SU(5) GUT with Additional Generations of Higgs Bosons

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The Standard Model Higgs Boson

- The interactions of the SM are chiral
  - Left and right handed leptons carry different charges
- Chiral theories like the SM cannot have fermion masses
  - Massless fermions contradict experiment
- Gauge invariant operators necessitate additional fields

$$\mathcal{L} = y_{f_{ij}} \bar{f}_{L_i} f_{R_j} h \qquad h \to \langle h \rangle$$

- A priori it appears SM violates flavor

$$\mathcal{L} = U^\dagger_{il} y_{u_{lm}} V_{mj} h \bar{q}_{L_i} u_{R_j} + U^\dagger_{il} y_{d_{lm}} W_{mj} h^* \bar{q}_{L_i} d_{R_j} + y_{L_{ij}} h \bar{L}_{L_i} e_{R_j}$$

Flavor Mixing: CKM Matrix

- Flavor violating couplings arise from additional interactions
  - Even minimal Higgs Boson sector gives flavor violation
- $y_N = 0$ leads to no CKM like matrix for leptons
- CKM matrix from rotating u_{L_i} and d_{L_i} separately
- W bosons mix u_{L_i} and d_{L_i} giving

$$\mathcal{L}_W = g_2 \bar{u}_{L_i} \gamma^\mu d_{L_i} \to g_2 \bar{u}'_{L_i} \gamma^\mu A^\dagger_{ik} B_{kj} d'_{L_j}$$

$$(M_{CKM})_{ij} = A^\dagger_{ik} B_{kj}$$

Difficulties of Additional Higgs Bosons in the SM

- Generic addition of a Higgs Boson to the SM
  - Doubles number of Yukawa couplings
  - Gives no additional reparameterizations
- Runge basis for two Higgs doublets (Only one vev)

$$\Phi_{vev} = \frac{v_1}{v}\Phi_1 + \frac{v_2}{v}\Phi_2$$
$$\Phi_{\perp} = \frac{v_2}{v}\Phi_2 - \frac{v_1}{v}\Phi_1$$
$$v^2 = v_1^2 + v_2^2$$

- Lagrangian in this basis

$$\begin{aligned}\mathcal{L} &= y_{u_i}\Phi_{vev}\bar{q}_{L_i}u_{R_i} + y_{d_i}\Phi^*_{vev}\bar{q}_{L_i}d_{R_i} + y_{L_i}\Phi_{vev}\bar{L}_{L_i}e_{R_i} + y_{N_i}\Phi^*_{vev}\bar{L}_{L_i} \\ &+ \xi_{u_{ij}}\Phi_{\perp}\bar{q}_{L_i}u_{R_j} + \xi_{d_{ij}}\Phi^*_{\perp}\bar{q}_{L_i}d_{R_j} + \xi_{L_{ij}}\Phi_{\perp}\bar{L}_{L_i}e_{R_j} + \xi_{N_{ij}}\Phi^*_{\perp}\bar{L}_{L_i}N_{R_j}\end{aligned}$$

Constraints on Additional Yukawa Couplings

- Each ξ will give a diagram contributing to FV
- Meson mass mixing will constrain the ξ couplings

Meson (quarks)	B_F	f_F (GeV)	$\Delta M_F^{\rm expt}$ (GeV)
K^0 ($\bar{s}d$)	0.79	0.159	$(3.476 \pm 0.006) \times 10^{-15}$
B_d^0 ($\bar{b}d$)	1.28	0.216	$(3.337 \pm 0.033) \times 10^{-13}$
D^0 ($\bar{c}u$)	0.82	0.165	$(0.95 \pm 0.37) \times 10^{-14}$

Table: Data associated with the neutral mesons K^0, B_d^0 and D^0. (borrowed from Gupta, Wells).

- Constraints on ξ form meson mass mixing

$$\xi_{ds} \leq 1 \times 10^{-5} \quad \xi_{uc} \leq 3 \times 10^{-5} \quad \xi_{db} \leq 4 \times 10^{-5} \quad \xi_{sb} \leq 2 \times 10^{-}$$

Z_2 odd Higgs Bosons in the SM

- Two ways to evaded constraints and avoid tuning
  1. Identical couplings for additional Higgs bosons

$$\Delta\mathcal{L}_f = y^d_{ij}\bar{Q}_i\, F_u(\{\Phi_k\})\, d_{jR} + y^u_{ij}\bar{Q}_i\, F_d(\{\Phi_k\})\, u_{jR} + y^e_{ij}\bar{L}_i\, F_e(\{\Phi_k\})\, e_{jR}$$

     - Reparametrization of fermions identical to SM
  2. Symmetries forbid coupling of additional Higgs boson to SM fermions

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{Hid}(\Phi'_k, \Phi_k, f'_i)$$

     - Additional Higgs bosons interact with SM through Higgs
  3. Or both of the above combined
- Additional Z_2 symmetry
  - SM fermions even or odd
  - SM Higgs even
  - Additional Higgs odd

Higgs bosons of Supersymmetry

- Higgs physics suggests SUSY (Stabilize Hierarchy)
- SUSY Higgs interactions falls under the 3rd
- Higgs interactions with SM constrained by Holomorphy
- Exact SUSY has acceptable small flavor violation (FV)
- SUSY breaking CAN introduce flavor violation
- MSSM plus Z_2 odd Higgs boson gives no new FV

$$W_{odd} = W_{MSSM} + \mu_{22} H_{u2} H_{d2}$$

SUSY and Grand Unification

- Gauge coupling unification in SUSY

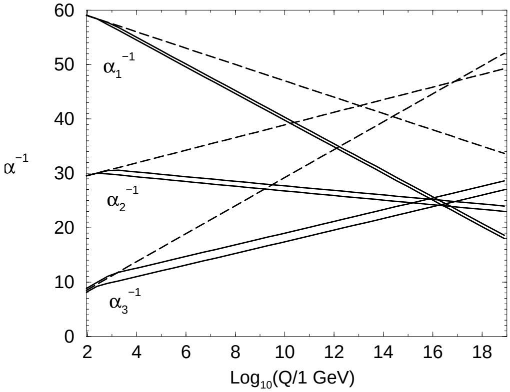


Figure: From Martins Supersymmetry Primer

Grand Unification in Supersymmetry

- If SUSY, Grand Unification likely
- Superpotential of SU(5) Grand Unification

$$W_{MSSM} = \frac{1}{3}\mathbf{Tr}\,\Sigma^3 + \frac{1}{2}fV\mathbf{Tr}\,\Sigma^2 + \lambda\bar{H}_\beta(\Sigma^\beta_\alpha + 3V\delta^\beta_\alpha)H^\alpha + \frac{1}{4}h^{ij}\epsilon_{\alpha\beta\gamma\delta\epsilon}\psi_i^{\alpha\beta}\psi_j^{\gamma\delta}H^\epsilon + \sqrt{2}f^{ij}\psi_i^{\alpha\beta}\phi_{j\alpha}\bar{H}_\beta.$$

- vev breaking SU(5) give doublet triplet splitting

$$\langle\Sigma\rangle = \begin{pmatrix} 2 & 0 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 & 0 \\ 0 & 0 & 2 & 0 & 0 \\ 0 & 0 & 0 & -3 & 0 \\ 0 & 0 & 0 & 0 & -3 \end{pmatrix}$$

- Doublet Triplet splitting important for proton stability
- Triplet Higgs must be very heavy ($m^2_{H_3} \sim 10^{16}$ GeV)

The Higgs bosons of a SUSY $SU(5) \times Z_2$ GUT

- Low scale Higgs superpotential of SUSY $SU(5) \times Z_2$

$$W_{Z_2} = -\mu H_3 \bar{H}_3 - \mu' H' \bar{H}'$$

- Two problems with this
  - Z_2 symmetry gives domain wall problem
  - Additional Higgs will be very hard to detect (aka boring)
- Fixed by adding explicit breaking of Z_2

$$W_{\not{Z}_2} = \epsilon (H \bar{H}' + H' \bar{H})$$

EWSB and the Higgs Triplet

- Masses of additional triplet and doublet identical
  - Doublet Higgs constrained by EWSB
  - Triplet Higgs constrained by absence of CCB
- EWSB requires at least one Higgs mass be negative

$$\begin{array}{ll} \epsilon^2 - m_3^2 - m_3\mu' < 0 & \text{for } \epsilon^2 > m_3^2 \\ m_3^2 - \epsilon^2 - m_3\mu' < 0 & \text{for } \epsilon^2 < m_3^2 \end{array}$$

- No CCB requires all Triplet Higgs mass be positive

$$\mu'^2 - m_3^2 > 0$$

Z_2 Odd Triplet Higgs

- Z_2 odd triplet Higgs bosons mix with SM triplet Higgs
- For $\mu_{GUT} \gg \mu', \epsilon$ mixing small

$$
\begin{aligned}
H &= \frac{\sqrt{2}}{2} H_1 + \frac{\sqrt{2}}{2} \bar{H}_1^* - \frac{\sqrt{2}\epsilon}{2\mu_{GUT}} H_2 - \frac{\sqrt{2}\epsilon}{2\mu_{GUT}} \bar{H}_2^* \\
\bar{H} &= -\frac{\sqrt{2}}{2} H_1^* + \frac{\sqrt{2}}{2} \bar{H}_1 - \frac{\sqrt{2}\epsilon}{2\mu_{GUT}} H_2^* + \frac{\sqrt{2}\epsilon}{2\mu_{GUT}} \bar{H}_2 .
\end{aligned}
$$

- But,$\mu_{GUT} \gg \mu', \epsilon$ lead to light triplet Higgs

$$
\begin{aligned}
m_{H_1}^2 &= \mu_{GUT}^2 + m_3^2 + 2\epsilon^2 \\
m_{\bar{H}_1}^2 &= \mu_{GUT}^2 - m_3^2 + 2\epsilon^2 \\
m_{H_2}^2 &= \mu'^2 + m_3^2 \\
m_{\bar{H}_2}^2 &= \mu'^2 - m_3^2
\end{aligned}
$$

Proton Decay From Z_2 Odd Higgs Bosons

- S-channel decay through odd Higgs bosons

$$\frac{A'_i}{A_{SM}} = \frac{\epsilon^2}{2m_{H_i}^2}$$

  - Enhanced if $2m_{H_i}^2 < \epsilon^2$

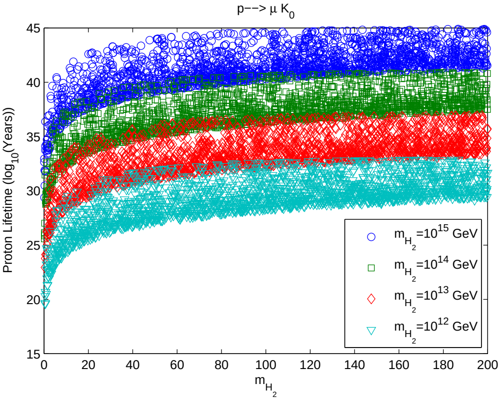
- Dimension 5 operators are always suppressed

$$\frac{A'_i}{A_{SM}} = \frac{\epsilon}{\mu_{GUT}} \frac{\epsilon}{m_{H_i}}$$

  - This contribution will be suppressed unless we fine tune

Parameter Space Constraints From Proton Decay

- The parameter space is only minimally constrained



BBN Constraints on Triplet Higgs Boson

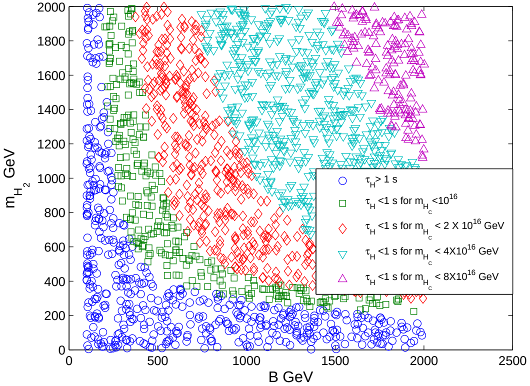
- Once Z_2 is broken the odd Higgs bosons will decay
- Decay only through mixing and will be quite suppressed
- Strongly interacting and can mess up BBN
- Must decay before BBN

$$\Gamma(H \to \bar{f}_i f_j) \propto |y_i|^2 m_H \frac{\epsilon^2}{\mu_{GUT}^2}$$

$$\frac{1}{\Gamma} \leq 1s$$

BBN Constraints on Parameter Space

- Very small values of m_H and ϵ forbidden by BBN constraints



Conclusions

- Additional Higgs bosons require symmetries to forbid FV
- Z_2 odd Higgs bosons will not introduce FV
- EWSB for SU(2) Higgs bosons and no CCB for SU(3) constrain the Z_2 breaking to be of EW scale
- EW scale Z_2 breaking can evade BBN/proton decay constraints
- Supersymmetric GUT with additional Z_2 odd Higgs boson will have an EW scale triplet
- Further analysis
  - Collider phenomenology of light Triplet Higgs boson
  - Possible motivations for this type of Higgs sector