New supersymmetric standard model with stable proton

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PRL 84, 5269 (2000)

hep-ph/003286 (to appear in PRD.)

§1 Introduction

MSSM

Problem of proton decay

Renormalizable B and/or L violating interactions

$$D^cD^cU^c, LQD^c, LLE^c, H_1H_1E^c, LH_2$$

$$\Downarrow$$

Proton decay

An ad hoc discrete symmetry is imposed through R-parity.

SM

The proton decay is forbidden by gauge symmetry.

The SSM with an extra U(1) gauge symmetry coupled to N=1 SUGRA is discussed.
The proton stability is guaranteed by U(1).

•μ-problem

Origin of the μ term ?

•Neutrino masses problem

Origins of N^c and Majorana mass ?

$$\Downarrow$$

No mass parameter

§2 Model

A minimal extension

	SU(3)	SU(2)	U(1)	U′(1)
Q^i	3	2	$\frac{1}{6}$	Q_Q
U^{ci}	3*	1	$-\frac{2}{3}$	Q_{U^c}
D^{ci}	3*	1	$\frac{1}{3}$	Q_{D^c}
L^i	1	2	$-\frac{1}{2}$	Q_L
N^{ci}	1	1	0	Q_{N^c}
E^{ci}	1	1	1	Q_{E^c}
H_1^j	1	2	$-\frac{1}{2}$	Q_{H_1}
H_2^j	1	2	$\frac{1}{2}$	Q_{H_2}
S^k	1	1	0	Q_S
K^l	3	1	Y_K	Q_K
K^{cl}	3*	1	$-Y_K$	Q_{K^c}

$i = 1, 2, 3 \quad j = 1, \cdots, n_H \quad k = 1, \cdots, n_S \quad l = 1, \cdots, n_K$

⟨ mass terms for quarks and charged leptons ⟩

$H_1QD^c, H_2QU^c, H_1LE^c$

⟨ mass terms for neutrinos ⟩

H_2LN^c, SN^cN^c

⟨ μ term ⟩

SH_1H_2

⟨ mass terms for K fermions ⟩

SKK^c

Anomalies free $\Rightarrow \begin{cases} (A)\ Y_K = \pm\frac{1}{3},\ n_H = 3,\ n_S = 3,\ n_K = 3 \\ (B)\ Y_K = \pm\frac{\sqrt{2}}{3},\ n_H = 2,\ n_S = 1,\ n_K = 3 \end{cases}$

(A)

• $Y_K = -\frac{1}{3}$

The particle contents of one generation can be embedded in the **27** of E_6.

B and/or L are violated D=4 couplings.

$U^c D^c K^c, LQK^c \Rightarrow$ fast proton decay

• $Y_K = \frac{1}{3}$

allowed couplings of D=4

$H_1 Q D^c, H_2 Q U^c, H_1 L E^c, H_2 L N^c, S N^c N^c, S H_1 H_2, S K K^c$

$\Rightarrow$ B is conserved.

lowest dimension couplings of B violation (D=6)

$$QQU^{c*}E^{c*},\quad QQD^{c*}N^{c*},\quad QU^{c*}D^{c*}L$$

$\Rightarrow$ The proton decay is adequately suppressed.

Particle contents

$\mathrm{Tr}[YY'] = 0, \qquad \mathrm{Tr}[Y'^2] = \mathrm{Tr}[Y^2]$

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U'(1)_{Y'}$
Q^i	3	2	$\frac{1}{6}$	$\frac{1}{12}$
U^{ci}	3^*	1	$-\frac{2}{3}$	$\frac{1}{12}$
D^{ci}	3^*	1	$\frac{1}{3}$	$\frac{7}{12}$
L^i	1	2	$-\frac{1}{2}$	$\frac{7}{12}$
N^{ci}	1	1	0	$-\frac{5}{12}$
E^{ci}	1	1	1	$\frac{1}{12}$
H_1^i	1	2	$-\frac{1}{2}$	$-\frac{2}{3}$
H_2^i	1	2	$\frac{1}{2}$	$-\frac{1}{6}$
S^i	1	1	0	$\frac{5}{6}$
K^i	3	1	$\frac{1}{3}$	$-\frac{2}{3}$
K^{ci}	3^*	1	$-\frac{1}{3}$	$-\frac{1}{6}$

$i = 1, 2, 3$

Superpotential

$$W = \eta_u^{ijk} H_2^i Q^j U^{ck} + \eta_d^{ijk} H_1^i Q^j D^{ck} + \eta_\nu^{ijk} H_2^i L^j N^{ck} + \eta_e^{ijk} H_1^i L^j E^{ck} + \lambda_N^{ijk} S^i N^{cj} N^{ck} + \lambda_H^{ijk} S^i H_1^j H_2^k + \lambda_K^{ijk} S^i K^j K^{ck}$$

Proton is sufficiently stable.

No mass parameter.

§3 Vacuum structure

- Couplings between different generations are not significant.
- Similar mass hierarchy of K fermions.

Only H_1^3, H_2^3, and S^3 may have non-vanishing VEVs.

Scalar potential

$$V = \frac{g_2^2}{8}\left(|H_1|^2 + |H_2|^2\right)^2 + \frac{g_1^2}{8}\left(|H_1|^2 - |H_2|^2\right)^2$$
$$+ \frac{g'^2}{72}\left(4|H_1|^2 + |H_2|^2 - 5|S|^2\right)^2$$
$$- \left(\frac{1}{2}g_2^2 - |\lambda_H|^2\right)|H_1 H_2|^2 + |\lambda_H|^2\left(|H_1|^2 + |H_2|^2\right)|S|^2$$
$$+ \left(B_H \lambda_H m_{3/2} S H_1 H_2 + \text{h.c.}\right) + M_{H_1}^2 |H_1|^2 + M_{H_2}^2 |H_2|^2 + M_S^2 |S|^2$$

g': U′(1) gauge coupling constant

• $g_2^2 > 2|\lambda_H|^2$ guarantees electric charge conservation.

$$\langle H_1 \rangle = \begin{pmatrix} v_1/\sqrt{2} \\ 0 \end{pmatrix}, \quad \langle H_2 \rangle = \begin{pmatrix} 0 \\ v_2/\sqrt{2} \end{pmatrix}, \quad \langle S \rangle = v_s/\sqrt{2}$$

v_1, v_2, v_s: real and non-negative

Experimental constraints on Z and Z′ bosons

Mass matrix $\begin{pmatrix} M_Z^2 & \Delta \\ \Delta & M_{Z'}^2 \end{pmatrix} \to \begin{pmatrix} M_{Z_1} & 0 \\ 0 & M_{Z_2} \end{pmatrix}$

$M_{Z_2} \gtrsim 600$ GeV

Mixing parameter $R \equiv \frac{\Delta^2}{M_Z^2 M_{Z'}^2} \lesssim 10^{-3}$

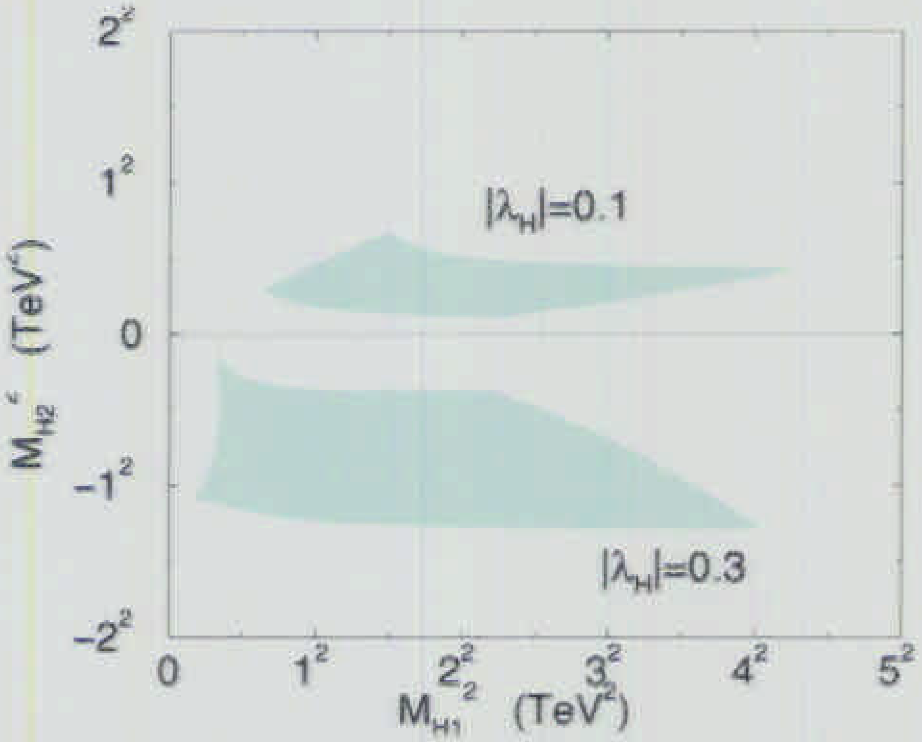
Parameters in V

$$g',\ |\lambda_H|,\ |B_H\lambda_H m_{3/2}|,\ M_{H_1}^2,\ M_{H_2}^2,\ M_S^2$$

$$g' = g_1,\quad |\lambda_H| = 0.1,\ 0.3,\quad |B_H\lambda_H m_{3/2}| = 0.1\ \text{TeV}$$

$$1 \leq v_2/v_1 \leq 35, \qquad M_{Z_2} \leq 2\ \text{TeV}$$

Allowed regions of $M_{H_1}^2$ and $M_{H_2}^2$



$$-1.5^2\ (\text{TeV}^2) \lesssim M_S^2 \lesssim -0.5^2\ (\text{TeV}^2)$$

- μ **parameter**

$$|\mu| = |\lambda_H| v_s/\sqrt{2}$$

$$\left.\begin{array}{r} |\lambda_H| = 0.2 \\ v_s = 3 \text{ TeV} \end{array}\right\} \qquad |\mu| \sim 420 \text{ GeV}$$

The μ parameter can have an appropriate magnitude for the EW symmetry breaking.

- **Neutrino masses**

$$\begin{pmatrix} 0 & -\eta_\nu v_2/\sqrt{2} \\ -\eta_\nu v_2/\sqrt{2} & \sqrt{2}\lambda_N v_s \end{pmatrix} \qquad m_\nu = |\eta_\nu|^2 v_2^2/2\sqrt{2}|\lambda_N| v_s$$

$$\left.\begin{array}{r} |\lambda_N| = 0.2 \\ v_s = 3 \text{ TeV} \\ |\eta_\nu| v_2 = 1 \text{ MeV} \end{array}\right\} m_\nu \sim 0.59 \text{ eV}$$

If $\eta_\nu \sim \eta_e$, the observed neutrinos have tiny masses.

- **Squark and slepton masses**

a typical scale of $M_{\tilde{q}}$ and $M_{\tilde{l}} \sim M_{H_1} \gtrsim 1$ TeV

The EDMs of the neutron and the electron become consistent with the experimental bounds without fine-tuning much CP-violating phases.

- **K fermions**

stable particles

$$m_K = \lambda_K v_s/\sqrt{2} \sim 0.1 - 1 \text{ TeV}$$

Relic density depends on various uncertain factors.

§4 Energy dependence

The low energy parameter values are derived from universal values at a high energy scale.

At a high energy scale $M_X \equiv 10^{17}$GeV

universal

The scalar masses-squared : $m_{3/2}^2$

The trilinear coupling constants : A

$$m_3 = m_2 = m_1 = m_1' \equiv m$$

$$\eta_u^X,\ \eta_d^X,\ \eta_\nu^X,\ \eta_e^X,\ \lambda_N^X,\ \lambda_H^X,\ \lambda_K^X$$

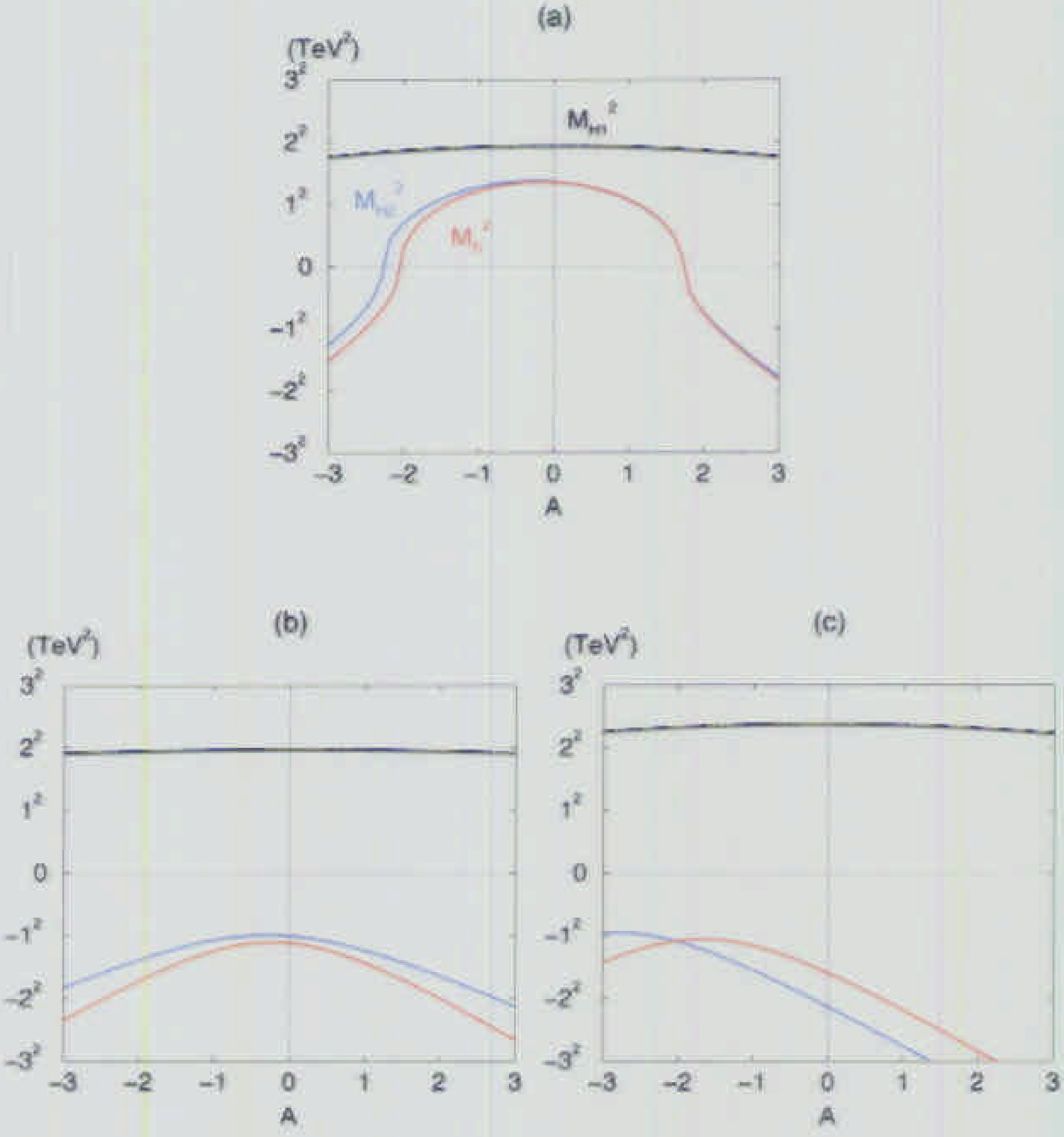
At a low energy scale $M \equiv 5 \times 10^2$GeV

The parameter values are determined by R.G.E.s.

$M_{H_1}^2, M_{H_2}^2, M_S^2$

$m_{3/2} = 2$ TeV, $\eta_d^X = \eta_\nu^X = \eta_e^X = 0$, $\lambda_N^X = \lambda_H^X = 0.2$

	(a)	(b)	(c)
$\eta_u^X,\ \lambda_K^X$	0.1	0.3	0.1
$m/m_{3/2}$	0.1	0.1	1



$M_{H_2}^2$ and M_S^2 are negative in various input parameter regions.

Explicit examples

$$
\begin{aligned}
A &= -1 \\
\eta_d^X &= \eta_\nu^X = \eta_e^X = 0, \qquad \eta_u^X = \lambda_N^X = \lambda_K^X = 0.2
\end{aligned}
$$

	(i)	(ii)	(iii)	(iv)
$m_{3/2}$ (TeV)	1.0	1.0	2.0	2.0
m (TeV)	0.3	0.5	0.3	0.5
η_d^X	0.007	0.002	0.010	0.005
λ_H^X	0.356	0.412	0.307	0.339
v_2/v_1	3.2	2.1	5.2	3.7
v_s (TeV)	2.4	3.5	3.8	4.4
M_{Z_2} (TeV)	0.73	1.05	1.14	1.32
R	1.2×10^{-4}	2.1×10^{-6}	9.7×10^{-5}	5.3×10^{-5}
M_{H^0} (TeV)	0.062	0.042	0.068	0.066
	0.73	1.05	1.15	1.33
	1.06	1.32	1.95	2.05
M_{A^0} (TeV)	1.06	1.32	1.95	2.05
$M_{H^\pm}$ (TeV)	1.06	1.32	1.95	2.05
M_W (GeV)	80	82	74	79
m_t (GeV)	166	161	160	166
m_b (GeV)	2.9	1.2	2.4	1.8

- The gauge symmetry breaking can be induced through radiative corrections.
- Certain parameter values at a high energy scale with the universal values $m_{3/2}^2$ and A lead to a plausible vacuum around the EW scale.
- The gauge coupling constants are not unified at the energy scale for possible grand unification.

§5 **Summary**

We have constructed a SSM based on SU(3)×SU(2)×U(1)×U′(1) gauge symmetry and $N = 1$ supergravity.

- The proton is stable by gauge symmetry.
- The effective μ parameter is given by the symmetry breaking
  $\Rightarrow |\mu| \sim$ EW scale
- The large Majorana masses are induced for the right-handed neutrinos. $\Rightarrow$ The ordinary neutrinos have tiny masses.

  A typical mass scale $\sim$ 1TeV
  $\Rightarrow$ The EDMs could become enough small without fine-tuning much CP-violating phases.

The energy dependencies of the model parameters have been studied.

- The masses-squared and the trilinear coupling constants of scalar fields could be universal at $\sim M_{pl}$.
- The gauge coupling constants are not unified.