Neutrino Mass Models-
An SO(10) GUT Perspective

R. N. Mohapatra

UNIVERSITY OF MARYLAND

"Smirnov-fest" GGI Florence,2012

.Complete neutrino physicist

-

Rock star of nu physics

2000-2012

Happy Birth Day Alexei !!

Outline of Talk

- Minimal SO(10) model for neutrinos and θ_{13}
- Proton decay window to GUT models for neutrinos:
- GUT scale baryogenesis revived
- Testing GUT theories by low energy measurements (other than p-decay)

Flavor puzzle in particle physics

- quark flavor puzzle: hierarchy in masses and mixings
- Neutrino mixngs: $\theta_{23} \sim 45^{0}$;$\theta_{12} \sim 33^{0}$,

mass hierarchy unknown but $\Delta m^2_{\odot}/\Delta m^2_A \sim \theta^2_C$

+Recent θ_{13} results:

- T2K: $0.03 \leq \sin^2(2\theta_{13}) \leq 0.28$
- MINOS: $0.00 \leq \sin^2(2\theta_{13}) \leq 0.12$
- Double Chooz: $\sin^2(2\theta_{13}) = 0.085 \pm 0.051$
- Daya Bay: $\sin^2 2\theta_{13} = 0.092 \pm 0.016 \pm 0.005$
- RENO expt. $\sin^2 2\theta_{13} = 0.103 \pm 0.013 \pm 0.011$
- Is there a Big Picture unifying quarks and leptons ?

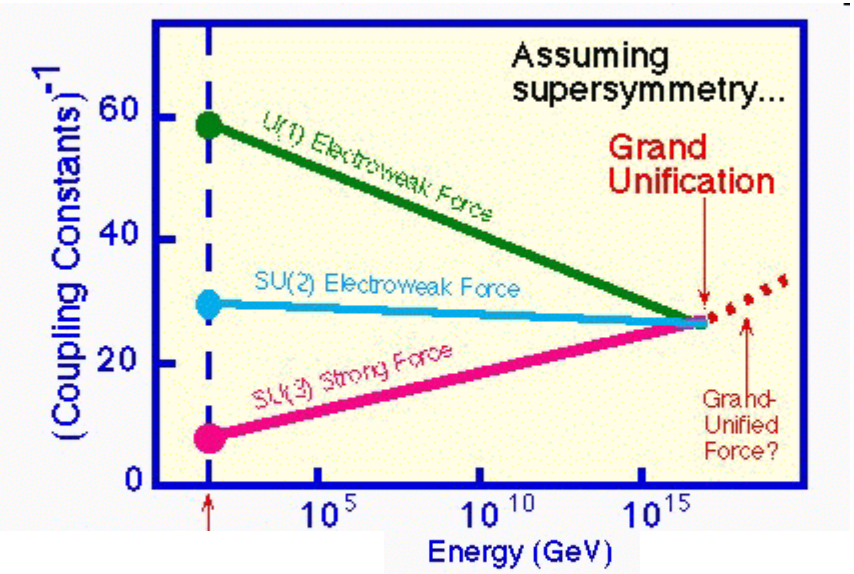
From Data to Physics

- Important for physics is the mass matrix, Mν:
- Near Maximal atmospheric angle already gives some idea:
- $M_\nu = \begin{pmatrix} - & - & - \\ - & m-\varepsilon & m \\ - & m & m \end{pmatrix}$ large solar $M_\nu = \begin{pmatrix} - & \sim\varepsilon & \sim\varepsilon \\ \sim\varepsilon & m-\varepsilon & m \\ \sim\varepsilon & m & m \end{pmatrix}$
- Quark mass matrix: $M_d \approx m_b \begin{pmatrix} \lambda^4 & \lambda^3 & \lambda^3 \\ \lambda^3 & \lambda^2 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$ $\lambda \sim .22$ $\sim \varepsilon$
- Can a physics big picture ever connect them or quarks and leptons are separate “beasts” ?

GUT approach

Recital of standard virtues of GUTs:

- $\alpha_i(M_Z)$ + SUSY at TeV→ couplings unify

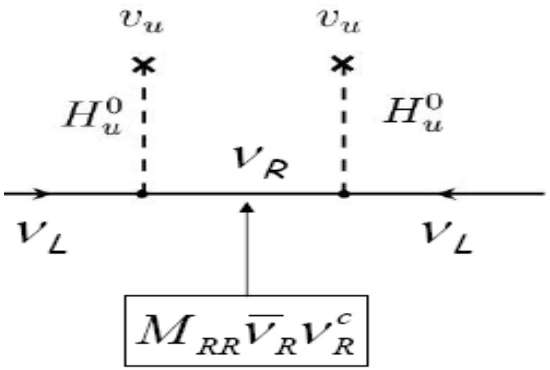


$$M_U \approx 10^{16}\,GeV$$

- Explains electric charge quantization
- Unifies all matter- connecting quark-lepton flavor

Is nu mass a messenger of GUT physics ?

- Coupling unification scale in susy: $\boxed{M_U \approx 10^{16}\,GeV}$
- Seesaw paradigm
- SM+ right handed neutrinos N_R with Majorana mass: $\cancel{B-L}$



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

MR Large→neutrino mass tiny

M$_R$ How Large ? GUTs→ $h_{\nu,33} \approx h_t$; Δm^2_{atm}→$M_R \approx 10^{14}\,GeV$

- Broken B-L sym.- part of BSM (GUT?) physics !!

GUT Scenarios

- SU(5) with 45+ N_R with Majorana mass near M_U

  -Why is M_N large?

  -60 parameters; Need symmetries to predict: (A_4 ,S_4, T′)

  (Altarelli, Feruglio; King, Luhn, Antusch, Spinrath; Chen, Mahanthappa; Hagedorn,Meroni, Petcov,Spinrath; Ishimori, Saga, Tanimoto, Shimizu; Bazzochi, Merlo….)

- Type II alternative: SU(5) +45+15

  - 45 parameters

  (Joaquim, Rossi; Hambye, RNM, Nasri, Yu….)

SO(10) SUSY GUT –dream picture for neutrinos

- SO(10) unifies all fermions/family (including RH nu) in single rep.

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

- Scales : SO(10) → MSSM → SM
- Contains all the ingredients for seesaw
- Minimal renormalizable models with 126-Higgs predictive for nu masses and mixings in terms of quark masses (18 parameters) (Babu,Mohapatra'93)
- 10+126+120 → 15 parameters (Dutta, Mimura, RNM'05; Bertolini,Frigerio, Malinsky; Aulakh, Garg; Grimus, Kuhbock most recent analysis Altarelli, Blankenburg'10)

Predictive SO(10)

- Quark lepton masses with 10(H)+126 (Δ) Higgs

$$W = h\psi\psi H + f\psi\psi\Delta$$

$$M_u = hv_{u,10} + fv_{u,126}$$

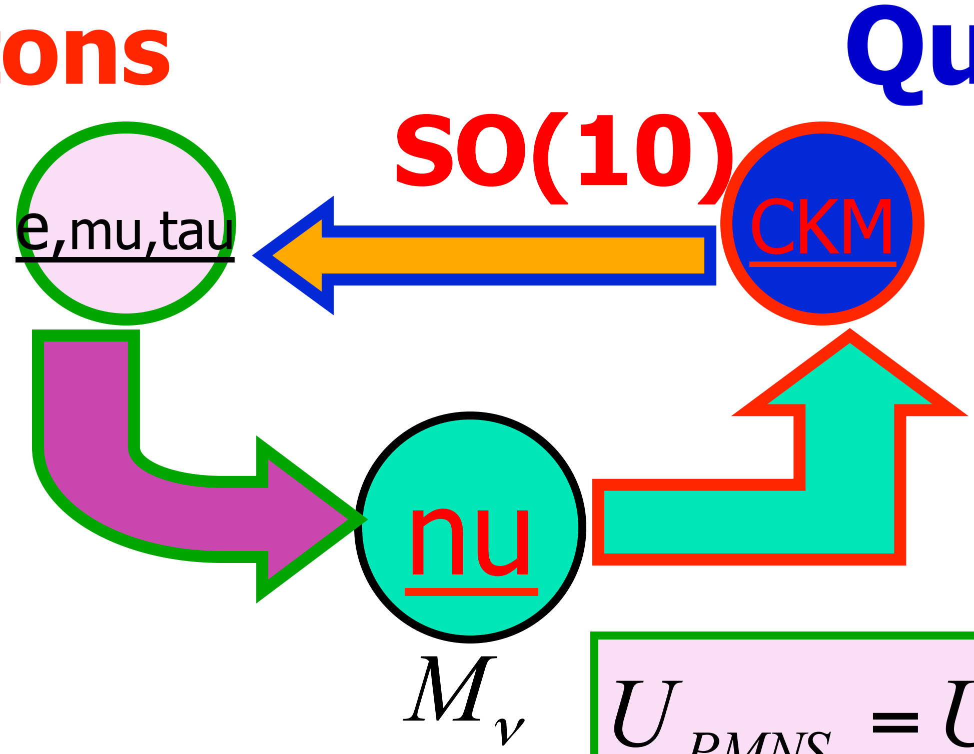
$$M_d = hv_{d,10} + fv_{d,126}$$

$$M_\ell = hv_{d,10} - 3fv_{d,126}$$

$$M_D = hv_{u,10} - 3fv_{u,126}$$

$$M_\nu = fv_L - M_D(fv_R)^{-1}M_D$$

Predictive Quark-lepton connection in minimal SO(10)$_{126}$



M_ν

Seesaw

$$U_{PMNS} = U_\ell^+ U_\nu$$

(Babu, Mohapatra'93; Fukuyama,Okada'02; Bajc, Senjanovic, Vissani'02; Goh, RNM, Ng'03; Aulakh,Bajc,Melfo,Senjanovic, Vissani; Fukuyama,Ilakovic,Meljanac,Kikuchi,Okada;Bertolini, Malisky, Schwetz; Babu, Macesanu; Joshipura,Patel)

SO(10) with Type II seesaw and large mixings

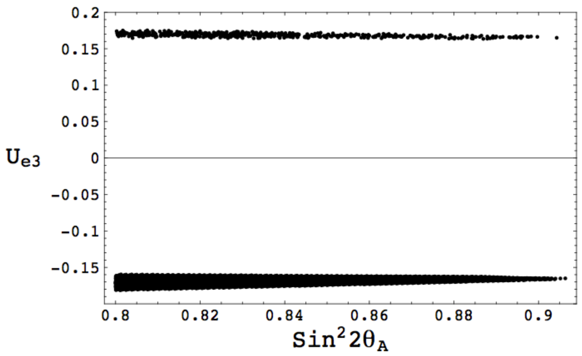
- **II seesaw** $\boxed{M_\nu \cong c(M_d - M_l)}$
- GUT relation $m_b \approx m_\tau + \lambda^2$ →

$$M_\nu \propto m_b \begin{pmatrix} \lambda^5 & \lambda^3 & \lambda^3 \\ \lambda^3 & \lambda^2 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} - m_\tau \begin{pmatrix} \lambda^6 & \sim\lambda^3 & \\ \lambda^3 & -3\lambda^2 & \lambda^2 \\ & \lambda^2 & 1 \end{pmatrix} \sim \lambda^2 \begin{pmatrix} \lambda^2 & \lambda^2 & \lambda \\ \lambda^2 & 1+\lambda & 1 \\ \lambda & 1 & 1 \end{pmatrix}$$

(Bajc, Senjanovic, Vissani' 02)

- Predicts $\theta_{13} \simeq .17$;$m_\odot / m_\oplus \sim \lambda$

(Goh, RNM, Ng, Phys.Lett. B570 (2003) 215)



(Daya Bay-RENO value ~0.15)

SO(10) with Type I+II

- **Why?**
- How well does the GUT relation $m_b \approx m_\tau$ +λ^2 work ?
- Quite well for susy SO(10) with large tanβ~50; within 2 sigma for tan β=10
- Large tanβ values have problem with p-decay
- Non-Susy no $m_b \approx m_\tau$
- More general analysis with I+II+CPV gives same large θ_{13}(Babu, Macesanu; Bertolini, Malinsky, Schwetz;'05)
- Large θ_{13} generic of 126 models with susy.

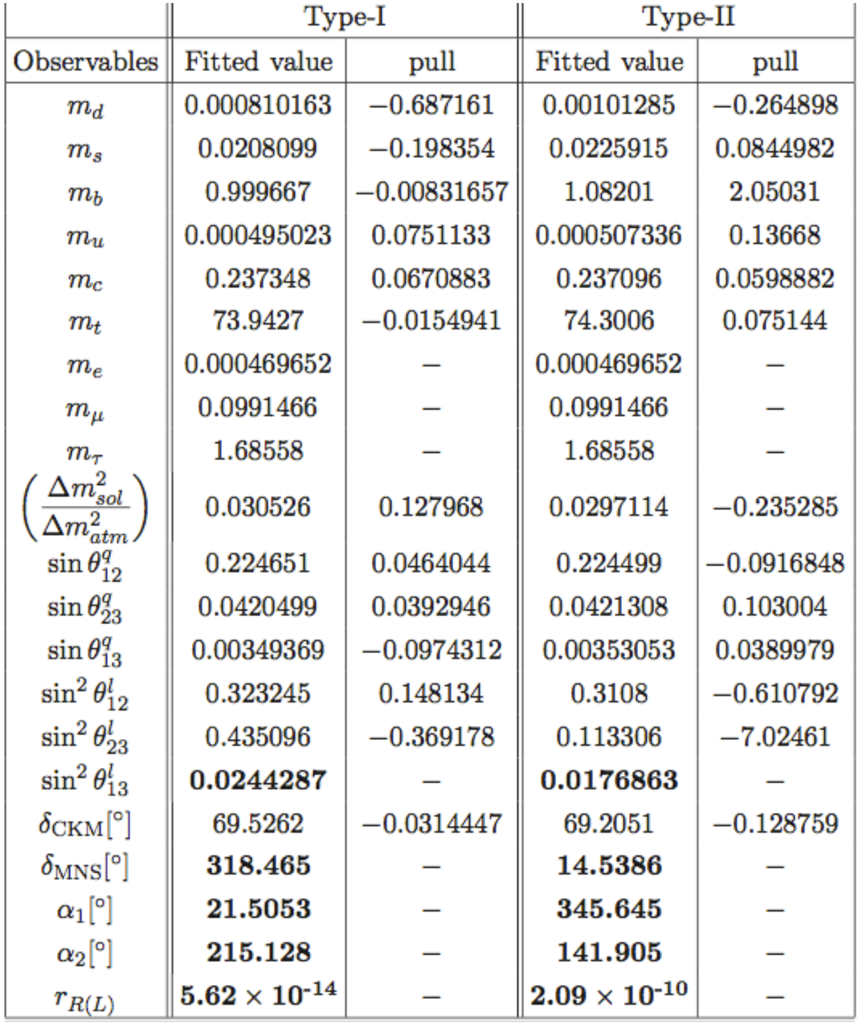
SO(10)$_{126}$ without susy

- b-τ does not work.
- Numerical fermion fits work for the minimal model still work with type I

(Joshipura and Patel’11)

$\sin^2 2\theta_{13}$ =.093 :Type I

Agrees with Daya Bay



	Type-I		Type-II	
Observables	Fitted value	pull	Fitted value	pull
m_d	0.000810163	−0.687161	0.00101285	−0.264898
m_s	0.0208099	−0.198354	0.0225915	0.0844982
m_b	0.999667	−0.00831657	1.08201	2.05031
m_u	0.000495023	0.0751133	0.000507336	0.13668
m_c	0.237348	0.0670883	0.237096	0.0598882
m_t	73.9427	−0.0154941	74.3006	0.075144
m_e	0.000469652	–	0.000469652	–
m_μ	0.0991466	–	0.0991466	–
m_τ	1.68558	–	1.68558	–
$\left(\frac{\Delta m^2_{sol}}{\Delta m^2_{atm}}\right)$	0.030526	0.127968	0.0297114	−0.235285
$\sin\theta^q_{12}$	0.224651	0.0464044	0.224499	−0.0916848
$\sin\theta^q_{23}$	0.0420499	0.0392946	0.0421308	0.103004
$\sin\theta^q_{13}$	0.00349369	−0.0974312	0.00353053	0.0389979
$\sin^2\theta^l_{12}$	0.323245	0.148134	0.3108	−0.610792
$\sin^2\theta^l_{23}$	0.435096	−0.369178	0.113306	−7.02461
$\sin^2\theta^l_{13}$	**0.0244287**	–	**0.0176863**	–
$\delta_{\mathrm{CKM}}[^\circ]$	69.5262	−0.0314447	69.2051	−0.128759
$\delta_{\mathrm{MNS}}[^\circ]$	**318.465**	–	**14.5386**	–
$\alpha_1[^\circ]$	**21.5053**	–	**345.645**	–
$\alpha_2[^\circ]$	**215.128**	–	**141.905**	–
$r_{R(L)}$	**5.62×10^{-14}**	–	**2.09×10^{-10}**	–

How to test the model ?

- Broken B-L – a key element of SO(10) seesaw
- p-decay tests-(Conventional B-L=0 modes do not test seesaw)
- μ➔ e+γ(does not test nonsusy seesaw)
- Look for p-decay modes violating B-L
- New result: SO(10) GUTs without SUSY→
- Observable proton decay modes with $\cancel{B-L}$
- New TeV mass color sextet particles at LHC
- Observable NN-bar oscillation

GUTs and p-decay

- Canonical GUT modes for p-decay:

$$p \to e^{+} + \pi^{0}; p \to K^{+}\bar{\nu}$$

- Conserve B-L=0
- D=6 operators in SM (Weinberg; Wilczek, Zee'79)

$$\mathcal{O}_1 = (d^c u^c)^*(Q_i L_j)\epsilon_{ij}, \quad \mathcal{O}_2 = (Q_i Q_j)(u^c e^c)^*\epsilon_{ij}, \quad \mathcal{O}_3 = (Q_i Q_j)(Q_k L_l)\epsilon_{ij}\epsilon_{kl}$$

$$\mathcal{O}_4 = (Q_i Q_j)(Q_k L_l)(\vec{\tau}\epsilon)_{ij} \cdot (\vec{\tau}\epsilon)_{kl}, \quad \mathcal{O}_5 = (d^c u^c)^*(u^c e^c)^* .$$

- Compare with d=5 operator *LHLH*

B-L=2 B-violation

(ii) D=7 : Have B-L=2 (Weinberg; Weldon, Zee'80)

$$\begin{aligned} \tilde{\mathcal{O}}_1 &= (d^c u^c)^* (d^c L_i)^* H_j^* \epsilon_{ij}, & \tilde{\mathcal{O}}_2 &= (d^c d^c)^* (u^c L_i)^* H_j^* \epsilon_{ij}, \\ \tilde{\mathcal{O}}_3 &= (Q_i Q_j)(d^c L_k)^* H_l^* \epsilon_{ij} \epsilon_{kl}, & \tilde{\mathcal{O}}_4 &= (Q_i Q_j)(d^c L_k)^* H_l^* (\vec{\tau}\epsilon)_{ij} \cdot (\vec{\tau}\epsilon)_{kl}, \\ \tilde{\mathcal{O}}_5 &= (Q_i e^c)(d^c d^c)^* H_i^*, & \tilde{\mathcal{O}}_6 &= (d^c d^c)^* (d^c L_i)^* H_i, \\ \tilde{\mathcal{O}}_7 &= (d^c D_\mu d^c)^* (\overline{L_i} \gamma^\mu Q_i), & \tilde{\mathcal{O}}_8 &= (d^c D_\mu L_i)^* (\overline{d^c} \gamma^\mu Q_i), \\ \tilde{\mathcal{O}}_9 &= (d^c D_\mu d^c)^* (\overline{d^c} \gamma^\mu e^c) \, . \end{aligned}$$

→ $n \rightarrow e^{-} \pi^{+}$

(iii) D=9: $u^c d^c d^c u^c d^c d^c$ B-L=2 → $n - \bar{n}$

(RNM, Marshak'80; Glashow'80)

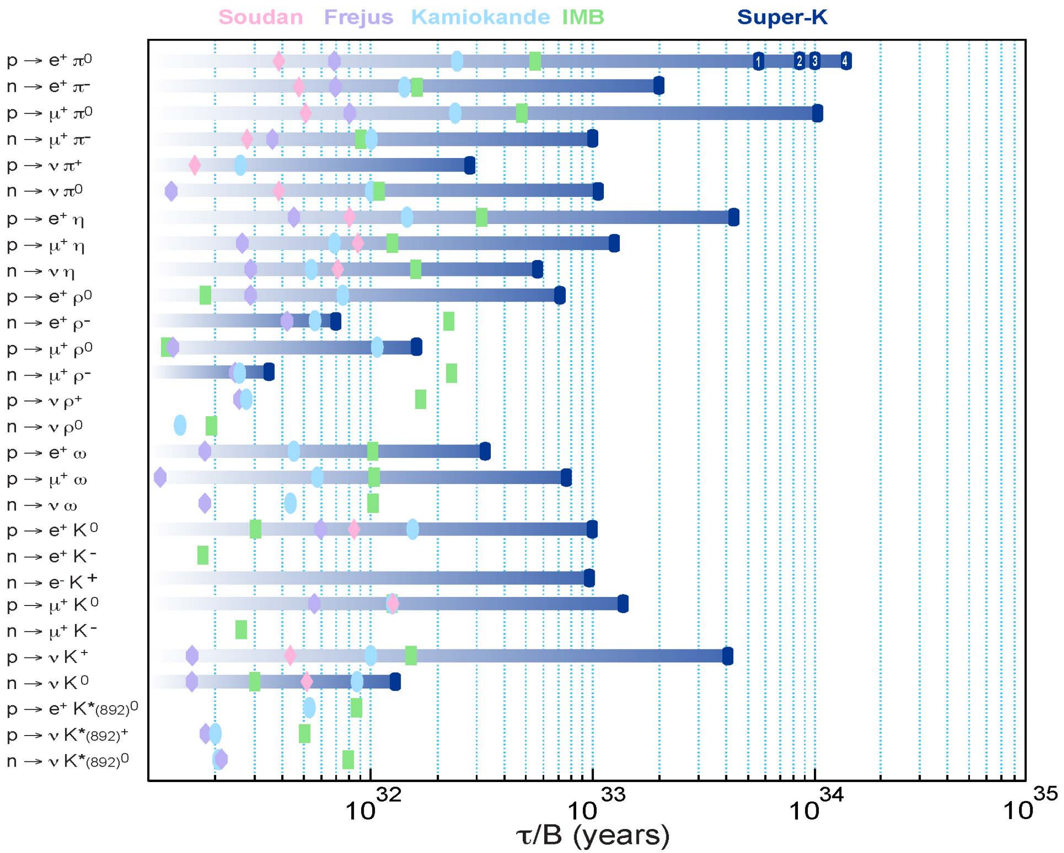
- Same property as seesaw –are they related to neutrino mass ? Are they present in GUT theories with seesaw?

$\cancel{B-L}$ modes in non-SUSY SO(10) for nu mass

- Key ingredient of minimal renorm. SO(10) models for nu mass is 126-Higgs field that leads to seesaw.
- If some of the {126} scalar fields remain at TeV to ~TeV scale, they can give enhanced B-violation with B-L=2 e.g. $n \to e^- \pi^+$ $n - \bar{n}$ oscillation (Babu, Mohapatra; arXiv: 1203:5544; 1205.5701)
- Can be observable in Hyper-K
- Is it consistent with coupling unification ?

Proton decay-expt status

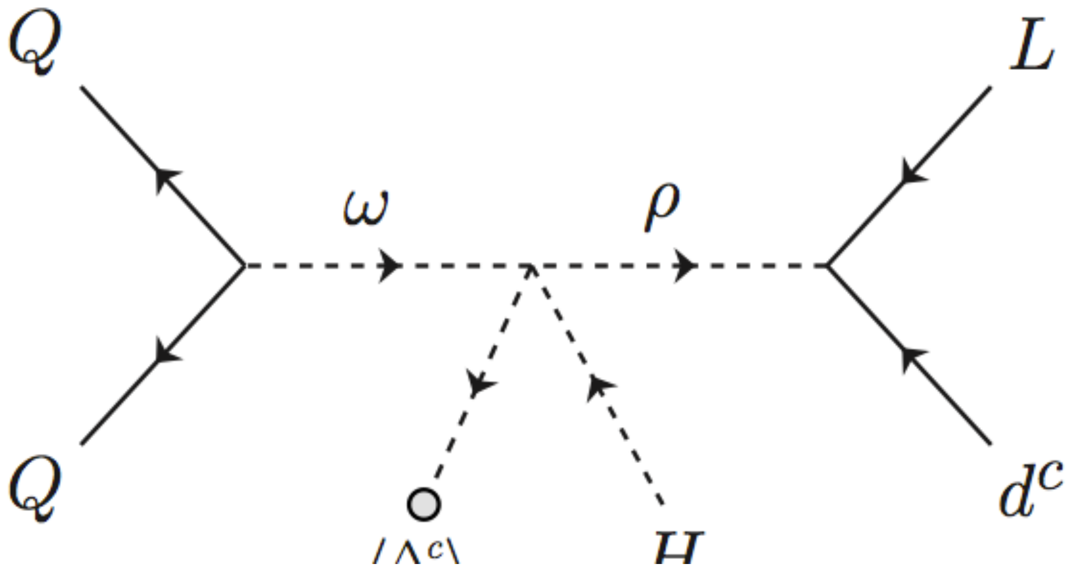
- Super-K limits



★ Hyper-K to push limits by factor 10

Intermediate scale Scalars and B-L=2 p-decay

- Diagram for neutron-decay: d=7 Operator O_2



$$\tilde{O}_2 = (Q_i Q_j)(d^c L_i)^* H_j^* \epsilon_{ij}\epsilon_{kl},$$

ω in {10, 126};

$\rho(3, 2, 1/6)$ {126}

$\omega\rho^* H$ in {126}^{4}

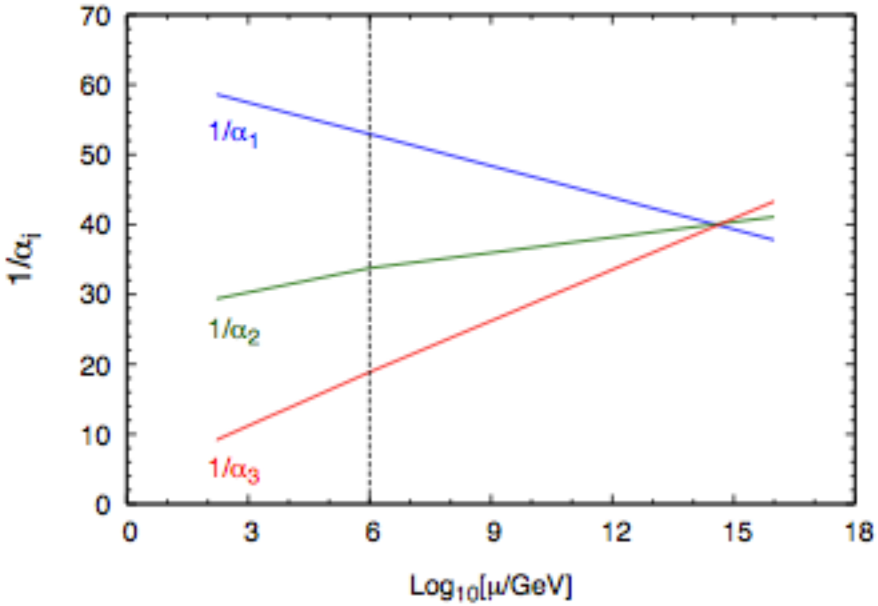
- Leads to $n \rightarrow e^- + \pi^+$ decay

Coupling unification and observability

- $A_{n\to e^-\pi^+} \sim \frac{f_{126}^2 v_{BL} v_{wk}}{M_\omega^2 M_\rho^2} \sim \frac{10^{-20}}{M_\rho^2}$

Observability→ $M_\rho \sim 10^5 GeV$; is it GUT allowed ?

Yes→



→ $\tau_p \sim 4 \times 10^{33} yrs$

Alternative SO(10) scenario

- Non-SUSY SO(10) does not unify without low scale particles, (Babu, Mohapatra, arXiv:1206.5701)
- Coupling unif with

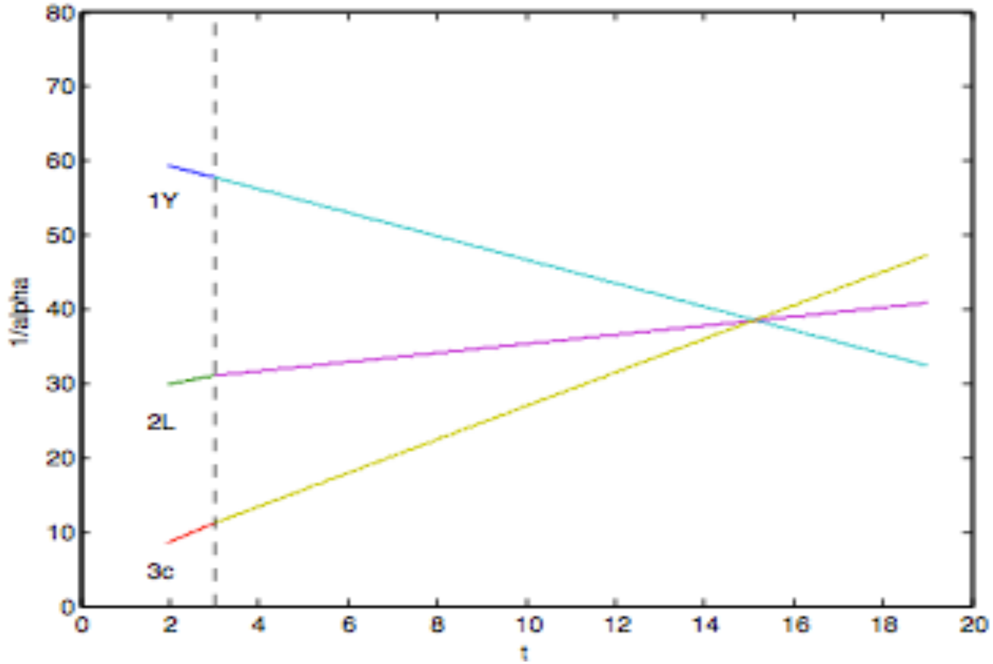
sub-TeV $\Delta_{ud}(6,1,\frac{1}{3})$

+ 2 SM triplets;

- Predicts seesaw scale

near M_U~$10^{15.7}$ GeV;

$\tau_{p\rightarrow e^+ + \pi^0} \sim 3\times 10^{34} yrs$

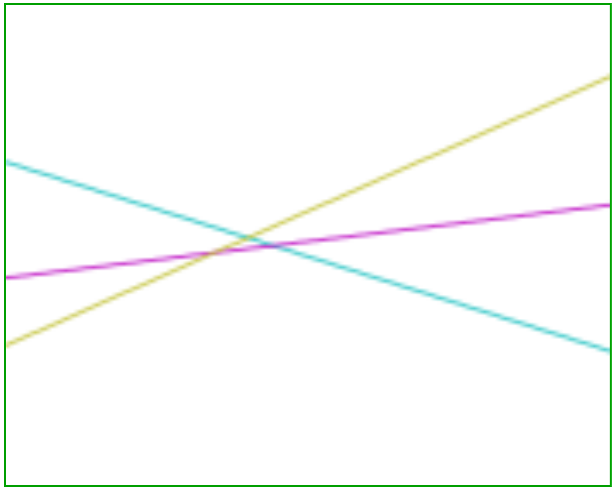


- Δ_{ud} mass ~2 TeV GeV
- B-L violation→GUT scale coupling $v_{BL}\Delta_{ud}\Delta_{ud}\Delta_{dd}$

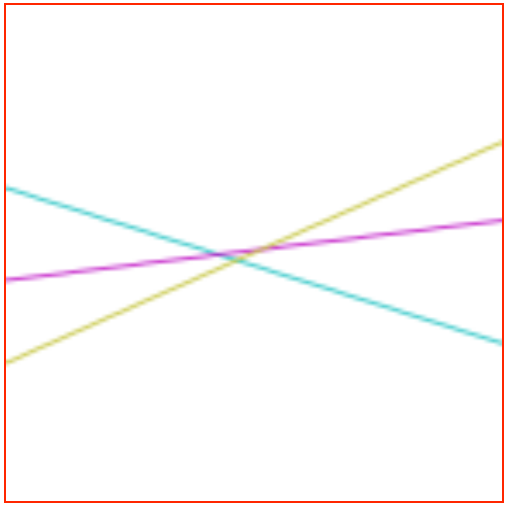
Scale sensitivity-1-loop

- Coupling unification is sensitive to sextet mass

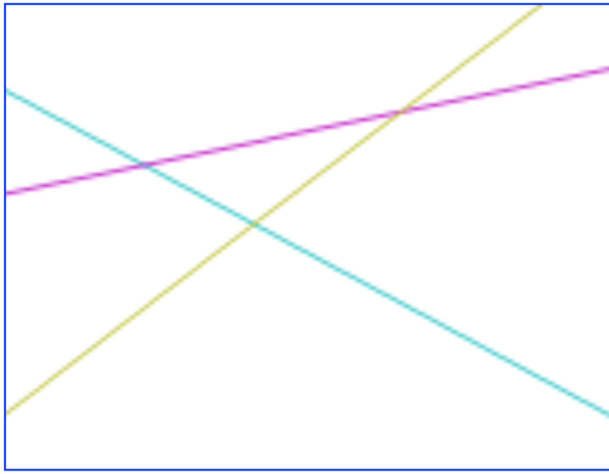
1 TeV



2 TeV

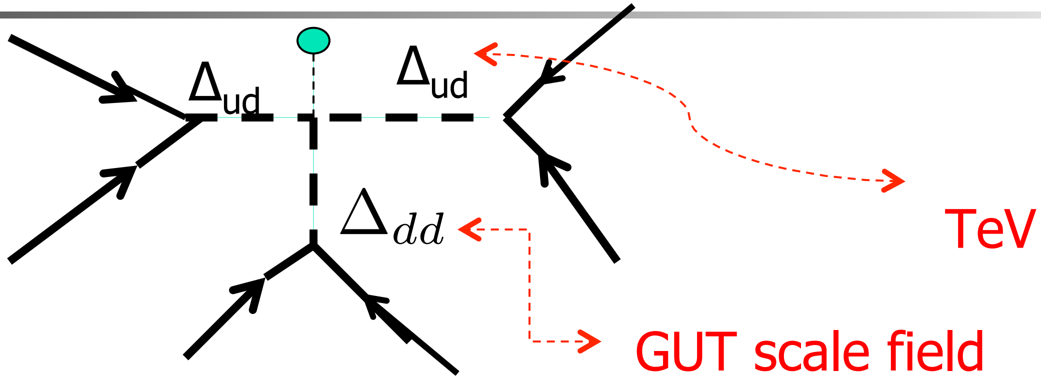


10 TeV



N-N-bar oscillation from $v_{BL}\Delta_{ud}\Delta_{ud}\Delta_{dd}$

- Diagram:



- $$G_{\Delta B=2} \simeq \frac{\lambda f_{11}^3 \eta^3}{\lambda' M_U M_{\Delta_{ud}}^4} \simeq \frac{\lambda}{\lambda'} 10^{-33} GeV^{-5}$$
- Predicts $\tau_{n-\bar{n}}$ ~10^{10} -10^{13} sec.
- Observable with current facilities: *Reactors, Project X at Fermilab, etc*

Color sextets Δ_{qq} @LHC

- **TeV scaleColor sextets** Can be searched at LHC:

(I) **Single production**: $\boxed{ud \longrightarrow \Delta_{ud} \longrightarrow tj}$

xsection calculated in (RNM, Okada, Yu' 07;) resonance peaks above SM background- decay to tj; $\sigma(tj) > \sigma(\bar{t}j)$

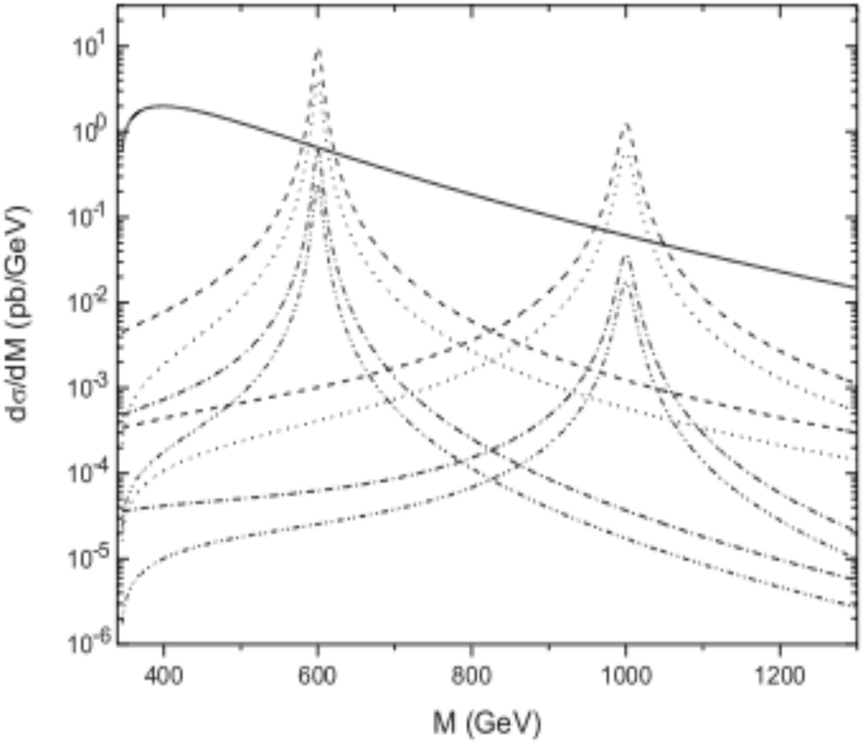
- **Important LHC signature:**

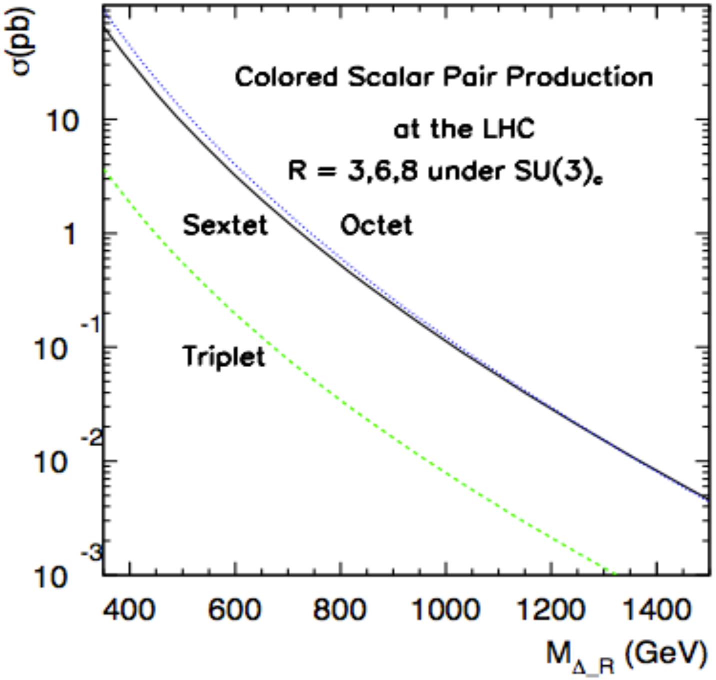
(II) **Drell-Yan pair production** $\boxed{q\bar{q} \rightarrow G \rightarrow \Delta_{ud}\overline{\Delta}_{ud}}$

- Leads to $tjtj$ final states: **LHC reach < TeV**

(Chen, Rentala, Wang; Berger, Cao, Chen, Shaughnessy, Zhang' 10; Han, Lewis' 09)

Cross sections for single and pair productions





14 TeV LHC

Seesaw in SU(5) and $\cancel{B-L}$ nucleon decays

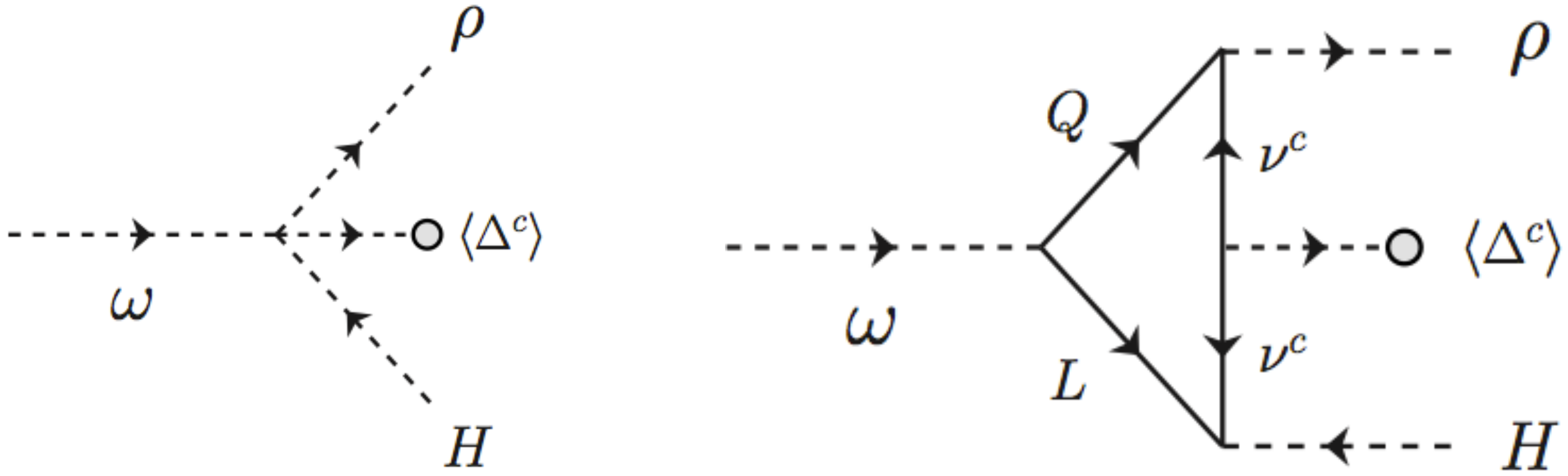
- SU(5) with type I and III seesaw:
- Required exotic Higgs couplings for BLV decay:

$$\omega\rho^* h; \eta^* \rho h; \rho^* \Phi h; \chi^* \eta h$$

- But ρ and η absent in SU(5) nu models with type I or III seesaw.→ hence no $\cancel{B-L}$ p-decays
- **Way to distinguish SU(5) vs SO(10)**
- SU(5) with type II seesaw→ {15}-field
- Leads to observable BLV n-decay but not nn-bar

Proton decay and baryogenesis connection

- Baryogenesis without leptogenesis
- Decays of ω→ρH can produce baryon asym.



- Graphs responsible; right order.
- Sphalerons do not wash away- it has B-L=2

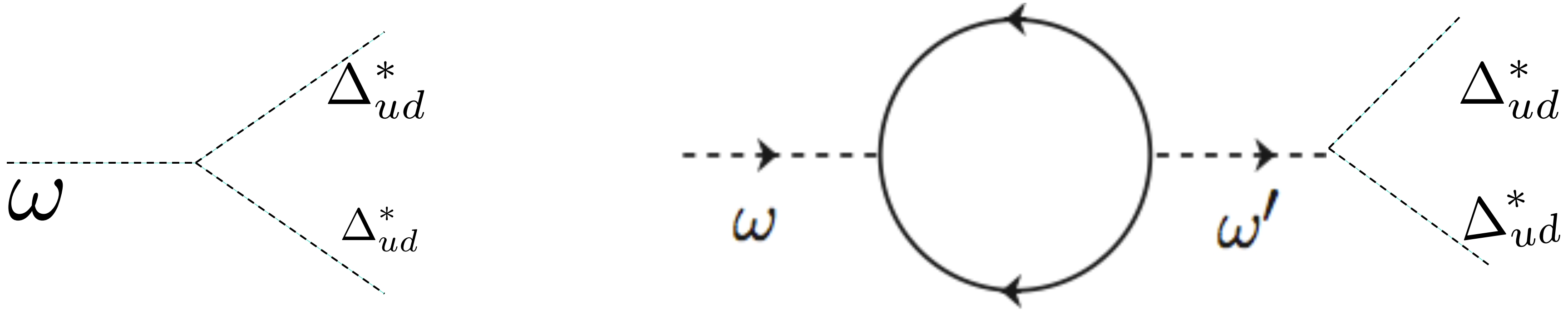
Asymmetry related to neutrino mass

- Asymmetry related to ω-couplings that are couplings of {10} and {126} and related to neutrino masses:

$$\epsilon^{(c)}_{B-L} = \frac{1}{\pi}\mathrm{Im}\left[\frac{\mathrm{Tr}\{Y_{d^c\nu^c\omega}\, Y^{\dagger}_{d^c L\rho}\, Y_{\nu^c L H}\, M_{\nu^c}\, F_2(M_{\nu^c})\}\, \lambda v_R}{|\lambda v_R|^2}\right]\mathrm{Br},$$

The color sextet model

- N-N-bar interactions go out of eq. around 10^{15} GeV;
- Two sources of matter-anti-matter asymmetry:
  (a) Leptogenesis
  (b) B-L violating GUT scale by $\Delta_{dd}(\omega)$ decay



Summary

- SO(10) GUTs with Type I or II seesaw promising

  - Is a natural home for neutrino masses and a unified description of quark and lepton flavor.
- Dayabay value of θ_{13} remarkably close to minimal $SO(10)_{126}$ predictions
- True test of GUTs-proton decay:
- Proton decay modes bearing seesaw signature (i.e. B-L=2) e.g. $n \rightarrow e^{-}\pi^{+}$, $n - \bar{n}$ observable !!
- Distinguishes SO(10) from SU(5) models:
- Revival of GUT scale baryogenesis

Understanding Flavor

- Where does the Yukawa texture come from ?
- Usual Lore:Zero fermion masses→ SM + RH nu → flavor symmetry group:

$$\boxed{U(3)_Q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e \times U(3)_N}$$

- Hope is that observed flavor structure is a consequence of breaking this symmetry-
- Implement this strategy using flavons whose vevs are Yukawa couplings ! (Altarelli, Feruglio;Hagedorn King, Luhn, Medeiros Varzielas, Ross; Chen, Mahanthappa,..)

Flavor in SO(10)$_{126}$ GUTs

- Note that dominant type II seesaw models demand→

$$f_{126} = \lambda^2 \begin{pmatrix} \lambda^2 & \lambda^2 & \lambda \\ \lambda^2 & 1+\lambda & 1 \\ \lambda & 1 & 1 \end{pmatrix}$$

- We need to understand this pattern that leads to the 10+126 model below the sym. Breaking scale !!
- An attempt with discrete family sym **S_4** above GUT scale with triplet flavons lead to this (Dutta, Mimura and RNM, 2010):

S_4 Theory predictions

- Realistic 10+126+10′ model with triplet flavons:

$$\phi_1 = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} 0 \\ -1 \\ 1 \end{pmatrix}, \quad \phi_3 = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

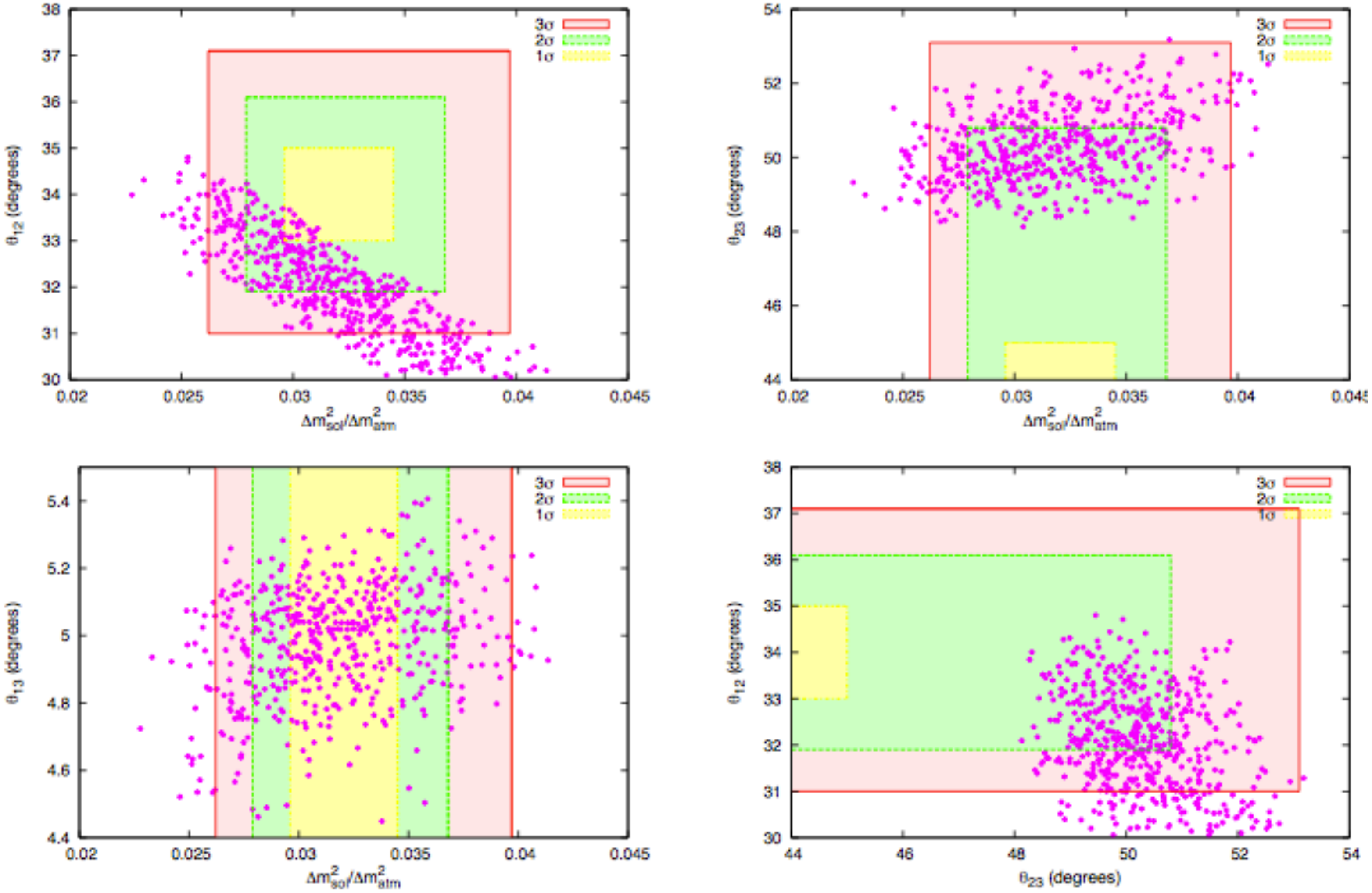
- Yukawa texture:

$$h \propto \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \; f \propto \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & -1 \\ 0 & -1 & 1 \end{pmatrix} + \lambda \begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{pmatrix} \quad h' \propto \begin{pmatrix} 0 & 1 & -1 \\ 1 & 0 & 0 \\ -1 & 0 & 0 \end{pmatrix}$$

Prediction of $\theta_{13}, \theta_{23}, \theta_{12}$

- Model correl.

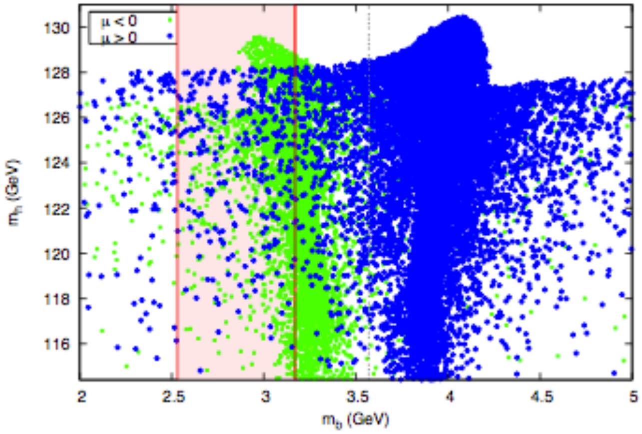
(Dev,Dutta, RNM, Severson’12)

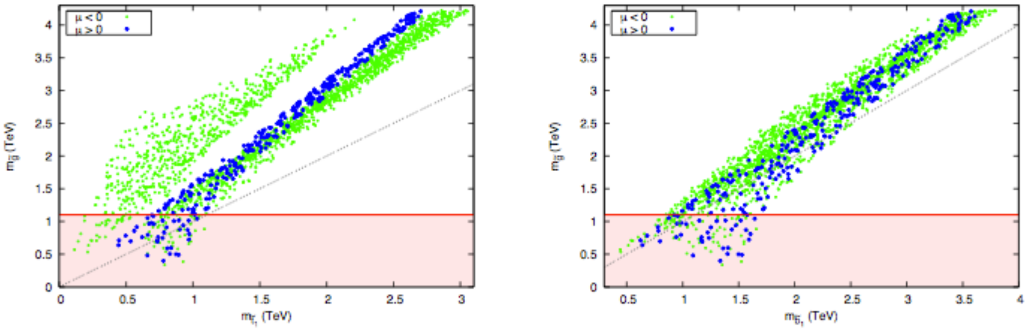


Implications for Higgs mass

- To fit m_b large threshold corrections needed- that requires large A-term in susy→
- Has implications

  for susy spectrum: stop-gluino masses



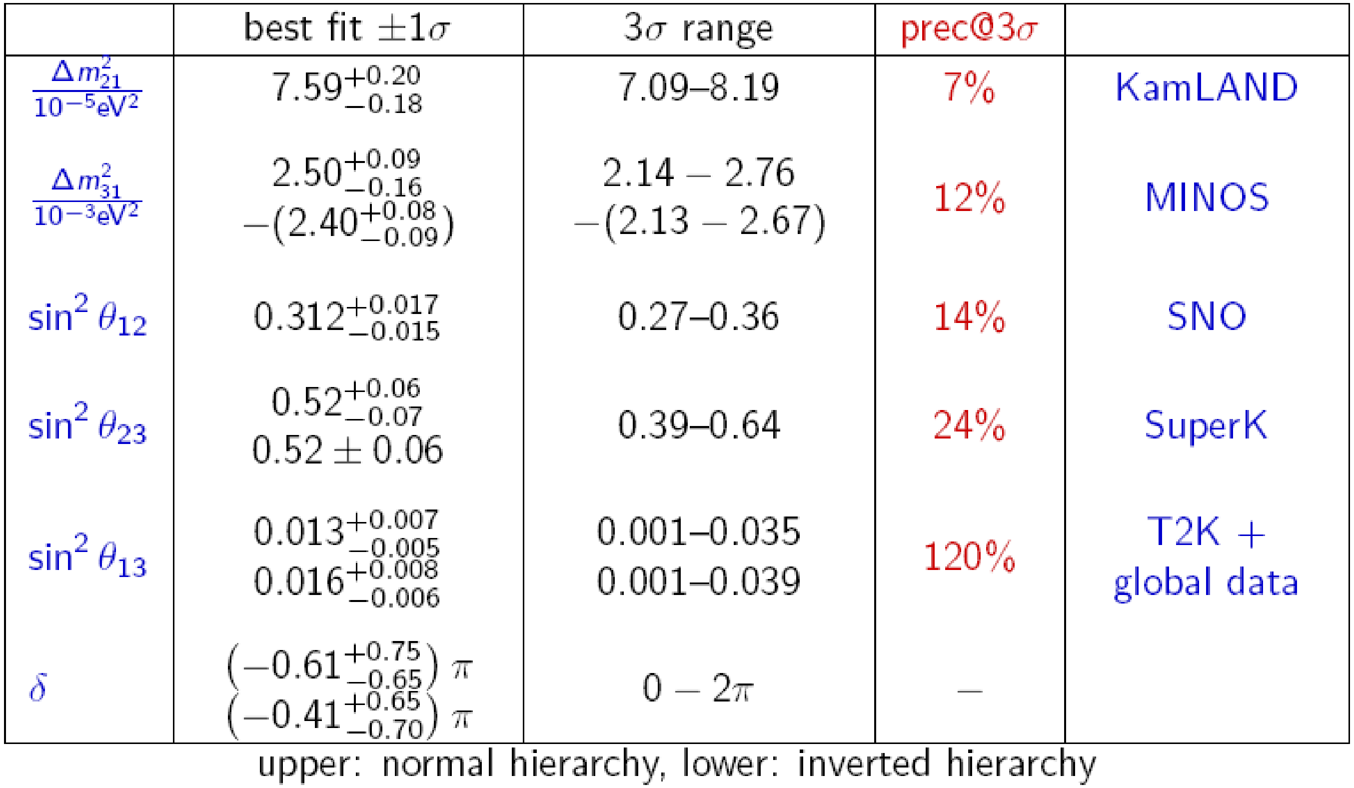


- 120 GeV < M_H <128 GeV.

Current best fit values

- Schwetz, Tortola, Valle :1108

Curious feature!



	best fit $\pm 1\sigma$	3σ range	prec@3σ	
$\frac{\Delta m^2_{21}}{10^{-5}\mathrm{eV}^2}$	$7.59^{+0.20}_{-0.18}$	7.09–8.19	7%	KamLAND
$\frac{\Delta m^2_{31}}{10^{-3}\mathrm{eV}^2}$	$2.50^{+0.09}_{-0.16}$ $-(2.40^{+0.08}_{-0.09})$	$2.14 - 2.76$ $-(2.13 - 2.67)$	12%	MINOS
$\sin^2\theta_{12}$	$0.312^{+0.017}_{-0.015}$	0.27–0.36	14%	SNO
$\sin^2\theta_{23}$	$0.52^{+0.06}_{-0.07}$ 0.52 ± 0.06	0.39–0.64	24%	SuperK
$\sin^2\theta_{13}$	$0.013^{+0.007}_{-0.005}$ $0.016^{+0.008}_{-0.006}$	0.001–0.035 0.001–0.039	120%	T2K + global data
δ	$\left(-0.61^{+0.75}_{-0.65}\right)\pi$ $\left(-0.41^{+0.65}_{-0.70}\right)\pi$	$0 - 2\pi$	–	

upper: normal hierarchy, lower: inverted hierarchy

$$\frac{\Delta m^2_\odot}{\Delta m^2_\oplus} \sim \theta^2_{Cabibbo}$$

General SM multiplets responsible for $\cancel{\text{B-L}}$ decays

- Multiplets: $h(1,2,+1/2),\quad \overline{h}(1,2,-1/2),\quad \omega(3,1,-1/3),\quad \omega^c(\overline{3},1,1/3),$ $\rho(3,2,1/6),\quad \overline{\rho}(\overline{3},2,-1/6),\quad \eta(3,1,2/3),\quad \overline{\eta}(\overline{3},1,-2/3),$ $\Phi(3,3,-1/3),\quad \overline{\Phi}(\overline{3},3,1/3),\quad \chi(3,2,7/6),\quad \overline{\chi}(\overline{3},2,-7/6),$ $\delta(3,1,-4/3),\quad \overline{\delta}(\overline{3},1,4/3)\,.$
- Couplings: $\omega\rho^* h; \eta^*\rho h; \rho^*\Phi h; \chi^*\eta h$

  Present in $(126)^4$ coupling in SO(10)

$$\begin{aligned}\mathcal{L}(16_i 16_j 10_H) &= h_{ij}\left[(u_i^c Q_j + \nu_i^c L_j)\,h - (d_i^c Q_j + e_i^c L_j)\,\overline{h} + \left(\frac{\epsilon}{2} Q_i Q_j + u_i^c e_j^c - d_i^c \nu_j^c\right)\omega\right.\\ &\left.\quad + (\epsilon u_i^c d_j^c + Q_i L_j)\,\omega^c\right], \qquad (6)\end{aligned}$$

$$\begin{aligned}\mathcal{L}(16_i 16_j \overline{126}_H) &= f_{ij}\left[(u_i^c Q_j - 3\nu_i^c L_j)\,h - (d_i^c Q_j - 3e_i^c L_j)\,\overline{h}\right.\\ &\quad +\sqrt{3}i\left(\frac{\epsilon}{2} Q_i Q_j - u_i^c e_j^c + \nu_i^c d_j^c\right)\omega_1 + \sqrt{3}i(Q_i L_j - \epsilon u_i^c d_j^c)\,\omega_1^c\\ &\quad +\sqrt{6}(d_i^c \nu_j^c + u_i^c e_j^c)\,\omega_2 + 2\sqrt{3}i\, d_i^c\, L_j\, \rho - 2\sqrt{3}i\, \nu_i^c\, Q_j\, \overline{\rho} + 2\sqrt{3}\, u_i^c\, \nu_j^c\, \eta\\ &\quad \left.-2\sqrt{3}i\, u_i^c\, L_j\, \chi + 2\sqrt{3}i\, e_i^c\, Q_j\, \overline{\chi} - 2\sqrt{3}\, d_i^c\, e_j^c\, \delta + \sqrt{6}i\, Q_i\, L_j\, \overline{\Phi} + \ldots\right], (7)\end{aligned}$$

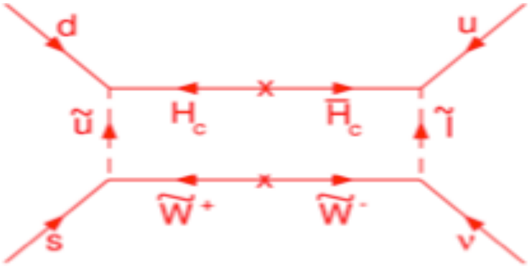
B-L conserving modes -- consistency check on model

- Gauge exchange

$p \to e^+ \pi^0$

$$\Gamma^{-1}(p \to e^+\pi^0) = (2.0 \times 10^{35}\ \mathrm{yr}) \times \left(\frac{\alpha_H}{0.01\ \mathrm{GeV}^3}\right)^{-2} \left(\frac{\alpha_G}{1/25}\right)^{-2} \left(\frac{A_R}{2.5}\right)^{-2} \left(\frac{M_X}{10^{16}\ \mathrm{GeV}}\right)^{4}$$

- Higgsino exchange



Model dependent –

Potentially “fatal”

(e.g. minimal SU(5))

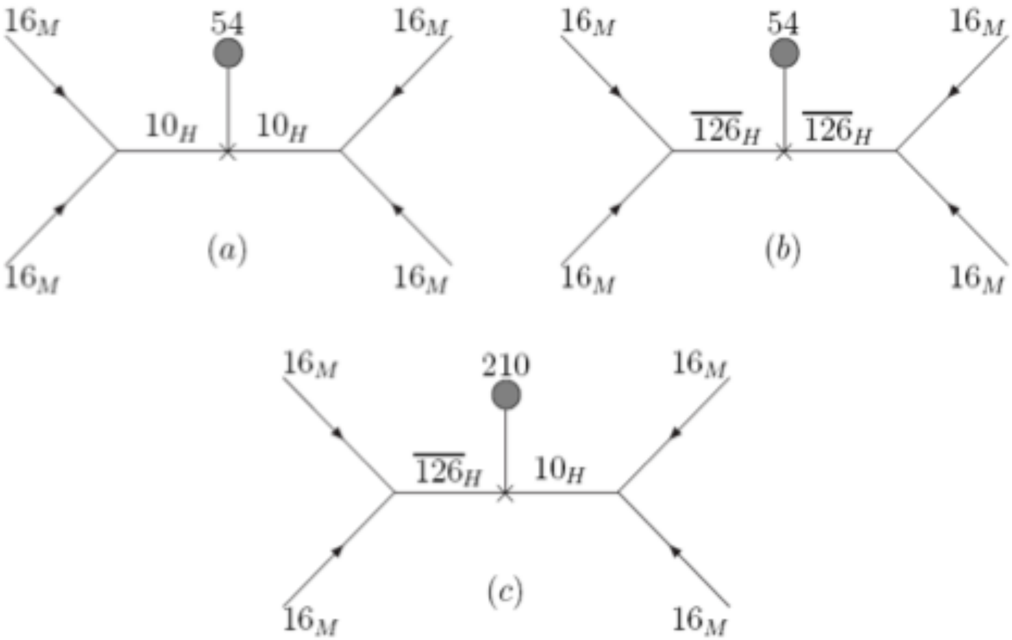
$p \to \bar{\nu} K^+$

$$\tau_p^{-1} \approx [\frac{f^2}{M_{H_c} M_{SUSY}}]^2 (\frac{\alpha}{4\pi})^2 m_p^5 \approx [10^{28} - 10^{32} yr]^{-1}$$

Proton decay -SUSY SO(10)

- Minimal 10+126
- cancellation

possible for <u>low tanβ</u>

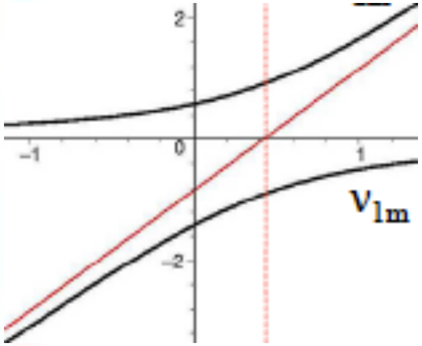


- A prediction

$\tau_{p \to \pi+\nu} < 6\text{x } 10^{32}$ yrs

(Goh, RNM, Nasri, Ng'05)

. Alexei enhancing



Rock star of nu Phys

Alexei in10 yrs

Wise Guru of nu physics