Dark Matter, Baryogenesis and (B-L) Violating Nucleon Decay in Unified Theories

K.S. Babu

Oklahoma State University

Unification Day 2 & NNN15

Stony Brook University

October 28-31, 2015

Outline

- Brief Introduction to Unification (without SUSY)
- Natural Dark matter from GUTs
- $|\Delta(B-L)| = 2$ Nucleon decay
- Baryogenesis via $|\Delta(B-L)| = 2$ Nucleon decay
- Summary

Unification of Forces and Matter

Electromagnetic, weak and strong forces share identical structure: all belong to gauge theories with unitary symmetry

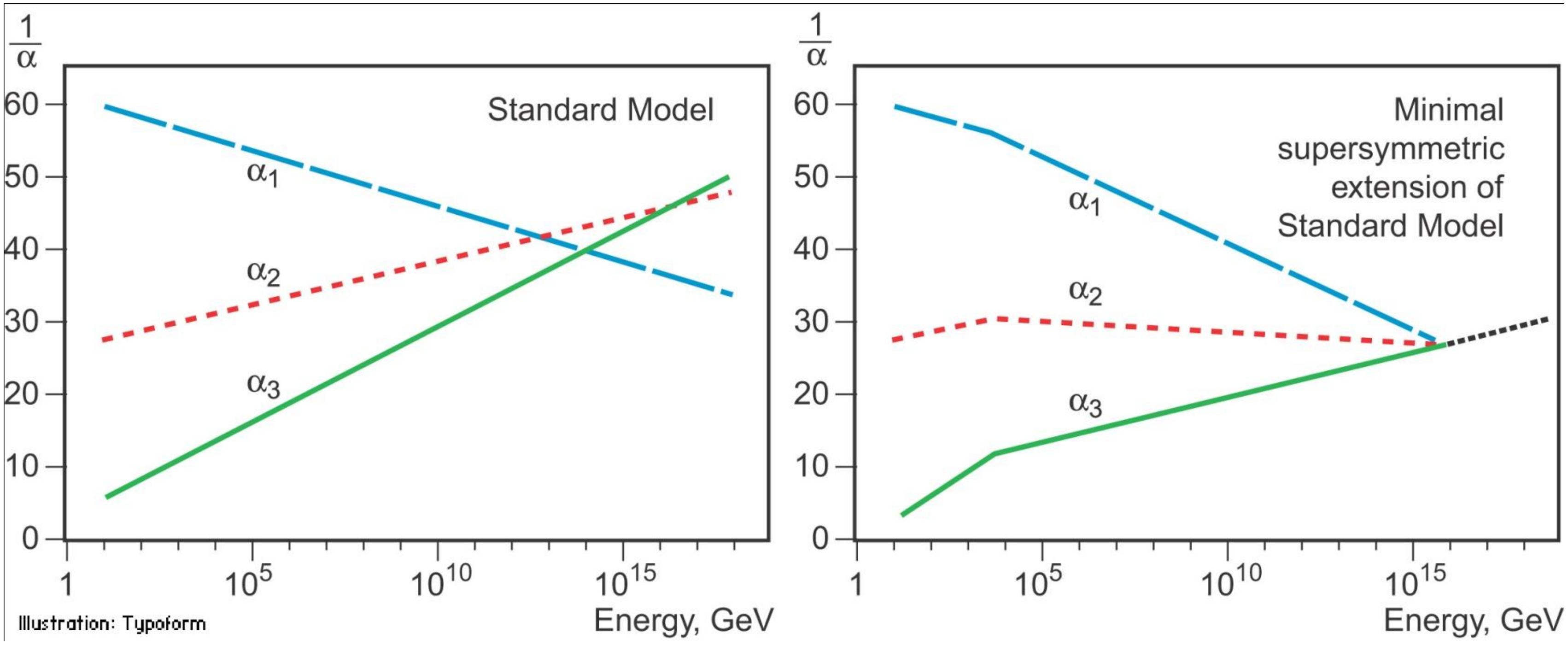
The high energy behavior of these theories support unification idea

Ordinary matter – quarks and leptons – fit neatly within multiplets of the unified symmetry

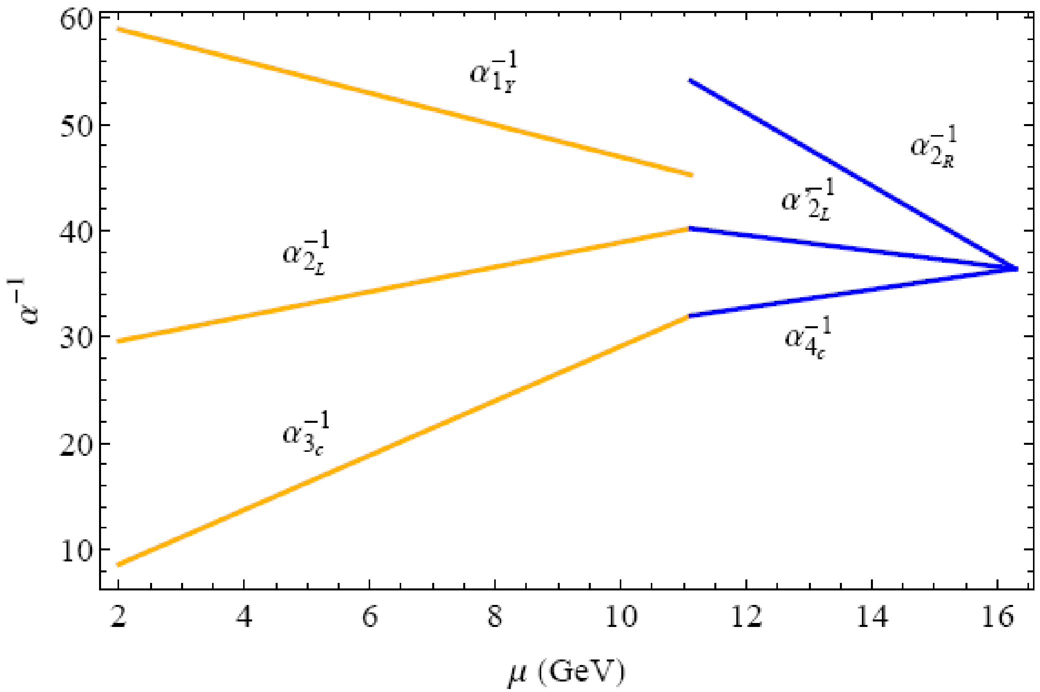
Unified theories are more predictive, many predictions agree with observations

Nucleon decay is the missing link; its discovery would be monumental

Evolution of gauge couplings with energy



Gauge coupling unification without supersymmetry



Intermediate Pati-Salam symmetry: $SU(2)_L \times SU(2)_R \times SU(4)_c$

May be identified as the Peccei-Quinn symmetry breaking scale

From Altarelli, Meloni (2013)

More Hints in favor of Unification

- 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
- Unification of gauge couplings with low energy SUSY
- $b - \tau$ unification
- Baryon asymmetry of the universe

Unifying Forces and Matter

First successful attempt by Pati and Salam (1973)

Based on $SU(4)_c \times SU(2)_L \times SU(2)_R$ gauge symmetry

$$\psi_L = \begin{pmatrix} u_1 & u_2 & u_3 & e \\ d_1 & d_2 & d_3 & \nu \end{pmatrix}_L, \quad \psi_R = \begin{pmatrix} u_1 & u_2 & u_3 & e \\ d_1 & d_2 & d_3 & \nu \end{pmatrix}_R$$

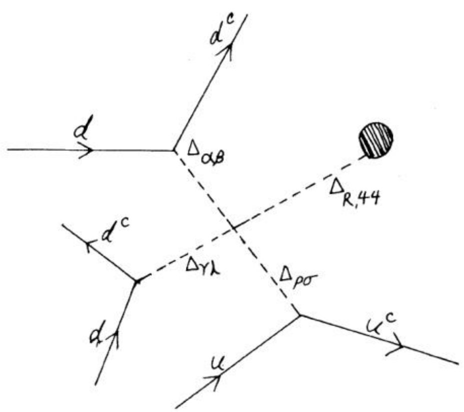
Lepton number identified as fourth color

Scale of $SU(4)_c$ breaking > 2300 TeV $(K_L \to \mu e)$

Baryon number violation occurs via scalar exchange with $|\Delta B| = 2$ selection rule

$n - \overline{n}$ oscillation occurs without proton decay

$$\mathcal{L}_{\text{eff}} = \frac{uddudd}{\Lambda^5}$$



Marshak, Mohapatra (1980)

Unification in SU(5)

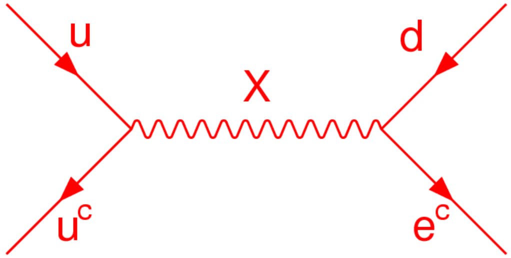
More complete unification of forces and matter discovered in SU(5) by Georgi and Glashow (1974)

$$\mathbf{10}: \begin{pmatrix} 0 & u_3^c & -u_2^c & u_1 & d_1 \\ -u_3^c & 0 & u_1^c & u_2 & d_2 \\ u_2^c & -u_1^c & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^c \\ -d_1 & -d_2 & -d_3 & -e^c & 0 \end{pmatrix} \qquad \bar{\mathbf{5}}: (d_1^c, d_2^c, d_3^c, e, -\nu_e)$$

Quarks and leptons are unified

Particles unify with antiparticles $\Rightarrow$ Matter is unstable

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



Matter Fields in SO(10)

$SO(10)$ theories contain Pati-Salam and $SU(5)$ features

All particles and antiparticles are unified in **16**

SO(10)

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

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

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

ν^c state crucial for neutrino mass generation

Standard Model

$$Q = \begin{pmatrix} u_1 & u_2 & u_3 \\ d_1 & d_2 & d_3 \end{pmatrix} \sim (3, 2, \frac{1}{6})$$

$$u^c = (\, u_1^c \quad u_2^c \quad u_3^c \,) \sim (\bar{3}, 1, -\frac{2}{3})$$

$$d^c = (\, d_1^c \quad d_2^c \quad d_3^c \,) \sim (\bar{3}, 1, \frac{1}{3})$$

$$L = \begin{pmatrix} \nu \\ e^- \end{pmatrix} \sim (1, 2, -\frac{1}{2})$$

$$e^c \sim (1, 1, +1)$$

$$\nu^c \sim (1, 1, 0)$$

Natural Dark Matter Candidate in SO(10)

$SO(10)$ theories have natural dark matter candidates

Representations of $SO(10)$ are tensorial or spinorial:

Tensors: $\Phi(1)$, $\Phi_\mu(10)$, $\Phi_{\mu\nu}(45, 54)$, $\Phi_{\mu\nu\rho}(120)$, $\Phi_{\mu\nu\rho\alpha}(210)$, $\Phi_{\mu\nu\rho\alpha\beta}(126)$

Spinors: $\Phi^a(16)$, $\Phi^a_\mu(144)$, $\Phi^a_{\mu\nu}(560)$

Standard Model fermions belong to **16**

Lightest Tensor Fermion or Spinor Scalar of $SO(10)$ will be absolutely stable

Higgs in tensor representations used

Mambrini, Nagata, Olive, Quivillon, Zheng (2015)
Babu, Khan, Malinsky (2015) – to appear

SO(10) Dark Matter Models: I

Simplest Model: Add a fermion wich is singlet (rank zero tensor) of $SO(10)$. It cannot mix with other fermions.

Mass of this singlet fermion ψ is around TeV

For effective annihilation, an $SO(10)$ singlet scalar S with mass of order TeV is used

S and H mix: Higgs portal DM

Here $SO(10)$ provides stability of DM

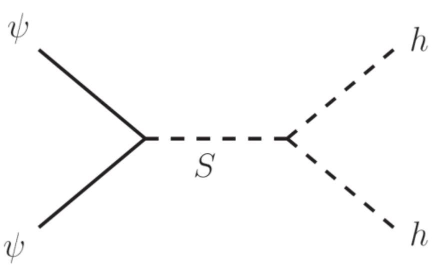
Such models have been studied extensively

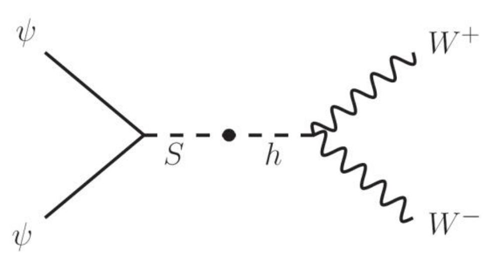
Esch, Klasen, Yaguna (2013) for recent study

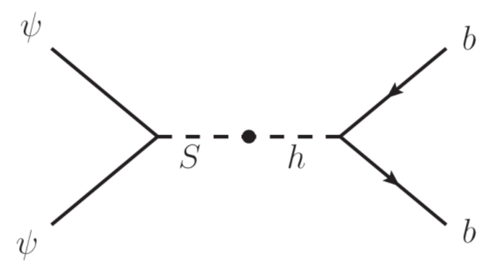
SO(10) Singlet Dark Matter Model

$$\mathcal{L}_\chi = -\frac{1}{2}\left(M_\chi \bar{\chi}\chi + g_s \phi \bar{\chi}\chi + i g_p \phi \bar{\chi}\gamma_5 \chi\right),$$

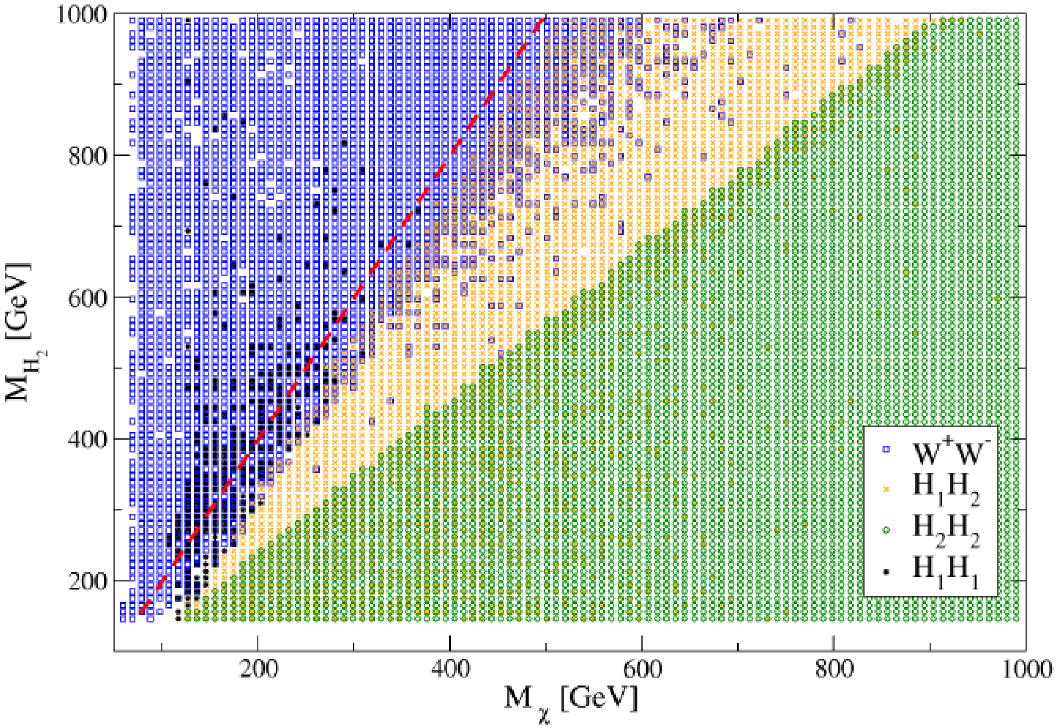
$$V(\phi, H) = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 - \frac{\mu_\phi^2}{2}\phi^2 + \frac{\lambda_\phi}{4}\phi^4 + \frac{\lambda_4}{2}\phi^2 H^\dagger H$$
$$+ \mu_1^3 \phi + \frac{\mu_3}{3}\phi^3 + \mu\, \phi (H^\dagger H),$$







Singlet Fermion Dark Matter Parameter Space



Esch, Klasen, Yaguna (2013)

SO(10) Dark Matter Models: II

A weak doublet vector-like fermion:

$$\psi = \begin{pmatrix} N \\ E \end{pmatrix}, \quad \psi^c = \begin{pmatrix} -E^c \\ N^c \end{pmatrix}$$

N here is the Dark Matter Majorana Fermion

If N mixes with a singlet fermion S: singlet-doublet DM*

Or N must have a Majorana mass > 100 keV via effective operator $\psi\psi HH$

Doublet arises from **10** of $SO(10)$

*Fayet (1974)
Arkani-Hamed, Delgado, Giudice (2006)
Cohen, Kearney, Pierce, Tucker-Smith (2011)

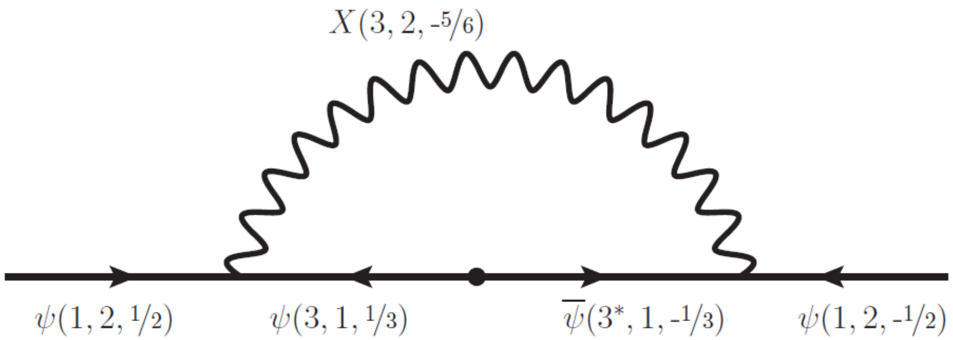
SO(10) Dark Matter Models: II

10 of $SO(10)$ contains a color triplet Dirac fermion

Natural scale of color triplet fermion is TeV

Otherwise Dark Matter mass will be pulled to GUT scale

$$M_{DM} \sim \frac{\alpha}{4\pi} M_T$$



If $\{45_H + 126_H\}$ Higgs break $SO(10)$, the entire 10-plet of fremions are degenerate in mass

Babu, Khan, Malinsky (2015)

Dark Matter Partner at LHC

Color Triplet partner of Dark Matter can be seen at LHC

Long-lived R-hadron search limit $\sim$ 1 TeV from LHC

Recent study of color-triplet scalar R-hadron:

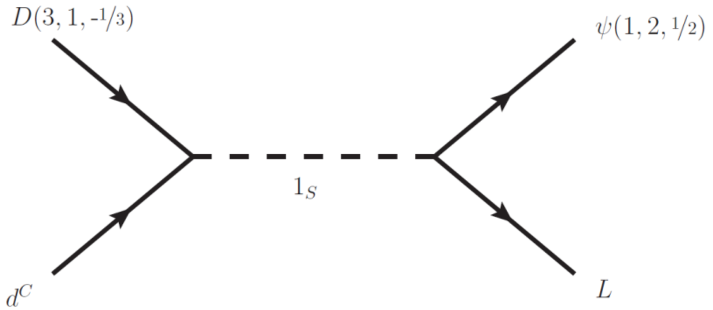
Barnard, Cox, Gherghetta, Spray (2015)

Relic density fixes Dark Matter mass near 1.1 TeV

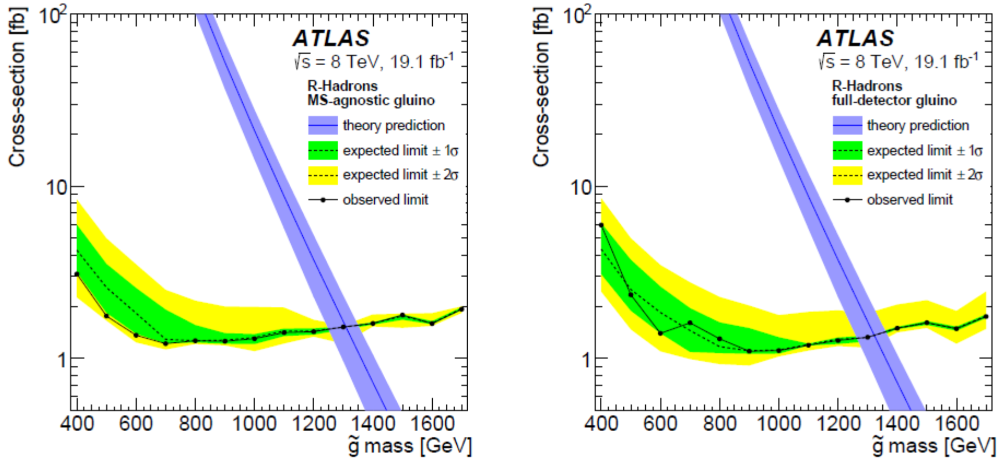
Color triplet mass near 2.5 – 3 TeV predicted

$$D \to dN\nu$$

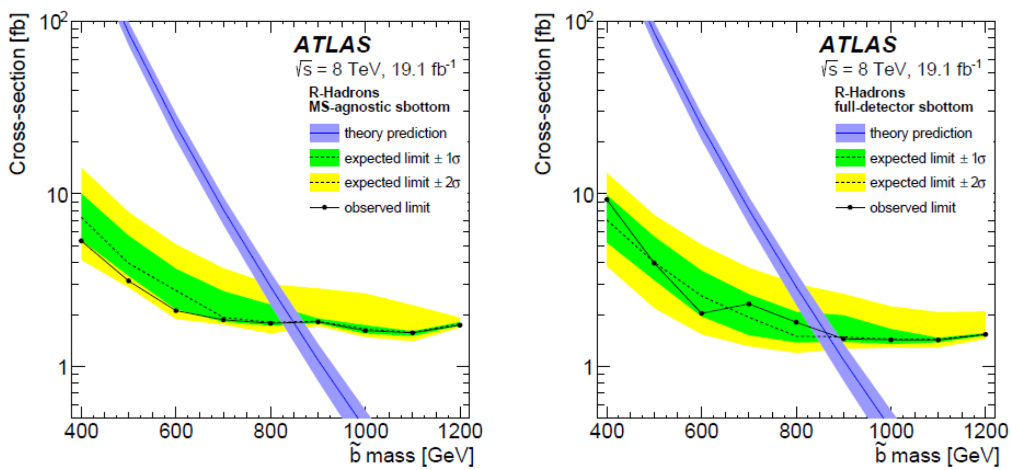
Lifetime $\sim$ 1 sec



ATLAS Limits on R-Hadrons



Limits on long-lived gluino



Limits on long-lived $\tilde{b}$

Unifying Dark Matter with Normal Matter

Dark Matter belonging to **10** + **1** of $SO(10)$ is intriguing

Normal matter **16** of $SO(10)$ may be unified with Dark Matter **10** + **1** into **27** of E_6

Ordinary Matter and Dark Matter are one and the same!

27_H of E_6 is fine as Higgs. Only tensors of $SO(10)$ (1 + 10) acquire VEVs, and not the spinor 16

Crucial Tests:

(a) Long-lived color triplet partner at LHC with mass $2.5 - 3$ TeV

(b) Signals of doublet-singlet dark matter

Baryogenesis and Grand Unification

The most popular mechanism for baryogenesis prior to 1985 was GUT scale baryogenesis

Impact of electroweak sphaleron on baryogenesis changed the picture drastically

Kuzmin, Rubakov, Shaposhnikov (1985)

Baryon asymmetry generated in decays of GUT scale particles washed out typically by sphalerons

Focus changed to Leptogenesis, which takes advantage of sphalerons

Fukugita, Yanagida (1986)

GUT scale baryogenesis mostly forgotten

Reviving GUT Scale Baryogenesis

In $SU(5)$ GUT, baryon number violating interactions conserve $B-L$ symmetry

Electroweak sphalerons wash out $B-L$ conserving asymmetry of $SU(5)$

$SO(10)$ GUTs contain $B-L$ as part of gauge symmetry

$B-L$ asymmetry is generated in $SO(10)$ that is sphaleron–proof

Asymmetry related to $B-L$ violating decay of nucleon

Alternative to Leptogenesis

K.S. Babu, R.N. Mohapatra, Phys. Rev. Lett. 109, 091803 (2012)
K.S. Babu, R.N. Mohapatra, Phys. Rev. D86, 035018 (2012)
K.S. Babu, R.N. Mohapatra, Phys. Lett. B715, 328 (2012)

(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)
Abbott, Wise (1980)

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 $n \to e^- K^+$, $n \to e^-\pi^+$ which require $\Delta(B - L) = -2$

(B-L) = 2 Operators

$d = 7$ baryon number violating operators:

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

Weinberg (1980)

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

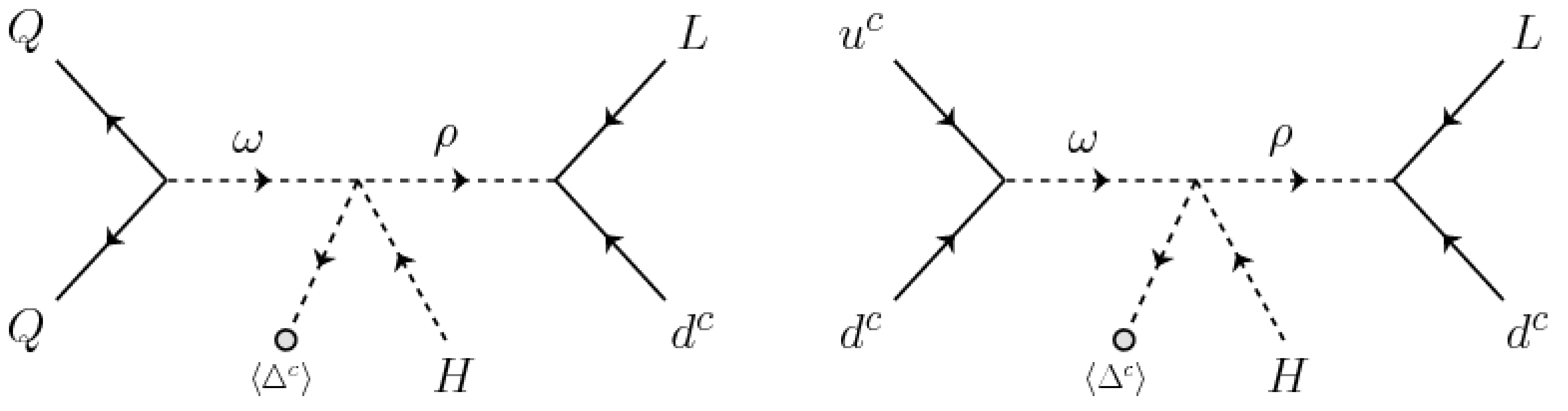
Complex conjugate operators have $(B - L) = -2$

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

Weldon, Zee (1980)
Vissani (1995)
Barr, Calmet (2012)
Nath, Syed (2015)

Origin of B-L =2 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

D=7 Operators from Yukawa couplings

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

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

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

$$h_{ij} = h_{ji}, \qquad f_{ij} = f_{ji}$$

Nath, Syed (2001)
Aulakh, Girdhar (2004)
Fukuyama et. al (2004)

SO(10) Yukawa Couplings (cont.)

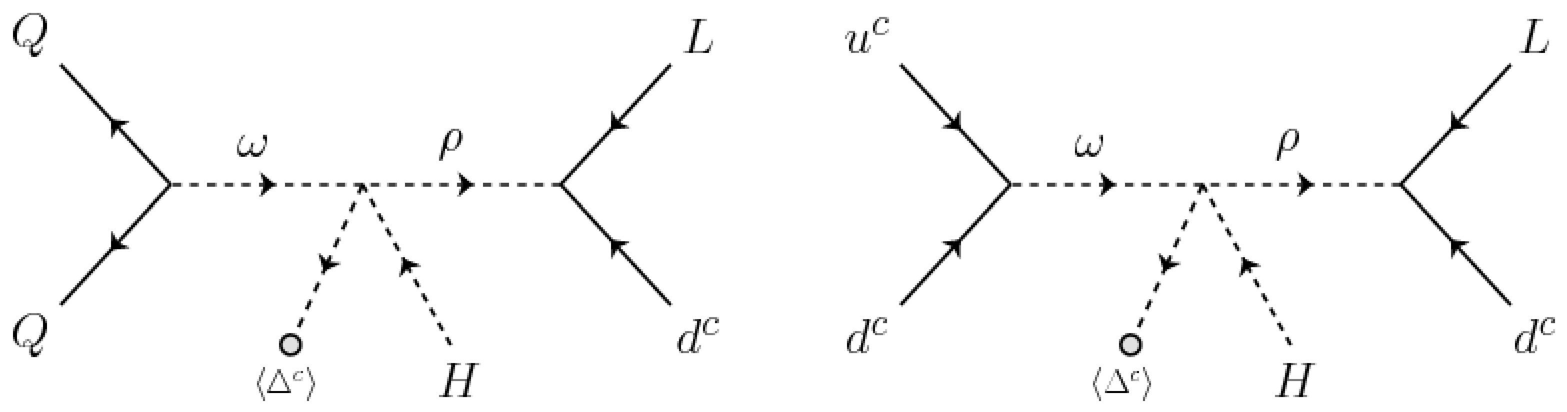
$$\begin{aligned}\mathcal{L}(16_i 16_j 120_H) \;=\; & \frac{g_{ij}}{2}\Big[(d_i Q^j + e_i^c L_j)\,\overline{h}_1 - (u_i^c Q_j + \nu_i^c L_j)\,h_1 - \sqrt{2} Q_i L_j\,\omega_1^c \\ & -\sqrt{2}(u_i^c e_j^c - d_i^c \nu_j^c)\,\omega_1 - \frac{i}{\sqrt{3}}(d_i^c Q_j - 3 e_i^c L_j)\,\overline{h}_2 + \frac{i}{\sqrt{3}}(u_i^c Q_j - 3\nu_i^c L_j)\,h_2 \\ & -2 e_i^c Q_j\,\overline{\chi} + 2\nu_i^c Q_j\,\overline{\rho} - 2 d_i^c L_j\,\rho + 2 u_i^c L_j\,\chi \\ & -i\,\epsilon\, d_i^c d_j^c\,\overline{\eta} + 2\,i\,u_i^c \nu_j^c\,\eta + \sqrt{2}\,i\,\epsilon\, d_i^c u_j^c\,\omega_2^c + \sqrt{2}\,i\,(d_i^c \nu_j^c - e_i^c u_j^c)\,\omega_2 \\ & -\frac{\epsilon}{\sqrt{2}} Q_i Q_j \Phi - \sqrt{2}\, Q_i L_j \overline{\Phi} + \ldots\Big]\,.\end{aligned}$$

$$g_{ij} = -g_{ji}$$

$SU(3)_C \times SU(2)_L \times U(1)_Y$ quantum numbers of sub-multiplets:

$$h(1,2,+1/2),\quad \overline{h}(1,2,-1/2),\quad \omega(3,1,-1/3),\quad \omega^c(\overline{3},1,1/3),$$
$$\rho(3,2,1/6),\quad \overline{\rho}(\overline{3},2,-1/6),\quad \eta(3,1,2/3),\quad \overline{\eta}(\overline{3},1,-2/3),$$
$$\Phi(3,3,-1/3),\quad \overline{\Phi}(\overline{3},3,1/3),\quad \chi(3,2,7/6),\quad \overline{\chi}(\overline{3},2,-7/6)\,.$$

Scalar Exchange for d=7 Operaotrs



Cubic scalar vertex arises from 126^4:

$(2,2,15)\cdot(2,2,15)\cdot(1,1,6)\cdot(1,3,\overline{10})$ under $SU(2)_L\times SU(2)_R\times SU(4)_C$.

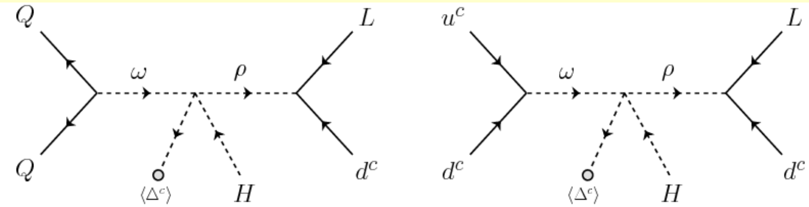
$\rho^*(\bar{3},2,-1/6)\subset(2,2,15)$, $H(1,2,1/2)\subset(2,2,15)$,
$\omega(3,1,-1/3)\subset(1,1,6)$

Leads to $\rho^*\omega H(\Delta^c)^\dagger$

$(126)^2\cdot(126^*)^2$, $(126)^2\cdot(126^*10)$ also contain $(2,2,15)\cdot(2,2,15)\cdot(1,3,10)\cdot(1,1,6)$ and thus $\rho^*\omega H(\Delta^c)^\dagger$

(B-L) Violating Nucleon Decay

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.

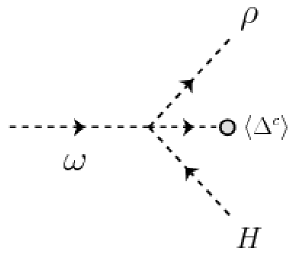
From $\eta\omega^* H$ diagram:

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

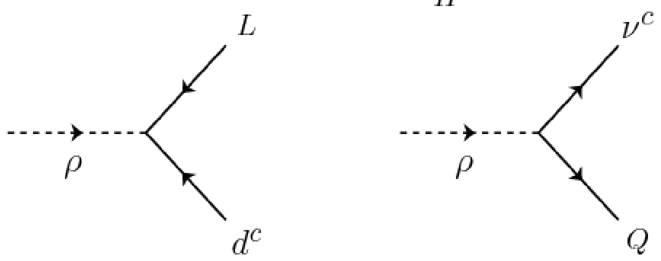
$Y = 10^{-2}$, $M_\rho = M_\eta = 10^{10}$ GeV, $v_R = 10^{11}$ GeV

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

(B-L) Asymmetry in Scalar Decay



Violates $B-L$



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

$(B-L)$ asymmetry parameter ϵ_{B-L}:

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

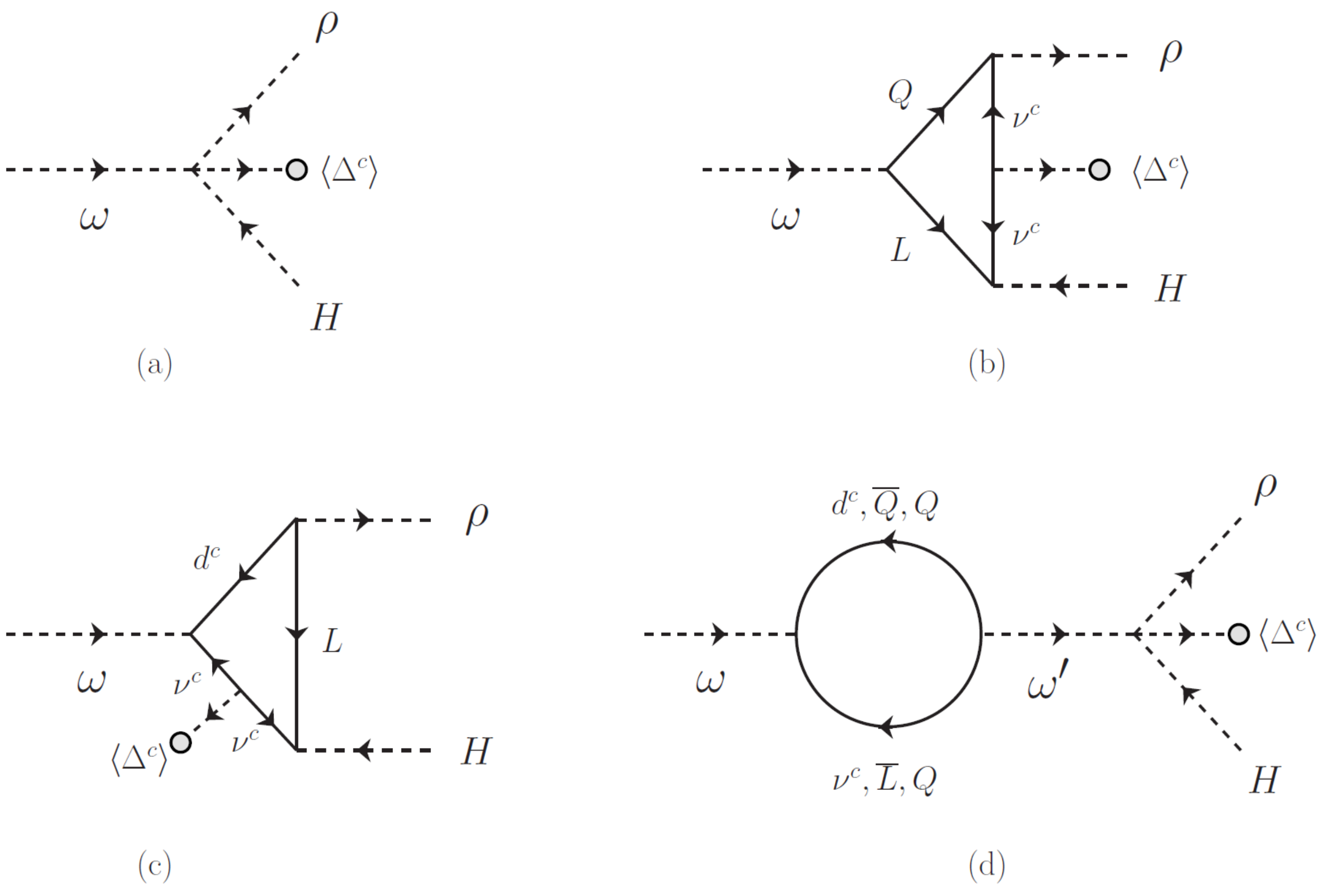
r is branching ratio for $\omega \to \rho H^*$

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

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

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

CP Violation



CP Asymmetry

$$\epsilon^{(b)}_{B-L} = -\frac{1}{\pi}\mathrm{Im}\left[\frac{\mathrm{Tr}\{Y^{\dagger}_{QL\omega^*}\, Y_{Q\nu^c\overline{\rho}}\, M_{\nu^c}\, F_1(M_{\nu^c})\, Y_{\nu^c LH})\}\,\lambda v_R}{|\lambda v_R|^2}\right]\mathrm{Br.}$$

$$F_1(M_j) = \ln\left(1+\frac{M^2_\omega}{M^2_j}\right) + \ominus\left(1-\frac{M^2_j}{M^2_\rho}\right)\left(1-\frac{M^2_j}{M^2_\rho}\right)$$

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

$$F_2(M_j) = \ln\left(1+\frac{M^2_\rho}{M^2_j}\right) + \ominus\left(1-\frac{M^2_j}{M^2_\omega}\right)\left(1-\frac{M^2_j}{M^2_\omega}\right)$$

$$\epsilon^{(d)}_{B-L} = \frac{1}{\pi}\mathrm{Im}\left[\frac{\mathrm{Tr}\{Y^{\dagger}_{d^c\nu^c\omega'}\, Y_{d^c\nu^c\omega}\, F_3(M_{\nu^c})\}(\lambda' v_R)^*(\lambda v_R)}{|\lambda v_R|^2}\right]\mathrm{Br}$$

$$F_3(M_j) = \left(\frac{M^2_\omega - M^2_j}{M^2_\omega - M^2_{\omega'}}\right)\ominus\left(1-\frac{M^2_j}{M^2_\omega}\right)\left(1-\frac{M^2_j}{M^2_\omega}\right)$$

(B-L) Asymmetry in Minimal Model

$$\epsilon_{B-L} \approx \frac{2\sqrt{3}}{\pi} \frac{|h_{33} f_3|^2}{|\lambda|} \left\{ 1 + \ln \left(1 + \frac{M_\rho^2}{M_{\nu_3^c}^2} \right) \right\} \sin \phi$$

$$\phi = \arg\{h_{33}^2 f_3^2 \lambda + \frac{\pi}{2}\}$$

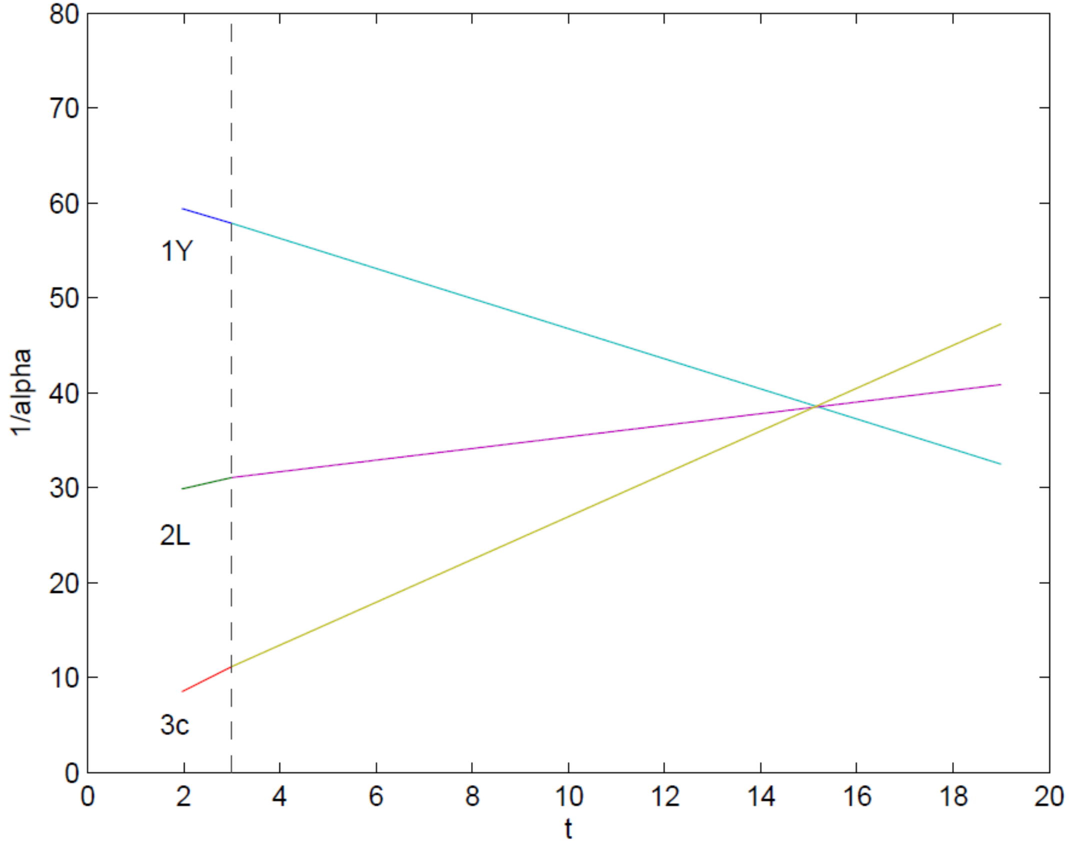
$$h_{33} = 0.6, \ \lambda = 0.6, \ f_3 = 10^{-2}, \ v_R = 10^{16} \text{ GeV}, \ \phi = 0.12$$

$$\Longrightarrow$$

$$\epsilon_{B-L} = 1.9 \times 10^{-5}, \ Br = 0.96, \ d = 5.6 \times 10^{-4}$$

$$Y_B = 8.2 \times 10^{-11}$$

TeV-scale Color Sextet scalar and unification



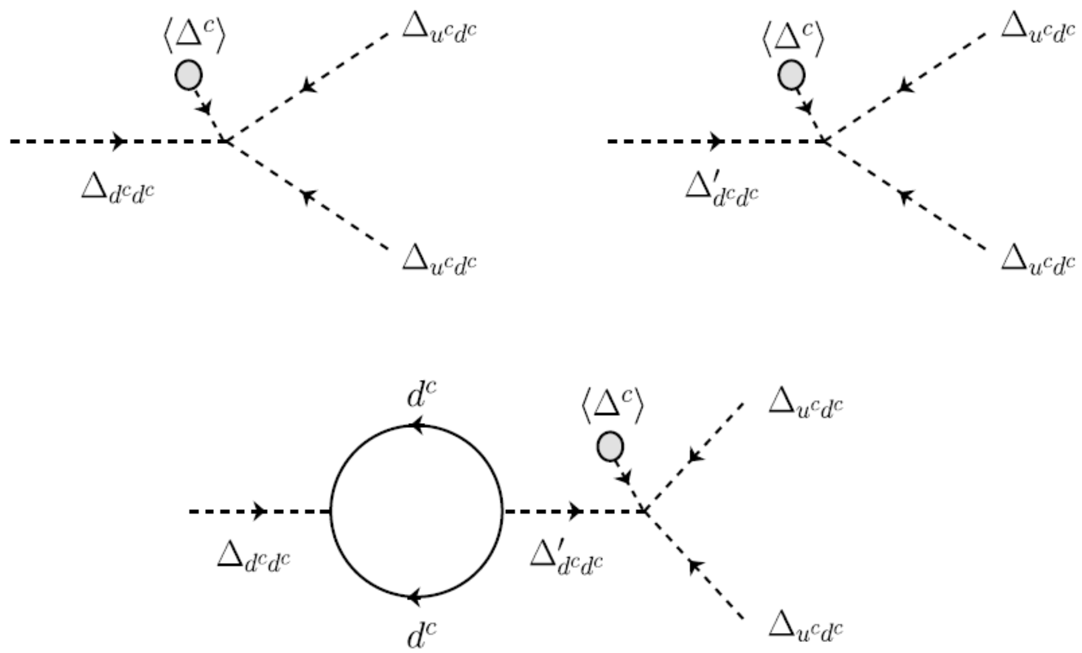
$\Delta_{u^c d^c}(6^*, 1, 1/3)$ scalar and a $(1, 3, 0)$ fermion at 1 TeV

$(1, 3, 0)$ fermion stable dark matter with mass $2.7 - 3$ TeV

K.S. Babu, R.N. Mohpatra (2012)

K.S. Babu, S. Khan, R.N. Mohapatra -- forthcoming

Baryongenesis via Color sextet decay



$\Delta_{d^c d^c}$: GUT mass; $\Delta_{u^c d^c}$: TeV mass

Minimal $SO(10)$ models have two $\Delta_{d^c d^c}$ (from **126** and **54**) and one $\Delta_{u^c d^c}$

$(B - L)$ asymmetry of the right order induced

Baryongenesis via Color sextet decay (cont.)

$(B-L)$ asymmetry parameter ϵ_{B-L}:

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

r is branching ratio for $\Delta_{d^c d^c} \to \Delta^*_{u^c d^c} \Delta^*_{u^c d^c}$

$\bar{r}$ is branching ratio for $\Delta^*_{d^c d^c} \to \Delta_{u^c d^c} \Delta_{u^c d^c}$

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

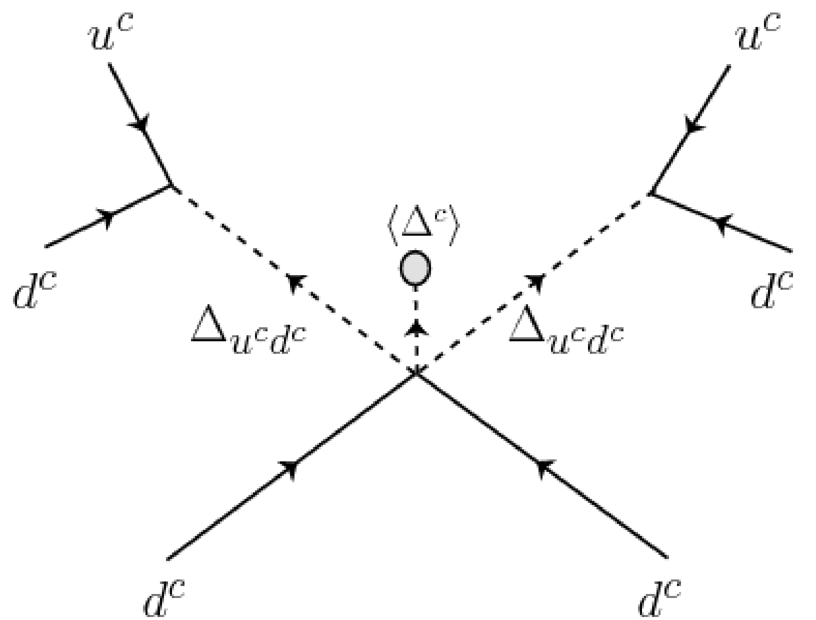
$$\eta = \frac{n_B}{s} \simeq \frac{\epsilon_{B-L}}{g^*} d$$

$$\epsilon_{B-L} \simeq \frac{2}{\pi |\lambda v_R|^2} \mathrm{Tr}(f^\dagger f) \mathrm{Im}[(\lambda v_R)(\lambda' v_R)^*] F \cdot \mathrm{Br}$$

$$F = \frac{M^2_{d^c d^c}}{M^2_{d^c d^c} - M'^2_{d^c d^c}}$$

$\eta_B \approx 10^{-10}$ naturally generated

Baryogenesis and n-nbar oscillations



$$M_{\delta_{u^c d^c}} = 1 \text{ TeV}, \; M_{\Delta_{d^c d^c}} = 10^{14} \text{ GeV}, \; f_{11} = 10^{-3}$$

$$\Longrightarrow \qquad \tau_{n-\overline{n}} = (10^9 - 10^{11}) \text{ sec.}$$

Summary and Conclusions

- $SO(10)$ Unified Theories may be realized without supersymmetry
- Natural Dark Matter candidate in $SO(10)$ with a possible colored partner
- New GUT scale baryogenesis in $SO(10)$ immune to sphaleron wash-out presented
- Baryon asymmetry related to $B - L$ violating nucleon decay