Neutrino Mass and Unification

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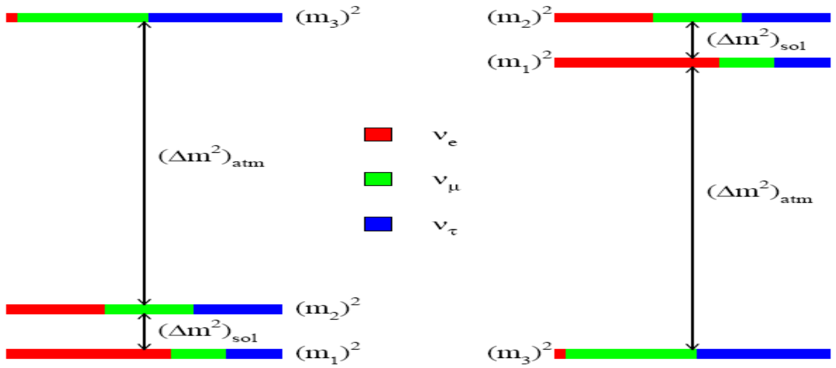
Implications of neutrino mass results for Theory

- **What we may have learnt ?**
- **What we need to learn and how ?**

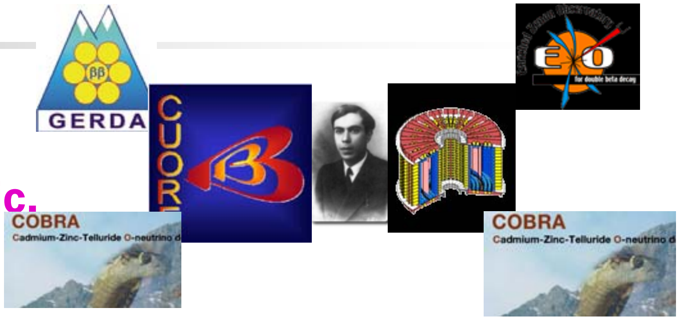
A subjective overview

Present information: Masses and mixings

- **Masses:** $\Delta m^2_{sol} \cong 7.67\times 10^{-5} eV^2$ **;** $\Delta m^2_{Atm} \cong 2.39\times 10^{-3} eV^2$
- **Mixings:** $\sin^2\theta_{12} \cong .312; \sin^2\theta_{23} \cong .466$ **;** $\sin^2\theta_{13} \le .04$
- **Overall mass scale:** < .1- 1 eV (roughly) (WMAP,..)
- **Mass ordering not known:**



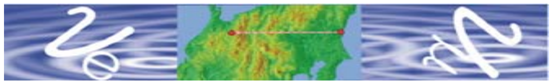
Need to know…



(i) Majorana or Dirac $\beta\beta_{0\nu}$

(Nucl matrix element : Fassler et al.; Talk by Simkovic, Suhonen ..)

(ii) Absolute mass scale:



(iii) Mass ordering:

(iv) Value of θ_{13}

(v) CP phase

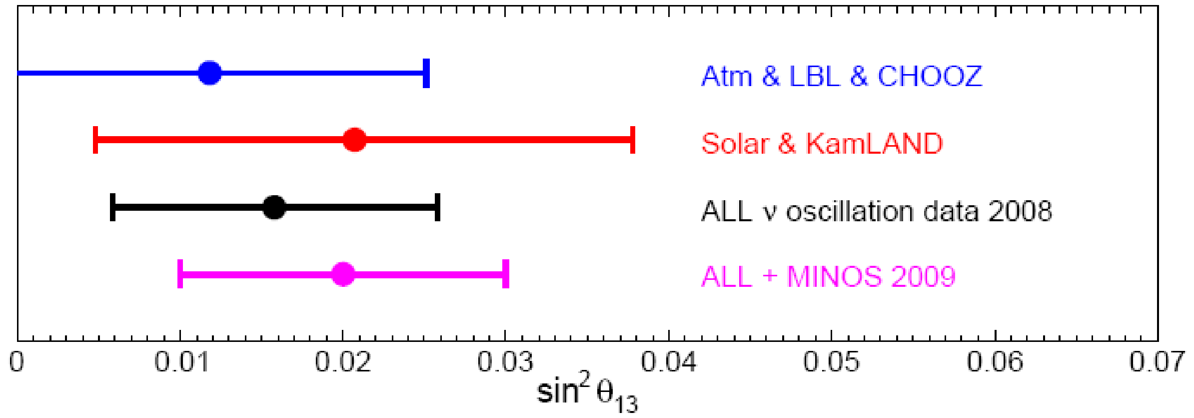
Dirac vs Majorana

- Very important for determining the nature of new physics:
- Can we tell experimentally?
- Observe $\beta\beta_{0\nu}$ → Majorana.
- If no signal till 20 meV→ could be Majorana with normal hierarchy;
- However, no $\beta\beta_{0\nu}$ signal till 20 meV + $\boxed{\Delta m_{23}^2 < 0}$ from long Baseline expts → strong hint for Dirac

Rest of this talk assumes Majorana nu

What is value of $\boxed{\theta_{13}}$?

- **Recent indications ?** (Fogli, Lisi, Marrone, Pallazo and Rotunno'08)



Too early for definite conclusion--However

Value of θ_{13} significant for new physics

Goal of Theory

- Determining and understanding the Neutrino mass matrix :
- Two parts to the story:

$$\boxed{M_\nu = m_\nu \times A_F}$$

(i) Scale m_ν

(ii) Flavor structure A_F

(The neutrino matrix)

Challenges

(i) Scale issue: Why $\boxed{m_\nu << m_{q,l}}$ **? :**

(ii) Flavor issues: A_F **?**

A. Milder mass hierarchy compared to quarks and charged leptons: $\boxed{\frac{m_{sol}}{m_{atm}} \approx \theta_C >> \frac{m_\mu}{m_\tau}, \frac{m_s}{m_b}}$

B. Neutrino mixing angles much larger than quark mixings: e.g. $\boxed{V^{l}_{23} \approx 0.7 >> V_{23}^{CKM} \approx 0.04}$ **etc.**

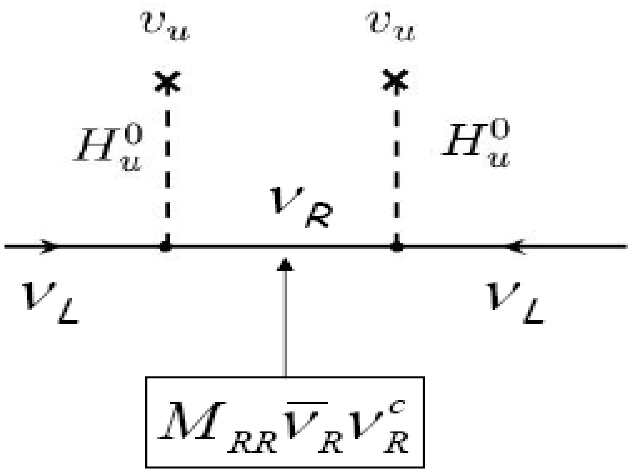
C. Quarks and leptons so different- are they unifiable ?

Why $\boxed{m_\nu << m_{q,l}}$?

Seesaw Paradigm

- Add right handed neutrinos N_R to SM with Majorana mass:

$$L_Y = h_\nu \bar{L} H N_R + M_R N N$$



$$\boxed{m_\nu \cong -\frac{h_\nu^2 v_{wk}^2}{M_R}}$$

- **Standard seesaw (Type I):**

- **Minkowski,Gell-Mann, Ramond, Slansky,Yanagida, Mohapatra,Senjanovic,Glashow**

Neutrino mass → new symmetry of Nature: B-L

- Why B-L Symmetry ?
- Seesaw scale M_R breaks this symmetry
- The question is why M_R << M_{Pl} ?
- Having a B-L symmetry explains this.
- Is it a global or local symmetry ?
- Most likely local since adding RH nu’s to SM makes B-L local sym. → Z’

Need to learn:

What is the B-L Scale M_R ?

- Two extreme cases: $m_D = hv_{wk}$
- $\boxed{m_D \approx m_t}$ (suggested by Q-L unif as in GUTs) **leads to**

  $M_R \approx 10^{14} GeV$ **-SCALE CLOSE TO GUT SCALE-**
- **Corresponding theory of seesaw is: SO(10) :**

- $\boxed{m_D \approx m_e}$ **Scale much lower** $M_R \approx$ **TeV ;**
- **Theory is left-right model based on**

  $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ **motivated independently**
  Considerations e.g. parity, CP etc.
  Physics accessible to LHC, $\beta\beta_{0\nu}$ decay etc.

Double (Inverse) Seesaw

- **Low scale seesaw with no small couplings:**
- RH neutrinos + 3 additional gauge singlet fermions → 3x3 neutrino matrix:

$$\begin{pmatrix} 0 & hv_{wk} & 0 \\ hv_{wk} & 0 & M \\ 0 & M & \mu \end{pmatrix}$$

$$m_D = hv_{wk}$$ **(RNM, Valle, 86)**

$$m_\nu \cong -m_D^T M^{-1} \mu M^{-1} m_D$$

- μ determines **both scale and flavor** structure;
- m_D decoupled from scale unlike type I; Seesaw scale can be in TeV range without small Yukawas

Second Challenge for theory: Large lepton mixings:

- **Could they be hints of new symmetries for leptons:**
- **(i) Near maximal** θ_{23}: very suggestive of $\mu-\tau$ exchange sym. for neutrino matrix: How maximal ?

(ii) Solar angle $\theta_{12} \approx 35^0$

suggests tribimaximal scheme if $\theta_{13} = 0$ **->**

$$V = \begin{pmatrix} \frac{\sqrt{6}}{3} & \frac{\sqrt{3}}{3} & 0 \\ -\frac{\sqrt{6}}{6} & \frac{\sqrt{3}}{3} & \frac{\sqrt{2}}{2} \\ \frac{\sqrt{6}}{6} & -\frac{\sqrt{3}}{3} & \frac{\sqrt{2}}{2} \end{pmatrix}$$

Wolfenstein; Harrison,Perkins,Scott; Xing,

The Neutrino Matrix:

- Flavor of the Neutrino flavor research

Find A_F

Generic mass matrix (NH) $\varepsilon_i \approx \lambda_{Cabibbo} << 1$

θ_{23} NEAR MAXIMAL

θ_{23} maximal

TBM

$$\begin{pmatrix} \varepsilon_5^{n\geq 1} & \varepsilon_4 & \varepsilon_3 \\ \varepsilon_4 & 1+\varepsilon_1 & -1 \\ \varepsilon_3 & -1 & 1+\varepsilon_2 \end{pmatrix} \rightarrow \begin{pmatrix} \varepsilon_5^{n\geq 1} & \varepsilon_3 & \varepsilon_3 \\ \varepsilon_3 & 1+\varepsilon_1 & -1 \\ \varepsilon_3 & -1 & 1+\varepsilon_1 \end{pmatrix} \rightarrow \begin{pmatrix} \varepsilon_1 & \varepsilon_3 & \varepsilon_3 \\ \varepsilon_3 & 1+\varepsilon_1 & -1+\varepsilon_3 \\ \varepsilon_3 & -1+\varepsilon_3 & 1+\varepsilon_1 \end{pmatrix}$$

$\rightarrow \mu \leftrightarrow \tau$ sym.

5 parameters

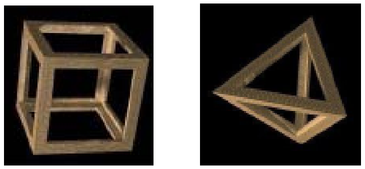
3 param.

2 param.

Understanding the pattern

- **GUTs:** **SO(10)**
- **Family symmetries** **motivated by TBM**:

$$S_{2(\mu-\tau)} \subset S_3, S_4, A_4, Z_2, \Delta(3n^2),\ldots$$

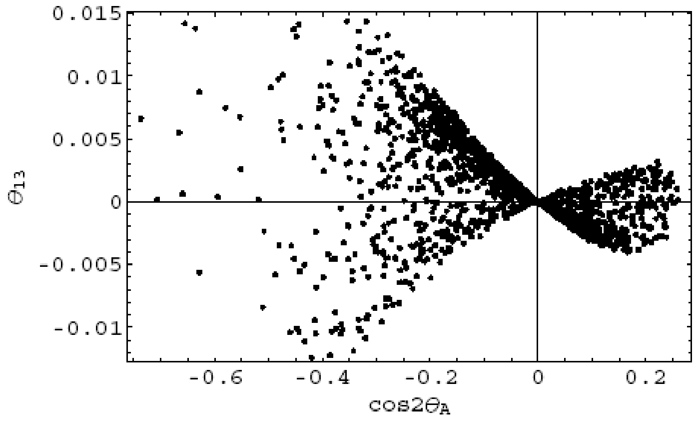


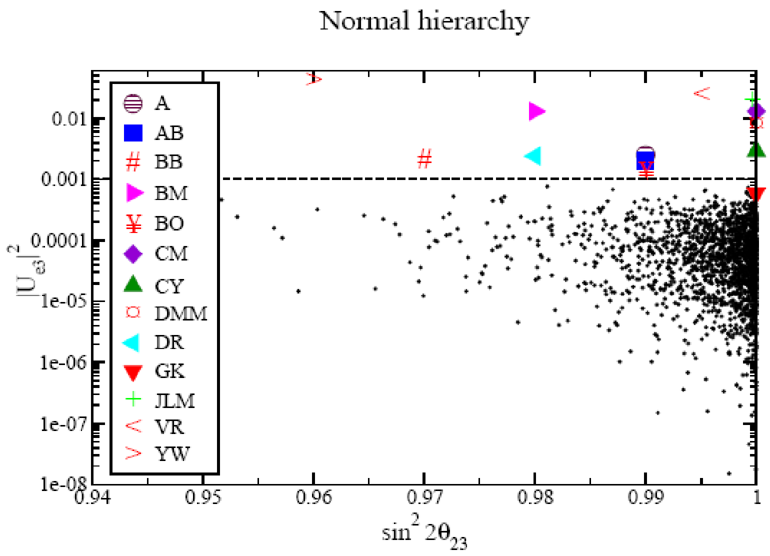
- **Non-zero θ_{13} will provide important clue about new physics- is it symmetry + corrections or perhaps TBM an accident ?**

(For extensive references, see G. Altarelli, Fermilab Neutrino summer school lectures; Talks at this school by M. Chen, R. Volkas, F. Feruglio)

θ_{13} :Discriminator between Symmetry vs GUTs

- **mu-tau sym** **TBM** **(Albright,Rodejohann)**





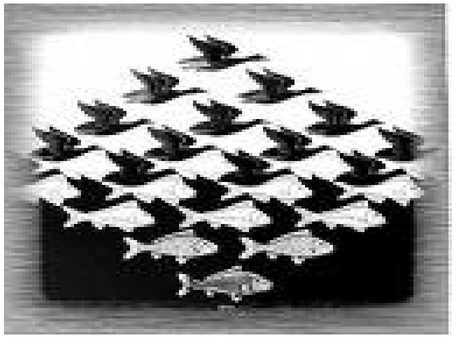
- correlation with atm mixing –
- GUT predictions generally larger than 0.03.

NEUTRINO MASS :A SIGNAL OF GRAND UNIFICATION ?

Grand unification hypothesis: all forces and all matter become one at high energies no matter how different they are at low energies.

Leptons→

quarks→



become same.

---- Explains charge quantization;

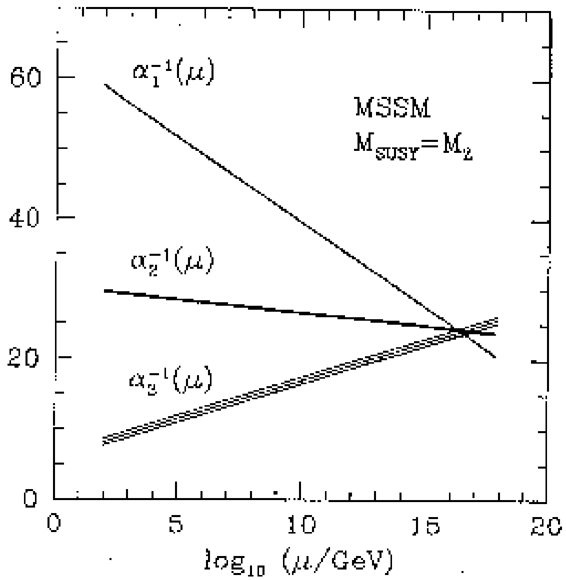
----High scale goes well with ideas in cosmology ;

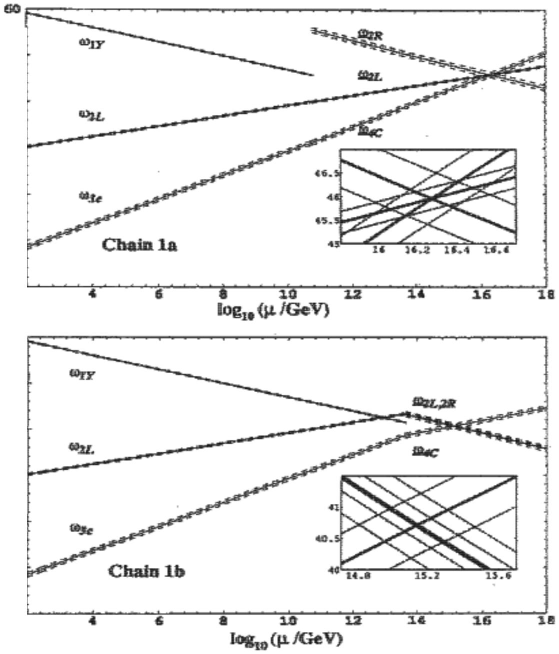
----Goes well with high scale version of seesaw.

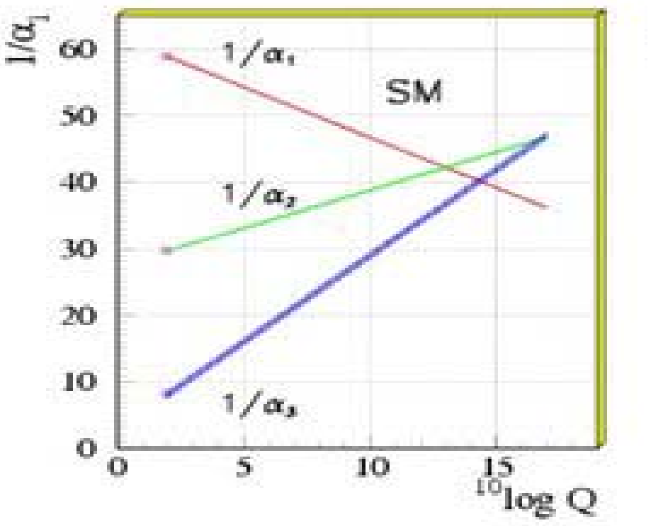
Some examples:

- SUSY Non-SUSY SO(10) SM

with seesaw





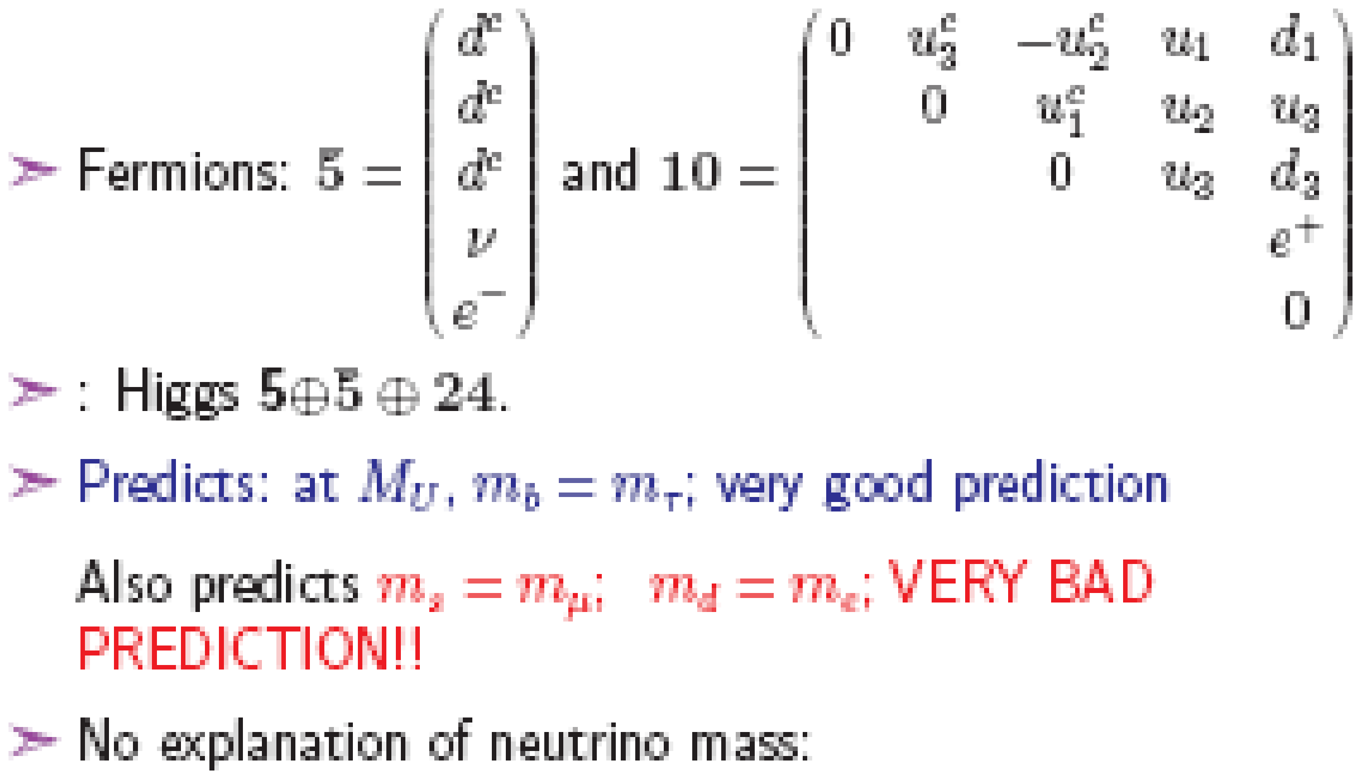


Scale of grand unification ~ $10^{16}\,GeV$

Which GUT group ?

- Two simplest are: SU(5) and SO(10):
- **(i) SU(5):**

  minimal:



➢ Fermions: $5 = \begin{pmatrix} d^c \\ d^c \\ d^c \\ \nu \\ e^- \end{pmatrix}$ and $10 = \begin{pmatrix} 0 & u_3^c & -u_2^c & u_1 & d_1 \\ & 0 & u_1^c & u_2 & u_3 \\ & & 0 & u_3 & d_3 \\ & & & & e^+ \\ & & & & 0 \end{pmatrix}$

➢ : Higgs $5 \oplus \bar{5} \oplus 24$.

➢ Predicts: at M_U, $m_b = m_\tau$; very good prediction

Also predicts $m_s = m_\mu$; $m_d = m_e$; VERY BAD PREDICTION!!

➢ No explanation of neutrino mass:

Why SU(5) not satisfactory

- Minimal model ruled out by proton decay !
- Not predictive for neutrinos- so no advantage of GUTs except scale !
- **However one nice feature**: $m_b = m_\tau$

SO(10)-Just right for neutrinos

- Minimal GUT group with complete fermion unification (per family) is SO(10)-its spinor rep contains all 16 needed fermions (including RH nu) in single rep.

$$\begin{pmatrix} u & u & u & \nu \\ d & d & d & e \end{pmatrix}_{L,R}$$

- **Georgi; Fritzsch, Minkowski (74)**
- **Contains B-L needed to understand why M_R<< M_Planck .**
- **B-L if properly broken also allows a naturally stable dark matter in MSSM.**
- **Also helps proton decay problem.**

Appraising SO(10) as a theory of neutrinos

- Quark lepton unif. means:

$M_d = M_l + \delta M$ and $M_u = M_{\nu^D} + \delta M'$

With δM small.

- This means quark and lepton mixings are similar – **Disaster** !!
- Most models keep breaking symmetry till they get $\delta M_{\nu^D} >> M_{u,d,l}$ and one gets large nu-mixings and a model. What trace is left of SO(10) ?

One exception !!

Minimal Predictive SO(10)

- **Minimal model: 10+126+..** (Babu, Mohapatra, 93)
- **Gives naturally stable dark matter without additional assumption.**

- **Relates RH neutrino spectrum to charged fermion spectrum reducing seesaw parameters;**

  i.e. RH mass M_N has similar hierarchy as m_D

- **Consequently type I inadequate: a new possibility emerges within the model.**

How does it work ?

- {126}-Higgs relates nu matrix A_F
to quark-lepton flavor

$$\boxed{M_\nu \cong c(M_d - M_l)}$$

(Bajc,Senjanovic,Vissani'02)

- Even though quark and lepton masses are strongly hierarchical, due to $m_b \approx m_\tau$, $\boxed{M_\nu}$ becomes less so and gives

$$M_\nu = m_b c \lambda^2 \begin{pmatrix} \lambda^2 & \lambda^2 & \lambda \\ \lambda^2 & 1+\lambda & 1 \\ \lambda & 1 & 1 \end{pmatrix}$$

λ= Cabibbo angle.

(Goh, RNM, Ng'03)

Predictions

- **Large solar and near maximal atmosph. mixing; diluted mass hierarchy, large θ_{13}**
- **Predictions: (qualitatively work very well.)**
- ★ θ_{12}, θ_{23} **large**

  ★ $\theta_{13} \approx \lambda$
- ★ $\frac{m_{solar}}{m_{atmos}} \sim \lambda$ **(Diluted hierarchy)**

A quantitative model that works: Improved SO(10)

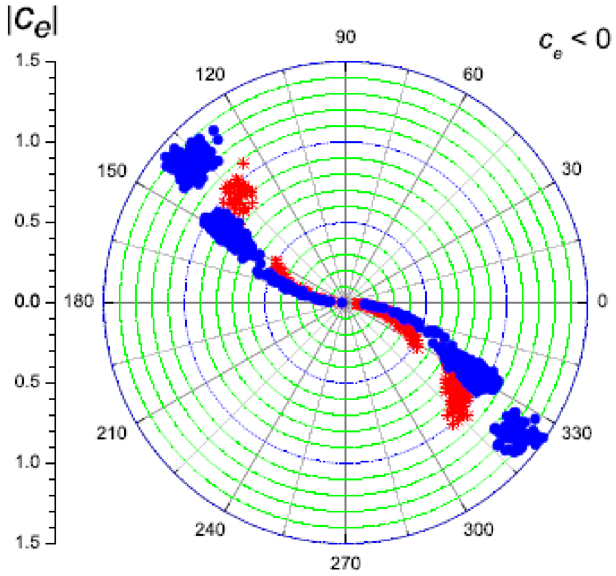
- **10+126 model-hard to include CKM CP violation !**
- **Requires cancellation for proton decay !**
- **10+120+126** model with spontaneous CP **solves CP problem**, **proton decay problems** while keeping neutrino sector predictive; :**(Dutta, Mimura, RNM,2005,06,07)**
- **Solution to proton decay dictates flavor texture:**

$$
\boxed{
\begin{aligned}
h_{10} &= \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}; \quad h_{126} = \begin{pmatrix} 0 & 0 & \lambda^3 \\ 0 & \lambda^2 & \lambda^2 \\ \lambda^3 & \lambda^2 & \lambda^2 \end{pmatrix}; \\
h_{120} &= \begin{pmatrix} 0 & \lambda^3 & \lambda^3 \\ -\lambda^3 & 0 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 0 \end{pmatrix};
\end{aligned}
}
$$

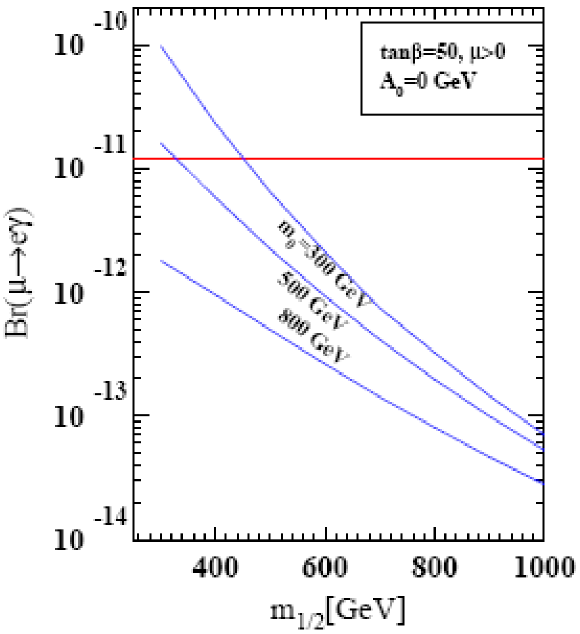
- **Predicts** $\boxed{\theta_{13} \geq 0.06}$

Other Predictions:

Dirac Phase:



mu→ e+gamma



$B(\mu \to e+\gamma) > 10^{-14}$ within range of

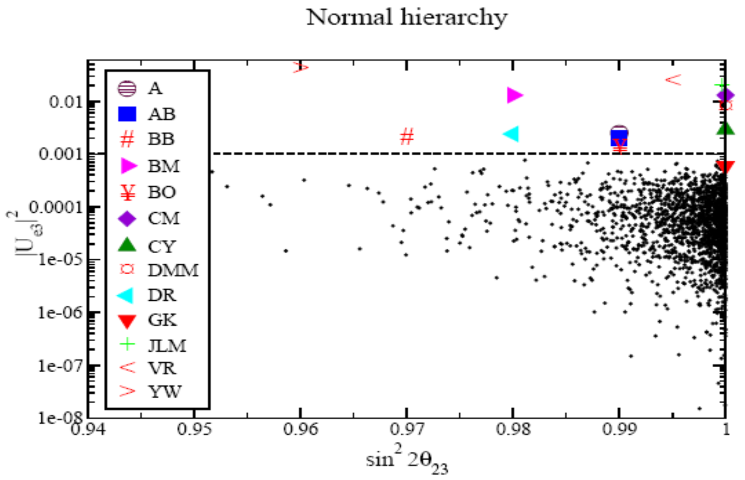
Further work on SO(10)+126 models

- Fukuyama, Okada
- Goh, RNM, Ng
- Babu, Macesanu
- Bertolini, Malinsky, Frigerio
- Bertolini, Malinsky, Schwetz
- Aulakh, Bajc, Melfo, Senjanovic, Vissani
- Fukuyama, Okada, Kikuchi, Melajnac, Iljakovic
- Aulakh, Giridhar
- Dutta, Mimura, RNM
- Grimus, Kuhboch
- Aulakh, Garg
- Joshipura, Kodrani, Patel

Neutrino SUSY GUT summary:

PREDICTIONS

- Large theta_13-;



- Mu→e+gamma within MEG range

ISSUES

- (i) True test of GUTs proton decay $\tau \approx 10^{35} - 10^{36}\, yrs$
- (ii) How to suppress dim 5 planck induced operator for proton decay: $\{\psi_m(16)\}^4 / M_{Pl}$; strength has to be less than 10^{-7}

Reasons to consider TeV scale Seesaw:

- Very hard to test high scale seesaw models !!
- Understanding the origin of matter within seesaw—

Seesaw and Origin of Matter:

- One advantage of seesaw is the possibility to understand origin of matter, using RH neutrino seesaw couplings. Leptogenesis
- **Proposal:** Heavy ν_R decays:

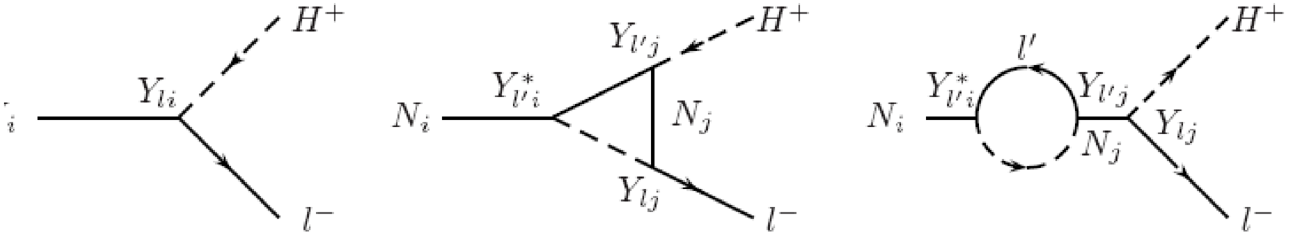
$$\nu_R \to L + H \qquad R = (1+\varepsilon)$$

$$\nu_R \to \overline{L} + \overline{H} \qquad \overline{R} = (1-\varepsilon)$$

- Generates lepton asymmetry which gets converted to baryons via sphaleron interactions; (Fukugita,Yanagida'86);

Two kinds of leptogenesis

- **Diagrams:**



- Two classes of models depending on RH masses
- **High Scale leptogenesis**: Adequate asymmetry; lightest RH nu $M \geq 10^9 GeV$ for hierarchical RH nu's.
  (Buchmuller, Plumacher,di Bari; Davidson, Ibarra)
- **Resonant leptogenesis**: **degenerate** N's, self energy diagram dominates: $\sim \dfrac{1}{M_i^2 - M_j^2 + M\Gamma}$;Resonance $M_i \cong M_j$; **works for all B-L scales**.

(Liu, Segre'94; Covi et al. Flanz et al.'95; Pilaftsis'97)

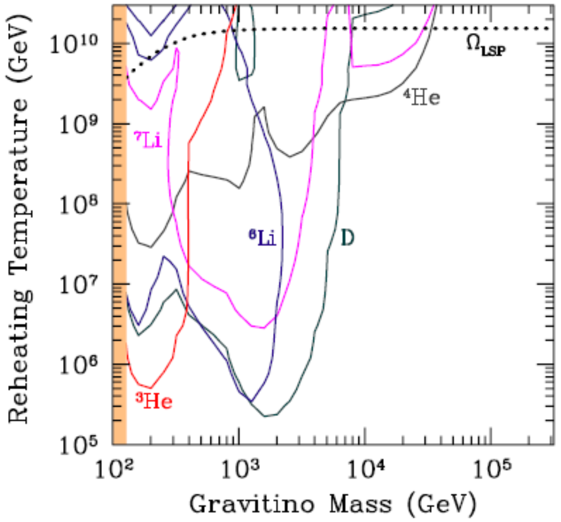
Issues with High scale SUSY Leptogenesis

- Adequate baryogenesis requires the lightest RH neutrino mass $M_N \geq 3\times 10^9$ GeV **(Davidson, Ibarra)**
- **Problem for supersymmetric models:**

they have gravitinos with TeV mass that are produced during inflation reheat along with all SM particles.

- **If stable Will overclose the universe for T_R>10^9 GeV.**
- **If unstable, live too long -effect the success of BBN.**

Kawasaki, Kohri, Moroi,Yatsuyanagi,2008)



Could Seesaw be a TeV scale phenomenon ?

- If so it is very likely that there is a new gauge symmety of Nature beyond SM that couples to RH neutrinos:
- The symmetry could involve either an extra Z' as in $SU(2)_L \times U(1)_{I_{3R}} \times U(1)_{B-L}$ or both WR and Z' as in left-right models.
- If masses are in few TeV range, production and decays at LHC could provide evidence of their existence via Z' decays $Z' \to NN; N \to lH$ and WR decays: $W_R^+ \to l^+ N$; $N \to lH$

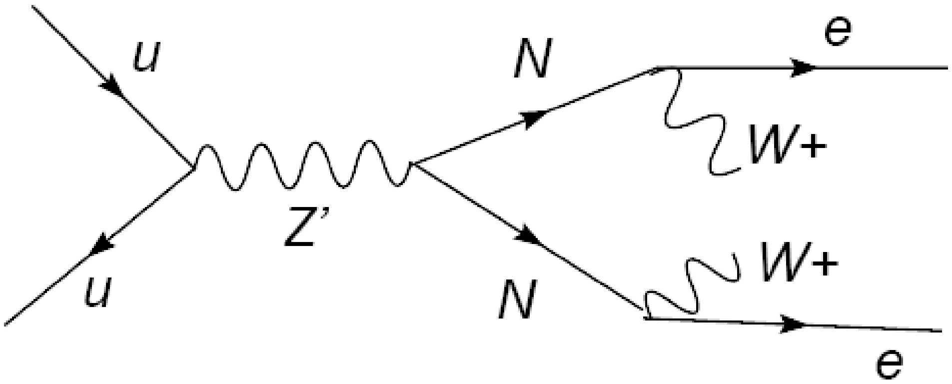
Current bounds on WR , Z'

- **Collider limits on W_R:** around 780
- **Low energy limits:** K-K-bar, CPV, edm etc: WR mass > 2.5 TeV **(Zhang,An,Ji,RNM,2008; adopted by PDG)**
- **Limits from Neutrinoless double beta decay+ vacuum stability:**

  WR mass > 1.5 TeV**.** **(Paes, Simkovic talk)**
- **Limits are lower for SUSYLR due to sparticle FCNC effects.** **(Zhang,An,Ji 2008)**
- **Z' mass bound: > 995 GeV** **(Langacker, Erler, Munir,Pena)**

Collider Signatures

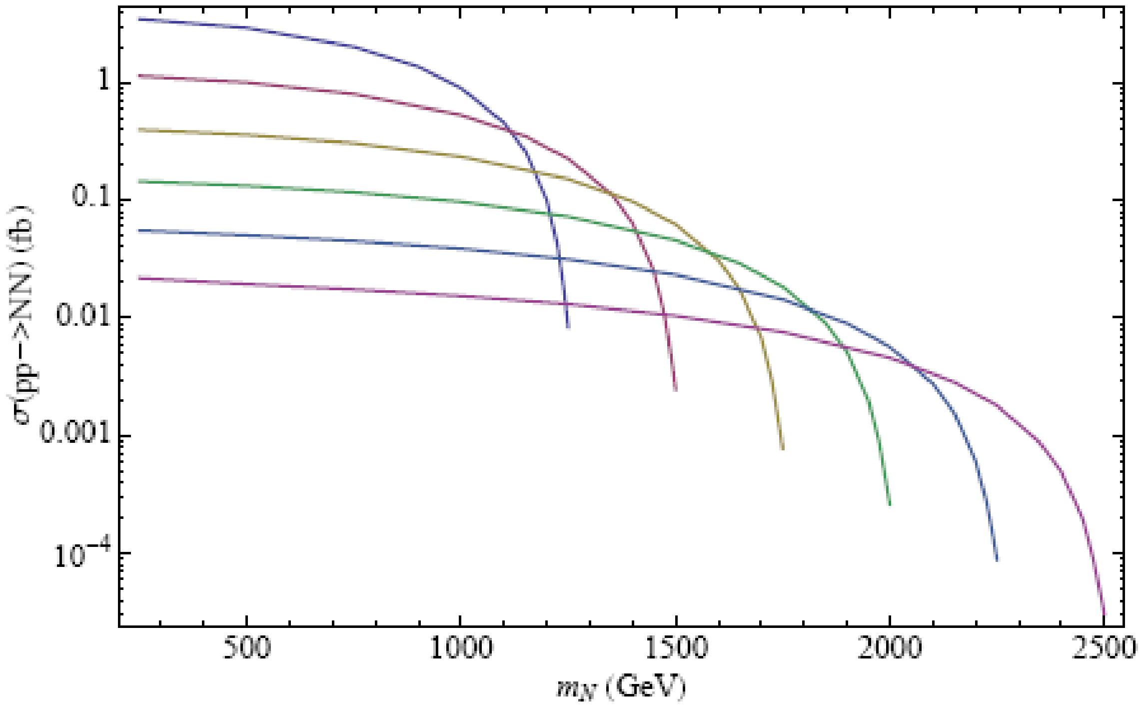
- **Seesaw effect observable at LHC even with tiny $\nu - N$ mixings as in generic neutrino models.**
- pp→ Z'+X; Z'→NN followed by N-decay;
- Like sign dileptons is the tell-tale seesaw signal.



- Keung-Senjanovic $$pp \to W_R^{+} \to l^{+} N$$ $$\hookrightarrow l^{+} jj$$

TeV Z’ cross section at LHC

- **LHC Z’ reach - 4 TeV**
- Cross section for pp→Z’→NN (Z’→NN branching ratio ~20%)



2.5 TeV Z’

to

5 TeV

Testing seesaw with Z’ decay

- **PP→Z’+X**; xsection for a 3 TeV Z’ ~fb
- Seesaw signal: N=Majorana
- **N→** $\ell^{\pm}\mathbf{W}^{\mp}$, $\overset{(-)}{\nu} + Z$ W→jj , $l\nu$
- **Di and Multi-lepton events**: (X=jjjj)

$$pp \to l^{\pm}l^{\pm}X\,, l^{\pm}l^{\pm}l^{\mp} + \not{E}, l^{\pm}l^{\pm}l^{\mp}l^{\mp} + \not{E}$$

- **Important for signal to bg: very high pT leptons coming from N-decay; inv mass reconstruction:**

(Del Aguila, Aguilar-Saavedra; P. Perez, Han, T. Li)

Does leptogenesis work with TeV Z' and WR ?

- **Conditions:**

(i) **RH neutrinos must be degenerate in mass to the level of** $M_1 - M_2 \sim 10^{-10} M$ since h~10^-5 ;

(ii) **Since there are fast processes at that temperature, the net lepton asymmetry and primordial lepton asym are related by**

$$\eta_B \simeq 10^{-2} \sum_{i,\alpha} \varepsilon_{i\alpha}\, \kappa_{i\alpha}$$

where κ <1- depends on Z' mediated $e^+e^- \to NN$ and inverse decay $lH \to N$

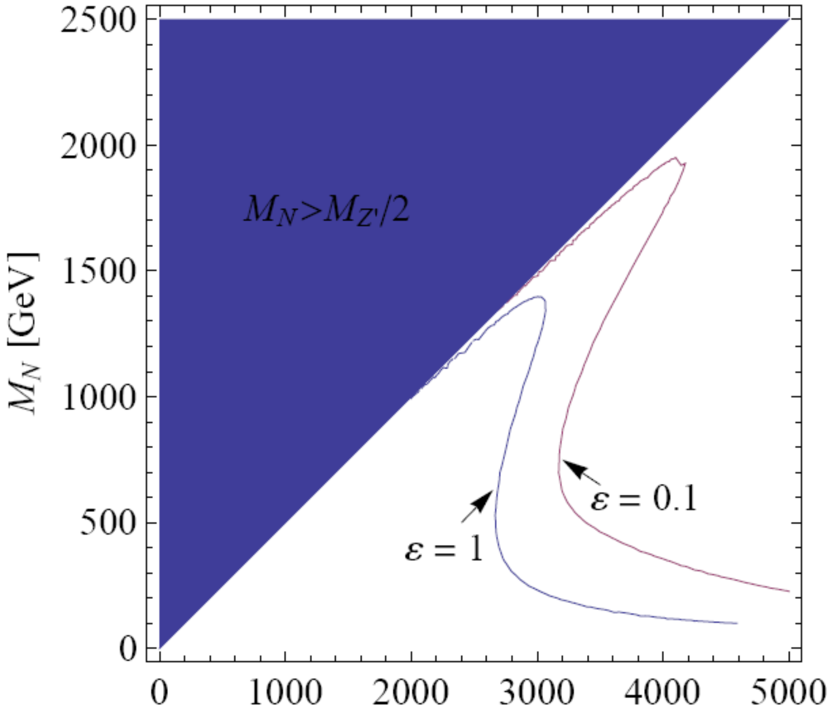
Not clear that a TeV scale Z' is even allowed by baryogenesis due to rapid rates ?

Lower bound on Z' mass from leptogenesis

- Lower the Z' mass, faster the scattering and less the efficiency

implying a lower limit on Z' mass !!

- **(Blanchet, Chacko, Granor, RNM: arXiv:0904.2974)**



★ **$M_{Z'} > 2.5$ -3.2 TeV for $M_{Z'} > 2M_N$ (Accessible at LHC)**

Limits on WR

- **Left-right Model:** $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$
- New fast processes that erase the lepton asymmetry: $e_R + u_R \to N + d_R$

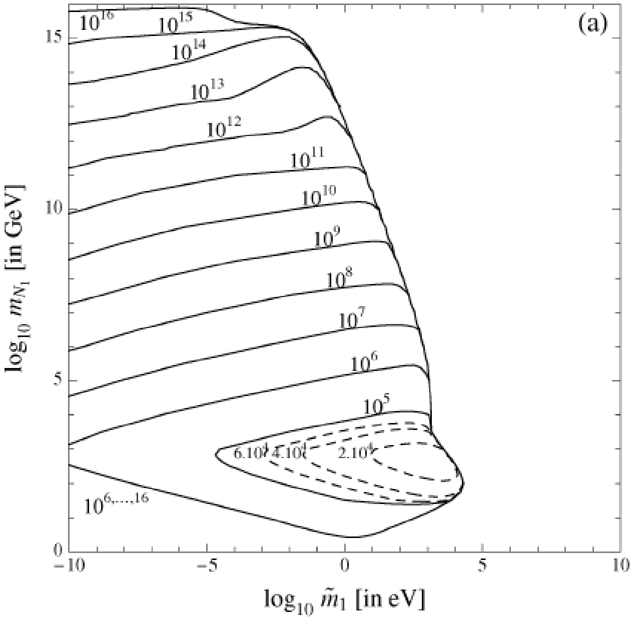
- Except when M_{W_R} > 18 TeV,

(Frere, Hambye and Vertongen)

Sym br. to $U(1)_{I_{3R}} \times U(1)_{B-L}$

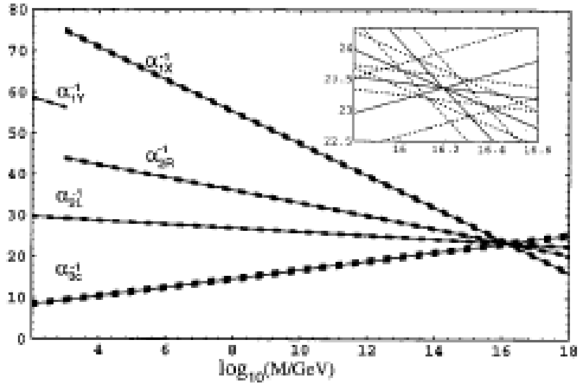
then to SM at TeV-

to do resonant lepto.



Unification Prospects for TeV seesaw: An SO(10) possibility

- TeV scale Triplets with B-L=2 hard to unify to SUSY SO(10).
- Both for TeV Z' and WR, unification possible with B-L =1 doublets breaking U(1)**B-L;** (Deshpande, Keith and Rizzo; 93; Malinsky, Romao, Valle'05);



- This has implications for neutrino mixing:

Double seesaw for Neutrino masses

- **B-L=1 breaking → inverse seesaw for neutrino masses**

$$\begin{pmatrix} 0 & hv_{wk} & 0 \\ hv_{wk} & 0 & M \\ 0 & M & \mu \end{pmatrix} \qquad m_\nu \cong -m_D^T M^{-1} \mu M^{-1} m_D$$

- **Unlike type I**, nu-N mixing m_D / M decoupled from neutrino mass- so can be large enhancing N-production at LHC.
- **Unlike type I,** Majorana character of RH N (amount of like sign dileptons) depends on how large $\frac{\mu}{M}$ is.
- **Unlike type I,** $\mu \to e + \gamma$ can be large without susy.
- Leptogenesis possible for $\frac{\mu}{M} > 10^{-6}$

Testing double seesaw

- Can lead to deviations from Unitarity for neutrino mixings (S. Antusch, C. Biggio, E. Fernandez-Martinez, M.B. Gavela, J. Lopez-Pavon Goswami, Ota; Altarelli, Meloni;Malinsky,Ohlsson,Zhang, Xing;)
- **Mixing matrix** $N = (1+\eta)U$
- **-Current limits on $\eta_{\alpha\beta}$: $\eta_{\mu\tau} < 5\times 10^{-3}$; $\eta_{e\mu} <$ 0.0001 on 12-element from Lepton flavor violation.**
- **Observable oscillation effect at near detector in neutrino factories as well as far detector. $\eta_{\mu\tau} < 10^{-4}$ attainable from SBL with 50 GeV E.**

Conclusion:

- **Need to know-Dirac vs Majorana:**

★ **What may we have learnt ?**

- Majorana nu→ seesaw good paradigm!!
- → may explain the origin of matter

★ **What we need to know ?**

Scale of new physics (e.g. B-L sym.)- **GUT vs TeV scale** ? May give a hint as to whether large mixing is from dynamics or symmetry.

- ★ mass ordering**,** theta_13 to understand $\mathbf{A}_F$

Large mixing fromDynamics:

Simple hierarchy to Double hierarchicy

- A possibility within type I seesaw:

$$m_\nu = -m_D \frac{1}{M_N} m_D^T$$

mD hierarchical in most models:

- $$m_\nu \sim \begin{pmatrix} \varepsilon_5^{n\geq 1} & \varepsilon_4 & \varepsilon_3 \\ \varepsilon_4 & 1+\varepsilon_1 & -1 \\ \varepsilon_3 & -1 & 1+\varepsilon_2 \end{pmatrix}$$

Not very hierarchical

- **That means MN could be "doubly" hierarchical:**

  (Altarelli, Feruglio, Masina; '03; He, Law, Volkas'08)

- **A recent example: mD=** $\mathrm{diag}(m_e, m_\mu, m_\tau)$ →

$$(M_N)_{\mathrm{NH}} = \frac{\lambda'}{6p^2 m_0} \begin{pmatrix} 4m_e^2 & -2m_e m_\mu & -2m_e m_\tau \\ -2m_e m_\mu & m_\mu^2 & m_\mu m_\tau \\ -2m_e m_\tau & m_\mu m_\tau & m_\tau^2 \end{pmatrix}$$

(Adulpravitchai,Lindner,Merle,RNM;arXiv:0908.0470)

Hierarchy Dilution by cancellation

- Suppose at very high scale, there is a sum-rule:

$$\boxed{M_\nu \cong c(M_d - M_l)}$$

- Since at high scale, $m_b \approx m_\tau$ most hierarchical term cancels out:

$$M_{d,l} = m_{b,\tau}\begin{pmatrix} \sim\lambda^4 & \sim\lambda^3 & \sim\lambda^3 \\ \sim\lambda^3 & \sim\lambda^2 & \sim\lambda^2 \\ \sim\lambda^4 & \sim\lambda^2 & 1 \end{pmatrix}$$

$\lambda =$ Cabibbo angle.

- **Sum rule →**

$$\mathcal{M}_\nu = m_b c\lambda^2\begin{pmatrix} \lambda^2 & \lambda^2 & \lambda \\ \lambda^2 & 1+\lambda & 1 \\ \lambda & 1 & 1 \end{pmatrix}$$

- (Bajc, Senjanovic, Vissani; Goh, RNM, Ng)