Questions and answers - Kendall Mahn Lecture

The following questions were submitted through Google Form. Some / all may have been answered in the Q&A session already. Nevertheless, we request our lecturers to provide written answers here for the benefit of those who could not attend that session. Thank you!

KM: Extra slides added to backup and uploaded to indico

Slide 26: Can you explain more why oscillation physics is independent of the Dirac/Majorana nature of the neutrino.

From the magnificent Michael Peskin: The “Majorana phases” in the neutrino mass matrix appear only in chirality-violating processes.
In long-baseline experiments, the production and detection of neutrinos both occur by weak current, which are chirality conserving. Thus, these phases must cancel out. To detect these phases, it is essential to have a chirality-violating process, such as neutrino-neutrino annihilation thorough the Majorana mass.

Practically, we see this In the oscillation probability-- it’s U U* combinations. When U -> U*, the phase terms on the diagonal, $e^{-i\,eta1}$, will go to $e^{-i\,eta1}$
so , then the two multiply to become 1, and a unitary matrix. No observable :(

Page 21. Which of the mass states does Katrin measure?

Added to p22. Indeed, the beta decay -- electrons are produced with electron (anti)neutrinos. So, it’s not a ‘definite’ mass state, but the mass of the state which corresponds to the electron flavor, or:

$$m_\beta^2 = \sum_i |U_{ei}|^2 m_i^2 .$$

More fun details in *Snowmass topical group on neutrino properties*

Page 5. What are Dirac or Majorana neutrino masses?

Great question! Michael Peskin kindly prepared some extra slides.

How to write a Lagrangian for neutrino mass:

Begin with

$$\mathcal{L} = \sum_j \overline{\psi}_j (i \not\partial) \psi_j - \quad ?$$

What terms without derivatives are allowed ?

Recall that the 4-component Dirac fermion is a reducible representation of the Lorentz group,

$$\Psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix} \qquad S^{\mu\nu} = \frac{i}{4}[\gamma^\mu, \gamma^\nu] = \begin{pmatrix} \sigma^{\mu\nu} & 0 \\ 0 & \overline{\sigma}^{\mu\nu} \end{pmatrix}$$

so ψ_L, ψ_R are independent fields. The kinetic term splits

$$\mathcal{L} = \psi_L^\dagger i\overline{\sigma}^\mu \partial_\mu \psi_L + \psi_R^\dagger \sigma^\mu \partial_\mu \psi_R$$

The two representations are complex conjugates of one another, that is

$\psi'_L = i\sigma^2 \psi_R^*$ transforms like ψ_L

In this language, the usual Dirac mass term is

$$\overline{\Psi}\Psi = \psi_R^\dagger \psi_L + h.c. = \epsilon_{ab} \psi'_a \psi_b + h.c.$$

x

If Ψ has lepton number L = 1, ψ_L has L = 1, but ψ'_L has L = -1. Then the usual Dirac mass term conserves L.

The most general fermion mass term is

$$M_{jk} \epsilon_{ab} \psi^j_a \psi^k_b + h.c.$$

where M_{ij} is a symmetric matrix. If M_{ij} pairs L = 1 fields with L = -1 fields, this is a "Dirac mass" and L is conserved. However, there is another possibility. The most striking case is with one chiral fermion

$$m \epsilon_{ab} \psi_a \psi_b + h.c.$$

This is the "Majorana mass". The physical fermion has 2 states, with +1/2 and -1/2 helicity. The -1/2 state is (mostly) a fermion, but the +1/2 state is mostly its antiparticle, an antifermion. L is not conserved.

In the Standard Model, ν_R has zero quantum numbers and can be omitted from the theory.

If neutrinos are massive, there are 3 possibilities:

1. ν_R does not exist; then all neutrino masses are Majorana. Also L is not conserved. The neutrino mass term needs 2 Higgs fields.

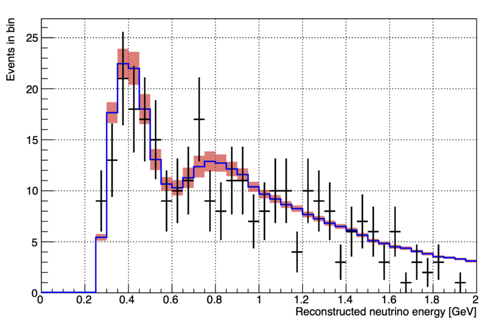
2. Neutrino masses are Dirac and and L is conserved. The mass term can come, as for quarks, from the Yukawa coupling to the Higgs.

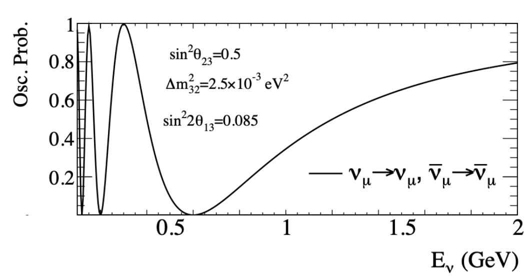
3. ν_R has both Majorana M and Dirac mass terms. The Majorana mass violates L but does not violate the SM gauge symmetries, so it can be very large: $M \gg m$. Then the masses are effectively Majorana, with

$$m(\nu_L) \sim m^2/M$$

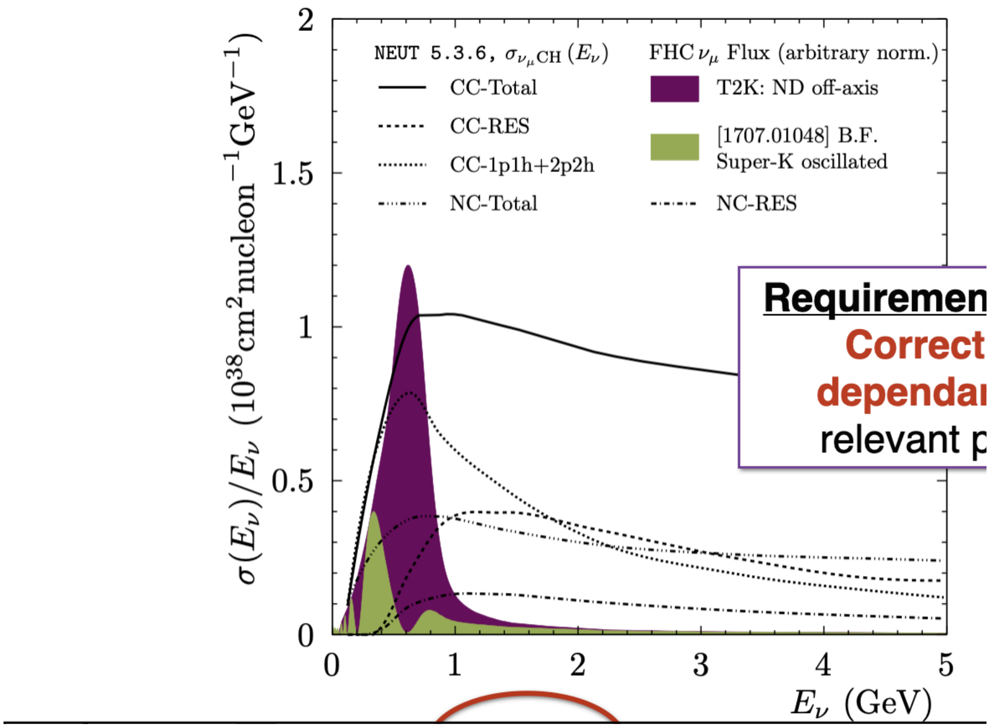
This is the seesaw mechanism of Yanagida and Gell-Mann, Ramond, and Slansky.

Page 41. Should the two distributions on the left have the same shape? You have explained that beams are not mono-energetic, and we need to smear over energy. It does not look like enough to explain the difference.





I think it's these two figures, right?
First, we are convolving the neutrino flux with the oscillation probability:



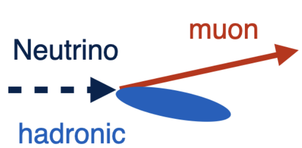
The above is the flux x osc prob, and we see the flux creates the low side falling edge of the T2K event rate.

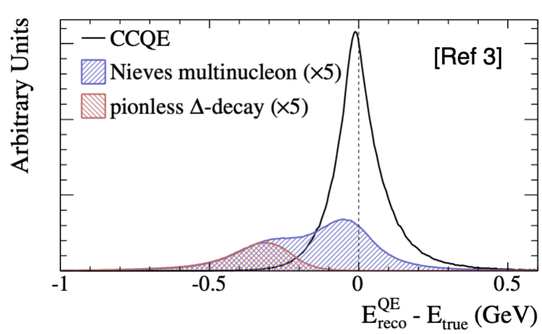
Then, to form an event rate, we multiply by cross section. See the cross section (divided by energy!) rises rapidly and then becomes flat e.g. the cross section is rising with energy.

Finally, the energy estimator is quite important:

$$E_\nu^{QE} = \frac{m_p^2 - m_n'^2 - m_\mu^2 + 2m'_n E_\mu}{2(m'_n - E_\mu + p_\mu \cos\theta_\mu)} \qquad E_\nu = E_\mu + \sum E_{hadronic}$$

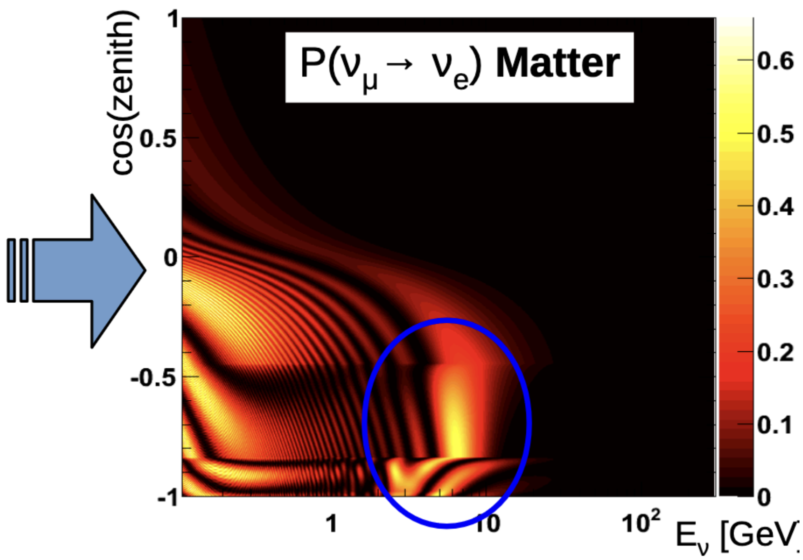
- Nuclear effects bias true and estimated neutrino energy





T2K 'assumes' simple QE kinematics, but processes at higher energy (2p2h, multinucleon) are reconstructed at lower energies. This bias creates a fill in in our 'dip' region; if we had no such backgrounds or the estimator was perfect, then the dip would go to zero.

Page 52. Question about the right figure. What are the reasons for the abrupt changes at certain values of zenith angle?



Alex Friedland to the rescue! The abrupt lines are the earths core, where the density is much different from the crust and markedly affect the matter effect (and, Kendall guess? the resonance breaks down?).

Page 73. Question about search for K+ -> l+ N. Don't kaon beams have much higher intensity of K+ and therefore be more sensitive?

The T2K beam is really intense! We just hit new beam records recently. Our decay volume is water cooled from the intensity of mesons produced. In addition, we have low mass time projection chambers in a magnetic field, which provide excellent sign selection and particle identification, both important when looking for anomalous signatures like HNL. Finally, the MicroBooNE experiment has also set relevant limits.