LBNF Theory Perspective

Leptonic CP Violation!

Precision mixing & masses, Matter Effects, "New Physics"…

Atm. Neutrinos, Supernova Neutrinos, Proton Decay…

Leptonic CP Violation

Requirements: 200kton H_2O or 40kton LArgon, 1-2MW protons

Long Baseline (>1000km)

~ 10 years

Neutrino Wide Band Beam (WBB) $E_\nu \approx 0.5$-5GeV

William J. Marciano

Jan 12, 2015

BROOKHAVEN NATIONAL LABORATORY

Primary LBNF Physics Goals

- ***Measure Leptonic CP Violation & phase δ***

  Our Origin (Leptogenesis Matter-antiMatter Asy.)

  Determine (Precisely) Neutrino Mass & Mixing Parameters

  Redundant Comparison Tests

  Understand Pattern (Underlying Symmetry eg A4)

  Search for "New Physics" eg very weakly coupled new long or short distance effects (in Matter)

  Search for Sterile Neutrinos (small mixing)

Other Physics

- ***Atm. vs Beam Neutrino Oscillations***
- ***Supernova Neutrinos (Relic & New),***
- ***Proton Decay (B-L=0)… Neutron-antiNeutron Osc. ΔB=2***

Broad Revolutionary Discovery Potential

Big Underground Detectors Originally Proposed for Proton Decay Searches Motivated by Grand Unification

Can 40kton LAr compete with HyperK (>500kton H_2O)?

3 Generation Mixing Formalism & Status)

$$\begin{pmatrix} |\nu_e> \\ |\nu_\mu> \\ |\nu_\tau> \end{pmatrix} = U \begin{pmatrix} |\nu_1> \\ |\nu_2> \\ |\nu_3> \end{pmatrix} \qquad (1)$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$c_{ij} = \cos\theta_{ij} \quad , \quad s_{ij} = \sin\theta_{ij}$$

$$J_{CP} \equiv \frac{1}{8}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}\sin\delta. \qquad (2)$$

Current Neutrino Mass & Mixing Parameters

- $\Delta m_{32}^2 = m_3^2 - m_2^2 = \pm\, 2.4(1)\times 10^{-3}$ eV^2
  (atmospheric, beam & reactor)
- $\Delta m_{21}^2 = m_2^2 - m_1^2 = +7.5(2) \times 10^{-5}$ eV^2 (solar)

(Very precise Minos, Daya Bay & KamLAND)

$|\Delta m_{21}^2/\Delta m_{32}^2 \approx 1/30|$ → CP Violation Exp Doable!

Hierarchy $m_3 > m_1$&m_2(normal) or $m_3 < m_1$&m_2(inverted)?

Large Mixing!

$\theta_{23} \sim 38\pm1°$	$\sin 2\theta_{23} \approx 0.97(1)$	(θ_{23} or $90° - \theta_{23}$) (atm.)
$\theta_{12} \sim 34\pm1°$	$\sin 2\theta_{12} = 0.93(2)$	(solar)
$\theta_{13} \leq 9.0\pm0.5°$	$\sin 2\theta_{13} = 0.31(1)$	(reactor)
	$0 \leq \delta \leq 360°$?	

$J_{CP} \sim 0.03\sin\delta$ (potentially large!) CKM~2×10^{-5}

What do we still need to learn?

1. **Sgn Δm_{32}^2?** Earth Matter Effect (SM or “New Physics”)
   (Important for Neutrinoless $\beta\beta$ Decay)

- 2. **Value of** δ?, J_{CP}?, CP Violation? ***(Holy Grail)***

- 3. **Precision** Δm_{32}^2, Δm_{21}^2, θ_{23}, θ_{12}, $\boldsymbol{\theta_{13}}$ (better than 1%!)
  Redundancy & neutrinos vs antineutrinos
  Unitarity Violation? – Sterile neutrino Mixing
- 4. **“New Physics”** - Sterile ν, ***Very Weak*** Long/Short
  Distance New Physics (*The Dark World?*)…

Leptonic CP Violation

$$P(\nu_\mu \to \nu_e) = P_I(\nu_\mu \to \nu_e) + P_{II}(\nu_\mu \to \nu_e) + P_{III}(\nu_\mu \to \nu_e)$$

$+$ matter $+$ smaller terms

$$\mathbf{P}_I(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)$$

$$\mathbf{P}_{II}(\nu_\mu \to \nu_e) = \tfrac{1}{2}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}$$
$$\sin\left(\frac{\Delta m^2_{21}L}{2E_\nu}\right) \times \left[\sin\delta\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\right.$$
$$\left. + \cos\delta\sin\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\cos\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\right]$$

$$\mathbf{P}_{III}(\nu_\mu \to \nu_e) = \sin^2 2\theta_{12}\cos^2\theta_{13}\cos^2\theta_{23}\sin^2\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)$$

For antineutrinos, $\delta \to -\delta$ and opposite matter effect.

CP Violation Asymmetry

$$A_{CP} \equiv \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \tag{3}$$

To leading order in Δm^2_{21} ($\sin^2 2\theta_{13}$ is not too small):

$$A_{CP} \simeq \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right) + \text{matter effects} \tag{4}$$

$$F.O.M. = \left(\frac{\delta A_{CP}}{A_{CP}}\right)^{-2} = \frac{A^2_{CP}N}{1 - A^2_{CP}} \tag{5}$$

N is the total number of $\nu_\mu \to \nu_e + \bar{\nu}_\mu \to \bar{\nu}_e$ events.Since N falls (roughly) as $\sin^2\theta_{13}$ and $A^2_{CP} \sim 1/\sin^2\theta_{13}$, to a first approximation the F.O.M.is independent of $\sin\theta_{13}$. Similarly, given E_ν the neutrino flux and consequently N falls as $1/L^2$ but that is canceled by L^2 in A^2_{CP}.

CP Violation Insensitivities

- To a very good approx., our statistical ability to determine δ or A_{cp} is **independent** of $\sin^2 2\theta_{13}$ (down to ~ 0.003) and the detector distance L (for long distance).

It turns out $\sin^2 2\theta_{13} \approx 0.1$!

about 2-3 times larger than assumed in early studies

precision θ_{13} & δ determination easier

Smaller A_{CP} Might help some systematics

CP Violation Requirements

- What does it take to measure δ to $\pm 15°$ in about 6×10^7 sec?

  Answer (Approx.): 200kton Water Cerenkov Detector

  Approx 20% Acceptance qr

  40 kton LArgon 90% Acceptance

  or Hybrid combination

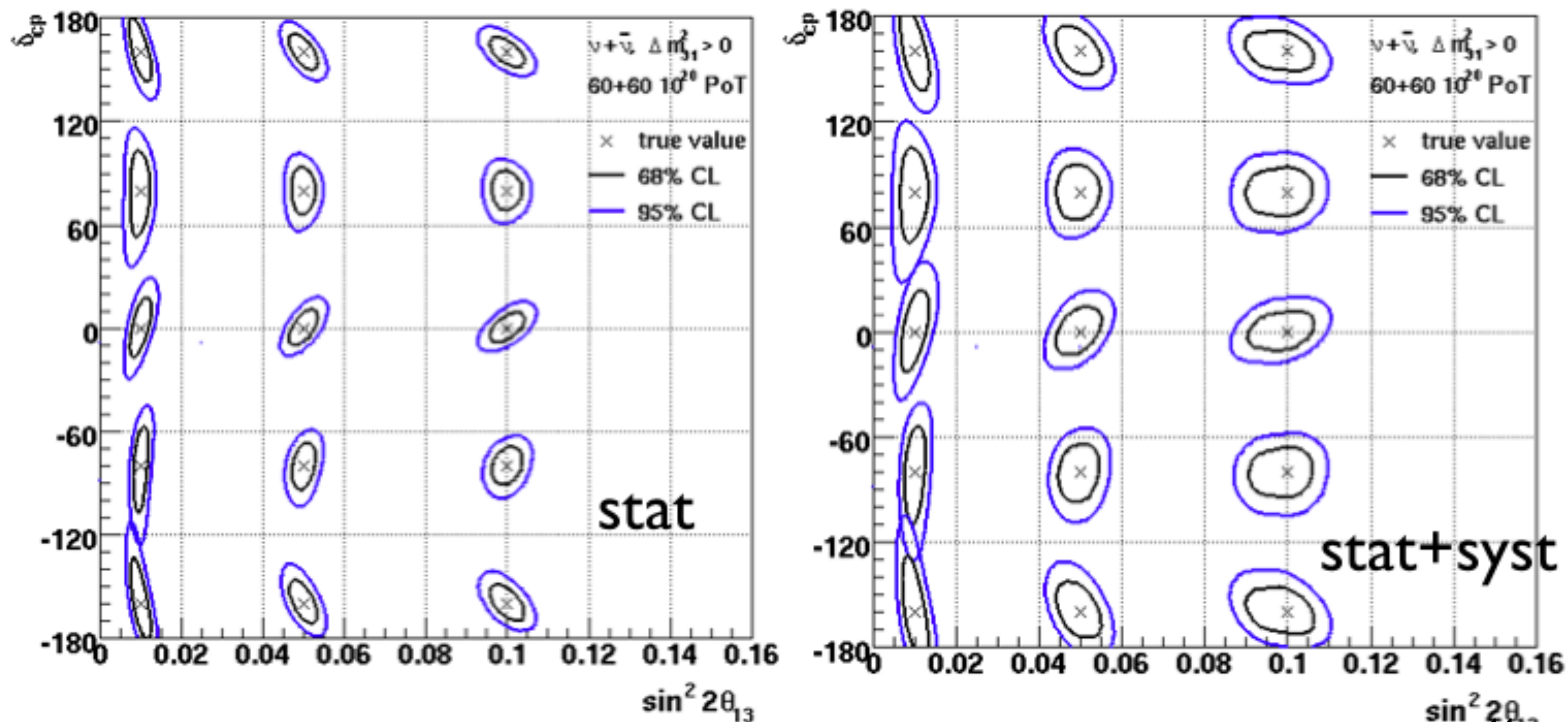
  \+ Traditional Horn Focused ν WBB powered by

  1-2MW proton accelerator ~10 years

CP Phase Insensitivity to θ_{13} Value

WCC 1300 km 300kT

(—95% CL —68% CL)



Δm^2_{32} and $\sin^2 2\theta_{32}$ can be measured in long baselines as functions of E_ν (also obtained from atmospheric ν).

$\nu_\mu \rightarrow \nu_\mu$ & anti$\nu_\mu \rightarrow$ antiν_μ Comparison

Usually phrased as a test of CPT (true in vacuum)

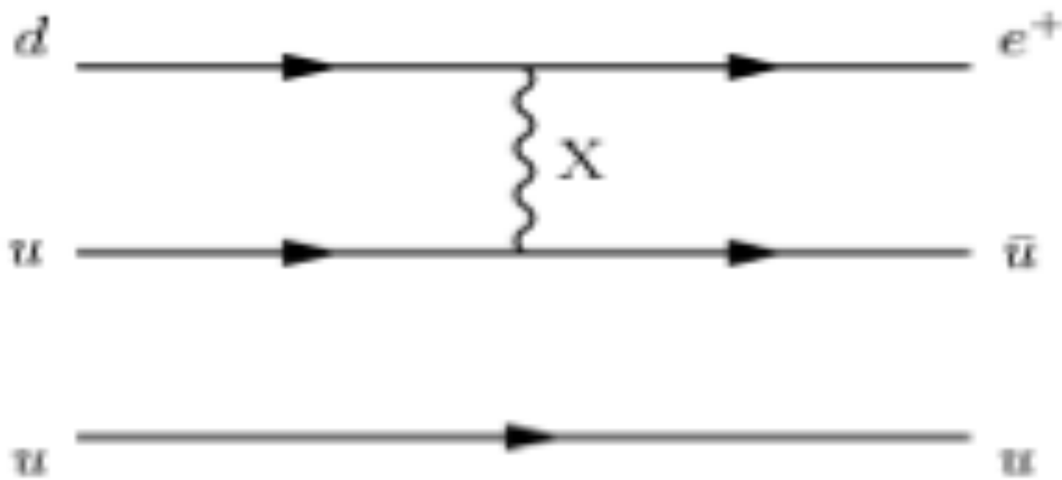
Apparent CPT violation → "New Physics" in ν interactions

(in matter) $\varepsilon\sqrt{2}G_F \nu\gamma_\mu\nu' f\gamma^\mu f$, f=e, u, d

Potential changes sign $\nu_\mu \rightarrow$ antiν_μ

Sterile Neutrinos? etc

($X^{\pm 4/3}$, $Y^{\pm 1/3}$) GUT Mediated Proton Decay



$p \rightarrow e^+\pi^0$, $e^+\omega$ or ρ^0….$\pi^+\nu$..

Similarly, $n \rightarrow e^+\pi^-$ (via $Y^{\pm 1/3}$)

***Isospin*: $\Gamma(n \rightarrow e^+\pi^-) = 2\Gamma(p \rightarrow e^+\pi^0)$**

$\Gamma(p \rightarrow \pi^+\nu) = 2\Gamma(n \rightarrow \pi^0\nu)$

SU(5) Expectations

proton lifetime ≈ bound neutron lifetime (±10-20%)

Br(**p➔e$^+$π^0) ≈ 0.35**

Br(**p➔e$^+$ω or ρ^0) ≈ 0.35 (multi-pion final states)**

Br(**p➔π$^+$ν) ≈ 0.15**

Br(**p➔**ρ$^+$**ν, e$^+$η, μ$^+$K^0…) ≈ 0.15**

Br(**n➔e$^+$π$^-$) ≈ 0.70**

Br(**n➔π^{0}ν) ≈ 0.07**

Water Cherenkov ≈ 45% p➔e$^+$π^0 acceptance

≈ 19% n➔e$^+$π$^-$ acceptance

Similar Sensitivity

LArgon Efficiencies

LArgon≈ 45% p➔$e^+\pi^0$ acceptance?

≈ 45% n➔$e^+\pi^-$ acceptance?

Can you do better?

Neutrino Backgrounds (smaller?)

Should be considered together: BR(Ar➔$e^+\pi^0/\pi^-$ +N')

(Includes pion charge exchange in the nucleus)

Roughly 3xBR(p➔$e^+\pi^0$) in LAr

Neutrino Background? LAr very clean!

After SuperK H_2O hits neutrino backgrounds!

Coupling Unification

Current Values: $\alpha_3(m_Z)=0.117(1)$

$\alpha_2(m_Z)=0.0338(1)$

$\alpha_1(m_Z)=0.0170(1)$

Come together but do *not* quite unify without an intermediate mass scale: m_{susy}, m_R SO(10), m_{scalar}…

Generic SUSY GUT ➔ $m_X \approx (1\text{TeV}/m_{susy})^{2/15} \times 10^{16}$GeV

(G. Sejanovic & WJM)

Also depends on other mass splittings (eg. Scalars)

Proton Partial Lifetime:

$\boldsymbol{\tau(p \rightarrow e^+\pi^0)} \approx (1\text{TeV}/m_{susy})^{8/15} \times 10^{35\pm1}$yr

Uncertainties: Matrix Elements (Lattice), $\alpha_3(m_Z)$, mass splittings, particle content…

Some Current SuperK Bounds

SuperK 22.5Kton Fiducial Vol. H_2O Cerenkov

Bounds on ***many*** p & n decay modes

$\tau(p \rightarrow e^+\pi^0) > 1\times10^{34}$yr (${m_X} > 5\times10^{15}$GeV)

$\tau(n \rightarrow e^+\pi^-) > 2\times10^{33}$yr

$\tau(p \rightarrow K^+\nu) > 3\times10^{33}$yr

Reaching asymptotic capabilities

Sensitivity goals for future detectors: ≥10xSuperK

$\tau(p \rightarrow e^+\pi^0) > 10^{35}$yr (${m_X} \geq 10^{16}$GeV)

$\tau(p \rightarrow K^+\nu) > 2\times10^{34}$yr

Also probe neutron-antineutron osc. ($\tau_{nnbar} > 10^9$sec)

Double proton decay $pp \rightarrow e^+e^+$

GUT Magnetic Monopole Catalysis of proton decay

Quantum Virtual Black Hole Effects

Future proton decay detectors

Given the SuperK bounds, the next generation water cerenkov detector should be at least 10x larger, i.e. ≥200Kton

A future LArgon detector should have **$\tau(p \rightarrow K^+ \nu) > 2\times10^{34}$yr** sensitivity, i.e. fiducial mass ≥35Kton

Those requirements are well matched to future neutrino Oscillation experiments designed to measure CP violation (differences between neutrinos and antineutrinos)

Japan HyperK: 20xSK H_2O, > Megawatt p, (off axis ν's), 5yrs
USA LBNE: 35 Kton LAr, 1-2 Megawatt p, (WBB ν's), 5yrs

LHC/ Proton Decay Complementarity

Current best experimental "hint" of SUSY

$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 287(63)(49) \times 10^{-11}$ (*3.5σ*)

suggests *$m_{susy} \approx 100\text{-}500GeV$*

some tension with LHC $m_{susy} \geq 1$ TeV (squarks & gluinos)

SUSY GUTS also prefer heavier $m_{susy} \approx 10TeV$

Heavier m_{susy} → shorter $\tau(p \to e^+\pi^0) \approx (1TeV/m_{susy})^{8/15} \times 10^{35\pm1}yr$

Heavier m_{susy} makes $p \to e^+\pi^0$ easier to observe!

but it makes direct SUSY at the LHC less likely

Together They Squeeze SUSY SU(5)

$1TeV < m_{susy} < 6000TeV$ (Currently) → 75TeV (better?)

Goals

Primary: CP violation in neutrino oscillations

LBNE: 1300km, WBB, 1-2MW, 40kton LAr, 10yrs

Proton Decay (10^{35}yr)

Similar Detector Requirements (Fortuitous)

Also: Atm & supernova ν, neutron-antineutron osc.,…

Sgn Δm_{32}^2? (Important for Neutrinoless ββ Decay)

Precision Δm_{32}^2, Δm_{21}^2, θ_{23}, θ_{12}, θ_{13} (goal? ±1%!)

"New Physics" - Sterile ν, ***Very Weak*** New Interactions…

Neutrino-antineutrino differences?

Anticipate (Hope For) Surprises

The Results Last Forever