Beyond the Standard Paradigm

- The standard paradigm or a landscape?
- Heavy $Z'$
- Extended Higgs
- Neutralinos
- Quasi-chiral exotics
References


The standard paradigm

- MSSM at TeV scale
- LSP WIMPs
- (Possibly) GUT at unification scale
  - Gauge unification
- Seesaw model for $m_\nu$
  - Leptogenesis
  - (Possibly) GUT relations for couplings (large representations?)
- SUSY breaking in hidden sector
Beyond the MSSM

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

Most of the problems of standard model remain, new ones introduced (FCNC, EDM)

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

Ingredients of 4d GUTs hard to embed in string, especially large Higgs representations, Yukawa relations

Remnants of GUT/Planck scale physics may survive to TeV scale

Specific string constructions often have extended gauge groups, exotics, extended Higgs/neutralino sectors (Defect or hint?)

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
- Non-standard $\nu$ mass (enhanced symmetries)
- Quasi-hidden (Strong coupling? SUSY breaking? Composite family?)
- Charge $1/2$ (Confinement?, Stable relic?)
- Time varying couplings
- LED (TeV black holes, stringy resonances)
- LIV, VEP (speeds, decays, (oscillations) of HE $\gamma$, $e$, gravity waves ($\nu$'s))
A TeV-Scale $Z'$

- 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, $(pp \to \mu^+\mu^-, e^+e^-, q\bar{q})$ (depends on couplings, exotics, sparticles)

- Diagnostics to 1-2 TeV (asymmetries, $y$ distributions, associated production, rare decays)
Implications of a TeV-scale $U(1)'$

- **Natural Solution to $\mu$ problem**
  \[ W \sim h S H_u H_d \rightarrow \mu_{\text{eff}} = h \langle S \rangle \]
  ("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

* Constraints on neutrino mass generation

* $Z'$ decays into sparticles/exotics

* 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 $\tan \beta$)
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 $\rightarrow$ FCNC (suppressed by Yukawas)
  - Significantly modify gauge unification (unless compensated)
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, sMSSM)

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

- 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 \( \mu \)


- 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

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### Models with Dynamical $\mu$

<table>
<thead>
<tr>
<th>Model</th>
<th>Symmetry</th>
<th>Superpotential</th>
<th>CP-even</th>
<th>CP-odd</th>
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<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>$Z_3^R, Z_7^R$</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>$U(1)'$</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>$h_s \hat{S} \hat{H}_u \cdot \hat{H}_d + \lambda_s \hat{S}_1 \hat{S}_2 \hat{S}_3$</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>
<tr>
<td>sMSSM</td>
<td>–</td>
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</table>

- **MSSM**: gaugino unification but general $\mu$
- **NMSSM** ("cubic"): may be domain wall problems ($Z_2^R$)
- **nMSSM** ("tadpole"): no domain walls; tadpoles from high order
- **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)
\[ V_F = |h_s H_u \cdot H_d + \xi_F M^2_n + \kappa S^2|^2 + |h_s S|^2 \left( |H_d|^2 + |H_u|^2 \right) \]

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

\[ + \frac{g_1'^2}{2} \left( Q_{H_d} |H_d|^2 + Q_{H_u} |H_u|^2 + Q_S |S|^2 \right)^2 \]

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

\[ + \left( A_s h_s S H_u \cdot H_d + \frac{\kappa}{3} A_\kappa S^3 + \xi_S M^3_n S + \text{h.c.} \right) \]

black = MSSM (with \( \mu = h_s \langle S \rangle \)); blue= extensions;

cyan = NMSSM; magenta = UMSSM; red= n/sMSSM
Mass matrices in \{H_d, H_u, S\} basis

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

\[
(M^0_+)^{dd} = \left[ \frac{G^2}{4} + Q_{H_d}^2 g_1' \right] v_d^2 + \left( \frac{h_s A_s}{\sqrt{2}} + \frac{h_s \kappa s}{2} + \frac{h_s \xi_F M^2_n}{s} \right) \frac{v_{us}}{v_d}
\]

\[
(M^0_+)^{du} = \left[ -\frac{G^2}{4} + h_s^2 + Q_{H_d} Q_{H_u} g_1^2 \right] v_d v_u - \left( \frac{h_s A_s}{\sqrt{2}} + \frac{h_s \kappa s}{2} + \frac{h_s \xi_F M^2_n}{s} \right) s
\]

\[
(M^0_+)^{ds} = \left[ h_s^2 + Q_{H_d} Q_{S} g_1^2 \right] v_d s - \left( \frac{h_s A_s}{\sqrt{2}} + h_s \kappa s \right) v_u
\]

\[
(M^0_+)^{uu} = \left[ \frac{G^2}{4} + Q_{H_u}^2 g_1' \right] v_u^2 + \left( \frac{h_s A_s}{\sqrt{2}} + \frac{h_s \kappa s}{2} + \frac{h_s \xi_F M^2_n}{s} \right) \frac{v_{ds}}{v_u}
\]

\[
(M^0_+)^{us} = \left[ h_s^2 + Q_{H_u} Q_{S} g_1^2 \right] v_u s - \left( \frac{h_s A_s}{\sqrt{2}} + h_s \kappa s \right) v_d
\]

\[
(M^0_+)^{ss} = \left[ Q_S^2 g_1^2 + 2 \kappa^2 \right] s^2 + \left( \frac{h_s A_s}{\sqrt{2}} - \frac{\sqrt{2} \xi_S M^3_n}{v_d v_u} \right) \frac{v_d v_u}{s} + \frac{\kappa A_{\kappa}}{\sqrt{2}} s
\]
• Also CP-odd and charged Higgs (CP breaking ignored)

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

• Theoretical upper limits on $H_1^0$ relaxed ($\rightarrow$ smaller $\tan \beta$ allowed)
  - MSSM
    $$M_{H_1^0}^2 \leq M_Z^2 \cos^2 2\beta + \tilde{\mathcal{M}}^{(1)}$$
    $$\tilde{\mathcal{M}}^{(1)} = (\mathcal{M}_{++}^{(1)})_{dd} \cos^2 \beta + (\mathcal{M}_{++}^{(1)})_{uu} \sin^2 \beta + (\mathcal{M}_{++}^{(1)})_{du} \sin 2\beta$$
  - NMSSM, n/sMSSM, and Peccei-Quinn limits
    $$M_{H_1^0}^2 \leq M_Z^2 \cos^2 2\beta + \frac{1}{2} h_s^2 v^2 \sin^2 2\beta + \tilde{\mathcal{M}}^{(1)}$$
  - UMSSM
    $$M_{H_1^0}^2 \leq M_Z^2 \cos^2 2\beta + \frac{1}{2} h_s^2 v^2 \sin^2 2\beta + g_Z^2 v^2 (Q_{H_d} \cos^2 \beta + Q_{H_u} \sin^2 \beta)^2 + \tilde{\mathcal{M}}^{(1)}$$
• Experimental LEP SM and MSSM bounds may be relaxed by singlet-doublet mixing (also by nonstandard decays)

- Reduced \( Z \bar{Z} H_i \) coupling

\[ \xi_{Z \bar{Z} H_i} = (R_+^{i1} \cos \beta + R_+^{i2} \sin \beta)^2 \]

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

- **MSSM limit** \((s \to \infty \text{ with } \mu_{\text{eff}} = h_s s / \sqrt{2} \text{ fixed})\) \(\to\) 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>
<thead>
<tr>
<th>Model</th>
<th>Limits</th>
<th>Symmetry</th>
<th>Effects</th>
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<tr>
<td>MSSM</td>
<td>(B \to 0)</td>
<td>(U(1)_{\text{PQ}})</td>
<td>(M_{A_1} \to 0)</td>
</tr>
<tr>
<td>NMSSM</td>
<td>(\kappa, A_\kappa \to 0)</td>
<td>(U(1)_{\text{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)_{\text{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>
\[ A_s = M_n = 500 \text{ GeV}, \ A_\kappa = -250 \text{ GeV}, \ h_s = \kappa = 0.5, \ \xi_{F,S} = -0.1 \]
The MSSM fraction \( \xi_{\text{MSSM}} \) is given by

\[
\xi_{\text{MSSM}}^{H_i} = \sum_{j=d}^{u} (R_{ij}^+)^2
\]
Production and decay rates modified. Standard Model modes ($5\sigma$), vs invisible decays, $H \to \chi^0 \chi^0$ (or $AA$), via WBF ($\xi^2 \gtrsim 0.25$).
Mass matrix \((M_{\chi^0})\) in basis \(\{\tilde{B}, \tilde{W}_3, \tilde{H}_1^0, \tilde{H}_2^0, \tilde{S}, \tilde{Z}'\}\):

\[
\begin{pmatrix}
M_1 & 0 & -g_1 v_1/2 & g_1 v_2/2 & 0 & 0 \\
0 & M_2 & g_2 v_1/2 & -g_2 v_2/2 & 0 & 0 \\
-g_1 v_1/2 & g_2 v_1/2 & 0 & -\mu_{\text{eff}} & -\mu_{\text{eff}} v_2/s & g_{Z'} Q'_{H_1} v_1 \\
g_1 v_2/2 & -g_2 v_2/2 & -\mu_{\text{eff}} & 0 & -\mu_{\text{eff}} v_1/s & g_{Z'} Q'_{H_2} v_2 \\
0 & 0 & -\mu_{\text{eff}} v_2/s & -\mu_{\text{eff}} v_1/s & \sqrt{2} \kappa s & g_{Z'} Q'_{S} s \\
0 & 0 & g_{Z'} Q'_{H_1} v_1 & g_{Z'} Q'_{H_2} v_2 & g_{Z'} Q'_{S} s & M_{1'}
\end{pmatrix}
\]

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

\(\text{(black = MSSM; blue = extensions; cyan = NMSSM; magenta = UMSSM)}\)

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(nearly) decoupled singlino

strongly mixed singlino

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singlino and gaugino fractions of $\chi_{1,2}$
branching fractions of $\chi_2 \rightarrow (Z, H_1) \chi_1$
Extended cascade diagrams for 3, 5, or 7 charged leptons
Decays into 3, 5, or 7 charged leptons

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Relic densities (heavy squarks and sleptons)
Spin independent detection cross sections

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Quasi-Chiral Exotics

(J. Kang, PL, B. Nelson, in progress)

- 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 $U(1)'$)
- $\begin{pmatrix} E^0 \\ E^- \end{pmatrix}_L + \begin{pmatrix} E^0 \\ E^- \end{pmatrix}_R$ ($SU(2)$ doublets, chiral wrt $U(1)'$)

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

$D$ or $\tilde{D}$ decay by

- $D \rightarrow u_i W^-, D \rightarrow d_i Z, D \rightarrow d_i H^0$ if driven by $D - d$ mixing (not in minimal $E_6$; FCNC) $\rightarrow m_D > 200$ GeV (future: $\sim 1$ TeV)
- $\tilde{D} \rightarrow$ 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) $\rightarrow$ hadronizes and escapes or stops in detector (Quasi-stable from HDO $\rightarrow \tau < 1/10$ yr)
Scalar and Fermion Mass Splittings

\[ \Delta_i \equiv m_{D1/2} - m_{D0}^{i} \quad \text{for} \quad M_D = m_{D1/2} = 300 \text{ GeV} \]
\[ \Delta_i \equiv m_{D_{1/2}} - m_{D_0^i} \quad \text{for} \quad M_{D_0} = 400 \text{ GeV} \]
Leptoquark and Diquark Couplings

- Consider single family of exotic $D + D^c$ and SM singlet $S$:

$$ W = h_s S H_u H_d + h_D S D D^c + \underbrace{W_{LQ} + W_{DQ}}_{\mu_{eff} = h_s \langle S \rangle \quad M_D = h_D \langle S \rangle \quad \text{only one (proton decay)}} $$

$$ W_{LQ} = \lambda_6 D u^c e^c + \lambda_7 D^c Q L \quad W_{DQ} = \lambda_9 D Q Q + \lambda_{10} D^c u^c d^c $$

- SINDRUM II: 

$$ \frac{\sigma(\mu^- T_i \rightarrow e^- T_i)}{\sigma(\mu^- T_i \rightarrow \text{capture})} < 4.3 \times 10^{-13} $$

$$ \Rightarrow |\lambda_{6,7}| < 3 \times 10^{-4} \left( \frac{m_{D^0}}{100 \ \text{GeV}} \right) $$

- $K_L - K_S$ mass difference: 

$$ \lambda_{9,10} < 0.04 \left( \frac{\max(m_{\tilde{u}_i}, m_{D^0})}{100 \ \text{GeV}} \right)^{1/2} $$

- Still have unbroken $R_p$, stable LSP
Production Cross Sections

\[ q + \bar{q} \rightarrow D_{1/2}^{LQ} + \bar{D}_{1/2}^{LQ}, \ D_{1/2}^{DQ} + \bar{D}_{1/2}^{DQ} \]
\[ g + g \rightarrow D_{1/2}^{LQ} + \bar{D}_{1/2}^{LQ}, \ D_{1/2}^{DQ} + \bar{D}_{1/2}^{DQ} \]
\[ q + \bar{q} \rightarrow (D_0^{LQ})_i + (\bar{D}_0^{LQ})_j, \ (D_0^{DQ})_i + (\bar{D}_0^{DQ})_j \]
\[ g + g \rightarrow (D_0^{LQ})_i + (\bar{D}_0^{LQ})_j, \ (D_0^{DQ})_i + (\bar{D}_0^{DQ})_j \]
\[ q + g \rightarrow (D_0^{LQ})_i + e^- \text{ or } \nu_e \]
\[ \bar{q} + g \rightarrow (D_0^{DQ})_i + \bar{q} \]
\[ \bar{u} + \bar{d} \rightarrow (D_0^{DQ})_i \text{ (resonant production)} \]
Decays

- **Mixing** (e.g., if $\tilde{\nu}$ or $\tilde{\nu}^c$ have vev)

  $$D_{1/2} \rightarrow dZ, \; dh, \; uW^-$$

- **No mixing: diquark induced (or leptoquark analog)**

  $$D_0 \rightarrow q^c q^c, \; \underbrace{D_{1/2}\chi^0, \; D_{1/2}\tilde{g}}_{\text{if allowed}}$$

  $$D_{1/2} \rightarrow D_0\chi^0, \; D_0\tilde{g}, \; \tilde{q}^c q^c \; (\text{if allowed})$$

  $$D_{1/2} \rightarrow (D_0^*\chi^0, \; \tilde{q}^c q^c) \rightarrow u^c d^c \chi^0 \; (\text{otherwise})$$
- **Quasi-stable** (e.g., $U(1)_N$ model)

\[ W = \frac{1}{M_*} (D^c Q H d S, \; D^c Q Q u^c, \; D^c Q L \nu^c) \]

\[ D_{1/2} \to dZ, \; dh, \; uW^-, \; dhs, \; q\bar{q}\bar{q}, \; q\bar{\ell}\bar{\ell}, \; \ell\bar{q}\bar{\ell} \]

- **Strong** (but model dependent) constraints from nucleosynthesis
  (e.g., $n \leftrightarrow p$ affects $^4He$)

- **LHC**: hadron and muon calorimeters; delayed decays
$W = \frac{1}{M^*} (D^c Q H_d S, \ D^c Q Q u^c, \ D^c Q L \nu^c)$ (one family)

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