Neutrino Mass Models in the LHC Era

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NOW,2010

Outline of Talk

0. Seesaw mechanism

1. Seesaw Scale: Theory insights, LHC, other searches

2. Large mixings and unification with quarks

3. A new possibility for neutrino masses

(only three active neutrinos will be considered-MINOS and MiniBooNe not discussed; see E. Akhmedov’s talk)

Neutrino Mass
→ New physics

- Standard model- no ν_R → $m_\nu = 0$
- Two possibilities for m_ν

(i) SM $+\nu_R$ ⇒ $L_Y = h_\nu \bar{L} H \nu_R + h.c.$ ⇒ $m_\nu = h_\nu v_{wk}$

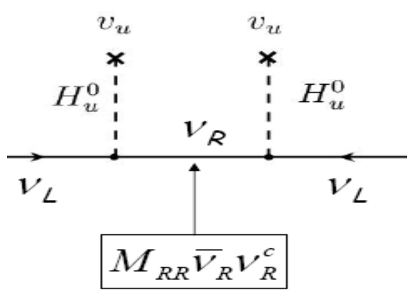
Observations→ $h_\nu \simeq 10^{-12}$: any justification ?

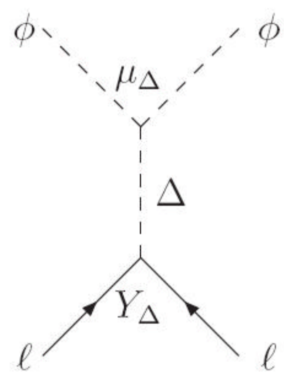
(ii) Mass from high scale physics: $\frac{LHLH}{M}$

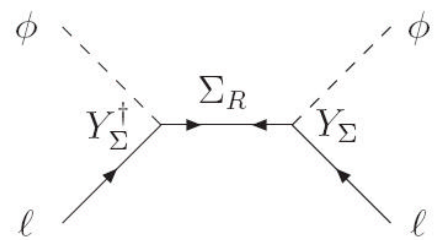
What is the new physics ?

- **Seesaw paradigm:** New fermions **N**$_R$ or Higgs

Type I	**Type II**	**Type III**	**Inverse**







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

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

$$m_\nu = -2Y_\Delta v^2 \frac{\mu_\Delta}{M_\Delta^2}\,.$$

$$m_\nu = -\frac{v^2}{2} Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma$$

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

N- Majorana | Triplet Higgs | Triplet Fermion | **N** – Dirac

Seesaw scale ?

- Seesaw assumption by itself cannot tell –need to know Dirac mass

- Plausible guesses motivate different scales

Is seesaw physics accessible at LHC ?

- **Type I case, if** $m_D \approx m_e$ **scale ~ TeV**
- Inverse seesaw → scale at TeV even with $m_D \approx m_t$
- if there is a 4th gen., M necessarily TeV.

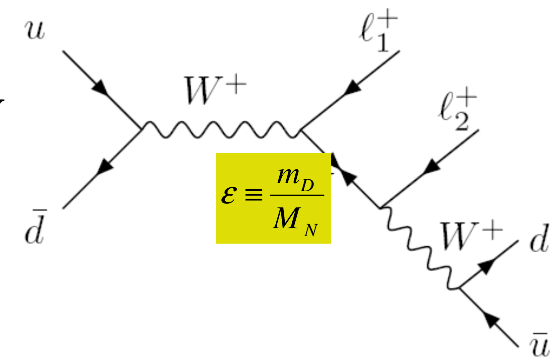
Scale being TeV- no guarantee of LHC visibility:

key parameter: $\varepsilon \equiv \frac{m_D}{M_N}$ $< 10^{-7}$ (type I); $> 10^{-3}$ (Inverse)

LHC signal for simplest TeV seesaw

- **Type I and Inverse:**
- Basic manifestations of seesaw: $\nu - N$ mixing

Collider production for $M_N < TeV$



- **Negligible for type I seesaw but observable for inverse seesaw $M_N \sim$ TeV**
- **Situation different with other seesaws and seesaw with gauge forces !!**

Type II and III at LHC

- New particles are SM non-singlets:
- **Type II**: $\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}$. **couples only to leptons**

$$u\bar{u} \to \delta^{++}\delta^{--}; u\bar{d} \to \delta^{++}\delta^{-}$$

directly probes neutrino mass matrix.

4-lepton signal $\ell^+\ell^+\ell^-\ell^-$ **(Han, Perez,Huang, Li, Wang;...)**

- **Type III**: $\Sigma = \begin{pmatrix} \Sigma^0/\sqrt{2} & \Sigma^+ \\ \Sigma^- & -\Sigma^0/\sqrt{2} \end{pmatrix}$.

$$\begin{aligned} q\bar{q} &\to Z^*/\gamma^* \to \Sigma^+\Sigma^- \\ q\bar{q}' &\to W^* \to \Sigma^+\Sigma^0 \end{aligned}$$

(Bajc, Senjanovic, Nemevsek)

Accessing seesaw scale in low energy expts

- Possible new operators from new physics:

Type I →

$$\delta\mathcal{L}^{d=6} = c^{d=6}_{\alpha\beta}\left(\overline{\ell_{L\alpha}}\tilde{\phi}\right) i\partial\!\!\!/ \left(\tilde{\phi}^{\dagger}\ell_{L\beta}\right)$$

ε^2

→Leads to non-unitarity of PMNS: SBL tests possible for $\varepsilon > 10^{-2}$

Current bounds:

$$|\eta| < \begin{pmatrix} 2.0\times10^{-3} & 3.5\times10^{-5} & 8.0\times10^{-3} \\ 3.5\times10^{-5} & 8.0\times10^{-4} & 5.1\times10^{-3} \\ 8.0\times10^{-3} & 5.1\times10^{-3} & 2.7\times10^{-3} \end{pmatrix}$$

- Type II: $\delta\mathcal{L}_{4F} = \frac{1}{M_\Delta{}^2}\left(\overline{\tilde{\ell}_L} Y_\Delta \vec{\tau}\,\ell_L\right)\left(\overline{\ell_L}\vec{\tau}\, Y^\dagger_\Delta\, \tilde{\ell}_L\right)$

- Type III: $\delta\mathcal{L}^{d=6} = c^{d=6}_{\alpha\beta}\left(\overline{\ell_{L\alpha}}\vec{\tau}\tilde{\phi}\right) i D\!\!\!\!/ \left(\tilde{\phi}^{\dagger}\vec{\tau}\ell_{L\beta}\right),$ $\sim\ \varepsilon^2$

Abada,Biggio, Gavela,Bonnet, Hambye; Antusch, Fernandez, Malinsky, Meloni, Ohlsson, Winter, Zhang,...

Seesaw and new gauge forces:

- **Seesaw strongly suggests gauge forces**
- **Type I** : why seesaw scale so far below Planck scale:
- **Inverse seesaw case**:
- **Why** $\begin{pmatrix} 0 & hv_{wk} & 0 \\ hv_{wk} & 0 & M \\ 0 & M & \mu \end{pmatrix}$ **why not** $\begin{pmatrix} 0 & hv_{wk} & h'v_{wk} \\ hv_{wk} & M' & M \\ h'v_{wk} & M & \mu \end{pmatrix}$

- **Local B-L** symmetry --a plausible answer !
- Collider profile of seesaw undergoes drastic change !!

What Gauge Symmetry ?

- **Standard model: gauge sym.** $SU(2)_L \times U(1)_Y$
- **Fermions:**

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad \begin{matrix} u_R \\ d_R \end{matrix}$$

$$m_\nu = 0 \quad \leftarrow \quad \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \quad e_R$$

- **N_R → Gauge group:**

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$

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

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

$W_L^\pm$ $\quad$ $W_R^\pm$ $\quad$ Z, Z', γ

- **New** $\quad$ ↑ ($W_R^\pm$) $\quad$ ↑ (Z')

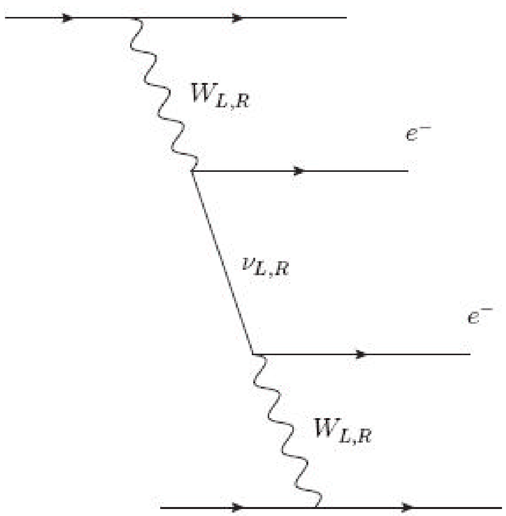
Bounds on LR Scale

- Most stringent bounds come from CP viol. Observables

  $\varepsilon, \varepsilon', d_n^e$ **; depends on how CP is introduced:**

  $M_{W_R} \geq 2.5 TeV$ to $4 TeV$ **Zhang et al; Maiezza et al.**

- New contributions to nu-less double beta decay **(Type I)** **(RNM, 86; Hirsch, Klapdor, Panella 96)**



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

From Ge76:

- Collider limits (D0,CDF) >750 GeV

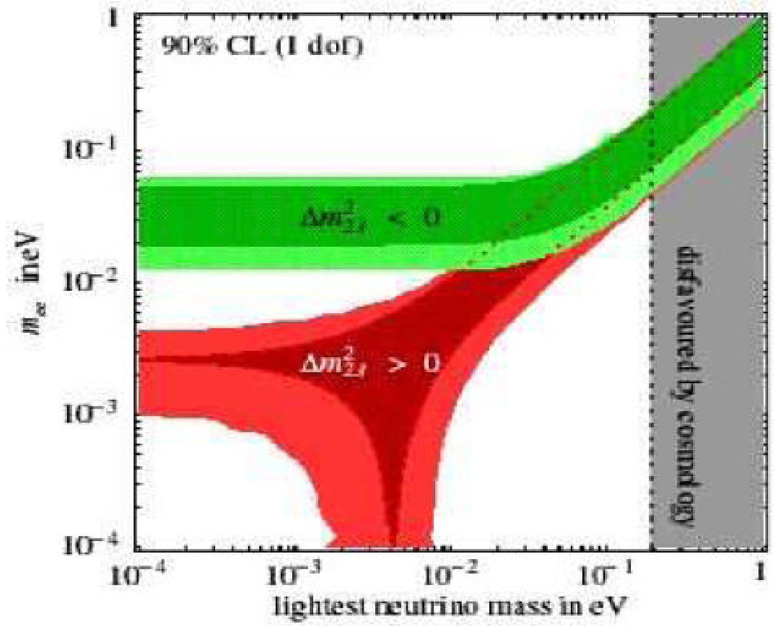
TeV WR signal from $\beta\beta_{0\nu}$

- **Nu contribution**:

  Inverse hierarchy

  Normal hierarchy

(Ferruglio, Strumia, Vissani;
Petcov, Passcoli, Bilenky)



Punch line:

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

→could be a signal of TeV WR   and type I

Theory insights into seesaw scale

- **Upper limits: Supersymmetry**

  Supersymmetry restricts potential for SUSY LR type I seesaw

$$M_{W_R} < \frac{M_{susy}}{f}$$

Kuchimanchi, RNM, 95

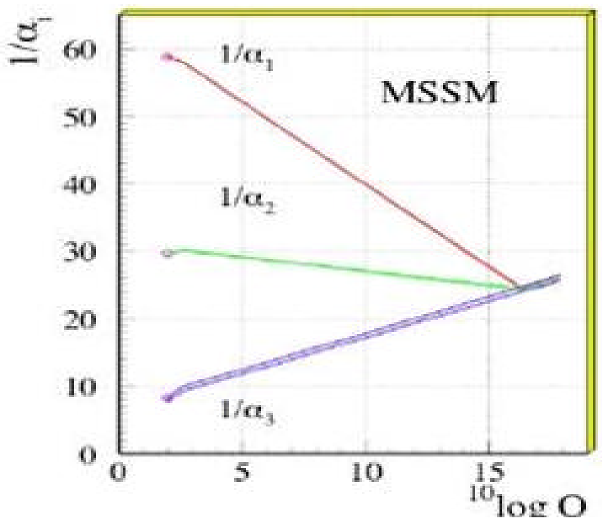
- **Sneutrino or KK Nu_R dark matter→**

$$M_{W_R} < \text{few TeV}$$

Kong, Matchev, Nasri;; Hsieh, Nasri, RNM

Is Grand unification idea any help ?

- **Gauge couplings unify with TeV scale SUSY-MSSM**



→Suggests grand unified Th.

- **Connects quark and lepton physics-**
- SU(5) does not help- Seesaw scale free parameter: (proton decay ?)

SO(10) just right:

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

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

- **Q-l unification predicts**

$$m_D \approx m_t$$

- **Type I case:** seesaw scale

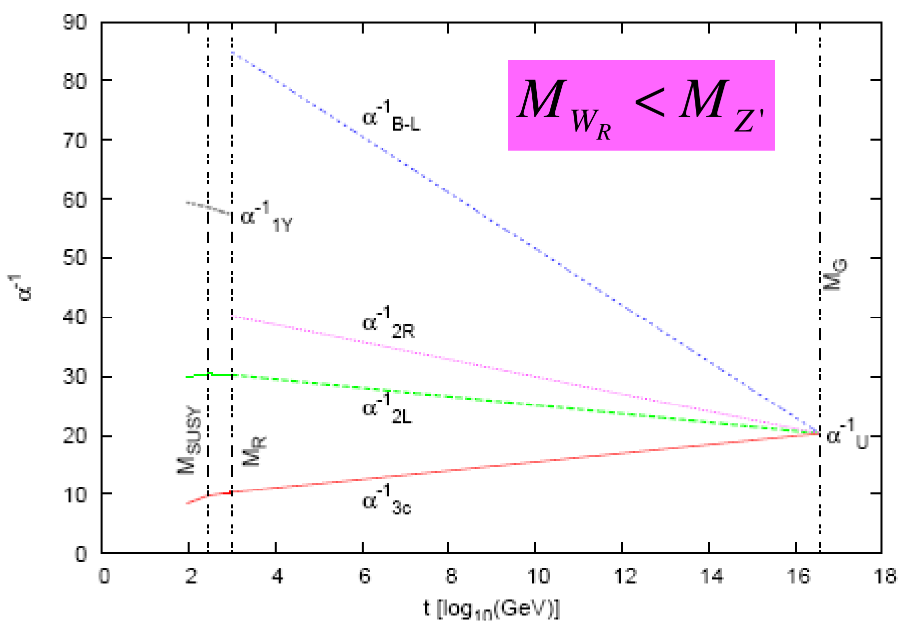
$$M_R \approx 10^{14} GeV$$

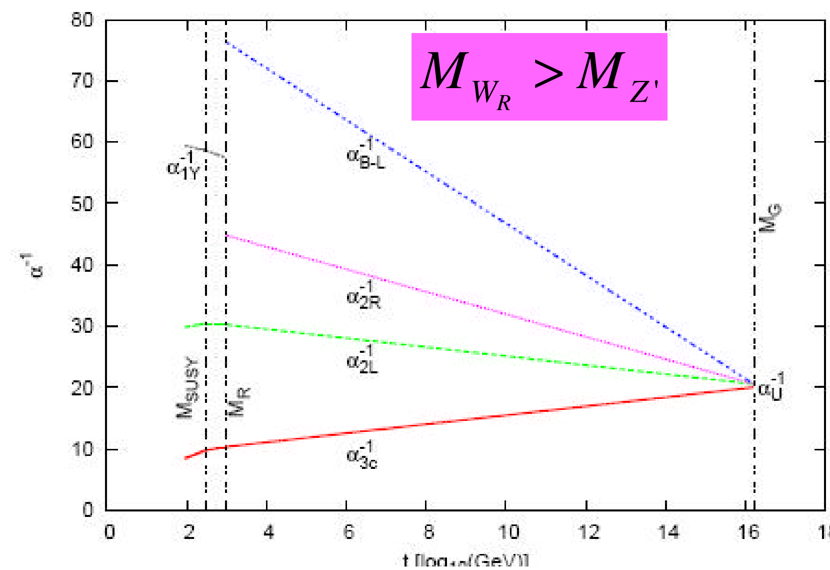
- **Very appealing picture: predictive with extra global family symmetries;**
- **TeV scale for type I does not unify:**

(Parida, Raichoudhuri, Majee, Sarkar; Kopp, Lindner,Niro, Underwood)

Inverse seesaw in SO(10) - LHC accessible

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





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

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

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

Leptogenesis and TeV WR

- Formula for baryon asym $$\eta_B \simeq 10^{-2} \sum_{i,\alpha} \varepsilon_{i\alpha}\, \kappa_{i\alpha}$$
- Resonant lepto: $\varepsilon \sim \frac{h_D^2 \delta}{\Delta M / M}$; $\kappa \sim \frac{D}{D+S} \exp[-W_{L=2}^{ID,..}]$
- **Type I case**: $h_D^2 \sim 10^{-12}; \rightarrow \frac{\Delta M}{M} \sim 10^{-12};$ S can be>> D
- Washout depends on WR mass: MWR > 17 TeV **(Frere, Hambye, Vertognen)**
- **Inverse seesaw** $h_D^2 \sim 10^{-2} \rightarrow D >> S; W_{L=2} \sim \frac{\mu}{M} \sim 10^{-7} \rightarrow \kappa$ ~1
- Not so sensitive dependence on WR. MWR > 1.5 TeV **(Blanchet, Dev, RNM, to appear)**

Type I vs Inverse left-right 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 xing a ε l/or (b) ex W_R nge
- **type I** : $\varepsilon << 10^{-3}, M_{W_R} < 4TeV$ negligible; $N \to l^{\pm} jj$
- **Signal** $pp \to l^{\pm} l^{\pm} jj + X$
- **Inv. Seesaw** $\varepsilon > 10^{-3}$ $N \to l^- jj, l^- l^+ \nu$ $pp \to lll\nu + X$

LHC reach < 4 TeV

- Determination of chirality: tb decay mode (Gopalakrishna, Han, Lewis, Si, Zhou)

2. Understanding Large mixings

Issue 1. Large lepton mixings: why ?

Leptons:

$$U_{PMNS} \approx \begin{pmatrix} \frac{\sqrt{6}}{3} & \frac{\sqrt{3}}{3} & 0 \\ -\frac{\sqrt{6}}{6} & \frac{\sqrt{3}}{3} & \frac{\sqrt{2}}{2} \\ \frac{\sqrt{6}}{6} & -\frac{\sqrt{3}}{3} & \frac{\sqrt{2}}{2} \end{pmatrix} + \delta U$$

Issue 2. How to have a unified understanding of quark and lepton mixings

$$U_{CKM} = \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

Lepton mixings

(i) Family symmetries :

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

- **Generically leads to TBM + small corrections**

(Talks by Morisi and Hagedorn)

(ii) Dynamical e.g. RH neutrino dominance **(King)**

generically predicts large θ_{13} **;**

→ no explanation of TBM;

A strategy for flavor unification

A

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

(Dutta, Mimura, RNM'PRD-09)

$$m_\nu = f v_L$$

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

→**Anarchic** **M_0, f** →**quark mixings small while lepton mixings large +** $m_b \cong m_\tau$

Natural in SO(10)+ type II seesaw

B **Rank 1 M_0** →**explains mass hierarchies**

An S_4 xSO(10)- example

- **Symmetries make theory predictive: e.g. S4**
- **Solar mass** $\frac{m_{solar}}{m_{atm}} \cong \lambda \cong \theta_c$ **Dutta, Mimura, RNM arXiv:0911.2242 , JHEP**
- **Bottom-tau:** $m_b \approx m_\tau$ **and** $m_\mu = -3m_s$
- **Leading order PMNS- Tri-bi-maximal**

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

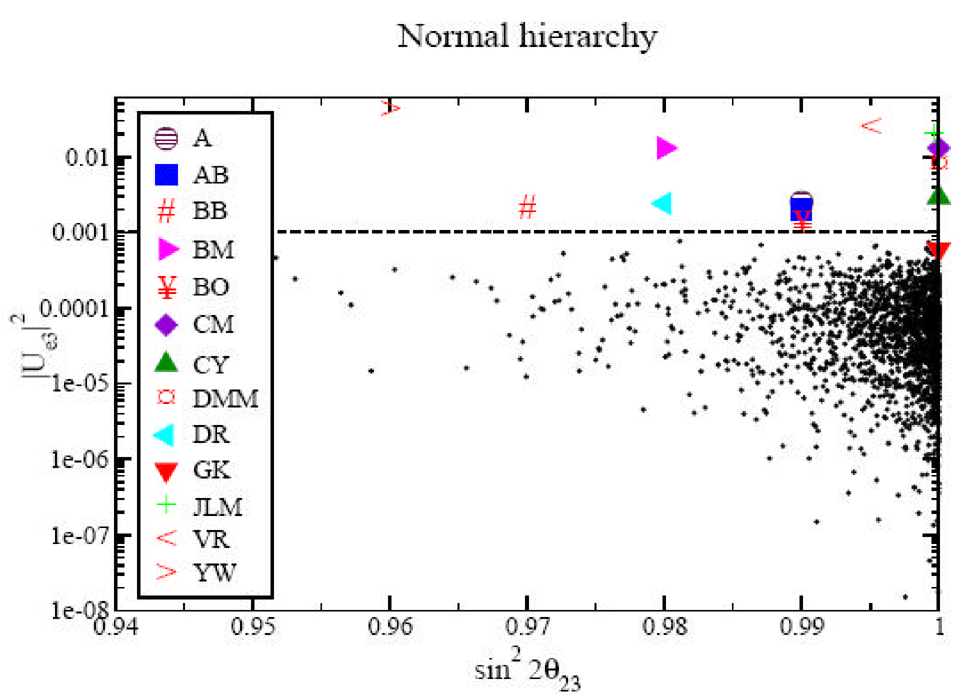
Bjorken, King, Pakvasa Ferrandis; Chen, Mahanthappa

- Prediction for atmospheric angle: $\theta_{23} \cong 35^0 - 40^0$
- Current fit: $\theta_{23}^0 = 42.8^{+4.7}_{-2.9}{}^{+10.7}_{-7.3}$ **(Gonzalez-Garcia, Maltoni, Salvado,2010)**

Generic GUT predictions

- **Normal hierarchy** $m_1 < m_{solar} < m_{atm}$
- θ_{13} **predictions for GUT vs non-GUT**

(Compilation by Albright, Rodejohann)



3. Schizophrenic neutrinos

- Common assumption: Neutrinos are either Dirac or Majorana
- **“Neutrino---neu-ter---(not either)”;** E. Lisi, Neutrino 2010 summary talk
- **Could it be that neutrinos are neither fully Dirac or fully Majorana but little bit of both i.e. Schizophrenic ?**

How could that be ?

- Experiments → **U**PMNS, which relates mass to flavor eigenstates

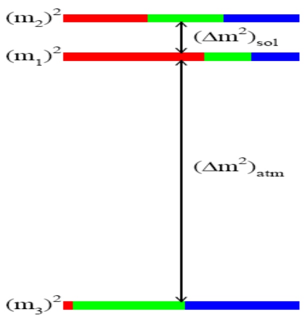
$$\nu_{flavor} = U_{PMNS} \nu_{mass}$$

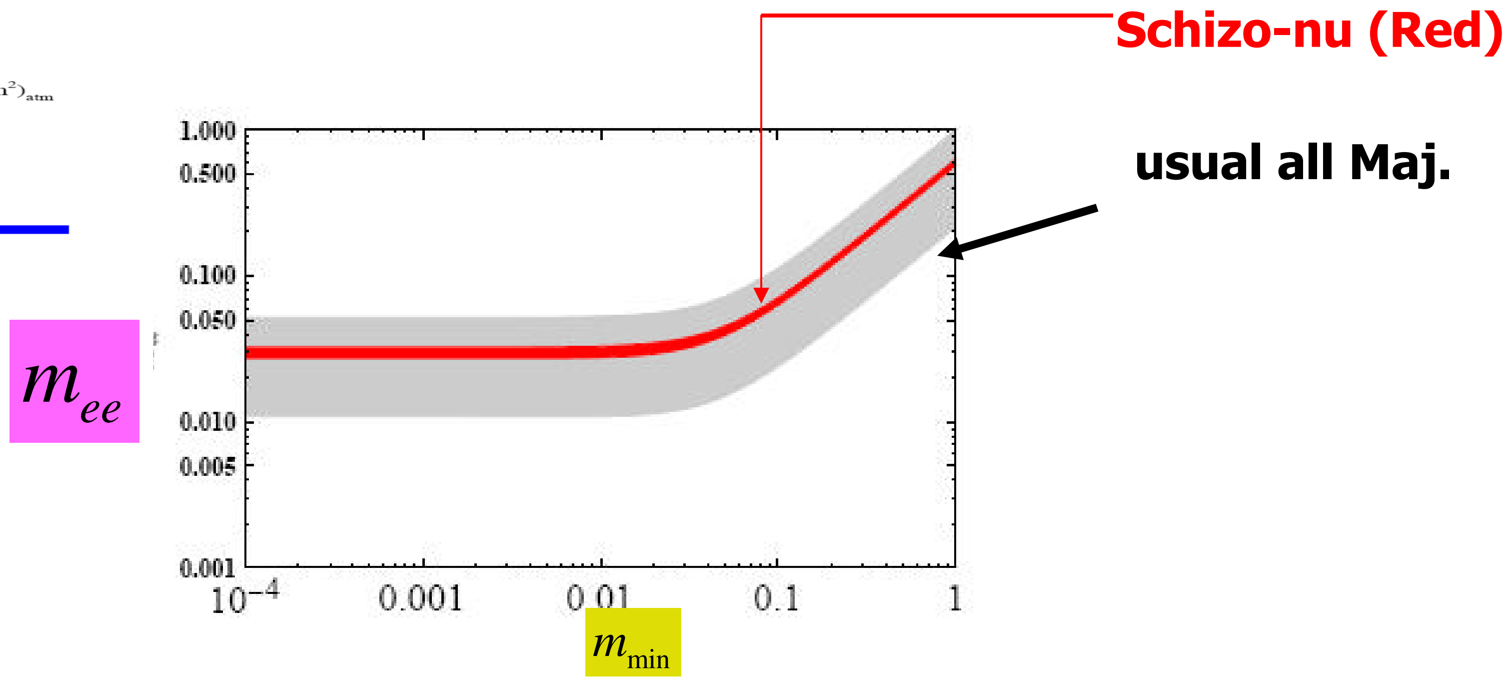
- May be some some **mass eigenstates** are Dirac –others Majorana; **each flavor will then be both Dirac and Majorana-** mixings and masses are unaffected.
- Specific example: $\nu_2 \equiv \frac{1}{\sqrt{3}}(\nu_e + \nu_\mu + \nu_\tau)$ Dirac -others Majorana
- Why this combo? S_3 sym permuting: (L_e, L_μ, L_τ)

{1}: $\frac{1}{\sqrt{3}}(L_e + L_\mu + L_\tau)$ **Dirac; {2}:** $[\frac{1}{\sqrt{2}}(L_\mu - L_\tau), \frac{1}{\sqrt{6}}(2L_e - L_\mu - L_\tau)]$ **Maj**

(Allahverdi, Dutta, RNM,arXiv:1008.1232)

Implications for Nu-less double beta decay-IH





- $M^{\beta\beta}_{min}$=17 meV (usual IH) vs 34 meV (Schizo-nu IH) –
  → schizo-nu easier to rule out if LBL→ IH

Why ? Inflation→ Schizophrenia

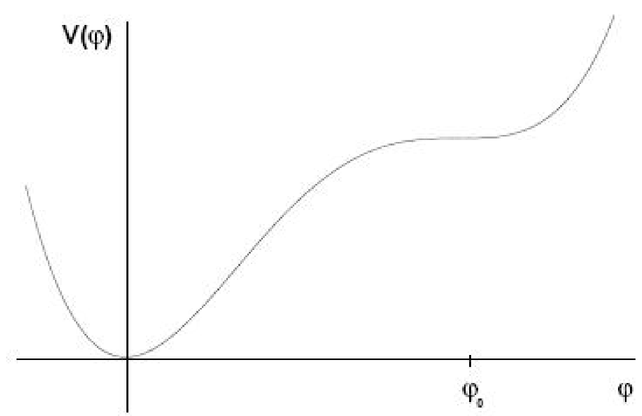
- **Susy B-L theory for seesaw→ 3 RH neutrinos**

→ To fit neutrino observations, we only need two RH nu's- **so what is the third one (N3) doing ?**

→ **Could its superpartner be the inflaton ?**

→ **Inflation requires ~flat potential;**

→ **In the B-L theory** $(\tilde{N}+\tilde{L}+H_u)$ **is one provided** h_D **is tiny.**



(Allahverdi, Kusenko, Mazumdar; Allahverdi, Dutta, Mazumdar)

Implications for neutrinos

- **How small is h_D ?**
- **COBE** $\frac{\delta\rho}{\rho} \sim 10^{-5}$ → $h_D \sim 10^{-12}$ **for only one RH neutrino; just right for a Dirac nu:**
- **That RH neutrino cannot mix with others to maintain flatness.**
- Immediately suggests this scenario for nu masses

Conclusion:

- **Seesaw:** Compelling big picture idea for neutrino masses;

(i) LHC can discover TeV scale seesaw;
even in SO(10) models; Must it discover ? NO

(ii) Most appealing neutrino models are based on type II+ SO(10) GUT seesaw; No LHC signal;
Can also unify flavor with extra sym.

(iii) An inflation inspired schizophrenic neutrino scenario.

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;

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

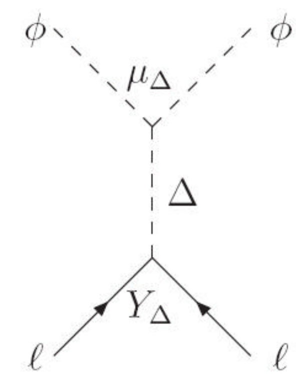
→suppressed for TeV B-L breaking.

SO(10) with type II seesaw → realization of flavor ansatz

- **SO(10)→ fermion mass formulae:**

$$
\begin{aligned}
Y_u &= h + r_2 f + r_3 h' \\
Y_d &= r_1(h + f + h') \\
Y_e &= r_1(h - 3f + c_e h')
\end{aligned}
$$

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



(Babu, Mohapatra'92)

Bajc, Senjanovic, Vissani'03

- **For f, h' << h, → yields ansatz part A** at **M_U;**
- **Rank (part B) from flavor symmetry:**
- **Rank solves the proton decay problem also**

LHC accessible non-seesaw models

- Seesaw scenarios based on operator: $\frac{LHLH}{M}$

- Higher the dimension of operator, lower the scale:
  e.g. $LLHH(H^{\dagger}H)/M^3$ **(Babu, Nandi and Tavartkiladze)**

→ TeV scale theory; predicts a field Φ^{+++} M< TeV
observable via decays: Φ^{+++} → $W^+W^+W^+$, $W^+\ell^+\ell^+$

Inverse Seesaw: details

- Rate plots: