Pattern of Neutrino Masses and Mixings

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Workshop on Neutrino Physics
July 27, 1999

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Apologies to many authors whose work is not cited herein

Atmospheric Nu Oscillations

- ν_μ, $\bar{\nu}_\mu$ disappearance, increasing with L

- best fit $\nu_\mu \to \nu_\tau$ oscillation parameters

  $\delta m^2_{\mathrm{atm}} = 3.5 \times 10^{-3}\ \mathrm{eV}^2$
  $\sin^2 2\theta_{\mathrm{atm}} = 1$

- $\nu_\mu \to \nu_\tau$ favored over $\nu_\mu \to \nu_s$

  * matter effects:
  up-mu data and higher energy PC data (2σ)

  * NC π^0 production Vissani, Smirnov (1998)

- no indication of ν_e, $\bar{\nu}_e$ oscillations

Neutrino Decay vs. Neutrino Oscillations for Atmospheric Neutrinos

[Barger, Learned, Pakvasa, Weiler (98) + Lipari, Lusignoli (99)]

- Mixing

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} \simeq \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

- Decay

$$\nu_2 \to \bar{\nu}_4 + J$$

Valle (1983)

- Survival probability

$$P(\nu_\mu \to \nu_\mu) = s^4 + c^4 e^{-\alpha L/E} + 2s^2c^2 e^{-\alpha L/2E} \cos\left(\frac{\delta m_{23}^2 L}{2E}\right)$$

- Choose $\delta m_{23}^2 < 10^{-4}\,\mathrm{eV}^2$ so oscillations play no role

$$P(\nu_\mu \to \nu_\mu) = \left(s^2 + c^2 e^{-\alpha L/2E}\right)^2$$

- Fit to SuperK data

$$\theta \simeq 57^\circ, \quad \alpha^{-1} = \tau_2/m_2 = 63\ \mathrm{km/GeV} \simeq \frac{16\pi}{g^2 \delta m_{24}^2}$$

- With constraint on $g^2\delta m_{24}^2$ from $K \to \pi + \text{neutrals}$

$$\delta m_{24}^2 > (14\ \mathrm{eV})^2$$

- So ν_2, ν_3 nearly degenerate, ν_4 light

$^2_3$ —— ν_μ, ν_τ

$^4_1$ —— ν_s, ν_e

$\nu_e \simeq \nu_1$ nearly unmixed because of more stringent bound on its Majoron coupling (SMA for solar deficit)

Best fits of decay and oscillation models of comparable quality

neutrino decay: monotonic decrease with L/E

neutrino oscillations: sinusoidal behavior in L/E
smeared by resolution
(averages to 1/2 at large L/E)

most easily distinguishable around $L/E \approx 400$ km/GeV

Long-baseline experiments

Decay model

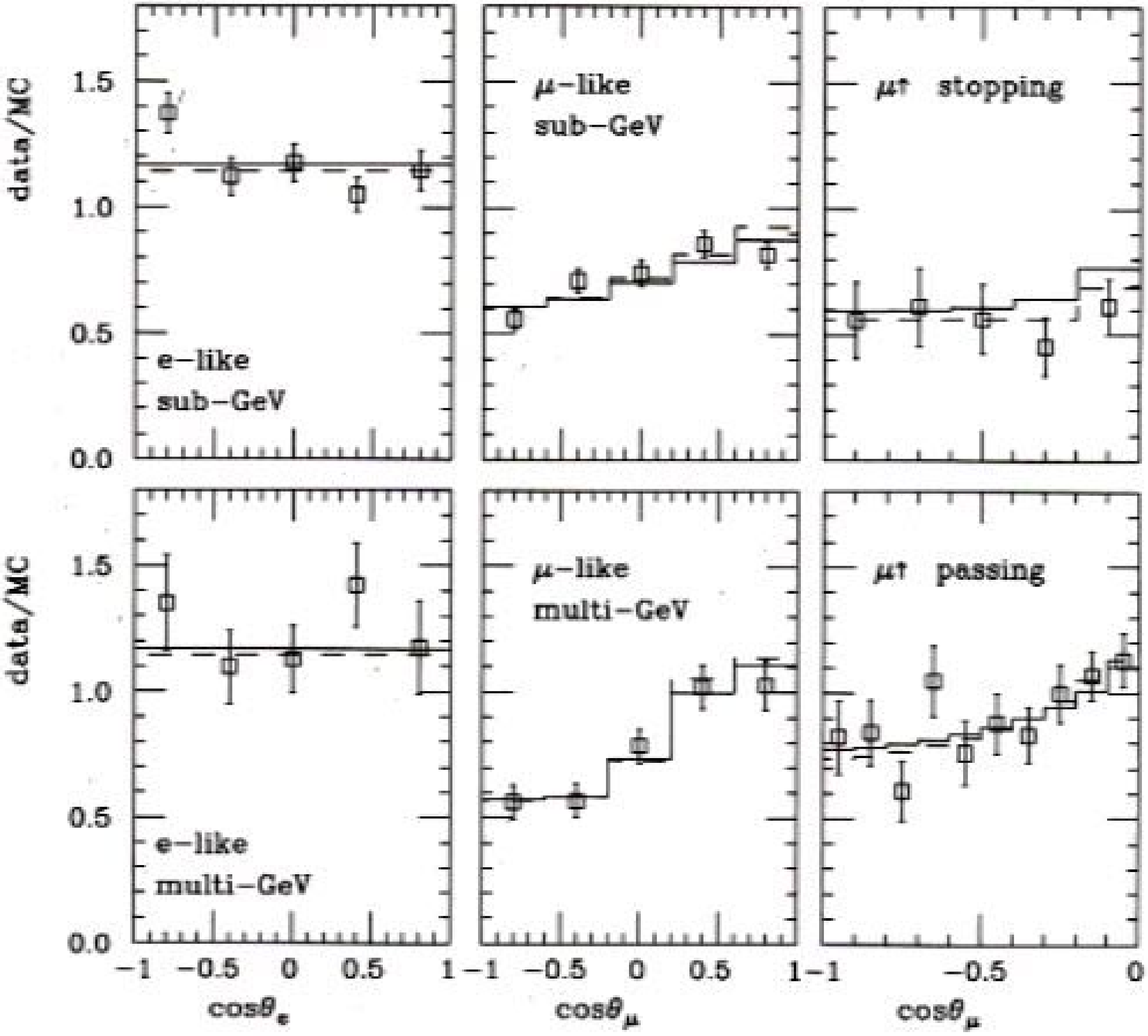
$$P(\nu_\mu \to \nu_\tau) = s^2 c^2 (1 - e^{-\alpha L/2E})^2$$

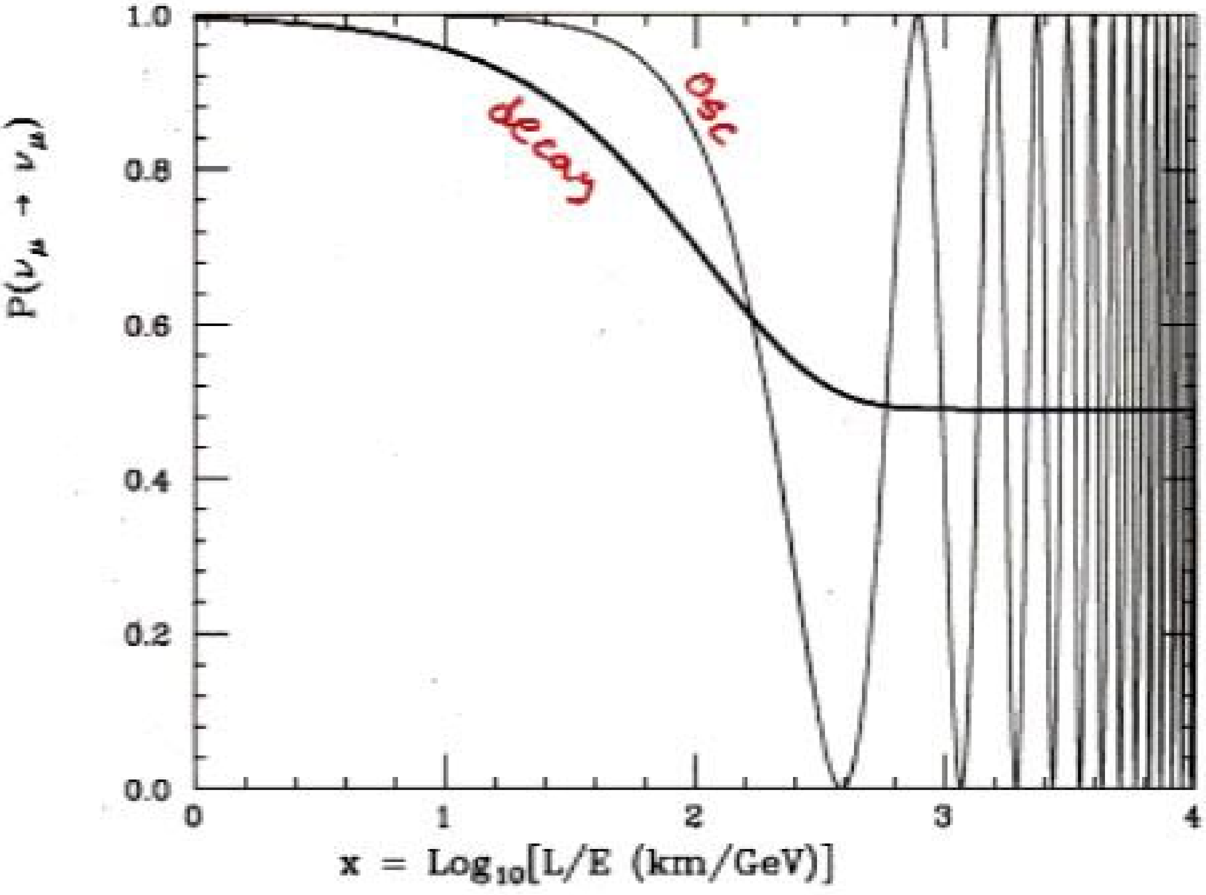
$$\neq 1 - P(\nu_\mu \to \nu_\mu)$$

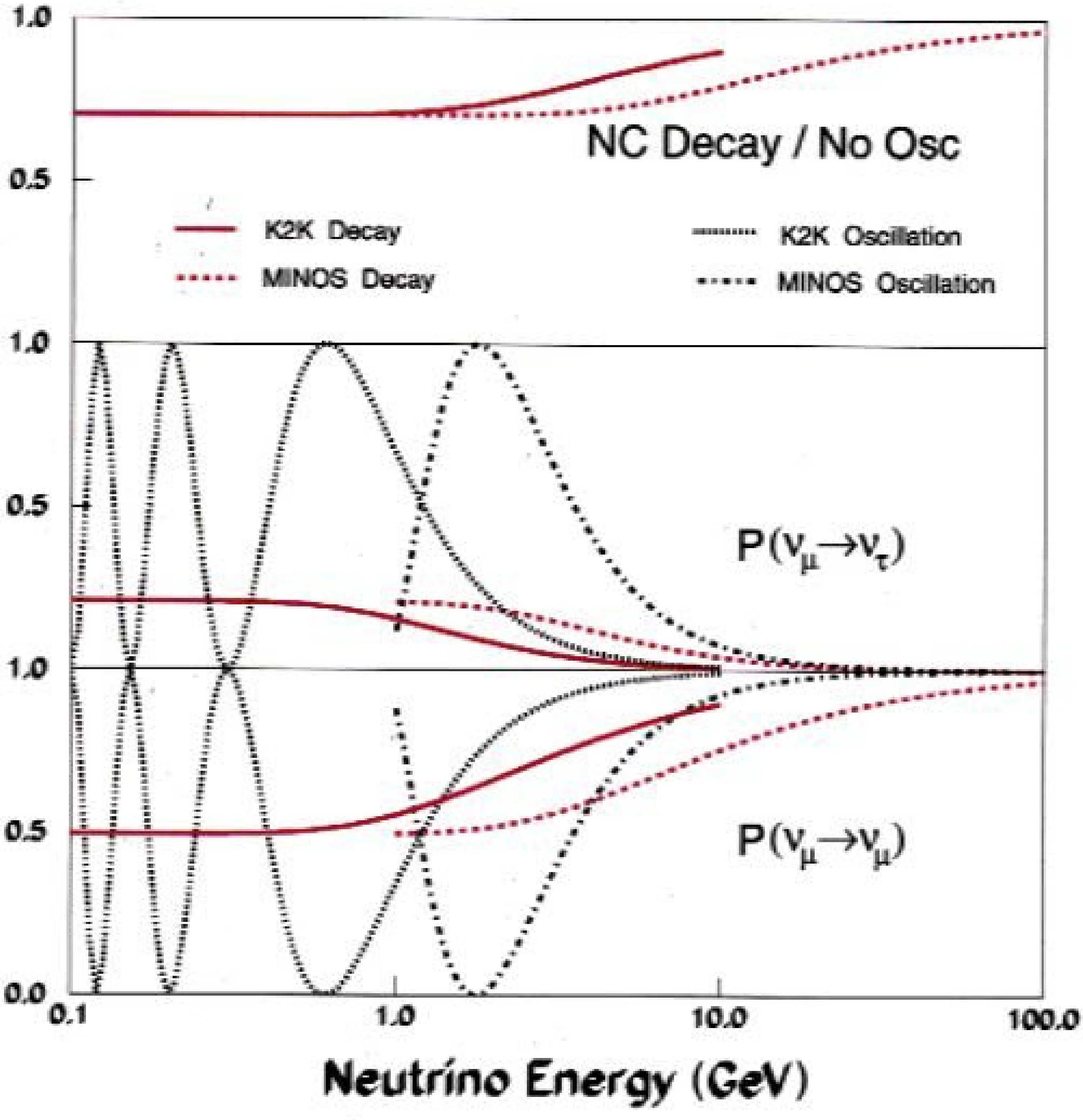
$$\frac{NC}{(NC)_{\text{no osc}}} = P(\nu_\mu \to \nu_\mu) + P(\nu_\mu \to \nu_\tau) = 1 - c^2 (1 - e^{-\alpha L/E})$$

K2K (250 km)	MINOS (732 km)
$E_\nu \simeq 1\text{–}2$ GeV	$\langle E_\nu \rangle = 3, 6, 12$ GeV
$L/E \approx 125\text{–}150$ km/GeV	$L/E \approx 50\text{–}250$ km/GeV

Both $P(\nu_\mu \to \nu_\mu)$ and NC can distinguish decay model from oscillations. MINOS may also detect taus.


data/MC
1.5
1.0
0.5
0.0
e–like
sub–GeV
μ–like
sub–GeV
μ↑ stopping
e–like
multi–GeV
μ–like
multi–GeV
μ↑ passing
−1
−0.5
0
0.5
1
$\cos\theta_e$
$\cos\theta_\mu$
$\cos\theta_\mu$


1.0
0.8
0.6
0.4
0.2
0.0
$P(\nu_\mu \to \nu_\mu)$
0
1
2
3
4
$x = \mathrm{Log}_{10}[L/E\ (\mathrm{km/GeV})]$
osc
decay


1.0
0.5
1.0
0.5
1.0
0.5
0.0
0.1
1.0
10.0
100.0
NC Decay / No Osc
K2K Decay
MINOS Decay
K2K Oscillation
MINOS Oscillation
$P(\nu_\mu \to \nu_\tau)$
$P(\nu_\mu \to \nu_\mu)$
Neutrino Energy (GeV)

Solar Nu Oscillations

- Standard Solar Model flux + ^{8}B normalization

Bahcall, Basu, Pinsonneault (1998)

- Experiments sample different energy ranges and find different ν_e flux deficits

-

Solutions	$\sin^2 2\theta$	δm^2
MSW (SA)	$\sim 10^{-2}$	$\sim 10^{-5}$ eV^2
MSW (LA)	~ 1	$\sim 2\text{–}8\times 10^{-5}$ eV^2
VO	~ 1	$\sim 4\times 10^{-10}$ eV^2

- E_e spectrum shape

MSW (SA)	gradual rise
MSW (LA)	flat
√ VO	sharp rise at $E > 12$ MeV natural
SuperK data	sharp rise at $E > 12$ MeV

Can rescue LA MSW by ~20× enhancement of SSM hep flux

Bahcall, Krastev, Smirnov (1999)

Gonzalez-Garcia et al. (1999)

- Night-Day dependence due to earth regeneration of ν_e

$$A_{n-d} = 2\left[\frac{\text{night} - \text{day}}{\text{night} + \text{day}}\right]$$

Baltz, Weneser (1994)
Maris, Petcov (1997)
Dighe, Liu, Smirnov (1999)
Guth, Randall, Serna (1999)

MSW (SA)	> 0 expected only for $\cos\theta_Z = -0.8$ to -1	
√ MSW (LA)	$\approx 0.04\left[\frac{5\times10^{-5}}{\Delta m^2}\right]$	Bahcall, Krastev (1999) uniform N excess in $\cos\theta_Z$
VO	$= 0$	
SuperK	0.060±0.036(stat)±0.008(syst) $(+1.6\sigma)$	

- Seasonal dependence [above $1/L^2$ flux variation due to dependence of $\sin^2(1.27\delta m^2 L/E)$ on L]

Barger, Phillips, Whisnant (1981)
Glashow, Krauss (1987)

MSW	= very small
√ VO	natural
SuperK	observed in $E_e > 12$ MeV data

708 day SuperK data show hints of seasonal and spectrum dependences consistent with vacuum oscillations

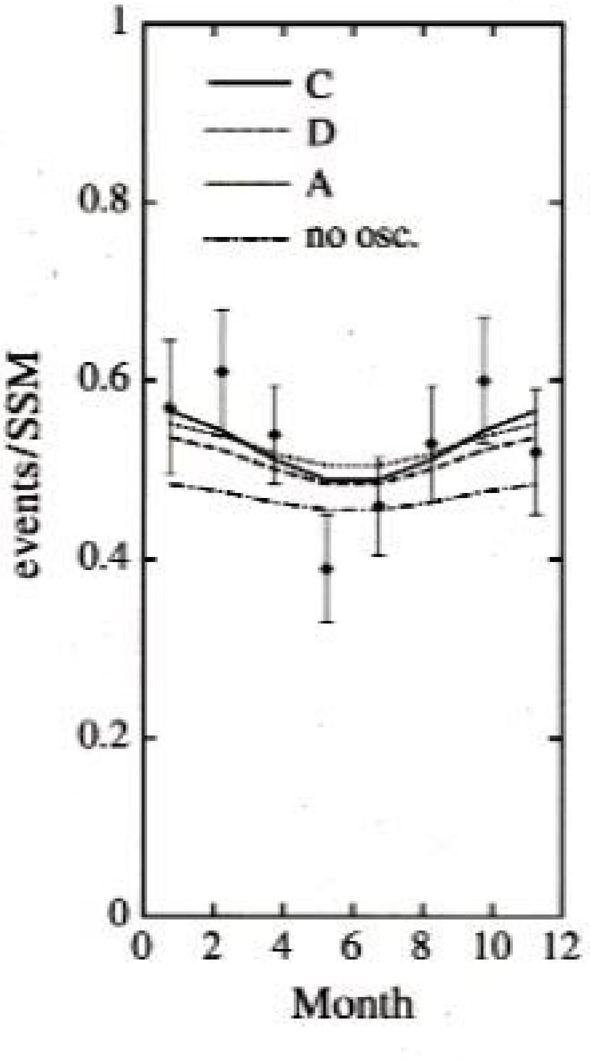
Best global fit to all solar neutrino data

$$\delta m^2 = 4.4 \times 10^{-10}\,\mathrm{eV}^2$$

$$\sin^2 2\theta = 0.93$$

$$\langle \lambda \rangle \simeq \frac{5}{2} \langle d_{\mathrm{ES}} \rangle$$

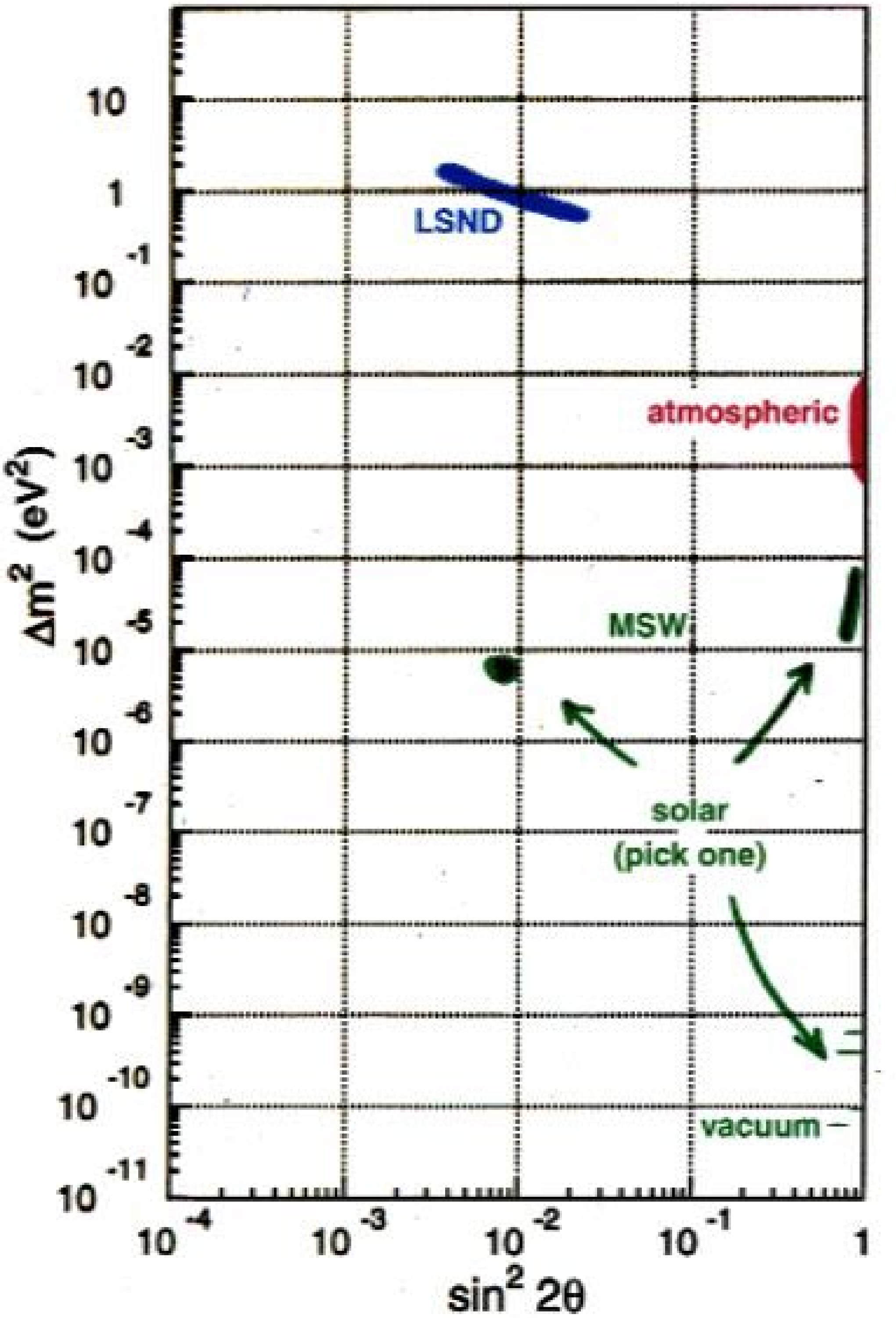
Seasonal $E_e = 11.5\text{–}20\ \mathrm{MeV}$



δm^2 (eV^2)	$\sin^2 2\theta$
4.4×10^{-10}	0.93
6.4×10^{-10}	1.0
0.65×10^{-10}	0.7

Barger, Whisnant
hep-ph/9903262

Summary of evidence



$\nu_\mu \leftrightarrow \nu_e$

$\nu_\mu \leftrightarrow \nu_\tau$

$\nu_{\rm sterile}$?

$\nu_e \leftrightarrow \nu_\mu$

ν_τ

$\nu_{\rm sterile}$

Hata, Langacker (1997)
Bahcall, Krastev, Smirnov (1999)
SuperK (1999)
Gonzalez-Garcia et al. (1999)

3 neutrino mixing $\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}_L = \mathrm{U}_{\mathrm{MNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$

Maki, Nakagawa, Sakata (1962)

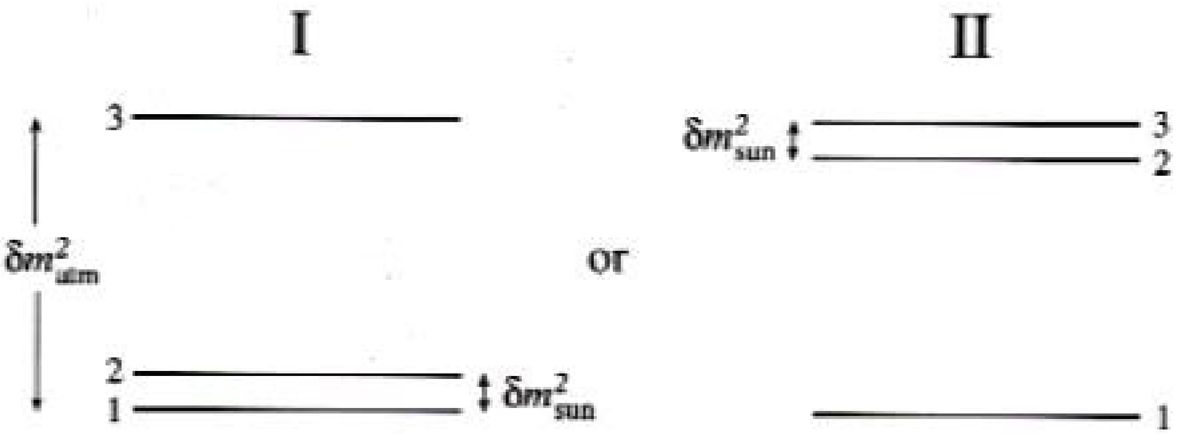
$$\mathrm{U}_{\mathrm{MNS}} =$$

$$\begin{pmatrix} c_1c_3 & c_1s_3 & s_1e^{-i\delta} \\ -c_2s_3 - s_1s_2c_3e^{i\delta} & c_2c_3 - s_1s_2s_3e^{i\delta} & c_1s_2 \\ s_2s_3 - s_1c_2c_3e^{i\delta} & -s_2c_3 - s_1c_2s_3e^{i\delta} & c_1c_2 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\phi_2} & 0 \\ 0 & 0 & e^{i(\phi_3+\delta)} \end{pmatrix}$$

$c_i \equiv \cos\theta_i \quad s_i \equiv \sin\theta_i$

extra Majorana phases
irrelevant to oscillations

to explain atm and solar data



Leading oscillation:

atmospheric and long-baseline

$$P(\nu_\alpha \to \nu_\beta) = A_{\alpha\beta} \sin^2 \Delta_{\text{atm}} \qquad \Delta_{\text{atm}} = \frac{1.27\delta m^2_{\text{atm}} L}{E}$$

$$A_{\mu\tau} = 4c_1^2 \sin^2 2\theta_2$$

$$A_{\mu e} = s_2^2 \sin^2 2\theta_1$$

$$A_{e\tau} = c_2^2 \sin^2 2\theta_1$$

Same for $\bar{\nu}$:
no $\cancel{CP}$ in leading oscillation
BPW (1980)

Super K atm

$\theta_2 \sim \pi/4$ maximal $\nu_\mu \to \nu_\tau$

$\theta_1 \sim 0$ minimal $\nu_e \to \nu_\mu, \nu_\tau$

2σ bounds
$|\theta_2 - 45^\circ| < 13^\circ$
$\theta_1 < 17^\circ$

Sub-leading oscillation

Solar $\nu_e \to c_2^2 \nu_\mu + s_2^2 \nu_\tau$ $(\theta_1 \sim 0)$

$$\frac{L}{E_\nu} \sim \frac{10^{10}\,\text{km}}{\text{GeV}} \qquad \langle \sin^2 \Delta_{\text{atm}} \rangle \to \frac{1}{2}$$

$$P(\nu_e \to \nu_e) = 1 - \frac{1}{2} \sin^2 2\theta_1 - c_1^4 \sin^2 2\theta_3 \sin^2 \Delta_{\text{sun}}$$

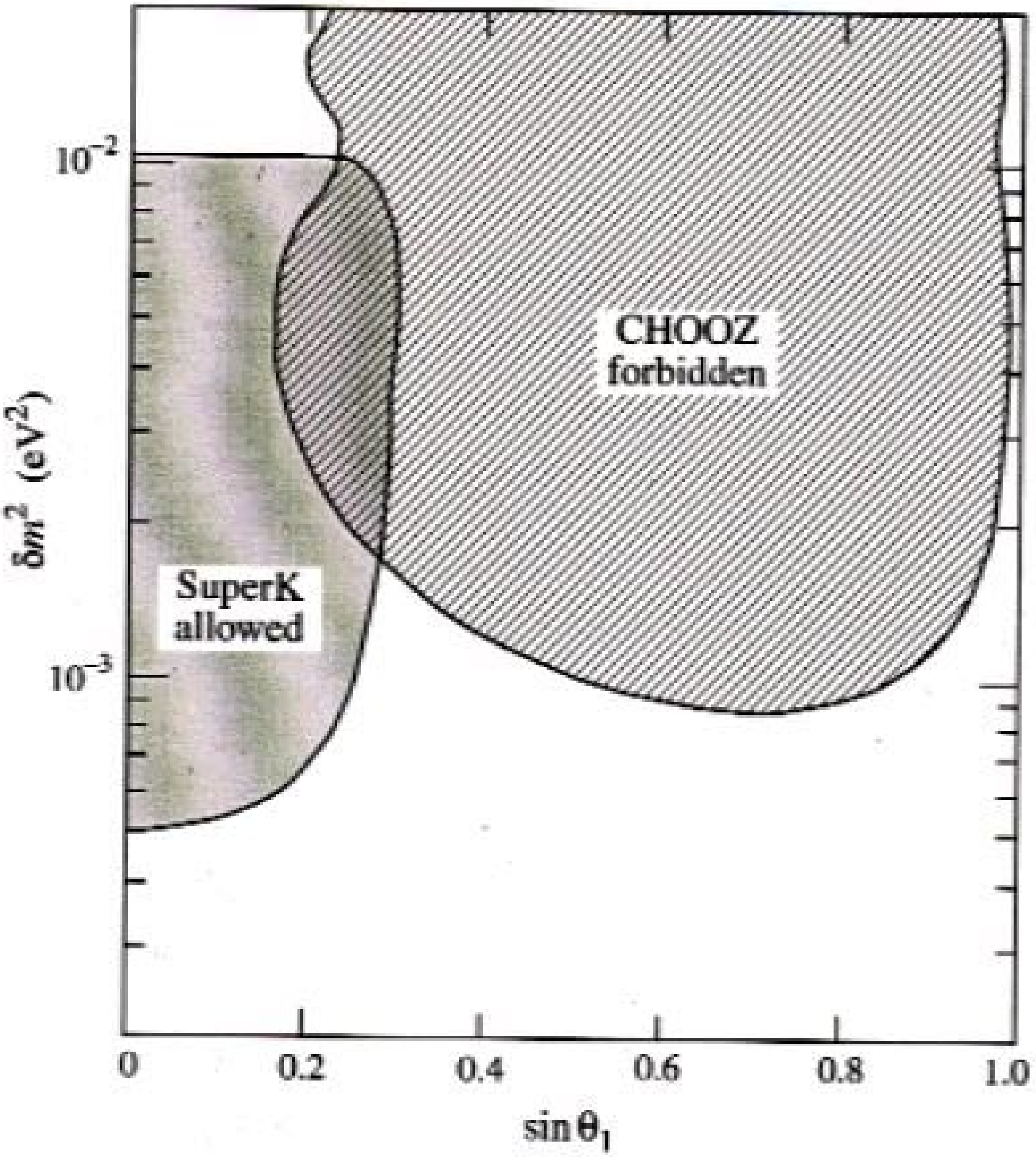
θ_3 determined by solar data

$\sin^2 2\theta_3 \sim 10^{-2}$ MSW(SA) or ~1 MSW (LA), VO

Reconstruction of neutrino MNS matrix achieved!
(except for phases and selection of solar solution)

Barbieri et al. (1998) Barger, Whisnant (1998)

Null $\bar{\nu}_e$ oscillation constraint from CHOOZ reactor



Barger, Whisnant (1998)

Fogli, Lisi, Marrone, Scioscia (1999)

Gonzalez-Garcia et al. (1999)

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_1 \sin^2 \Delta_{atm}$$

CHOOZ limit improves θ_1 bound

ATM / SOLAR decoupling occurs at $\theta_1 = 0$

- SOLAR $\nu_e \to \nu_e$ depends only on θ_3
- ATM $\nu_\mu \to \nu_\tau$ depends only on θ_2
- ATM / LBL $\nu_e \to \nu_\tau$ vanishes at $\theta_1 = 0$

Bi-Maximal mixing

Hints:

$$\sin^2 2\theta_{\rm ATM} = 1$$

$$\sin^2 2\theta_{\rm SUN} \approx 1$$ VO or MSW(LA)

Unique matrix for maximal mixing in both atm and solar sectors

$$U = \begin{pmatrix} 1/\sqrt{2} & -1/\sqrt{2} & 0 \\ 1/2 & 1/2 & -1/\sqrt{2} \\ 1/2 & 1/2 & 1/\sqrt{2} \end{pmatrix}$$

Barger, Pakvasa, Weiler, Whisnant (1998)

Baltz, Goldhaber, Goldhaber (1998)

$$P(\nu_\mu \to \nu_\tau) = \sin^2 \Delta_{\rm ATM} - \tfrac{1}{4}\sin^2 \Delta_{\rm SUN}$$

$$P(\nu_e \to \nu_\mu) = \tfrac{1}{2}\sin^2 \Delta_{\rm SUN} \qquad (50\%)$$

$$P(\nu_e \to \nu_\tau) = \tfrac{1}{2}\sin^2 \Delta_{\rm SUN} \qquad (50\%)$$

$$[\Delta \equiv 1.27\delta m^2 L/E]$$

No LSND Effect / no CPV

$U_{e3} = 0 \Longrightarrow$ only $\nu_\mu \to \nu_\tau$ oscillations at the atm scale

Absolute neutrino mass scale

(inferred limits)

$$m_3^2 - m_1^2 = \delta m^2_{\rm atm}$$

$$m_2^2 - m_1^2 = \delta m^2_{\rm sun}$$

$$\langle m^2_{\nu_e} \rangle = \sum |U^2_{ej}| m_j^2 \simeq m_3^2 \sum |U^2_{ej}| + \mathcal{O}(\delta m^2_{\rm atm})$$

Experimental end-point limits

$\langle m^2_{\nu_e} \rangle < (2.5 \text{ eV})^2$ Troitsk

$\langle m^2_{\nu_e} \rangle < (3 \text{ eV})^2$ Mainz

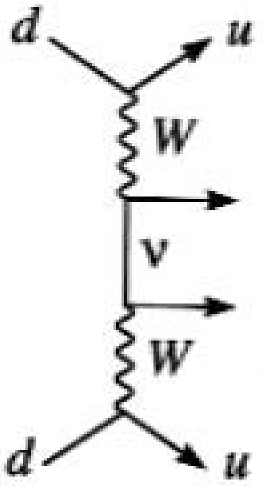
$\Rightarrow$ $\boxed{m_j < 2.5 \text{ eV for all } j}$

Barger, Weiler,
Whisnant (1998)

Also

$$m_{\rm max} \geq \sqrt{\delta m^2_{\rm atm}} \geq 0.025 \text{eV}$$

Majorana neutrino mass in 0νββ decay



Doi et al. (1981)
Minakata, Yasuda (1997)
Georgi, Glashow (1999)
BW (1999)

0νββ decay rate determined by $\nu_e\nu_e$ element of neutrino mass matrix (M_{ee})

I. $|M_{ee}| = |c_1^2 c_3^2 m_1 + c_1^2 s_3^2 m_2 e^{i\phi_2} + s_1^2 m_3 e^{i\phi_3}|$

II. $m_1 \leftrightarrow m_3$ in I

Present limit	$\lvert M_{ee}\rvert < 0.2$ eV	Baudis et al. hep-ex/9902014
Future sensitivity	$\lvert M_{ee}\rvert < 0.01$ eV	GENIUS expt. MOON

$|M_{ee}|$ constraint (with $\delta m^2_{ij} \ll 1\ \mathrm{eV}^2$)

- MSW (SA)

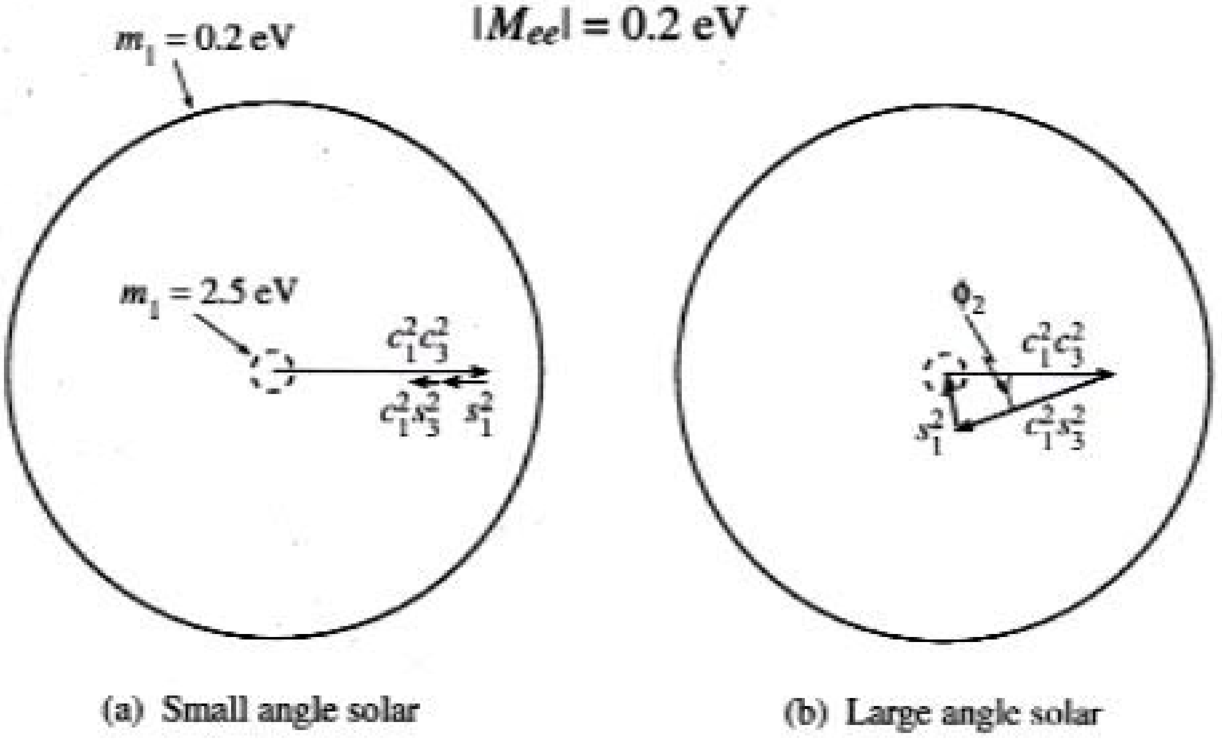
$\Sigma m_\nu < 0.75$ eV (Majorana nu)

- MSW (LA) or VO

naturally satisfied if ν_1 and ν_2 have opposite CP-parity

$|M_{ee}| = 0.2$ eV

$s_1 < 0.3$
ATM data



(a) Small angle solar

(s_3 small)

(b) Large angle solar

Beyond 3 neutrinos

Motivations

- explain LSND effect

Bilenky, Giunti, Grimus (1998)
Barger, Pakvasa, Weiler, Whisnnat (1998)
Gibbons et al. (1998)

or

- account for *r*-process nucleosynthesis

McLaughlin et al. (1999)

sterile neutrinos are compatible with BBN N_ν limit if mixing is very small

Barbieri and Dolgov (1990)

$$\delta m^2_{4i} \sin^2 2\theta_{4i} \lesssim 10^{-7}\,\mathrm{eV}$$

Lepton-number violation partially alleviates BBN crisis $(\delta N_{\mathrm{eff}}^{\mathrm{BBN}} \sim -0.5)$

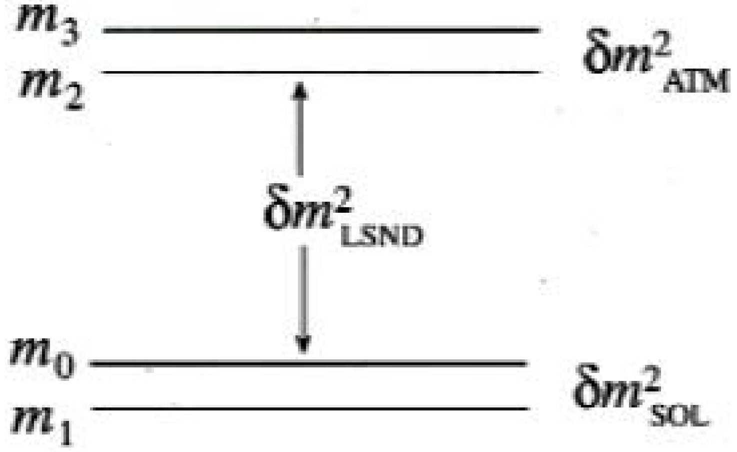
Foot, Volkas (1998)
Shi, Fuller, Abazajian (1998)

4ν oscillations with LSND

	LSND	ATM	MSW (SA) SOLAR
$\nu_\mu \to \nu_e$	▲		
$\nu_\mu \to \nu_\tau$		●	
$\nu_e \to \nu_s$			■

4ν mass matrix can be constructed that consistently explains LSND, ATM, and SOLAR data by oscillations

2+2 mass hierarchy required for consistency with short-baseline limits

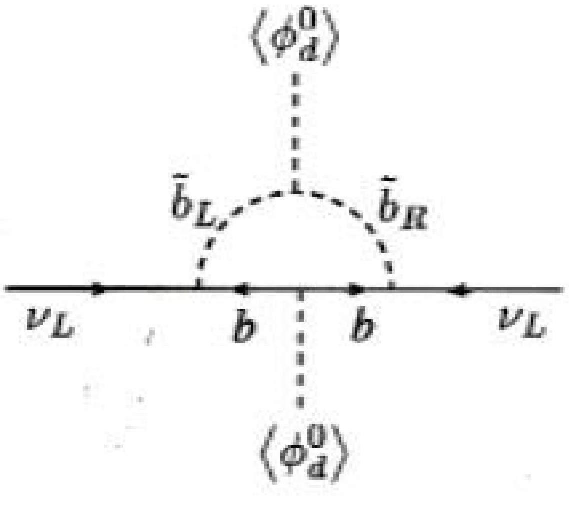


$m_0 > m_1$ for resonant matter oscillations in Sun

$$m_3 \gtrsim \sqrt{\delta m^2_{\text{LSND}}} \gtrsim 0.5 \text{ eV}$$

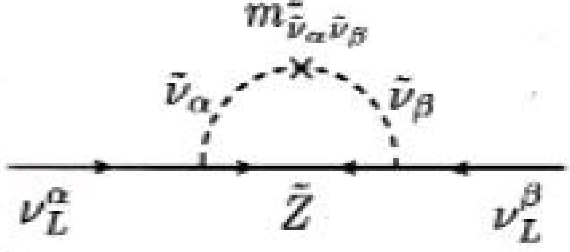
Supersymmetry and M_ν

- **SUSY radiative masses**



Drees, Pakvasa, Tata, ter Veldhuis (97)
R-parity violation

Kaplan, Nelson (99)
bi-linear R-parity violation



Davidson, King (98)

- **Unification models** (assume mass matrix textures; usually invoke see-saw)

SO(10)	Albright, Babu, Bar (98, 99) Wilczek (98)
SU(5)	Hagiwara et al. (98) Altarelli, Feruglio (98)
Flipped SU(5)	J. Ellis et al. (98)
Anomalous U(1)	Irges, Lavignac, Ramond (98)
U(2) flavor symmetry	Barbieri et al. (98) Carone & Hall (97)
U(1) family symmetries	King (99), Allanach (98)
$U(1)^2$	Froggett, Gibson, Nielsen (98)

Typical Unified Model Predictions

- neutrinos are Majorana
- neutrino masses are hierarchical
- no cosmologically significant dark matter
- large $\nu_\mu - \nu_\tau$ oscillations are accommodated, but came somewhat as a surprise
- mixing of ν_μ and ν_τ not fully maximal
- → small angle MSW solar solution
- no LSND effect

If either VO or MSW (LA) are the solar solution, then most proposed unified models are rejected

Long Baseline Goals

Vacuum osc studies

K2K (KEK → SuperK)
MINOS (Fermilab → Soudan)
(CERN → Gran Sasso)
Mu Ring (Fermilab → Soudan)
etc.

Geer (1998)
Quigg (1998)

- Precise $\delta m^2_{\rm atm}$ (~1% measurement)
- Reconstruction of MNS mixing matrix (determine θ_1, θ_2). If MSW (LA) solar solution, may also determine θ_3

Matter osc studies

Fermilab → Gran Sasso
Fermilab → Australia

- Observe matter effects on oscillations in very long baseline experiment (different for ν_e and $\bar{\nu}_e$); determine sign of δm^2
- Observe matter resonance effects in propagation through earth's core
- Test for CP and T
  Apparent CP-odd asymmetry is induced by matter

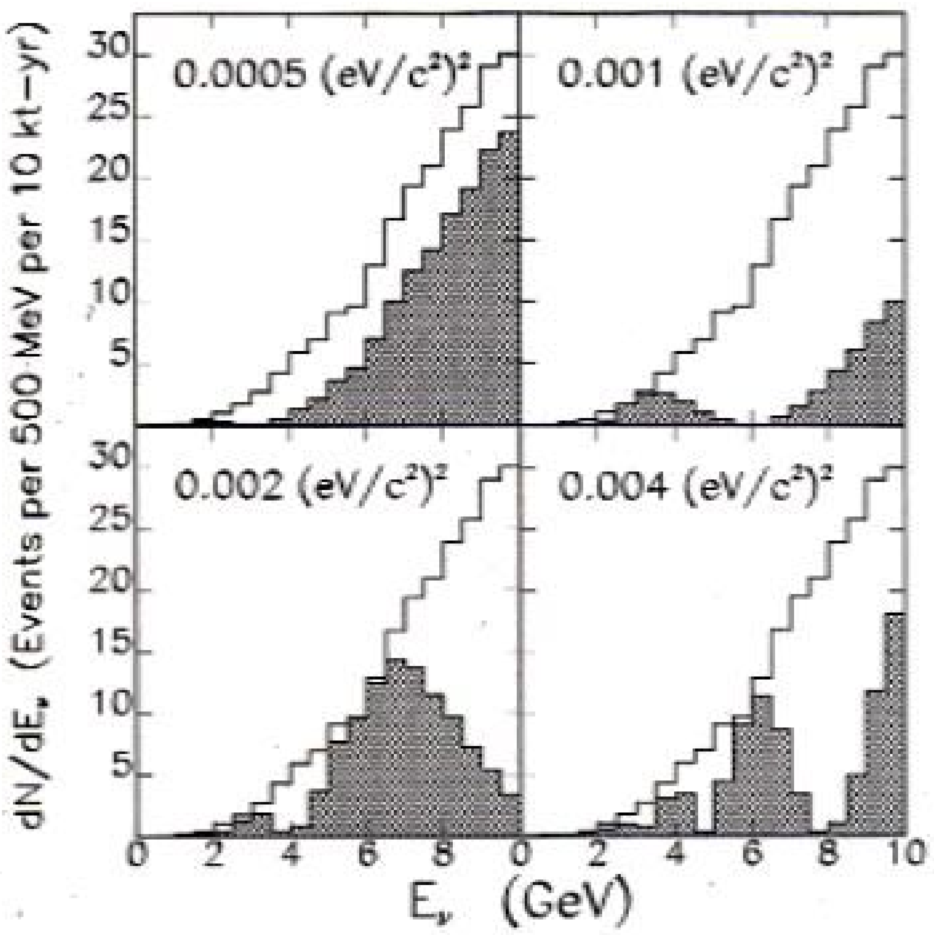


FIG. 12. Modified ν_μ CC interaction spectra for a 10 GeV muon storage ring neutrino source located at FNAL and a detector at the Gran Sasso underground laboratory, shown for several values of the oscillation parameter Δm^2, assuming $\sin^2 2\theta = 1$. In each of the four panels the upper curves show the unmodulated spectrum, and the lower curves the modulated spectrum corresponding to the indicated Δm^2.

SUMMARY

- Neutrino physics has moved us beyond the Standard Model

- From oscillation effects, we already have a surprising amount of information about the neutrino mass hierarchy and mixing pattern

- Reconstruction of the 3 neutrino mixing matrix is on the horizon

- Long baseline experiments are the next frontier for precision measurements

- SuperK / SNO / . . . will differentiate the solar solutions

- The absolute neutrino mass scale remains to be fixed

- $0\nu\beta\beta$ decay can discern Majorana neutrinos and either bound Σm_ν or determine its value

- Cosmology (CMB, large scale structure) can tell us if $\Sigma m_\nu > 0.4$ eV

- Convergence of particle physics, nuclear physics, and cosmology to solve neutrino mass issues

- Many models proposed for lepton and neutrino mass matrices, but no obvious synthesis yet