Searching for new physics with neutrinos

Patrick Huber

University of Wisconsin, Madison

NuFact 06 Workshop
August 24-30, 2006
University of California, Irvine

Outline

- Why neutrinos?
- Neutrino oscillations
- New physics in oscillations
  - Phase effects
  - Damping effects
  - Mixing effects
- CPT violation
- Large extra dimensions
- Mass varying neutrinos
- Outlook

Why neutrinos?

Neutrinos are the only neutral fundamental fermions

- no EM (strong) interactions
  - hard to do experiments
  - escape dense environments
- no gauge charge $\longrightarrow$ Majorana masses
- right handed neutrino are gauge-singlets
- weak interaction $\longrightarrow$ copious astro-physical production
- wide variety of sources
- they oscillate

Neutrino oscillation

For oscillation we need

- set of production/detection states – usually flavor

$$|\nu_\alpha\rangle$$

- set of propagation states – usually mass

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle \quad \text{with} \quad UU^\dagger = U^\dagger U = \mathbf{1}$$

- propagation states with different phase evolution

$$(m_i^2 - m_j^2)\frac{L}{E}$$

Neutrino oscillation - continued

If there is a medium

- matter potential – usually flavor diagonal

$$\frac{V}{2E}\mathrm{diag}(1,0,\ldots)$$

new physics (NP) can enter at every step…

NP in the mixing matrix U

- mixing with sterile neutrinos
- non-unitarity

$$UU^\dagger \neq \mathbf{1}$$

- new Fermi-type four-point vertices (lepton flavor violation)

Usually also affect the form of the matter potential and may have side effects on decays as well

NP in the propagation

- neutrino decay
- Lorentz invariance violation (LIV)
- violation of equivalence principle (VEP)
- quantum decoherence
- . . .

Change the energy and baseline dependence of oscillation. At one (or a narrow range of) energy and baseline all of them can give the same phenomenology like oscillation.

NP everywhere

- mass varying neutrinos
- different masses and mixings for neutrinos and anti-neutrinos (direct CPT violation)
- violation of the spin-statistics theorem, neutrinos obey a mixture of Bose and Fermi statistic
- …

Phenomenological approach

- varying degree of theoretical motivation/justification
- many ideas inspired by some other problem, *e.g.* LSND, Dark energy
- general case involves a large number of new parameters
- existing data has to be accounted for

Phase effects

Effects on the oscillation phase can be parameterized

$$\Delta\phi = \sigma_\pm \Delta\delta_{ij} E^n$$

where $\Delta\delta_{ij} = (\delta_i - \delta_j)$ and δ_i is the new property which differs between different propagation states $|\nu_i\rangle$. $\sigma_\pm$ decides whether neutrinos and anti-neutrinos have a same sign correction or not.

Lorentz invariance violation

Simplest Ansatz:

- rotational and translation invariance are preserved
- different objects have a different maximum speed

Replace mass eigenstates with velocity eigenstates the phase difference is now proportional to

$$(E_2 - E_1)L \simeq (v_2 - v_1)EL$$

Violation of equiv. principle

Assume ν_1 and ν_2 couple differently to gravity

$$\Delta\phi = (\gamma_2 - \gamma_1)|\Phi|EL$$

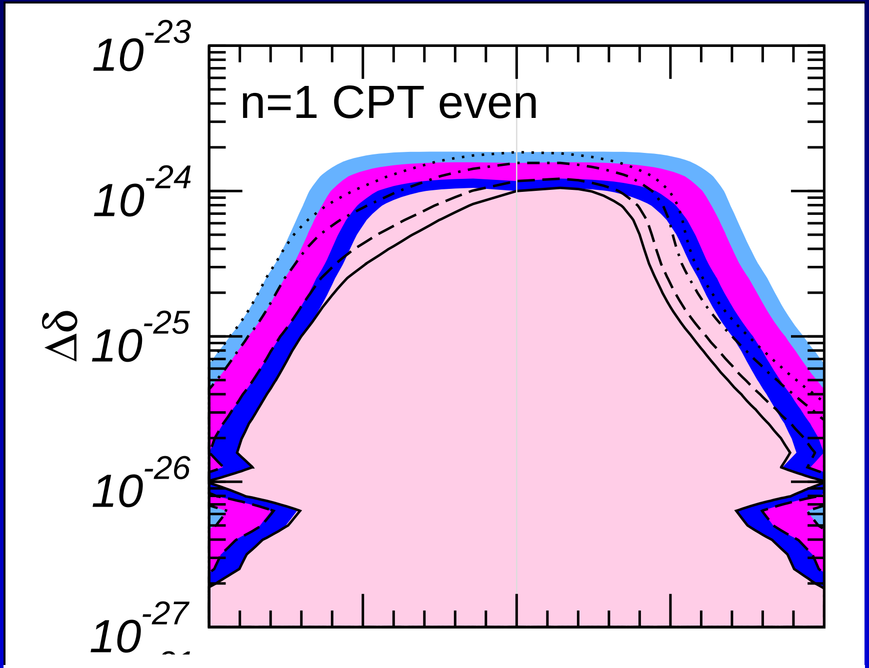
where Φ is the gravitational potential.
There is a number of further possibility like $\Delta\phi$ is energy independent *asf*.

Phase effects & data

Atmospheric neutrino data are the most sensitive probe for those effects.

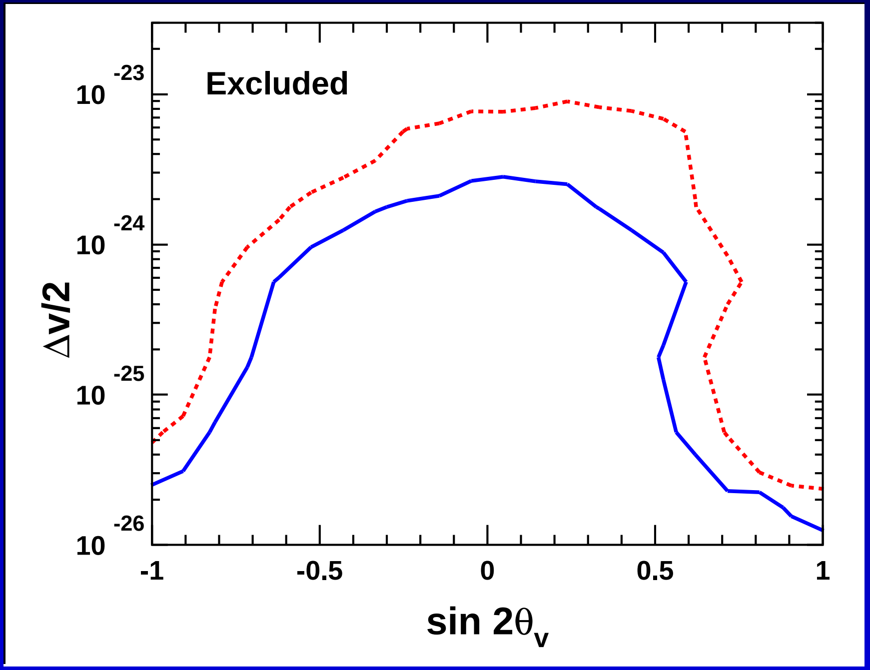
for $\Delta\phi \propto EL$

Super-K & K2K



M.C Gonzalez-Garcia, M. Maltoni, 2004.

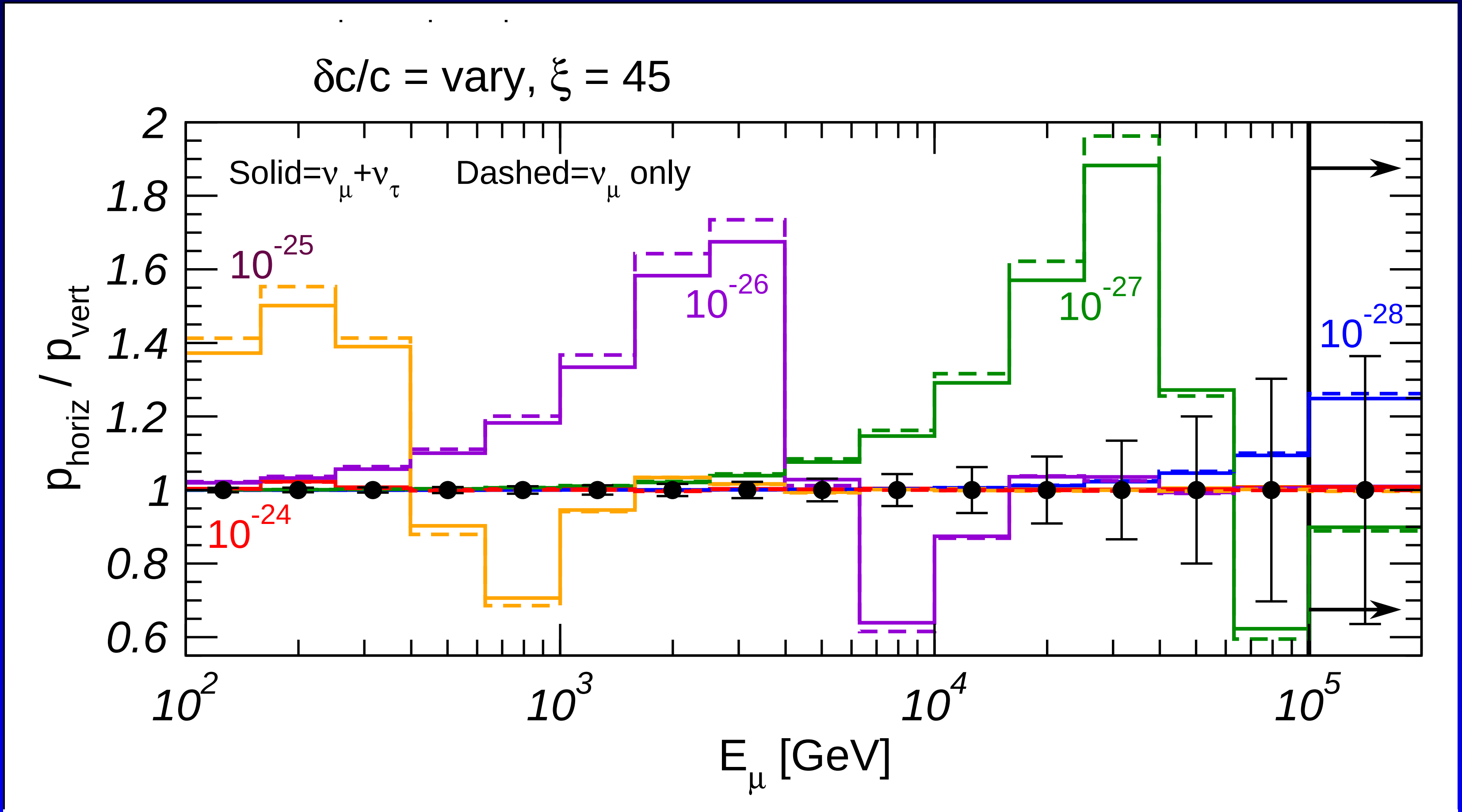
MACRO



MACRO, 2005.

Future sensitivties

IceCube will have a very large ($\mathcal{O}(10^6)$) sample of high energy $10 - 10^5\,\mathrm{GeV}$ atmospheric neutrino events



M.C Gonzalez-Garcia, F. Halzen, M. Maltoni, 2005.

Interpretation of bounds

Typically one would these effects expect to be introduced like

$$\delta v = a\frac{p}{M_{\mathrm{Pl}}} + b\left(\frac{p}{M_{\mathrm{Pl}}}\right)^2 + \ldots$$

Thus the existing bound from atmospheric data $p \sim 1\,\mathrm{GeV}$ and $\delta v < 10^{-24}$ imply $a < 10^{-5}$. IceCube would improve that to $\delta v < 10^{-28}$ and $p \sim 10^5\,\mathrm{GeV}$ and thus $a < 10^{-15}$ and $b \lesssim 1$.
UHECν should be very sensitive since LE is very large and they will improve the bounds further Hooper, Morgan and Winstanley 2005.

Damping effects

The Schroedinger equation only applies to isolated, non-dissipative systems. For interacting, dissipative systems we use the Liouville equation for the density matrix ρ with a decoherence term

$$\dot{\rho} = -i[H, \rho] - D[\rho]$$

With some reasonable assumptions, like positive eigenvalues of ρ, constant average energy, increasing entropy *etc.*, we get

$$D[\rho] = \sum_n \{\rho, D_n D_n^\dagger\} - 2 D_n D_n^\dagger$$

Lindblad 1976

Damping effects

The general solution for the conversion probability then reads in the two-flavor case

$$P_{\alpha\beta} = 1 - \sin^2 2\theta \left(1 - e^{-\gamma L} \cos \frac{\Delta m^2 L}{2E}\right)$$

Usually γ will be parameterized as

$$\gamma = \gamma_n \left(\frac{E}{E_0}\right)^n$$

Neutrino decay

Neutrino decay is described by

$$H_{\mathrm{eff}} = H - i\Gamma$$

with $\Gamma = \mathrm{diag}(a_1, a_2, a_3)/2$ in mass basis and the a_i are given by

$$a_i = \Gamma_i \frac{m_i}{E}$$

The resulting damping factor is

$$\gamma_{ij} = \frac{\Gamma_i m_i - \Gamma_j m_j}{2} \frac{L}{E} \propto E^{-1}$$

Lindner, Ohlsson, Winter, 2001, 2002.

Quantum decoherence

In many models of a theory quantum gravity space-time no longer is smooth but becomes as so called space-time foam: black-holes are created and evaporate via Hawking radiation. Furthermore it is assumed that gravity breaks all *global* quantum numbers, like baryon number, lepton number *asf*. Hence a neutrino moving through this background could be absorbed by black-hole and be re-emitted in the annihilation. In that process it would lose the information about it's flavor (global quantum number) and this process would give rise to non-zero $D[\rho] \sim E^{n+1}/M_{\mathrm{Pl}}^{n}$

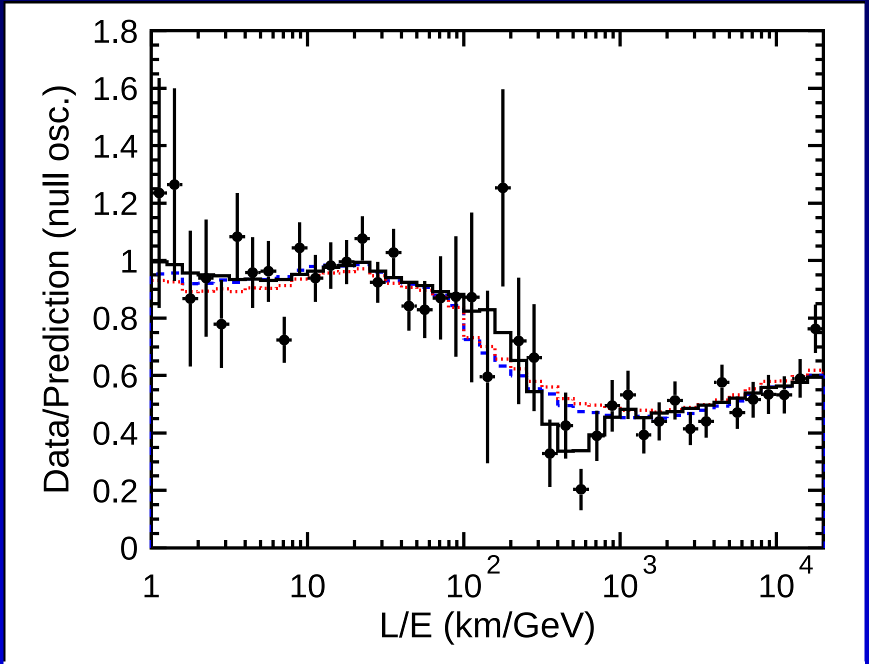
Ellis, Hagelin, Nanopoulos, Srednicki 1984.

Bounds on γ

Decoherence with a $\gamma_{-1} \sim 10^{-22}\,\mathrm{GeV}$ could in principle account for the atmospheric neutrino data

Lisi, Marrone, Montanino, 2000.

Recent SK data is sensitive to the L/E distribution



Super-Kamiokande 2004.

$\gamma_{-1} \leq 10^{-21}\,\mathrm{GeV}$ at more than $3\,\sigma$ CL

Future sensitivities

LBL experiments like a neutrino factory would have similar or slightly better sensitivities like SK data
Blennow, Ohlsson, Winter, 2005

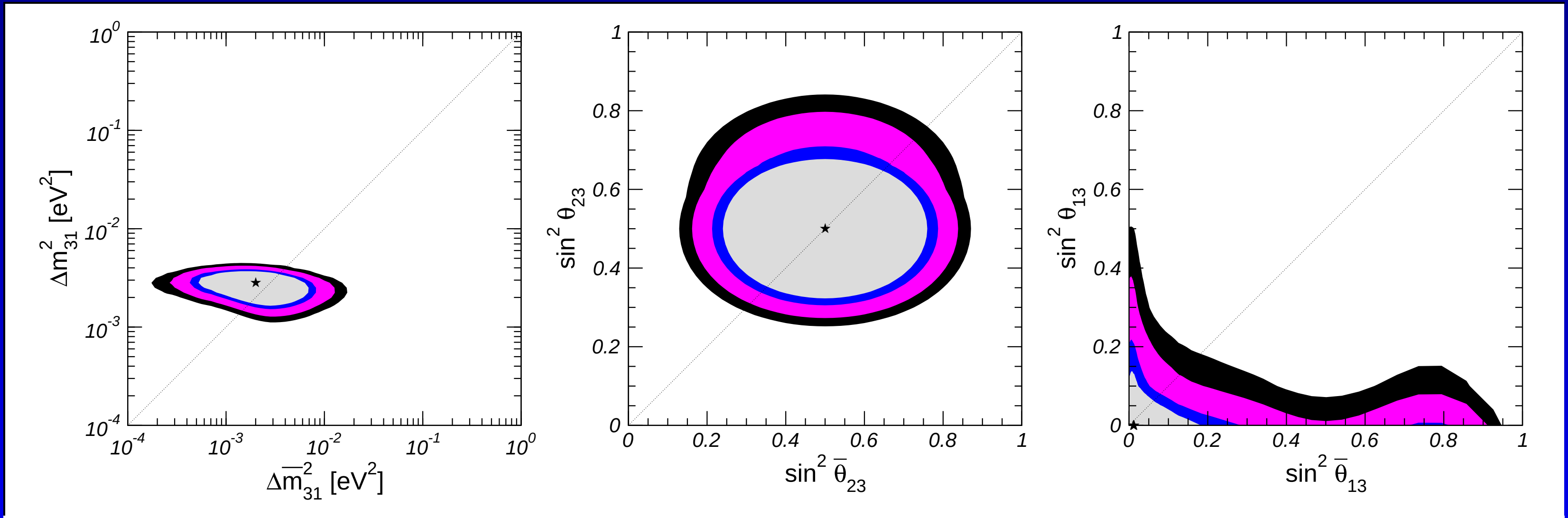
The most sensitive proposed so far would be the observation of the flavor ratio of UHECν originating in β-decay. The neutrinos which start as pure $\bar{\nu}_e$ beam would arrive as 1:1:1 mixture of flavors if decoherence is present. Cygnus OB2 as source and IceCube as detector could yield $\gamma_{-1} \leq 10^{-34}\,\mathrm{GeV}$
Anchordoqui, *et al.*, 2005.

CPT violation

CPT violation has been introduced to accommodate LSND. Masses and mixings of neutrinos and anti-neutrinos are regarded as independent parameters

Barenboim, Borissov, Lykken, 2002.

A subsequent careful analysis shows that this is not a viable explanation of the data and that there is no indication of CPT violation



Gonzalez-Garcia, Maltoni, Schwetz, 2003.

Mixing effects

Effects in mixing are also called non-standard interactions (NSI). NSI can enter at the source (N doesn't have to be unitary).

$$|\nu_\alpha\rangle = \sum_i N^S_{\alpha i} |\nu_i\rangle$$

or in the detection process

$$|\nu_\alpha\rangle = \sum_i N^D_{\alpha i} |\nu_i\rangle$$

or during propagation as additional matter effects

$$\mathrm{diag}(1, 0, \ldots) + N^P$$

Grossman, 1995; Ota, Sato, Yamashita, 2001.

Unitarity violation

In minimal unitarity violation (MUV) only three light neutrinos and unitarity violation only in neutrinos is considered.

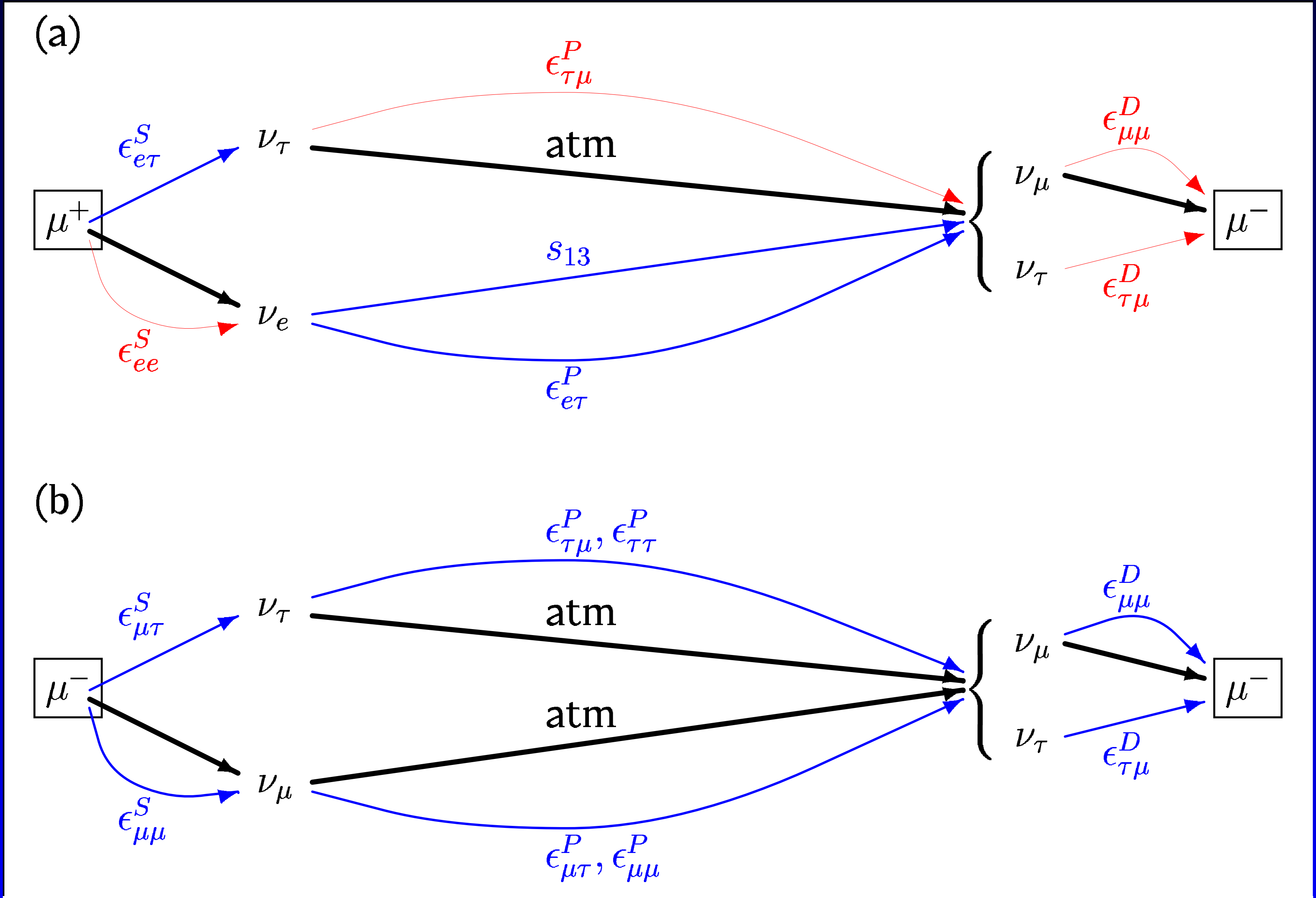
- $N^S = N^D$
- zero distance flavor conversion
- constraints from electro-weak decays
- affects matter potential

$$|NN^\dagger| = \begin{pmatrix} 1.002 \pm 0.005 & < 7.2 \cdot 10^{-5} & < 1.6 \cdot 10^{-2} \\ < 7.2 \cdot 10^{-5} & 1.003 \pm 0.005 & < 1.3 \cdot 10^{-2} \\ < 1.6 \cdot 10^{-2} & < 1.3 \cdot 10^{-2} & 1.003 \pm 0.005 \end{pmatrix}$$

Antusch, *et al.*, 2006.

NSI and Oscillation

The presence of NSI allows new transition paths



Current bounds on NSI

Atmospheric neutrino data yield the following bounds

$$|\epsilon_{\mu\mu}| < 0.068 \quad |\epsilon_{\mu\tau}| < 0.013$$

Gonzalez-Garcia, Maltoni, 2004.

Three flavor case

$$|\epsilon_{e\tau} < 0.38| \quad |\epsilon_{ee}| < \mathcal{O}(1) \quad |\epsilon_{\tau\tau}| < \mathcal{O}(1)$$

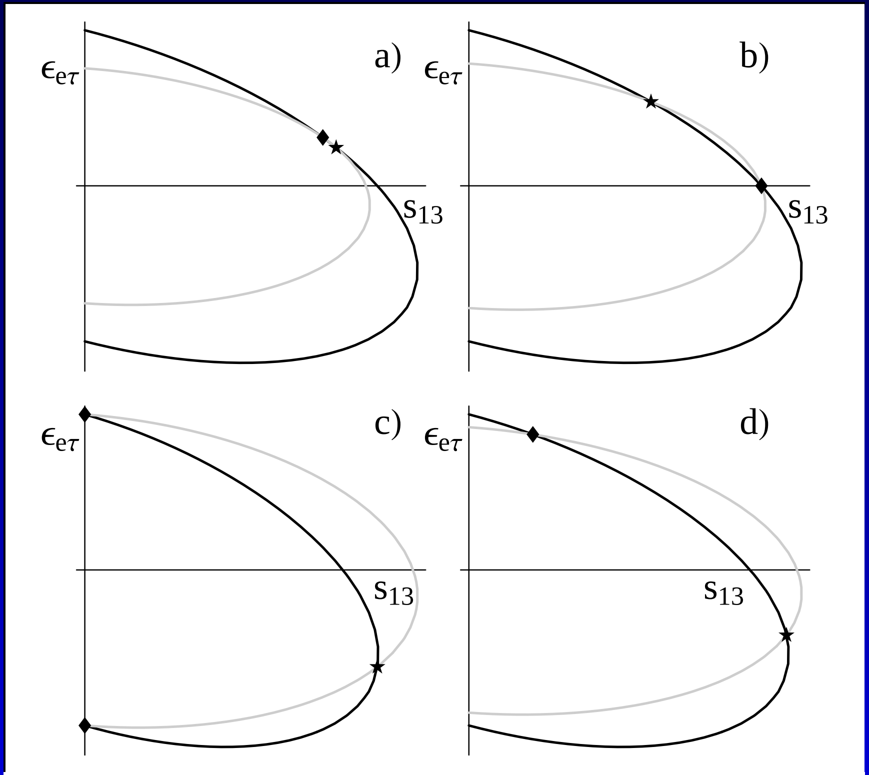
Friedland, Lunardini, Maltoni, 2005.

MINOS is in principle also sensitive, but much less than atmospheric data. Bounds of order 1 seem possible.

Kitazawa, Sugiyama, Yasuda, 2006; Friedland, Lunardini, 2006.

NSI in LBL

Future LBL will look for $\nu_\mu \longrightarrow \nu_e$ which is sensitive to $\epsilon_{e\tau}$. There will be interference effects with θ_{13} and a possible confusion.



PH, Valle, 2001.

PH, Schwetz, Valle, 2001.

The degree of confusion very much depends on the sensitivity toward ν_τ appearance

Campanelli, Romanino, 2002.

Large extra dimensions

- SM fields are confined to the 4d brane, only SM singlets can propagate in the bulk $\longrightarrow \nu_R$
- The coupling of ν_L to ν_R is suppressed by the overlap of the wave function of the bulk and brane states

$$m_\nu = \kappa \frac{m_R}{\sqrt{V_n M_*^n}}$$

- Dirac masses of the right order of magnitude arise naturally $M_{\mathrm{Pl}}^2 = M_*^{n+2} V_n$

$$m_\nu \sim 10^{-4}\,\mathrm{eV} \frac{M_*}{1\,\mathrm{TeV}}$$

Arkani-Hamed, *et al.*, 1998.

Mass varying neutrinos – I

MVN can provide a solution to Dark Energy, replacing quintessence.

- neutrino is coupled to a new, very light scalar
- introduces dependence of neutrino mass on the neutrino density
- could introduce dependence of neutrino mass on matter density

Fardon, Nelson, Weiner, 2004.

Mass varying neutrinos – II

- Solar neutrinos do allow for sizeable MVN effects, even if m_ν depends on the electron density Barger, Huber, Marfatia, 2005.
- Solar neutrinos constrain the MVN parameters, even if m_ν only depends on the neutrino density Cirelli, Gonzalez-Garcia, Pena-Garay, 2005
- Reactor experiments allow for engineered matter densities, hence sensitive tests of dependence of m_ν on the matter density Schwetz, Winter 2006.
- EHECν absorption probes m_ν at high z Ringwald, Schrempp, 2006.

Summary

Neutrinos are a unique window to otherwise inaccessible physics

- mixes with SM singlet fermions
- very sensitive quantum interferometer
- can probe Planck-scale effects on space-time structure
- provides another piece of the flavor puzzle
- orthogonal information to LHC and the Terascale

There is lots of work to do!