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Neutrino SuperBeams at Fermilab

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ABSTRACT

In this talk I will give a brief description of long baseline neutrino physics, the LBNE experiment and Project X at Fermilab.

1. Flavor content of the massive neutrinos

Traditionally the neutrino mass eigenstates, ν_1, ν_2 and ν_3, have been labelled such that:

$$\nu_e \text{ component of } \nu_1 \quad > \quad \nu_e \text{ component of } \nu_2 \quad > \quad \nu_e \text{ component of } \nu_3.$$

See Fig. 1 for the current information on the neutrino mass.

Therefore, the PMNS matrix elements for the ν_e flavor satisfy $|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$ and since the only elements that have been measured by experiment so far are $|U_{e2}|^2$, $|U_{e3}|^2$ and $|U_{\mu 3}|^2$, it is useful to choose a representation of this mixing matrix such that these elements are given approximately by the sine of a mixing angle,

$$\begin{aligned}
\sin^2\theta_{13} &\equiv |U_{e3}|^2, \\
\sin^2\theta_{12} &\equiv \frac{|U_{e2}|^2}{(1-|U_{e3}|^2)} \approx |U_{e2}|^2, \\
\sin^2\theta_{23} &\equiv \frac{|U_{\mu 3}|^2}{(1-|U_{e3}|^2)} \approx |U_{\mu 3}|^2
\end{aligned}$$

this is standard representation found in the PDG. The $\approx$ follows from the fact that we know that $|U_{e3}|^2 << 1$.

At 2σ we have the following experimental limits, see Fig. 2:

$$\begin{aligned}
\sin^2\theta_{13} &< 0.04 \quad \approx \left(\frac{\delta m^2_{21}}{\delta m^2_{31}}\right)^1 \\
|\sin^2\theta_{12} - \frac{1}{3}| &< 0.04 \quad \approx \left(\frac{\delta m^2_{21}}{\delta m^2_{31}}\right)^1 \\
|\sin^2\theta_{23} - \frac{1}{2}| &< 0.12 \quad \approx \left(\frac{\delta m^2_{21}}{\delta m^2_{31}}\right)^{0.6}
\end{aligned} \tag{1}$$

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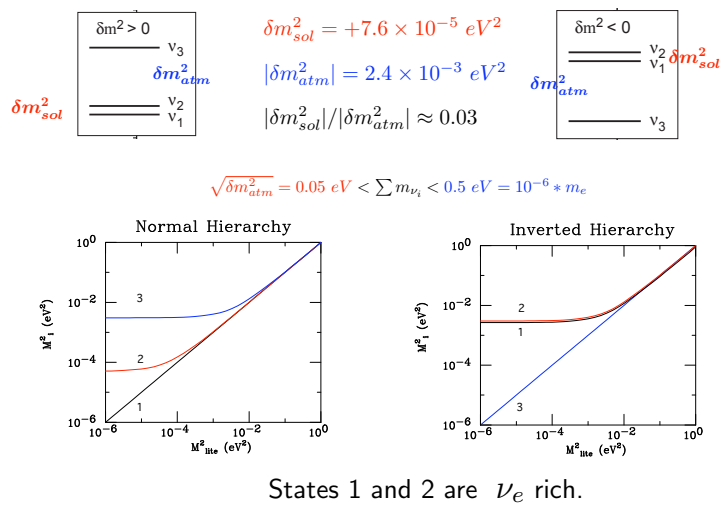

Figure 1: What is known about the mass of the neutrino.

where I have compared the size of the uncertainties to another small number appearing in the neutrino sector, the ratio of solar δm^2, δm^2_{21}, to the atmospheric δm^2, δm^2_{31}. The ratio $\delta m^2_{21}/\delta m^2_{31} \approx 0.03$.

The point in parameter space such that $(\sin^2\theta_{13},\ \sin^2\theta_{12},\ \sin^2\theta_{23}) = (0,\ \frac{1}{3},\ \frac{1}{2})$ is known as Tri-Bimaximal mixing, [1] & [2], and it is clear from Eq. (1) that nature has chosen a point close to tribimaximal mixing. Is this an accident or is it some kind of symmetry? To answer this question one needs to experimentally push on the limits in Eq. (1) to

$$\left(\frac{\delta m^2_{21}}{\delta m^2_{31}}\right)^n$$

where n=2 as the next round of experiments but eventually to high powers. It's

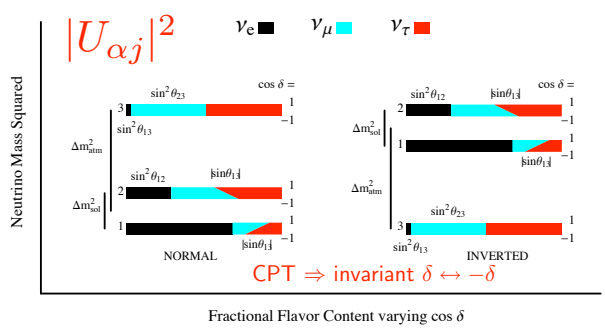

Figure 2: The flavor content of the neutrino mass eigenstates[3]. The width of the lines is used to show how these fractions change as $\cos\delta_{CP}$ varies from -1 to +1. Of course, this figure must be the same for neutrinos and anti-neutrinos if CPT is conserved.

possible the symmetry is not exact and there is some breaking about this tribimaximal point, then one would expect the deviations from tribimaximal to be related to one another by some small parameter. What is this small parameter and what are the relationships? In many ways this puzzle is much like determining the rules of chess when one has only been given a particular end game.

2. Long Baseline Physics: $\nu_\mu \longrightarrow \nu_e$

The amplitude for $\nu_\mu \to \nu_e$ can be simple written a sum of three amplitudes, one associated with each neutrino mass eigenstate,

$$U^*_{\mu 1} e^{-i m_1^2 L/2E} U_{e1} + U^*_{\mu 2} e^{-i m_2^2 L/2E} U_{e2} + U^*_{\mu 3} e^{-i m_3^2 L/2E} U_{e3}.$$

The first term can be eliminated using the unitarity of the MNS matrix and thus the appearance probability can be written as follows[4)]

$$P(\nu_\mu \to \nu_e) \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}} \right|^2 . \tag{2}$$

Δ_{jk} is used as a shorthand for the the kinematic phase, $\delta m^2_{jk} L/4E$. As the notation suggests the amplitude $\sqrt{P_{atm}}$ only depends on δm^2_{31} and $\sqrt{P_{sol}}$ only depends on δm^2_{21}. For propagation in the matter, these amplitudes are simple given by

$$\begin{aligned} \sqrt{P_{atm}} &= \sin\theta_{23} \ \sin 2\theta_{13} \ \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \ \Delta_{31} \\ \sqrt{P_{sol}} &= \cos\theta_{23} \ \sin 2\theta_{12} \ \frac{\sin(aL)}{(aL)} \ \Delta_{21}. \end{aligned} \tag{3}$$

The matter potential is given by $a = G_F N_e/\sqrt{2} \approx (4000\ km)^{-1}$ and the sign of Δ_{31} (and Δ_{32}) determines the hierarchy; normal $\Delta_{31} > 0$ whereas inverted $\Delta_{31} < 0$. When a is set to zero one recovers the vacuum result. See Fig.3 [5)].

For anti-neutrinos $a \to -a$ and $\delta \to -\delta$. Thus the phase between $\sqrt{P_{atm}}$ and $\sqrt{P_{sol}}$ changes from $(\Delta_{32} + \delta)$ to $(\Delta_{32} - \delta)$. This changes the interference term from

$$2\sqrt{P_{atm}}\sqrt{P_{sol}} \cos(\Delta_{32} + \delta) \ \Rightarrow \ 2\sqrt{P_{atm}}\sqrt{P_{sol}} \cos(\Delta_{32} - \delta). \tag{4}$$

Expanding $\cos(\Delta_{32} \pm \delta)$, one has a CP conserving part $2\sqrt{P_{atm}}\sqrt{P_{sol}} \cos\Delta_{32} \cos\delta$ and the CP violating part

$$\mp 2\sqrt{P_{atm}}\sqrt{P_{sol}} \sin\Delta_{32} \sin\delta. \tag{5}$$

Therefore CP violation is maximum when $\Delta_{32} = (2n+1)\frac{\pi}{2}$ and grows as n grows. Notice also, that for this term to be non-zero the kinematical phase Δ_{32} cannot be $n\pi$. This is the neutrino counter part to the non-zero strong phase requirement for CP violation in the quark sector.

The asymmetry between $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ is a maximum when $\sqrt{P_{atm}} = \sqrt{P_{sol}}$. At the first oscillation maximum, $\Delta_{31} = \pi/2$, this occurs when $\sin^2 2\theta_{13} = 0.002$ in vacuum. For values of $\sin^2 2\theta_{13} < 0.002$ the oscillation probabilities are dominated by P_{sol} and thus observing the effects of non-zero $\sin^2 2\theta_{13}$ become increasing more challenging.

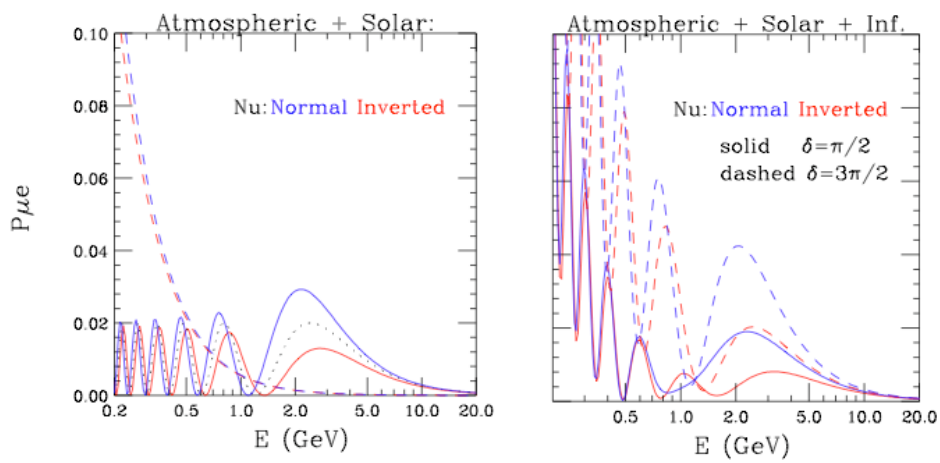

Figure 3: The left panel shows the two components P_{atm} and P_{sol} in matter for the normal and inverted hierarchies for $\sin^2 2\theta_{13} = 0.04$ and a baseline of 1200 km. The right panel shows the total probability including the interference term between the two components for various values of the CP phase δ for the neutrino. Notice that the coherent sum of two amplitudes shows a rich structure depending on the hierarchy and value of CP phase. These curves can also be interpreted as anti-neutrino probabilities if one interchanges the hierarchy AND the values of the CP phase.

2.1. Magic and Bi-magic Baselines:

The magic baselines occurs when

$$\begin{aligned} \sqrt{P_{sol}} &= 0 \\ \text{i.e.} \quad aL = (n+1)\pi \quad &\text{for} \quad n = 0, 1, 2, \ldots \end{aligned}$$

for the earth densities this occurs for L=7500 km. Then the $P(\nu_\mu \to \nu_e)$ is given by

$$P(\nu_\mu \to \nu_e) = P_{atm}$$

which only depends on the θ_{13} and the hierarchy. So at this baseline there is no sensitivity to CP violation.

The bi-magic baseline is when $\sqrt{P_{atm}}$ is maximum for one hierarchy and zero for the other hierarchy.

$$P_{atm}|_{IH} = 0 \text{ and } P_{atm}|_{NH} \text{ is max. at } E_{IH}$$
$$\text{and}$$
$$P_{atm}|_{NH} = 0 \text{ and } P_{atm}|_{IH} \text{ is max. at } E_{NH}$$

With earth densities this occurs for a baseline of 2540 km and E_{IH}=3.3 GeV and E_{NH}=1.9 GeV (flip when ν and $\bar{\nu}$ interchange). This is approximately the Fermilab to Yucca Mtn. baseline!

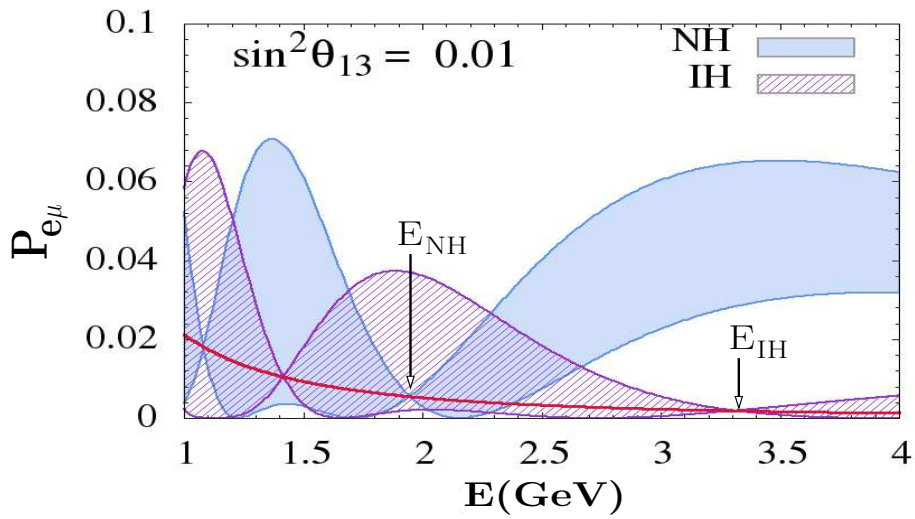

Figure 4: Oscillation probabilities at the Bi-magic baseline where there is maximum separation between the hierarchy at certain energies.

3. Long Baseline Neutrino Experiment (LBNE)

LBNE is a new neutrino experiment more than a 1000 km from Fermilab in a westerly direction, see ref. [7]. The most likely site for this experiment is DUSEL at the Homestake Mine which is 1300km from Fermilab. Given the uncertainties of DUSEL, possible alternative sites that have been considered and their distances from Fermilab are Henderson Mine (1300 km), WIPP (1500 km) and Yucca Mountain (2300 km).

The far LBNE detector would be on-axis either as a 100 kton water Cerenkov detector similar to SuperK or a 17 kton Liquid Argon (LAr) TPC detector. Given the extra sensitivity and π^0 background rejection capabilities of LAr especially for ν_e events, the physics reach of these two detectors is expected to be approximately equal. A new beamline at Fermilab would be required for this experiment. Initially it would be powered by the current proton accelerators at Fermilab with a power of 700kW protons on target. However, the traditional facilities would be designed to handle the 2MW of power possible from the proposed Project X. A suite of precision near detectors would also be required so as to measure the neutrino beam with unprecedented precision.

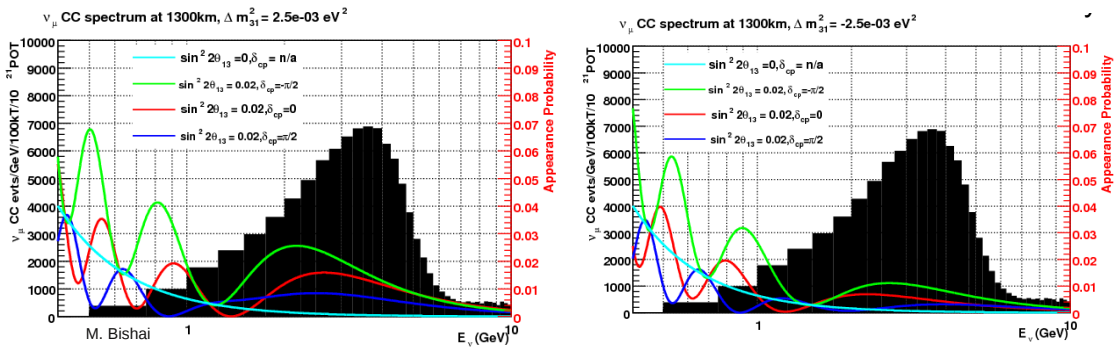

Figure 5: Beam profile with oscillation probabilities.

The water cerenkov detector could be built with little R&D but would have to be larger than LAr due to it's lower efficiency. Whereas substantial R&D is required for a large LAr TPC but this technology has a higher efficiency than water cervenkov due to it's better discrimination of electron and gamma (π^0) events. LAr also has a enhanced sensitivity to proton decay in the $K^+\nu$ channel over water Cerenkov which also makes it an attractive alternative assuming a successful R&D program. If affordable, a combination of both detectors would be very powerful.

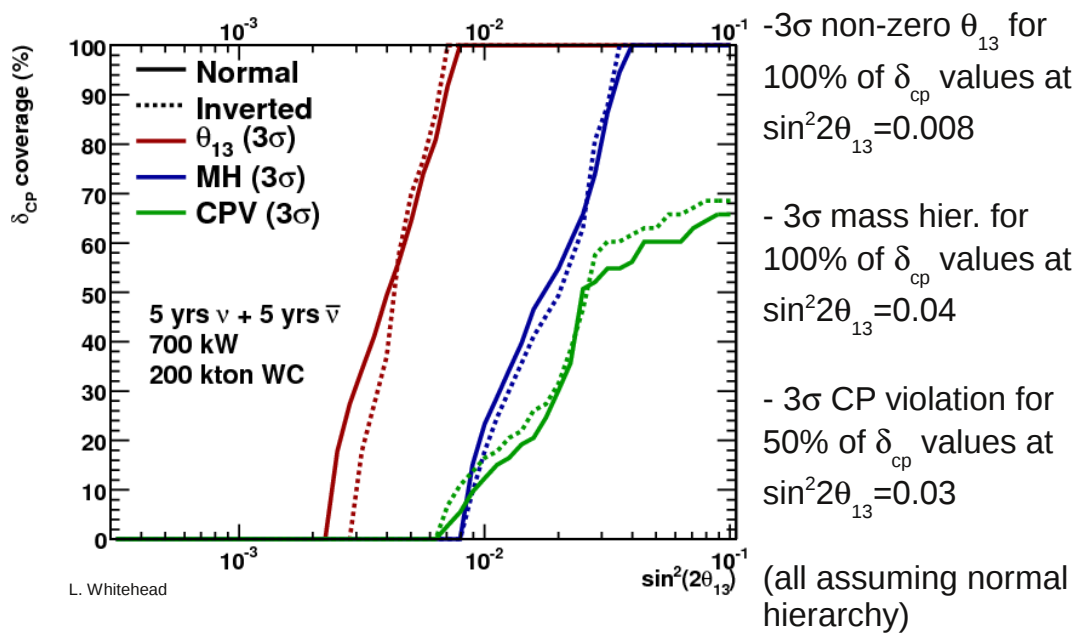

Figure 6: Physics reach of LBNE.

4. Project X and Neutrinos

Project X is the generic name given to a new intense proton source at Fermilab, see ref. [8]. The requirements for Project X are as follows:

- A neutrino beam for long baseline neutrino oscillation experiments 2 MW proton source at 60-120 GeV
- High intensity, low energy protons for kaon and muon based precision experiments Operations simultaneous with the neutrino program
- A path toward a muon source for possible future Neutrino Factory and/or a Muon Collider Requires ∼4 MW at ∼5-15 GeV
- Possible missions beyond P5 Standard Model Tests with nuclei and energy applications

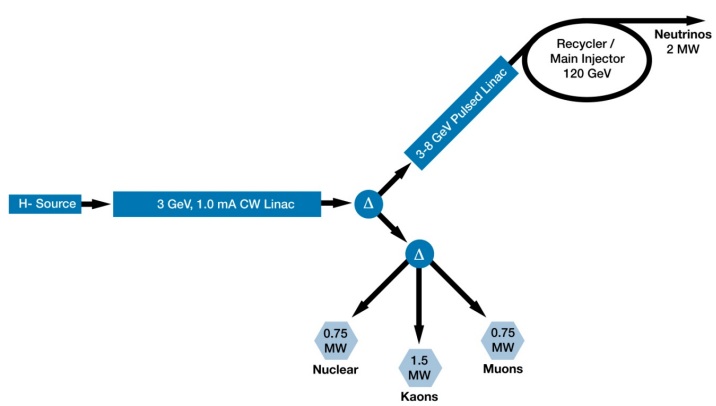

Figure 7: Sketch of the layout of Project X

These are achieved by the following machines:

- 3 GeV CW superconducting H- linac with 1 mA average beam current:
  - Flexible provision for variable beam structures to multiple users (CW at time scales >1 μsec, 10% DF at < 1 μsec)
  - Supports rare processes programs at 3 GeV
  - Provision for 1 GeV extraction for nuclear energy program
- 3-8 GeV pulsed linac capable of delivering 300 kW at 8 GeV:

- Supports the neutrino program
- Establishes a path toward a muon based facility
- Upgrades to the Recycler and Main Injector to provide > 2 MW to the neutrino production target at 60-120 GeV.

Utilization of a CW linac creates a facility that is unique in the world, with performance that cannot be matched in a synchrotron-based facility.

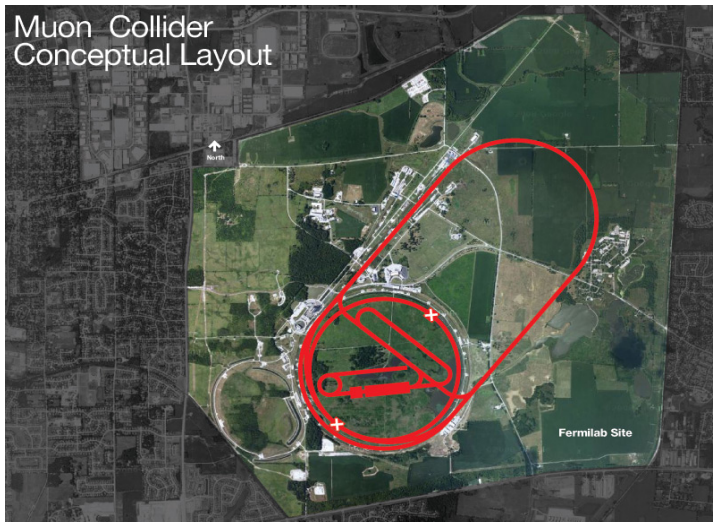

Figure 8: Neutrino Factory / Muon Collider on the Fermilab site.

4.1. Joint Project X/ Neutrino Factory / Muon Collider Strategy:

Project X shares many features with the proton driver required for a Neutrino Factory or Muon Collider

- NF and MC require ∼4 MW @ 10±5 GeV
- Primary issues are related to beam format
- NF wants proton beam on target consolidated in a few bunches; Muon Collider requires single bunch
- Project X linac is not capable of delivering this format

It is inevitable that a new ring(s) will be required to produce the correct beam format for targeting.

5. Summary and Conclusions

A brief outline of the physics of long baseline neutrino experiments, LBNE and Project X at Fermilab is given in this talk.

6. Acknowledgements

I thank Prof. Milla Baldo-Ceolin for organizing this wonderfully workshop for many, many years and the current organizers for continuing this wonderful tradition.

7. References

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