Is nothing sacred?

~~CPT~~ in neutrino physics

Gabriela Barenboim
Fermilab

* The Golden Age of neutrino physics is <u>now</u>

neutrino masses are not just a bunch of new parameters

→ if Majorana, lepton number is not conserved

→ if Dirac masses :

$$\int d^4x \left(\lambda_i \langle H \rangle \bar{\nu}_L^i \nu_R^i + h.c. \right)$$

new hierarchy of Yukawa couplings

new degrees of freedom

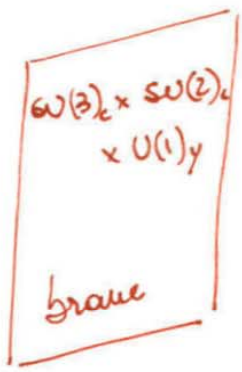
Dirac masses for neutrinos

$\longrightarrow$ right handed neutrinos ν_R^i $\quad i = 1, 2, 3$

$*$ these are <u>singlets</u> under $SU(3)_c \times SU(2)_L \times U(1)_Y$

$\longrightarrow$ messengers of new physics ?

e.g. if SM gauge bosons lie on a brane



$\sim\sim$ gravitons

——— ν_R^i

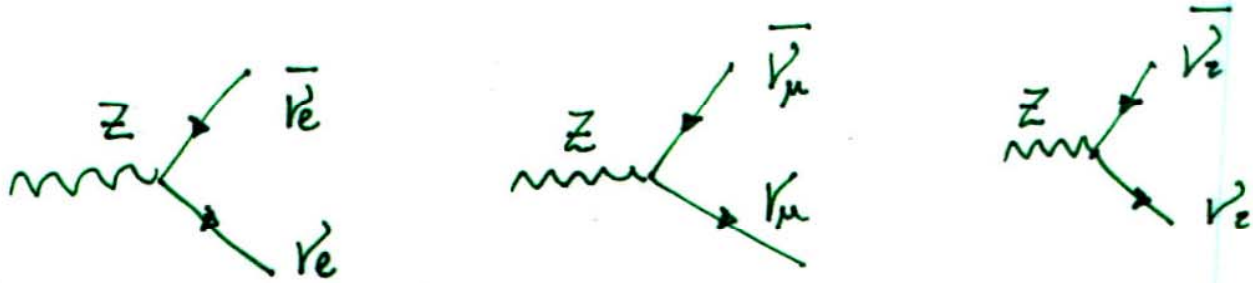
higher dimensional "bulk"

So, <u>especially</u> for gravity and neutrinos, do not assume what you haven't measured

neutrino oscillations

ν oscillations $\longleftrightarrow$ ν masses

LEP



there are three active ν flavours (with $m_\nu < 45$ GeV

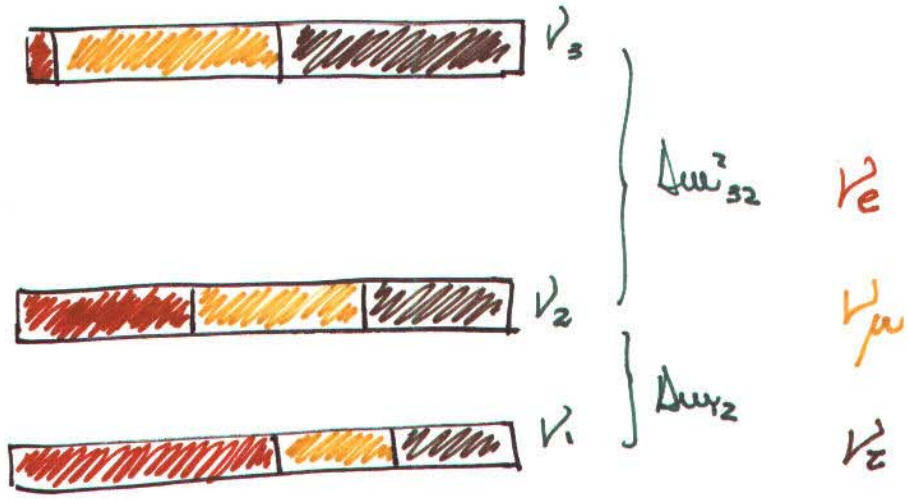
flavour eigenstates $\neq$ mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

mass eigenstates

flavour eigenstates

3x3 unitary matrix



this picture is consistent with three low expts

* CHOOZ : reactor $\bar{\nu}_e$'s stay $\bar{\nu}_e$'s on short baselines $U_{es} \ll 1$

* Super K : 1 GeV ν_μ and $\bar{\nu}_\mu$'s from decay of cosmic ray $\pi^\pm$ have a survival prob. that varies <u>a lot</u> on baselines ~ 1000 km

* SNO : ν_e's from the Sun arrive at the Earth as $1/3$ ν_e's and $(\nu_\mu + \nu_\tau)\,\frac{2}{3}$

A nice consistent picture of ν oscillations

except for one thing ....

LSND

pure beam of $\bar{\nu}_\mu$'s over a short baseline produce

some $\bar{\nu}_e$'s (and wants some $\Delta m^2 \approx 1\,eV^2$!)

But we already used up our two adjustable Δm^2

What is going on here ?

Three possible explanations have been offered ....

1. The LSND expt

is wrong!

→ the Mini BOONE expt at

Fermilab will confirm or disconfirm

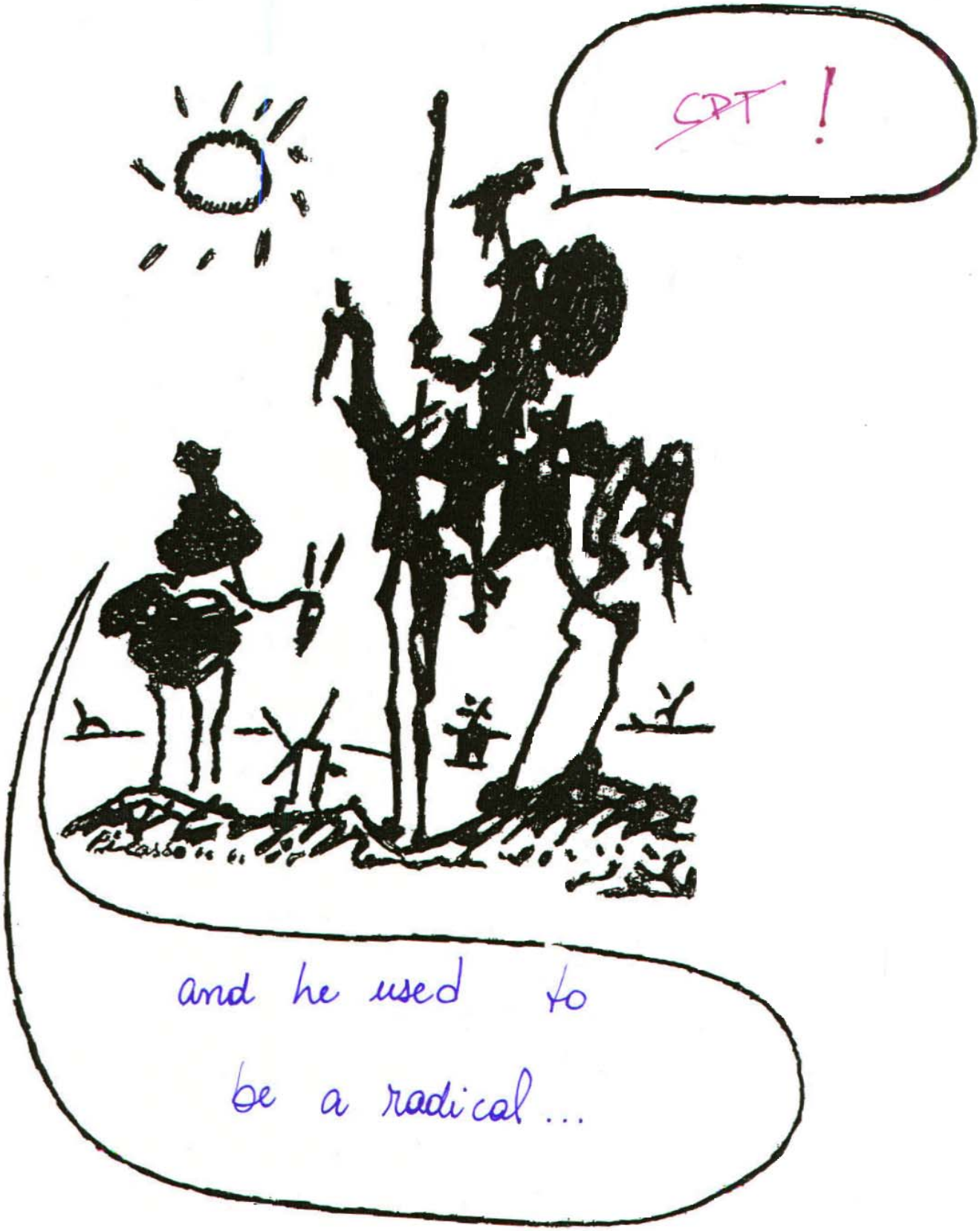
LSND

started running last summer

2. sterile neutrinos

→ disfavored by SNO + Super K

(no new physics explanation fits!)


SPT !
and he used to
be a radical...

3rd explanation

✓ spectrum violates CPT

i.e. neutrinos have different masses from antineutrinos !

seems like a crazy idea, since normally CPT guarantees that antiparticles have the same mass as their partner particle

e.g. Dirac fermions $(i\not{\partial} - m)\psi = 0$

mass term $m\left(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L\right)$ CPT even

particle modes $\psi_+(x) = u_+(p) e^{-ipx}$ $p^2 = m^2$, $p_0 > 0$

antiparticle modes $\psi_-(x) = u_-(p) e^{-ipx}$ $p^2 = m^2$, $p_0 < 0$

where $(\not{p} - m)\, u_\pm(p) = 0$

we usually write $u_+(p) = u(p)$; $u_-(p) = v(-p)$

General solution of the Dirac equ

$$\Psi(x) = \int \frac{d^3p}{(2\pi)^3} \frac{1}{\sqrt{2E_p}} \sum_{s=1,2} \left[a_p^s u^s(p) e^{-ipx} + b_p^{s\dagger} v^s(p) e^{ipx} \right]$$

and

$$H = \int \frac{d^3p}{(2\pi)^3} \sum_s E_p \left(a_p^{s\dagger} a_p^s + b_p^{s\dagger} b_p^s \right)$$

a CPT violating ν mass spectrum would result from a free Hamiltonian like

$$H = \int \frac{d^3p}{(2\pi)^3} \sum_s \left(\sqrt{\vec{p}^2 + m^2}\, a_p^{s\dagger} a_p^s + \sqrt{\vec{p}^2 + \bar{m}^2}\, b_p^{s\dagger} b_p^s \right)$$

$$m \neq \bar{m}$$

→ defines a Lorentz invariant Fock space with unitary time evolution

→ violates CPT, can't come from a local field theory!

Does this crazy idea allow us to explain all existing ν oscillation data?

Yes!

Why does it work?

→ solar ν's are all ν_e's

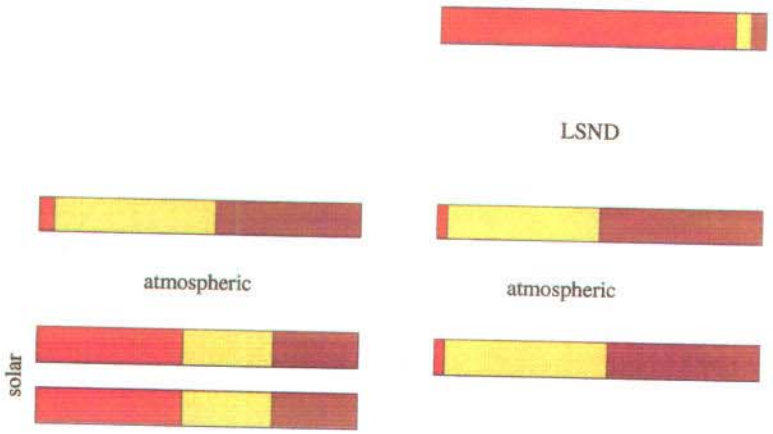
→ atmospheric is a mixture of $\nu_{\mu,e}$ and $\bar{\nu}_{\mu,e}$ (but less sensitive to antineutrinos)

→ reactor ν's are $\bar{\nu}_e$'s

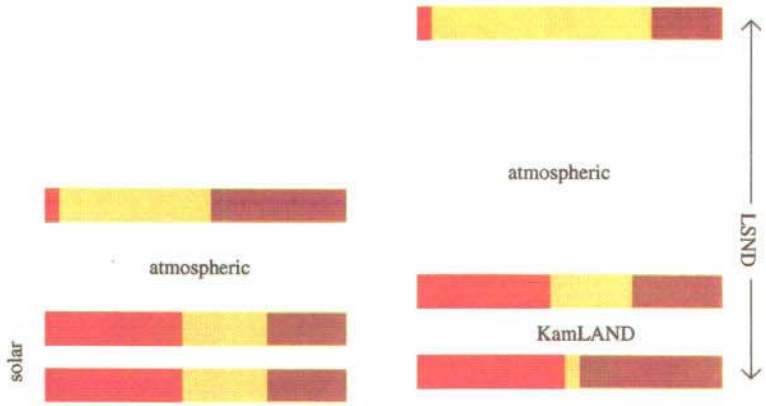
→ LSND is $\bar{\nu}_\mu \to \bar{\nu}_e$

How does it work?

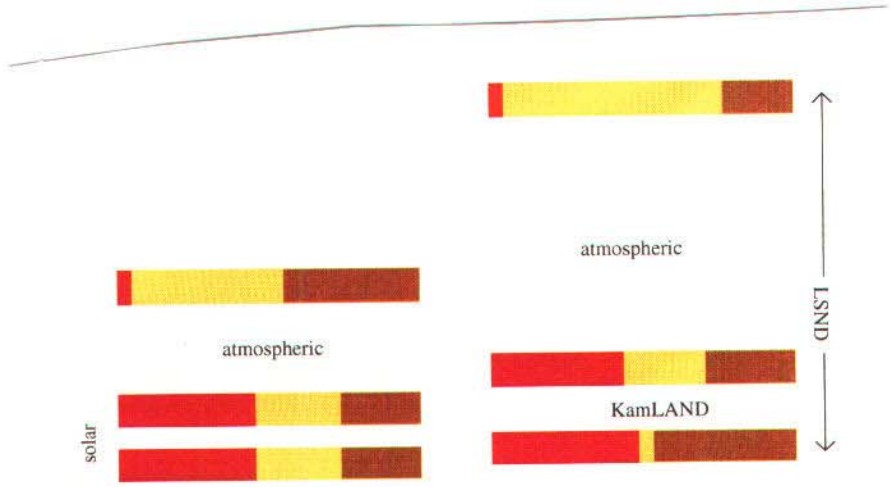
$U_{e3} \cong 1$



$U_{e3} \approx 0$



CPT violating ν spectrum number 2



Key experiments to test this solution

1. Mini BOONE (confirm LSND)

2. Borexino + SNO
   versus Kam LAND

3. MINOS atmospheric

A (field theory!) model of $\not{CPT}$ neutrino masses

The CPT theorem only depends on

→ Lorentz invariance

→ locality

(spin-statistics, vacuum non degeneracy)

3 ways to get $\not{CPT}$

→ explicit Lorentz breaking (bad!)

→ spontaneous Lorentz breaking (dangerous)

→ nonlocality (dangerous because generically will imply breakdown of causality)

Note: we want $\not{CPT}$ only in the neutrino sector of the SM, plus loop effects $\sim \frac{m_\nu^2}{M_Z^2}$

A non local theory of fermions

Any free massive particle obeys the Klein-Gordon equ

$$-\vec{p}^2 + E^2 = m^2$$

for spin 1/2, we can take the square root

Dirac equ $\quad (\not{p} - m) u_\pm(p) = 0$

$$\psi_\pm^0(x) = u_\pm(p)\, e^{-ipx}$$

let's take a different square root

$$\left[\not{p} - m\,\epsilon(p^0)\right] u_\pm(p) = 0$$

$$\epsilon(p^0) = \text{sign of } p^0$$

$$\left[\epsilon(p^0)\right]^2 = 1$$

Dirac theory $\left.\begin{matrix} u_+(p) \\ u_-(p) \end{matrix}\right\}$ are written $\begin{matrix} u(p) \\ v(-p) \end{matrix}$

$$(\not{p} - m)\, u(p) = 0$$

$$(-\not{p} - m)\, v(p) = 0$$

"homeotic" $\psi^h(x)$ $\quad (\not{p} - m)\, u(p) = 0$

$$(\not{p} - m)\, \tilde{u}(p) = 0$$

$$\psi^h(x) = \int \frac{d^3p}{(2\pi)^3} \frac{1}{\sqrt{2E_p}} \sum_s \left[a_p^s\, u^s(p)\, e^{-ipx} + b_p^{s\dagger}\, \tilde{u}^s(p)\, e^{ipx} \right]$$

Dirac eqn is replaced by

$$i \not{\partial}\, \psi^h(x) = \frac{-im}{\pi} \int dt' \frac{1}{t - t'}\, \psi^h(t', \vec{x})$$

The action of the free homeotic theory is nonlocal

(too bad ?)

no! remember that $\left\{ a_{\vec{p}}^{r}, a_{\vec{q}}^{s+} \right\} = \left\{ b_{\vec{p}}^{r}, b_{\vec{q}}^{s+} \right\} = (2\pi)^3 \delta^3(\vec{p}-\vec{q}) \delta^{rs}$

and

$$H = \int \frac{d^3p}{(2\pi)^3} \sum_s E_p \left(a_p^{s+} a_p^s + b_p^{s+} b_p^s \right)$$

and

$$Q = \int \frac{d^3p}{(2\pi)^3} \sum_s \left(a_p^{s+} a_p^s - b_p^{s+} b_p^s \right)$$

is a conserved charge from the global $U(1)$ symmetry of the action

and the theory is Lorentz invariant !

So far we have done nothing

the free Dirac theory $\equiv$ free homeotic theory

in fact

there is a transformation

$$\psi^h(x) = O \cdot \psi^D(x)$$

such that the non local action collapses

back to

$$\int d^4x \; \bar{\psi}^D_{(x)} (\not{\partial} - m) \psi^D(x)$$

but ...

although CPT is conserved ....

→ CPT operator is γ_5 acting on Dirac spinors

but it is $\gamma_2 \gamma_5$ on homeotic spinors

→ homeotic spinors are noncanonical

$$\left\{ \psi^{h+}_{aL}(x), \psi^{h}_{bL}(y) \right\}_{ET} = \delta^3(x-y)\, \delta_{ab}$$

$$\left\{ \psi^{h+}_{aR}(x), \psi^{h}_{bR}(y) \right\}_{ET} = \delta^3(x-y)\, \delta_{ab}$$

$$\left\{ \psi^{h+}_{aL}(x), \psi^{h}_{bR}(y) \right\}_{ET} = m\, \underbrace{D(x-y)}_{\int \frac{d^3p}{(2\pi)^3} \frac{1}{2E} e^{-ip(x-y)}}\, \gamma^0_{ab}$$

The Trick

couple a left-handed Dirac spinor to a right-handed homeotic spinor

$$m_{\cancel{CPT}} \int d^4x \left(\overline{\Psi}_L^D(x) \cdot \Psi_R^h(x) + h.c. \right)$$

This is a $\cancel{CPT}$ mass for neutrinos

→ the ν_L^i of the SM are standard Dirac Weyl (they must be!)

→ ν_R is a SM singlet so it is our "natural" candidate to be different

or if you like, this is just a trick for writing nonlocal but causal couplings that break CPT

in such a scenario, a mass term

$$m\left(\bar{\nu}_L^{D}\,\nu_R^{h} + \bar{\nu}_R^{h}\,\nu_L^{D}\right)$$

is hermitian but violates CPT !!

gives

$$2m\; a_p^{D+} a_p^{h} + 2E_p\; a_p^{D+} b_{-p}^{h+} + h.c$$

compared to Dirac mass term

$$m\; a_p^{+D} a_p^{0} + m\; b_p^{D+} b_p^{D}$$

Parting thoughts

→ There is room for big surprises in neutrino physics

- LSND / MiniBOONE
- Borexino
- SK - K2K

⋮

→ Making models of CPT violation stretches our understanding of quantum field theory