Phenomenology of FUTURE LBL experiments

LECTURE I

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1. The present knowledge on lepton mixing

We consider the Dirac mass term m_D of a general neutrino mass lagrangian, only.

Pontecorvo-Maki-Nakagawa-Sakata:

$$\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{ATMOSPHERIC}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{CONNECTION}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{SOLAR}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\phi_1} & 0 \\ 0 & 0 & e^{i\phi_2} \end{pmatrix}}_{\text{MAJORANA PHASES}}$$

Free independent parameters in oscillation phenomena:

$$\begin{cases} \Delta m^2_{ATM}, \ \Delta m^2_{SOL} \\ \theta_{12}, \theta_{13}, \theta_{23} \\ \delta \end{cases}$$

A recent GLOBAL ANALYSIS of existing data gives:

$$\begin{cases} \theta_{12} = 34^\circ \\ \theta_{23} = 42^\circ \quad (\theta_{23} \in [36^\circ, 52^\circ] \text{ at } 2\sigma) \\ \theta_{13} = 5^\circ \quad (\theta_{13} \in [0^\circ, 10^\circ] \text{ at } 2\sigma) \end{cases}$$

$$\begin{cases} \Delta m^2_{SOL} = 7.9 \times 10^{-5}\ eV^2 \\ \Delta m^2_{ATM} = 2.4 \times 10^{-3}\ eV^2 \end{cases}$$

Fogli, Lisi, Marrone, Palazzo, hep-ph/0506083

UNKNOWNS:

1) θ_{13} is non-zero?

2) θ_{23} is non-maximal?
   which is the θ_{23}-octant?

3) $\Delta m^2_{ATM} > 0$ OR $\Delta m^2_{ATM} < 0$?

4) LEPTONIC CP-VIOLATION OCCURS?
   ($\theta_{13} \neq 0$ AND $\delta \neq 0$)

2. Physical interest of the unknowns

First of all, remember that we have been measuring the

CKM matrix elements

for APPROX 40 YEARS and only now (with BaBar and Belle) we have pin down the hadronic CP-violating phase.

However, we have more than the

INTEREST in measuring the SM parameters:

the CKM/PMNS matrix elements are key ingredients to solve the

FLAVOUR PROBLEM

i.e. $\boxed{\text{why fermion masses in the SM are what they are ?}}$

$\Downarrow$

$\boxed{\text{is there a theory of Yukawa couplings ?}}$

In most of TEXTURE MODELS the two SMALL PARAMETERS

$$\boxed{\sin\theta_{13}\,,\ \frac{1}{\sqrt{2}}-\sin\theta_{23}\ \sim \epsilon}$$

are SMALL BUT NOT VANISHING.

Looking for the value of θ_{13} and for deviation of θ_{23} from maximality is crucial for model building.

The NEUTRINO MASS HIERARCHY is important, for instance, in

COSMOLOGY

From cosmological bounds we have

$$\sum_i m_i \leqslant 1\ \mathrm{eV}$$

but from oscillations we know that at least one neutrino has a mass of at least

$$m_i \gtrsim 0.05\ \mathrm{eV} = \sqrt{\Delta m^2_{ATM}}$$

Therefore, if the lightest neutrino is massless,

$$\begin{cases} 0.05\ \mathrm{eV} \leqslant \sum_i m_i \leqslant 1\ \mathrm{eV} & \text{NORMAL HIERARCHY} \\ 0.1\ \mathrm{eV} \leqslant \sum_i m_i \leqslant 1\ \mathrm{eV} & \text{INVERTED HIERARCHY} \end{cases}$$

This is important to compute

Ω_ν (ν density in the universe)

Finally, the most difficult parameter to measure is

the CP-violating phase δ

At present, the **most promising** models to generate

BARYON ASYMMETRY

are those in which

LEPTON ASYMMETRY $\longrightarrow$ BARYON ASYMMETRY

non-perturbative process that conserve B-L

to generate a LEPTON ASYMMETRY
leptonic CP-violation is needed
(plus other conditions)

This mechanism is called
LEPTOGENESIS

3. How to look for unknowns ?

We can use either NATURAL SOURCES (sun, supernovae, cosmic rays ...) OR TERRESTRIAL LBL EXPERIMENTS :

(1) REACTORS : $\bar{\nu}_e$

(2) CONVENTIONAL BEAMS :

$$\pi \to \mu \ \boxed{\nu_\mu \ (\bar{\nu}_\mu)}$$

(3) BETA-BEAMS : $\nu_e, \bar{\nu}_e$

(4) NEUTRINO FACTORY :

$$\mu \to e \ \boxed{\nu_e \ \bar{\nu}_\mu \ (\bar{\nu}_e \ \nu_\mu)}$$

There are no available ideas for intense ν_τ beams $\Rightarrow$ we can measure :

$$\begin{cases} P_{ee}, P_{e\mu}, P_{e\tau} \\ P_{\mu\mu}, P_{\mu\tau}, P_{\mu e} \end{cases}$$

4. Reactors

Consider the P_{ee} probability in vacuum:

$$\boxed{P_{ee} = 1 - \sin^2 2\theta_{13} \cdot \sin^2\left[\frac{\Delta m^2_{ATM} L}{4E}\right] - \sin^2 2\theta_{12} \cdot \sin^2\left[\frac{\Delta m^2_{SOL} L}{4E}\right]}$$

To maximize the θ_{13}-term, then

$$\left(\frac{L}{E}\right) = \frac{\pi}{2}\,\frac{1}{k\,\Delta m^2_{ATM}} \sim 500$$ [illegible]

with $k = 1.27 \left[\frac{GeV}{eV^2\,km}\right]$.

To maximize the θ_{12}-term, then

$$\left(\frac{L}{E}\right) = \frac{\pi}{2}\,\frac{1}{k\,\Delta m^2_{SOL}} \sim 15.000 \left[\frac{km}{GeV}\right]$$

For $E \sim 1\,MeV \Rightarrow \begin{cases} L_{atm} \sim 0.5\,km \\ L_{sol} \sim 150\,km \end{cases}$

If we look for θ_{13} then $L = O(1\,\mathrm{km})$:

the vacuum approx. is appropriate.

POSITIVE:

a CLEAN handle to look for θ_{13}

NEGATIVE:

not sensitive to θ_{23}, δ and to the sign of Δm^2_{ATM}

Example: at the Double Chooz proposal

$\langle E \rangle = 4\,\mathrm{MeV}, \quad L = 1.05\,\mathrm{km}$

$$\begin{cases} [\sin^2 2\theta_{13}]_{min} = 0.03 \\ [\theta_{13}]_{min} = 5^\circ \end{cases}$$

Problem: it is SYSTEMATIC DOMINATED

5. Beams and superbeams

Two possible channels:

$P_{\mu\mu}$: ν_μ disappearance

$P_{\mu e}$: ν_e appearance

+ If very energetic neutrinos are produced

$P_{\mu\tau}$: ν_τ appearance

Some examples:

the SPL $\Rightarrow$ $\langle E \rangle = 0.27$ GeV

$L = 130$ km on peak

T2K $\Rightarrow$ $\langle E \rangle = 0.7$ GeV

$L = 295$ km ~ on peak

For this range of energy and for on-peak baselines,

VACUUM APPROX HOLDS

Consider $P_{\mu\mu}$ in vacuum :

$$\boxed{\begin{aligned} P_{\mu\mu} = 1 - \sin^2 2\theta_{23} \Big[& \sin^2 \frac{\Delta L}{2} \\ & - c_{12}^2 \sin \frac{\Delta_\odot L}{2} \sin \Delta L \\ & + c_{12}^2 \sin^2 \frac{\Delta_\odot L}{2} \cos \Delta L \Big] \\ & - c_{23}^4 \sin^2 2\theta_{12} \sin^2 \frac{\Delta_\odot L}{2} \\ & - s_{23}^2 \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\delta \cdot \\ & \qquad \sin \frac{\Delta_\odot L}{2} \cdot \sin \Delta L \\ & + s_{23}^2 \cos 2\theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta L}{2} \end{aligned}}$$

Sensitive to: θ_{13}, δ

sign of $\Delta = \dfrac{\Delta m^2_{ATM}}{2E}$

θ_{23}-octant

On peak we lose sensitivity to δ and sign(Δ);
sensitivity to θ_{23}-octant is suppressed by two powers of $\theta_{13} / \Delta_\odot L$

It is difficult to measure θ_{13} in ν_μ disappearance experiments because of the LEADING TERM

$$P_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2 \frac{\Delta L}{2} + \dots$$

Consider $P_{\mu e}$ in vacuum:

$$\boxed{\begin{aligned} P_{\mu e} = {} & S_{23}^2 \sin^2 2\theta_{13} \sin^2 \frac{\Delta L}{2} \\ & + C_{23}^2 \sin^2 2\theta_{12} \sin^2 \frac{\Delta_\odot L}{2} \\ & + \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\left[\frac{\Delta L}{2} + \delta\right] \cdot \\ & \qquad \sin \frac{\Delta_\odot L}{2} \sin \frac{\Delta L}{2} \end{aligned}}$$

Through $P_{\mu e}$ appearance it has been computed the following:

$$\theta_{13}^{min} = \underset{\substack{\uparrow \\ \text{T2K-I}}}{3.3^\circ} \Big/ \underset{\substack{\uparrow \\ \text{NO}\nu\text{A}}}{3.5^\circ}$$

After REACTORS and FIRST GENERATION SUPERBEAMS (T2K-I and NOvA) we will face a forking path:

- either we have observed a signal in $\nu_\mu \to \nu_e$ oscillation, and then $\theta_{13} > 3^\circ - 4^\circ$:

  increase the power of SB's and the mass of the detector
  T2K-II.

- or we have no signal: $\theta_{13} < 3^\circ - 4^\circ$

  GO TO NEW BEAMS

  $\left\{ \begin{array}{l} \beta\text{-Beams} \\ \text{Neutrino Factory} \end{array} \right.$

c. Beta Beams

The range of neutrino energies considered at present for ^6He | ^{18}Ne β-decays is:

$E = [0.3 - 3]$ GeV $\Rightarrow$ $P_{e\tau}$ CLOSED

$L_{peak} = [150 - 1500]$ Km $\Rightarrow$ matter effects

At second order in θ_{13} and $\delta m^2 / \Delta m^2$:

$$\boxed{P_{e\mu} = X \sin^2 2\theta_{13} + Y \sin 2\theta_{13} \cos\left[\frac{\Delta L}{2} \mp \delta\right] + Z}$$

where:

$$X = S_{23}^2 \cdot \left(\frac{\Delta m^2}{A \mp \Delta m^2}\right)^2 \cdot \sin^2\left[\frac{(A \mp \Delta m^2) L}{4E}\right]$$

$$Y = \sin 2\theta_{12} \sin 2\theta_{23} \cdot \left(\frac{\delta m^2}{A}\right) \sin\left(\frac{AL}{4E}\right) \cdot \left(\frac{\Delta m^2}{A \mp \Delta m^2}\right) \sin \frac{(A \mp \Delta m^2) L}{4E}$$

$$Z = C_{23}^2 \sin^2 2\theta_{12} \left(\frac{\delta m^2}{A}\right)^2 \sin^2 \frac{AL}{4E}$$

Notice that

- sensitivity to sign(Δm^2) comes through X and Y
- sensitivity to θ_{23}-octant comes through X and Z
- sensitivity to CP-violation comes through interference term Y

If θ_{13} vanishes:

NO SENSITIVITY TO sign(Δm^2)

NO SENSITIVITY TO δ

However, this is certainly the best channel to look for θ_{13}, δ:

GOLDEN CHANNEL

At the βBeam, just look for muons in a ν_e($\bar{\nu}_e$) beam

7. Parametric degeneracies

Imagine that your goal is a measurement of (θ_{13}, δ) through $P_{e\mu}$ or $P_{\mu e}$ oscillation:

- if θ_{13} is large enough to be measured, the interference term Y is also large:

  $\theta_{13} - \delta$ correlation

  $$\Downarrow$$

  $$\boxed{P_{e\mu}(\bar{\theta}_{13}, \bar{\delta}) = P_{e\mu}(\theta_{13}, \delta)}$$

- if you have ν_e and $\bar{\nu}_e$ beams, two intersections:

  $$\boxed{P^{\pm}_{e\mu}(\bar{\theta}_{13}, \bar{\delta}) = P^{\pm}_{e\mu}(\theta_{13}, \delta)}$$

TRIGONOMETRIC DEGENERACY

Remember, however, that you do not know two other things:

$s_\Delta \equiv \mathrm{sign}(\Delta m^2_{23})$ $\qquad$ $\mathrm{sign}[\tan 2\theta_{23}] \equiv s_\theta$

three-family atmo analysis solves it

Thus, in the (θ_{13},δ) plane:

$$\bar{P}^{\pm}_{e\mu} = P^{\pm}_{e\mu}(\bar{\theta}_{13},\bar{\delta},\bar{s}_\Delta,\bar{s}_\theta) = P^{\pm}_{e\mu}(\theta_{13},\delta,\bar{s}_\Delta,\bar{s}_\theta)$$

and

$$\boxed{\begin{aligned} \bar{P}^{\pm}_{e\mu} &= P^{\pm}_{e\mu}(\theta_{13},\delta,-\bar{s}_\Delta,\bar{s}_\theta) \\ \bar{P}^{\pm}_{e\mu} &= P^{\pm}_{e\mu}(\theta_{13},\delta,\bar{s}_\Delta,-\bar{s}_\theta) \\ \bar{P}^{\pm}_{e\mu} &= P^{\pm}_{e\mu}(\theta_{13},\delta,-\bar{s}_\Delta,-\bar{s}_\theta) \end{aligned}}$$

sign clones

octant clones

mixed clones

Overall degeneracy:

$(\bar{\theta}_{13},\bar{\delta})$ + seven clones

EIGHTFOLD DEGENERACY

Notice two things:

- the position of the clones in the (θ_{13}, δ) plane is ENERGY DEPENDENT
- the position of the clones in the (θ_{13}, δ) plane GETS CLOSER TO $(\bar{\theta}_{13}, \bar{\delta})$ for $\theta_{13} \to 0$

This means that:

1) either you have an
   ENERGY DEPENDENT SIGNAL
   or you need
   OTHER CHANNELS
   → both things true at the
   NEUTRINO FACTORY

2) the impact of the clones is larger for LARGE θ_{13}
   → bad news for SUPERBEAMS

8. The Neutrino Factory

The Neutrino Factory with $E_\mu = 20 - 50$ GeV and $L = 700 - 7000$ Km has a very

BROAD ENERGY SPECTRUM

↳ energy resolution can be used to solve degeneracies

Secondly, the $P_{e\tau}$ channel OPENS:

$$\boxed{P_{e\tau} = X_\tau \sin^2 2\theta_{13} - Y \cos\left[\frac{\Delta}{2} \mp \delta\right] \sin 2\theta_{13} + Z_\tau}$$

notice this sign

$$\begin{cases} X_\tau = X\big|_{s_{23} \to c_{23}} \\ Z_\tau = Z\big|_{c_{23} \to s_{23}} \end{cases}$$

This is called the

SILVER CHANNEL

and helps in solving degeneracies

9. Summary of first lecture

1) REACTORS: only θ_{13} can be measured

2) DISAPPEARANCE AT SUPERBEAMS:
subleading effects in θ_{13}, s_{Δ}, s_{θ}
and δ difficult to disentangle

3) $P_{e\mu}$ and $P_{\mu e}$ at
SUPERBEAMS, βBEAMS or the NUFACT
best channel to look for (θ_{13}, δ);
also sensitive to s_{Δ}, s_{θ}

PLAGUED BY DEGENERACIES

⇓

we need HEAVY WEAPONRY:

combination of ENERGY BINS
BASELINES
CHANNELS

Examples in the second lecture!