Large Theta(13) From Minimal SO(10) Unification

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Outline

Quantitative predictions for neutrino masses and mixing angles can be made in unified theories based on $SO(10)$

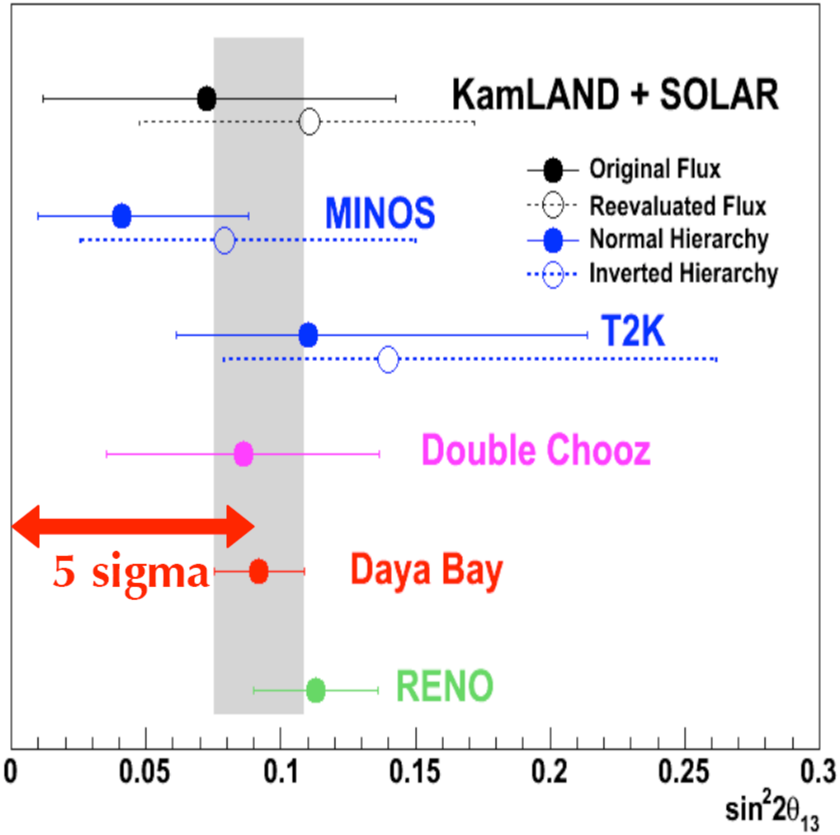
No family symmetry is assumed

New GUT scale baryogenesis mechanism tied to neutrino masses

Novel $B-L$ violating nucleon decay such as $n \to e^- K^+$

K.S. Babu and C. Macesanu, Phys. Rev. D72, 115003 (2005)
K.S. Babu and R.N. Mohapatra, arXiv: 1203.5544 [hep-ph]

Recent Results on Theta(13)



$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.006(\text{syst})$ **Daya Bay**

$\sin^2 2\theta_{13} = 0.113 \pm 0.013(\text{stat}) \pm 0.019(\text{syst})$ **RENO**

Global Fit to Neutrino Oscillations

Quantity	Value
$\Delta m^2_{21} (\mathrm{eV}^2)$	$(7.59 \pm 0.21) \times 10^{-5}$
$\Delta m^2_{31} (\mathrm{eV}^2)$	$(2.53^{+0.13}_{-0.08}) \times 10^{-3}$ (NH) $-(2.4^{+0.1}_{-0.07}) \times 10^{-3}$ (IH)
$\sin^2 \theta_{12}$	$0.320^{+0.015}_{-0.017}$
$\sin^2 \theta_{23}$	$0.49^{+0.08}_{-0.05}$ $0.53^{+0.08}_{-0.07}$
$\sin^2 \theta_{13}$	$0.026^{+0.003}_{-0.004}$ $0.027^{+0.003}_{-0.004}$

Forero, Tortola, Valle, 2012

Finding Order in Ferrmion Mass Spectrum

Fermion masses in units of m_t

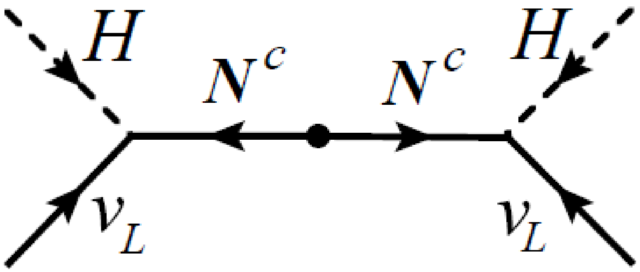
$$
\begin{aligned}
m_t &= 1.0 & m_b &= 1.67 \times 10^{-2} \\
m_c &= 3.6 \times 10^{-3} & m_s &= 3.1 \times 10^{-4} \\
m_u &= 1.3 \times 10^{-5} & m_d &= 2.3 \times 10^{-5}
\end{aligned}
$$

$$
\begin{aligned}
m_\tau &= 1.0 \times 10^{-2} & m_3 &= 2.9 \times 10^{-13} \\
m_\mu &= 6.2 \times 10^{-4} & m_2 &= 5.2 \times 10^{-14} \\
m_e &= 3.0 \times 10^{-6} & m_1 &= < m_2
\end{aligned}
$$

$$
V_q = \begin{pmatrix} 0.976 & 0.22 & 0.004 \\ \text{-}0.22 & 0.98 & 0.04 \\ 0.007 & \text{-}0.04 & 1 \end{pmatrix} \qquad U_\ell = \begin{pmatrix} 0.85 & \text{-}0.54 & 0.16 \\ 0.33 & 0.62 & \text{-}0.72 \\ \text{-}0.40 & \text{-}0.59 & \text{-}0.70 \end{pmatrix}
$$

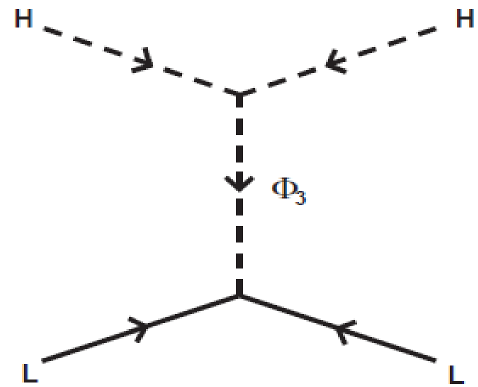
$$
\text{Im}\left(\frac{V_{ub}V_{cs}}{V_{us}V_{cb}}\right) = 0.34
$$

Small Neutrino Masses from Seesaw



Type I Seesaw

$N^c(1,1,0)$: Right-handed neutrino



Type II Seesaw

$\Phi(1,3,1)$: Higgs triplet

$SO(10)$ models generate both types of contributions

$$\mathcal{L}_{\text{eff}} = \frac{LLHH}{M}$$

Neutrino data suggest $M \approx 10^{15}$ GeV

Neutrino Masses in Unified Theories

- Electric charge quantization
  - $Q_p = -Q_e$ to better than 1 part in 10^{21}
- Miraculous cancellation of anomalies
- Quantum numbers of quarks and leptons
- **Existence of ν_R and thus neutrino mass via seesaw**
- Unification of gauge couplings with low energy SUSY
- $b - \tau$ unification
- Baryon asymmetry of the universe

Quantum Numbers of Fermions in SO(10)

$u_r : \{-++\ +-\}$	$d_r : \{-++\ -+\}$	$u_r^c : \{+--\ ++\}$	$d_r^c : \{+--\ --\}$
$u_b : \{+-+\ +-\}$	$d_b : \{+-+\ -+\}$	$u_b^c : \{-+-\ ++\}$	$d_b^c : \{-+-\ --\}$
$u_g : \{++-\ +-\}$	$d_g : \{++-\ -+\}$	$u_g^c : \{--+\ ++\}$	$d_g^c : \{--+\ --\}$
$\nu : \{---\ +-\}$	$e : \{---\ -+\}$	$\nu^c : \{+++\ ++\}$	$e^c : \{+++\ --\}$

16 of $SO(10)$

Frist 3 spins refer to color, last 2 are weak spins

$$Y = \frac{1}{3}\Sigma(C) - \frac{1}{2}\Sigma(W)$$

Eg: $Y(e^c) = \frac{1}{3}(3) - \frac{1}{2}(-2) = 2$

Minimal SO(10) Model

$$\mathcal{L}_{\mathsf{Yukawa}} = Y_{10}\,\mathbf{16}\,\mathbf{16}\,\mathbf{10}_H + Y_{126}\,\mathbf{16}\,\mathbf{16}\,\overline{\mathbf{126}}_H$$

Two Yukawa matrices determine all fermion masses and mixings, including the neutrinos

$$\begin{aligned} M_u &= \kappa_u Y_{10} + \kappa'_u Y_{126} \\ M_d &= \kappa_d Y_{10} + \kappa'_d Y_{126} \\ M_\nu^D &= \kappa_u Y_{10} - 3\kappa'_u Y_{126} \\ M_l &= \kappa_d Y_{10} - 3\kappa'_d Y_{126} \end{aligned}$$

$$\begin{aligned} M_{\nu R} &= \langle \Delta_R \rangle\, Y_{126} \\ M_{\nu L} &= \langle \Delta_L \rangle\, Y_{126} \end{aligned}$$

Model has only 11 real parameters plus 7 phases

Babu, Mohapatra (1993)
Fukuyama, Okada (2002)
Bajc, Melfo, Senjanovic, Vissani (2004)
Fukuyama, Ilakovac, Kikuchi, Meljanac, Okada (2004)
Aulakh et al (2004)

Bertolini, Frigerio, Malinsky (2004)
Babu, Macesanu (2005)
Bertolini, Malinsky, Schwetz (2006)
Dutta, Mimura, Mohapatra (2007)
Bajc, Dorsner, Nemevsek (2009)

Specific Example: Type I Seesaw

Input at the GUT scale:

$$
\begin{aligned}
m_u &= 0.0006745 & m_c &= 0.3308 & m_t &= 97.335\\
m_d &= 0.0009726 & m_s &= 0.02167 & m_b &= 1.1475\\
m_e &= 0.000344 & m_\mu &= 0.0726 & m_\tau &= 1.350\ \text{GeV}\\
s_{12} &= 0.2248 & s_{23} &= 0.03278 & s_{13} &= 0.00216\\
& & \delta_{CKM} &= 1.193\ .
\end{aligned}
$$

Output for neutrinos:

$$\sin^2\theta_{12} \simeq 0.27,\ \ \sin^2 2\theta_{23} \simeq 0.90,\ \ \sin^2 2\theta_{13} \simeq 0.08$$

$$m_i = \{0.0021 e^{0.11 i},\ 0.0098 e^{-3.08 i},\ 0.048\}\ \text{eV}$$

$$\Delta m^2_{23}/\Delta m^2_{12} \simeq 24$$

K.S. Babu and C. Macesanu (2005)

Specific Example: Type II Seesaw

Input at the GUT scale:

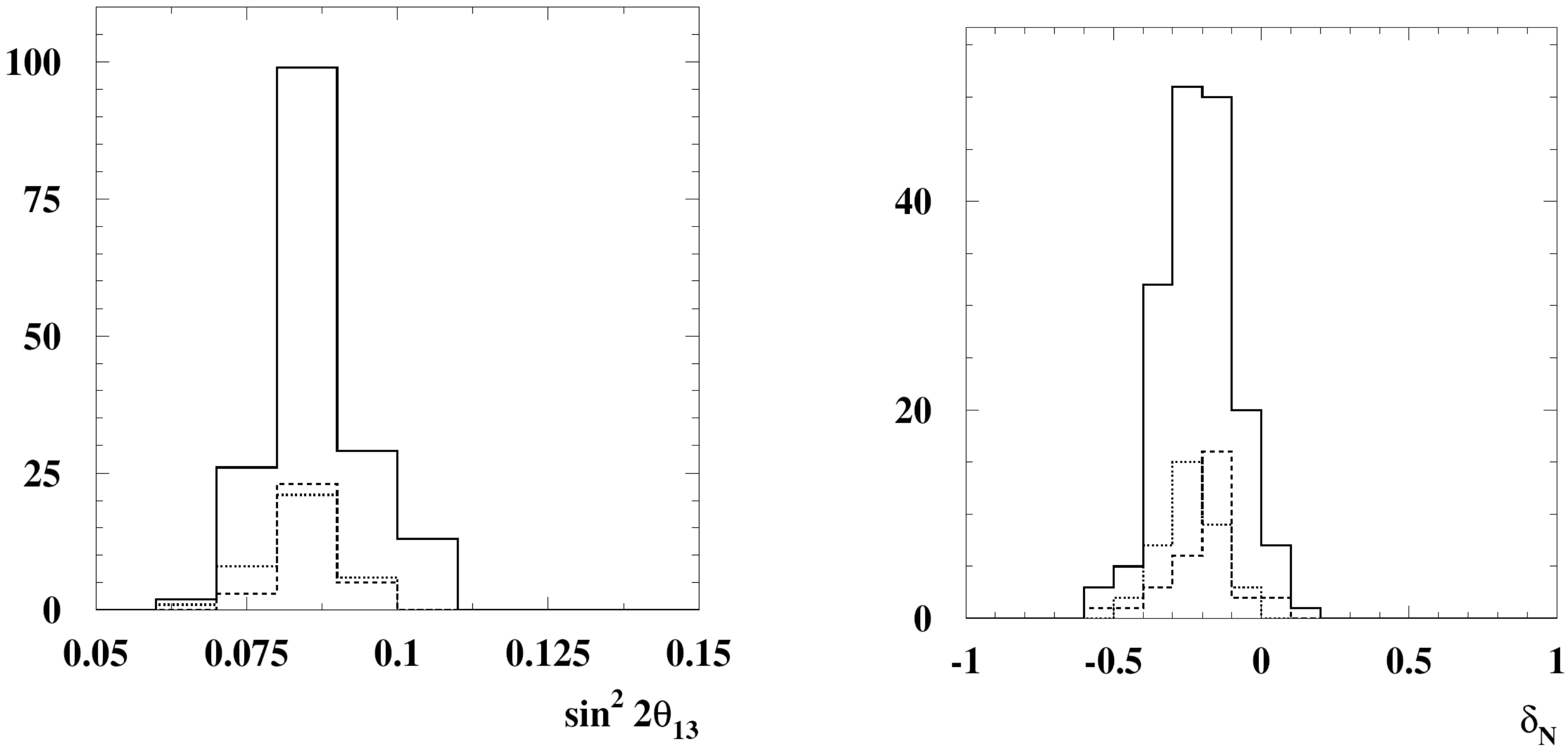
$$m_u = 0.0008185 \quad m_c = 0.3772 \quad m_t = 139.876$$
$$m_d = 0.0015588 \quad m_s = 0.03554 \quad m_b = 2.3547$$
$$m_e = 0.000525 \quad m_\mu = 0.1107 \quad m_\tau = 2.420 \text{ GeV}$$
$$s_{12} = 0.225 \quad s_{23} = 0.0297 \quad s_{13} = 0.00384$$
$$\delta_{CKM} = 1.4 \ .$$

Output for neutrinos:

$$\sin^2 2\theta_{12} \simeq 0.7 \ , \ \sin^2 2\theta_{23} \simeq 0.88 \ , \ \sin^2 2\theta_{13} \simeq 0.094$$
$$\Delta m^2_{23}/\Delta m^2_{12} \simeq 18$$
$$m_{\nu i} \simeq \{0.0016 e^{0.27i} \ , \ 0.011 e^{-2.86i} \ , \ 0.048\} \text{ eV}$$

K.S. Babu and C. Macesanu (2005)

Theta(13) in Minimal SO(10)



$\sin^2 2\theta_{13}$ and CP violating phase δ_N

K.S. Babu and C. Macesanu (2005)

$\sin^2 2\theta_{13} = 0.092 \pm 0.016 \pm 0.005$ 5.2σ effect

Global Fit to Minimal SO(10)

	A	B	C	D	C1	C2
Observables	Pulls obtained for best fit solution					
(m_u/m_c)	-0.00668428	0.0276825	0.0259467	0.120767	-0.0212532	0.0356043
(m_c/m_t)	0.56521	0.157569	0.0201093	0.0730136	0.130288	0.320944
(m_d/m_s)	-1.21642	-0.891034	-0.27664	-1.36265	-1.04724	-1.57673
(m_s/m_b)	0.112798	0.440678	0.163272	0.752408	0.884723	0.789053
(m_e/m_μ)	0.0590249	-0.00627804	0.3944	0.0396087	0.0297987	0.0555931
(m_μ/m_τ)	0.182548	0.103214	0.821485	0.0192305	0.26316	0.121145
(m_b/m_τ)	0.87282	2.20829	2.79368	2.34331	0.26656	0.407798
$\left(\frac{\Delta m^2_{\rm sol}}{\Delta m^2_{\rm atm}}\right)$	0.256292	0.116314	-0.14908	0.230056	0.0188227	-0.0140039
$\sin\theta^q_{12}$	0.0730813	0.0702755	0.0399788	0.105989	0.0779176	0.127757
$\sin\theta^q_{23}$	-0.0311676	-0.172792	-0.471738	-0.0960437	-0.757038	-0.945821
$\sin\theta^q_{13}$	1.33502	-0.0354198	0.494732	0.606606	0.890741	1.17758
$\sin^2\theta^l_{12}$	0.00836789	-0.106439	-0.599727	-0.27881	-0.63356	-0.510182
$\sin^2\theta^l_{23}$	-1.53367	-4.97038	-4.95673	-4.70944	-2.56294	-1.84412
$\delta_{\rm CKM}[^\circ]$	-0.345931	-0.163765	-0.600814	-0.214459	-0.650554	-0.75885
χ^2_{min}	**6.9367**	**30.70**	**34.52**	**30.68**	**10.804**	**9.3559**

Observables	Corresponding Predictions at GUT scale					
$\sin^2\theta^l_{13}$	0.0226508	0.0190847	0.0206716	0.0196974	0.0239619	0.0209208
$\delta_{\rm MNS}[^\circ]$	19.9399	18.9784	19.5619	11.92	358.789	1.78569
$\alpha_1[^\circ]$	337.171	346.627	344.795	350.595	12.4786	349.711
$\alpha_2[^\circ]$	147.364	151.912	146.886	161.702	194.023	168.156
$r_L m_\tau[{\rm GeV}]$	8.37×10^{-10}	6.0×10^{-10}	6.49×10^{-10}	6.94×10^{-10}	7.15×10^{-10}	9.1×10^{-10}

Type I Seesaw: SUSY

Joshipura, Patel (2011)

Global Fit to Minimal SO(10)

	A	**B**	**C**	**D**	**C1**	**C2**
Observables	Pulls obtained for best fit solution					
(m_u/m_c)	0.0486938	−0.180782	0.0653101	0.0053847	0.0467579	−0.0119661
(m_c/m_t)	1.22599	0.130589	0.246294	0.146932	0.297256	0.273346
(m_d/m_s)	−0.229546	−0.730641	0.223201	−0.748148	−2.2904	−0.689684
(m_s/m_b)	−0.932536	−0.886438	−0.977249	−1.05766	0.735548	0.000467775
(m_e/m_μ)	0.0340323	0.442759	0.103692	−0.476364	0.0649144	−0.0648856
(m_μ/m_τ)	0.310305	−0.526529	0.881934	0.938701	0.705648	0.0178824
(m_b/m_τ)	−0.486477	−0.194215	0.0172182	−0.34079	0.789868	−0.734937
$\left(\frac{\Delta m^2_{\rm sol}}{\Delta^2_{\rm atm}}\right)$	0.122267	−0.10063	−0.00563647	−0.120429	−0.180164	0.158557
$\sin\theta^q_{12}$	0.0432634	0.227948	0.0186715	0.084149	0.130301	0.0922391
$\sin\theta^q_{23}$	−0.281221	−0.0401177	−0.167224	0.0649082	−0.273222	−1.17651
$\sin\theta^q_{13}$	1.37864	−0.275689	0.926186	0.559003	1.48675	0.248759
$\sin^2\theta^l_{12}$	−0.0528379	−0.0598219	−0.38133	−0.172148	−0.746107	0.0694831
$\sin^2\theta^l_{23}$	−1.22555	−1.27077	−1.43475	0.0548963	−1.99485	−0.946001
$\delta_{\rm CKM}[^\circ]$	−0.291137	0.397159	−0.350422	−0.755859	−0.956628	−0.3197
χ^2_{min}	**6.3479**	**3.7962**	**5.0715**	**3.8665**	**14.789**	**3.4746**

Observables	Corresponding Predictions at GUT scale					
$\sin^2\theta^l_{13}$	0.0223307	0.0194886	0.0218753	0.0186789	0.0253152	0.0205366
$\delta_{\rm MNS}[^\circ]$	2.41793	4.52493	6.08769	335.07	357.142	14.7651
$\alpha_1[^\circ]$	347.106	8.42838	7.64991	28.0261	14.5679	1.13126
$\alpha_2[^\circ]$	163.759	191.241	188.713	218.586	196.273	177.828
$r_R\left(\frac{m_t^2}{m_\tau}\right)$ [GeV]	1.77×10^{-10}	2.63×10^{-10}	2.50×10^{-10}	4.02×10^{-10}	7.3×10^{-11}	2.82×10^{-10}

Type II Seesaw: SUSY

Global Fit to Minimal SO(10)

	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	–
$\left(\frac{\Delta m^2_{\rm sol}}{\Delta m^2_{\rm atm}}\right)$	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**	–
$\delta_{\rm CKM}[^\circ]$	69.5262	−0.0314447	69.2051	−0.128759
$\delta_{\rm MNS}[^\circ]$	**318.465**	–	**14.5386**	–
$\alpha_1[^\circ]$	**21.5053**	–	**345.645**	–
$\alpha_2[^\circ]$	**215.128**	–	**141.905**	–
$r_{R(L)}$	$\mathbf{5.62\times10^{-14}}$	–	$\mathbf{2.09\times10^{-10}}$	–
χ^2		**0.710777**		**54.1197**

Type I & II Seesaw: non-SUSY

(B-L) – Violation in SO(10)

B violation can occur in the standard model only through effective higher dimensional operators

$d = 6$ baryon number violating operators:

$$\begin{aligned}
\mathcal{O}_1 &= (d^c u^c)^* (Q_i L_j) \epsilon_{ij} \\
\mathcal{O}_2 &= (Q_i Q_j)(u^c e^c)^* \epsilon_{ij} \\
\mathcal{O}_3 &= (Q_i Q_j)(Q_k L_l) \epsilon_{ij} \epsilon_{kl} \\
\mathcal{O}_4 &= (Q_i Q_j)(Q_k L_l)(\vec{\tau}\epsilon)_{ij} \cdot (\vec{\tau}\epsilon)_{kl} \\
\mathcal{O}_5 &= (d^c u^c)^* (u^c e^c)^*
\end{aligned}$$

Weinberg (1979)
Wilczek, Zee (1979)

These operators carry $B = 1$ and $L = 1$, and thus $(B - L) = 0$

Allow nucleon decay such as $p \to e^+ \pi^0, \overline{\nu} K^+$ and $n \to e^+ \pi^-, \overline{\nu} \pi^0$

Forbid decays such as $p \to \nu K^+$ and $n \to e^- K^+$ which require $\Delta(B - L) = -2$

B violation beyond the leading order

$d = 7$ baryon number violating operators:

$$\mathcal{O}'_1 = (d^c u^c)^* (d^c L_i)^* H_j^* \epsilon_{ij}, \qquad \mathcal{O}'_2 = (d^c d^c)^* (u^c L_i)^* H_j^* \epsilon_{ij},$$

$$\mathcal{O}'_3 = (Q_i Q_j)(d^c L_k)^* H_l^* \epsilon_{ij} \epsilon_{kl}, \qquad \mathcal{O}'_4 = (Q_i Q_j)(d^c L_k)^* H_l^* (\vec{\tau}\epsilon)_{ij} \cdot (\vec{\tau}\epsilon)_{kl},$$

$$\mathcal{O}'_5 = (Q_i e^c)(d^c d^c)^* H_i^*, \qquad \mathcal{O}'_6 = (d^c d^c)^* (d^c L_i)^* H_i,$$

$$\mathcal{O}'_7 = (d^c D_\mu d^c)^* (\overline{L}_i \gamma^\mu Q_i), \qquad \mathcal{O}'_8 = (d^c D_\mu L_i)^* (\overline{d^c} \gamma^\mu Q_i),$$

$$\mathcal{O}'_9 = (d^c D_\mu d^c)^* (\overline{d^c} \gamma^\mu e^c)$$

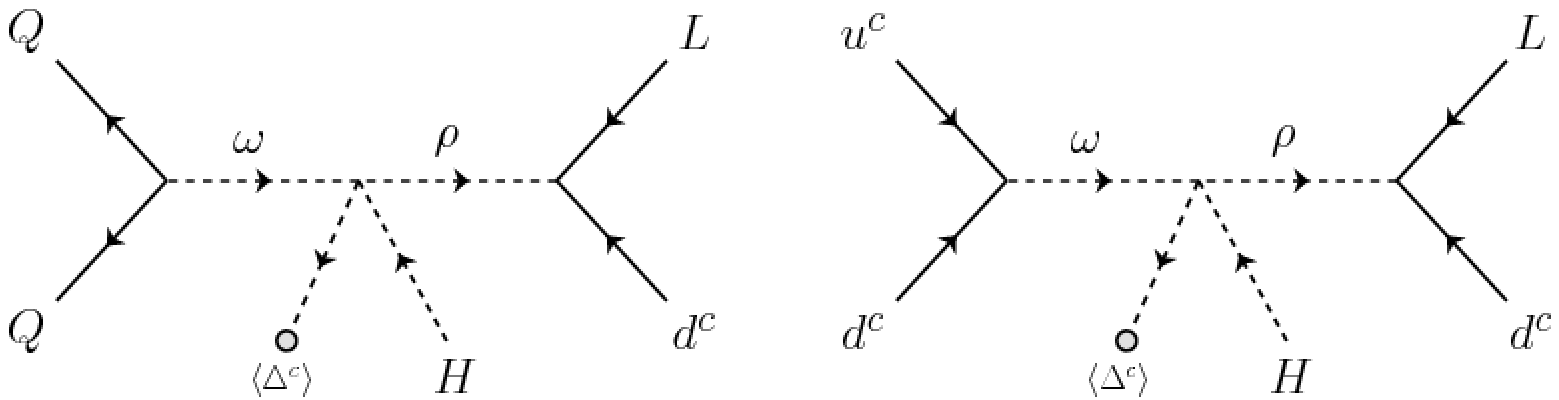
All operators have $B = 1$, $L = -1$, and thus $(B - L) = +2$

Complex conjugate operators have $(B - L) = -2$

Lead to decays such as $p \to \nu K^+$ and $n \to e^- K^+$ which require $\Delta(B - L) = -2$

Origin of d = 7 operators in SO(10)

$16_i 16_j$ bilinears can couple to 10_H, $\overline{126}_H$ and 120_H

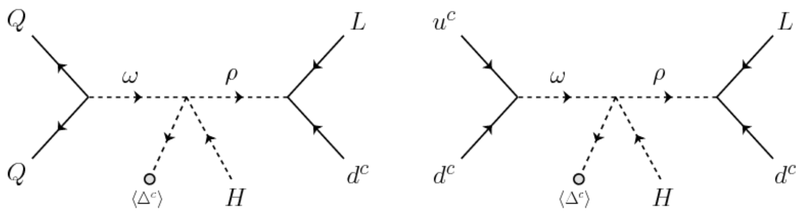


$\omega(3, 1, -1/3)$, $\rho(3, 2, 1/6)$

Minimal $SO(10)$ models contain these $d = 7$ operators

B-L violating nucleon decay rates

From scalar exchange:



$$\Gamma(n \to e^- \pi^+) \approx \frac{|Y|^4}{16\pi} \frac{\beta_H^2 m_p}{f_\pi^2} \left(\frac{\lambda v v_R}{M_\rho^2} \right)^2 \frac{1}{M_\omega^4}$$

$Y = 10^{-3}$, $M_\omega = 10^{12}$ GeV, $M_\rho = 10^9$ GeV, $v_R = 10^{16}$ GeV

$\Rightarrow \tau_n \approx 10^{33}$ yrs.

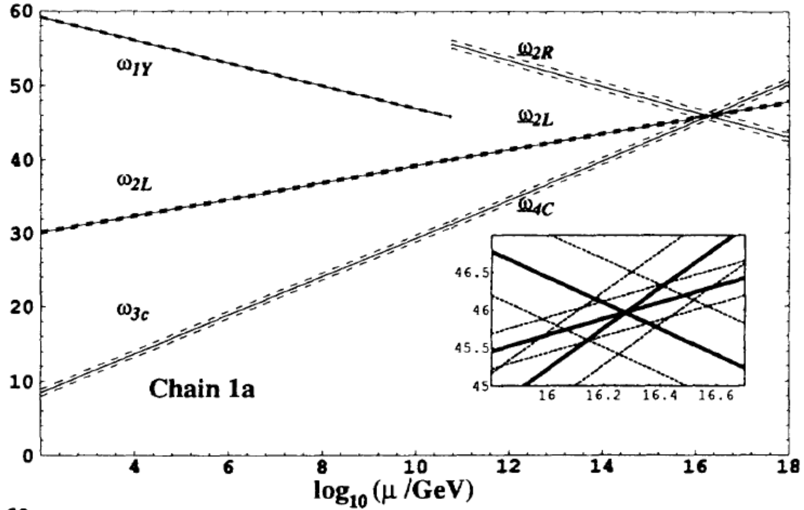
From $\eta\omega^* H$ diagram:

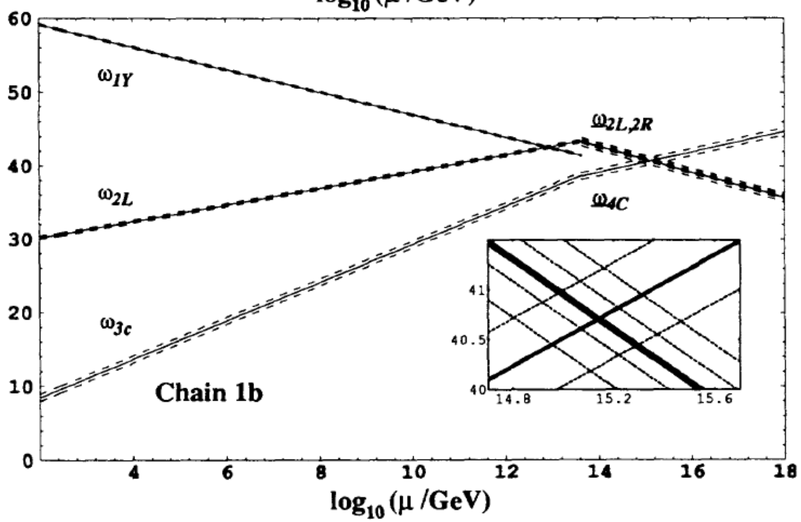
$$\Gamma(n \to e^- \pi^+) \approx \frac{|Y|^4}{16\pi} \frac{\beta_H^2 m_p}{f_\pi^2} \left(\frac{\lambda v v_R}{M_\rho^2} \right)^2 \frac{1}{M_\eta^4}$$

$Y = 10^{-3}$, $M_\rho = M_\eta = 10^{10}$ GeV, $v_R = 10^{11}$ GeV, $Y = 10^{-2}$

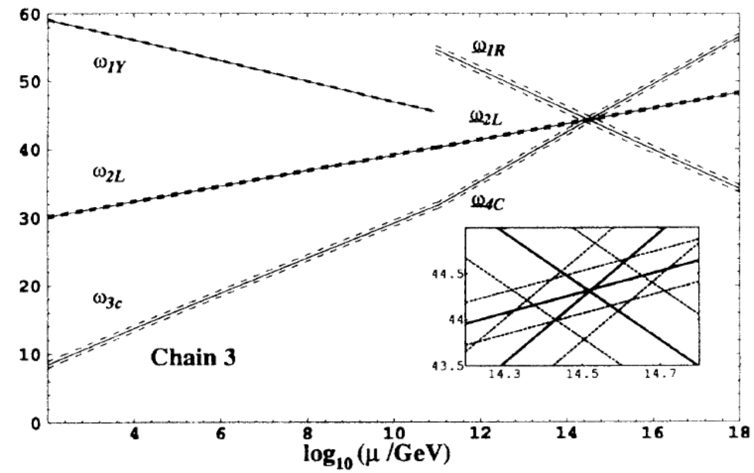
$\Rightarrow \tau_p \approx 10^{33}$ yrs.

Intermediate scale in non-SUSY SO(10)





Mohapatra, Parida (1992)
Pal, Keith, Deshpande (1992)



$SU(2)_L \times U(1)_R \times SU(4)_C$

$SU(2)_L \times SU(2)_R \times SU(4)_C$ symmtry

Revival of GUT scale Baryogenesis

In $SU(5)$ decays of heavy gauge bosons of color triplet scalars can generate baryon asymmetry

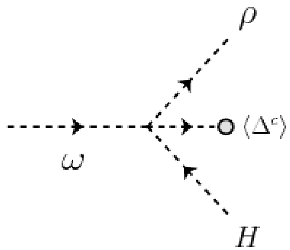
This asymmetry is however washed out by electroweak sphalerons since $(B-L)$ is preserved

In $SO(10)$, $\omega \to \rho + H^*$ decay violated $(B-L)$ by two units and can lead to sphaleron-proof baryon asymmetry

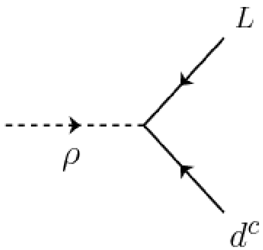
$V_Q \to V^*_{u^c} H$ also generates similar B asymmetry

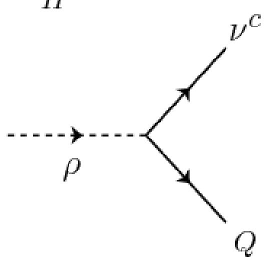
$B-L$ violating nucleon decay and baryon asymmetry arise from same operators

B-L asymmetry in scalar decays



Violates $B-L$





$(B-L)(\rho) = 4/3$, $(B-L)(\omega) = -2/3$, $(B-L)(H) = 0$

$(B-L)$ asymmetry parameter ϵ_{B-L}:

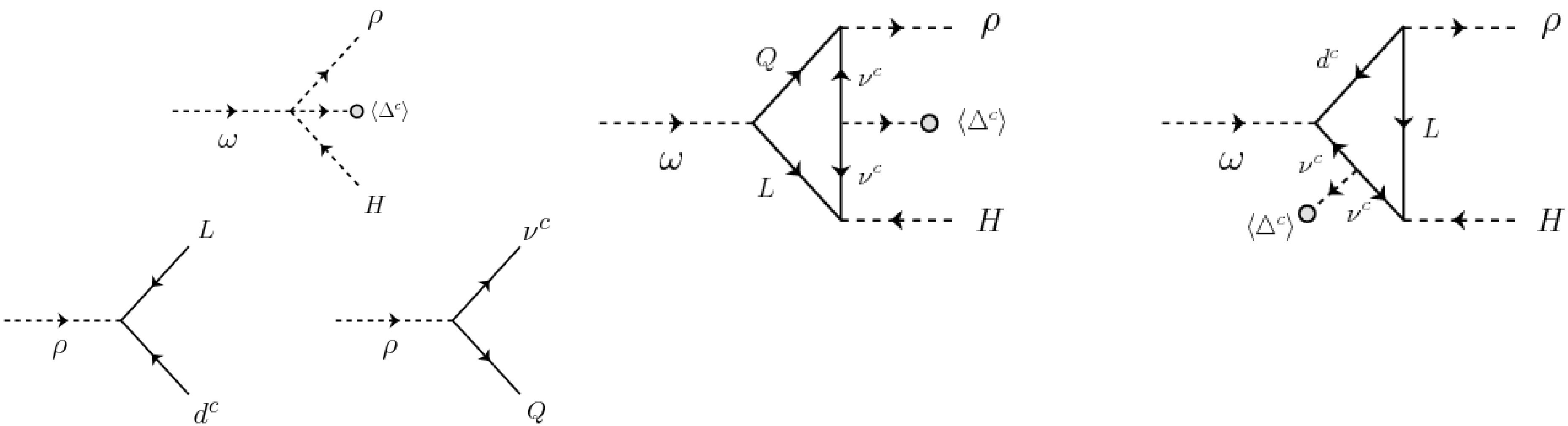
$$\epsilon_{B-L} = (r - \bar{r})(B_1 - B_2)$$

r is branching ratio for $\omega \to \rho H^*$

$\bar{r}$ is branching ratio for $\omega^* \to \rho^* H$

$B_1 = 4/3, \quad B_2 = 0$ ($B-L$ of two final states)

$$\eta = \frac{n_B}{s} \simeq \frac{\epsilon_{B-L}}{g^*} d$$



$$\epsilon^{(i)}_{B-L} = -\frac{1}{2\pi}\mathrm{Im}\left[\frac{\mathrm{Tr}\{Y^{\dagger}_{d^c\nu^c\omega}\, Y_{d^c L\bar{\rho}}\, Y^{*}_{\nu^c LH}\, M_{\nu^c}\, f_1(M_{\nu^c})\}\, \lambda v_R}{|\lambda v_R|^2}\right]$$

$$f_1(M_j) = \ln\left(1 + \frac{M_\rho^2}{M_j^2}\right) + \Theta\left(1 - \frac{M_j^2}{M_\omega^2}\right)\left(1 - \frac{M_j^2}{M_\omega^2}\right)$$

B-L asymmetry in scalar decays (cont.)

$$\epsilon^{(ii)}_{B-L} = \frac{1}{2\pi}\mathrm{Im}\left[\frac{\mathrm{Tr}\{Y^{\dagger}_{QL\omega^*}\, Y_{Q\nu^c\bar{\rho}}\, M_{\nu^c}\, f_2(M^c_\nu)\, Y_{\nu^c LH})\}\, \lambda v_R}{|\lambda v_R|^2}\right]$$

$$f_2(M_j) = \ln\left(1 + \frac{M^2_\omega}{M^2_j}\right) + \Theta\left(1 - \frac{M^2_j}{M^2_\rho}\right)\left(1 - \frac{M^2_j}{M^2_\rho}\right)$$

ω decay out of equilibrium for $M_\omega > 10^{12}$ GeV and Yukawa couplings of order 10^{-2}

Dilution factor is naturally of order one.

$\eta \approx 10^{-10}$ arises naturally

In minimal models, only two Yukawa matrices exist

For $h \approx 0.5$, $f \approx 10^{-2}$, $M_{\nu^c} \approx 10^{14}$ GeV,
$M_\rho \approx 10^{13}$ GeV, $\epsilon_{B-L} \approx 10^{-6}$

Summary and Conclusions

- Measurement of θ_{13} fits naturally in minimal $SO(10)$ models
- This class of minimal GUTs naturally predict large neutrino mixing simultaneously with small quark mixings
- New GUT scale baryogenesis immune to sphaleron wash-out presented
- Quark and lepton masses, neutrino mixing angles and baryogenesis inter-connected
- Observable $(B-L)$–violating nucleon decay such as $n \to e^- K^+$