Phenomenology of Neutrino Oscillations

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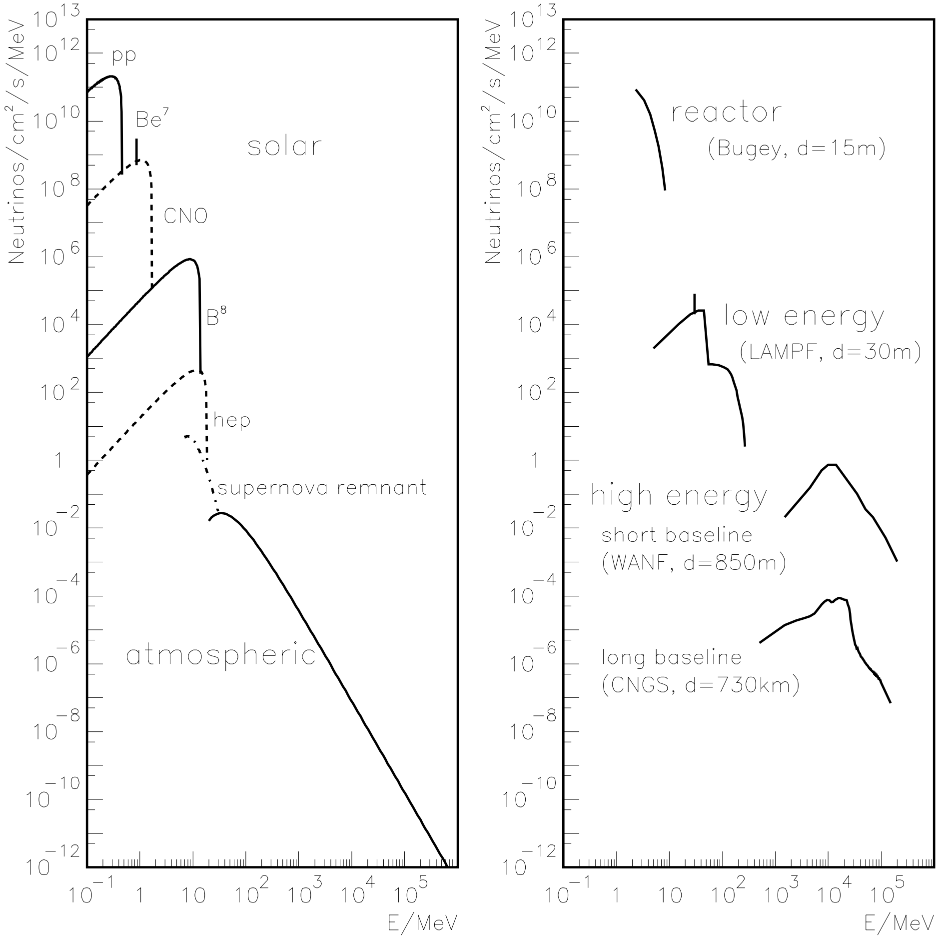
- ⇝ Neutrino Oscillations in Vacuum
- ⇝ Neutrinos and Antineutrinos
- ⇝ CPT, CP and T symmetries
- ⇝ Types of experiments
- ⇝ Neutrino Oscillations in Matter (brief)
- ⇝ Experimental results

NEUTRINO FLUXES



LAMPF = Los Alamos, WANF = CERN, CNGS = CERN→Gran Sasso

A. Geiser, Rept. Prog. Phys. 63 (2000) 1779

! detectable neutrinos are extremely relativistic !

Only neutrinos with energy larger than some fraction of MeV are detectable!

Charged-Current Processes: Threshold

☼ $\nu_e + {}^{37}\text{Cl} \to {}^{37}\text{Ar} + e^-$ $\quad E_{\text{th}} = 0.81\,\text{MeV}$

☼ $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$ $\quad E_{\text{th}} = 0.233\,\text{MeV}$

♁ $\bar{\nu}_e + p \to n + e^+$ $\quad E_{\text{th}} = 1.8\,\text{MeV}$

♁ $\nu_\mu + n \to p + \mu^-$ $\quad E_{\text{th}} = 110\,\text{MeV}$

♁ $\nu_\mu + e^- \to \nu_e + \mu^-$ $\quad E_{\text{th}} \simeq \frac{m_\mu^2}{2m_e} = 10.9\,\text{GeV}$

$$\boxed{\begin{aligned} \nu + A \to B + C \quad &\Rightarrow \quad s = 2Em_A + m_A^2 \geq (m_B + m_C)^2 \\ &\Rightarrow \quad E_{\text{th}} = \frac{(m_B + m_C)^2}{2m_A} - \frac{m_A}{2} \end{aligned}}$$

Elastic Scattering Processes: Cross Section $\propto$ Energy

☼ $\nu + e^- \to \nu + e^-$ $\quad \sigma(E) \sim \sigma_0\, E/m_e$

Background $\Rightarrow E_{\text{th}}^{\text{SK}} \simeq 5\,\text{MeV}$ $\quad \sigma_0 \sim 10^{-44}\,\text{cm}^2$

Cosmological Bound : $\boxed{\sum_{\text{light } \nu} m_\nu \lesssim 5\,\text{eV}}$

$\Downarrow$

! detectable neutrinos are extremely relativistic !

Neutrino Oscillations in Vacuum

(Bilenky & Pontecorvo, Phys. Rep. 41 (1978) 225)

Neutrino production:

$$j_\rho^{\text{CC}\dagger} = 2 \sum_{\alpha=e,\mu,\tau} \overline{\alpha_L}\, \gamma_\rho\, \nu_{\alpha L}\,, \qquad \nu_{\alpha L} = \sum_k U_{\alpha k} \nu_{kL}$$

Flavor states: $\quad |\nu_\alpha\rangle = \sum_k U_{\alpha k}^* |\nu_k\rangle$

$$\langle 0|\nu_{\alpha L}|\nu_\beta\rangle = \sum_{k,j} U_{\alpha k} U_{\beta j}^* \underbrace{\langle 0|\nu_{kL}|\nu_j\rangle}_{\propto \delta_{kj}} \propto \sum_k U_{\alpha k} U_{\beta k}^* = \delta_{\alpha\beta}$$

$\mathcal{H}|\nu_k\rangle = E_k|\nu_k\rangle \Rightarrow$ Time evolution: $|\nu_k(t)\rangle = e^{-iE_k t}|\nu_k\rangle$

Propagating neutrino:

$$|\nu_\alpha(t)\rangle = \sum_k U_{\alpha k}^* e^{-iE_k t}|\nu_k\rangle$$

$$|\nu_k\rangle = \sum_{\beta=e,\mu,\tau} U_{\beta k}|\nu_\beta\rangle$$

$$|\nu_\alpha(t)\rangle = \sum_{\beta=e,\mu,\tau} \underbrace{\left(\sum_k U_{\alpha k}^* e^{-iE_k t} U_{\beta k}\right)}_{\mathcal{A}_{\nu_\alpha \to \nu_\beta}(t)} |\nu_\beta\rangle$$

Transition probability:

$$P_{\nu_\alpha \to \nu_\beta}(t) = |\langle \nu_\beta|\nu_\alpha(t)\rangle|^2 = \left|\mathcal{A}_{\nu_\alpha \to \nu_\beta}(t)\right|^2$$

$$P_{\nu_\alpha\to\nu_\beta}(t) = \left| \sum_k U_{\alpha k}^* e^{-iE_k t} U_{\beta k} \right|^2$$

$$= \left| \cancel{e^{-iE_1 t}} \sum_k U_{\alpha k}^* e^{-i(E_k - E_1)t} U_{\beta k} \right|^2$$

The transition probability depends only on the energy differences $E_k - E_1$

Relativistic Approximation

$$E_k = \sqrt{p^2 + m_k^2} \simeq p + \frac{m_k^2}{2p} = E + \frac{m_k^2}{2E}$$

$$\boxed{\begin{array}{c}\text{assumption}\\ p_k = p = E\end{array}}$$

$$E_k - E_j \simeq \frac{\Delta m_{kj}^2}{2E} \qquad \boxed{\Delta m_{kj}^2 \equiv m_k^2 - m_j^2}$$

$$(E_k - E_j)\, t \simeq \frac{\Delta m_{kj}^2 L}{2E}$$

$$\boxed{\begin{array}{c}\text{approximation}\\ t \simeq L\end{array}}$$

$$\boxed{P_{\nu_\alpha\to\nu_\beta}(L) = \left| \sum_k U_{\alpha k}^* U_{\beta k} \exp\left(-i \frac{\Delta m_{k1}^2 L}{2E} \right) \right|^2}$$

$$\boxed{P_{\nu_\alpha\to\nu_\beta}(L) = \left| \sum_k U_{\alpha k}^* U_{\beta k} \exp\left(-i \frac{\Delta m_{k1}^2 L}{2E} \right) \right|^2}$$

Two Generations: $k = 1, 2$

$$U = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix} \qquad \Delta m^2 \equiv \Delta m_{21}^2 \equiv m_2^2 - m_1^2$$

Transition $(\alpha \neq \beta)$: $\boxed{P_{\nu_\alpha\to\nu_\beta}(L) = \sin^2 2\vartheta \, \sin^2\left(\frac{\Delta m^2 L}{4E} \right)}$

Survival $\alpha = \beta$: $[P_{\nu_\alpha\to\nu_\alpha}(L) = 1 - P_{\nu_\alpha\to\nu_\beta}(L)]$

$$\boxed{P_{\nu_\alpha\to\nu_\alpha}(L) = 1 - \sin^2 2\vartheta \, \sin^2\left(\frac{\Delta m^2 L}{4E} \right)}$$

General formula for any number of generations

$$\boxed{\begin{aligned} P_{\nu_\alpha\to\nu_\beta}(L) = {} & \sum_k |U_{\alpha k}|^2 |U_{\beta k}|^2 \\ & + 2\mathrm{Re} \sum_{k>j} U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^* \exp\left(-i \frac{\Delta m_{kj}^2 L}{2E} \right) \end{aligned}}$$

NEUTRINOS AND ANTINEUTRINOS

$$P_{\nu_\alpha \to \nu_\beta}(L) = \sum_k |U_{\alpha k}|^2 |U_{\beta k}|^2 + 2\mathrm{Re} \sum_{k>j} U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^* \exp\left(-i \frac{\Delta m_{kj}^2 L}{2E}\right)$$

Antineutrinos are described by CP-conjugated fields:

$$\nu^{\mathrm{CP}} = \gamma^0 \mathcal{C} \overline{\nu}^T = -\mathcal{C} \nu^*$$

C $\Longrightarrow$ Particle $\leftrightarrows$ Antiparticle

P $\Longrightarrow$ Left-Handed $\leftrightarrows$ Righ-Handed

Fields: $\nu_{\alpha L} = \sum_k U_{\alpha k} \nu_{kL} \xrightarrow{\mathrm{CP}} \nu_{\alpha L}^{\mathrm{CP}} = \sum_k U_{\alpha k}^* \nu_{kL}^{\mathrm{CP}}$

States: $|\nu_\alpha\rangle = \sum_k U_{\alpha k}^* |\nu_k\rangle \xrightarrow{\mathrm{CP}} |\bar{\nu}_\alpha\rangle = \sum_k U_{\alpha k} |\bar{\nu}_k\rangle$

NEUTRINOS $U \leftrightarrows U^*$ ANTINEUTRINOS

$$P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta}(L) = \sum_k |U_{\alpha k}|^2 |U_{\beta k}|^2 + 2\mathrm{Re} \sum_{k>j} U_{\alpha k} U_{\beta k}^* U_{\alpha j}^* U_{\beta j} \exp\left(-i \frac{\Delta m_{kj}^2 L}{2E}\right)$$

CPT Symmetry

$$\boxed{P_{\nu_\alpha \to \nu_\beta} = P_{\bar{\nu}_\beta \to \bar{\nu}_\alpha}}$$

Survival : $\boxed{P_{\nu_\alpha \to \nu_\alpha} = P_{\bar{\nu}_\alpha \to \bar{\nu}_\alpha}}$

Reactor oscillation results for ν_e are valid also for $\bar{\nu}_e$!

CPT Asymmetries:

$$A_{\alpha\beta}^{(\mathrm{CPT})} = P_{\nu_\alpha \to \nu_\beta} - P_{\bar{\nu}_\beta \to \bar{\nu}_\alpha}$$

Quantum Field Theory $\Rightarrow$ $A_{\alpha\beta}^{(\mathrm{CPT})} = 0$

Indeed:

$$P_{\nu_\alpha \to \nu_\beta}(L) = \sum_k |U_{\alpha k}|^2 |U_{\beta k}|^2 + 2\mathrm{Re} \sum_{k>j} U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^* \exp\left(-i \frac{\Delta m_{kj}^2 L}{2E}\right)$$

is invariant under CPT:

$$U \leftrightarrows U^* \qquad \alpha \leftrightarrows \beta$$

CP Symmetry

$$\boxed{P_{\nu_\alpha\to\nu_\beta} = P_{\bar\nu_\alpha\to\bar\nu_\beta}}$$

CP Asymmetries:

$$A^{(\mathrm{CP})}_{\alpha\beta} = P_{\nu_\alpha\to\nu_\beta} - P_{\bar\nu_\alpha\to\bar\nu_\beta}$$

$$\begin{aligned} A^{(\mathrm{CP})}_{\alpha\beta}(L) \quad &= 2\mathrm{Re}\sum_{k>j} U^*_{\alpha k}U_{\beta k}U_{\alpha j}U^*_{\beta j}\exp\left(-i\frac{\Delta m^2_{kj}L}{2E}\right) \\ &- 2\mathrm{Re}\sum_{k>j} U_{\alpha k}U^*_{\beta k}U^*_{\alpha j}U_{\beta j}\exp\left(-i\frac{\Delta m^2_{kj}L}{2E}\right) \end{aligned}$$

$$\boxed{A^{(\mathrm{CP})}_{\alpha\beta}(L) = 4\sum_{k>j} J_{\alpha\beta;kj}\sin\left(\frac{\Delta m^2_{kj}L}{2E}\right)}$$

Jarlskog rephasing invariants: $\boxed{U_{\alpha k}\to e^{i\lambda_\alpha}U_{\alpha k}e^{i\eta_k}}$

$$\boxed{J_{\alpha\beta;kj} = \mathrm{Im}\left[U^*_{\alpha k}U_{\beta k}U_{\alpha j}U^*_{\beta j}\right]}$$

$\rightsquigarrow$ Violation of CP symmetry depends on Jarlskog rephasing invariants

$\rightsquigarrow$ $\left\langle A^{(\mathrm{CP})}_{\alpha\beta}\right\rangle = 0 \Rightarrow$ Measurement of CP violation needs measurement of oscillations.

T Symmetry

$$\boxed{P_{\nu_\alpha\to\nu_\beta} = P_{\nu_\beta\to\nu_\alpha}}$$

T Asymmetries:

$$A^{(\mathrm{T})}_{\alpha\beta} = P_{\nu_\alpha\to\nu_\beta} - P_{\nu_\beta\to\nu_\alpha}$$

$$\begin{aligned} A^{(\mathrm{T})}_{\alpha\beta}(L) \quad &= 2\mathrm{Re}\sum_{k>j} U^*_{\alpha k}U_{\beta k}U_{\alpha j}U^*_{\beta j}\exp\left(-i\frac{\Delta m^2_{kj}L}{2E}\right) \\ &- 2\mathrm{Re}\sum_{k>j} U^*_{\beta k}U_{\alpha k}U_{\beta j}U^*_{\alpha j}\exp\left(-i\frac{\Delta m^2_{kj}L}{2E}\right) \end{aligned}$$

$$\boxed{A^{(\mathrm{T})}_{\alpha\beta}(L) = 4\sum_{k>j} J_{\alpha\beta;kj}\sin\left(\frac{\Delta m^2_{kj}L}{2E}\right)}$$

$\rightsquigarrow$ $\boxed{A^{(\mathrm{T})}_{\alpha\beta}(L) = A^{(\mathrm{CP})}_{\alpha\beta}(L)}$

$\rightsquigarrow$ Violation of T symmetry depends on Jarlskog rephasing invariants

$\rightsquigarrow$ $\left\langle A^{(\mathrm{T})}_{\alpha\beta}\right\rangle = 0 \Rightarrow$ Measurement of T violation needs measurement of oscillations.

TYPES OF EXPERIMENTS

Two-Neutrino Mixing $\Rightarrow$ $\boxed{P_{\nu_\alpha \to \nu_\beta}(L) = \sin^2 2\vartheta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)}$

SBL $\quad L/E \lesssim 1\,\mathrm{eV}^{-2} \quad \Delta m^2 \gtrsim 0.1\,\mathrm{eV}^2$ (high statistics)

Reactor SBL: $L \sim 10\,\mathrm{m}, \ E \sim 1\,\mathrm{MeV}$

Accelerator SBL: $L \sim 1\,\mathrm{km}, \ E \gtrsim 1\,\mathrm{GeV}$

LBL & ATM $\quad L/E \lesssim 10^4\,\mathrm{eV}^{-2} \quad \Delta m^2 \gtrsim 10^{-4}\,\mathrm{eV}^2$

Reactor LBL: $L \sim 1\,\mathrm{km}, \ E \sim 1\,\mathrm{MeV}$ CHOOZ, PALO VERDE

Accelerator LBL: $L \sim 10^3\,\mathrm{km}, \ E \gtrsim 1\,\mathrm{GeV}$ MINOS, CNGS

Atmospheric: $L \sim 10^2 - 10^4\,\mathrm{km}, \ E \sim 0.1 - 10^2\,\mathrm{GeV}$

Kamiokande, IMB, Super-Kamiokande, Soudan, MACRO

SUN $\quad L/E \sim 10^{11}\,\mathrm{eV}^{-2} \quad \Delta m^2 \gtrsim 10^{-11}\,\mathrm{eV}^2$

$L \sim 10^8\,\mathrm{km}, \ E \sim 0.1 - 10\,\mathrm{MeV}$

Homestake, Kamiokande, GALLEX, SAGE,

Super-Kamiokande, GNO, SNO

Matter Effect (MSW Resonant Transitions)

$10^{-4} \lesssim \sin^2 2\vartheta \lesssim 1 \qquad 10^{-8}\,\mathrm{eV}^2 \lesssim \Delta m^2 \lesssim 10^{-4}\,\mathrm{eV}^2$

MSW EFFECT

RESONANT TRANSITIONS IN MATTER

$(\nu_e \leftrightarrows \nu_\mu)$

$$\underbrace{M^2}_{\text{mass-squared matrix in vacuum}} \xrightarrow{MATTER} M^2 + \underbrace{2EV_{CC}}_{\text{potential due to coherent forward CC elastic scattering}} = \underbrace{M^2_{\text{eff}}}_{\text{effective mass-squared matrix in matter}}$$

$V_{CC} = \sqrt{2} G_F N_e \qquad A_{CC} \equiv 2EV_{CC} = 2\sqrt{2} E G_F N_e$

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \frac{M^2}{2E}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} \xrightarrow{MATTER} i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \frac{M^2_{\text{eff}}}{2E}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \frac{1}{4E}\begin{pmatrix}-\Delta m^2 c_{2\vartheta} + 2A_{CC} & \Delta m^2 s_{2\vartheta}\\ \Delta m^2 s_{2\vartheta} & \Delta m^2 c_{2\vartheta}\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

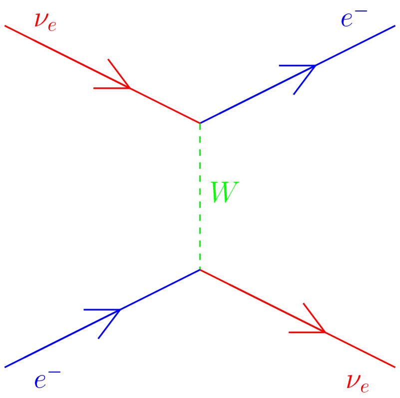
Effective Mixing Angle in Matter: $\tan 2\vartheta_M = \dfrac{\tan 2\vartheta}{1 - \frac{A_{CC}}{\Delta m^2 \cos 2\vartheta}}$

Resonance: $A_{CC}^R = \Delta m^2 \cos 2\vartheta \Longrightarrow N_e^R = \dfrac{\Delta m^2 \cos 2\vartheta}{2\sqrt{2} E G_F}$

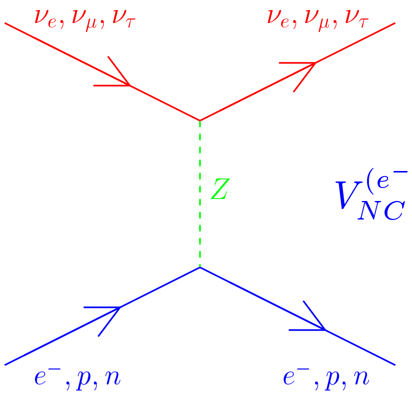
Effective Squared-Mass Difference:

$$\Delta m^2_{\text{eff}} = \sqrt{\left(\Delta m^2 \cos 2\vartheta - A_{CC}\right)^2 + \left(\Delta m^2 \sin 2\vartheta\right)^2}$$

EFFECTIVE POTENTIAL IN MATTER



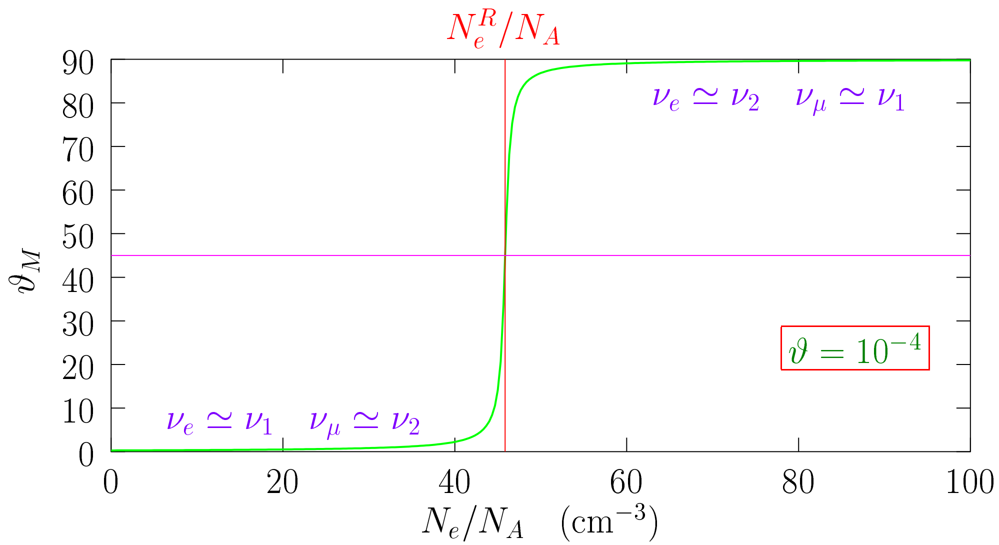
$$V_{CC} = \sqrt{2} G_F N_e$$



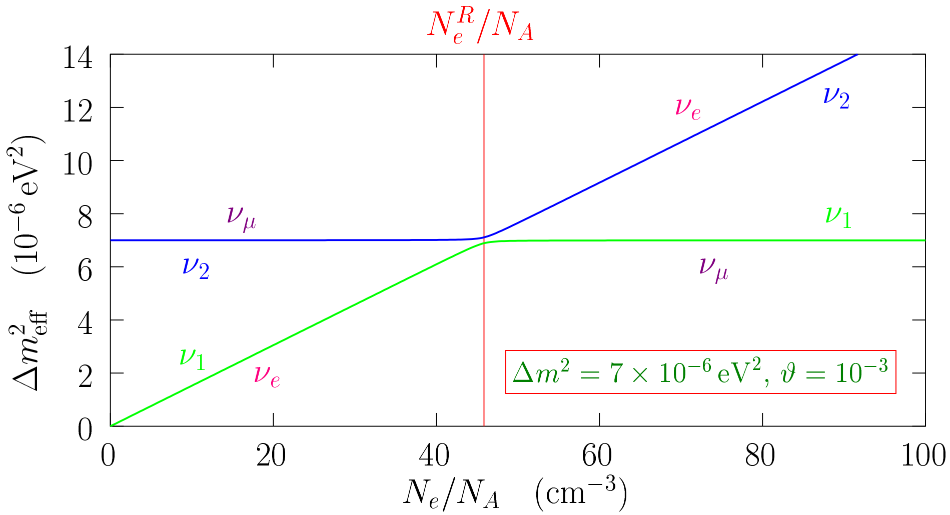
$$V_{NC}^{(e^-)} = -V_{NC}^{(p)} \Rightarrow V_{NC} = -\frac{\sqrt{2}}{2} G_F N_n$$

$$V_e = V_{CC} + V_{NC} \,, \quad V_\mu = V_\tau = V_{NC}$$

$$\overline{V}_{CC} = -V_{CC} \,, \quad \overline{V}_{NC} = -V_{NC}$$



$$\nu_e = \cos\vartheta\,\nu_1 + \sin\vartheta\,\nu_2 \qquad \nu_\mu = -\sin\vartheta\,\nu_1 + \cos\vartheta\,\nu_2$$



IN NEUTRINO OSCILLATIONS DIRAC ~ MAJORANA

Evolution of Amplitudes: $\frac{\mathrm{d}\nu_\alpha}{\mathrm{d}t} = \frac{1}{2E} \left(U M^2 U^\dagger + 2EV \right)_{\alpha\beta} \nu_\beta$

Dirac: $U^{(\mathrm{D})}$

Majorana: $U^{(\mathrm{M})} = U^{(\mathrm{D})} D(\lambda)$

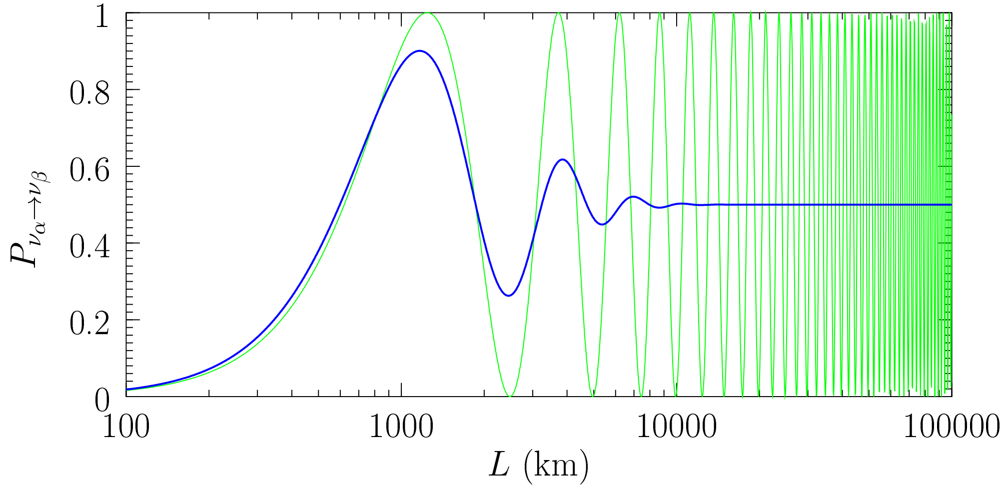
$$D(\lambda) = \begin{pmatrix} 1 & 0 & \cdots & 0 \\ 0 & e^{i\lambda_{21}} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & e^{i\lambda_{N1}} \end{pmatrix} \Rightarrow D^\dagger = D^{-1}$$

$$M^2 = \begin{pmatrix} m_1^2 & 0 & \cdots & 0 \\ 0 & m_2^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & m_N^2 \end{pmatrix} \Rightarrow D M^2 = M^2 D \Rightarrow D M^2 D^\dagger = M^2$$

$$U^{(\mathrm{M})} M^2 (U^{(\mathrm{M})})^\dagger = U^{(\mathrm{D})} D M^2 D^\dagger (U^{(\mathrm{D})})^\dagger = U^{(\mathrm{D})} M^2 (U^{(\mathrm{D})})^\dagger$$

AVERAGE OVER ENERGY SPECTRUM

$$P_{\nu_\alpha \to \nu_\beta}(L) = \frac{1}{2} \sin^2 2\vartheta \left[1 - \cos\left(\frac{\Delta m^2 L}{2E} \right) \right] \qquad (\alpha \neq \beta)$$



$$\Delta m^2 = 10^{-3}\,\mathrm{eV}\,, \quad \sin^2 2\vartheta = 1$$

$$\langle E \rangle = 1\,\mathrm{GeV}\,, \quad \Delta E = 0.2\,\mathrm{GeV}$$

$$\langle P_{\nu_\alpha \to \nu_\beta} \rangle = \frac{1}{2} \sin^2 2\vartheta \left[1 - \int \cos\left(\frac{\Delta m^2 L}{2E} \right) \phi(E)\, \mathrm{d}E \right]$$

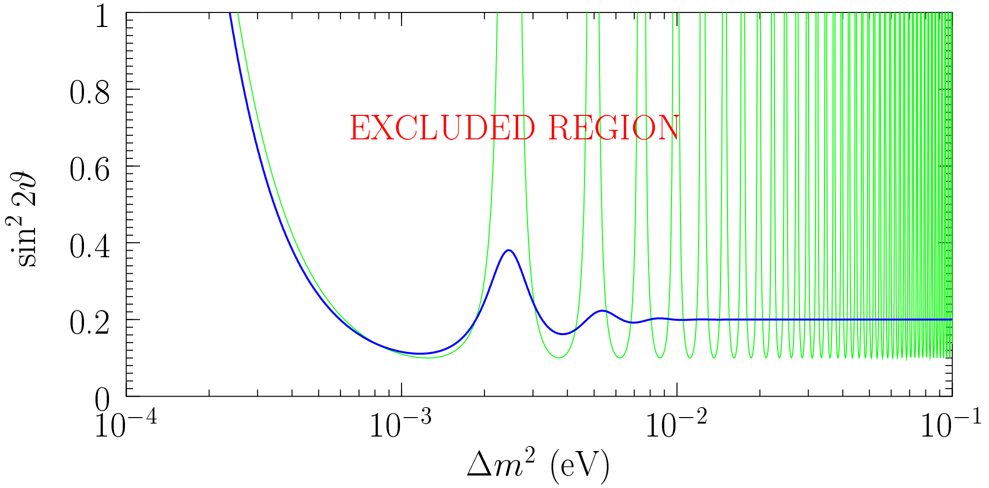
$$\text{Experiment}: P_{\nu_\alpha\to\nu_\beta} \leq P^0_{\nu_\alpha\to\nu_\beta}$$

$$\Downarrow$$

$$\frac{1}{2}\sin^2 2\vartheta \left[1 - \cos\left(\frac{\Delta m^2 L}{2E}\right)\right] \leq P^0_{\nu_\alpha\to\nu_\beta}$$

$$\Downarrow$$

$$\sin^2 2\vartheta \leq \frac{2P^0_{\nu_\alpha\to\nu_\beta}}{1-\cos\left(\frac{\Delta m^2 L}{2E}\right)}$$



$$L = 10^3\,\text{km}\,, \quad P^0_{\nu_\alpha\to\nu_\beta} = 10^{-1}$$

$$\sin^2 2\vartheta \leq \frac{2P^0_{\nu_\alpha\to\nu_\beta}}{1-\int\cos\left(\frac{\Delta m^2 L}{2E}\right)\phi(E)\,\mathrm{d}E}$$

EXCLUSION CURVES

$$\boxed{P_{\nu_\alpha\to\nu_\beta}(L,E) = \sin^2 2\vartheta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)}$$

$(\Delta m^2)_{\text{min}}$

$$\frac{\Delta m^2 L}{4E} \ll 1 \quad \Rightarrow \quad P \simeq \sin^2 2\vartheta \left(\frac{\Delta m^2 L}{4E}\right)^2$$

$$\Delta m^2 \simeq \frac{\sqrt{P}}{\frac{L}{4E}\sin 2\vartheta} \quad \Rightarrow \quad \boxed{(\Delta m^2)_{\text{min}} \simeq \frac{4\sqrt{\langle P\rangle}}{\langle L/E\rangle}}$$

$(\sin^2 2\vartheta)_{\text{min}}$

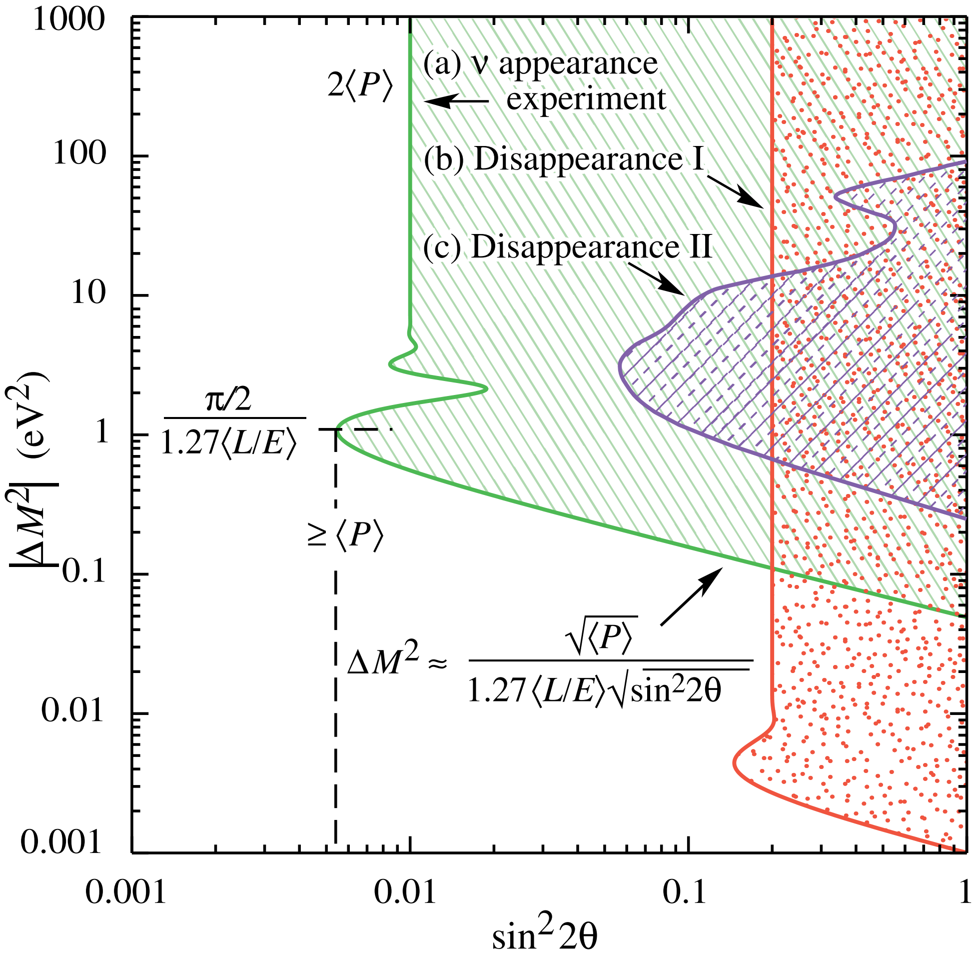
$$\Delta m^2 \simeq \frac{2\pi}{\langle L/E\rangle} \quad \Rightarrow \quad \frac{\Delta m^2 L}{4E} \simeq \frac{\pi}{2}$$

$$\boxed{(\sin^2 2\vartheta)_{\text{min}} \gtrsim \langle P\rangle}$$

$\sin^2 2\vartheta$ for Large Δm^2

$$\frac{\Delta m^2 L}{4E} \gg 1 \quad \Rightarrow \quad \langle P\rangle = \frac{1}{2}\sin^2 2\vartheta \quad \Rightarrow \quad \boxed{\sin^2 2\vartheta = 2\langle P\rangle}$$

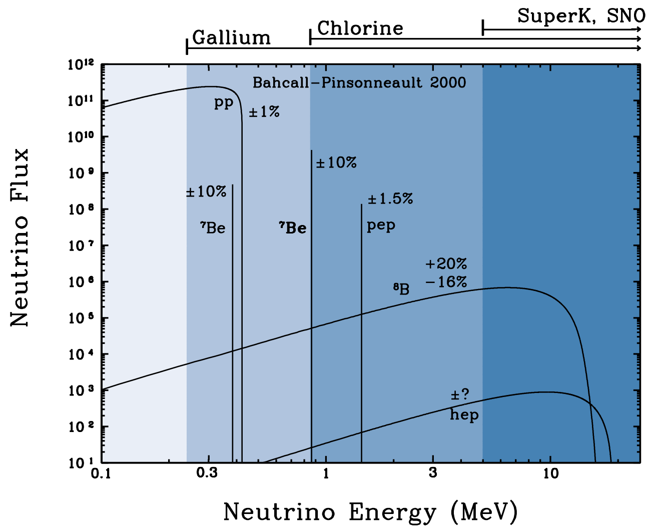
$\sin^2 2\vartheta$–Δm^2 PLOTS

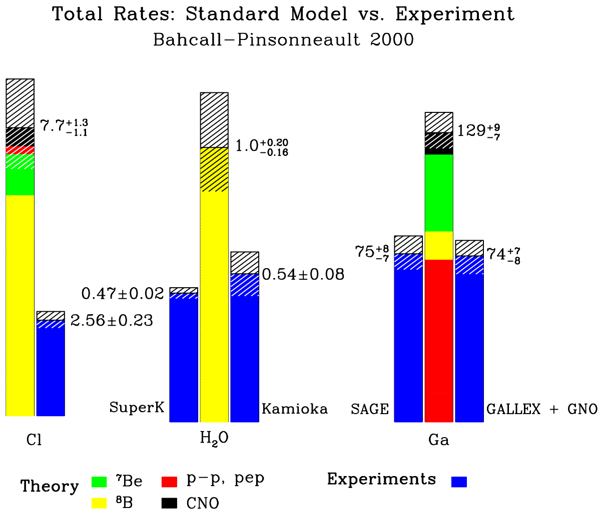


Particle Data Group, The Review of Particle Physics, http://pdg.ge.infn.it

$$\frac{\Delta m^2 L}{4E} = 1.27\,\frac{\Delta m^2(\mathrm{eV}^2)\,L(\mathrm{m})}{4E(\mathrm{MeV})} = 1.27\,\frac{\Delta m^2(\mathrm{eV}^2)\,L(\mathrm{km})}{4E(\mathrm{GeV})}$$

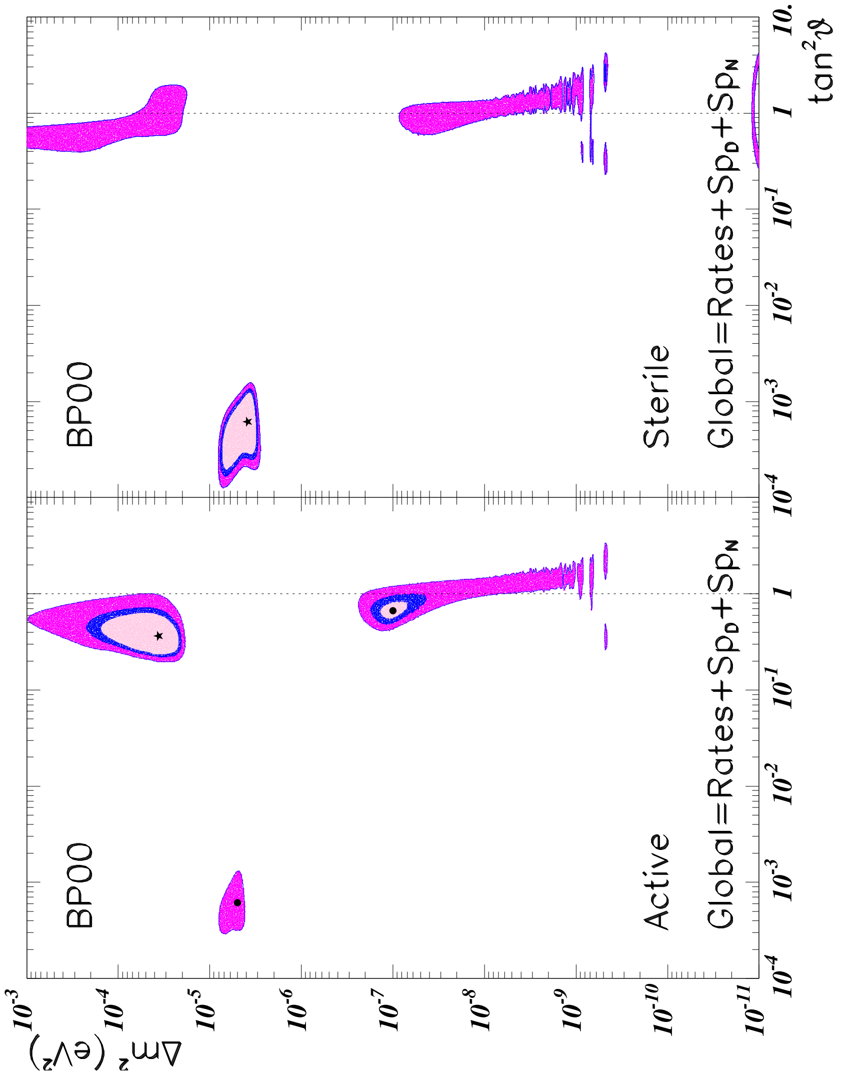
SOLAR NEUTRINOS





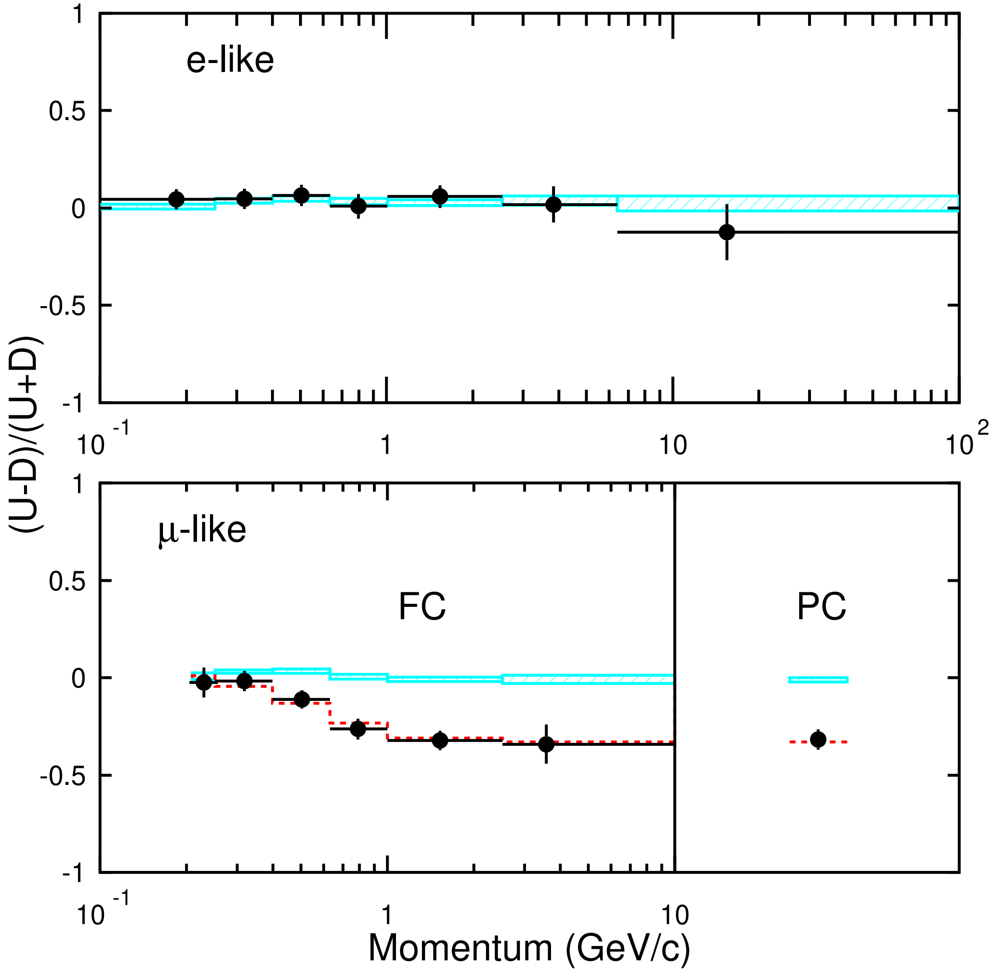
J.N. Bahcall, http://www.sns.ias.edu/ jnb

SOLAR NEUTRINO FIT



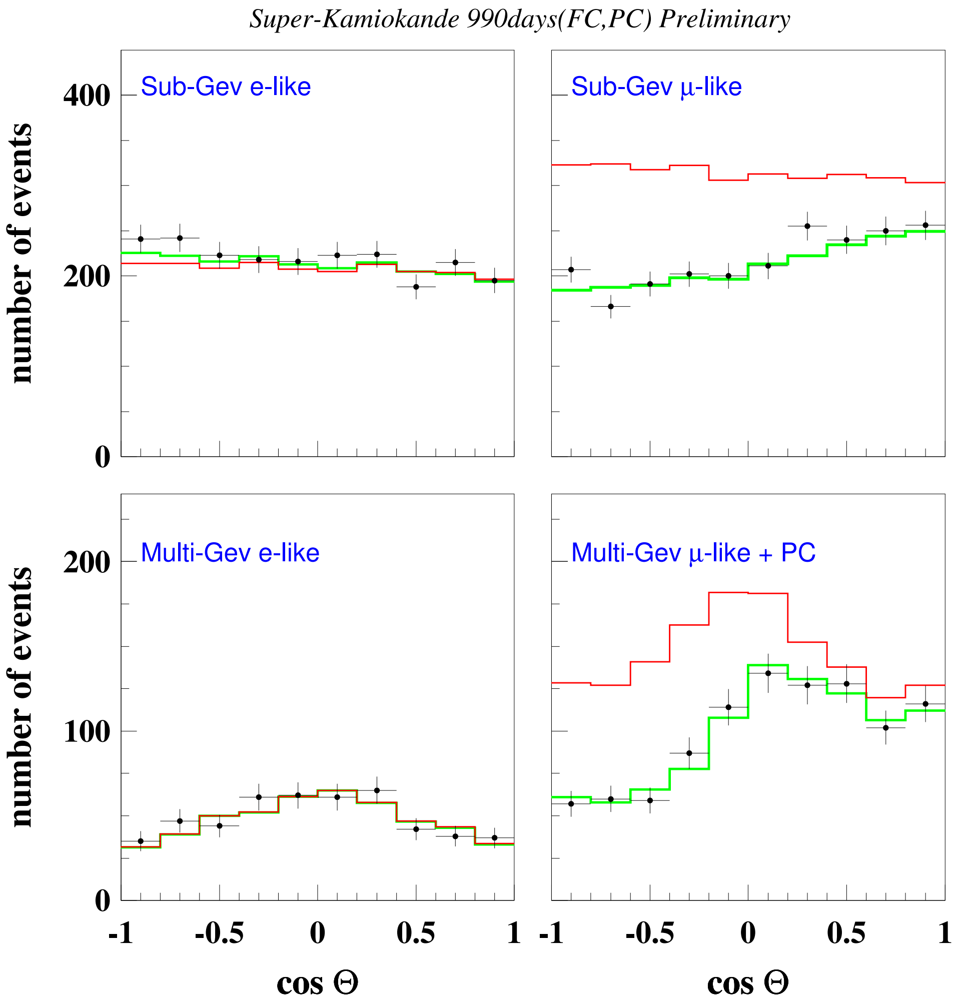
M.C. Gonzalez-Garcia, C. Peña-Garay, Phys. Rev. D 63 (2001) 073013

SUPER-KAMIOKANDE UP-DOWN ASYMMETRY



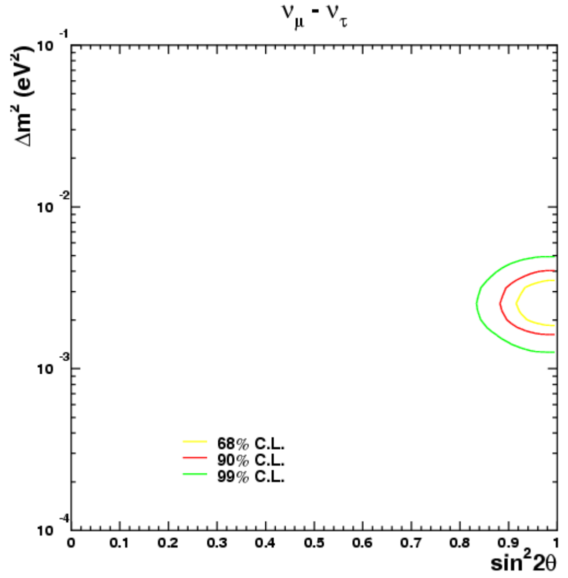
$$A_\mu = \left(\frac{U-D}{U+D}\right)_\mu = -0.311 \pm 0.043 \pm 0.01 \qquad (7\sigma)$$

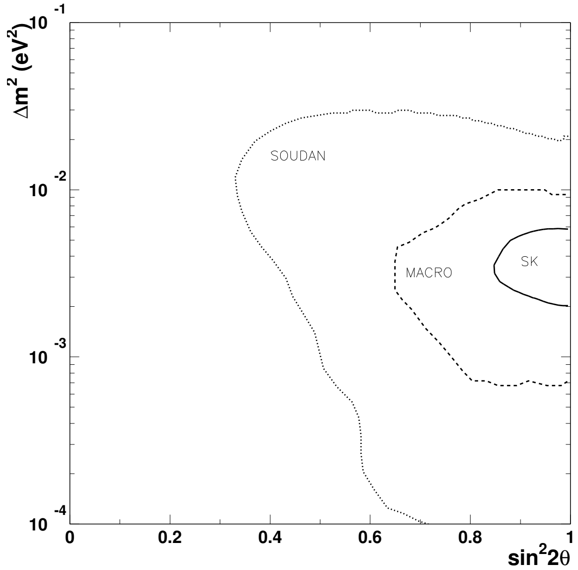
SUPER-KAMIOKANDE ANGULAR DISTRIBUTION



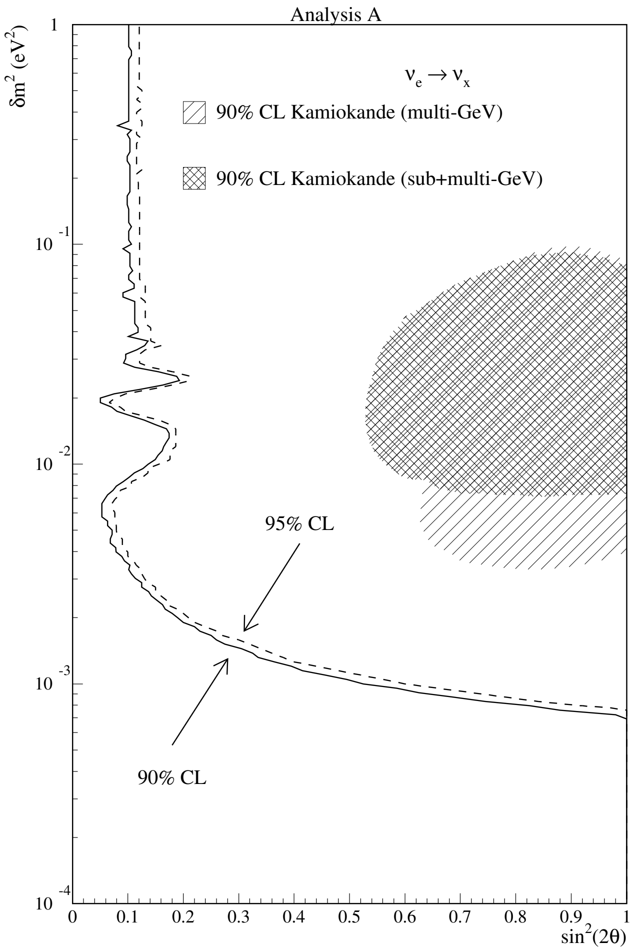
SUPER-KAMIOKANDE, http://www-sk.icrr.u-tokyo.ac.jp

SUPER-KAMIOKANDE ALLOWED REGION



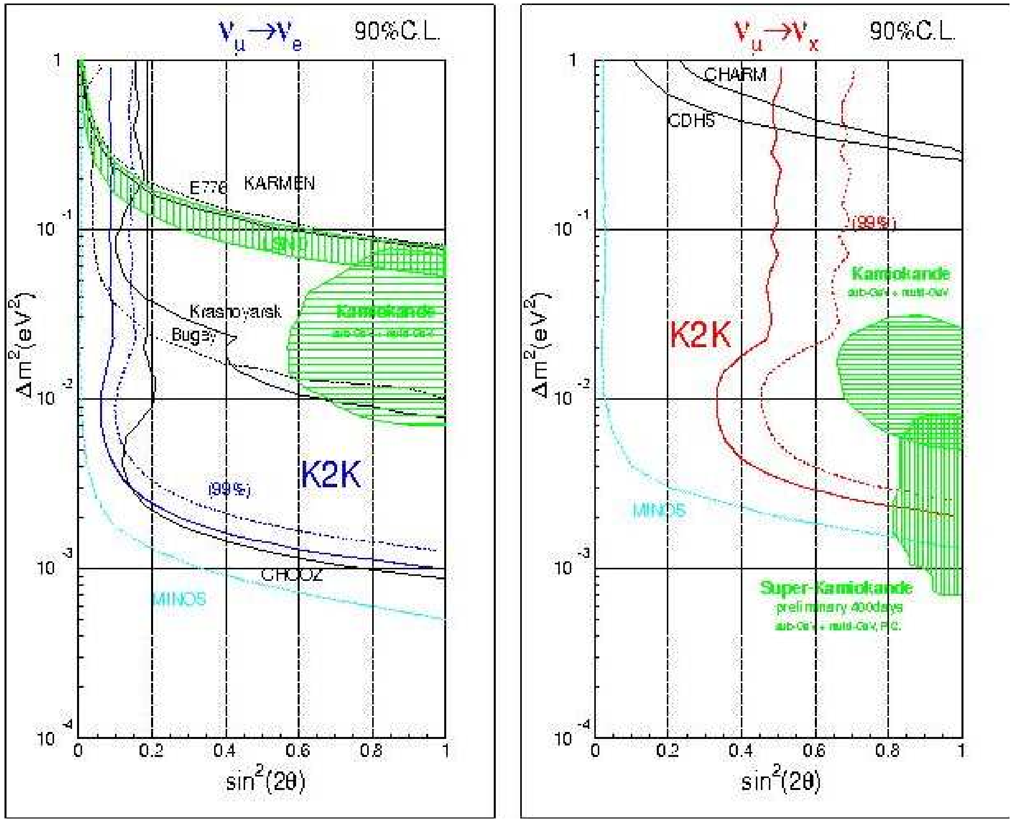


CHOOZ



CHOOZ, http://www.pi.infn.it/chooz

K2K

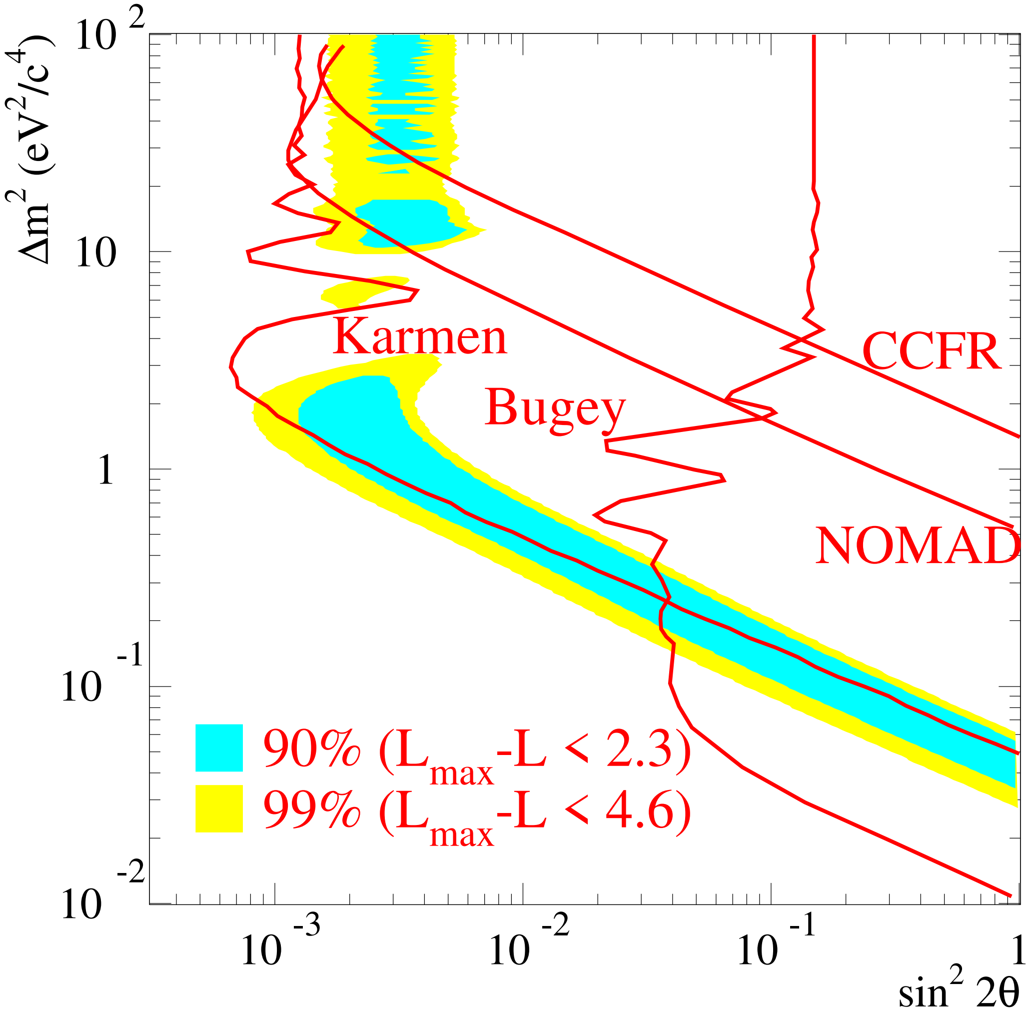


K2K, http://neutrino.kek.jp

K2K events, January 2001 (hep-ex/0104014)

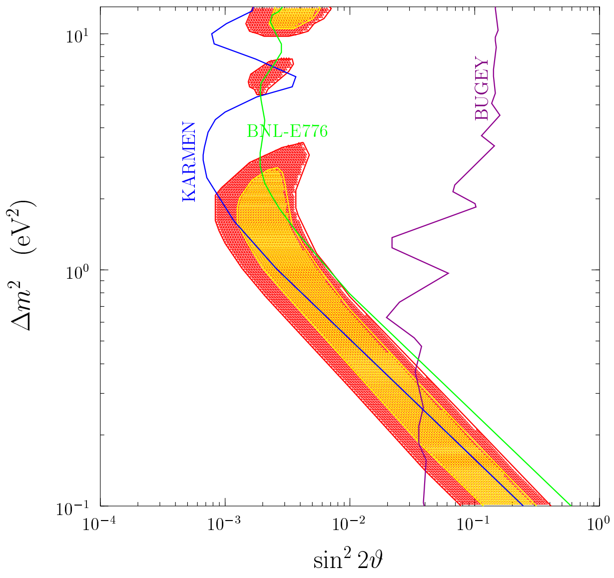
Data: 28 Expected: 37.8 ± 3.8 ($P = 9.6\%$)

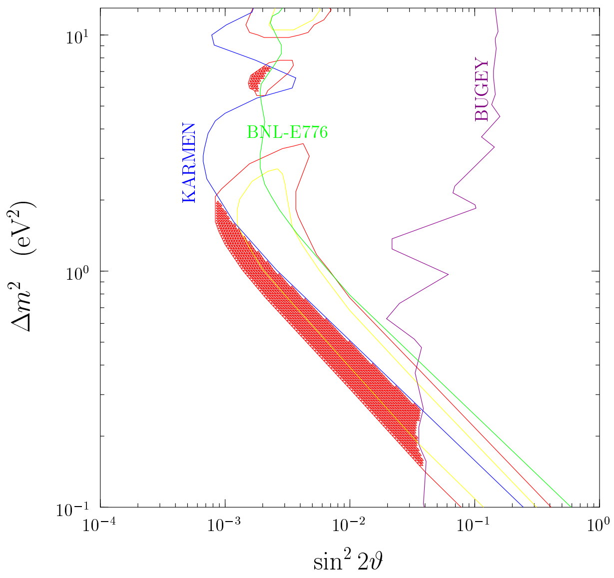
LSND



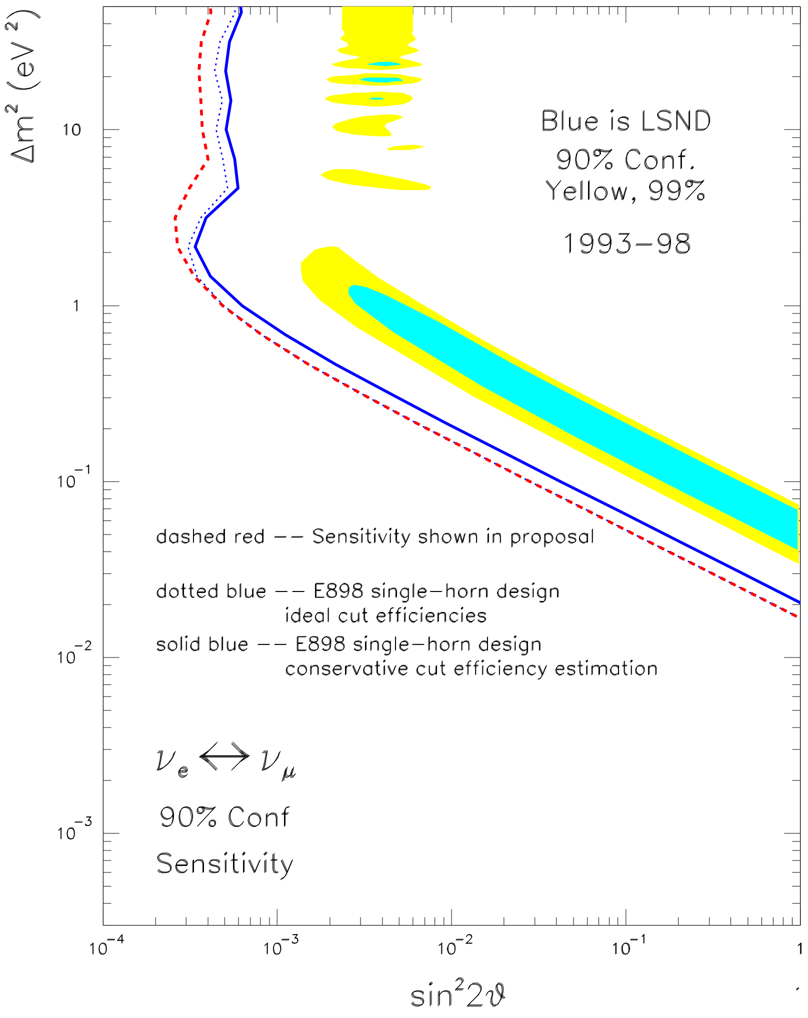
LSND, hep-ex/0104049 (http://www.neutrino.lanl.gov/LSND)

LSND



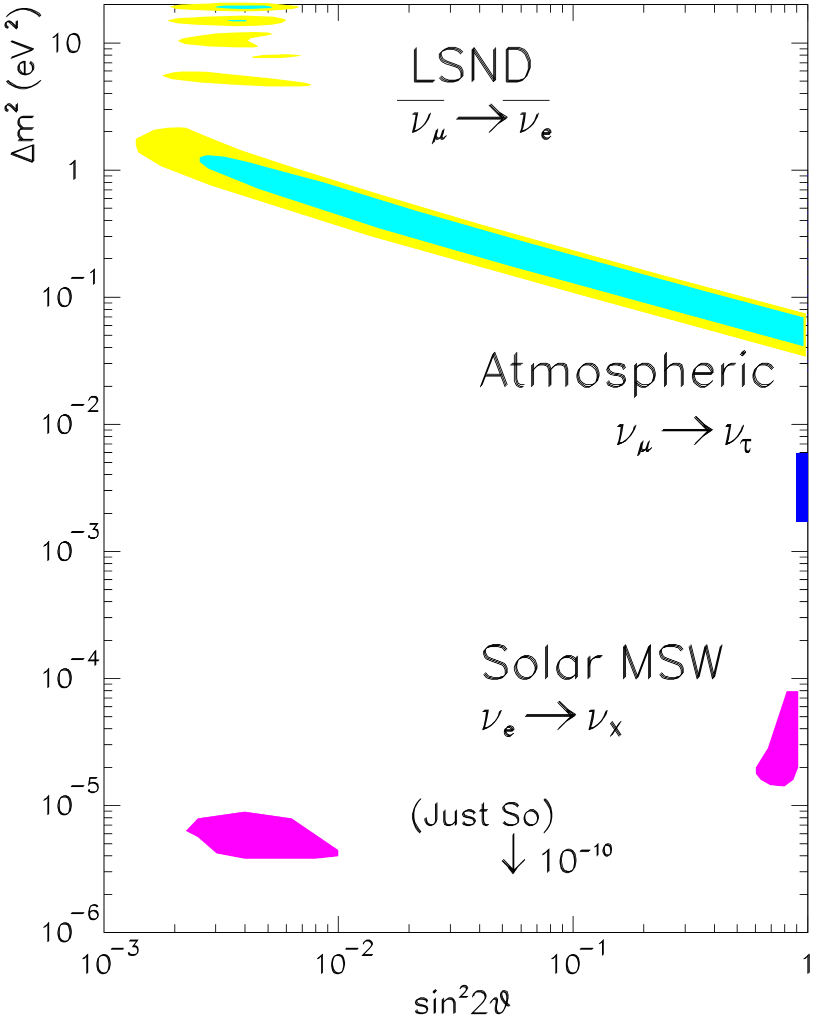


MiniBooNE



MiniBooNE, http://www-boone.fnal.gov

THREE OSCILLATION SIGNALS



GLOBAL VISION