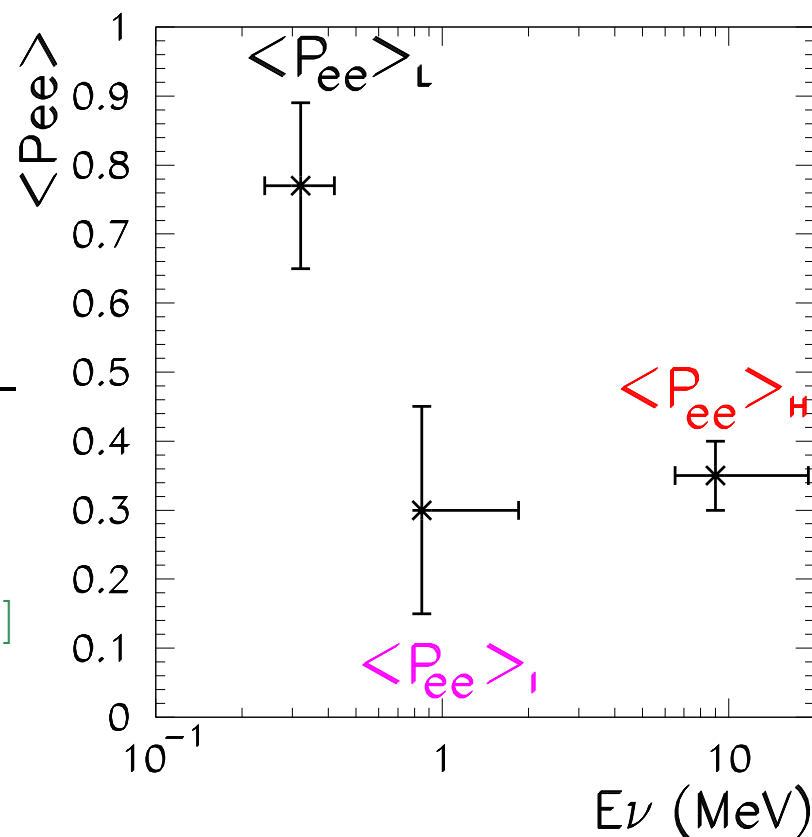
Low E: pp with survival $\langle P_{ee} \rangle_L$

Intermediate E: ${}^7\text{B}$, pep , CNO with $\langle P_{ee} \rangle_I$

High E: ${}^8\text{B}$ with survival $\langle P_{ee} \rangle_H$

- 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	$f_B \langle P_{ee} \rangle_H$
SNO NC	1.01 ± 0.23	f_B



Barger et al., hep-ph/0204253

Solar Oscillations: Impact of SNO

SNO coll., nucl-ex/0204009

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

Bandyopadhyay *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

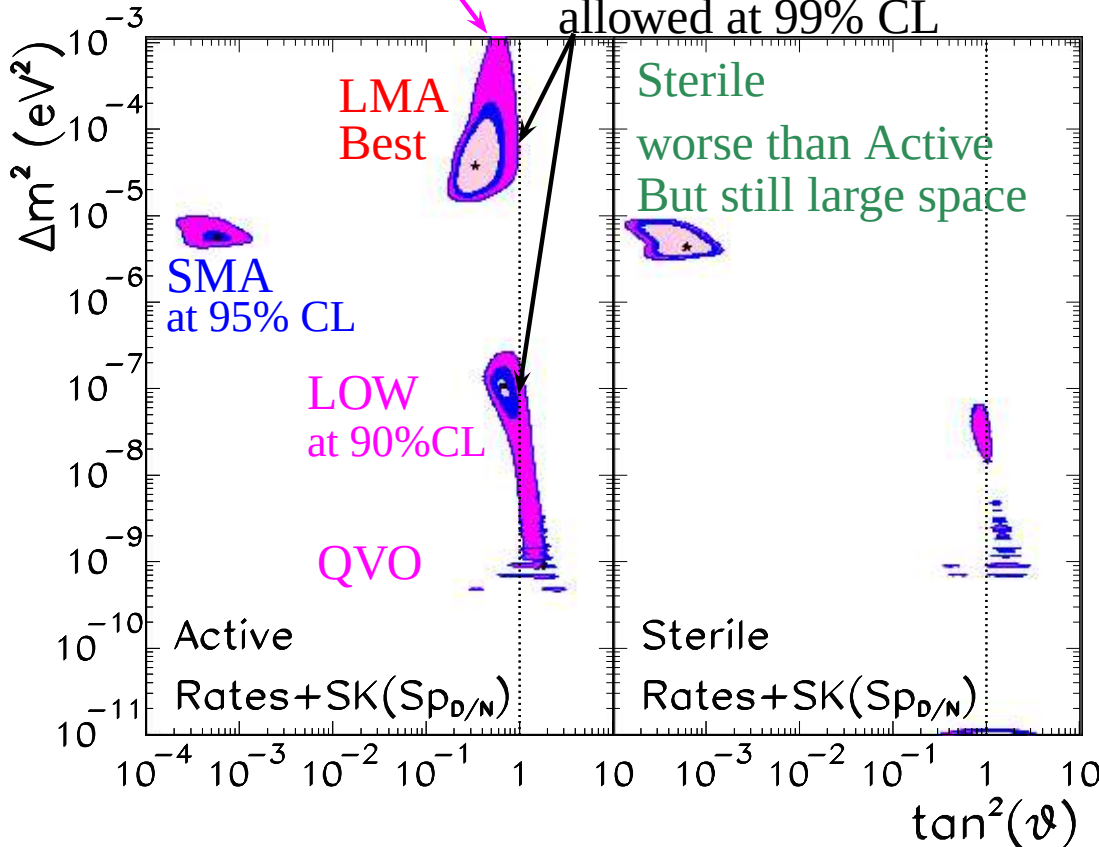
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Detailed SK E and t dependence
New SNO day-night spectrum

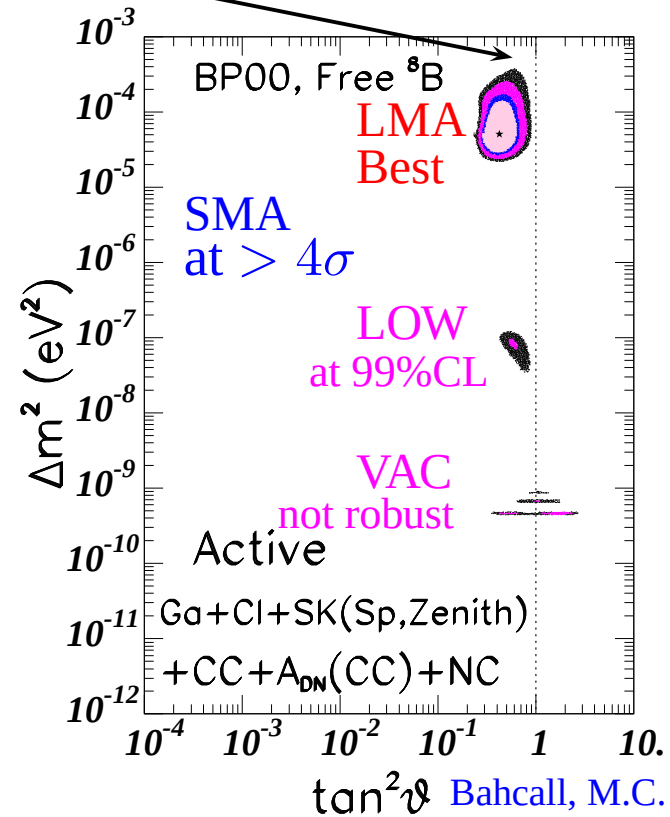
ICHEP02

No upper Δm^2 bound at 99% CL
CHOOZ $\Rightarrow \Delta m^2 \lesssim 8 \times 10^{-4} \text{ eV}^2$

Maximal mixing
allowed at 99% CL



At 3σ :
 $\Delta m^2 \lesssim 4 \times 10^{-4} \text{ eV}^2$
Maxmix
not allowed



CL

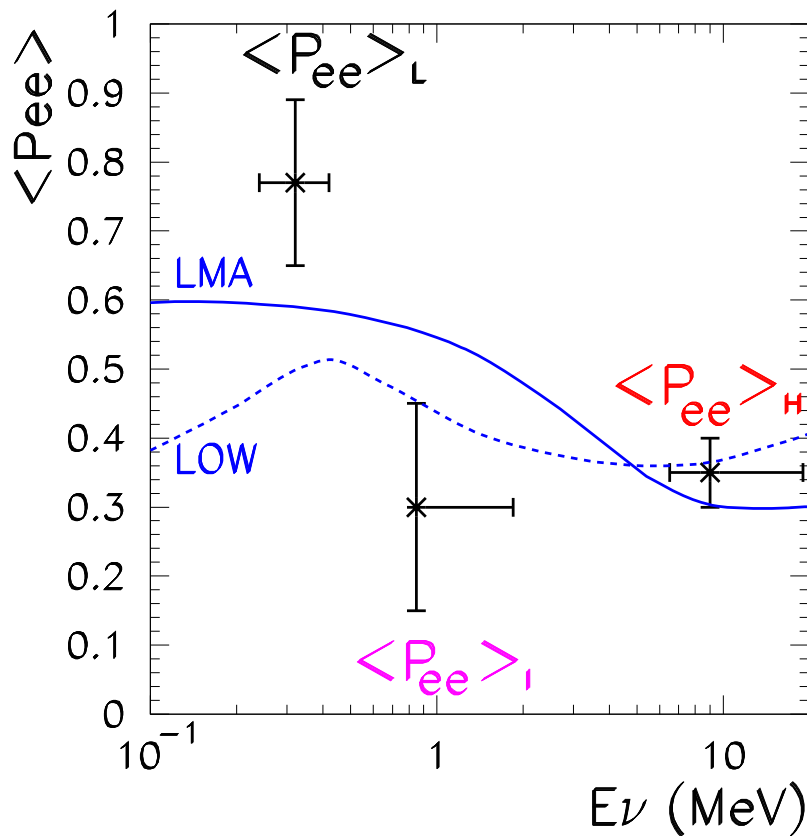
3 σ

99

95

90

LMA/LOW Comparison



LOW gives worse fit to low energies rate

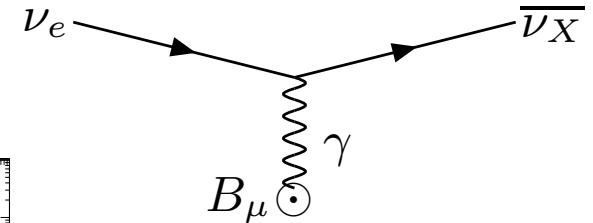
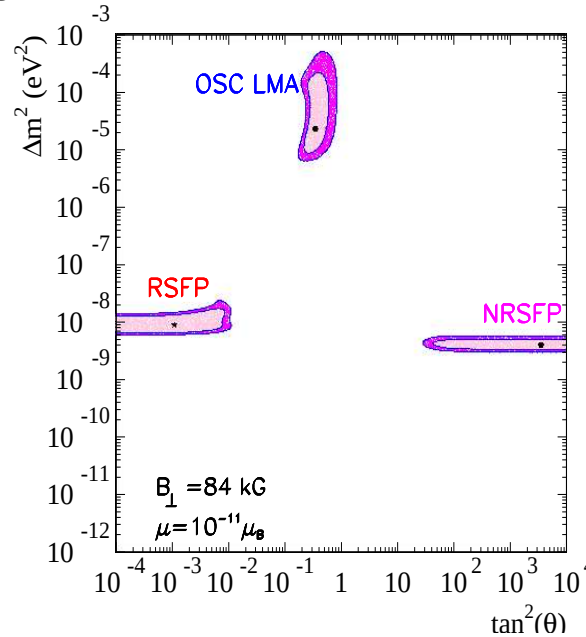
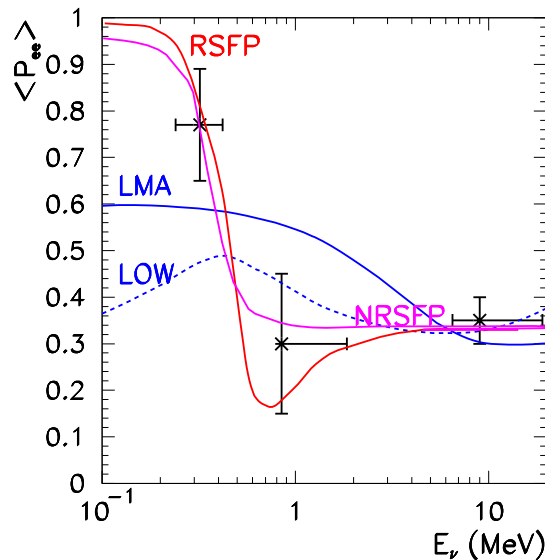
Also worse fit to SK zenith-spectrum

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



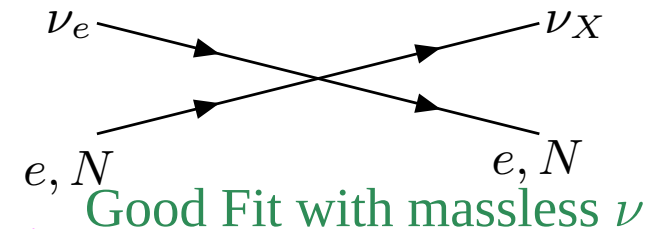
Good Fit with different
mass and mixing
than oscillations

– Flavour Changing ν interactions (Wolfenstein)

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

- In general additional parameters: ν magnetic moment, magnetic field, FC couplings etc... are not very “natural”

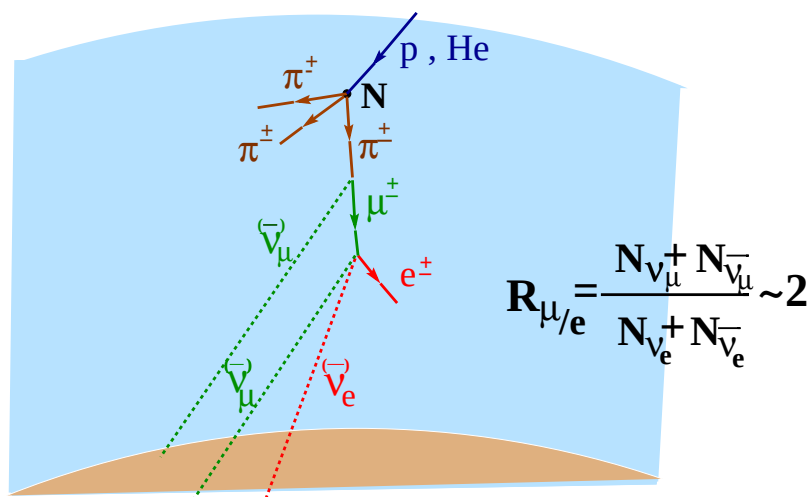
- Oscillation signal in KamLAND [would] rule them out



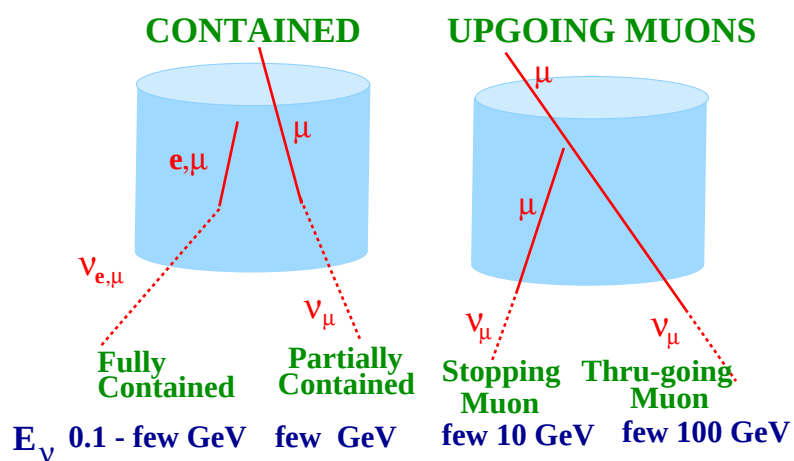
Good Fit with massless ν

Atmospheric Neutrinos

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

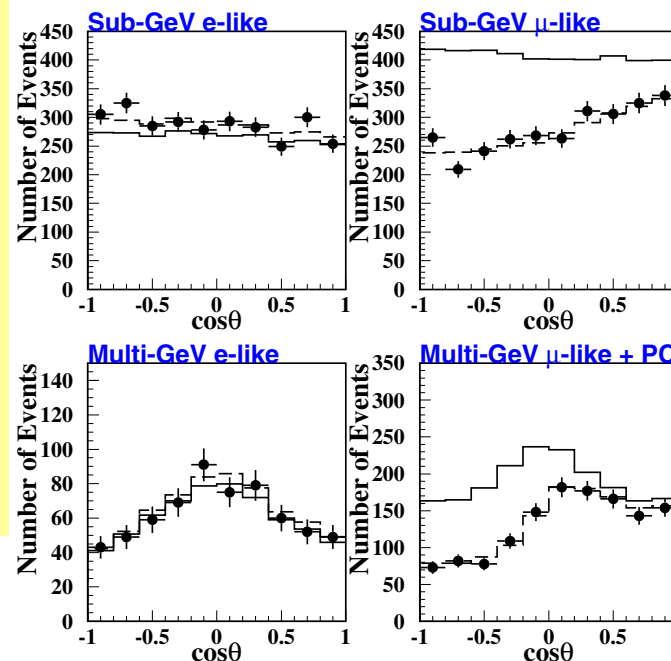


EVENT CLASSIFICATION

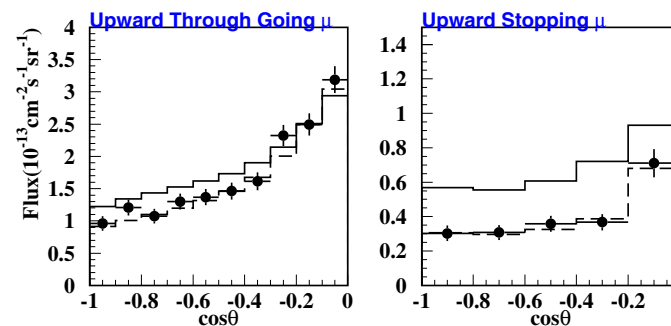


Angular Distribution at SK

ν_e in agreement with SM



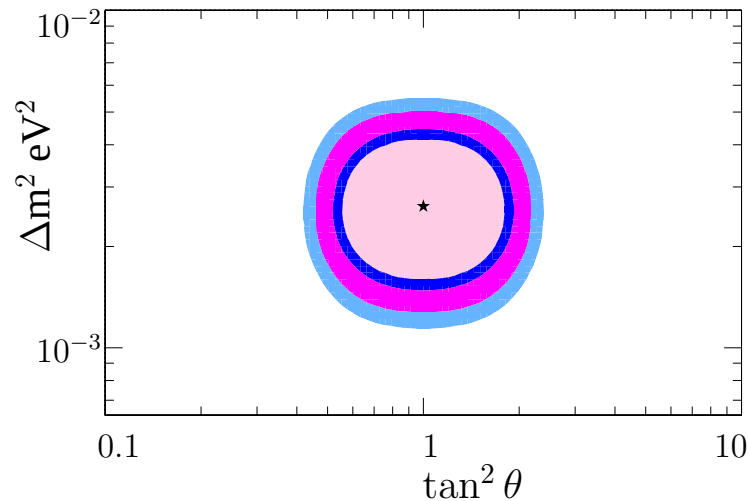
→ Deficit grows with L



→ Decreases with E

Atmospheric Oscillation Solutions

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



Best fit:

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

$$\tan^2 \theta = 1$$

Confirmed within statistics by K2K

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

Different L/E dependence:

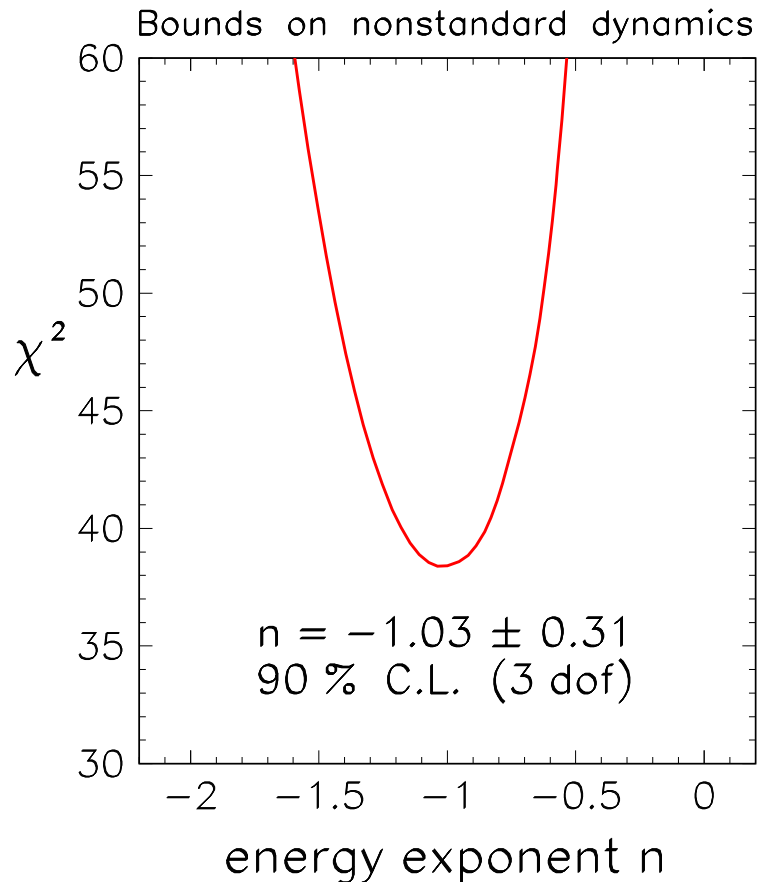
$$P_{\mu\tau} = \alpha \sin^2(\beta L E^n)$$

$n = -1$ oscillations

$n = 1$ Viol Equiv. Principle

$n = 1$ Viol Lorentz invariance

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

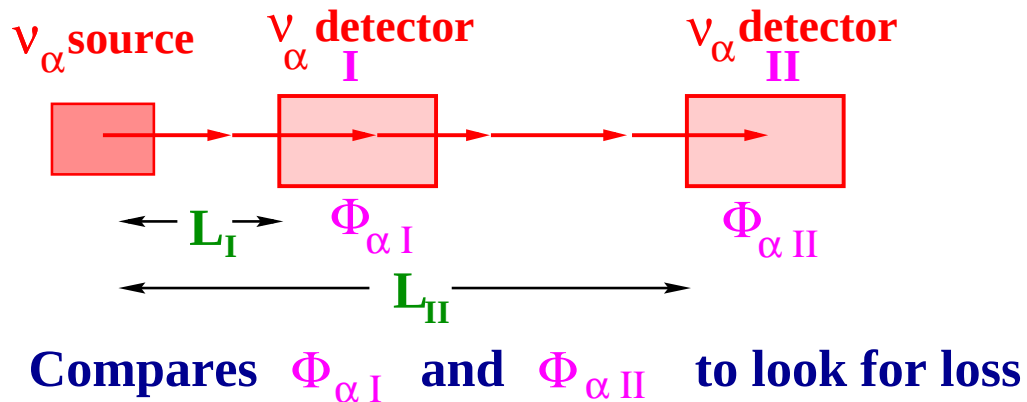


Fogli, Lisi and Marrone hep-ph/0105139

Chooz

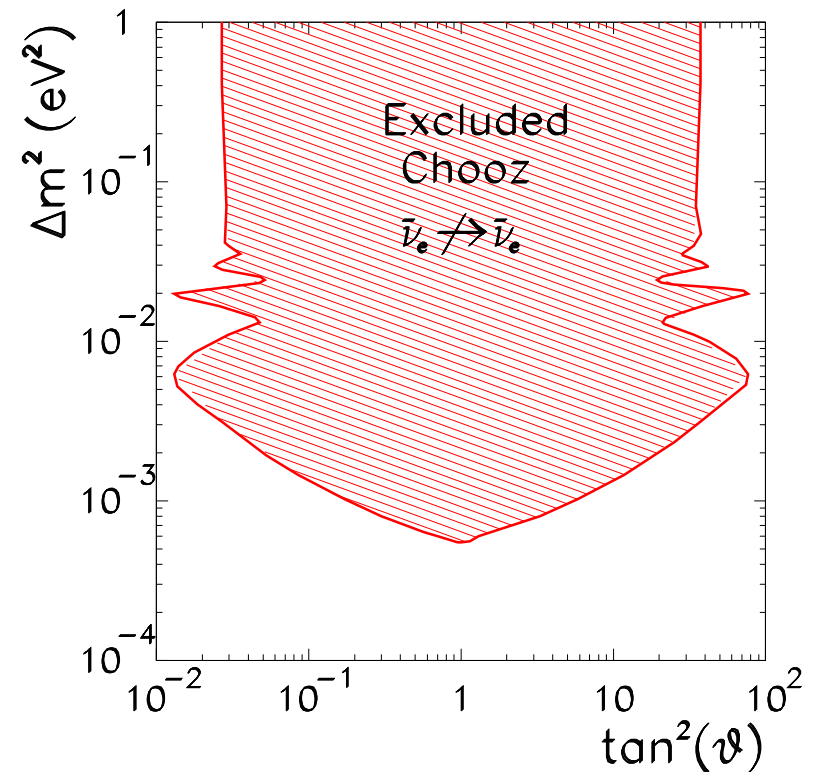
• Disappearance Experiment

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

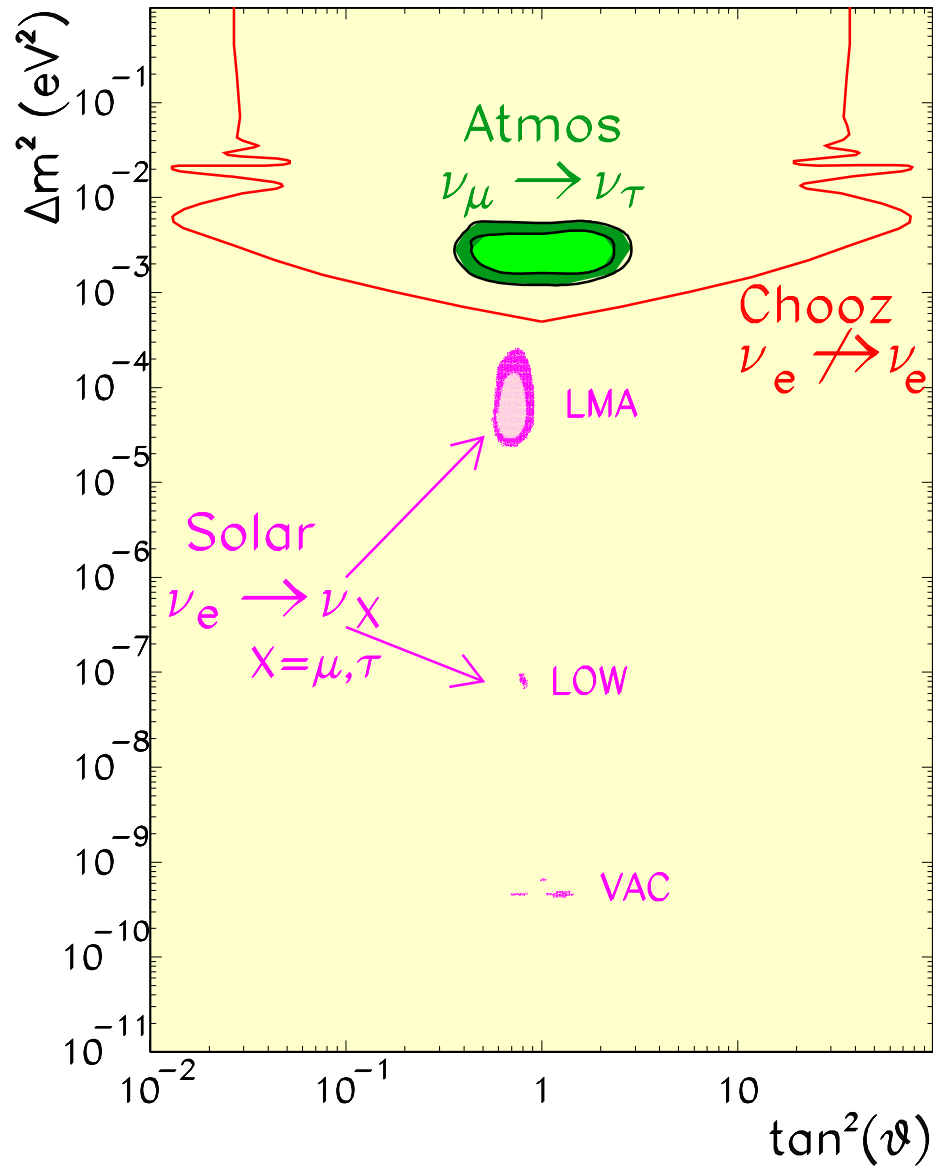


If CPT is conserved:

- Constraints solar oscillations for $\Delta m_{\odot}^2 \gtrsim 8 \times 10^{-4} \text{ eV}^2$.
- Constraints $\nu_{\mu} \rightarrow \nu_e$ component of atmospheric oscillations



Solar + Atmospheric 3ν Oscillations



Goal: to fit this with 3ν mixing

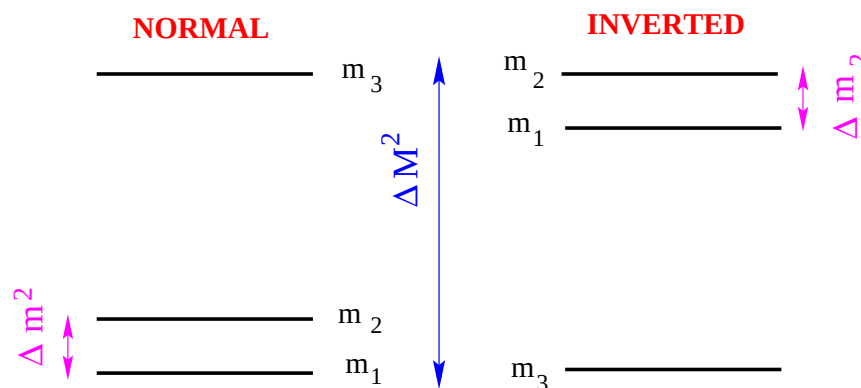
Hope: to learn more than with separate 2ν solar and 2ν atm analysis

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 $\Rightarrow \Delta m^2 = \Delta m_{\odot}^2 \ll \Delta M^2 \simeq \pm \Delta m_{atm}^2 \simeq \pm \Delta m_{32}^2 \simeq \pm \Delta m_{31}^2$

$\Rightarrow$ 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					
Atmos	X	X	X	X	X	X	X		X	X		X		X?
Chooz	X	X		X	X		X	X	X					

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

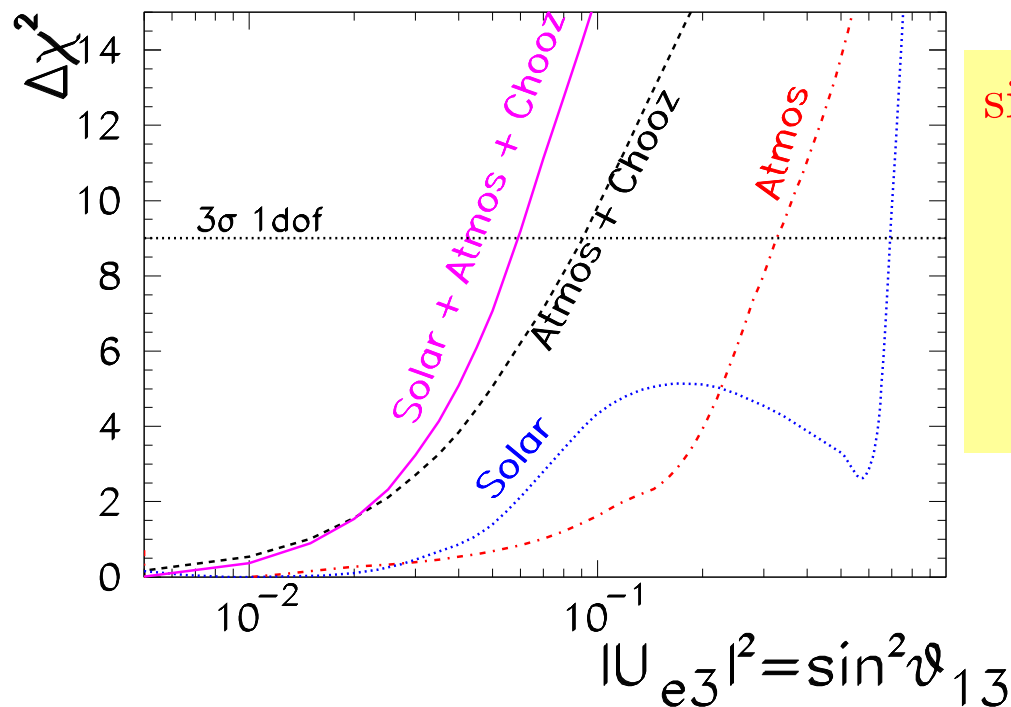
- In the Hierarchical approximation $\Delta m^2 \ll \Delta M^2$

* For $\theta_{13} = 0$ solar and atmospheric oscillations decouple $\Rightarrow$ Normal $\equiv$ Inverted

- Solar $\rightarrow \Delta m^2 = \Delta m_{\odot}^2 \quad \theta_{12} = \theta_{\odot}$
- Atmospheric $\rightarrow \Delta M^2 = \Delta m_{atm}^2 \quad \theta_{23} = \theta_{atm}$

* For $\theta_{13} \neq 0$ solar and atmospheric couple through θ_{13}

But all data prefers θ_{13} small



$$\sin^2 \theta_{13} < 0.06 \text{ (3}\sigma \text{ 1dof)}$$

$$\Downarrow$$

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

$$\Delta M^2, \tan^2 \theta_{23}$$

very similar to 2ν analysis

Solar + Atmospheric 3ν Oscillations

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

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

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

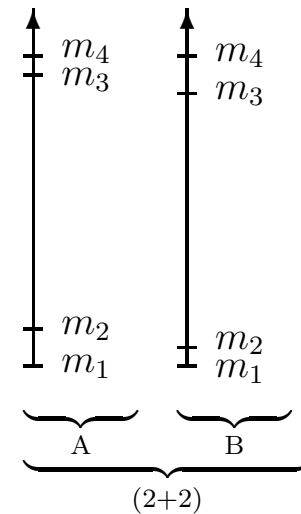
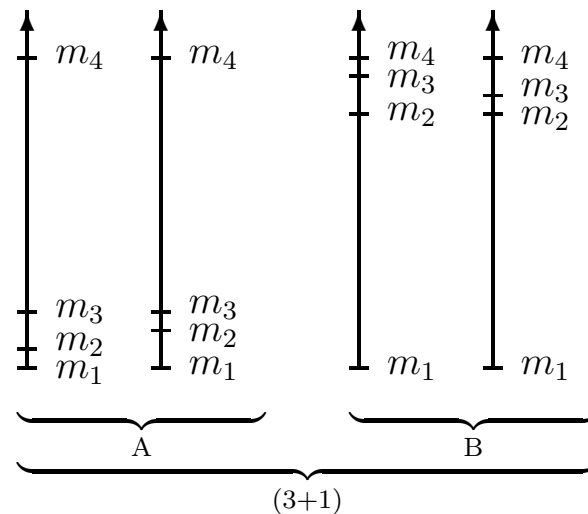
Still open questions $\left\{ \begin{array}{l} \text{Is } \theta_{13} \neq 0? \\ \text{Is there CP violation in the leptons (is } \delta \neq 0, \pi)? \\ \text{Are neutrino masses:} \\ \quad \text{hierarchical: } m_i - m_j \sim m_i + m_j? \\ \quad \text{degenerated: } m_i - m_j \ll m_i + m_j? \\ \text{Dirac or Majorana? what about the Majorana Phases?} \end{array} \right.$

LSND: Sterile Neutrinos and 4 ν mixing

- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ at $L/E \sim 1 \text{ m/MeV} \Rightarrow \Delta m_{\text{LSND}}^2 \simeq 1 \text{ eV}^2$

$$\Delta m_{\text{LSND}}^2 \gg \Delta m_{\text{atm}}^2 \gg \Delta m_\odot^2$$

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

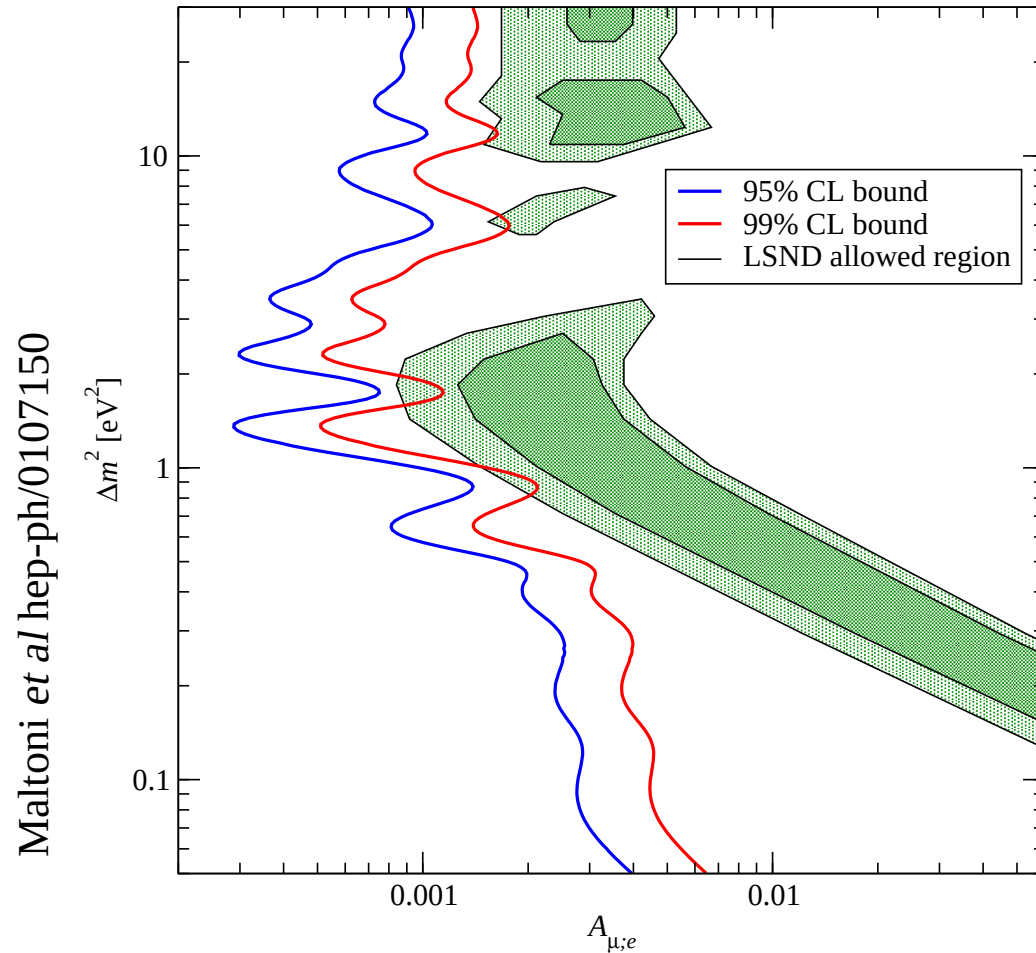


- None of them gives satisfactory description of data

(Talk by Giunti at NEU2)

Wait for MiniBooNE

• 3 + 1:



$$\sin^2 2\theta_{\text{LSND}} = 4|U_{e4}|^2|U_{\mu4}|^2$$

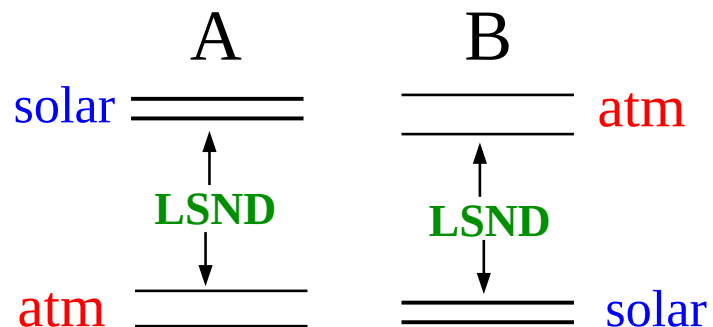
$|U_{e4}|^2$ constrained by Bugey

$|U_{\mu4}|^2$ constrained
by CDHSW+ATM

⇒ 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: $\nu_e \rightarrow \nu_+$ $\nu_+ \simeq \sin \eta \nu_s + \cos \eta \nu_\tau$

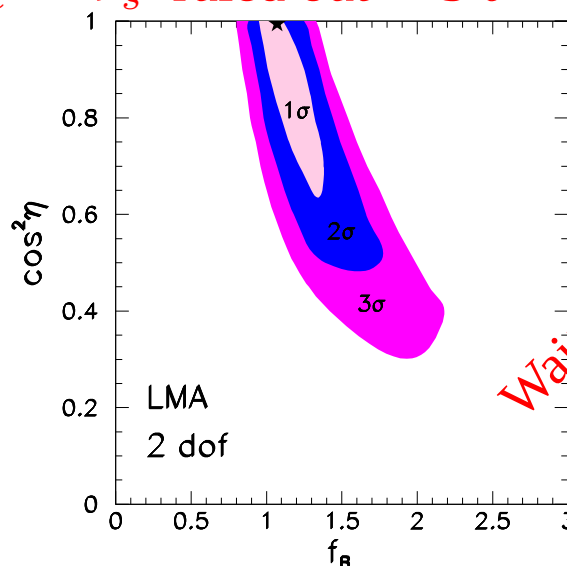
Atm: $\nu_\mu \rightarrow \nu_-$ $\nu_- \simeq \cos \eta \nu_s - \sin \eta \nu_\tau$

– From atmospheric neutrinos: $\nu_\mu \rightarrow \nu_s$ disfavoured $\gtrsim 99\%$ CL
sterile mixing allowed if all U angles are included in fit

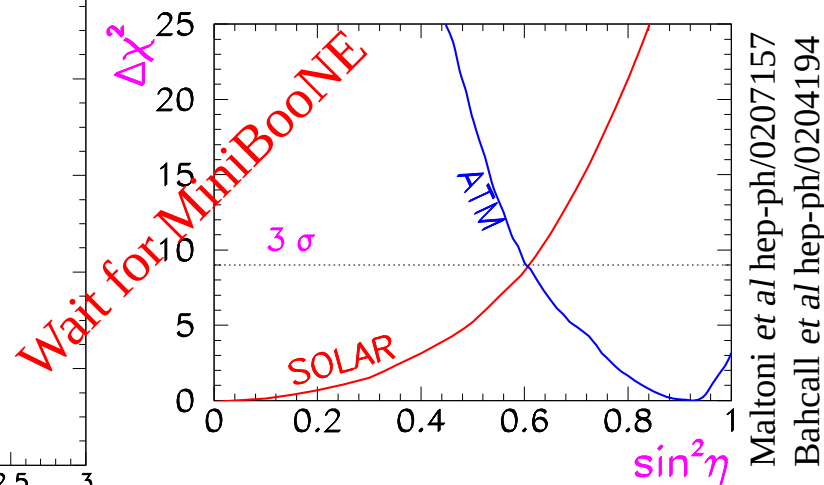
– From solar neutrinos: $\nu_e \rightarrow \nu_s$ ruled out $\sim 5\sigma$

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



Difficult compromise



Maltoni et al hep-ph/0207157
Bahcall et al hep-ph/0204194

Alternative Explanations for LSND

- Lepton Number violation μ decay: $\mu^+ \rightarrow e^+ \bar{\nu}_e \bar{\nu}_i$

Pakvasa; Bergman, Klapdor and Paes; Babu and Pakvasa

Talk by Babu at NEU2

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

Murayama and Yanagida PLB (2001);

Pakvasa hep-ph/0110175;

Barenboim et al hep-ph/0108199, hep-ph/0201134

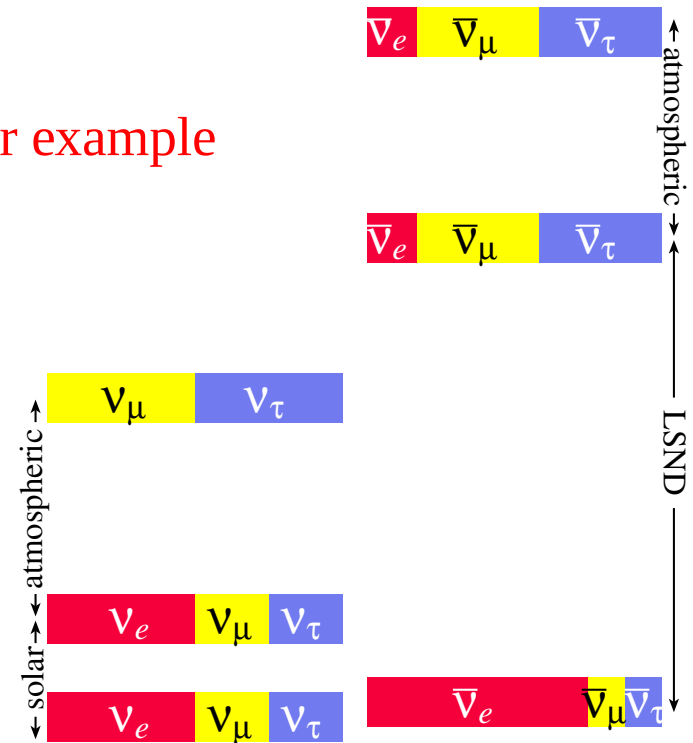
, Skadghauge hep-ph/0112189

– Imminent tests of CPT in neutrinos:

- * KamLAND $\bar{\nu}_e$ versus solar ν_e disappearance
- * MiniBooNE $\nu_\mu \rightarrow \nu_e$ versus LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- * 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



Murayama and Yanagida
Strumia hep-ph 0201134

III. Some Implications

In the SM:

- There are no right-handed neutrinos
⇒ No renormalizable (ie $\dim \leq 4$) gauge-invariant operator for tree level ν mass
- SM gauge invariance also implies an accidental symmetry
 $G_{\text{SM}}^{\text{global}} = U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$
⇒ *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
 - ⇒ 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 : Λ_{NP}

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

- The same particle content as the SM and same pattern of symmetry breaking
- But there can be non-renormalizable (dim > 4) operators

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

First NP effect $\Rightarrow$ dim=5 operator

There is only one!

$$\mathcal{O}_5 = \frac{Z_{ij}^\nu}{\Lambda_{\text{NP}}} \phi \phi L_i L_j$$

which after symmetry breaking

induces a ν Majorana mass

$$(M_\nu)_{ij} = \frac{Z_{ij}^\nu}{2} \frac{v^2}{\Lambda_{\text{NP}}}$$

$\mathcal{O}_5$ 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 $\sim \lambda^f v$
- $m_\nu > \sqrt{\Delta m_{\text{atm}}^2} \sim 0.05 \text{ eV} \Rightarrow \Lambda_{\text{NP}} < 10^{15} \text{ GeV}$
- If $Z_{ij}^\nu \gtrsim 10^{-4} \Rightarrow 10^{10} < \Lambda_{\text{NP}} < 10^{15} \text{ GeV}$
- 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

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

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

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”

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

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

Lessons:

– $\mathcal{L}_{\text{NP}}$ 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 $\mathcal{L}_{\text{NP}}$

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

This is the see-saw

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:

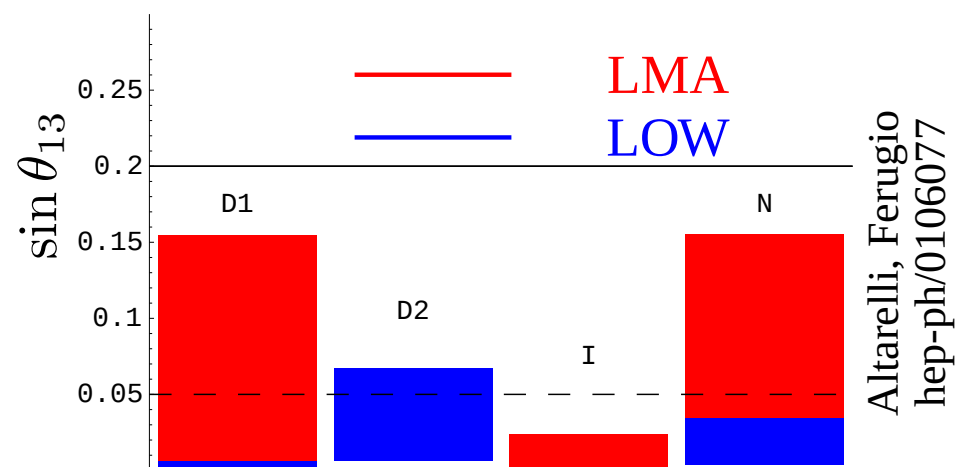
$$\begin{array}{cccc}
 \text{Degenerate 1} & \text{Degenerate 2} & \text{Normal} & \text{Inverted} \\
 m \begin{pmatrix} \delta & -\frac{1}{\sqrt{2}} & \frac{(1-\epsilon)}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} & \frac{(1+\eta)}{2} & \frac{(1+\eta-\epsilon)}{2} \\ \frac{(1-\epsilon)}{\sqrt{2}} & \frac{(1+\eta-\epsilon)}{2}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

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

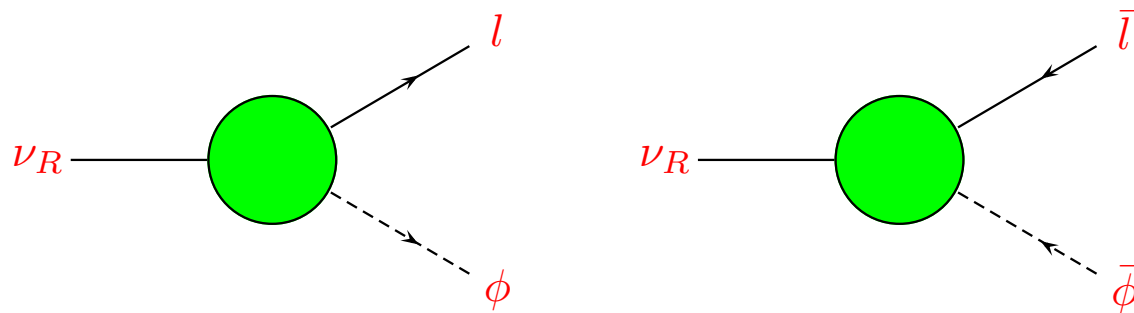
But if there is an intermediate scale (for example SUSY)
 $\Rightarrow Br(\tau \rightarrow \mu\gamma)$ or $Br(\mu \rightarrow e\gamma)$ could be observable

Other Side Effects

Side Effect 2: We are here! (Leptogenesis)

- Majorana $m_\nu \Rightarrow \mathcal{L} \Rightarrow$ Baryon asymmetry can be generated
- How? In the Early Universe via **decay of heavy ν_R**

Fukugita and Yanagida



If $\mathcal{CP} : \Gamma(\nu_R \rightarrow \phi l_L) \neq \Gamma(\nu_R \rightarrow \bar{\phi} \bar{l}_L)$

And decay is **out of equilibrium**:

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

} ΔL is generated

At the electroweak transition sphaleron processes

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

- Details are model dependent $\left(\begin{smallmatrix} \text{Buchmüller, Plümacher...} \\ \text{Talk by Zing} \end{smallmatrix} \right)$ but

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

IV. Future

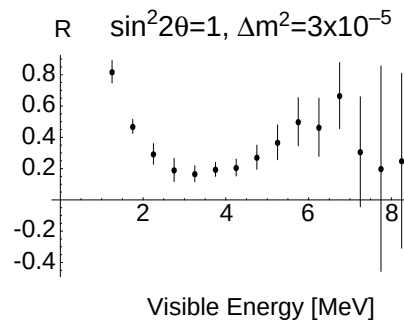
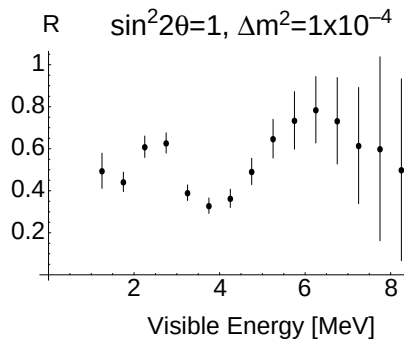
KamLAND

First terrestrial experiment to test solar problem

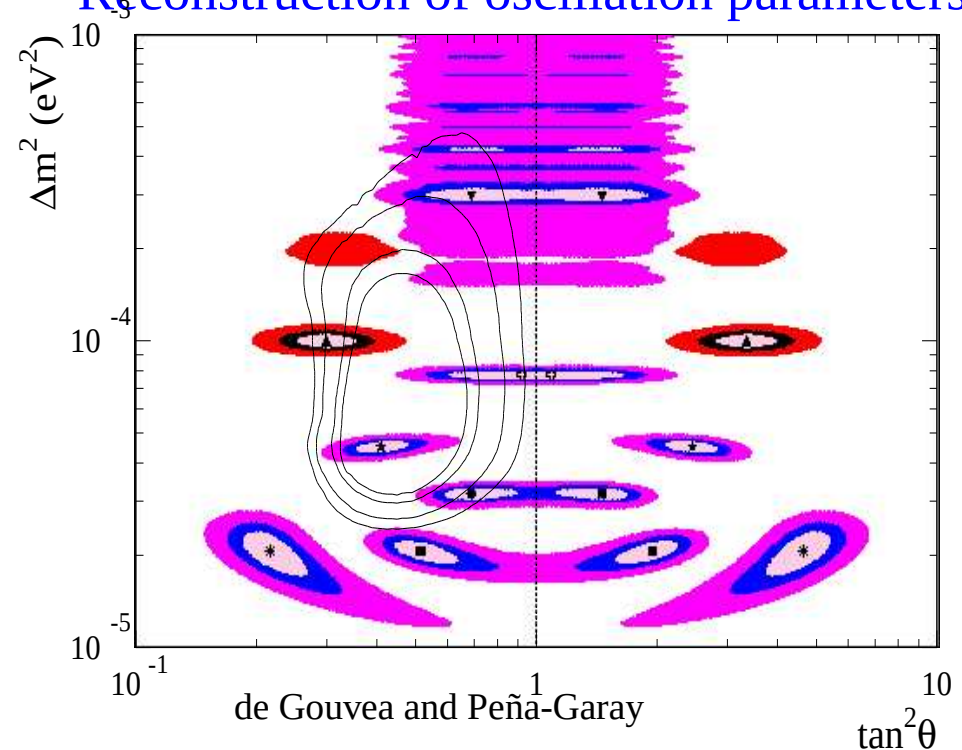
- Search $\bar{\nu}_e$ from $L \sim 200$ km (17 reactors), $E_\nu \sim$ few MeV
- Definite test of LMA: It will verify/exclude it SOON

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

Murayama and Pierce; Barger, Marfatia and Wood



Reconstruction of oscillation parameters



de Gouvea and Peña-Garay

– 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

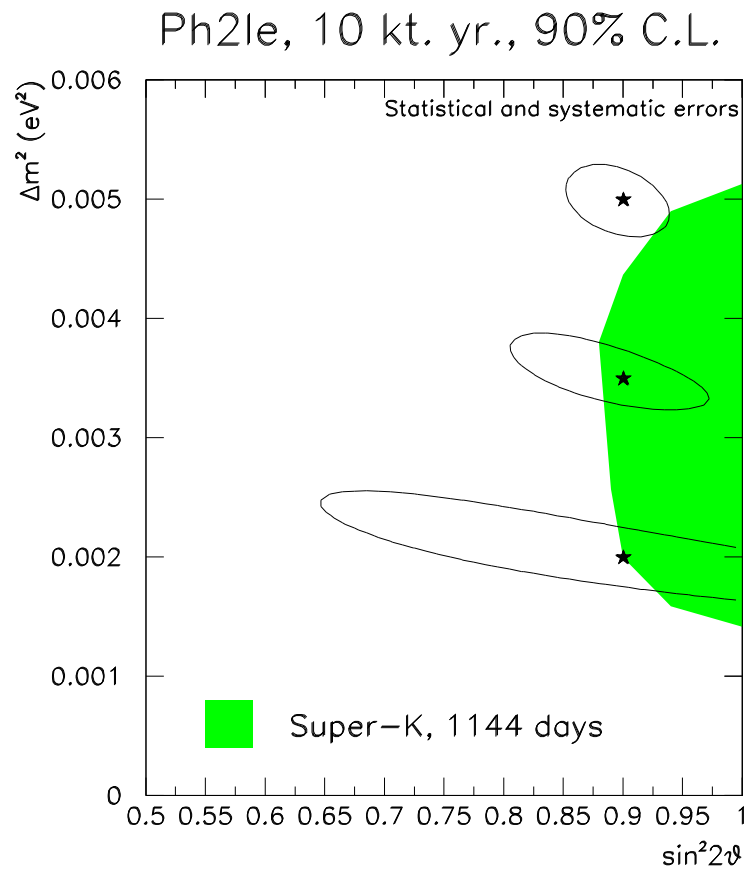
Future LBL: MINOS and CNGS

– K2K : confirms so far Atmospheric Oscillations

– MINOS:

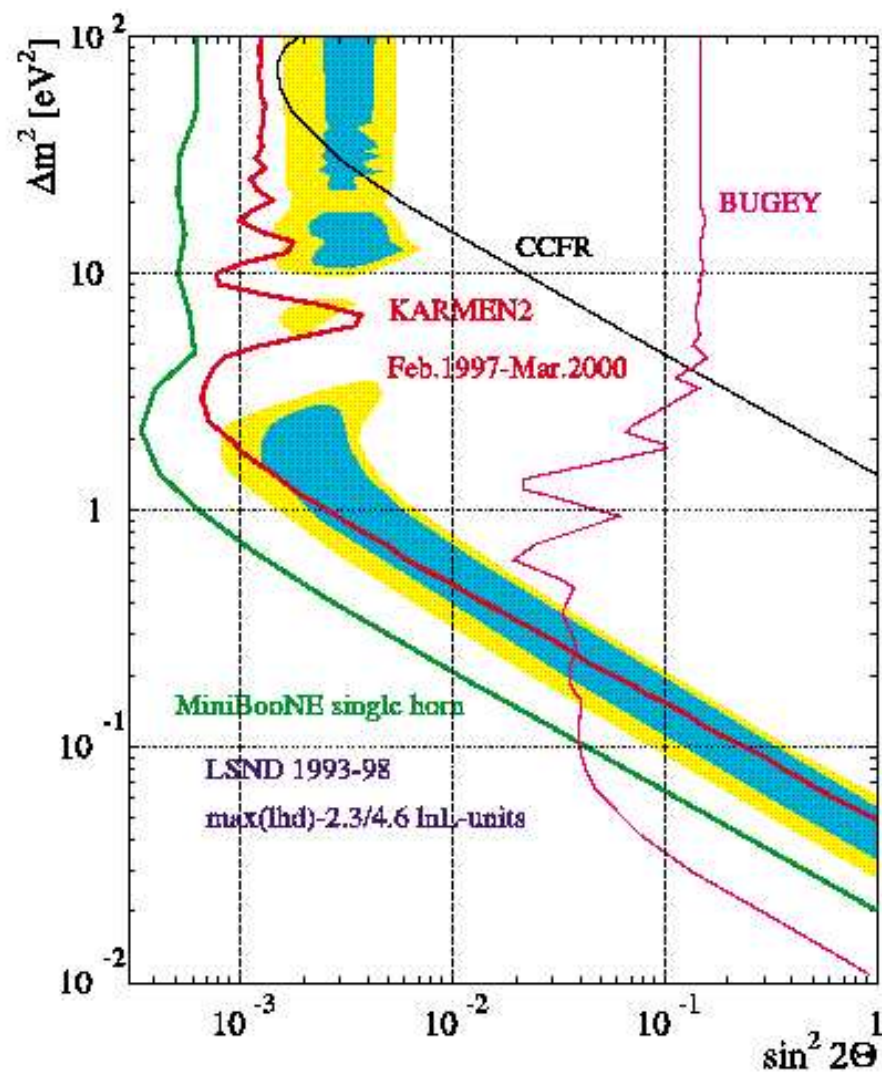
Precision measurement
of Δm_{23}^2 , $\tan^2 \theta_{23}$

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 $[(*), (**)]$
- **CP:** Δm_{21}^2 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:

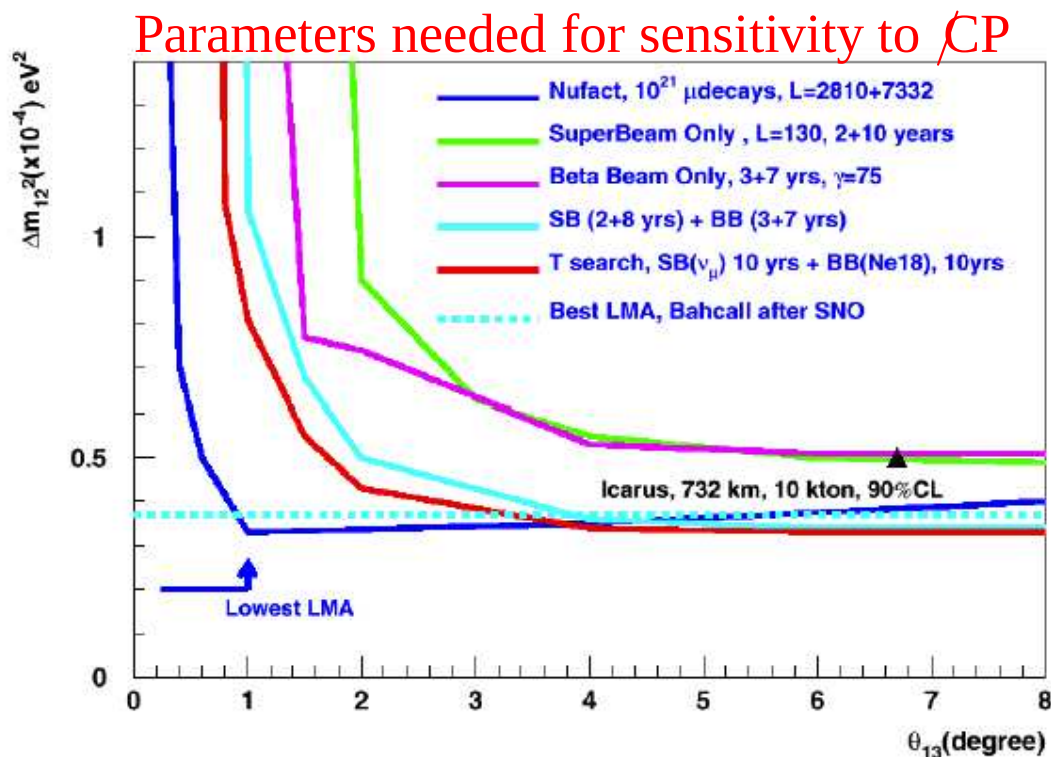
clean ν beam from μ decay

Cervera, Burguet-Castell, Gavela, Gomez-Cadenas, Hernandez, Mena

Barger Geer, Marfatia, Raja, Whisnant

Huber, Lindner, Winter

...



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:

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

$$m_{\nu_e} = m_{eff}^\beta = \sum m_j |U_{ej}|^2 < 2.2 \text{ eV} \quad \begin{array}{l} \text{(at 95 \% CL)} \\ \text{(Mainz \& Troisk experiments)} \end{array}$$

- Katrin proposed to improve present sensitivity to $m_{eff}^\beta \sim 0.3 \text{ eV}$

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

$$\begin{array}{ll} |\langle m_{ee} \rangle| = \left| \sum U_{ej}^2 m_j \right| < 0.35 \text{ eV} & \text{({}^{75}\text{Ge Heidelberg-Moscow experiment})} \\ \text{+ theor. uncert.} < 1.05 \text{ eV} & \text{(at 90\% CL)} \end{array}$$

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

- 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_{eff}^β may allow to discriminate between mass schemes and give information on Majorana CP phases

Bilenky, Farzan, Giunti, Grimus, 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 ν 's : Verification of Flavour Conversion at 5σ

Atmospheric ν 's: high confidence of L/E dependence

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

Solar ν 's : Imminently KamLAND and soon BOREXINO

should be able to approach us to the final answer

Atmospheric ν '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

ν' 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