Beyond the MSSM

- Beyond the MSSM
- Heavy $Z'$
- Higgs
- Neutralinos
- Exotics
- Neutrino Mass in Strings

Davis (May 1, 2006)  Paul Langacker (Penn)
References

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Beyond the MSSM

Even if supersymmetry holds, MSSM may not be the full story

Most of the problems of standard model remain (hierarchy of electroweak and Planck scales is stabilized but not explained)

$\mu$ problem introduced: $W_\mu = \mu \hat{H}_u \cdot \hat{H}_d$, $\mu = O($electroweak$)$

Could be that all new physics is at GUT/Planck scale, but with remnants surviving to TeV scale

Specific string constructions often have extended gauge groups, exotics, extended Higgs/neutralino sectors

Important to explore alternatives/extensions to MSSM

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Remnants Physics from the Top-Down

- $Z'$ or other gauge
- Extended Higgs/neutralino (doublet, singlet)
- Quasi-Chiral Exotics
- Charge $1/2$ (Confinement?, Stable relic?)
- Quasi-hidden (Strong coupling? SUSY breaking? Composite family?)
- Time varying couplings
- LED (TeV black holes, stringy resonances)
- LIV, VEP (e.g., maximum speeds, decays, (oscillations) of HE $\gamma$, $e$, gravity waves ($\nu$'s))

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Strings, GUTs, DSB, little Higgs, LED often involve extra $Z'$

Typically $M_{Z'} > 600 - 900$ GeV (Tevatron, LEP 2, WNC);
$|\theta_{Z-Z'}| < \text{few} \times 10^{-3}$ ($Z$-pole)
(CDF di-electron: 850 ($Z_{\text{seq}}$), 740 ($Z_{\chi}$), 725 ($Z_{\psi}$), 745 ($Z_{\eta}$))

Discovery to $M_{Z'} \sim 5 - 8$ TeV at LHC, ILC,
$(pp \rightarrow e^+e^-, \mu^+\mu^-, q\bar{q})$ (depends on couplings, exotics, sparticles)

Diagnostics to 1-2 TeV (asymmetries, $y$ distributions, associated production, rare decays)
- Extra $U(1)'$ and SM singlets extremely common
- Radiative breaking of electroweak (SUGRA or gauge mediated) often yield EW/TeV scale $Z'$ (unless breaking along flat direction $\rightarrow$ intermediate scale)
- Breaking due to negative mass$^2$ for scalar $S$ (driven by large Yukawa) or by $A$ term
Implications of a TeV-scale $U(1)'$

- **Natural Solution to $\mu$ problem** $W \sim h S H_u H_d \rightarrow \mu_{eff} = h\langle S \rangle$  
  ("stringy version" of NMSSM)

- **Extended Higgs sector**
  - Relaxed upper limits, couplings, parameter ranges (e.g., $\tan \beta$ can be close to 1)
  - Higgs singlets needed to break $U(1)'$
  - Doublet-singlet mixing $\rightarrow$ highly non-standard collider signatures

- **Large $A$ term and possible tree-level $CP$ violation** (no new EDM constraints) $\rightarrow$ electroweak baryogenesis
• **Extended neutralino sector**
  - Additional neutralinos, non-standard couplings, e.g., light singlino-dominated, extended cascades
  - Enhanced possibilities for cold dark matter, $g_\mu - 2$ (even small $\tan \beta$)

• **Exotics (anomaly-cancellation)**
  - May decay by mixing; by diquark or leptoquark coupling; or be quasi-stable

• **$Z'$ decays into sparticles/exotics**

• **Constraints on neutrino mass generation**

• **Flavor changing neutral currents (for non-universal $U(1)'$ charges)**
  - Tree-level effects in $B$ decay competing with SM loops (or with enhanced loops in MSSM with large $\tan \beta$)
UMSSM: **SUSY-breaking scale models** (Demir et al)
- $M_{Z'} \sim M_Z$, leptophobic
- $M_{Z'} \gtrsim 10M_Z$ by modest tuning

sMSSM: **Secluded sector models** (Erler, PL, Li)
- Approximately flat direction, broken by small ($\sim 0.05$) Yukawa
- $Z'$ breaking decoupled from effective $\mu$ term
- Four SM singlets: $S, S_{1,2,3}$, doublets $H_{1,2}$
- Off-diagonal Yukawas
- Can be consistent with minimal gauge unification
Superpotential: \[ W = h S H_1 H_2 + \lambda S_1 S_2 S_3 \]

Potential: \[ V = V_F + V_D + V_{soft} \]

\[
V_F = h^2 \left( |H_1|^2 |H_2|^2 + |S|^2 |H_1|^2 + |S|^2 |H_2|^2 \right) \\
+ \lambda^2 \left( |S_1|^2 |S_2|^2 + |S_2|^2 |S_3|^2 + |S_3|^2 |S_1|^2 \right)
\]

\[
V_D = \frac{G^2}{8} \left( |H_2|^2 - |H_1|^2 \right)^2 \\
+ \frac{1}{2} g_Z^2 \left( Q_S |S|^2 + Q_{H_1} |H_1|^2 + Q_{H_2} |H_2|^2 + \sum_{i=1}^{3} Q_{S_i} |S_i|^2 \right)^2
\]

where \( G^2 = g_1^2 + g_2^2 \).
\[
V_{soft} = m_{H_1}^2 |H_1|^2 + m_{H_2}^2 |H_2|^2 + m_S^2 |S|^2 + \sum_{i=1}^{3} m_{S_i}^2 |S_i|^2
\]
\[
- \left( A_h h S H_1 H_2 + A_\lambda \lambda S_1 S_2 S_3 + H.C. \right)
\]
\[
+ \left( m_{S S_1}^2 S S_1 + m_{S S_2}^2 S S_2 + m_{S_1 S_2}^2 S_1^\dagger S_2 + H.C. \right)
\]

- \( \langle S_i \rangle \sim m_{S_i}/\lambda \) large for small \( \lambda \)
- Breaking along \( D(U(1)') \sim 0 \)
- Smaller \( \langle S \rangle, \langle H_i \rangle \), dominated by \( h A_h \): \( \tan \beta \sim 1, \langle S \rangle \sim \langle H_i \rangle \)
- Large doublet-singlet mixing
- Two sectors nearly decoupled
- Mixed soft terms break two global symmetries
- Tree-level CP breaking in \( S, S_i \) sector in general (Important for baryogenesis; little effect on EDMs)
Extended Higgs Sector

- Standard model singlets $S_i$ and additional doublet pairs $H_{u,d}$ very common.

- Additional doublet pairs
  - Richer spectrum, decay possibilities
  - May be needed (or expand possibilities for) quark/lepton masses/mixings (e.g., stringy symmetries may restrict single Higgs couplings to one or two families)
  - Extra neutral Higgs → FCNC (suppressed by Yukawas)
  - Significantly modify gauge unification
Higgs singlets $S_i$

- Standard model singlets extremely common in string constructions
- Needed to break extra $U(1)'$ gauge symmetries
- Solution to $\mu$ problem ($U(1)'$, NMSSM, nMSSM)

$$W \sim h_s \hat{S} \hat{H}_u \hat{H}_d \rightarrow \mu_{eff} = h_s \langle S \rangle$$

- Relaxed upper limits, couplings, parameter ranges (e.g., $\tan \beta = v_u/v_d$ can be close to 1), singlet-doublet mixing
- Large $A$ term and possible tree-level $CP$ violation $\rightarrow$ electroweak baryogenesis
Dynamical $\mu$


- V. Barger, PL and H. S. Lee,
  “Lightest neutralino in extensions of the MSSM,”

- Abel, Bagger, Barger, Bastero-Gil, Batra, Birkedal, Carena, Chang, Choi, Cvetic, Dedes, Delgado, Demir, Dermisek, Dobrescu, Drees, Ellis, Ellwanger, Erler, Espinosa, Everett, Fox, Godbole, Gunion, Haber, Han, Hooper, Hugonie, Kaplan, King, Landsberg, Li, Matchev, McElrath, Menon, Miller, Moretti, Morrissey, Nevzorov, Panagiotakopoulos, Perelstein, Pilaftsis, Poppitz, Randall, Rosner, Roy, Sarkar, Sopczak, Tait, Tamvakis, Vempati, Wagner, Weiner, White, Zerwas, Zhang
Models with Dynamical $\mu$

<table>
<thead>
<tr>
<th>Model</th>
<th>Symmetry</th>
<th>Superpotential</th>
<th>CP-even</th>
<th>CP-odd</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSSM</td>
<td>–</td>
<td>$\mu \hat{H}_u \cdot \hat{H}_d$</td>
<td>$H_1^0, H_2^0$</td>
<td>$A_2^0$</td>
</tr>
<tr>
<td>NMSSM</td>
<td>$Z_3$</td>
<td>$h_s \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3$</td>
<td>$H_1^0, H_2^0, H_3^0$</td>
<td>$A_1^0, A_2^0$</td>
</tr>
<tr>
<td>nMSSM</td>
<td>$Z_5^R, Z_7^R$</td>
<td>$h_s \hat{S} \hat{H}_u \cdot \hat{H}_d + \xi_F M_n^2 \hat{S}$</td>
<td>$H_1^0, H_2^0, H_3^0$</td>
<td>$A_1^0, A_2^0$</td>
</tr>
<tr>
<td>UMSSM</td>
<td>$U(1)'$</td>
<td>$h_s \hat{S} \hat{H}_u \cdot \hat{H}_d$</td>
<td>$H_1^0, H_2^0, H_3^0$</td>
<td>$A_2^0$</td>
</tr>
<tr>
<td>sMSSM</td>
<td>$U(1)'$</td>
<td>$h_s \hat{S} \hat{H}_u \cdot \hat{H}_d + \lambda_s \hat{S}_1 \hat{S}_2 \hat{S}_3$</td>
<td>$H_1^0, H_2^0, H_3^0$, $H_4^0, H_5^0, H_6^0$</td>
<td>$A_1^0, A_2^0, A_3^0, A_4^0$</td>
</tr>
</tbody>
</table>

- **MSSM**: gaugino unification but general $\mu$
- **NMSSM**: may be domain wall problems ($Z_2^R$?)
- **nMSSM**: avoids domain walls; tadpoles from high order loops
- **UMSSM**: additional $Z'$ ($\mu_{eff}, M_{Z'}$ generated by single $S$)
- **sMSSM**: stringy NMSSM w. decoupled $\mu_{eff}, M_{Z'}$
  ($\hat{H}_u, \hat{H}_d, \hat{S}$ reduces to nMSSM in $S_i$ decoupling limit $\rightarrow n/sMSSM$)

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A Unified Analysis of Higgs and Neutralino Sectors

\[ V_F = |h_s H_u \cdot H_d + \xi_F M_n^2 + \kappa S^2|^2 + |h_s S|^2 (|H_d|^2 + |H_u|^2) \]

\[ V_D = \frac{G^2}{8} (|H_d|^2 - |H_u|^2)^2 + \frac{g_2^2}{2} (|H_d|^2 |H_u|^2 - |H_u \cdot H_d|^2) \]

\[ + \frac{g_{1'}^2}{2} (Q_{H_d} |H_d|^2 + Q_{H_u} |H_u|^2 + Q_S |S|^2)^2 \]

\[ V_{soft} = m_d^2 |H_d|^2 + m_u^2 |H_u|^2 + m_s^2 |S|^2 \]

\[ + \left( A_s h_s S H_u \cdot H_d + \frac{\kappa}{3} A \kappa S^3 + \xi S M_n^3 S + h.c. \right) \]

black = MSSM (with \( \mu = h_s \langle S \rangle \)); blue= extensions;
cyane = NMSSM; magenta = UMSSM; red= n/sMSSM

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Mass matrices in \( \{H_d, H_u, S\} \) basis

- **CP-even (tree level)** \( \langle H^0_{u,d} \rangle \equiv v_{u,d}/\sqrt{2}, \langle S \rangle \equiv s/\sqrt{2} \)

\[
\begin{align*}
(M^0_+)^{dd} &= \left[ \frac{G^2}{4} + Q^2_{Hd}g_1' \right] v_d^2 + \left( \frac{h_s A_s}{\sqrt{2}} + \frac{h_s \kappa s}{2} + \frac{h_s \xi F M_n^2}{s} \right) \frac{v_u s}{v_d} v_d \\
(M^0_+)^{du} &= \left[ -\frac{G^2}{4} + h_s^2 + Q_{Hd} Q_{H u} g_1'^2 \right] v_d v_u - \left( \frac{h_s A_s}{\sqrt{2}} + \frac{h_s \kappa s}{2} + \frac{h_s \xi F M_n^2}{s} \right) s \\
(M^0_+)^{ds} &= \left[ h_s^2 + Q_{Hd} Q_S g_1'^2 \right] v_d s - \left( \frac{h_s A_s}{\sqrt{2}} + h_s \kappa s \right) v_u \\
(M^0_+)^{uu} &= \left[ \frac{G^2}{4} + Q^2_{H u} g_1'^2 \right] v_u^2 + \left( \frac{h_s A_s}{\sqrt{2}} + \frac{h_s \kappa s}{2} + \frac{h_s \xi F M_n^2}{s} \right) \frac{v_d s}{v_u} v_u \\
(M^0_+)^{us} &= \left[ h_s^2 + Q_{H u} Q_S g_1'^2 \right] v_u s - \left( \frac{h_s A_s}{\sqrt{2}} + h_s \kappa s \right) v_d \\
(M^0_+)^{ss} &= \left[ Q_S^2 g_1'^2 + 2 \kappa^2 \right] s^2 + \left( \frac{h_s A_s}{\sqrt{2}} - \frac{\sqrt{2} \xi S M_n^3}{v_d v_u} \right) \frac{v_d v_u}{s} + \frac{\kappa A_\kappa}{\sqrt{2}} s
\end{align*}
\]

\[\text{Davis (May 1, 2006)} \quad \text{Paul Langacker (Penn)}\]
• Also CP-odd and charged Higgs (CP breaking ignored)

• Leading loop corrections (top-stop loops) are common

• Theoretical upper limits on $H_1^0$ relaxed ($\rightarrow$ smaller $\tan \beta$ allowed)

  - MSSM
    \[ M_{H_1^0}^2 \leq M_Z^2 \cos^2 2\beta + \tilde{M}^{(1)} \]
    \[ \tilde{M}^{(1)} = (M_+^{(1)})_{dd} \cos^2 \beta + (M_+^{(1)})_{uu} \sin^2 \beta + (M_+^{(1)})_{du} \sin 2\beta \]

  - NMSSM, n/sMSSM, and Peccei-Quinn limits
    \[ M_{H_1^0}^2 \leq M_Z^2 \cos^2 2\beta + \frac{1}{2} h_s^2 v^2 \sin^2 2\beta + \tilde{M}^{(1)} \]

  - UMSSM
    \[ M_{H_1^0}^2 \leq M_Z^2 \cos^2 2\beta + \frac{1}{2} h_s^2 v^2 \sin^2 2\beta + g_Z^2 v^2 (Q_{H_d} \cos^2 \beta + Q_{H_u} \sin^2 \beta)^2 + \tilde{M}^{(1)} \]
- Experimental LEP SM and MSSM bounds may be relaxed by singlet-doublet mixing

- Reduced $ZZH_i$ coupling

$$\xi_{ZZH_i} = (R_1^i \cos \beta + R_2^i \sin \beta)^2$$

- Also, $Z \rightarrow HA$, $Z$ width, $\chi^{\pm}$ mass, $Z - Z'$ mixing, $V$ minimum, RGE
Limiting Cases

- **MSSM limit** ($s \to \infty$ with $\mu_{\text{eff}} = h_s s / \sqrt{2}$ fixed) $\to$ two MSSM-like CP-even Higgs and one largely singlet (heavy in UMSSM, light in n/sMSSM, depends on $\kappa$ in NMSSM)

- **PQ and R limits** (massless pseudoscalar)

<table>
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<tr>
<th>Model</th>
<th>Limits</th>
<th>Symmetry</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSSM</td>
<td>$B \to 0$</td>
<td>$U(1)_{PQ}$</td>
<td>$M_{A_1} \to 0$</td>
</tr>
<tr>
<td>NMSSM</td>
<td>$\kappa, A_\kappa \to 0$</td>
<td>$U(1)_{PQ}$</td>
<td>$M_{A_1} \to 0$</td>
</tr>
<tr>
<td>NMSSM</td>
<td>$A_s, A_\kappa \to 0$</td>
<td>$U(1)_R$</td>
<td>$M_{A_1} \to 0$</td>
</tr>
<tr>
<td>n/sMSSM</td>
<td>$\xi_F, \xi_S \to 0$</td>
<td>$U(1)_{PQ}$</td>
<td>$M_{A_1} \to 0$</td>
</tr>
<tr>
<td>UMSSM</td>
<td>$g_1' \to 0$</td>
<td>$U(1)$</td>
<td>$M_{Z'}, M_{A_1} \to 0$</td>
</tr>
</tbody>
</table>
\( A_s = M_n = 500 \text{ GeV}, \ A_\kappa = -250 \text{ GeV}, \ h_s = \kappa = 0.5, \ \xi_{F,S} = -0.1 \)
(MSSM fraction $\xi_{\text{MSSM}}^{H_i} = \sum_{j=d}^{u} (R_{ij}^2)$)
Higgs Mass (GeV)

CP-Even Higgs Mass Range

MSSM
NMSSM
n/sMSSM
UMSSM

LEP & $\alpha_{ZZ}$

Th.

0
50
100
150
200
Higgs Mass (GeV)

0
CP-Odd Higgs Mass Range

MSSM
NMSSM
n/sMSSM
UMSSM

LEP & $\alpha_{ZZ}$

0
50
100
150
200
Higgs Mass (GeV)

0

Charged Higgs Mass Range

MSSM
NMSSM
n/sMSSM
UMSSM

LEP

0
50
100
150
200
Higgs Mass (GeV)

0

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Lightest Higgs Decays

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Invisible Decays

(a)

(b)

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$H_{1,2} \rightarrow A_1 A_1$

![Graph showing $M_{H_i}$ vs $M_{A_i}$](image_a)

![Branching Fraction vs Higgs Mass](image_b)
Higgs boson masses

As the Higgs boson mass increases, the total width decreases significantly. Therefore, in the n/sMSSM and NMSSM, the Higgs boson masses can be lower than in the SM.
Lightest Neutralino

Mass matrix \((M_{\chi^0})\) in basis \(\{\tilde{B}, \tilde{W}_3, \tilde{H}^0_1, \tilde{H}^0_2, \tilde{S}, \tilde{Z}'\}\):

\[
\begin{pmatrix}
M_1 & 0 & -g_1v_1/2 & g_1v_2/2 & 0 & 0 \\
0 & M_2 & g_2v_1/2 & -g_2v_2/2 & 0 & 0 \\
-g_1v_1/2 & g_2v_1/2 & 0 & -\mu_{eff} & -\mu_{eff}v_2/s & g_{Z'}Q'_{H_1}v_1 \\
g_1v_2/2 & -g_2v_2/2 & -\mu_{eff} & 0 & -\mu_{eff}v_1/s & g_{Z'}Q'_{H_2}v_2 \\
0 & 0 & -\mu_{eff}v_2/s & -\mu_{eff}v_1/s & \sqrt{2}\kappa s & g_{Z'}Q'_S s \\
0 & 0 & g_{Z'}Q'_{H_1}v_1 & g_{Z'}Q'_{H_2}v_2 & g_{Z'}Q'_S s & M_1' \\
\end{pmatrix}
\]

\((\langle S \rangle \equiv s/\sqrt{2}, \langle H^0_i \rangle \equiv \frac{v_i}{\sqrt{2}}, \sqrt{v_1^2 + v_2^2} \equiv v \simeq 246 \text{ GeV}, Q'_\phi = \phi U(1)' \text{ charge})\)

(black = MSSM; blue = extensions; cyan = NMSSM; magenta = UMSSM)
(Relic density in nMSSM from $\chi_{1}^{0}\chi_{1}^{0} \rightarrow Z$ only; may be $\chi_{1}^{0} \rightarrow$ secluded in sMSSM)
(Relic density and $g_\mu - 2$ in n/sMSSM)
• Often $\chi_2^0, \ldots, \chi_5^0$ are MSSM-like with light singlino-dominated $\chi_1^0$
• MSSM-like cascades with extra $\chi_2^0 \rightarrow \chi_1^0 + (l\bar{l}, q\bar{q}, Z, h)$
• Often $\chi_2^0 \rightarrow \chi_1^0 + (Z, h); \quad \chi_1^+ \rightarrow \chi_1^0 + (W^+, H^+)$ are open (e.g., $\chi_1^+ \chi_2^0 \rightarrow W^+ h + \not{E}_T \rightarrow l^+ b \bar{b} + \not{E}_T$)

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• Often find exotic (wrt $SU(2) \times U(1)$) quarks or leptons at TeV scale
  – Assume non-chiral wrt SM gauge group (strong constraints from precision EW, especially on extra or mirror families)
  – Can be chiral wrt extra $U(1)'s$ or other extended gauge
  – Usually needed for $U(1)'$ anomaly cancellation
  – Modify gauge unification unless in complete GUT multiplets
  – Can also be more extreme exotics (e.g., adjoints, symmetric, fractional charge, mixed quasi-hidden)
  – Experimental limits relatively weak
• Examples in 27-plet of $E_6$

- $D_L + D_R$ ($SU(2)$ singlets, chiral wrt $U(1)'$)

- \[
\left( \begin{array}{c}
E^0 \\
E^-
\end{array} \right)_L + \left( \begin{array}{c}
E^0 \\
E^-
\end{array} \right)_R
\] ($SU(2)$ doublets, chiral wrt $U(1)'$)

• Pair produce $D + \bar{D}$ by QCD processes (smaller rate for exotic leptons)

• $D$ or $\tilde{D}$ decay by

- $D \to u_i W^-, \ D \to d_i Z, \ D \to d_i H^0$ if driven by $D - d$ mixing (not in minimal $E_6$; FCNC) $\to m_D \gtrsim 200$ GeV (future: $\sim 1$ TeV)

- $\tilde{D} \to$ quark jets if driven by diquark operator $\bar{u}u\bar{D}$, or quark jet + lepton for leptoquark operator $lq\bar{D}$ (still have stable LSP)

- May be stable at renormalizable level due to accidental symmetry (e.g., from extended gauge group) $\to$ hadronizes and escapes or stops in detector (Quasi-stable from HDO $\to \tau < 1/10$ yr)
Neutrino Mass

- Nonzero mass may be first break with standard model

- Enormous theoretical effort: GUT, family symmetries, bottom up
  - Majorana masses may be favored because not forbidden by SM gauge symmetries
  - GUT (+ family symmetry) seesaw (heavy Majorana singlet). Usually ordinary hierarchy.
• Very little work from string constructions, even though may be Planck scale effect (Witten; Coriano, Faraggi, Thormeier; Ellis, Leontaris, Lola, Nanopoulos; Ibanez, Marchesano, Rabadan)

• Key ingredients of most bottom up models forbidden in known constructions (heterotic or intersecting brane) (Due to string symmetries or constraints, not simplicity or elegance)

  – “Right-handed” neutrinos may not be gauge singlets
  – Large representations difficult to achieve (bifundamentals, singlets, or adjoints)
  – GUT Yukawa relations broken
  – String symmetries/constraints severely restrict couplings, e.g., Majorana masses, or simultaneous Dirac and Majorana masses
• Dirac masses

- Can achieve small Dirac masses (neutrino or other) by higher dimensional operators or by large intersection areas

\[ L_\nu \sim \left( \frac{S}{M_{Pl}} \right)^p LN^c_L H_2, \quad \langle S \rangle \ll M_{Pl} \]

\[ \Rightarrow m_D \sim \left( \frac{\langle S \rangle}{M_{Pl}} \right)^p \langle H_2 \rangle \]

- Large \( p \Rightarrow \langle S \rangle \) close to \( M_{Pl} \) (e.g., anomalous \( U(1)_A \))
- Small \( p \Rightarrow \) intermediate scale \( \ll M_{Pl} \)
- Similar HDO may give light steriles and ordinary/sterile mixing
• **Majorana masses**

  – Existing intersecting brane models: conserved $L$; no diagonal (Majorana) triangles

  – Heterotic: can one generate large effective $m_S$ from

    \[ W_\nu \sim c_{ij} \frac{S^{q+1}}{M_{Pl}^q} N_i N_j \quad \Rightarrow \quad (m_S)_{ij} \sim c_{ij} \frac{\langle S \rangle^{q+1}}{M_{Pl}^q}, \]

    consistent with $D$ and $F$ flatness?

  – Can one have such terms simultaneously with Dirac couplings, consistent with flatness and other constraints?

  – Are bottom-up model assumptions for relations to quark, charged lepton masses maintained?
• The $Z_3$ Heterotic Orbifold (Giedt, Kane, PL, Nelson, hep-th/0502032)
  - Systematically studied large class of vacua
    * Is minimal seesaw common?
    * If rare, possibly guidance to model building
    * Clues to textures, etc.
  - Several models from each of 20 patterns; superpotential through degree 9; huge number of $D$ flat directions reduced greatly by $F$-flatness
  - Only two patterns had Majorana mass operators
    \[ \langle S_1 \cdots S_{n-2} \rangle_{NN/M_{PL}^{n-3}} \]
  - None had simultaneous Dirac operators
    \[ \langle S'_1 \cdots S'_{d-3} \rangle_{NLH_u/M_{PL}^{d-3}} \]
    leading to $\Delta m^2 > 10^{-10}$ eV$^2$ (one apparent model ruined by off-diagonal Majorana)
– Feature of $Z_3$ orbifold? Or more general?
– Systematic searches in other constructions important (Is seesaw generic? Rare? Alternatives?)
– Alternatives:
  * Small Dirac? (by HDO (common in constructions) or LED)
  * Extended seesaw? $m_\nu \sim m_D^{2+k}/M^{1+k}$, with $k \geq 1$ (TeV scale physics?)
  * Loops, $R_P$ breaking? (TeV physics)
  * Higgs triplet? (higher Kač-Moody or intersecting brane)
    - Inverted hierarchy with bimaximal mixing
    - Solar mixing non-maximal $\rightarrow$ small (Cabibbo-like) charged lepton mixing
    - $U_{e3}$ close to Chooz limit
Conclusions

• Combination of theoretical ideas and new experimental facilities may allow testable theory to Planck scale

• From the bottom up: there may be more at TeV scale than (minimal SUGRA) MSSM (e.g., $Z'$, extended Higgs/neutralino, quasi-chiral exotics)

• From the top down: there may be more at TeV scale than (minimal SUGRA) MSSM

• Dynamical $\mu$ term leads to very rich Higgs/neutralino physics at colliders and for cosmology

• Consider alternatives to the minimal seesaw
The $\mu$ problem

Superpotential: $W = \mu \hat{H}_u \hat{H}_d + h_t \hat{Q} \hat{H}_u \hat{d}^c \Rightarrow$

$\begin{align*}
L_{\text{fermion}} &= \mu \hat{H}_u \hat{H}_d + h_t (\hat{Q} \hat{H}_u \hat{d}^c + \hat{Q} \hat{H}_u \hat{d}^c + \hat{Q} \hat{H}_u \hat{d}^c ) \\
&\text{Higgsino mass} \quad \text{top Yukawa} \quad \text{Higgsino--quark--squark}
\end{align*}$

$-L^W_{\text{scalar}} = \sum_\phi \left| \frac{\delta W}{\delta \phi} \right|^2 = \mu^2 (|H_u|^2 + |H_d|^2) + h_t \text{ terms}$

$Higgs \ masses$

$-L^D = \frac{g^2 + g'^2}{8} (|H_u|^2 - |H_d|^2)^2 + \text{charged Higgs, squark, slepton}$

$-L^{\text{soft}} = m_u^2 |H_u|^2 + m_d^2 |H_d|^2 + (m_3^2 H_u H_d + \text{h.c.})$

$+ \text{squark/slepton} + M_3 \tilde{g} \tilde{g} \quad M_2 \tilde{w} \tilde{w} \quad M_1 \tilde{b} \tilde{b}$

Higgs masses
• Soft terms set EW scale, e.g., \( m_{\text{soft}} \sim F^2/M_{\text{pl}}, \ F \sim 10^{11} \ \text{GeV}, \ M_{\text{pl}} \sim 10^{19} \ \text{GeV} \)

• \( \mu \) problem: \( \mu \) is supersymmetric \( \Rightarrow \) could be very large (or exactly zero in string theory), but need \( \mu \sim m_{\text{soft}} \lesssim 1 \ \text{TeV} \)

• Two classes of solutions
  
  – Generate \( \mu \) in hidden sector along with \( m_{\text{soft}} \)
  
  – Dynamical: \( \mu \equiv 0 \) by symmetry or string, but

\[
W = h_s \underbrace{\hat{S}}_{\text{SM singlet}} \hat{H}_u \hat{H}_d \Rightarrow \mu_{\text{eff}} = h_s \langle S \rangle, \quad \langle S \rangle \sim m_{\text{soft}}
\]

(Examples: \( Z' \) models, NMSSM, nMSSM)
By the strict $\alpha_{ZZ'}$ limit. This is also seen in Fig 6, where we plot the Higgs masses versus the singlet VEV.
We show this dependence in Fig. 7 for the all Higgs bosons of each...
\[ \frac{1}{2} \xi S \sqrt{2} M \mathcal{N} \mathcal{S} \mathcal{S}, \ (64) \]

which forces the parameter \( \xi S \) to be negative in this limit. Therefore, a largely singlet

\[ \text{n/sMSSM, } M_n = 500 \text{ GeV} \]

is valid.

\[ \mu_{S} \]

\[ H^\pm \]
Higgs masses also scale with increasing \( s \) for most of the models in this parameter range. However, the corresponding...
All models, PQ limit

\[ \tan \beta = 2 \]

\[ s = 500 \text{ GeV} \]

The Higgs masses also scale with increasing \( s \) for most of the models in this parameter range. However, the corresponding...
Higgs Mass (GeV)
0.0001
0.001
0.01
0.1
1
Branching Fraction
SM
H1 MSSM
H1 NMSSM
H1 ... ∗ and ZZ∗ can be larger than
the corresponding SM branching fractions, as seen in Fig 10. These enhancements are due
• Often \( \chi_2^0 \rightarrow \chi_1^0 + (Z, h) \); \( \chi_1^+ \rightarrow \chi_1^0 + (W^+, H^+) \) open w. fairly light \( \chi_1^+ \), \( \chi_2^0 \) (e.g., \( \chi_1^+ \chi_2^0 \rightarrow W^+ h + E_T \rightarrow l^+ b \bar{b} + E_T \), or \( \chi_1^+ \chi_2^0 \rightarrow W^+ Z + E_T \rightarrow l^+ l' \bar{l}' + E_T \))

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