CPT Violation and Neutrino Physics

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Dave Ayres Rocks! , Argonne, September 3rd, 2008

CPT Symmetry

- The Standard Model of particle physics is based on a gauge field theory, with local interactions between gauge fields and fermion and scalar fields.
- The Hamiltonian operator of the system is hermitian and the theory is Lorentz invariant
- Hermiticity of the Hamiltonian implies unitary evolution in time.
- The CPT Theorem sates that a four dimensional theory, with local interactions, Lorentz invariance and an hermitian Hamiltonian should preserve CPT (Schwinger, Luders, Pauli, Jost)
- CPT symmetry establishes a connection between reactions involving particles and the time reversal reaction of their antiparticles.
- In particular, implies the equality of masses and widths of particles and antiparticles

Dave Ayres Thesis work and CPT

- CPT symmetry is then, related to fundamental symmetries of nature and therefore it its breakdown is more difficult to conceive than the one of P, C or T.
- But physics is an experimental science and even apparent fundamental symmetries may be broken.
- During his thesis Dave Ayres worked on the ratio of the negatively and positively charged pion masses and lifetimes. Any difference from one in those ratios would indicate, in principle, a violation of CPT.
- He was able to show the proper Lorentz symmetry relation between the lifetime at rest and the one in the relativistic limit

Comparison of π^+ and π^- Lifetimes*

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(Received 28 November 1966)

A check on *CPT* invariance has been made by comparing the lifetimes of the charged pion and its antipion. The fraction of surviving pions in beams of π^+ and π^- which were nearly identical in their spatial and momentum distributions were measured at ten positions along the beam using a liquid-hydrogen differential Čerenkov counter. Over 100 successive π^+-π^--π^+ comparisons were made. Because of the method used, many possible systematic errors which affect an absolute lifetime measurement cancel out in determining the ratio of the lifetimes. The ratio measurement gave $(\tau_+/\tau_-)-1=0.0056\pm0.0028$ and the absolute π^+ lifetime was found to be 26.6 ± 0.2 nsec.

Important Test of CPT Invariance
and Precise Determination of pion lifetime

CHARGED-PION LIFETIME AND A LIMIT ON A FUNDAMENTAL LENGTH*†

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The lifetime of the charged pion has been determined in flight. The agreement of our result, 26.02 ±0.04 nsec, with experiments of comparable precision made with pions at rest provides the most precise verification of time dilation. In the model of Lundberg and Rédei this comparison sets an upper limit on a fundamental length of 3×10^{-15} cm. Using the measurements of velocity and momentum for both π^+ and π^-, we also obtain $m(\pi^+)/m(\pi^-)=1.0002\pm0.0005$.

Fundamental Lorentz and CPT symmetry predictions verified !

Dave also proposed an experiment to perform similar measurements in the Kaon system

Today, the Kaon system provides some of the stringent tests of CPT

CPT violation in Neutral Kaon Sector

- One can start with the Kaon mass and width in the basis $K^0 - \bar{K}^0$

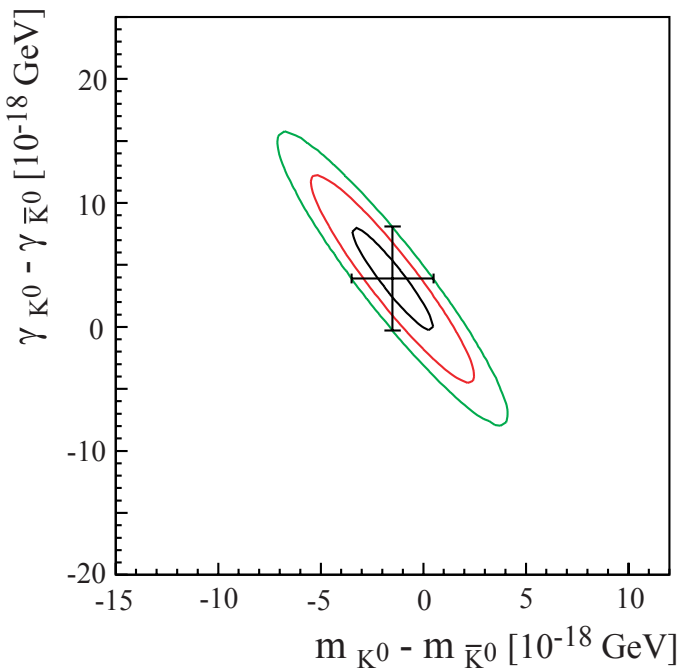
$$\frac{d}{dt}\Psi = -i\Lambda\Psi \ , \qquad \Lambda \equiv M - \frac{i}{2}\Gamma$$

- CPT implies equality of diagonal terms of 2 by 2 matrices

$$\delta = \frac{\Lambda_{\overline{K}^0\overline{K}^0} - \Lambda_{K^0K^0}}{2(\lambda_L - \lambda_S)}$$

Eigenvalues

$$A_{CPT} = \frac{P[\overline{K}^0 \to \overline{K}^0(t)] - P[K^0 \to K^0(t)]}{P[\overline{K}^0 \to \overline{K}^0(t)] + P[K^0 \to K^0(t)]} = 4\mathrm{Re}(\delta)$$



CPT invariance

- Today we know that neither C, nor CP or T are preserved in nature.
- However, there has been no evidence of violation of CPT at a fundamental level
- In particular, masses of all particles and antiparticles we know of are the same within a good precision
- Lorentz symmetry seems to be preserved and all known interactions may be interpreted as the result of local interactions of propagating boson and fermion fields
- If there is a violation of CPT it should be tiny. Any such violation would be transmitted to other sectors of the theory
- It is natural to speculate that any CPT effect will be a product of quantum gravity effects, suppressed by $1/M_{Pl}$. It may be more visible in for instance, mass differences in the neutrino sector, which are themselves See-saw suppressed.
- Let me emphasize that there is no proof I know of, of the necessity of CPT violation by quantum gravity effects.

Implications of CPT in Neutrino Physics

- As stated before, CPT invariance provides a relation between transition rates of particles and antiparticles propagating in the reverse direction of time. For instance, considering neutrino mixing effects

$$\text{CPT invariance} \quad \Longrightarrow \quad P_{\nu_b \to \nu_a}(t) = P_{\bar{\nu}_a \to \bar{\nu}_b}(t).$$

- In general, this is a necessary test of CPT conservation. However, preservation of the above property in certain channels does not rule out CPT violation.

- People have thought of making use of the possible violation of the above identity to solve problems in the neutrino sector, without adding new neutrino species beyond the three conventional ones.

Motivation for CPT Violation

- Part of the motivation to consider CPT violation in neutrinos came from the LSND result (Murayama, Yanagida'00; Barenboim, Lykken '01)
- The need for more than two independent mass differences in a theory with three neutrinos could be fulfilled by CPT violation.
- Today it has been understood the different masses for particles and antiparticles can only be realized by breaking the Lorentz symmetry (Greenberg '02). So, the treatment of taking conventional oscillation formulae with suitable mass differences is not justified a priori.
- Moreover, this hypothesis had been disfavored by the Kamland and Miniboone experiments, as I will explain below.
- But a different implementation of CPT violation in the neutrino sector remains a possibility that must be tested experimentally.

CPT Violation?

H. Murayama

"A desperate remedy…"

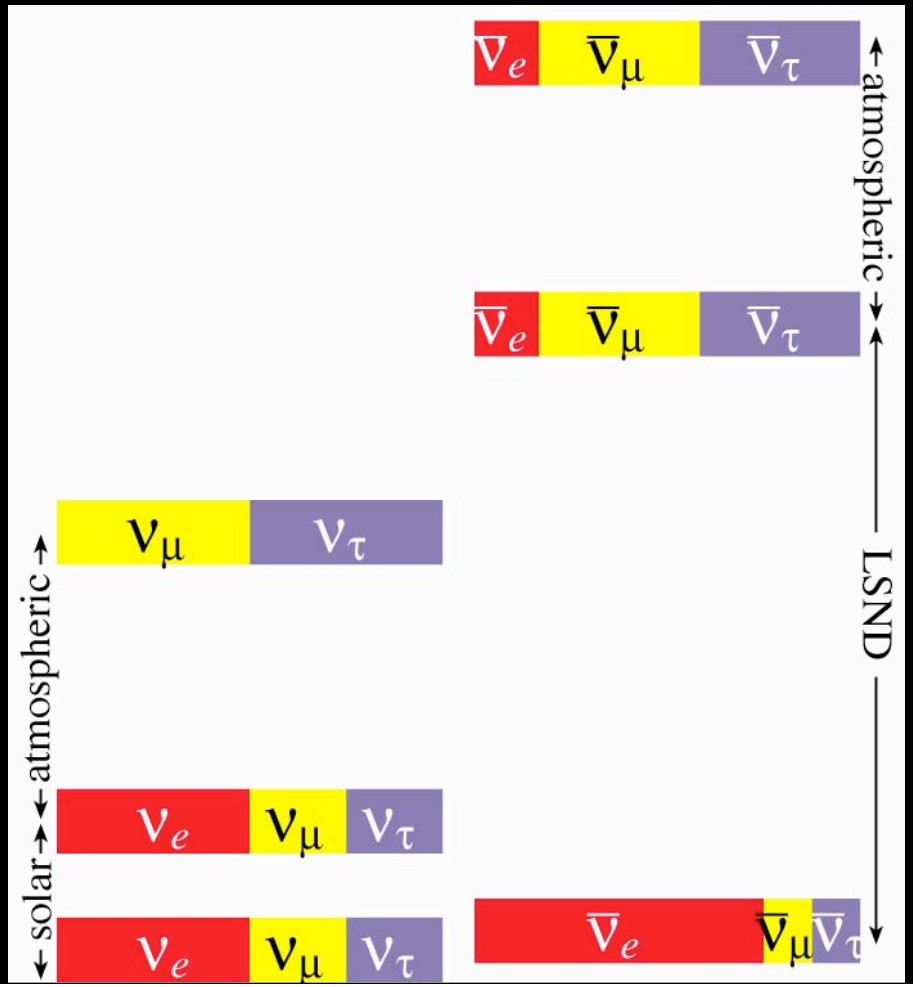
- LSND evidence:

  anti-neutrinos

- Solar evidence:

  neutrinos

- If neutrinos and anti-neutrinos have different mass spectra, atmospheric, solar, LSND accommodated without a sterile neutrino



Old Treatment

- The idea was to consider a hamiltonian that leads to different masses for particles and antiparticles

$$H = \sum_{\vec{p}} \sqrt{p^2 + m^2} a^\dagger a + \sqrt{p^2 + \bar{m}^2} b^\dagger b$$

- This was conceived to be proceeding from a Lorentz invariant theory, but probably not local.

- Different ideas of how to generate this effect, for instance from the interaction of the left-handed neutrinos with a CPT violating right-handed neutrino living in the bulk of extra dimensions. (Barenboim, Lykken, Borissov, Smirnov)

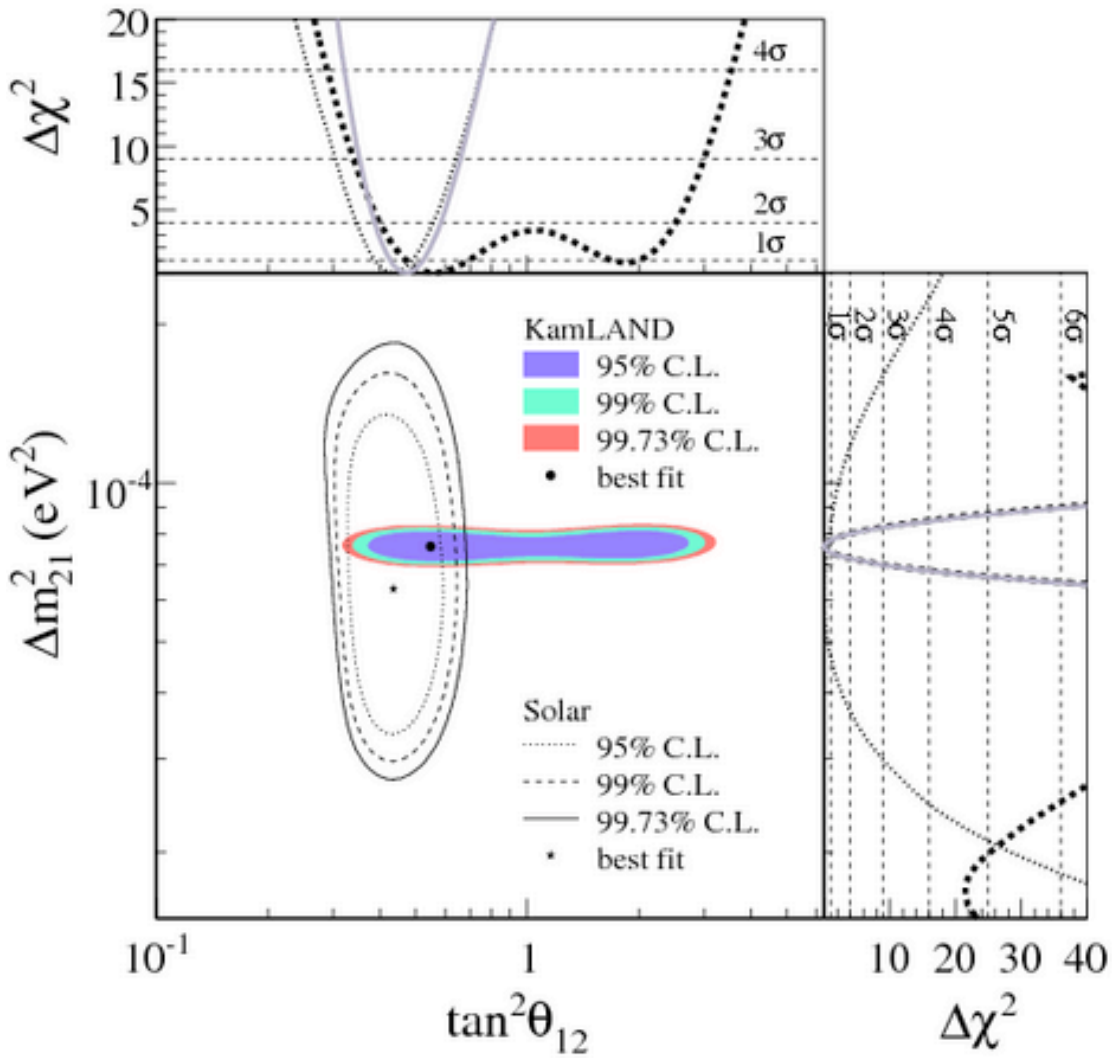
- There is also the intriguing relation linking the bounds in the Kaon system to the indicated LSND range :

$$m_{K^0} - m_{\overline{K}^0} < 0.4 \cdot 10^{-9} \mathrm{eV} \longrightarrow m_{K^0}{}^2 - m_{\overline{K}^0}{}^2 < 0.2 \mathrm{eV}^2$$

Tests of the old idea

- Even if we considered the framework to be theoretically consistent, the demand of different mass differences for particles and antiparticles makes the idea testable at other experiments.
- For instance MiniBoone would not be testing LSND unless it ran in antineutrino mode
- But also, Kamland (reactor anti-neutrino experiment) should not confirm the standard solar oscillation results
- Kamland "confirmed" LMA (Large mixing angle MSW solution) and therefore exluded CPT violation of this particular type.

Kamland Results



Alternative Simple Model of CPT Violation

V. Kostelecky and M. Mewes '03

- A simple CPT and Lorentz violating model may be defined from the following Lagrangian:

$$\mathcal{L} \supset \tfrac{1}{2} i \overline{L}_a \gamma^\mu \overleftrightarrow{D}_\mu L_a - \boxed{(a_L)_{\mu ab} \overline{L}_a \gamma^\mu L_b} + \tfrac{1}{2} i \boxed{(c_L)_{\mu\nu ab} \overline{L}_a \gamma^\mu \overleftrightarrow{D}^\nu L_b}$$

CPT Violation

Lorentz Violation

- No neutrino masses, but preferred vector and tensor directions. The Hamiltonian (energy) defines the dispersion relation

$$(h_{\rm eff})_{ab} = |\vec{p}|\delta_{ab} + \frac{1}{|\vec{p}|}[(a_L)^\mu p_\mu - (c_L)^{\mu\nu} p_\mu p_\nu]_{ab}.$$

- The new coefficients are assumed to be small and to leading order one obtains the usual dispersion relation: $p_\mu = (|\vec{p}|; -\vec{p})$.

- Still, the dispersion relation looks very different from the usual massive neutrino one $E \simeq |\vec{p}| + m^2/(2|\vec{p}|)$

- It is obvious that the new coefficients can induce small differences in the propagation of different neutrino species and hence to oscillations. Observe that while the first leads to no energy dependence, the effects of the second one grow with energy !

Oscillation Effects

- First, the effects are characterized by $a_L L$ and $c_L LE$
- The second important property is directionality. One has to choose the coefficients with values defined by their directions
- Usual choice is to take the sun centered celestial equatorial system, with Z axis along the earth rotation axis and X axis along the vernal equinox
- Then, one can define the coordinates in this system (T, X, Y, Z) or polar coordinates $\hat{p} = (\sin\Theta\cos\Phi, \sin\Theta\sin\Phi, \cos\Theta)$
- Coefficients taken are chosen to minimize large terrestrial effects:

$$(a_L)^Z_{e\mu} = (a_L)^Z_{e\tau} \equiv \check{a}/\sqrt{2}.$$

$$\frac{4}{3}(c_L)^{TT}_{ee} \equiv 2\mathring{c}$$

Oscillation Formulae

$$P_{\nu_e \to \nu_e} = 1 - 4\sin^2\theta\cos^2\theta\sin^2(\Delta_{31}L/2),$$

$$P_{\nu_e \leftrightarrow \nu_\mu} = P_{\nu_e \leftrightarrow \nu_\tau} = 2\sin^2\theta\cos^2\theta\sin^2(\Delta_{31}L/2),$$

$$\begin{aligned}
P_{\nu_\mu \to \nu_\mu} &= P_{\nu_\tau \to \nu_\tau} = 1 - \sin^2\theta\sin^2(\Delta_{21}L/2) \\
&\qquad - \sin^2\theta\cos^2\theta\sin^2(\Delta_{31}L/2) \\
&\qquad - \cos^2\theta\sin^2(\Delta_{32}L/2), \\
P_{\nu_\mu \leftrightarrow \nu_\tau} &= \sin^2\theta\sin^2(\Delta_{21}L/2) \\
&\qquad - \sin^2\theta\cos^2\theta\sin^2(\Delta_{31}L/2) \\
&\qquad + \cos^2\theta\sin^2(\Delta_{32}L/2),
\end{aligned}$$

where

$$\begin{aligned}
\Delta_{21} &= \sqrt{(\mathring{c}E)^2 + (\check{a}\cos\Theta)^2} + \mathring{c}E, \\
\Delta_{31} &= 2\sqrt{(\mathring{c}E)^2 + (\check{a}\cos\Theta)^2}, \\
\Delta_{32} &= \sqrt{(\mathring{c}E)^2 + (\check{a}\cos\Theta)^2} - \mathring{c}E, \\
\sin^2\theta &= \tfrac{1}{2}[1 - \mathring{c}E/\sqrt{(\mathring{c}E)^2 + (\check{a}\cos\Theta)^2}],
\end{aligned}$$

Properties

- The above model shares many properties with the usual CPT conserving model
- At energies above a critical one, $E_0 = |\check{a}|/\mathring{c}$, $\sin^2\theta$ vanishes
- So, muon-tau neutrino conversion is described by the usual maximal mixing formulae, with

$$\Delta_{32} \simeq \check{a}^2 \cos^2\Theta / 2\mathring{c}E.$$

- Even the energy dependence looks like the conventional one, but in this case is induce by a large entry in the Hamiltonian that induces an energy dependent See-saw !
- But it still contains a directional dependence, making the pseudo-mass difference maximal in the north-south celestial direction
- However, for $\Delta m^2_{0^\circ} = 10^{-3}\ \mathrm{eV}^2$ and $E_0 = 0.1\ \mathrm{GeV}$ averaged zenith dependence similar to conventional one

Further Properties

- It can be shown that the solar neutrino data may also be reproduced by this model (Kostelecky and Mewes'03)
- The same is true for the Kamland experiment
- However, long base-line experiments like MINOS, K2K, Opera, Icarus, Nova, T2K, have the ability to test this model
- The reason is that these experiments have beams in different directions and the pseudomass $\Delta m^2_\Theta = \Delta m^2_{0^\circ} \cos^2 \Theta$ depends on it.
- Of course, if all experiments are consistent with a mass difference hypothesis, it is difficult to accept a priori a different, CPT violating framework, to explain the same effects.
- But experiments have the last word, as usual.

Short baseline effects

- In general, for arbitrary Hamiltonian coefficients, there are other interesting effects. For instance, in short baseline experiments, directional effects may be important
- The direction of the neutrino beam will change at the sidereal frequency $\omega_\oplus = 2\pi/(23\ \mathrm{h}\ 56\ \mathrm{min})$
- For instance,

$$P_{\bar{\nu}_\mu \to \bar{\nu}_e} \simeq \frac{L^2}{(\hbar c)^2} | (\mathcal{C})_{\bar{e}\bar{\mu}} + (\mathcal{A}_s)_{\bar{e}\bar{\mu}} \sin \omega_\oplus T_\oplus + (\mathcal{A}_c)_{\bar{e}\bar{\mu}} \cos \omega_\oplus T_\oplus + (\mathcal{B}_s)_{\bar{e}\bar{\mu}} \sin 2\omega_\oplus T_\oplus + (\mathcal{B}_c)_{\bar{e}\bar{\mu}} \cos 2\omega_\oplus T_\oplus |^2$$

- The coefficients have some dependence, which for short baselilne may be just expanded as a constant plus a linear effect in energy. The coefficients in the above equation depend on the directional coefficients of the original hamiltonian in a linear (but complex) way.

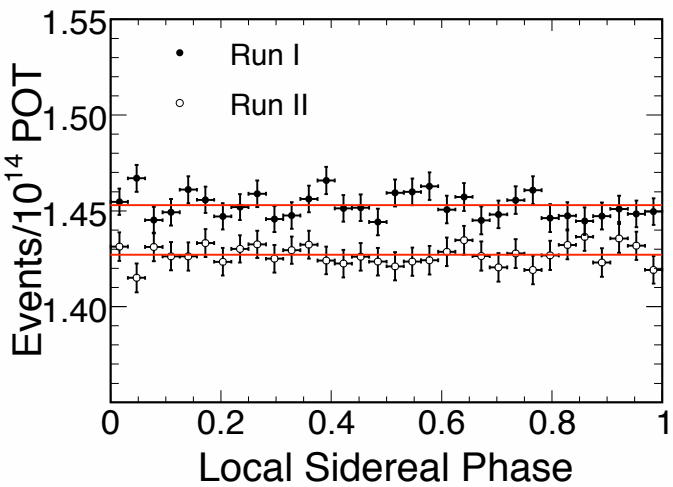
Tests at MINOS near detector

- Tests of possible Lorentz and CPT violation effects were performed at MINOS ND (750 m)
- Two runs

TABLE I: Run Parameters

	CC Events	POT	Run Dates
Run I	1.82×10^6	1.25×10^{20}	May05 – Feb06
Run II	1.62×10^6	1.14×10^{20}	Sept06 – Mar07

- Considering the local sidereal phase $\mathrm{LST} \times (\omega_\oplus / 2\pi)$



Effects consistent with statistical fluctuactions: Limits on Lorentz and CPT violation coefficients

Limits on Lorentz and CPT violating coefficients

Testing Lorentz Invariance and CPT Conservation with NuMI Neutrinos in the MINOS Near Detector

P. Adamson,[9] C. Andreopoulos,[19] K. E. Arms,[15] R. Armstrong,[12] D. J. Auty,[23] D. S. Ayres,[1] B. Baller,[9] G. Barr,[17]

TABLE III: Limits to SME coefficients for $\nu_\mu \to \nu_x$ in terms of the suppression factor $m_W/m_P \sim 10^{-17}$; a_L have units of (GeV) and c_L are unitless.

	$\times 10^{-17}$		$\times 10^{-17}$
a_L^X	3.0×10^{-3}	a_L^Y	3.0×10^{-3}
c_L^{TX}	0.9×10^{-5}	c_L^{TY}	0.9×10^{-5}
c_L^{XX}	5.6×10^{-4}	c_L^{YY}	5.5×10^{-4}
c_L^{XY}	2.7×10^{-4}	c_L^{YZ}	1.2×10^{-4}
c_L^{XZ}	1.3×10^{-4}	–	–

Conclusions

- CPT Violation is related to fundamental symmetries and properties of quantum field theory, and therefore more difficult to violate than C, P or T (all of the violated in the SM).
- No evidence of CPT violation in the well measured Kaon and pion systems
- Suggestion that LSND results may be a result of CPT violation are proven to be wrong
- CPT violation in the neutrino sector should have a more complex implementation than just mass differences between particles and antiparticles
- Searches for CPT violation should, of course, continue. We don't know what the God Nature has designed for us.
- We rely on the insightful view and dedicated work of physicists, like Dave Ayres, to uncover it.