VIEWING LEPTON MIXING THROUGH THE CABIBBO HAZE

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BASED ON :

hep-ph/0503222
(A. DATTA, L.E., P. RAMOND)

hep-ph/0510256
(L.E.)

hep-ph/0512188
(H. DAVOUDIASL, L.E.)

WORK IN PREPARATION
(L.E., P. RAMOND)

INTRODUCTION / MOTIVATION

FLAVOR PUZZLE OF STANDARD MODEL →

ORIGIN OF FERMION MASSES, MIXINGS

SM → PARAMETRIZED BY YUKAWA COUPLINGS → $Y_L^+ ; Y_U ; Y_R ; H$

- NO GUIDELINES, PRINCIPLES TO DETERMINE THEM

- SYMMS OF SM → CLASSES OF MODELS (TOP-DOWN APPROACH)

ULTIMATE GOAL:

SATISFACTORY, CREDIBLE FLAVOR THEORY

(VERY DIFFICULT !!)

RECENTLY → RENAISSANCE IN STUDIES OF

SM FLAVOR PUZZLE

FROM EXCITING EXPERIMENTAL PROGRESS

IN NEUTRINO SECTOR

ν OSCILLATIONS →

- ν's ARE MASSIVE
- LEPTON MIXING IS OBSERVABLE

BEYOND THE STANDARD MODEL →

" ν STANDARD MODEL "

FURTHERMORE →

THE ν DATA SHOW STRIKING DIFFERENCES

B/W QUARKS + LEPTONS

→ PARADIGM SHIFT

(Q-L UNIFICATION ?)

MASSIVE NEUTRINOS →

FIRST CONCRETE EVIDENCE OF

BEYOND STANDARD MODEL PHYSICS !

ν MASS REQUIRES →

- INTRODUCING SM GAUGE SINGLETS ν_R

+/OR

- TERMS WHICH VIOLATE SM GLOBAL SYMMS

$$Y_{ij}\,\bar{L}_{Li}\,H\,\nu_{Rj} + \left\{ \frac{\lambda_{ij}}{\Lambda}\,(L_{Li}H)(L_{Lj}H) + \dots \right\} + \frac{1}{2} M_{ij}\,\nu_{Ri}\nu_{Rj}$$

$\Delta I_W = \pm 1/2$ ↕ "USUAL" DIRAC MASS

$\Delta I_W = 1$

$\Delta I_W = 0$

VIOLATE LEPTON #

MAJORANA MASS TERMS

RICH FRAMEWORK FOR FLAVOR PUZZLE

(PROTOTYPE → NEUTRINO SEESAW)

$m_\nu \equiv Y\langle H\rangle \ll M \qquad m_\nu \sim \frac{m^2}{M}$

✓ PARADIGM SHIFT FOR FLAVOR PUZZLE

DATA ⟶

QUARK SECTOR

HIERARCHICAL MASSES

(3RD GENERATION ~ ELECTROWEAK)

SMALL MIXINGS →

LARGEST IN $1 \leftrightarrow 2$ GENERATION

CABIBBO ANGLE $\lambda \equiv \sin\theta_C = 0.22$

$O(1)$ CP VIOLATION

LEPTON SECTOR

CHARGED LEPTONS → HIERARCHICAL MASSES

(3RD GENERATION ≳ EW)

NEUTRINOS → HIERARCHY ? ULTRALIGHT

(MILDER ?)

LARGE MIXINGS

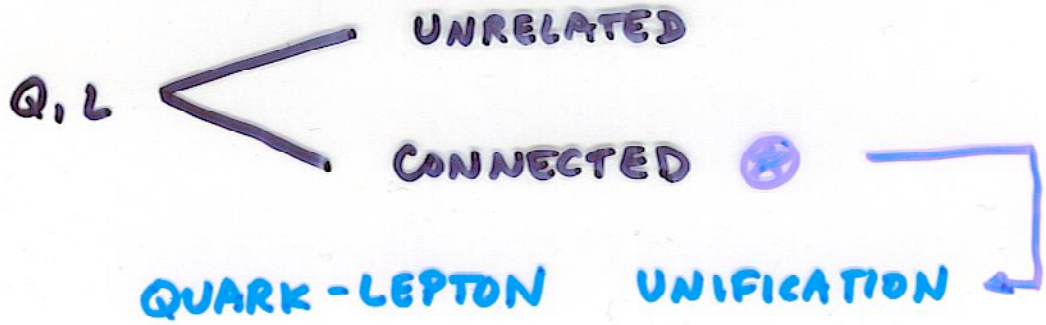
NONGENERIC PATTERN !

(2 LARGE + 1 SMALL)

~~CP~~ ?

ATTACKING THE FLAVOR PUZZLE

2 STRATEGIES →



THIS TALK →

EXPLORE ASPECTS OF FLAVOR PUZZLE WITHIN STRING/UNIFICATION CONTEXT

MAIN FOCUS →

- EXPLORE HYPOTHESIS THAT Q, L MIXINGS CAN BE UNDERSTOOD AS ("BOTTOM-UP") CABIBBO EXPANSIONS

BRIEFLY →

- ORIGIN OF LARGE MIXINGS ← "TOP-DOWN"

- SEESAW ALTERNATIVE w/ $\langle q_L \bar{q}_R \rangle$ → → NEW PHYSICS AT TeV SCALE

OUTLINE OF PRESENTATION

- THE DATA $\longrightarrow$ ν SM $U_{CKM} \cdot U_{MNSP}$

- IS CABIBBO HIDING IN THE LEPTON SECTOR?

  GENERAL LESSONS FROM Q-L UNIFICATION

  PHYSICS OF $\lambda \to 0$ LIMIT

  (CABIBBO HAZE)

- PARAMETRIZING $U_{MNSP}(\lambda)$

  PHENOMENOLOGICAL APPROACH

- THEORETICAL FRAMEWORK $\longrightarrow$

  1. ORIGIN OF LARGE ANGLES
     (W/IN SEESAW)

     (W/ RAMOND)

  2. SEESAW ALTERNATIVE $\longrightarrow$
     m_ν FROM QCD CONFINEMENT

     Q $\longrightarrow$ L CONNECTION

     (W/ H. DAVOUDIASL '05)

THE DATA: MASSES

ASSUME: 3 NEUTRINO MIXING

(CAVEAT: LSND. MINI BOONE ?)

SOLAR: $\Delta m^2_{\odot} \simeq 8 \times 10^{-5}\ eV^2$

ATMOSPHERIC: $\Delta m^2_{\oplus} \simeq 2 \times 10^{-3}\ eV^2$

COSMOLOGY (WMAP): $\sum_i m_i < 0.7\ eV$

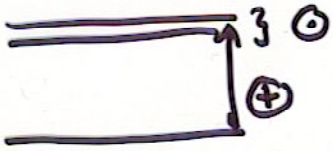
→ ULTRALIGHT MASSES

COMPARE → ($Q, L^+ \rightarrow$ O(MeV) ~~O(100 GeV)~~)

MASS PATTERNS →

- NORMAL HIERARCHY

- INVERTED



- QUASI-DEGENERATE

THE DATA – MIXINGS

LEPTON MIXING MNSP MATRIX

(3 FAMILIES)
(IGNORE LSND)

MAKI, NAKAGAWA, SAKATA '62
PONTECORVO '57

$$U_{MNSP} = R_1(\theta_\oplus)\, R_2(\theta_{13}, \delta_{MNSP})\, R_3(\theta_\odot)\, P$$

("DIRAC" on δ_{MNSP}; "MAJORANA" on P)

$$|U_{MNSP}| \cong \begin{pmatrix} \cos\theta_\odot & \sin\theta_\odot & \epsilon \\ -\cos\theta_\oplus \sin\theta_\odot & \cos\theta_\oplus \cos\theta_\odot & \sin\theta_\oplus \\ \sin\theta_\oplus \sin\theta_\odot & -\sin\theta_\oplus \cos\theta_\odot & \cos\theta_\oplus \end{pmatrix}$$

DATA (2005):

(3σ)

SOLAR: $\theta_\odot = 33.9^\circ \,{}^{+2.4^\circ}_{-2.2^\circ}$

HOMESTAKE, KAM, SUPERK, KAMLAND
SNO – nucl-ex/0502021

ATMOSPHERIC: $\theta_\oplus = 45^\circ \pm 10^\circ$

SUPER K, hep-ex/0501064

CHOOZ: $|\epsilon|^2 = \sin^2\theta_{13} < 0.05$

$\theta_{13} \lesssim 13^\circ$

CHOOZ
PALOVERDE

2 LARGE ANGLES
1 SMALL ANGLE

~~CP~~ PHASES – ?

COMPARE → QUARK MIXING :

$$U_{CKM} = R_1(\theta_{23}^{CKM})\, R_2(\theta_{13}^{CKM}, \delta_{CKM})\, R_3(\theta_{12}^{CKM})$$

$\theta_C \longleftrightarrow \theta_{12}^{CKM} = 12.96^\circ \pm 0.09^\circ$ CABIBBO ANGLE

$\theta_{23}^{CKM} = 2.37^\circ \pm 0.09^\circ$

$\theta_{13}^{CKM} = 0.21^\circ \pm 0.08^\circ$

PDG (2004) (DIRECT + UNITARITY)

3 SMALL ANGLES !

CP VIOLATION → 1 "DIRAC" PHASE δ

Jarlskog

INVARIANT MEASURE OF ~~CP~~ →

$$J = \mathrm{Im}\left(U_{ip}\, U_{jq}\, U_{iq}^*\, U_{jp}^*\right)$$

$$\sim \sin 2\theta_{12}^{CKM} \sin 2\theta_{13}^{CKM} \sin 2\theta_{23}^{CKM} \sin\delta_{CKM}$$

SM → $J_{CKM} \sim 10^{-5}$

$\delta_{CKM} \sim 60^\circ \pm 14^\circ$ (PDG)

1 LARGE PHASE

MIXINGS →

↓ CHALLENGE FOR FLAVOR PUZZLE →

EXPLAINING 2 LARGE, 1 SMALL MIXING ANGLE IN 3-FAMILY MODELS.

"NOT GENERIC!"

(QUARKS) 3 SMALL ANGLES → M_ν ~ DIAGONAL

1 LARGE, 2 SMALL → M_ν ~ DEGENERATE ROW OR COLUMN

(RANK(M_ν) < 3 AT LO.)

3 LARGE ANGLES → M_ν "ANARCHY"

2 LARGE, 1 SMALL →

SMALL ANGLE FINE-TUNING

UNLESS THEORY ENGINEERS CANCELLATION

(NON-ABELIAN ?)

USE Q-L UNIFICATION → LESSONS FROM QUARKS

QUARKS: WOLFENSTEIN PARAMETRIZATION

U_{CKM} EXPANSION IN CABIBBO ANGLE

$$\lambda \equiv \sin\theta_C = 0.22$$

$$U_{CKM} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$$J_{CP} \sim A^2\lambda^6\eta$$

PRACTICAL FOR PHENOMENOLOGY.
GUIDELINE FOR THEORY?

ASSUME:

- $\lambda \to 0$ LIMIT
  MEANINGFUL FOR THEORY

- U_{MNSP} ALSO AN EXPANSION IN λ

MORE ON THE $\lambda \to 0$ LIMIT

QUARK MIXINGS → $\theta_{12} \sim \lambda$, $\theta_{23} \sim \lambda^2$, $\theta_{13} \sim \lambda^3$

$U_{CKM} \to 1$ AS $\lambda \to 0$

MASS HIERARCHIES → MASS RATIOS MAY ALSO BE GOVERNED BY λ

QUARKS + CHARGED LEPTONS:

INTERFAMILY HIERARCHY: (AT $M \sim M_{GUT}$)

$\frac{m_u}{m_t} \sim \lambda^8$, $\frac{m_c}{m_t} \sim \lambda^4$

$\frac{m_d}{m_b} \sim \lambda^4$, $\frac{m_s}{m_b} \sim \lambda^2$

$\frac{m_e}{m_\tau} \sim \lambda^5$, $\frac{m_\mu}{m_\tau} \sim \lambda^2$

INTRAFAMILY HIERARCHY: (AT $M \sim M_{GUT}$)

$\frac{m_b}{m_t} \sim \lambda^3$ $\quad$ $\frac{m_b}{m_\tau} \sim 1$

NEUTRINOS:

$\sqrt{\frac{\Delta m^2_\odot}{\Delta m^2_\oplus}} \sim \lambda$ → VARIOUS PARAMS POSSIBLE

$\lambda \to 0$ → FERMION MASSES → 0 (SUBSET OF) → DEGENERATE SUBSPACE

FIRST, FOCUS ON MIXINGS ⟶

CABIBBO EFFECTS IN FERMION MIXING →

- QUARKS :

  DEVIATIONS FROM ZERO MIXING

  $(\lambda, \lambda^2, \lambda^3)$

- LEPTONS :

  DEVIATIONS FROM UNKNOWN MIXING

  (U_{MNSP} UNKNOWN AS $\lambda \to 0$)

"BARE" MIXINGS SCREENED BY

CABIBBO HAZE

LEPTONIC CABIBBO SHIFTS →

$O(\lambda) \to \lesssim 13°$

$\theta(\lambda^2) \to \lesssim 3°$

SYSTEMATIC CLASSIFICATION

OF LEPTONIC CABIBBO EFFECTS

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FIRST → MOTIVATE HYPOTHESIS

IS CABIBBO ANGLE EXPECTED IN LEPTON SECTOR ?

• LESSON FROM GRAND UNIFICATION →

LEAKAGE OF CABIBBO EFFECTS
FROM QUARKS TO LEPTONS

• NUMEROLOGY → HINTS OF CABIBBO IN THE DATA ?

SEESAW MECHANISM + GRAND UNIFICATION

SM: DIRAC FERMION MASSES

$$M_Q^D = U_Q D_Q V_Q^\dagger$$

M_Q^D: EM CHARGE; D_Q: DIAG. MASS E-VALS

QUARKS → $U_{CKM} = U_{2/3}^\dagger U_{-1/3}$

LEPTONS → $U_{MNSP} = U_{-1}^\dagger \hat{U}_0$

ν MASSES → SEESAW MECHANISM (E.G.)

$$M_\nu^{(seesaw)} = M_0^D M_M^{-1} M_0^{D\,T}$$

$$\hat{U}_0 = U_0 \mathcal{F}$$

WHERE $\mathcal{F} D_\nu \mathcal{F}^T = D_0 V_0^\dagger M_M^{-1} V_0^* D_0$

DATTA, LING, RAMOND '03

$$U_{MNSP} = U_{-1}^\dagger U_0 \mathcal{F}$$

$\mathcal{F}$: EXTRA SEESAW INGREDIENT

GRAND UNIPICATION →

RELATION B/W DIRAC MASS MATRICES

$$SU(5): \quad M^D_{-1/3} \sim M^{D\,T}_{-1}$$
$$SO(10): \quad M^D_{2/3} \sim M^D_0$$
$$\Big\} \rightarrow U_{-1/3} \sim V^*_{-1}, \quad U_{2/3} \sim U_0$$

$$U_{MNSP} = U^\dagger_{-1} U_0 \mathcal{F}$$
$$= \underline{V^T_{-1/3} U_{-1/3}} U^\dagger_{CKM} \mathcal{F}$$

DOWN QUARK SECTOR →

↕ (5 or SU(5))

IF $M^D_{-1/3} = M^{D\,T}_{-1/3}$ (SYMMETRIC YUKAWAS)

→ $\boxed{U_{MNSP} = U^\dagger_{CKM} \mathcal{F}}$

RAMOND '04

CABIBBO HAZE → 2 LARGE ANGLES IN $\mathcal{F}$ SHIFTED BY CABIBBO-SIZED EFFECTS

GRAND UNIFICATION →

EXPECT CABIBBO-SIZED PERTURBATIONS IN LEPTON AS WELL AS QUARK SECTOR

TRUE GENERICALLY FOR MODEL-BUILDING SCHEMES A LA FROGGAT-NIELSEN WITH

$$H f_{L_i} f_{R_j} \frac{\phi^{(n_{ij})}}{M} \qquad \frac{\langle\phi\rangle}{M} \sim \lambda$$

(WITH Q, L FLAVOR SYMM BROKEN BY ϕ)

CIRCUMSTANTIAL EVIDENCE ?

MORE "ν MEROLOGY" →

$$\theta_\odot \approx 45^\circ - \theta_C$$

$$\uparrow$$

$$\theta_\oplus \; ?$$

$$\theta_{13} \lesssim \theta_C$$

"QUARK-LEPTON COMPLEMENTARITY" (WELL STUDIED)

MINAKATA, SMIRNOV
MOHAPATRA
FRAMPTON
OHLSSON
KING
RODEJOHANN
⋮

HERE: CLASSIFY VARIOUS POSSIBILITIES

PARAMETRIZING U_{MNSP} →

SYSTEMATICS OF THE APPROACH

DEVELOP "WOLFENSTEIN PARAMETRIZATION(S)"
FOR THE LEPTON SECTOR

QUARKS : $U_{CKM}(\lambda) = \underline{1} + \theta(\lambda)$

LEPTONS : $U_{MNSP}(\lambda) = \underline{W} + \theta(\lambda)$

RANGE OF POSSIBILITIES FOR BARE LEPTON MIXINGS W

W PERTURBED BY UNITARY $V(\lambda)$

$$V(\lambda) = 1 + \theta(\lambda)$$

NEW FEATURE →

$$[W, V(\lambda)] \neq 0$$

INGREDIENTS →

1. BARE LEPTON MIXINGS : hep-ph/0510626

PARAMETRIZE U_{MNSP} IN $\lambda \to 0$ LIMIT →

$$W = R_1(\eta_\oplus)\, R_2(\eta_{13})\, R_3(\eta_\odot)\, P$$

ASSUME: "DIRAC" PHASES ABSENT

"MAJORANA" PHASES PRESENT

$P = \mathrm{diag}(e^{i\alpha_1}, e^{i\alpha_2}, e^{i\alpha_3})$

(ONLY PHASE DIFFERENCES OBSERVABLE)

α_{12} , α_{23}

W CHARACTERIZED BY # LARGE ANGLES →

✓ • 3 LARGE ANGLES.

CHOOZ ANGLE "DOWNSHIFTED" TO $\lesssim O(\lambda)$

✓ • 2 LARGE ANGLES. $(\eta_{13} = 0)$ (hep-ph/0503222)

CHOOZ ANGLE (+ DIRAC ~~CP~~) CABIBBO EFFECTS

✓ • 1 LARGE ANGLE. $(\eta_\odot = \eta_{13} = 0)$

CHOOZ + SOLAR ANGLES (+ DIRAC ~~CP~~) CABIBBO EFFECTS

X • 0 LARGE ANGLES? IMPLAUSIBLE.