Neutrino Mass and Flavor Unification

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Neutrino Mass- What we do and don't know ?

- **Masses:** $\Delta m^2_{sol} \cong 7.67\times10^{-5} eV^2$ **;** $\Delta m^2_{Atm} \cong 2.39\times10^{-3} eV^2$
- **Mixings:** $\sin^2\theta_{12} \cong .312; \sin^2\theta_{23} \cong .466$**;** $\sin^2\theta_{13} \leq .04$
- **Overall mass scale:** < .1- 1 eV (roughly)
- **To be determined** (expts in progress or planning)

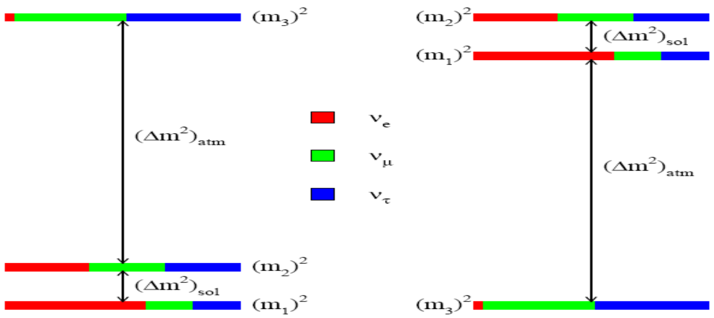
  (i) Majorana or Dirac ?

  (ii) Mass ordering: NH or IH

  (iii) Value of θ_{13}

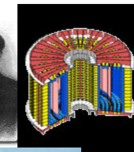
  (iv) Any possible CP violation ?

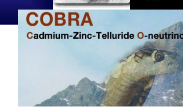
  (v) Leptonic unitarity



Many experiments on the way

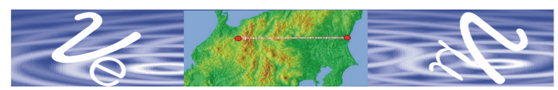
(i) Majorana or Dirac $\beta\beta_{0\nu}$





(ii) Absolute mass scale:

(iii) Mass ordering:



(iv) Value of θ_{13}

(v) CP phase

Challenge for Theory

- **Neutrino mass** → New physics beyond SM:

- Two important issues:
- **<u>New mass scale</u>**

  Is it accessible at the LHC ?

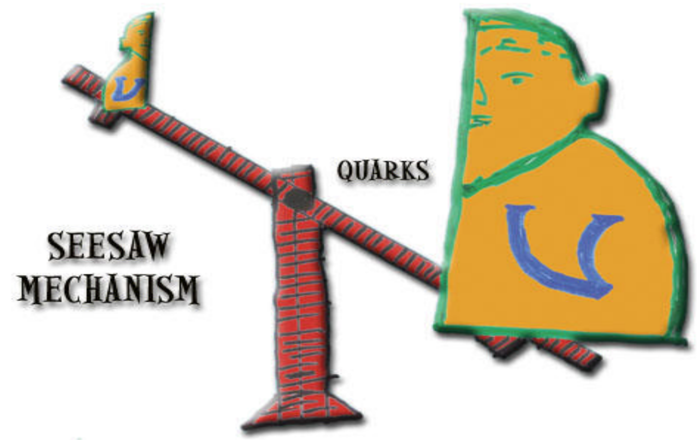
- **<u>Understanding flavor</u>** : Can we have a unified understanding quark- lepton mixings ?

1. Mass scale

WHY $m_{\nu} << m_{q,l}$ **?**

- **Seesaw Paradigm:** **Add heavy right handed neutrinos** N **to SM**

  and Seesaw:



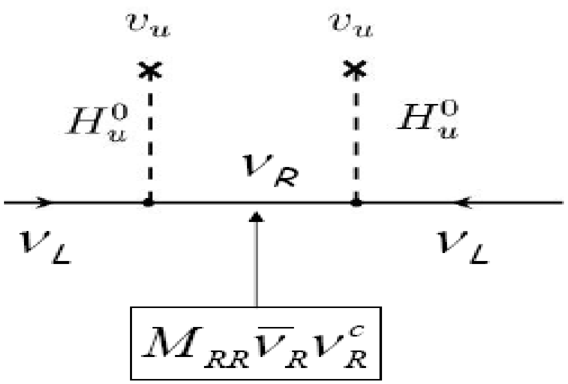
Seesaw scale is the new physics scale !!

- Two different seesaws depending on whether N Majorana or Dirac

Type I Seesaw

- **Majorana** N

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



- M_R Breaks **B-L** : New scale and new symmetry:
- After EWSB

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

-Neutrino majorana- $\beta\beta_{0\nu}$ **a key test:**

$\frac{m_D}{M_R} \equiv \frac{h_\nu v_{wk}}{M_R}$ **a parameter for collider test** $\sim 10^{-7} - 10^{-10}$ **type I**

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

Inverse Seesaw

- **Mostly Dirac** N **i.e. add another singlet** S

$$L_Y = h_\nu \bar{L} H N_R + M S N_R + \mu S S \qquad \mu << M$$

$$(\nu_L, \nu_R, S)$$

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

(RNM'86; RNM, Valle'86)

- Seesaw testing parameter $\frac{m_D}{M} \sim 10^{-3}$ or larger;

Possible Seesaw scale

- **Neutrino masses do not determine seesaw scale**
- $m_D \approx m_t$ → $M_R \approx 10^{14} GeV$; **Mu**~ 10^{16} GeV

  Both $m_D \approx m_t$ **and high seesaw scale i**ndication for SUSYGUTs; **No collider signals** ! **(Common Lore)**

- $m_D \approx m_e$ → B-L scale at **TeV** ★

- Inverse seesaw → B-L at TeV even with $m_D \approx m_t$ ★

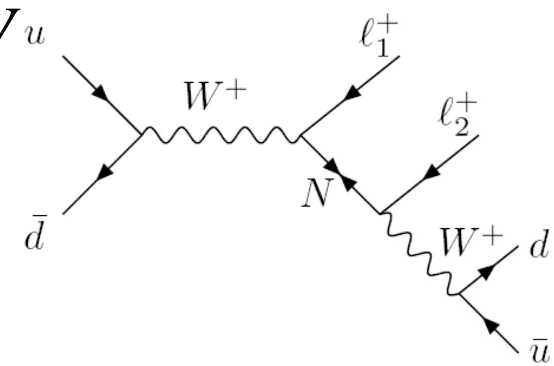
  Both collider accessible

Searching for TeV seesaw

- Manifestations via $\nu - N$ mixing $\frac{m_D}{M}$

(a) collider production for $M_N < TeV$

del Aguila, Saavedra, Pittau'06; Han, Atre,Pascoli,Zhang'09



(b) Leptonic non-unitarity:

(Antusch, Gavela, Biggio, Fernandez,...)

- **Both negligible for type I seesaw but observable for inverse seesaw $M_N \sim$ TeV**
- **Situation different with gauge forces !!**

How plausible are new gauge forces ?

- **Type I** : why is seesaw scale so far below Planck scale: **Local B-L** symmetry - a plausible answer !
- **Inverse seesaw case**:
- **Why** $\begin{pmatrix} 0 & hv_{wk} & 0 \\ hv_{wk} & 0 & M \\ 0 & M & \mu \end{pmatrix}$ **why not** $\begin{pmatrix} 0 & hv_{wk} & h'v_{wk} \\ hv_{wk} & M' & M \\ h'v_{wk} & M & \mu \end{pmatrix}$
- **New Gauge symmetry can explain this !!**

A concrete realization:
Left-Right Sym model

- $N_R \rightarrow$ **Gauge group**: $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$
- **New W' and Z'** $W_L^{\pm}$ $W_R^{\pm}$ Z, Z', γ
- **Fermion assignment**

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \overset{P}{\Leftrightarrow} \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \overset{P}{\Leftrightarrow} \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$$

- ***Two Avatars of Low scale LR:***
  - ⇨ **type I** $\phi(2,2,0)\ ; \Delta_R(1,3,+2) \oplus \Delta_L(3,1,+2)$
  - ⇨ **Inverse seesaw** $\phi(2,2,0) + \chi_L(2,1,-1) + \chi_R(1,2,-1)$

Bound on LR scale

- Most stringent bounds come from CP viol. Observables e.g. $\varepsilon, \varepsilon', d_n^e$; **clearly depends on how CP is introduced:**

Two minimal scenarios

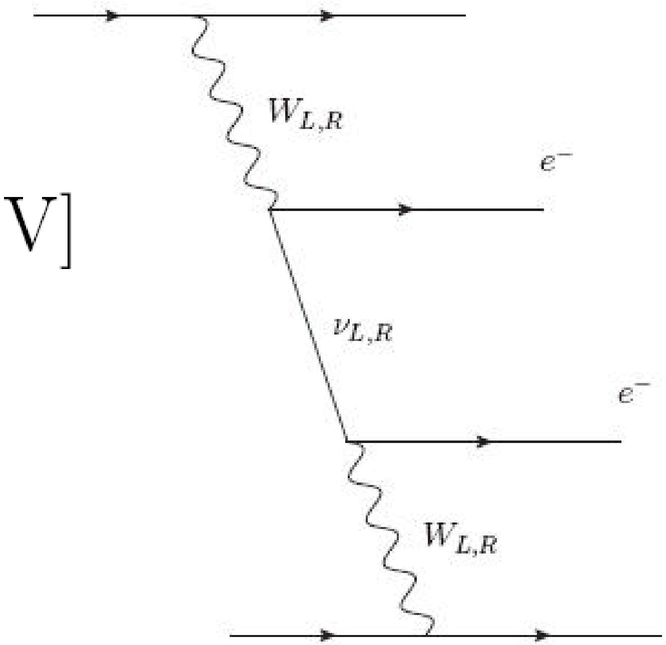
- **Parity defined as usual:($\psi_L \leftrightarrow \psi_R$) minimal model:**
- $\theta_L^{CKM} = \theta_R$ **;**2 CP phases $M_{W_R} \geq 4TeV$ **(An,Ji,Zhang,RNM '07)**
- **Parity as C (as in SUSY i.e. $\psi \leftrightarrow \psi^c$)** **(Maezza, Nesti Nemevsek,Senjanovic'10)**

$$M_{W_R} \geq 2.5TeV$$

- **With SUSY: bounds weaker: > 1-2 TeV** **(An, Ji, Zhang'08)**
- **Collider (CDF,D0) 640-750 GeV.**

Bounds from Nu-less double beta decay

- New contributions from WR-N exchange **(only for Case I)** (RNM, 86; Hirsch, Klapdor, Panella 96)
- **Diagram:**



$$\rightarrow \quad m_{W_R} \geq 1.1 \left(\frac{\langle m_N^{(V)} \rangle}{1\text{TeV}} \right)^{(-1/4)} [\text{TeV}]$$

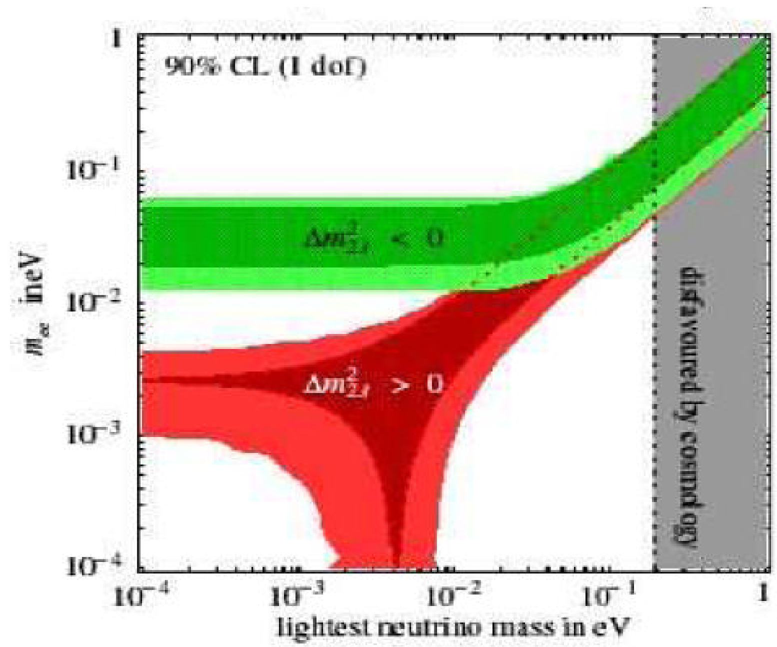
From Ge76:

TeV Seesaw signal from $\beta\beta_{0\nu}$

- **Nu contribution**:

  Inverse hierarchy

  Normal hierarchy



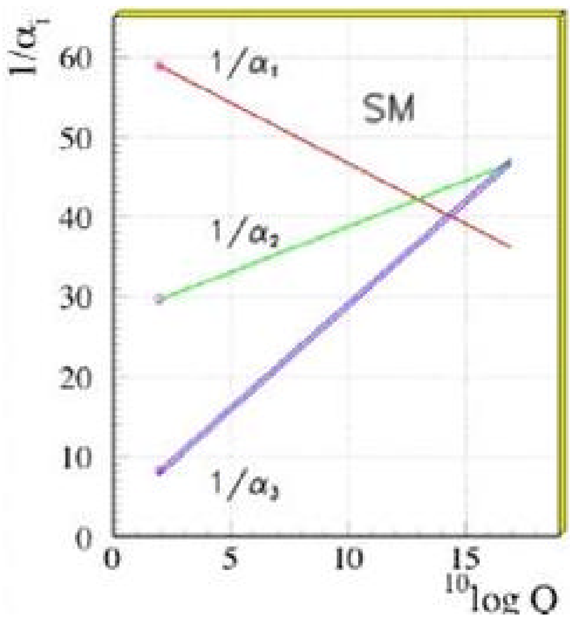
Punch line:

- **Suppose long baseline** → $\Delta m^2_{31} > 0$
- **and nonzero signal for** $\beta\beta_{0\nu}$ (+ RP if susy)

→could be a signal of TeV WR and type I

Grand unification prospects of TeV seesaw

- Major selling point of MSSM: **gauge couplings unify with TeV scale new physics**



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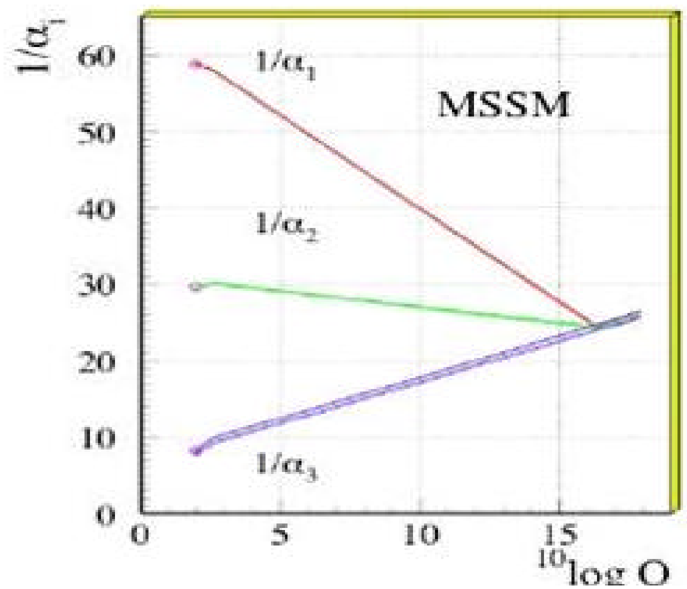


- **How does seesaw physics affect unification ?**
- **Can seesaw physics coexist w/MSSM at TeV ?**

SO(10)- Natural GUT for LR Seesaw

- {16 }- spinor for all matter
  -includes RH neutrino

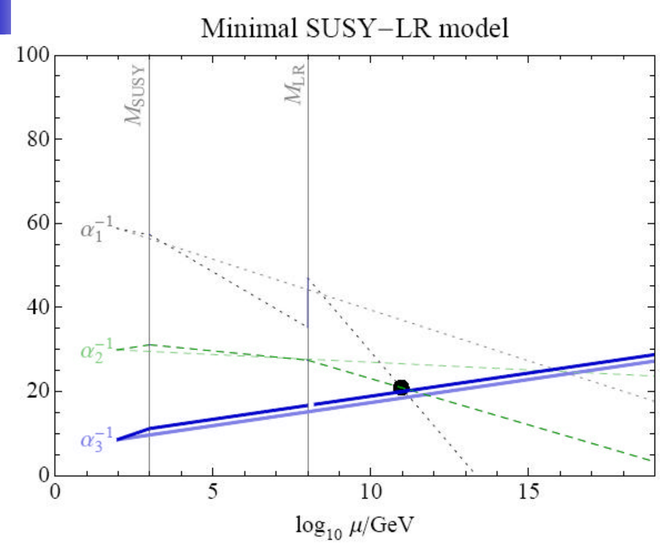
$$\begin{pmatrix} u & u & u & \nu \\ d & d & d & e \end{pmatrix}_{L,R}$$

- **SO(10) contains left-right group**

$$SO(10) \supset SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \otimes SU(3)_c$$

- **A long standing question: does TeV scale LR unify to SO(10) ?**
- **If yes LHC can be a machine that probes grand unification !**

TeV type I does not grand unify:



M_R (GeV)	μ_0 (GeV)
10^3	7.76×10^{13}
10^5	4.56×10^{14}
10^7	2.56×10^{15}
10^8	6.16×10^{15}
10^9	1.44×10^{16}
10^{10}	3.46×10^{16}
10^{11}	8.31×10^{16}

Landau Pole

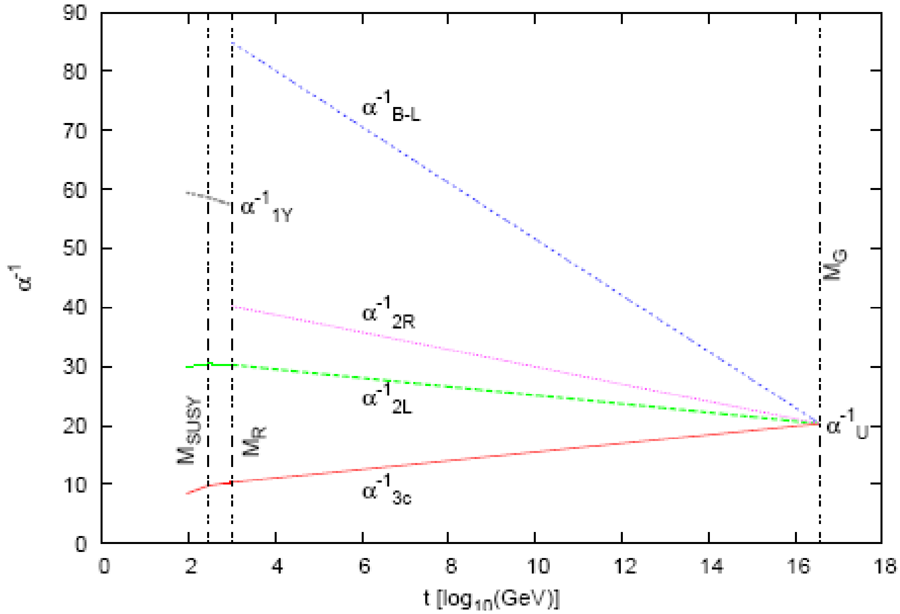
(Kopp, Lindner, Niro, Underwood'09)

(Parida, Sarkar, Majee, Raichaudhuri'09)

- **Type I: only unification route**
  - $SO(10) \xrightarrow{M_G} 3_c 2_L 1_Y (\text{MSSM}) \xrightarrow{M_{SUSY}} 3_c 2_L 1_Y (\text{SM}) \xrightarrow{M_Z} 3_c 1_Q$
- $M_{U,BL} \cong 2 \times 10^{16}\, GeV$ no new TeV physics besides MSSM

TeV Inverse Seesaw (LR) does unify

- New result! Inverse seesaw does unify –TeV WR and Z'



-does give realistic fermion mass fits;
-OK with proton decay

$$m_{\tilde{q}_{1,2}} \geq TeV$$

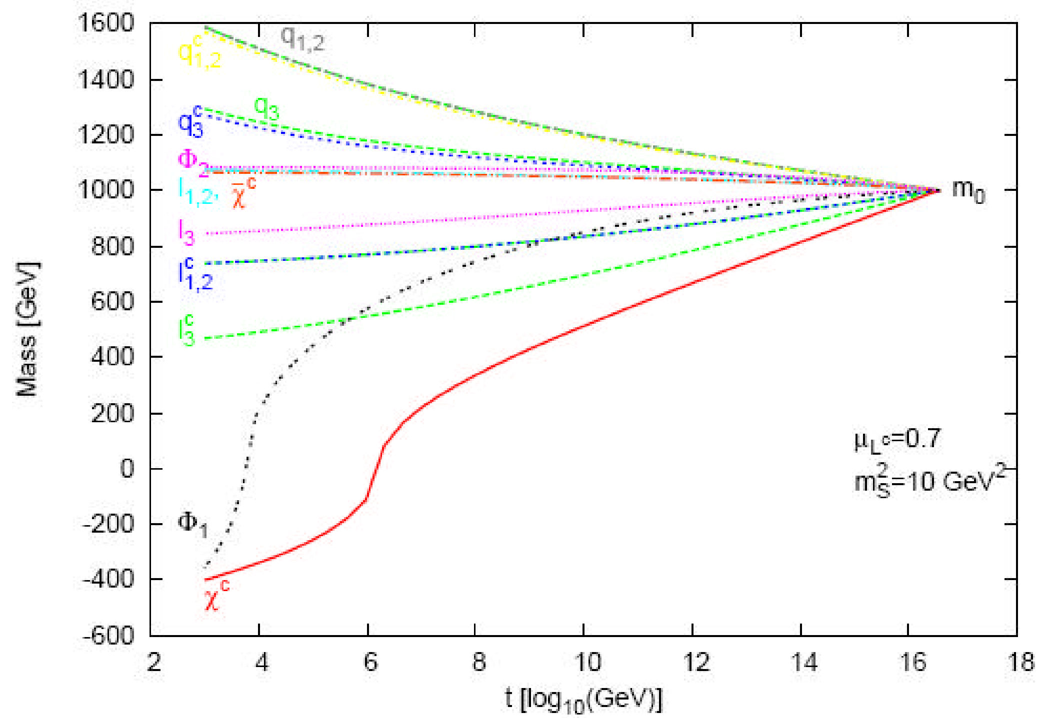
- $SO(10) \xrightarrow{M_G} 3_c 2_L 2_R 1_{B-L} \xrightarrow{M_R} 3_c 2_L 1_Y(\mathrm{MSSM}) \xrightarrow{M_{SUSY}} 3_c 2_L 1_Y(\mathrm{SM}) \xrightarrow{M_Z} 3_c 1_Q$

$$M_U \cong 10^{16} GeV; M_{BL,R} \cong TeV$$

(Dev, RNM, 09; PRD; arXiv: 1003:6102);

Radiative Breaking of B-L, SM in TeV seesaw SO(10)

- Positive spartner mass square at GUT scale-
- RGE turns them negaitve much like SM with large t-mass
- (Dev, RNM'10)



Other advantages of a Low seesaw scale

- **Leptogenesis-** : High scale leptogenesis + hierarchical NR (as in type I or II SO(10) →

$$M_N \geq 10^9 GeV \quad vs \quad T_R < 10^6 - 10^9 GeV$$

adequate leptogenesis   gravitino reheat constraint

→ Low scale resonant leptogen as alternative:

- **Suppression of proton decay**: High scale seesaw SO(10) with 16-Higgs has proton decay problem from operator;

$$\frac{(16_m)^3 16_H}{M_{Pl}}$$

→suppressed for TeV B-L breaking.

Type I vs Inverse seesaw at LHC

- WR and Z′: $u\bar{d} \to W_R \to l^+ N$; $u\bar{u} \to Z' \to NN$

(Keung, Senjanovic; Han, Perez,Huang,Li, Wang; Del Aguila, Aguilar-Saavedra; de Blas, Azuelos,

- N-decay: (a) νN mixing and/or (b) W_R exchange
- **type I** $\theta_{\nu N} << 10^{-3}, M_{W_R} < 4TeV$ (a) negligible; $N \to l^{\pm} jj$
- **Signal: like sign dileptons+jets; no missing E**
- **Inv. Seesaw**: $\theta_{\nu N} > 10^{-3}$ → $N \to l^- jj, l^- l^+ \nu$
- **Trileptons; no same sign dileptons; dominantly** $\tau^{\mp} l^{\pm} l^{\pm}$

- Background from $t\bar{t}nj, WZnj, WWnj, \ldots$

Other signals

- **TeV type I Seesaw requires B-L=2 Higgs:**

$$\Delta = \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta^+ & \Delta^{++} \\ \Delta^0 & -\frac{1}{\sqrt{2}}\Delta^+ \end{pmatrix} \qquad \Delta^{++} \rightarrow \mu^+\mu^+, ee, \tau\tau$$

- Doubly charged Higgs→**Four lepton signals at LHC**
- **Leptonic non-unitarity for inverse seesaw:**
- Can be probed in Short baseline neutrino expts $\nu_\mu - \nu_\tau$
  also $\mu \rightarrow e + \gamma$ **B** $\sim 10^{-15}$
- **(Ilakovac, Pilaftsis; Antusch, Gavela, Biggio, Fernandez, Malinsky, Ohlsson, Zhang,)**
- $\delta U_{PMNS} \sim \left(\frac{m_D}{M_N}\right)^2 > 10^{-6}$ $\quad |\eta| < \begin{pmatrix} 2.0\times10^{-3} & 3.5\times10^{-5} & 8.0\times10^{-3} \\ 3.5\times10^{-5} & 8.0\times10^{-4} & 5.1\times10^{-3} \\ 8.0\times10^{-3} & 5.1\times10^{-3} & 2.7\times10^{-3} \end{pmatrix}$ **Current bds**:

2. Understanding Flavor

(i) Mass hierarchies

(ii) Strange mixing patterns:

Leptons: **Quarks:**

$$U_{PMNS} \approx \begin{pmatrix} \frac{\sqrt{6}}{3} & \frac{\sqrt{3}}{3} & 0 \\ -\frac{\sqrt{6}}{6} & \frac{\sqrt{3}}{3} & \frac{\sqrt{2}}{2} \\ \frac{\sqrt{6}}{6} & -\frac{\sqrt{3}}{3} & \frac{\sqrt{2}}{2} \end{pmatrix} \quad U_{CKM} = \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

(Harrison, Perkins, Scott; He, Zee, Xing,..)

Mass Texture

- **Up-quark and charged lepton diagonal basis:**
- $$M_d = m_b \begin{pmatrix} \lambda^5 & \lambda^3 & \lambda^3 \\ \lambda^3 & \lambda^2 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \quad M_\nu \cong \begin{pmatrix} \varepsilon_1 & \varepsilon_3 & \varepsilon_3 \\ \varepsilon_3 & 1+\varepsilon_1 & -1+\varepsilon_3 \\ \varepsilon_3 & -1+\varepsilon_3 & 1+\varepsilon_1 \end{pmatrix}$$
- $\varepsilon_i \sim \lambda$ = Cabibbo angle

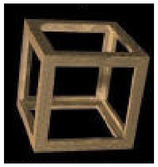
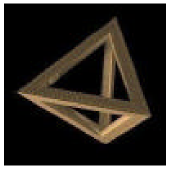
Strategy for texture

- Key idea: SM has a large sym for zero fermion masses : **[SU(3)]^5**;
- **Choose subgroup**: Discrete subgroup with 3-d. rep.
- **Replace Yukawa's by scalar fields (flavons);**
- **Minima of the flavon theory determines Yukawas:**

Application to Neutrinos

- **Successful Family symmetries for TBM:**

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

Flavon fields are triplets:

(Ma, Rajasekaran; Babu, Ma, Valle, King, Ross; Altarelli, Feruglio, Chen, Mahanthappa; Everett, Ramond; Luhn, Nasri, Yu, RNM, Hagedorn, Morissi, Bazzocchi, Merlo, Toorop,Tanimoto, Shimizu, Ishimori,…)

How can we unify with quarks ?

Grand unified theories:

A new high scale Ansatz for unifying quark-lepton flavor

A

$$M_u = M_0 + \delta_u$$
$$M_d = rM_0 + \delta_d$$
$$M_l = rM_0 + \delta_l$$

(Dutta, Mimura, RNM'PRD-09)

$$m_\nu = f v_L$$

$$\delta_{u,d,l} << M_0$$

- f diagonal.
- Anarchic M_0, quark mixings small while lepton mixings large.

B **<u>Rank 1 M_0</u>** → explains mass hierarchies +

$$m_b \cong m_\tau$$

A SUSY SO(10) realization

- **Fermions in {16}:**

- **$16_m \times 16_m = \{10\}_H + \{120\}_H + \{126\}_H$**

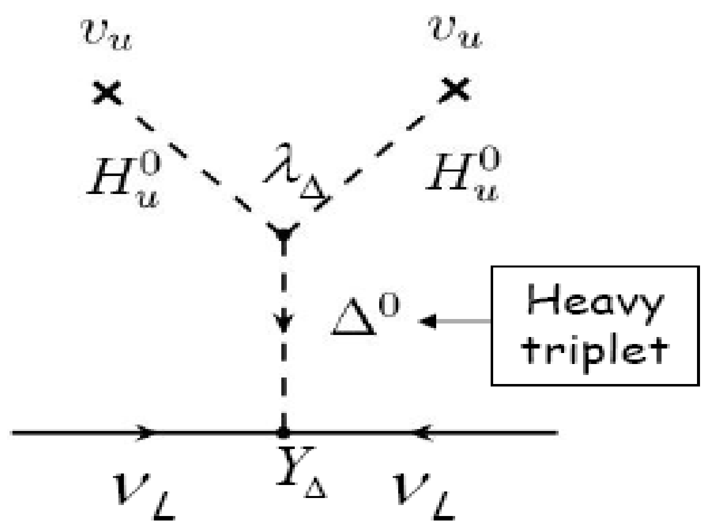
- Fermion masses from Yukawas as in SM:

$$L_Y = h\, 16 \cdot 16 \cdot 10_H + f\, 16 \cdot 16 \cdot \overline{126}_H + h'\, 16 \cdot 16 \cdot [120, 10]_H$$

(Babu, Mohapatra, 93)

Neutrino mass formula in GUT scale B-L in SO(10):

$$m_\nu = f v_\Delta - M_D \frac{1}{f v_{BL}} M_D^T$$



- **Type II seesaw**:

SO(10) with GUT scale B-L → unified approach to flavor

- → fermion mass formulae:
- $$Y_u = h + r_2 f + r_3 h'$$
  $$Y_d = r_1(h + f + h')$$
  $$Y_e = r_1(h - 3f + c_e h')$$

$$m_\nu \cong f v_\Delta$$

(Babu, Mohapatra'92)

Bajc, Senjanovic, Vissani'03

- For f, h' << h, → yields ansatz part A at M_U;
- Rank from flavor symmetry: e.g. $S_4, \Delta(27), ..$

An S_4 xSO(10)- example

- **Solar mass** $\frac{m_{solar}}{m_{atm}} \cong \lambda \cong \theta_c$

Dutta, Mimura, RNM arXiv:0911.2242

- **Bottom-tau:** $m_b \approx m_\tau$ **and** $m_\mu = -3m_s$

- **Leading order PMNS: U** $= \begin{pmatrix} \frac{\sqrt{6}}{3} & \frac{\sqrt{3}}{3} & 0 \\ -\frac{\sqrt{6}}{6} & \frac{\sqrt{3}}{3} & \frac{\sqrt{2}}{2} \\ \frac{\sqrt{6}}{6} & -\frac{\sqrt{3}}{3} & \frac{\sqrt{2}}{2} \end{pmatrix}$

- **Corrections: Testable**

Bjorken, King, Pakvasa Ferrandis; Chen, Mahanthappa

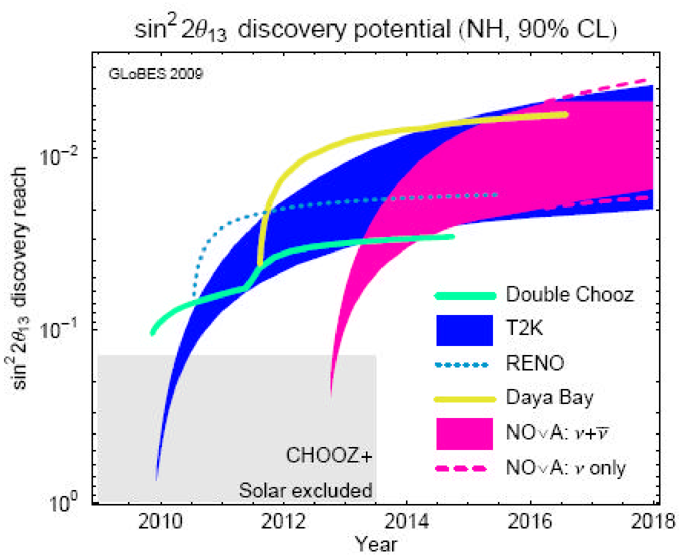
$$\theta_{13} = \frac{\theta_c}{3\sqrt{2}} \cong 0.05$$

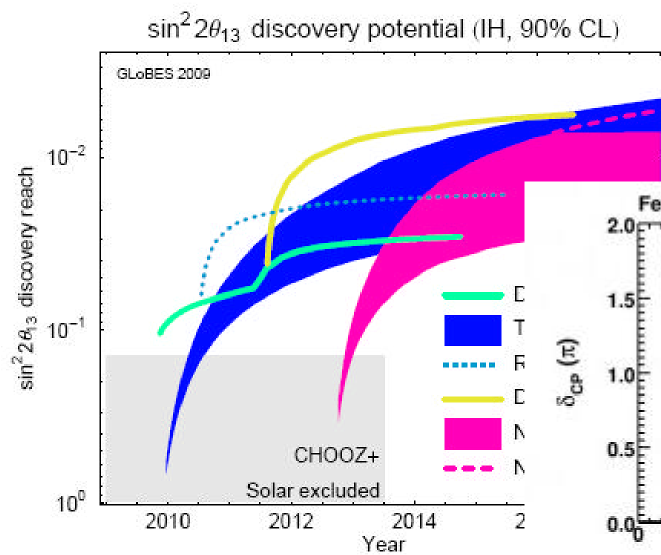
- Double beta mass 3 meV.

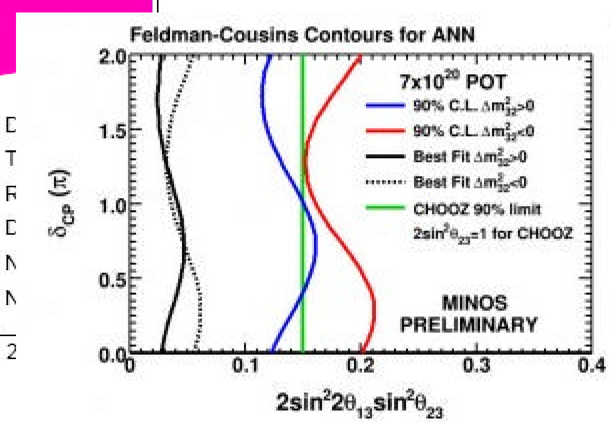
Prospects for measuring θ_{13}

- Reactor, Long base line e.g. MINOS, T2K, NoVA:

(Lindner, Huber,Schwetz,Winter'09)







Our prediction $\sin^2 2\theta_{13} > 0.01$ **MINOS**

Conclusion:

- **TeV scale WR compatible with SO(10) GUT; Can be tested at LHC; New dark matter candidate:**

- **New unified approach to flavor based on typeII+ SO(10)- testable via theta_13. Can also be extended to inverse seesaw case.**

New Dark matter in TeV scale Inverse seesaw:

- If super-partner of RH neutrino is the lightest, it will be stable due to R-parity- become DM.

$$W = W_{MSSM} + h_\nu LHN + f\nu_R NS + \mu SS$$

- Soft breaking:

$$-L = -L_{soft}^{MSSM} + M^2 \tilde{N}\tilde{N} + M_S^2 \tilde{S}\tilde{S} + A\tilde{L}H\tilde{N} + B\tilde{N}\tilde{S}$$

- **Lightest linear combination is dark matter:**

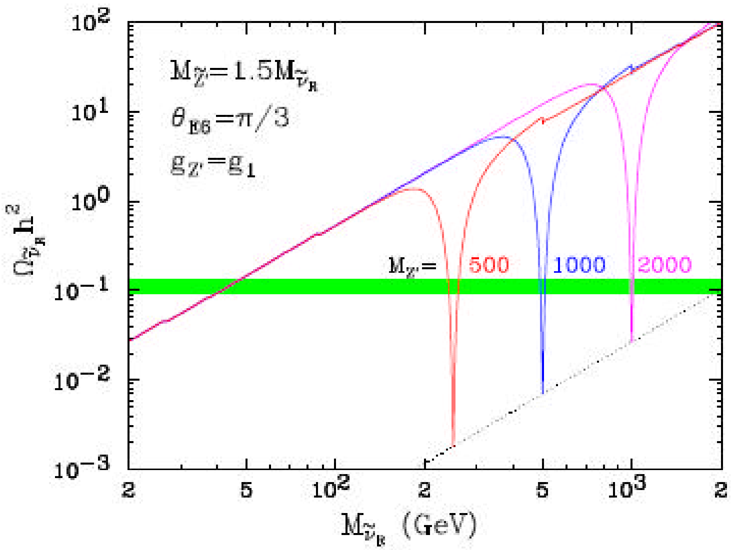
(Fornengo, Arina, Bazzochi, Romao, Valle'08) (Matchev, Lee, Nasri'08)

- **Minimal Type I case**: **Usual Bino-Higgsino**

Dark matter in TeV scale Inverse seesaw:

- **Inverse seesaw case: New DM** : $\tilde{\nu}^c$:**Two contributions to relic density:**

Z' exchange No or small Z' effect



$M_{Z'} \geq 2.5TeV$