Neutrino Oscillations and Mass, and CP Violations

- Review the status and prospects for measurements of the neutrino masses and mixings.
  - Mainly concentrating on terrestrial neutrino beam sources
- How does this couple to an underground laboratory?

Neutrino Oscillation Measurements

Solar and Atmospheric results determine Δm_{12}^2, θ_{12}, Δm_{23}^2, θ_{23}

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$= \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric: θ_{23} ??? Solar: θ_{12}

Need to measure: Sign of Δm_{23}^2 , ~~CP~~ phase δ , θ_{13} ($\nu_e \to \nu_\mu$)

- Measurements of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ yields θ_{13} and δ
  - θ_{13} key parameter for osc. phenomenolgy since θ_{12} and θ_{23} are both large
    - Determines whether CP violation is accessible

Why Are Neutrino Oscillation Measurements Important?

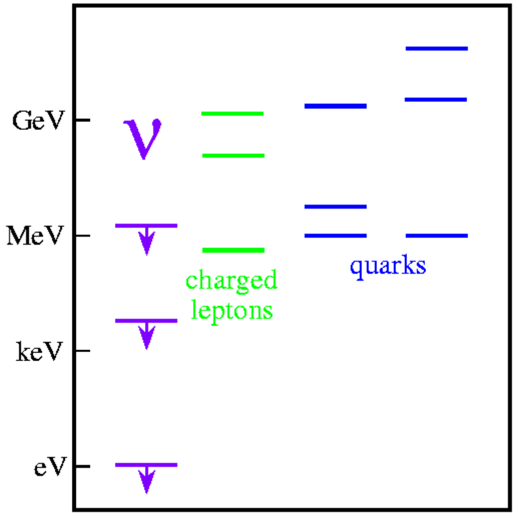
- Give a window on physics at high mass scales: unification, physics of flavor, and extra dimensions
  - Why are the neutrino masses so small?
  - Are there additional “sterile” neutrinos?
  - Why are their mixings so large?
  - Is there a connection between the lepton and baryon sector?
  - Is there CP violation, T violation, or CPT violation in the leptons?

- Neutrino masses and mixing are important to understanding astrophysical models of:
  - Supernovae, galactic structure formation, etc.

Should remember that neutrino oscillations only measure mass differences (m_1^2-m_2^2)

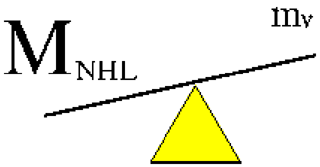
- ***Need tritium decay (KATRIN) or double beta decay to measure one mass ⇒ Are ν masses hierarchical or degenerate?***

Neutrino Masses: Theoretical Ideas



- **No fundamental reason why neutrinos must be massless**
  - But why are they much lighter than other particles?
- **Modified Higgs sector to accommodate neutrino mass**
- **Extra Dimensions**
  - Neutrinos live outside of 3 + 1 space
- **Grand Unified Theories**
  - Dirac and Majorana Mass
    ⇒ See-saw Mechanism

$$\mathcal{M} = \begin{pmatrix} m_M^L & m_D \\ m_D & m_M^R \end{pmatrix}$$



  - **Many of these models have at least one Electroweak isosinglet ν**
  - Right-handed partner of the left-handed ν
  - Mass uncertain from light (< 1 eV) to heavy (>10^{16} eV)
  - Would be "sterile" – Doesn't couple to standard W and Z bosons

$$m_N \approx M, \quad m_\nu \approx \left| \mu - \frac{m_D^2}{M} \right|$$

Need neutrino oscillations to measure small neutrino masses

Matter-Antimatter Asymmetry (ΔB ≠ 0) from Leptogenesis

MNS Lepton Mixing Matrix

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

$$\begin{pmatrix} 0.7 & 0.7 & < 0.2 e^{i\delta}\,? \\ -0.5 & 0.5 & 0.7 \\ 0.5 & -0.5 & 0.7 \end{pmatrix}$$

$$\begin{pmatrix} big & big & small\,? \\ big & big & big \\ big & big & big \end{pmatrix}$$

CKM Quark Mixing Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} U_{ud} & U_{us} & U_{ub} \\ U_{cd} & U_{cs} & U_{cb} \\ U_{td} & U_{ts} & U_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} 0.97 & 0.22 & 0.003 e^{i\delta} \\ -0.22 & 0.97 & 0.04 \\ 0.01 & -0.04 & 0.999 \end{pmatrix}$$

$$\begin{pmatrix} big & small & very\ tiny \\ small & big & tiny \\ tiny & tiny & big \end{pmatrix}$$

δ gives CP violation

Why?

- Hard to generate a baryon asymmetry (ΔB ≠ 0) using quark matrix CP violation
- Generate ΔL ≠ 0 using CP or CPT violation in the lepton sector
  - B-L processes then convert a neutrino excess to baryon excess.
    - Sign and magnitude may be able to generate the observed baryon asymmetry in the universe

Neutrino Oscillation Experiments

- Current Oscillation Experiments
  - K2K ν_μ dissappearance 250km from KEK to SuperK detector
  - MiniBooNE $\nu_\mu \rightarrow \nu_e$ appearance in the LSND Δm^2 region
  - NuMI/Minos at Fermilab and CNGS at CERN
    Long-baseline (~750km) ν_μ experiments in atmospheric Δm^2 region

- Near term offaxis experiments
  - JHF to SuperK Offaxis experiment – 22kton detector
  - NuMI/Minos Offaxis experiment (Proposed) – ~20kton detector

- Neutrino Superbeam Experiments (Combine with large p-decay detectors?)
  - BNL (AGS upgrade) to NUSL
  - Fermilab (proton driver upgrade) to NUSL
  - JHF(Phase II) to HyperK at Kamiokande laboratory
  - CERN SPL (Supercond. Proton Linac) to Frejus

- Future Neutrino Factory using a muon storage ring.

Strawperson Roadmap

- Stage 0: Current near term program
- NuMI (K2K) checks atmospheric oscillations and measures Δm^2_{23} to about 10%
- MiniBooNE makes definitive check of LSND and measures associated Δm^2

- Stage 1 - Constrain / measure $\sin^2 2\theta_{13}$
- NuMI /MINOS on-axis probes $\sin^2 2\theta_{13} > 0.06$ @ 90%CL
- NuMI/JHF offaxis could go down to $\sin^2 2\theta_{13} > 0.01$ @ 90%CL
- FNAL to NUSL with 100kton detector?

- Stage 2 - Measure CP violation and sign of Δm^2_{23} with conventional superbeams and very large detectors (500 to 1000ktons)
- Must have $\sin^2 2\theta_{13} > 0.01$
- Need to measure $P(\nu_\mu \rightarrow \nu_e)$ then $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- Need increased rate (especially for $\bar{\nu}$'s) $\Rightarrow$ Need high intensity proton sources

- Stage 3 - Measurements with Neutrino Factory
- Map out CP violation with precision for $\sin^2 2\theta_{13} > 0.01$
- Probe $\nu_\mu \rightarrow \nu_e$ transitions down to $\sin^2 2\theta_{13} > 0.001$

Requirements for Neutrino Oscillation Experiments

- Need high intensity beam with energy tuned at the oscillation maximum for the given baseline.
  - Neutrino sources (Labs) and possible detector sites

- Many detector technologies do not need to be underground
  - Due to beam duty cycle, only need small overburden to reduce cosmic background

- Superbeam experiments measuring CP violation require very large, costly detectors
  - Couple detectors to p-decay, supernova, etc. measurements
    - ⇒ Detector needs to be in an Underground Lab
    - ⇒ Detector technology needs to be compatible with p-decay etc. but compromises may be necessary
      - ➢ Water Cerenkov Detector or
      - ➢ Liquid Argon Detector

If MiniBooNE Confirms LSND

- Three distinct Δm^2 values ⇒ How do we fit everything in?
    - Need more long and short-baseline experiments

  - Difficult to fit everything with the three standard neutrinos
    - But may be uncertainties in some of the Δm^2 measurements or other explanations for one of the oscillation results?
    - Need accurate Δm^2 and oscillatory behavior measurements
      - Terrestrial ν_μ and ν_e beams and reactor sources

  - Sterile Neutrinos (Add one or more sterile neutrinos)
    - Sterile/active mixing
    - Need better measurements of sterile component in "solar" and "atmospheric" oscillations

  - CPT violation
    - LSND measures anti-neutrino oscillations and
      Solar experiments measure neutrino oscillations

    ⇒ Need to make measurements with both neutrino and anti-neutrino sources (+ KAMLAND)

Neutrino Oscillation Program Thru ~2010

Pursue oscillation parameter measurements with longbaseline experiments!

- Need to measure $\sin^2\theta_{13}$, sign of Δm^2_{23}, and probe for CP violation

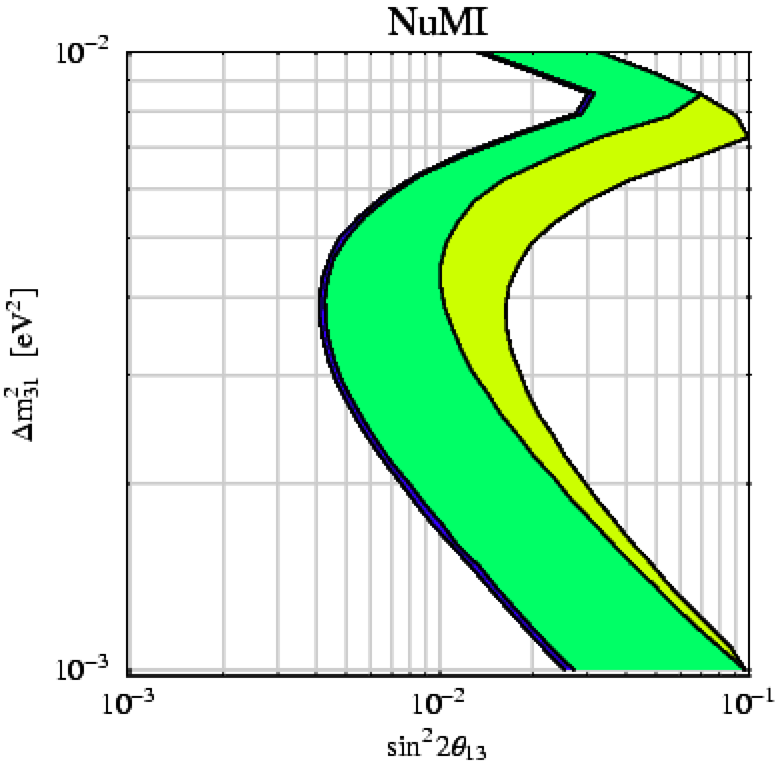
- Some information will come from on-axis experiments at Fermilab/CERN
  - For example, NuMI/Minos has sensitivity for $\sin^2 2\theta_{13} > 0.06$ @ 90%CL

- Off-axis experiments (Probe $\sin^2 2\theta_{13} > 0.01$ @ 90%CL)
  - Off-axis gives beam with narrow energy distribution that is tunable
    - JHF to SuperK
    - Fermilab NuMI to Offaxis detector

  - May also see first signs of CP violation
    - Combination of two baselines (JHF and NuMI) may be important for removing correlations and ambiguities

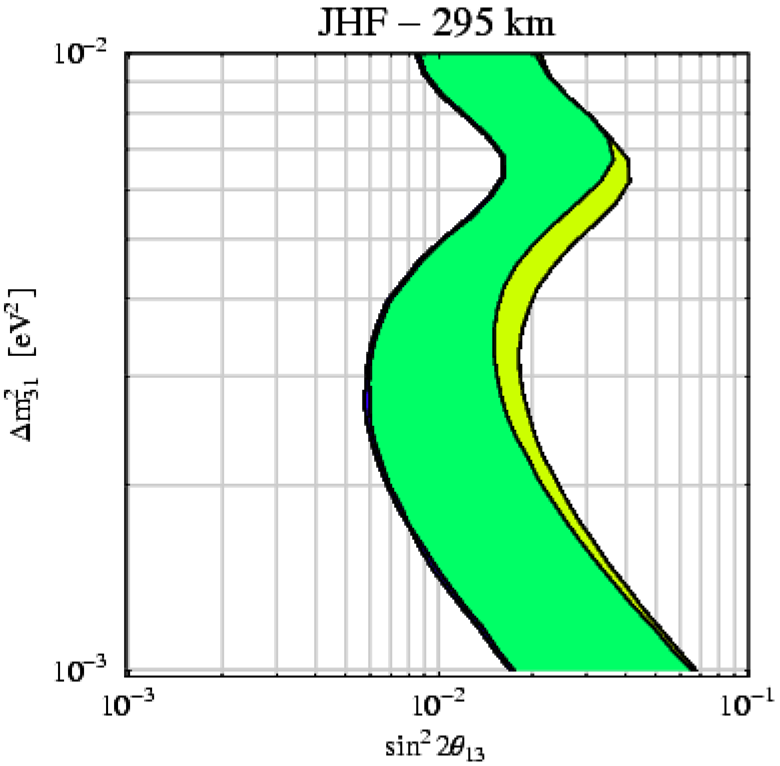
Sensitivity of Off-Axis NuMI and JHF

NuMI Offaxis Sensitivity:
5yrs @ 4x10^{20} p/yr
with 20 kton detector



	ν_μ CC	NC	Beam ν_e	Signal ν_e
all	12104	5696	295.4	293
after cuts		10.2	10.2	85.5

JHF Offaxis Sensitivity:
5yrs with JHF Phase I and
SuperK detector



	ν_μ CC	NC	Beam ν_e	Signal ν_e
all	10714	4080	292	302
after cuts	1.8	9.3	11	123

Above event samples assume $\sin^2 2\theta_{13}=0.1$ and $\Delta m^2 = 3\times10^{-3}$eV^2

Next Step: Neutrino Superbeam Experiments

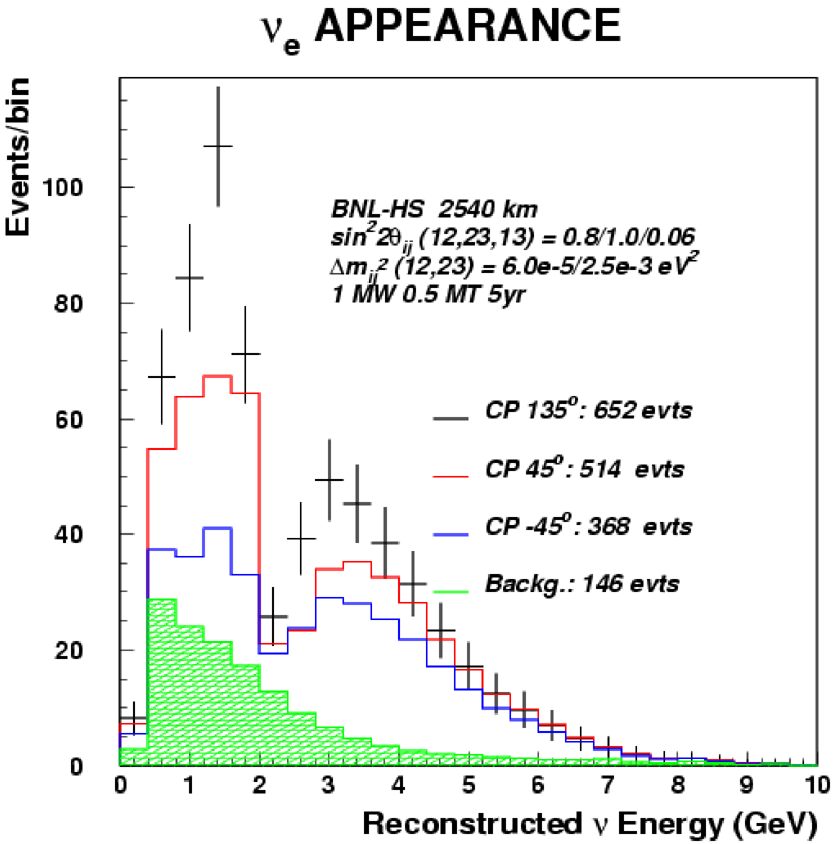
If $\sin^2 2\theta_{13} > 0.01$, design experiment to measure δ (CP violation parameter) and the sign of Δm^2_{23}

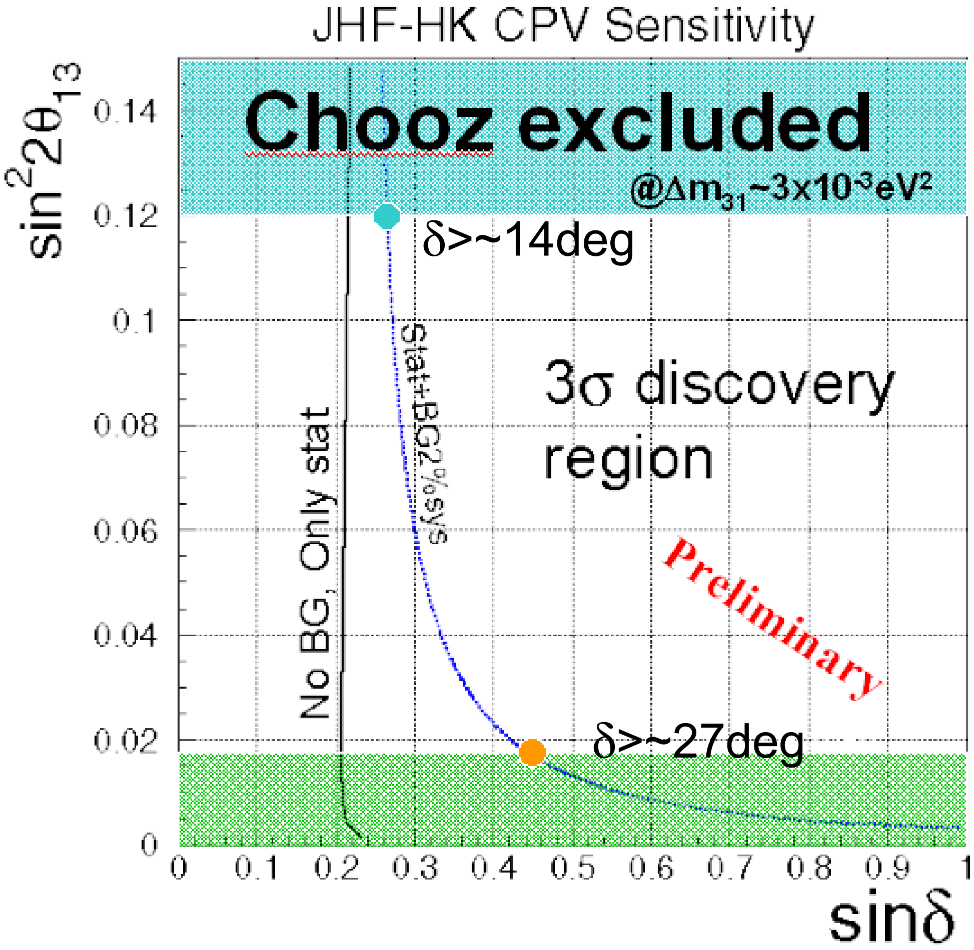
- Need high intensity proton sources coupled with very large underground combined function detectors
  - JHF Phase II to HyperK detector
    - $\langle E_\nu \rangle \approx 700$ MeV beam using 4MW JHF to 1000kton water Cerenkov
    - CP violation 3σ discovery reach for $\sin^2 2\theta_{13} > 0.02$ (2yr for nu's and 6 yrs for nubars)
  - BNL Upgraded AGS to NUSL
    - Very longbaseline with wide-band beam gives dramatically large effects Use 1MW AGS beam with $0.5 < E_\nu < 5$ GeV and 500 kton water Cerenkov
    - Combined oscillation measurements for the 1st,2nd,3rd….. osc. maximum gives 0.5-1 GeV Solar LMA, 1-3 GeV CP effects, 3-5 GeV matter effects
  - Fermilab Proton Driver to NUSL
    - Upgrade proton driver to 1-4MW combined with 500kton water Cerenkov or Liq. Argon ⇒ Fit first and second maximum for neutrinos and antineutrinos
    - Possibly also NuMI to Canada
  - CERN SPL to UNO-type detector at Frejus
    - $\langle E_\nu \rangle \approx 250$MeV with L=133km for 5 years UNO-type detector (660tons) ⇒ $\sin^2 2\theta_{13} > 0.002$ @ 90%CL

Example Sensitivities for Superbeam Experiments

δ_{CP} **Measurement. BNL-to-NUSL**

2540 km, 1 MW, 500kT, 5×10^7 **sec**





Can measure δ_{CP} to ±20°

Summary of Neutrino Osc. In an Underground Lab

- If CP violation is accessible experimentally, a very high-intensity neutrino superbeam coupled with a ~500 kton detector in an underground lab will be important for precision measurements
  - It is natural to couple the detector to a p-decay experiment which would need to be constructed in an underground Lab.
  - Program will cost on order ~$1Billion for detector and beam.

- But the combined scientific measurements from such an experiment are really impressive and important
  - Unique way to probe physics at ultra high energy scales through proton decay and neutrino mass measurements
  - May provide the key to understanding the baryon asymmetry in the universe