Neutrino Mass and Implications Beyond the Neutrino Sector

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Why is neutrino mass physics important ?

☞ **Two major unresolved issues in particle physics**

➢ (i) ORIGIN OF MASS
(Issue: Higgs boson and its vev: SUSY, Extra Dimension etc. are likely to throw light on this)

➢ ORIGIN OF FLAVOR

Issues are origin of three generations, mixings, CP violation, strong CP etc.

(Neutrino oscillation and non-oscillation searches, B-physics, searches for rare processes will throw light on these questions.)

➢ Both VITAL to unravel the nature of new physics.

$m_\nu \neq 0$ and Flavor Physics for Leptons

☞

- $m_\nu = 0$ in the standard model; → e, μ, τ are "mass locked" (no mixings) and therefore Leptons are " FLAVOR STERILE" !

- Once $m_\nu \neq 0$, leptons develop a full flavor physics.

- One may hope that in the true theory quark and lepton flavor physics may be related. (as in GUT theories) or it may reveal new symmetries.

Plan of the talk

☞

- ➢ WHAT WE KNOW AND WHAT WE NEED TO KNOW ABOUT NEUTRINOS ?

CP violation in the ν sector:

- ➢ SEESAW MECHANISM AS A WAY TO UNDERSTAND NEUTRINOS AND WHAT DOES IT TELL US ABOUT NEW PHYSICS BEYOND THE NEUTRINO SECTOR

(i) Leptogenesis and lepton edm;

(ii) Grand unification and lepton flavor violation

(iii) Possible signature in the B-sector.

WHAT WE KNOW :MIXINGS:

☞ $m_{\nu_i} \neq 0$; $\theta_{ij} \neq 0$

- $$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\alpha i} K \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$
- where $U_{PMNS} =$
$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & c_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$
- $K \; = \; diag(e^{i\phi_1}, e^{i\phi_2}, 1)$

☞ **VALUES OF θ_{ij} at 3σ**

- SOLAR: $sin^2 2\theta_{12} \simeq 0.71 - 0.93$
- ATMOS: $sin^2 2\theta_{23} \simeq 0.89 - 1.00$
- REACTOR: $\theta_{13} \leq 0.23$

MASSES

☞ **We only know mass two difference squares**

ATMOS: 1.4×10^{-3} **eV**$^2 \leq |\Delta m^2_{13}| \leq 3.3 \times 10^{-3}$ **eV**^{2}**;** **(**3σ**)**

MINOS result:

$$\Delta m^2_{13} \;=\; 3.05^{+0.60}_{-0.55}(stat) \pm 0.12(syst) \times 10^{-3}\ \textbf{eV}^2;$$

SOLAR: 7.2×10^{-5} **eV**$^2 \leq |\Delta m^2_{12}| \leq 9.3 \times 10^{-5}$ **eV**^{2}**;** **(**3σ**)**

WHAT WE DO NOT KNOW

☞ Mass Pattern:

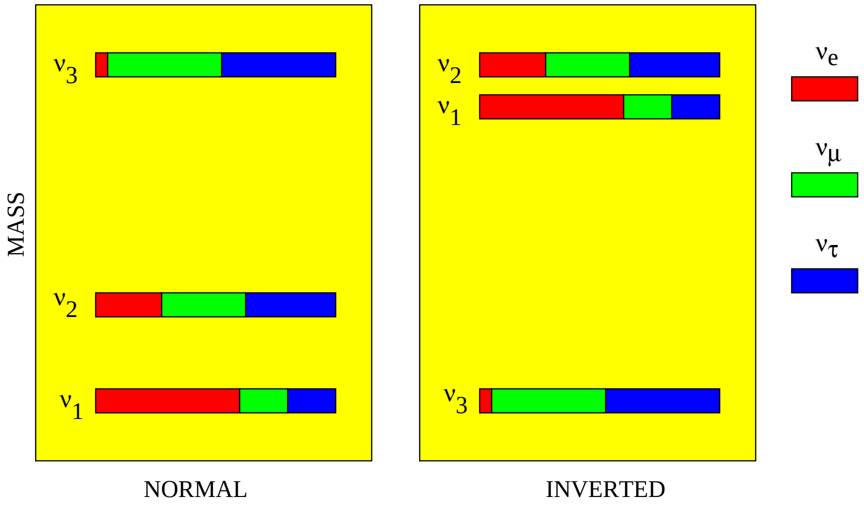


Figure 1: Two possible pattern of masses; Compare with quarks for which $m_{u,d} \ll m_{c,s} \ll m_{t,b}$

(iii) Quasi-degenerate: $m_1 \simeq m_2 \simeq m_3$

☞ **Is neutrino its own antiparticle ? Signal: ν-less double beta decay:** $2N \longrightarrow 2P + 2e^{-}$

☞ **What is θ_{13} and is there CP violation in the lepton sector ?**

CP violation in the neutrino sector

☞ **Neutrino mixing matrix:**

$$U_{MNSP}K \simeq \begin{pmatrix} ce^{i\phi_1} & se^{i\phi_2} & s_{13}e^{-i\delta} \\ -\frac{s}{\sqrt{2}}e^{i\phi_1} & \frac{c}{\sqrt{2}}e^{i\phi_2} & \frac{1}{\sqrt{2}} \\ +\frac{s}{\sqrt{2}}e^{i\phi_1} & -\frac{c}{\sqrt{2}}e^{i\phi_2} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$c = cos\theta_{\odot}; s = sin\theta_{\odot}$.

Unlike the quark sector, for 3 Gen, there are three phases;

$\phi_{1,2}$ **are Majorana phases and** δ **is the Dirac phase.**

Bilenky, Hosek, Petcov (80); Schecter, Valle (80); Doi et al. (81); Kayser (89).

☞ **Analog of** $J^{\ell}_{CP} \sim \frac{1}{4}sin2\theta_{\odot}sin\theta_{13}sin\delta \gg J^{q}_{CP}$

Only Dirac phase is measurable in oscillations.

Looking for Dirac CP phase

☞ **(i)** $P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \simeq 16 J^\ell_{CP} K_{12} K_{23} K_{31} \neq 0$ **where**
$K_{ii'} \equiv sin[1.27 \delta m^2_{ii'} (eV^2) \frac{L(km)}{E(GeV)}]$**;**

(ii) If θ_{13} is known and sizable and mass hierarchy is determined independently, Looking only at $P(\nu_\mu - \nu_e)$ also can uncover CP violation:

☞ **long base line experiments NoVa, T2K, T2HK .**

CP coverage in proposed experiments

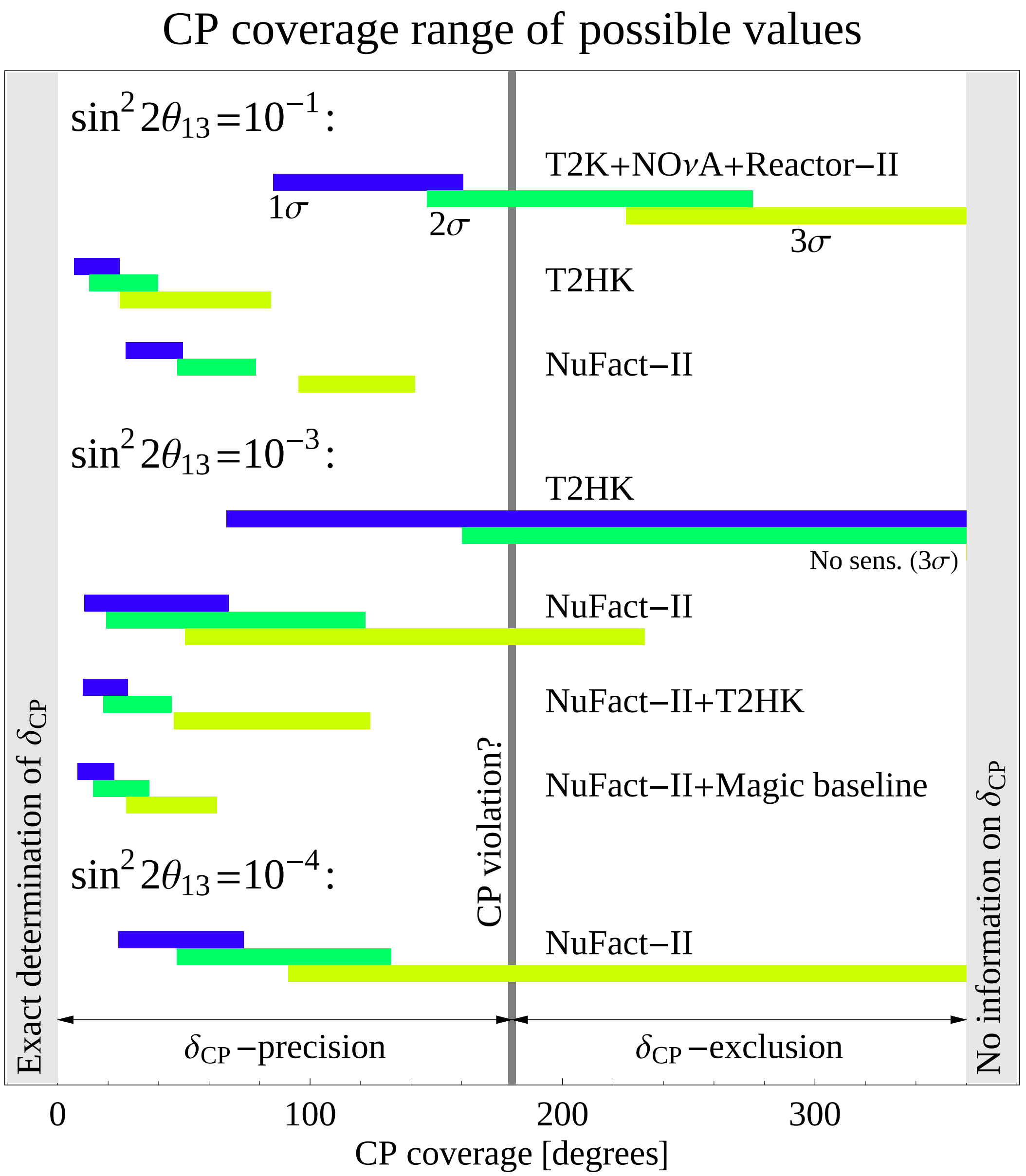


Figure 2: **Lindner, Huber, Winter (2004): CP coverage summary by various proposed expts.)**

How to seek the Majorana phase ?

☞ **Oscillations cannot probe the Majorana phases $\phi_{1,2}$**

Possibility in $\beta\beta_{0\nu}$ decay

$$M_{\beta\beta} \propto [m_1 c^2 e^{2i\phi_1} + m_2 s^2 e^{2i\phi_2} + m_3 s_{13}^2 e^{-2i\delta}]$$

For quasidegenerate neutrino case:

$$M_{\beta\beta} \propto m_0 \sqrt{[1 - sin^2 2\theta_\odot sin^2(\phi_1 - \phi_2)/2]}$$

m_0 can be measured in Katrin if $m_0 \geq 0.2$ eV so that the phase difference $\phi_1 - \phi_2$ can be measured in $\beta\beta_{0\nu}$ decay, if neutrinos are quasidegenerate as has been claimed in the Heidelberg-Moscow Ge expt.

Process inherently CP even; Is there a CP odd effect from Majorana phases?

Manifest CP violation and Majorana phases

de Gouvea, Kayser, RNM, 2003

☞ **Two examples of manifest CP violating processes**

Ex. 1: $A(\nu_\alpha \rightarrow \bar{\nu}_\beta) = \Sigma_i \lambda_i U_{\alpha i} U_{\beta i} \frac{m_i}{E} e^{-im_i^2 L/2E}$

Manifestly CP violating observable:
$\Gamma - \bar{\Gamma} = \frac{sin^2 2\theta}{E^2} m_1 m_2 sin \frac{\Delta m^2}{2E} sin(\phi_1 - \phi_2)$**:**
Unfortunately not very observable!

☞ **A much more interesting Example:**

$\Gamma(N_R \rightarrow \ell^- + H^+) - \Gamma(N_R \rightarrow \ell^+ + H^-)$**:**
For superheavy RH neutrinos, this is relevant in the early universe; for TeV RH neutrinos, could be testable in colliders and lepton flavor violating processes.

θ_{13} and lepton flavor physics

☞ **An example of how a high precision measurement of lepton mixing angle θ_{13} can shed light on lepton flavor physics.**

Present atmospheric neutrino data suggests a possible $\mu - \tau$ exchange symmetry for lepton.

A very small θ_{13} suitably correlated to $\pi/4 - \theta_{23}$ will provide strong evidence in favor of that.

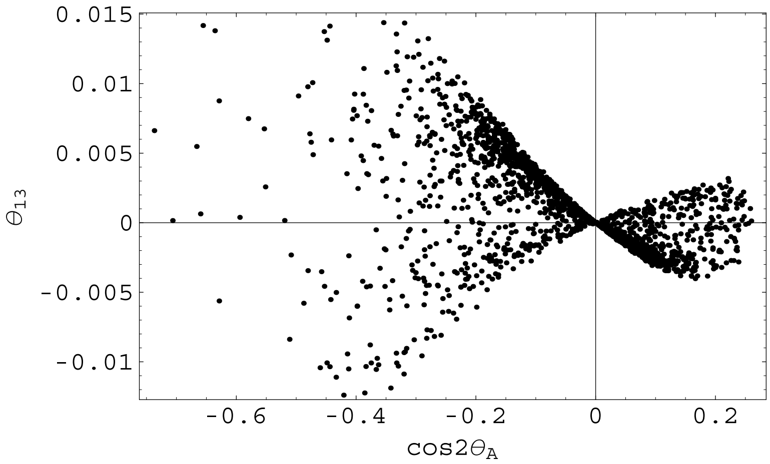


Figure 3: **Departure from $\mu - \tau$ symmetry and correlation between θ_{13} and θ_A Yu and RNM**

Challenges of neutrino mass

☞ **(i) Why $m_\nu \ll m_{e,u,d}$?**

(ii) How to understand the large mixings ?
or why the neutrino mass matrix looks as follows:

☞ **Normal Hierarchy:**e, μ, τ **mass eigenstates.**

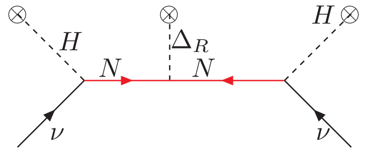
➢ $\mathcal{M}_\nu = \sqrt{\Delta m^2_A} \begin{pmatrix} d\epsilon^n & b\epsilon & a\epsilon \\ b\epsilon & 1+\epsilon & 1 \\ a\epsilon & 1 & 1+c\epsilon \end{pmatrix}; n \geq 1.$

➢ whereas

$$M_q \sim m_{t,b} \begin{pmatrix} \lambda^4 & b\lambda^3 & a\lambda^3 \\ b\lambda^3 & \lambda^2 & \lambda^2 \\ a\lambda^3 & \lambda^2 & 1 \end{pmatrix}.$$

Small m_ν and Seesaw Mechanism

☞ **Std model + RH neutrino N_R**



☞ $\mathcal{M}_\nu \simeq -\frac{h_\nu^2 v^2}{M_R}$; $\to m_{\nu_i} \ll m_{u,d,e\ldots}$.

Minkowski (77); Gell-Mann, Ramond, Slansky; Yanagida; Glashow; R. N. M., Senjanovic (1979)

Implications of Seesaw

☞

- ➢ Seesaw breaks $B - L$ and $\Delta(B - L) = 2 \rightarrow$ leads to Majorana neutrinos and nonzero $\beta\beta_{0\nu}$ decay
- ➢ Typical range of seesaw scales $M_{seesaw} \sim 10^{11} - 10^{15}$ GeV, to fit atmospheric data ($m_{\nu_3} \sim 0.05$ eV) for $m_{D,33} \sim m_\tau - m_t$.
- ➢ Masses of the RH neutrinos close to GUT scale which has implications for cosmology as well as perhaps grand unification of forces.
- ➢ Neutrino flavor pattern is a consequence of flavor structure of RH neutrinos and can therefore be very different from that of quarks.

Flavor physics implications from Seesaw

☞ **Suppose RH neutrinos are mass eigenstates; then large neutrino mixings imply large 23 and 33 elements of Dirac coupling $h_D \bar{L} H N_R$.**

Without supersymmetry, seesaw has no low energy consequences beyond the neutrino sector e.g. for LFV;

However, in supersymmetric theories, superpartners remember high scale effects through radiative corrections; these can induce large 23 and 12 slepton mixing, which in turn can induce significant $\tau \rightarrow \mu + \gamma$ and $\mu \rightarrow e + \gamma$.

Borzumati and Masiero

Lepton flavor violation in supersymmetric see-saw models

☞ **Large atmospheric mixing leads to observable** $\mu \to e + \gamma$

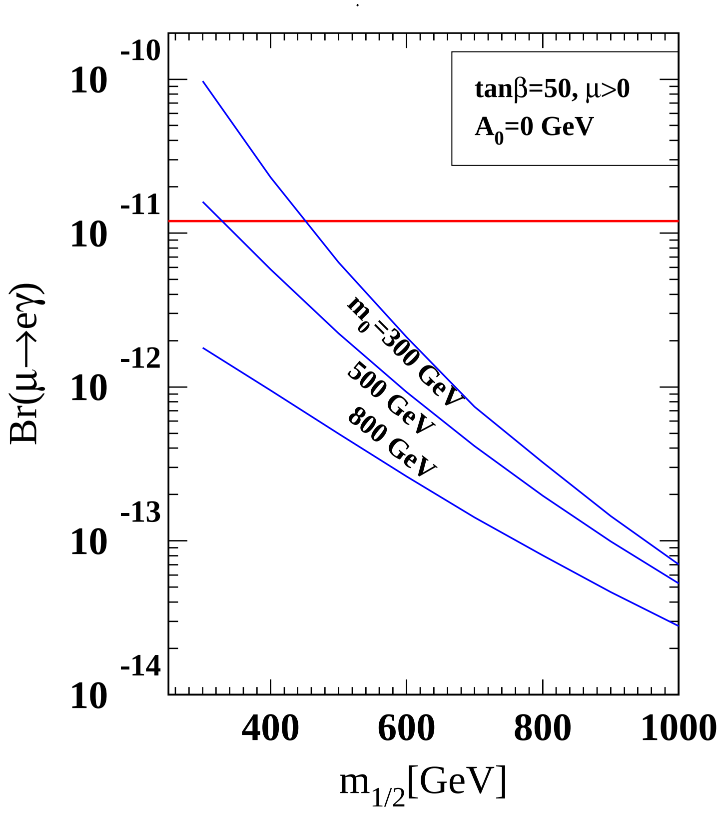


Figure 4: $\mu \to e + \gamma$ in a particular class of seesaw models (Dutta, Mimura, RNM,2005)

☞ **Present upper limit:(Los Alamos MEGA expt:** $B \leq 1.2 \times 10^{-11}$**; MEG (PSI) goal:** 10^{-14}**)**

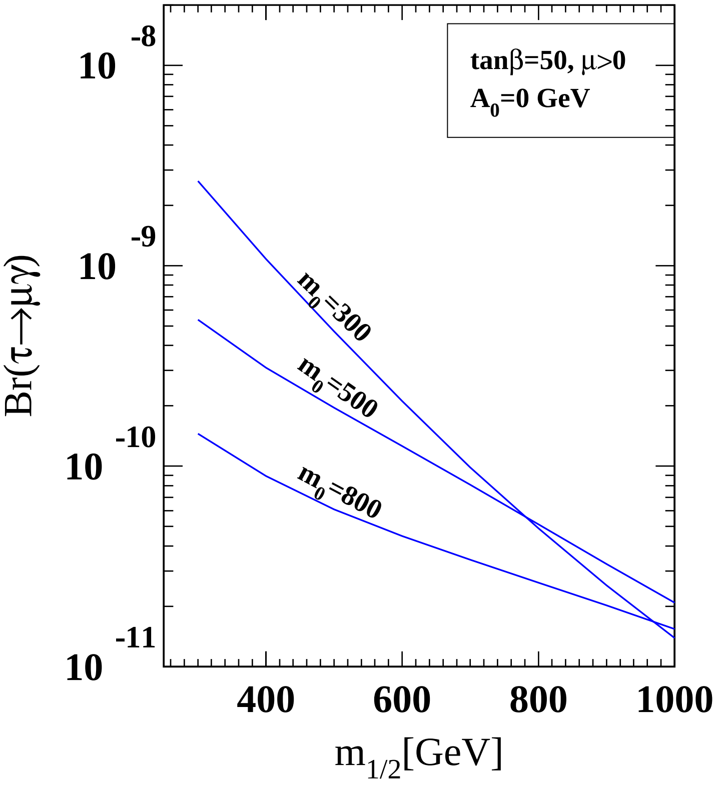


Figure 5: $\tau \longrightarrow \mu + \gamma$ in the same seesaw model (Dutta, Mimura, RNM,2005)

Seesaw and Understanding the origin of matter

☞ **why is $\frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6 \times 10^{-10}$?**

- If there is CP violation in the lepton sector (in particular in RH neutrino couplings), then
- $\Gamma(N_R \rightarrow \ell + H) - \Gamma(N_R \rightarrow \bar{\ell} + H) \neq 0 \rightarrow$ lepton asymmetry;
- baryon violation at the weak scale converts the lepton asymmetry into baryon asymmetry.
- Same physics used for generating small neutrino masses.
- Therefore in generic seesaw models leptogenesis implies CP violation in the neutrino sector.
- The hope is that discovery of neutrino CP violation would throw light on the important cosmological question of origin of matter.

Fukugita, Yanagida, 1986; Kuzmin, Rubakov and Shaposnikov (85)

Lepton edms as tests of Seesaw, leptogenesis

☞ **In leptogenesis models, CP violation will “sip” down from high scale to the neutrino mixings via the seesaw mechanism and can give rise to effects such elctron and muon edm.**

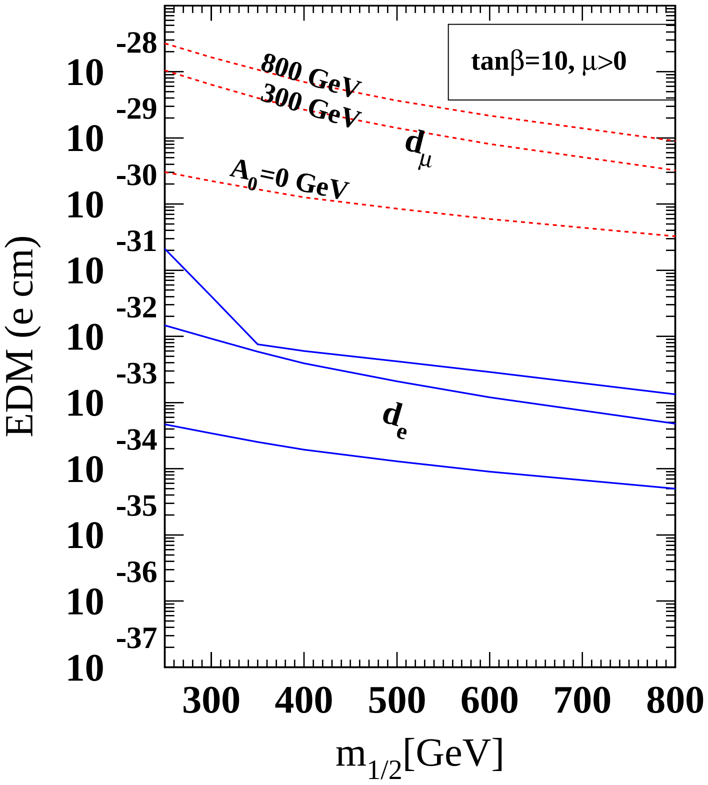


Figure 6: Typical values of electron and muon edm in seesaw models that explain the origin of matter: (Dutta and RNM, 2003)

☞ Present expt limits and future possibilities

d_e : **Now:** $\leq 7 \times 10^{-28}$ **ecm; Future:** 10^{-32} **ecm;**

d_μ : **Now:** $\leq 3.7 \times 10^{-19}$ **ecm; Future:** $10^{-24} - 10^{-26}$ **ecm;**

Implications for quarks

☞ Hints from data

- ➢ Recall the three generation mass matrix for ν's.
- ➢ $$\mathcal{M}_\nu = \sqrt{\Delta m^2_A}\begin{pmatrix} d\epsilon^n & b\epsilon & a\epsilon \\ b\epsilon & 1+\epsilon & 1 \\ a\epsilon & 1 & 1+c\epsilon \end{pmatrix}; n \geq 1.$$
- ➢ Compare with: $$\mathcal{M}_d = m_b\begin{pmatrix} d\lambda^4 & b\lambda^3 & a\lambda^3 \\ b\lambda^3 & \lambda^2 & \lambda^2 \\ a\lambda^3 & \lambda^2 & 1 \end{pmatrix};$$
- ➢ $$\epsilon \simeq \sqrt{\frac{\Delta m^2_\odot}{\Delta m^2_A}} \simeq \lambda$$
- ➢ Is this an indication of quark-lepton connection ? We explore this later.

m_ν and Grand unification

☞

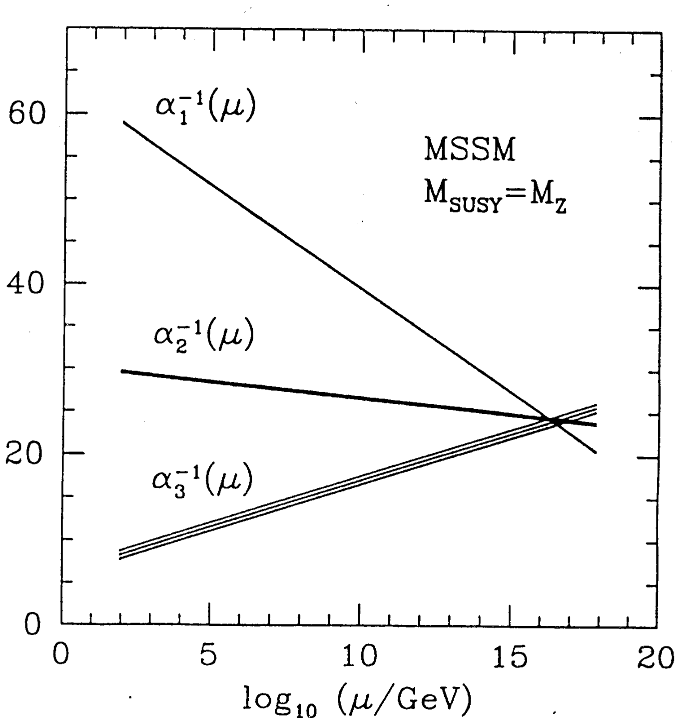


Figure 7: Coupling unification in supersymmetric theories

$M_U \simeq 2 \times 10^{16}$ GeV; not far from $M_{seesaw} \sim 2 \times 10^{14}$ GeV

$M_R \simeq M_U$

☞

- raises the hope that seesaw scale and GUT scale are same;
- Perhaps neutrino masses and mixings can be predicted due to higher symmetry of GUT theories which will reduce number of free parameters;
- Key question is what is the GUT theory ?

SO(10) SUSY GUT and neutrinos

☞ **unification of all 16 fermions of one generation**

- ➢ $\begin{pmatrix} u & u & u & \nu \\ d & d & d & e \end{pmatrix}_{L,R}$ into **16** dim. rep of SO(10)
- ➢ Contains the N_R needed for seesaw automatically
- ➢ Contains the B-L subgroup which broken appropriately, gives R-parity as a natural symmetry and hence a stable dark matter
- ➢ None of these properties hold for SU(5)

SO(10) scenarios and their predictions

☞ **Key issue is how to understand the large mixings leptons while keeping quark mixings small .**

Two ways:

- **Lopsided SO(10) models**

Albright, Barr; Ji, Li, RNM (2005)..

☞ **Large θ_A is related to large $s_R - b_R$ mixing.**
-Together with supersymmetry, this can lead to large $\tilde{b}_R - \tilde{s}_R$ mixing $\delta_{RR,23} \sim 0.5$. This adds new

contribution to $b \to s\gamma$ and ΔM_s, edm of the strange quark etc. and can lead to observable effects.

☞ **If $\delta_{RR,23}$ is complex, it can also contribute to mercury edm.**

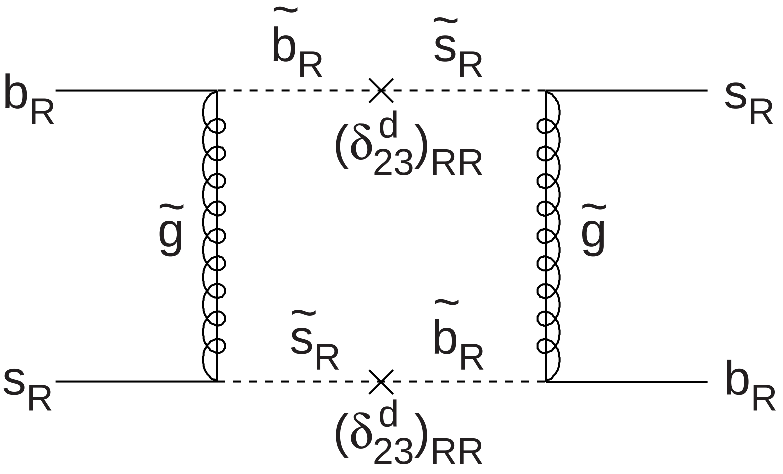


Figure 8: **Gluino contribution to ΔM_s**

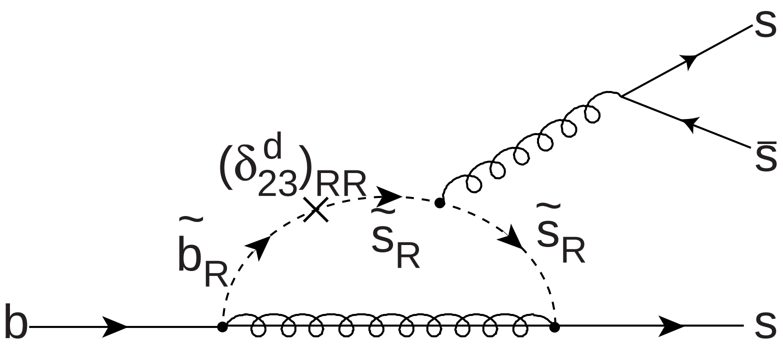


Figure 9: **Contribution of $\delta_{RR,23}$ to $b \rightarrow s + q\bar{q}$**

Present status

☞ • $\Delta M_s \propto \delta_{RR,23}\delta_{LL,23}$
DØ collaboration report (2006):
$17\,\mathrm{ps}^{-1} \;<\; \Delta M_s \;<\; 21\,\mathrm{ps}^{-1} \quad 90\%\ \mathrm{C.L.}\ ,$

- $2.0 \times 10^{-4} \leq B(b \rightarrow s + \gamma) \leq 4.5 \times 10^{-4}$

- **Hg edm limit:** $d_{Hg} \leq 1.9 \times 10^{-28}$ **ecm;**

Limits $\delta_{LL,23}\delta_{LR,33}\delta_{32,RR}$**.**

Implies following constraints on $\delta_{RR,23}$**:**

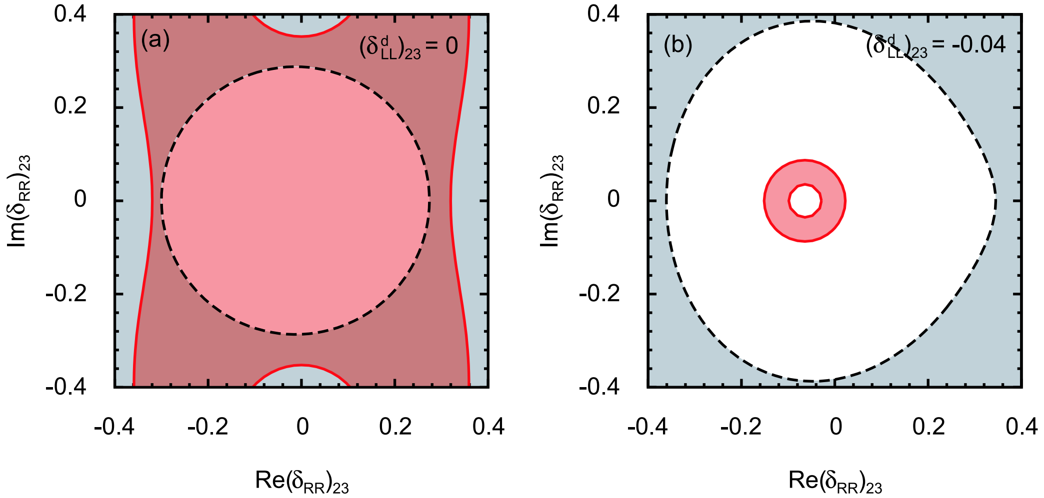


Figure 10: **(a)** $\delta_{LL,23} = 0$ **and (b)** $\delta_{LL,23} = -0.04$**;** $m_{\tilde{g}} = m_{\tilde{q}} \sim 500$ **GeV; Endo and Mishima (2006)**

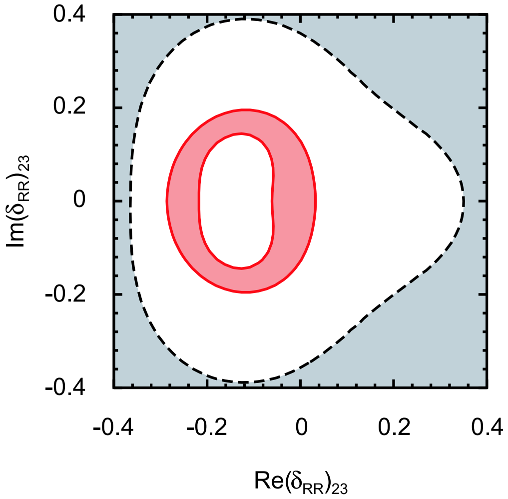


Figure 11: **Same for $m_{\tilde{g}} = 300$ GeV and $m_{\tilde{q}} \sim$ TeV; Endo and Mishima (2006)**

☞ **These upper limits are barely consistent with prediction of lopsided neutrino models-already mercury edm upper limit requires fine cancellations. A class of models for neutrino mass are now being tightly constrained by B-observations.**

Minimal SO(10) models

☞ **Lopsided models need extra symmetries to ensure stable dark matter and have too many parameters; so to make predictions, one needs to impose extra symmetries.**

An alternative route that avoids these problems:

Babu, RNM (92); Bajc, Senjanovic, Vissani (2002); Goh, RNM, Ng (03)

☞ • **Here large leptonic mixings arise due to sumrule for neutrino mass at** M_U

$$\mathcal{M}_\nu \;=\; 10^{-11}(M_d - M_l)$$

Large neutrino mixings from $b-\tau$ unification

☞ **Note that:**

$$\mathcal{M}_{d,l} = m_{b,\tau}\begin{pmatrix} d\lambda^4 & b\lambda^3 & a\lambda^3 \\ b\lambda^3 & \lambda^2 & \lambda^2 \\ a\lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

This implies that:

$$\mathcal{M}_\nu \; = m_b c \begin{pmatrix} \lambda^4 & \lambda^4 & \lambda^3 \\ \lambda^4 & \lambda^2+\lambda^3 & \lambda^2 \\ \lambda^3 & \lambda^2 & \lambda^2 \end{pmatrix}$$

since at GUT scale $m_b \simeq m_\tau(1+\lambda^2)$

(λ is Cabibbo angle.)

- **Leads to large mixings θ_{23} and large θ_{12}; measurable θ_{13}**
- $\sqrt{\frac{\Delta m^2_\odot}{\Delta m^2_A}} \sim \lambda$

Quark mixing parameters λ explains lepton flavor pattern!!

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Predictions of this class of SO(10) models with CP violation included

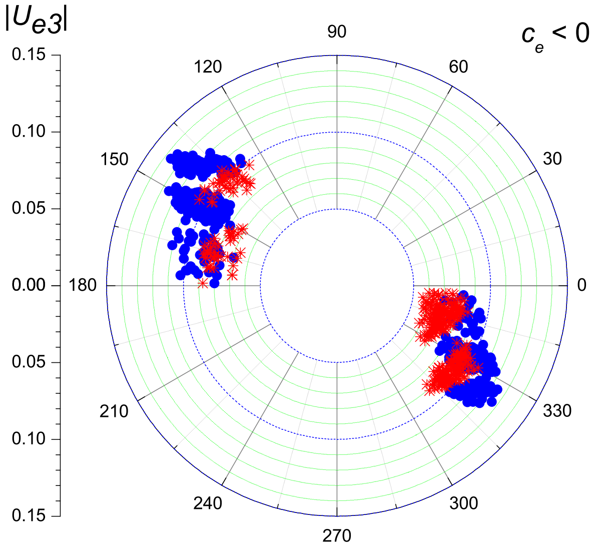

Figure 12: Prediction of the leptonic CP phase in an SO(10) model as a function of U_{e3}.**Dutta, Mimura and RNM (2005)**

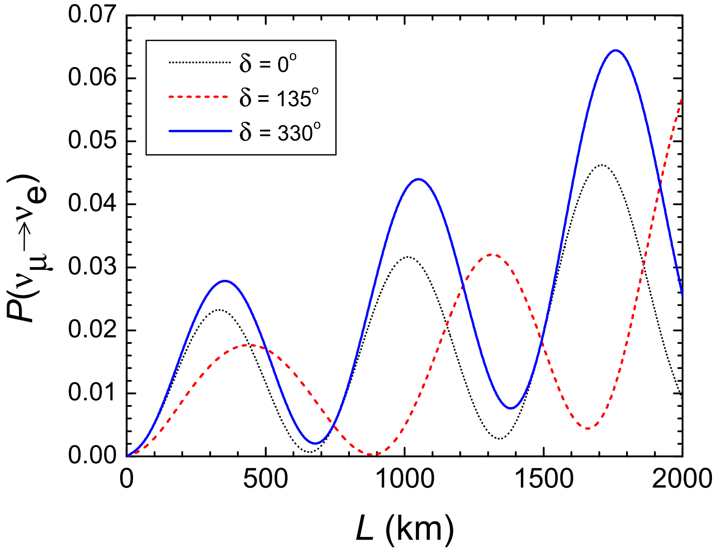

Figure 13: $P_{\nu_\mu - \nu_e}$ as a function of L(km) DMM(2005)

☞ **Testable in upcoming long base line experiments !!**

What progress have we made towards a unified unravelling of quark and lepton flavor puzzle ?

☞ **We now have simple grand unified frameworks that correlate quark and lepton flavor structure making testable predictions !!**

Given their disparate flavor structure, it was not obvious that this could be done.

Next step would be to discover flavor symmetries that would make this flavor structure follow naturally and even perhaps predict as much of it as possible.

Possible such symmetries are S_4, A_4 or $SU(3)$ etc.

Conclusions from Neutrino observations

☞ • Seesaw a dominant paradigm:
that connects leptons to quarks via grand unified theories.

• Seesaw idea testable in LFV, edm of leptons.

• B-physics already on the verge of ruling out neutrino GUT models.

• CP violating effects in leptons connect neutrino physics to origin of matter and must therefore be searched.

• On the whole, the answers to the flavor puzzle of both quarks and leptons may be hidden in the neutrino sector and GUT theories are providing viable frameworks for exploring this possibility.